Search for displaced muonic lepton jets from light Higgs boson decay in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


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Search for displaced muonic lepton jets from light Higgs boson decay in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

A search is performed for collimated muon pairs displaced from the primary vertex produced in the decay of long-lived neutral particles in proton–proton collisions at $\sqrt{s} = 7$ TeV centre-of-mass energy, with the ATLAS detector at the LHC. In a 1.9 fb$^{-1}$ event sample collected during 2011, the observed data are consistent with the Standard Model background expectations. Limits on the product of the production cross section and the branching ratio of a Higgs boson decaying to hidden-sector neutral long-lived particles are derived as a function of the particles’ mean lifetime.

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The search presented in this Letter focuses on neutral particles decaying to the simplest type of muon jets (MJ’s), containing only two muons; prompt MJ searches have been performed both at the Tevatron [17,18] and at the LHC [19]. Other searches for displaced decays of a light Higgs boson to heavy fermion pairs have also been performed at the LHC [20].

The benchmark model used for this analysis is a simplified scenario where the Higgs boson decays to a pair of neutral hidden fermions ($f_{a2} \rightarrow f_{a1} \gamma d$) of each, which decays to one long-lived $\gamma d$ and one stable neutral hidden fermion ($f_{a1}$) that escapes the detector unnoticed, resulting in two lepton jets from the $\gamma d$ decays in the final state (see Fig. 1). The mass of the $\gamma d$ (0.4 GeV) is chosen to provide a sizeable branching ratio to muons [14].

3. Signal and background simulation

The set of parameters used to generate the signal Monte Carlo samples is listed in Table 1. The Higgs boson is generated through the gluon–gluon fusion production mechanism which is the dominant process for a low mass Higgs boson. The gluon–gluon fusion Higgs boson production cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV, estimated at the next-to-next-to-leading order (NNLO) [22], is $σ_{SM} = 24.0$ pb for $m_H = 100$ GeV and $σ_{SM} = 12.1$ pb for $m_H = 140$ GeV. The PYTHIA generator [23] is used, linked together with MadGraph4.4.2 [24] and BRIDGE [25], for gluon–gluon fusion production of the Higgs boson and the subsequent decay to hidden-sector particles.

As discussed in the introduction, the signal is chosen to enable a study of rare, non-SM, Higgs boson decays in the (possibly extended) Higgs sector. To do so we choose two points which envelope a mass range covering the 126 GeV resonance. The lower mass point, $m_H = 100$ GeV, is chosen to be compatible with the decay-mode-independent search by OPAL at LEP [26]. The higher mass point, $m_H = 140$ GeV, is chosen well below the WW threshold, where a sizeable branching ratio into a hidden sector may be naturally achieved. The masses of $f_{a2}$ and $f_{a1}$ are chosen so that a large fraction of the Higgs boson mass is unobservable. The masses of $f_{a2}$ and $f_{a1}$ are expected to be $140$ GeV, $m_{\gamma d}$, and $m_{\gamma d}$ [mm] (expressed throughout this Letter $m_H$ and $m_{\gamma d}$ decays are expected to have the required four-muon final state. The mean lifetime $\tau$ of the $\gamma d$ (expressed throughout this Letter $m_H$) is a free parameter of the model. In the generated samples $\tau$ is chosen so that a large fraction of the decays occur inside the sensitive ATLAS detector volume, i.e., up to 7 m in radius and 13 m along the z-axis, where the trigger chambers of the middle stations are located. The detection efficiency can then be estimated for a range of $\gamma d$ mean lifetimes through re-weighting of the generated samples.

Potential backgrounds include all the processes which lead to real prompt muons in the final state such as the SM processes $W +$ jets, $Z +$ jets, $t\bar{t}$, WW, ZZ, and $WW$. However, the main contribution to the background is expected from processes giving a high production rate of secondary muons which do not point to the primary vertex, such as decays in flight of $K/\pi$ and heavy flavour decays in multi-jet processes, or muons due to cosmic rays. The prompt lepton background samples are generated using PYTHIA ($W +$ jets, and $Z +$ jets) and MC@NLO [27] ($t\bar{t}$, WW, ZZ, and ZZ).
The generated Monte Carlo events are processed through the full ATLAS simulation chain based on GEANT4 [28,29]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. All Monte Carlo samples are reweighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data. For the multi-jet background evaluation a data-driven method is used. The cosmic-ray background is also evaluated from data.

4. The kinematics of the signal

The main kinematic characteristics of the signal sample are:

• The $\gamma d$ pair are emitted approximately back-to-back in $\phi$, with an angular spread of the distribution due to the emission of the $f_{d1}$.

• The average $p_T$ of the $\gamma d$ in the laboratory frame is about 20 GeV for $m_H = 100$ GeV and 30 GeV for $m_H = 140$ GeV; due to the small mass of the $\gamma d$, large boost factors in the decay length should be expected.

• Fig. 2 shows the distribution of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between the two muons from the $\gamma d$ decay. The $\Delta R$ is computed at the decay vertex of the $\gamma d$ from the vector momenta of the two muons. Due to the small mass of the $\gamma d$ the $\Delta R$ is almost always below 0.1.

Since the two $f_{d1}$ are, like the two $\gamma d$, emitted back-to-back in $\phi$, the observed missing transverse momentum $E_T^{miss}$, computed at the event-generator level, is small and cannot be used as a discriminating variable against the background.

5. Data samples and trigger selection

The dataset used for this analysis was collected at a centre-of-mass energy of 7 TeV during the first part of 2011, where a low level of pile-up events in the same bunch-crossing was present (an average of $\approx 6$ interactions per crossing). Only periods in which all ATLAS subdetectors were operational are used. The total integrated luminosity used is 1.94 ± 0.07 fb$^{-1}$ [30,31]. All events are required to have at least one reconstructed vertex along the beam line with at least three associated tracks, each with $p_T \geq 0.4$ GeV. The primary interaction vertex is defined to be the vertex whose constituent tracks have the largest $\sum p_T^2$. This analysis deals with displaced $\gamma d$ decays with final states containing only muons. Signal events are therefore characterized by a four-muon final state with the four muons coming from two displaced decay vertices. Due to the relatively low $p_T$ of the muons and due to the displaced decay vertex, a low-$p_T$ multi-muon trigger with muons reconstructed only in the MS is needed. In order to have an acceptably low trigger rate at a low $p_T$ threshold, a multiplicity of at least three muons is required. Candidate events are collected using an unprescaled HLT trigger with three reconstructed muons of $p_T \geq 6$ GeV, seeded by a L1-accept with three different muon ROIs. These muons are reconstructed only in the MS, since muons originating from a neutral particle decaying outside the pixel detector will not have a matching track in the ID tracking system. The trigger efficiency for the Monte Carlo signal samples, defined as the fraction of events passing the trigger requirement with respect to the events satisfying the analysis selection criteria (described in Section 6) is 0.32 ± 0.01 stat for $m_H = 100$ GeV and 0.31 ± 0.01 stat for $m_H = 140$ GeV.

The main reason for the relatively low trigger efficiency is the small opening $\Delta R$ between the two muons of the $\gamma d$ decay ($\Delta R < 0.1$) shown in Fig. 2. These values of $\Delta R$ are often smaller than the L1 trigger granularity; in this case the L1 produces only one ROI. The trigger only fires if at least one of the $\gamma d$ produces two distinct L1 ROIs. The single $\gamma d$ ROI efficiency, $\varepsilon_{2ROI} (\varepsilon_{1ROI})$, defined as the fraction of $\gamma d$ passing the offline selection that give two (one) trigger ROIs is 0.296 ± 0.004 stat (0.626 ± 0.004 stat) for $m_H = 100$ GeV and 0.269 ± 0.003 stat (0.653 ± 0.003 stat) for $m_H = 140$ GeV. Fig. 3 shows the $\varepsilon_{2ROI}$ as a function of the dark photon $\eta$ and of the $\Delta R$ of the two muons from the $\gamma d$ decay. The increased trigger granularity in the endcap and the efficiency decrease at small values of $\Delta R$ are clearly visible.

The systematic uncertainty on the trigger efficiency is estimated with a sample of $J/\psi \rightarrow \mu^+ \mu^-$ from collision data and a corresponding sample of Monte Carlo events, using the tag-and-probe (TP) method. A cut on $\Delta R < 0.1$ between the two muons is used to reproduce the small track-to-track spatial separation in the MS of the signal. The tag is a (MS + ID) combined muon, defined as a MS-reconstructed muon that is associated with a trigger object and combined with a matching "good ID track". Good ID tracks must have at least one hit in the pixel detector, at least six hits in the silicon micro-strip detectors and at least six hits in the straw-tube tracker. The probe is a good ID track which, when combined with the tag track, gives an invariant mass inside a 100 MeV window around the $J/\psi$ mass. A muon ROI that matches the probe in $\eta$ and $\phi$, and is different from the ROI associated with the tag, is searched for. The number of probes with a matched ROI divided by the number of probes without a matched ROI gives the $\varepsilon_{2ROI}/\varepsilon_{1ROI}$ ratio. Values of $\varepsilon_{2ROI}/\varepsilon_{1ROI} = 0.42 \pm 0.05$ stat for the $J/\psi \rightarrow \mu^+ \mu^-$ data and $\varepsilon_{2ROI}/\varepsilon_{1ROI} = 0.39 \pm 0.05$ stat for the corresponding Monte Carlo sample are obtained. The relative statistical uncertainty on the difference between these two estimates is 17% and this is taken conservatively to be the systematic uncertainty on the trigger efficiency.

6. Muon Jet reconstruction and event selection

MJs from displaced $\gamma d$ decays are characterized by a pair of muons in a narrow cone, produced away from the primary vertex of the event. Consequently tracks reconstructed in the MS with a good quality track fit [32] are used. MJs are identified using a simple clustering algorithm that associates all the muons in cones of $\Delta R = 0.2$, starting with the muon with highest $p_T$. The size of the cone takes into account the multiple scattering of the muons in the calorimeters. All the muons found in the cone are associated with a MJ. After this procedure, if any muons are unassociated with a MJ the search is repeated for this remainder, starting again with the highest $p_T$ muon. This continues until all possible MJs

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2 High pile-up levels will introduce a pile-up dependence for the isolation variables used in the analysis and needs to be further investigated.
For the background coming from cosmic-ray muons (mainly pairs of almost parallel cosmic-ray muons crossing the detector) a cut on the impact parameters of the muon tracks with respect to the primary interaction vertex is used.

The final set of selection criteria used is the following:

- Topology cut: events are required to have exactly two MJs, \(N_MJ = 2\).
- MJ isolation: require MJ isolation with \(E_T^{\text{isol}} \leq 5\) GeV for both MJs in the event.
- Require \(|\Delta \phi| \geq 2\) between the two MJs.
- Require opposite charges for the two muons in a MJ (\(Q_{MJ} = 0\)).
- Require a cut on the transverse and longitudinal impact parameters of the muons with respect to the primary vertex: \(|d_0| < 200\) mm and \(|z_0| < 270\) mm.
- Require \(\sum p_T^{\text{ID}} < 3\) GeV for both MJs.

The distributions of the relevant variables used in the selection before each step of the cut flow are shown in Fig. 4. The results are summarized in Table 2. No events survive the selection in the data sample whereas the expected signals from Monte Carlo simulation, assuming the Higgs boson SM production cross section, 100% branching ratio for \(H \rightarrow \gamma \gamma\), and the parameters given in Table 1, are 75 or 48 events for Higgs boson masses of 100 GeV and 140 GeV respectively. The method used to estimate the cosmic-ray and multi-jet background yields, quoted in Table 2, is discussed in Section 7.

The resulting single \(\gamma \gamma\) reconstruction efficiency for the mean lifetimes given in Table 1 is shown in Fig. 5 as a function of \(\eta\), the \(\Delta R\) separation of the two muons from the \(\gamma \gamma\) decay and the decay length in the transverse plane, \(L_{xy}\), of the \(\gamma \gamma\). The efficiency is defined as the number of \(\gamma \gamma\) passing the offline selection divided by the number of \(\gamma \gamma\) in the spectrometer acceptance \(|\eta| \leq 2.4\) with both muons having \(p_T \geq 6\) GeV. The low reconstruction efficiency at very short \(L_{xy}\) is a consequence of the \(\sum p_T^{\text{ID}}\) cut.

The systematic uncertainty on the reconstruction efficiency is evaluated using a tag-and-probe method by comparing the reconstruction efficiency \(E_{TP}^{\text{MC}}\) for \(J/\psi \rightarrow \mu^+ \mu^-\) samples from collision data and \(J/\psi \rightarrow \mu^+ \mu^-\) Monte Carlo simulation. The tag-and-probe definitions and the cut on \(\Delta R \leq 0.1\) between the two muons are the same as in Section 5. To measure the reconstruction efficiency the ID probe track is associated with a MS-only muon track, different from the one associated with the tag. The result is shown in Fig. 6.

The relative difference between the result obtained from the \(J/\psi \rightarrow \mu^+ \mu^-\) data and the \(J/\psi \rightarrow \mu^+ \mu^-\) Monte Carlo sample in the same range of \(\Delta R \leq 0.1\), as for the signal, is taken as the systematic uncertainty on the reconstruction efficiency and amounts to 13%.

7. Multi-jet and cosmic-ray background evaluation

To estimate the multi-jet background contamination in the signal region we use a data-driven ABCD method slightly modified to cope with the problem of the very low number of events in the control regions. The ABCD method assumes that two variables can be identified, which are relatively uncorrelated, and which can each be used to separate signal and background. It is assumed that the multi-jet background distribution can be factorized in the MJ \(E_T^{\text{isol}} - |\Delta \phi|\) plane. The region A is defined by \(E_T^{\text{isol}} \leq 5\) GeV and \(|\Delta \phi| < 2\); the region B, defined by \(E_T^{\text{isol}} \leq 5\) GeV and \(|\Delta \phi| > 2\), is the signal region. The regions C and D are the anti-isolated regions \((E_T^{\text{isol}} > 5\) GeV\) and they are defined by \(|\Delta \phi| < 2\) and \(|\Delta \phi| > 2\), respectively. Neglecting the signal contamination in regions A, C and
as the systematic uncertainty, that amounts to the requirements on the impact parameters with respect to the bunch crossing was not active in all the runs). No events survived the ratio and for the active time (since the trigger in the empty bunch crossings). The number of events collected by the trigger being active when there are no collisions (empty bunch crossings). The number of triggered events is rescaled by the collision to empty bunch crossing ratio and for the active time (since the trigger in the empty bunch crossing was not active in all the runs). No events survived the requirements on the impact parameters with respect to the primary vertex (|d₀| < 200 mm and |z₀| < 270 mm), resulting in a cosmic-ray contamination estimate of \( \frac{1}{3} \). The final yields for the different background sources are summarized in Table 2.

### 8. Systematic uncertainties

The following effects are considered as possible sources of systematic uncertainty:

- **Luminosity**
  
  The overall normalization uncertainty of the integrated luminosity is 3.7% [30,31].

- **Muon momentum resolution**
  
  The systematic uncertainty on the muon momentum resolution for MS-only muons has been evaluated by smearing and shifting the momenta of the muons by scale factors derived from \( Z \rightarrow \mu\mu \) data-Monte Carlo comparison, and by observing the effect of this shift on the signal efficiency. The overall effect of the muon momentum resolution uncertainty is negligible.

- **Trigger**
  
  The systematic uncertainty on the single \( \gamma \mu \) trigger efficiency, evaluated using a tag-and-probe method is 17% (see Section 5).

- **Reconstruction efficiency**
  
  The systematic uncertainty on the reconstruction efficiency, evaluated using a tag-and-probe method for the single \( \gamma \mu \) reconstruction efficiency, is 13% (see Section 6).

- **Effect of pile-up**
  
  The systematic uncertainty on the signal efficiency related to the effect of pile-up is evaluated by comparing the number of signal events after imposing all the selection criteria on the signal Monte Carlo sample increasing the average number of interactions per crossing from \( \approx 6 \) to \( \approx 16 \). This systematic uncertainty is negligible.
The ATLAS detector at the LHC was used to search for a light Higgs boson decaying into a pair of hidden fermions ($f_{d1}$), each of which decays to a stable hidden fermion ($f_d$), resulting in two muon jets from the $f_d$ decay in the final state. In a 1.9 fb$^{-1}$ sample of $\sqrt{s} = 7$ TeV proton-proton collisions no events consistent with this Higgs boson decay mode are observed. The observed data are consistent with the Standard Model background expectations.

Limits are set on the $\sigma \times BR$ to $H \rightarrow f_d f_d + X$, according to the model of Fig. 1, as a function of the long-lived particle mean lifetime for $m_H = 100$ GeV and $m_H = 140$ GeV with the chosen $f_d$ mass that gives a decay branching ratio of 45% for $f_d \rightarrow \mu \mu$. Assuming the SM production rate for a 140 GeV Higgs boson, its branching ratio to two hidden-sector photons is found to be below 10%, at 95% CL for hidden photon $\gamma$ in the range 7 mm $\leqslant$ $\tau_f$ $\leqslant$ 82 mm. Bounds

### 9. Results and interpretation

The efficiency of the selection criteria described above is evaluated for the simulated signal samples (see Table 1) as a function of the mean lifetime of the $\gamma_d$. The signal Monte Carlo events are weighted by the detection probability of the two $\gamma_d$ in the various parts of the detector, generating their decay points according to a chosen value of the $\gamma_d$ lifetime, with $\tau_f$ ranging from 0 to 700 mm. In this way the number of expected signal events is predicted as function of the $\gamma_d$ mean lifetime. These numbers, together with the expected number of background events (multi-jet and cosmic rays) and taking into account the zero data events surviving the selection criteria in 1.9 fb$^{-1}$, are used as input to obtain limits at the 95% confidence level (CL). The CLs method [33] is used to set 95% CL upper limits on the cross section times branching ratio ($\sigma \times BR$) for the process $H \rightarrow \gamma_d \gamma_d + X$, according to the model of Fig. 1. Here the branching ratio of $\gamma_d \rightarrow \mu \mu$ is set to 45% with the $\gamma_d$ mass set to 0.4 GeV, as previously discussed. The $\sigma \times BR$ is given as a function of the $\gamma_d$ mean lifetime, expressed as $ct$ for $m_H = 100$ GeV and $m_H = 140$ GeV. These limits are shown on Fig. 7. Table 3 shows the ranges in which the $\gamma_d$ cut is excluded at the 95% CL for $H \rightarrow \gamma_d \gamma_d + X$ branching ratios of 100% and 10%.

### 10. Conclusions

The ATLAS detector at the LHC was used to search for a light Higgs boson decaying into a pair of hidden fermions ($f_{d1}$), each of which decays to a $\gamma_d$ and to a stable hidden fermion ($f_d$), resulting in two muon jets from the $f_d$ decay in the final state. In a 1.9 fb$^{-1}$ sample of $\sqrt{s} = 7$ TeV proton-proton collisions no events consistent with this Higgs boson decay mode are observed. The observed data are consistent with the Standard Model background expectations.

### Table 3

<table>
<thead>
<tr>
<th>Higgs boson mass [GeV]</th>
<th>Excluded $ct$ [mm] (BR(100%))</th>
<th>Excluded $ct$ [mm] (BR(10%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$1 \leqslant ct \leqslant 670$</td>
<td>$5 \leqslant ct \leqslant 159$</td>
</tr>
<tr>
<td>140</td>
<td>$1 \leqslant ct \leqslant 430$</td>
<td>$7 \leqslant ct \leqslant 82$</td>
</tr>
</tbody>
</table>

### Effect of $\sum p_T^{\text{ID}}$ cut

Since the $\sum p_T^{\text{ID}}$ cut could affect the minimum $ct$ value that can be excluded, the effect of this cut on the signal Monte Carlo has been studied. A variation of 10% on the $\sum p_T^{\text{ID}}$ cut results in a relative variation of $\leqslant 1\%$ on the signal, which can therefore be neglected.

### Background evaluation

The systematic uncertainties that can affect the background estimation are related to the data-driven method used. The functional model used to fit the $\sum p_T^{\text{ID}}$ distribution is varied to evaluate the systematic uncertainty in the modelling of its shape, which also includes the effect of the $\sum p_T^{\text{ID}}$ cut on the background estimation. This systematic uncertainty amounts to $\pm 0.06$ events. The effect of signal leakage is also negligible.
Fig. 7. The 95% upper limits on the $\sigma \times BR$ for the process $H \to \gamma \gamma + X$ as a function of the dark photon $c$ for the benchmark sample with (a) $m_H = 100$ GeV and with (b) $m_H = 140$ GeV, assuming the Higgs boson SM production cross section. The expected limit is shown as the dashed curve and the solid curve shows the observed limit. The horizontal lines correspond to the Higgs boson SM production cross sections at the two mass values.

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References

Department of Physics, University of British Columbia, Vancouver, BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, WI, United States
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, CT, United States
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
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, United States.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at Fermilab, Batavia, IL, United States.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
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, United States.
Also at Departamento de Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Manhattan College, New York, NY, United States.
Also at School of Physics, Shandong University, Shandong, China.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
Also at DSM/IPHT, Institut de Recherches sur les Lois Fondamentales de l’Univers, CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at California Institute of Technology, Pasadena, CA, United States.
Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Department of Physics, University of California, Berkeley, CA, United States, and Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA, United States.
Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Deceased.