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Published in:
Physical Review D. Particles, Fields, Gravitation, and Cosmology

DOI:
10.1103/PhysRevD.88.012001

Link to publication

Citation for published version (APA):
https://doi.org/10.1103/PhysRevD.88.012001

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Search for nonpointing photons in the diphoton and $E_T^{\text{miss}}$ final state in $\sqrt{s} = 7$ TeV proton-proton collisions using the ATLAS detector

G. Aad et al.*
(ATLAS Collaboration)
(Received 23 April 2013; published 1 July 2013)

A search has been performed for photons originating in the decay of a neutral long-lived particle, exploiting the capabilities of the ATLAS electromagnetic calorimeter to make precise measurements of the flight direction of photons, as well as the calorimeter’s excellent time resolution. The search has been made in the diphoton plus missing transverse energy final state, using the full data sample of 4.8 fb$^{-1}$ of 7 TeV proton-proton collisions collected in 2011 with the ATLAS detector at the LHC. No excess is observed above the background expected from Standard Model processes. The results are used to set exclusion limits in the context of gauge mediated supersymmetry breaking models, with the lightest neutralino being the next-to-lightest supersymmetric particle and decaying with a lifetime in excess of 0.25 ns into a photon and a gravitino.

DOI: 10.1103/PhysRevD.88.012001
PACS numbers: 12.60.Jv, 13.85.Qk, 13.85.Rm

I. INTRODUCTION

Supersymmetry (SUSY) [1–9], a theoretically well-motivated candidate for physics beyond the Standard Model (SM), predicts the existence of a new SUSY partner (sparticle) for each of the SM particles, with identical quantum numbers except differing by half a unit of spin. In R-parity conserving SUSY models [10–14], these sparticles could be produced in pairs in proton-proton ($pp$) collisions at the CERN Large Hadron Collider (LHC), and would decay in cascades involving other sparticles and SM particles until the lightest SUSY particle (LSP), which is stable, is produced. In gauge mediated supersymmetry breaking (GMSB) models [15–20], the LSP is the gravitino ($\tilde{G}$), GMSB phenomenology is largely determined by the properties of the next-to-lightest neutralino ($\tilde{\chi}^0_1$) as the NLSP. In the SPS8 set of models, the effective scale of SUSY breaking, denoted $\Lambda$, is a free parameter. In addition, the $\tilde{\chi}^0_1$ proper decay length, $c\tau(\tilde{\chi}^0_1)$, is a free parameter of the theory.

For the range of SPS8 $\Lambda$ values relevant for this analysis, SUSY production is dominated by electroweak pair production of gauginos, and, in particular, of $\tilde{\chi}^0_2 \tilde{\chi}^0_1$ and $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ pairs. In the SPS8 models, the dominant decay mode of the NLSP is $\tilde{\chi}^0_1 \rightarrow \gamma + \tilde{G}$. Previous ATLAS analyses have assumed prompt NLSP decays, with $c\tau(\tilde{\chi}^0_1) < 0.1$ mm, and therefore searched for an excess production of diphoton events that, due to the escaping gravitinos, exhibit significant missing transverse momentum ($E_T^{\text{miss}}$). The latest such ATLAS results [22] use the full 2011 data set and, within the context of SPS8 models, exclude values of $\Lambda < 196$ TeV, corresponding to $m(\tilde{\chi}^0_1) > 280$ GeV, at the 95% confidence level (C.L.). The limits on SPS8 models are less stringent in the case of a longer-lived NLSP. For example, recent CMS 95% C.L. limits [23], obtained using the $E_T^{\text{miss}}$ spectrum of events with at least three jets and one or two photons, coupled with measurements of the photon arrival time, require $m(\tilde{\chi}^0_1) > 220$ GeV for $c\tau(\tilde{\chi}^0_1) < 500$ mm.

The analysis reported in this paper uses the full data sample of 4.8 fb$^{-1}$ of 7 TeV $pp$ collisions collected in 2011 with the ATLAS detector at the LHC, and considers the scenario where the $\tilde{\chi}^0_1$ has a finite lifetime and can travel some distance from its production point before decaying. The search is performed in an inclusive sample of candidate diphoton + $E_T^{\text{miss}}$ events.

The long-lived NLSP scenario introduces the possibility of a decay photon being produced after a finite delay and with a flight direction that does not point back to the primary vertex (PV) of the event. The analysis searches for such “nonpointing photons” by exploiting the fine segmentation of the ATLAS electromagnetic (EM) calorimeter to measure the flight direction of photons. The variable used as a measure of the degree of nonpointing of the photon is $z_{\text{DCA}}$, the difference between the $z$ coordinate of the photon extrapolated back to its distance of...
closest approach to the beamline (i.e. \( x = y = 0 \)) and \( z_{PV} \), the \( z \) coordinate of the PV. The search for nonpointing photons is then performed by fitting the shape of the \( z_{DCA} \) distribution obtained for photons in the signal region, defined as diphoton events with \( E_T^{miss} > 75 \) GeV, to a combination of templates that describe the \( z_{DCA} \) distribution for the expected signal and background events. In addition, the excellent time resolution of the calorimeter is exploited to measure the arrival times of the photons, providing a cross-check of the results.

II. THE ATLAS DETECTOR

The ATLAS detector [24] covers nearly the entire solid angle around the collision point, and consists of an inner tracking detector surrounded by a solenoid, EM and hadronic calorimeters, and a muon spectrometer incorporating three large toroidal magnet systems. The ATLAS inner-detector system (ID) is immersed in a 2 T axial magnetic field, provided by a thin superconducting solenoid located before the calorimeters, and provides charged particle tracking in the pseudorapidity range \( |\eta| < 2.5 \). The ID consists of three detector subsystems, beginning closest to the beam line with the high-granularity silicon pixel detector, followed at larger radii by the silicon microstrip tracker and then the straw-tube-based transition radiation tracker. The ID allows an accurate reconstruction of tracks from the primary \( pp \) collision and precise determination of the location of the PV. The ID also identifies tracks from secondary vertices, permitting the efficient identification of photons that convert to electron-positron pairs as they pass through the detector material.

This analysis relies heavily on the capabilities of the ATLAS calorimeter system, which covers the pseudorapidity range \( |\eta| < 4.9 \). Finely segmented EM calorimetry is provided by barrel (\( |\eta| < 1.475 \)) and end-cap (\( 1.375 < |\eta| < 3.2 \)) lead/liquid-argon (lead/LAr) EM sampling calorimeters. An additional thin LAr presampler covering \( |\eta| < 1.8 \) allows reactions for energy losses in material upstream of the EM calorimeters. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within \( |\eta| < 1.7 \), and two copper/LAr hadronic end-cap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for EM and hadronic measurements, respectively. Outside the ATLAS calorimeters lies the muon spectrometer, which identifies and measures the deflection of muons up to \( |\eta| = 2.7 \), in a magnetic field generated by superconducting air-core toroidal magnet systems.

A. Pointing resolution

The EM calorimeter is segmented into three layers in depth, that are used to measure the longitudinal profile of the shower. The first layer uses highly granular “strips” segmented in the \( \eta \) direction, designed to allow efficient discrimination between single photon showers and two overlapping showers originating, for example, from the decay of a \( \pi^0 \) meson. The second layer collects most of the energy deposited in the calorimeter by EM showers initiated by electrons or photons. Very high energy showers can leave significant energy deposits in the third layer, which can also be used to correct for energy leakage beyond the EM calorimeter. By measuring precisely the centroids of the EM shower in the first and second layers, the flight direction of photons can be determined. In the ATLAS \( H \rightarrow \gamma \gamma \) analysis [25] that contributed to the discovery of a Higgs boson, this capability of the EM calorimeter was used to help choose the PV from which the two photons originated, thereby improving the diphoton invariant mass resolution and sensitivity of the search. The analysis described in this paper uses the measurement of the photon flight direction to search for photons that do not point back to the PV. The angular resolution of the EM calorimeter’s measurement of the flight direction of prompt photons is about 60 mrad/\( \sqrt{E} \), where \( E \) is the energy measured in GeV. This angular precision corresponds, in the EM barrel calorimeter, to a resolution on \( z_{DCA} \) of about 15 mm for prompt photons with energies in the range of 50–100 GeV. Given the geometry, the \( z_{DCA} \) resolution is worse for photons reconstructed in the end-cap calorimeters, so the pointing analysis is restricted to photon candidates in the EM barrel calorimeter.

While the geometry of the EM calorimeter has been optimized for detecting particles that point back to near the nominal interaction point at the center of the detector (i.e. \( x = y = z = 0 \)), the fine segmentation allows good pointing performance to be achieved over a wide range of photon impact angles. Figure 1 shows, as a function of \( \left| z_{DCA} \right| \), the pointing resolution for photons from GMSB signal MC samples plotted as a function of \( \left| z_{DCA} \right| \). The pointing resolution is also shown for \( Z \rightarrow ee \) data and MC, for which the primary vertex position, \( z_{PV} \), serves the role of \( z_{DCA} \).

FIG. 1 (color online). Pointing resolution obtained for EM showers in the ATLAS LAr EM barrel calorimeter. The pointing resolution for photons from GMSB signal MC samples is plotted as a function of \( \left| z_{DCA} \right| \). The pointing resolution is also shown for \( Z \rightarrow ee \) data and MC, for which the primary vertex position, \( z_{PV} \), serves the role of \( z_{DCA} \).
The expected pointing resolution for SPS8 signal photons from Monte Carlo (MC) simulations, obtained by fitting to a Gaussian the difference between the value of $z_{\text{DCA}}$ obtained from the calorimeter measurement and the MC generator-level information. The pointing resolution degrades with increasing $|z_{\text{DCA}}|$, but remains much smaller than $|z_{\text{DCA}}|$ in the region where the signal is expected.

The calorimeter pointing performance has been verified in data by using the finite spread of the LHC collision region along the $z$ axis. Superimposed on Fig. 1 is the pointing resolution achieved for a sample of electrons from $Z \rightarrow ee$ events, where the distance, $z_{\text{PV}}$, between the PV and the nominal center of the detector serves the role of $z_{\text{DCA}}$. In this case, the pointing resolution is obtained by fitting to a Gaussian the difference between $z_{\text{PV}}$, as determined with high precision using tracking information, and the calorimeter measurement of the origin of the electron, along the beam line. Figure 1 shows that similar pointing performance is observed for electrons and for photons, as expected given their similar EM shower developments. This similarity validates the use of a sample of electrons from $Z \rightarrow ee$ events to study the pointing performance for photons. The expected pointing performance for electrons in a MC sample of $Z \rightarrow ee$ events is also shown on Fig. 1, and is consistent with the data. The level of agreement between MC simulation and data over the range of values that can be accessed in the data gives confidence in the extrapolation using MC simulation to the larger deviations from pointing characteristic of the signal photons.

B. Timing resolution

Photons from NLSP decays would reach the LAr calorimeter with a slight delay compared to prompt photons. This delay results mostly from the flight time of the heavy NLSP, as well as some effect due to the longer geometric path of a nonpointing photon produced in the NLSP decay. The EM calorimeter, with its novel “accordion” design, and its readout, which incorporates fast shaping, has excellent timing performance. Quality control tests during production of the electronics required the clock jitter on the LAr readout boards to be less than 20 ps, with typical values of 10 ps [26]. Calibration tests of the overall electronic readout performed in situ in the ATLAS cavern show a timing resolution of $\approx 70$ ps [27], limited not by the readout but by the jitter of the calibration pulse injection system. Test-beam measurements [28] of production EM barrel calorimeter modules demonstrated a timing resolution of $\approx 100$ ps in response to high energy electrons.

For this analysis, the arrival time of an EM shower is measured using the second-layer EM calorimeter cell with the maximum energy deposit. During 2011, the various LAr channels were timed-in online with a precision of about 1 ns. A large sample of $W \rightarrow ev$ events was used to determine several calibration corrections which were applied to further optimize the timing resolution for EM clusters. The calibration includes corrections of various offsets in the timing of individual channels, corrections for the energy dependence of the timing, and flight-path corrections depending on the position of the PV. The corrections determined using the $W \rightarrow ev$ events were subsequently applied to electron candidates in $Z \rightarrow ee$ events to validate the procedure as well as to determine the timing performance in an independent data sample. Figure 2 shows the time resolution achieved as a function of the energy deposited in the second-layer cell used in the time measurement. The time resolution, $\sigma(t)$, is expected to follow the form $\sigma(t) = a/E \oplus b$, where $E$ is the energy measured in GeV and $\oplus$ indicates addition in quadrature. Superimposed on Fig. 2 is the result of a fit of the resolution to this form, where the parameters $a$ and $b$ multiply the so-called noise term and constant term, respectively. A timing resolution of $\approx 290$ ps is achieved for a large energy deposit. By comparing the arrival times of the two electrons in $Z \rightarrow ee$ events, this resolution is understood to include a correlated contribution of $\approx 220$ ps, as expected due to the spread in $pp$ collision times caused by the lengths of individual proton bunches along the LHC beam line. Subtracting this beam contribution in quadrature, the obtained timing resolution for the calorimeter is $\approx 190$ ps.

To cover the full dynamic range of physics signals of interest, the ATLAS LAr calorimeter readout boards [26] employ three overlapping linear gain scales, dubbed high, medium, and low, where the relative gain of successive scale is reduced by a factor of about 10. For a given event, any individual LAr readout channel is digitized using the

\begin{equation}
\frac{\text{Time Resolution}}{\text{Cell Energy}} = \begin{cases} 
\text{ATLAS} \\
\text{Data 2011} \\
\text{Fit} 
\end{cases}
\end{equation}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{time_resolution}
\caption{Time resolution obtained for EM showers in the ATLAS LAr EM barrel calorimeter, as a function of the energy deposited in the second-layer cell with the maximum deposited energy. Superimposed is the result of the fit described in the text. The data are shown for electrons read out using high gain, and the errors shown are statistical only.}
\end{figure}
III. DATA AND MONTE CARLO SIMULATION SAMPLES

This analysis uses a data sample of $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV, recorded with the ATLAS detector in 2011. The data sample, after applying quality criteria that require all ATLAS subdetector systems to be functioning normally, corresponds to a total integrated luminosity of $4.8 \pm 0.1$ fb$^{-1}$.

While all background studies, apart from some cross-checks, are performed with data, MC simulations are used to study the response to SPS8 GMSB signal models, as a function of the free parameters $\Lambda$ and $c\tau$. The other SPS8 model parameters are fixed to the following values: the messenger mass $M_{\text{mess}} = 2\Lambda$, the number of SU(5) messengers $N_3 = 1$, the ratio of the vacuum expectation values of the two Higgs doublets $\tan \beta = 15$, and the Higgs-sector mixing parameter $\mu > 0$ [21]. The SPS8 SUSY mass spectra, branching ratios, and decay widths are calculated using ISAJET [29] version 7.80. The signal yield is normalized to the central value of the GMSB signal cross section, as calculated at next-to-leading order (NLO) using PROSPINO [30] version 2.1 with the CTEQ6.6m [31] parton distribution functions (PDFs). The total uncertainty on the signal cross section, times the signal acceptance and efficiency, including more stringent cuts on these variables, as well as requirements on additional variables describing the shower shape in the second layer of the EM calorimeter, as well as leakage of energy into the hadronic calorimeter. The tight photon identification, designed for higher purity photon identification with still reasonable efficiency, includes more stringent cuts on these variables, as well as requirements on additional variables describing the shower in the first layer of the EM calorimeter. The various selection criteria do not depend on the transverse momentum of the photon ($E_T$), but do vary as a function of $\eta$ in order to take into account variations in the calorimeter geometry and in the thickness of the upstream material. For more details, see Ref. [37].

The measurement of $E_T^{\text{miss}}$ [39] is based on energy deposits in calorimeter cells inside three-dimensional clusters with $|\eta| < 4.5$. The energy of each cluster is calibrated to correct for the different response to electromagnetically and hadronically induced showers, energy loss in dead material, and out-of-cluster energy. The value of $E_T^{\text{miss}}$ is corrected for contributions from any muons identified in the event, by adding in the energy derived from the properties of reconstructed muon tracks.

V. EVENT SELECTION

The selected events were collected by an online trigger requiring the presence of at least two loose photon candidates, each with $E_T > 20$ GeV and $|\eta| < 2.5$. To ensure the selected events resulted from a beam collision, events are required to have at least one PV candidate with five or more associated tracks. In case of multiple vertices, the PV is chosen as the vertex with the greatest sum of the square of the transverse momenta of all associated tracks.

The offline photon selection requires the two photon candidates to each have $E_T > 50$ GeV, and to satisfy $|\eta| < 2.37$, excluding the transition region of $1.37 < |\eta| < 1.52$ between the barrel and end-cap EM calorimeters. In addition, both photons are required to be

gain scale that provides optimal energy resolution, given the energy deposited in that calorimeter cell. The results in Fig. 2 are those obtained for electrons where the time was measured using a second-layer cell readout using high gain, for which the $W \rightarrow e\nu$ sample used to calibrate the timing is large. Calibration samples for the medium and low gain scales are smaller, resulting in reduced precision. The timing resolutions obtained are about 400 ps for medium gain and about 1 ns for low gain.
isolated: after correcting for contributions from pileup and the deposition ascribed to the photon itself [37], the transverse energy deposited in the calorimeter in a cone of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around each photon candidate must be less than 5 GeV [40].

Due mostly to the inclusion of cuts on the EM shower shape in the very finely segmented strips of the first EM calorimeter layer, the efficiency of the tight photon identification decreases with $|z_{\text{DCA}}|$ for values of $|z_{\text{DCA}}|$ larger than $\approx 100$ mm. The loose efficiency remains flat over a wider range of $|z_{\text{DCA}}|$, up to values of $\approx 250$ mm, after which it decreases less rapidly than the tight efficiency. The event selection requires at least one of the isolated photon candidates to pass the tight photon identification requirements, while the other must pass the loose photon identification cuts. The selected sample will therefore be referred to hereafter as the tight-loose (TL) diphoton sample. To reduce the potential bias in the pointing measurement that results from applying the photon identification procedure, the looseness of the selection requirements, for examples of $\Lambda$ and $\tau$. The signal pointing distributions, normalized to unit area, are used as signal templates, hereafter referred to as $T_{\text{sig}}$. Since the $T_{\text{sig}}$ shape is determined using MC simulations, systematic uncertainties in the shape are included to account for possible differences in pointing performance between MC simulation and data. In particular, the presence of pileup in the collisions could impact the pointing resolution, due both to energy deposits in the calorimeter from additional minimum bias collisions and to the possibility of misidentifying the PV. These effects are modeled in the MC simulation. However, as a conservative estimate of the systematic $T_{\text{sig}}$ shape variations that could occur due to pileup, the differences are taken between the nominal shape and those from the two sub-samples which are obtained by dividing the MC samples roughly in two according to the number of PV candidates identified in each event. The $T_{\text{sig}}$ distributions, along with their statistical and total uncertainties, are shown in Fig. 3 for $\Lambda = 120$ TeV and for NLSP lifetime values of $\tau = 0.5$ and 30 ns.

### VI. SIGNAL AND BACKGROUND MODELING

#### A. SPS8 GMSB signal

The shape of the $z_{\text{DCA}}$ distribution, alternately denoted hereafter as the pointing distribution, that is expected for photons from NLSP decays in events passing the selection cuts is determined using the SPS8 GMSB MC signal samples described previously, for various values of $\Lambda$ and $\tau$. The signal pointing distributions, normalized to unit area, are used as signal templates, hereafter referred to as $T_{\text{sig}}$. Since the $T_{\text{sig}}$ shape is determined using MC simulations, systematic uncertainties in the shape are included to account for possible differences in pointing performance between MC simulation and data. In particular, the presence of pileup in the collisions could impact the pointing resolution, due both to energy deposits in the calorimeter from additional minimum bias collisions and to the possibility of misidentifying the PV. These effects are modeled in the MC simulation. However, as a conservative estimate of the systematic $T_{\text{sig}}$ shape variations that could occur due to pileup, the differences are taken between the nominal shape and those from the two sub-samples which are obtained by dividing the MC samples roughly in two according to the number of PV candidates identified in each event. The $T_{\text{sig}}$ distributions, along with their statistical and total uncertainties, are shown in Fig. 3 for $\Lambda = 120$ TeV and for NLSP lifetime values of $\tau = 0.5$ and 30 ns.

#### B. Backgrounds

The background is expected to be completely dominated by $p\bar{p}$ collision events, with possible backgrounds due to cosmic rays, beam-halo events, or other noncollision processes being negligible. The source of the loose photon in background events contributing to the selected TL sample is expected to be either a prompt photon, an electron misidentified as a photon, or a jet misidentified as a photon. In each case, the object providing the loose photon signature originates from the PV. The pointing and timing distributions expected for these background sources are determined using data control samples. Given their similar EM shower developments, the pointing resolution is similar for prompt photons and for electrons. The $z_{\text{DCA}}$ distribution expected for prompt photons and for electrons is therefore modeled using electrons in $Z \rightarrow ee$ data events. The $Z \rightarrow ee$ event selection requires a pair of oppositely charged electron candidates, each of which has $p_T > 25$ GeV and $|\eta| < 2.37$ (excluding the transition region between the barrel and end-cap calorimeters). One of the electron candidates, dubbed the “tag,” is

![Table I. The total signal acceptance times efficiency, in percent, of the event selection requirements, for sample SPS8 model points with various $\Lambda$ and $\tau$ values. The uncertainties shown are statistical only.](image)

<table>
<thead>
<tr>
<th>$\tau$ (ns)</th>
<th>$\Lambda$ (TeV)</th>
<th>80</th>
<th>120</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>15.3 ± 0.3</td>
<td>29.6 ± 0.3</td>
<td>45.1 ± 0.3</td>
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</tr>
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<tr>
<td>6</td>
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<td>5.38 ± 0.02</td>
<td>8.06 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.39 ± 0.01</td>
<td>1.006 ± 0.005</td>
<td>1.43 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.175 ± 0.005</td>
<td>0.384 ± 0.002</td>
<td>0.510 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.090 ± 0.004</td>
<td>0.164 ± 0.001</td>
<td>0.196 ± 0.002</td>
<td></td>
</tr>
</tbody>
</table>
required to pass additional selection cuts on the EM shower topology and tracking information designed to identify a high-purity sample of electrons. The second electron candidate, dubbed the “probe,” is restricted to the range $|\eta| < 1.37$. The dielectron invariant mass is required to agree with the value of the $Z$ mass within 10 GeV, a requirement that produces a sufficiently clean sample of $Z \rightarrow ee$ events. To avoid any bias, the pointing resolution for electrons is determined using the distribution measured for the probe electrons. The pointing distribution determined from $Z \rightarrow ee$ events, normalized to unit area, is used as the pointing template for prompt photons and electrons, and is referred to hereafter as $T_{e/\gamma}$.

While the EM showers of electrons and photons are similar, there are some differences. In particular, electrons traversing the material of the ID may emit bremsstrahlung photons, widening the resulting EM shower. In addition, photons can convert into electron-positron pairs in the material of the ID. In general, the EM showers of unconverted photons are slightly narrower than those of electrons, which are in turn slightly narrower than those of converted photons. The EM component of the background in the signal region includes a mixture of electrons, converted photons, and unconverted photons. Therefore, using electrons from $Z \rightarrow ee$ events to model the EM showers of the loose photon candidates in the signal region can slightly underestimate the pointing resolution in some cases, and slightly overestimate it in others. The pointing distribution from $Z \rightarrow ee$ events is taken as the nominal $T_{e/\gamma}$ shape. The distributions from MC samples of unconverted and converted photons, with similar kinematic properties as expected for signal photons, are separately taken to provide conservative estimates of the possible variations in the $T_{e/\gamma}$ shape which could result from not separating these various contributions. The $T_{e/\gamma}$ distribution, along with its statistical and total uncertainties, is shown superimposed on Fig. 3.

Due to their wider showers in the calorimeter, jets have a wider $z_{DCA}$ distribution than prompt photons and electrons. The sample of events passing the TL selection, but with the additional requirement that $E_T^{miss} < 20$ GeV, is used as a data control sample that includes jets with properties similar to the background contributions expected in the signal region. The $E_T^{miss}$ requirement serves to render negligible any possible signal contribution in this control sample. The shape of the $z_{DCA}$ distribution for the loose photon in these events, normalized to unit area, is used as a template, referred to hereafter as $T_{E_T^{miss}<20}$, in the final fit to the signal region. The TL sample with $E_T^{miss} < 20$ GeV should be dominated by jet-jet, jet-$\gamma$ and $\gamma\gamma$ events. Therefore, the $T_{E_T^{miss}<20}$ GeV template includes contributions from photons as well as from jets faking the loose photon signature. When using the template in the fit to extract the final results, it is not necessary to separate the photon and jet contributions. Instead, the relative fraction of the two background templates is treated as a nuisance parameter in the fitting procedure, as discussed in Sec. VIII.

The pointing resolution depends on the value of $E_T$ of the photon candidate. Applying the shape of the $T_{E_T^{miss}<20}$ GeV template to describe events in the signal region, defined with $E_T^{miss} > 75$ GeV, therefore implicitly

![FIG. 3 (color online). The $z_{DCA}$ templates from $Z \rightarrow ee$ events, from the TL control sample with $E_T^{miss}$ less than 20 GeV, and for MC simulations of GMSB signals with $\Lambda = 120$ TeV and values for the NLSP lifetime of $\tau = 0.5$ and 30 ns. The data points show the statistical errors, while the shaded bands show the total uncertainties, with statistical and systematic contributions added in quadrature. The first (last) bin includes the contribution from underflows (overflows).]

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relies on the assumption that the $E_T$ distributions for photon candidates are similar in both regions. However, since $E_T^{\text{miss}}$ is essentially a negative vector sum of the $E_T$ values of the energy depositions in the calorimeter, it is expected that there should be a correlation between the value of $E_T^{\text{miss}}$ and the $E_T$ distributions of the physics objects in the event. This correlation is indeed observed in the TL control regions: the samples with higher $E_T^{\text{miss}}$ values have higher average photon $E_T$ values. Increasing the minimum $E_T$ requirement on the photons to 60 GeV in the $E_T^{\text{miss}} < 20$ GeV control sample selects events with kinematic properties that are more similar to those of events in the signal region, and therefore the $E_T > 60$ GeV cut is applied to determine the nominal $T_{E_T^{\text{miss}}<20}$ GeV template shape. Conservative possible systematic variations of this shape are taken to be the template shapes with $E_T$ cuts of 50 and 70 GeV on the photon candidates. The $T_{E_T^{\text{miss}}<20}$ GeV template, along with its statistical and total uncertainties, is shown superimposed on Fig. 3.

The distribution of arrival times of the photon candidates is used in the analysis as a cross-check. Figure 4 shows the timing distribution expected for selected signal events, for $\Lambda = 120$ TeV and for NLSP lifetime values of $\tau = 0.5$ and 30 ns. The expectations for the backgrounds are determined using the same data control samples described above. It is expected that the performance of the calorimeter timing measurement, as determined using the second-layer cell with the maximum deposited energy, should be rather insensitive to the details of the EM shower development. It was verified that the timing distribution of electrons in $Z \rightarrow ee$ events is very similar to that of loose photon candidates in the TL control sample with $E_T^{\text{miss}} < 20$ GeV. Therefore, the timing distribution determined with the larger $Z \rightarrow ee$ sample is characteristic of the timing performance expected for all prompt backgrounds, and is shown superimposed on Fig. 4.

VII. SYSTEMATIC UNCERTAINTIES

When fitting the photon pointing distribution in data to the templates describing the expectations from signal and background, the total number of events is normalized to the 46 events observed in the data in the signal region. In addition, the background templates are determined using data. Thus, the analysis does not rely on predictions of the background normalization or composition, and there are therefore no systematic uncertainties to consider regarding the normalization of the backgrounds. As a result, the various systematic uncertainties relevant for the analysis can be divided into two types, namely, “flat” uncertainties that are not a function of $z_{\text{DCA}}$ but that affect the overall expected signal yield, and “shape” uncertainties related to the shapes of the unit-normalized signal and background pointing templates.

The shape uncertainties, which are correlated across $z_{\text{DCA}}$ bins, are discussed in Sec. VI; their sizes within each bin are depicted in Fig. 3. The control region of TL events with $E_T^{\text{miss}}$ values in the intermediate range from 20–75 GeV is well described by a fit using the $T_{e/\gamma}$ and $T_{E_T^{\text{miss}}<20}$ GeV distributions, providing further validation of the background template shapes and their associated systematic uncertainties.

The various flat systematic uncertainties are summarized in Table II, including the uncertainty on the integrated luminosity of $\pm 1.8\%$ [41]. The uncertainty on the trigger efficiency is $\pm 2.1\%$, which includes a contribution of $\pm 0.5\%$ for the determination of the diphoton trigger efficiency using a bootstrap method [42], and a contribution of

![FIG. 4 (color online). The distribution of photon arrival times ($t_\gamma$) expected for SPS8 GMSB signal models with $\Lambda = 120$ TeV and for NLSP lifetime values of $\tau = 0.5$ and 30 ns. Superimposed is the expectation for prompt backgrounds, as determined using electrons from $Z \rightarrow ee$ events. The uncertainties shown are statistical only.](image)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>$\pm 1.8%$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\pm 2.1%$</td>
</tr>
<tr>
<td>Photon ID and $E_T$ scale/resolution</td>
<td>$\pm 4.4%$</td>
</tr>
<tr>
<td>Photon isolation</td>
<td>$\pm 1.4%$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$: $E_T$ scale/resolution</td>
<td>$\pm (1.1–8.2)%$</td>
</tr>
<tr>
<td>Signal PDF and scale uncertainties</td>
<td>$\pm (4.7–6.4)%$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$\pm (7.2–11.7)%$</td>
</tr>
</tbody>
</table>


±2% taken as a conservative estimate of any possible dependence of the trigger efficiency on $z_{DCA}$ or on the delay of signal photons. Uncertainties on the photon selection, the photon energy scale, and the detailed material composition of the detector, as described in Ref. [22], result in an uncertainty of ±4.4%. The uncertainty due to the photon isolation requirement was estimated by varying the energy leakage and the pileup corrections independently, resulting in an uncertainty of ±1.4%. Systematic uncertainties due to the $E_T^{miss}$ reconstruction, estimated by varying the cluster energies and the $E_T^{miss}$ resolution between the measured performance and MC expectations [39], contribute an uncertainty in the range of ±(1.1–8.2)%, with the higher uncertainty values applicable for lower values of $\Lambda$. As described in Sec. III, variations in the calculated NLO signal cross sections, times the signal acceptance and efficiency, at the level of ±(4.7–6.4)% occur when varying the PDFs and factorization and renormalization scales. Adding these flat systematic uncertainties in quadrature gives a total systematic uncertainty on the signal yield in the range of ±(7.2–11.7)% to which is added a contribution in the range of ±(0.7–5.0)% due to statistical uncertainties in the signal MC predictions.

VIII. RESULTS AND INTERPRETATION

The $z_{DCA}$ distribution for the 46 loose photons of the events in the signal region with $E_T^{miss} > 75$ GeV is shown in Fig. 5. As expected for SM backgrounds, the distribution is rather narrow, and there is no obvious sign of a significant excess in the tails that would be expected for GMSB signal photons originating in the decays of long-lived neutralinos. There are three events with $|z_{DCA}| > 200$ mm including one with a value of $z_{DCA} = 752$ mm. Some additional information about these three events is summarized in Table III.

The timing distribution for the 46 events in the signal region with $E_T^{miss} > 75$ GeV is shown in Fig. 6. The timing distribution is rather narrow, in agreement with the background-only expectation that is shown superimposed on Fig. 6, and there is no significant excess in the positive tail that would be expected for GMSB signal photons. The photon with the largest time value has $t = 1.2$ ns, and is

<table>
<thead>
<tr>
<th>Run number</th>
<th>Event number</th>
<th>$E_T^{miss}$ (GeV)</th>
<th>$E_T$ (GeV)</th>
<th>$z_{DCA}$ (mm)</th>
<th>$t_x$ (ps)</th>
<th>$E_T$ (GeV)</th>
<th>$z_{DCA}$ (mm)</th>
<th>$t_x$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>186721</td>
<td>30399675</td>
<td>77.1</td>
<td>75.9</td>
<td>−274</td>
<td>360</td>
<td>72.0</td>
<td>22</td>
<td>580</td>
</tr>
<tr>
<td>187552</td>
<td>14929851</td>
<td>77.3</td>
<td>59.4</td>
<td>−262</td>
<td>1200</td>
<td>87.2</td>
<td>−120</td>
<td>240</td>
</tr>
<tr>
<td>191920</td>
<td>14157929</td>
<td>77.9</td>
<td>56.6</td>
<td>752</td>
<td>2</td>
<td>54.2</td>
<td>5</td>
<td>−200</td>
</tr>
</tbody>
</table>
measured using a calorimeter cell that was read out with medium gain. This photon corresponds to one of the three events with $|z_{DCA}| > 200$ mm that are described in Table III, but not to the most extreme pointing outlier. For the other two events in Table III, the timing is consistent with the hypothesis that the photon candidate is in time.

To determine the final results, the pointing distribution shown in Fig. 5 is fitted using the pointing templates described previously. The binning shown in Fig. 5 is used in the fit. The background contribution is modeled in the fit as a weighted sum of the $T_{e/\gamma}$ and $T_{E_\gamma^{miss}<20 \text{ GeV}}$ templates. Background-only fits are performed to determine the compatibility of the observed pointing distribution with the background-only hypothesis. Signal-plus-background fits are performed to determine, via profile likelihood fits, the 95% C.L. limit on the signal strength, $\mu$, defined as the number of fitted signal events divided by the SPS8 expectation for the signal yield. In both cases, the overall normalization is constrained to the 46 events observed in the signal region in data, and the relative weighting of the two background templates is treated as a nuisance parameter in the fit.

Table IV shows the number of observed events in the various bins of $z_{DCA}$ shown in Fig. 5, except that the number of $z_{DCA}$ bins is reduced for display purposes by a factor of 2 by taking the absolute value of $z_{DCA}$. Included in Table IV are the results from the background-only and signal-plus-background fit, for the case of $\Lambda = 120$ TeV and $\tau = 6$ ns. Comparing the first two rows of Table IV shows that there is fair agreement between the observed data and the results of the background-only fit, though there is some excess seen in the data for larger $|z_{DCA}|$ values. The $p_0$ value for the background-only hypothesis is $\approx 0.060$, indicating that the slight excess has a significance equivalent to $\approx 1.5\sigma$. The excess is dominated by the outlier photon with $z_{DCA} = 752$ mm; removing this event from the distribution and performing a new fit, one obtains a $p_0$ value of $\approx 0.30$, indicating in this case a much better agreement with the background-only model.

The last three rows of Table IV show the results of the signal-plus-background fit for the case of $\Lambda = 120$ TeV and $\tau = 6$ ns, including the total number of fitted events in each $|z_{DCA}|$ bin, as well as the separate contributions from signal and from background. For this case, the signal-plus-background fit returns a central value for the signal strength of $\mu = 0.20 \pm 0.19$, and the fitted value of the nuisance parameter specifying the fraction of the background that is attributed to the $T_{E_\gamma^{miss}<20 \text{ GeV}}$ template is $0.32 \pm 0.38$. The fit results are used to determine, via the CLs method [43], 95% C.L. limits on the number of signal events. The results, derived within the RooStats framework [44], are determined for both the observed limit, where the fit is performed to the pointing distribution of the 46 observed events in the signal region, and for the expected limit, where the fit is performed to ensembles of pseudoexperiments generated according to the background-only hypothesis.

### Table IV

| $|z_{DCA}|$ range [mm] | Data | Bkg only | Signal | Plus | Bkg |
|-----------------------|------|----------|--------|------|-----|
| 0–20                  | 27   | 25.0 ± 2.2 | 25.1 ± 4.2 | 24.4 ± 4.2 |
| 20–40                 | 7    | 9.1 ± 0.8  | 9.3 ± 1.5  | 8.8 ± 1.5  |
| 40–60                 | 4    | 3.8 ± 0.3  | 3.3 ± 0.7  | 2.9 ± 0.8  |
| 60–80                 | 1    | 2.1 ± 0.5  | 1.6 ± 0.6  | 1.3 ± 0.7  |
| 80–100                | 1    | 1.4 ± 0.4  | 1.1 ± 0.4  | 0.8 ± 0.6  |
| 100–200               | 1    | 3.0 ± 1.1  | 2.6 ± 1.0  | 1.4 ± 1.5  |
| 200–400               | 2    | 1.3 ± 0.5  | 1.8 ± 0.8  | 0.5 ± 0.7  |
| 400–600               | 0    | 0.2 ± 0.1  | 0.7 ± 0.5  | 0.1 ± 0.1  |
| >600                  | 1    | 0.08 ± 0.03 | 0.5 ± 0.4  | 0.03 ± 0.04 |

The numbers of signal and background events from the signal-plus-background fit are negatively correlated.
The slight excess for larger $|z_{\text{DCA}}|$ values leads to a result where the observed limit on the number of signal events is somewhat less restrictive than the expected limit. For the example of $\Lambda = 120$ TeV and $\tau = 6$ ns, the observed (expected) 95% C.L. limit is 18.3 (9.8) signal events.

By repeating the statistical procedure for various $\Lambda$ and $\tau$ values, the limits are determined as a function of these SPS8 model parameters. The left plot of Fig. 7 shows the 95% C.L. limits on the number of signal events versus $\tau$, for the case with $\Lambda = 120$ TeV. The right plot of Fig. 7 shows the 95% C.L. limits on the allowed cross section versus $\tau$, also for the case with $\Lambda = 120$ TeV. Each plot includes a curve indicating the SPS8 theory prediction for $\Lambda = 120$ TeV. The intersections where the limits cross the theory prediction show that, for $\Lambda = 120$ TeV, values of $\tau$ below 8.7 ns are excluded at 95% C.L., whereas the expected limit would exclude values of $\tau$ below 14.6 ns.

Comparing with the theoretical cross section of the SPS8 GMSB model, the results are converted into an exclusion region in the two-dimensional plane of $\Lambda$ versus $\tau$.
SEARCH FOR NONPOINTING PHOTONS IN THE 

\( \Lambda \), as shown in Fig. 8. Also shown in the figure are corresponding limits on the lifetime versus the masses of the lightest neutralino and lightest charginos, where the relation between \( \Lambda \) and sparticle masses is taken from the theory.

IX. CONCLUSIONS

A search has been performed for nonpointing photons in the diphoton plus \( E_T^{\text{miss}} \) final state, using the full data sample of 7 TeV pp collisions recorded in 2011 with the ATLAS detector at the LHC. The analysis uses the capability of the ATLAS LAr calorimeter to measure the flight direction of photons to perform the search, with the precision measurement of the arrival time of photons used as a cross-check of the results.

No significant evidence for nonpointing photons is observed. Interpreted in the context of the GMSB SPS8 benchmark model, the results provide 95% C.L. exclusion limits in the plane of \( \tau \) (the lifetime of the lightest neutralino) versus \( \Lambda \) (the effective scale of SUSY breaking) or, alternatively, versus the mass of the lightest neutralino. For example, for \( \Lambda = 70 \text{ TeV} \) (160 TeV), NLSP lifetimes between 0.25 and 50.7 ns (2.7 ns) are excluded at 95% C.L.

ACKNOWLEDGMENTS

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; STSC, 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; DNR, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSR and NSRF, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, 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, United Kingdom; DOE and NSF, United States of America. 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-T2 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA) and in the Tier-2 facilities worldwide.

SEARCH FOR NONPOINTING PHOTONS IN THE...

(ATLAS Collaboration)

1School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4Department of Physics, Ankara University, Ankara, Turkey
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bDepartment of Physics, Gazi University, Ankara, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4dTurkish Atomic Energy Authority, Ankara, Turkey
5LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, Arizona State University, Tucson, Arizona, USA
8Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
13aInstitute of Physics, University of Belgrade, Belgrade, Serbia
13bVinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19aDepartment of Physics, Bogazici University, Istanbul, Turkey
19bDepartment of Physics, Bogazici University, Istanbul, Turkey
19cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
19dINFN Sezione di Bologna, Italy
20aDipartimento di Fisica, Università di Bologna, Bologna, Italy
21Physikalisches Institut, University of Bonn, Bonn, Germany
22Department of Physics, Boston University, Boston, Massachusetts, USA
23Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24aFederal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
24bFederal University of Sao Joao del Rei (UFSG), Sao Joao del Rei, Brazil
24cInstituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26National Institute of Physics and Nuclear Engineering, Bucharest, Romania
012001-20
SEARCH FOR NONPOINTING PHOTONS IN THE ...

PHYSICAL REVIEW D 88, 012001 (2013)
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston, Louisiana, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal, Quebec City, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
Group of Particle Physics, University of Montreal, Montreal, Quebec City, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D. V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal
Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Laboratorio de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal.
Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Department of Physics, California State University, Fresno, CA, USA.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Louisiana Tech University, Ruston, LA, USA.
Also at Dep Fisica and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at DESY, Hamburg and Zeuthen, Germany.
Also at Faculty of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia.
Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.
Also at Physics Department, Brookhaven National Laboratory, Upton, NY, USA.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.