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Author/s:

Aad, G;Abbott, B;Abbott, DC;Abud, AA;Abeling, K;Abhayasinghe, DK;Abidi, SH;AbouZeid, OS;Abraham, NL;Abramowicz, H;Abreu, H;Abulaiti, Y;Acharya, BS;Achkar, B;Adam, L;Bourdarios, CA;Adamczyk, L;Adamek, L;Adelman, J;Adersberger, M;Adiguzel, A;Adorni, S;Adye, T;Affolder, AA;Afik, Y;Agapopoulou, C;Agaras, MN;Aggarwal, A;Agheorghiesei, C;Aguilar-Saavedra, JA;Ahmad, A;Ahmadov, F;Ahmed, WS;Ai, X;Aielli, G;Akatsuka, S;Akesson, TPA;Akilli, E;Akimov, A;Al Khoury, K;Alberghi, GL;Albert, J;Verzini, MJA;Alderweireldt, S;Aleksa, M;Aleksandrov, IN;Alexa, C;Alexopoulos, T;Alfonsi, A;Alfonsi, F;Alhroob, M;Ali, B;Ali, S;Aliev, M;Alimonti, G;Allaire, C;Allbrooke, BMM;Allen, BW;Allport, PP;Aloisio, A;Alonso, F;Alpigiani, C;Alshehri, AA;Camelia, EA;Alvarez Estevez, M;Alviggi, MG;Amaral Coutinho, Y;Ambler, A;Ambroz, L;Amelung, C;Amidei, D;Amor Dos Santos, SP;Amoroso, S;Amrouche, CS;An, F;Anastopoulos, C;Andari, N;Andeen, T;Anders, CF;Anders, JK;Andrean, SY;Andreazza, A;Andrei, V;Anelli, CR;Angelidakis, S;Angerami, A;Anisenkov, A;Annovi, A;Antel, C;Anthony, MT;Antipov, E;Antonelli, M;Antrim, DJA;Anulli, F;Aoki, M;Aparisi Pozo, JA;Aparo, MA;Aperio Bella, L;Araujo Ferraz, V;Araujo Pereira, R;Arcangeletti, C;Arce, ATH;Arduh, FA;Arguin, J-F;Argyropoulos, S;Arling, J-H;Armbruster, AJ;Armstrong, A;Arnaez, O;Arnold, H;Tame, ZPA;Artoni, G;Artz, S;Asai, S;Asawatavonvanich, T;Asbah, N;Asimakopoulou, EM;Asquith, L;Assahsah, J;Assamagan, K;Astalos, R;Atkin, RJ;Atkinson, M;Atlay, NB;Atmani, H;Augsten, K;Avolio, G;Ayoub, MK;Azuelos, G;Bachacou, H;Bachas, K;Backes, M;Backman, F;Bagnaia, P;Bahmani, M;Bahrasemani, H;Bailey, AJ;Bailey, VR;Baines, JT;Bakalis, C;Baker, OK;Bakker, PJ;Gupta, DB;Balaji, S;Baldin, EM;Balek, P;Balli, F;Balunas, WK;Balz, J;Banas, E;Bandieramonte, M;Bandyopadhyay, A;Banerjee, S;Barak, L;Barbe, WM;Barberio, EL;Barberis, D;Barbero, M;Barbour, G;Barillari, T;Barisits, M-S;Barkeloo, J;Barklow, T;Barnea, R;Barnett, BM;Barnett, RM;Barnovska-Blenessy, Z;Baroncelli, A;Barone, G;Barr, AJ;Barranco Navarro, L;Barreiro, F;Guimaraes da Costa, JB;Barron, U;Barsov, S;Bartels, F;Bartoldus, R;Bartolini, G;Barton, AE;Bartos, P;Basalaev, A;Basan, A;Bassalat, A;Basso, MJ;Bates, RL;Batlamous, S;Batley, JR;Batool, B;Battaglia, M;Bauce, M;Bauer, F;Bauer, KT;Bawa, HS;Beacham, JB;Beau, T;Beauchemin, PH;Becherer, F;Bechtel, P;Beck, HC;Beck, HP;Becker, K;Becot, C;Beddall, A;Beddall, AJ;Bednyakov, VA;Bedognetti, M;Beermann, TA;Begalli, M;Begel, M;Behera, A;Behr, JK;Beisiegel, F;Belfkir, M;Bell, AS;Bella, G;Bellagamba, L;Bellerive, A;Bellos, P;Beloborodov, K;Belotskiy, K;Belyaev, NL;Bencheekroun, D;Benekos, N;Benhammou, Y;Benjamin, DP;Benoit, M;Bensinger, JR;Bentvelsen, S;Beresford, L;Beretta, M;Berge, D;Kuutmann, EB;Berger, N;Bergmann, B;Bergsten, LJ;Beringer, J;Berlendis, S;Bernardi, G;Bernius, C;Bernlochner, FU;Berry, T;Berta, P;Bertella, C;Berthold, A;Bertram, IA;Bylund, OB;Besson, N;Bethani, A;Bethke, S;Betti, A;Bevan, AJ;Beyer, J;Bhattacharya, DS;Bhattarai, P;Bi, R;Bianchi, RM;Biebel, O;Biedermann, D;Bielski, R;Bierwagen, K;Biesuz, N;Biglietti, M;Billoud, TR;Bindi,

M;Bingul, A;Bini, C;Biondi, S;Birman, M;Bisanz, T;Biswal, JP;Biswas, D;Bitadze, A;Bittrich, C;Bjorke, K;Blazek, T;Bloch, I;Blocker, C;Blue, A;Blumenschein, U;Bobbink, GJ;Bobrovnikov, VS;Bocchetta, SS;Bocci, A;Boerner, D;Bogavac, D;Bogdanchikov, AG;Bohm, C;Boisvert, V;Bokan, P;Bold, T;Bolz, AE;Bomben, M;Bona, M;Bonilla, JS;Boonekamp, M;Booth, CD;Borecka-Bielska, HM;Borgna, LS;Borisov, A;Borissov, G;Bortfeldt, J;Bortoletto, D;Boscherini, D;Bosman, M;Sola, JDB;Bouaouda, K;Boudreau, J;Bouhova-Thacker, E;Boumediene, D;Boutle, SK;Boveia, A;Boyd, J;Boye, D;Boyko, IR;Bozson, AJ;Bracinik, J;Brahimi, N;Brandt, G;Brandt, O;Braren, F;Brau, B;Brau, JE;Madden, WDB;Brendlinger, K;Brenner, L;Brenner, R;Bressler, S;Brickwedde, B;Briglin, DL;Britton, D;Britzger, D;Brock, I;Brock, R;Brooijmans, G;Brooks, WK;Brost, E;de Renstrom, PAB;Bruncko, D;Bruni, A;Bruni, G;Bruni, LS;Bruno, S;Bruschi, M;Bruscino, N;Bryngemark, L;Buanes, T;Buat, Q;Buchholz, P;Buckley, AG;Budagov, IA;Bugge, MK;Buehrer, F;Bulekov, O;Bullard, BA;Burch, TJ;Burdin, S;Burgard, CD;Burger, AM;Burghgrave, B;Burr, JTP;Burton, CD;Burzynski, JC;Buescher, V;Buschmann, E;Bussey, PJ;Butler, JM;Buttar, CM;Butterworth, JM;Butti, P;Buttinger, W;Vazquez, CJB;Buzatu, A;Buzykaev, AR;Cabras, G;Cabrera Urban, S;Caforio, D;Cai, H;Cairo, VMM;Cakir, O;Calace, N;Calafiura, P;Calderini, G;Calfayan, P;Callea, G;Caloba, LP;Caltabiano, A;Calvente Lopez, S;Calvet, D;Calvet, S;Calvet, TP;Calvetti, M;Toro, RC;Camarda, S;Camarero Munoz, D;Camarri, P;Camerlingo, MT;Cameron, D;Camincher, C;Campana, S;Campanelli, M;Camplani, A;Campoverde, A;Canale, V;Canesse, A;Bret, MC;Cantero, J;Cao, T;Cao, Y;Garrido, MDMC;Capua, M;Cardarelli, R;Cardillo, F;Carducci, G;Carli, I;Carli, T;Carlino, G;Carlson, BT;Carlson, EM;Carminati, L;Carney, RMD;Caron, S;Carquin, E;Carra, S;Carter, JWS;Carter, TM;Casado, MP;Casha, AF;Castillo, FL;Castillo Garcia, L;Castillo Gimenez, V;Castro, NF;Catinaccio, A;Catmore, JR;Cattai, A;Cavaliere, V;Cavallaro, E;Cavasinni, V;Celebi, E;Celli, F;Cerdeja Alberich, L;Cerny, K;Cerqueira, AS;Cerri, A;Cerrito, L;Cerutti, F;Cervelli, A;Cetin, SA;Chadi, Z;Chakraborty, D;Chan, J;Chan, WS;Chan, WY;Chapman, JD;Chargeishvili, B;Charlton, DG;Charman, TP;Chau, CC;Che, S;Chekanov, S;Chekulaev, S;Chelkov, GA;Chen, B;Chen, C;Chen, CH;Chen, H;Chen, J;Chen, S;Chen, SJ;Chen, X;Chen, Y;Chen, Y-H;Cheng, HC;Cheng, HJ;Cheplakov, A;Cheremushkina, E;El Moursli, RC;Cheu, E;Cheung, K;Chevalerias, TJA;Chevalier, L;Chiarella, V;Chiarelli, G;Chiodini, G;Chisholm, AS;Chitan, A;Chiu, I;Chiu, YH;Chizhov, M;Choi, K;Chomont, AR;Chouridou, S;Chow, YS;Christopher, LD;Chu, MC;Chu, X;Chudoba, J;Chwastowski, JJ;Chytka, L;Cieri, D;Ciesla, KM;Cinca, D;Cindro, V;Cioara, IA;Ciocio, A;Ciotto, F;Citron, ZH;Citterio, M;Ciubotaru, DA;Ciungu, BM;Clark, A;Clark, MR;Clark, PJ;Clawson, SE;Clement, C;Coadou, Y;Cobal, M;Coccaro, A;Cochran, J;Lopes De Sa, RC;Cohen, H;Coimbra, AEC;Cole, B;Colijn, AP;Collot, J;Conde Muino, P;Connell, SH;Connelly, IA;Constantinescu, S;Conventi, F;Cooper-Sarkar, KAM;Cormier, F;Cormier, KJR;Corpe, LD;Corradi, M;Corrigan, EE;Corriveau, F;Costa, MJ;Costanza, F;Costanzo, D;Cowan, G;Cowley, JW;Crane, J;Cranmer, K;Crawley, SJ;Creager, RA;Crepe-Renaudin, S;Crescioli, F;Cristinziani, M;Croft, V;Crosetti, G;Cueto, A;Donszelmann, TC;Cukierman, AR;Cunningham, WR;Czekierda, S;Czodrowski, P;Czurylo, MM;De Sousa, MJDCS;Pinto, JVDF;Da Via, C;Dabrowski, W;Dachs, F;Dado, T;Dahbi, S;Dallapiccola, C;Dam, M;D'Amico, V;Damp, J;Dandoy, JR;Daneri, MF;Dann, NS;Danninger, M;Darbo, G;Dartsi, O;Dattagupta, A;Daubney, T;D'Auria, S;David, C;Davidek, T;Davis, DR;Dawson, I;De, K;De Asmundis, R;De Beurs, M;De Castro, S;De Cecco, S;De Groot, N;de Jong, P;De la Torre, H;De Maria, A;De Pedis, D;De Salvo, A;De Sanctis, U;De Santis, M;De Santo, A;De Regie, JBDV;Debenedetti, C;Dedovich, D;Deiana, AM;Del Peso, J;Diaz, YD;Delgove, D;Deliot, F;Delitzsch, CM;Della Pietra, M;Della Volpe, D;Dell'Acqua, A;Dell'Asta, L;Delmastro, M;Delporte, C;Delsart, PA;DeMarco, DA;Demers, S;Demichev, M;Demontigny, G;Denisov, SP;D'Eramo, L;Derendarz, D;Derkaoui,

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Title:

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Combination of the W boson polarization measurements in top quark decays using ATLAS and CMS data at $\sqrt{s} = 8$ TeV



The ATLAS and CMS collaborations

E-mail: atlas.publications@cern.ch,
cms-publication-committee-chair@cern.ch

ABSTRACT: The combination of measurements of the W boson polarization in top quark decays performed by the ATLAS and CMS collaborations is presented. The measurements are based on proton-proton collision data produced at the LHC at a centre-of-mass energy of 8 TeV, and corresponding to an integrated luminosity of about 20 fb^{-1} for each experiment. The measurements used events containing one lepton and having different jet multiplicities in the final state. The results are quoted as fractions of W bosons with longitudinal (F_0), left-handed (F_L), or right-handed (F_R) polarizations. The resulting combined measurements of the polarization fractions are $F_0 = 0.693 \pm 0.014$ and $F_L = 0.315 \pm 0.011$. The fraction F_R is calculated from the unitarity constraint to be $F_R = -0.008 \pm 0.007$. These results are in agreement with the standard model predictions at next-to-next-to-leading order in perturbative quantum chromodynamics and represent an improvement in precision of 25 (29)% for F_0 (F_L) with respect to the most precise single measurement. A limit on anomalous right-handed vector (V_R), and left- and right-handed tensor (g_L, g_R) tWb couplings is set while fixing all others to their standard model values. The allowed regions are $[-0.11, 0.16]$ for V_R , $[-0.08, 0.05]$ for g_L , and $[-0.04, 0.02]$ for g_R , at 95% confidence level. Limits on the corresponding Wilson coefficients are also derived.

KEYWORDS: Hadron-Hadron scattering (experiments), Top physics

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1 Introduction

The large number of top quarks produced at the CERN LHC provides an excellent laboratory for the study of their production and decay properties. Precise predictions of some of these properties are available in the standard model (SM) of particle physics, and are tested through detailed comparisons to data. Potential deviations between data and predictions could reveal important information on the existence of new physics beyond the SM. The properties of the top quark decay vertex tWb are governed by the structure of the weak interaction. In the SM, this interaction has a $V - A$ structure, where V and A refer to the vector and axial-vector components of the weak current. This structure, along with the masses of the particles involved, determines the fractions of

W bosons with longitudinal (F_0), left-handed (F_L), and right-handed (F_R) polarizations, referred to as *polarization fractions*. Theoretical calculations at next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) predict the fractions to be $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$, and $F_R = 0.0017 \pm 0.0001$ [1], assuming a top quark mass of 172.8 ± 1.3 GeV. Thus, the SM predictions can be tested in high-precision measurements of the polarization fractions, and potential new physics processes that modify the structure of the tWb vertex can be probed.

Experimentally, polarization fractions can be measured in events containing top quarks, using the kinematic properties of its decay products.

For semileptonically decaying top quarks, i.e. $t \rightarrow W(\rightarrow \ell\nu)b$ (with lepton ℓ = electron, muon, or τ), the polarization angle θ^* is defined as the angle between the direction of the charged lepton and the reversed direction of the b quark, both in the rest frame of the W boson. The distribution of the variable $\cos\theta^*$ is particularly sensitive to the polarization fractions. The differential decay rate is given by

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4} (1 - \cos^2\theta^*) F_0 + \frac{3}{8} (1 - \cos\theta^*)^2 F_L + \frac{3}{8} (1 + \cos\theta^*)^2 F_R. \quad (1.1)$$

In a similar way, θ^* can be defined for the hadronically decaying top quarks, i.e. $t \rightarrow W(\rightarrow q'\bar{q})b$, by replacing the charged lepton with the down-type quark (q'). In the measurements used in this paper, only angles from top quarks decaying semileptonically to electrons or muons are considered. Imposing a unitarity constraint between the three polarization fractions, $F_0 + F_L + F_R = 1$, results in two independent observables.

The W boson polarization fractions have been measured in proton-antiproton collisions by the CDF and D0 experiments [2] at a centre-of-mass energy of 1.96 TeV with experimental uncertainties of 10–15% in F_0 and F_L . The ATLAS and CMS collaborations have performed measurements at the LHC in proton-proton (pp) collisions at $\sqrt{s} = 7$ [3, 4] and 8 [5–7] TeV, reaching a precision in F_0 and F_L of 3–5%. All measurements are in agreement with the SM NNLO predictions within their experimental uncertainties. However, these experimental uncertainties are larger than those of the current theoretical predictions, which are less than 2%. Improving the experimental precision motivates the combination of the ATLAS and CMS measurements: combining measurements based on independent data sets reduces the statistical uncertainty, while the overall uncertainty can be further decreased by exploiting the differences in experimental systematic effects stemming from the use of the two detectors and different analysis methods.

This paper describes the combination of the W boson polarization fractions measured by the ATLAS and CMS collaborations based on data collected at $\sqrt{s} = 8$ TeV, in final states enhanced in top quark pair ($t\bar{t}$) [5, 6] and single top quark [7] production processes. The paper is structured as follows: the measurements included in the combination are briefly described in section 2. Section 3 lists the sources of systematic uncertainty considered in the input measurements. The correlations between the measured values included in this combination are categorized in section 4, and presented for each source of systematic uncertainty. In section 5, the results of the combination and their interpretation in terms of new physics using the effective field theory approach are described. A summary and conclusions are presented in section 6.

2 The ATLAS and CMS measurements

Three measurements of the W boson polarization in the top quark decay from top quark pair production events in the ℓ +jets channel and one from events with a single top quark signature are the four input measurements in this combination. The measurements based on $t\bar{t}$ production events were performed by the ATLAS [5] and CMS [6] experiments, where the latter was separated in electron and muon channels. The measurement from events with a single top quark signature was performed by the CMS [7] experiment.

The measurements were based on pp collision data at $\sqrt{s} = 8$ TeV, corresponding to integrated luminosities of 20.2 and 19.7 fb $^{-1}$ for the ATLAS and CMS experiments, respectively. The 7 TeV measurements [3, 4] are not included in this combination since they are based on smaller data sets, and, having relatively large systematic uncertainties, their contribution to the combination is expected to be marginal. All measurements were based on fits where the polarization fractions were adjusted to describe the observed $\cos\theta^*$ distributions of the semileptonically decaying top quark, taking into account the SM predictions for the backgrounds. These measurements are summarized in the rest of the section. Detailed descriptions of the ATLAS and CMS detectors can be found elsewhere [8, 9].

2.1 The ATLAS measurement

The contributing input from the ATLAS experiment to this combination is described in ref. [5] and denoted “ATLAS” in the following. In this measurement, the event selection was defined to efficiently select events from top quark pair decays in the ℓ +jets channel, i.e. exactly one reconstructed electron or muon and at least four jets, of which at least two were tagged as b jets, and minimizing background contributions, e.g. from W/Z+jets and multijet productions. The latter corresponds to events including jets misidentified as leptons, or non-prompt leptons from hadron decay passing the ℓ +jets selection. The $t\bar{t}$ system was fully reconstructed via a kinematic likelihood fit technique [10], which maps the four decay quarks (two b quarks and two light quarks from the W boson decay) to four reconstructed jets, utilising Breit-Wigner distributions for the W boson and top quark masses, as well as transfer functions to map the reconstructed jet and lepton energies to the parton or true lepton level, respectively.

The W boson polarization was measured in the single-lepton channels from $t\bar{t}$ events using a template fit method. Dedicated $t\bar{t}$ templates of the $\cos\theta^*$ distribution for each polarization configuration were produced by reweighting the simulated SM $t\bar{t}$ events. Additional templates for background processes were also produced.

The templates were fit to the $\cos\theta^*$ distribution in data using different templates for the electron and muon channels, via a binned likelihood fit as:

$$\mathcal{L} = \prod_{k=1}^{n_{\text{bins}}} \frac{N_{\text{exp}}(k)^{N_{\text{data}}(k)}}{[N_{\text{data}}(k)]!} \exp[-N_{\text{exp}}(k)] \prod_{j=1}^{n_{\text{bkg}}} \frac{1}{\sqrt{2\pi}\sigma_{\text{bkg},j}} \exp\left(-\frac{(N_{\text{bkg},j} - \hat{N}_{\text{bkg},j})^2}{2\sigma_{\text{bkg},j}^2}\right), \quad (2.1)$$

where $N_{\text{data}}(k)$ and $N_{\text{exp}}(k)$ represented the number of observed and the total number of expected events (sum of signal and background events) in each bin k of the $\cos\theta^*$ distribution.

bution, respectively. The number of events for each background source j is represented by $N_{\text{bkg},j}$. The expected number of events for each background source j , $\hat{N}_{\text{bkg},j}$, and the uncertainties in the normalization of the background events, $\sigma_{\text{bkg},j}$, were used to constrain the fit. Therefore, the uncertainties in the polarization fractions obtained from the fit included both the statistical and systematic uncertainties in the background normalizations. The final result was obtained by a simultaneous fit of the electron and muon channel templates to the data. A common parameter was used to scale each of the backgrounds in the electron and muon channel in a fully correlated manner, except in the case of the nonprompt-lepton background for which two separate, uncorrelated, parameters were used. The contribution from W +jets events was split into different quark flavour samples and scaled by the calibration factors derived from sidebands in data. These procedures were found to cover the corresponding shape uncertainties in the nonprompt-lepton and W +jets contributions. The uncertainty in the shape of the contributions from single top quark and diboson events was found to be negligible.

2.2 The CMS measurements

Three CMS measurements contribute to this combination. The results presented in ref. [6] used similar final states to those in ATLAS: one lepton and four or more jets, of which at least two were tagged as b jets. The $t\bar{t}$ system was fully reconstructed using a constrained kinematic fit. The unmeasured longitudinal momentum of the neutrino was inferred by the kinematic constraints.

The measurement was performed by maximizing the binned Poisson likelihood function,

$$\mathcal{L} = \prod_{k=1}^{n_{\text{bins}}} \frac{N_{\text{exp}}(k)^{N_{\text{data}}(k)}}{[N_{\text{data}}(k)]!} \exp[-N_{\text{exp}}(k)], \quad (2.2)$$

where $N_{\text{data}}(k)$ is the number of observed events in each bin k of the reconstructed $\cos\theta^*$ distribution, and $N_{\text{exp}}(k)$ is the number of expected events from Monte Carlo (MC) simulation for a given polarization configuration $\vec{F} \equiv (F_0, F_L, F_R)$, including signal and background events. During each step of the maximization, $N_{\text{exp}}(k)$ was modified for different values of the polarization fractions $\vec{F}$ using a reweighting procedure based on eq. (1.1). Weights are applied to the events at the generated level, so that the $\cos\theta^*$ distribution generated according to eq. (1.1) corresponds to alternative values of $\vec{F}$. Backgrounds that did not involve a top quark did not change $N_{\text{exp}}(k)$ for different values of $\vec{F}$. The ATLAS and CMS measurements considered the variations on $N_{\text{exp}}(k)$ coming from all top quark events passing the selection, either ℓ +jets or non- ℓ +jets, including τ +jets and dilepton $t\bar{t}$ processes. In addition, the CMS analyses took into account the variations arising from single top quark processes, which were treated as a background in the ATLAS measurement. The normalization of the $t\bar{t}$ process was left free in the fit.

In order to allow a more detailed account of the correlations with the other measurements, the two lepton channels, e +jets and μ +jets, enter the combination as two separate measurements, referred to as “CMS (e +jets)” and “CMS (μ +jets)” throughout this paper, respectively. In the ATLAS measurement, the fractions were obtained simultaneously using the events from the two channels, therefore this separation is not available.

The third CMS input [7] included in the combination used a final state targeting t -channel single top quark topologies instead of $t\bar{t}$ events. The event selection required exactly one electron or muon, and exactly two jets, one of which was tagged as a b jet. This selection is orthogonal to that of the CMS (e+jets) and CMS (μ +jets) analyses, making the three of them statistically independent. Nevertheless, while the expected amount of selected t -channel single top quark events corresponded to only about 13% of the sample, the expected contribution from the $t\bar{t}$ process amounted to about 35%, and needed to be taken into account as part of the signal. The largest background came from the W +jets process. This contribution was fully estimated from data, and corresponded to about 36% of the selected sample. Other processes, such as multijet and Z +jets production, accounted for the remaining 16% of the sample.

The fitting procedure applied in ref. [6] was slightly modified for the single top quark topology measurement. In this case, because of the different background composition with respect to the $t\bar{t}$ analysis, the normalizations of the single top quark and $t\bar{t}$ processes were fixed according to their predicted cross section values. On the other hand, the normalization of the W +jets sample was left free in the fit to be adjusted simultaneously with the F_0 and F_L fractions, and treated independently in the e+jets and μ +jets channels. Moreover, the fractions were extracted by maximizing a combined likelihood function, constructed from the two likelihood functions of the electron and muon channels, taking into account the correlations between them. Therefore, although based on two single-lepton channels, this measurement contributes to the combination as one single input, denoted as “CMS (single top)” in the following.

2.3 The W boson polarization values from the input measurements

The polarization fractions from the input measurements before applying the modifications concerning the combination (as discussed in section 3), and their uncertainties are summarized in table 1. The first quoted uncertainty in the ATLAS measurement includes the statistical uncertainties and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic uncertainty. For CMS measurements, the first uncertainty is statistical, while the second is the total systematic uncertainty, including that on background determination.

In order to harmonize the treatment of the systematic uncertainties evaluation across the input measurements, some of them are modified before performing the combination process. The following modifications are applied (as detailed in section 3):

- The uncertainty values in the ATLAS measurement are symmetrized.
- The $t\bar{t}$ modelling uncertainties in the CMS (e+jets) and CMS (μ +jets) measurements are recalculated without the contributions from the limited number of events in the samples used to estimate them.
- The uncertainty due to the top quark mass used in the ATLAS measurement is increased from a variation of ± 0.7 GeV to ± 1.0 GeV.

Measurement	F_0	F_L	F_R
ATLAS (ℓ +jets)	$0.709 \pm 0.012 \pm 0.015$	$0.299 \pm 0.008 \pm 0.013$	$-0.008 \pm 0.006 \pm 0.012$
CMS (e+jets)	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
CMS (μ +jets)	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
CMS (single top)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

Table 1. Summary of the published ATLAS and CMS measurements for 8 TeV data. The first quoted uncertainty in the ATLAS measurement includes statistical uncertainties and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic contribution. For CMS measurements, the first uncertainty is statistical while the second is the total systematic uncertainty, including that on background determination.

3 Sources of systematic uncertainty

The effects of various systematic uncertainties on the input results were studied individually for each measurement. In the ATLAS measurement, the impact of systematic uncertainties was evaluated with alternative pseudo-data distributions built from the altered signal and background contributions. The alternative pseudo-data distributions were produced by varying each source of systematic uncertainty by one standard deviation ($\pm 1\sigma$). The CMS measurements also used pseudo-data to estimate the uncertainties due to parton distribution functions (PDFs), size of the simulated samples, and single top quark analysis specific uncertainties. The other uncertainties were estimated by replacing the nominal sample with alternative samples containing simulated events modified according to each of the systematic variations, and repeating the fit.

As the algorithm used to perform the combination accepts only symmetric uncertainties (more details in section 5), the uncertainties in the ATLAS measurement are symmetrized by assigning the average uncertainty value between the up and down variations in each uncertainty source. A test is performed by replacing the average uncertainty value with the largest shift among the up and down variations. No variation in the combination results is observed, i.e. the central values of the polarization fractions, combination uncertainty, and total correlation remain unchanged. In addition, common uncertainty categories are established by merging and regrouping various uncertainties in each individual input measurement.

In the following, the categorization of the systematic uncertainties considered for the combination is presented. The categories, assumed to be independent from each other, comprise sources of uncertainties that have similar origins, easing the treatment of correlations discussed in section 4.

3.1 Limited size of the data and simulated samples, backgrounds, and integrated luminosity

Statistical uncertainty, background determination, and integrated luminosity (stat+bkg). The uncertainties in the ATLAS measurement from the fit included both the statistical uncertainty in the data and the systematic uncertainty in the background normalizations

via priors for the background yields. The shape of the multijet processes was determined from data, while for the other background events it was fully determined from simulation. The impact of the 1.9% integrated luminosity uncertainty [11] was found to be negligible because of the background normalization treatment in the fit.

In the CMS measurements, the uncertainties in the expected backgrounds included shape and normalization effects, and were estimated by varying them separately within their uncertainties and repeating the measurement. The multijet background in all CMS measurements as well as the normalization of the W+jets contribution in the CMS (single top) case were derived exclusively from data. All other background processes, as well as $t\bar{t}$, and single top quark processes in the CMS (single top) measurement were estimated using simulation, normalized to the integrated luminosity of the data samples. These were affected by the uncertainties in their predicted cross sections, and the integrated luminosity determination. The CMS integrated luminosity uncertainty of 2.6% [12] had a sizeable effect only on the CMS (single top) measurement.

Size of simulated samples. This category accounts for the limited number of simulated events for the nominal samples in all input measurements. Both ATLAS and CMS evaluated this uncertainty by performing pseudo-experiments. In the CMS (e+jets) and CMS (μ +jets) measurements, the limited number of simulated events was also considered for the $t\bar{t}$ samples used for the estimation of the modelling uncertainties. In order to perform a consistent combination, the $t\bar{t}$ modelling uncertainties in the CMS (e+jets) and CMS (μ +jets) measurements are recalculated without the contributions from the limited number of events in the samples used to estimate them. The impact of this modification on the relative uncertainty in the measurements is found to be in the order of $O(10^{-4})$.

3.2 Detector modelling

Jets. In all input measurements in this combination, the same jet clustering algorithm, the anti- k_T algorithm [13, 14], was used, with the radius parameter R of 0.4 and 0.5 for the ATLAS and CMS experiments, respectively. However, in the ATLAS measurement the jets were built from energy deposits in the calorimeter [15], while in the CMS analyses they were reconstructed from particle-flow [16] objects. Thus, the two experiments used different calibration procedures and uncertainties for jets. The following categories comprise various sources of uncertainty related to the reconstruction and energy calibration of jets.

- *Jet energy scale (JES):* the JES uncertainty in the ATLAS and CMS analyses was composed of different uncertainty sources, such as jet flavour dependence, the additional interactions in the same or nearby bunch crossings (pileup), calibrations from Z+jets or γ +jets processes, and other components. In general, these components have different level of correlations among the two experiments and have been used to evaluate the total JES correlation (as detailed in section 5.1). The final JES uncertainty used in this combination is quoted in tables 2–4 and results from grouping all JES uncertainty components into a single number.
- *Jet energy resolution (JER):* this category includes contributions due to the uncertainties in the modelling of the jet energy resolution. The momenta of the jets in

	ATLAS		
	F_0	F_L	$\rho_{\text{ATLAS}}(F_0, F_L)$
Measured value	0.709	0.299	
Uncertainty category			
<i>Samples size and background determination</i>			
Stat+bkg	0.012	0.008	−1.00
Size of simulated samples	0.009	0.006	−1.00
<i>Detector modelling</i>			
JES	0.005	0.003	−0.94
JER	0.006	0.003	−0.92
JVF	0.003	0.002	−0.99
Jet reconstruction efficiency	<0.001	<0.001	−1.00
Lepton efficiency	0.004	0.002	−0.99
b tagging	0.002	0.001	−0.84
Pileup	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
<i>Signal modelling</i>			
Top quark mass	0.002	0.007	−1.00
Simulation model choice	0.003	0.004	0.99
Radiation and scales	0.003	0.006	−0.91
Top quark p_T	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
PDF	0.003	0.004	−1.00
Single top method	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
<i>Total uncertainties</i>			
Systematic uncertainty	0.014	0.013	−0.82
Total uncertainty	0.019	0.015	−0.80

Table 2. Uncertainties in F_0 , F_L and their corresponding correlations from the ATLAS measurement. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by “*n.a.*”. The line “Systematic uncertainty” represents the quadratic sum of all the systematic uncertainty sources except for the uncertainty in the background determination, which is included in the “Stat+bkg” category. The quoted correlation values are obtained via the procedures described in section 4.1.

simulation were smeared so that the jet energy resolution in simulation agrees with that in data. Both experiments used a similar method to estimate this uncertainty.

- *Jet vertex fraction (JVF)*: to suppress jets from pileup, in the ATLAS measurement jets were required to fulfil the JVF criterion. The corresponding uncertainty was eval-

	CMS e+jets			CMS μ +jets		
	F_0	F_L	$\rho_{\text{CMS}}^{\text{e+jets}}(F_0, F_L)$	F_0	F_L	$\rho_{\text{CMS}}^{\mu\text{+jets}}(F_0, F_L)$
Measured value	0.705	0.304		0.685	0.328	
Uncertainty category						
<i>Samples size and background determination</i>						
Stat+bkg	0.028	0.011	−0.87	0.016	0.010	−0.88
Size of simulated samples	0.002	0.001	−0.95	0.002	0.001	−0.96
<i>Detector modelling</i>						
JES	0.004	0.003	−1.00	0.005	0.003	−1.00
JER	0.001	0.002	−1.00	0.004	0.003	−1.00
JVF	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
Jet reconstruction efficiency	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
Lepton efficiency	0.001	0.002	−1.00	0.001	0.001	−1.00
b tagging	0.001	<0.001	−1.00	0.001	<0.001	−1.00
Pileup	0.001	0.001	−1.00	<0.001	<0.001	−1.00
<i>Signal modelling</i>						
Top quark mass	0.012	0.008	−0.99	0.009	0.006	−1.00
Simulation model choice	0.015	0.010	−0.87	0.008	0.004	0.20
Radiation and scales	0.007	0.005	−1.00	0.014	0.006	−0.83
Top quark p_T	0.011	0.010	−1.00	<0.001	0.001	−1.00
PDF	0.004	0.001	−0.92	0.002	0.001	−0.15
Single top method	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
<i>Total uncertainties</i>						
Systematic uncertainty	0.024	0.018	−0.93	0.020	0.010	−0.71
Total uncertainty	0.037	0.021	−0.87	0.025	0.014	−0.78

Table 3. Uncertainties in F_0 , F_L and their corresponding correlations from the CMS e+jets and μ +jets measurements. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by “*n.a.*”. The line “Systematic uncertainty” represents the quadratic sum of all the systematic uncertainty sources except for the uncertainties in the background determination and the integrated luminosity, which are included in the “Stat+bkg” category. The quoted correlation values are obtained via the procedures described in section 4.1.

uated in the measurement by changing the nominal JVF cutoff value and repeating the measurement [17]. In the CMS measurements, pileup events were removed at the event reconstruction level with the particle-flow algorithm. In this case, uncertainties in jet reconstruction due to pileup were covered by the JES and pileup categories, and are not added as a separate source.

- *Jet reconstruction efficiency:* a systematic uncertainty was included in the ATLAS measurement to account for the jet reconstruction efficiency mismatch between simulation and data. In the CMS measurements, this uncertainty is included in the JES uncertainty.

	CMS (single top)		
	F_0	F_L	$\rho_{\text{CMS}}^{\text{st}}(F_0, F_L)$
Measured value	0.720	0.298	
Uncertainty category			
<i>Samples size and background determination</i>			
Stat+bkg	0.041	0.031	−0.90
Size of simulated samples	0.020	0.012	−0.96
<i>Detector modelling</i>			
JES	0.004	0.004	−1.00
JER	0.001	0.001	−1.00
JVF	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
Jet reconstruction efficiency	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
Lepton efficiency	<0.001	<0.001	−1.00
b tagging	0.006	0.006	−1.00
Pileup	0.003	0.003	−1.00
<i>Signal modelling</i>			
Top quark mass	0.005	0.007	−1.00
Simulation model choice	0.002	0.003	−1.00
Radiation and scales	0.023	0.019	−1.00
Top quark p_T	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
PDF	0.004	0.004	−0.97
Single top method	0.012	0.015	−1.00
<i>Total uncertainties</i>			
Systematic uncertainty	0.035	0.029	−0.96
Total uncertainty	0.054	0.043	−0.92

Table 4. Uncertainties in F_0 , F_L and their corresponding correlations from the CMS (single top) measurement. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by “*n.a.*”. The line “Systematic uncertainty” represents the quadratic sum of all the systematic uncertainty sources except for the uncertainties in the background determination and the integrated luminosity, which are included in the “Stat+bkg” category. The quoted correlation values are obtained via the procedures described in section 4.1.

Lepton efficiency. For all measurements, this category accounted for the uncertainties in the scale factors used to correct the simulated samples so that the efficiencies for lepton selection, reconstruction, and identification observed in data were well reproduced by the simulation. Since the samples were collected using single-lepton triggers, uncertainties in

the trigger efficiencies were also included. All corrections were applied as functions of p_T and η of the leptons. This uncertainty was found to be negligible for the CMS (single top) measurement, compared to other uncertainties.

b tagging. In this category, uncertainties on the scale factors used to correct the simulation for different efficiencies for tagging jets originating from b quarks (tag) or for those originating from c or light partons wrongly identified as b jets (mistag) were taken into account. This difference was accounted for by assigning scale factors to the jets, dependent on the p_T and η as well as on the flavour of the jet. In the ATLAS measurement, additionally, an uncertainty was assigned to account for the extrapolation of the b tagging efficiency measurement to the high- p_T region.

Pileup. In both the ATLAS and the CMS analyses, pileup effects were taken into account in the simulation of signal and background events. The distribution of pileup was adjusted to reflect the measured instantaneous luminosities per bunch in data. In the CMS measurements, this uncertainty was estimated by varying the pp cross section used to estimate the number of pileup in data within its uncertainty, and recalculating the weights applied to the simulation. In the ATLAS measurement, the uncertainty in the description of extra energy deposited due to pileup interactions was treated as a separate missing transverse momentum (p_T^{miss}) scale uncertainty. The impact on the measured W boson polarization fractions from this uncertainty was found to be negligible, and therefore was not considered.

3.3 Signal modelling

Top quark mass. In all four analyses, the effect of the uncertainty in the top quark mass was estimated by repeating the measurements using simulated samples with different input top quark masses for the signal process. In the ATLAS measurement, this effect was evaluated using an uncertainty of ± 0.70 GeV in the top quark mass as given by the ATLAS measurement [18]. In the CMS measurements on the other hand, an uncertainty of ± 1.0 GeV in the top quark mass was assumed. In order to keep consistency across the various input measurements, this effect in the ATLAS measurement is reestimated using the original estimation method described in ref. [5], accounting for a variation of ± 1.0 GeV in the top quark mass. The impact of this modification in the ATLAS input result is negligible.

Simulation model choice. The impact of using different MC event generators and their interfaced showering and hadronization models was estimated in all input measurements. In the ATLAS measurement, the impact of the choice of different MC event generators was assessed by comparing events produced by POWHEG-BOX [19–23] and MC@NLO [24–26], both interfaced to HERWIG [27] for showering and hadronization. To evaluate the impact of the different parton shower and hadronization models, the POWHEG+HERWIG sample was compared to POWHEG+PYTHIA [28]. For the CMS (e+jets) and CMS (μ +jets) measurements, the uncertainties were estimated by replacing the events produced by MADGRAPH [29] interfaced with PYTHIA with MC@NLO interfaced with the HERWIG generator and additionally, varying the kinematic scale used to match jets to partons (matching

threshold) by twice and half its central value. In the CMS (single top) measurement, the uncertainty in the choice of different MC generators was estimated as the difference between the POWHEG+PYTHIA and the COMPHEP [30] generators.

Radiation and scales. In all four analyses, this category represents the uncertainty associated with initial- and final-state radiation (ISR/FSR) estimated using simulated samples of $t\bar{t}$ events where the renormalization and factorization scales (μ_R and μ_F) were simultaneously set to twice and half the default value in the matrix element (ME) calculations. In the CMS measurements, the μ_R and μ_F in the parton shower were also varied simultaneously to those used in the ME calculations. However, in the ATLAS measurement, a different set of tuned parameters of the PYTHIA parton shower with a modified strong coupling α_S was used to account for low and high radiation to match the variation of scales in the ME calculations. The detailed list of modified parameters is given in ref. [31]. Furthermore, in the ATLAS measurement the value of the damping parameter (h_{damp}) in POWHEG-BOX was set to twice the top quark mass for the high-radiation sample. In addition to changing it in the $t\bar{t}$ background, the CMS (single top) measurement varied the scales used in the single top quark simulated samples.

Top quark p_T . In previous CMS analyses of $t\bar{t}$ events, described e.g. in ref. [32], the shape of the p_T spectrum for top quarks was found to be softer than the predictions from MADGRAPH simulation. The effect of this mismodelling on the CMS (e+jets) and CMS (μ +jets) measurements was estimated by reweighting the simulated $t\bar{t}$ sample to describe the data. The difference in the polarization fractions with the default sample to the reweighted sample was taken as a systematic uncertainty. On the other hand, the top quark p_T distribution did not exhibit, within uncertainties, a significant difference with the predictions in the single top quark enriched phase space, therefore no systematic uncertainty was assigned in the CMS (single top) measurement. In the ATLAS measurement, this mismodelling was checked to be covered by the simulation model choice uncertainties, and therefore no additional uncertainty for the top quark p_T spectrum was considered.

PDF. The uncertainty due to the choice of PDFs in all input measurements was evaluated by varying the eigenvalues of different PDF sets following the PDF4LHC recommendations [33, 34]. In the ATLAS measurement, the differences between three PDF sets: CT10 [35], MSTW2008 [36], and NNPDF 2.3 [37] were taken into account. Uncertainties related to the choice of PDF set in the CMS (e+jets) and CMS (μ +jets) measurements were estimated by replacing CTEQ6L1 [38] used to generate the nominal samples, with NNPDF 2.1 [39] and MSTW2008. A similar procedure was adopted in the CMS (single top) measurement, where the default CTEQ6.6M [40] set was replaced with CT10 instead.

Single top quark analysis method. In addition to the systematic uncertainties considered for the $t\bar{t}$ measurement, a few specific uncertainties were included for the CMS (single top) measurement. For the specific case of single top quark processes, unlike for $t\bar{t}$ production, the polarization fractions can also be altered at the production level. To study this effect, pseudo-data were generated from samples simulated using COMPHEP and SINGLE

Measurement	Fraction	ATLAS F_0	CMS (e+jets) F_0	CMS (μ +jets) F_0	CMS (single top) F_0
ATLAS	F_0	+1	$\rho_{\text{LHC}}(F_0, F_0)$	$\rho_{\text{LHC}}(F_0, F_0)$	$\rho_{\text{LHC}}(F_0, F_0)$
CMS (e+jets)	F_0	$\rho_{\text{LHC}}(F_0, F_0)$	+1	$\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_0, F_0)$	$\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$
CMS (μ +jets)	F_0	$\rho_{\text{LHC}}(F_0, F_0)$	$\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_0, F_0)$	+1	$\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$
CMS (single top)	F_0	$\rho_{\text{LHC}}(F_0, F_0)$	$\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$	$\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$	+1
ATLAS	F_L	$\rho_{\text{ATLAS}}(F_0, F_L)$	$-\rho_{\text{LHC}}(F_0, F_0)$	$-\rho_{\text{LHC}}(F_0, F_0)$	$-\rho_{\text{LHC}}(F_0, F_0)$
CMS (e+jets)	F_L	$-\rho_{\text{LHC}}(F_0, F_0)$	$\rho_{\text{CMS}}^{e+\text{jets}}(F_0, F_L)$	$-\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_0, F_0)$	$-\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$
CMS (μ +jets)	F_L	$-\rho_{\text{LHC}}(F_0, F_0)$	$-\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_0, F_0)$	$\rho_{\text{CMS}}^{\mu+\text{jets}}(F_0, F_L)$	$-\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$
CMS (single top)	F_L	$-\rho_{\text{LHC}}(F_0, F_0)$	$-\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$	$-\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_0, F_0)$	$\rho_{\text{CMS}}^{\text{st}}(F_0, F_L)$

Table 5. Summary of the correlation categories considered in the combination. The correlations among the F_L measurements are not shown for brevity.

TOP [41] event generators with varied values of the couplings g_L , V_R , and V_L (as described in section 5.2) both at the single top quark production and decay, and the polarization fractions values were extracted using the analysis fitting framework. The differences between the generated and fitted values were taken as the systematic uncertainty. Secondly, a small difference in the generated W boson polarization fraction values was observed for the $t\bar{t}$ events, simulated with MADGRAPH, and single top quark events, simulated with POWHEG. This difference of about 0.01 was taken into account as an uncertainty in the measurement. Finally, the effect of fixing the signal normalization in the fit was considered. All these uncertainties are merged into a single uncertainty, referred to as *Single top method* in tables 2–4 and 6–7.

In all input measurements, the uncertainty in the modelling of colour reconnection was found to be negligible and therefore was not considered.

4 Correlations and uncertainties in the ATLAS and CMS measurements

4.1 Correlations

Four pairs of longitudinal and left-handed polarization fractions from four input measurements, as described in section 2 are used in the combination. The correlations between the input values are defined taking into account the unitarity relation between the polarization fractions in each measurement and the correlations among the measurements. The groups of correlations are listed in table 5 and defined as follows:

- *Correlations within the same measurement:* because of the unitarity constraint, and given that $F_R \approx 0$, the observed values of F_0 and F_L within one single measurement are usually highly anticorrelated. In the ATLAS measurement, this correlation is estimated for each systematic uncertainty source from its corresponding covariance matrix. For categories with multiple sources of systematic uncertainty, the sum of the individual covariance matrices is used to calculate the correlation. In the CMS analyses, this group of correlations is estimated from the covariance propagation of

Uncertainty Category	$\rho_{\text{LHC}}(F_i, F_i)$	$\rho_{\text{CMS}}^{\text{e}, \mu + \text{jets}}(F_i, F_i)$	$\rho_{\text{CMS}}^{\text{st}, \ell + \text{jets}}(F_i, F_i)$
<i>Samples size and background determination</i>			
Stat+bkg	0.0	0.0 [†]	0.0 [†]
Size of simulated samples	0.0	0.0	0.0
<i>Detector modelling</i>			
JES	0.2 [†]	1.0	1.0
JER	0.0	1.0	1.0
JVF	0.0*	0.0*	0.0*
Jet reconstruction efficiency	0.0*	0.0*	0.0*
Lepton efficiency	0.0	0.0	0.0
b tagging	0.0	1.0	1.0
Pileup	0.0*	1.0	1.0
<i>Signal modelling</i>			
Top quark mass	1.0	1.0	1.0
Simulation model choice	1.0	1.0	1.0
Radiation and scales	0.5 [†]	1.0	1.0 [†]
Top quark p_T	0.0*	1.0	0.0*
PDF	1.0	1.0	1.0
Single top method	0.0*	0.0*	0.0*

Table 6. Input correlations across different measurements, as explained in section 4.1. The values stand for the correlations $\rho(F_i, F_i)$, with i being either 0 or L. The correlations of the type $\rho(F_0, F_L)$ are assumed to be $\rho(F_0, F_L) = -\rho(F_0, F_0) = -\rho(F_L, F_L)$. In case an uncertainty is not applicable, the correlation value is set to zero and marked with an asterisk. The correlations marked with a dagger sign are those that are not precisely determined and checks are performed to test the stability of the results against these assumptions.

the expression $F_R = 1 - F_0 - F_L$ as

$$\rho(F_0, F_L) = \frac{\sigma^2(F_R) - \sigma^2(F_0) - \sigma^2(F_L)}{2\sigma(F_0)\sigma(F_L)}, \quad (4.1)$$

where $\sigma(F_i)$ is the uncertainty in the polarization fraction F_i , which is directly obtained from the individual measurements. This is done for all sources of systematic uncertainty. For systematic uncertainty categories with multiple sources, e.g. ‘stat+bkg’ including statistical uncertainty, background determination, and others, $\sigma^2(F_i)$ is defined as the quadratic sum of the individual uncertainty sources.

ATLAS+CMS combination		
	F_0	F_L
Fractions	0.693	0.315
Uncertainty category		
<i>Samples size and background determination</i>		
Stat+bkg	0.009	0.006
Size of simulated samples	0.005	0.003
<i>Detector modelling</i>		
JES	0.004	0.002
JER	0.004	0.002
JVF	0.001	0.001
Jet reconstruction	<0.001	<0.001
Lepton efficiency	0.002	0.001
b tagging	0.001	0.001
Pileup	<0.001	<0.001
<i>Signal modelling</i>		
Top quark mass	0.003	0.004
Simulation model choice	0.006	0.005
Radiation and scales	0.005	0.004
Top quark p_T	0.001	0.002
PDF	0.001	0.001
Single top method	0.001	<0.001
Total uncertainty	0.014	0.011

Table 7. Results of the ATLAS and CMS combination: W boson polarization fraction values and uncertainties. The combined F_0 and F_L values are anticorrelated, with $\rho=-0.85$.

This group of correlations is denoted in this document as $\rho_{\text{ATLAS}}, \rho_{\text{CMS}}^{\text{e+jets}}, \rho_{\text{CMS}}^{\mu+\text{jets}}$, and $\rho_{\text{CMS}}^{\text{st}}$ for the ATLAS, CMS (e+jets), CMS (μ +jets), and CMS (single top) measurements, respectively.

- *Correlations between measurements within the CMS experiment:* for each source of systematic uncertainty, the correlations between the polarization fractions in the CMS (e+jets) and CMS (μ +jets) measurements are denoted $\rho_{\text{CMS}}^{\text{e},\mu+\text{jets}}(F_i, F_j)$, where i and j stand for 0 or L. The correlations between CMS (single top) and CMS (e+jets) are assumed to be the same as those between the CMS (single top) and CMS (μ +jets) measurements for each source of the uncertainty, and are denoted generically $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_j)$. The relations $\rho_{\text{CMS}}(F_0, F_0) = \rho_{\text{CMS}}(F_L, F_L) = -\rho_{\text{CMS}}(F_0, F_L)$

are assumed in all CMS measurements. In this hypothesis, the strong anti-correlation observed for F_0 and F_L within the same measurement (as described above) is assumed to hold also across different measurements.

The uncertainties associated with the limited size of the data and simulated samples, and background estimation are assumed to be uncorrelated (as also discussed in sections 4.2 and 5.1). The lepton efficiency uncertainty is assumed to be uncorrelated between the CMS (e+jets) and CMS (μ +jets) measurements, and partially correlated with the CMS (single top) measurement. All other sources of uncertainty are assumed to be fully correlated.

- *Correlations between the ATLAS and CMS experiments:* for each source of systematic uncertainty, the correlation between the measured polarization fractions F_i by the ATLAS and CMS experiments, $\rho(F_i^{\text{ATLAS}}, F_j^{\text{CMS}})$ is presented by $\rho_{\text{LHC}}(F_i, F_j)$, where $\rho_{\text{LHC}}(F_0, F_0) = \rho_{\text{LHC}}(F_L, F_L) = -\rho_{\text{LHC}}(F_0, F_L)$ are assumed.

The uncertainties associated with the detector modelling (except for the JES) as well as the method-specific uncertainty are assumed to be uncorrelated, i.e. $\rho_{\text{LHC}}(F_0, F_0) = 0$.

The uncertainty associated with the radiation and scales, and the JES are assumed to be partially correlated with $\rho_{\text{LHC}}(F_0, F_0)$ estimated to be 0.5 and 0.2, respectively (see sections 4.2 and 5.1 for details). All other sources of uncertainty are assumed to be fully correlated, i.e. $\rho_{\text{LHC}}(F_0, F_0) = +1$.

4.2 Correlation choices for the partially correlated uncertainties

Although the correlations between the measurements are well known for most of the systematic uncertainty sources, some of them, in particular those that are partially correlated, are not very accurately determined. This section describes how these values are estimated for the combination. Stability tests are performed to verify the robustness of the combination against these correlation assumptions, as discussed in section 5.1.

In the CMS measurements, the uncertainties in the background determination (shape and normalization), integrated luminosity, and the statistical uncertainty were estimated independently and grouped into a single uncertainty category (stat+bkg) for coherence with the ATLAS treatment. The major components of the stat+bkg category in the CMS (e+jets) and CMS (μ +jets) measurements are the uncertainty in the determination of the background events from multijet and W+jets production. The former is estimated from data, and therefore uncorrelated between all CMS measurements, while W+jets production, as well as the other minor backgrounds are estimated from simulation, and therefore at least partially correlated between the measurements. For the CMS (single top) case, the major component of this category is the statistical uncertainty, which is uncorrelated with the other measurements. The normalization of W+jets production, a major background in the CMS (single top) analysis, is estimated from data, and therefore it is uncorrelated to the other CMS measurements. On the other hand, the W+jets production shape, as well as the modelling of other background event sources and signal events, rely on simulation, which may lead to a nonzero $\rho_{\text{CMS}}^{\text{st}, \ell + \text{jets}}(F_i, F_i)$ correlation. Neglecting the small correlations

that could arise from the W+jets production shape and the background modelling from simulation, the values $\rho_{\text{CMS}}^{\text{e},\mu+\text{jets}}(F_i, F_j) = 0$ and $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_i) = 0$ are assumed for the combination, and the impact of this assumption is studied via the stability tests.

In all ATLAS and CMS measurements, the JES systematic uncertainty is estimated from different components, which are characterized by different levels of correlations among the two experiments. These components are categorized as fully correlated, such as gluon-initiated jet fragmentation; partially correlated, such as modelling uncertainties from *in situ* techniques, such as Z-jet, γ -jet, and multijet balance techniques; and uncorrelated, such as statistical and detector-related uncertainties. These correlations have been evaluated and are described in ref. [42]. In the ATLAS measurement, the contribution from the uncorrelated (partially correlated) components to the total JES uncertainty is found to be about 70 (20)%, and the total JES uncertainty is dominated by the uncorrelated jet flavour composition component. In the CMS measurements, because JES uncertainties are small, the breakdown into components was not done. Therefore, assuming a similar JES uncertainty composition between the two experiments, the value of $\rho_{\text{LHC}}(F_i, F_i)$ is found to be 0.2.

In the ATLAS and CMS analyses, different approaches were used to estimate the radiation and scales uncertainties, as described in section 3.3. In the CMS (single top) measurement, this uncertainty is estimated by varying the scales μ_{R} and μ_{F} for the simulations of both the $t\bar{t}$ and the single top quark processes. While the $t\bar{t}$ component, which is dominant, is fully correlated to the analogous uncertainties in the ATLAS, CMS (e+jets), and CMS (μ +jets) measurements, the smaller component from the single top quark μ_{R} and μ_{F} scales is uncorrelated with the other measurements. Since the effects being studied are the same, but the methods are different, the values of $\rho_{\text{LHC}}(F_i, F_i)$ and $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_i)$ are not well known, and are assumed to be 0.5 and 1.0, respectively.

4.3 Summary of the uncertainties and correlations of the input measurements

For each systematic uncertainty category, the correlations between the measured polarization fractions for the input measurements are given in table 6. A breakdown of the uncertainties in the input measurements of F_0 and F_{L} as well as their correlations, are presented in tables 2–4. The uncertainties are grouped according to the categories listed in section 3.

Figure 1 presents the total correlation values between the input measurements. Typically, F_0 and F_{L} are highly anticorrelated within the same measurement. The three $t\bar{t}$ measurements (ATLAS, CMS (e+jets), and CMS (μ +jets)) are also correlated or anticorrelated, with the absolute values of the correlations ranging around 30 to 40%. The correlations of the CMS (single top) measurement with the CMS (e+jets) and CMS (μ +jets) measurements are around 20% in the absolute value, and are generally smaller with the ATLAS measurement.

5 Results

The combination is performed by finding the best linear unbiased estimator (BLUE) [43, 44] with the method implemented in ref. [45]. The BLUE method finds the coefficients of the

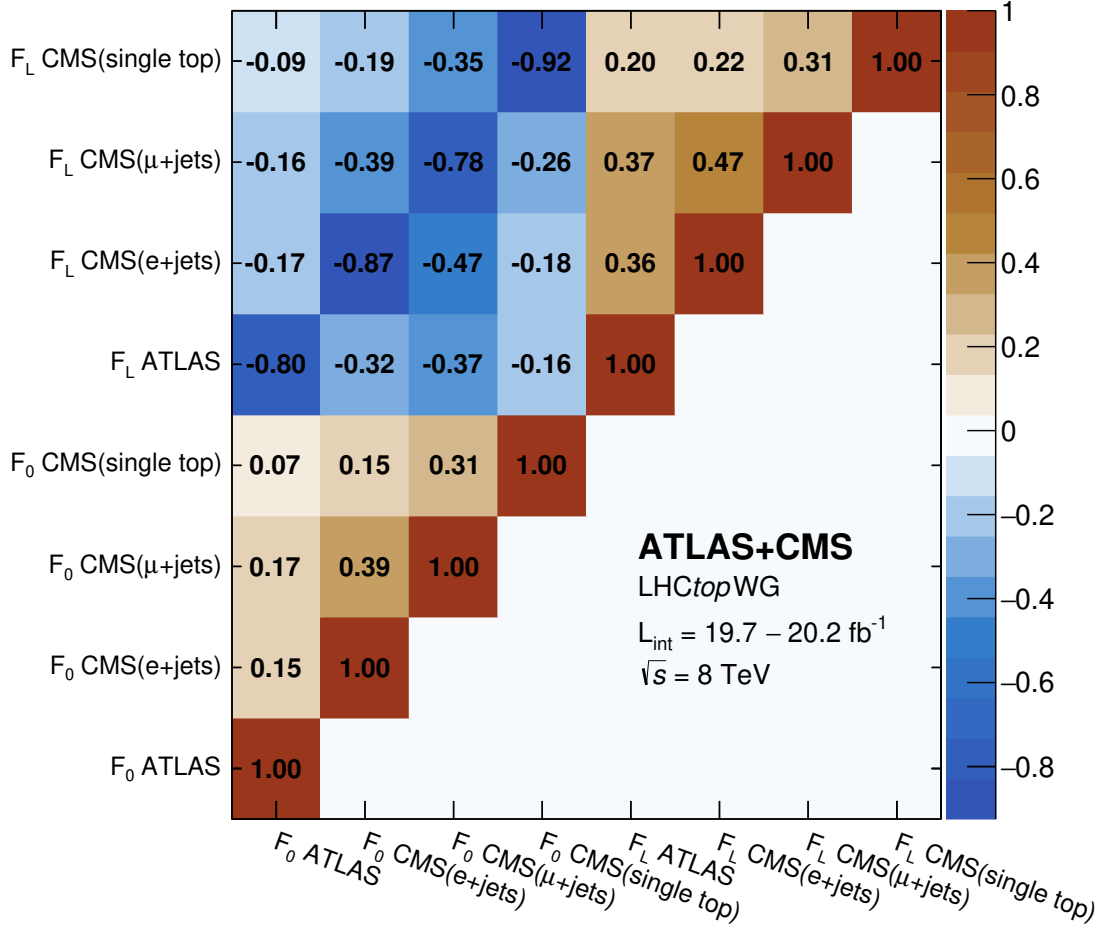


Figure 1. The total correlation between the input measurements of the combination.

linear combination of the input measurements by minimizing the total uncertainty of the combined result, taking into account both the statistical and systematic uncertainties, as well as the correlations between the inputs. In this analysis, the measurements of F_0 and F_L are combined while F_R is obtained as $F_R = 1 - F_0 - F_L$. As no further constraints on the observables were placed, values outside the range $[0, 1]$ are allowed for the three polarization fractions. The total correlation between F_0 and F_L obtained from the combination is taken into account in the estimation of the uncertainty in the F_R value.

The results of the combination of the polarization fractions measurements are

$$F_0 = 0.693 \pm 0.009 \text{ (stat+bkg)} \pm 0.011 \text{ (syst)},$$

$$F_L = 0.315 \pm 0.006 \text{ (stat+bkg)} \pm 0.009 \text{ (syst)},$$

with a total correlation of -0.85 . Using the unitarity constraint on the polarization fractions, the fraction of events with a W boson with right-handed polarization is calculated to be

$$F_R = -0.008 \pm 0.005 \text{ (stat+bkg)} \pm 0.006 \text{ (syst)},$$

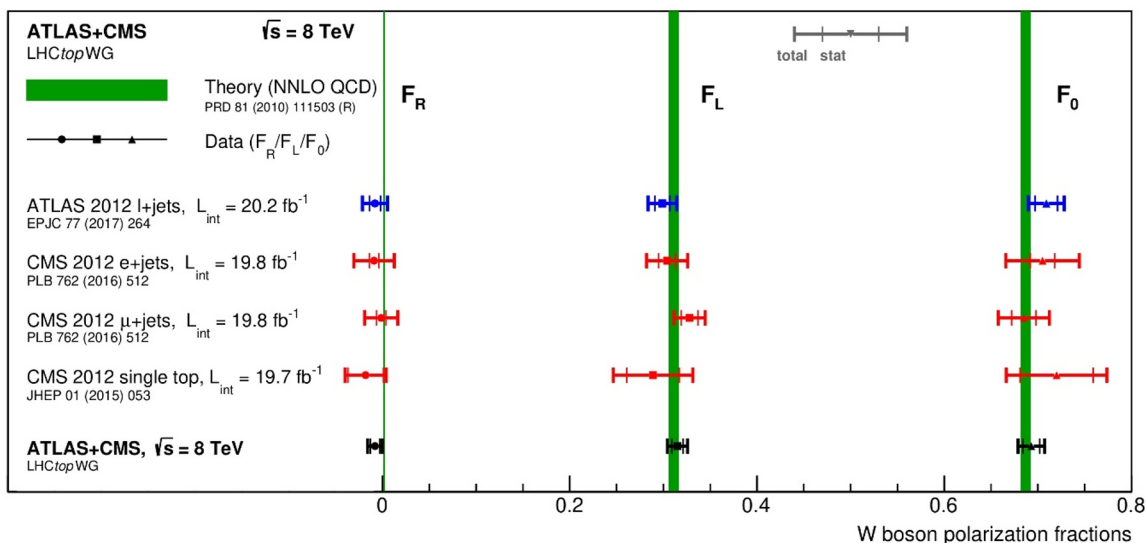


Figure 2. Overview of the four measurements, as well as the results of the combination. The inner and outer error bars correspond to the statistical and the total uncertainties, respectively. The inner bars for the combination include also the background determination uncertainties. The vertical solid line indicates the predictions of NNLO QCD calculations [1].

where the first quoted uncertainty includes the statistical part and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic contribution. From these results, an upper limit of $F_R < 0.007$ at 95% confidence level (CL) is set. The limit is set using the Feldman-Cousins method [46], considering that F_R follows a normal distribution, and that it is physically bound to $F_R \geq 0$. The relative uncertainty on F_0 and F_L is 2.0 and 3.5%, respectively, including systematic and statistical components.

Figure 2 shows an overview of the four measurements included in the combination and the result of the combination together with the polarization fractions predicted by NNLO QCD calculations. The uncertainties in the NNLO predictions, presented with vertical bands, include an uncertainty of 1.3 GeV in the top quark mass, uncertainties in the b quark and W boson masses, and in α_S . The combined F_R value is negative, as this is not explicitly forbidden in the combination, but compatible with the predictions within the uncertainties. The measurements are consistent with each other and with the NNLO QCD prediction.

The χ^2 and upper tail probability of the combination are 4.3 and 64% respectively. The combination includes four sets of measurements, each composed of two highly anti-correlated observables, and two fit parameters of the combination, i.e. the combined F_0 and F_L . A detailed breakdown of the uncertainties is presented in table 7. The dominant uncertainties are those arising from the statistical uncertainty on data and background estimation (stat+bkg), followed by the uncertainties in the radiation and scales modelling, the limited size of the simulated samples, and simulation model choice. The total detector modelling uncertainty is minor, smaller than the uncertainties in the stat+bkg category. The measurement with the highest impact in the determination of F_0 is ATLAS, while CMS

$(\mu+\text{jets})$ dominates the combined F_L determination. The impact of the CMS (e+jets) and CMS $(\mu+\text{jets})$ measurements is not directly comparable to the other input measurements that already include the electron and muon channels together. As a test, the combination is repeated, using a pre-combined CMS (e+jets) + CMS $(\mu+\text{jets})$ input, and the results are unchanged. The ATLAS+CMS combined fractions and uncertainties are identical in both cases, with a small variation on the resulting (F_0, F_L) correlation, being 1.5% smaller for the cross-check combination.

In another test, the CMS (single top) measurement was removed from the combination. The impact on the combined fractions and uncertainties is less than 1.5%.

The combination yields an important improvement in precision, as compared to the most precise individual published measurements [5, 6]. Improvements of 25 and 29% relative to the most precise single measurement are found for the precision of the combined measurements of F_0 and F_L , respectively. The improvement is estimated with respect to the published values of the W boson polarization fraction determination that is given in table 1. The total correlation between the combined fractions is similar to those in the input measurements, and their uncertainties are smaller. These two factors lead to a combined right-handed polarization fraction F_R that is almost a factor two more precise than in previous publications.

5.1 Stability tests

The hypotheses assumed for the correlations between the measurements, as defined in sections 4.1 and 4.2, are based on the best knowledge of the similarities and differences in the detectors, analysis methods, and simulations used in each measurement. Nevertheless, some of these correlations cannot be precisely determined. The checks described in this section are performed to test the stability of the results against this potential lack of knowledge.

$\rho_{\text{LHC}}(F_i, F_i)$ hypothesis (with $i = 0, L$) for the JES uncertainty. The correlation value $\rho_{\text{LHC}}(F_i, F_i) = 0.2$ was estimated according to the prescription given in ref. [42] and the description in section 4.2. The impact of this assumption is evaluated by repeating the combination by varying $\rho_{\text{LHC}}(F_i, F_i)$ in the interval between 0.0 and 0.4, in steps of 0.1. The fraction values and uncertainties remained unchanged in the entire probed range. The χ^2 of the fit, the probability, and the total (F_0, F_L) correlation are found to be stable with a relative shift of less than 0.5%.

$\rho_{\text{LHC}}(F_i, F_i)$ and $\rho_{\text{CMS}}^{\text{st}, \ell+\text{jets}}(F_i, F_i)$ hypotheses for the radiation and scales uncertainties. Although addressing similar effects, the radiation and scales uncertainties are estimated in three different ways for ATLAS, CMS (single top), and the other CMS measurements, with different levels of correlations among them. Therefore, the two hypotheses, $\rho_{\text{LHC}}(F_i, F_i) = 0.5$ and $\rho_{\text{CMS}}^{\text{st}, \ell+\text{jets}}(F_i, F_i) = 1$, are tested simultaneously, by variation in steps of 0.1 in the interval between 0 and 0.5 for $\rho_{\text{LHC}}(F_i, F_i)$ and between 0.6 and 1.0 for $\rho_{\text{CMS}}^{\text{st}, \ell+\text{jets}}(F_i, F_i)$. The resulting polarization fraction mean values and uncertainties remained unchanged in the whole ranges. Small variations, below the percent level, are observed for the total correlation and fit probability.

JES versus radiation and scales correlations. Since the JES and radiation and scales uncertainties are among the dominant sources of uncertainty with significant correlation between measurements, an additional test was performed varying the two correlation hypotheses simultaneously, rather than separately. The results of this test also show stable combination with maximum relative shifts of about 2% for the χ^2 and probability and about 0.6% for the total correlation. The combined fractions and uncertainties are found to be stable, with negligible variations for all probed hypotheses.

$\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_i, F_i)$ and $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_i)$ hypothesis for statistical+background uncertainty. Small correlations that could arise from the background modelling from simulated samples are neglected in the combination by assuming $\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_i, F_i) = 0$ and $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_i) = 0$. In order to investigate the effect of these hypotheses, the combination was repeated by varying $\rho_{\text{CMS}}^{e,\mu+\text{jets}}(F_i, F_i)$ and $\rho_{\text{CMS}}^{\text{st},\ell+\text{jets}}(F_i, F_i)$, using for both the same correlation values in the range $[0.0, 0.7]$ in steps of 0.1. In the interval between 0.0 and 0.6, the fraction values are varied by a maximum of 1.3%, with F_0 going from 0.693 to 0.687, and F_L from 0.314 to 0.319. At 0.7, the combination yields $F_0 = 0.684 \pm 0.014$ and $F_L = 0.321 \pm 0.010$, which is the maximum variation observed in all tests performed in this study. However, in this case the fit probability decreases to 28%, suggesting that the correlation assumption of 0.7 is less favoured. The fit combination does not converge for unreasonable values, i.e. correlation values above 0.7.

In conclusion, the tests reported in this section indicate that the combined results are robust against variations of some poorly known or unknown input correlations. The correlations are varied over a large range, and in all cases the observed deviation from the nominal results are well covered by the uncertainties in the combined result.

5.2 Limits on anomalous couplings

The result of the combination of the polarization fractions measurements can be used to set limits on beyond-the-SM physics contributing to the tWb vertex. In the two approaches presented in this section, only new physics contributions to the top quark decay vertex are considered — effects at the production vertex in single top quark processes are disregarded.

In a first approach, the structure of the tWb vertex is parameterized in a general form in effective field theory, expanding the SM Lagrangian to include dimension-six terms

$$\mathcal{L}_{\text{tWb}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}, \quad (5.1)$$

where $V_{L,R}$ and $g_{L,R}$ are left- and right-handed vector and tensor couplings, respectively. Here, $P_{L,R}$ refers to the left- and right-handed chirality projection operators, m_W to the W boson mass, and g to the weak coupling constant, as detailed in refs. [47, 48]. In the SM, V_L is given by the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{tb} , with a measured value of ≈ 1 , while $V_R = g_L = g_R = 0$ at the tree level. Using this formalism, the polarization fractions can be translated into the couplings V_L , V_R , g_L , and g_R (as discussed e.g. in ref. [49]). The two independent W boson polarization measurements, F_0 and F_L , cannot fully constrain the four tWb couplings. Therefore additional assumptions have to be made. Figure 3 shows the limits on the left- and right-handed tensor couplings,

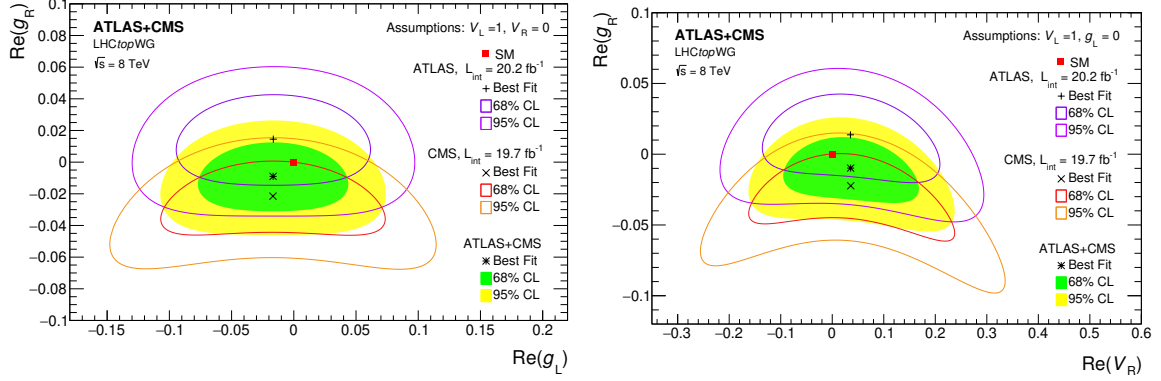


Figure 3. Allowed regions for the tWb anomalous (left) left- and right-handed tensor couplings, and (right) right-handed vector and tensor coupling. The limits are obtained from the ATLAS, CMS, and the combined measurements of the W boson polarization fractions at 68 and 95% CL. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The anomalous couplings are assumed to be real.

Coupling	95% CL interval		
	ATLAS	CMS	ATLAS+CMS combination
$\text{Re}(V_R)$	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
$\text{Re}(g_L)$	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
$\text{Re}(g_R)$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

Table 8. Allowed ranges for the anomalous couplings V_R , g_L , and g_R at 95% CL. The limit on each coupling is obtained while fixing all other couplings to their SM value. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The anomalous couplings are assumed to be real.

while the other couplings are fixed to their SM values, as well as limits on the right-handed vector and tensor couplings, with the other couplings fixed to their SM values. Limits on these anomalous couplings are set using the *EFTfitter* tool [50]. The anomalous couplings are assumed to introduce no additional CP violation, and are taken to be real. The allowed regions at 68 and 95% CL and the most probable couplings values are shown, as derived from the measured polarization fractions reported in refs. [5, 6], and from the combined results presented in this paper. A second region allowed by the W boson polarization measurements around $\text{Re}(g_R) = 0.8$ is excluded by the single top quark cross section measurements [51, 52], and therefore is not shown in this figure. Table 8 shows the 95% CL intervals for each anomalous coupling, while fixing all others to their SM values. These limits correspond to the set of smallest intervals containing 95% of the marginalized posterior distribution for the corresponding parameter.

In a similar way, limits are set in terms of Wilson coefficients. In this second approach, effects of beyond-the-SM physics at a high scale Λ are described by an effective Lagrangian [47, 53–56] as

$$-L^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) + \dots \quad (5.2)$$

Coefficient	95% CL interval		
	ATLAS	CMS	ATLAS+CMS combination
$C_{\phi\phi}^*$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C_{bW}^*	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

Table 9. Allowed ranges for the Wilson coefficients $C_{\phi\phi}^*$, C_{bW}^* , and C_{tW} at 95% CL. The limit on each coefficient is obtained while fixing all other coefficients to their SM values. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The numerical values are obtained by setting the Λ scale to 1 TeV, and the coefficients are assumed to be real.

where O_x are dimension-six gauge-invariant operators and C_x are the complex constants known as Wilson coefficients that give the strength of the corresponding operator. Only dimension-six operators are considered in this analysis. The relevant operators affecting the general effective tWb vertex can be found, e.g. in ref. [56]. Three of these operators are of particular interest, since the measurement of the W boson polarization is able to constrain their corresponding Wilson coefficients. These operators are:

$$\begin{aligned}
O_{\phi\phi} &= i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R), \\
O_{tW} &= (\bar{q}_L \sigma^{\mu\nu} \tau^I t_R) \tilde{\phi} W_{\mu\nu}^I, \quad \text{and} \\
O_{bW} &= (\bar{q}_L \sigma^{\mu\nu} \tau^I b_R) \phi W_{\mu\nu}^I,
\end{aligned} \tag{5.3}$$

where ϕ represents a weak doublet of the Higgs field, t_R and b_R are the weak singlets of the right-handed top and bottom quark fields, $q_L^T = (t, b)_L$ denotes the $SU(2)_L$ weak doublet of the third generation left-handed quark fields, and τ^I is the usual Pauli matrix. Assuming the Wilson coefficients to be real, they can be trivially parameterized as functions of the anomalous couplings of eq. (5.1) (as shown e.g. in refs. [48, 56]), thus, as functions of the W polarization fractions. The limits on each Wilson coefficient are derived from the measured fractions, as done for the anomalous couplings, fixing all others to their SM value, i.e. to zero. They are shown at 95% CL in table 9.

6 Summary

The combination of measurements of the W boson polarization in top quark decays performed by the ATLAS and CMS collaborations is presented. The measurements are based on proton-proton collision data produced at the LHC at a centre-of-mass energy of 8 TeV, and corresponding to an integrated luminosity of about 20 fb^{-1} for each experiment. The fractions of W bosons with longitudinal (F_0) and left-handed (F_L) polarizations were measured in events containing a single lepton and multiple jets, enhanced in $t\bar{t}$ or single top quark production processes. The results of the combination are

$$\begin{aligned}
F_0 &= 0.693 \pm 0.009 (\text{stat+bkg}) \pm 0.011 (\text{syst}), \\
F_L &= 0.315 \pm 0.006 (\text{stat+bkg}) \pm 0.009 (\text{syst}),
\end{aligned}$$

where “stat+bkg” stands for the sum of the statistical and background determination uncertainties, and “syst” for the remaining systematic uncertainties. The fraction of W

bosons with right-handed polarization, F_R , is estimated assuming that the sum of all polarization fractions equals unity, and by taking into account the correlation coefficient of the combination, -0.85 . This leads to

$$F_R = -0.008 \pm 0.005 (\text{stat+bkg}) \pm 0.006 (\text{syst}),$$

which corresponds to $F_R < 0.007$ at 95% confidence level.

The results are consistent with the standard model predictions at next-to-next-to-leading-order precision in perturbative quantum chromodynamics. A limit on each anomalous tWb coupling is set while fixing all others to their standard model values, with the allowed regions being $[-0.11, 0.16]$ for V_R , $[-0.08, 0.05]$ for g_L , and $[-0.04, 0.02]$ for g_R , at 95% confidence level. All couplings are assumed to be real. Limits on Wilson coefficients are also derived in a similar manner.

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The ATLAS collaboration

G. Aad¹⁰², B. Abbott¹²⁸, D.C. Abbott¹⁰³, A. Abed Abud³⁶, K. Abeling⁵³, D.K. Abhayasinghe⁹⁴, S.H. Abidi¹⁶⁶, O.S. AbouZeid⁴⁰, N.L. Abraham¹⁵⁵, H. Abramowicz¹⁶⁰, H. Abreu¹⁵⁹, Y. Abulaiti⁶, B.S. Acharya^{67a,67b,n}, B. Achkar⁵³, L. Adam¹⁰⁰, C. Adam Bourdarios⁵, L. Adamczyk^{84a}, L. Adamek¹⁶⁶, J. Adelman¹²¹, M. Adersberger¹¹⁴, A. Adiguzel^{12c}, S. Adorni⁵⁴, T. Adye¹⁴³, A.A. Affolder¹⁴⁵, Y. Afik¹⁵⁹, C. Agapopoulou⁶⁵, M.N. Agaras³⁸, A. Aggarwal¹¹⁹, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{139f,139a,ae}, A. Ahmad³⁶, F. Ahmadov⁸⁰, W.S. Ahmed¹⁰⁴, X. Ai¹⁸, G. Aielli^{74a,74b}, S. Akatsuka⁸⁶, T.P.A. Åkesson⁹⁷, E. Akilli⁵⁴, A.V. Akimov¹¹¹, K. Al Khoury⁶⁵, G.L. Alberghi^{23b,23a}, J. Albert¹⁷⁵, M.J. Alconada Verzini¹⁶⁰, S. Alderweireldt³⁶, M. Aleksa³⁶, I.N. Aleksandrov⁸⁰, C. Alexa^{27b}, T. Alexopoulos¹⁰, A. Alfonsi¹²⁰, F. Alfonsi^{23b,23a}, M. Alhroob¹²⁸, B. Ali¹⁴¹, S. Ali¹⁵⁷, M. Aliev¹⁶⁵, G. Alimonti^{69a}, C. Allaire³⁶, B.M.M. Allbrooke¹⁵⁵, B.W. Allen¹³¹, P.P. Allport²¹, A. Aloisio^{70a,70b}, F. Alonso⁸⁹, C. Alpigiani¹⁴⁷, A.A. Alshehri⁵⁷, E. Alunno Camelia^{74a,74b}, M. Alvarez Estevez⁹⁹, M.G. Alvigi^{70a,70b}, Y. Amaral Coutinho^{81b}, A. Ambler¹⁰⁴, L. Ambroz¹³⁴, C. Amelung²⁶, D. Amidei¹⁰⁶, S.P. Amor Dos Santos^{139a}, S. Amoroso⁴⁶, C.S. Amrouche⁵⁴, F. An⁷⁹, C. Anastopoulos¹⁴⁸, N. Andari¹⁴⁴, T. Andeen¹¹, C.F. Anders^{61b}, J.K. Anders²⁰, S.Y. Andrean^{45a,45b}, A. Andreazza^{69a,69b}, V. Andrei^{61a}, C.R. Anelli¹⁷⁵, S. Angelidakis³⁸, A. Angerami³⁹, A.V. Anisenkov^{122b,122a}, A. Annovi^{72a}, C. Antel⁵⁴, M.T. Anthony¹⁴⁸, E. Antipov¹²⁹, M. Antonelli⁵¹, D.J.A. Antrim¹⁷⁰, F. Anulli^{73a}, M. Aoki⁸², J.A. Aparisi Pozo¹⁷³, M.A. Aparo¹⁵⁵, L. Aperio Bella^{15a}, V. Araujo Ferraz^{81b}, R. Araujo Pereira^{81b}, C. Arcangeletti⁵¹, A.T.H. Arce⁴⁹, F.A. Arduh⁸⁹, J-F. Arguin¹¹⁰, S. Argyropoulos⁵², J.-H. Arling⁴⁶, A.J. Armbruster³⁶, A. Armstrong¹⁷⁰, O. Arnaez¹⁶⁶, H. Arnold¹²⁰, Z.P. Arrubarrena Tame¹¹⁴, G. Artoni¹³⁴, S. Artz¹⁰⁰, S. Asai¹⁶², T. Asawatavonvanich¹⁶⁴, N. Asbah⁵⁹, E.M. Asimakopoulou¹⁷¹, L. Asquith¹⁵⁵, J. Assahsah^{35d}, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{33a}, M. Atkinson¹⁷², N.B. Atlay¹⁹, H. Atmani⁶⁵, K. Augsten¹⁴¹, G. Avolio³⁶, M.K. Ayoub^{15a}, G. Azuelos^{110,am}, H. Bachacou¹⁴⁴, K. Bachas¹⁶¹, M. Backes¹³⁴, F. Backman^{45a,45b}, P. Bagnaia^{73a,73b}, M. Bahmani⁸⁵, H. Bahrsemani¹⁵¹, A.J. Bailey¹⁷³, V.R. Bailey¹⁷², J.T. Baines¹⁴³, C. Bakalis¹⁰, O.K. Baker¹⁸², P.J. Bakker¹²⁰, D. Bakshi Gupta⁸, S. Balaji¹⁵⁶, E.M. Baldin^{122b,122a}, P. Balek¹⁷⁹, F. Balli¹⁴⁴, W.K. Balunas¹³⁴, J. Balz¹⁰⁰, E. Banas⁸⁵, M. Bandieramonte¹³⁸, A. Bandyopadhyay²⁴, Sw. Banerjee^{180,i}, L. Barak¹⁶⁰, W.M. Barbe³⁸, E.L. Barberio¹⁰⁵, D. Barberis^{55b,55a}, M. Barbero¹⁰², G. Barbour⁹⁵, T. Barillari¹¹⁵, M-S. Barisits³⁶, J. Barkeloo¹³¹, T. Barklow¹⁵², R. Barnea¹⁵⁹, B.M. Barnett¹⁴³, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{60a}, A. Baroncelli^{60a}, G. Barone²⁹, A.J. Barr¹³⁴, L. Barranco Navarro^{45a,45b}, F. Barreiro⁹⁹, J. Barreiro Guimarães da Costa^{15a}, U. Barron¹⁶⁰, S. Barsov¹³⁷, F. Bartels^{61a}, R. Bartoldus¹⁵², G. Bartolini¹⁰², A.E. Barton⁹⁰, P. Bartos^{28a}, A. Basalae⁴⁶, A. Basan¹⁰⁰, A. Bassalat^{65,aj}, M.J. Basso¹⁶⁶, R.L. Bates⁵⁷, S. Batlamous^{35e}, J.R. Batley³², B. Batool¹⁵⁰, M. Battaglia¹⁴⁵, M. Bause^{73a,73b}, F. Bauer¹⁴⁴, K.T. Bauer¹⁷⁰, H.S. Bawa³¹, J.B. Beacham⁴⁹, T. Beau¹³⁵, P.H. Beauchemin¹⁶⁹, F. Becherer⁵², P. Bechtel²⁴, H.C. Beck⁵³, H.P. Beck^{20,q}, K. Becker¹⁷⁷, C. Becot⁴⁶, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁸⁰, M. Bedognetti¹²⁰, C.P. Bee¹⁵⁴, T.A. Beermann¹⁸¹, M. Begalli^{81b}, M. Begel²⁹, A. Behera¹⁵⁴, J.K. Behr⁴⁶, F. Beisiegel²⁴, A.S. Bell⁹⁵, G. Bella¹⁶⁰, L. Bellagamba^{23b}, A. Bellerive³⁴, P. Bellos⁹, K. Beloborodov^{122b,122a}, K. Belotskiy¹¹², N.L. Belyaev¹¹², D. Bencheikroun^{35a}, N. Benekos¹⁰, Y. Benhammou¹⁶⁰, D.P. Benjamin⁶, M. Benoit⁵⁴, J.R. Bensinger²⁶, S. Bentvelsen¹²⁰, L. Beresford¹³⁴, M. Beretta⁵¹, D. Berge¹⁹, E. Bergeas Kuutmann¹⁷¹, N. Berger⁵, B. Bergmann¹⁴¹, L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁷, G. Bernardi¹³⁵, C. Bernius¹⁵², F.U. Bernlochner²⁴, T. Berry⁹⁴, P. Berta¹⁰⁰, C. Bertella^{15a}, I.A. Bertram⁹⁰, O. Bessidskaia Bylund¹⁸¹, N. Besson¹⁴⁴, A. Bethani¹⁰¹,

S. Bethke¹¹⁵, A. Betti⁴², A.J. Bevan⁹³, J. Beyer¹¹⁵, D.S. Bhattacharya¹⁷⁶, P. Bhattacharai²⁶, R. Bi¹³⁸, R.M. Bianchi¹³⁸, O. Biebel¹¹⁴, D. Biedermann¹⁹, R. Bielski³⁶, K. Bierwagen¹⁰⁰, N.V. Biesuz^{72a,72b}, M. Biglietti^{75a}, T.R.V. Billoud¹¹⁰, M. Bindi⁵³, A. Bingul^{12d}, C. Bini^{73a,73b}, S. Biondi^{23b,23a}, M. Birman¹⁷⁹, T. Bisanz⁵³, J.P. Biswal³, D. Biswas^{180,i}, A. Bitadze¹⁰¹, C. Bittrich⁴⁸, K. Bjørke¹³³, T. Blazek^{28a}, I. Bloch⁴⁶, C. Blocker²⁶, A. Blue⁵⁷, U. Blumenschein⁹³, G.J. Bobbink¹²⁰, V.S. Bobrovnikov^{122b,122a}, S.S. Bocchetta⁹⁷, A. Bocci⁴⁹, D. Boerner⁴⁶, D. Bogavac¹⁴, A.G. Bogdanchikov^{122b,122a}, C. Bohm^{45a}, V. Boisvert⁹⁴, P. Bokan^{53,171}, T. Bold^{84a}, A.E. Bolz^{61b}, M. Bomben¹³⁵, M. Bona⁹³, J.S. Bonilla¹³¹, M. Boonekamp¹⁴⁴, C.D. Booth⁹⁴, H.M. Borecka-Bielska⁹¹, L.S. Borgna⁹⁵, A. Borisov¹²³, G. Borissov⁹⁰, J. Bortfeldt³⁶, D. Bortoletto¹³⁴, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola¹⁰⁴, K. Bouaouda^{35a}, J. Boudreau¹³⁸, E.V. Bouhova-Thacker⁹⁰, D. Boumediene³⁸, S.K. Boutle⁵⁷, A. Boveia¹²⁷, J. Boyd³⁶, D. Boye^{33c}, I.R. Boyko⁸⁰, A.J. Bozson⁹⁴, J. Bracinik²¹, N. Brahimi¹⁰², G. Brandt¹⁸¹, O. Brandt³², F. Braren⁴⁶, B. Brau¹⁰³, J.E. Brau¹³¹, W.D. Breaden Madden⁵⁷, K. Brendlinger⁴⁶, L. Brenner⁴⁶, R. Brenner¹⁷¹, S. Bressler¹⁷⁹, B. Brickwedde¹⁰⁰, D.L. Briglin²¹, D. Britton⁵⁷, D. Britzger¹¹⁵, I. Brock²⁴, R. Brock¹⁰⁷, G. Brooijmans³⁹, W.K. Brooks^{146d}, E. Brost²⁹, P.A. Bruckman de Renstrom⁸⁵, D. Bruncko^{28b}, A. Bruni^{23b}, G. Bruni^{23b}, L.S. Bruni¹²⁰, S. Bruno^{74a,74b}, M. Bruschi^{23b}, N. Bruscino^{73a,73b}, L. Bryngemark⁹⁷, T. Buanes¹⁷, Q. Buat³⁶, P. Buchholz¹⁵⁰, A.G. Buckley⁵⁷, I.A. Budagov⁸⁰, M.K. Bugge¹³³, F. Bühner⁵², O. Bulekov¹¹², T.J. Burch¹²¹, S. Burdin⁹¹, C.D. Burgard¹²⁰, A.M. Burger¹²⁹, B. Burghgrave⁸, J.T.P. Burr⁴⁶, C.D. Burton¹¹, J.C. Burzynski¹⁰³, V. Büscher¹⁰⁰, E. Buschmann⁵³, P.J. Bussey⁵⁷, J.M. Butler²⁵, C.M. Buttar⁵⁷, J.M. Butterworth⁹⁵, P. Butti³⁶, W. Buttinger³⁶, C.J. Buxo Vazquez¹⁰⁷, A. Buzatu¹⁵⁷, A.R. Buzykaev^{122b,122a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷³, D. Caforio⁵⁶, H. Cai¹⁷², V.M.M. Cairo¹⁵², O. Cakir^{4a}, N. Calace³⁶, P. Calafiura¹⁸, G. Calderini¹³⁵, P. Calfayan⁶⁶, G. Callea⁵⁷, L.P. Caloba^{81b}, A. Caltabiano^{74a,74b}, S. Calvente Lopez⁹⁹, D. Calvet³⁸, S. Calvet³⁸, T.P. Calvet¹⁵⁴, M. Calvetti^{72a,72b}, R. Camacho Toro¹³⁵, S. Camarda³⁶, D. Camarero Munoz⁹⁹, P. Camarri^{74a,74b}, M.T. Camerlingo^{75a,75b}, D. Cameron¹³³, C. Camincher³⁶, S. Campana³⁶, M. Campanelli⁹⁵, A. Camplani⁴⁰, A. Campoverde¹⁵⁰, V. Canale^{70a,70b}, A. Canesse¹⁰⁴, M. Cano Bret⁷⁸, J. Cantero¹²⁹, T. Cao¹⁶⁰, Y. Cao¹⁷², M.D.M. Capeans Garrido³⁶, M. Capua^{41b,41a}, R. Cardarelli^{74a}, F. Cardillo¹⁴⁸, G. Carducci^{41b,41a}, I. Carli¹⁴², T. Carli³⁶, G. Carlino^{70a}, B.T. Carlson¹³⁸, E.M. Carlson^{175,167a}, L. Carminati^{69a,69b}, R.M.D. Carney¹⁵², S. Caron¹¹⁹, E. Carquin^{146d}, S. Carrá⁴⁶, J.W.S. Carter¹⁶⁶, M.P. Casado^{14,e}, A.F. Casha¹⁶⁶, F.L. Castillo¹⁷³, L. Castillo Garcia¹⁴, V. Castillo Gimenez¹⁷³, N.F. Castro^{139a,139e}, A. Catinaccio³⁶, J.R. Catmore¹³³, A. Cattai³⁶, V. Cavaliere²⁹, E. Cavallaro¹⁴, V. Cavasinni^{72a,72b}, E. Celebi^{12b}, L. Cerda Alberich¹⁷³, K. Cerny¹³⁰, A.S. Cerqueira^{81a}, A. Cerri¹⁵⁵, L. Cerrito^{74a,74b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a}, S.A. Cetin^{12b}, Z. Chadi^{35a}, D. Chakraborty¹²¹, J. Chan¹⁸⁰, W.S. Chan¹²⁰, W.Y. Chan⁹¹, J.D. Chapman³², B. Chargeishvili^{158b}, D.G. Charlton²¹, T.P. Charman⁹³, C.C. Chau³⁴, S. Che¹²⁷, S. Chekanov⁶, S.V. Chekulaev^{167a}, G.A. Chelkov⁸⁰, B. Chen⁷⁹, C. Chen^{60a}, C.H. Chen⁷⁹, H. Chen²⁹, J. Chen^{60a}, J. Chen³⁹, J. Chen²⁶, S. Chen¹³⁶, S.J. Chen^{15c}, X. Chen^{15b}, Y. Chen^{60a}, Y.-H. Chen⁴⁶, H.C. Cheng^{63a}, H.J. Cheng^{15a}, A. Cheplakov⁸⁰, E. Cheremushkina¹²³, R. Cherkaoui El Moursli^{35e}, E. Cheu⁷, K. Cheung⁶⁴, T.J.A. Chevalérias¹⁴⁴, L. Chevalier¹⁴⁴, V. Chiarella⁵¹, G. Chiarelli^{72a}, G. Chiodini^{68a}, A.S. Chisholm²¹, A. Chitan^{27b}, I. Chiu¹⁶², Y.H. Chiu¹⁷⁵, M.V. Chizhov⁸⁰, K. Choi¹¹, A.R. Chomont^{73a,73b}, S. Chouridou¹⁶¹, Y.S. Chow¹²⁰, M.C. Chu^{63a}, X. Chu^{15a,15d}, J. Chudoba¹⁴⁰, J.J. Chwastowski⁸⁵, L. Chytka¹³⁰, D. Cieri¹¹⁵, K.M. Ciesla⁸⁵, D. Cinca⁴⁷, V. Cindro⁹², I.A. Cioară^{27b}, A. Ciochio¹⁸, F. Ciotto^{70a,70b}, Z.H. Citron^{179,j}, M. Citterio^{69a}, D.A. Ciubotaru^{27b}, B.M. Ciungu¹⁶⁶, A. Clark⁵⁴, M.R. Clark³⁹, P.J. Clark⁵⁰, S.E. Clawson¹⁰¹, C. Clement^{45a,45b}, Y. Coadou¹⁰², M. Cobal^{67a,67c}, A. Coccaro^{55b}, J. Cochran⁷⁹, R. Coelho Lopes De Sa¹⁰³, H. Cohen¹⁶⁰, A.E.C. Coimbra³⁶, B. Cole³⁹, A.P. Colijn¹²⁰, J. Collot⁵⁸, P. Conde Muiño^{139a,139h},

S.H. Connell^{33c}, I.A. Connelly⁵⁷, S. Constantinescu^{27b}, F. Conventi^{70a,an}, A.M. Cooper-Sarkar¹³⁴, F. Cormier¹⁷⁴, K.J.R. Cormier¹⁶⁶, L.D. Corpe⁹⁵, M. Corradi^{73a,73b}, E.E. Corrigan⁹⁷, F. Corriveau^{104,ac}, A. Cortes-Gonzalez³⁶, M.J. Costa¹⁷³, F. Costanza⁵, D. Costanzo¹⁴⁸, G. Cowan⁹⁴, J.W. Cowley³², J. Crane¹⁰¹, K. Cranmer¹²⁵, S.J. Crawley⁵⁷, R.A. Creager¹³⁶, S. Crépé-Renaudin⁵⁸, F. Crescioli¹³⁵, M. Cristinziani²⁴, V. Croft¹⁶⁹, G. Crosetti^{41b,41a}, A. Cueto⁵, T. Cuhadar Donszelmann¹⁷⁰, A.R. Cukierman¹⁵², W.R. Cunningham⁵⁷, S. Czekierda⁸⁵, P. Czodrowski³⁶, M.M. Czurylo^{61b}, M.J. Da Cunha Sargedas De Sousa^{60b}, J.V. Da Fonseca Pinto^{81b}, C. Da Via¹⁰¹, W. Dabrowski^{84a}, F. Dachs³⁶, T. Dado^{28a}, S. Dahbi^{33e}, T. Dai¹⁰⁶, C. Dallapiccola¹⁰³, M. Dam⁴⁰, G. D'amen²⁹, V. D'Amico^{75a,75b}, J. Damp¹⁰⁰, J.R. Dandoy¹³⁶, M.F. Daneri³⁰, N.S. Dann¹⁰¹, M. Danninger¹⁵¹, V. Dao³⁶, G. Darbo^{55b}, O. Dartsis⁵, A. Dattagupta¹³¹, T. Daubney⁴⁶, S. D'Auria^{69a,69b}, C. David^{167b}, T. Davidek¹⁴², D.R. Davis⁴⁹, I. Dawson¹⁴⁸, K. De⁸, R. De Asmundis^{70a}, M. De Beurs¹²⁰, S. De Castro^{23b,23a}, S. De Cecco^{73a,73b}, N. De Groot¹¹⁹, P. de Jong¹²⁰, H. De la Torre¹⁰⁷, A. De Maria^{15c}, D. De Pedis^{73a}, A. De Salvo^{73a}, U. De Sanctis^{74a,74b}, M. De Santis^{74a,74b}, A. De Santo¹⁵⁵, K. De Vasconcelos Corga¹⁰², J.B. De Vivie De Regie⁶⁵, C. Debenedetti¹⁴⁵, D.V. Dedovich⁸⁰, A.M. Deiana⁴², J. Del Peso⁹⁹, Y. Delabat Diaz⁴⁶, D. Delgove⁶⁵, F. Deliot^{144,p}, C.M. Delitzsch⁷, M. Della Pietra^{70a,70b}, D. Della Volpe⁵⁴, A. Dell'Acqua³⁶, L. Dell'Asta^{74a,74b}, M. Delmastro⁵, C. Delporte⁶⁵, P.A. Delsart⁵⁸, D.A. DeMarco¹⁶⁶, S. Demers¹⁸², M. Demichev⁸⁰, G. Demontigny¹¹⁰, S.P. Denisov¹²³, L. D'Eramo¹³⁵, D. Derendarz⁸⁵, J.E. Derkaoui^{35d}, F. Derue¹³⁵, P. Dervan⁹¹, K. Desch²⁴, C. Deterre⁴⁶, K. Dette¹⁶⁶, C. Deutsch²⁴, M.R. Devesa³⁰, P.O. Deviveiros³⁶, F.A. Di Bello^{73a,73b}, A. Di Ciaccio^{74a,74b}, L. Di Ciaccio⁵, W.K. Di Clemente¹³⁶, C. Di Donato^{70a,70b}, A. Di Girolamo³⁶, G. Di Gregorio^{72a,72b}, B. Di Micco^{75a,75b}, R. Di Nardo^{75a,75b}, K.F. Di Petrillo⁵⁹, R. Di Sipio¹⁶⁶, C. Diaconu¹⁰², F.A. Dias⁴⁰, T. Dias Do Vale^{139a}, M.A. Diaz^{146a}, J. Dickinson¹⁸, E.B. Diehl¹⁰⁶, J. Dietrich¹⁹, S. Díez Cornell⁴⁶, A. Dimitrievska¹⁸, W. Ding^{15b}, J. Dingfelder²⁴, F. Dittus³⁶, F. Djama¹⁰², T. Djobava^{158b}, J.I. Djuvsland¹⁷, M.A.B. Do Vale^{81c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁷, J. Dolejsi¹⁴², Z. Dolezal¹⁴², M. Donadelli^{81d}, B. Dong^{60c}, J. Donini³⁸, A. D'Onofrio^{15c}, M. D'Onofrio⁹¹, J. Dopke¹⁴³, A. Doria^{70a}, M.T. Dova⁸⁹, A.T. Doyle⁵⁷, E. Drechsler¹⁵¹, E. Dreyer¹⁵¹, T. Dreyer⁵³, A.S. Drobac¹⁶⁹, D. Du^{60b}, Y. Duan^{60b}, F. Dubinin¹¹¹, M. Dubovsky^{28a}, A. Dubreuil⁵⁴, E. Duchovni¹⁷⁹, G. Duckeck¹¹⁴, O.A. Ducu¹¹⁰, D. Duda¹¹⁵, A. Dudarev³⁶, A.C. Dudder¹⁰⁰, E.M. Duffield¹⁸, L. Dufflot⁶⁵, M. Dührssen³⁶, C. Dülsen¹⁸¹, M. Dumancic¹⁷⁹, A.E. Dumitriu^{27b}, A.K. Duncan⁵⁷, M. Dunford^{61a}, A. Duperrin¹⁰², H. Duran Yildiz^{4a}, M. Düren⁵⁶, A. Durglishvili^{158b}, D. Duschinger⁴⁸, B. Dutta⁴⁶, D. Duvnjak¹, G.I. Dyckes¹³⁶, M. Dyndal³⁶, S. Dysch¹⁰¹, B.S. Dziedzic⁸⁵, K.M. Ecker¹¹⁵, M.G. Eggleston⁴⁹, T. Eifert⁸, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof¹⁷¹, H. El Jarrari^{35e}, R. El Kosseifi¹⁰², V. Ellajosyula¹⁷¹, M. Ellert¹⁷¹, F. Ellinghaus¹⁸¹, A.A. Elliot⁹³, N. Ellis³⁶, J. Elmsheuser²⁹, M. Elsing³⁶, D. Emelianov¹⁴³, A. Emerman³⁹, Y. Enari¹⁶², M.B. Epland⁴⁹, J. Erdmann⁴⁷, A. Ereditato²⁰, P.A. Erland⁸⁵, M. Errenst³⁶, M. Escalier⁶⁵, C. Escobar¹⁷³, O. Estrada Pastor¹⁷³, E. Etzion¹⁶⁰, H. Evans⁶⁶, M.O. Evans¹⁵⁵, A. Ezhilov¹³⁷, F. Fabbri⁵⁷, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁹, G. Facini¹⁷⁷, R.M. Faisca Rodrigues Pereira^{139a}, R.M. Fakhruddinov¹²³, S. Falciano^{73a}, P.J. Falke²⁴, S. Falke³⁶, J. Faltova¹⁴², Y. Fang^{15a}, Y. Fang^{15a}, G. Fanourakis⁴⁴, M. Fanti^{69a,69b}, M. Faraj^{67a,67c,r}, A. Farbin⁸, A. Farilla^{75a}, E.M. Farina^{71a,71b}, T. Farooque¹⁰⁷, S.M. Farrington⁵⁰, P. Farthouat³⁶, F. Fassi^{35e}, P. Fassnacht³⁶, D. Fassouliotis⁹, M. Faucci Giannelli⁵⁰, W.J. Fawcett³², L. Fayard⁶⁵, O.L. Fedin^{137,o}, W. Fedorko¹⁷⁴, A. Fehr²⁰, M. Feickert¹⁷², L. Feligioni¹⁰², A. Fell¹⁴⁸, C. Feng^{60b}, M. Feng⁴⁹, M.J. Fenton¹⁷⁰, A.B. Fenyuk¹²³, S.W. Ferguson⁴³, J. Ferrando⁴⁶, A. Ferrante¹⁷², A. Ferrari¹⁷¹, P. Ferrari¹²⁰, R. Ferrari^{71a}, D.E. Ferreira de Lima^{61b}, A. Ferrer¹⁷³, D. Ferrere⁵⁴, C. Ferretti¹⁰⁶, F. Fiedler¹⁰⁰, A. Filipčić⁹², F. Filthaut¹¹⁹, K.D. Finelli²⁵, M.C.N. Fiolhais^{139a,139c,a}, L. Fiorini¹⁷³, F. Fischer¹¹⁴, W.C. Fisher¹⁰⁷, I. Fleck¹⁵⁰,

P. Fleischmann¹⁰⁶, T. Flick¹⁸¹, B.M. Flierl¹¹⁴, L. Flores¹³⁶, L.R. Flores Castillo^{63a},
F.M. Follega^{76a,76b}, N. Fomin¹⁷, J.H. Foo¹⁶⁶, G.T. Forcolin^{76a,76b}, A. Formica¹⁴⁴, F.A. Förster¹⁴,
A.C. Forti¹⁰¹, E. Fortin¹⁰², M.G. Foti¹³⁴, D. Fournier⁶⁵, H. Fox⁹⁰, P. Francavilla^{72a,72b},
S. Francescato^{73a,73b}, M. Franchini^{23b,23a}, S. Franchino^{61a}, D. Francis³⁶, L. Franco⁵,
L. Franconi²⁰, M. Franklin⁵⁹, A.N. Fray⁹³, P.M. Freeman²¹, B. Freund¹¹⁰, W.S. Freund^{81b},
E.M. Freundlich⁴⁷, D.C. Frizzell¹²⁸, D. Froidevaux³⁶, J.A. Frost¹³⁴, M. Fujimoto¹²⁶,
C. Fukunaga¹⁶³, E. Fullana Torregrosa¹⁷³, T. Fusayasu¹¹⁶, J. Fuster¹⁷³, A. Gabrielli^{23b,23a},
A. Gabrielli¹⁸, S. Gadatsch⁵⁴, P. Gadow¹¹⁵, G. Gagliardi^{55b,55a}, L.G. Gagnon¹¹⁰, B. Galhardo^{139a},
G.E. Gallardo¹³⁴, E.J. Gallas¹³⁴, B.J. Gallop¹⁴³, G. Galster⁴⁰, R. Gamboa Goni⁹³, K.K. Gan¹²⁷,
S. Ganguly¹⁷⁹, J. Gao^{60a}, Y. Gao⁵⁰, Y.S. Gao^{31,l}, C. García¹⁷³, J.E. García Navarro¹⁷³,
J.A. García Pascual^{15a}, C. Garcia-Argos⁵², M. Garcia-Sciveres¹⁸, R.W. Gardner³⁷, N. Garelli¹⁵²,
S. Gargiulo⁵², C.A. Garner¹⁶⁶, V. Garonne¹³³, S.J. Gasirowski¹⁴⁷, P. Gaspar^{81b},
A. Gaudiello^{55b,55a}, G. Gaudio^{71a}, I.L. Gavrilenko¹¹¹, A. Gavriluk¹²⁴, C. Gay¹⁷⁴, G. Gaycken⁴⁶,
E.N. Gazis¹⁰, A.A. Geanta^{27b}, C.M. Gee¹⁴⁵, C.N.P. Gee¹⁴³, J. Geisen⁹⁷, M. Geisen¹⁰⁰,
C. Gemme^{55b}, M.H. Genest⁵⁸, C. Geng¹⁰⁶, S. Gentile^{73a,73b}, S. George⁹⁴, T. Geralis⁴⁴,
L.O. Gerlach⁵³, P. Gessinger-Befurt¹⁰⁰, G. Gessner⁴⁷, S. Ghasemi¹⁵⁰, M. Ghasemi Bostanabad¹⁷⁵,
M. Ghneimat¹⁵⁰, A. Ghosh⁶⁵, A. Ghosh⁷⁸, B. Giacobbe^{23b}, S. Giagu^{73a,73b}, N. Giangiacomi^{23b,23a},
P. Giannetti^{72a}, A. Giannini^{70a,70b}, G. Giannini¹⁴, S.M. Gibson⁹⁴, M. Gignac¹⁴⁵, D. Gillberg³⁴,
G. Gilles¹⁸¹, D.M. Gingrich^{3,am}, M.P. Giordani^{67a,67c}, P.F. Giraud¹⁴⁴, G. Giugliarelli^{67a,67c},
D. Giugni^{69a}, F. Giuli^{74a,74b}, S. Gkaitatzis¹⁶¹, I. Gkialas^{9,g}, E.L. Gkoukousis¹⁴,
P. Gkoutoumis¹⁰, L.K. Gladilin¹¹³, C. Glasman⁹⁹, J. Glatzer¹⁴, P.C.F. Glaysheer⁴⁶, A. Glazov⁴⁶,
G.R. Gledhill¹³¹, I. Gnesi^{41b}, M. Goblirsch-Kolb²⁶, D. Godin¹¹⁰, S. Goldfarb¹⁰⁵, T. Golling⁵⁴,
D. Golubkov¹²³, A. Gomes^{139a,139b}, R. Goncalves Gama⁵³, R. Gonçalo^{139a}, G. Gonella¹³¹,
L. Gonella²¹, A. Gongadze⁸⁰, F. Gonnella²¹, J.L. Gonski³⁹, S. González de la Hoz¹⁷³,
S. Gonzalez Fernandez¹⁴, C. Gonzalez Renteria¹⁸, R. Gonzalez Suarez¹⁷¹, S. Gonzalez-Sevilla⁵⁴,
G.R. Gonzalvo Rodriguez¹⁷³, L. Goossens³⁶, N.A. Gorasia²¹, P.A. Gorbounov¹²⁴, H.A. Gordon²⁹,
B. Gorini³⁶, E. Gorini^{68a,68b}, A. Gorišek⁹², A.T. Goshaw⁴⁹, M.I. Gostkin⁸⁰, C.A. Gottardo¹¹⁹,
M. Gouighri^{35b}, A.G. Goussiou¹⁴⁷, N. Govender^{33c}, C. Goy⁵, E. Gozani¹⁵⁹, I. Grabowska-Bold^{84a},
E.C. Graham⁹¹, J. Gramling¹⁷⁰, E. Gramstad¹³³, S. Grancagnolo¹⁹, M. Grandi¹⁵⁵,
V. Gratchev¹³⁷, P.M. Gravila^{27f}, F.G. Gravili^{68a,68b}, C. Gray⁵⁷, H.M. Gray¹⁸, C. Grefe²⁴,
K. Gregersen⁹⁷, I.M. Gregor⁴⁶, P. Grenier¹⁵², K. Grevtsov⁴⁶, C. Grieco¹⁴, N.A. Grieser¹²⁸,
A.A. Grillo¹⁴⁵, K. Grimm^{31,k}, S. Grinstein^{14,x}, J.-F. Grivaz⁶⁵, S. Groh¹⁰⁰, E. Gross¹⁷⁹,
J. Grosse-Knetter⁵³, Z.J. Grout⁹⁵, C. Grud¹⁰⁶, A. Grummer¹¹⁸, J.C. Grundy¹³⁴, L. Guan¹⁰⁶,
W. Guan¹⁸⁰, C. Gubbels¹⁷⁴, J. Guenther³⁶, A. Guerguichon⁶⁵, J.G.R. Guerrero Rojas¹⁷³,
F. Guescini¹¹⁵, D. Guest¹⁷⁰, R. Gugel⁵², T. Guillemin⁵, S. Guindon³⁶, U. Gul⁵⁷, J. Guo^{60c},
W. Guo¹⁰⁶, Y. Guo^{60a}, Z. Guo¹⁰², R. Gupta⁴⁶, S. Gurbuz^{12c}, G. Gustavino¹²⁸, M. Guth⁵²,
P. Gutierrez¹²⁸, C. Gutsche⁹⁵, C. Guyot¹⁴⁴, C. Gwenlan¹³⁴, C.B. Gwilliam⁹¹, A. Haas¹²⁵,
C. Haber¹⁸, H.K. Hadavand⁸, A. Hader^{60a}, M. Haleem¹⁷⁶, J. Haley¹²⁹, J.J. Hall¹⁴⁸,
G. Halladjian¹⁰⁷, G.D. Hallewell¹⁰², K. Hamacher¹⁸¹, P. Hamal¹³⁰, K. Hamano¹⁷⁵,
H. Hamdaoui^{35e}, M. Hamer²⁴, G.N. Hamity⁵⁰, K. Han^{60a,w}, L. Han^{60a}, S. Han^{15a}, Y.F. Han¹⁶⁶,
K. Hanagaki^{82,u}, M. Hance¹⁴⁵, D.M. Handl¹¹⁴, B. Haney¹³⁶, M.D. Hank³⁷, R. Hankache¹³⁵,
E. Hansen⁹⁷, J.B. Hansen⁴⁰, J.D. Hansen⁴⁰, M.C. Hansen²⁴, P.H. Hansen⁴⁰, E.C. Hanson¹⁰¹,
K. Hara¹⁶⁸, T. Harenberg¹⁸¹, S. Harkusha¹⁰⁸, P.F. Harrison¹⁷⁷, N.M. Hartman¹⁵²,
N.M. Hartmann¹¹⁴, Y. Hasegawa¹⁴⁹, A. Hasib⁵⁰, S. Hassani¹⁴⁴, S. Haug²⁰, R. Hauser¹⁰⁷,
L.B. Havener³⁹, M. Havranek¹⁴¹, C.M. Hawkes²¹, R.J. Hawkings³⁶, S. Hayashida¹¹⁷,
D. Hayden¹⁰⁷, C. Hayes¹⁰⁶, R.L. Hayes¹⁷⁴, C.P. Hays¹³⁴, J.M. Hays⁹³, H.S. Hayward⁹¹,
S.J. Haywood¹⁴³, F. He^{60a}, M.P. Heath⁵⁰, V. Hedberg⁹⁷, S. Heer²⁴, A.L. Heggelund¹³³,
K.K. Heidegger⁵², W.D. Heidorn⁷⁹, J. Heilman³⁴, S. Heim⁴⁶, T. Heim¹⁸, B. Heinemann^{46,ak},

J.J. Heinrich¹³¹, L. Heinrich³⁶, J. Hejbal¹⁴⁰, L. Helary^{61b}, A. Held¹²⁵, S. Hellesund¹³³, C.M. Helling¹⁴⁵, S. Hellman^{45a,45b}, C. Helsens³⁶, R.C.W. Henderson⁹⁰, Y. Heng¹⁸⁰, L. Henkelmann³², A.M. Henriques Correia³⁶, H. Herde²⁶, Y. Hernández Jiménez^{33e}, H. Herr¹⁰⁰, M.G. Herrmann¹¹⁴, T. Herrmann⁴⁸, G. Herten⁵², R. Hertenberger¹¹⁴, L. Hervas³⁶, T.C. Herwig¹³⁶, G.G. Hesketh⁹⁵, N.P. Hessey^{167a}, H. Hibi⁸³, A. Higashida¹⁶², S. Higashino⁸², E. Higón-Rodríguez¹⁷³, K. Hildebrand³⁷, J.C. Hill³², K.K. Hill²⁹, K.H. Hiller⁴⁶, S.J. Hillier²¹, M. Hils⁴⁸, I. Hinchliffe¹⁸, F. Hinterkeuser²⁴, M. Hirose¹³², S. Hirose⁵², D. Hirschbuehl¹⁸¹, B. Hiti⁹², O. Hladik¹⁴⁰, D.R. Hlaluku^{33e}, J. Hobbs¹⁵⁴, N. Hod¹⁷⁹, M.C. Hodgkinson¹⁴⁸, A. Hoecker³⁶, D. Hohn⁵², D. Hohov⁶⁵, T. Holm²⁴, T.R. Holmes³⁷, M. Holzbock¹¹⁴, L.B.A.H. Hommels³², T.M. Hong¹³⁸, J.C. Honig⁵², A. Hönle¹¹⁵, B.H. Hooberman¹⁷², W.H. Hopkins⁶, Y. Horii¹¹⁷, P. Horn⁴⁸, L.A. Horyn³⁷, S. Hou¹⁵⁷, A. Hoummada^{35a}, J. Howarth⁵⁷, J. Hoya⁸⁹, M. Hrabovsky¹³⁰, J. Hrdinka⁷⁷, I. Hristova¹⁹, J. Hrivnac⁶⁵, A. Hrynevich¹⁰⁹, T. Hryn'ova⁵, P.J. Hsu⁶⁴, S.-C. Hsu¹⁴⁷, Q. Hu²⁹, S. Hu^{60c}, Y.F. Hu^{15a,15d}, D.P. Huang⁹⁵, Y. Huang^{60a}, Y. Huang^{15a}, Z. Hubacek¹⁴¹, F. Hubaut¹⁰², M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³⁴, M. Huhtinen³⁶, R.F.H. Hunter³⁴, P. Huo¹⁵⁴, N. Huseynov^{80,ad}, J. Huston¹⁰⁷, J. Huth⁵⁹, R. Hyneman¹⁰⁶, S. Hyrych^{28a}, G. Iacobucci⁵⁴, G. Iakovidis²⁹, I. Ibragimov¹⁵⁰, L. Iconomidou-Fayard⁶⁵, P. Iengo³⁶, R. Ignazzi⁴⁰, O. Igonkina^{120,z,*}, R. Iguchi¹⁶², T. Iizawa⁵⁴, Y. Ikegami⁸², M. Ikeno⁸², D. Iliadis¹⁶¹, N. Ilic^{119,166,ac}, F. Iltzsche⁴⁸, G. Introzzi^{71a,71b}, M. Iodice^{75a}, K. Iordanidou^{167a}, V. Ippolito^{73a,73b}, M.F. Isacson¹⁷¹, M. Ishino¹⁶², W. Islam¹²⁹, C. Issever^{19,46}, S. Istin¹⁵⁹, F. Ito¹⁶⁸, J.M. Iturbe Ponce^{63a}, R. Iuppa^{76a,76b}, A. Ivina¹⁷⁹, H. Iwasaki⁸², J.M. Izen⁴³, V. Izzo^{70a}, P. Jacka¹⁴⁰, P. Jackson¹, R.M. Jacobs⁴⁶, B.P. Jaeger¹⁵¹, V. Jain², G. Jäkel¹⁸¹, K.B. Jakobi¹⁰⁰, K. Jakobs⁵², T. Jakoubek¹⁴⁰, J. Jamieson⁵⁷, K.W. Janas^{84a}, R. Jansky⁵⁴, M. Janus⁵³, P.A. Janus^{84a}, G. Jarlskog⁹⁷, A.E. Jaspan⁹¹, N. Javadov^{80,ad}, T. Javůrek³⁶, M. Javurkova¹⁰³, F. Jeanneau¹⁴⁴, L. Jeanty¹³¹, J. Jejelava^{158a}, A. Jelinskas¹⁷⁷, P. Jenni^{52,b}, N. Jeong⁴⁶, S. Jézéquel⁵, H. Ji¹⁸⁰, J. Jia¹⁵⁴, H. Jiang⁷⁹, Y. Jiang^{60a}, Z. Jiang¹⁵², S. Jiggins⁵², F.A. Jimenez Morales³⁸, J. Jimenez Pena¹¹⁵, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶⁴, H. Jivan^{33e}, P. Johansson¹⁴⁸, K.A. Johns⁷, C.A. Johnson⁶⁶, R.W.L. Jones⁹⁰, S.D. Jones¹⁵⁵, S. Jones⁷, T.J. Jones⁹¹, J. Jongmanns^{61a}, P.M. Jorge^{139a}, J. Jovicevic³⁶, X. Ju¹⁸, J.J. Junggeburth¹¹⁵, A. Juste Rozas^{14,x}, A. Kaczmarska⁸⁵, M. Kado^{73a,73b}, H. Kagan¹²⁷, M. Kagan¹⁵², A. Kahn³⁹, C. Kahra¹⁰⁰, T. Kaji¹⁷⁸, E. Kajomovitz¹⁵⁹, C.W. Kalderon²⁹, A. Kaluza¹⁰⁰, A. Kamenshchikov¹²³, M. Kaneda¹⁶², N.J. Kang¹⁴⁵, S. Kang⁷⁹, Y. Kano¹¹⁷, J. Kanzaki⁸², L.S. Kaplan¹⁸⁰, D. Kar^{33e}, K. Karava¹³⁴, M.J. Kareem^{167b}, I. Karkanias¹⁶¹, S.N. Karpov⁸⁰, Z.M. Karpova⁸⁰, V. Kartvelishvili⁹⁰, A.N. Karyukhin¹²³, A. Kastanas^{45a,45b}, C. Kato^{60d,60c}, J. Katzy⁴⁶, K. Kawade¹⁴⁹, K. Kawagoe⁸⁸, T. Kawaguchi¹¹⁷, T. Kawamoto¹⁴⁴, G. Kawamura⁵³, E.F. Kay¹⁷⁵, S. Kazakos¹⁴, V.F. Kazanin^{122b,122a}, R. Keeler¹⁷⁵, R. Kehoe⁴², J.S. Keller³⁴, E. Kellermann⁹⁷, D. Kelsey¹⁵⁵, J.J. Kempster²¹, J. Kendrick²¹, K.E. Kennedy³⁹, O. Kepka¹⁴⁰, S. Kersten¹⁸¹, B.P. Kerševan⁹², S. Ketabchi Haghighat¹⁶⁶, M. Khader¹⁷², F. Khalil-Zada¹³, M. Khandoga¹⁴⁴, A. Khanov¹²⁹, A.G. Kharlamov^{122b,122a}, T. Kharlamova^{122b,122a}, E.E. Khoda¹⁷⁴, A. Khodinov¹⁶⁵, T.J. Khoo⁵⁴, E. Khramov⁸⁰, J. Khubua^{158b}, S. Kido⁸³, M. Kiehn⁵⁴, C.R. Kilby⁹⁴, E. Kim¹⁶⁴, Y.K. Kim³⁷, N. Kimura⁹⁵, O.M. Kind¹⁹, B.T. King^{91,*}, D. Kirchmeier⁴⁸, J. Kirk¹⁴³, A.E. Kiryunin¹¹⁵, T. Kishimoto¹⁶², D.P. Kisliuk¹⁶⁶, V. Kitali⁴⁶, C. Kitsaki¹⁰, O. Kivernyk²⁴, T. Klapdor-Kleingrothaus⁵², M. Klassen^{61a}, C. Klein³⁴, M.H. Klein¹⁰⁶, M. Klein⁹¹, U. Klein⁹¹, K. Kleinknecht¹⁰⁰, P. Klimek¹²¹, A. Klimentov²⁹, T. Klingl²⁴, T. Klioutchnikova³⁶, F.F. Klitzner¹¹⁴, P. Kluit¹²⁰, S. Kluth¹¹⁵, E. Kneringer⁷⁷, E.B.F.G. Knoops¹⁰², A. Knue⁵², D. Kobayashi⁸⁸, T. Kobayashi¹⁶², M. Kobel⁴⁸, M. Kocian¹⁵², T. Kodama¹⁶², P. Kodys¹⁴², D.M. Koeck¹⁵⁵, P.T. Koenig²⁴, T. Koffas³⁴, N.M. Köhler³⁶, M. Kolb¹⁴⁴, I. Koletsou⁵, T. Komarek¹³⁰, T. Kondo⁸², K. Köneke⁵², A.X.Y. Kong¹, A.C. König¹¹⁹, T. Kono¹²⁶, V. Konstantinides⁹⁵, N. Konstantinidis⁹⁵, B. Konya⁹⁷,

R. Kopeliansky⁶⁶, S. Koperny^{84a}, K. Korcyl⁸⁵, K. Kordas¹⁶¹, G. Koren¹⁶⁰, A. Korn⁹⁵,
I. Korolkov¹⁴, E.V. Korolkova¹⁴⁸, N. Korotkova¹¹³, O. Kortner¹¹⁵, S. Kortner¹¹⁵,
V.V. Kostyukhin^{148,165}, A. Kotskechagia⁶⁵, A. Kotwal⁴⁹, A. Koulouris¹⁰,
A. Kourkouveli-Charalampidi^{71a,71b}, C. Kourkouvelis⁹, E. Kourlitis¹⁴⁸, V. Kouskoura²⁹,
A.B. Kowalewska⁸⁵, R. Kowalewski¹⁷⁵, W. Kozanecki¹⁰¹, A.S. Kozhin¹²³, V.A. Kramarenko¹¹³,
G. Kramberger⁹², D. Krasnopevtsev^{60a}, M.W. Krasny¹³⁵, A. Krasznahorkay³⁶, D. Krauss¹¹⁵,
J.A. Kremer¹⁰⁰, J. Kretzschmar⁹¹, P. Krieger¹⁶⁶, F. Krieter¹¹⁴, A. Krishnan^{61b}, K. Krizka¹⁸,
K. Kroeninger⁴⁷, H. Kroha¹¹⁵, J. Kroll¹⁴⁰, J. Kroll¹³⁶, K.S. Krowpman¹⁰⁷, U. Kruchonak⁸⁰,
H. Krüger²⁴, N. Krumnack⁷⁹, M.C. Kruse⁴⁹, J.A. Krzysiak⁸⁵, T. Kubota¹⁰⁵, O. Kuchinskaia¹⁶⁵,
S. Kunday^{4b}, J.T. Kuechler⁴⁶, S. Kuehn³⁶, A. Kugel^{61a}, T. Kuhl⁴⁶, V. Kukhtin⁸⁰,
Y. Kulchitsky^{108,af}, S. Kuleshov^{146b}, Y.P. Kulinich¹⁷², M. Kuna⁵⁸, T. Kunigo⁸⁶, A. Kupco¹⁴⁰,
T. Kupfer⁴⁷, O. Kuprash⁵², H. Kurashige⁸³, L.L. Kurchaninov^{167a}, Y.A. Kurochkin¹⁰⁸,
A. Kurova¹¹², M.G. Kurth^{15a,15d}, E.S. Kuwertz³⁶, M. Kuze¹⁶⁴, A.K. Kvam¹⁴⁷, J. Kvita¹³⁰,
T. Kwan¹⁰⁴, L. La Rotonda^{41b,41a}, F. La Ruffa^{41b,41a}, C. Lacasta¹⁷³, F. Lacava^{73a,73b},
D.P.J. Lack¹⁰¹, H. Lacker¹⁹, D. Lacour¹³⁵, E. Ladygin⁸⁰, R. Lafaye⁵, B. Laforge¹³⁵,
T. Lagouri^{146b}, S. Lai⁵³, I.K. Lakomic^{84a}, S. Lammers⁶⁶, W. Lampl⁷, C. Lampoudis¹⁶¹,
E. Lançon²⁹, U. Landgraf⁵², M.P.J. Landon⁹³, M.C. Lanfermann⁵⁴, V.S. Lang⁵², J.C. Lange⁵³,
R.J. Langenberg¹⁰³, A.J. Lankford¹⁷⁰, F. Lanni²⁹, K. Lantzsch²⁴, A. Lanza^{71a},
A. Lapertosa^{55b,55a}, S. Laplace¹³⁵, J.F. Laporte¹⁴⁴, T. Lari^{69a}, F. Lasagni Manghi^{23b,23a},
M. Lassnig³⁶, T.S. Lau^{63a}, A. Laudrain⁶⁵, A. Laurier³⁴, M. Lavorgna^{70a,70b}, S.D. Lawlor⁹⁴,
M. Lazzaroni^{69a,69b}, B. Le¹⁰¹, E. Le Guirriec¹⁰², A. Lebedev⁷⁹, M. LeBlanc⁷, T. LeCompte⁶,
F. Ledroit-Guillon⁵⁸, A.C.A. Lee⁹⁵, C.A. Lee²⁹, G.R. Lee¹⁷, L. Lee⁵⁹, S.C. Lee¹⁵⁷, S. Lee⁷⁹,
B. Lefebvre^{167a}, H.P. Lefebvre⁹⁴, M. Lefebvre¹⁷⁵, C. Leggett¹⁸, K. Lehmann¹⁵¹, N. Lehmann²⁰,
G. Lehmann Miotto³⁶, W.A. Leight⁴⁶, A. Leisos^{161,v}, M.A.L. Leite^{81d}, C.E. Leitgeb¹¹⁴,
R. Leitner¹⁴², D. Lellouch^{179,*}, K.J.C. Leney⁴², T. Lenz²⁴, R. Leone⁷, S. Leone^{72a},
C. Leonidopoulos⁵⁰, A. Leopold¹³⁵, C. Leroy¹¹⁰, R. Les¹⁶⁶, C.G. Lester³², M. Levchenko¹³⁷,
J. Levêque⁵, D. Levin¹⁰⁶, L.J. Levinson¹⁷⁹, D.J. Lewis²¹, B. Li^{15b}, B. Li¹⁰⁶, C-Q. Li^{60a}, F. Li^{60c},
H. Li^{60a}, H. Li^{60b}, J. Li^{60c}, K. Li¹⁴⁷, L. Li^{60c}, M. Li^{15a,15d}, Q. Li^{15a,15d}, Q.Y. Li^{60a}, S. Li^{60d,60c},
X. Li⁴⁶, Y. Li⁴⁶, Z. Li^{60b}, Z. Li¹⁰⁴, Z. Liang^{15a}, M. Liberatore⁴⁶, B. Liberti^{74a}, A. Liblong¹⁶⁶,
K. Lie^{63c}, S. Lim²⁹, C.Y. Lin³², K. Lin¹⁰⁷, T.H. Lin¹⁰⁰, R.A. Linck⁶⁶, R.E. Lindley⁷,
J.H. Lindon²¹, A.L. Lioni⁵⁴, E. Lipeles¹³⁶, A. Lipniacka¹⁷, T.M. Liss^{172,al}, A. Lister¹⁷⁴,
J.D. Little⁸, B. Liu⁷⁹, B.L. Liu⁶, H.B. Liu²⁹, H. Liu¹⁰⁶, J.B. Liu^{60a}, J.K.K. Liu³⁷, K. Liu^{60d},
M. Liu^{60a}, P. Liu^{15a}, Y. Liu⁴⁶, Y. Liu^{15a,15d}, Y.L. Liu¹⁰⁶, Y.W. Liu^{60a}, M. Livan^{71a,71b},
A. Lleres⁵⁸, J. Llorente Merino¹⁵¹, S.L. Lloyd⁹³, C.Y. Lo^{63b}, E.M. Lobodzinska⁴⁶, P. Loch⁷,
S. Loffredo^{74a,74b}, T. Lohse¹⁹, K. Lohwasser¹⁴⁸, M. Lokajicek¹⁴⁰, J.D. Long¹⁷², R.E. Long⁹⁰,
L. Longo³⁶, K.A.Looper¹²⁷, I. Lopez Paz¹⁰¹, A. Lopez Solis¹⁴⁸, J. Lorenz¹¹⁴,
N. Lorenzo Martinez⁵, A.M. Lory¹¹⁴, P.J. Lösel¹¹⁴, A. Lösle⁵², X. Lou⁴⁶, X. Lou^{15a}, A. Lounis⁶⁵,
J. Love⁶, P.A. Love⁹⁰, J.J. Lozano Bahilo¹⁷³, M. Lu^{60a}, Y.J. Lu⁶⁴, H.J. Lubatti¹⁴⁷, C. Luci^{73a,73b},
A. Lucotte⁵⁸, C. Luedtke⁵², F. Luehring⁶⁶, I. Luise¹³⁵, L. Luminari^{73a}, B. Lund-Jensen¹⁵³,
M.S. Lutz¹⁶⁰, D. Lynn²⁹, H. Lyons⁹¹, R. Lysak¹⁴⁰, E. Lytken⁹⁷, F. Lyu^{15a}, V. Lyubushkin⁸⁰,
T. Lyubushkina⁸⁰, H. Ma²⁹, L.L. Ma^{60b}, Y. Ma⁹⁵, G. Maccarrone⁵¹, A. Macchiolo¹¹⁵,
C.M. Macdonald¹⁴⁸, J. Machado Miguens¹³⁶, D. Madaffari¹⁷³, R. Madar³⁸, W.F. Mader⁴⁸,
M. Madugoda Ralalage Don¹²⁹, N. Madysa⁴⁸, J. Maeda⁸³, T. Maeno²⁹, M. Maerker⁴⁸,
V. Magerl⁵², N. Magini⁷⁹, J. Magro^{67a,67c,r}, D.J. Mahon³⁹, C. Maidantchik^{81b}, T. Maier¹¹⁴,
A. Maio^{139a,139b,139d}, K. Maj^{84a}, O. Majersky^{28a}, S. Majewski¹³¹, Y. Makida⁸², N. Makovec⁶⁵,
B. Malaescu¹³⁵, Pa. Malecki⁸⁵, V.P. Maleev¹³⁷, F. Malek⁵⁸, U. Mallik⁷⁸, D. Malon⁶, C. Malone³²,
S. Maltezos¹⁰, S. Malyukov⁸⁰, J. Mamuzic¹⁷³, G. Mancini⁵¹, I. Mandić⁹²,
L. Manhaes de Andrade Filho^{81a}, I.M. Maniatis¹⁶¹, J. Manjarres Ramos⁴⁸, K.H. Mankinen⁹⁷,

A. Mann¹¹⁴, A. Manousos⁷⁷, B. Mansoulie¹⁴⁴, I. Manthos¹⁶¹, S. Manzoni¹²⁰, A. Marantis¹⁶¹,
 G. Marceca³⁰, L. Marchese¹³⁴, G. Marchiori¹³⁵, M. Marcisovsky¹⁴⁰, L. Marcoccia^{74a,74b},
 C. Marcon⁹⁷, C.A. Marin Tobon³⁶, M. Marjanovic¹²⁸, Z. Marshall¹⁸, M.U.F. Martensson¹⁷¹,
 S. Marti-Garcia¹⁷³, C.B. Martin¹²⁷, T.A. Martin¹⁷⁷, V.J. Martin⁵⁰, B. Martin dit Latour¹⁷,
 L. Martinelli^{75a,75b}, M. Martinez^{14,x}, P. Martinez Agullo¹⁷³, V.I. Martinez Outschoorn¹⁰³,
 S. Martin-Haugh¹⁴³, V.S. Martoiu^{27b}, A.C. Martyniuk⁹⁵, A. Marzin³⁶, S.R. Maschek¹¹⁵,
 L. Masetti¹⁰⁰, T. Mashimo¹⁶², R. Mashinistov¹¹¹, J. Masik¹⁰¹, A.L. Maslennikov^{122b,122a},
 L. Massa^{23b,23a}, P. Massarotti^{70a,70b}, P. Mastrandrea^{72a,72b}, A. Mastroberardino^{41b,41a},
 T. Masubuchi¹⁶², D. Matakias²⁹, A. Matic¹¹⁴, N. Matsuzawa¹⁶², P. Mättig²⁴, J. Maurer^{27b},
 B. Maček⁹², D.A. Maximov^{122b,122a}, R. Mazini¹⁵⁷, I. Maznas¹⁶¹, S.M. Mazza¹⁴⁵,
 J.P. Mc Gowan¹⁰⁴, S.P. Mc Kee¹⁰⁶, T.G. McCarthy¹¹⁵, W.P. McCormack¹⁸, E.F. McDonald¹⁰⁵,
 J.A. Mcfayden³⁶, G. Mchedlidze^{158b}, M.A. McKay⁴², K.D. McLean¹⁷⁵, S.J. McMahon¹⁴³,
 P.C. McNamara¹⁰⁵, C.J. McNicol¹⁷⁷, R.A. McPherson^{175,ac}, J.E. Mdhluli^{33e}, Z.A. Meadows¹⁰³,
 S. Meehan³⁶, T. Megy³⁸, S. Mehlhase¹¹⁴, A. Mehta⁹¹, B. Meirose⁴³, D. Melini¹⁵⁹,
 B.R. Mellado Garcia^{33e}, J.D. Mellenthin⁵³, M. Melo^{28a}, F. Meloni⁴⁶, A. Melzer²⁴, S.B. Menary¹⁰¹,
 E.D. Mendes Gouveia^{139a,139e}, L. Meng³⁶, X.T. Meng¹⁰⁶, S. Menke¹¹⁵, E. Meoni^{41b,41a},
 S. Mergelmeyer¹⁹, S.A.M. Merkt¹³⁸, C. Merlassino¹³⁴, P. Mermod⁵⁴, L. Merola^{70a,70b},
 C. Meroni^{69a}, G. Merz¹⁰⁶, O. Meshkov^{113,111}, J.K.R. Meshreki¹⁵⁰, A. Messina^{73a,73b}, J. Metcalfe⁶,
 A.S. Mete⁶, C. Meyer⁶⁶, J-P. Meyer¹⁴⁴, H. Meyer Zu Theenhausen^{61a}, F. Miano¹⁵⁵, M. Michetti¹⁹,
 R.P. Middleton¹⁴³, L. Mijović⁵⁰, G. Mikenberg¹⁷⁹, M. Mikestikova¹⁴⁰, M. Mikuž⁹², H. Mildner¹⁴⁸,
 M. Milesi¹⁰⁵, A. Milic¹⁶⁶, C.D. Milke⁴², D.W. Miller³⁷, A. Milov¹⁷⁹, D.A. Milstead^{45a,45b},
 R.A. Mina¹⁵², A.A. Minaenko¹²³, M. Miñano Moya¹⁷³, I.A. Minashvili^{158b}, A.I. Mincer¹²⁵,
 B. Mindur^{84a}, M. Mineev⁸⁰, Y. Minegishi¹⁶², L.M. Mir¹⁴, M. Mironova¹³⁴, A. Mirto^{68a,68b},
 K.P. Mistry¹³⁶, T. Mitani¹⁷⁸, J. Mitrevski¹¹⁴, V.A. Mitsou¹⁷³, M. Mittal^{60c}, O. Miú¹⁶⁶,
 A. Miucci²⁰, P.S. Miyagawa¹⁴⁸, A. Mizukami⁸², J.U. Mjörnmark⁹⁷, T. Mkrtchyan^{61a},
 M. Mlynarikova¹⁴², T. Moa^{45a,45b}, S. Mobius⁵³, K. Mochizuki¹¹⁰, P. Mogg¹¹⁴, S. Mohapatra³⁹,
 R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁷, K. Mönig⁴⁶, E. Monnier¹⁰², A. Montalbano¹⁵¹,
 J. Montejo Berlingen³⁶, M. Montella⁹⁵, F. Monticelli⁸⁹, S. Monzani^{69a}, N. Morange⁶⁵,
 D. Moreno^{22a}, M. Moreno Llácer¹⁷³, C. Moreno Martinez¹⁴, P. Morettini^{55b}, M. Morgenstern¹⁵⁹,
 S. Morgenstern⁴⁸, D. Mori¹⁵¹, M. Morii⁵⁹, M. Morinaga¹⁷⁸, V. Morisbak¹³³, A.K. Morley³⁶,
 G. Mornacchi³⁶, A.P. Morris⁹⁵, L. Morvaj¹⁵⁴, P. Moschovakos³⁶, B. Moser¹²⁰, M. Mosidze^{158b},
 T. Moskalets¹⁴⁴, H.J. Moss¹⁴⁸, J. Moss^{31,m}, E.J.W. Moyse¹⁰³, S. Muanza¹⁰², J. Mueller¹³⁸,
 R.S.P. Mueller¹¹⁴, D. Muenstermann⁹⁰, G.A. Mullier⁹⁷, D.P. Mungo^{69a,69b},
 J.L. Munoz Martinez¹⁴, F.J. Munoz Sanchez¹⁰¹, P. Murin^{28b}, W.J. Murray^{177,143},
 A. Murrone^{69a,69b}, M. Muškinja¹⁸, C. Mwewa^{33a}, A.G. Myagkov^{123,ah}, A.A. Myers¹³⁸,
 J. Myers¹³¹, M. Myska¹⁴¹, B.P. Nachman¹⁸, O. Nackenhorst⁴⁷, A.Nag Nag⁴⁸, K. Nagai¹³⁴,
 K. Nagano⁸², Y. Nagasaka⁶², J.L. Nagle²⁹, E. Nagy¹⁰², A.M. Nairz³⁶, Y. Nakahama¹¹⁷,
 K. Nakamura⁸², T. Nakamura¹⁶², H. Nanjo¹³², F. Napolitano^{61a}, R.F. Naranjo Garcia⁴⁶,
 R. Narayan⁴², I. Naryshkin¹³⁷, T. Naumann⁴⁶, G. Navarro^{22a}, P.Y. Nechaeva¹¹¹, F. Nechansky⁴⁶,
 T.J. Neep²¹, A. Negri^{71a,71b}, M. Negrini^{23b}, C. Nellist¹¹⁹, M.E. Nelson^{45a,45b}, S. Nemecek¹⁴⁰,
 M. Nessi^{36,d}, M.S. Neubauer¹⁷², F. Neuhaus¹⁰⁰, M. Neumann¹⁸¹, R. Newhouse¹⁷⁴,
 P.R. Newman²¹, C.W. Ng¹³⁸, Y.S. Ng¹⁹, Y.W.Y. Ng¹⁷⁰, B. Ngair^{35e}, H.D.N. Nguyen¹⁰²,
 T. Nguyen Manh¹¹⁰, E. Nibigira³⁸, R.B. Nickerson¹³⁴, R. Nicolaidou¹⁴⁴, D.S. Nielsen⁴⁰,
 J. Nielsen¹⁴⁵, N. Nikiforou¹¹, V. Nikolaenko^{123,ah}, I. Nikolic-Audit¹³⁵, K. Nikolopoulos²¹,
 P. Nilsson²⁹, H.R. Nindhito⁵⁴, Y. Ninomiya⁸², A. Nisati^{73a}, N. Nishu^{60c}, R. Nisius¹¹⁵, I. Nitsche⁴⁷,
 T. Nitta¹⁷⁸, T. Nobe¹⁶², Y. Noguchi⁸⁶, I. Nomidis¹³⁵, M.A. Nomura²⁹, M. Nordberg³⁶,
 T. Novak⁹², O. Novgorodova⁴⁸, R. Novotny¹⁴¹, L. Nozka¹³⁰, K. Ntekas¹⁷⁰, E. Nurse⁹⁵,
 F.G. Oakham^{34,am}, H. Oberlack¹¹⁵, J. Ocariz¹³⁵, A. Ochi⁸³, I. Ochoa³⁹, J.P. Ochoa-Ricoux^{146a},

K. O'Connor²⁶, S. Oda⁸⁸, S. Odaka⁸², S. Oerdek⁵³, A. Ogrodnik^{84a}, A. Oh¹⁰¹, S.H. Oh⁴⁹, C.C. Ohm¹⁵³, H. Oide¹⁶⁴, M.L. Ojeda¹⁶⁶, H. Okawa¹⁶⁸, Y. Okazaki⁸⁶, M.W. O'Keefe⁹¹, Y. Okumura¹⁶², T. Okuyama⁸², A. Olariu^{27b}, L.F. Oleiro Seabra^{139a}, S.A. Olivares Pino^{146a}, D. Oliveira Damazio²⁹, J.L. Oliver¹, M.J.R. Olsson¹⁷⁰, A. Olszewski⁸⁵, J. Olszowska⁸⁵, D.C. O'Neil¹⁵¹, A.P. O'Neill¹³⁴, A. Onofre^{139a,139e}, P.U.E. Onyisi¹¹, H. Oppen¹³³, R.G. Oreamuno Madriz¹²¹, M.J. Oreglia³⁷, G.E. Orellana⁸⁹, D. Orestano^{75a,75b}, N. Orlando¹⁴, R.S. Orr¹⁶⁶, V. O'Shea⁵⁷, R. Ospanov^{60a}, G. Otero y Garzon³⁰, H. Otono⁸⁸, P.S. Ott^{61a}, G.J. Ottino¹⁸, M. Ouchrif^{35d}, J. Ouellette²⁹, F. Ould-Saada¹³³, A. Ouraou¹⁴⁴, Q. Ouyang^{15a}, M. Owen⁵⁷, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, J. Pacalt¹³⁰, H.A. Pacey³², K. Pachal⁴⁹, A. Pacheco Pages¹⁴, C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸², G. Palacino⁶⁶, S. Palazzo⁵⁰, S. Palestini³⁶, M. Palka^{84b}, D. Pallin³⁸, P. Palmi^{84a}, I. Panagoulas¹⁰, C.E. Pandini³⁶, J.G. Panduro Vazquez⁹⁴, P. Pani⁴⁶, G. Panizzo^{67a,67c}, L. Paolozzi⁵⁴, C. Papadatos¹¹⁰, K. Papageorgiou^{9,g}, S. Parajuli⁴², A. Paramonov⁶, C. Paraskevopoulos¹⁰, D. Paredes Hernandez^{63b}, S.R. Paredes Saenz¹³⁴, B. Parida¹⁶⁵, T.H. Park¹⁶⁶, A.J. Parker³¹, M.A. Parker³², F. Parodi^{55b,55a}, E.W. Parrish¹²¹, J.A. Parsons³⁹, U. Parzefall⁵², L. Pascual Dominguez¹³⁵, V.R. Pascuzzi¹⁸, J.M.P. Pasner¹⁴⁵, F. Pasquali¹²⁰, E. Pasqualucci^{73a}, S. Passaggio^{55b}, F. Pastore⁹⁴, P. Pasuwan^{45a,45b}, S. Patariaia¹⁰⁰, J.R. Pater¹⁰¹, A. Pathak^{180,i}, J. Patton⁹¹, T. Pauly³⁶, J. Parkes¹⁵², B. Pearson¹¹⁵, M. Pedersen¹³³, L. Pedraza Diaz¹¹⁹, R. Pedro^{139a}, T. Peiffer⁵³, S.V. Peleganchuk^{122b,122a}, O. Penc¹⁴⁰, H. Peng^{60a}, B.S. Peralva^{81a}, M.M. Perego⁶⁵, A.P. Pereira Peixoto^{139a}, L. Pereira Sanchez^{45a,45b}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{69a,69b}, H. Pernegger³⁶, S. Perrella^{139a}, A. Perrevoort¹²⁰, K. Peters⁴⁶, R.F.Y. Peters¹⁰¹, B.A. Petersen³⁶, T.C. Petersen⁴⁰, E. Petit¹⁰², A. Petridis¹, C. Petridou¹⁶¹, P. Petroff⁶⁵, F. Petrucci^{75a,75b}, M. Pettee¹⁸², N.E. Pettersson¹⁰³, K. Petukhova¹⁴², A. Peyaud¹⁴⁴, R. Pezoa^{146d}, L. Pezzotti^{71a,71b}, T. Pham¹⁰⁵, F.H. Phillips¹⁰⁷, P.W. Phillips¹⁴³, M.W. Phipps¹⁷², G. Piacquadio¹⁵⁴, E. Pianori¹⁸, A. Picazio¹⁰³, R.H. Pickles¹⁰¹, R. Piegaia³⁰, D. Pietreanu^{27b}, J.E. Pilcher³⁷, A.D. Pilkington¹⁰¹, M. Pinamonti^{67a,67c}, J.L. Pinfold³, C. Pitman Donaldson⁹⁵, M. Pitt¹⁶⁰, L. Pizzimento^{74a,74b}, M.-A. Pleier²⁹, V. Pleskot¹⁴², E. Plotnikova⁸⁰, P. Podberezko^{122b,122a}, R. Poettgen⁹⁷, R. Poggi⁵⁴, L. Poggioli¹³⁵, I. Pogrebnyak¹⁰⁷, D. Pohl²⁴, I. Pokharel⁵³, G. Polesello^{71a}, A. Poley¹⁸, A. Policicchio^{73a,73b}, R. Polifka¹⁴², A. Polini^{23b}, C.S. Pollard⁴⁶, V. Polychronakos²⁹, D. Ponomarenko¹¹², L. Pontecorvo³⁶, S. Popa^{27a}, G.A. Popeneciu^{27d}, L. Portales⁵, D.M. Portillo Quintero⁵⁸, S. Pospisil¹⁴¹, K. Potamianos⁴⁶, I.N. Potrap⁸⁰, C.J. Potter³², H. Potti¹¹, T. Poulsen⁹⁷, J. Poveda¹⁷³, T.D. Powell¹⁴⁸, G. Pownall⁴⁶, M.E. Pozo Astigarraga³⁶, P. Pralavorio¹⁰², S. Prell⁷⁹, D. Price¹⁰¹, M. Primavera^{68a}, S. Prince¹⁰⁴, M.L. Proffitt¹⁴⁷, N. Proklova¹¹², K. Prokofiev^{63c}, F. Prokoshin⁸⁰, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{84a}, D. Pudzha¹³⁷, A. Puri¹⁷², P. Puzo⁶⁵, J. Qian¹⁰⁶, Y. Qin¹⁰¹, A. Quadt⁵³, M. Queitsch-Maitland³⁶, A. Qureshi¹, M. Racko^{28a}, F. Ragusa^{69a,69b}, G. Rahal⁹⁸, J.A. Raine⁵⁴, S. Rajagopalan²⁹, A. Ramirez Morales⁹³, K. Ran^{15a,15d}, T. Rashid⁶⁵, D.M. Rauch⁴⁶, F. Rauscher¹¹⁴, S. Rave¹⁰⁰, B. Ravina¹⁴⁸, I. Ravinovich¹⁷⁹, J.H. Rawling¹⁰¹, M. Raymond³⁶, A.L. Read¹³³, N.P. Readioff⁵⁸, M. Reale^{68a,68b}, D.M. Rebuffi^{71a,71b}, G. Redlinger²⁹, K. Reeves⁴³, L. Rehnisch¹⁹, J. Reichert¹³⁶, D. Reikher¹⁶⁰, A. Reiss¹⁰⁰, A. Rej¹⁵⁰, C. Rembser³⁶, A. Renardi⁴⁶, M. Renda^{27b}, M. Rescigno^{73a}, S. Resconi^{69a}, E.D. Resseguie¹⁸, S. Rettie⁹⁵, B. Reynolds¹²⁷, E. Reynolds²¹, O.L. Rezanova^{122b,122a}, P. Reznicek¹⁴², E. Ricci^{76a,76b}, R. Richter¹¹⁵, S. Richter⁴⁶, E. Richter-Was^{84b}, O. Ricken²⁴, M. Ridel¹³⁵, P. Rieck¹¹⁵, O. Rifki⁴⁶, M. Rijssenbeek¹⁵⁴, A. Rimoldi^{71a,71b}, M. Rimoldi⁴⁶, L. Rinaldi^{23b}, G. Ripellino¹⁵³, I. Riu¹⁴, J.C. Rivera Vergara¹⁷⁵, F. Rizatdinova¹²⁹, E. Rizvi⁹³, C. Rizzi³⁶, R.T. Roberts¹⁰¹, S.H. Robertson^{104,ac}, M. Robin⁴⁶, D. Robinson³², C.M. Robles Gajardo^{146d}, M. Robles Manzano¹⁰⁰, A. Robson⁵⁷, A. Rocchi^{74a,74b}, E. Rocco¹⁰⁰, C. Roda^{72a,72b}, S. Rodriguez Bosca¹⁷³, D. Rodriguez Rodriguez¹⁷³, A.M. Rodríguez Vera^{167b}, S. Roe³⁶, O. Røhne¹³³, R. Röhrig¹¹⁵, R.A. Rojas^{146d}, B. Roland⁵²,

C.P.A. Roland⁶⁶, J. Roloff²⁹, A. Romaniouk¹¹², M. Romano^{23b,23a}, N. Rompotis⁹¹, M. Ronzani¹²⁵, L. Roos¹³⁵, S. Rosati^{73a}, G. Rosin¹⁰³, B.J. Rosser¹³⁶, E. Rossi⁴⁶, E. Rossi^{75a,75b}, E. Rossi^{70a,70b}, L.P. Rossi^{55b}, L. Rossini^{69a,69b}, R. Rosten¹⁴, M. Rotaru^{27b}, B. Rottler⁵², D. Rousseau⁶⁵, G. Rovelli^{71a,71b}, A. Roy¹¹, D. Roy^{33e}, A. Rozanov¹⁰², Y. Rozen¹⁵⁹, X. Ruan^{33e}, F. Rühr⁵², A. Ruiz-Martinez¹⁷³, A. Rummeler³⁶, Z. Rurikova⁵², N.A. Rusakovich⁸⁰, H.L. Russell¹⁰⁴, L. Rustige^{38,47}, J.P. Rutherford⁷, E.M. Rüttinger¹⁴⁸, M. Rybar³⁹, G. Rybkin⁶⁵, E.B. Rye¹³³, A. Ryzhov¹²³, J.A. Sabater Iglesias⁴⁶, P. Sabatini⁵³, S. Sacerdoti⁶⁵, H.F.W. Sadrozinski¹⁴⁵, R. Sadykov⁸⁰, F. Safai Tehrani^{73a}, B. Safarzadeh Samani¹⁵⁵, M. Safdari¹⁵², P. Saha¹²¹, S. Saha¹⁰⁴, M. Sahinsoy^{61a}, A. Sahu¹⁸¹, M. Saimpert³⁶, M. Saito¹⁶², T. Saito¹⁶², H. Sakamoto¹⁶², D. Salamani⁵⁴, G. Salamanna^{75a,75b}, J.E. Salazar Loyola^{146d}, A. Salnikov¹⁵², J. Salt¹⁷³, A. Salvador Salas¹⁴, D. Salvatore^{41b,41a}, F. Salvatore¹⁵⁵, A. Salvucci^{63a,63b,63c}, A. Salzburger³⁶, J. Samarati³⁶, D. Sammel⁵², D. Sampsonidis¹⁶¹, D. Sampsonidou¹⁶¹, J. Sánchez¹⁷³, A. Sanchez Pineda^{67a,36,67c}, H. Sandaker¹³³, C.O. Sander⁴⁶, I.G. Sanderswood⁹⁰, M. Sandhoff¹⁸¹, C. Sandoval^{22a}, D.P.C. Sankey¹⁴³, M. Sannino^{55b,55a}, Y. Sano¹¹⁷, A. Sansoni⁵¹, C. Santoni³⁸, H. Santos^{139a,139b}, S.N. Santpur¹⁸, A. Santra¹⁷³, A. Sapronov⁸⁰, J.G. Saraiva^{139a,139d}, O. Sasaki⁸², K. Sato¹⁶⁸, F. Sauerburger⁵², E. Sauvan⁵, P. Savard^{166,am}, R. Sawada¹⁶², C. Sawyer¹⁴³, L. Sawyer^{96,ag}, C. Sbarra^{23b}, A. Sbrizzi^{23a}, T. Scanlon⁹⁵, J. Schaarschmidt¹⁴⁷, P. Schacht¹¹⁵, B.M. Schachtner¹¹⁴, D. Schaefer³⁷, L. Schaefer¹³⁶, J. Schaeffer¹⁰⁰, S. Schaepe³⁶, U. Schäfer¹⁰⁰, A.C. Schaffer⁶⁵, D. Schaile¹¹⁴, R.D. Schamberger¹⁵⁴, E. Schanet¹¹⁴, N. Scharmberg¹⁰¹, V.A. Schegelsky¹³⁷, D. Scheirich¹⁴², F. Schenck¹⁹, M. Schernau¹⁷⁰, C. Schiavi^{55b,55a}, L.K. Schildgen²⁴, Z.M. Schillaci²⁶, E.J. Schioppa^{68a,68b}, M. Schioppa^{41b,41a}, K.E. Schleicher⁵², S. Schlenker³⁶, K.R. Schmidt-Sommerfeld¹¹⁵, K. Schmieden³⁶, C. Schmitt¹⁰⁰, S. Schmitt⁴⁶, S. Schmitz¹⁰⁰, J.C. Schmoeckel⁴⁶, L. Schoeffel¹⁴⁴, A. Schoening^{61b}, P.G. Scholer⁵², E. Schopf¹³⁴, M. Schott¹⁰⁰, J.F.P. Schouwenberg¹¹⁹, J. Schovancova³⁶, S. Schramm⁵⁴, F. Schroeder¹⁸¹, A. Schulte¹⁰⁰, H-C. Schultz-Coulon^{61a}, M. Schumacher⁵², B.A. Schumm¹⁴⁵, Ph. Schune¹⁴⁴, A. Schwartzman¹⁵², T.A. Schwarz¹⁰⁶, Ph. Schwemling¹⁴⁴, R. Schwienhorst¹⁰⁷, A. Sciandra¹⁴⁵, G. Sciolla²⁶, M. Scodeggio⁴⁶, M. Scornajenghi^{41b,41a}, F. Scuri^{72a}, F. Scutti¹⁰⁵, L.M. Scyboz¹¹⁵, C.D. Sebastiani^{73a,73b}, P. Seema¹⁹, S.C. Seidel¹¹⁸, A. Seiden¹⁴⁵, B.D. Seidlitz²⁹, T. Seiss³⁷, C. Seitz⁴⁶, J.M. Seixas^{81b}, G. Sekhniaidze^{70a}, S.J. Sekula⁴², N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁹, C. Serfon²⁹, L. Serin⁶⁵, L. Serkin^{67a,67b}, M. Sessa^{60a}, H. Severini¹²⁸, S. Sevova¹⁵², F. Sforza^{55b,55a}, A. Sfyrila⁵⁴, E. Shabalina⁵³, J.D. Shahinian¹⁴⁵, N.W. Shaikh^{45a,45b}, D. Shaked Renous¹⁷⁹, L.Y. Shan^{15a}, M. Shapiro¹⁸, A. Sharma¹³⁴, A.S. Sharma¹, P.B. Shatalov¹²⁴, K. Shaw¹⁵⁵, S.M. Shaw¹⁰¹, M. Shehade¹⁷⁹, Y. Shen¹²⁸, A.D. Sherman²⁵, P. Sherwood⁹⁵, L. Shi¹⁵⁷, S. Shimizu⁸², C.O. Shimmin¹⁸², Y. Shimogama¹⁷⁸, M. Shimojima¹¹⁶, I.P.J. Shipsey¹³⁴, S. Shirabe¹⁶⁴, M. Shiyakova^{80,aa}, J. Shlomi¹⁷⁹, A. Shmeleva¹¹¹, M.J. Shochet³⁷, J. Shojaii¹⁰⁵, D.R. Shope¹²⁸, S. Shrestha¹²⁷, E.M. Shrif^{33e}, E. Shulga¹⁷⁹, P. Sicho¹⁴⁰, A.M. Sickles¹⁷², P.E. Sidebo¹⁵³, E. Sideras Haddad^{33e}, O. Sidiropoulou³⁶, A. Sidoti^{23b,23a}, F. Siegert⁴⁸, Dj. Sijacki¹⁶, M.Jr. Silva¹⁸⁰, M.V. Silva Oliveira^{81a}, S.B. Silverstein^{45a}, S. Simion⁶⁵, R. Simoniello¹⁰⁰, C.J. Simpson-allso²¹, S. Simsek^{12b}, P. Sinervo¹⁶⁶, V. Sinetckii¹¹³, S. Singh¹⁵¹, M. Sioli^{23b,23a}, I. Siral¹³¹, S.Yu. Sivoklov¹¹³, J. Sjölin^{45a,45b}, A. Skaf⁵³, E. Skorda⁹⁷, P. Skubic¹²⁸, M. Slawinska⁸⁵, K. Sliwa¹⁶⁹, R. Slovak¹⁴², V. Smakhtin¹⁷⁹, B.H. Smart¹⁴³, J. Smiesko^{28b}, N. Smirnov¹¹², S.Yu. Smirnov¹¹², Y. Smirnov¹¹², L.N. Smirnova^{113,s}, O. Smirnova⁹⁷, J.W. Smith⁵³, M. Smizanska⁹⁰, K. Smolek¹⁴¹, A. Smykiewicz⁸⁵, A.A. Snegarev¹¹¹, H.L. Snoek¹²⁰, I.M. Snyder¹³¹, S. Snyder²⁹, R. Sobie^{175,ac}, A. Soffer¹⁶⁰, A. Sogaard⁵⁰, F. Sohns⁵³, C.A. Solans Sanchez³⁶, E.Yu. Soldatov¹¹², U. Soldevila¹⁷³, A.A. Solodkov¹²³, A. Soloshenko⁸⁰, O.V. Solovyanov¹²³, V. Solovyev¹³⁷, P. Sommer¹⁴⁸, H. Son¹⁶⁹, W. Song¹⁴³, W.Y. Song^{167b}, A. Sopczak¹⁴¹, A.L. Sopio⁹⁵, F. Sopkova^{28b}, C.L. Sotiropoulou^{72a,72b}, S. Sottocornola^{71a,71b}, R. Soualah^{67a,67c,f}, A.M. Soukharev^{122b,122a}, D. South⁴⁶, S. Spagnolo^{68a,68b}, M. Spalla¹¹⁵,

M. Spangenberg¹⁷⁷, F. Spanò⁹⁴, D. Sperlich⁵², T.M. Spieker^{61a}, G. Spigo³⁶, M. Spina¹⁵⁵, D.P. Spiteri⁵⁷, M. Spousta¹⁴², A. Stabile^{69a,69b}, B.L. Stamas¹²¹, R. Stamen^{61a}, M. Stamenkovic¹²⁰, E. Stanecka⁸⁵, B. Stanislaus¹³⁴, M.M. Stanitzki⁴⁶, M. Stankaityte¹³⁴, B. Stapf¹²⁰, E.A. Starchenko¹²³, G.H. Stark¹⁴⁵, J. Stark⁵⁸, P. Staroba¹⁴⁰, P. Starovoitov^{61a}, S. Stärz¹⁰⁴, R. Staszewski⁸⁵, G. Stavropoulos⁴⁴, M. Stegler⁴⁶, P. Steinberg²⁹, A.L. Steinhebel¹³¹, B. Stelzer¹⁵¹, H.J. Stelzer¹³⁸, O. Stelzer-Chilton^{167a}, H. Stenzel⁵⁶, T.J. Stevenson¹⁵⁵, G.A. Stewart³⁶, M.C. Stockton³⁶, G. Stoicea^{27b}, M. Stolarski^{139a}, S. Stonjek¹¹⁵, A. Straessner⁴⁸, J. Strandberg¹⁵³, S. Strandberg^{45a,45b}, M. Strauss¹²⁸, P. Strizenec^{28b}, R. Ströhmer¹⁷⁶, D.M. Strom¹³¹, R. Stroynowski⁴², A. Strubig⁵⁰, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁸, N.A. Styles⁴⁶, D. Su¹⁵², W. Su^{60c}, S. Suchek^{61a}, V.V. Sulin¹¹¹, M.J. Sullivan⁹¹, D.M.S. Sultan⁵⁴, S. Sultansoy^{4c}, T. Sumida⁸⁶, S. Sun¹⁰⁶, X. Sun¹⁰¹, K. Suruliz¹⁵⁵, C.J.E. Suster¹⁵⁶, M.R. Sutton¹⁵⁵, S. Suzuki⁸², M. Svatos¹⁴⁰, M. Swiatlowski^{167a}, S.P. Swift², T. Swirski¹⁷⁶, A. Sydorenko¹⁰⁰, I. Sykora^{28a}, M. Sykora¹⁴², T. Sykora¹⁴², D. Ta¹⁰⁰, K. Tackmann^{46,y}, J. Taenzer¹⁶⁰, A. Taffard¹⁷⁰, R. Tafirout^{167a}, R. Takashima⁸⁷, K. Takeda⁸³, T. Takeshita¹⁴⁹, E.P. Takeva⁵⁰, Y. Takubo⁸², M. Talby¹⁰², A.A. Talyshev^{122b,122a}, K.C. Tam^{63b}, N.M. Tamir¹⁶⁰, J. Tanaka¹⁶², R. Tanaka⁶⁵, S. Tapia Araya¹⁷², S. Tapprogge¹⁰⁰, A. Tarek Abouelfadl Mohamed¹⁰⁷, S. Tarem¹⁵⁹, K. Tariq^{60b}, G. Tarna^{27b,c}, G.F. Tartarelli^{69a}, P. Tas¹⁴², M. Tasevsky¹⁴⁰, T. Tashiro⁸⁶, E. Tassi^{41b,41a}, A. Tavares Delgado^{139a}, Y. Tayalati^{35e}, A.J. Taylor⁵⁰, G.N. Taylor¹⁰⁵, W. Taylor^{167b}, H. Teagle⁹¹, A.S. Tee⁹⁰, R. Teixeira De Lima¹⁵², P. Teixeira-Dias⁹⁴, H. Ten Kate³⁶, J.J. Teoh¹²⁰, S. Terada⁸², K. Terashi¹⁶², J. Terron⁹⁹, S. Terzo¹⁴, M. Testa⁵¹, R.J. Teuscher^{166,ac}, S.J. Thais¹⁸², N. Themistokleous⁵⁰, T. Theveneaux-Pelzer⁴⁶, F. Thiele⁴⁰, D.W. Thomas⁹⁴, J.O. Thomas⁴², J.P. Thomas²¹, E.A. Thompson⁴⁶, P.D. Thompson²¹, E. Thomson¹³⁶, E.J. Thorpe⁹³, R.E. Ticse Torres⁵³, V.O. Tikhomirov^{111,ai}, Yu.A. Tikhonov^{122b,122a}, S. Timoshenko¹¹², P. Tipton¹⁸², S. Tisserant¹⁰², K. Todome^{23b,23a}, S. Todorova-Nova¹⁴², S. Todt⁴⁸, J. Tojo⁸⁸, S. Tokár^{28a}, K. Tokushuku⁸², E. Tolley¹²⁷, K.G. Tomiwa^{33e}, M. Tomoto¹¹⁷, L. Tompkins¹⁵², P. Tornambe¹⁰³, E. Torrence¹³¹, H. Torres⁴⁸, E. Torró Pastor¹⁴⁷, C. Tosciri¹³⁴, J. Toth^{102,ab}, D.R. Tovey¹⁴⁸, A. Traet¹⁷, C.J. Treado¹²⁵, T. Trefzger¹⁷⁶, F. Tresoldi¹⁵⁵, A. Tricoli²⁹, I.M. Trigger^{167a}, S. Trincaz-Duvold¹³⁵, D.A. Trischuk¹⁷⁴, W. Trischuk¹⁶⁶, B. Trocmé⁵⁸, A. Trofymov⁶⁵, C. Troncon^{69a}, F. Trovato¹⁵⁵, L. Truong^{33c}, M. Trzebinski⁸⁵, A. Trzupek⁸⁵, F. Tsai⁴⁶, J.C.-L. Tseng¹³⁴, P.V. Tsiarehka^{108,af}, A. Tsirigotis^{161,v}, V. Tsiskaridze¹⁵⁴, E.G. Tskhadadze^{158a}, M. Tsopoulou¹⁶¹, I.I. Tsukerman¹²⁴, V. Tsulaia¹⁸, S. Tsuno⁸², D. Tsybychev¹⁵⁴, Y. Tu^{63b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tumbure^{27a}, A.N. Tuna⁵⁹, S. Turchikhin⁸⁰, D. Turgeman¹⁷⁹, I. Turk Cakir^{4b,t}, R.J. Turner²¹, R.T. Turra^{69a}, P.M. Tuts³⁹, S. Tzamarias¹⁶¹, E. Tzovara¹⁰⁰, G. Ucchielli⁴⁷, K. Uchida¹⁶², F. Ukegawa¹⁶⁸, G. Unal³⁶, A. Undrus²⁹, G. Unel¹⁷⁰, F.C. Ungaro¹⁰⁵, Y. Unno⁸², K. Uno¹⁶², J. Urban^{28b}, P. Urquijo¹⁰⁵, G. Usai⁸, Z. Uysal^{12d}, V. Vacek¹⁴¹, B. Vachon¹⁰⁴, K.O.H. Vadla¹³³, A. Vaidya⁹⁵, C. Valderanis¹¹⁴, E. Valdes Santurio^{45a,45b}, M. Valente⁵⁴, S. Valentini^{23b,23a}, A. Valero¹⁷³, L. Valéry⁴⁶, R.A. Vallance²¹, A. Vallier³⁶, J.A. Valls Ferrer¹⁷³, T.R. Van Daalen¹⁴, P. Van Gemmeren⁶, I. Van Vulpen¹²⁰, M. Vanadia^{74a,74b}, W. Vandelli³⁶, M. Vandenbroucke¹⁴⁴, E.R. Vandewall¹²⁹, A. Vaniachine¹⁶⁵, D. Vannicola^{73a,73b}, R. Vari^{73a}, E.W. Varnes⁷, C. Varni^{55b,55a}, T. Varol¹⁵⁷, D. Varouchas⁶⁵, K.E. Varvell¹⁵⁶, M.E. Vasile^{27b}, G.A. Vasquez¹⁷⁵, F. Vazeille³⁸, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder³⁶, J. Veatch⁵³, V. Vecchio¹⁰¹, M.J. Veen¹²⁰, L.M. Veloce¹⁶⁶, F. Veloso^{139a,139c}, S. Veneziano^{73a}, A. Ventura^{68a,68b}, N. Venturi³⁶, A. Verbitskyi¹¹⁵, V. Vercesi^{71a}, M. Verducci^{72a,72b}, C.M. Vergel Infante⁷⁹, C. Vergis²⁴, W. Verkerke¹²⁰, A.T. Vermeulen¹²⁰, J.C. Vermeulen¹²⁰, C. Vernieri¹⁵², M.C. Vetterli^{151,am}, N. Viaux Maira^{146d}, T. Vickey¹⁴⁸, O.E. Vickey Boeriu¹⁴⁸, G.H.A. Viehhauser¹³⁴, L. Vigani^{61b}, M. Villa^{23b,23a}, M. Villaplana Perez³, E.M. Villhauer⁵⁰, E. Vilucchi⁵¹, M.G. Vinciter³⁴, G.S. Virdee²¹, A. Vishwakarma⁴⁶, C. Vittori^{23b,23a}, I. Vivarelli¹⁵⁵, M. Vogel¹⁸¹, P. Vokac¹⁴¹,

S.E. von Buddenbrock^{33e}, E. Von Toerne²⁴, V. Vorobel¹⁴², K. Vorobev¹¹², M. Vos¹⁷³, J.H. Vosseveld⁹¹, M. Vozak¹⁰¹, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹⁴¹, M. Vreeswijk¹²⁰, R. Vuillermet³⁶, I. Vukotic³⁷, S. Wada¹⁶⁸, P. Wagner²⁴, W. Wagner¹⁸¹, J. Wagner-Kuhr¹¹⁴, S. Wahdan¹⁸¹, H. Wahlberg⁸⁹, R. Wakasa¹⁶⁸, V.M. Walbrecht¹¹⁵, J. Walder⁹⁰, R. Walker¹¹⁴, S.D. Walker⁹⁴, W. Walkowiak¹⁵⁰, V. Wallangen^{45a,45b}, A.M. Wang⁵⁹, A.Z. Wang¹⁸⁰, C. Wang^{60c}, F. Wang¹⁸⁰, H. Wang¹⁸, H. Wang³, J. Wang^{63a}, J. Wang^{61b}, P. Wang⁴², Q. Wang¹²⁸, R.-J. Wang¹⁰⁰, R. Wang^{60a}, R. Wang⁶, S.M. Wang¹⁵⁷, W.T. Wang^{60a}, W. Wang^{15c}, W.X. Wang^{60a}, Y. Wang^{60a}, Z. Wang^{60c}, C. Wanotayaroj⁴⁶, A. Warburton¹⁰⁴, C.P. Ward³², D.R. Wardrope⁹⁵, N. Warrack⁵⁷, A. Washbrook⁵⁰, A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁷, B.M. Waugh⁹⁵, A.F. Webb¹¹, C. Weber²⁹, M.S. Weber²⁰, S.A. Weber³⁴, S.M. Weber^{61a}, A.R. Weidberg¹³⁴, J. Weingarten⁴⁷, M. Weirich¹⁰⁰, C. Weiser⁵², P.S. Wells³⁶, T. Wenaus²⁹, T. Wengler³⁶, S. Wenig³⁶, N. Wermes²⁴, M.D. Werner⁷⁹, M. Wessels^{61a}, T.D. Weston²⁰, K. Whalen¹³¹, N.L. Whallon¹⁴⁷, A.M. Wharton⁹⁰, A.S. White¹⁰⁶, A. White⁸, M.J. White¹, D. Whiteson¹⁷⁰, B.W. Whitmore⁹⁰, W. Wiedenmann¹⁸⁰, C. Wiel⁴⁸, M. Wielers¹⁴³, N. Wieseotte¹⁰⁰, C. Wiglesworth⁴⁰, L.A.M. Wiik-Fuchs⁵², H.G. Wilkens³⁶, L.J. Wilkins⁹⁴, H.H. Williams¹³⁶, S. Williams³², C. Willis¹⁰⁷, S. Willocq¹⁰³, P.J. Windischhofer¹³⁴, I. Wingerter-Seetz⁵, E. Winkels¹⁵⁵, F. Winklmeier¹³¹, B.T. Winter⁵², M. Wittgen¹⁵², M. Wobisch⁹⁶, A. Wolf¹⁰⁰, T.M.H. Wolf¹²⁰, R. Wolff¹⁰², R. Wölker¹³⁴, J. Wollrath⁵², M.W. Wolter⁸⁵, H. Wolters^{139a,139c}, V.W.S. Wong¹⁷⁴, N.L. Woods¹⁴⁵, S.D. Worm⁴⁶, B.K. Wosiek⁸⁵, K.W. Woźniak⁸⁵, K. Wraight⁵⁷, S.L. Wu¹⁸⁰, X. Wu⁵⁴, Y. Wu^{60a}, T.R. Wyatt¹⁰¹, B.M. Wynne⁵⁰, S. Xella⁴⁰, Z. Xi¹⁰⁶, L. Xia¹⁷⁷, X. Xiao¹⁰⁶, X. Xie^{60a}, I. Xiotidis¹⁵⁵, D. Xu^{15a}, H. Xu^{60a}, H. Xu^{60a}, L. Xu²⁹, T. Xu¹⁴⁴, W. Xu¹⁰⁶, Z. Xu^{60b}, Z. Xu¹⁵², B. Yabsley¹⁵⁶, S. Yacoub^{33a}, K. Yajima¹³², D.P. Yallup⁹⁵, N. Yamaguchi⁸⁸, Y. Yamaguchi¹⁶⁴, A. Yamamoto⁸², M. Yamatani¹⁶², T. Yamazaki¹⁶², Y. Yamazaki⁸³, J. Yan^{60c}, Z. Yan²⁵, H.J. Yang^{60c,60d}, H.T. Yang¹⁸, S. Yang^{60a}, T. Yang^{63c}, X. Yang^{60b,58}, Y. Yang¹⁶², Z. Yang^{60a}, W.-M. Yao¹⁸, Y.C. Yap⁴⁶, Y. Yasu⁸², E. Yatsenko^{60c,60d}, H. Ye^{15c}, J. Ye⁴², S. Ye²⁹, I. Yeletsikh⁸⁰, M.R. Yexley⁹⁰, E. Yigitbasi²⁵, P. Yin³⁹, K. Yorita¹⁷⁸, K. Yoshihara⁷⁹, C.J.S. Young³⁶, C. Young¹⁵², J. Yu⁷⁹, R. Yuan^{60b,h}, X. Yue^{61a}, M. Zaazoua^{35e}, B. Zabinski⁸⁵, G. Zacharis¹⁰, E. Zaffaroni⁵⁴, J. Zahreddine¹³⁵, A.M. Zaitsev^{123,ah}, T. Zakareishvili^{158b}, N. Zakharchuk³⁴, S. Zambito⁵⁹, D. Zanzi³⁶, D.R. Zaripovas⁵⁷, S.V. Zeißner⁴⁷, C. Zeitnitz¹⁸¹, G. Zemaityte¹³⁴, J.C. Zeng¹⁷², O. Zenin¹²³, T. Ženiš^{28a}, D. Zerwas⁶⁵, M. Zgubić¹³⁴, B. Zhang^{15c}, D.F. Zhang^{15b}, G. Zhang^{15b}, J. Zhang⁶, Kaili. Zhang^{15a}, L. Zhang^{15c}, L. Zhang^{60a}, M. Zhang¹⁷², R. Zhang¹⁸⁰, S. Zhang¹⁰⁶, X. Zhang^{60c}, X. Zhang^{60b}, Y. Zhang^{15a,15d}, Z. Zhang^{63a}, Z. Zhang⁶⁵, P. Zhao⁴⁹, Z. Zhao^{60a}, A. Zhemchugov⁸⁰, Z. Zheng¹⁰⁶, D. Zhong¹⁷², B. Zhou¹⁰⁶, C. Zhou¹⁸⁰, H. Zhou⁷, M.S. Zhou^{15a,15d}, M. Zhou¹⁵⁴, N. Zhou^{60c}, Y. Zhou⁷, C.G. Zhu^{60b}, C. Zhu^{15a,15d}, H.L. Zhu^{60a}, H. Zhu^{15a}, J. Zhu¹⁰⁶, Y. Zhu^{60a}, X. Zhuang^{15a}, K. Zhukov¹¹¹, V. Zhulanov^{122b,122a}, D. Zieminska⁶⁶, N.I. Zimine⁸⁰, S. Zimmermann⁵², Z. Zinonos¹¹⁵, M. Ziolkowski¹⁵⁰, L. Živković¹⁶, G. Zobernig¹⁸⁰, A. Zoccoli^{23b,23a}, K. Zoch⁵³, T.G. Zorbas¹⁴⁸, R. Zou³⁷, L. Zwalinski³⁶

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany NY, United States of America

³ Department of Physics, University of Alberta, Edmonton AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul;

(c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁷ Department of Physics, University of Arizona, Tucson AZ, United States of America

⁸ Department of Physics, University of Texas at Arlington, Arlington TX, United States of America

⁹ Physics Department, National and Kapodistrian University of Athens, Athens, Greece

- ¹⁰ *Physics Department, National Technical University of Athens, Zografou, Greece*
- ¹¹ *Department of Physics, University of Texas at Austin, Austin TX, United States of America*
- ¹² ^(a) *Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;* ^(b) *Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;* ^(c) *Department of Physics, Bogazici University, Istanbul;* ^(d) *Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
- ¹³ *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- ¹⁴ *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
- ¹⁵ ^(a) *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* ^(b) *Physics Department, Tsinghua University, Beijing;* ^(c) *Department of Physics, Nanjing University, Nanjing;* ^(d) *University of Chinese Academy of Science (UCAS), Beijing, China*
- ¹⁶ *Institute of Physics, University of Belgrade, Belgrade, Serbia*
- ¹⁷ *Department for Physics and Technology, University of Bergen, Bergen, Norway*
- ¹⁸ *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America*
- ¹⁹ *Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- ²⁰ *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- ²¹ *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ²² ^(a) *Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá;* ^(b) *Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia*
- ²³ ^(a) *INFN Bologna and Università di Bologna, Dipartimento di Fisica;* ^(b) *INFN Sezione di Bologna, Italy*
- ²⁴ *Physikalisches Institut, Universität Bonn, Bonn, Germany*
- ²⁵ *Department of Physics, Boston University, Boston MA, United States of America*
- ²⁶ *Department of Physics, Brandeis University, Waltham MA, United States of America*
- ²⁷ ^(a) *Transilvania University of Brasov, Brasov;* ^(b) *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* ^(c) *Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;* ^(d) *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;* ^(e) *University Politehnica Bucharest, Bucharest;* ^(f) *West University in Timisoara, Timisoara, Romania*
- ²⁸ ^(a) *Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;* ^(b) *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ²⁹ *Physics Department, Brookhaven National Laboratory, Upton NY, United States of America*
- ³⁰ *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³¹ *California State University, CA, United States of America*
- ³² *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ³³ ^(a) *Department of Physics, University of Cape Town, Cape Town;* ^(b) *iThemba Labs, Western Cape;* ^(c) *Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;* ^(d) *University of South Africa, Department of Physics, Pretoria;* ^(e) *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³⁴ *Department of Physics, Carleton University, Ottawa ON, Canada*
- ³⁵ ^(a) *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, Casablanca;* ^(b) *Faculté des Sciences, Université Ibn-Tofail, Kénitra;* ^(c) *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;* ^(d) *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;* ^(e) *Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ³⁶ *CERN, Geneva, Switzerland*
- ³⁷ *Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America*
- ³⁸ *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*

- ³⁹ *Nevis Laboratory, Columbia University, Irvington NY, United States of America*
- ⁴⁰ *Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ⁴¹ ^(a) *Dipartimento di Fisica, Università della Calabria, Rende;* ^(b) *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴² *Physics Department, Southern Methodist University, Dallas TX, United States of America*
- ⁴³ *Physics Department, University of Texas at Dallas, Richardson TX, United States of America*
- ⁴⁴ *National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- ⁴⁵ ^(a) *Department of Physics, Stockholm University;* ^(b) *Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁶ *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁷ *Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁸ *Institut für Kern und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁹ *Department of Physics, Duke University, Durham NC, United States of America*
- ⁵⁰ *SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵¹ *INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵² *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵³ *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵⁴ *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ⁵⁵ ^(a) *Dipartimento di Fisica, Università di Genova, Genova;* ^(b) *INFN Sezione di Genova, Italy*
- ⁵⁶ *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁷ *SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁸ *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁹ *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America*
- ⁶⁰ ^(a) *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;* ^(b) *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;* ^(c) *School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai;* ^(d) *Tsung-Dao Lee Institute, Shanghai, China*
- ⁶¹ ^(a) *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;*
- ⁶² ^(b) *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶³ *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ⁶⁴ ^(a) *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;*
- ⁶⁵ ^(b) *Department of Physics, University of Hong Kong, Hong Kong;* ^(c) *Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶⁶ *Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁷ *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
- ⁶⁸ *Department of Physics, Indiana University, Bloomington IN, United States of America*
- ⁶⁹ ^(a) *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;* ^(b) *ICTP, Trieste;* ^(c) *Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- ⁷⁰ ^(a) *INFN Sezione di Lecce;* ^(b) *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ⁷¹ ^(a) *INFN Sezione di Milano;* ^(b) *Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁷² ^(a) *INFN Sezione di Napoli;* ^(b) *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ⁷³ ^(a) *INFN Sezione di Pavia;* ^(b) *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ⁷⁴ ^(a) *INFN Sezione di Pisa;* ^(b) *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ⁷⁵ ^(a) *INFN Sezione di Roma;* ^(b) *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ⁷⁶ ^(a) *INFN Sezione di Roma Tor Vergata;* ^(b) *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ⁷⁷ ^(a) *INFN Sezione di Roma Tre;* ^(b) *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ⁷⁸ ^(a) *INFN-TIFPA;* ^(b) *Università degli Studi di Trento, Trento, Italy*

- 77 *Institut für Astro und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- 78 *University of Iowa, Iowa City IA, United States of America*
- 79 *Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*
- 80 *Joint Institute for Nuclear Research, Dubna, Russia*
- 81 ^(a) *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;* ^(b) *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* ^(c) *Universidade Federal de São João del Rei (UFSJ), São João del Rei;* ^(d) *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- 82 *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- 83 *Graduate School of Science, Kobe University, Kobe, Japan*
- 84 ^(a) *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;* ^(b) *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- 85 *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- 86 *Faculty of Science, Kyoto University, Kyoto, Japan*
- 87 *Kyoto University of Education, Kyoto, Japan*
- 88 *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- 89 *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- 90 *Physics Department, Lancaster University, Lancaster, United Kingdom*
- 91 *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- 92 *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- 93 *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- 94 *Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- 95 *Department of Physics and Astronomy, University College London, London, United Kingdom*
- 96 *Louisiana Tech University, Ruston LA, United States of America*
- 97 *Fysiska institutionen, Lunds universitet, Lund, Sweden*
- 98 *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- 99 *Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- 100 *Institut für Physik, Universität Mainz, Mainz, Germany*
- 101 *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- 102 *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- 103 *Department of Physics, University of Massachusetts, Amherst MA, United States of America*
- 104 *Department of Physics, McGill University, Montreal QC, Canada*
- 105 *School of Physics, University of Melbourne, Victoria, Australia*
- 106 *Department of Physics, University of Michigan, Ann Arbor MI, United States of America*
- 107 *Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America*
- 108 *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
- 109 *Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
- 110 *Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- 111 *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- 112 *National Research Nuclear University MEPhI, Moscow, Russia*
- 113 *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- 114 *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- 115 *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- 116 *Nagasaki Institute of Applied Science, Nagasaki, Japan*
- 117 *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- 118 *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*

- ¹¹⁹ *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹²⁰ *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹²¹ *Department of Physics, Northern Illinois University, DeKalb IL, United States of America*
- ¹²² ^(a) *Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk;* ^(b) *Novosibirsk State University Novosibirsk, Russia*
- ¹²³ *Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- ¹²⁴ *Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre “Kurchatov Institute”, Moscow, Russia*
- ¹²⁵ *Department of Physics, New York University, New York NY, United States of America*
- ¹²⁶ *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- ¹²⁷ *Ohio State University, Columbus OH, United States of America*
- ¹²⁸ *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*
- ¹²⁹ *Department of Physics, Oklahoma State University, Stillwater OK, United States of America*
- ¹³⁰ *Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹³¹ *Institute for Fundamental Science, University of Oregon, Eugene, OR, United States of America*
- ¹³² *Graduate School of Science, Osaka University, Osaka, Japan*
- ¹³³ *Department of Physics, University of Oslo, Oslo, Norway*
- ¹³⁴ *Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹³⁵ *LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France*
- ¹³⁶ *Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America*
- ¹³⁷ *Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia*
- ¹³⁸ *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America*
- ¹³⁹ ^(a) *Laboratório de Instrumentação e Física Experimental de Partículas — LIP, Lisboa;*
^(b) *Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;*
^(c) *Departamento de Física, Universidade de Coimbra, Coimbra;* ^(d) *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* ^(e) *Departamento de Física, Universidade do Minho, Braga;*
^(f) *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);*
^(g) *Departamento de Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica;* ^(h) *Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- ¹⁴⁰ *Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- ¹⁴¹ *Czech Technical University in Prague, Prague, Czech Republic*
- ¹⁴² *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹⁴³ *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴⁴ *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹⁴⁵ *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America*
- ¹⁴⁶ ^(a) *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* ^(b) *Universidad Andres Bello, Department of Physics, Santiago;* ^(c) *Instituto de Alta Investigación, Universidad de Tarapacá;* ^(d) *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹⁴⁷ *Department of Physics, University of Washington, Seattle WA, United States of America*
- ¹⁴⁸ *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁹ *Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁵⁰ *Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁵¹ *Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- ¹⁵² *SLAC National Accelerator Laboratory, Stanford CA, United States of America*
- ¹⁵³ *Physics Department, Royal Institute of Technology, Stockholm, Sweden*

- ¹⁵⁴ *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America*
¹⁵⁵ *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
¹⁵⁶ *School of Physics, University of Sydney, Sydney, Australia*
¹⁵⁷ *Institute of Physics, Academia Sinica, Taipei, Taiwan*
¹⁵⁸ ^(a) *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* ^(b) *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
¹⁵⁹ *Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
¹⁶⁰ *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
¹⁶¹ *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
¹⁶² *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
¹⁶³ *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
¹⁶⁴ *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
¹⁶⁵ *Tomsk State University, Tomsk, Russia*
¹⁶⁶ *Department of Physics, University of Toronto, Toronto ON, Canada*
¹⁶⁷ ^(a) *TRIUMF, Vancouver BC;* ^(b) *Department of Physics and Astronomy, York University, Toronto ON, Canada*
¹⁶⁸ *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
¹⁶⁹ *Department of Physics and Astronomy, Tufts University, Medford MA, United States of America*
¹⁷⁰ *Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America*
¹⁷¹ *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁷² *Department of Physics, University of Illinois, Urbana IL, United States of America*
¹⁷³ *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia, Spain*
¹⁷⁴ *Department of Physics, University of British Columbia, Vancouver BC, Canada*
¹⁷⁵ *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
¹⁷⁶ *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
¹⁷⁷ *Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁸ *Waseda University, Tokyo, Japan*
¹⁷⁹ *Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
¹⁸⁰ *Department of Physics, University of Wisconsin, Madison WI, United States of America*
¹⁸¹ *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁸² *Department of Physics, Yale University, New Haven CT, United States of America*
^a *Also at Borough of Manhattan Community College, City University of New York, New York NY, United States of America*
^b *Also at CERN, Geneva, Switzerland*
^c *Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
^d *Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
^e *Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
^f *Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates*
^g *Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece*
^h *Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America*

- ⁱ Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America
- ^j Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel
- ^k Also at Department of Physics, California State University, East Bay, United States of America
- ^l Also at Department of Physics, California State University, Fresno, United States of America
- ^m Also at Department of Physics, California State University, Sacramento, United States of America
- ⁿ Also at Department of Physics, King's College London, London, United Kingdom
- ^o Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- ^p Also at Department of Physics, University of Adelaide, Adelaide, Australia
- ^q Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- ^r Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy
- ^s Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ^t Also at Giresun University, Faculty of Engineering, Giresun, Turkey
- ^u Also at Graduate School of Science, Osaka University, Osaka, Japan
- ^v Also at Hellenic Open University, Patras, Greece
- ^w Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
- ^x Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^y Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^z Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ^{aa} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
- ^{ab} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{ac} Also at Institute of Particle Physics (IPP), Vancouver, Canada
- ^{ad} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^{ae} Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain
- ^{af} Also at Joint Institute for Nuclear Research, Dubna, Russia
- ^{ag} Also at Louisiana Tech University, Ruston LA, United States of America
- ^{ah} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{ai} Also at National Research Nuclear University MEPhI, Moscow, Russia
- ^{aj} Also at Physics Department, An-Najah National University, Nablus, Palestine
- ^{ak} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- ^{al} Also at The City College of New York, New York NY, United States of America
- ^{am} Also at TRIUMF, Vancouver BC, Canada
- ^{an} Also at Università di Napoli Parthenope, Napoli, Italy
- * Deceased

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schöffbeck, M. Spanring, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello², A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, L. Moureaux, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, I. Khvastunov³, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silva⁵, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins⁶, D. Matos Figueiredo, M. Medina Jaime⁷, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista^a, Universidade Federal do ABC^b, São Paulo, Brazil

C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, D.S. Lemos, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China

W. Fang², X. Gao², L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸, H.S. Chen⁸, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Zhejiang University, Hangzhou, China

M. Xiao

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt**

A.A. Abdelalim^{11,12}, S. Abu Zeid¹³

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,
M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén,
K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri,
S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup,
B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁴,
M. Titov, G.B. Yu

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut
Polytechnique de Paris**

S. Ahuja, C. Amendola, F. Beaudette, M. Bonanomi, P. Busson, C. Charlot, B. Diab,
G. Falgagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez,
M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois,
A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram¹⁵, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard,
E. Conte¹⁵, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, N. Tonon,
P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique
des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹⁰

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

G. Flügge, W. Haj Ahmad¹⁶, O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁸, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁹, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem¹⁸, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmänn, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaupt, C.E.N. Niemeyer, A. Reimers,

O. Rieger, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann¹⁷, C. Heidecker, U. Husemann, M.A. Iqbal, S. Kudella, S. Maier, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniowski

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók²¹, R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²², F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karanasi²¹, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati²⁴, C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁵, D.K. Sahoo²⁴, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra²⁶, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁷, M. Bharti²⁷, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁷, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber²⁸, M. Maity²⁹, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh²⁷, S. Thakur²⁷

Indian Institute of Technology Madras, Madras, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

D. Dutta, V. Jha, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India

S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b}, R. Aly^{a,b,30}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, J.A. Merlin^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,31}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Albergo^{a,b,32}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,32}, C. Tuve^{a,b}

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, F. Fiori^{a,c}, E. Focardi^{a,b}, G. Latino^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a, A. Beschi^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,17}, M.E. Dinardo^{a,b}, P. Dini^a, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi^a, D. Menasce^a, F. Monti^{a,b}, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,17}, D. Zuolo^{a,b}

INFN Sezione di Napoli^a, Università di Napoli ‘Federico II’^b, Napoli, Italy, Università della Basilicata^c, Potenza, Italy, Università G. Marconi^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Layer^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,17}, P. Paolucci^{a,17}, B. Rossi^a, C. Sciacca^{a,b}, E. Voevodina^{a,b}

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy, Università di Trento^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh^{a,b}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

A. Braghieri^a, D. Fiorina^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell’Orso^a, S. Donato^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^a, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Rome, Italy

F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^a, M. Diemoz^a, E. Longo^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, C. Quaranta^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b}, R. Tramontano^{a,b}

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy, Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, J.R. González Fernández^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspá^{a,c}, R. Salvatico^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, D. Trocino^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Kyung Hee University, Department of Physics

J. Goh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

University of Seoul, Seoul, Korea

D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia

V. Veckalns³³

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic³, N. Raicevic

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler, P. Lujan

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szeleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisenz, V. Palichik, V. Pereygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, A. Nikitenko⁴¹, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia

M. Chadeeva⁴², P. Parygin, D. Philippov, V. Rusinov, E. Zhemchugov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴³, L. Dudko, V. Klyukhin, N. Korneeva, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴⁴, V. Blinov⁴⁴, T. Dimova⁴⁴, L. Kardapoltsev⁴⁴, Y. Skovpen⁴⁴

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences

P. Adzic⁴⁵, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, CristinaF. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Mar-

tinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo⁴⁶, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

D.U.J. Sonnadara

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁴⁷, D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban²⁰, J. Kaspar, J. Kieseler, M. Krammer¹, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabad, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁴⁸, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. AMSLER⁵⁰, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

National Central University, Chung-Li, Taiwan

C.M. Kuo, W. Lin, A. Roy, T. Sarkar²⁹, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, A. Celik⁵¹, S. Damarseckin⁵², Z.S. Demiroglu, F. Dolek, C. Dozen⁵³, I. Dumanoglu⁵⁴, G. Gokbulut, EmineGurpinar Guler⁵⁵, Y. Guler, I. Hos⁵⁶, C. Isik, E.E. Kangal⁵⁷, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁵⁸, A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁹, G. Karapinar⁶⁰, M. Yalvac⁶¹

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁶², O. Kaya⁶³, Ö. Özçelik, S. Tekten⁶⁴, E.A. Yetkin⁶⁵

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak⁵⁴, Y. Komurcu, S. Sen⁶⁶

Istanbul University, Istanbul, Turkey

S. Cerci⁶⁷, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁶⁷

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

E. Bhal, S. Bologna, J.J. Brooke, D. Burns⁶⁸, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL⁷⁰, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, M. Komm, J. Langford, L. Lyons, A.-M. Magnan, S. Malik,

A. Martelli, V. Milosevic, A. Morton, J. Nash⁷¹, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, U.S.A.

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, U.S.A.

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, U.S.A.

A. Buccilli, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, U.S.A.

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, U.S.A.

G. Benelli, B. Burkle, X. Coubez¹⁸, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁷², K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁷³, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, U.S.A.

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, U.S.A.

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, U.S.A.

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara — Department of Physics, Santa Barbara, U.S.A.

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, U.S.A.

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. McDermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁴³, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, M. Wang, H.A. Weber, A. Woodard

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, U.S.A.

Y.R. Joshi

Florida State University, Tallahassee, U.S.A.

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, V. Kumar, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, U.S.A.

M. Alhusseini, B. Bilki⁵⁵, K. Dilsiz⁷⁴, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁷⁵, A. Moeller, J. Nachtman, H. Ogul⁷⁶, Y. Onel, F. Ozok⁷⁷, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi⁷⁸

Johns Hopkins University, Baltimore, U.S.A.

B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vami

The University of Kansas, Lawrence, U.S.A.

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, U.S.A.

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, U.S.A.

R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb

State University of New York at Buffalo, Buffalo, U.S.A.

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, U.S.A.

S. Bhattacharya, J. Bueghly, G. Fedi, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko³⁷, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf

The Ohio State University, Columbus, U.S.A.

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, U.S.A.

G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.

A. Barker, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, U.S.A.

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, U.S.A.

A. Baty, U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, U.S.A.

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, U.S.A.

H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷⁹, M. Dalchenko, M. De Mattia, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁸⁰, H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, U.S.A.

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

University of Wisconsin — Madison, Madison, WI, U.S.A.

K. Black, T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at Université Libre de Bruxelles, Bruxelles, Belgium

3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

6: Also at UFMS, Nova Andradina, Brazil

7: Also at Universidade Federal de Pelotas, Pelotas, Brazil

8: Also at University of Chinese Academy of Sciences, Beijing, China

- 9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
- 10: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 11: Also at Helwan University, Cairo, Egypt
- 12: Now at Zewail City of Science and Technology, Zewail, Egypt
- 13: Also at Ain Shams University, Cairo, Egypt
- 14: Also at Purdue University, West Lafayette, U.S.A.
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 19: Also at University of Hamburg, Hamburg, Germany
- 20: Also at Brandenburg University of Technology, Cottbus, Germany
- 21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 25: Also at Institute of Physics, Bhubaneswar, India
- 26: Also at G.H.G. Khalsa College, Punjab, India
- 27: Also at Shoolini University, Solan, India
- 28: Also at University of Hyderabad, Hyderabad, India
- 29: Also at University of Visva-Bharati, Santiniketan, India
- 30: Now at INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy
- 31: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 32: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, U.S.A.
- 41: Also at Imperial College, London, United Kingdom
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at California Institute of Technology, Pasadena, U.S.A.
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at Università degli Studi di Siena, Siena, Italy
- 47: Also at INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy, Pavia, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 51: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey
- 52: Also at Şirnak University, Şirnak, Turkey

- 53: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
- 54: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 55: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 56: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
- 57: Also at Mersin University, Mersin, Turkey
- 58: Also at Piri Reis University, Istanbul, Turkey
- 59: Also at Ozyegin University, Istanbul, Turkey
- 60: Also at Izmir Institute of Technology, Izmir, Turkey
- 61: Also at Bozok Universitetsi Rektörlüğü, Yozgat, Turkey
- 62: Also at Marmara University, Istanbul, Turkey
- 63: Also at Milli Savunma University, Istanbul, Turkey
- 64: Also at Kafkas University, Kars, Turkey
- 65: Also at Istanbul Bilgi University, Istanbul, Turkey
- 66: Also at Hacettepe University, Ankara, Turkey
- 67: Also at Adiyaman University, Adiyaman, Turkey
- 68: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 69: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 70: Also at IPPP Durham University, Durham, United Kingdom
- 71: Also at Monash University, Faculty of Science, Clayton, Australia
- 72: Also at Bethel University, St. Paul, Minneapolis, U.S.A., St. Paul, U.S.A.
- 73: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 74: Also at Bingol University, Bingol, Turkey
- 75: Also at Georgian Technical University, Tbilisi, Georgia
- 76: Also at Sinop University, Sinop, Turkey
- 77: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 78: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 79: Also at Texas A&M University at Qatar, Doha, Qatar
- 80: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea