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Search for contact interactions in dilepton events from pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

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ABSTRACT

This Letter presents a search for contact interactions in the dielectron and dimuon channels using data from proton–proton collisions produced by the LHC at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. The data sample, collected in 2011, corresponds to an integrated luminosity of 1.08 and 1.21 fb^{-1} in the e^+e^- and $\mu^+\mu^-$ channels, respectively. No significant deviations from the standard model are observed. Using a Bayesian approach with a prior flat in $1/\Lambda^2$, the following 95% CL lower limits are placed on the energy scale of $\ell\ell qq$ contact interactions: $\Lambda^- > 10.1$ TeV ($\Lambda^+ > 9.4$ TeV) in the electron channel and $\Lambda^- > 8.0$ TeV ($\Lambda^+ > 7.0$ TeV) in the muon channel for constructive (destructive) interference in the left–left isoscalar contact interaction model. Limits are also provided for a prior flat in $1/\Lambda^4$.

1. Introduction

A wide range of new physics phenomena can produce modifications to the dilepton mass spectra predicted by the standard model (SM) such as quark/lepton compositeness, extra dimensions, and new gauge bosons. The predicted form of these deviations is often either a resonance or an excess in the number of events in the spectra at high mass. This Letter reports on a search for such an excess in dilepton events produced in proton–proton collisions at the LHC [1]. An interpretation of these data in the context of contact interactions (CI) is presented, including the first limits with the ATLAS detector in the dielectron channel and an update of the search performed using 2010 data in the dimuon channel [2]. A separate paper describes the search for new heavy resonances in the dilepton mass spectra performed using the same ATLAS dataset [3].

If quarks and leptons are composite, with at least one common constituent, the interaction of these constituents would likely be manifested through an effective four-fermion contact interaction at energies well below the compositeness scale. Such a contact interaction could also describe a new interaction with a messenger too heavy for direct observation at the LHC, in analogy with Fermi's nuclear β decay theory [4].

The Lagrangian for a general contact interaction has the form [5]

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}\big[\eta_{LL}\overline{\psi}_L\gamma_\mu\psi_L\overline{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\overline{\psi}_R\gamma_\mu\psi_R\overline{\psi}_R\gamma^\mu\psi_R + 2\eta_{LR}\overline{\psi}_L\gamma_\mu\psi_L\overline{\psi}_R\gamma^\mu\psi_R\big], \quad (1)$$

where g is a coupling constant chosen to obey $g^2/4\pi = 1$, Λ is the contact interaction scale, which in the context of compositeness models is the energy scale below which fermion constituents are bound, and $\psi_{L,R}$ are left-handed and right-handed fermion fields, respectively. The parameters η_{ij}, where i and j are L or R, define the chiral structure (left or right) of the new interaction. Specific models are constructed by setting different combinations of these parameters to assume values of -1, 0 or $+1$. The addition of this contact interaction term to the SM Lagrangian alters the Drell–Yan (DY) production cross section ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$). The largest deviations, either constructive or destructive, are expected at high dilepton invariant mass and are determined by the scale Λ and the sign of the parameter η_{ij}. This analysis interprets the data in the context of the left–left isoscalar model (LLIM), which is commonly used as a benchmark for contact interaction searches [6]. The LLIM is defined by setting $\eta_{LL} = \pm 1$ and $\eta_{RR} = \eta_{LR} = 0$.

With the introduction of a contact interaction, the differential cross section for the process $q\bar{q} \to \ell^+\ell^-$ can be written

$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{\mathrm{DY}}}{dm_{\ell\ell}} - \eta_{LL}\frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}, \quad (2)$$

where $m_{\ell\ell}$ is the final-state dilepton mass. The expression above includes an SM DY term, as well as DY-CI interference (F_I) and pure contact interaction (F_C) terms (see Ref. [7] for the full form

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of this expression). At the largest Λ values to which this analysis is sensitive, both interference and pure contact interaction terms play a significant role. For example, at dilepton masses greater than 300 GeV and $\Lambda = 9$ TeV, the magnitude of the interference term is about 1.5 times that of the pure contact interaction term.

The present analysis focuses on identifying a broad deviation from the SM dilepton mass spectra, which are expected to be dominated by the DY process. Current experimental bounds on Λ (see below) indicate any deviation from a new interaction would appear at masses well above the Z boson peak. Consequently, the search region is restricted to dilepton masses above 150 GeV. The analysis exploits the high pp collision energy of the LHC and the capabilities of the ATLAS detector to identify and reconstruct electrons and muons at high momentum.

Previous searches for contact interactions have been carried out in neutrino scattering [8], as well as at electron–positron [9–13], electron–proton [14,15], and hadron colliders [16–24]. In the case of *eeqq* contact interactions, the best limits in the LLIM for all quark flavors come from e^+e^- experiments with $\Lambda^- > 7.2$ TeV and $\Lambda^+ > 12.9$ TeV [9] at 95% confidence level (CL) for $\eta_{LL} = -1$ and $+1$, respectively. These limits assume that contact interactions of electrons with all quark flavors are of the same strength. Best limits set in the specific case of first generation quarks are $\Lambda^- > 9.1$ TeV and $\Lambda^+ > 8.6$ TeV [13] at 95% CL. In the case of $\mu\mu qq$ contact interactions, the best limits are $\Lambda^- > 4.9$ TeV and $\Lambda^+ > 4.5$ TeV from the ATLAS analysis of the 2010 data [2].

2. ATLAS detector and data sample

ATLAS is a multipurpose particle detector [25]. It consists of an inner tracking detector surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. Charged particle tracks are reconstructed using the inner detector, which comprises a silicon pixel detector, a silicon-strip tracker, and a transition radiation tracker, covering the pseudorapidity range $|\eta| < 2.5$.[1] A hermetic calorimeter, which covers $|\eta| < 4.9$, surrounds the superconducting solenoid. The liquid-argon electromagnetic calorimeter, which plays an important role in electron identification and measurement, is finely segmented, with readout granularity (η, ϕ) varying by layer and cells as small as 0.025×0.025 extending to $|\eta| < 2.5$, to provide excellent energy and position resolution. The electron energy resolution is dominated at high energy by a constant term equal to 1.2% in the barrel ($|\eta| < 1.37$) and 1.8% in the endcaps ($1.52 < |\eta| < 2.47$). Hadron calorimetry is provided by an iron-scintillator tile calorimeter in the central rapidity range $|\eta| < 1.7$ and a liquid-argon calorimeter in the rapidity range $1.5 < |\eta| < 4.9$. Another key detector component for this analysis is the muon spectrometer, which is designed to identify muons and measure their momenta with high accuracy. The currently achieved resolution for momenta transverse to the beam line (p_T) of 1 TeV ranges from 15% (central) to 44% (for $|\eta| > 2$). The muon system comprises three toroidal magnet systems, a trigger system consisting of resistive plate chambers in the barrel and thin-gap chambers in the endcaps, providing triggering capability up to $|\eta| = 2.4$, and a set of precision monitored drift tubes and cathode strip chambers in the region $|\eta| < 2.7$.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center 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 $\eta = -\ln\tan(\theta/2)$.

The data sample for this analysis was collected during LHC operation in the first half of 2011 and corresponds to a total integrated luminosity of 1.08 and 1.21 fb^{-1} in the e^+e^- and $\mu^+\mu^-$ channels, respectively. It was collected with stable beam conditions and an operational inner detector. For the electron (muon) channel, the calorimeter (muon spectrometer) was also required to be operational. Events were selected by requiring that they pass the single electron (muon) trigger with a transverse momentum p_T threshold of 20 (22) GeV. This analysis follows the same event selection as the search for new heavy resonances. A summary is provided below, a more complete description can be found in Ref. [3].

3. Signal and background modeling

This analysis looks for deviations from the expected SM dilepton spectra. The largest SM contribution comes from DY followed by semileptonic decay of $t\bar{t}$ pairs, electroweak diboson production (WW, WZ, and ZZ), and production of jets in association with a W boson (W + jets). In addition, multi-jet production (QCD) is a significant background in the electron channel. With the exception of QCD, Monte Carlo (MC) simulation was used to model these backgrounds.

DY events were generated with Pythia 6.421 [26] and Mrst2007 LO* parton distribution functions (PDFs) [27]. Signal DY + CI samples in the LLIM were generated with the same version of Pythia for the full dilepton differential cross section as shown in Eq. (2). This ensured that the interference term F_I was properly included. All quark flavors contributed to the contact interaction in these signal samples. Diboson processes were produced with Herwig 6.510 [28] using Mrst2007 LO* PDFs. The W + jets background was generated with Alpgen [29] and Cteq6l1 [30] PDFs, and the $t\bar{t}$ background with Mc@nlo 3.41 [31] and Cteq6.6 [32] PDFs. For the latter two, Jimmy 4.31 [33] was used to describe multiple parton interactions and Herwig to describe the remaining underlying event and parton showers. Photos [34] was used to handle the final-state photon radiation for all MC samples. Furthermore, higher order QCD corrections were implemented via a mass-dependent K-factor defined as the ratio between the next-to-next-to-leading order (NNLO) Z/γ^* cross section, calculated using Phozpr [35] and Mstw2008 PDFs [36], and the LO cross section. This QCD K-factor was applied to both DY and DY + CI samples. Likewise, DY and DY + CI samples are corrected with a mass-dependent K-factor accounting for higher-order electroweak corrections arising from virtual heavy gauge boson loops that are calculated using Horace [37]. Finally, the generated samples were processed through a full simulation of the ATLAS detector [38] based on the Geant 4 package [39].

For both channels, the QCD multi-jet background is evaluated from data due to poor modeling and low MC statistics. In the electron channel, a reversed electron identification technique is used to select a sample of events in which both electrons fail a subset of the electron identification criteria (see further discussion below). This sample is then used to determine the shape of the QCD background as a function of dielectron invariant mass. This template shape and the sum of the DY, dibosons, $t\bar{t}$, and W + jets backgrounds normalized by their cross sections (including higher order corrections) are fitted to the observed dielectron mass distribution in the range between 70 and 200 GeV to determine the normalization of the QCD contribution. The above QCD background estimate is cross-checked with two other methods described in Ref. [3] in order to determine its systematic uncertainty. In particular, these cross-checks set bounds on the potential bias in the QCD mass spectrum introduced by the reversed identification technique. In the muon channel, the QCD background is much smaller and is also evaluated from data. A reverse isolation method is utilized: a QCD sample is selected from data by requiring two non-isolated muons with $0.1 < \Sigma p_T(R < 0.3)/p_T(\mu) < 1.0$, where $\Sigma p_T(R < 0.3)$ is the sum of the p_T of the tracks in a cone of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ around the direction of the muon. The normalization for this sample is obtained from the ratio of isolated to non-isolated dimuon events in QCD $c\bar{c}$ and $b\bar{b}$ MC, where the isolation requirement is $\Sigma p_T(R < 0.3)/p_T(\mu) < 0.05$. Muons from light hadron decays are not a significant source of background at the high momenta relevant to this analysis.

4. Event selection

Events passing the trigger selection described above are required to have a pair of either electrons or muons with p_T greater than 25 GeV to ensure maximal trigger efficiency. To reject cosmic ray events and beam halo background, events are required to have a reconstructed vertex with at least three charged particle tracks with $p_T > 0.4$ GeV. If several such vertices are found, the vertex with the largest Σp_T^2 is selected as the primary vertex of the event, where the sum is over all charged particles associated with the given vertex. Electron candidates are confined in $|\eta| < 2.47$, with the detector crack region $1.37 \leqslant |\eta| \leqslant 1.52$ excluded because of degraded energy resolution. Muon candidates are required to be within the inner detector acceptance.

Electron candidates are formed from clusters of cells reconstructed in the electromagnetic calorimeter. Identification criteria on the transverse shower shape, the longitudinal leakage into the hadronic calorimeter, and the association to an inner detector track are applied to the cluster to satisfy the medium electron definition [40]. The electron energy is obtained from the calorimeter measurements and its direction from the associated inner detector track. A hit in the first layer of the pixel detector is required (if an active pixel layer is traversed) to suppress background from photon conversions. Further QCD jet background suppression is achieved by demanding the highest p_T electron in the event to be isolated. To that effect, the sum of the calorimeter transverse momenta around the electron direction $\Sigma p_T(R < 0.2)$ must be less than 7 GeV. The core of the electron energy deposition is excluded and the sum is corrected for transverse shower leakage and pile-up from additional pp collisions. In addition, the two electron candidates are not required to have opposite charge because of possible charge mis-identification either due to bremsstrahlung or to the limited momentum resolution of the inner detector at very high p_T. If the event contains more than two selected electrons, the two electrons with the highest p_T are chosen. For these selection criteria, the overall event acceptance for signal events has a small dependence on the dielectron mass above 500 GeV and a value of approximately 65% at 1 TeV.

Muon candidates are required to be of opposite charge and are reconstructed independently in both the inner detector and the muon spectrometer. The momentum is taken from a combined fit to the measurements from both subsystems. To obtain optimal momentum resolution and accurate modeling by the simulation, the muon candidates are required to satisfy the following requirements in the muon spectrometer: have at least three hits in each of the inner, middle, and outer detectors, and at least one hit in the non-bending xy plane. To suppress background from cosmic rays, requirements are imposed on the muon impact parameter and primary vertex (PV): transverse impact parameter $|d_0| < 0.2$ mm, z coordinate with respect to the PV $|z_0 - z_{\mathrm{PV}}| < 1$ mm, and z position of the PV $|z_{\mathrm{PV}}| < 200$ mm. Muons are also required to be isolated to reduce background from jets: $\Sigma p_T(R < 0.3)/p_T(\mu) < 0.05$, as explained in the previous section. If more than one opposite-sign muon pair is found in an event, the pair with the largest $p_T(\mu^+) + p_T(\mu^-)$ is chosen. The overall event acceptance for signal events has only a weak dependence on the dimuon mass with a value of approximately 40% at 1 TeV. Stringent requirements on the presence of hits in all three layers of the muon spectrometer and the limited three-layer geometrical coverage are the primary reason for the lower acceptance relative to the electron channel.

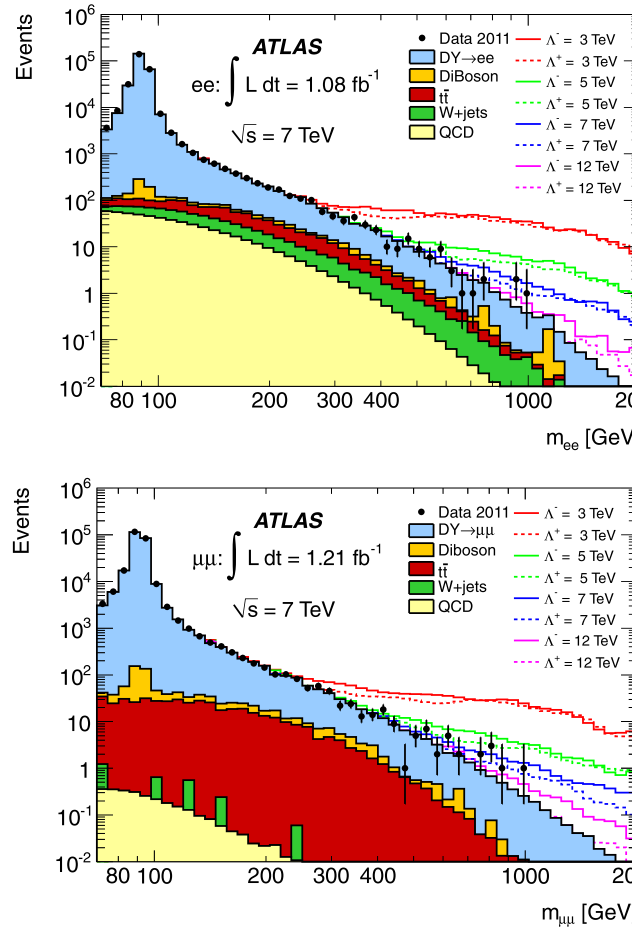

Fig. 1. Dielectron (top) and dimuon (bottom) invariant mass distributions for data (points) and Monte Carlo simulation (histograms). The open histograms correspond to the distributions expected in the presence of contact interactions with different values of Λ for both constructive (solid histograms) and destructive (dashed histograms) interference.

Extensive comparisons between data and MC simulation were performed at the level of single-lepton distributions to confirm that the simulation reproduces the selected data well, especially at high momentum.

Fig. 1 displays the dielectron and dimuon mass spectra for all selected events with invariant mass greater than 70 GeV. The expected event yields for the different processes are obtained by first normalizing each MC process by its cross section (including higher order corrections) and then normalizing the total MC event yield plus the data-derived QCD background to the data in the Z peak region (dilepton mass between 70 and 110 GeV). Good agreement is observed between the data and the SM prediction over the whole dilepton mass range. A quantitative comparison is provided in Tables 1 and 2. A slight excess of events observed at high dimuon mass is consistent with a statistical fluctuation. The most significant deviation in the number of dimuon events occurs for events with mass greater than 800 GeV. In this region, the Poisson probability for observing 5 or more events where 2.1 are expected is 6.2%. The muon tracks in the five data events were inspected in detail and no problem was found.

Table 1
Expected and observed numbers of events in the electron channel. The total expected yield is normalized to the data in the Z peak control region between 70 and 110 GeV. The errors quoted originate from both systematic uncertainties and limited MC statistics, except the error on the total expected yield in the normalization region which is given by the square root of the number of observed events.

m_{ee} [GeV]	70–110	110–130	130–150	150–170	170–200	200–240	240–300
DY	258 482 ± 410	3185 ± 110	1183 ± 46	608 ± 28	473 ± 24	312 ± 18	196 ± 9
$t\bar{t}$	218 ± 36	87 ± 7	64 ± 5	51 ± 2	51 ± 2	37 ± 2	30 ± 1
Dibosons	368 ± 19	31 ± 2	24 ± 2	15 ± 1	16 ± 1	14 ± 1	8 ± 1
W + jets	150 ± 100	57 ± 11	40 ± 9	27 ± 6	26 ± 6	20 ± 5	14 ± 4
QCD	332 ± 60	80 ± 42	50 ± 20	32 ± 7	29 ± 7	19 ± 15	12 ± 9
Total	259 550 ± 510	3440 ± 120	1361 ± 50	733 ± 30	595 ± 25	401 ± 24	260 ± 13
Data	259 550	3419	1362	758	578	405	256

m_{ee} [GeV]	300–400	400–550	550–800	800–1200	1200–1800	1800–3000
DY	105.0 ± 5.0	41.0 ± 2.2	12.8 ± 0.8	2.5 ± 0.2	0.29 ± 0.05	< 0.05
$t\bar{t}$	14.9 ± 0.8	4.5 ± 0.2	1.0 ± 0.1	0.10 ± 0.02	< 0.05	< 0.05
Dibosons	7.5 ± 1.1	2.1 ± 0.4	1.0 ± 0.3	0.3 ± 0.1	< 0.05	< 0.05
W + jets	9.0 ± 3.2	3.5 ± 1.6	1.0 ± 0.7	0.2 ± 0.3	< 0.05	< 0.05
QCD	5.5 ± 4.4	1.5 ± 1.2	0.3 ± 0.2	< 0.05	< 0.05	< 0.05
Total	141.9 ± 8.0	52.6 ± 3.0	16.1 ± 1.1	3.0 ± 0.4	0.33 ± 0.05	< 0.05
Data	147	48	17	3	0	0

Table 2
Expected and observed numbers of events in the dimuon channel. The total expected yield is normalized to the data in the Z peak control region between 70 and 110 GeV. The errors quoted originate from both systematic uncertainties and limited MC statistics, except the error on the total expected yield in the normalization region which is given by the square root of the number of observed events.

$m_{\mu\mu}$ [GeV]	70–110	110–130	130–150	150–170	170–200	200–240	240–300
DY	236 405 ± 320	3133 ± 90	1076 ± 36	548 ± 22	417 ± 18	249 ± 13	153 ± 7
$t\bar{t}$	193 ± 21	70 ± 9	51 ± 7	34 ± 4	38 ± 4	30 ± 3	21 ± 2
Diboson	307 ± 16	25 ± 2	19 ± 2	13 ± 2	12 ± 1	10 ± 1	8 ± 1
W + jets	1 ± 1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
QCD	1 ± 1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Total	236 908 ± 490	3229 ± 90	1147 ± 37	595 ± 22	467 ± 19	290 ± 13	182 ± 8
Data	236 908	3211	1132	621	443	279	195

$m_{\mu\mu}$ [GeV]	300–400	400–550	550–800	800–1200	1200–1800	1800–3000
DY	80.8 ± 3.9	31.0 ± 1.7	9.2 ± 0.6	1.8 ± 0.2	0.22 ± 0.04	< 0.05
$t\bar{t}$	11.7 ± 1.2	3.5 ± 0.3	0.7 ± 0.1	0.06 ± 0.02	< 0.05	< 0.05
Diboson	6.7 ± 1.1	1.0 ± 0.4	0.7 ± 0.3	< 0.05	< 0.05	< 0.05
W + jets	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
QCD	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Total	99.3 ± 4.2	35.5 ± 1.8	10.6 ± 0.7	1.9 ± 0.2	0.22 ± 0.04	< 0.05
Data	83	39	12	5	0	0

5. Systematic uncertainties

Since the MC event yields are normalized to the number of events observed in the Z peak region, only mass-dependent systematic uncertainties need to be considered, except for a 5% overall uncertainty in the knowledge of the Z/γ^* cross section in the normalization region. This overall uncertainty is required since the cross section change due to the new physics is defined with respect to the SM cross section. The dominant uncertainties are of theoretical origin but experimental sources are also considered.

Theoretical uncertainties in the predicted event yields arise from the limited knowledge of PDFs, α_S, QCD and electroweak K-factors, and Z/γ^* cross section. The finite available MC statistics are also taken into account. The uncertainty due to the PDF and α_S is estimated using the MSTW2008 PDF eigenvector set and additional PDFs corresponding to variations in α_S. The resulting effect is about 4% at the Z pole growing with increasing mass to 10% at 1.5 TeV. Uncertainties due to QCD and electroweak K-factors are estimated to grow from 0.3% and 0.4% at the Z pole to 3% and 4.5% at 1.5 TeV, respectively, for both electron and muon channels. Estimates for the QCD K-factor are obtained by varying the renormalization and factorization scales independently by factors of two, then adding the impact of those variations linearly. The uncertainty in the electroweak K-factor is evaluated from the effect of neglecting real boson emission, varying the electroweak scheme definitions as implemented in PYTHIA and HORACE, as well as of the effect of higher order electroweak and $\mathcal{O}(\alpha\alpha_S)$ corrections. For the electron channel, the QCD background estimate is subject to an uncertainty derived from a comparison with different background estimate methods (see discussion above). For the muon channel, the QCD background uncertainty is negligible.

Experimental uncertainties originate from the energy/momentum resolution, as well as the trigger, reconstruction and identification efficiencies. In the electron channel, the uncertainty in the constant term, which dominates the energy resolution at high energy, has a negligible impact on the analysis. Knowledge of the energy scale also has a negligible effect. The electron reconstruction and identification uncertainty results in a 1.5% effect, which is estimated by studying the impact of the isolation requirement on the dielectron mass distribution. In the muon channel, the momentum resolution is dominated by the quality of the muon spectrometer alignment. The uncertainty in the alignment is evaluated directly from dedicated toroid field-off runs and redundant momentum measurements in overlapping small and large chambers. These experimental uncertainties are found to have minimal impact on the dimuon mass distribution. Finally, a systematic error

Table 3
Expected numbers of events in the signal region of the analysis for various contact interaction scales with constructive (Λ^-) and destructive (Λ^+) interference in the electron channel. The errors quoted originate from both systematic uncertainties and limited MC statistics.

m_{ee} [GeV]	150–170	170–200	200–240	240–300	300–400
$\Lambda^- = 3$ TeV	785 ± 29	649 ± 26	467 ± 22	383 ± 19	343 ± 12
$\Lambda^- = 4$ TeV	781 ± 28	647 ± 26	437 ± 21	326 ± 17	223 ± 7
$\Lambda^- = 5$ TeV	734 ± 27	612 ± 24	405 ± 19	298 ± 16	181 ± 6
$\Lambda^- = 7$ TeV	691 ± 26	638 ± 25	406 ± 19	259 ± 15	163 ± 5
$\Lambda^- = 12$ TeV	721 ± 26	604 ± 24	336 ± 17	234 ± 14	149 ± 5
$\Lambda^+ = 3$ TeV	770 ± 28	642 ± 24	424 ± 20	331 ± 17	269 ± 9
$\Lambda^+ = 4$ TeV	745 ± 27	591 ± 23	385 ± 19	277 ± 16	166 ± 5
$\Lambda^+ = 5$ TeV	702 ± 25	607 ± 23	350 ± 17	258 ± 15	151 ± 5
$\Lambda^+ = 7$ TeV	672 ± 25	600 ± 23	399 ± 19	251 ± 14	142 ± 5
$\Lambda^+ = 12$ TeV	749 ± 27	593 ± 23	403 ± 19	274 ± 15	137.9 ± 4.4

m_{ee} [GeV]	400–550	550–800	800–1200	1200–1800	1800–3000
$\Lambda^- = 3$ TeV	286 ± 11	269 ± 12	207 ± 11	112 ± 8	30.3 ± 3.4
$\Lambda^- = 4$ TeV	132 ± 5	109.1 ± 4.9	80.5 ± 4.1	29.8 ± 2.3	10.9 ± 1.3
$\Lambda^- = 5$ TeV	82.7 ± 3.6	57.3 ± 2.6	35.5 ± 1.9	14.8 ± 1.1	3.9 ± 0.5
$\Lambda^- = 7$ TeV	68.3 ± 2.9	29.0 ± 1.4	11.2 ± 0.7	4.0 ± 0.4	1.08 ± 0.17
$\Lambda^- = 12$ TeV	57.3 ± 2.6	18.8 ± 1.1	5.0 ± 0.4	1.00 ± 0.13	0.15 ± 0.05
$\Lambda^+ = 3$ TeV	215 ± 8	239 ± 11	185 ± 10	107 ± 7	28.4 ± 3.2
$\Lambda^+ = 4$ TeV	100.9 ± 3.8	78.1 ± 3.6	60.7 ± 3.2	31.5 ± 2.2	8.7 ± 1.0
$\Lambda^+ = 5$ TeV	64.4 ± 2.7	36.2 ± 1.8	25.4 ± 1.3	12.7 ± 0.9	3.5 ± 0.4
$\Lambda^+ = 7$ TeV	56.3 ± 2.5	20.3 ± 1.1	7.7 ± 0.5	3.58 ± 0.28	0.83 ± 0.12
$\Lambda^+ = 12$ TeV	52.4 ± 2.4	14.4 ± 0.9	3.29 ± 0.28	0.46 ± 0.08	0.075 ± 0.026

Table 4
Expected numbers of events in the signal region of the analysis for various contact interaction scales with constructive (Λ^-) and destructive (Λ^+) interference in the muon channel. The errors quoted originate from both systematic uncertainties and limited MC statistics.

$m_{\mu\mu}$ [GeV]	150–170	170–200	200–240	240–300	300–400
$\Lambda^- = 3$ TeV	638 ± 28	547 ± 26	371 ± 22	285 ± 19	263 ± 13
$\Lambda^- = 4$ TeV	618 ± 27	513 ± 24	287 ± 18	228 ± 15	163 ± 7
$\Lambda^- = 5$ TeV	572 ± 26	478 ± 23	357 ± 20	206 ± 14	131 ± 6
$\Lambda^- = 7$ TeV	571 ± 25	496 ± 23	294 ± 18	187 ± 14	113 ± 5
$\Lambda^- = 12$ TeV	606 ± 26	441 ± 22	252 ± 16	191 ± 14	100.0 ± 3.8
$\Lambda^+ = 3$ TeV	602 ± 26	417 ± 21	332 ± 19	205 ± 15	186 ± 10
$\Lambda^+ = 4$ TeV	575 ± 25	456 ± 22	286 ± 17	182 ± 13	112 ± 5
$\Lambda^+ = 5$ TeV	554 ± 25	483 ± 23	289 ± 17	167 ± 12	102.0 ± 4.0
$\Lambda^+ = 7$ TeV	557 ± 24	435 ± 21	292 ± 18	196 ± 14	102.0 ± 4.4
$\Lambda^+ = 12$ TeV	576 ± 25	421 ± 21	256 ± 16	186 ± 13	100.0 ± 3.9

$m_{\mu\mu}$ [GeV]	400–550	550–800	800–1200	1200–1800	1800–3000
$\Lambda^- = 3$ TeV	192 ± 11	185 ± 12	151 ± 12	60 ± 9	18 ± 7
$\Lambda^- = 4$ TeV	97 ± 5	73 ± 5	50.3 ± 4.0	17.9 ± 2.9	6.8 ± 2.4
$\Lambda^- = 5$ TeV	62.8 ± 3.3	37.5 ± 2.2	21.8 ± 1.8	8.7 ± 1.3	2.8 ± 1.0
$\Lambda^- = 7$ TeV	45.9 ± 2.4	19.5 ± 1.2	7.9 ± 0.7	3.0 ± 0.5	0.59 ± 0.38
$\Lambda^- = 12$ TeV	38.0 ± 2.0	14.0 ± 0.9	2.90 ± 0.26	0.91 ± 0.24	0.11 ± 0.14
$\Lambda^+ = 3$ TeV	152 ± 9	153 ± 11	131 ± 11	63 ± 8	19 ± 6
$\Lambda^+ = 4$ TeV	68.2 ± 3.7	54.7 ± 3.7	42.8 ± 3.4	22.2 ± 2.7	7.4 ± 2.1
$\Lambda^+ = 5$ TeV	51.0 ± 2.5	24.9 ± 1.6	15.7 ± 1.3	8.0 ± 1.0	2.9 ± 0.8
$\Lambda^+ = 7$ TeV	33.9 ± 1.8	13.3 ± 0.8	5.04 ± 0.43	1.85 ± 0.32	0.63 ± 0.30
$\Lambda^+ = 12$ TeV	34.0 ± 1.8	10.1 ± 0.6	1.73 ± 0.18	0.25 ± 0.12	0.07 ± 0.10

growing from 0.3% at the Z pole to 4.5% at 1.5 TeV is assigned to the muon reconstruction efficiency to account conservatively for its small p_T dependence due to occasional large energy loss from bremsstrahlung.

6. Statistical analysis

The data analysis proceeds with a Bayesian method to compare the observed event yields with the expected yields for a range of different contact interaction model parameters. Specifically, the number μ of expected events in each of the mass bins defined in Tables 1 and 2 is

$$\mu = n_{\text{DY+CI}}(\theta, \bar{\nu}) + n_{\text{non-DY bg}}(\bar{\nu}), \quad (3)$$

where $n_{\text{DY+CI}}(\theta, \bar{\nu})$ is the number of events predicted by the Pythia DY + CI MC for a particular choice of contact interaction model parameter θ, $n_{\text{non-DY bg}}(\bar{\nu})$ is the number of non-DY background events, and $\bar{\nu}$ represents the set of Gaussian nuisance parameters that account for systematic uncertainties in these numbers as discussed above. The parameter θ corresponds to a choice of energy scale Λ and interference parameter η_{LL}. The complete set of μ values used in this analysis is shown in Tables 3 and 4 for the electron and muon channels, respectively. For each mass bin, a second order polynomial is used to model the dependence of μ on $1/\Lambda^2$.

The likelihood of observing a set of $\bar{n}$ events in N invariant mass bins is given by a product of Poisson probabilities for each mass bin k:

$$\mathcal{L}(\bar{n} \mid \theta, \bar{\nu}) = \prod_{k=1}^{N} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!}. \quad (4)$$

Table 5
Expected and observed 95% CL lower limits on the contact interaction energy scale Λ for the electron and muon channels, as well as for the combination of those channels. Separate results are provided for the different choices of flat priors: $1/\Lambda^2$ and $1/\Lambda^4$.

Channel	Prior	Expected limit (TeV)		Observed limit (TeV)	
		Constr.	Destr.	Constr.	Destr.
e^+e^-	$1/\Lambda^2$	9.6	9.3	10.1	9.4
	$1/\Lambda^4$	8.9	8.6	9.2	8.6
$\mu^+\mu^-$	$1/\Lambda^2$	8.9	8.6	8.0	7.0
	$1/\Lambda^4$	8.3	7.9	7.6	6.7
Comb.	$1/\Lambda^2$	10.4	10.1	10.2	8.8
	$1/\Lambda^4$	9.6	9.4	9.4	8.4

According to Bayes' theorem, the posterior probability for the parameter θ given $\bar{n}$ observed events is

$$\mathcal{P}(\theta \mid \bar{n}) = \frac{1}{\mathcal{Z}}\mathcal{L}_{\mathcal{M}}(\bar{n} \mid \theta)P(\theta), \tag{5}$$

where $\mathcal{Z}$ is a normalization constant and the marginalized likelihood $\mathcal{L}_{\mathcal{M}}$ corresponds to the likelihood after all nuisance parameters have been integrated out. This integration is performed assuming that the nuisance parameters are correlated across all mass bins and that they affect both signal and background expectations, except for the electroweak K-factor that only affects the DY and DY + CI components. The prior probability $P(\theta)$ is chosen to be flat in $1/\Lambda^2$, motivated by the form of Eq. (2). The 95% CL limit is then obtained by finding the value Λ_{lim} satisfying $\int_0^{\theta_{\text{lim}}} \mathcal{P}(\theta \mid \bar{n})\,d\theta = 0.95$, where $\theta = 1/\Lambda^2$. The above calculations have been performed with the Bayesian Analysis Toolkit (BAT) [41].

7. Results

To test the consistency between the data and the standard model, a likelihood ratio test was performed by producing a set of 1000 SM-like pseudoexperiments and comparing the likelihood ratio between the signal + background and pure background hypotheses obtained in the data to the results of the pseudoexperiments. The signal + background likelihood is evaluated at the Λ value that maximizes it. The derived *p-value*, corresponding to the probability of observing a fluctuation in the pseudoexperiments that is at least as signal-like as that seen in the data (i.e. with a maximum likelihood ratio greater or equal to that obtained in the data), is estimated to be 39% (79%) in the electron channel and 21% (5%) in the muon channel for constructive (destructive) interference. These values indicate that there is no significant evidence for contact interactions in the analyzed data and thus limits are set on the contact interaction scale Λ.

Using the Bayesian method described above, the expected 95% CL lower limit values on the energy scale Λ are found to be 9.6 ± 1.0 TeV for constructive interference ($\eta_{LL} = -1$) and 9.3 ± 1.0 TeV for destructive interference ($\eta_{LL} = +1$) in the electron channel. The corresponding expected limits in the muon channel are 8.9 ± 0.9 TeV and 8.6 ± 0.9 TeV. The quoted uncertainties correspond to the 68% range of limits surrounding the median value of all limits obtained with a set of 1000 pseudoexperiments. Stronger limits are expected in the electron channel than in the muon channel due to the significantly larger acceptance for the dielectron selection.

The observed limits (at 95% CL) are $\Lambda^- > 10.1$ TeV ($\Lambda^+ > 9.4$ TeV) in the electron channel and $\Lambda^- > 8.0$ TeV ($\Lambda^+ > 7.0$ TeV) in the muon channel for constructive (destructive) interference. These limits are summarized in Table 5.

If instead of choosing the prior to be flat in $1/\Lambda^2$, it is selected to be flat in $1/\Lambda^4$ to match the form of the pure CI term in Eq. (2), the observed limit in the electron channel becomes weaker by 0.9 TeV (0.8 TeV) for constructive (destructive) interference. The corresponding shift to lower values is 0.4 TeV (0.3 TeV) in the muon channel, see Table 5.

The quoted limits have been obtained with electroweak corrections applied to both DY and DY + CI samples for consistency, although part of the electroweak corrections cannot be computed reliably due to the unknown new physics represented by the contact interaction. However, this particular choice does not affect the observed limits significantly and results in slightly more conservative limits. The limits obtained without electroweak corrections improve by less than 0.1 TeV.

Finally, a limit is set on the combination of the electron and muon channels, assuming lepton universality, by computing a combined posterior probability for the two channels. The following sources of systematic uncertainty are treated as fully correlated between the two channels: PDF and α_S, QCD and electroweak K-factors, and Z/γ^* cross section for normalization. The resulting combined limits are $\Lambda^- > 10.2$ TeV and $\Lambda^+ > 8.8$ TeV for the $1/\Lambda^2$ prior. Table 5 summarizes all limits for the two priors considered in this study and shows that the combined limit is weaker than the electron channel limit in the case of destructive interference. This is due to the slight excess of events observed in the muon channel for masses greater than 800 GeV, an excess that gives an increase in the likelihood that is stronger for destructive interference than it is for constructive interference.

8. Conclusions

A search for contact interactions in e^+e^- and $\mu^+\mu^-$ events produced in proton–proton collisions at $\sqrt{s} = 7$ TeV has been performed. The analysis uses early 2011 run data amounting to 1.08 (1.21) fb^{-1} of pp collisions in the electron (muon) channel collected with the ATLAS detector. The dilepton mass distributions do not display significant deviations from the standard model. Using a Bayesian approach with a $1/\Lambda^2$ prior, as was done in most previous searches at hadron colliders, the following 95% CL limits are set on the energy scale of contact interactions: $\Lambda^- > 10.1$ TeV ($\Lambda^+ > 9.4$ TeV) in the electron channel and $\Lambda^- > 8.0$ TeV ($\Lambda^+ > 7.0$ TeV) in the muon channel for constructive (destructive) interference in the left–left isoscalar compositeness model. Somewhat weaker limits are obtained with a prior flat in $1/\Lambda^4$. These limits are the most stringent to date on $\mu\mu qq$ contact interactions and exceed the best existing limits set by a single experiment on $eeqq$ contact interactions for light-quark flavors.

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