The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/132608

Please be advised that this information was generated on 2020-02-13 and may be subject to change.
Search for Scalar Diphoton Resonances in the Mass Range 65–600 GeV with the ATLAS Detector in pp Collision Data at $\sqrt{s} = 8$ TeV

G. Aad et al.∗

(ATLAS Collaboration)

(Received 25 July 2014; published 20 October 2014)

A search for scalar particles decaying via narrow resonances into two photons in the mass range 65–600 GeV is performed using 20.3 fb⁻¹ of $\sqrt{s} = 8$ TeV pp collision data collected with the ATLAS detector at the Large Hadron Collider. The recently discovered Higgs boson is treated as a background. No significant evidence for an additional signal is observed. The results are presented as limits at the 95% confidence level on the production cross section of a scalar boson times branching ratio into two photons, in a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The upper limits set extend over a considerably wider mass range than previous searches.

DOI: 10.1103/PhysRevLett.113.171801

PACS numbers: 14.80.Da, 13.85.Qk, 14.70.Bh, 14.80.Ec

In July 2012, the ATLAS and CMS collaborations reported the discovery of a new particle [1,2] whose measured couplings and properties are compatible with the standard model Higgs boson (H) [3–6]. However, several extensions to the standard model—in particular, models featuring an extended Higgs sector [7–13]—predict new scalar resonances below or above the H mass which may be narrow when their branching ratio to two photons is non-negligible.

This Letter presents a search for a scalar particle X of mass $m_X$ decaying via narrow resonances into two photons. It extends the method developed for the measurement of the H couplings in the $H \rightarrow \gamma\gamma$ channel [3] to the range 65 < $m_X$ < 600 GeV. Analytical descriptions of the signal and background distributions are fitted to the measured diphoton invariant mass spectrum $m_{\gamma\gamma}$ to determine the signal and background yields. The result is presented as a limit on the production cross section times the branching ratio $BR(X \rightarrow \gamma\gamma)$, restricted to a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The resonance with mass $m_X$ is considered narrow when its intrinsic width is smaller than 0.09 GeV + 0.01$m_X$. This upper limit is defined such that the bias in the number of fitted signal events is kept below 10%. This ensures that the diphoton invariant mass width is dominated by the experimental resolution in the ATLAS detector. Model-dependent interference effects between the resonance and the continuum diphoton background are not considered.

The ATLAS detector [14] at the LHC [15] covers the pseudorapidity range $|\eta| < 4.9$ and the full azimuthal angle $\phi$. It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$, surrounded by electromagnetic and hadronic calorimeters and an external muon spectrometer.

The search is carried out using the $\sqrt{s} = 8$ TeV pp collision data set collected in 2012, with stable beam conditions and all ATLAS subsystems operational, which corresponds to an integrated luminosity of $L = 20.3 \pm 0.6$ fb⁻¹ [17]. The data were recorded using a diphoton trigger that required two electromagnetic clusters with transverse energies $E_T$ above 20 GeV, both fulfilling identification criteria based on shower shapes in the electromagnetic calorimeter. The efficiency of the diphoton trigger [18] is (98.7 ± 0.5)% for signal events passing the analysis selection.

The event selection requires at least one reconstructed primary vertex with two or more tracks with transverse momenta $p_T > 0.4$ GeV, and at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$, excluding the barrel and end cap transition region of the calorimeter, $1.37 < |\eta| < 1.56$.

Photon reconstruction is seeded by clusters of electromagnetic calorimeter cells. Clusters without matching tracks are classified as unconverted photons. Clusters with matched tracks are considered as electron candidates but are classified as converted photons if they are associated with two tracks consistent with a $\gamma \rightarrow e^+e^−$ conversion process, or a single track leaving no hit in the innermost layer of the inner tracking detector. The photon energy calibration procedure is the same as in Ref. [3].

Photon candidates are required to fulfill identification criteria based on shower shapes in the electromagnetic calorimeter, and on energy leakage into the hadronic calorimeter [19]. Identification efficiencies, averaged over $\eta$, range from 70% to above 99% for the $E_T$ range under consideration. To further reduce the background from jets, the calorimeter isolation transverse energy $E_T^{iso}$ is required.
to be smaller than 6 GeV, where $E_T^{\text{iso}}$ is defined as the sum of transverse energies of the positive-energy topological clusters [20] within a cone of size $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ around the photon candidate. The core of the photon shower is excluded, and $E_T^{\text{iso}}$ is corrected for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pileup are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the track isolation—defined as the scalar sum of the $p_T$ of the primary vertex tracks with $p_T > 1$ GeV in a $\Delta R = 0.2$ cone around the photon candidate, excluding the conversion tracks—is required to be smaller than 2.6 GeV.

The $m_{\gamma\gamma}$ invariant mass is evaluated using the leading photon ($\gamma_1$) and subleading photon ($\gamma_2$) energies measured in the calorimeter, the azimuthal angle $\Delta \phi$ and the pseudorapidity $\Delta \eta$ separations between the photons determined from their positions in the calorimeter, and the position of the reconstructed diphoton vertex [3].

After selection, the data sample consists of a continuum background with dominantly $\gamma\gamma$, $\gamma$-jet, and jet-jet events and Drell–Yan (DY) production of electron pairs where both electrons are misidentified as photons. Two peaking backgrounds arise from the $Z$ boson component of the DY and from $H \to \gamma\gamma$.

To increase the sensitivity, the search is split into two analyses: a categorized low-mass analysis covering the range $65 < m_X < 110$ GeV and an inclusive high-mass analysis covering $110 < m_X < 600$ GeV. To provide sidebands on both sides of the tested mass point $m_X$, the $m_{\gamma\gamma}$ ranges are wider than the $m_X$ ranges probed and overlap at the transition between the two analyses.

The low-mass analysis requires a precise modeling of the DY background, dominated by the $Z$ boson resonance, where both electrons are misidentified as photons, mostly classified as converted photons. The loss of signal sensitivity is mitigated by separating the events into three categories with different signal-to-background ratios, according to the conversion status of the photon pair: two unconverted (UU), one converted and one unconverted (CU), or two converted (CC) photons. Table 1 shows the fractions of signal and DY events expected in each category.

In each category, the $Z$ resonance shape is described by a double-sided Crystal Ball function [23]. Because of the limited size of the fully simulated $Z \to ee$ sample [25,26] where both electrons are misidentified as photons, the shape parameters are determined by a fit to a dielectron data sample, where both electrons are required to fulfill shower shape identification criteria and the same $E_T$ thresholds as the photons.

Since most of the electrons misidentified as photons underwent large bremsstrahlung, the invariant mass distribution of the $Z$ boson reconstructed as a photon pair is wider and shifted to lower masses by up to 2 GeV with respect to the $Z$ boson mass reconstructed as an electron pair. The $Z \to ee$ invariant mass distributions extracted from data in each category are transformed by applying $E_T$-dependent shifts and smearing factors to the electron $E_T$ and $\phi$, to match the kinematics of the electrons misidentified as photons. Two sets of transformations are derived for $\gamma_1$ and $\gamma_2$ depending on their conversion status, using a $Z \to ee$ sample generated with POWHEG [27,28], interfaced with PYTHIA8 [29] for showering and hadronization. Figure 1 illustrates the effect of the electrons’ transformations on the invariant mass shapes in the fully simulated $Z \to ee$ sample. Systematic uncertainties on the template shapes and the $Z$ peak position are evaluated by varying the parameters of the electrons’ transformations by $\pm 1\sigma$.

The DY normalization is computed from the $e \to \gamma$ fake rates, defined as the ratios of $e\gamma$ to $ee$ pairs measured in $Z \to ee$ data, separately for $\gamma_1$ and $\gamma_2$ and each conversion status. A correction factor obtained from fully simulated $Z \to ee$ events is applied to account for additional effects, mainly the differences in isolation efficiencies and vertex reconstruction efficiency between $\gamma\gamma$ and $ee$ events. The associated uncertainties (9% to 25%) are dominated by the

<table>
<thead>
<tr>
<th>$\gamma\gamma$ category</th>
<th>UU</th>
<th>CU</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{data}}$</td>
<td>272184</td>
<td>253804</td>
<td>63224</td>
</tr>
<tr>
<td>$N_{\text{DY}}$</td>
<td>$1080 \pm 260$</td>
<td>$3400 \pm 600$</td>
<td>$2700 \pm 250$</td>
</tr>
<tr>
<td>$f_{\text{DY}}$</td>
<td>15.0%</td>
<td>47.3%</td>
<td>37.7%</td>
</tr>
<tr>
<td>$f_X$</td>
<td>48.7%</td>
<td>42.5%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

FIG. 1 (color online). Invariant mass distributions in the CC category for fully simulated $Z \to ee$ events reconstructed as $ee$ (dotted lines), reconstructed as $\gamma\gamma$ (squares), and reconstructed as $ee$ after transforming the electrons to match the kinematics of the electrons misidentified as converted photons (circles).

TABLE I. Number of diphoton events in data ($N_{\text{data}}$), number of expected Drell–Yan events ($N_{\text{DY}}$), fractions of expected signal ($f_X$), and Drell–Yan ($f_{\text{DY}}$) in each conversion category for the low-mass analysis. The signal fraction is given for $m_X = 90$ GeV but the mass dependence is negligible.
subtraction of the continuum background and the detector material description.

The determination of the analytical form of the continuum background and the corresponding uncertainties follow the method detailed in Ref. [1]. The sum of a Landau distribution and an exponential distribution is used over the full \( m_{\gamma\gamma} \) range. The bias on the signal yield induced by the analytical shape function is required to be lower than 20\% of the statistical uncertainty on the fitted signal yield for the background-only spectrum. This bias is measured from a large sample generated from a parametrized detector response and is accounted for by a mass-dependent uncertainty. Figure 2 shows background-only fits to the response and is accounted for by a mass-dependent uncertainty. Figure 2 shows background-only fits to the data in the low-mass analysis for the three conversion categories.

In the high-mass analysis, relative cuts \( E_T^{\ell}\!/m_{\gamma\gamma} > 0.4 \) and \( E_T^{\ell}\!/m_{\gamma\gamma} > 0.3 \) are added to the selection requirements to reduce the continuum backgrounds and thereby increase the signal sensitivity. In total, 108 654 events with \( 100 < m_{\gamma\gamma} < 800 \) GeV are selected.

To determine the continuum background shape over this large mass range, an exponential of a second-order polynomial is fitted inside a sliding \( m_{\gamma\gamma} \) window of width \( 80 \cdot (m_X - 110 \text{ GeV})/110 + 20 \text{ GeV} \), centered on the mass point \( m_X \). The analytical shape and the fit window width are chosen to fulfill the signal yield bias criterion, as defined for the low-mass analysis, to minimize the statistical uncertainty on the background.

The \( H \) background shape is modeled by a double-sided Crystal Ball function and normalized for \( m_H = 125.9 \text{ GeV} \) [30,31] using the most up-to-date standard model cross-section calculations and corrections [34] of the five main production modes: gluon fusion (ggF), vector-boson fusion (VBF), Higgsstrahlung (WH, ZH), and associated production with a top quark pair (t\(H\)). The ggF and VBF samples are simulated with the POWHEG generator interfaced with PYTHIA8. The \( WH, ZH, \) and t\(H\) samples are simulated with PYTHIA8. Figure 3 shows background-only fits to the data in the high-mass analysis.

The expected invariant mass distribution of the narrow resonance signal \( X \) is also modeled with a double-sided Crystal Ball function in the mass range \( 65 \leq m_X \leq 600 \text{ GeV} \), using fully simulated ggF(X) samples generated as for \( H \), where \( H \) is replaced by a scalar boson with a constant width of 4 MeV. Polynomial parametrizations of the signal shape parameters as a function of \( m_X \) are obtained from a simultaneous fit to all the generated mass points \( m_X \), separately for the high-mass analysis and the three low-mass analysis categories. The signal shape parameters extracted from ggF(X) are compared to the other production modes: VBF(X), WX, ZX, and t\(X\); the bias on the signal yield due to the choice of ggF(X) shape is negligible. The systematic uncertainty on the signal shape due to the photon energy resolution uncertainty ranges from 10\% to 40\% as a function of \( m_X \) [3]. The systematic uncertainty on the \( X \) peak position due to the photon energy scale uncertainty is 0.6\% [3].

The fiducial cross section \( \sigma_{\text{fid}}BR(X \rightarrow \gamma\gamma) \) includes an efficiency correction factor \( C_X \) through

\[
\sigma_{\text{fid}}BR(X \rightarrow \gamma\gamma) = \frac{N_{\text{data}}}{C_X C} \quad \text{with} \quad C_X = \frac{N_{\text{MC}}^{\text{fid}}}{N_{\text{MC}}^{\text{data}}},
\]

FIG. 2 (color online). Background-only fits to the data (black dots) as functions of the diphoton invariant mass \( m_{\gamma\gamma} \) for the three conversion categories in the low-mass range. The solid lines show the sum of the Drell–Yan and the continuum background components. The dashed lines show the continuum background component only.

FIG. 3 (color online). Background-only fits to the data (black dots) as functions of the diphoton invariant mass \( m_{\gamma\gamma} \) for the inclusive high-mass analysis. The solid line shows the sum of the Higgs boson and the continuum background components. The dashed line shows the continuum background component only.
where $N_{\text{data}}$ is the number of fitted signal events in data, $N_{\text{reco}}^{MC}$ the number of simulated signal events passing the selection criteria and $N_{\text{fid}}^{MC}$ the number of simulated signal events generated within the fiducial volume. The fiducial volume, defined from geometrical and kinematical constraints at the generated particle level, is optimized to reduce the model dependence of $C_X$ using fully simulated samples of the five $X$ production modes to cover a large variety of topologies. The photon selection at generation level is similar to the selection applied to the data: two photons with $E_T > 22$ GeV and $|\eta| < 2$ are required; for $m_X$ greater than 110 GeV, the relative cuts $E^{\gamma_1}_T/m_{\gamma\gamma} > 0.4$ and $E^{\gamma_2}_T/m_{\gamma\gamma} > 0.3$ are imposed. The particle isolation, defined as the scalar sum of $p_T$ of all the stable particles (except neutrinos) found within a $\Delta R = 0.4$ cone around the photon direction, is required to be less than 12 GeV. The $C_X$ factor is parametrized from the ggF($X$) samples and ranges from 0.56 to 0.71 as a function of $m_X$. Systematic uncertainties include the maximum difference between the $C_X$ of the five production modes, the effect of the underlying event (U.E.) and pileup.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and $H$ shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with $2.1 \sigma$ and $2.2 \sigma$ local significances above the background are observed over the full mass range $65$–$600$ GeV, for $m_X = 201$ GeV and $m_X = 530$ GeV, respectively. This corresponds to a deviation of less than $0.5 \sigma$ from the background-only hypothesis. Consequently, a 95% limit on $\sigma_{\text{fid}} BR(X \rightarrow \gamma\gamma)$ is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of $C_X$. In the high-mass analysis, the largest uncertainties arise from the energy resolution and the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Signal and Higgs boson yield} & \textbf{Z component of Drell–Yan} \\
\hline
Luminosity & 2.8\% \\
Trigger & 0.5\% \\
$\gamma$ identification$^a$ & 1.6\%–2.7\% \\
$\gamma$ isolation$^a$ & 1\%–6\% \\
Energy resolution$^{a,b}$ & 10\%–40\% \\
Signal and Higgs boson peak position & 0.6\% \\
Energy scale & \\
Continuum $\gamma\gamma$, $\gamma j$, $jj$, DY & \\
Signal bias$^a$ & 1–67 events \\
\hline
\end{tabular}
\caption{Summary of the systematic uncertainties.}
\end{table}

$^a$Mass dependent.
$^b$Category dependent.
$^c$Factorization scale plus parton density function uncertainties [34].

$\mathrm{C}_X$ of the five production modes, the effect of the underlying event (U.E.) and pileup.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and $H$ shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with $2.1 \sigma$ and $2.2 \sigma$ local significances above the background are observed over the full mass range $65$–$600$ GeV, for $m_X = 201$ GeV and $m_X = 530$ GeV, respectively. This corresponds to a deviation of less than $0.5 \sigma$ from the background-only hypothesis. Consequently, a 95% limit on $\sigma_{\text{fid}} BR(X \rightarrow \gamma\gamma)$ is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of $C_X$. In the high-mass analysis, the largest uncertainties arise from the energy resolution and the

\begin{figure}[h]
\centering
\includegraphics{figure4}
\caption{(color online). Observed and expected 95\% C.L. limit on the fiducial cross section times branching ratio $BR(X \rightarrow \gamma\gamma)$ as a function of $m_X$ in the range $65 < m_X < 600$ GeV. The discontinuity in the limit at $m_X = 110$ GeV (vertical dashed line) is due to the transition between the low-mass and high-mass analyses. The green and yellow bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit. The inset shows a zoom around the transition point.}
\end{figure}
theoretical uncertainty on the production rate of the standard model Higgs boson around 126 GeV.

The observed and expected limits, shown in Fig. 4, are in good agreement, consistent with the absence of a signal. The limits on $\sigma_{\text{fid}} BR(X \rightarrow \gamma\gamma)$ for an additional scalar resonance range from 90 fb for $m_X = 65$ GeV to 1 fb for $m_X = 600$ GeV. These results extend over a considerably wider mass range than the previous searches by the ATLAS and CMS collaborations [1,35], are complementary to spin-2 particles searches [36,37], and are the first such limits independent of the event topology.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS and CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; DOE and NSF, U.S. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, and Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom) and BNL (U.S.), and in the Tier-2 facilities worldwide.

[16] 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 line. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, θ, φ) are used in the transverse plane, with φ being the azimuthal angle around the beam line. Observables labeled transverse are projected into the x-y plane. The pseudorapidity is defined in terms of the polar angle θ as $η = -\ln[\tan(\theta/2)]$.
[23] A double-sided Crystal Ball function is composed of a Gaussian distribution at the core, connected with two power-law distributions describing the lower and upper tails [24].
[31] Differences between this choice of reference mass and the new mass measurements [32,33] are covered by the energy scale uncertainties listed in Table II.
<table>
<thead>
<tr>
<th>Names</th>
<th>Institutions</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Tsiskaridze, V. Tsiskaridze, V. Tsuchida</td>
<td>Department of Physics, University of Adelaide, Adelaide, Australia</td>
<td></td>
</tr>
<tr>
<td>A. Todorache, A. Todorache, A. Touna</td>
<td>Physics Department, SUNY Albany, Albany, New York, USA</td>
<td></td>
</tr>
<tr>
<td>M. Uhlenbrock, V. Ukegawa, D. Ungaro, F. Vazquez</td>
<td>Department of Physics, University of Alberta, Edmonton, Alberta, Canada</td>
<td></td>
</tr>
<tr>
<td>D. Turecek, I. Turk Cakir, R. Turra</td>
<td>Department of Physics, Ankara University, Ankara, Turkey</td>
<td></td>
</tr>
<tr>
<td>A. Tudorache, V. Tudorache, A. N. Tuna</td>
<td>Department of Physics, Gazi University, Ankara, Turkey</td>
<td></td>
</tr>
</tbody>
</table>

**PRL 113, 171801 (2014)**

**Physical Review Letters week ending 24 October 2014**

**Abstract**

(Atlas Collaboration)

1. Department of Physics, University of Adelaide, Adelaide, Australia
2. Physics Department, SUNY Albany, Albany, New York, USA
3. Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4. Department of Physics, Ankara University, Ankara, Turkey
5. Department of Physics, Gazi University, Ankara, Turkey

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Institution(s)</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Tsiskaridze, V. Tsiskaridze, V. Tsuchida</td>
<td>Department of Physics, University of Adelaide, Adelaide, Australia</td>
<td></td>
</tr>
<tr>
<td>A. Todorache, A. Todorache, A. Touna</td>
<td>Physics Department, SUNY Albany, Albany, New York, USA</td>
<td></td>
</tr>
<tr>
<td>M. Uhlenbrock, V. Ukegawa, D. Ungaro, F. Vazquez</td>
<td>Department of Physics, University of Alberta, Edmonton, Alberta, Canada</td>
<td></td>
</tr>
<tr>
<td>D. Turecek, I. Turk Cakir, R. Turra</td>
<td>Department of Physics, Ankara University, Ankara, Turkey</td>
<td></td>
</tr>
<tr>
<td>A. Tudorache, V. Tudorache, A. N. Tuna</td>
<td>Department of Physics, Gazi University, Ankara, Turkey</td>
<td></td>
</tr>
</tbody>
</table>

**Declaration**

1. Department of Physics, University of Adelaide, Adelaide, Australia
2. Physics Department, SUNY Albany, Albany, New York, USA
3. Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4. Department of Physics, Ankara University, Ankara, Turkey
5. Department of Physics, Gazi University, Ankara, Turkey

**PRL 113, 171801 (2014)**

**Physical Review Letters week ending 24 October 2014**

**Abstract**

(Atlas Collaboration)

1. Department of Physics, University of Adelaide, Adelaide, Australia
2. Physics Department, SUNY Albany, Albany, New York, USA
3. Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4. Department of Physics, Ankara University, Ankara, Turkey
5. Department of Physics, Gazi University, Ankara, Turkey

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Institution(s)</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Tsiskaridze, V. Tsiskaridze, V. Tsuchida</td>
<td>Department of Physics, University of Adelaide, Adelaide, Australia</td>
<td></td>
</tr>
<tr>
<td>A. Todorache, A. Todorache, A. Touna</td>
<td>Physics Department, SUNY Albany, Albany, New York, USA</td>
<td></td>
</tr>
<tr>
<td>M. Uhlenbrock, V. Ukegawa, D. Ungaro, F. Vazquez</td>
<td>Department of Physics, University of Alberta, Edmonton, Alberta, Canada</td>
<td></td>
</tr>
<tr>
<td>D. Turecek, I. Turk Cakir, R. Turra</td>
<td>Department of Physics, Ankara University, Ankara, Turkey</td>
<td></td>
</tr>
<tr>
<td>A. Tudorache, V. Tudorache, A. N. Tuna</td>
<td>Department of Physics, Gazi University, Ankara, Turkey</td>
<td></td>
</tr>
</tbody>
</table>

**Declaration**

1. Department of Physics, University of Adelaide, Adelaide, Australia
2. Physics Department, SUNY Albany, Albany, New York, USA
3. Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4. Department of Physics, Ankara University, Ankara, Turkey
5. Department of Physics, Gazi University, Ankara, Turkey

171801-13
Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

Turkish Atomic Energy Authority, Ankara, Turkey

LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

Department of Physics, University of Arizona, Tucson, Arizona, USA

Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA

Physics Department, University of Athens, Athens, Greece

Physics Department, National Technical University of Athens, Zografou, Greece

Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

Institute of Physics, University of Belgrade, Belgrade, Serbia

Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA

Department of Physics, Humboldt University, Berlin, Germany

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

Department of Physics, Bogazici University, Istanbul, Turkey

Department of Physics, Dokuz Eylül University, Izmir, Turkey

Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

INFN Sezione di Bologna, Italy

Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston, Massachusetts, USA

Department of Physics, Brandeis University, Waltham, Massachusetts, USA

Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil

Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil

Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton, New York, USA

National Institute of Physics and Nuclear Engineering, Bucharest, Romania

National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania

University Politehnica Bucharest, Bucharest, Romania

West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa, Ontario, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Department of Modern Physics, University of Science and Technology of China, Anhui, China

Department of Physics, Nanjing University, Jiangsu, China

School of Physics, Shandong University, Shandong, China

Physics Department, Shanghai Jiao Tong University, Shanghai, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, New York, USA

Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

Dipartimento di Fisica, Università della Calabria, Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
<table>
<thead>
<tr>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>139 Department of Physics, University of Washington, Seattle, Washington, USA</td>
</tr>
<tr>
<td>140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom</td>
</tr>
<tr>
<td>141 Department of Physics, Shinshu University, Nagano, Japan</td>
</tr>
<tr>
<td>142 Fachbereich Physik, Universität Siegen, Siegen, Germany</td>
</tr>
<tr>
<td>143 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada</td>
</tr>
<tr>
<td>144 SLAC National Accelerator Laboratory, Stanford, California, USA</td>
</tr>
<tr>
<td>145 Department of Mathematics, Physics &amp; Informatics, Comenius University, Bratislava, Slovak Republic</td>
</tr>
<tr>
<td>145a Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic</td>
</tr>
<tr>
<td>145b Department of Physics, University of Cape Town, Cape Town, South Africa</td>
</tr>
<tr>
<td>146 Department of Physics, University of Johannesburg, Johannesburg, South Africa</td>
</tr>
<tr>
<td>147 School of Physics, University of the Witwatersrand, Johannesburg, South Africa</td>
</tr>
<tr>
<td>147a Department of Physics, Stockholm University, Sweden</td>
</tr>
<tr>
<td>147b The Oskar Klein Centre, Stockholm, Sweden</td>
</tr>
<tr>
<td>148 Physics Department, Royal Institute of Technology, Stockholm, Sweden</td>
</tr>
<tr>
<td>149 Departments of Physics &amp; Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA</td>
</tr>
<tr>
<td>150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom</td>
</tr>
<tr>
<td>151 School of Physics, University of Sydney, Sydney, Australia</td>
</tr>
<tr>
<td>152 Institute of Physics, Academia Sinica, Taipei, Taiwan</td>
</tr>
<tr>
<td>153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel</td>
</tr>
<tr>
<td>154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel</td>
</tr>
<tr>
<td>155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece</td>
</tr>
<tr>
<td>156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan</td>
</tr>
<tr>
<td>157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan</td>
</tr>
<tr>
<td>158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan</td>
</tr>
<tr>
<td>159 Department of Physics, University of Toronto, Toronto, Ontario, Canada</td>
</tr>
<tr>
<td>160 TRIUMF, Vancouver, British Columbia, Canada</td>
</tr>
<tr>
<td>160a Department of Physics and Astronomy, York University, Toronto, Ontario, Canada</td>
</tr>
<tr>
<td>161 Department of Physics and Chemistry, University of Tsukuba, Tsukuba, Japan</td>
</tr>
<tr>
<td>162 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA</td>
</tr>
<tr>
<td>163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia</td>
</tr>
<tr>
<td>164 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA</td>
</tr>
<tr>
<td>165 INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy</td>
</tr>
<tr>
<td>165a ICTP, Trieste, Italy</td>
</tr>
<tr>
<td>165b Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy</td>
</tr>
<tr>
<td>165c Dipartimento di Fisica, Università di Milano, Milano, Italy</td>
</tr>
<tr>
<td>166 Department of Physics, University of Illinois, Urbana, Illinois, USA</td>
</tr>
<tr>
<td>167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden</td>
</tr>
<tr>
<td>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-CNMI), University of Valencia and CSIC, Valencia, Spain</td>
</tr>
<tr>
<td>169 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada</td>
</tr>
<tr>
<td>170 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada</td>
</tr>
<tr>
<td>171 Department of Physics, University of Warwick, Coventry, United Kingdom</td>
</tr>
<tr>
<td>172 Waseda University, Tokyo, Japan</td>
</tr>
<tr>
<td>173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel</td>
</tr>
<tr>
<td>174 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA</td>
</tr>
<tr>
<td>175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany</td>
</tr>
<tr>
<td>176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany</td>
</tr>
<tr>
<td>177 Department of Physics, Yale University, New Haven, Connecticut, USA</td>
</tr>
<tr>
<td>178 Yerevan Physics Institute, Yerevan, Armenia</td>
</tr>
<tr>
<td>179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France</td>
</tr>
</tbody>
</table>

*Deceased.
† Also at Department of Physics, King’s College London, London, United Kingdom.
‡ Also at Department of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
§ Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
¶ Also at TRIUMF, Vancouver BC, Canada.
‖ Also at Department of Physics, California State University, Fresno CA, USA.
¶¶ Also at Tomsk State University, Tomsk, Russia.
‖‖ Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
§§ Also at Università di Napoli Parthenope, Napoli, Italy.
¶¶¶ Also at Institute of Particle Physics (IPP), Canada.

117801-17