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Regular Article - Experimental Physics

Search for contact interactions and large extra dimensions in the dilepton channel using proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration[⋆]

CERN, 1211 Geneva 23, Switzerland

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Abstract A search is conducted for non-resonant new phenomena in dielectron and dimuon final states, originating from either contact interactions or large extra spatial dimensions. The LHC 2012 proton–proton collision dataset recorded by the ATLAS detector is used, corresponding to 20 fb^{-1} at $\sqrt{s}$ = 8 TeV. The dilepton invariant mass spectrum is a discriminating variable in both searches, with the contact interaction search additionally utilizing the dilepton forward-backward asymmetry. No significant deviations from the Standard Model expectation are observed. Lower limits are set on the $\ell\ell qq$ contact interaction scale Λ between 15.4 TeV and 26.3 TeV, at the 95 % credibility level. For large extra spatial dimensions, lower limits are set on the string scale M_S between 3.2 TeV to 5.0 TeV.

1 Introduction

Many theories beyond the Standard Model (SM) predict new phenomena which give rise to dilepton final states, such as new resonances. These have been searched for using the ATLAS detector at the Large Hadron Collider (LHC) and are reported elsewhere [1]. In this paper, a complementary search is performed for new phenomena that appear as broad deviations from the SM in the dilepton invariant mass distribution or in the angular distribution of the leptons (where the leptons considered in this analysis are electrons or muons). The phenomena under investigation are contact interactions (CI) and large extra dimensions (LED).

2 Theoretical motivation

The presence of a new interaction can be detected at an energy much lower than that required to produce direct evidence of the existence of a new gauge boson. The charged weak interaction responsible for nuclear β decay provides such an example. A non-renormalizable description of this process was successfully formulated by Fermi in the form of a four-fermion contact interaction [2]. A contact interaction can also accommodate deviations from the SM in proton–proton scattering due to quark and lepton compositeness, where a characteristic energy scale Λ corresponds to the binding energy between fermion constituents. A new interaction or compositeness in the process $q\overline{q} \to \ell^+\ell^-$ can be described by the following four-fermion contact interaction Lagrangian [3,4]

$$\begin{aligned}\mathscr{L} = \frac{g^2}{\Lambda^2}\,[&\eta_{\mathrm{LL}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})\,(\overline{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}})\\ &+\eta_{\mathrm{RR}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})\,(\overline{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}})\\ &+\eta_{\mathrm{LR}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})\,(\overline{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}})\\ &+\eta_{\mathrm{RL}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})\,(\overline{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}})],\end{aligned}$$

where g is a coupling constant chosen by convention to satisfy $g^2/4\pi = 1$, Λ is the contact interaction scale, and $q_{\mathrm{L,R}}$ and $\ell_{\mathrm{L,R}}$ are left-handed and right-handed quark and lepton fields, respectively. The parameters η_{ij}, where i and j are L or R (left or right), define the chiral structure of the new interaction. Different chiral structures are investigated here, with the left-right model obtained by setting $\eta_{\mathrm{LR}} = \eta_{\mathrm{RL}} = \pm 1$ and $\eta_{\mathrm{LL}} = \eta_{\mathrm{RR}} = 0$. Likewise, the left-left and right-right models are obtained by setting the corresponding parameters to ± 1, and the others to zero. The sign of η_{ij} determines whether the interference is constructive ($\eta_{ij} = -1$) or destructive ($\eta_{ij} = +1$). The cross-section for the process $q\overline{q} \to \ell^+\ell^-$ in the presence of these contact interaction models can be written as:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{DY}} - \eta_{ij}\frac{F_{\mathrm{I}}}{\Lambda^2} + \frac{F_{\mathrm{C}}}{\Lambda^4}, \tag{1}$$

where the first term accounts for the $q\overline{q} \to Z/\gamma^* \to \ell^+\ell^-$ Drell–Yan (DY) process, the second term corresponds to the interference between the DY and CI processes, and the third term describes the pure CI process. These two latter terms

⋆ e-mail: atlas.publications@cern.ch

include F_{I} and F_{C}, respectively, which are functions of the cross-section, and do not depend on Λ. The relative impact of the interference and pure CI terms depends on both the dilepton mass and Λ. For example, the magnitude of the interference term for dilepton masses above 600 GeV is about twice as large as that of the pure CI term at $\Lambda = 14$ TeV; the interference becomes increasingly dominant for higher values of Λ.

There are other models which predict deviations from the SM in the dilepton mass spectrum, and seek to address the vast hierarchy between the electroweak (EW) and Planck scales, such as the solution proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD) [5]. In this model, gravity is allowed to propagate in large flat extra spatial dimensions, thereby diluting its apparent effect in 3+1 spacetime dimensions. The flat n extra dimensions are of common size R ($\sim$1 μm–1 mm for $n = 2$) and are compactified on an n-dimensional torus. The fundamental Planck scale in (4+n)-dimensions, M_{D}, is related to the Planck scale, M_{Pl}, by Gauss's law $M_{\mathrm{Pl}}^2 \sim M_{\mathrm{D}}^{n+2} R^n$. It is thus possible for M_{D} to be in the TeV range for sufficiently large volumes ($\propto R^n$). In this model, the SM particles and their interactions are confined to a four-dimensional submanifold, whereas gravitons may also propagate into extra dimensions of size R. This gives rise to a tower of Kaluza–Klein (KK) graviton modes with a mass spacing inversely proportional to R. Values for M_{D} at the TeV scale imply very small mass differences between KK modes and thus an essentially continuous mass spectrum.

The production of dileptons via virtual KK graviton exchange involves a sum over many KK modes that needs to be cut off at some value. In this paper, the ultraviolet cutoff is chosen to be the string scale, M_{S} [6], which sets the context in which this search and its results should be interpreted, and is chosen for consistency with previous searches. This scale is related to M_{D} via the Gamma function, Γ, by [7]

$$M_{\mathrm{S}} = 2\sqrt{\pi}\left[\Gamma\left(\frac{n}{2}\right)\right]^{1/(n+2)} M_{\mathrm{D}}.$$

The cross-section for $q\bar{q}/gg \rightarrow \ell^+\ell^-$ in the presence of large extra dimensions can be expressed as

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{DY}} + \mathscr{F}\frac{F_{\mathrm{int}}}{M_{\mathrm{S}}^4} + \mathscr{F}^2\frac{F_{\mathrm{G}}}{M_{\mathrm{S}}^8}, \tag{2}$$

where σ_{DY} is the DY cross-section, and F_{int} and F_{G} are functions of the cross-sections (they do not depend on M_{S}) involving the interference and pure KK graviton effects, respectively. The strength of the interaction is characterized by $\mathscr{F}/M_{\mathrm{S}}^4$, where the dimensionless parameter $\mathscr{F}$ varies in the different calculations provided by Giudice–Rattazzi–Wells (GRW) [8], Hewett [9] and Han–Lykken–Zhang (HLZ) [10].

The different values are:

$$\mathscr{F} = 1, \quad \text{(GRW)}$$
$$\mathscr{F} = \frac{2\lambda}{\pi} = \frac{\pm 2}{\pi}, \quad \text{(Hewett)}$$
$$\mathscr{F} = \log\left(\frac{M_{\mathrm{S}}^2}{s}\right) \quad \text{for } n = 2, \quad \text{(HLZ)}$$
$$\mathscr{F} = \frac{2}{n-2} \quad \text{for } n > 2. \text{ (HLZ)}.$$

In the Hewett formalism, $\lambda = \pm 1$ is introduced to allow for constructive or destructive interference with the DY process. Unlike the situation with contact interactions described above, interference effects between the DY and virtual KK graviton processes are small due to dilepton production by virtual KK gravitons being predominantly gluon-induced rather than quark-induced.

Previous searches for CI have been carried out in neutrino–nucleus and electron–electron scattering [11], as well as electron–positron [12,13], electron–proton [14], and proton–antiproton colliders [15,16]. Searches for CI have also been performed by the ATLAS and CMS Collaborations [17,18]. The strongest exclusion limits for $\ell\ell qq$ CI in which all quark flavours contribute come from the previous ATLAS non-resonant dilepton analysis conducted using 5 fb^{-1} of proton–proton (pp) collision data at $\sqrt{s} = 7$ TeV [17]. That combined analysis of the dielectron and dimuon channels set lower limits at 95 % credibility level (C.L.) on the left-left model of $\Lambda > 13.9$ TeV and $\Lambda > 10.2$ TeV, for constructive and destructive interference, respectively, given a uniform positive $1/\Lambda^2$ prior.

Previous searches for evidence of ADD-model extra dimensions via virtual KK graviton exchange have been performed at electron–positron [19], electron–proton [20], and proton–antiproton colliders [16]. Searches have also been performed at the LHC by the ATLAS and CMS Collaborations [17,21]. The most stringent results come from the ATLAS search in the dilepton channel and subsequent combination with the diphoton channel result using 5 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV [17]. That analysis set lower limits on M_{S} at 95 % C.L. in the GRW formalism of 3.5 TeV and 3.4 TeV for $1/M_{\mathrm{S}}^4$ and $1/M_{\mathrm{S}}^8$ priors, respectively.

3 The ATLAS detector

The ATLAS detector [22] consists of an Inner Detector (ID) surrounded by a solenoid magnet for tracking charged particles, and a calorimeter for capturing particles that interact electromagnetically or hadronically, to measure their energy. A Muon Spectrometer (MS) and toroidal magnet system provide tracking for muons, which typically escape the calorimeter.

The ID is immersed in a 2.0 T axial magnetic field and provides charged-particle tracking up to $|\eta|$ of 2.5.[1] It is composed of a pixel detector, a silicon-strip tracker, and a transition radiation tracker.

The calorimeter system surrounds the solenoid and extends up to $|\eta| = 4.9$. One of its main components is a lead and liquid-argon electromagnetic sampling calorimeter, covering $|\eta| < 3.2$ with a fine segmentation varying by layer. This provides precise energy and position measurements for electrons and photons. Another electromagnetic calorimeter, in the forward direction up to $|\eta| = 4.9$, uses liquid-argon active elements and copper as an absorber. Further from the interaction point lies an iron and scintillator tile calorimeter up to $|\eta| = 1.7$ and a copper and liquid-argon calorimeter up to $|\eta| = 3.2$ for hadronic energy measurements. A hadronic calorimeter in the forward region, up to $|\eta| = 4.9$, uses liquid-argon active elements combined with tungsten as an absorber.

The outermost detector is the MS, which consists of layers of precision tracking chambers and trigger chambers to enable reconstruction of muons with $|\eta| < 2.7$. Precision tracking is provided by monitored drift tube chambers, complemented by a layer of cathode strip chambers in the innermost layer in the forward region. Triggering is handled by resistive plate chambers in the barrel ($|\eta| < 1.05$) and thin-gap chambers in the endcap ($1.05 < |\eta| < 2.4$). One barrel and two endcap toroidal magnet systems provide the bending force to measure muon momentum.

The triggering of events to be recorded by the ATLAS detector is handled by a three-level system [22] which consists of a level-1 hardware trigger, and the high-level trigger (HLT). The HLT is made up of the level-2 trigger, which uses regions of interest, and the event filter, which is based on standard ATLAS event reconstruction and analysis algorithms.

4 Data and Monte Carlo samples

This search uses the LHC 2012 dataset from pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of approximately 20 fb^{-1}. The peak luminosity during this period was 7.7×10^{33} cm^{-2} s^{-1}, with an average number of pp interactions per bunch crossing (pile-up) of $\langle \mu \rangle = 20.7$.

The main background comes from the irreducible DY process. The photon-induced (PI) process is also an irreducible contribution which produces two leptons, arising from a $\gamma\gamma$ initial state via $\hat{t}$– and $\hat{u}$– channel processes. The PI process is not a major background, although it is important in the description of the lepton angular distribution. The reducible, but non-negligible, backgrounds are $t\bar{t}$ and single top-quark production, multi-jet, W+jets, and diboson (WW, WZ, and ZZ) processes. Monte Carlo (MC) simulation is used to estimate all of these backgrounds, with the exception of the multi-jet and W+jets backgrounds, which are estimated with a data-driven fake-factor method, as described in Sect. 5. The multi-jet and W+jets backgrounds are found to be negligible in the dimuon channel [1].

All MC samples were passed through a simulation of the ATLAS detector using GEANT4 [23–25]. The DY background is generated with POWHEG [26] for the next-to-leading-order (NLO) matrix elements using the CT10 [27] parton distribution functions (PDF) and PYTHIA 8.165 [28] for parton showering and hadronization. To correct the DY cross-section from NLO to next-to-next-to-leading-order (NNLO), a dilepton mass-dependent QCD+EW K-factor is calculated with FEWZ 3.1 [29] using the MSTW2008NNLO [30,31] PDF (with CT10 as the base NLO PDF) to take into account higher-order QCD and EW corrections. The photon-induced background is generated with PYTHIA 8.165 at LO using the MRST2004QED [32] PDF. The top-quark production processes are simulated using MC@NLO 4.06 [33] with the CT10 PDF to generate the matrix elements, JIMMY 4.31 [34] to describe multiple parton interactions, and HERWIG 6.520 [35] to describe the remaining underlying event and parton showers. Higher-order corrections are calculated with Top++ 2.0 [36] to derive a K-factor which scales this background description from NLO to NNLO in QCD, including resummation of next-to-next-to-leading-logarithmic (NNLL) soft gluon terms. The diboson processes are generated with HERWIG 6.520 at leading-order (LO) using the CTEQ6L1 PDF [37], and these cross-sections are extrapolated to NLO using dilepton mass-independent K-factors.

The CI signal processes are generated using PYTHIA 8.165 at LO with the MSTW2008LO PDF. The CI cross-section is scaled from LO to NNLO, again using FEWZ with the MSTW2008NNLO PDF to calculate a dilepton mass-dependent QCD+EW K-factor. The ADD LED signal process is simulated with the multi-leg LO generator SHERPA 1.3.1 [7] using the CTEQ6L1 PDF. No higher-order correction is applied to the ADD LED cross-section.

To ensure adequate modelling of the data by the MC simulation, data-derived corrections are applied to the simulation. These include electron energy scale corrections [38], muon momentum corrections [39], and pile-up corrections. They also include trigger, lepton identification, and reconstruction scale factors [38,39], which are all found to be very close to unity. A summary of the generator, parton shower, and PDF information used for all signal and background MC samples used in this search can be found in Table 1.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

Table 1 Summary of MC sample information for signal and background processes used in this search. The columns from left to right give the process of interest, generator, matrix-element order, parton shower program, and PDF utilized

Process	Generator	Order	Parton Shower / Hadronization	PDF
$q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$	POWHEG [26]	NLO	PYTHIA 8.165 [28]	CT10 [27]
$\gamma\gamma/\gamma q/\gamma\bar{q} \to \ell^+\ell^-$	PYTHIA 8.165 [28]	LO	PYTHIA 8.165 [28]	MRST2004QED [32]
$t\bar{t} \to \ell X, Wt \to X$	MC@NLO 4.06 [33]	NLO	JIMMY 4.31 [34] + HERWIG 6.520 [35]	CT10 [27]
$WW, WZ, ZZ \to \ell X/\ell\nu/\ell\ell$	HERWIG 6.520 [35]	LO	HERWIG 6.520 [35]	CTEQ6L1 [37]
CI: $q\bar{q} \to \ell^+\ell^-$	PYTHIA 8.165 [28]	LO	PYTHIA 8.165 [28]	MSTW2008LO [30,31]
ADD: $q\bar{q}/gg \to G^* \to \ell^+\ell^-$	SHERPA 1.3.1 [7]	LO (multi-leg)	SHERPA 1.3.1 [7]	CTEQ6L1 [37]

5 Event selection and background estimation

Events in the ee channel are required to have passed a two-object trigger with transverse momentum (p_{T}) thresholds of 35 GeV and 25 GeV. Events in the $\mu\mu$ channel are required to have passed at least one of two single-object triggers with p_{T} thresholds of 36 GeV and 24 GeV. The higher threshold trigger is used to recover small efficiency losses due to the online muon isolation requirement imposed by the lower threshold trigger. The overall efficiency for dilepton events to fire either of these triggers is found to be > 99 %. In both channels, events are required to have at least one primary vertex with more than two tracks.

In the dielectron channel, events are retained if at least two electrons fulfil the following criteria: the electrons satisfy $|\eta| < 2.47$ (excluding the transition region between the barrel and endcap, $1.37 < |\eta| < 1.52$), the leading and sub-leading electrons have $p_{\mathrm{T}} > 40$ GeV and 30 GeV, respectively, and the electrons satisfy a set of electron identification criteria which are designed to reject jets misidentified as electrons [38]. For the leading and sub-leading electrons, the calorimeter isolation must be less than $(0.007 \times E_{\mathrm{T}}) + 5.0$ GeV, and $(0.022 \times E_{\mathrm{T}}) + 6.0$ GeV, respectively (where E_{T} is the transverse energy in units of GeV). The electron calorimeter isolation is calculated as the $\sum E_{\mathrm{T}}$ in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$, excluding the electron E_{T}. This measure of isolation is corrected for E_{T}-dependent leakage, and pile-up effects which are parameterised as a function of the number of primary vertices in the event. If more than one electron pair exists in the event, the one with the largest scalar sum of E_{T} is chosen. The two electrons in the selected pair are then required to have opposite charge and have dilepton mass greater than 80 GeV.

In the dimuon channel, events are retained if at least two muons fulfil the following criteria: the muons have $p_{\mathrm{T}} > 25$ GeV, pass track quality requirements, and meet longitudinal ($|z_0| < 1$ mm) and transverse ($|d_0| < 0.2$ mm) track impact parameter requirements with respect to the primary vertex. Muons are also required to be isolated: the $\sum p_{\mathrm{T}}$ of all additional tracks within $\Delta R = 0.3$ of the muon must be less than 5 % of the muon p_{T}. Muons are reconstructed by combining tracks from both the ID and MS systems. The MS hit requirements are particularly stringent to improve the momentum resolution, minimize tails in the dimuon mass distribution, and improve modelling by the simulation. Muon tracks are required to include at least three hits in each of three precision MS chambers and have at least one hit in the non-bending plane (ϕ) of two separate chambers to determine the ϕ coordinate and thus a good estimate of the non-uniform toroidal magnetic field. If those tracks include hits in precision chambers that have either no alignment or poor alignment, the tracks are rejected. Finally, the independent ID and MS track $q/p_{\mathrm{T}}^{\mathrm{track}}$ must agree within five standard deviations of the standalone measurement uncertainties added in quadrature. The muon acceptance is highest in the pseudo-rapidity region up to approximately 2.5. If more than two muons satisfy these criteria, the pair of oppositely charged muons with the highest scalar sum of p_{T} is selected. The final requirement is that the dimuon mass must be greater than 80 GeV.

The event selection detailed above is applied to the data and all MC background samples. The acceptance times efficiency for DY events with dilepton mass of 1 TeV (2 TeV) is found to be 67 % (67 %) in the dielectron channel and 47 % (45 %) in the dimuon channel. The selection efficiency is lower for the dimuon channel mainly because of the strict MS hit requirements.

The dominant DY background, as well as the PI background, $t\bar{t}$ and single top-quark production processes, and diboson processes, are all modelled with MC as described in Sect. 4. The combined multi-jet & W+jets background which only affects the electron channel is estimated using a data-driven method designed to describe events which contain a maximum of one real lepton, and one or more jets or photons which are misidentified as a lepton. The details of this method are provided in Ref. [1]. For the top and combined multi-jet & W+jets backgrounds, fits are used to describe the shape of the background dilepton mass distribution with a phenomenologically motivated three-parameter (p_1, p_2, p_3) function ($y(x) = p_1\, x^{p_2 + p_3 \log x}$, where $x = \mathrm{m}_{\ell\ell}$) at high

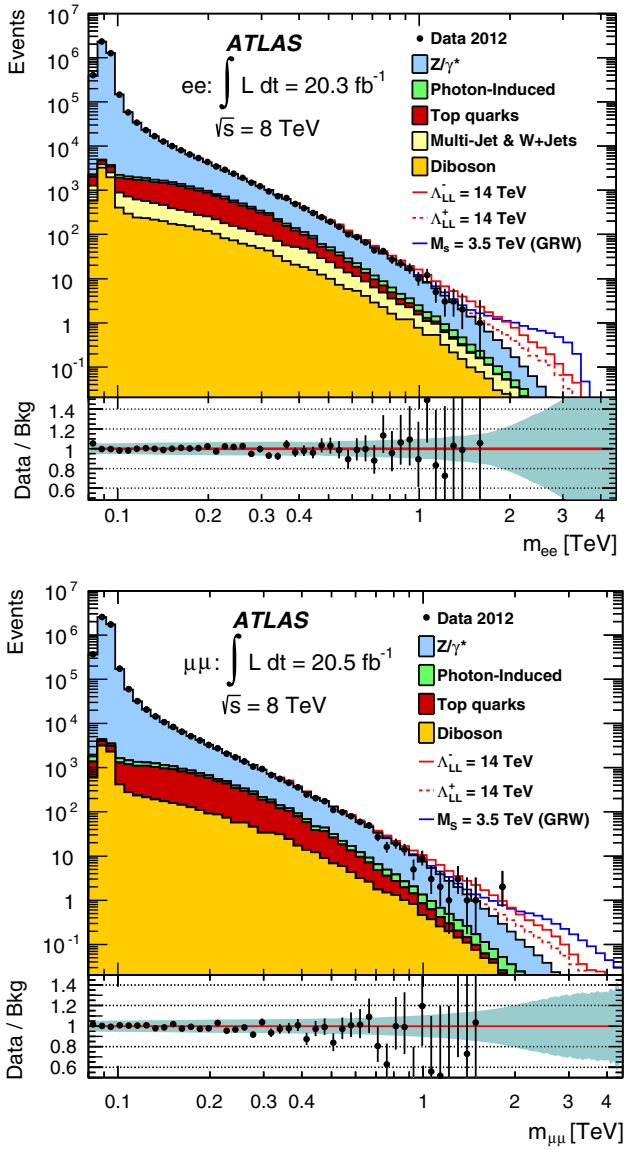


Fig. 1 Reconstructed dielectron (*top*) and dimuon (*bottom*) mass distributions for data and the SM background estimate. Also shown are the predictions for a benchmark Λ value in the LL contact interaction model and benchmark M_S value in the GRW ADD model. The distribution bin width is constant in $\log(m_{\ell\ell})$. The ratio is presented with the total systematic uncertainty overlaid as a band

masses, where the statistical uncertainty becomes large. The fit to the top-quarks background is performed in a similar manner to Ref. [1] using the mass range 200–700 GeV to match the fit to the MC distribution, and the resultant fit as the extrapolated top background estimate above 500 GeV. The choice of extrapolation point is found to have a negligible effect on the fit; however, the range of the fit and the uncertainty on the fit parameters are included in the systematic uncertainty. For the fit describing the combined multi-jet & W+jets background at high mass, the lower edge of the fit range is varied from 425 GeV to 600 GeV and the upper edge from 700 GeV to 1200 GeV, with the extrapolation point fixed to 500 GeV. The uncertainty on this fit is negligible compared to the systematic uncertainty assigned to the data-driven method, as described in Sect. 7.

In this analysis, the normalization, control, and search regions are defined based on the dilepton mass. In the normalization region with mass between 80 GeV and 120 GeV, the total background estimate is scaled to data. This protects the analysis against mass-independent systematic uncertainties. The control region, defined by the mass range from 120 GeV to 400 GeV, is used to check the quality of the background modelling since the signal contribution is negligible in this region. After the normalization procedure, good agreement is found in the control region, as displayed in Fig. 1. The small deviation observed in the first bin of the dielectron mass distribution (Fig. 1) corresponds to an effect that is less than 0.2 % of the total number of events in the normalization region. Thus it has a negligible effect. The search is then conducted in the mass region 400–4500 GeV.

6 Event yields

In the CI search, six broad dilepton mass bins are used in the search region from 400 GeV to 4500 GeV. For the ADD search region, a single dilepton mass bin is employed in the range 1900–4500 GeV, where the lower mass boundary is optimized based on the strongest expected exclusion limit.

The dielectron (dimuon) channel event yields are presented in Table 2 (Table 3) for the CI search and both channels are presented in Table 4 for the ADD LED search. Dilepton mass distributions for data and the predicted background are shown in Fig. 1 for both channels, along with a few benchmark CI and ADD signals overlaid.

The dilepton invariant mass is commonly used as the discriminating variable for a CI search. However, the lepton decay angle also has high discriminating power from DY events in certain cases such as the left-right model. Therefore, the dilepton decay angle, θ^*, is also used as a discriminating variable in the CI search. The angle θ^* is defined in the Collins–Soper (CS) frame [40], which is constructed with the z-axis bisecting the angle between the two incoming parton momenta, and the x-axis perpendicular to the incoming parton momentum plane. As the incoming parton information from pp collisions is unknown, the direction of the dilepton system is taken to be the direction of the incoming quark (as opposed to anti-quark). This introduces a dilution of any asymmetry in the $\cos\theta^*$ distribution (leading to derived angular variables being described as "uncorrected"). The angle θ^* is then taken as the angle between this z-axis and the outgoing negatively charged lepton, using the formula

$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|} \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}},$$

Table 2 Expected and observed event yields in the dielectron channel. The predicted yields are shown for SM background as well as for SM+CI for several CI signal scenarios. The quoted errors consist of both the statistical and systematic uncertainties added in quadrature

Process	m_{ee} [GeV]					
	400–550	550–800	800–1200	1200–1800	1800–3000	3000–4500
Drell–Yan	910 ± 70	302 ± 25	63 ± 6	8.2 ± 1.2	0.64 ± 0.17	0.006 ± 0.004
Top quarks	153 ± 13	35.2 ± 2.7	3.06 ± 0.18	0.140 ± 0.008	<0.004	<0.001
Multi-Jet & W+Jets	88 ± 18	27 ± 5	5.8 ± 1.2	0.87 ± 0.17	0.11 ± 0.02	0.0058 ± 0.0012
Diboson	62.2 ± 3.5	22.3 ± 1.3	5.4 ± 0.4	0.83 ± 0.05	0.075 ± 0.006	<0.001
Photon-Induced	40 ± 40	17 ± 17	4 ± 4	0.7 ± 0.7	0.08 ± 0.08	0.0016 ± 0.0016
Total SM	1260 ± 100	404 ± 35	82 ± 9	10.8 ± 1.6	0.91 ± 0.21	0.014 ± 0.005
Data	1262	388	84	7	0	0
SM+CI ($\Lambda^{-}_{\mathrm{LL}} = 14$ TeV)	1310 ± 110	440 ± 40	108 ± 10	20.9 ± 1.9	4.2 ± 0.4	0.141 ± 0.028
SM+CI ($\Lambda^{-}_{\mathrm{LL}} = 20$ TeV)	1290 ± 110	430 ± 40	90 ± 10	14.4 ± 1.7	2.01 ± 0.25	0.045 ± 0.012
SM+CI ($\Lambda^{-}_{\mathrm{LR}} = 14$ TeV)	1340 ± 110	460 ± 40	118 ± 10	26.3 ± 2.1	6.0 ± 0.5	0.28 ± 0.05
SM+CI ($\Lambda^{-}_{\mathrm{LR}} = 20$ TeV)	1290 ± 110	420 ± 40	98 ± 10	15.7 ± 1.7	2.58 ± 0.28	0.078 ± 0.018
SM+CI ($\Lambda^{-}_{\mathrm{RR}} = 14$ TeV)	1310 ± 110	440 ± 40	108 ± 10	20.8 ± 1.9	3.78 ± 0.34	0.23 ± 0.04
SM+CI ($\Lambda^{-}_{\mathrm{RR}} = 20$ TeV)	1290 ± 110	430 ± 40	91 ± 10	14.3 ± 1.7	1.86 ± 0.24	0.072 ± 0.015
SM+CI ($\Lambda^{+}_{\mathrm{LL}} = 14$ TeV)	1230 ± 110	380 ± 40	79 ± 9	12.2 ± 1.7	2.08 ± 0.25	0.075 ± 0.015
SM+CI ($\Lambda^{+}_{\mathrm{LL}} = 20$ TeV)	1230 ± 110	390 ± 40	77 ± 9	10.0 ± 1.6	0.95 ± 0.22	0.029 ± 0.008
SM+CI ($\Lambda^{+}_{\mathrm{LR}} = 14$ TeV)	1200 ± 110	400 ± 40	88 ± 10	18.9 ± 1.8	4.2 ± 0.4	0.191 ± 0.034
SM+CI ($\Lambda^{+}_{\mathrm{LR}} = 20$ TeV)	1210 ± 110	390 ± 40	81 ± 9	11.5 ± 1.6	1.65 ± 0.24	0.058 ± 0.013
SM+CI ($\Lambda^{+}_{\mathrm{RR}} = 14$ TeV)	1230 ± 110	380 ± 40	79 ± 9	12.1 ± 1.7	2.26 ± 0.26	0.098 ± 0.018
SM+CI ($\Lambda^{+}_{\mathrm{RR}} = 20$ TeV)	1230 ± 110	390 ± 40	77 ± 9	10.2 ± 1.6	1.06 ± 0.22	0.036 ± 0.009

Table 3 Expected and observed event yields in the dimuon channel. The predicted yields are shown for SM background as well as for SM+CI for several CI signal scenarios. The quoted errors consist of both the statistical and systematic uncertainties added in quadrature

Process	$m_{\mu\mu}$ [GeV]					
	400–550	550–800	800–1200	1200–1800	1800–3000	3000–4500
Drell–Yan	670 ± 50	217 ± 18	45 ± 5	5.9 ± 0.8	0.58 ± 0.12	0.027 ± 0.008
Top quarks	128 ± 10	16.3 ± 1.4	1.66 ± 0.11	0.103 ± 0.007	<0.005	<0.002
Diboson	47.6 ± 2.7	15.3 ± 0.9	3.75 ± 0.26	0.556 ± 0.030	0.056 ± 0.005	<0.003
Photon-Induced	34 ± 34	13 ± 13	3.3 ± 3.3	0.5 ± 0.5	0.07 ± 0.07	<0.006
Total SM	880 ± 60	261 ± 22	54 ± 6	7.2 ± 1.0	0.71 ± 0.14	0.032 ± 0.009
Data	814	265	47	7	1	0
SM+CI ($\Lambda^{-}_{\mathrm{LL}} = 14$ TeV)	900 ± 60	285 ± 23	70 ± 6	14.4 ± 1.2	2.89 ± 0.33	0.18 ± 0.04
SM+CI ($\Lambda^{-}_{\mathrm{LL}} = 20$ TeV)	870 ± 60	265 ± 23	58 ± 6	10.0 ± 1.1	1.49 ± 0.18	0.103 ± 0.022
SM+CI ($\Lambda^{-}_{\mathrm{LR}} = 14$ TeV)	930 ± 60	292 ± 23	79 ± 6	16.9 ± 1.4	3.9 ± 0.4	0.38 ± 0.08
SM+CI ($\Lambda^{-}_{\mathrm{LR}} = 20$ TeV)	910 ± 60	281 ± 23	61 ± 6	10.7 ± 1.1	1.76 ± 0.20	0.139 ± 0.029
SM+CI ($\Lambda^{-}_{\mathrm{RR}} = 14$ TeV)	900 ± 60	285 ± 23	70 ± 6	13.8 ± 1.2	2.80 ± 0.32	0.20 ± 0.04
SM+CI ($\Lambda^{-}_{\mathrm{RR}} = 20$ TeV)	870 ± 60	265 ± 23	58 ± 6	10.1 ± 1.1	1.29 ± 0.17	0.09 ± 0.02
SM+CI ($\Lambda^{+}_{\mathrm{LL}} = 14$ TeV)	870 ± 60	252 ± 23	51 ± 6	7.5 ± 1.0	1.45 ± 0.18	0.113 ± 0.023
SM+CI ($\Lambda^{+}_{\mathrm{LL}} = 20$ TeV)	890 ± 60	247 ± 23	50 ± 6	6.4 ± 1.0	0.74 ± 0.15	0.048 ± 0.013
SM+CI ($\Lambda^{+}_{\mathrm{LR}} = 14$ TeV)	860 ± 60	256 ± 23	57 ± 6	12.2 ± 1.1	2.79 ± 0.31	0.28 ± 0.06
SM+CI ($\Lambda^{+}_{\mathrm{LR}} = 20$ TeV)	880 ± 60	252 ± 23	50 ± 6	7.5 ± 1.0	1.15 ± 0.16	0.092 ± 0.019
SM+CI ($\Lambda^{+}_{\mathrm{RR}} = 14$ TeV)	870 ± 60	252 ± 23	51 ± 6	8.0 ± 1.0	1.36 ± 0.18	0.138 ± 0.026
SM+CI ($\Lambda^{+}_{\mathrm{RR}} = 20$ TeV)	890 ± 60	247 ± 23	50 ± 6	6.5 ± 1.0	0.70 ± 0.15	0.052 ± 0.013

Table 4 Expected and observed event yields in the dielectron (second column) and dimuon (third column) channels in the ADD search for large extra dimensions. The expected yields for the SM plus two GRW ADD parameter points are also shown. The quoted errors consist of both the statistical and systematic uncertainties added in quadrature

Process	m_{ee} [GeV]	$m_{\mu\mu}$ [GeV]
	1900–4500	1900–4500
Drell–Yan	0.43 ± 0.12	0.44 ± 0.09
Top quarks	<0.002	<0.006
Multi-Jet & W+Jets	0.062 ± 0.012	<0.001
Diboson	0.053 ± 0.005	0.047 ± 0.005
Photon-Induced	0.06 ± 0.06	0.05 ± 0.05
Total SM	0.61 ± 0.13	0.54 ± 0.09
Data	0	0
SM+ADD ($M_S = 3.5$ TeV)	5.8 ± 0.5	3.9 ± 0.4
SM+ADD ($M_S = 4.0$ TeV)	2.56 ± 0.24	1.69 ± 0.14

where $p_n^{\pm}$ denotes $\frac{1}{\sqrt{2}}(E \pm p_z)$ and $n = 1$ or 2 corresponds to the negatively charged or positively charged leptons, respectively. From this angle, a forward-backward asymmetry, which is sensitive to the chiral structure of the interaction, is defined as follows:

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}},$$

where N_{F} (N_{B}) is the number of events with $\cos\theta^*$ greater (smaller) than zero. The discrimination between CI+SM and the SM-only background is due to the couplings of the CI model, which predicts a larger A_{FB} than the SM background for the CI signal in the left-left and right-right model, and an equally large but opposite-sign A_{FB} for the left-right model. If a CI signal were present in nature this would therefore lead to a modest increase in the total measured A_{FB} as a function of dilepton mass for the left-left and right-right model, and a substantial decrease in the measured A_{FB} for the left-right model. Therefore in the CI search, each dilepton mass bin is further divided into forward and backward events for the statistical interpretation of the results. Figures 2 and 3 present the data and background for $\cos\theta^*$ and A_{FB} as a function of dilepton mass, respectively, in both channels. These distributions also display CI signal predictions.

Good agreement is observed between the data and the background model in both the dilepton mass and A_{FB} distributions.

7 Systematic uncertainties

The total background estimate is normalized by scaling to data in the dilepton mass region 80–120 GeV. This protects the analysis against mass-independent systematic uncertainties (such as the luminosity uncertainty), as any constant scale factor cancels. However, mass-dependent systematic uncertainties affect the shape of the discriminating variables and are therefore considered as nuisance parameters in the statistical interpretation.

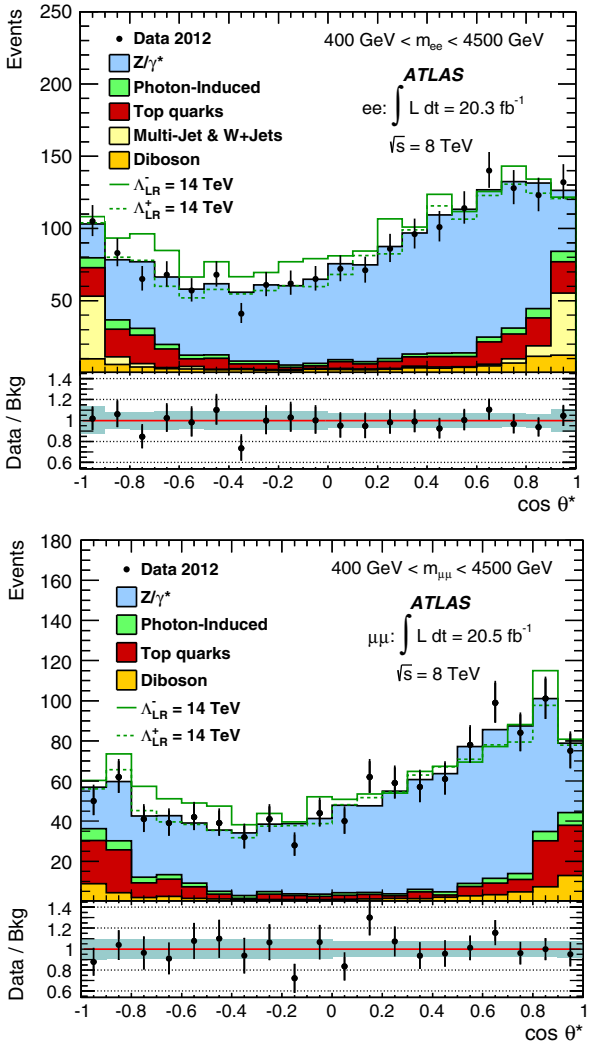


Fig. 2 Reconstructed $\cos\theta^*$ distributions for data and the SM background estimate in the dielectron (*top*) and dimuon (*bottom*) channels. Results are shown for the contact interaction signal region for dilepton masses between 400 GeV and 4500 GeV. Also shown are the predictions for a benchmark Λ value in the LR contact interaction model. The ratio is presented with the total systematic uncertainty overlaid as a band

Experimental uncertainties originate from the following sources: lepton trigger and reconstruction efficiencies, lepton energy and momentum scale and resolution, lepton charge misidentification, multi-jet & W+jets background estimate (in the ee channel), beam energy scale, and MC statistics.

It is important to control the lepton momentum uncertainty, as mismodelling of the resolution could result in a broad signal-like excess (or deficit) in the dilepton mass distribution. The muon momentum resolution depends crit-

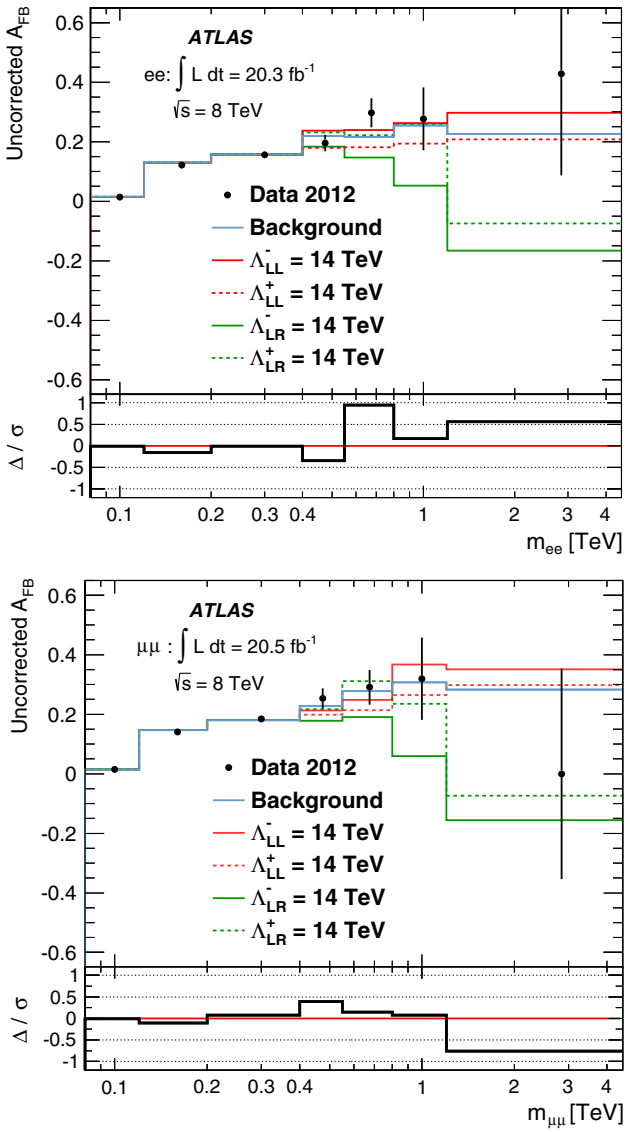


Fig. 3 Reconstructed A_{FB} distributions for data and the SM background estimate as a function of dielectron (*top*) and dimuon (*bottom*) mass. Also shown are the predictions of different benchmark Λ values for the LL and LR contact interaction model (the RR model is very similar to the LL case). The ratio displays the background-subtracted data (Δ) divided by the total uncertainty (σ) in each bin

ically on the quality of the MS chamber alignment. Resolution uncertainties are determined from dedicated data-taking periods with no magnetic field in the MS and from studies of muon tracks passing through the overlap region between chambers in the small and large sectors of the MS where the independent track momenta reconstructed from these adjacent sectors can be compared directly. The electron momentum uncertainty is negligible.

Another important experimental uncertainty is the charge misidentification which can arise from two main sources: track curvature and "trident" events. The latter occurs when a hard bremsstrahlung is emitted by a high-momentum lepton, and a subsequent photon conversion gives rise to a high-momentum track with a charge opposite to that of the initial lepton, but which is selected erroneously. To study the trident source of charge misidentification, dedicated MC samples were generated with the amount of detector material varied by up to 20 % of a radiation length. To study the track curvature source, various investigations were carried out wherein additional charge misidentification is injected into the simulation to ascertain its effect, and the ID track resolution in q/p is varied to assess the probability of a change of charge sign. As these systematic uncertainty studies found a negligible change in charge misidentification, a conservative uncertainty of 20 % with respect to the measured charge misidentification rate in Drell–Yan MC simulation was applied. For the dielectron channel, the charge misidentification systematic uncertainty can be as large as 3 %. For the dimuon channel, this is covered by the resolution uncertainty and is negligible.

The uncertainty on the data-driven estimate of the combined multi-jet & W+jets background is assessed by comparing complementary estimation methods (giving a maximum deviation of 18 % from the nominal method) and variations of the real-electron contamination suppression requirements in the nominal method (resulting in deviations of up to 5 %). The addition of these effects in quadrature gives a total systematic uncertainty on the data-driven estimate of 20 %. A detailed description of this procedure is given in Ref. [1].

A systematic uncertainty on the LHC beam energy of 0.65 % [41] is assessed for both the signal and background processes.

The statistical uncertainty of the MC samples is included as a systematic uncertainty for both the signal and the background. This includes the fit uncertainty due to the high-mass extrapolation of the top-quarks background, which is described in Sect. 5.

The theoretical uncertainties are the variations among the PDF eigenvector sets, the effect of PDF choice, the PDF α_S scale, the EW higher-order corrections, the photon-induced contributions, and the DY cross-section uncertainty. The effect of these uncertainties on the background yield are taken into account with a standard procedure where event weights are used to create systematically shifted distributions, which are then used as nuisance parameters in the statistical interpretation. However, for the signal yields one does not want to introduce a bias via the specific theoretical uncertainty choices, and therefore these are only taken into account by the effect that they have on the signal acceptance times efficiency. This effect was found to be negligible in all cases except for the PDF variation in the ADD search, where an additional uncertainty of 6 % (3 %) is included in the dielectron (dimuon) channel as a nuisance parameter in the statistical interpretation. For the CI search, systematic uncertainties are taken into account as a function of dilepton mass for forward and backward events separately, to account for any variation in the uncertainty which might affect the expected asymme-

Table 5 Summary of the systematic uncertainties taken into account for the total expected number of events. Values are provided at $m_{\ell\ell}$ = 1 TeV (2 TeV) to give representative estimates relevant to this search. The PDF variation values shown for signal are based on CI. For the ADD signal they are uniform at 6 % and 3 % in the dielectron and dimuon channels, respectively. Signal systematic uncertainties are assessed as a function of the corresponding parameter of interest but are not found to vary greatly. N/A indicates that the uncertainty is not applicable

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	4.0 % (4.0 %)	N/A	4.0 % (4.0 %)	N/A
PDF Variation	<0.1 % (0.2 %)	5.0 % (11.0 %)	<0.1 % (<0.1 %)	5.0 % (12.0 %)
PDF Choice	N/A	1.0 % (7.0 %)	N/A	1.0 % (6.0 %)
α_S	N/A	1.0 % (3.0 %)	N/A	1.0 % (3.0 %)
EW Corrections	N/A	1.0 % (2.0 %)	N/A	1.0 % (3.0 %)
Photon-Induced	N/A	7.0 % (12.0 %)	N/A	6.5 % (9.5 %)
Efficiency	1.0 % (2.0 %)	1.0 % (2.0 %)	3.0 % (6.0 %)	3.0 % (6.0 %)
Scale & Resolution	1.2 % (2.4 %)	1.2 % (2.4 %)	1.0 % (4.0 %)	1.0 % (4.0 %)
Electron Charge Misident.	1.2 % (2.0 %)	1.2 % (2.0 %)	N/A	N/A
Multi-Jet & W+Jets	N/A	3.0 % (5.0 %)	N/A	N/A
Beam Energy	1.0 % (3.0 %)	1.0 % (3.0 %)	1.0 % (3.0 %)	2.0 % (3.0 %)
MC Statistics	3.0 % (3.0 %)	0.5 % (0.5 %)	3.0 % (3.0 %)	0.5 % (0.5 %)
Total	5.5 % (6.9 %)	9.5 % (19.4 %)	6.0 % (9.3 %)	9.2 % (18.7 %)

try. For example, the largest systematic uncertainty in this search is the background PDF variation, which has an effect in the dielectron (dimuon) channel of 11 % (12 %) at a mass of 2 TeV. When separated into forward and backward regions at the same dielectron (dimuon) mass, this uncertainty is 10 % (8.5 %) and 16 % (15 %), respectively. Likewise the PI uncertainty in the dielectron (dimuon) channel of 12 % (9.5 %) at a mass of 2 TeV, becomes 10 % (7.5 %) and 16 % (13 %), when separated into forward and backward regions, respectively. The other sources of systematic uncertainty were found to not have a strong dependence between forward and backward events. The different sources of PDF uncertainty are assessed by utilizing the MSTW2008NNLO PDF error set (90 % C.L.) and by following the procedure detailed in Ref. [1,42]. The uncertainty due to the choice of PDF is investigated by comparing the central values of various PDFs, namely MSTW2008NNLO, CT10NNLO [43], NNPDF2.3 [44], ABM11 [45], and HERAPDF1.5 [46]. All except for ABM11 are found to be within the MSTW2008NNLO 90 % C.L. uncertainty, and so the variation from ABM11 with respect to the MSTW2008NNLO central value, outside of the MSTW2008NNLO 90 % C.L. uncertainty, is taken as a separate systematic uncertainty due to PDF choice. VRAP [47] is used to assess the α_S systematic uncertainty, along with scale uncertainties which are estimated by varying the nominal renormalization and factorization scales simultaneously by a factor of two. A study to ascertain the photon-induced background estimate uncertainty was performed in Ref. [1], and found that the nominal MRST2004QED PDF gives an upper estimate of the PI contribution. Varying the assumed quark masses showed that the lower bound of this estimate gives fairly small PI contributions. Therefore the PI background estimate is assigned a conservative uncertainty of 100 %. A uniform uncertainty of 4 % due to the uncertainty on the Z/γ^* NNLO cross-section (using MSTW2008NNLO 90 % C.L.) in the normalization region was determined in Ref. [1] and is applied to signal event yields due to the normalization procedure. The variation due to the cross-section uncertainty in the other background MC samples was found to be negligible. All systematic uncertainties are treated as uncorrelated, and a summary of the systematic uncertainties at dilepton masses of 1 and 2 TeV is presented in Table 5.

8 Statistical interpretation

A Bayesian approach is used for the statistical interpretation of the results, using a uniform positive prior as a function of the parameter of interest to quantify any observed excess. In the absence of a signal, 95 % C.L. lower exclusion limits are set on that parameter. The total number of expected events μ in each search region can be expressed as

$$\mu = n_{\mathrm{s}}(\Theta, \overline{\Omega}) + n_{\mathrm{b}}(\overline{\Omega}),$$

where $n_s(\Theta, \overline{\Omega})$ is the number of events predicted by the CI or ADD signal for a particular choice of model parameter Θ. The quantity $n_b(\overline{\Omega})$ is the total number of background events, and in both cases $\overline{\Omega}$ represents the set of Gaussian nuisance parameters that account for systematic uncertainties on the number of respective signal and background events. The

parameter Θ corresponds to a choice of contact interaction scale Λ and interference parameter η_{ij} in the case of the CI interpretation, and a choice of string scale M_S and specific formalism (GRW, Hewett, or HLZ) in the case of the ADD interpretation.

The likelihood of observing n events given the new physics parameter Θ and nuisance parameters $\overline{\Omega}$ is then the product of Poisson probabilities for each mass–cos θ^* bin k:

$$\mathscr{L}(n \mid \Theta, \overline{\Omega}) = \prod_{l=1}^{N_{\text{channel}}} \prod_{k=1}^{N_{\text{bin}}} \frac{\mu_{lk}^{n_{lk}} e^{-\mu_{lk}}}{n_{lk}!},$$

where n_{lk} is the number of events observed in data, and μ_{lk} is the total number of expected events (signal plus background), both in mass–cos θ^* bin k and channel l (where the channel can be dielectron or dimuon). According to Bayes' theorem, the posterior probability for the parameter Θ, given n observed events, is then

$$\mathscr{P}(\Theta \mid n) = \frac{1}{\mathscr{Z}} \mathscr{L}_{\mathscr{M}}(n \mid \Theta) P(\Theta),$$

where $\mathscr{Z}$ is a normalization constant and the marginalized likelihood $\mathscr{L}_{\mathscr{M}}$ corresponds to the likelihood after all nuisance parameters are integrated out. This integration is performed assuming that the nuisance parameters are correlated across all dilepton mass–cos θ^* bins. The nuisance parameters that are treated as correlated between both channels are: PDF uncertainties, EW corrections, photon-induced, beam energy, and normalization. All other sources are treated as uncorrelated. Table 5 shows which nuisance parameters are taken into account for the signal and background expectations. The prior probability $P(\Theta)$ is chosen to be uniform and positive in either $1/\Lambda^2$ or $1/\Lambda^4$ for the CI analysis, and either $1/M_S^4$ or $1/M_S^8$ for the ADD analysis. These choices are motivated by the form of Eqs. (1) and (2), to give the reader a sense of how the interplay in these forms can affect the result. The 95 % C.L. limit is then obtained by finding the value Θ_{lim} satisfying $\int_0^{\Theta_{\text{lim}}} \mathscr{P}(\Theta \mid n)\, d\Theta = 0.95$, where Θ is chosen to be $1/\Lambda^2$, $1/\Lambda^4$, $1/M_S^4$ or $1/M_S^8$.

The calculations are performed with the Bayesian Analysis Toolkit [48], which uses a Markov Chain Monte Carlo technique to integrate over the nuisance parameters. For each physics model, 1000 pseudo-experiments (PEs) are run to obtain an adequate SM-only expected distribution; the PE with the median parameter of interest value provides the expected limit, with $\pm 1\ \sigma$ and $\pm 2\ \sigma$ intervals also obtained from this set of 1000 PEs correspondingly. In order to quantify the consistency between the data and the background expectation, the likelihood ratio is computed for the signal-plus-background and background-only hypotheses, where the signal-plus-background likelihood (given the prior) is evaluated at the Θ value that maximizes the likelihood. The distribution of negative log-likelihood-ratio (LLR) values is then used to compute the p-value by calculating the fraction of PEs that have a more signal-like LLR value than the observed LLR value in data. The p-value is the probability of observing an excess, at least as signal-like as the one observed in data, given that only background exists.

9 Results

Good agreement is observed between the data and expected background yields. The most significant deviation from the expected background is seen in the dimuon channel for the CI search, with a p-value of 8 % in the LL model with destructive interference given the $1/\Lambda^2$ prior. In the ADD search, the most significant excess is also observed in the dimuon channel, with a p-value of 6 % in the GRW formalism for the $1/M_S^4$ prior. In neither case is the deviation significant. The expected and observed 95 % C.L. lower exclusion limits are set on the parameter of interest in each search, with the resulting limits for the CI and ADD search presented in Tables 6 and 7 respectively, including conversions to other formalisms. These results are also displayed graphically in Fig. 4 for the CI search given the $1/\Lambda^2$ prior and Fig. 5 for the ADD search given the $1/M_S^8$ prior. In the case of the ADD interpretation, the limits obtained with a prior uniform and positive in signal cross-section are found to be consistent with those obtained with the uniform positive $1/M_S^8$ prior.

For the ADD search results, the similar expected and observed exclusion limits within the separate channels are

Table 6 Expected and observed 95 % C.L. lower exclusion limits on Λ for the LL, LR, and RR contact interaction search using a uniform positive prior in $1/\Lambda^2$ or $1/\Lambda^4$. The dielectron, dimuon, and combined dilepton channel limits are shown for both the constructive and destructive interference cases

Expected and observed lower limits on Λ [TeV]							
Channel	Prior	Left-Left		Left-Right		Right-Right	
		Const.	Destr.	Const.	Destr.	Const.	Destr.
Exp: ee	$1/\Lambda^2$	19.1	14.0	22.0	17.4	19.0	14.2
Obs: ee		20.7	16.4	25.2	19.2	20.2	16.6
Exp: ee	$1/\Lambda^4$	17.4	13.0	20.1	16.3	17.2	13.1
Obs: ee		18.6	14.7	22.2	17.7	18.3	14.9
Exp: $\mu\mu$	$1/\Lambda^2$	18.0	12.7	21.6	16.3	17.7	13.0
Obs: $\mu\mu$		16.7	12.5	20.5	14.9	16.5	12.7
Exp: $\mu\mu$	$1/\Lambda^4$	16.2	12.0	19.8	15.3	16.2	12.1
Obs: $\mu\mu$		15.6	11.8	19.0	14.3	15.4	11.9
Exp: $\ell\ell$	$1/\Lambda^2$	21.4	14.7	24.8	18.5	21.0	15.0
Obs: $\ell\ell$		21.6	17.2	26.3	19.0	21.1	17.5
Exp: $\ell\ell$	$1/\Lambda^4$	19.1	13.8	23.1	17.6	19.1	14.2
Obs: $\ell\ell$		19.6	15.4	23.8	17.8	19.3	15.6

Table 7 Expected and observed 95 % C.L. lower exclusion limits on M_S, using a uniform positive prior in $1/M_S^4$ or $1/M_S^8$. The dielectron, dimuon, and combined dilepton channel limits are shown for ADD signal in the GRW, Hewett and HLZ formalisms

Expected and observed lower limits on M_S [TeV]									
Channel	Prior	GRW	Hewett	HLZ					
				$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Exp: ee	$1/M_S^4$	4.0	3.5	3.6	4.7	4.0	3.6	3.3	3.1
Obs: ee	$1/M_S^4$	4.0	3.5	3.6	4.7	4.0	3.6	3.3	3.1
Exp: ee	$1/M_S^8$	3.7	3.3	3.1	4.4	3.7	3.4	3.1	3.0
Obs: ee	$1/M_S^8$	3.7	3.3	3.1	4.4	3.7	3.4	3.1	3.0
Exp: $\mu\mu$	$1/M_S^4$	3.7	3.3	3.4	4.4	3.7	3.4	3.1	3.0
Obs: $\mu\mu$	$1/M_S^4$	3.7	3.3	3.4	4.4	3.7	3.4	3.1	3.0
Exp: $\mu\mu$	$1/M_S^8$	3.5	3.1	3.1	4.2	3.5	3.2	3.0	2.8
Obs: $\mu\mu$	$1/M_S^8$	3.5	3.1	3.1	4.2	3.5	3.2	3.0	2.8
Exp: $\ell\ell$	$1/M_S^4$	4.0	3.6	3.9	4.8	4.0	3.6	3.4	3.2
Obs: $\ell\ell$	$1/M_S^4$	4.2	3.8	4.2	5.0	4.2	3.8	3.6	3.4
Exp: $\ell\ell$	$1/M_S^8$	3.8	3.4	3.5	4.6	3.8	3.5	3.2	3.1
Obs: $\ell\ell$	$1/M_S^8$	4.0	3.6	3.7	4.7	4.0	3.6	3.4	3.2

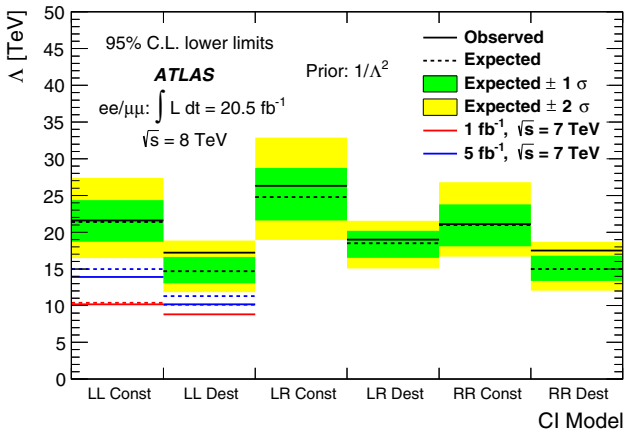


Fig. 4 Summary of 95 % C.L. lower exclusion limits on Λ for the combined dilepton contact interaction search, using a uniform positive prior in $1/\Lambda^2$. Previous ATLAS search results [17,49] are also presented for comparison. Exclusion limits were previously only set on the LL model

due to the small number of expected SM background events, which arise from the high mass threshold chosen for that search. This leads a large fraction of the PEs to return a result of zero expected events, and the median value of the ensemble (taken as the expected limit) to therefore also be zero expected events. For the combined dilepton channel, the total number of expected SM background events is large enough that a wider range of limits is obtained in the ensemble of PEs and the slight data deficit translates into stronger observed limits than expected.

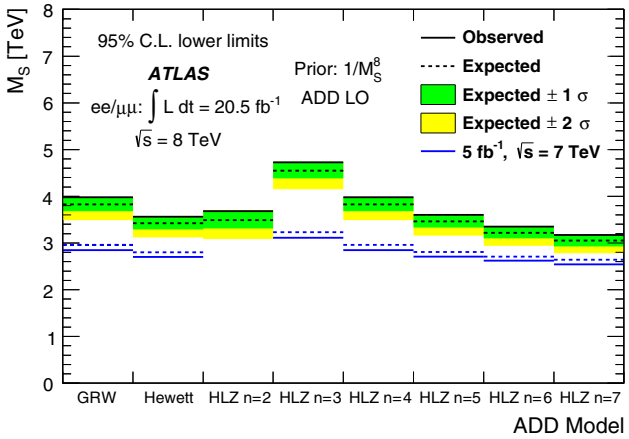


Fig. 5 Summary of 95 % C.L. lower exclusion limits on M_S for the combined dilepton ADD large extra dimensions search, using a uniform positive prior in $1/M_S^8$. Previous ATLAS search results [17] are also presented for comparison. Exclusion limits were not previously set on the HLZ $n = 2$ ADD model

10 Conclusions

A search for non-resonant new phenomena in the dilepton channel has been carried out using the 2012 LHC proton–proton collision dataset of 20 fb^{-1} at $\sqrt{s} = 8$ TeV. This study builds upon previous ATLAS searches, using both dilepton invariant mass and the lepton $\cos\theta^*$ distribution (and by proxy A_{FB}) as search variables. No significant deviations from the Standard Model predictions are observed and lower limits are placed on the scale of contact interactions and large extra dimensions. The most restrictive 95 % C.L. limits are obtained by combining the dielectron and dimuon channels, yielding $\Lambda > 26.3$ TeV for the left-right contact interaction model with constructive interference and a prior flat in $1/\Lambda^2$, and $M_S > 5.0$ TeV for the HLZ $n = 3$ ADD model with a prior flat in $1/M_S^4$.

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Tassi[37a,37b], A. Tavares Delgado[125a,125b], Y. Tayalati[136d], F. E. Taylor[93], G. N. Taylor[87], W. Taylor[160b], F. A. Teischinger[30], M. Teixeira Dias Castanheira[75], P. Teixeira-Dias[76], K. K. Temming[48], H. Ten Kate[30], P. K. Teng[152], J. J. Teoh[117], S. Terada[65], K. Terashi[156], J. Terron[81], S. Terzo[100], M. Testa[47], R. J. Teuscher[159,i], J. Therhaag[21], T. Theveneaux-Pelzer[34], J. P. Thomas[18], J. Thomas-Wilsker[76], E. N. Thompson[35], P. D. Thompson[18], P. D. Thompson[159], R. J. Thompson[83], A. S. Thompson[53], L. A. Thomsen[36], E. Thomson[121], M. Thomson[28], W. M. Thong[87], R. P. Thun[88,*], F. Tian[35], M. J. Tibbetts[15], V. O. Tikhomirov[95,ag], Yu. A. Tikhonov[108,t], S. Timoshenko[97], E. Tiouchichine[84], P. Tipton[177], S. Tisserant[84], T. Todorov[5], S. Todorova-Nova[128], B. Toggerson[7], J. Tojo[69], S. Tokár[145a], K. Tokushuku[65], K. Tollefson[89], L. Tomlinson[83], M. Tomoto[102], L. Tompkins[31], K. Toms[104], N. D. Topilin[64], E. Torrence[115], H. Torres[143], E. Torró Pastor[168], J. Toth[84,ah], F. Touchard[84], D. R. Tovey[140], H. L. Tran[116], T. Trefzger[175], L. Tremblet[30], A. Tricoli[30], I. M. Trigger[160a], S. Trincaz-Duvoid[79], M. F. Tripiana[12], W. Trischuk[159], B. Trocmé[55], C. Troncon[90a], M. Trottier-McDonald[143], M. Trovatelli[135a,135b], P. True[89], M. Trzebinski[39], A. Trzupek[39], C. Tsarouchas[30], J.C-L. Tseng[119], P. V. Tsiareshka[91], D. Tsionou[137], G. Tsipolitis[10], N. Tsirintanis[9], S. Tsiskaridze[12], V. Tsiskaridze[48], E. G. Tskhadadze[51a], I. I. Tsukerman[96], V. Tsulaia[15], S. Tsuno[65], D. Tsybychev[149], A. Tudorache[26a], V. Tudorache[26a], A. N. Tuna[121], S. A. Tupputi[20a,20b], S. Turchikhin[98,af], D. Turecek[127], I. Turk Cakir[4d], R. Turra[90a,90b], P. M. Tuts[35], A. Tykhonov[49], M. Tylmad[147a,147b], M. Tyndel[130], K. Uchida[21], I. Ueda[156], R. Ueno[29], M. Ughetto[84], M. Ugland[14], M. Uhlenbrock[21], F. Ukegawa[161], G. Unal[30], A. Undrus[25], G. Unel[164], F. C. Ungaro[48], Y. Unno[65], C. Unverdorben[99], D. Urbaniec[35], P. Urquijo[87], G. Usai[8], A. Usanova[61], L. Vacavant[84], V. Vacek[127], B. Vachon[86], N. Valencic[106], S. Valentinetti[20a,20b], A. Valero[168], L. Valery[34], S. Valkar[128], E. Valladolid Gallego[168], S. Vallecorsa[49], J. A. Valls Ferrer[168], W. Van Den Wollenberg[106], P. C. Van Der Deijl[106], R. van der Geer[106], H. van der Graaf[106], R. Van Der Leeuw[106], D. van der Ster[30], N. van Eldik[30], P. van Gemmeren[6], J. Van Nieuwkoop[143], I. van Vulpen[106], M. C. van Woerden[30], M. Vanadia[133a,133b], W. Vandelli[30], R. Vanguri[121], A. Vaniachine[6], P. Vankov[42], F. Vannucci[79], G. Vardanyan[178], R. Vari[133a], E. W. Varnes[7], T. Varol[85], D. Varouchas[79], A. Vartapetian[8], K. E. Varvell[151], F. Vazeille[34], T. Vazquez Schroeder[54], J. Veatch[7], F. Veloso[125a,125c], S. Veneziano[133a], A. Ventura[72a,72b], D. Ventura[85], M. Venturi[170], N. Venturi[159], A. Venturini[23], V. Vercesi[120a], M. Verducci[133a,133b], W. Verkerke[106], J. C. Vermeulen[106], A. Vest[44], M. C. Vetterli[143,d], O. Viazlo[80], I. Vichou[166], T. Vickey[146c,ai], O. E. Vickey Boeriu[146c], G. H. A. Viehhauser[119], S. Viel[169], R. Vigne[30], M. Villa[20a,20b], M. Villaplana Perez[90a,90b], E. Vilucchi[47], M. G. Vincter[29], V. B. Vinogradov[64], J. Virzi[15], I. Vivarelli[150], F. Vives Vaque[3], S. Vlachos[10], D. Vladoiu[99], M. Vlasak[127], A. Vogel[21], M. Vogel[32a], P. Vokac[127], G. Volpi[123a,123b], M. Volpi[87], H. von der Schmitt[100], H. von Radziewski[48], E. von Toerne[21], V. Vorobel[128], K. Vorobev[97], M. Vos[168], R. Voss[30], J. H. Vossebeld[73], N. Vranjes[137], M. Vranjes Milosavljevic[106], V. Vrba[126], M. Vreeswijk[106], T. Vu Anh[48], R. Vuillermet[30], I. Vukotic[31], Z. Vykydal[127], P. Wagner[21], W. Wagner[176], H. Wahlberg[70], S. Wahrmund[44], J. Wakabayashi[102], J. Walder[71], R. Walker[99], W. Walkowiak[142], R. Wall[177], P. Waller[73], B. Walsh[177], C. Wang[152,aj],

C. Wang[45], F. Wang[174], H. Wang[15], H. Wang[40], J. Wang[42], J. Wang[33a], K. Wang[86], R. Wang[104], S. M. Wang[152], T. Wang[21], X. Wang[177], C. Wanotayaroj[115], A. Warburton[86], C. P. Ward[28], D. R. Wardrope[77], M. Warsinsky[48], A. Washbrook[46], C. Wasicki[42], P. M. Watkins[18], A. T. Watson[18], I. J. Watson[151], M. F. Watson[18], G. Watts[139], S. Watts[83], B. M. Waugh[77], S. Webb[83], M. S. Weber[17], S. W. Weber[175], J. S. Webster[31], A. R. Weidberg[119], P. Weigell[100], B. Weinert[60], J. Weingarten[54], C. Weiser[48], H. Weits[106], P. S. Wells[30], T. Wenaus[25], D. Wendland[16], Z. Weng[152,ae], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Wessels[58a], J. Wetter[162], K. Whalen[29], A. White[8], M. J. White[1], R. White[32b], S. White[123a,123b], D. Whiteson[164], D. Wicke[176], F. J. Wickens[130], W. Wiedenmann[174], M. Wielers[130], P. Wienemann[21], C. Wiglesworth[36], L. A. M. Wiik-Fuchs[21], P. A. Wijeratne[77], A. Wildauer[100], M. A. Wildt[42,ak], H. G. Wilkens[30], J. Z. Will[99], H. H. Williams[121], S. Williams[28], C. Willis[89], S. Willocq[85], A. Wilson[88], J. A. Wilson[18], I. Wingerter-Seez[5], F. Winklmeier[115], B. T. Winter[21], M. Wittgen[144], T. Wittig[43], J. Wittkowski[99], S. J. Wollstadt[82], M. W. Wolter[39], H. Wolters[125a,125c], B. K. Wosiek[39], J. Wotschack[30], M. J. Woudstra[83], K. W. Wozniak[39], M. Wright[53], M. Wu[55], S. L. Wu[174], X. Wu[49], Y. Wu[88], E. Wulf[35], T. R. Wyatt[83], B. M. Wynne[46], S. Xella[36], M. Xiao[137], D. Xu[33a], L. Xu[33b,al], B. Yabsley[151], S. Yacoob[146b,am], R. Yakabe[66], M. Yamada[65], H. Yamaguchi[156], Y. Yamaguchi[117], A. Yamamoto[65], K. Yamamoto[63], S. Yamamoto[156], T. Yamamura[156], T. Yamanaka[156], K. Yamauchi[102], Y. Yamazaki[66], Z. Yan[22], H. Yang[33e], H. Yang[174], U. K. Yang[83], Y. Yang[110], S. Yanush[92], L. Yao[33a], W-M. Yao[15], Y. Yasu[65], E. Yatsenko[42], K. H. Yau Wong[21], J. Ye[40], S. Ye[25], I. Yeletskikh[64], A. L. Yen[57], E. Yildirim[42], M. Yilmaz[4b], R. Yoosoofmiya[124], K. Yorita[172], R. Yoshida[6], K. Yoshihara[156], C. Young[144], C. J. S. Young[30], S. Youssef[22], D. R. Yu[15], J. Yu[8], J. M. Yu[88], J. Yu[113], L. Yuan[66], A. Yurkewicz[107], I. Yusuff[28,an], B. Zabinski[39], R. Zaidan[62], A. M. Zaitsev[129,aa], A. Zaman[149], S. Zambito[23], L. Zanello[133a,133b], D. Zanzi[100], C. Zeitnitz[176], M. Zeman[127], A. Zemla[38a], K. Zengel[23], O. Zenin[129], T. Ženiš[145a], D. Zerwas[116], G. Zevi della Porta[57], D. Zhang[88], F. Zhang[174], H. Zhang[89], J. Zhang[6], L. Zhang[152], X. Zhang[33d], Z. Zhang[116], Z. Zhao[33b], A. Zhemchugov[64], J. Zhong[119], B. Zhou[88], L. Zhou[35], N. Zhou[164], C. G. Zhu[33d], H. Zhu[33a], J. Zhu[88], Y. Zhu[33b], X. Zhuang[33a], K. Zhukov[95], A. Zibell[175], D. Zieminska[60], N. I. Zimine[64], C. Zimmermann[82], R. Zimmermann[21], S. Zimmermann[21], S. Zimmermann[48], Z. Zinonos[54], M. Ziolkowski[142], G. Zobernig[174], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[103a,103b], V. Zutshi[107], L. Zwalinski[30]

[1] Department of Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, SUNY Albany, Albany, NY, USA
[3] Department of Physics, University of Alberta, Edmonton, AB, Canada
[4] (a) Department of Physics, Ankara University, Ankara, Turkey; (b) Department of Physics, Gazi University, Ankara, Turkey; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey; (d) Turkish Atomic Energy Authority, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
[7] Department of Physics, University of Arizona, Tucson, AZ, USA
[8] Department of Physics, The University of Texas at Arlington, Arlington, TX, USA
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
[13] (a) Institute of Physics, University of Belgrade, Belgrade, Serbia; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA, USA
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, UK
[19] (a) Department of Physics, Bogazici University, Istanbul, Turkey; (b) Department of Physics, Dogus University, Istanbul, Turkey; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
[20] (a) INFN Sezione di Bologna, Bologna, Italy; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany

[22] Department of Physics, Boston University, Boston, MA, USA
[23] Department of Physics, Brandeis University, Waltham, MA, USA
[24] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil; [(b)] Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil; [(d)] Instituto de Fisica, Universidade de Sao Paulo, São Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton, NY, USA
[26] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest, Romania; [(b)] Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania; [(c)] University Politehnica Bucharest, Bucharest, Romania; [(d)] West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, UK
[29] Department of Physics, Carleton University, Ottawa, ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago, IL, USA
[32] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
[33] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; [(b)] Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China; [(c)] Department of Physics, Nanjing University, Nanjing, Jiangsu, China; [(d)] School of Physics, Shandong University, Jinan, Shandong, China; [(e)] Physics Department,, Shanghai Jiao Tong University, Shanghai, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35] Nevis Laboratory, Columbia University, Irvington, NY, USA
[36] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[37] [(a)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy; [(b)] Dipartimento di Fisica, Università della Calabria, Rende, Italy
[38] [(a)] Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków, Poland; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
[39] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
[40] Physics Department, Southern Methodist University, Dallas, TX, USA
[41] Physics Department, University of Texas at Dallas, Richardson, TX, USA
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham, NC, USA
[46] SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova, Genoa, Italy; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, UK
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
[56] Department of Physics, Hampton University, Hampton, VA, USA
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] Department of Physics, Indiana University, Bloomington, IN, USA

[61] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62] University of Iowa, Iowa City, IA, USA
[63] Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
[64] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66] Graduate School of Science, Kobe University, Kobe, Japan
[67] Faculty of Science, Kyoto University, Kyoto, Japan
[68] Kyoto University of Education, Kyoto, Japan
[69] Department of Physics, Kyushu University, Fukuoka, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, UK
[72] [(a)] INFN Sezione di Lecce, Lecce, Italy; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] School of Physics and Astronomy, Queen Mary University of London, London, UK
[76] Department of Physics, Royal Holloway University of London, Surrey, UK
[77] Department of Physics and Astronomy, University College London, London, UK
[78] Louisiana Tech University, Ruston, LA, USA
[79] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[80] Fysiska institutionen, Lunds universitet, Lund, Sweden
[81] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[82] Institut für Physik, Universität Mainz, Mainz, Germany
[83] School of Physics and Astronomy, University of Manchester, Manchester, UK
[84] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[85] Department of Physics, University of Massachusetts, Amherst, MA, USA
[86] Department of Physics, McGill University, Montreal, QC, Canada
[87] School of Physics, University of Melbourne, Parkville, VIC, Australia
[88] Department of Physics, The University of Michigan, Ann Arbor, MI, USA
[89] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
[90] [(a)] INFN Sezione di Milano, Milan, Italy; [(b)] Dipartimento di Fisica, Università di Milano, Milan, Italy
[91] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[92] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[93] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA
[94] Group of Particle Physics, University of Montreal, Montreal, QC, Canada
[95] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[96] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[97] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[98] D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[99] Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany
[100] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany
[101] Nagasaki Institute of Applied Science, Nagasaki, Japan
[102] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[103] [(a)] INFN Sezione di Napoli, Naples, Italy; [(b)] Dipartimento di Fisica, Università di Napoli, Naples, Italy
[104] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
[105] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
[106] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
[107] Department of Physics, Northern Illinois University, DeKalb, IL, USA
[108] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[109] Department of Physics, New York University, New York, NY, USA
[110] Ohio State University, Columbus, OH, USA
[111] Faculty of Science, Okayama University, Okayama, Japan

[112] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA
[113] Department of Physics, Oklahoma State University, Stillwater, OK, USA
[114] Palacký University, RCPTM, Olomouc, Czech Republic
[115] Center for High Energy Physics, University of Oregon, Eugene, OR, USA
[116] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[117] Graduate School of Science, Osaka University, Osaka, Japan
[118] Department of Physics, University of Oslo, Oslo, Norway
[119] Department of Physics, Oxford University, Oxford, UK
[120] [(a)] INFN Sezione di Pavia, Pavia, Italy; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[121] Department of Physics, University of Pennsylvania, Philadelphia, PA, USA
[122] Petersburg Nuclear Physics Institute, Gatchina, Russia
[123] [(a)] INFN Sezione di Pisa, Pisa, Italy; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[124] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA
[125] [(a)] Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisbon, Portugal; [(b)] Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal; [(c)] Department of Physics, University of Coimbra, Coimbra, Portugal; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal; [(e)] Departamento de Fisica, Universidade do Minho, Braga, Portugal; [(f)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain; [(g)] Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[126] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[127] Czech Technical University in Prague, Prague, Czech Republic
[128] Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
[129] State Research Center Institute for High Energy Physics, Protvino, Russia
[130] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
[131] Physics Department, University of Regina, Regina, SK, Canada
[132] Ritsumeikan University, Kusatsu, Shiga, Japan
[133] [(a)] INFN Sezione di Roma, Rome, Italy; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy
[134] [(a)] INFN Sezione di Roma Tor Vergata, Rome, Italy; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy
[135] [(a)] INFN Sezione di Roma Tre, Rome, Italy; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Rome, Italy
[136] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco; [(b)] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Marrakech, Morocco; [(d)] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco; [(e)] Faculté des Sciences, Université Mohammed V-Agdal, Rabat, Morocco
[137] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[138] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA
[139] Department of Physics, University of Washington, Seattle, WA, USA
[140] Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
[141] Department of Physics, Shinshu University, Nagano, Japan
[142] Fachbereich Physik, Universität Siegen, Siegen, Germany
[143] Department of Physics, Simon Fraser University, Burnaby, BC, Canada
[144] SLAC National Accelerator Laboratory, Stanford, CA, USA
[145] [(a)] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[146] [(a)] Department of Physics, University of Cape Town, Cape Town, South Africa; [(b)] Department of Physics, University of Johannesburg, Johannesburg, South Africa; [(c)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[147] [(a)] Department of Physics, Stockholm University, Stockholm, Sweden; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[148] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[149] Departments of Physics and Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, USA
[150] Department of Physics and Astronomy, University of Sussex, Brighton, UK

[151] School of Physics, University of Sydney, Sydney, Australia
[152] Institute of Physics, Academia Sinica, Taipei, Taiwan
[153] Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
[154] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[155] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[156] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[157] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[158] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[159] Department of Physics, University of Toronto, Toronto, ON, Canada
[160] [(a)] TRIUMF, Vancouver, BC, Canada; [(b)] Department of Physics and Astronomy, York University, Toronto, ON, Canada
[161] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[162] Department of Physics and Astronomy, Tufts University, Medford, MA, USA
[163] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[164] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA
[165] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; [(b)] ICTP, Trieste, Italy; [(c)] Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[166] Department of Physics, University of Illinois, Urbana, IL, USA
[167] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[168] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[169] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[170] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[171] Department of Physics, University of Warwick, Coventry, UK
[172] Waseda University, Tokyo, Japan
[173] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[174] Department of Physics, University of Wisconsin, Madison, WI, USA
[175] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[176] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[177] Department of Physics, Yale University, New Haven, CT, USA
[178] Yerevan Physics Institute, Yerevan, Armenia
[179] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a] Also at Department of Physics, King's College London, London, UK
[b] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
[d] Also at TRIUMF, Vancouver, BC, Canada
[e] Also at Department of Physics, California State University, Fresno, CA, USA
[f] Also at Tomsk State University, Tomsk, Russia
[g] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[h] Also at Università di Napoli Parthenope, Naples, Italy
[i] Also at Institute of Particle Physics (IPP), Victoria, Canada
[j] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
[k] Also at Chinese University of Hong Kong, Hong Kong, China
[l] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
[m] Also at Louisiana Tech University, Ruston, LA, USA
[n] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
[o] Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA
[p] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
[q] Also at CERN, Geneva, Switzerland
[r] Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
[s] Also at Manhattan College, New York, NY, USA

[t] Also at Novosibirsk State University, Novosibirsk, Russia
[u] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[v] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[w] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[x] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[y] Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
[z] Also at Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy
[aa] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
[ab] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ac] Also at International School for Advanced Studies (SISSA), Trieste, Italy
[ad] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
[ae] Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
[af] Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[ag] Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[ah] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ai] Also at Department of Physics, Oxford University, Oxford, UK
[aj] Also at Department of Physics, Nanjing University, Jiangsu, China
[ak] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[al] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA
[am] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
[an] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
* Deceased