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


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ATLAS Collaboration

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 dimuon channel [2]. In the dilepton mass spectra performed using the same ATLAS dataset [3], 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. 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 ηLL = ±1 and ηRR = ηLR = 0.

With the introduction of a contact interaction, the differential cross section for the process q̅q → ℓ⁺ℓ⁻ can be written

\[ \frac{dσ}{dm_{ℓℓ}} = \frac{dσ_{DY}}{dm_{ℓℓ}} - \frac{F_L(m_{ℓℓ})}{A^2} - \frac{F_R(m_{ℓℓ})}{A^4}, \]

where m_{ℓℓ} is the final-state dilepton mass. The expression above includes an SM DY term, as well as DY-CI interference (F_L) and pure contact interaction (F_R) terms (see Ref. [7] for the full form...
of this expression). At the largest $\Lambda$ 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 $\Lambda$ (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 $eegq$ 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 $\eta = -1$ 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 $|\eta| < 2.5$. 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 $(\eta, \phi)$ varying by layer and cells as small as 0.025 x 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 $|\eta| < 2.7$.

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 $\text{PYTHIA~6.421}$ [26] and $\text{MRST2007}$ LO$^*$ parton distribution functions (PDFs) [27]. Signal $DY +$ CI samples in the LLIM were generated with the same version of $\text{PYTHIA}$ 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 $\text{HERWIG~6.510}$ [28] using $\text{MRST2007}$ LO$^*$ PDFs. The $W +$ jets background was generated with $\text{ALPGEN}$ [29] and $\text{CTEQ6.1L}$ [30] PDFs, and the $t\bar{t}$ background with $\text{MC@NLO}$ 3.41 [31] and $\text{CTEQ6.6}$ [32] PDFs. For the latter two, $\text{JIMMY} 4.31$ [33] was used to describe multiple parton interactions and $\text{HERWIG}$ to describe the remaining underlying event and parton showers. $\text{PHOTOS}$ [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) $Z/\gamma^*$ cross section, calculated using $\text{PHOZPR}$ [35] and $\text{MSTW2008}$ 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 $\text{HORACE}$ [37]. Finally, the generated samples were processed through a full simulation of the ATLAS detector [38] based on the $\text{GEANT} 4$ 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 $cc$ and $bb$ 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 $\Sigma p_T^2$ 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 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 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.

Data of dimuon events observed at high momentum is consistent with a statistical fluctuation. The most significant deviation in the number of dimuon events occurs for dimuon 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.

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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.
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 $O(\alpha_s)$ 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 ($A^-$) and destructive ($A^+$) interference in the electron channel. The errors quoted originate from both systematic uncertainties and limited MC statistics.

\[
\begin{array}{|c|c|c|c|c|}
\hline
m_{\ell\ell} \text{ [GeV]} & 150-170 & 170-200 & 200-240 & 240-300 & 300-400 \\
\hline
A^- = 3 \text{ TeV} & 785 \pm 29 & 649 \pm 26 & 467 \pm 22 & 383 \pm 19 & 343 \pm 12 \\
A^- = 4 \text{ TeV} & 781 \pm 28 & 647 \pm 26 & 437 \pm 21 & 326 \pm 17 & 223 \pm 7 \\
A^- = 5 \text{ TeV} & 734 \pm 27 & 612 \pm 24 & 405 \pm 19 & 298 \pm 16 & 181 \pm 6 \\
A^- = 7 \text{ TeV} & 691 \pm 26 & 638 \pm 25 & 406 \pm 19 & 259 \pm 15 & 163 \pm 5 \\
A^- = 12 \text{ TeV} & 721 \pm 26 & 604 \pm 24 & 336 \pm 17 & 234 \pm 14 & 149 \pm 5 \\
A^+ = 3 \text{ TeV} & 770 \pm 28 & 642 \pm 24 & 424 \pm 20 & 331 \pm 17 & 269 \pm 9 \\
A^+ = 4 \text{ TeV} & 745 \pm 27 & 591 \pm 23 & 385 \pm 19 & 277 \pm 16 & 166 \pm 5 \\
A^+ = 5 \text{ TeV} & 702 \pm 25 & 607 \pm 23 & 350 \pm 17 & 258 \pm 15 & 151 \pm 5 \\
A^+ = 7 \text{ TeV} & 672 \pm 25 & 600 \pm 23 & 399 \pm 19 & 251 \pm 14 & 142 \pm 5 \\
A^+ = 12 \text{ TeV} & 749 \pm 27 & 593 \pm 23 & 403 \pm 19 & 274 \pm 15 & 137 \pm 4 \\
\hline
\end{array}
\]

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

\[
\begin{array}{|c|c|c|c|c|}
\hline
m_{\ell\ell} \text{ [GeV]} & 400-550 & 550-600 & 800-1200 & 1200-1800 & 1800-3000 \\
\hline
A^- = 3 \text{ TeV} & 286 \pm 11 & 269 \pm 12 & 207 \pm 11 & 112 \pm 8 & 30.3 \pm 3.4 \\
A^- = 4 \text{ TeV} & 132 \pm 5 & 109.5 \pm 4.9 & 80.5 \pm 4.1 & 29.8 \pm 2.3 & 10.9 \pm 1.3 \\
A^- = 5 \text{ TeV} & 82.7 \pm 3.6 & 57.3 \pm 2.6 & 35.5 \pm 1.9 & 14.8 \pm 1.1 & 3.9 \pm 0.5 \\
A^- = 7 \text{ TeV} & 683 \pm 29 & 290 \pm 14 & 112 \pm 0.7 & 40.0 \pm 0.4 & 1.08 \pm 0.17 \\
A^- = 12 \text{ TeV} & 573 \pm 2.6 & 18.8 \pm 11 & 5.0 \pm 0.4 & 1.00 \pm 0.13 & 0.15 \pm 0.05 \\
A^+ = 3 \text{ TeV} & 215 \pm 8 & 239 \pm 11 & 185 \pm 10 & 107 \pm 7 & 28.4 \pm 3.2 \\
A^+ = 4 \text{ TeV} & 1009 \pm 3.8 & 78.1 \pm 3.6 & 60.7 \pm 3.2 & 31.5 \pm 2.2 & 8.7 \pm 1.0 \\
A^+ = 5 \text{ TeV} & 644.4 \pm 2.7 & 36.2 \pm 1.8 & 25.4 \pm 1.3 & 12.7 \pm 0.9 & 3.5 \pm 0.4 \\
A^+ = 7 \text{ TeV} & 563 \pm 2.5 & 20.3 \pm 1.1 & 7.7 \pm 0.5 & 3.58 \pm 0.28 & 0.83 \pm 0.12 \\
A^+ = 12 \text{ TeV} & 52.4 \pm 2.4 & 14.4 \pm 0.9 & 3.29 \pm 0.28 & 0.46 \pm 0.08 & 0.075 \pm 0.026 \\
\hline
\end{array}
\]

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 $\mu$ of expected events in each of the mass bins defined in Tables 1 and 2 is

\[
\mu = n_{DY+Cl}(\theta, \bar{\nu}) + n_{\text{non-DY}} \text{ bg}(\bar{\nu}),
\]

where $n_{DY+Cl}(\theta, \bar{\nu})$ is the number of events predicted by the PYTHIA $DY+Cl$ MC for a particular choice of contact interaction model parameter $\theta$, $n_{\text{non-DY}} \text{ bg}(\bar{\nu})$ 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 $\theta$ corresponds to a choice of energy scale $\Lambda$ and interference parameter $n_{IL}$. The complete set of $\mu$ 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 $\mu$ 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 $k$:

\[
\mathcal{L}(\bar{n} | \theta, \bar{\nu}) = \prod_{k=1}^{N} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!}.
\]
According to Bayes’ theorem, the posterior probability for the parameter $\theta$ given $n$ observed events is

$$P(\theta | \hat{n}) = \frac{1}{Z} \mathcal{L}_M(\hat{n} | \theta) P(\theta),$$

(5)

where $Z$ is a normalization constant and the marginalized likelihood $\mathcal{L}_M$ 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 $\Lambda_{\text{lim}}$ satisfying $\int_{\Lambda_{\text{lim}}}^{\Lambda_{\text{max}}} P(\theta | \hat{n}) \, d\theta = 0.95$, where $\hat{n} = 1/\Lambda^2$. The above calculations have been performed with the Bayesian Analysis Toolkit (BAT) [41].

Table 5

<table>
<thead>
<tr>
<th>Channel</th>
<th>Prior</th>
<th>Expected limit (TeV)</th>
<th>Observed limit (TeV)</th>
</tr>
</thead>
<tbody>
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<td>$1/\Lambda^2$</td>
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<td>9.3</td>
</tr>
<tr>
<td></td>
<td>$1/\Lambda^4$</td>
<td>8.9</td>
<td>8.6</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>$1/\Lambda^2$</td>
<td>8.9</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>$1/\Lambda^4$</td>
<td>8.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Comb.</td>
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<td>10.4</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>$1/\Lambda^4$</td>
<td>9.6</td>
<td>9.4</td>
</tr>
</tbody>
</table>

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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