Search for dark matter candidates and large extra dimensions in events with a photon and missing transverse momentum in pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector


DOI
10.1103/PhysRevLett.110.011802

Publication date
2013

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
Search for Dark Matter Candidates and Large Extra Dimensions in Events with a Photon and Missing Transverse Momentum in \( pp \) Collision Data at \( \sqrt{s} = 7 \) TeV with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 20 September 2012; published 3 January 2013)

Results of a search for new phenomena in events with an energetic photon and large missing transverse momentum in proton-proton collisions at \( \sqrt{s} = 7 \) TeV are reported. Data collected by the ATLAS experiment at the LHC corresponding to an integrated luminosity of 4.6 fb\(^{-1}\) are used. Good agreement is observed between the data and the standard model predictions. The results are translated into exclusion limits on models with large extra spatial dimensions and on pair production of weakly interacting dark matter candidates.

DOI: 10.1103/PhysRevLett.110.011802

PACS numbers: 13.85.Rm, 13.85.Qk, 14.70.Kv, 14.80.Rt

Events with an energetic photon and large missing momentum in the final state constitute a clean and distinctive signature in searches for new physics at colliders. In particular, monophoton, and monojet final states have been studied \([1–8]\) in the context of searches for supersymmetry and large extra spatial dimensions (LED), aiming to provide a solution to the mass hierarchy problem, and the search for weakly interacting massive particles (WIMPs) as candidates for dark matter (DM).

The Arkani-Hamed, Dimopoulos, and Dvali (ADD) model for LED \([9]\) explains the large difference between the electroweak unification scale \( O(10^2) \) GeV and the Planck scale \( M_{Pl} \sim O(10^{19}) \) GeV by postulating the presence of \( n \) extra spatial dimensions of size \( R \), and defining a fundamental Planck scale in \( 4 + n \) dimensions, \( M_P \), given by \( M_{Pl}^4 \sim M_P^2 R^n \). The extra spatial dimensions are compactified, resulting in a Kaluza-Klein tower of massive graviton modes. At hadron colliders, these graviton modes may escape detection and can be produced in association with an energetic photon or a jet, leading to a monophoton or monojet signature.

The presence of a nonbaryonic DM component in the Universe is inferred from the observation of its gravitational interactions \([10]\), although its nature is otherwise unknown. A WIMP \( \chi \) with mass \( m_\chi \) in the range between 1 GeV and a few TeV is a plausible candidate for DM. It could be detected via its scattering with heavy nuclei \([11]\), the detection of cosmic rays (energetic photons, electrons, positrons, protons, antiprotons, or neutrinos) from \( \chi \bar{\chi} \) annihilation in astrophysical sources \([10]\), or via \( \chi \bar{\chi} \) pair production at colliders where the WIMPs do not interact with the detector and the event is identified by the presence of an energetic photon or jet from initial-state radiation. The interaction of WIMPs with standard model (SM) particles is assumed to be driven by a mediator with mass at the TeV scale and described using a nonrenormalizable effective theory \([12]\) with several operators. The vertex coupling is suppressed by an effective cutoff mass scale \( M_* \sim M/\sqrt{\mathcal{G}_{182}} \), where \( M \) denotes the mass of the mediator and \( g_1 \) and \( g_2 \) are the couplings of the mediator to the WIMP and SM particles.

This Letter reports results of the search for new phenomena in the monophoton final state, based on \( \sqrt{s} = 7 \) TeV proton-proton collision data corresponding to an integrated luminosity of 4.6 fb\(^{-1}\) collected with the ATLAS detector at the LHC during 2011. The ATLAS detector is described in detail elsewhere \([13]\). The data are collected using a three-level trigger system that selects events with missing transverse momentum greater than 70 GeV. In the analysis, events are required to have a reconstructed primary vertex and \( E_T^{\text{miss}} \) > 150 GeV, where \( E_T^{\text{miss}} \) is computed as the magnitude of the vector sum of the transverse momentum of all noise-suppressed calorimeter topological clusters with \(|\eta| < 4.9\) \([14,15]\). A photon is also required with transverse momentum \( p_T > 150 \) GeV and \(|\eta| < 2.37\), excluding the calorimeter barrel or endcap transition regions \( 1.37 < |\eta| < 1.52\) \([13]\). With these criteria, the trigger selection is more than 98% efficient, as determined using events selected with a muon trigger. The cluster energies are corrected for the different response of the calorimeters to hadronic jets, \( \tau \) leptons, electrons or photons, as well as dead material and out-of-cluster energy losses. The photon candidate must pass tight identification criteria \([16]\) and is required to be isolated: the energy not associated with the photon cluster in a cone of radius \( \Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2} = 0.4 \) around the candidate is required to be less than 5 GeV. Jets are defined using the anti-\(k_T\) jet algorithm \([17]\) with the distance parameter set to \( R = 0.4 \). The measured jet \( p_T \) is corrected for detector

*Full author list given at the end of the article.
effects and for contributions from multiple proton-proton interactions per beam bunch crossing (pileup) \[18\].

Events with more than one jet with \(p_T > 30\) GeV and \(|\eta| < 4.5\) are rejected. Events with one jet are retained to increase the signal acceptance and reduce systematic uncertainties related to the modeling of initial-state radiation. The reconstructed photon, \(E_T^{\text{miss}}\) vector, and jets (if found) are required to be well separated in the transverse plane with \(\Delta \phi (\gamma, E_T^{\text{miss}}) > 0.4\), \(\Delta R (\gamma, \text{jet}) > 0.4\), and \(\Delta \phi (\text{jet}, E_T^{\text{miss}}) > 0.4\). Additional quality criteria \[19\] are applied to ensure that jets and photons are not produced by noisy calorimeter cells, and to avoid problematic detector regions. Events with identified electrons or muons are vetoed to reject mainly \(W/Z + \gamma\) backgrounds.

Electron (muon) candidates are required to have \(p_T > 20\) GeV and \(|\eta| < 2.47\) (\(p_T > 10\) GeV and \(|\eta| < 2.4\)), and to pass the medium (combined) criteria \[20\]. The final data sample contains 116 events, where 88 and 28 events have zero and one jet, respectively.

The SM background to the monophoton signal is dominated by the irreducible \(Z(\rightarrow \nu \bar{\nu}) + \gamma\) process, and receives contributions from \(W/Z + \gamma\) events with unidentified electrons, muons or hadronic \(\tau\) decays, and \(W/Z + \gamma\) events with an electron or jet misreconstructed as a photon. In addition, the monophoton sample receives small contributions from top-quark, \(\gamma \gamma\), diboson (\(WW, ZZ, WZ\)), \(\gamma +\) jets, and multijet processes.

Background samples of simulated \(W/Z + \gamma\) events are generated using ALPGEN 2.13 \[21\], interfaced to HERWIG 6.510 \[22\] with Jimmy 4.31 [23], and SHERPA 1.2.3 [24], using CTEQ6L1 [25] parton distribution functions (PDFs) and requiring a minimum photon \(p_T\) of 40 GeV. Background samples of \(W/Z + \gamma\) and \(W + \gamma\) processes are generated using ALPGEN plus HERWIG/JIMMY, with CTEQ6L1 PDFs. Top-quark production samples are generated using MC@NLO 4.01 [26] and CT10 [27] PDFs, while diboson processes are generated using HERWIG/JIMMY normalized to next-to-leading-order (NLO) predictions with MRST2007 [28] PDFs. Multijet and \(\gamma \gamma\) processes are generated using PYTHIA 6.426 [29] with MRST2007 PDFs.

Signal Monte Carlo (MC) samples are generated according to the ADD model using the PYTHIA 8.150 leading-order (LO) perturbative QCD (pQCD) implementation with default settings, requiring a minimum photon \(p_T\) of 80 GeV, and an ATLAS tune for the underlying event (UE) contribution [30] including the CTEQ6L1 PDFs. The number of extra dimensions \(n\) is varied from 2 to 6 and values of \(M_\chi\) in the 1–2 TeV range are considered. For consistency with a previous monojet analysis performed in ATLAS \[7,8\], the yields corresponding to CTEQ6.6 [31] PDFs are used, as obtained by reweighting these samples. The samples are normalized to NLO total cross sections [32]. The LO-to-NLO factors decrease from 1.5 to 1.1 as \(n\) increases.

Simulated events corresponding to the \(\chi \bar{\chi} + \gamma\) process with a minimum photon \(p_T\) of 80 GeV are generated using LO matrix elements from MADGRAPH [33] interfaced to PYTHIA 6.426 using CTEQ6L1 PDFs. Values for \(m_\chi\) between 1 GeV and 1.3 TeV are considered. In this analysis, WIMPs are assumed to be Dirac fermions and the vertex operator is taken to have the structure of a scalar, vector, axial-vector or tensor, corresponding, respectively, to the operators \(D_1, D_5, D_8\), and \(D_9\) in Refs. \[12,34\]. These operators correspond to spin-independent (\(D_1\) and \(D_5\)) and spin-dependent (\(D_8\) and \(D_9\)) interactions. The MC samples are passed through a full simulation [35] of the ATLAS detector and trigger system, based on GEANT4 [36]. The simulated events are reconstructed and analyzed as the data.

The normalization of the MC predictions for the dominant \(W/Z + \gamma\) background processes are set using scale factors determined in a data control sample, resulting in a significant reduction of the background uncertainties. A \(\gamma + \mu + E_T^{\text{miss}}\) control sample with an identified muon is defined by inverting the muon veto in the nominal event selection criteria discussed above. According to the simulation, the sample contains a 71% (19%) contribution from \(W + \gamma\) (\(Z + \gamma\)) processes. This control sample is used to normalize separately the \(W + \gamma\) and \(Z + \gamma\) MC predictions determined by ALPGEN and SHERPA, respectively. In each case, the scale factor is defined as the ratio of the data to the given MC prediction, after the contributions from the rest of the background processes are subtracted. The scale factors, extracted simultaneously to take into account correlations, are \(k(W + \gamma) = 1.0 \pm 0.2\) and \(k(Z + \gamma) = 1.1 \pm 0.2\), where statistical and systematic uncertainties are included (see below).

Dedicated studies are performed to determine the probability for electrons or jets to be identified as photons, resulting in data-driven estimates of \(W/Z + \gamma\) background contributions. (1) A data sample of \(Z\) boson candidates is employed to compute the fraction of electrons from the \(Z\) boson decay that are reconstructed as photons. This fraction decreases from 2% to 1% as \(p_T\) increases from 150 to 300 GeV, and increases from 1% to 3% as \(|\eta|\) increases. These rates are employed to determine the \(W(\rightarrow \ell \nu) +\) jets background in the signal region, for which a control data sample selected with the nominal selection criteria and an electron instead of a photon is used. This results in a total \(W(\rightarrow \ell \nu) +\) jet background estimation of 14 ± 6 events, where the uncertainty is dominated by the limited size of the control data sample. (2) Control samples enhanced in jets identified as photons are defined using nominal selection criteria with nonisolated photon candidates and/or photon candidates passing a loose selection [16] but not the nominal identification requirements. The ratio of isolated to nonisolated photons in the loose-photon selected sample together with the number of nonisolated photons passing the nominal
identification requirements are used to determine the rate of jets identified as photons in the signal region, after the contribution from $W/Z + \gamma$ processes has been subtracted. This gives an estimate of $4.3 \pm 1.9 W/Z + \text{jet}$ background events.

The $\gamma + \text{jet}$ and multijet background contributions to the signature of a photon and large $E_{T}^{\text{miss}}$ originate from the misreconstruction of the energy of a jet in the calorimeter. The direction of the $E_{T}^{\text{miss}}$ vector therefore tends to be aligned with the jet. These background contributions are determined from data using a control sample with the nominal selection criteria and at least one jet with $p_T > 30 \text{ GeV}$ and $\Delta \phi(\text{jet}, E_{T}^{\text{miss}}) < 0.4$. After the subtraction of electroweak boson and top-quark production processes, a linear extrapolation of the measured $p_T$ spectrum to $p_T < 30 \text{ GeV}$ leads to an estimate of $1.0 \pm 0.5$ background events in the signal region, where the uncertainty is due to the ambiguity in the functional form used in the extrapolation. Background contributions from top-quark, $\gamma\gamma$, and diboson production processes, determined using MC samples, are small. Finally, noncollision backgrounds are negligible.

A detailed study of systematic uncertainties on the background predictions has been performed. An uncertainty of $0.3\%$ to $1.5\%$ on the absolute photon energy scale [16], depending on the photon $p_T$ and $\eta$, translates into a $0.9\%$ uncertainty on the total background prediction. Uncertainties on the simulated photon energy resolution, photon isolation, and photon identification efficiency introduce a combined $1.1\%$ uncertainty on the background yield. Uncertainties on the simulated lepton identification efficiencies introduce a $0.3\%$ uncertainty on the background predictions. The uncertainty on the absolute jet energy scale [18] and jet energy resolution introduce $0.9\%$ and $1.2\%$ uncertainties on the background estimation, respectively. A $10\%$ uncertainty on the absolute energy scale for low $p_T$ jets and unclustered energy in the calorimeter, and a $6.6\%$ uncertainty on the subtraction of pileup contributions, are taken into account. They affect the $E_{T}^{\text{miss}}$ determination and translate into $0.8\%$ and $0.3\%$ uncertainties on the background yield, respectively. The dependence of the predicted $W/Z + \gamma$ backgrounds on the parton shower and hadronization model used in the MC simulations is studied by comparing the predictions from SHERPA and ALPGEN. This results in a conservative $6.9\%$ uncertainty on the total background yield. Uncertainties due to the choice of PDFs and the variation of the renormalization and factorization scales in the $W/Z + \gamma$ MC samples introduce an additional $1.0\%$ uncertainty on the total background yields. Other sources of systematic uncertainty related to the trigger selection, the lepton $p_T$ scale and resolution, the pileup description, background normalization of the top quark, $\gamma\gamma$ and diboson contributions, and a $1.8\%$ uncertainty on the total luminosity [37] introduce a combined uncertainty of less than $0.5\%$ on the total predicted yields. The different sources of uncertainty are added in quadrature, resulting in a total $15\%$ uncertainty on the background prediction.

In Table I, the observed number of events and the SM predictions are presented. The data are in agreement with the SM background-only hypothesis with a $p$ value of 0.2. Figure 1 shows the measured $E_{T}^{\text{miss}}$ distribution compared to the background predictions. The results are expressed in terms of model-independent $90\%$ and $95\%$ confidence level (C.L.) upper limits on the visible cross section, defined as the production cross section times acceptance times efficiency $(\sigma \times A \times \epsilon)$, using the CL$_s$ modified frequentist approach [38] and considering the systematic uncertainties on the SM backgrounds and on the integrated luminosity. Values of $\sigma \times A \times \epsilon$ above $5.6$ fb and $6.8$ fb are excluded at $90\%$ C.L. and $95\%$ C.L., respectively. Typical event selection efficiencies of $\epsilon \sim 75\%$ are found in simulated ADD and WIMP signal samples.

The results are translated into $95\%$ C.L. limits on the parameters of the ADD model. The typical $A \times \epsilon$ of the selection criteria is $20.0 \pm 0.4$(stat) $\pm 1.6$(syst)$\%$, approximately independent of $n$ and $M_D$. Experimental

<table>
<thead>
<tr>
<th>Background source</th>
<th>Prediction</th>
<th>±(stat)</th>
<th>±(syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu}) + \gamma$</td>
<td>93</td>
<td>±16</td>
<td>±8</td>
</tr>
<tr>
<td>$Z/\gamma'(\rightarrow \ell^+\ell^-) + \gamma$</td>
<td>0.4</td>
<td>±0.2</td>
<td>±0.1</td>
</tr>
<tr>
<td>$W(\rightarrow \ell\nu) + \gamma$</td>
<td>24</td>
<td>±5</td>
<td>±2</td>
</tr>
<tr>
<td>$W/Z + \text{jets}$</td>
<td>18</td>
<td>⋯</td>
<td>6</td>
</tr>
<tr>
<td>Top</td>
<td>0.07</td>
<td>±0.07</td>
<td>±0.01</td>
</tr>
<tr>
<td>$WW, WZ, ZZ, \gamma\gamma$</td>
<td>0.3</td>
<td>±0.1</td>
<td>±0.1</td>
</tr>
<tr>
<td>$\gamma + \text{jets and multijet}$</td>
<td>1.0</td>
<td>⋯</td>
<td>±0.5</td>
</tr>
<tr>
<td>Total background</td>
<td>137</td>
<td>±18</td>
<td>±9</td>
</tr>
</tbody>
</table>

Events in data (4.6 fb$^{-1}$) | 116 |

FIG. 1 (color online). The measured $E_{T}^{\text{miss}}$ distribution (black dots) compared to the SM (solid lines), SM + ADD (dashed lines), and SM + WIMP (dotted lines) predictions, for two particular ADD and WIMP scenarios.

011802-3
uncertainties related to the photon, jet, and $E_{\text{T}}^{\text{miss}}$ scales and resolutions, the photon reconstruction, the trigger efficiency, the pileup description, and the luminosity introduce a 6.8% uncertainty on the signal yield. Uncertainties related to the modeling of the initial- and final-state gluon radiation translate into a 3.5% uncertainty on the ADD signal yield. Systematic uncertainties due to PDFs result in a 0.8% to 1.4% uncertainty on the signal $A \times \epsilon$ and a 4% to 11% uncertainty on the signal cross section, increasing as $n$ increases. Variations of the renormalization and factorization scales by factors of 2 and $1/2$ introduce a 0.6% uncertainty on the signal $A \times \epsilon$ and an uncertainty on the signal cross section that decreases from 9% to 5% as $n$ increases.

Figure 2 shows the expected and observed 95% C.L. lower limits on $M_D$ as a function of $n$, as determined using the CL$_s$ method and considering uncertainties on both signal and SM background predictions. Values of $M_D$ below 1.93 TeV ($n = 2$), 1.83 TeV ($n = 3$ or 4), 1.86 TeV ($n = 5$), and 1.89 TeV ($n = 6$) are excluded at 95% C.L. The observed limits decrease by 3% to 2% after considering the $-1\sigma$ uncertainty from PDFs, scale variations, and parton shower modeling in the ADD theoretical predictions (dashed lines in Fig. 2). These results improve upon previous limits on $M_D$ from LEP and Tevatron experiments [1–3]. In this analysis, no weights are applied for signal events in the phase space region with $\hat{s} > M_D^2$, which is sensitive to the unknown ultraviolet behavior of the theory. For $M_D$ values close to the observed limits, the visible signal cross sections decrease by 15% to 75% as $n$ increases when truncated samples with $\hat{s} < M_D^2$ are considered. This analysis probes a kinematic range for which the model predictions are defined but ambiguous.

Similarly, 90% C.L. upper limits on the pair-production cross section of dark matter WIMP candidates are determined. The $A \times \epsilon$ of the selection criteria are typically $11.0 \pm 0.2$(stat) $\pm 1.6$(syst)% for the D1 operator, $18.0 \pm 0.3$(stat) $\pm 1.4$(syst)% for the D5 and D8 operators, and $23.0 \pm 0.3$(stat) $\pm 2.1$(syst)% for the D9 operator, with a moderate dependence on $m_{\chi}$. Experimental uncertainties, as discussed above, translate into a 6.6% uncertainty on the signal yields. Theoretical uncertainties on initial- and final-state gluon radiation introduce a 3.5% to 10% uncertainty on the signal yields. The uncertainties related to PDFs result in 1.0% to 8.0% and 5.0% to 30% uncertainties on the signal $A \times \epsilon$ and cross section, respectively. Variations of the renormalization and factorization scales lead to a change of 1.0% to 2.0% and 8.0% in the signal $A \times \epsilon$ and cross section, respectively. In the case of the D1 (D5) spin-independent operator, values of $M_\chi$ below 31 and 5 GeV (585 and 156 GeV) are excluded at 90% C.L. for $m_\chi$ equal to 1 GeV and 1.3 TeV, respectively. Values of $M_\chi$ below 585 and 100 GeV (794 and 188 GeV) are excluded for the D8 (D9) spin-dependent operator for $m_\chi$ equal to 1 GeV and 1.3 TeV, respectively. These results can be translated into upper limits on the nucleon-WIMP interaction cross section using the prescription in Refs. [12,39]. Figure 3 shows 90% C.L. upper limits on the nucleon-WIMP cross section as a function of $m_\chi$. In the case of the D1 (D5) spin-independent interaction, nucleon-WIMP cross sections above $2.7 \times 10^{-39}$ cm$^2$ and $5.8 \times 10^{-34}$ cm$^2$ (2.2 $\times$ 10$^{-39}$ cm$^2$ and 1.7 $\times$ 10$^{-36}$ cm$^2$) are excluded at 90% C.L. for $m_\chi = 1$ GeV and $m_\chi = 1.3$ TeV, respectively. Spin-dependent interactions cross sections in the range $7.6 \times 10^{-41}$ cm$^2$ to $3.4 \times 10^{-37}$ cm$^2$ (2.2 $\times$ 10$^{-41}$ cm$^2$ to $2.7 \times 10^{-38}$ cm$^2$) are excluded at 90% C.L. for the D8 (D9) operator and $m_\chi$ varying between 1 GeV and 1.3 TeV. The quoted observed limits on $M_\chi$ typically decrease by 2% to 10% if the $-1\sigma$ theoretical uncertainty is considered. This translates into a 10% to 50% increase of the quoted nucleon-WIMP cross section limits. The exclusion in the region 1 GeV < $m_\chi$ < 3.5 GeV (1 GeV < $m_\chi$ < 1 TeV) for spin-independent (spin-dependent)
nucleon-WIMP interactions is driven by the results from collider experiments, with the assumption of the validity of the effective theory, and is still dominated by the monojet results. The cross section upper limits improve upon CDF results [4] and are similar to those obtained by the CMS experiment [5,6].

In summary, we report results on the search for new phenomena in events with an energetic photon and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC, based on ATLAS data corresponding to an integrated luminosity of 4.6 fb$^{-1}$. The measurements are in agreement with the SM predictions for the background. The results are translated into model-independent 90% and 95% confidence level upper limits on $\sigma \times A \times e$ of 5.6 and 6.8 fb, respectively. The results are presented in terms of improved limits on $M_D$ versus the number of extra spatial dimensions in the ADD model and upper limits on the spin-independent and spin-dependent contributions to the nucleon-WIMP elastic cross section as a function of the WIMP mass.

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 and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MÉRYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS, and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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, U.K.; 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, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.), and BNL (U.S.) and in the Tier-2 facilities worldwide.

[15] ATLAS uses a cylindrical coordinate system about the beam axis with polar angle $\theta$ and azimuthal angle $\phi$. Anticlockwise beam direction defines the positive $z$ axis, while the positive $x$ axis is defined as pointing from the collision point to the center of the LHC ring and the positive $y$ axis points upwards. We define transverse energy $E_T = E \sin \theta$, transverse momentum $p_T = p \sin \theta$, and pseudorapidity $\eta = -\ln(\tan(\theta/2))$.
The strange and charm quark masses (relevant for the $D_1$ operator) are set to 0.1 and 1.42 GeV, respectively.

In consultation with the authors of Ref. [12], a factor $4.7 \times 10^{-39}$ cm$^2$ is used in the cross section formula for $D_8$ and $D_9$ operators instead of the quoted $9.18 \times 10^{-39}$ cm$^2$. 


(Atlas Collaboration)

1 School of Chemistry and 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
4a Department of Physics, Ankara University, Ankara, Turkey
4b Department of Physics, Dumlupinar University, Kutahya, Turkey
4c Department of Physics, Gazi University, Ankara, Turkey
4d Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4e Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7 Department of Physics, University of Arizona, Tucson, Arizona, USA
8 Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
13a Institute of Physics, University of Belgrade, Belgrade, Serbia
13b Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19a Department of Physics, Bogazici University, Istanbul, Turkey
19b Division of Physics, Dogus University, Istanbul, Turkey
19c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
19d Department of Physics, Istanbul Technical University, Istanbul, Turkey
20a INFN Sezione di Bologna, Bologna, Italy
20b Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, Massachusetts, USA
23 Department of Physics, Brandeis University, Waltham, Massachusetts, USA

PRL 110, 011802 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

011802-14
169 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
170 Department of Physics, University of Warwick, Coventry, United Kingdom
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
176 Department of Physics, Yale University, New Haven, Connecticut, USA
177 Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Deceased.
b Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal.
c Also at Faculdade de Ciencias and CFNU1, Universidade de Lisboa, Lisboa, Portugal.
d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
e Also at TRIUMF, Vancouver, British Columbia, Canada.
f Also at Department of Physics, California State University, Fresno, CA, USA.
g Also at Novosibirsk State University, Novosibirsk, Russia.
h Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
i Also at Department of Physics, UASLP, San Luis Potosí, Mexico.
j Also at Università di Napoli Parthenope, Napoli, Italy.
k Also at Institute of Particle Physics (IPP), Canada.
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
m Also at Louisiana Tech University, Ruston, LA, USA.
n Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
o Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
p Also at Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada.
q Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
t Also at Manhattan College, New York, NY, USA.
u Also at School of Physics, Shandong University, Shandong, China.
v Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
w Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
y Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
aa Also at Section of Physique, Université de Genève, Geneva, Switzerland.
bb Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
cc Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
ccd Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
nee Also at California Institute of Technology, Pasadena, CA, USA.
ff Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
egg Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
ghh Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.
ii Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
jj Also at Department of Physics, Oxford University, Oxford, United Kingdom.
kk Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
ll Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
m Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.