

MIT Open Access Articles

Measurement of $W\#$ and $Z\#$ production cross sections in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous triple gauge couplings with the ATLAS detector

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Aad, G., B. Abbott, J. Abdallah, S. Abdel Khalek, A.A. Abdelalim, O. Abdinov, B. Abi, et al. "Measurement of $W\gamma$ and $Z\gamma$ Production Cross Sections in Pp Collisions at $\sqrt{s} = 7$ TeV and Limits on Anomalous Triple Gauge Couplings with the ATLAS Detector." *Physics Letters B* 717, no. 1–3 (October 2012): 49–69. © 2012 CERN

As Published: <http://dx.doi.org/10.1016/j.physletb.2012.09.017>

Publisher: Elsevier

Persistent URL: <http://hdl.handle.net/1721.1/91976>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of use: Creative Commons Attribution





Measurement of $W\gamma$ and $Z\gamma$ production cross sections in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous triple gauge couplings with the ATLAS detector [☆]

ATLAS Collaboration ^{*}

ARTICLE INFO

Article history:

Received 11 May 2012

Received in revised form 20 August 2012

Accepted 8 September 2012

Available online 12 September 2012

Editor: H. Weerts

ABSTRACT

This Letter presents measurements of $l^{\pm}\nu\gamma$ and $l^+l^-\gamma$ ($l = e, \mu$) production in 1.02 fb^{-1} of pp collision data recorded at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC in the first half of 2011. Events dominated by $W\gamma$ and $Z\gamma$ production with leptonic decays of the W and Z bosons are selected, and their production cross sections and kinematic properties are measured in several ranges of the photon transverse energy. The results are compared to Standard Model predictions and are used to determine limits on anomalous $WW\gamma$ and $ZZ\gamma/Z\gamma\gamma$ couplings.

© 2012 CERN. Published by Elsevier B.V. All rights reserved.

1. Introduction

The Standard Model (SM) predicts self-couplings of the W boson, the Z boson and the photon through the non-Abelian $SU(2)_L \times U(1)_Y$ gauge group of the electroweak sector. Experimental tests of these predictions have been made in $p\bar{p}$ and pp collider experiments through the s -channel production of one of the gauge bosons and its subsequent coupling to a final state boson pair such as WW , WZ , and $W\gamma$ (s -channel production of ZZ and $Z\gamma$ are forbidden in the SM). The production cross sections are sensitive to the couplings at the triple gauge-boson (TGC) vertices and therefore provide direct tests of SM predictions. Deviations of the TGC from the SM expectation could occur from a composite structure of the W and Z bosons, or from the presence of new bosons that decay to SM vector boson pairs. Previous measurements of $W\gamma$ and $Z\gamma$ production have been made at the Tevatron by the CDF [1] and D0 [2,3] Collaborations, and at the CERN Large Hadron Collider (LHC) by the ATLAS [4] and CMS [5] Collaborations.

In this Letter we report measurements of the production of $W\gamma$ and $Z\gamma$ boson pairs from pp collisions provided by the LHC, at a centre-of-mass energy of 7 TeV. The analysis presented here uses a data sample corresponding to an integrated luminosity of 1.02 fb^{-1} collected by the ATLAS experiment in the first half of 2011. Events triggered by high transverse energy (E_T) electrons and high transverse momentum (p_T) muons are used to select $pp \rightarrow l^{\pm}\nu\gamma + X$ and $pp \rightarrow l^+l^-\gamma + X$ production. Several processes contribute to these final states, including final state radiation (FSR) of photons from charged leptons in inclusive W or Z production, radiation

of photons from initial or final state quarks in W or Z production, and radiation of photons directly from W bosons through the $WW\gamma$ vertex.

The production processes are categorized according to the photon transverse energy. The event sample with low E_T^γ photons includes a large contribution from W/Z boson decays with final state radiation. For a better comparison to SM predictions, the events are analyzed both inclusively, with no requirements on the recoil system, and exclusively, requiring that there is no hard jet. The inclusive $V\gamma$ ($V = W$ or Z) event sample includes significant contributions of photons from final state parton fragmentation, whereas for exclusive $V\gamma$ events, the photons originate primarily as radiation from initial state quarks in W and Z production, or from the $WW\gamma$ vertex in $W\gamma$ events. The measurements of exclusive $V\gamma$ events with high E_T^γ photons are used to extract limits on anomalous triple gauge-boson couplings (aTGCs). The observed limits are compared with the corresponding measurements at the Tevatron [1–3] and LEP [6], as well as the measurements from CMS [5].

2. The ATLAS detector and the data sample

The ATLAS detector [7] is composed of an inner tracking system (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of three subsystems: the pixel and silicon microstrip (SCT) detectors cover the pseudorapidity range $|\eta| < 2.5$,¹ while the Transition Radiation

[☆] © CERN for the benefit of the ATLAS Collaboration.

^{*} E-mail address: atlas.publications@cern.ch.

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 along the beam

Tracker (TRT) has an acceptance range of $|\eta| < 2.0$. The calorimeter system covers the range $|\eta| < 4.9$ and is composed of sampling calorimeters with either liquid argon (LAR) or scintillating tiles as the active media. In the region $|\eta| < 2.5$, the EM LAR calorimeter is finely segmented and plays an important role in electron and photon identification. The MS is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, and a system of three stations of chambers for the trigger and precise measurements of muon tracks. Data were collected during the first half of 2011 from pp collisions. Events were selected by triggers requiring at least one identified electron with $E_T > 20$ GeV or a muon with $p_T > 18$ GeV. The total integrated luminosity used for this measurement is 1.02 fb^{-1} with an uncertainty of 3.7% [8,9].

3. Simulation of $W\gamma$ and $Z\gamma$ events and backgrounds

Monte Carlo (MC) event samples, including a full simulation [10] of the ATLAS detector with GEANT4 [11], are used to compare the data to the SM signal and background expectations. All MC samples are simulated with in-time pile-up (multiple pp interactions within a single bunch crossing) and out-of-time pile-up (signals from neighbouring bunch crossings). The average number of in-time pile-up for the data sample used for this analysis is 6 and extends to about 12.

The production $pp \rightarrow l^\pm \nu \gamma + X$ is modelled with the ALPGEN generator [12] interfaced to HERWIG [13] for parton shower and fragmentation processes, and to JIMMY [14] for underlying event simulation. The modelling of $pp \rightarrow l^+ l^- \gamma + X$ process is performed with SHERPA generator [15] since the simulation of this process is not available in ALPGEN. The CTEQ6L1 [16] and CTEQ6.6M [17] parton distribution functions (PDF) are used for samples generated with ALPGEN and SHERPA, respectively. The FSR photons from charged leptons is handled by PHOTOS [19] for the ALPGEN sample, and by the SHERPA generator for the SHERPA sample. All the signal production processes, including the photon fragmentation, are simulated by these two generators. The ALPGEN sample is generated with leading-order (LO) matrix elements for final states with up to five partons, whereas the SHERPA sample is generated with LO matrix elements for final states with up to three partons. The $Z \rightarrow ll$ and $W \rightarrow \tau \nu$ backgrounds are modelled with PYTHIA [18]. The radiation of photons from charged leptons is treated in PYTHIA using PHOTOS. TAUOLA [20] is used for τ lepton decays. The POWHEG [21] generator is used to simulate $t\bar{t}$ production, interfaced to PYTHIA for parton showering. The WW and single-top quark productions are modelled by MC@NLO [22,23], interfaced to HERWIG for parton showering and fragmentation. The next-to-leading-order (NLO) cross-section predictions are used to normalize the simulated background events. Other backgrounds are derived from data as described in Section 6.

4. Reconstruction and selection of $W\gamma$ and $Z\gamma$ candidates

The W and Z bosons are selected through their decays into $e\nu$, $\mu\nu$ and e^+e^- , $\mu^+\mu^-$, respectively. The $W\gamma$ final state consists of an isolated electron or muon, large missing transverse momentum due to the undetected neutrino, and an isolated photon. The $Z\gamma$ final state contains one e^+e^- or $\mu^+\mu^-$ pair and an isolated photon.

pipe. 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 $\eta = -\text{In} \tan(\theta/2)$. The distance ΔR in the η - ϕ space is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Collision events are selected by requiring at least one reconstructed vertex with at least three charged particle tracks. If more than one vertex satisfies the vertex selection requirement, the vertex with the highest sum of the p_T^2 of the associated tracks is chosen.

An electron candidate is obtained from an energy cluster in the EM calorimeter associated with a reconstructed charged particle in the ID. The electron's E_T must be greater than 25 GeV. To avoid the transition regions between the calorimeters, the electron cluster must satisfy $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The selection of $W(\rightarrow e\nu)\gamma$ events requires one electron passing tight identification cuts [24]. Two oppositely charged electrons passing medium identification cuts [24] are required in the $Z(\rightarrow e^+e^-)\gamma$ selection. To reduce the background due to a jet misidentified as an electron in the $W\gamma$ analysis, a calorimeter-based isolation requirement $E_T^{\text{iso}} < 6$ GeV is applied to the electron candidate. E_T^{iso} is the total transverse energy recorded in the calorimeters within a cone of radius $\Delta R = 0.3$ around the electron direction (excluding the energy from the electron cluster). E_T^{iso} is corrected for leakage of the electron energy outside the electron cluster and for contributions from the underlying event and pile-up [25].

Muon candidates are identified by associating complete tracks or track segments in the MS to tracks in the ID [26]. Each selected muon candidate is a combined track originating from the primary vertex with transverse momentum $p_T > 25$ GeV and $|\eta| < 2.4$. It is required to be isolated by imposing $R^{\text{iso}}(\mu) < 0.1$, where $R^{\text{iso}}(\mu)$ is the sum of the track p_T in a $\Delta R = 0.2$ cone around the muon direction divided by the muon p_T . For the $W(\rightarrow \mu\nu)\gamma$ measurement at least one muon candidate is required in the event, whereas for the $Z(\rightarrow \mu^+\mu^-)\gamma$ measurement, the selected events must have exactly two oppositely charged muon candidates.

Photon candidates use clustered energy deposits in the EM calorimeter in the range $|\eta| < 2.37$ (excluding the calorimeter transition region $1.37 < |\eta| < 1.52$) with $E_T > 15$ GeV. Requirements on the shower shape [25] are applied to suppress the background from multiple showers produced in meson (e.g. π^0 , η) decays. To further reduce this background, a photon isolation requirement $E_T^{\text{iso}} < 6$ GeV is applied. The definition of photon isolation is similar to the electron isolation described above.

The reconstruction of the missing transverse momentum (E_T^{miss}) [27] is based on the energy deposits in calorimeter cells inside three-dimensional clusters. Corrections for the calorimeter response to hadrons, dead material, out-of-cluster energy, as well as muon momentum are applied. A selection requirement of $E_T^{\text{miss}} > 25$ GeV is applied in the $W\gamma$ analysis.

Jets are reconstructed from calorimeter clusters using the anti- k_t jet clustering algorithm [28] with radius parameter $R = 0.4$. The selected jets are required to have $p_T > 30$ GeV with $|\eta| < 4.4$, and to be well separated from the lepton and photon candidates ($\Delta R(e/\mu/\gamma, \text{jet}) > 0.6$). In the exclusive $W\gamma$ and $Z\gamma$ analyses, events with one or more jets are vetoed.

For each selected $W\gamma$ candidate event, in addition to the presence of one high p_T lepton, one high E_T isolated photon and large E_T^{miss} , the transverse mass of the lepton- E_T^{miss} system is required to

be $m_T(l, \nu) = \sqrt{2p_T(l) \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi)} > 40$ GeV, where $\Delta\phi$ is the azimuthal separation between the directions of the lepton and the missing transverse momentum vector. A Z -veto requirement is applied in the electron channel of the $W\gamma$ analysis by asking that the electron-photon invariant mass ($m_{e\gamma}$) is not within 10 GeV of the Z boson mass.

For $Z\gamma$ candidates, the invariant mass of the two oppositely charged leptons is required to be greater than 40 GeV. In both $W\gamma$ and $Z\gamma$ analyses, a requirement $\Delta R(l, \gamma) > 0.7$ is applied to suppress the contributions from FSR photons in W and Z boson decays.

5. Signal efficiencies

The efficiencies of the lepton selections, and the lepton triggers, are first estimated from the $W/Z + \gamma$ signal MC events and then corrected with scale factors derived using high purity lepton data samples from W and Z boson decays to account for small discrepancies between the data and the MC simulation [24–26,29].

The average efficiency for the tight electron selection in $W\gamma$ events is $(74.9 \pm 1.2)\%$. For the medium quality electron selection in $Z\gamma$ events, the efficiency is $(96.4 \pm 1.4)\%$ and $(91.0 \pm 1.6)\%$ for the leading and sub-leading electron, respectively. The electron-isolation efficiency is $> 99\% \pm 1\%$. The uncertainties reported throughout this Letter, unless stated otherwise, reflect the combined statistical and systematic uncertainties. The efficiency of the electron trigger, which is used to select the data sample for the electron decay channels, is found to be $> 99.5\%$ for both tight and medium electron candidates.

The muon-identification efficiency for the $W\gamma$ and $Z\gamma$ analyses is estimated to be $(90 \pm 1)\%$. The muon-isolation efficiency is $> 99\%$ with negligible uncertainty. The efficiency of the muon trigger to select the $W\gamma$ and $Z\gamma$ events is $(83 \pm 1)\%$ and $(97 \pm 1)\%$, respectively.

The photon identification efficiency is determined from $W\gamma$ and $Z\gamma$ MC samples where the shower shape distributions are corrected to account for the observed small discrepancies between data and simulation. The photon identification efficiency increases with the photon E_T , and is estimated to be 68%, 88% and 90% for photons with $E_T > 15, 60$ and 100 GeV, respectively. The main sources of systematic uncertainty come from the imperfect knowledge of the material in front of the calorimeter, the background contamination in the samples used to determine the corrections to the shower shape variables, and pile-up effects [25]. The systematic uncertainty in the identification efficiency due to the uncertainty in the photon contributions from quark/gluon fragmentation is also considered. The overall relative uncertainty in the photon identification efficiency is 11% for $E_T > 15$ GeV, decreasing to 4.5% for $E_T > 60$ or 100 GeV. The photon isolation efficiency is estimated using $W\gamma$ and $Z\gamma$ signal MC events and cross-checked with data using electrons from $Z \rightarrow e^+e^-$ decays [24]. The estimated efficiency varies from $(98 \pm 1.5)\%$ for $E_T > 15$ GeV to $(91 \pm 2.5)\%$ for $E_T > 100$ GeV.

6. Background determination and signal yield

The dominant source of background in this analysis comes from $V + \text{jets}$ ($V = W$ or Z) events where photons from the decays of mesons produced in jet fragmentation (mainly $\pi^0 \rightarrow \gamma\gamma$) pass the photon selection criteria. Since the fragmentation functions of quarks and gluons into hadrons are poorly constrained by experiments, these processes may not be well modelled by the MC simulation. Therefore the $V + \text{jets}$ backgrounds are derived from data.

For the $W\gamma$ analysis, another important source of background which is not well modelled by MC simulations is the $\gamma + \text{jets}$ process. These background events can be misidentified as $W\gamma$ events when there are leptons from heavy quark decays (or the hadrons inside jets are misidentified as leptons) and large apparent E_T^{miss} is created by the mis-measurement of the jet energies.

The background contributions from $W + \text{jets}$ and $\gamma + \text{jets}$ events in the $W\gamma$ analysis, or from $Z + \text{jets}$ events in the $Z\gamma$ analysis, are estimated from data.

The $Z \rightarrow l^+l^-$ process is also one of the dominant backgrounds in the $W\gamma$ analysis. Its contribution is estimated from MC simulation, since this process is well understood and modelled. Other backgrounds such as those from $t\bar{t}$ decay for the $Z\gamma$ analysis, and

those from electroweak (EW) processes ($W \rightarrow \tau\nu, WW$), single top and $t\bar{t}$ for the $W\gamma$ analysis, are less important and are estimated from MC simulation. These processes, together with the $Z \rightarrow l^+l^-$ background, are referred to collectively as “EW + $t\bar{t}$ background”.

The misidentified photons (leptons) in $V + \text{jets}$ ($\gamma + \text{jets}$) events are more likely to fail the photon (lepton) isolation criteria. A “pass-to-fail” ratio f_γ (f_l) is defined as the ratio of photon (lepton) candidates passing the photon (lepton) isolation criteria to the number of candidates failing the isolation requirement. The ratio f_γ is measured in $W \rightarrow l\nu$ ($Z \rightarrow l^+l^-$) events with one “low quality” photon candidate. A “low quality” photon candidate is defined as one that fails the photon shower-shape selection criteria, but passes a background-enriching subset of these criteria. The ratio f_e is measured in a control sample, which requires the events to pass all the $W + \gamma$ selection criteria, except the E_T^{miss} requirement. The control sample for f_μ measurement is defined in a way similar to that used for f_e , except that in addition the muon track is required to have a large impact parameter in order to enhance the heavy flavor component. The estimated contribution of $V + \text{jets}$ is obtained by multiplying the measured f_γ by the number of events passing all $V + \gamma$ selections, except the photon isolation requirement. Similarly the $\gamma + \text{jets}$ background is estimated using the measured f_l .

The accuracy of the $W/Z/\gamma + \text{jets}$ background determination has been assessed in detail. The ratios f_γ and f_l , which are measured in background-enriched samples, may be biased due to the different composition of these samples and the signal sample. To estimate the uncertainty in f_γ from this source, two sets of alternative selections, with tighter and looser background selection requirements, are used to obtain alternative control samples. f_e is also measured in an alternative control sample selected by requiring that events pass all $W + \gamma$ selection criteria, except that the electron fails the tight identification criteria but passes the low quality criteria. To determine the systematic uncertainty on f_μ , the E_T^{miss} and impact parameter requirements for the muon track are varied to obtain alternative control samples. The $W/Z/\gamma + \text{jets}$ background estimates from the alternative control samples are consistent with those obtained from the nominal samples, and the differences are assigned as systematic uncertainties. The changes in the background estimates from varying the photon or lepton isolation requirements are also assigned as systematic uncertainties.

Extrapolation methods are used to cross-check the $W/Z/\gamma + \text{jets}$ background estimates in the high E_T^γ region, where few events are available. The extrapolation method scales the well-measured background level in the low E_T^γ region to the high E_T^γ region using the E_T^γ distribution shape obtained from control samples. The differences between results obtained from the nominal and extrapolation methods are used as additional uncertainties.

The uncertainties on the “ $tt + \text{EW}$ ” background include the theoretical uncertainty on the NLO cross section (between 6%–7% depending on the process), the luminosity uncertainty (3.7%) [8,9] and the experimental systematic uncertainty. The latter is dominated by the uncertainties on the jet energy scale (5%) and the EM shower shape modelling in the MC simulation (4%–11%).

A summary of background contributions and signal yields in the $W\gamma$ and $Z\gamma$ analyses is given in Table 1 and Table 2, respectively. The photon transverse energy and jet multiplicity distributions from the selected $W\gamma$ and $Z\gamma$ events are shown in Fig. 1 and Fig. 2, respectively. The data are compared to the sum of the backgrounds and the SM signal predictions. The distributions for the expected $W\gamma$ and $Z\gamma$ signal are taken from signal MC simulation and normalized to the extracted number of signal events shown in Table 1 ($N_{W\gamma}^{\text{sig}}$) and Table 2 ($N_{Z\gamma}^{\text{sig}}$).

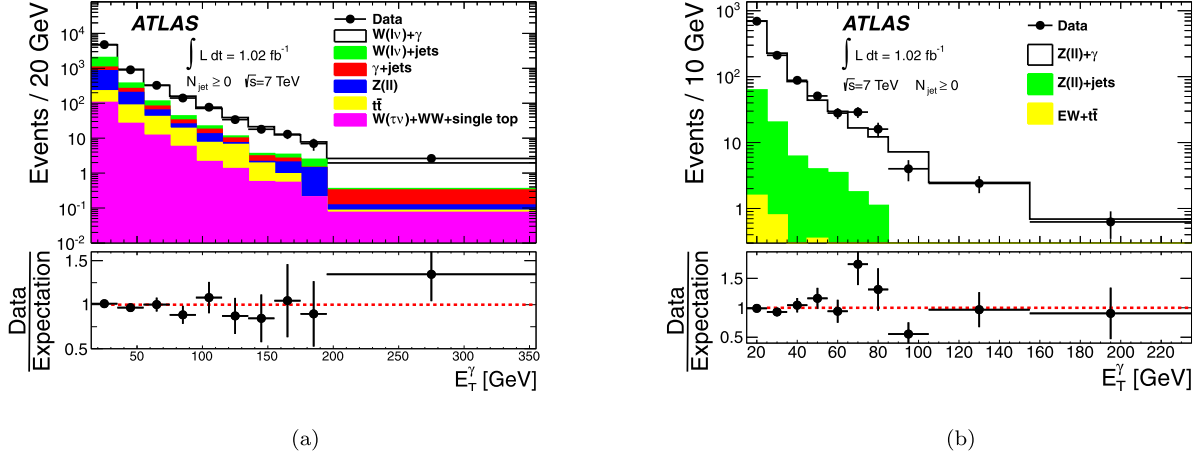


Fig. 1. Distributions of the photon transverse energy for the combined electron and muon decay channels in (a) $W\gamma$ candidate events and (b) $Z\gamma$ candidate events, with no requirements on the recoil system. The selection criteria are defined in Section 4. The distributions for the expected signals are taken from the MC simulation and normalized to the extracted number of signal events shown in Table 1 and Table 2. The ratio between the number of candidates observed in the data and the number of expected candidates from the signal MC simulation and from the background processes is also shown.

Table 1

Expected numbers of background events, observed numbers of signal events ($N_{W\gamma}^{\text{sig}}$) and total numbers of events passing the selection requirements in the data ($N_{W\gamma}^{\text{obs}}$) for the $pp \rightarrow e\nu\gamma$ channel and the $pp \rightarrow \mu\nu\gamma$ channel in different E_T^{γ} and jet multiplicity regions. The combined statistical and systematic uncertainties are shown. The uncertainty on the background prediction is dominated by systematic uncertainties in all regions. The contribution from the EW background is dominated by the $Z \rightarrow e^+e^-(\mu^+\mu^-)$ process.

| | $pp \rightarrow e\nu\gamma$ | $pp \rightarrow \mu\nu\gamma$ | $pp \rightarrow e\nu\gamma$ | $pp \rightarrow \mu\nu\gamma$ |
|----------------------------|---|-------------------------------|--|-------------------------------|
| Region | $E_T^{\gamma} > 15 \text{ GeV}$ $N_{\text{jet}} \geq 0$ | | $E_T^{\gamma} > 15 \text{ GeV}$ $N_{\text{jet}} = 0$ | |
| $N_{W\gamma}^{\text{obs}}$ | 2649 | 3621 | 1666 | 2238 |
| W + jets | 439 ± 108 | 685 ± 162 | 242 ± 68 | 473 ± 128 |
| γ + jets | 255 ± 58 | 67 ± 16 | 119 ± 34 | 28.9 ± 7.4 |
| EW | 405 ± 53 | 519 ± 67 | 229 ± 30 | 366 ± 48 |
| $t\bar{t}$ | 85 ± 11 | 152 ± 20 | 1.6 ± 0.4 | 8.1 ± 1.3 |
| $N_{W\gamma}^{\text{sig}}$ | 1465 ± 139 | 2198 ± 183 | 1074 ± 91 | 1362 ± 145 |
| Region | $E_T^{\gamma} > 60 \text{ GeV}$ $N_{\text{jet}} \geq 0$ | | $E_T^{\gamma} > 60 \text{ GeV}$ $N_{\text{jet}} = 0$ | |
| $N_{W\gamma}^{\text{obs}}$ | 216 | 307 | 76 | 104 |
| W + jets | 14.2 ± 6.9 | 27.1 ± 10.1 | 6.4 ± 3.5 | 12.9 ± 5.9 |
| γ + jets | 10.8 ± 6.6 | 7.1 ± 5.1 | 5.5 ± 4.2 | $1.7^{+4.5}_{-0.7}$ |
| EW | 32.0 ± 3.6 | 29.9 ± 3.6 | 9.2 ± 1.8 | 12.6 ± 2.0 |
| $t\bar{t}$ | 13.1 ± 1.4 | 29.5 ± 3.2 | 0.3 ± 0.2 | 2.4 ± 0.6 |
| $N_{W\gamma}^{\text{sig}}$ | 146 ± 16 | 214 ± 19 | 54.6 ± 9.4 | 74.4 ± 11.4 |
| Region | $E_T^{\gamma} > 100 \text{ GeV}$ $N_{\text{jet}} \geq 0$ | | $E_T^{\gamma} > 100 \text{ GeV}$ $N_{\text{jet}} = 0$ | |
| $N_{W\gamma}^{\text{obs}}$ | 61 | 85 | 21 | 18 |
| W + jets | 4.5 ± 2.8 | 2.8 ± 2.1 | 2.9 ± 2.2 | $0.4^{+0.7}_{-0.4}$ |
| γ + jets | 2.4 ± 2.4 | $2.4^{+2.7}_{-2.4}$ | $1.0^{+2.3}_{-1.0}$ | $0.2^{+0.7}_{-0.2}$ |
| EW | 5.8 ± 1.1 | 8.0 ± 1.8 | 2.5 ± 0.8 | 4.0 ± 1.1 |
| $t\bar{t}$ | 3.4 ± 0.6 | 7.6 ± 0.9 | 0.2 ± 0.1 | 0.6 ± 0.3 |
| $N_{W\gamma}^{\text{sig}}$ | 44.9 ± 7.7 | 64.2 ± 8.9 | 14.4 ± 5.0 | 12.8 ± 3.8 |

7. Cross-section measurements

The cross sections of the $W\gamma$ and $Z\gamma$ processes are measured as a function of the photon E_T^{γ} threshold. The measurements are

Table 2

Expected numbers of background events ($N_{Z\gamma}^{\text{BG}}$), observed numbers of signal events ($N_{Z\gamma}^{\text{sig}}$) and total numbers of events passing the selection requirements in the data ($N_{Z\gamma}^{\text{obs}}$) for the $pp \rightarrow e^+e^-\gamma$ channel and the $pp \rightarrow \mu^+\mu^-\gamma$ channel in different E_T^{γ} and jet multiplicity regions. The combined statistical and systematic uncertainties are shown. The uncertainty on the background prediction is dominated by systematic uncertainties in all regions. The background comes predominantly from Z + jets events.

| | $e^+e^-\gamma$ | $\mu^+\mu^-\gamma$ | $e^+e^-\gamma$ | $\mu^+\mu^-\gamma$ |
|----------------------------|--|--------------------|---|--------------------|
| Region | $E_T^{\gamma} > 15 \text{ GeV}$ $N_{\text{jet}} \geq 0$ | | $E_T^{\gamma} > 15 \text{ GeV}$ $N_{\text{jet}} = 0$ | |
| $N_{Z\gamma}^{\text{obs}}$ | 514 | 634 | 376 | 495 |
| $N_{Z\gamma}^{\text{BG}}$ | 43.7 ± 16.5 | 56.8 ± 16.2 | 29.3 ± 11.0 | 39.3 ± 15.8 |
| $N_{Z\gamma}^{\text{sig}}$ | 471 ± 28 | 578 ± 29 | 347 ± 22 | 456 ± 27 |
| Region | $E_T^{\gamma} > 60 \text{ GeV}$ $N_{\text{jet}} \geq 0$ | | $E_T^{\gamma} > 60 \text{ GeV}$ $N_{\text{jet}} = 0$ | |
| $N_{Z\gamma}^{\text{obs}}$ | 40 | 46 | 24 | 32 |
| $N_{Z\gamma}^{\text{BG}}$ | 4.1 ± 2.4 | 5.1 ± 3.3 | 1.6 ± 1.6 | 2.1 ± 2.1 |
| $N_{Z\gamma}^{\text{sig}}$ | 35.9 ± 6.7 | 40.9 ± 7.1 | 22.4 ± 5.1 | 29.9 ± 5.9 |

performed in the fiducial region, defined at the particle level using the objects and event kinematic selection criteria described in Section 4, and then extrapolated to an extended fiducial region (as defined in Table 3) common to the electron and muon final states. Particle level is the simulation stage where stable particles, with lifetimes exceeding 10 ps, are produced from the hard scattering or after hadronization, but before interacting with the detector. The extrapolation is performed to correct for the signal acceptance loss in the calorimeter transition region ($1.37 < |\eta| < 1.52$) for electrons and photons, for the loss in the high η region ($2.4 < |\eta| < 2.47$) for muons, for the loss due to the Z -veto requirement in the $W\gamma$ electron channel, and for the loss due to the transverse mass selection criteria in the $W\gamma$ analysis. Jets at the particle level are reconstructed in MC-generated events by applying the anti- k_t jet reconstruction algorithm with a radius parameter $R = 0.4$ to all final state stable particles. To account for the effect of final state QED radiation, the energy of the generated lepton at the particle level is defined as the energy of the lepton after radiation plus the energy of all radiated photons within $\Delta R < 0.1$ around the lepton direction. Isolated photons with $\epsilon_h^p < 0.5$ are considered as signal, where ϵ_h^p is defined at particle level as the ratio between the sum

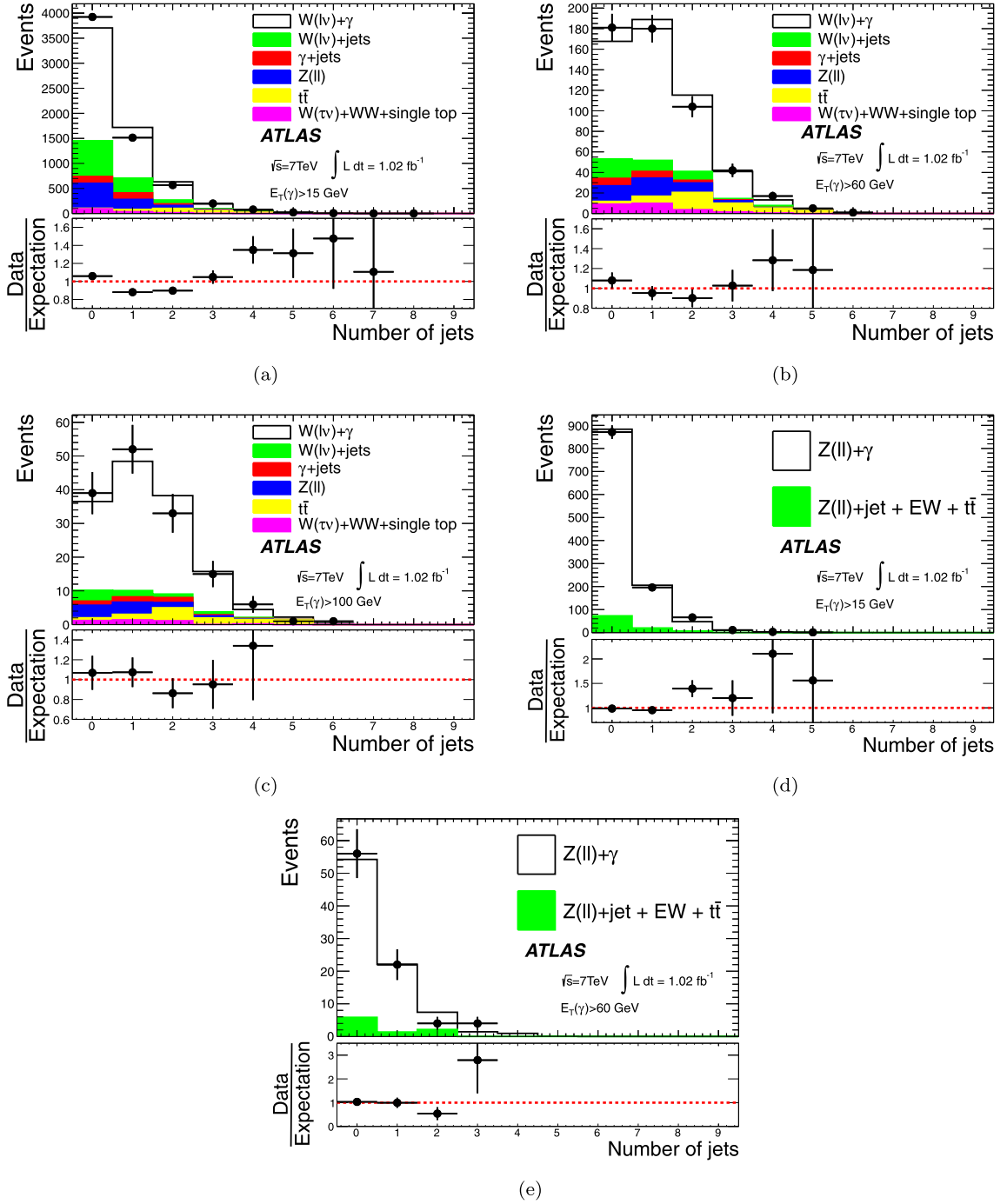


Fig. 2. Distributions of the jet multiplicity for the combined electron and muon decay channels in (a) $W\gamma$ candidate events with $E_T^\gamma > 15$ GeV, (b) $W\gamma$ candidate events with $E_T^\gamma > 60$ GeV, (c) $W\gamma$ candidate events with $E_T^\gamma > 100$ GeV, (d) $Z\gamma$ candidate events with $E_T^\gamma > 15$ GeV, and (e) $Z\gamma$ candidate events with $E_T^\gamma > 60$ GeV. The selection criteria are defined in Section 4. Distributions for expected signal contribution are taken from signal MC simulation and normalized to the extracted number of signal events as shown in Table 1 and Table 2. The ratio between the number of candidates observed in the data and the number of expected candidates from the signal MC simulation and from the background processes is also shown.

of the energies carried by final state particles in a cone $\Delta R < 0.4$ around the photon direction and the energy carried by the photon.

The measurements of cross sections for the processes $pp \rightarrow l\nu\gamma + X$ and $pp \rightarrow l^+l^-\gamma + X$ are expressed as

$$\sigma_{pp \rightarrow l\nu\gamma(l^+l^-\gamma)}^{\text{ext-fid}} = \frac{N_{W\gamma(Z\gamma)}^{\text{sig}}}{A_{W\gamma(Z\gamma)} \cdot C_{W\gamma(Z\gamma)} \cdot L} \quad (1)$$

where

- $N_{W\gamma}^{\text{sig}}$ and $N_{Z\gamma}^{\text{sig}}$ denote the numbers of background-subtracted signal events passing the selection criteria of the analyses in the $W\gamma$ and $Z\gamma$ channels. These numbers are listed in Table 1 and Table 2.
- L denotes the integrated luminosities for the channels of interest (1.02 fb^{-1}).
- $C_{W\gamma}$ and $C_{Z\gamma}$ denote the ratios of the number of generated events which pass the final selection requirements after recon-

Table 3

Definition of the extended fiducial region where the cross sections are evaluated; p_T^γ is the transverse momentum of the neutrino from W decays.

| Cuts | $pp \rightarrow l\nu\gamma$ | $pp \rightarrow l^+l^-\gamma$ |
|--------|---|---------------------------------------|
| Lepton | $p_T^l > 25$ GeV $p_T^\nu > 25$ GeV $ \eta_l < 2.47$ | $p_T^l > 25$ GeV $ \eta_l < 2.47$ |
| Boson | | $m_{l+l^-} > 40$ GeV |
| Photon | Low E_T^γ : $E_T^\gamma > 15$ GeV Medium E_T^γ : $E_T^\gamma > 60$ GeV High E_T^γ : $E_T^\gamma > 100$ GeV $ \eta^\gamma < 2.37$, $\Delta R(l, \gamma) > 0.7$ photon isolation fraction $\epsilon_h^p < 0.5$ | |
| Jet | $E_T^{\text{jet}} > 30$ GeV, $ \eta^{\text{jet}} < 4.4$ $\Delta R(e/\mu/\gamma, \text{jet}) > 0.6$ Inclusive: $N^{\text{jet}} \geq 0$, Exclusive: $N^{\text{jet}} = 0$ | |

struction to the number of generated events at particle level found within the fiducial region [26].

- $A_{W\gamma}$ and $A_{Z\gamma}$ denote the acceptances, defined at particle level as the ratio of the number of generated events found within the fiducial region to the number of generated events within the extended fiducial region.

The correction factors $C_{W\gamma}$ and $C_{Z\gamma}$ are shown in Table 4. They are determined using the $W/Z + \gamma$ signal MC events and corrected with scale factors to account for small discrepancies between data and simulation. The uncertainties on $C_{W\gamma}$ and $C_{Z\gamma}$ due to the object selection efficiency are described in Section 5. The uncertainties on $C_{W\gamma}$ and $C_{Z\gamma}$ due to the energy scale and resolution of the objects are summarized below.

The muon momentum scale and resolution are studied by comparing the invariant mass distribution of $Z \rightarrow \mu^+\mu^-$ events in data and MC simulation [26]. The uncertainty in the acceptance of the $W\gamma$ or $Z\gamma$ signal events due to the uncertainties in the muon momentum scale and resolution is $<1\%$. Similarly the uncertainty due to the uncertainties in the EM energy scale and resolution is found to be $<2.5\%$. The uncertainty from the jet energy scale and resolution on the exclusive $W\gamma$ and $Z\gamma$ signal acceptance varies in the range 5%–7%. The uncertainty due to the E_T^{miss} requirement is estimated to be 3%. It is due to several factors, including the uncertainty on the energy scale of the clusters reconstructed in the calorimeter that are not associated with any identified objects, and uncertainties from pile-up and muon momentum correction.

The overall relative uncertainties in $C_{W\gamma}$ and $C_{Z\gamma}$ are as large as 12.5% in the low E_T^γ fiducial region and as large as 8.3% in the medium and high E_T^γ fiducial region. They are dominated by the photon identification efficiency and the jet energy scale.

The acceptances $A_{W\gamma}$ and $A_{Z\gamma}$ are calculated using the signal MC simulation and shown in Table 4. The systematic uncertainties are dominated by the limited knowledge of the PDFs ($<1\%$) and of the renormalization and factorization scales ($<1\%$ for low E_T^γ region, $<3.5\%$ for medium and high E_T^γ region).

Assuming lepton universality for the W and Z boson decays, the measured cross sections in the two channels are combined to reduce the statistical uncertainty. For the combination, it is assumed that the uncertainties on the lepton trigger and identification efficiencies are uncorrelated. All other uncertainties, such as the uncertainties in the photon efficiency, background estimation, and jet energy scale, are assumed to be fully correlated. The

Table 4

Summary of acceptance $A_{W\gamma}$ ($A_{Z\gamma}$) and correction factors $C_{W\gamma}$ ($C_{Z\gamma}$) for the calculation of the $W\gamma$ ($Z\gamma$) production cross sections.

| E_T^γ | > 15 GeV | > 60 GeV | > 100 GeV |
|---------------|--------------------------------------|-------------------|-------------------|
| | $N_{\text{jet}} = 0, e$ channel | | |
| $C_{W\gamma}$ | 0.402 ± 0.049 | 0.574 ± 0.045 | 0.517 ± 0.043 |
| $A_{W\gamma}$ | 0.762 ± 0.006 | 0.685 ± 0.017 | 0.672 ± 0.019 |
| $C_{Z\gamma}$ | 0.397 ± 0.045 | 0.592 ± 0.044 | – |
| $A_{Z\gamma}$ | 0.829 ± 0.014 | 0.834 ± 0.008 | – |
| | $N_{\text{jet}} = 0, \mu$ channel | | |
| $C_{W\gamma}$ | 0.453 ± 0.054 | 0.653 ± 0.057 | 0.675 ± 0.059 |
| $A_{W\gamma}$ | 0.908 ± 0.006 | 0.764 ± 0.019 | 0.708 ± 0.017 |
| $C_{Z\gamma}$ | 0.459 ± 0.052 | 0.641 ± 0.044 | – |
| $A_{Z\gamma}$ | 0.915 ± 0.016 | 0.917 ± 0.008 | – |
| | $N_{\text{jet}} \geq 0, e$ channel | | |
| $C_{W\gamma}$ | 0.453 ± 0.053 | 0.598 ± 0.036 | 0.576 ± 0.035 |
| $A_{W\gamma}$ | 0.725 ± 0.050 | 0.657 ± 0.011 | 0.666 ± 0.017 |
| $C_{Z\gamma}$ | 0.421 ± 0.044 | 0.609 ± 0.036 | – |
| $A_{Z\gamma}$ | 0.826 ± 0.014 | 0.836 ± 0.050 | – |
| | $N_{\text{jet}} \geq 0, \mu$ channel | | |
| $C_{W\gamma}$ | 0.511 ± 0.057 | 0.650 ± 0.035 | 0.624 ± 0.035 |
| $A_{W\gamma}$ | 0.872 ± 0.005 | 0.776 ± 0.019 | 0.747 ± 0.023 |
| $C_{Z\gamma}$ | 0.485 ± 0.055 | 0.645 ± 0.035 | – |
| $A_{Z\gamma}$ | 0.915 ± 0.016 | 0.917 ± 0.005 | – |

Table 5

Measured cross sections for the $pp \rightarrow l\nu\gamma + X$ and $pp \rightarrow ll\gamma + X$ processes at $\sqrt{s} = 7$ TeV in the extended fiducial region defined in Table 3. The first uncertainty is statistical and the second is systematic. The 3.7% luminosity uncertainty is not included.

| | $\sigma^{\text{ext-fid}}$ [pb] | $\sigma^{\text{ext-fid}}$ [pb] |
|--------------------|-------------------------------------|-------------------------------------|
| | $E_T^\gamma > 15$ GeV exclusive | $E_T^\gamma > 15$ GeV inclusive |
| $e\nu\gamma$ | $3.42 \pm 0.14 \pm 0.50$ | $4.35 \pm 0.16 \pm 0.64$ |
| $\mu\nu\gamma$ | $3.23 \pm 0.14 \pm 0.48$ | $4.82 \pm 0.15 \pm 0.64$ |
| $l\nu\gamma$ | $3.32 \pm 0.10 \pm 0.48$ | $4.60 \pm 0.11 \pm 0.64$ |
| $e^+e^-\gamma$ | $1.03 \pm 0.06 \pm 0.13$ | $1.32 \pm 0.07 \pm 0.16$ |
| $\mu^+\mu^-\gamma$ | $1.06 \pm 0.05 \pm 0.12$ | $1.27 \pm 0.06 \pm 0.15$ |
| $l^+l^-\gamma$ | $1.05 \pm 0.04 \pm 0.12$ | $1.29 \pm 0.05 \pm 0.15$ |
| | $E_T^\gamma > 60$ GeV exclusive | $E_T^\gamma > 60$ GeV inclusive |
| $e\nu\gamma$ | $0.14 \pm 0.02 \pm 0.02$ | $0.36 \pm 0.03 \pm 0.03$ |
| $\mu\nu\gamma$ | $0.15 \pm 0.02 \pm 0.02$ | $0.41 \pm 0.03 \pm 0.03$ |
| $l\nu\gamma$ | $0.15 \pm 0.01 \pm 0.02$ | $0.38 \pm 0.02 \pm 0.03$ |
| $e^+e^-\gamma$ | $0.044 \pm 0.010 \pm 0.004$ | $0.069 \pm 0.012 \pm 0.006$ |
| $\mu^+\mu^-\gamma$ | $0.050 \pm 0.010 \pm 0.004$ | $0.068 \pm 0.011 \pm 0.005$ |
| $l^+l^-\gamma$ | $0.047 \pm 0.007 \pm 0.004$ | $0.068 \pm 0.008 \pm 0.005$ |
| | $E_T^\gamma > 100$ GeV exclusive | $E_T^\gamma > 100$ GeV inclusive |
| $e\nu\gamma$ | $0.040 \pm 0.011 \pm 0.009$ | $0.114 \pm 0.018 \pm 0.010$ |
| $\mu\nu\gamma$ | $0.026 \pm 0.008 \pm 0.003$ | $0.135 \pm 0.018 \pm 0.010$ |
| $l\nu\gamma$ | $0.030 \pm 0.006 \pm 0.006$ | $0.125 \pm 0.013 \pm 0.010$ |

measured production cross sections for the $pp \rightarrow l\nu\gamma + X$ and $pp \rightarrow l^+l^-\gamma + X$ processes are summarized in Table 5.

8. Comparison with theoretical predictions

The MCFM [30] program is used to predict the NLO cross section for $pp \rightarrow l^\pm\nu\gamma + X$ and $pp \rightarrow l^+l^-\gamma + X$ production. It includes photons from direct $W\gamma$ and $Z\gamma$ diboson production, from final state radiation off the leptons in the W/Z decays and from quark/gluon fragmentation into an isolated photon. Possible effects

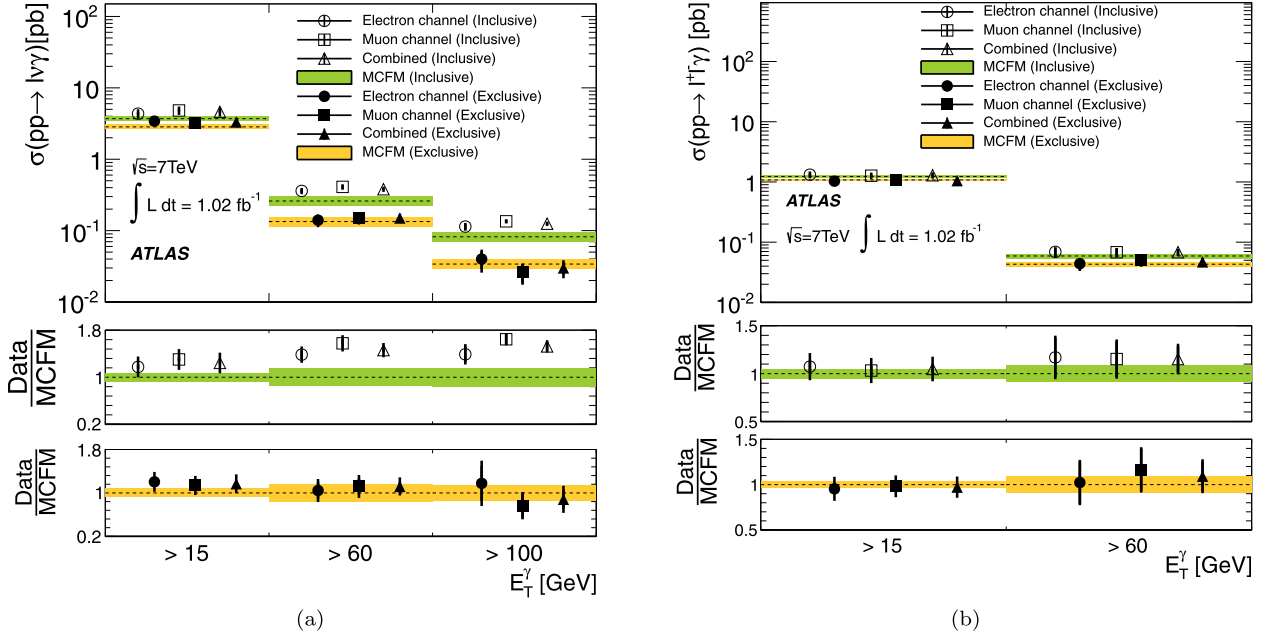


Fig. 3. The measured cross section for (a) $W\gamma$ production, (b) $Z\gamma$ production as a function of the photon transverse energy, in the extended fiducial region as defined in Table 3, together with the SM model prediction. Results of the measurement are shown for the electron and muon final states as well as for their combination. The lower plots show the ratio between the data and the prediction of the MCFM generator.

Table 6

Expected NLO inclusive and exclusive cross sections for the $pp \rightarrow l^\pm \nu \gamma + X$ and $pp \rightarrow l^+ l^- \gamma + X$ processes in the extended fiducial region as defined in Table 3. The cross sections are quoted at particle (parton) level as described in the text.

| Channel | E_T^γ (GeV) | Cross section exclusive | Cross section inclusive |
|-----------------------------------|--------------------|---|---|
| $pp \rightarrow l^\pm \nu \gamma$ | >15 | 2.84 ± 0.20 pb (2.61 ± 0.16 pb) | 3.70 ± 0.28 pb (3.58 ± 0.26 pb) |
| $pp \rightarrow l^\pm \nu \gamma$ | >60 | 134 ± 21 fb (118 ± 16 fb) | 260 ± 38 fb (255 ± 35 fb) |
| $pp \rightarrow l^\pm \nu \gamma$ | >100 | 34 ± 5 fb (31 ± 4 fb) | 82 ± 13 fb (80 ± 12 fb) |
| $pp \rightarrow l^+ l^- \gamma$ | >15 | 1.08 ± 0.04 pb (1.03 ± 0.04 pb) | 1.23 ± 0.06 pb (1.22 ± 0.05 pb) |
| $pp \rightarrow l^+ l^- \gamma$ | >60 | 43 ± 4 fb (40 ± 3 fb) | 59 ± 5 fb (58 ± 5 fb) |

of composite W and Z boson structure can be simulated through the introduction of aTGCs. Event generation is done using the MSTW2008NLO [31] parton distribution functions and the default electroweak parameters of MCFM. The kinematic requirements for the parton-level generation are the same as those chosen at particle level for the extended fiducial cross-section measurements (see Table 3). The resulting parton-level SM predictions for the cross sections are summarized by the numbers in parentheses in Table 6. These are quoted as *inclusive*, using only the lepton and photon selection cuts, and *exclusive*, requiring no quark/gluon with $|\eta| < 4.4$ and $E_T > 30$ GeV in the final state. The cross-section uncertainties are dominated by the PDF uncertainty, the scale uncertainty and the uncertainty due to the photon isolation fraction. The scale uncertainty is evaluated by varying the renormalization and factorization scales by factors of 2 and 1/2 around the nominal scale $M_{W/Z}$. The PDF uncertainty is estimated using the MSTW2008NLO PDFs' error eigenvectors at their 90% confidence-level (CL) limits. The uncertainty due to photon isolation fraction is evaluated by varying ϵ_h from 0.0 to 1.0. Here ϵ_h is defined at parton level as the ratio of the sum of the energies carried by the partons in the cone $\Delta R < 0.4$ around the photon direction to the energy carried

by the photon. The variation in the predicted cross section due to the choice of ϵ_h threshold is a conservative estimate of the uncertainty in matching the parton-level photon isolation to the photon isolation criteria applied in the experimental measurement. The total uncertainties in the $W\gamma$ ($Z\gamma$) NLO cross-section predictions are 7% (5%) for photon $E_T^\gamma > 15$ GeV and 14% (8%) for photon $E_T^\gamma > 60$ GeV.

To compare the SM cross-section predictions to the measured cross section, the theoretical predictions must be corrected for the difference between jets defined at the parton level (single quarks or gluons) and jets defined at the particle level as done for the cross-section measurement. These corrections account for the difference in jet definitions and in photon isolation definitions between the particle level and the parton level. The ALPGEN + HERWIG (for $W\gamma$) and SHERPA (for $Z\gamma$) MC samples are used to estimate these parton-to-particle scale factors $S_{W\gamma}$ and $S_{Z\gamma}$. They increase the parton-level cross sections by typically 5% with uncertainties that vary from 2% to 9% depending on the channel. These uncertainties for $W\gamma$ events are evaluated by comparing the differences in predictions made using ALPGEN and SHERPA. The uncertainties for $Z\gamma$ events are evaluated by comparing two SHERPA $Z\gamma$ signal samples with different configurations: the nominal sample is generated with up to three partons in the matrix element calculations, the alternative sample is generated with at most one parton.

The SM predictions for the particle-level (parton-level) cross sections are summarized in Table 6. The uncertainties quoted include those from the MCFM parton-level generator predictions, photon isolation matching to the data, and the scaling from parton to particle-level cross sections. Fig. 3 presents a summary of all cross-section measurements of $W\gamma$ and $Z\gamma$ production made in this study and the corresponding particle-level SM expectations. There is good agreement between the measured cross sections for the exclusive events and the MCFM prediction.

For inclusive production, the MCFM NLO cross-section prediction includes real parton emission processes only up to one radiated quark or gluon. The lack of higher-order QCD contributions results in an underestimation of the predicted cross sections as shown

Table 7

The measured and expected 95% CL intervals on the charged ($\Delta\kappa_\gamma$, λ_γ) and neutral (h_3^V , h_3^Z , h_4^V , h_4^Z) anomalous couplings. The results obtained using different Λ values are shown. The two numbers in each parentheses denote the 95% CL interval.

| | Measured | Measured | Expected |
|-----------------------|-------------------|---------------------|---------------------|
| Λ | 2 TeV | ∞ | ∞ |
| $\Delta\kappa_\gamma$ | (−0.36, 0.41) | (−0.33, 0.37) | (−0.33, 0.36) |
| λ_γ | (−0.079, 0.074) | (−0.060, 0.060) | (−0.063, 0.055) |
| Λ | 1.5 TeV | ∞ | ∞ |
| h_3^V | (−0.074, 0.071) | (−0.028, 0.027) | (−0.027, 0.027) |
| h_3^Z | (−0.051, 0.068) | (−0.022, 0.026) | (−0.022, 0.025) |
| h_4^V | (−0.0028, 0.0027) | (−0.00021, 0.00021) | (−0.00021, 0.00021) |
| h_4^Z | (−0.0024, 0.0023) | (−0.00022, 0.00021) | (−0.00022, 0.00021) |

in Fig. 3, especially for events with high E_T^γ photons, which have significant contributions from multi-jet final states. Fig. 2 shows that the multi-jet contribution is important in the $W\gamma$ processes. Therefore higher-order jet production is needed in the MC simulation (see Section 3) to describe the photon transverse energy spectrum with the inclusive selection and the jet multiplicity distribution in $W\gamma$ and $Z\gamma$ events, as shown in Fig. 1 and Fig. 2.

9. Limits on anomalous triple gauge couplings

The spectra of high energy photons in $W\gamma$ and $Z\gamma$ events are sensitive to new phenomena that alter the couplings among the gauge bosons. These effects can be described by modifying the $WW\gamma$ coupling κ_γ from its SM value of one and adding terms with new couplings to the $WW\gamma$ and $ZV\gamma$ ($V = \gamma$ or Z) interaction Lagrangian. Assuming C and P conservation separately, the anomalous TGC (aTGC) parameters are generally chosen as λ_γ and $\Delta\kappa_\gamma$ ($\Delta\kappa_\gamma = \kappa_\gamma - 1$) for the $WW\gamma$ vertex [32,33], and h_3^V and h_4^V for the $ZV\gamma$ vertices [34]. Form factors are introduced to avoid unitarity violation at very high energy. Typical choices of these form factors for the $WW\gamma$ aTGCs are: $\Delta\kappa_\gamma(s) = \Delta\kappa_\gamma/(1 + \hat{s}/\Lambda^2)^2$ and $\lambda_\gamma(s) = \lambda_\gamma/(1 + \hat{s}/\Lambda^2)^2$ [33]. For the $ZV\gamma$ aTGCs, conventional choices of form factors are $h_3^V(s) = h_3^V/(1 + \hat{s}/\Lambda^2)^3$ and $h_4^V(s) = h_4^V/(1 + \hat{s}/\Lambda^2)^4$ [34]. Here $\sqrt{\hat{s}}$ is the $W\gamma$ or $Z\gamma$ invariant mass and Λ is the new physics energy scale. To compare with the existing limits by D0 [3] and CDF [1], Λ is chosen as 2 TeV in the $W\gamma$ analysis and 1.5 TeV in the $Z\gamma$ analysis. The results with energy cutoff $\Lambda = \text{inf}$ are also presented as a comparison in the unitarity violation scheme. Deviations of the aTGC parameters from the SM predictions of zero lead to an excess of high energy photons associated with the W and Z bosons.

Measurements of the exclusive extended fiducial cross sections for $W\gamma$ production with $E_T^\gamma > 100$ GeV and $Z\gamma$ production with $E_T^\gamma > 60$ GeV are used to extract aTGC limits. The cross-section predictions with aTGCs ($\sigma_{W\gamma}^{\text{aTGC}}$ and $\sigma_{Z\gamma}^{\text{aTGC}}$) are obtained from the MCFM generator. The number of expected $W\gamma$ events in the exclusive extended fiducial region ($N_{W\gamma}^{\text{aTGC}}(\Delta\kappa_\gamma, \lambda_\gamma)$) for given aTGCs are obtained as $N_{W\gamma}^{\text{aTGC}}(\Delta\kappa_\gamma, \lambda_\gamma) = \sigma_{W\gamma}^{\text{aTGC}} \times C_{W\gamma} \times A_{W\gamma} \times S_{W\gamma} \times L$. For the $Z\gamma$ case, $N_{Z\gamma}^{\text{aTGC}}(h_3^V, h_4^V)$ or $N_{Z\gamma}^{\text{aTGC}}(h_3^Z, h_4^Z)$ are obtained in a similar way. The anomalous couplings influence the kinematic properties of $W\gamma$ and $Z\gamma$ events and thus the corrections for event reconstruction ($C_{W\gamma}$ and $C_{Z\gamma}$). The maximum variations of $C_{W\gamma}$ and $C_{Z\gamma}$ within the measured aTGC limits are quoted as additional systematic uncertainties. The limits on a given aTGC parameter (e.g. h_3^V) are extracted from the Bayesian posterior, given the extended fiducial measurements. The Bayesian posterior probability density function is obtained by integrating over the nuisance

parameters corresponding to all systematic uncertainties and assuming a flat Bayesian prior in h_3^V . This calculation has been done for multiple values of the scale parameter Λ in order to be able to compare these results with those from LEP [6], Tevatron [1–3] and CMS [5]. The limits are defined as the values of aTGC parameters which demarcate the central 95% of the integral of the likelihood distribution. The resulting allowed ranges for the anomalous couplings are shown in Table 7 for $WW\gamma$ and $ZV\gamma$. The results are also shown in Fig. 4, along with the LEP, Tevatron and CMS measurements.

10. Summary

The production of $W\gamma$ and $Z\gamma$ boson pairs in 7 TeV pp collisions has been studied using 1.02 fb^{-1} of data collected with the ATLAS detector. The measurements have been made using the $pp \rightarrow l^\pm \nu \gamma + X$ and $pp \rightarrow l^+ l^- \gamma + X$ final states, where the charged lepton is an electron or muon and the photons are required to be isolated. The results are compared to SM predictions using a NLO parton-level generator. The NLO SM predictions for the exclusive $W\gamma$ and $Z\gamma$ production cross sections agree well with the data for events with both low (15 GeV) and high (60 GeV or 100 GeV) photon E_T^γ thresholds. For the high photon thresholds, where multi-jet production dominates, the measured inclusive $W\gamma$ cross sections are higher than the NLO calculations for the inclusive $pp \rightarrow l^\pm \nu \gamma + X$ process, which do not include multiple quark/gluon emission. The measurements are also compared to LO MC generators with multiple quark/gluon emission in the matrix element calculations. These LO MC predictions reproduce the shape of the photon E_T^γ spectrum and the kinematic properties of the leptons and jets in the $W\gamma$ and $Z\gamma$ candidate events.

The measurements of exclusive $W\gamma$ ($Z\gamma$) production with $E_T^\gamma > 100$ (60) GeV are used to constrain anomalous triple gauge couplings (λ_γ , $\Delta\kappa_\gamma$, h_3^V and h_4^V). No evidence for physics beyond the SM is observed. The limits obtained in this study are compatible with those from LEP and Tevatron and are more stringent than previous LHC results.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We also thank John Campbell, Keith Ellis and Ciaran Williams for their advice about theory calculations using the MCFM program.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3–CNRS, CEA–DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTB, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS

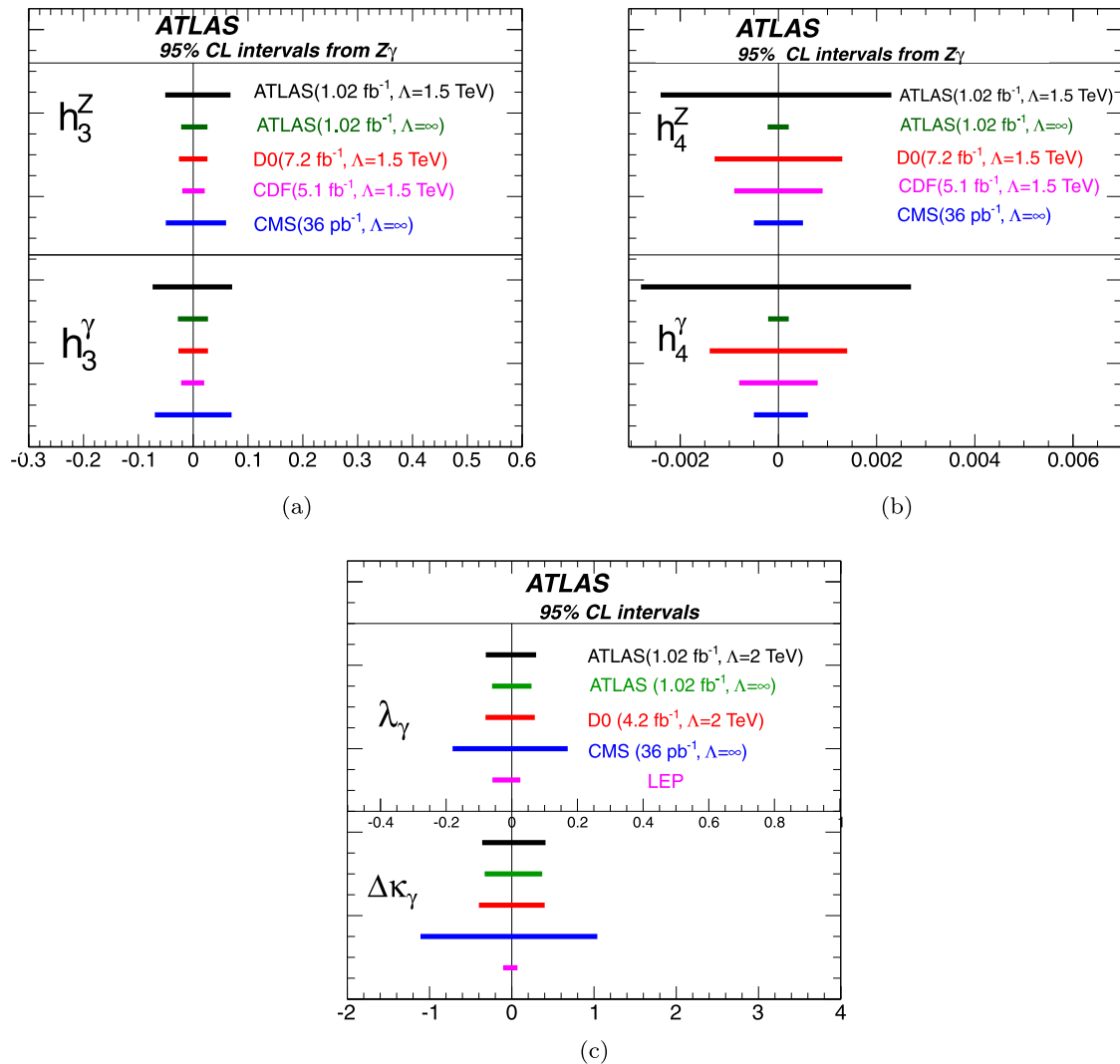


Fig. 4. The 95% CL intervals for anomalous couplings from ATLAS, D0 [3], CDF [1], CMS [5] and LEP [6] for (a), (b) the neutral aTGCs h_3^Z , h_3^γ , h_4^Z , h_4^γ as obtained from $Z\gamma$ events, and (c) the charged aTGCs $\Delta\kappa_\gamma$, λ_γ . Integrated luminosities and new physics scale parameter Λ are shown. The ATLAS, CMS and Tevatron results for the charged aTGCs are measured from $W\gamma$ production. The LEP charged aTGC results are obtained from WW production, which is sensitive also to the WWZ couplings and hence required some assumptions about the relations between the $WW\gamma$ and WWZ aTGCs [6,35–37]. The sensitivity of the LEP data to neutral aTGCs is much smaller than that of the hadron colliders; therefore the LEP results have not been included in (a) and (b).

Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

- [1] CDF Collaboration, T. Aaltonen, et al., Phys. Rev. D 82 (2010) 031103.
- [2] D0 Collaboration, V. Abazov, et al., Phys. Rev. Lett. 100 (2008) 241805.
- [3] D0 Collaboration, V. Abazov, et al., Phys. Rev. D 85 (2012) 052001.
- [4] ATLAS Collaboration, J. High Energy Phys. 1109 (2011) 072.
- [5] CMS Collaboration, Phys. Lett. B 701 (2011) 535.
- [6] LEP Collaborations: ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, LEP Electroweak Working Group, arXiv:hep-ex/0612034.
- [7] ATLAS Collaboration, JINST 3 (2008) S08003.
- [8] ATLAS Collaboration, Eur. Phys. J. C 71 (2011) 1630.
- [9] ATLAS Collaboration, ATLAS conference note: ATLAS-CONF-2011-116, 2011, <http://cdsweb.cern.ch/record/1376384>.
- [10] ATLAS Collaboration, Eur. Phys. J. C 70 (2010) 823.
- [11] S. Agostinelli, et al., Nucl. Instrum. Methods A 506 (2003) 250.
- [12] M.L. Mangano, et al., J. High Energy Phys. 0307 (2003) 001.
- [13] G. Corcella, et al., J. High Energy Phys. 0101 (2001) 010.
- [14] J.M. Butterworth, J.R. Forshaw, M.H. Seymour, Z. Phys. C 72 (1996) 637.
- [15] T. Gleisberg, et al., J. High Energy Phys. 0402 (2004) 056.
- [16] J. Pumplin, et al., J. High Energy Phys. 0207 (2002) 012.
- [17] P.M. Nadolsky, et al., Phys. Rev. D 78 (2008) 013004.
- [18] T. Sjöstrand, S. Mrenna, P.Z. Skands, J. High Energy Phys. 0605 (2006) 026.
- [19] P. Golonka, Z. Was, Eur. Phys. J. C 45 (2006) 97.
- [20] N. Davidson, G. Nanava, T. Przedzinski, E. Richter-Was, Z. Was, arXiv:1002.0543, 2010.
- [21] S. Frixione, P. Nason, C. Oleari, J. High Energy Phys. 0711 (2007) 070.
- [22] S. Frixione, B.R. Webber, J. High Energy Phys. 0206 (2002) 029.
- [23] S. Frixione, F. Stoeckli, P. Torrielli, B.R. Webber, J. High Energy Phys. 1101 (2011) 053.
- [24] ATLAS Collaboration, Eur. Phys. J. C 72 (2012) 1909.

- [25] ATLAS Collaboration, Phys. Rev. D 83 (2011) 052005.
 [26] ATLAS Collaboration, J. High Energy Phys. 1012 (2010) 060.
 [27] ATLAS Collaboration, Eur. Phys. J. C 72 (2012) 1844.
 [28] M. Cacciari, G.P. Salam, G. Soyez, J. High Energy Phys. 0804 (2008) 063.
 [29] ATLAS Collaboration, Phys. Lett. B 698 (2011) 325.
 [30] J.M. Campbell, R.K. Ellis, C. Williams, J. High Energy Phys. 1107 (2011) 018.
 [31] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur. Phys. J. C 63 (2009) 189.
 [32] U. Baur, E.L. Berger, Phys. Rev. D 41 (1990) 1476.
 [33] U. Baur, T. Han, J. Ohnemus, Phys. Rev. D 48 (1993) 5140.
 [34] U. Baur, E.L. Berger, Phys. Rev. D 47 (1993) 4889.
 [35] K. Hagiwara, S. Ishihara, R. Szalapski, D. Zeppenfeld, Phys. Lett. B 283 (1992) 353.
 [36] K. Hagiwara, S. Ishihara, R. Szalapski, D. Zeppenfeld, Phys. Rev. D 48 (1993) 2182.
 [37] G. Gounaris, et al., Physics at LEP2, vol. 1, pp. 525–576, CERN-96-01-V-1, arXiv:hep-ph/9601233.

ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abdinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹³⁶, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, L. Adamczyk³⁷, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, A. Akiyama⁶⁶, M.S. Alam¹, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob^{164a,164c}, M. Aliev¹⁵, G. Alimonti^{89a}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁷, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso⁷⁹, B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b}, K. Amako⁶⁵, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,b}, N. Amram¹⁵³, C. Anastopoulos²⁹, L.S. Ancu¹⁶, N. Andari¹¹⁵, T. Andeen³⁴, C.F. Anders²⁰, G. Anders^{58a}, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³, L. Aperio Bella⁴, R. Apolle^{118,c}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁴, S. Arfaoui¹⁴⁸, J.-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, O. Arnaez⁸¹, V. Arnal⁸⁰, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷³, S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵, K. Assamagan²⁴, A. Astbury¹⁶⁹, B. Aubert⁴, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aurousseau^{145a}, G. Avolio¹⁶³, R. Avramidou⁹, D. Axen¹⁶⁸, G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, M. Backes⁴⁹, M. Backhaus²⁰, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁴, S. Baker⁷⁷, E. Banas³⁸, P. Banerjee⁹³, Sw. Banerjee¹⁷³, D. Banfi²⁹, A. Bangert¹⁵⁰, V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷², S.P. Baranov⁹⁴, A. Barbaro Galtieri¹⁴, T. Barber⁴⁸, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, A.E. Barton⁷¹, V. Bartsch¹⁴⁹, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, F. Bauer¹³⁶, H.S. Bawa^{143,e}, S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹, R. Beccherle^{50a}, P. Bechtel²⁰, H.P. Beck¹⁶, S. Becker⁹⁸, M. Beckingham¹³⁸, K.H. Becks¹⁷⁵, A.J. Beddall^{18c}, A. Beddall^{18c}, S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³, M. Begel²⁴, S. Behar Harpaz¹⁵², P.K. Behera⁶², M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹, M. Bellomo²⁹, A. Belloni⁵⁷, O. Beloborodova^{107,f}, K. Belotskiy⁹⁶, O. Beltramello²⁹, O. Benary¹⁵³, D. Bencheikroun^{135a}, K. Bendtz^{146a,146b}, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²², K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹, E. Berglund¹⁰⁵, J. Beringer¹⁴, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶, C. Bertella⁸³, A. Bertin^{19a,19b}, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁴, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁵, A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵, J.-B. Blanchard¹³⁶, G. Blanchot²⁹, T. Blazek^{144a}, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁴, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁵, N. Boelaert³⁵, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁷, V. Boldea^{25a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Bondioli¹⁶³, M. Boonekamp¹³⁶, C.N. Booth¹³⁹, S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borisso⁷¹, I. Borjanovic^{12a},

M. Borri⁸², S. Borroni⁸⁷, V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹,
 H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹,
 D. Boumediene³³, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁴, N.I. Bozhko¹²⁸,
 I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, P. Branchini^{134a}, A. Brandt⁷, G. Brandt¹¹⁸, O. Brandt⁵⁴,
 U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun¹⁷⁵, B. Brelief¹⁵⁸, J. Bremer²⁹, K. Brendlinger¹²⁰,
 R. Brenner¹⁶⁶, S. Bressler¹⁷², D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, E. Brodet¹⁵³,
 F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², H. Brown⁷,
 P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{19a}, G. Bruni^{19a},
 M. Bruschi^{19a}, T. Buanes¹³, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, N.J. Buchanan², P. Buchholz¹⁴¹,
 R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹,
 L. Bugge¹¹⁷, O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³,
 T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²¹,
 C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁷, S. Cabrera Urbán¹⁶⁷, D. Caforio^{19a,19b}, O. Cakir^{3a},
 P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³,
 S. Calvet³³, R. Camacho Toro³³, P. Camarri^{133a,133b}, D. Cameron¹¹⁷, L.M. Caminada¹⁴, S. Campana²⁹,
 M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli^{30,g}, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b},
 M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo⁸¹,
 R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{31b},
 G.D. Carrillo Montoya¹⁷³, A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,h}, D. Casadei¹⁰⁸, M.P. Casado¹¹,
 M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,i}, E. Castaneda-Miranda¹⁷³,
 V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, A. Catinaccio²⁹, J.R. Catmore²⁹, A. Cattai²⁹,
 G. Cattani^{133a,133b}, S. Caughron⁸⁸, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b},
 F. Ceradini^{134a,134b}, A.S. Cerqueira^{23b}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷, S.A. Cetin^{18b}, A. Chafaq^{135a},
 D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁶, K. Chan², B. Chapleau⁸⁵, J.D. Chapman²⁷, J.W. Chapman⁸⁷,
 E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸², C.A. Chavez Barajas²⁹, S. Cheatham⁸⁵, S. Chekanov⁵,
 S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁴, S. Chen^{32c}, X. Chen¹⁷³,
 A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁴, E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶,
 G. Chiefari^{102a,102b}, L. Chikovani^{51a}, J.T. Childers²⁹, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁷,
 R.T. Chislett⁷⁷, M.V. Chizhov⁶⁴, G. Choudalakis³⁰, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸,
 D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a},
 D. Cinca³³, V. Cindro⁷⁴, C. Ciocca^{19a}, A. Ciocio¹⁴, M. Cirilli⁸⁷, M. Citterio^{89a}, M. Ciubancan^{25a},
 A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, R.W. Clifft¹²⁹,
 Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro¹³⁸, J. Cochran⁶³, P. Coe¹¹⁸, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵,
 E. Cogneras¹⁷⁸, J. Colas⁴, A.P. Colijn¹⁰⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵, G. Colon⁸⁴,
 P. Conde Muñio^{124a}, E. Coniavitis¹¹⁸, M.C. Conidi¹¹, M. Consonni¹⁰⁴, S.M. Consonni^{89a,89b},
 V. Consorti⁴⁸, S. Constantinescu^{25a}, C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,j}, M. Cooke¹⁴,
 B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁴, T. Cornelissen¹⁷⁵, M. Corradi^{19a}, F. Corriveau^{85,k},
 A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹,
 L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli^{122a,122b},
 M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b}, S. Crépé-Renaudin⁵⁵, C.-M. Cuciuc^{25a},
 C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, M. Curatolo⁴⁷, C.J. Curtis¹⁷, C. Cuthbert¹⁵⁰,
 P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴³, Z. Czynzula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³,
 A. D'Orazio^{132a,132b}, C. Da Via⁸², W. Dabrowski³⁷, A. Dafinca¹¹⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴, M. Dam³⁵,
 M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson²⁹, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b},
 W. Davey²⁰, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, E. Davies^{118,c}, M. Davies⁹³, A.R. Davison⁷⁷,
 Y. Davygora^{58a}, E. Dawe¹⁴², I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²², K. De⁷, R. de Asmundis^{102a},
 S. De Castro^{19a,19b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵,
 H. De la Torre⁸⁰, L. de Mora⁷¹, L. De Nooij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis^{164a,164c},
 A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b}, W.J. Dearnaley⁷¹, R. Debbé²⁴,
 C. Debenedetti⁴⁵, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²⁰, C. Del Papa^{164a,164c}, J. Del Peso⁸⁰,
 T. Del Prete^{122a,122b}, T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴, A. Dell'Acqua²⁹, L. Dell'Asta²¹,
 M. Della Pietra^{102a,j}, D. della Volpe^{102a,102b}, M. Delmastro⁴, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸, S. Demers¹⁷⁶,

M. Demichev⁶⁴, B. Demirköz^{11,l}, J. Deng¹⁶³, S.P. Denisov¹²⁸, D. Derendarz³⁸, J.E. Derkaoui^{135d},
 F. Derue⁷⁸, P. Dervan⁷³, K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸,
 S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,m}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹,
 B. Di Girolamo²⁹, S. Di Luise^{134a,134b}, A. Di Mattia¹⁷³, B. Di Micco²⁹, R. Di Nardo⁴⁷,
 A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c}, E.B. Diehl⁸⁷, J. Dietrich⁴¹,
 T.A. Dietzsch^{58a}, S. Diglio⁸⁶, K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a},
 F. Dittus²⁹, F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{23c}, A. Do Valle Wemans^{124a,n}, T.K.O. Doan⁴,
 M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos²⁹, E. Dobson^{29,o}, J. Dodd³⁴, C. Doglioni⁴⁹, T. Doherty⁵³,
 Y. Doi^{65,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{23d},
 M. Donega¹²⁰, J. Donini³³, J. Dopke²⁹, A. Doria^{102a}, A. Dos Anjos¹⁷³, A. Dotti^{122a,122b}, M.T. Dova⁷⁰,
 A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, J. Drees¹⁷⁵, H. Drevermann²⁹, M. Dris⁹, J. Dubbert⁹⁹, S. Dube¹⁴,
 E. Duchovni¹⁷², G. Duckeck⁹⁸, A. Dudarev²⁹, F. Dudziak⁶³, M. Dührssen²⁹, I.P. Duerdoth⁸², L. Duflot¹¹⁵,
 M.-A. Dufour⁸⁵, M. Dunford²⁹, H. Duran Yildiz^{3a}, R. Duxfield¹³⁹, M. Dwuznik³⁷, F. Dydak²⁹,
 M. Düren⁵², J. Ebke⁹⁸, S. Eckweiler⁸¹, K. Edmonds⁸¹, C.A. Edwards⁷⁶, N.C. Edwards⁵³, W. Ehrenfeld⁴¹,
 T. Eifert¹⁴³, G. Eigen¹³, K. Einsweiler¹⁴, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶,
 S. Elles⁴, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹, D. Emelianov¹²⁹,
 R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹, A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, D. Eriksson^{146a},
 J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, C. Escobar¹²³,
 X. Espinal Curull¹¹, B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etievre¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴,
 H. Evans⁶⁰, L. Fabbri^{19a,19b}, C. Fabre²⁹, R.M. Fakhruddinov¹²⁸, S. Falciano^{132a}, Y. Fang¹⁷³,
 M. Fanti^{89a,89b}, A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹¹⁸,
 P. Farthouat²⁹, P. Fassnacht²⁹, D. Fassouliotis⁸, B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵,
 S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a}, O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸,
 L. Felgioni⁸³, D. Fellmann⁵, C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando¹⁰⁹,
 S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴¹, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a},
 D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³⁰,
 F. Fiedler⁸¹, A. Filipčič⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,h}, L. Fiorini¹⁶⁷,
 A. Firan³⁹, G. Fischer⁴¹, P. Fischer²⁰, M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹,
 P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³,
 M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁶, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, D. Fournier¹¹⁵, H. Fox⁷¹,
 P. Francavilla¹¹, S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷², M. Franklin⁵⁷, S. Franz²⁹,
 M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁷, C. Friedrich⁴¹, F. Friedrich⁴³, R. Froeschl²⁹,
 D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa²⁹, B.G. Fulsom¹⁴³, J. Fuster¹⁶⁷,
 C. Gabaldon²⁹, O. Gabizon¹⁷², T. Gadfort²⁴, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸,
 E.J. Gallas¹¹⁸, V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,e}, A. Gaponenko¹⁴,
 F. Garbersson¹⁷⁶, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, R.W. Gardner³⁰, N. Garelli²⁹,
 H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶,
 P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, E.N. Gazis⁹, P. Ge^{32d}, Z. Gece¹⁶⁸,
 C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a},
 A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, P. Gerlach¹⁷⁵,
 A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b},
 V. Giakoumopoulou⁸, V. Giangiobbe¹¹, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson²⁹,
 D. Gillberg²⁸, A.R. Gillman¹²⁹, D.M. Gingrich^{2,d}, J. Ginzburg¹⁵³, N. Giokaris⁸, M.P. Giordani^{164c},
 R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³,
 P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁵,
 G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹,
 C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷, T. Golling¹⁷⁶, A. Gomes^{124a,b}, L.S. Gomez Fajardo⁴¹,
 R. Gonçalo⁷⁶, J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰, S. Gonzalez¹⁷³,
 S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹¹, M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹,
 J.J. Goodson¹⁴⁸, L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵,
 B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸, B. Gosdzik⁴¹, A.T. Goshaw⁵, M. Gosselink¹⁰⁵,
 M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶³, M. Goughri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹,

A.G. Goussiou¹³⁸, C. Goy⁴, S. Gozpinar²², I. Grabowska-Bold³⁷, P. Grafström²⁹, K.-J. Grahn⁴¹,
 F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray²⁹, J.A. Gray¹⁴⁸,
 E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³, Z.D. Greenwood^{24,m}, K. Gregersen³⁵, I.M. Gregor⁴¹,
 P. Grenier¹⁴³, J. Griffiths¹³⁸, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁷, S. Grinstein¹¹, Y.V. Grishkevich⁹⁷,
 J.-F. Grivaz¹¹⁵, E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶,
 C. Guicheney³³, A. Guida^{72a,72b}, S. Guindon⁵⁴, H. Guler^{85,p}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁴,
 V.N. Gushchin¹²⁸, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸,
 C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner⁹⁹,
 F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁷, D. Hall¹¹⁸, J. Haller⁵⁴, K. Hamacher¹⁷⁵,
 P. Hamal¹¹³, M. Hamer⁵⁴, A. Hamilton^{145b,q}, S. Hamilton¹⁶¹, L. Han^{32b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰,
 M. Hance¹⁴, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵,
 P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷,
 R.D. Harrington⁴⁵, O.M. Harris¹³⁸, K. Harrison¹⁷, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶,
 S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁸, M. Havranek²⁰,
 B.M. Hawes¹¹⁸, C.M. Hawkes¹⁷, R.J. Hawkings²⁹, A.D. Hawkins⁷⁹, D. Hawkins¹⁶³, T. Hayakawa⁶⁶,
 T. Hayashi¹⁶⁰, D. Hayden⁷⁶, H.S. Hayward⁷³, S.J. Haywood¹²⁹, L. He^{32b}, M. He^{32d}, S.J. Head¹⁷,
 V. Hedberg⁷⁹, L. Heelan⁷, S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵, L. Helary⁴, C. Heller⁹⁸,
 M. Heller²⁹, S. Hellman^{146a,146b}, D. Hellmich²⁰, C. Helsens¹¹, R.C.W. Henderson⁷¹, M. Henke^{58a},
 A. Henrichs⁵⁴, A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³, C. Hensel⁵⁴,
 T. Henß¹⁷⁵, C.M. Hernandez⁷, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, G. Herten⁴⁸, R. Hertenberger⁹⁸,
 L. Hervas²⁹, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁷, K.H. Hiller⁴¹, S. Hillert²⁰,
 S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴², D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸,
 N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹, M.R. Hoferkamp¹⁰³, J. Hoffman³⁹,
 D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸,
 T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, C. Horn¹⁴³, S. Horner⁴⁸, J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹,
 A. Hoummada^{135a}, J. Howarth⁸², I. Hristova¹⁵, J. Hrivnac¹¹⁵, I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu⁸¹,
 S.-C. Hsu¹⁴, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰, A. Huettmann⁴¹, T.B. Huffman¹¹⁸,
 E.W. Hughes³⁴, G. Hughes⁷¹, M. Huhtinen²⁹, M. Hurwitz¹⁴, U. Husemann⁴¹, N. Huseynov^{64,r},
 J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹, M. Ibbotson⁸², I. Ibragimov¹⁴¹, R. Ichimiya⁶⁶,
 L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵,
 Y. Ilchenko³⁹, D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{134a},
 K. Iordanidou⁸, V. Ippolito^{132a,132b}, A. Irlés Quiles¹⁶⁷, C. Isaksson¹⁶⁶, A. Ishikawa⁶⁶, M. Ishino⁶⁷,
 R. Ishmukhametov³⁹, C. Issever¹¹⁸, S. Istin^{18a}, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁵, J.M. Izen⁴⁰,
 V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹, V. Jain⁶⁰, K. Jakobs⁴⁸,
 S. Jakobsen³⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen²⁹, A. Jantsch⁹⁹, M. Janus⁴⁸,
 G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴, M.K. Jha^{19a},
 H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b}, M. Jimenez Belenguer⁴¹, S. Jin^{32a}, O. Jinnouchi¹⁵⁷,
 M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a},
 P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶, K. Jon-And^{146a,146b}, G. Jones¹¹⁸, R.W.L. Jones⁷¹, T.J. Jones⁷³,
 C. Joram²⁹, P.M. Jorge^{124a}, K.D. Joshi⁸², J. Jovicevic¹⁴⁷, T. Jovin^{12b}, X. Ju¹⁷³, C.A. Jung⁴², R.M. Jungst²⁹,
 V. Juranek¹²⁵, P. Jussel⁶¹, A. Juste Rozas¹¹, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarska³⁸, P. Kadlecik³⁵,
 M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴, S. Kama³⁹,
 N. Kanaya¹⁵⁵, M. Kaneda²⁹, S. Kaneti²⁷, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵, B. Kaplan¹⁷⁶,
 A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁵³, M. Karagounis²⁰, K. Karakostas⁹, M. Karnevskiy⁴¹, V. Kartvelishvili⁷¹,
 A.N. Karyukhin¹²⁸, L. Kashif¹⁷³, G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kataoka⁴,
 Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁶, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹,
 M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁴,
 J.S. Keller¹³⁸, J. Kennedy⁹⁸, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵,
 K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁴,
 A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁷, G. Khorauli²⁰, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵,
 E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b}, M.S. Kim², S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁵,
 B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielewska³⁷,

T. Kittelmann¹²³, A.M. Kiver¹²⁸, E. Kladiva^{144b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁴, R. Klingenberg⁴², J.A. Klinger⁸², E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, N.S. Knecht¹⁵⁸, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, M. Kocian¹⁴³, P. Kodys¹²⁶, K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁸, E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴³, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸, M. Kollefrath⁴⁸, A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{41,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t}, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁵, S. Koperny³⁷, K. Korcyl³⁸, K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰, S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁴, C. Kourkoumelis⁸, V. Kouskoura¹⁵⁴, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, J.K. Kraus²⁰, F. Krejci¹²⁷, J. Kretschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁴, H. Krüger²⁰, T. Kruker¹⁶, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruth²⁰, T. Kubota⁸⁶, S. Kudah^{3a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹, D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰, S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁷⁸, N. Kundu¹¹⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁵, A. La Rosa⁴⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna²⁹, L. Lambourne⁷⁷, C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzsch¹⁷⁵, S. Laplace⁷⁸, C. Lapoire²⁰, J.F. Laporte¹³⁶, T. Lari^{89a}, A. Larner¹¹⁸, M. Lassnig²⁹, P. Laurelli⁴⁷, V. Lavorini^{36a,36b}, W. Lavrijsen¹⁴, P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹¹, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, B.C. LeGeyt¹²⁰, F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, X. Lei⁶, M.A.L. Leite^{23d}, R. Leitner¹²⁶, D. Lellouch¹⁷², B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi²⁹, K. Leonhardt⁴³, S. Leontsinis⁹, C. Leroy⁹³, J.-R. Lessard¹⁶⁹, J. Lesser^{146a}, C.G. Lester²⁷, C.M. Lester¹²⁰, J. Levêque⁴, D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²⁰, M. Leyton¹⁵, B. Li⁸³, H. Li^{173,u}, S. Li^{32b,v}, X. Li⁸⁷, Z. Liang^{118,w}, H. Liao³³, B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, C. Limbach²⁰, A. Limosani⁸⁶, M. Limper⁶², S.C. Lin^{151,x}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, A. Lipniacka¹³, T.M. Liss¹⁶⁵, D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu¹⁵¹, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁴, R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe^{143,e}, F. Lu^{32a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁵, W. Lukas⁶¹, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷³, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a}, R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁵, S. Mättig⁴¹, L. Magnoni²⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸, S. Mahmoud⁷³, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a}, A. Maio^{124a,b}, S. Majewski²⁴, Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶, B. Malaescu²⁹, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁵, C. Malone¹⁴³, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov²⁹, R. Mameghani⁹⁸, J. Mamuzic^{12b}, A. Manabe⁶⁵, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangeard⁸⁸, L. Manhaes de Andrade Filho^{23a}, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁸, F. Marchese^{133a,133b}, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquim^{23a}, Z. Marshall²⁹, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, B. Martin²⁹, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁷, V.J. Martin⁴⁵,

B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷,
 A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵,
 R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴,
 P. Mastrandrea^{132a,132b}, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, P. Matricon¹¹⁵, H. Matsumoto¹⁵⁵,
 H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶, C. Mattravers^{118,c}, J. Maurer⁸³, S.J. Maxfield⁷³, D.A. Maximov^{107,f},
 A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰, L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, S.P. Mc Kee⁸⁷,
 A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶,
 J.A. MCFayden¹³⁹, H. McGlone⁵³, G. Mchedlidze^{51b}, T. McLaughlan¹⁷, S.J. McMahon¹²⁹,
 R.A. McPherson^{169,k}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁵, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹,
 T. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase³⁵, A. Mehta⁷³, K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³⁰,
 B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶², Z. Meng^{151,u}, A. Mengarelli^{19a,19b},
 S. Menke⁹⁹, E. Meoni¹¹, K.M. Mercurio⁵⁷, P. Mermod⁴⁹, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰,
 H. Merritt¹⁰⁹, A. Messina^{29,y}, J. Metcalfe¹⁰³, A.S. Mete⁶³, C. Meyer⁸¹, C. Meyer³⁰, J.-P. Meyer¹³⁶,
 J. Meyer¹⁷⁴, J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶³, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a},
 R.P. Middleton¹²⁹, S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷², M. Mikesikova¹²⁵, M. Mikuž⁷⁴,
 D.W. Miller³⁰, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷²,
 A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁴,
 Y. Ming¹⁷³, L.M. Mir¹¹, G. Mirabelli^{132a}, A. Misiejuk⁷⁶, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵,
 P.S. Miyagawa¹³⁹, K. Miyazaki⁶⁶, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, S. Moed⁵⁷, V. Moeller²⁷,
 K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, J. Monk⁷⁷,
 E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶,
 C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹,
 M. Moreno Llácer¹⁶⁷, P. Morettini^{50a}, M. Morgenstern⁴³, M. Morii⁵⁷, J. Morin⁷⁵, A.K. Morley²⁹,
 G. Mornacchi²⁹, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³,
 E. Mountricha^{9,z}, S.V. Mouraviev⁹⁴, E.J.W. Moyses⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰,
 T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann²⁹, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵,
 E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁵, A. Nagarkar¹⁰⁹,
 Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz²⁹, Y. Nakahama²⁹, K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵,
 I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,c}, T. Nattermann²⁰, T. Naumann⁴¹,
 G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹,
 A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi^{29,aa},
 M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁶,
 R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷,
 N. Nikiporou³⁴, A. Nikiporov¹⁵, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos²⁴,
 H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁶, R. Nisius⁹⁹, L. Nodulman⁵,
 M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, M. Nordberg²⁹, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁵, L. Nozka¹¹³,
 I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷,
 B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{28,d},
 H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda¹⁵⁵, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁴,
 C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, S. Okada⁶⁶, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵,
 A. Olariu^{25a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{31a}, M. Oliveira^{124a,h}, D. Oliveira Damazio²⁴,
 E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, A. Onofre^{124a,ab}, P.U.E. Onyisi³⁰,
 C.J. Oram^{159a}, M.J. Oreglia³⁰, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{72a,72b}, I. Orlov¹⁰⁷,
 C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶,
 J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a},
 A. Ovcharova¹⁴, M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{18a}, N. Ozturk⁷, A. Pacheco Pages¹¹,
 C. Padilla Aranda¹¹, S. Pagan Griso¹⁴, E. Paganis¹³⁹, F. Paige²⁴, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b},
 C.P. Paleari⁶, S. Palestini²⁹, D. Pallin³³, A. Palma^{124a}, J.D. Palmer¹⁷, Y.B. Pan¹⁷³, E. Panagiotopoulou⁹,
 B. Panes^{31a}, N. Panikashvili⁸⁷, S. Panitkin²⁴, D. Pantea^{25a}, A. Papadelis^{146a}, Th.D. Papadopoulou⁹,
 A. Paramonov⁵, D. Paredes Hernandez³³, W. Park^{24,ac}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴,
 U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a}, F. Pastore^{134a,134b},
 Fr. Pastore⁷⁶, G. Pásztor^{49,ad}, S. Patariaia¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹,

M. Pecsý^{144a}, M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶, H. Peng^{32b}, B. Penning³⁰,
 A. Penson³⁴, J. Penwell⁶⁰, M. Perantoni^{23a}, K. Perez^{34,ae}, T. Perez Cavalcanti⁴¹, E. Perez Codina^{159a},
 M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴,
 S. Persema^{3a}, V.D. Peshekhonov⁶⁴, K. Peters²⁹, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁴,
 A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴²,
 R. Pezoa^{31b}, A. Phan⁸⁶, P.W. Phillips¹²⁹, G. Piacquadio²⁹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b},
 S.M. Piec⁴¹, R. Piegaia²⁶, D.T. Pignotti¹⁰⁹, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,b},
 M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold², B. Pinto^{124a}, O. Pirotte²⁹, C. Pizio^{89a,89b},
 M. Plamondon¹⁶⁹, M.-A. Pleier²⁴, E. Plotnikova⁶⁴, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³,
 L. Poggioli¹¹⁵, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio^{36a,36b}, A. Polini^{19a},
 J. Poll⁷⁵, V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a},
 B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso²⁹, G.E. Pospelov⁹⁹,
 S. Pospisil¹²⁷, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard²⁹, J. Poveda¹⁷³, V. Pozdnyakov⁶⁴,
 R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁴, S. Prasad²⁹, R. Pravahan²⁴, S. Prell⁶³, K. Pretzl¹⁶, D. Price⁶⁰,
 J. Price⁷³, L.E. Price⁵, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{31b}, S. Protopopescu²⁴,
 J. Proudfoot⁵, X. Prudent⁴³, M. Przybycien³⁷, H. Przysiezniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴,
 E. Pueschel⁸⁴, J. Purdham⁸⁷, M. Purohit^{24,ac}, P. Puzo¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, Z. Qin⁴¹,
 A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷³, F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radescu⁴¹, P. Radloff¹¹⁴,
 T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁴, S. Rajagopalan²⁴,
 M. Rammensee⁴⁸, M. Rammes¹⁴¹, A.S. Randle-Conde³⁹, K. Randrianarivony²⁸, F. Rauscher⁹⁸,
 T.C. Rave⁴⁸, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuszi^{119a,119b}, A. Redelbach¹⁷⁴, G. Redlinger²⁴,
 R. Reece¹²⁰, K. Reeves⁴⁰, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², C. Rembser²⁹, Z.L. Ren¹⁵¹,
 A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹,
 E. Richter-Was^{4,af}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a},
 R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,k},
 A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁷, J.E.M. Robinson⁷⁷, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶,
 C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, A. Roe⁵⁴, S. Roe²⁹, O. Röhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶,
 M. Romano^{19a,19b}, G. Romeo²⁶, E. Romero Adam¹⁶⁷, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹,
 A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶³, P.L. Rosendahl¹³, O. Rosenthal¹⁴¹,
 L. Rossetlet⁴⁹, V. Rossetti¹¹, E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{25a}, I. Roth¹⁷², J. Rothberg¹³⁸,
 D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{32a,ag}, F. Rubbo¹¹, I. Rubinskiy⁴¹,
 B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴³, G. Rudolph⁶¹, F. Rühr⁶, F. Ruggieri^{134a,134b},
 A. Ruiz-Martinez⁶³, V. Rumiantsev^{91,*}, L. Rummyantsev⁶⁴, K. Runge⁴⁸, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴,
 J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵,
 N.C. Ryder¹¹⁸, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a},
 H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salek²⁹, D. Salihagic⁹⁹,
 A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴,
 A. Salzburger²⁹, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷,
 H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵, T. Sandoval²⁷, C. Sandoval¹⁶²,
 R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³,
 R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a}, T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁷,
 F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵, N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage⁴, E. Sauvan⁴,
 J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³, D.O. Savu²⁹, L. Sawyer^{24,m}, D.H. Saxon⁵³, J. Saxon¹²⁰,
 C. Sbarra^{19a}, A. Sbrizzi^{19a,19b}, O. Scallion⁹³, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵,
 P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹, S. Schaepe²⁰, S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸,
 R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³,
 M.I. Scherzer³⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{36a,36b}, S. Schlenker²⁹, E. Schmidt⁴⁸,
 K. Schmieden²⁰, C. Schmitt⁸¹, S. Schmitt^{58b}, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹,
 D. Schouten^{159a}, J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²⁰,
 J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸,
 B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸,
 R. Schwienhorst⁸⁸, R. Schwierz⁴³, J. Schwindling¹³⁶, T. Schwindt²⁰, M. Schwoerer⁴, G. Sciolla²²,

W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴¹, E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³,
 J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, S.J. Sekula³⁹, K.E. Selbach⁴⁵, D.M. Seliverstov¹²¹, B. Sellden^{146a},
 G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴, R. Seuster⁹⁹,
 H. Severini¹¹¹, A. Sfyrla²⁹, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶,
 M. Shapiro¹⁴, P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, A. Shibata¹⁰⁸,
 H. Shichi¹⁰¹, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³⁰,
 D. Short¹¹⁸, S. Shrestha⁶³, E. Shulga⁹⁶, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸,
 Dj. Sijacki^{12a}, O. Silbert¹⁷², J. Silva^{124a}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷,
 O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁵,
 P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa¹⁷⁴, A. Sircar²⁴, A.N. Sisakyan⁶⁴, S.Yu. Sivoklokov⁹⁷,
 J. Sjölin^{146a,146b}, T.B. Sjrursen¹³, L.A. Skinnari¹⁴, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹,
 M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, V. Smakhtin¹⁷², B.H. Smart⁴⁵, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶,
 L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹,
 K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁴, M. Soares^{124a}, R. Sobie^{169,k},
 J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁶, U. Soldevila¹⁶⁷,
 E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, H.Y. Song^{32b}, N. Soni²,
 V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁷, R. Soualah^{164a,164c}, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b},
 F. Spanò⁷⁶, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, R. Spiwoks²⁹, M. Spousta¹²⁶, T. Spreitzer¹⁵⁸,
 B. Spurlock⁷, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka³⁸, R.W. Stanek⁵,
 C. Stanescu^{134a}, M. Stanescu-Bellu⁴¹, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵,
 P. Starovoitov⁴¹, A. Staude⁹⁸, P. Stavina^{144a}, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷,
 B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart²⁹,
 J.A. Stillings²⁰, M.C. Stockton⁸⁵, K. Stoerig⁴⁸, G. Stoica^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷,
 A. Straessner⁴³, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³,
 M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹,
 J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵, N.A. Styles⁴¹, D.A. Soh^{151,w}, D. Su¹⁴³,
 H.S. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, K. Suita⁶⁶, M. Suk¹²⁶, V.V. Sulin⁹⁴,
 S. Sultansoy^{3d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{36a,36b},
 M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶,
 J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴¹, A. Taffard¹⁶³, R. Tafirout^{159a}, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹,
 H. Takai²⁴, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵, M. Talby⁸³, A. Talyshev^{107,f},
 M.C. Tamsett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶,
 N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁸, G.F. Tartarelli^{89a}, P. Tas¹²⁶,
 M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹²,
 G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶,
 K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Testa⁴⁷,
 R.J. Teuscher^{158,k}, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸, M. Thioye¹⁷⁶, S. Thoma⁴⁸, J.P. Thomas¹⁷,
 E.N. Thompson³⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁵,
 E. Thomson¹²⁰, M. Thomson²⁷, R.P. Thun⁸⁷, F. Tian³⁴, M.J. Tibbetts¹⁴, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴,
 Y.A. Tikhonov^{107,f}, S. Timoshenko⁹⁶, P. Tipton¹⁷⁶, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, T. Todorov⁴,
 S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁵, S. Tokár^{144a}, K. Tokunaga⁶⁶, K. Tokushuku⁶⁵,
 K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³⁰, K. Toms¹⁰³, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁴,
 I. Torchiani²⁹, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torrón Pastor¹⁶⁷, J. Toth^{83,ad}, F. Touchard⁸³, D.R. Tovey¹³⁹,
 T. Trefzger¹⁷⁴, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvoid⁷⁸, T.N. Trinh⁷⁸,
 M.F. Tripiana⁷⁰, W. Trischuk¹⁵⁸, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trotter-McDonald¹⁴², M. Trzebinski³⁸,
 A. Trzupek³⁸, C. Tsarouchas²⁹, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehka⁹⁰, D. Tsionou^{4,ah},
 G. Tsipolitis⁹, V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁴, J.-W. Tsung²⁰,
 S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{25a}, V. Tudorache^{25a}, J.M. Tuggle³⁰, M. Turala³⁸,
 D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁴, A. Tykhonov⁷⁴,
 M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Uglund¹³,
 M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁵,
 D. Urbaniec³⁴, G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴,

J. Valenta¹²⁵, P. Valente^{132a}, S. Valentineti^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster²⁹, N. van Eldik²⁹, P. van Gemmeren⁵, I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli²⁹, A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, R. Vari^{132a}, E.W. Varnes⁶, T. Varol⁸⁴, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura¹³⁸, M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴³, M.C. Vetterli^{142.d}, I. Vichou¹⁶⁵, T. Vickey^{145b,ai}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincter²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁴, M. Virchaux^{136,*}, J. Virzi¹⁴, O. Vitells¹⁷², M. Viti⁴¹, I. Vivarelli⁴⁸, F. Vives Vaque², S. Vlachos⁹, D. Vladoiu⁹⁸, M. Vlasak¹²⁷, A. Vogel²⁰, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁵, J.H. Vosseveld⁷³, N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁵, P. Wagner¹²⁰, H. Wahlen¹⁷⁵, S. Wahrmond⁴³, J. Wakabayashi¹⁰¹, S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷³, H. Wang^{32b,qj}, J. Wang¹⁵¹, J. Wang⁵⁵, R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²⁰, A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁵, C. Wasicki⁴¹, P.M. Watkins¹⁷, A.T. Watson¹⁷, I.J. Watson¹⁵⁰, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²², P.S. Wells²⁹, T. Wenaus²⁴, D. Wendland¹⁵, Z. Weng^{151,w}, T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, A. White⁷, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, F. Wicek¹¹⁵, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wielers¹²⁹, P. Wienemann²⁰, C. Wiglesworth⁷⁵, L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁷, A. Wildauer¹⁶⁷, M.A. Wildt^{41,s}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸, H. Wolters^{124a,h}, W.C. Wong⁴⁰, G. Wooden⁸⁷, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸², K.W. Wozniak³⁸, K. Wraight⁵³, C. Wright⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{32b,ak}, E. Wulf³⁴, B.M. Wynne⁴⁵, S. Xella³⁵, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{32b,z}, D. Xu¹³⁹, B. Yabsley¹⁵⁰, S. Yacoob^{145b}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶⁰, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{32a}, Y. Yao¹⁴, Y. Yasu⁶⁵, G.V. Ybeles Smit¹³⁰, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosofmiya¹²³, K. Yorita¹⁷¹, R. Yoshida⁵, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, B. Zabinski³⁸, R. Zaidan⁶², A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, L. Zanello^{132a,132b}, A. Zaytsev¹⁰⁷, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁵, A. Zemla³⁸, C. Zendler²⁰, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zinonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b,qj}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹, J. Zhu⁸⁷, Y. Zhu^{32b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶⁰, R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{19a,19b}, A. Zsenei²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalinski²⁹

¹ University at Albany, Albany, NY, United States

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

⁶ Department of Physics, University of Arizona, Tucson, AZ, United States

⁷ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

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
- 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
- 22 Department of Physics, Brandeis University, Waltham, MA, United States
- 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
- 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
- 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, Aubiere Cedex, France
- 34 Nevis Laboratory, Columbia University, Irvington, NY, United States
- 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
- 40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
- 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
- 45 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
- 47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
- 48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- 49 Section de Physique, Université de Genève, Geneva, Switzerland
- 50 ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- 51 ^(a) E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- 56 Department of Physics, Hampton University, Hampton, VA, United States
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- 58 ^(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
- 59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 60 Department of Physics, Indiana University, Bloomington, IN, United States
- 61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 62 University of Iowa, Iowa City, IA, United States
- 63 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- 64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 66 Graduate School of Science, Kobe University, Kobe, Japan
- 67 Faculty of Science, Kyoto University, Kyoto, Japan
- 68 Kyoto University of Education, Kyoto, Japan
- 69 Department of Physics, Kyushu University, Fukuoka, Japan
- 70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 71 Physics Department, Lancaster University, Lancaster, United Kingdom
- 72 ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 77 Department of Physics and Astronomy, University College London, London, United Kingdom
- 78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 79 Fysiska Institutionen, Lunds Universitet, Lund, Sweden
- 80 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 81 Institut für Physik, Universität Mainz, Mainz, Germany
- 82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 84 Department of Physics, University of Massachusetts, Amherst, MA, United States
- 85 Department of Physics, McGill University, Montreal, QC, Canada
- 86 School of Physics, University of Melbourne, Victoria, Australia

- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁸⁹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹³ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ Skobel'syn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁷ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York, NY, United States
- ¹⁰⁹ Ohio State University, Columbus, OH, United States
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹² Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹³ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁵ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁶ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁷ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁸ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹¹⁹ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²⁰ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²¹ Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²² ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²³ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁴ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; ^(b) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- ¹²⁵ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁶ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁸ State Research Center Institute for High Energy Physics, Protvino, Russia
- ¹²⁹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁰ Physics Department, University of Regina, Regina, SK, Canada
- ¹³¹ Ritsumeikan University, Kusatsu, Shiga, Japan
- ¹³² ^(a) INFN Sezione di Roma I; ^(b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ¹³³ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- ¹³⁵ ^(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;
- ¹³⁶ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
- ¹³⁷ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- ¹³⁸ Department of Physics, University of Washington, Seattle, WA, United States
- ¹³⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴⁰ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴¹ Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴² Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford, CA, United States
- ¹⁴⁴ ^(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
- ¹⁴⁵ ^(a) Department of Physics, University of Johannesburg, Johannesburg; ^(b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁶ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁷ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁸ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- ¹⁴⁹ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵⁰ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵¹ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵² Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵³ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁴ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁵ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁶ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁷ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁸ Department of Physics, University of Toronto, Toronto, ON, Canada
- ¹⁵⁹ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- ¹⁶⁰ Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
- ¹⁶¹ Science and Technology Center, Tufts University, Medford, MA, United States

- ¹⁶² Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
¹⁶³ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
¹⁶⁴ ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
¹⁶⁵ Department of Physics, University of Illinois, Urbana, IL, United States
¹⁶⁶ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁶⁷ 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
¹⁶⁸ Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷¹ Waseda University, Tokyo, Japan
¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷³ Department of Physics, University of Wisconsin, Madison, WI, United States
¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁵ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁶ Department of Physics, Yale University, New Haven, CT, United States
¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia
¹⁷⁸ Domaine Scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

^a Also at Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal.

^b Also at Faculdade de Ciências 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.

^f Also at Novosibirsk State University, Novosibirsk, Russia.

^g Also at Fermilab, Batavia, IL, United States.

^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.

ⁿ Also at Departamento de Física and CEFITEC of Faculdade de Ciências 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.

^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 à l'Energie Atomique), Gif-sur-Yvette, France.

^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland.

^{ab} Also at Departamento de Física, Universidade de Minho, Braga, Portugal.

^{ac} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

^{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.

^{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 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom.

^{aj} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{ak} Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

* Deceased.