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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

The ATLAS Collaboration

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1. Introduction

A search is presented for long-lived neutral particles decaying to final states containing collimated muon pairs in proton-proton collisions at $\sqrt{s} = 7$ TeV centre-of-mass energy. The event sample, collected during 2011 at the LHC with the ATLAS detector, corresponds to an integrated luminosity of 1.9 fb^{-1}. The model considered in this analysis consists of a Higgs boson decaying to a new hidden sector of particles which finally produce two sets of collimated muon pairs, but the search described is equally valid for other, distinct models such as heavier Higgs boson doublets, singlet scalars or a Z' that decay to a hidden sector and eventually produce collimated muon pairs.

Recently, evidence for the production of a boson with a mass of about 126 GeV has been published by ATLAS [1] and CMS [2]. The observation is compatible with the expected production and decay of the Standard Model (SM) Higgs boson [3–5] at this mass. Testing the SM Higgs hypothesis is currently of utmost importance. To this end two effects may be considered: (i) additional resonances which arise in an extended Higgs sector found in many extensions of the SM, or (ii) rare Higgs boson decays which may deviate from those predicted by the SM. In this Letter we search for a scalar that decays to a light hidden sector, focusing on the 100 GeV to 140 GeV mass range. In doing so, we cover both of the above aspects, deriving constraints on additional Higgs-like bosons, as well as placing bounds on the branching ratio of the discovered 126 GeV resonance into a hidden sector of the kind described below.

The phenomenology of light hidden sectors has been studied extensively over the past few years [6–10]. Possible characteristic topological signatures of such extensions of the SM are "lepton jets". A lepton jet is a cluster of highly collimated particles: electrons, muons and possibly pions [7, 11–13]. These arise if light unstable particles with masses in the MeV to GeV range (for example dark photons, γ_d) reside in the hidden sector and decay predominantly to SM particles. At the LHC, hidden-sector particles may be produced with large boosts, causing the visible decay products to form jet-like structures. Hidden-sector particles such as γ_d may be long-lived, resulting in decay lengths comparable to, or larger than, the detector dimensions. The production of lepton jets can occur through various channels. For instance, in supersymmetric models, the lightest visible superpartner may decay into the hidden sector. Alternatively, a scalar particle that couples to the visible sector may also couple to the hidden sector through Yukawa couplings or the scalar potential. This analysis is focused on the case where the Higgs boson decays to the hidden sector [14, 15]. The SM Higgs boson has a narrow width into SM final states if $m_H < 2m_W$. Consequently, any new (non-SM) coupling to additional states, which reside in a hidden sector, may contribute significantly to the Higgs boson decay branching ratios. Even with new couplings, the total Higgs boson width is typically small, well below the order of one GeV. If a SM-like Higgs boson is confirmed, it will remain important to constrain possible rare decays, e.g. into lepton jets.

Neutral particles with large decay lengths and collimated final states represent, from an experimental point of view, a challenge both for the trigger and for the reconstruction capabilities of the detector. Collimated particles in the final state can be hard to disentangle due to the finite granularity of the detectors; moreover, in the absence of inner tracking detector information and a primary vertex constraint, it is difficult to reconstruct charged-particle tracks from decay vertices far from the interaction point (IP). The ATLAS detector [16] is equipped with a muon spectrometer (MS) with high-granularity tracking detectors that allow charged-particle tracks to be reconstructed in a standalone configuration using only the muon detector information (MS-only). This is a crucial feature for detecting muons not originating from the primary interaction vertex.

The search presented in this Letter focuses on neutral particles decaying to the simplest type of muon jets (MJs), 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_{d2}) each of which decays to one long-lived γ_d and one stable neutral hidden fermion (f_{d1}) that escapes the detector unnoticed, resulting in two lepton jets from the γ_d decays in the final state (see Fig. 1). The mass of the γ_d (0.4 GeV) is chosen to provide a sizeable branching ratio to muons [14].

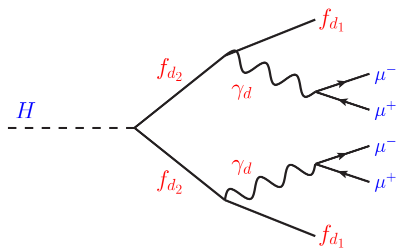

Figure 1: Schematic picture of the Higgs boson decay chain, H→2(f_{d2} → $f_{d1}\gamma_d$). The Higgs boson decays to two hidden fermions (f_{d2}). Each hidden fermion decays to a γ_d and to a stable hidden fermion (f_{d1}), resulting in two muon jets from the γ_d decays in the final state.

2. The ATLAS Detector

ATLAS is a multi-purpose detector [16] at the LHC, consisting of an inner tracking system (ID) embedded in a superconducting solenoid, which provides a 2 T magnetic field parallel to the beam direction, electromagnetic and hadronic calorimeters and a muon spectrometer using three air-core toroidal magnet systems[1]. The trigger system has three levels [21] called Level-1 (L1), Level-2 (L2) and Event Filter (EF). L1 is a hardware-based system using information from the calorimeter and muon spectrometer, and defines one or more Regions of Interest (ROIs), geometrical regions of the detector, identified by (η, ϕ) coordinates, containing interesting physics objects. L2 and the EF (globally called the High Level Trigger, HLT) are software-based systems and can access information from all sub-detectors. The ID, consisting of silicon pixel and micro-strip detectors and a straw-tube tracker, provides precision tracking of charged particles for $|\eta| \leq 2.5$. The electromagnetic and hadronic calorimeter system covers $|\eta| \leq 4.9$ and, at $\eta = 0$, has a total depth of 9.7 interaction lengths (22 radiation lengths in the electromagnetic part). The MS provides trigger information ($|\eta| \leq 2.4$) and momentum measurements ($|\eta| \leq 2.7$) for charged particles entering the spectrometer. It consists of one barrel and two endcap parts, each with 16 sectors in ϕ, equipped with precision tracking chambers and fast detectors for triggering. Monitored drift tubes are used for precision tracking in the region $|\eta| \leq 2.0$ and cathode strip chambers are used for $2.0 \leq |\eta| \leq 2.7$. The MS detectors are arranged in three stations of increasing distance from the IP: inner, middle and outer. The air core toroidal magnetic field allows an accurate charged particle reconstruction independent of the ID information. The three planes of trigger chambers (resistive plate chambers in the barrel and the thin gap chambers in the endcaps) are located in middle and outer (only in the barrel) stations. The L1 muon trigger requires hits in the middle stations to create a low tranverse momentum ($p_{\rm T}$) muon ROI or hits in both the middle and outer stations for a high $p_{\rm T}$ ROI. The muon ROIs have a spatial extent of 0.2×0.2 ($\Delta\eta \times \Delta\phi$) in the barrel and of 0.1×0.1 in the endcap. L1 ROI information seeds, at HLT level, the reconstruction of muon momenta using the precision chamber information. In this way sharp trigger thresholds up to 40 GeV can be obtained.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the beam pipe axis. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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 $\sigma_{\rm SM}$ = 24.0 pb for m_H = 100 GeV and $\sigma_{\rm SM}$ = 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_{d2} and f_{d1} are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at $m_{f_{d1}} + m_{\gamma_d} = m_{f_{d2}}$. For the chosen dark photon mass (0.4 GeV), the γ_d decay branching ratios are expected to be [14]: 45% e^+e^-, 45% $\mu^+\mu^-$, 10% $\pi^+\pi^-$. Thus 20% of the Higgs $H\rightarrow \gamma_d\ \gamma_d + X$ decays are expected to have the required four-muon final state.

The mean lifetime τ of the γ_d (expressed throughout this Letter as τ times the speed of light c) is a free parameter of the model. In the generated samples $c\tau$ 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 γ_d mean lifetime through re-weighting of the generated samples.

Higgs mass [GeV]	$m_{f_{d2}}$ [GeV]	$m_{f_{d1}}$ [GeV]	γ_d mass [GeV]	$c\tau$ [mm]
100	5.0	2.0	0.4	47
140	5.0	2.0	0.4	36

Table 1: Parameters used for the Monte Carlo simulation. The last column is the γ_d mean lifetime τ multiplied by the speed of light c, expressed in mm.

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, WZ, and ZZ. 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/π 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, WZ, 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 re-weighted 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 γ_d pair are emitted approximately back-to-back in ϕ, with an angular spread of the distribution due to the emission of the f_{d1}.

- The average p_T of the γ_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 γ_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 γ_d decay. The ΔR is computed at the decay vertex of the γ_d from the vector momenta of the two muons. Due to the small mass of the γ_d the ΔR is almost always below 0.1.

Since the two f_{d1} are, like the two γ_d, emitted back-to-back in ϕ, 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.

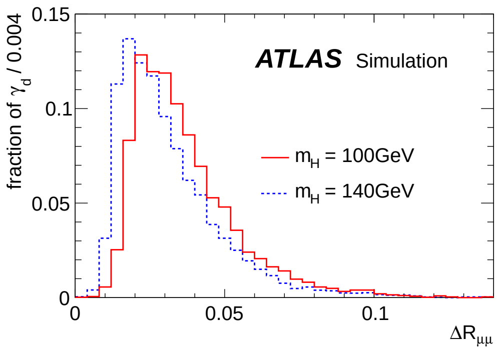

Figure 2: ΔR distribution between the two muons from the γ_d decay for the signal Monte Carlo samples with m_H = 100 GeV and m_H = 140 GeV.

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 $\pm$ 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 Σp_T^2. This analysis deals with displaced γ_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 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 $0.32 \pm 0.01_{\text{stat}}$ for m_H = 100 GeV and $0.31 \pm 0.01_{\text{stat}}$ for m_H = 140 GeV.

The main reason for the relatively low trigger efficiency is the small opening ΔR between the two muons of the γ_d decay ($\Delta R \leq 0.1$) shown in Fig. 2. These values of ΔR 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 γ_d produces two distinct L1 ROIs. The single γ_d ROI efficiency, $\varepsilon_{2\text{ROI}}$ ($\varepsilon_{1\text{ROI}}$), defined as the fraction of γ_d passing the offline selection that give two (one) trigger ROIs is $0.296 \pm 0.004_{\text{stat}}$ ($0.626 \pm 0.004_{\text{stat}}$) for m_H = 100 GeV and $0.269 \pm 0.003_{\text{stat}}$ ($0.653 \pm 0.003_{\text{stat}}$) for m_H = 140 GeV. Fig. 3 shows the $\varepsilon_{2\text{ROI}}$ as a function of the dark photon η and of the ΔR of the two muons from the γ_d decay. The increased trigger granularity in the endcap and the efficiency decrease at small values of ΔR are clearly visible.

The systematic uncertainty on the trigger efficiency is estimated with a sample of $J/\psi \to \mu^+\mu^-$ from collision data and a corresponding sample of Monte Carlo events, using the tag-and-probe (TP) method. A cut on $\Delta R \leq 0.1$ 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/ψ mass. A muon ROI that matches the probe in η and ϕ, 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 $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI}$ ratio. Values of $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI}$ = 0.42±0.05$_{stat}$ for the $J/\psi \rightarrow \mu^{+}\mu^{-}$ data and $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI}$ = 0.39±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.

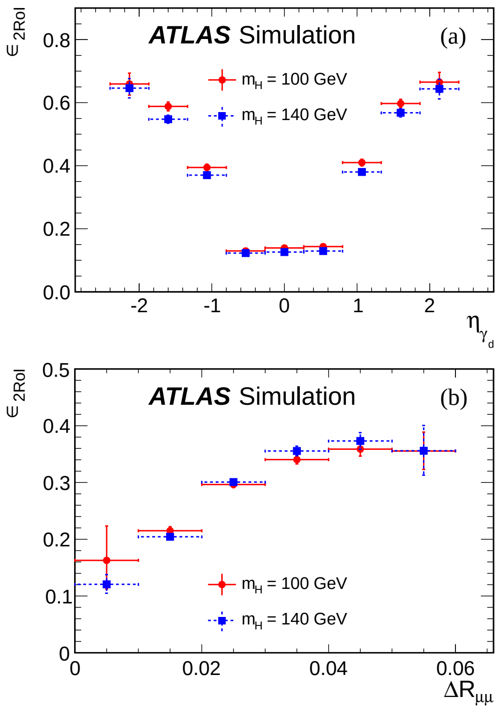

Figure 3: ε_{2ROI} as a function (a) of the η of the γ_d and (b) of the ΔR of the muon pair for the Monte Carlo samples with Higgs boson masses of 100 GeV and 140 GeV. The errors are statistical only.

6. Muon Jets reconstruction and event selection

MJs from displaced γ_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 ΔR = 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 are formed. The MJ direction and momentum are obtained from the vector sum over all muons in the MJ. Only MJs with two reconstructed muons are accepted and only events with two MJs are kept for the subsequent analysis.

The possible contribution to the background of SM processes which lead to real prompt muon pairs in the final state is evaluated using simulated samples. After the trigger and the requirement of having two MJs in the event, their contributions have been found to be negligible. The only significant background sources are expected to be 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/π and heavy flavour decays in multi-jet production, or cosmic-ray muons not pointing to the primary vertex.

In order to separate the signal from the background, a number of discriminating variables have been studied. The multi-jet background can be significantly reduced by using calorimeter isolation requirements around the MJ direction. The calorimetric isolation variable E^{isol}_T is defined as the difference between the transverse calorimetric energy E_T in a cone of ΔR = 0.4 around the highest p_T muon of the MJ and the E_T in a cone of ΔR = 0.2; a cut $E^{isol}_T \leq 5$ GeV keeps almost all the signal. The isolation modelling is validated for real isolated muons with a sample of muons coming from $Z \rightarrow \mu\mu$ decays. To further improve the signal-to-background ratio, two additional discriminating variables are used: $\Delta\phi$ between the two MJs and Σp^{ID}_T for the MJ, defined as the scalar sum of the transverse momentum of the tracks, measured in the ID, inside a cone ΔR = 0.4 around the direction of the MJ. The muon tracks of the MJ in the ID, if any, are not removed from the isolation sum, so that prompt muons, which give a reconstructed track in both the ID and MS, will contribute to the Σp^{ID}_T. As a consequence a cut on Σp^{ID}_T of a few GeV will remove prompt MJs or MJs with very short decay length.

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 $E^{isol}_T \leq 5$ 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 $\Sigma p^{ID}_T < 3$ GeV for both MJs.

The distributions of the relevant variables at the different steps 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 100% branching ratio for $H\rightarrow \gamma_d\,\gamma_d$+$X$ and the parameters given in Table 1, are 75 or 48 events for Higgs boson masses

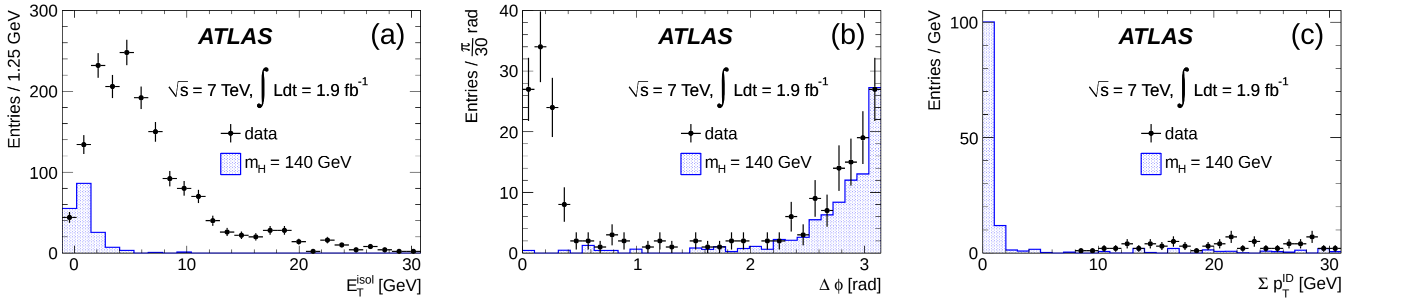

Figure 4: Control plots for the cut variables on Monte Carlo (m_H = 140 GeV) and on data. (a) Distribution of the calorimetric isolation around the MJ direction E_T^{isol} after the requirement of two MJs in the event. (b) Distribution of $\Delta\phi$ between the two MJs after the requirement of the isolation cut. (c) Distribution of Σp_T^{ID} of the MJ after the requirement of the impact parameters cut. The points show the data and the histogram is the signal Monte Carlo normalized to 1.9 fb^{-1}. The uncertainties are statistical only.

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 γ_d reconstruction efficiency for the mean lifetimes given in Table 1 is shown in Fig. 5 as a function of η, the ΔR separation of the two muons from the γ_d decay and the decay length in the transverse plane, L_{xy}, of the γ_d. The efficiency is defined as the number of γ_d passing the offline selection divided by the number of γ_d 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 Σp_T^{ID} cut.

The systematic uncertainty on the reconstruction efficiency is evaluated using a tag-and-probe method by comparing the reconstruction efficiency $\varepsilon_{\text{rec}}^{\text{TP}}$ 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 $|\Delta\phi| \geq 2$, 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 $|\Delta\phi| \geq 2$, respectively. Neglect-

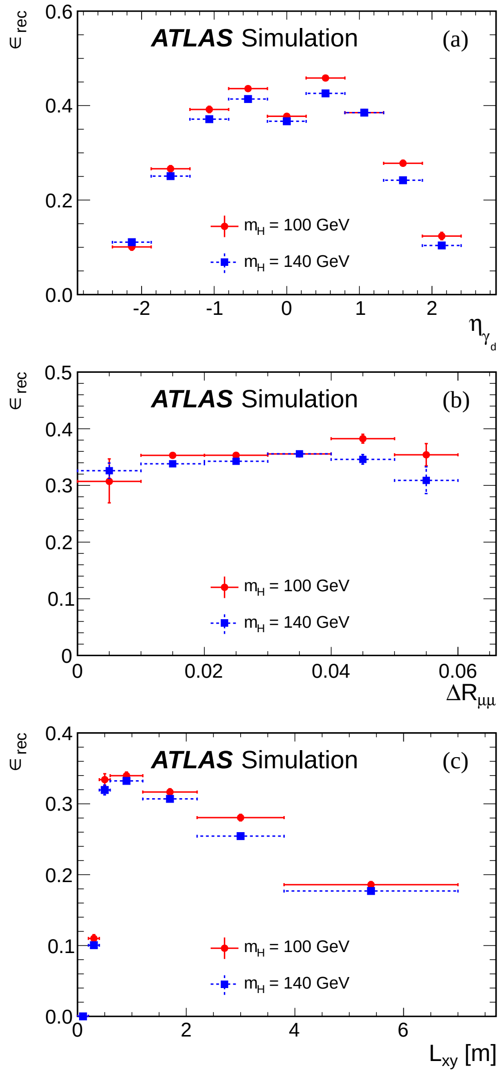

Figure 5: γ_d reconstruction efficiency ε_{rec} as a function (a) of η, (b) of ΔR and (c) of the transverse decay length of the γ_d for m_H = 100 GeV and m_H = 140 GeV and for the mean lifetimes given in Table 1. The reconstruction efficiency is defined as the number of γ_d passing the offline selection divided by the number of γ_d in the spectrometer acceptance ($|\eta| \leq 2.4$) with both muons having $p_T \geq 6$ GeV. The uncertainties are statistical only.

cut	cosmic-rays	multi-jet	total background	$m_H =$ 100 GeV	$m_H =$ 140 GeV	data
$N_{MJ} = 2$	3.0 ± 2.1	N/A	N/A	$135{\pm}11^{+29}_{-21}$	$90{\pm}9^{+17}_{-13}$	871
$E_T^{isol} \leq 5$ GeV	3.0 ± 2.1	N/A	N/A	$132{\pm}11^{+28}_{-21}$	$88{\pm}9^{+17}_{-13}$	219
$\lvert\Delta\phi\rvert \geq 2$	1.5 ± 1.5	$153 \pm 18 \pm 9$	$155 \pm 18 \pm 9$	$123{\pm}11^{+26}_{-19}$	$81{\pm}9^{+15}_{-12}$	104
$Q_{MJ} = 0$	1.5 ± 1.5	$57 \pm 15 \pm 22$	$59 \pm 15 \pm 22$	$121{\pm}11^{+26}_{-19}$	$79{\pm}8^{+15}_{-12}$	80
$\lvert d_0\rvert, \lvert z_0\rvert$	$0^{+1.64}_{-0}$	$111{\pm}39{\pm}63$	$111{\pm}39{\pm}63$	$105{\pm}10^{+22}_{-16}$	$66{\pm}8^{+12}_{-10}$	70
$\Sigma p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06{\pm}0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75{\pm}9^{+16}_{-12}$	$48{\pm}7^{+9}_{-7}$	0

Table 2: Cut flow for the signal selection on signal Monte Carlo, the corresponding cosmic-ray background, the multi-jet background estimation from the ABCD method (described in Section 7) and the data; the yields are normalized to an integrated luminosity of 1.9 fb^{-1}. The first uncertainties are statistical and the second systematic.

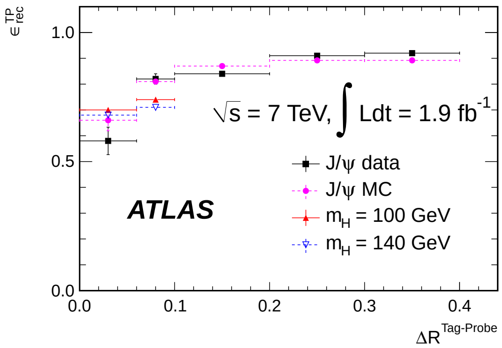

Figure 6: Tag-and-probe reconstruction efficiency ε^{TP}_{rec} as a function of the ΔR between the two muons, evaluated on a sample of $J/\psi \to \mu^+\mu^-$ from collision data and a corresponding sample of Monte Carlo events. The ε^{TP}_{rec} for the signal Monte Carlo, evaluated with a similar tag-and-probe method, is also shown. The uncertainties are statistical only.

ing the signal contamination in regions A, C and D ($E_T^{isol} > 5$ GeV or $|\Delta\phi| < 2$) the number of multi-jet background events in the signal region can be evaluated as $N_B = N_D \times N_A/N_C$. Due to the very low number of events in the control regions the values of N_A, N_C and N_D as a function of the cut on the final discriminant variable Σp_T^{ID} are extracted by modelling the Σp_T^{ID} distributions with bifurcated Gaussian templates, with parameters fitted from the data in the corresponding regions, and by integrating the fitted function in the range $0 < \Sigma p_T^{ID} < 3$ GeV. The low statistics in the four regions at each step of the cut flow give rise to large fluctuations in the multi-jet background estimate. The extracted yields are $N_A = (7.1 \pm 1.5_{stat}) \cdot 10^{-3}$, $N_C = (1.81 \pm 1.0_{stat}) \cdot 10^{-2}$ and $N_D = (1.51 \pm 0.07_{stat}) \cdot 10^{-1}$ and the estimated number of multi-jet background events in the signal region is $N_B = 0.06 \pm 0.02_{stat}$. Possible sources of systematic uncertainty related to the background estimation method are also evaluated. The functional form is changed and the procedure to estimate the number of multi-jet background events in the signal region is repeated. The difference in N_B is taken as the systematic uncertainty in the modelling of the multi-jet background shape and it amounts to $^{+0.66}_{-0.06}$. The effect of possible signal leakage in the background regions is also considered and is found to be negligible.

The background induced by muons from cosmic-ray showers is evaluated using events collected by the trigger 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 ($|d_0| < 200$ mm and $|z_0| < 270$ mm), resulting in a cosmic-ray contamination estimate of $0^{+1.64}_{-0}$. 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 normalisation 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 $Z \to \mu\mu$ 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 γ_d 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 γ_d 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 ≈ 6 to ≈ 16. This systematic uncertainty is negligible.

- **Effect of $\Sigma p_{\mathrm{T}}^{\mathrm{ID}}$ cut**
  Since the $\Sigma p_{\mathrm{T}}^{\mathrm{ID}}$ cut could affect the minimum $c\tau$ value that can be excluded, the effect of this cut on the signal Monte Carlo has been studied. A variation of 10% on the $\Sigma p_{\mathrm{T}}^{\mathrm{ID}}$ cut results in a relative variation of <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 $\Sigma p_{\mathrm{T}}^{\mathrm{ID}}$ distribution is varied to evaluate the systematic uncertainty in the modelling of its shape, which also includes the effect of the $\Sigma p_{\mathrm{T}}^{\mathrm{ID}}$ cut on the background estimation. This systematic uncertainty amounts to $^{+0.66}_{-0.06}$ events. The effect of signal leakage is also negligible.

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 γ_d. Using pseudo-experiments with $c\tau$ ranging from 0 to 700 mm the number of γ_d that decay in each region of the detector is weighted by the corresponding total efficiency for that region. In this way the number of expected signal events is predicted as a function of the γ_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 $H\to \gamma_d\, \gamma_d + X$. Here the branching ratio of $\gamma_d \to \mu\, \mu$ is set to 45% with the γ_d mass set to 0.4 GeV, as previously discussed. The $\sigma\times$BR is given as a function of the γ_d mean lifetime, expressed as $c\tau$ 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 γ_d $c\tau$ is excluded at the 95% *CL* for $H\to \gamma_d\, \gamma_d + X$ branching ratios of 100% and 10%.

Higgs boson mass [GeV]	excluded $c\tau$ [*mm*] BR(100%)	excluded $c\tau$ [*mm*] BR(10%)
100	$1 \le c\tau \le 670$	$5 \le c\tau \le 159$
140	$1 \le c\tau \le 430$	$7 \le c\tau \le 82$

Table 3: Ranges in which γ_d $c\tau$ is excluded at 95% *CL* for $m_H =$ 100 GeV and $m_H =$ 140 GeV, assuming 100% and 10% branching ratio of $H\to \gamma_d\, \gamma_d + X$.

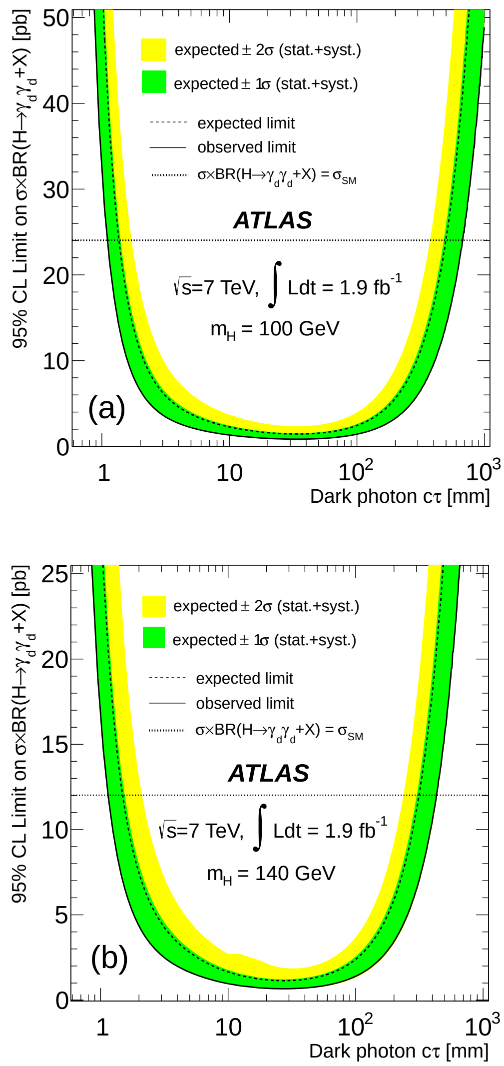

Figure 7: The 95% upper limits on the $\sigma\times$BR for the process $H\to \gamma_d\, \gamma_d + X$ as a function of the dark photon $c\tau$ for the benchmark sample with (a) $m_H =$ 100 GeV and with (b) $m_H =$ 140 GeV. The expected limit is shown as the dashed curve and the solid curve shows the observed limit. The horizontal lines correspond to the Higgs boson SM cross sections at the two mass values.

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_{d2}), each of which decays to a γ_d and to a stable hidden fermion (f_{d1}), resulting in two muon jets from the γ_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 $H\to \gamma_d\, \gamma_d + X$ as a function of the long-lived particle mean lifetime for m_H = 100 GeV and 140 GeV with the chosen γ_d mass that gives a decay branching ratio of 45% for $\gamma_d \to \mu\, \mu$. 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 $c\tau$ in the range 7 mm $\le c\tau \le$ 82 mm. Bounds on the $\sigma\times$BR of a 126 GeV Higgs boson may be conservatively extracted using the corresponding 140 GeV exclusion curve.

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The ATLAS Collaboration

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R. Caputo[80], R. Cardarelli[132a], T. Carli[29], G. Carlino[101a], L. Carminati[88a,88b], B. Caron[84], S. Caron[103], E. Carquin[31b], G.D. Carrillo-Montoya[172], A.A. Carter[74], J.R. Carter[27], J. Carvalho[123a,h], D. Casadei[107], M.P. Casado[11], M. Cascella[121a,121b], C. Caso[49a,49b,*], A.M. Castaneda Hernandez[172,i], E. Castaneda-Miranda[172], V. Castillo Gimenez[166], N.F. Castro[123a], G. Cataldi[71a], P. Catastini[56], A. Catinaccio[29], J.R. Catmore[29], A. Cattai[29], G. Cattani[132a,132b], S. Caughron[87], V. Cavaliere[164], P. Cavalleri[77], D. Cavalli[88a], M. Cavalli-Sforza[11], V. Cavasinni[121a,121b], F. Ceradini[133a,133b], A.S. Cerqueira[23b], A. Cerri[29], L. Cerrito[74], F. Cerutti[46], S.A. Cetin[18b], A. Chafaq[134a], D. Chakraborty[105], I. Chalupkova[125], K. Chan[2], P. Chang[164], B. Chapleau[84], J.D. Chapman[27], J.W. Chapman[86], E. Chareyre[77], D.G. Charlton[17], V. Chavda[81], C.A. Chavez Barajas[29], S. Cheatham[84], S. Chekanov[5], S.V. Chekulaev[158a], G.A. Chelkov[63], M.A. Chelstowska[103], C. Chen[62], H. Chen[24], S. Chen[32c], X. Chen[172], Y. Chen[34], A. Cheplakov[63], R. Cherkaoui El Moursli[134e], V. Chernyatin[24], E. Cheu[6], S.L. Cheung[157], L. Chevalier[135], G. Chiefari[101a,101b], L. Chikovani[50a,*], J.T. Childers[29], A. Chilingarov[70], G. Chiodini[71a], A.S. Chisholm[17], R.T. Chislett[76], A. Chitan[25a], M.V. Chizhov[63], G. Choudalakis[30], S. Chouridou[136], I.A. Christidi[76], A. Christov[47], D. Chromek-Burckhart[29], M.L. Chu[150], J. Chudoba[124], G. Ciapetti[131a,131b], A.K. Ciftci[3a], R. Ciftci[3a], D. Cinca[33], V. Cindro[73], C. Ciocca[19a,19b], A. Ciocio[14], M. Cirilli[86], P. Cirkovic[12b], Z.H. Citron[171], M. Citterio[88a], M. Ciubancan[25a], A. Clark[48], P.J. Clark[45], R.N. Clarke[14], W. Cleland[122], J.C. Clemens[82], B. Clement[54], C. Clement[145a,145b], Y. Coadou[82], M. Cobal[163a,163c], A. Coccaro[137], J. Cochran[62], J.G. Cogan[142], J. Coggeshall[164], E. Cogneras[177], J. Colas[4], S. Cole[105], A.P. Colijn[104], N.J. Collins[17], C. Collins-Tooth[52], J. Collot[54], T. Colombo[118a,118b], G. Colon[83], P. Conde Muiño[123a], E. Coniavitis[117], M.C. Conidi[11], S.M. Consonni[88a,88b], V. Consorti[47], S. Constantinescu[25a], C. Conta[118a,118b], G. Conti[56], F. Conventi[101a,j], M. Cooke[14], B.D. Cooper[76], A.M. Cooper-Sarkar[117], K. Copic[14], T. Cornelissen[174], M. Corradi[19a], F. Corriveau[84,k], A. Cortes-Gonzalez[164], G. Cortiana[98], G. Costa[88a], M.J. Costa[166], D. Costanzo[138], D. Côté[29], L. Courneyea[168], G. Cowan[75], C. Cowden[27], B.E. Cox[81], K. Cranmer[107], F. Crescioli[121a,121b], M. Cristinziani[20], G. Crosetti[36a,36b], S. Crépé-Renaudin[54], C.-M. Cuciuc[25a], C. Cuenca Almenar[175], T. Cuhadar Donszelmann[138], M. Curatolo[46], C.J. Curtis[17], C. Cuthbert[149], P. Cwetanski[59], H. Czirr[140], P. Czodrowski[43], Z. Czyczula[175], S. D'Auria[52], M. D'Onofrio[72], A. D'Orazio[131a,131b], M.J. Da Cunha Sargedas De Sousa[123a], C. Da Via[81], W. Dabrowski[37], A. Dafinca[117], T. Dai[86], C. Dallapiccola[83], M. Dam[35], M. Dameri[49a,49b], D.S. Damiani[136], H.O. Danielsson[29], V. Dao[48], G. Darbo[49a], G.L. Darlea[25b], J.A. Dassoulas[41], W. Davey[20], T. Davidek[125], N. Davidson[85], R. Davidson[70], E. Davies[117,c], M. Davies[92], O. Davignon[77], A.R. Davison[76], Y. Davygora[57a], E. Dawe[141], I. Dawson[138], R.K. Daya-Ishmukhametova[22], K. De[7], R. de Asmundis[101a], S. De Castro[19a,19b], S. De Cecco[77], J. de Graat[97], N. De Groot[103], P. de Jong[104], C. De La Taille[114], H. De la Torre[79], F. De Lorenzi[62], L. de Mora[70], L. De Nooij[104], D. De Pedis[131a], A. De Salvo[131a], U. De Sanctis[163a,163c], A. De Santo[148], J.B. De Vivie De Regie[114], G. De Zorzi[131a,131b], W.J. Dearnaley[70], R. Debbe[24], C. Debenedetti[45], B. Dechenaux[54], D.V. Dedovich[63], J. Degenhardt[119], C. Del Papa[163a,163c], J. Del Peso[79], T. Del Prete[121a,121b], T. Delemontex[54], M. Deliyergiyev[73], A. Dell'Acqua[29], L. Dell'Asta[21], M. Della Pietra[101a,j], D. della Volpe[101a,101b], M. Delmastro[4], P.A. Delsart[54], C. Deluca[104], S. Demers[175], M. Demichev[63], B. Demirkoz[11,l], J. Deng[162], S.P. Denisov[127], D. Derendarz[38], J.E. Derkaoui[134d], F. Derue[77], P. Dervan[72], K. Desch[20], E. Devetak[147], P.O. Deviveiros[104], A. Dewhurst[128], B. DeWilde[147], S. Dhaliwal[157], R. Dhullipudi[24,m], A. Di Ciaccio[132a,132b], L. Di Ciaccio[4], A. Di Girolamo[29], B. Di Girolamo[29], S. Di Luise[133a,133b], A. Di Mattia[172], B. Di Micco[29], R. Di Nardo[46], A. Di Simone[132a,132b], R. Di Sipio[19a,19b], M.A. Diaz[31a], E.B. Diehl[86], J. Dietrich[41], T.A. Dietzsch[57a], S. Diglio[85], K. Dindar Yagci[39], J. Dingfelder[20], F. Dinut[25a], C. Dionisi[131a,131b], P. Dita[25a], S. Dita[25a], F. Dittus[29], F. Djama[82], T. Djobava[50b], M.A.B. do Vale[23c], A. Do Valle Wemans[123a,n], T.K.O. Doan[4], M. Dobbs[84], R. Dobinson[29,*], D. Dobos[29], E. Dobson[29,o], J. Dodd[34], C. Doglioni[48], T. Doherty[52], Y. Doi[64,*], J. Dolejsi[125], I. Dolenc[73], Z. Dolezal[125], B.A. Dolgoshein[95,*], T. Dohmae[154], M. Donadelli[23d], J. Donini[33], J. Dopke[29], A. Doria[101a], A. Dos Anjos[172], A. Dotti[121a,121b], M.T. Dova[69], A.D. Doxiadis[104], A.T. Doyle[52], N. Dressnandt[119], M. Dris[9], J. Dubbert[98], S. Dube[14], E. Duchovni[171], G. Duckeck[97], D. Duda[174], A. Dudarev[29], F. Dudziak[62], M. Dührssen[29], I.P. Duerdoth[81], L. Duflot[114], M-A. Dufour[84], L. Duguid[75], M. Dunford[29], H. Duran Yildiz[3a], R. Duxfield[138], M. Dwuznik[37], F. Dydak[29], M. Düren[51], W.L. Ebenstein[44], J. Ebke[97], S. Eckweiler[80], K. Edmonds[80], W. Edson[1], C.A. Edwards[75], N.C. Edwards[52], W. Ehrenfeld[41], T. Eifert[142], G. Eigen[13], K. Einsweiler[14], E. Eisenhandler[74], T. Ekelof[165], M. El Kacimi[134c], M. Ellert[165], S. Elles[4], F. Ellinghaus[80], K. Ellis[74], N. Ellis[29], J. Elmsheuser[97], M. Elsing[29], D. Emeliyanov[128], R. Engelmann[147], A. Engl[97], B. Epp[60], J. Erdmann[53], A. Ereditato[16], D. Eriksson[145a], J. Ernst[1], M. Ernst[24], J. Ernwein[135], D. Errede[164], S. Errede[164], E. Ertel[80], M. Escalier[114], H. Esch[42], C. Escobar[122], X. Espinal Curull[11], B. Esposito[46], F. Etienne[82], A.I. Etienvre[135], E. Etzion[152], D. Evangelakou[53], H. Evans[59], L. Fabbri[19a,19b], C. Fabre[29], R.M. Fakhrutdinov[127], S. Falciano[131a], Y. Fang[172], M. Fanti[88a,88b], A. Farbin[7], A. Farilla[133a], J. Farley[147], T. Farooque[157], S. Farrell[162], S.M. Farrington[169], P. Farthouat[29], F. Fassi[166], P. Fassnacht[29], D. Fassouliotis[8], B. Fatholahzadeh[157], A. Favareto[88a,88b], L. Fayard[114], S. Fazio[36a,36b], R. Febbraro[33], P. Federic[143a], O.L. Fedin[120], W. Fedorko[87], M. Fehling-Kaschek[47], L. Feligioni[82], D. Fellmann[5], C. Feng[32d], E.J. Feng[5], A.B. Fenyuk[127], J. Ferencei[143b], W. Fernando[5], S. Ferrag[52], J. Ferrando[52], V. Ferrara[41], A. Ferrari[165], P. Ferrari[104], R. Ferrari[118a], D.E. Ferreira de Lima[52], A. Ferrer[166], D. Ferrere[48], C. Ferretti[86], A. Ferretto Parodi[49a,49b], M. Fiascaris[30], F. Fiedler[80], A. Filipčič[73], F. Filthaut[103],

M. Fincke-Keeler[168], M.C.N. Fiolhais[123a,h], L. Fiorini[166], A. Firan[39], G. Fischer[41], M.J. Fisher[108], M. Flechl[47], I. Fleck[140], J. Fleckner[80], P. Fleischmann[173], S. Fleischmann[174], T. Flick[174], A. Floderus[78], L.R. Flores Castillo[172], M.J. Flowerdew[98], T. Fonseca Martin[16], A. Formica[135], A. Forti[81], D. Fortin[158a], D. Fournier[114], A.J. Fowler[44], H. Fox[70], P. Francavilla[11], M. Franchini[19a,19b], S. Franchino[118a,118b], D. Francis[29], T. Frank[171], S. Franz[29], M. Fraternali[118a,118b], S. Fratina[119], S.T. French[27], C. Friedrich[41], F. Friedrich[43], R. Froeschl[29], D. Froidevaux[29], J.A. Frost[27], C. Fukunaga[155], E. Fullana Torregrosa[29], B.G. Fulsom[142], J. Fuster[166], C. Gabaldon[29], O. Gabizon[171], A. Gabrielli[131a,131b], T. Gadfort[24], S. Gadomski[48], G. Gagliardi[49a,49b], P. Gagnon[59], C. Galea[97], B. Galhardo[123a], E.J. Gallas[117], V. Gallo[16], B.J. Gallop[128], P. Gallus[124], K.K. Gan[108], Y.S. Gao[142,e], A. Gaponenko[14], F. Garberson[175], M. Garcia-Sciveres[14], C. García[166], J.E. García Navarro[166], R.W. Gardner[30], N. Garelli[29], H. Garitaonandia[104], V. Garonne[29], C. Gatti[46], G. Gaudio[118a], B. Gaur[140], L. Gauthier[135], P. Gauzzi[131a,131b], I.L. Gavrilenko[93], C. Gay[167], G. Gaycken[20], E.N. Gazis[9], P. Ge[32d], Z. Gecse[167], C.N.P. Gee[128], D.A.A. Geerts[104], Ch. Geich-Gimbel[20], K. Gellerstedt[145a,145b], C. Gemme[49a], A. Gemmell[52], M.H. Genest[54], S. Gentile[131a,131b], M. George[53], S. George[75], P. Gerlach[174], A. Gershon[152], C. Geweniger[57a], H. Ghazlane[134b], N. Ghodbane[33], B. Giacobbe[19a], S. Giagu[131a,131b], V. Giakoumopoulou[8], V. Giangiobbe[11], F. Gianotti[29], B. Gibbard[24], A. Gibson[157], S.M. Gibson[29], M. Gilchriese[14], D. Gillberg[28], A.R. Gillman[128], D.M. Gingrich[2,d], J. Ginzburg[152], N. Giokaris[8], M.P. Giordani[163c], R. Giordano[101a,101b], F.M. Giorgi[15], P. Giovannini[98], P.F. Giraud[135], D. Giugni[88a], M. Giunta[92], P. Giusti[19a], B.K. Gjelsten[116], L.K. Gladilin[96], C. Glasman[79], J. Glatzer[47], A. Glazov[41], K.W. Glitza[174], G.L. Glonti[63], J.R. Goddard[74], J. Godfrey[141], J. Godlewski[29], M. Goebel[41], T. Göpfert[43], C. Goeringer[80], C. Gössling[42], S. Goldfarb[86], T. Golling[175], A. Gomes[123a,b], L.S. Gomez Fajardo[41], R. Gonçalo[75], J. Goncalves Pinto Firmino Da Costa[41], L. Gonella[20], S. Gonzalez[172], S. González de la Hoz[166], G. Gonzalez Parra[11], M.L. Gonzalez Silva[26], S. Gonzalez-Sevilla[48], J.J. Goodson[147], L. Goossens[29], P.A. Gorbounov[94], H.A. Gordon[24], I. Gorelov[102], G. Gorfine[174], B. Gorini[29], E. Gorini[71a,71b], A. Gorišek[73], E. Gornicki[38], B. Gosdzik[41], A.T. Goshaw[5], M. Gosselink[104], M.I. Gostkin[63], I. Gough Eschrich[162], M. Gouighri[134a], D. Goujdami[134c], M.P. Goulette[48], A.G. Goussiou[137], C. Goy[4], S. Gozpinar[22], I. Grabowska-Bold[37], P. Grafström[19a,19b], K-J. Grahn[41], F. Grancagnolo[71a], S. Grancagnolo[15], V. Grassi[147], V. Gratchev[120], N. Grau[34], H.M. Gray[29], J.A. Gray[147], E. Graziani[133a], O.G. Grebenyuk[120], T. Greenshaw[72], Z.D. Greenwood[24,m], K. Gregersen[35], I.M. Gregor[41], P. Grenier[142], J. Griffiths[7], N. Grigalashvili[63], A.A. Grillo[136], S. Grinstein[11], Ph. Gris[33], Y.V. Grishkevich[96], J.-F. Grivaz[114], E. Gross[171], J. Grosse-Knetter[53], J. Groth-Jensen[171], K. Grybel[140], D. Guest[175], C. Guicheney[33], S. Guindon[53], U. Gul[52], H. Guler[84,p], J. Gunther[124], B. Guo[157], J. Guo[34], P. Gutierrez[110], N. Guttman[152], O. Gutzwiller[172], C. Guyot[135], C. Gwenlan[117], C.B. Gwilliam[72], A. Haas[142], S. Haas[29], C. Haber[14], H.K. Hadavand[39], D.R. Hadley[17], P. Haefner[20], F. Hahn[29], S. Haider[29], Z. Hajduk[38], H. Hakobyan[176], D. Hall[117], J. Haller[53], K. Hamacher[174], P. Hamal[112], K. Hamano[85], M. Hamer[53], A. Hamilton[144b,q], S. Hamilton[160], L. Han[32b], K. Hanagaki[115], K. Hanawa[159], M. Hance[14], C. Handel[80], P. Hanke[57a], J.R. Hansen[35], J.B. Hansen[35], J.D. Hansen[35], P.H. Hansen[35], P. Hansson[142], K. Hara[159], G.A. Hare[136], T. Harenberg[174], S. Harkusha[89], D. Harper[86], R.D. Harrington[45], O.M. Harris[137], J. Hartert[47], F. Hartjes[104], T. Haruyama[64], A. Harvey[55], S. Hasegawa[100], Y. Hasegawa[139], S. Hassani[135], S. Haug[16], M. Hauschild[29], R. Hauser[87], M. Havranek[20], C.M. Hawkes[17], R.J. Hawkings[29], A.D. Hawkins[78], D. Hawkins[162], T. Hayakawa[65], T. Hayashi[159], D. Hayden[75], C.P. Hays[117], H.S. Hayward[72], S.J. Haywood[128], M. He[32d], S.J. Head[17], V. Hedberg[78], L. Heelan[7], S. Heim[87], B. Heinemann[14], S. Heisterkamp[35], L. Helary[21], C. Heller[97], M. Heller[29], S. Hellman[145a,145b], D. Hellmich[20], C. Helsens[11], R.C.W. Henderson[70], M. Henke[57a], A. Henrichs[53], A.M. Henriques Correia[29], S. Henrot-Versille[114], C. Hensel[53], T. Henß[174], C.M. Hernandez[7], Y. Hernández Jiménez[166], R. Herrberg[15], G. Herten[47], R. Hertenberger[97], L. Hervas[29], G.G. Hesketh[76], N.P. Hessey[104], E. Higón-Rodriguez[166], J.C. Hill[27], K.H. Hiller[41], S. Hillert[20], S.J. Hillier[17], I. Hinchliffe[14], E. Hines[119], M. Hirose[115], F. Hirsch[42], D. Hirschbuehl[174], J. Hobbs[147], N. Hod[152], M.C. Hodgkinson[138], P. Hodgson[138], A. Hoecker[29], M.R. Hoeferkamp[102], J. Hoffman[39], D. Hoffmann[82], M. Hohlfeld[80], M. Holder[140], S.O. Holmgren[145a], T. Holy[126], J.L. Holzbauer[87], T.M. Hong[119], L. Hooft van Huysduynen[107], S. Horner[47], J-Y. Hostachy[54], S. Hou[150], A. Hoummada[134a], J. Howard[117], J. Howarth[81], I. Hristova[15], J. Hrivnac[114], T. Hryn'ova[4], P.J. Hsu[80], S.-C. Hsu[14], D. Hu[34], Z. Hubacek[126], F. Hubaut[82], F. Huegging[20], A. Huettmann[41], T.B. Huffman[117], E.W. Hughes[34], G. Hughes[70], M. Huhtinen[29], M. Hurwitz[14], U. Husemann[41], N. Huseynov[63,r], J. Huston[87], J. Huth[56], G. Iacobucci[48], G. Iakovidis[9], M. Ibbotson[81], I. Ibragimov[140], L. Iconomidou-Fayard[114], J. Idarraga[114], P. Iengo[101a], O. Igonkina[104], Y. Ikegami[64], M. Ikeno[64], D. Iliadis[153], N. Ilic[157], T. Ince[20], J. Inigo-Golfin[29], P. Ioannou[8], M. Iodice[133a], K. Iordanidou[8], V. Ippolito[131a,131b], A. Irles Quiles[166], C. Isaksson[165], M. Ishino[66], M. Ishitsuka[156], R. Ishmukhametov[39], C. Issever[117], S. Istin[18a], A.V. Ivashin[127], W. Iwanski[38], H. Iwasaki[64], J.M. Izen[40], V. Izzo[101a], B. Jackson[119], J.N. Jackson[72], P. Jackson[142], M.R. Jaekel[29], V. Jain[59], K. Jakobs[47], S. Jakobsen[35], T. Jakoubek[124], J. Jakubek[126], D.K. Jana[110], E. Jansen[76], H. Jansen[29], A. Jantsch[98], M. Janus[47], G. Jarlskog[78], L. Jeanty[56], I. Jen-La Plante[30], D. Jennens[85], P. Jenni[29], A.E. Loevschall-Jensen[35], P. Jež[35], S. Jézéquel[4], M.K. Jha[19a], H. Ji[172], W. Ji[80], J. Jia[147], Y. Jiang[32b], M. Jimenez Belenguer[41], S. Jin[32a], O. Jinnouchi[156], M.D. Joergensen[35], D. Joffe[39], M. Johansen[145a,145b], K.E. Johansson[145a], P. Johansson[138], S. Johnert[41], K.A. Johns[6], K. Jon-And[145a,145b], G. Jones[169], R.W.L. Jones[70], T.J. Jones[72], C. Joram[29], P.M. Jorge[123a], K.D. Joshi[81], J. Jovicevic[146], T. Jovin[12b], X. Ju[172], C.A. Jung[42], R.M. Jungst[29], V. Juranek[124], P. Jussel[60], A. Juste Rozas[11], S. Kabana[16], M. Kaci[166], A. Kaczmarska[38], P. Kadlecik[35], M. Kado[114], H. Kagan[108], M. Kagan[56], E. Kajomovitz[151], S. Kalinin[174], L.V. Kalinovskaya[63], S. Kama[39], N. Kanaya[154], M. Kaneda[29], S. Kaneti[27], T. Kanno[156], V.A. Kantserov[95], J. Kanzaki[64], B. Kaplan[107], A. Kapliy[30], J. Kaplon[29], D. Kar[52], M. Karagounis[20], K. Karakostas[9], M. Karnevskiy[41], V. Kartvelishvili[70], A.N. Karyukhin[127], L. Kashif[172], G. Kasieczka[57b], R.D. Kass[108], A. Kastanas[13], M. Kataoka[4], Y. Kataoka[154], E. Katsoufis[9], J. Katzy[41], V. Kaushik[6], K. Kawagoe[68], T. Kawamoto[154], G. Kawamura[80], M.S. Kayl[104], S. Kazama[154], V.A. Kazanin[106], M.Y. Kazarinov[63], R. Keeler[168], P.T. Keener[119], R. Kehoe[39], M. Keil[53], G.D. Kekelidze[63], J.S. Keller[137], M. Kenyon[52], O. Kepka[124], N. Kerschen[29], B.P. Kerševan[73], S. Kersten[174], K. Kessoku[154], J. Keung[157], F. Khalil-zada[10], H. Khandanyan[145a,145b], A. Khanov[111], D. Kharchenko[63], A. Khodinov[95], A. Khomich[57a], T.J. Khoo[27], G. Khoriauli[20], A. Khoroshilov[174], V. Khovanskiy[94], E. Khramov[63], J. Khubua[50b], H. Kim[145a,145b], S.H. Kim[159], N. Kimura[170], O. Kind[15], B.T. King[72], M. King[65], R.S.B. King[117], J. Kirk[128], A.E. Kiryunin[98], T. Kishimoto[65], D. Kisielewska[37], T. Kitamura[65], T. Kittelmann[122], K. Kiuchi[159], E. Kladiva[143b], M. Klein[72], U. Klein[72], K. Kleinknecht[80], M. Klemetti[84], A. Klier[171], P. Klimek[145a,145b], A. Klimentov[24], R. Klingenberg[42], J.A. Klinger[81], E.B. Klinkby[35], T. Klioutchnikova[29], P.F. Klok[103], S. Klous[104], E.-E. Kluge[57a], T. Kluge[72], P. Kluit[104], S. Kluth[98], N.S. Knecht[157], E. Kneringer[60], E.B.F.G. Knoops[82], A. Knue[53], B.R. Ko[44], T. Kobayashi[154], M. Kobel[43], M. Kocian[142], P. Kodys[125], K. Köneke[29], A.C. König[103], S. Koenig[80], L. Köpke[80], F. Koetsveld[103], P. Koevesarki[20], T. Koffas[28], E. Koffeman[104], L.A. Kogan[117], S. Kohlmann[174], F. Kohn[53], Z. Kohout[126], T. Kohriki[64], T. Koi[142], G.M. Kolachev[106,*], H. Kolanoski[15], V. Kolesnikov[63], I. Koletsou[88a], J. Koll[87], M. Kollefrath[47], A.A. Komar[93], Y. Komori[154], T. Kondo[64], T. Kono[41,s], A.I. Kononov[47], R. Konoplich[107,t], N. Konstantinidis[76], S. Koperny[37], K. Korcyl[38], K. Kordas[153], A. Korn[117], A. Korol[106], I. Korolkov[11], E.V. Korolkova[138], V.A. Korotkov[127], O. Kortner[98], S. Kortner[98], V.V. Kostyukhin[20], S. Kotov[98], V.M. Kotov[63], A. Kotwal[44], C. Kourkoumelis[8], V. Kouskoura[153], A. Koutsman[158a], R. Kowalewski[168], T.Z. Kowalski[37], W. Kozanecki[135], A.S. Kozhin[127], V. Kral[126], V.A. Kramarenko[96], G. Kramberger[73], M.W. Krasny[77], A. Krasznahorkay[107], J.K. Kraus[20], S. Kreiss[107], F. Krejci[126], J. Kretzschmar[72], N. Krieger[53], P. Krieger[157], K. Kroeninger[53], H. Kroha[98], J. Kroll[119], J. Kroseberg[20], J. Krstic[12a], U. Kruchonak[63], H. Krüger[20], T. Kruker[16], N. Krumnack[62], Z.V. Krumshteyn[63], T. Kubota[85], S. Kuday[3a], S. Kuehn[47], A. Kugel[57c], T. Kuhl[41], D. Kuhn[60], V. Kukhtin[63], Y. Kulchitsky[89], S. Kuleshov[31b], C. Kummer[97], M. Kuna[77], J. Kunkle[119], A. Kupco[124], H. Kurashige[65], M. Kurata[159], Y.A. Kurochkin[89], V. Kus[124], E.S. Kuwertz[146], M. Kuze[156], J. Kvita[141], R. Kwee[15], A. La Rosa[48], L. La Rotonda[36a,36b], L. Labarga[79], J. Labbe[4], S. Lablak[134a], C. Lacasta[166], F. Lacava[131a,131b], H. Lacker[15], D. Lacour[77], V.R. Lacuesta[166], E. Ladygin[63], R. Lafaye[4], B. Laforge[77], T. Lagouri[79], S. Lai[47], E. Laisne[54], M. Lamanna[29], L. Lambourne[76], C.L. Lampen[6], W. Lampl[6], E. Lancon[135], U. Landgraf[47], M.P.J. Landon[74], J.L. Lane[81], V.S. Lang[57a], C. Lange[41], A.J. Lankford[162], F. Lanni[24], K. Lantzsch[174], S. Laplace[77], C. Lapoire[20], J.F. Laporte[135], T. Lari[88a], A. Larner[117], M. Lassnig[29], P. Laurelli[46], V. Lavorini[36a,36b], W. Lavrijsen[14], P. Laycock[72], O. Le Dortz[77], E. Le Guirriec[82], C. Le Maner[157], E. Le Menedeu[11], T. LeCompte[5], F. Ledroit-Guillon[54], H. Lee[104], J.S.H. Lee[115], S.C. Lee[150], L. Lee[175], M. Lefebvre[168], M. Legendre[135], F. Legger[97], C. Leggett[14], M. Lehmacher[20], G. Lehmann Miotto[29], X. Lei[6], M.A.L. Leite[23d], R. Leitner[125], D. Lellouch[171], B. Lemmer[53], V. Lendermann[57a], K.J.C. Leney[144b], T. Lenz[104], G. Lenzen[174], B. Lenzi[29], K. Leonhardt[43], S. Leontsinis[9], F. Lepold[57a], C. Leroy[92], J-R. Lessard[168], C.G. Lester[27], C.M. Lester[119], J. Levêque[4], D. Levin[86], L.J. Levinson[171], A. Lewis[117], G.H. Lewis[107], A.M. Leyko[20], M. Leyton[15], B. Li[82], H. Li[172,u], S. Li[32b,v], X. Li[86], Z. Liang[117,w], H. Liao[33], B. Liberti[132a], P. Lichard[29], M. Lichtnecker[97], K. Lie[164], W. Liebig[13], C. Limbach[20], A. Limosani[85], M. Limper[61], S.C. Lin[150,x], F. Linde[104], J.T. Linnemann[87], E. Lipeles[119], A. Lipniacka[13], T.M. Liss[164], D. Lissauer[24], A. Lister[48], A.M. Litke[136], C. Liu[28], D. Liu[150], H. Liu[86], J.B. Liu[86], L. Liu[86], M. Liu[32b], Y. Liu[32b], M. Livan[118a,118b], S.S.A. Livermore[117], A. Lleres[54], J. Llorente Merino[79], S.L. Lloyd[74], E. Lobodzinska[41], P. Loch[6], W.S. Lockman[136], T. Loddenkoetter[20], F.K. Loebinger[81], A. Loginov[175], C.W. Loh[167], T. Lohse[15], K. Lohwasser[47], M. Lokajicek[124], V.P. Lombardo[4], R.E. Long[70], L. Lopes[123a], D. Lopez Mateos[56], J. Lorenz[97], N. Lorenzo Martinez[114], M. Losada[161], P. Loscutoff[14], F. Lo Sterzo[131a,131b], M.J. Losty[158a,*], X. Lou[40], A. Lounis[114], K.F. Loureiro[161], J. Love[5], P.A. Love[70], A.J. Lowe[142,e], F. Lu[32a], H.J. Lubatti[137], C. Luci[131a,131b], A. Lucotte[54], A. Ludwig[43], D. Ludwig[41], I. Ludwig[47], J. Ludwig[47], F. Luehring[59], G. Luijckx[104], W. Lukas[60], D. Lumb[47], L. Luminari[131a], E. Lund[116], B. Lund-Jensen[146], B. Lundberg[78], J. Lundberg[145a,145b], O. Lundberg[145a,145b], J. Lundquist[35], M. Lungwitz[80], D. Lynn[24], E. Lytken[78], H. Ma[24], L.L. Ma[172], G. Maccarrone[46], A. Macchiolo[98], B. Maček[73], J. Machado Miguens[123a], R. Mackeprang[35], R.J. Madaras[14], H.J. Maddocks[70], W.F. Mader[43], R. Maenner[57c], T. Maeno[24], P. Mättig[174], S. Mättig[80], L. Magnoni[162], E. Magradze[53], K. Mahboubi[47], S. Mahmoud[72], G. Mahout[17], C. Maiani[135], C. Maidantchik[23a], A. Maio[123a,b], S. Majewski[24], Y. Makida[64], N. Makovec[114], P. Mal[135], B. Malaescu[29], Pa. Malecki[38], P. Malecki[38], V.P. Maleev[120], F. Malek[54], U. Mallik[61], D. Malon[5], C. Malone[142], S. Maltezos[9], V. Malyshev[106], S. Malyukov[29], R. Mameghani[97], J. Mamuzic[12b], A. Manabe[64], L. Mandelli[88a], I. Mandić[73], R. Mandrysch[15], J. Maneira[123a], A. Manfredini[98], P.S. Mangeard[87], L. Manhaes de Andrade Filho[23b], J.A. Manjarres Ramos[135], A. Mann[53], P.M. Manning[136], A. Manousakis-Katsikakis[8], B. Mansoulie[135], A. Mapelli[29], L. Mapelli[29], L. March[79], J.F. Marchand[28], F. Marchese[132a,132b], G. Marchiori[77], M. Marcisovsky[124],

C.P. Marino[168], F. Marroquim[23a], Z. Marshall[29],
F.K. Martens[157], L.F. Marti[16], S. Marti-Garcia[166], B. Martin[29],
B. Martin[87], J.P. Martin[92], T.A. Martin[17], V.J. Martin[45],
B. Martin dit Latour[48], S. Martin-Haugh[148], M. Martinez[11],
V. Martinez Outschoorn[56], A.C. Martyniuk[168], M. Marx[81],
F. Marzano[131a], A. Marzin[110], L. Masetti[80], T. Mashimo[154],
R. Mashinistov[93], J. Masik[81], A.L. Maslennikov[106],
I. Massa[19a,19b], G. Massaro[104], N. Massol[4], P. Mastrandrea[147],
A. Mastroberardino[36a,36b], T. Masubuchi[154], P. Matricon[114],
H. Matsunaga[154], T. Matsushita[65], C. Mattravers[117,c],
J. Maurer[82], S.J. Maxfield[72], A. Mayne[138], R. Mazini[150],
M. Mazur[20], L. Mazzaferro[132a,132b], M. Mazzanti[88a],
J. Mc Donald[84], S.P. Mc Kee[86], A. McCarn[164],
R.L. McCarthy[147], T.G. McCarthy[28], N.A. McCubbin[128],
K.W. McFarlane[55,*], J.A. Mcfayden[138], G. Mchedlidze[50b],
T. Mclaughlan[17], S.J. McMahon[128], R.A. McPherson[168,k],
A. Meade[83], J. Mechnich[104], M. Mechtel[174], M. Medinnis[41],
R. Meera-Lebbai[110], T. Meguro[115], R. Mehdiyev[92],
S. Mehlhase[35], A. Mehta[72], K. Meier[57a], B. Meirose[78],
C. Melachrinos[30], B.R. Mellado Garcia[172], F. Meloni[88a,88b],
L. Mendoza Navas[161], Z. Meng[150,u], A. Mengarelli[19a,19b],
S. Menke[98], E. Meoni[160], K.M. Mercurio[56], P. Mermod[48],
L. Merola[101a,101b], C. Meroni[88a], F.S. Merritt[30], H. Merritt[108],
A. Messina[29,y], J. Metcalfe[24], A.S. Mete[162], C. Meyer[80],
C. Meyer[30], J-P. Meyer[135], J. Meyer[173], J. Meyer[53],
T.C. Meyer[29], J. Miao[32d], S. Michal[29], L. Micu[25a],
R.P. Middleton[128], S. Migas[72], L. Mijović[135], G. Mikenberg[171],
M. Mikestikova[124], M. Mikuž[73], D.W. Miller[30], R.J. Miller[87],
W.J. Mills[167], C. Mills[56], A. Milov[171], D.A. Milstead[145a,145b],
D. Milstein[171], A.A. Minaenko[127], M. Miñano Moya[166],
I.A. Minashvili[63], A.I. Mincer[107], B. Mindur[37], M. Mineev[63],
Y. Ming[172], L.M. Mir[11], G. Mirabelli[131a], J. Mitrevski[136],
V.A. Mitsou[166], S. Mitsui[64], P.S. Miyagawa[138],
J.U. Mjörnmark[78], T. Moa[145a,145b], V. Moeller[27], K. Mönig[41],
N. Möser[20], S. Mohapatra[147], W. Mohr[47], R. Moles-Valls[166],
A. Molfetas[29], J. Monk[76], E. Monnier[82],
J. Montejo Berlingen[11], F. Monticelli[69], S. Monzani[19a,19b],
R.W. Moore[2], G.F. Moorhead[85], C. Mora Herrera[48],
A. Moraes[52], N. Morange[135], J. Morel[53], G. Morello[36a,36b],
D. Moreno[80], M. Moreno Llácer[166], P. Morettini[49a],
M. Morgenstern[43], M. Morii[56], A.K. Morley[29],
G. Mornacchi[29], J.D. Morris[74], L. Morvaj[100], H.G. Moser[98],
M. Mosidze[50b], J. Moss[108], R. Mount[142], E. Mountricha[9,z],
S.V. Mouraviev[93,*], E.J.W. Moyse[83], F. Mueller[57a],
J. Mueller[122], K. Mueller[20], T.A. Müller[97], T. Mueller[80],
D. Muenstermann[29], Y. Munwes[152], W.J. Murray[128],
I. Mussche[104], E. Musto[101a,101b], A.G. Myagkov[127],
M. Myska[124], J. Nadal[11], K. Nagai[159], R. Nagai[156],
K. Nagano[64], A. Nagarkar[108], Y. Nagasaka[58], M. Nagel[98],
A.M. Nairz[29], Y. Nakahama[29], K. Nakamura[154],
T. Nakamura[154], I. Nakano[109], G. Nanava[20], A. Napier[160],
R. Narayan[57b], M. Nash[76,c], T. Nattermann[20], T. Naumann[41],
G. Navarro[161], H.A. Neal[86], P.Yu. Nechaeva[93], T.J. Neep[81],
A. Negri[118a,118b], G. Negri[29], M. Negrini[19a], S. Nektarijevic[48],
A. Nelson[162], T.K. Nelson[142], S. Nemecek[124], P. Nemethy[107],
A.A. Nepomuceno[23a], M. Nessi[29,aa], M.S. Neubauer[164],
M. Neumann[174], A. Neusiedl[80], R.M. Neves[107], P. Nevski[24],
F.M. Newcomer[119], P.R. Newman[17], V. Nguyen Thi Hong[135],
R.B. Nickerson[117], R. Nicolaidou[135], B. Nicquevert[29],
F. Niedercorn[114], J. Nielsen[136], N. Nikiforou[34], A. Nikiforov[15],
V. Nikolaenko[127], I. Nikolic-Audit[77], K. Nikolics[48],
K. Nikolopoulos[17], H. Nilsen[47], P. Nilsson[7], Y. Ninomiya[154],
A. Nisati[131a], R. Nisius[98], T. Nobe[156], L. Nodulman[5],
M. Nomachi[115], I. Nomidis[153], S. Norberg[110], M. Nordberg[29],
P.R. Norton[128], J. Novakova[125], M. Nozaki[64], L. Nozka[112],
I.M. Nugent[158a], A.-E. Nuncio-Quiroz[20],
G. Nunes Hanninger[85], T. Nunnemann[97], E. Nurse[76],
B.J. O'Brien[45], S.W. O'Neale[17,*], D.C. O'Neil[141],
V. O'Shea[52], L.B. Oakes[97], F.G. Oakham[28,d], H. Oberlack[98],
J. Ocariz[77], A. Ochi[65], S. Oda[68], S. Odaka[64], J. Odier[82],
H. Ogren[59], A. Oh[81], S.H. Oh[44], C.C. Ohm[29], T. Ohshima[100],
H. Okawa[24], Y. Okumura[30], T. Okuyama[154], A. Olariu[25a],
A.G. Olchevski[63], S.A. Olivares Pino[31a], M. Oliveira[123a,h],
D. Oliveira Damazio[24], E. Oliver Garcia[166], D. Olivito[119],
A. Olszewski[38], J. Olszowska[38], A. Onofre[123a,ab],
P.U.E. Onyisi[30], C.J. Oram[158a], M.J. Oreglia[30], Y. Oren[152],
D. Orestano[133a,133b], N. Orlando[71a,71b], I. Orlov[106],
C. Oropeza Barrera[52], R.S. Orr[157], B. Osculati[49a,49b],
R. Ospanov[119], C. Osuna[11], G. Otero y Garzon[26],
J.P. Ottersbach[104], M. Ouchrif[134d], E.A. Ouellette[168],
F. Ould-Saada[116], A. Ouraou[135], Q. Ouyang[32a],
A. Ovcharova[14], M. Owen[81], S. Owen[138], V.E. Ozcan[18a],
N. Ozturk[7], A. Pacheco Pages[11], C. Padilla Aranda[11],
S. Pagan Griso[14], E. Paganis[138], C. Pahl[98], F. Paige[24], P. Pais[83],
K. Pajchel[116], G. Palacino[158b], C.P. Paleari[6], S. Palestini[29],
D. Pallin[33], A. Palma[123a], J.D. Palmer[17], Y.B. Pan[172],
E. Panagiotopoulou[9], P. Pani[104], N. Panikashvili[86],
S. Panitkin[24], D. Pantea[25a], A. Papadelis[145a],
Th.D. Papadopoulou[9], A. Paramonov[5],
D. Paredes Hernandez[33], W. Park[24,ac], M.A. Parker[27],
F. Parodi[49a,49b], J.A. Parsons[34], U. Parzefall[47], S. Pashapour[53],
E. Pasqualucci[131a], S. Passaggio[49a], A. Passeri[133a],
F. Pastore[133a,133b,*], Fr. Pastore[75], G. Pásztor[48,ad],
S. Pataraia[174], N. Patel[149], J.R. Pater[81], S. Patricelli[101a,101b],
T. Pauly[29], M. Pecsy[143a], S. Pedraza Lopez[166],
M.I. Pedraza Morales[172], S.V. Peleganchuk[106], D. Pelikan[165],
H. Peng[32b], B. Penning[30], A. Penson[34], J. Penwell[59],
M. Perantoni[23a], K. Perez[34,ae], T. Perez Cavalcanti[41],
E. Perez Codina[158a], M.T. Pérez García-Estañ[166],
V. Perez Reale[34], L. Perini[88a,88b], H. Pernegger[29],
R. Perrino[71a], P. Perrodo[4], V.D. Peshekhonov[63], K. Peters[29],
B.A. Petersen[29], J. Petersen[29], T.C. Petersen[35], E. Petit[4],
A. Petridis[153], C. Petridou[153], E. Petrolo[131a],
F. Petrucci[133a,133b], D. Petschull[41], M. Petteni[141], R. Pezoa[31b],
A. Phan[85], P.W. Phillips[128], G. Piacquadio[29], A. Picazio[48],
E. Piccaro[74], M. Piccinini[19a,19b], S.M. Piec[41], R. Piegaia[26],
D.T. Pignotti[108], J.E. Pilcher[30], A.D. Pilkington[81], J. Pina[123a,b],
M. Pinamonti[163a,163c], A. Pinder[117], J.L. Pinfold[2], B. Pinto[123a],
C. Pizio[88a,88b], M. Plamondon[168], M.-A. Pleier[24],
E. Plotnikova[63], A. Poblaguev[24], S. Poddar[57a], F. Podlyski[33],
L. Poggioli[114], D. Pohl[20], M. Pohl[48], G. Polesello[118a],
A. Policicchio[36a,36b], A. Polini[19a], J. Poll[74],
V. Polychronakos[24], D. Pomeroy[22], K. Pommès[29],
L. Pontecorvo[131a], B.G. Pope[87], G.A. Popeneciu[25a],

D.S. Popovic[12a], A. Poppleton[29], X. Portell Bueso[29], G.E. Pospelov[98], S. Pospisil[126], I.N. Potrap[98], C.J. Potter[148], C.T. Potter[113], G. Poulard[29], J. Poveda[59], V. Pozdnyakov[63], R. Prabhu[76], P. Pralavorio[82], A. Pranko[14], S. Prasad[29], R. Pravahan[24], S. Prell[62], K. Pretzl[16], D. Price[59], J. Price[72], L.E. Price[5], D. Prieur[122], M. Primavera[71a], K. Prokofiev[107], F. Prokoshin[31b], S. Protopopescu[24], J. Proudfoot[5], X. Prudent[43], M. Przybycien[37], H. Przysiezniak[4], S. Psoroulas[20], E. Ptacek[113], E. Pueschel[83], J. Purdham[86], M. Purohit[24,ac], P. Puzo[114], Y. Pylypchenko[61], J. Qian[86], A. Quadt[53], D.R. Quarrie[14], W.B. Quayle[172], F. Quinonez[31a], M. Raas[103], V. Radeka[24], V. Radescu[41], P. Radloff[113], T. Rador[18a], F. Ragusa[88a,88b], G. Rahal[177], A.M. Rahimi[108], D. Rahm[24], S. Rajagopalan[24], M. Rammensee[47], M. Rammes[140], A.S. Randle-Conde[39], K. Randrianarivony[28], F. Rauscher[97], T.C. Rave[47], M. Raymond[29], A.L. Read[116], D.M. Rebuzzi[118a,118b], A. Redelbach[173], G. Redlinger[24], R. Reece[119], K. Reeves[40], E. Reinherz-Aronis[152], A. Reinsch[113], I. Reisinger[42], C. Rembser[29], Z.L. Ren[150], A. Renaud[114], M. Rescigno[131a], S. Resconi[88a], B. Resende[135], P. Reznicek[97], R. Rezvani[157], R. Richter[98], E. Richter-Was[4,af], M. Ridel[77], M. Rijpstra[104], M. Rijssenbeek[147], A. Rimoldi[118a,118b], L. Rinaldi[19a], R.R. Rios[39], I. Riu[11], G. Rivoltella[88a,88b], F. Rizatdinova[111], E. Rizvi[74], S.H. Robertson[84,k], A. Robichaud-Veronneau[117], D. Robinson[27], J.E.M. Robinson[81], A. Robson[52], J.G. Rocha de Lima[105], C. Roda[121a,121b], D. Roda Dos Santos[29], A. Roe[53], S. Roe[29], O. Røhne[116], S. Rolli[160], A. Romaniouk[95], M. Romano[19a,19b], G. Romeo[26], E. Romero Adam[166], N. Rompotis[137], L. Roos[77], E. Ros[166], S. Rosati[131a], K. Rosbach[48], A. Rose[148], M. Rose[75], G.A. Rosenbaum[157], E.I. Rosenberg[62], P.L. Rosendahl[13], O. Rosenthal[140], L. Rosselet[48], V. Rossetti[11], E. Rossi[131a,131b], L.P. Rossi[49a], M. Rotaru[25a], I. Roth[171], J. Rothberg[137], D. Rousseau[114], C.R. Royon[135], A. Rozanov[82], Y. Rozen[151], X. Ruan[32a,ag], F. Rubbo[11], I. Rubinskiy[41], N. Ruckstuhl[104], V.I. Rud[96], J.T. Ruderman[137,ah], C. Rudolph[43], G. Rudolph[60], F. Rühr[6], A. Ruiz-Martinez[62], L. Rumyantsev[63], Z. Rurikova[47], N.A. Rusakovich[63], J.P. Rutherfoord[6], C. Ruwiedel[14,*], P. Ruzicka[124], Y.F. Ryabov[120], M. Rybar[125], G. Rybkin[114], N.C. Ryder[117], A.F. Saavedra[149], I. Sadeh[152], H.F-W. Sadrozinski[136], R. Sadykov[63], F. Safai Tehrani[131a], H. Sakamoto[154], G. Salamanna[74], A. Salamon[132a], M. Saleem[110], D. Salek[29], D. Salihagic[98], A. Salnikov[142], J. Salt[166], B.M. Salvachua Ferrando[5], D. Salvatore[36a,36b], F. Salvatore[148], A. Salvucci[103], A. Salzburger[29], D. Sampsonidis[153], B.H. Samset[116], A. Sanchez[101a,101b], V. Sanchez Martinez[166], H. Sandaker[13], H.G. Sander[80], M.P. Sanders[97], M. Sandhoff[174], T. Sandoval[27], C. Sandoval[161], R. Sandstroem[98], D.P.C. Sankey[128], A. Sansoni[46], C. Santamarina Rios[84], C. Santoni[33], R. Santonico[132a,132b], H. Santos[123a], J.G. Saraiva[123a], T. Sarangi[172], E. Sarkisyan-Grinbaum[7], F. Sarri[121a,121b], G. Sartisohn[174], O. Sasaki[64], Y. Sasaki[154], N. Sasao[66], I. Satsounkevitch[89], G. Sauvage[4,*], E. Sauvan[4], J.B. Sauvan[114], P. Savard[157,d], V. Savinov[122], D.O. Savu[29], L. Sawyer[24,m], D.H. Saxon[52], J. Saxon[119], C. Sbarra[19a], A. Sbrizzi[19a,19b], D.A. Scannicchio[162], M. Scarcella[149], J. Schaarschmidt[114], P. Schacht[98], D. Schaefer[119], U. Schäfer[80], S. Schaepe[20], S. Schaetzel[57b], A.C. Schaffer[114], D. Schaile[97], R.D. Schamberger[147], A.G. Schamov[106], V. Scharf[57a], V.A. Schegelsky[120], D. Scheirich[86], M. Schernau[162], M.I. Scherzer[34], C. Schiavi[49a,49b], J. Schieck[97], M. Schioppa[36a,36b], S. Schlenker[29], E. 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Shamim[113], L.Y. Shan[32a], J.T. Shank[21], Q.T. Shao[85], M. Shapiro[14], P.B. Shatalov[94], K. Shaw[163a,163c], D. Sherman[175], P. Sherwood[76], A. Shibata[107], S. Shimizu[100], M. Shimojima[99], T. Shin[55], M. Shiyakova[63], A. Shmeleva[93], M.J. Shochet[30], D. Short[117], S. Shrestha[62], E. Shulga[95], M.A. Shupe[6], P. Sicho[124], A. Sidoti[131a], F. Siegert[47], Dj. Sijacki[12a], O. Silbert[171], J. Silva[123a], Y. Silver[152], D. Silverstein[142], S.B. Silverstein[145a], V. Simak[126], O. Simard[135], Lj. Simic[12a], S. Simion[114], E. Simioni[80], B. Simmons[76], R. Simoniello[88a,88b], M. Simonyan[35], P. Sinervo[157], N.B. Sinev[113], V. Sipica[140], G. Siragusa[173], A. Sircar[24], A.N. Sisakyan[63,*], S.Yu. Sivoklokov[96], J. Sjölin[145a,145b], T.B. Sjursen[13], L.A. Skinnari[14], H.P. Skottowe[56], K. Skovpen[106], P. Skubic[110], M. Slater[17], T. Slavicek[126], K. Sliwa[160], V. Smakhtin[171], B.H. Smart[45], S.Yu. Smirnov[95], Y. Smirnov[95], L.N. Smirnova[96], O. Smirnova[78], B.C. Smith[56], D. Smith[142], K.M. Smith[52], M. Smizanska[70], K. Smolek[126], A.A. Snesarev[93], S.W. Snow[81], J. Snow[110], S. Snyder[24], R. Sobie[168,k], J. Sodomka[126], A. Soffer[152], C.A. Solans[166], M. Solar[126], J. Solc[126], E.Yu. Soldatov[95], U. Soldevila[166], E. Solfaroli Camillocci[131a,131b], A.A. Solodkov[127], O.V. Solovyanov[127], V. Solovyev[120], N. Soni[85], V. Sopko[126], B. Sopko[126], M. Sosebee[7], R. Soualah[163a,163c], A. Soukharev[106], S. Spagnolo[71a,71b], F. Spanò[75], R. Spighi[19a], G. Spigo[29], R. Spiwoks[29], M. Spousta[125,ai], T. Spreitzer[157], B. Spurlock[7], R.D. St. Denis[52], J. Stahlman[119], R. Stamen[57a], E. Stanecka[38], R.W. Stanek[5], C. Stanescu[133a], M. Stanescu-Bellu[41], S. Stapnes[116], E.A. Starchenko[127], J. Stark[54], P. Staroba[124], P. Starovoitov[41], R. Staszewski[38], A. Staude[97], P. Stavina[143a,*], G. Steele[52], P. Steinbach[43], P. Steinberg[24], I. Stekl[126], B. Stelzer[141], H.J. Stelzer[87], O. Stelzer-Chilton[158a], H. Stenzel[51], S. Stern[98], G.A. Stewart[29], J.A. Stillings[20], M.C. Stockton[84], K. Stoerig[47], G. Stoicea[25a],

S. Stonjek[98], P. Strachota[125], A.R. Stradling[7], A. Straessner[43], J. Strandberg[146], S. Strandberg[145a,145b], A. Strandlie[116], M. Strang[108], E. Strauss[142], M. Strauss[110], P. Strizenec[143b], R. Ströhmer[173], D.M. Strom[113], J.A. Strong[75,*], R. Stroynowski[39], J. Strube[128], B. Stugu[13], I. Stumer[24,*], J. Stupak[147], P. Sturm[174], N.A. Styles[41], D.A. Soh[150,w], D. Su[142], HS. Subramania[2], A. Succurro[11], Y. Sugaya[115], C. Suhr[105], M. Suk[125], V.V. Sulin[93], S. Sultansoy[3d], T. Sumida[66], X. Sun[54], J.E. Sundermann[47], K. Suruliz[138], G. Susinno[36a,36b], M.R. Sutton[148], Y. Suzuki[64], Y. Suzuki[65], M. Svatos[124], S. Swedish[167], I. Sykora[143a], T. Sykora[125], J. Sánchez[166], D. Ta[104], K. Tackmann[41], A. Taffard[162], R. Tafirout[158a], N. Taiblum[152], Y. Takahashi[100], H. Takai[24], R. Takashima[67], H. Takeda[65], T. Takeshita[139], Y. Takubo[64], M. Talby[82], A. Talyshev[106,f], M.C. Tamsett[24], K.G. Tan[85], J. Tanaka[154], R. Tanaka[114], S. Tanaka[130], S. Tanaka[64], A.J. Tanasijczuk[141], K. Tani[65], N. Tannoury[82], S. Tapprogge[80], D. Tardif[157], S. Tarem[151], F. Tarrade[28], G.F. Tartarelli[88a], P. Tas[125], M. Tasevsky[124], E. Tassi[36a,36b], M. Tatarkhanov[14], Y. Tayalati[134d], C. Taylor[76], F.E. Taylor[91], G.N. Taylor[85], W. Taylor[158b], M. Teinturier[114], F.A. Teischinger[29], M. Teixeira Dias Castanheira[74], P. Teixeira-Dias[75], K.K. Temming[47], H. Ten Kate[29], P.K. Teng[150], S. Terada[64], K. Terashi[154], J. Terron[79], M. Testa[46], R.J. Teuscher[157,k], J. Therhaag[20], T. Theveneaux-Pelzer[77], S. Thoma[47], J.P. Thomas[17], E.N. Thompson[34], P.D. Thompson[17], P.D. Thompson[157], A.S. Thompson[52], L.A. Thomsen[35], E. Thomson[119], M. Thomson[27], W.M. Thong[85], R.P. Thun[86], F. Tian[34], M.J. Tibbetts[14], T. Tic[124], V.O. Tikhomirov[93], Y.A. Tikhonov[106,f], S. Timoshenko[95], P. Tipton[175], S. Tisserant[82], T. Todorov[4], S. Todorova-Nova[160], B. Toggerson[162], J. Tojo[68], S. Tokár[143a], K. Tokushuku[64], K. Tollefson[87], M. Tomoto[100], L. Tompkins[30], K. Toms[102], A. Tonoyan[13], C. Topfel[16], N.D. Topilin[63], I. Torchiani[29], E. Torrence[113], H. Torres[77], E. Torró Pastor[166], J. Toth[82,ad], F. Touchard[82], D.R. Tovey[138], T. Trefzger[173], L. Tremblet[29], A. Tricoli[29], I.M. Trigger[158a], S. Trincaz-Duvoid[77], M.F. Tripiana[69], N. Triplett[24], W. Trischuk[157], B. Trocmé[54], C. Troncon[88a], M. Trottier-McDonald[141], M. Trzebinski[38], A. Trzupek[38], C. Tsarouchas[29], J.C-L. Tseng[117], M. Tsiakiris[104], P.V. Tsiareshka[89], D. Tsionou[4,aj], G. Tsipolitis[9], S. Tsiskaridze[11], V. Tsiskaridze[47], E.G. Tskhadadze[50a], I.I. Tsukerman[94], V. Tsulaia[14], J.-W. Tsung[20], S. Tsuno[64], D. Tsybychev[147], A. Tua[138], A. Tudorache[25a], V. Tudorache[25a], J.M. Tuggle[30], M. Turala[38], D. Turecek[126], I. Turk Cakir[3e], E. Turlay[104], R. Turra[88a,88b], P.M. Tuts[34], A. Tykhonov[73], M. Tylmad[145a,145b], M. Tyndel[128], G. Tzanakos[8], K. Uchida[20], I. Ueda[154], R. Ueno[28], M. Ugland[13], M. Uhlenbrock[20], M. Uhrmacher[53], F. Ukegawa[159], G. Unal[29], A. Undrus[24], G. Unel[162], Y. Unno[64], D. Urbaniec[34], G. Usai[7], M. Uslenghi[118a,118b], L. Vacavant[82], V. Vacek[126], B. Vachon[84], S. Vahsen[14], J. Valenta[124], S. Valentinetti[19a,19b], A. Valero[166], S. Valkar[125], E. Valladolid Gallego[166], S. Vallecorsa[151], J.A. Valls Ferrer[166], R. Van Berg[119], P.C. Van Der Deijl[104], R. van der Geer[104], H. van der Graaf[104], R. Van Der Leeuw[104], E. van der Poel[104], D. van der Ster[29], N. van Eldik[29], P. van Gemmeren[5], I. van Vulpen[104], M. Vanadia[98], W. Vandelli[29], A. Vaniachine[5], P. Vankov[41], F. Vannucci[77], R. Vari[131a], E.W. Varnes[6], T. Varol[83], D. Varouchas[14], A. Vartapetian[7], K.E. Varvell[149], V.I. Vassilakopoulos[55], F. Vazeille[33], T. Vazquez Schroeder[53], G. Vegni[88a,88b], J.J. Veillet[114], F. Veloso[123a], R. Veness[29], S. Veneziano[131a], A. Ventura[71a,71b], D. Ventura[83], M. Venturi[47], N. Venturi[157], V. Vercesi[118a], M. Verducci[137], W. Verkerke[104], J.C. Vermeulen[104], A. Vest[43], M.C. Vetterli[141,d], I. Vichou[164], T. Vickey[144b,ak], O.E. Vickey Boeriu[144b], G.H.A. Viehhauser[117], S. Viel[167], M. Villa[19a,19b], M. Villaplana Perez[166], E. Vilucchi[46], M.G. Vincter[28], E. Vinek[29], V.B. Vinogradov[63], M. Virchaux[135,*], J. Virzi[14], O. Vitells[171], M. Viti[41], I. Vivarelli[47], F. Vives Vaque[2], S. Vlachos[9], D. Vladoiu[97], M. Vlasak[126], A. Vogel[20], P. Vokac[126], T. Volansky[152], G. Volpi[46], M. Volpi[85], G. Volpini[88a], H. von der Schmitt[98], H. von Radziewski[47], E. von Toerne[20], V. Vorobel[125], V. Vorwerk[11], M. Vos[166], R. Voss[29], T.T. Voss[174], J.H. Vossebeld[72], N. Vranjes[135], M. Vranjes Milosavljevic[104], V. Vrba[124], M. Vreeswijk[104], T. Vu Anh[47], R. Vuillermet[29], I. Vukotic[30], W. Wagner[174], P. Wagner[119], H. Wahlen[174], S. Wahrmund[43], J. Wakabayashi[100], S. Walch[86], J. Walder[70], R. Walker[97], W. Walkowiak[140], R. Wall[175], P. Waller[72], B. Walsh[175], C. Wang[44], H. Wang[172], H. Wang[32b,al], J. Wang[150], J. Wang[54], R. Wang[102], S.M. Wang[150], T. Wang[20], A. Warburton[84], C.P. Ward[27], M. Warsinsky[47], A. Washbrook[45], C. Wasicki[41], I. Watanabe[65], P.M. Watkins[17], A.T. Watson[17], I.J. Watson[149], M.F. Watson[17], G. Watts[137], S. Watts[81], A.T. Waugh[149], B.M. Waugh[76], M.S. Weber[16], P. Weber[53], A.R. Weidberg[117], P. Weigell[98], J. Weingarten[53], C. Weiser[47], H. Wellenstein[22], P.S. Wells[29], T. Wenaus[24], D. Wendland[15], Z. Weng[150,w], T. Wengler[29], S. Wenig[29], N. Wermes[20], M. Werner[47], P. Werner[29], M. Werth[162], M. Wessels[57a], J. Wetter[160], C. Weydert[54], K. Whalen[28], S.J. Wheeler-Ellis[162], A. White[7], M.J. White[85], S. White[121a,121b], S.R. Whitehead[117], D. Whiteson[162], D. Whittington[59], F. Wicek[114], D. Wicke[174], F.J. Wickens[128], W. Wiedenmann[172], M. Wielers[128], P. Wienemann[20], C. Wiglesworth[74], L.A.M. Wiik-Fuchs[47], P.A. Wijeratne[76], A. Wildauer[98], M.A. Wildt[41,s], I. Wilhelm[125], H.G. Wilkens[29], J.Z. Will[97], E. Williams[34], H.H. Williams[119], W. Willis[34], S. Willocq[83], J.A. Wilson[17], M.G. Wilson[142], A. Wilson[86], I. Wingerter-Seez[4], S. Winkelmann[47], F. Winklmeier[29], M. Wittgen[142], S.J. Wollstadt[80], M.W. Wolter[38], H. Wolters[123a,h], W.C. Wong[40], G. Wooden[86], B.K. Wosiek[38], J. Wotschack[29], M.J. Woudstra[81], K.W. Wozniak[38], K. Wraight[52], M. Wright[52], B. Wrona[72], S.L. Wu[172], X. Wu[48], Y. Wu[32b,am], E. Wulf[34], B.M. Wynne[45], S. Xella[35], M. Xiao[135], S. Xie[47], C. Xu[32b,z], D. Xu[138], B. Yabsley[149], S. Yacoob[144a,an], M. Yamada[64], H. Yamaguchi[154], A. Yamamoto[64], K. Yamamoto[62], S. Yamamoto[154], T. Yamamura[154], T. Yamanaka[154], J. Yamaoka[44], T. Yamazaki[154], Y. 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L. Yuan[65], A. Yurkewicz[105], M. Byszewski[29], B. Zabinski[38], R. Zaidan[61], A.M. Zaitsev[127], Z. Zajacova[29], L. Zanello[131a,131b], D. Zanzi[98], A. Zaytsev[24], C. Zeitnitz[174], M. Zeman[124], A. Zemla[38], C. Zendler[20], O. Zenin[127], T. Ženiš[143a], Z. Zinonos[121a,121b], S. Zenz[14], D. Zerwas[114], G. Zevi della Porta[56], Z. Zhan[32d], D. Zhang[32b,al], H. Zhang[87], J. Zhang[5], X. Zhang[32d], Z. Zhang[114], L. Zhao[107], T. Zhao[137], Z. Zhao[32b], A. Zhemchugov[63], J. Zhong[117], B. Zhou[86], N. Zhou[162], Y. Zhou[150], C.G. Zhu[32d], H. Zhu[41], J. Zhu[86], Y. Zhu[32b], X. Zhuang[97], V. Zhuravlov[98], D. Zieminska[59], N.I. Zimin[63], R. Zimmermann[20], S. Zimmermann[20], S. Zimmermann[47], M. Ziolkowski[140], R. Zitoun[4], L. Živković[34], V.V. Zmouchko[127,*], G. Zobernig[172], A. Zoccoli[19a,19b], M. zur Nedden[15], V. Zutshi[105], L. Zwalinski[29].

[1] Physics Department, SUNY Albany, Albany NY, United States of America
[2] Department of Physics, University of Alberta, Edmonton AB, Canada
[3] [(a)]Department of Physics, Ankara University, Ankara; [(b)]Department of Physics, Dumlupinar University, Kutahya; [(c)]Department of Physics, Gazi University, Ankara; [(d)]Division of Physics, TOBB University of Economics and Technology, Ankara; [(e)]Turkish Atomic Energy Authority, Ankara, Turkey
[4] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[5] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[6] Department of Physics, University of Arizona, Tucson AZ, United States of America
[7] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[8] Physics Department, University of Athens, Athens, Greece
[9] Physics Department, National Technical University of Athens, Zografou, Greece
[10] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[11] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[12] [(a)]Institute of Physics, University of Belgrade, Belgrade; [(b)]Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[13] Department for Physics and Technology, University of Bergen, Bergen, Norway
[14] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
[15] Department of Physics, Humboldt University, Berlin, Germany
[16] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[17] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[18] [(a)]Department of Physics, Bogazici University, Istanbul; [(b)]Division of Physics, Dogus University, Istanbul; [(c)]Department of Physics Engineering, Gaziantep University, Gaziantep; [(d)]Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19] [(a)]INFN Sezione di Bologna; [(b)]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20] Physikalisches Institut, University of Bonn, Bonn, Germany
[21] Department of Physics, Boston University, Boston MA, United States of America
[22] Department of Physics, Brandeis University, Waltham MA, United States of America
[23] [(a)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)]Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)]Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[24] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[25] [(a)]National Institute of Physics and Nuclear Engineering, Bucharest; [(b)]University Politehnica Bucharest, Bucharest; [(c)]West University in Timisoara, Timisoara, Romania
[26] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[27] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[28] Department of Physics, Carleton University, Ottawa ON, Canada
[29] CERN, Geneva, Switzerland
[30] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[31] [(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32] [(a)]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)]Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)]Department of Physics, Nanjing University, Jiangsu; [(d)]School of Physics, Shandong University, Shandong, China
[33] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[34] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[35] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36] [(a)]INFN Gruppo Collegato di Cosenza; [(b)]Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[38] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39] Physics Department, Southern Methodist University, Dallas TX, United States of America
[40] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[41] DESY, Hamburg and Zeuthen, Germany
[42] Institut für Experimentelle Physik IV, Technische

Universität Dortmund, Dortmund, Germany
[43] Institut für Kern-und Teilchenphysik, Technical University Dresden, Dresden, Germany
[44] Department of Physics, Duke University, Durham NC, United States of America
[45] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[47] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[48] Section de Physique, Université de Genève, Geneva, Switzerland
[49] [(a)]INFN Sezione di Genova; [(b)]Dipartimento di Fisica, Università di Genova, Genova, Italy
[50] [(a)]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[51] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[52] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[53] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[54] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[55] Department of Physics, Hampton University, Hampton VA, United States of America
[56] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[57] [(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[58] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[59] Department of Physics, Indiana University, Bloomington IN, United States of America
[60] Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[61] University of Iowa, Iowa City IA, United States of America
[62] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[63] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[64] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[65] Graduate School of Science, Kobe University, Kobe, Japan
[66] Faculty of Science, Kyoto University, Kyoto, Japan
[67] Kyoto University of Education, Kyoto, Japan
[68] Department of Physics, Kyushu University, Fukuoka, Japan
[69] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[70] Physics Department, Lancaster University, Lancaster, United Kingdom
[71] [(a)]INFN Sezione di Lecce; [(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[72] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[73] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[74] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[75] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[76] Department of Physics and Astronomy, University College London, London, United Kingdom
[77] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[78] Fysiska institutionen, Lunds universitet, Lund, Sweden
[79] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[80] Institut für Physik, Universität Mainz, Mainz, Germany
[81] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[82] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[83] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[84] Department of Physics, McGill University, Montreal QC, Canada
[85] School of Physics, University of Melbourne, Victoria, Australia
[86] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[87] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[88] [(a)]INFN Sezione di Milano; [(b)]Dipartimento di Fisica, Università di Milano, Milano, Italy
[89] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[90] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[91] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[92] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[93] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[94] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[95] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[96] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[97] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[98] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[99] Nagasaki Institute of Applied Science, Nagasaki, Japan
[100] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

101 [(a)]INFN Sezione di Napoli; [(b)]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
102 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
103 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
104 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
105 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
106 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
107 Department of Physics, New York University, New York NY, United States of America
108 Ohio State University, Columbus OH, United States of America
109 Faculty of Science, Okayama University, Okayama, Japan
110 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
111 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
112 Palacký University, RCPTM, Olomouc, Czech Republic
113 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
114 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
115 Graduate School of Science, Osaka University, Osaka, Japan
116 Department of Physics, University of Oslo, Oslo, Norway
117 Department of Physics, Oxford University, Oxford, United Kingdom
118 [(a)]INFN Sezione di Pavia; [(b)]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
119 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
120 Petersburg Nuclear Physics Institute, Gatchina, Russia
121 [(a)]INFN Sezione di Pisa; [(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
123 [(a)]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; [(b)]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
124 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
125 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
126 Czech Technical University in Prague, Praha, Czech Republic
127 State Research Center Institute for High Energy Physics, Protvino, Russia
128 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
129 Physics Department, University of Regina, Regina SK, Canada
130 Ritsumeikan University, Kusatsu, Shiga, Japan
131 [(a)]INFN Sezione di Roma I; [(b)]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
132 [(a)]INFN Sezione di Roma Tor Vergata; [(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
133 [(a)]INFN Sezione di Roma Tre; [(b)]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
134 [(a)]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)]Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
135 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
137 Department of Physics, University of Washington, Seattle WA, United States of America
138 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
139 Department of Physics, Shinshu University, Nagano, Japan
140 Fachbereich Physik, Universität Siegen, Siegen, Germany
141 Department of Physics, Simon Fraser University, Burnaby BC, Canada
142 SLAC National Accelerator Laboratory, Stanford CA, United States of America
143 [(a)]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
144 [(a)]Department of Physics, University of Johannesburg, Johannesburg; [(b)]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
145 [(a)]Department of Physics, Stockholm University; [(b)]The Oskar Klein Centre, Stockholm, Sweden
146 Physics Department, Royal Institute of Technology, Stockholm, Sweden
147 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
148 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
149 School of Physics, University of Sydney, Sydney, Australia
150 Institute of Physics, Academia Sinica, Taipei, Taiwan
151 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
154 International Center for Elementary Particle Physics and

Department of Physics, The University of Tokyo, Tokyo, Japan
[155] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[156] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[157] Department of Physics, University of Toronto, Toronto ON, Canada
[158] [(a)]TRIUMF, Vancouver BC; [(b)]Department of Physics and Astronomy, York University, Toronto ON, Canada
[159] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[160] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
[161] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[162] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[163] [(a)]INFN Gruppo Collegato di Udine; [(b)]ICTP, Trieste; [(c)]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[164] Department of Physics, University of Illinois, Urbana IL, United States of America
[165] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[166] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[167] Department of Physics, University of British Columbia, Vancouver BC, Canada
[168] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[169] Department of Physics, University of Warwick, Coventry, United Kingdom
[170] Waseda University, Tokyo, Japan
[171] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[172] Department of Physics, University of Wisconsin, Madison WI, United States of America
[173] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[174] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[175] Department of Physics, Yale University, New Haven CT, United States of America
[176] Yerevan Physics Institute, Yerevan, Armenia
[177] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[d] Also at TRIUMF, Vancouver BC, Canada
[e] Also at Department of Physics, California State University, Fresno CA, United States of America
[f] Also at Novosibirsk State University, Novosibirsk, Russia
[g] Also at Fermilab, Batavia IL, United States of America
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal
[i] Also at Department of Physics, UASLP, San Luis Potosi, 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, United States of America
[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 QC, 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, United States of America
[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, Guanzhou, 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 de Physique, Université de Genève, Geneva, Switzerland
[ab] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
[ac] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
[ad] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ae] Also at California Institute of Technology, Pasadena CA, United States of America
[af] Also at Institute of Physics, Jagiellonian University, Krakow, Poland
[ag] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[ah] Also at Miller Institute for Basic Research in Science, University of California at Berkeley, Berkeley CA, United

States of America
[ai] Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
[aj] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[ak] Also at Department of Physics, Oxford University, Oxford, United Kingdom
[al] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[am] Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[an] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
[*] Deceased