

Lawrence Berkeley National Laboratory

Recent Work

Title

Searches for exclusive Higgs and Z boson decays into $J/\psi \gamma$, $\psi(2S) \gamma$, and $\Upsilon(nS) \gamma$ at $s=13\text{TeV}$ with the ATLAS detector

Permalink

<https://escholarship.org/uc/item/18w5m0n9>

Journal

Physics Letters B, 786

ISSN

0370-2693

Authors

Aaboud, M
Aad, G
Abbott, B
et al.

Publication Date

2018-11-01

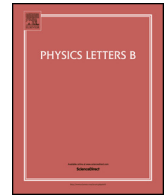
DOI

10.1016/j.physletb.2018.09.024

License

CC BY 4.0

Peer reviewed



Searches for exclusive Higgs and Z boson decays into $J/\psi \gamma$, $\psi(2S) \gamma$, and $\Upsilon(nS) \gamma$ at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration ^{*}

ARTICLE INFO

Article history:

Received 3 July 2018

Received in revised form 23 August 2018

Accepted 12 September 2018

Available online 14 September 2018

Editor: M. Doser

ABSTRACT

Searches for the exclusive decays of the Higgs and Z bosons into a J/ψ , $\psi(2S)$, or $\Upsilon(nS)$ ($n = 1, 2, 3$) meson and a photon are performed with a pp collision data sample corresponding to an integrated luminosity of 36.1 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above the expected backgrounds, and 95% confidence-level upper limits on the branching fractions of the Higgs boson decays to $J/\psi \gamma$, $\psi(2S) \gamma$, and $\Upsilon(nS) \gamma$ of 3.5×10^{-4} , 2.0×10^{-3} , and $(4.9, 5.9, 5.7) \times 10^{-4}$, respectively, are obtained assuming Standard Model production. The corresponding 95% confidence-level upper limits for the branching fractions of the Z boson decays are 2.3×10^{-6} , 4.5×10^{-6} and $(2.8, 1.7, 4.8) \times 10^{-6}$, respectively.

© 2018 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Following the observation of a Higgs boson H with a mass of approximately 125 GeV by the ATLAS and CMS collaborations [1,2], detailed measurements of its properties show no deviations from the Standard Model (SM) [3]. However, its role in fermion mass generation is still to be shown experimentally. In the SM, this mass generation is implemented through Yukawa interactions, and many theories beyond the SM predict substantial modifications of the relevant Higgs boson couplings to fermions. The ATLAS and CMS collaborations have reported measurements of the Higgs coupling to a third-generation fermion with a significance greater than five standard deviations in the $H \rightarrow \tau^+ \tau^-$ channel [3–5]. In addition, progress has been made in the third-generation quark sector with indirect evidence of the coupling of the Higgs boson to the top quark [3]. This was recently complemented by direct observation of the associated production of the Higgs boson with a top-quark pair ($t\bar{t}H$) [6,7]. Evidence of Higgs boson decays into $b\bar{b}$ has also been found with a significance in excess of three standard deviations by both ATLAS and CMS [8–10]. No experimental evidence of Higgs boson decays into the first- and second-generation fermions has yet been found, but direct searches were recently performed by the ATLAS Collaboration for $H \rightarrow c\bar{c}$ [11] and $H \rightarrow \mu^+ \mu^-$ [12,13] and by the CMS Collaboration for $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow e^+ e^-$ decays [14].

The Standard Model Higgs boson decays $H \rightarrow J/\psi \gamma$ and $H \rightarrow \psi(2S) \gamma$ offer an opportunity to access the c -quark Yukawa

coupling [15,16] in a manner complementary to studies of the inclusive decay $H \rightarrow c\bar{c}$. The branching fraction for $H \rightarrow J/\psi \gamma$ has been calculated within the SM to be $\mathcal{B}(H \rightarrow J/\psi \gamma) = (2.99^{+0.16}_{-0.15}) \times 10^{-6}$ [17]. Other recent results on these calculations are given in Refs. [18–20]. For $H \rightarrow \psi(2S) \gamma$ the branching fraction was calculated by the authors of Ref. [17] to be $\mathcal{B}(H \rightarrow \psi(2S) \gamma) = (1.03 \pm 0.06) \times 10^{-6}$ using an estimate for the value of the order- v^2 NRQCD long-distance matrix element.

The corresponding decays in the bottomonium sector, $H \rightarrow \Upsilon(1S, 2S, 3S) \gamma$, can provide, in combination with $H \rightarrow b\bar{b}$ decays, information about the real and imaginary parts of the b -quark coupling to the Higgs boson [19], which could probe potential CP violation in the Higgs sector. However, the expected SM branching fractions, $\mathcal{B}(H \rightarrow \Upsilon(nS) \gamma) = (5.22^{+2.02}_{-1.70}, 1.42^{+0.72}_{-0.57}, 0.91^{+0.48}_{-0.38}) \times 10^{-9}$ ($n = 1, 2, 3$) [17,18], are smaller due to a cancellation between the “direct” and “indirect” amplitudes. The direct amplitude proceeds through the $H \rightarrow q\bar{q}$ coupling with a subsequent photon emission before the $q\bar{q}$ hadronisation to $\Upsilon(nS)$. The indirect amplitude proceeds via the $H\gamma\gamma$ coupling followed by the fragmentation $\gamma^* \rightarrow \Upsilon(nS)$.

Deviations of the c - and b -quark Yukawa couplings from the SM expectations can lead to significant increases in the branching fractions for exclusive decays. These deviations can arise in beyond-the-SM theories; for example, the quark masses might not originate entirely from the Higgs mechanism but could also be induced by other subdominant sources of electroweak symmetry breaking [21]. Other scenarios include the minimal flavour violation framework [22], the Froggatt–Nielsen mechanism [23], the Higgs-dependent Yukawa couplings model [24], the Randall–Sundrum family of models [25], and the possibility of the Higgs boson being

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

a composite pseudo-Goldstone boson [26]. An overview of relevant models of physics beyond-the-SM is provided in Ref. [27].

Decays of the Higgs boson into a heavy, vector quarkonium state, $Q \equiv J/\psi$ or $\Upsilon(nS)$, and a photon were searched for by the ATLAS Collaboration with up to 19.2 fb^{-1} of data collected at $\sqrt{s} = 8 \text{ TeV}$ [28], resulting in 95% confidence level (CL) upper limits of 1.5×10^{-3} for $\mathcal{B}(H \rightarrow J/\psi \gamma)$ and $(1.3, 1.9, 1.3) \times 10^{-3}$ for $\mathcal{B}(H \rightarrow \Upsilon(nS) \gamma)$ ($n = 1, 2, 3$). The former decay mode was also searched for by the CMS Collaboration [29], yielding a similar upper limit. In addition, the ATLAS Collaboration searched for the rare Higgs decays $H \rightarrow \phi \gamma$ and $H \rightarrow \rho \gamma$ [30,31].

Owing to the large Z boson production cross section at the LHC, rare Z boson decays can be probed at much lower rates than for Higgs boson decays into the same final state. Branching fractions for $Z \rightarrow Q \gamma$ decays have been calculated to be between 10^{-8} and 10^{-7} for both the $Z \rightarrow J/\psi \gamma$ and $Z \rightarrow \Upsilon(nS) \gamma$ decays [32–34]. Measurements of the branching fractions for these decays would provide a sensitive test of the SM and the factorisation approach in quantum chromodynamics (QCD), since the power corrections in terms of the ratio of the QCD energy scale to the vector-boson mass are small [33]. ATLAS searched for Z boson decays into J/ψ or $\Upsilon(nS)$ ($n = 1, 2, 3$) and a photon with 20.3 fb^{-1} of data collected at $\sqrt{s} = 8 \text{ TeV}$ [28], resulting in 95% CL upper limits of 2.6×10^{-6} and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively. ATLAS also searched for the decay modes $Z \rightarrow \phi \gamma$ and $Z \rightarrow \rho \gamma$ [30,31].

This Letter describes searches for Higgs and Z boson decays into the exclusive final states $J/\psi \gamma$, $\psi(2S) \gamma$, and $\Upsilon(nS) \gamma$ ($n = 1, 2, 3$) with $J/\psi \rightarrow \mu^+ \mu^-$, $\psi(2S) \rightarrow \mu^+ \mu^-$, and $\Upsilon(nS) \rightarrow \mu^+ \mu^-$ using ATLAS data collected in 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$. Throughout the remainder of this Letter, where no distinction is relevant, the J/ψ and $\psi(2S)$ states are referred to collectively as the $\psi(nS)$ states.

2. ATLAS detector

ATLAS [35] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.¹ It consists of an inner tracking detector, electromagnetic and hadronic calorimeters, and a muon spectrometer.

The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$ and is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. At small radii, a high-granularity silicon pixel detector surrounds the vertex region and typically provides four measurements per track. It is followed by a silicon microstrip tracker, which provides eight measurement points per track. The silicon detectors are complemented by a gas-filled straw-tube transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$ with typically 35 measurements per track.

Electromagnetic (EM) calorimetry within the region $|\eta| < 3.2$ is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) EM calorimeters with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in upstream material; for $|\eta| < 2.5$ the EM calorimeter is divided into three layers in depth. A steel/scintillator-tile calorimeter provides hadronic calorimetry for $|\eta| < 1.7$. LAr technology with copper as absorber is used for the hadronic calorimeters in the endcap region $1.5 < |\eta| < 3.2$. The solid-angle coverage is completed with forward copper/LAr and

tungsten/LAr calorimeter modules in $3.1 < |\eta| < 4.9$ optimised for EM and hadronic measurements, respectively.

The muon spectrometer surrounds the calorimeters and has separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field provided by three air-core superconducting toroidal magnets. The precision chamber system covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel and thin gap chambers in the endcap regions.

A two-level trigger and data acquisition system is used to record events for offline analysis [36]. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to at most 100 kHz. It is followed by a software-based high-level trigger which filters events using the full detector information and outputs events for permanent storage at an average rate of 1 kHz.

3. Data and simulated data

The search is performed with a sample of pp collision data recorded at a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity of 36.1 fb^{-1} . The integrated luminosity of the data sample has an uncertainty of 2.1% derived using the method described in Ref. [37]. Events are retained for further analysis only if they were collected under stable LHC beam conditions and all relevant detector components were fully functional.

The data samples used in this analysis were collected by a combination of two triggers [36]. The first required an isolated photon with transverse momentum p_T^γ greater than 35 GeV and at least one muon with p_T^μ greater than 18 GeV. The second required an isolated photon with $p_T^\gamma > 25 \text{ GeV}$ and a muon with $p_T^\mu > 24 \text{ GeV}$. The use of two triggers with differing transverse momentum thresholds on the photon and muon objects offers an increased trigger efficiency with respect to the case of either trigger used alone.

Higgs boson production was modelled using the POWHEG-Box v2 Monte Carlo (MC) event generator [38–42] with CT10 parton distribution functions [43] for the gluon-gluon fusion (ggH) and vector-boson fusion (VBF) processes. Both processes were calculated up to next-to-leading order (NLO) in α_s . POWHEG-Box was interfaced with PYTHIA8.186 [44,45] to model the parton shower, hadronisation, and underlying event with the AZNLO set of tuned parameters [46]. Additional contributions from the associated production of a Higgs boson and a W or Z boson (denoted WH and ZH , respectively) were modelled by the PYTHIA8.186 event generator [44,45] with NNPDF23LO parton distribution functions [47] and the A14 set of tuned parameters for hadronisation and the underlying event [48]. The production rates for the SM Higgs boson with $m_H = 125 \text{ GeV}$, obtained from the compilation in Ref. [27], are assumed throughout this analysis. The ggH production is normalised such that it reproduces the total cross section predicted by a next-to-next-to-next-to-leading-order QCD calculation with NLO electroweak corrections applied [49–52]. The VBF production is normalised to an approximate next-to-next-to-leading-order (NNLO) QCD cross section with NLO electroweak corrections applied [53–55]. The production of WH and ZH is normalised to cross sections calculated at NNLO in QCD with NLO electroweak corrections [56,57] including the NLO QCD corrections [58] for $gg \rightarrow ZH$. The production of a Higgs boson in association with $t\bar{t}$ ($t\bar{t}H$) or $b\bar{b}$ ($b\bar{b}H$) is accounted for by scaling the total cross section used to normalise the ggH signal sample, assuming the signal efficiency of these processes to be equal to that for ggH . The ad-

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 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 z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

dition of $t\bar{t}H$ and $b\bar{b}H$ to the ggH signal changes the acceptance by less than 1%.

The POWHEG-Box v2 event generator was also used to model inclusive Z boson production. PYTHIA8.186 [44,45] with CTEQ6L1 parton distribution functions [59] and the AZNLO set of hadronisation and underlying-event parameters [46] was used to simulate parton showering and hadronisation. The prediction is normalised to the total cross section obtained from the measurement in Ref. [60], which has an uncertainty of 2.9%. This conservatively assumes the luminosity component of the uncertainty to be completely uncorrelated with that of this search.

The Higgs and Z boson decays were simulated as a cascade of two-body decays, accounting for effects of the quarkonium helicity on the $\mu^+\mu^-$ kinematics. The quarkonium state is simulated to be transversely polarised in the case of the Higgs boson decay and longitudinally polarised in the case of the Z boson decay [34]. The branching fractions for the decays $Q \rightarrow \mu^+\mu^-$ are taken from Ref. [61]. The simulated events were passed through the detailed GEANT 4 simulation of the ATLAS detector [62,63] and processed with the same software used to reconstruct the data.

4. Event selection for $\psi(nS)\gamma \rightarrow \mu^+\mu^-\gamma$ and $\Upsilon(nS)\gamma \rightarrow \mu^+\mu^-\gamma$

Muons are reconstructed from ID tracks combined with independent muon spectrometer tracks or track segments [64] and are required to have $p_T^\mu > 3$ GeV and pseudorapidity $|\eta^\mu| < 2.5$. Candidate $Q \rightarrow \mu^+\mu^-$ decays are reconstructed from pairs of oppositely charged muons consistent with originating from a common vertex. The highest- p_T muon in a pair, called the leading muon in the following, is required to have $p_T^\mu > 18$ GeV. Dimuons with a mass $m_{\mu^+\mu^-}$ within $2.0 < m_{\mu^+\mu^-} < 4.2$ GeV are identified as $\psi(nS) \rightarrow \mu^+\mu^-$ candidates. Dimuons with $8.0 < m_{\mu^+\mu^-} < 12.0$ GeV are considered to be $\Upsilon(nS) \rightarrow \mu^+\mu^-$ candidates.

Selected $Q \rightarrow \mu^+\mu^-$ candidates are subjected to isolation and vertex-quality requirements. In this case, the primary pp vertex is defined as the reconstructed vertex with the highest $\sum_i p_{Ti}^2$ of all associated tracks used to form the vertex. The sum of the p_T of the tracks within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 10$ GeV/ p_T^μ (with a maximum ΔR of 0.3) of the leading muon is required to be less than 6% of the muon p_T [65]. To mitigate the effects of multiple pp interactions in the same or neighbouring bunch crossings, only ID tracks that originate from the primary vertex are considered. The transverse momentum of the ID track associated with the leading muon is subtracted from the sum, and the subleading muon is also subtracted if it falls within the isolation cone. To reject backgrounds from b -hadron decays, the signed projection of the Q candidate's flight distance between the primary pp vertex and the dimuon vertex onto the direction of its transverse momentum is required to be less than three times its uncertainty.

Photons are reconstructed from clusters of energy in the electromagnetic calorimeter. Clusters without matching ID tracks are classified as unconverted photon candidates while clusters matched to ID tracks consistent with the hypothesis of a photon conversion into e^+e^- are classified as converted photon candidates [66]. Reconstructed photon candidates are required to have transverse momentum $p_T^\gamma > 35$ GeV and pseudorapidity $|\eta^\gamma| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta^\gamma| < 1.52$, and to satisfy the “tight” photon identification criteria [66]. Isolation requirements are imposed to further suppress the contamination from jets. The sum of the transverse momenta of all tracks originating from the primary vertex, within $\Delta R = 0.2$ of the photon direction, excluding those associated with reconstructed photon conversions, is required to be less than 5% of p_T^γ . In addition to this track isolation criterion, a calorime-

ter isolation criterion is applied where the sum of the transverse momenta of calorimeter energy clusters within $\Delta R = 0.4$ of the photon direction, excluding the transverse energy of the reconstructed photon, is required to be less than $(2.45 \text{ GeV} + 0.022 p_T^\gamma)$. The effects of multiple pp interactions in the events are also accounted for in the calorimeter isolation measurements.

Combinations of a $Q \rightarrow \mu^+\mu^-$ candidate and a photon satisfying $\Delta\phi(Q, \gamma) > \pi/2$ are retained for further analysis. When multiple combinations are possible, a situation that arises in only a few percent of the events, the combination of the highest- p_T photon and the Q candidate with an invariant mass closest to the respective quarkonium mass is retained. To improve the sensitivity of the $\Upsilon(nS)\gamma$ analysis in resolving the individual $\Upsilon(nS)$ states, the events are classified into two exclusive categories based upon the pseudorapidity of the muons. Events where both muons are within the region $|\eta^\mu| < 1.05$ constitute the “barrel” (B) category. Events where at least one of the muons is outside the region $|\eta^\mu| < 1.05$ constitute the “endcap” (EC) category.

To maintain a single search region, while ensuring near-optimal sensitivity for both the Higgs and Z boson analyses, the transverse momentum of the Q candidate p_T^Q is required to be greater than a value that varies as a function of the invariant mass of the three-body system $m_{Q\gamma}$. For the $\psi(nS) \rightarrow \mu^+\mu^-$ ($\Upsilon(nS) \rightarrow \mu^+\mu^-$) selection, p_T^Q thresholds of 40 GeV (34 GeV) and 54.4 GeV (52.7 GeV) are imposed for the regions $m_{Q\gamma} \leq 91$ GeV and $m_{Q\gamma} \geq 140$ GeV, respectively. The thresholds are varied between their minimum and maximum values as a linear function of $m_{Q\gamma}$ in the region $91 \text{ GeV} < m_{Q\gamma} < 140 \text{ GeV}$.

5. Signal modelling

For the $\psi(nS)\gamma \rightarrow \mu^+\mu^-\gamma$ final state, the total signal efficiencies (kinematic acceptance, trigger, reconstruction, identification, and isolation efficiencies) are 19% and 11% for the Higgs and Z boson decays, respectively. The corresponding efficiencies for the $\Upsilon(nS)\gamma \rightarrow \mu^+\mu^-\gamma$ final states are 22–23% and 15–16%, respectively. The difference in efficiency between the Higgs and Z boson decays arises primarily from the softer p_T^γ and $p_T^{\mu\mu}$ distributions associated with $Z \rightarrow Q\gamma$ production, as seen by comparing Figs. 1(a) and 1(b) for the $J/\psi\gamma$ case and Figs. 1(c) and 1(d) for the $\Upsilon(nS)\gamma$ case.

Accounting for quarkonium helicity effects in the $Q \rightarrow \mu^+\mu^-$ decays leads to a 3–4% decrease of the expected Higgs boson efficiency and a corresponding 6–9% increase of the expected Z boson efficiency, relative to the efficiency for an isotropic decay.

The $m_{\mu^+\mu^-}$ resolution is 1.6–1.8% for both the Higgs and Z boson decays. For each of the final states, a two-dimensional ($m_{\mu^+\mu^-}$ and $m_{\mu^+\mu^-}$) probability density function (pdf) is used to model the signal. The Higgs boson signals are modelled with two-dimensional multivariate Gaussian distributions, which retain the correlation between $m_{\mu^+\mu^-}$ and $m_{\mu^+\mu^-}$ of the final states. For the Z boson decays, the $m_{\mu^+\mu^-}$ distributions of the signal are modelled with Voigtian pdfs (a convolution of Breit-Wigner and Gaussian pdfs) corrected with mass-dependent efficiency factors, and the $m_{\mu^+\mu^-}$ distributions are modelled as Gaussian pdfs.

The $m_{\mu^+\mu^-}$ distribution for selected $\psi(nS)\gamma$ candidates, which pass the background generation region criteria described in Section 6, is shown in Fig. 2(a) and exhibits clear peaks at the J/ψ and $\psi(2S)$ masses. In Figs. 2(b) and 2(c), the corresponding distributions for the selected $\Upsilon(nS)\gamma$ candidates are shown, where the $\Upsilon(1S, 2S, 3S)$ peaks can be observed. The $\psi(nS)$ and $\Upsilon(nS)$ peaks are fitted with Gaussian pdfs and are used to cross-check the parameters obtained from the fit to simulated signal event samples, while the background is modelled with a Chebychev polynomial function. The experimental resolution in $m_{\mu^+\mu^-}$ is approximately

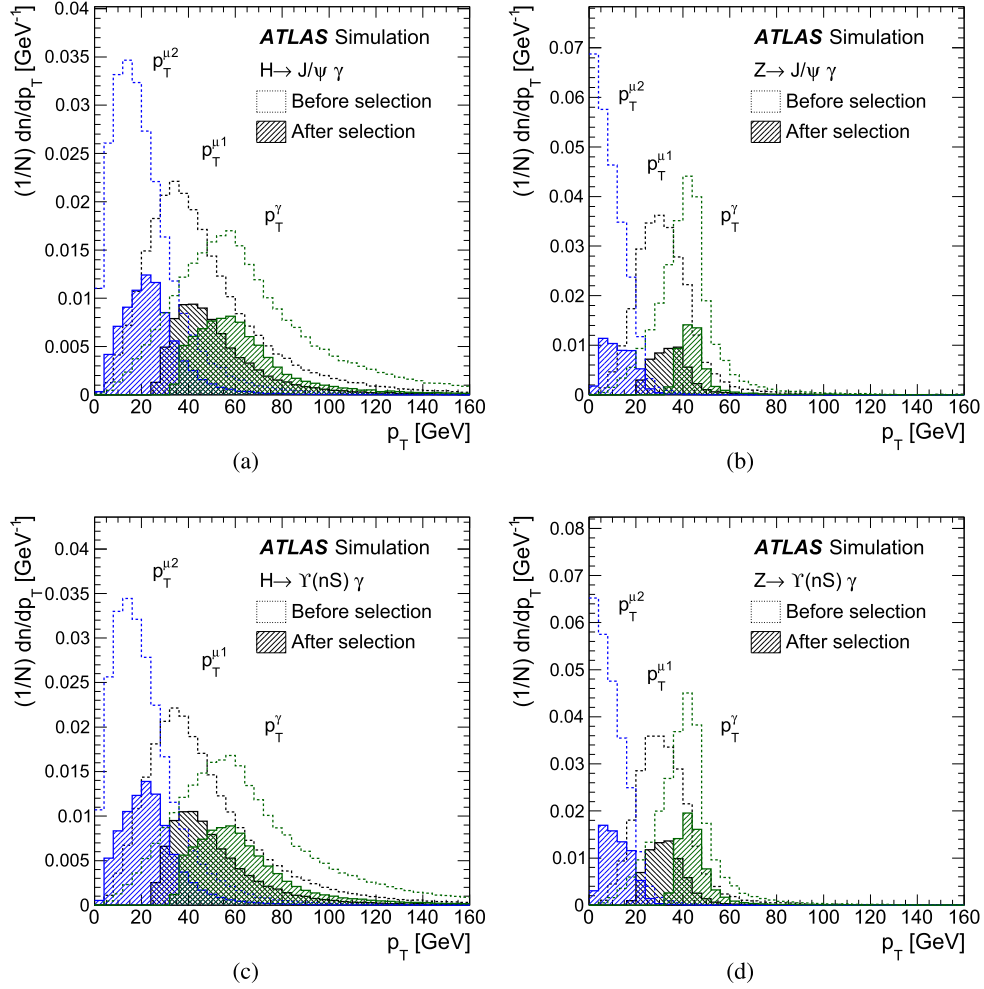


Fig. 1. Generator-level transverse momentum (p_T) distributions of the photon and of the muons, ordered in p_T , for (a) $H \rightarrow J/\psi \gamma$, (b) $Z \rightarrow J/\psi \gamma$, (c) $H \rightarrow \Upsilon(nS) \gamma$ and (d) $Z \rightarrow \Upsilon(nS) \gamma$ simulated signal events, respectively. The leading muon candidate is denoted by $p_T^{\mu 1}$ and the subleading candidate by $p_T^{\mu 2}$. The hatched histograms denote the full event selection while the dashed histograms show the events at generator level that fall within the analysis geometric acceptance (both muons are required to have $|\eta^\mu| < 2.5$ while the photon is required to have $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.52$). The dashed histograms are normalised to unity, and the relative difference between the two sets of distributions corresponds to the effects of reconstruction, trigger, and event selection efficiencies.

54 MeV for the $J/\psi \gamma$ candidates (43 MeV for events in the barrel category and 64 MeV for events in the endcap category).

6. Background modelling

The dominant source of background exhibits a non-resonant $m_{\mu^+\mu^- \gamma}$ distribution and is composed of two distinct contributions: genuine $Q \rightarrow \mu^+\mu^-$ decays and non-resonant dimuon production. The decay $Z \rightarrow \mu^+\mu^- \gamma$ with final-state radiation (Z FSR) constitutes a further, smaller background contribution exhibiting a characteristic resonant structure in the $m_{\mu^+\mu^- \gamma}$ distribution.

The $m_{\mu^+\mu^- \gamma}$ continuum background is modelled with a non-parametric data-driven approach using templates to describe the kinematic distributions. The normalisation of the background is extracted directly from a fit to the data. The shape of the background model in the final discriminant variable is also profiled in the fit. A similar procedure was used in the earlier search for Higgs and Z boson decays into $J/\psi \gamma$ and $\Upsilon(nS) \gamma$ [28] and the searches for Higgs and Z boson decays into $\phi \gamma$ and $\rho \gamma$ [30,31].

The background model uses a sample of 5500 $\psi(nS) \gamma$ and 2300 $\Upsilon(nS) \gamma$ candidate events. These events pass all of the kinematic selection requirements described previously, except that the photon and Q candidates are not required to satisfy the nominal isolation requirements and a looser minimum p_T^Q requirement of

30 GeV is imposed. These events define the background-dominated “generation region” (GR). From these events, pdfs are constructed to describe the distributions of the relevant kinematic and isolation variables and their most important correlations. The data control samples are corrected for contamination from $Z \rightarrow \mu^+\mu^- \gamma$ decays.

The pdfs of these kinematic and isolation variables are sampled to generate an ensemble of pseudocandidates, each with complete Q and γ four-vectors and the associated Q and photon isolation values. The important correlations among the kinematic and isolation variables of the background events, in particular between p_T^Q and p_T^γ , are retained in the generation of the pseudocandidates through the following sampling scheme:

- Initially, a value for p_T^Q is sampled from the corresponding pdf.
- The distribution of p_T^γ is parameterised in bins of p_T^Q , and a value is sampled from the corresponding bin given the previously sampled value of p_T^Q . The muon isolation variables are parameterised in bins of p_T^Q and p_T^γ and sampled according to the previously selected values.
- The distributions of the pseudorapidity difference between Q and γ , $\Delta\eta(Q, \gamma)$, the photon calorimeter isolation variable,

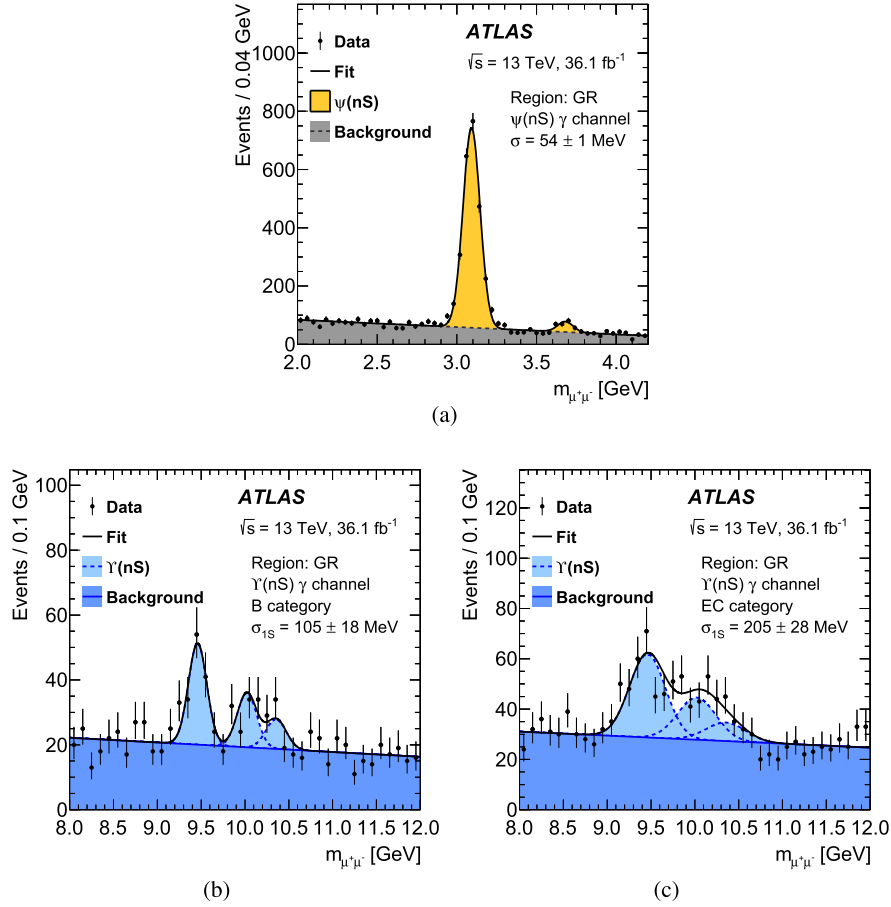


Fig. 2. Distribution of $\mu^+\mu^-$ invariant mass for (a) $\psi(nS)\gamma$ and $Y(nS)\gamma$ ((b) barrel and (c) endcap categories) candidates. The candidates satisfy the event selection but without the nominal isolation requirements and with a looser minimum p_T^Q requirement of 30 GeV. These events constitute the background “generation region” defined in Section 6.

and their correlations are parameterised in a binned two-dimensional distribution in the same bins of p_T^Q used to describe the p_T^γ and muon isolation variables.

- Given the selected values of relative photon calorimeter isolation and p_T^Q , a value for the relative photon track isolation is sampled.
- Given the selected values of $\Delta\eta(Q, \gamma)$ and p_T^Q , a value is sampled for the azimuthal angular separation between Q and γ , $\Delta\phi(Q, \gamma)$.
- Values for η^Q and ϕ^Q are sampled from a binned histogram of the corresponding distributions in the data control sample. These are combined with $\Delta\eta(Q, \gamma)$ and $\Delta\phi(Q, \gamma)$ to give the values of η^γ and ϕ^γ .
- A value for m_Q is sampled from within the required region of $m_{\mu^+\mu^-}$. Separate pdfs are used to describe the $m_{\mu^+\mu^-}$ distributions of resonant $\psi(nS)$ and $Y(nS)$ production and non-resonant dimuons, which is referred to as “combinatoric” in the following.

The use of this procedure ensures a good description of the background and avoids any reliance on the accuracy or limited sample size of simulated background events.

The nominal selection requirements are imposed and the surviving pseudocandidates are used to construct templates for the $m_{Q\gamma}$ distributions which are then smoothed using a Gaussian kernel density estimation [67]. Potential contamination of the GR sample from signal events is expected to be negligible, and it was verified, through signal injection tests, that such a potential sig-

nal contamination would not affect the shape of the background model.

The normalisation of the exclusive background from Z FSR is determined directly from the fit to the data. The shape of this background in the $m_{\mu^+\mu^-\gamma}$ distribution is modelled with a Voigtian pdf, while the $m_{\mu^+\mu^-}$ distribution is modelled with a first order polynomial. The parameters of the former pdf are derived from the simulated $Z \rightarrow Q\gamma$ signal samples. The parameters of the latter pdf are determined directly in the fit to data.

To validate this background model with data, the $m_{Q\gamma}$ distributions in several regions defined by kinematic and isolation requirements looser than the nominal signal requirements are used to compare the prediction of the background model with the data. Three validation regions are defined using the GR selection as the basis and adding either the p_T^Q requirement (VR1), or the muon isolation requirements (VR2), or the photon isolation requirement (VR3). The $m_{Q\gamma}$ distributions in these validation regions are shown in Fig. 3 for the $\psi(nS)\gamma$ and the $Y(nS)\gamma$ final states. The background model is found to describe the data well in all validation regions.

7. Systematic uncertainties

The systematic uncertainties in the expected signal yields are summarised in Table 1. Uncertainties in the Higgs production cross sections are obtained from Ref. [27]. The Z boson production cross section uncertainty is taken from the measurement in Ref. [60].

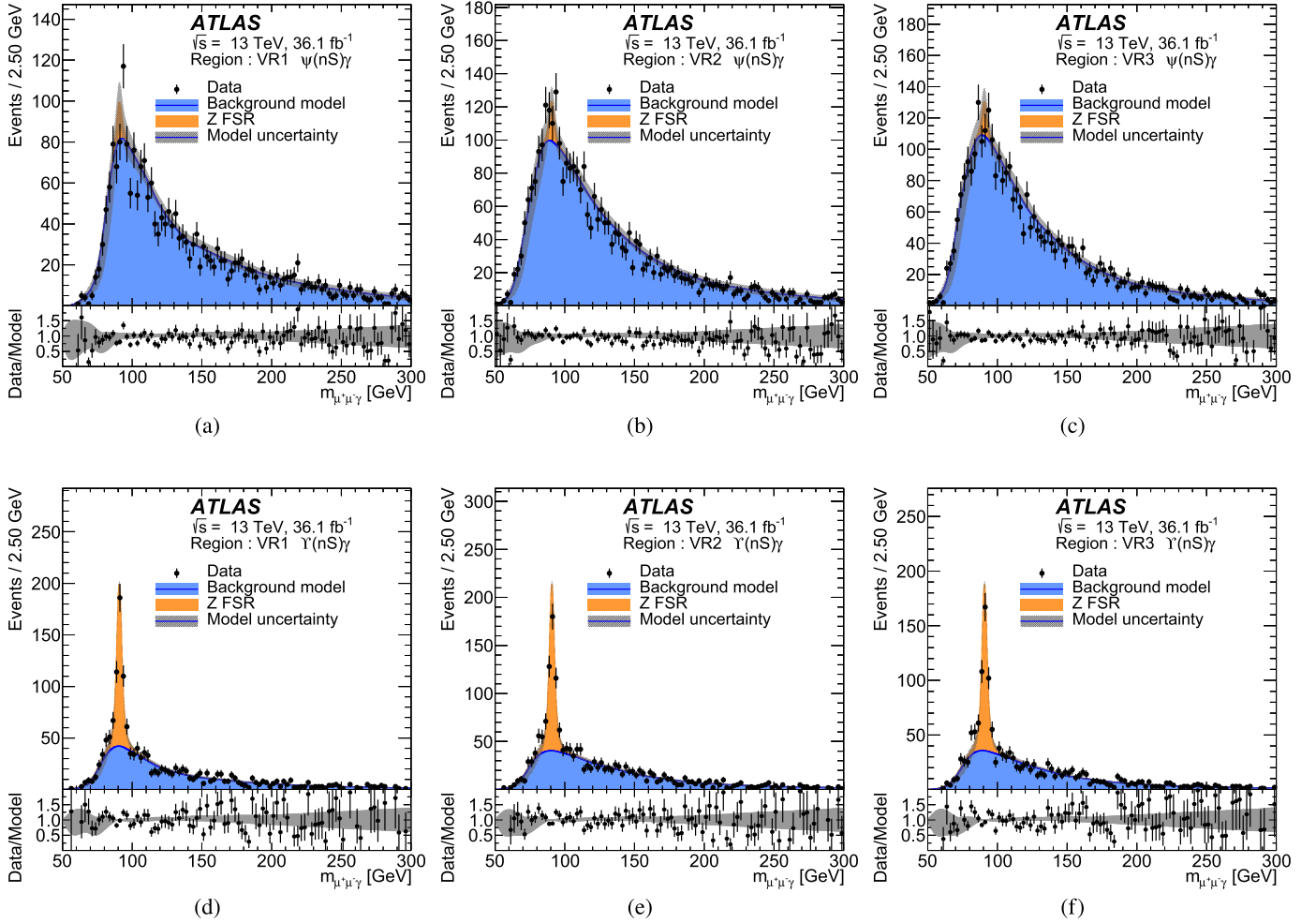


Fig. 3. The distribution of $m_{\mu^+\mu^-\gamma}$ in data compared to the prediction of the background model for ((a), (b) and (c)) $H(Z) \rightarrow \psi(nS)\gamma$ and ((d), (e) and (f)) $H(Z) \rightarrow \Upsilon(nS)\gamma$ in the VR1, VR2 and VR3 validation regions. Z FSR refers to the $Z \rightarrow \mu^+\mu^-\gamma$ background contribution. The background model is normalised to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modelling procedure.

The uncertainty in the acceptance of the Higgs boson signal due to missing higher orders in the generator, parton distribution functions, underlying-event set of tuned parameters, and parton showering is estimated by studying the effect of the different variations on the acceptance at generator level. The total uncertainty in the acceptance due to these effects is estimated to be 1.8%. For the Z boson, the respective uncertainty is determined to be 6% by comparing the generator-level acceptance predictions of the nominal simulated sample with those of MADGRAPH5_AMC@NLO v2.2.2 [68] and SHERPA 2.2.1 [69].

Trigger efficiencies for photons are determined from samples enriched with $Z \rightarrow e^+e^-$ events in data [70]. The systematic uncertainty in the expected signal yield associated with the trigger efficiency is estimated to be 2.0%. Photon identification efficiencies are determined using the enriched $Z \rightarrow e^+e^-$ events, as well as inclusive photon events and $Z \rightarrow \ell\ell\gamma$ events [66,71]. The impact on the yields of the photon identification efficiency uncertainties, for both the converted and unconverted photons, are 1.4% for the Higgs and Z boson signals. The effect of the muon reconstruction and identification efficiency uncertainty is 2.8% [65].

The photon energy scale uncertainty, determined from $Z \rightarrow e^+e^-$ events and validated using $Z \rightarrow \ell\ell\gamma$ events [72,73], is propagated through the simulated signal samples as a function of η^γ and p_T^γ . The uncertainty associated with the determination of the photon energy scale and resolution in the simulation is 0.3% in

the yield of the Higgs and Z boson signal. Similarly, the systematic uncertainty associated with the scale of the muon momentum measurement is 0.2% [65]. The effect of the energy/momentum scale and resolution uncertainties on the signal shape is negligible for the Higgs and Z boson signals. For the Z FSR background shape, the effect is 0.2% on the mean value of the $m_{\mu^+\mu^-\gamma}$ distribution. Including the corresponding nuisance parameter results in a 0.5% change in the expected limit of the $Z \rightarrow \Upsilon(nS)\gamma$ channels with negligible impact in the other channels.

The shape of the background model is allowed to vary around the nominal shape, and the parameters controlling these systematic variations are treated as nuisance parameters in the maximum-likelihood fit described in Section 8. Three such shape variations are implemented through scale variations on the p_T^γ distribution in the model, linear distortions of the shape of the $\Delta\phi(Q, \gamma)$ distribution, and a global tilt of the three-body mass distribution around a pivot point. The first two variations are straightforward alterations to the underlying kinematics of the pseudocandidates, which cause corresponding changes in the three-body mass. The third variation is applied directly to the final three-body mass template. These systematic uncertainties allow the background template to adjust to the observed distribution in data.

Table 1

Summary of the systematic uncertainties in the expected signal yields.

Source of systematic uncertainty	Yield uncertainty $H(Z) \rightarrow Q\gamma$
Total $H(Z)$ cross section	7.0% (2.9%)
Integrated luminosity	2.1%
$H(Z)$ QCD modelling	1.8% (6%)
Trigger efficiency	2.0%
Photon identification	1.4%
Muon identification and reconstruction	2.8%
Photon energy scale	0.3%
Muon momentum scale	0.2%

8. Results

The data are compared with background and signal predictions using a two-dimensional (2D) simultaneous unbinned maximum-likelihood fit to the $m_{\mu^+\mu^-}\gamma$ and $m_{\mu^+\mu^-}$ distributions. A simultaneous 2D fit is required to distinguish the Z FSR background from the $Z \rightarrow Q\gamma$ signal and the non-resonant background. The parameters of interest are the Higgs and Z boson signal normalisations. Systematic uncertainties are modelled using additional nuisance parameters in the fit; in particular, the background normalisations are free parameters. The fit uses the selected events with $m_{Q\gamma} < 300$ GeV.

In total, 1033 events were observed in the $\psi(nS)\gamma$ and 906 in the $\Upsilon(nS)\gamma$ signal regions. The expected and observed numbers of background events within the $m_{Q\gamma}$ ranges relevant to the Higgs and Z boson signals are shown in Table 2. The results of the background-only fits for the $\psi(nS)\gamma$ and $\Upsilon(nS)\gamma$ analyses are shown in Fig. 4.

The systematic uncertainties described in Section 7 result in a 1.0% increase of the expected 95% CL upper limit on the branching fraction of the $H \rightarrow \psi(nS)\gamma$ decays. For the $Z \rightarrow \psi(nS)\gamma$ decays, the effect is larger, 2.6%, mostly due to the systematic uncertainty in the background shape. Similar behaviour is observed in the $\Upsilon(nS)\gamma$ analysis with systematic uncertainties resulting in a 2.5–2.7% deterioration in the sensitivity to the $H \rightarrow \Upsilon(nS)\gamma$ decays and a 2.8–2.9% deterioration in the sensitivity to the $Z \rightarrow \Upsilon(nS)\gamma$ decays, also mostly due to the systematic uncertainty in the background shape.

On the basis of the fit to the observed data, the largest excess observed is 2.2σ in the search for $Z \rightarrow J/\psi\gamma$. Upper limits are set on the branching fractions for the Higgs and Z boson decays into $Q\gamma$ using the CL_s modified frequentist formalism [74] with the profile-likelihood-ratio test statistic [75] and the asymptotic approximations derived in Ref. [76]. The expected SM production cross section is assumed for the Higgs boson [27], while the ATLAS measurement of the inclusive Z boson cross section is used for the Z boson signal [60], as discussed in Section 3. The results are summarised in Table 3. The observed 95% CL upper limits on the branching fractions for Higgs and Z boson decays into $J/\psi\gamma$ and $\psi(2S)\gamma$ are $(3.5, 20) \times 10^{-4}$ and $(2.3, 4.5) \times 10^{-6}$,

Table 2

The number of observed events and the mean expected background, with its total uncertainty, for the $m_{Q\gamma}$ ranges of interest. The expected Z and Higgs boson contributions are shown for branching fraction values of 10^{-6} and 10^{-3} , respectively. These values are motivated by the expected sensitivity of the search to the respective branching fractions.

$m_{\mu^+\mu^-}$ mass range [GeV]		Observed (expected background)				Z signal for $\mathcal{B} = 10^{-6}$	H signal for $\mathcal{B} = 10^{-3}$
		$m_{\mu^+\mu^-\gamma}$ mass range [GeV]					
		81–101		120–130			
$J/\psi\,\gamma$	2.9–3.3	92	(89 $\pm$ 6)	20	(23.6 $\pm$ 1.3)	13.7 $\pm$ 1.1	22.2 $\pm$ 1.9
$\psi(2S)\,\gamma$	3.5–3.9	43	(42 $\pm$ 5)	8	(10.0 $\pm$ 0.8)	1.82 $\pm$ 0.14	2.96 $\pm$ 0.25
$\Upsilon(1S)\,\gamma$	9.0–10.0	115	(126 $\pm$ 8)	9	(13.6 $\pm$ 1.2)	7.8 $\pm$ 0.6	10.7 $\pm$ 0.9
$\Upsilon(2S)\,\gamma$	9.5–10.5	106	(121 $\pm$ 8)	8	(12.6 $\pm$ 1.4)	5.9 $\pm$ 0.5	8.1 $\pm$ 0.7
$\Upsilon(3S)\,\gamma$	10.0–11.0	112	(113 $\pm$ 8)	7	(10.6 $\pm$ 1.2)	7.1 $\pm$ 0.6	9.2 $\pm$ 0.8

Table 3

Expected and observed branching fraction upper limits at 95% CL for the $H(Z) \rightarrow J/\psi\gamma$, $H(Z) \rightarrow \psi(2S)\gamma$, and $H(Z) \rightarrow \Upsilon(nS)\gamma$ ($n = 1, 2, 3$) analyses, assuming SM production for the Higgs and Z bosons. The $\pm 1\sigma$ intervals of the expected limits are also given.

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow J/\psi\gamma) [10^{-4}]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \rightarrow \psi(2S)\gamma) [10^{-4}]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \rightarrow J/\psi\gamma) [10^{-6}]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \rightarrow \psi(2S)\gamma) [10^{-6}]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \rightarrow \Upsilon(1S)\gamma) [10^{-4}]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \rightarrow \Upsilon(2S)\gamma) [10^{-4}]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \rightarrow \Upsilon(3S)\gamma) [10^{-4}]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \rightarrow \Upsilon(1S)\gamma) [10^{-6}]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \rightarrow \Upsilon(2S)\gamma) [10^{-6}]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \rightarrow \Upsilon(3S)\gamma) [10^{-6}]$	$3.0^{+1.3}_{-0.8}$	4.8

respectively. The corresponding limits for the Higgs and Z boson decays into $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) are $(4.9, 5.9, 5.7) \times 10^{-4}$ and $(2.8, 1.7, 4.8) \times 10^{-6}$, respectively. Upper limits at 95% CL on the product of the production cross section times branching fraction are determined for the Higgs boson decays, yielding 19 fb for the $H \rightarrow J/\psi\gamma$ decay, 110 fb for the $H \rightarrow \psi(2S)\gamma$ decay, and (28, 33, 32) fb for the $H \rightarrow \Upsilon(nS)\gamma$ ($n = 1, 2, 3$) decays.

9. Summary

Searches for the exclusive decays of Higgs and Z bosons into $J/\psi\gamma$, $\psi(2S)\gamma$, and $\Upsilon(nS)\gamma$ have been performed with a $\sqrt{s} = 13$ TeV pp collision data sample collected with the ATLAS detector at the LHC corresponding to an integrated luminosity of 36.1 fb^{-1} . No significant excess of events is observed above the background expectations. The obtained 95% CL upper limits are $\mathcal{B}(H \rightarrow J/\psi\gamma) < 3.5 \times 10^{-4}$ and $\mathcal{B}(Z \rightarrow J/\psi\gamma) < 2.3 \times 10^{-6}$ for the $J/\psi\gamma$ final state. The corresponding upper limits are $\mathcal{B}(H \rightarrow \psi(2S)\gamma) < 2.0 \times 10^{-3}$ and $\mathcal{B}(Z \rightarrow \psi(2S)\gamma) < 4.5 \times 10^{-6}$ for the $\psi(2S)\gamma$ final state. The 95% CL upper limits $\mathcal{B}(H \rightarrow \Upsilon(nS)\gamma) < (4.9, 5.9, 5.7) \times 10^{-4}$ and $\mathcal{B}(Z \rightarrow \Upsilon(nS)\gamma) < (2.8, 1.7, 4.8) \times 10^{-6}$ are set for the $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) final states. These upper limits represent an improvement by a factor of approximately two relative to the earlier $H(Z) \rightarrow J/\psi\gamma$ and $H(Z) \rightarrow \Upsilon(nS)\gamma$ results from the ATLAS Collaboration using up to 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data with the addition of the first upper limits on the $H/Z \rightarrow \psi(2S)\gamma$ decays.

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.

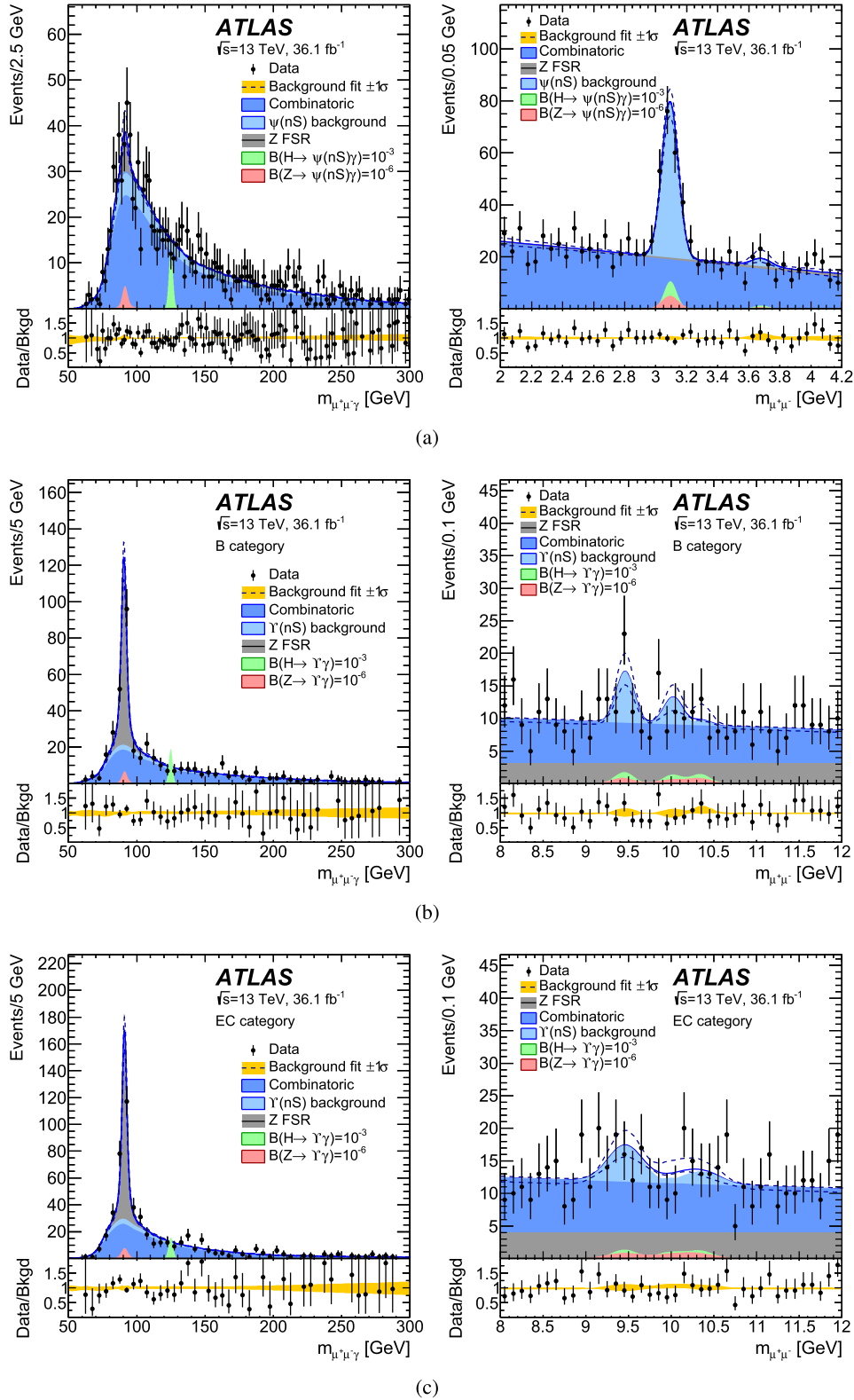


Fig. 4. The $m_{\mu^+\mu^-\gamma}$ and $m_{\mu^+\mu^-}$ distributions for the selected (a) $\psi(nS)\gamma$ and $\Upsilon(nS)\gamma$ ((b) barrel and (c) endcap categories) candidates along with the results of the maximum-likelihood fits with background-only models. Z FSR refers to the $Z \rightarrow \mu^+\mu^-\gamma$ background contribution. The solid blue line denotes the full fit result and the dashed blue lines correspond to its $\pm 1\sigma$ uncertainty band. The ratios of the data to the background-only fits are also shown. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [77].

References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* 716 (2012) 1, arXiv:1207.7214 [hep-ex].
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* 716 (2012) 30, arXiv:1207.7235 [hep-ex].
- [3] ATLAS and CMS Collaborations, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* 08 (2016) 045, arXiv:1606.02266 [hep-ex].
- [4] ATLAS Collaboration, Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, *J. High Energy Phys.* 04 (2015) 117, arXiv:1501.04943 [hep-ex].
- [5] CMS Collaboration, Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons, *J. High Energy Phys.* 05 (2014) 104, arXiv:1401.5041 [hep-ex].
- [6] CMS Collaboration, Observation of $t\bar{t}H$ production, *Phys. Rev. Lett.* 120 (23) (2018) 231801, arXiv:1804.02610 [hep-ex].
- [7] ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, arXiv:1806.00425 [hep-ex], 2018.
- [8] ATLAS Collaboration, Evidence for the $H \rightarrow b\bar{b}$ decay with the ATLAS detector, *J. High Energy Phys.* 12 (2017) 024, arXiv:1708.03299 [hep-ex].
- [9] CMS Collaboration, Evidence for the Higgs boson decay to a bottom quark-antiquark pair, *Phys. Lett. B* 780 (2018) 501, arXiv:1709.07497 [hep-ex].
- [10] CDF and D0 Collaborations, Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron, *Phys. Rev. Lett.* 109 (2012) 071804, arXiv:1207.6436 [hep-ex].
- [11] ATLAS Collaboration, Search for the decay of the Higgs boson to charm quarks with the ATLAS experiment, *Phys. Rev. Lett.* 120 (21) (2018) 211802, arXiv:1802.04329 [hep-ex].
- [12] ATLAS Collaboration, Search for the dimuon decay of the Higgs boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. Lett.* 119 (2017) 051802, arXiv:1705.04582 [hep-ex].
- [13] ATLAS Collaboration, Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector, *Phys. Lett. B* 738 (2014) 68, arXiv:1406.7663 [hep-ex].
- [14] CMS Collaboration, Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC, *Phys. Lett. B* 744 (2015) 184, arXiv:1410.6679 [hep-ex].
- [15] G.T. Bodwin, F. Petriello, S. Stoynev, M. Velasco, Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling, *Phys. Rev. D* 88 (2013) 053003, arXiv:1306.5770 [hep-ph].
- [16] M. Doroshenko, V. Kartvelishvili, E. Chikvani, S. Esakiya, Vector quarkonium in decays of heavy Higgs particles, *Yad. Fiz.* 46 (1987) 864.
- [17] G.T. Bodwin, H.S. Chung, J.-H. Ee, J. Lee, Addendum: New approach to the resummation of logarithms in Higgs-boson decays to a vector quarkonium plus a photon [Phys. Rev. D 95 (2017) 054018], *Phys. Rev. D* 96 (2017) 116014, arXiv:1710.09872 [hep-ph].
- [18] G.T. Bodwin, H.S. Chung, J.-H. Ee, J. Lee, New approach to the resummation of logarithms in Higgs-boson decays to a vector quarkonium plus a photon, *Phys. Rev. D* 95 (2017) 054018, arXiv:1603.06793 [hep-ph].
- [19] M. König, M. Neubert, Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings, *J. High Energy Phys.* 08 (2015) 012, arXiv:1505.03870 [hep-ph].
- [20] G.T. Bodwin, H.S. Chung, J.-H. Ee, J. Lee, F. Petriello, Relativistic corrections to Higgs-boson decays to quarkonia, *Phys. Rev. D* 90 (2014) 113010, arXiv:1407.6695 [hep-ph].
- [21] G. Perez, Y. Soreq, E. Stamou, K. Tobioka, Constraining the charm Yukawa and Higgs-quark coupling universality, *Phys. Rev. D* 92 (2015) 033016, arXiv:1503.00290 [hep-ph].
- [22] G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia, Minimal flavor violation: an effective field theory approach, *Nucl. Phys. B* 645 (2002) 155, arXiv:hep-ph/0207036.
- [23] C.D. Froggatt, H.B. Nielsen, Hierarchy of quark masses, Cabibbo angles and CP violation, *Nucl. Phys. B* 147 (1979) 277.
- [24] G.F. Giudice, O. Lebedev, Higgs-dependent Yukawa couplings, *Phys. Lett. B* 665 (2008) 79, arXiv:0804.1753 [hep-ph].
- [25] L. Randall, R. Sundrum, Large mass hierarchy from a small extra dimension, *Phys. Rev. Lett.* 83 (1999) 3370, arXiv:hep-ph/9905221.
- [26] M.J. Dugan, H. Georgi, D.B. Kaplan, Anatomy of a composite Higgs model, *Nucl. Phys. B* 254 (1985) 299.
- [27] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, 2016, CERN-2017-002-M, arXiv:1610.07922 [hep-ph].
- [28] ATLAS Collaboration, Search for Higgs and Z boson decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS detector, *Phys. Rev. Lett.* 114 (2015) 121801, arXiv:1501.03276 [hep-ex].
- [29] CMS Collaboration, Search for a Higgs boson decaying into $\gamma^*\gamma \rightarrow \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Lett. B* 753 (2016) 341, arXiv:1507.03031 [hep-ex].
- [30] ATLAS Collaboration, Search for Higgs and Z boson decays to $\phi\gamma$ with the ATLAS detector, *Phys. Rev. Lett.* 117 (2016) 111802, arXiv:1607.03400 [hep-ex].
- [31] ATLAS Collaboration, Search for exclusive Higgs and Z boson decays to $\phi\gamma$ and $\rho\gamma$ with the ATLAS detector, arXiv:1712.02758 [hep-ex], 2017.
- [32] G.T. Bodwin, H.S. Chung, J.-H. Ee, J. Lee, Z-boson decays to a vector quarkonium plus a photon, *Phys. Rev. D* 97 (2018) 016009, arXiv:1709.09320 [hep-ph].
- [33] Y. Grossman, M. König, M. Neubert, Exclusive radiative decays of W and Z bosons in QCD factorization, *J. High Energy Phys.* 04 (2015) 101, arXiv:1501.06569 [hep-ph].
- [34] T.-C. Huang, F. Petriello, Rare exclusive decays of the Z-boson revisited, *Phys. Rev. D* 92 (2015) 014007, arXiv:1411.5924 [hep-ph].
- [35] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, *J. Instrum.* 3 (2008) S08003.
- [36] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, *Eur. Phys. J. C* 77 (2017) 317, arXiv:1611.09661 [hep-ex].
- [37] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC, *Eur. Phys. J. C* 76 (2016) 653, arXiv:1608.03953 [hep-ex].
- [38] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2004) 040, arXiv:hep-ph/0409146.
- [39] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, arXiv:0709.2092 [hep-ph].
- [40] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, arXiv:1002.2581 [hep-ph].
- [41] S. Alioli, P. Nason, C. Oleari, E. Re, NLO Higgs boson production via gluon fusion matched with shower in POWHEG, *J. High Energy Phys.* 04 (2009) 002, arXiv:0812.0578 [hep-ph].
- [42] P. Nason, C. Oleari, NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG, *J. High Energy Phys.* 02 (2010) 037, arXiv:0911.5299 [hep-ph].

- [43] H.-L. Lai, et al., New parton distributions for collider physics, *Phys. Rev. D* 82 (2010) 074024, arXiv:1007.2241 [hep-ph].
- [44] T. Sjöstrand, S. Mrenna, P.Z. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* 178 (2008) 852, arXiv:0710.3820 [hep-ph].
- [45] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* 05 (2006) 026, arXiv:hep-ph/0603175.
- [46] ATLAS Collaboration, Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *J. High Energy Phys.* 09 (2014) 145, arXiv:1406.3660 [hep-ex].
- [47] R.D. Ball, et al., Parton distributions with LHC data, *Nucl. Phys. B* 867 (2013) 244, arXiv:1207.1303 [hep-ph].
- [48] ATLAS Collaboration, ATLAS Run 1 Pythia8 Tunes, Tech. Rep. ATL-PHYS-PUB-2014-021, CERN, 2014, <https://cds.cern.ch/record/1966419>.
- [49] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger, Higgs boson gluon-fusion production in QCD at three loops, *Phys. Rev. Lett.* 114 (2015) 212001, arXiv:1503.06056 [hep-ph].
- [50] C. Anastasiou, et al., High precision determination of the gluon fusion Higgs boson cross-section at the LHC, *J. High Energy Phys.* 05 (2016) 058, arXiv:1602.00695 [hep-ph].
- [51] S. Actis, G. Passarino, C. Sturm, S. Uccirati, NLO electroweak corrections to Higgs boson production at hadron colliders, *Phys. Lett. B* 670 (2008) 12, arXiv:0809.1301 [hep-ph].
- [52] C. Anastasiou, R. Boughezal, F. Petriello, Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion, *J. High Energy Phys.* 04 (2009) 003, arXiv:0811.3458 [hep-ph].
- [53] M. Ciccolini, A. Denner, S. Dittmaier, Strong and electroweak corrections to the production of a Higgs boson + 2 jets via weak interactions at the large hadron collider, *Phys. Rev. Lett.* 99 (2007) 161803, arXiv:0707.0381 [hep-ph].
- [54] M. Ciccolini, A. Denner, S. Dittmaier, Electroweak and QCD corrections to Higgs production via vector-boson fusion at the CERN LHC, *Phys. Rev. D* 77 (2008) 013002, arXiv:0710.4749 [hep-ph].
- [55] P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro, Higgs boson production via vector-boson fusion at next-to-next-to-leading order in QCD, *Phys. Rev. Lett.* 105 (2010) 011801, arXiv:1003.4451 [hep-ph].
- [56] O. Brein, A. Djouadi, R. Harlander, NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders, *Phys. Lett. B* 579 (2004) 149, arXiv:hep-ph/0307206 [hep-ph].
- [57] A. Denner, S. Dittmaier, S. Kallweit, A. Mück, Electroweak corrections to Higgs-strahlung off W/Z bosons at the Tevatron and the LHC with HAWK, *J. High Energy Phys.* 03 (2012) 075, arXiv:1112.5142 [hep-ph].
- [58] L. Altenkamp, S. Dittmaier, R.V. Harlander, H. Rzehak, T.J.E. Zirke, Gluon-induced Higgs-strahlung at next-to-leading order QCD, *J. High Energy Phys.* 02 (2013) 078, arXiv:1211.5015 [hep-ph].
- [59] J. Pumplin, et al., New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* 07 (2002) 012, arXiv:hep-ph/0201195.
- [60] ATLAS Collaboration, Measurement of $W^\pm$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 759 (2016) 601, arXiv:1603.09222 [hep-ex].
- [61] C. Patrignani, et al., Review of particle physics, *Chin. Phys. C* 40 (2016) 100001.
- [62] S. Agostinelli, et al., GEANT4: a simulation toolkit, *Nucl. Instrum. Methods, Sect. A* 506 (2003) 250.
- [63] ATLAS Collaboration, The ATLAS simulation infrastructure, *Eur. Phys. J. C* 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].
- [64] ATLAS Collaboration, Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton-proton collision data, *Eur. Phys. J. C* 74 (2014) 3130, arXiv:1407.3935 [hep-ex].
- [65] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 76 (2016) 292, arXiv:1603.05598 [hep-ex].
- [66] ATLAS Collaboration, Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data, *Eur. Phys. J. C* 76 (2016) 666, arXiv:1606.01813 [hep-ex].
- [67] K. Cranmer, Kernel estimation in high-energy physics, *Comput. Phys. Commun.* 136 (2001) 198, arXiv:hep-ex/0011057.
- [68] J. Alwall, et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, arXiv:1405.0301 [hep-ph].
- [69] T. Gleisberg, et al., Event generation with SHERPA 1.1, *J. High Energy Phys.* 02 (2009) 007, arXiv:0811.4622 [hep-ph].
- [70] ATLAS Collaboration, Performance of the electron and photon trigger in p-p collisions at $\sqrt{s} = 7$ TeV, ATLAS-CONF-2011-114, <http://cds.cern.ch/record/1375551>, 2011.
- [71] ATLAS Collaboration, Photon Identification in 2015 ATLAS Data, ATL-PHYS-PUB-2016-014, CERN, 2016, <https://cds.cern.ch/record/2203125>.
- [72] ATLAS Collaboration, Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data, *Eur. Phys. J. C* 74 (2014) 3071, arXiv:1407.5063 [hep-ex].
- [73] ATLAS Collaboration, Electron and photon energy calibration with the ATLAS detector using data collected in 2015 at $\sqrt{s} = 13$ TeV, ATL-PHYS-PUB-2016-015, CERN, 2016, <https://cds.cern.ch/record/2203514>.
- [74] A.L. Read, Presentation of search results: the CLs technique, *J. Phys. G* 28 (2002) 2693.
- [75] J. Neyman, E.S. Pearson, On the problem of the most efficient tests of statistical hypotheses, *Philos. Trans. R. Soc. Lond., Ser. A, Contain. Pap. Math. Phys. Character* 231 (1933) 289, ISSN: 02643952, <http://www.jstor.org/stable/91247>.
- [76] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, arXiv:1007.1727 [physics.data-an], *Eur. Phys. J. C* 73 (2013) 2501, Erratum.
- [77] ATLAS Collaboration, ATLAS Computing Acknowledgements ATL-GEN-PUB-2016-002, <https://cds.cern.ch/record/2202407>.

The ATLAS Collaboration

M. Aaboud^{34d}, G. Aad⁹⁹, B. Abbott¹²⁴, O. Abidinov^{13,*}, B. Abeloos¹²⁸, D.K. Abhayasinghe⁹¹, S.H. Abidi¹⁶⁴, O.S. AbouZeid³⁹, N.L. Abraham¹⁵³, H. Abramowicz¹⁵⁸, H. Abreu¹⁵⁷, Y. Abulaiti⁶, B.S. Acharya^{64a,64b,o}, S. Adachi¹⁶⁰, L. Adamczyk^{81a}, J. Adelman¹¹⁹, M. Adersberger¹¹², A. Adiguzel^{12c,ah}, T. Adye¹⁴¹, A.A. Affolder¹⁴³, Y. Afik¹⁵⁷, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{136f,136a}, F. Ahmadov^{77,af}, G. Aielli^{71a,71b}, S. Akatsuka⁸³, T.P.A. Åkesson⁹⁴, E. Akilli⁵², A.V. Akimov¹⁰⁸, G.L. Alberghi^{23b,23a}, J. Albert¹⁷³, P. Albicocco⁴⁹, M.J. Alconada Verzini⁸⁶, S. Alderweireldt¹¹⁷, M. Aleksa³⁵, I.N. Aleksandrov⁷⁷, C. Alexa^{27b}, T. Alexopoulos¹⁰, M. Alhroob¹²⁴, B. Ali¹³⁸, G. Alimonti^{66a}, J. Alison³⁶, S.P. Alkire¹⁴⁵, C. Allaire¹²⁸, B.M.M. Allbrooke¹⁵³, B.W. Allen¹²⁷, P.P. Allport²¹, A. Aloisio^{67a,67b}, A. Alonso³⁹, F. Alonso⁸⁶, C. Alpigiani¹⁴⁵, A.A. Alshehri⁵⁵, M.I. Alstady⁹⁹, B. Alvarez Gonzalez³⁵, D. Álvarez Piqueras¹⁷¹, M.G. Alviggi^{67a,67b}, B.T. Amadio¹⁸, Y. Amaral Coutinho^{78b}, L. Ambroz¹³¹, C. Amelung²⁶, D. Amidei¹⁰³, S.P. Amor Dos Santos^{136a,136c}, S. Amoroso⁴⁴, C.S. Amrouche⁵², C. Anastopoulos¹⁴⁶, L.S. Ancu⁵², N. Andari¹⁴², T. Andeen¹¹, C.F. Anders^{59b}, J.K. Anders²⁰, K.J. Anderson³⁶, A. Andreazza^{66a,66b}, V. Andrei^{59a}, C.R. Anelli¹⁷³, S. Angelidakis³⁷, I. Angelozzi¹¹⁸, A. Angerami³⁸, A.V. Anisenkov^{120b,120a}, A. Annovi^{69a}, C. Antel^{59a}, M.T. Anthony¹⁴⁶, M. Antonelli⁴⁹, D.J.A. Antrim¹⁶⁸, F. Anulli^{70a}, M. Aoki⁷⁹, J.A. Aparisi Pozo¹⁷¹, L. Aperio Bella³⁵, G. Arabidze¹⁰⁴, J.P. Araque^{136a}, V. Araujo Ferraz^{78b}, R. Araujo Pereira^{78b}, A.T.H. Arce⁴⁷, R.E. Ardell⁹¹, F.A. Arduh⁸⁶, J-F. Arguin¹⁰⁷, S. Argyropoulos⁷⁵, A.J. Armbruster³⁵, L.J. Armitage⁹⁰, A. Armstrong¹⁶⁸, O. Arnaez¹⁶⁴, H. Arnold¹¹⁸, M. Arratia³¹, O. Arslan²⁴, A. Artamonov^{109,*}, G. Artoni¹³¹, S. Artz⁹⁷, S. Asai¹⁶⁰, N. Asbah⁴⁴, A. Ashkenazi¹⁵⁸, E.M. Asimakopoulou¹⁶⁹, L. Asquith¹⁵³, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{32a}, M. Atkinson¹⁷⁰, N.B. Atlay¹⁴⁸, K. Augsten¹³⁸, G. Avolio³⁵, R. Avramidou^{58a},

M.K. Ayoub^{15a}, G. Azuelos^{107,au}, A.E. Baas^{59a}, M.J. Baca²¹, H. Bachacou¹⁴², K. Bachas^{65a,65b}, M. Backes¹³¹, P. Bagnaia^{70a,70b}, M. Bahmani⁸², H. Bahrasemani¹⁴⁹, A.J. Bailey¹⁷¹, J.T. Baines¹⁴¹, M. Bajic³⁹, C. Bakalis¹⁰, O.K. Baker¹⁸⁰, P.J. Bakker¹¹⁸, D. Bakshi Gupta⁹³, E.M. Baldin^{120b,120a}, P. Balek¹⁷⁷, F. Balli¹⁴², W.K. Balunas¹³³, J. Balz⁹⁷, E. Banas⁸², A. Bandyopadhyay²⁴, S. Banerjee^{178,k}, A.A.E. Bannoura¹⁷⁹, L. Barak¹⁵⁸, W.M. Barbe³⁷, E.L. Barberio¹⁰², D. Barberis^{53b,53a}, M. Barbero⁹⁹, T. Barillari¹¹³, M.-S. Barisits³⁵, J. Barkeloo¹²⁷, T. Barklow¹⁵⁰, N. Barlow³¹, R. Barnea¹⁵⁷, S.L. Barnes^{58c}, B.M. Barnett¹⁴¹, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{58a}, A. Baroncelli^{72a}, G. Barone²⁶, A.J. Barr¹³¹, L. Barranco Navarro¹⁷¹, F. Barreiro⁹⁶, J. Barreiro Guimarães da Costa^{15a}, R. Bartoldus¹⁵⁰, A.E. Barton⁸⁷, P. Bartos^{28a}, A. Basalae¹³⁴, A. Bassalat¹²⁸, R.L. Bates⁵⁵, S.J. Batista¹⁶⁴, S. Batlamous^{34e}, J.R. Batley³¹, M. Battaglia¹⁴³, M. Bause^{70a,70b}, F. Bauer¹⁴², K.T. Bauer¹⁶⁸, H.S. Bawa^{150,m}, J.B. Beacham¹²², T. Beau¹³², P.H. Beauchemin¹⁶⁷, P. Bechtel²⁴, H.C. Beck⁵¹, H.P. Beck^{20,r}, K. Becker⁵⁰, M. Becker⁹⁷, C. Becot⁴⁴, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁷⁷, M. Bedognetti¹¹⁸, C.P. Bee¹⁵², T.A. Beermann³⁵, M. Begalli^{78b}, M. Begel²⁹, A. Behera¹⁵², J.K. Behr⁴⁴, A.S. Bell⁹², G. Bella¹⁵⁸, L. Bellagamba^{23b}, A. Bellerive³³, M. Bellomo¹⁵⁷, P. Bellos⁹, K. Belotskiy¹¹⁰, N.L. Belyaev¹¹⁰, O. Benary^{158,*}, D. Benchekroun^{34a}, M. Bender¹¹², N. Benekos¹⁰, Y. Benhammou¹⁵⁸, E. Benhar Noccioli¹⁸⁰, J. Benitez⁷⁵, D.P. Benjamin⁴⁷, M. Benoit⁵², J.R. Bensinger²⁶, S. Bentvelsen¹¹⁸, L. Beresford¹³¹, M. Beretta⁴⁹, D. Berge⁴⁴, E. Bergeaas Kuutmann¹⁶⁹, N. Berger⁵, L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁷, N.R. Bernard¹⁰⁰, G. Bernardi¹³², C. Bernius¹⁵⁰, F.U. Bernlochner²⁴, T. Berry⁹¹, P. Berta⁹⁷, C. Bertella^{15a}, G. Bertoli^{43a,43b}, I.A. Bertram⁸⁷, G.J. Besjes³⁹, O. Bessidskaia Bylund¹⁷⁹, M. Bessner⁴⁴, N. Besson¹⁴², A. Bethani⁹⁸, S. Bethke¹¹³, A. Betti²⁴, A.J. Bevan⁹⁰, J. Beyer¹¹³, R.M. Bianchi¹³⁵, O. Biebel¹¹², D. Biedermann¹⁹, R. Bielski³⁵, K. Bierwagen⁹⁷, N.V. Biesuz^{69a,69b}, M. Biglietti^{72a}, T.R.V. Billoud¹⁰⁷, M. Bindi⁵¹, A. Bingul^{12d}, C. Bini^{70a,70b}, S. Biondi^{23b,23a}, M. Birman¹⁷⁷, T. Bisanz⁵¹, J.P. Biswal¹⁵⁸, C. Bittrich⁴⁶, D.M. Bjergaard⁴⁷, J.E. Black¹⁵⁰, K.M. Black²⁵, T. Blazek^{28a}, I. Bloch⁴⁴, C. Blocker²⁶, A. Blue⁵⁵, U. Blumenschein⁹⁰, Dr. Blunier^{144a}, G.J. Bobbink¹¹⁸, V.S. Bobrovnikov^{120b,120a}, S.S. Bocchetta⁹⁴, A. Bocci⁴⁷, D. Boerner¹⁷⁹, D. Bogavac¹¹², A.G. Bogdanchikov^{120b,120a}, C. Böhm^{43a}, V. Boisvert⁹¹, P. Boka¹⁶⁹, T. Bold^{81a}, A.S. Boldyrev¹¹¹, A.E. Bolz^{59b}, M. Bomben¹³², M. Bona⁹⁰, J.S. Bonilla¹²⁷, M. Boonekamp¹⁴², A. Borisov¹⁴⁰, G. Borissov⁸⁷, J. Bortfeldt³⁵, D. Bortoletto¹³¹, V. Bortolotto^{71a,61b,61c,71b}, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola³⁰, K. Bouaouda^{34a}, J. Boudreau¹³⁵, E.V. Bouhova-Thacker⁸⁷, D. Boumediene³⁷, C. Bourdarios¹²⁸, S.K. Boutle⁵⁵, A. Boveia¹²², J. Boyd³⁵, D. Boye^{32b}, I.R. Boyko⁷⁷, A.J. Bozson⁹¹, J. Bracinik²¹, N. Brahimi⁹⁹, A. Brandt⁸, G. Brandt¹⁷⁹, O. Brandt^{59a}, F. Braren⁴⁴, U. Bratzler¹⁶¹, B. Brau¹⁰⁰, J.E. Brau¹²⁷, W.D. Breaden Madden⁵⁵, K. Brendlinger⁴⁴, A.J. Brennan¹⁰², L. Brenner⁴⁴, R. Brenner¹⁶⁹, S. Bressler¹⁷⁷, B. Brickwedde⁹⁷, D.L. Briglin²¹, D. Britton⁵⁵, D. Britzger^{59b}, I. Brock²⁴, R. Brock¹⁰⁴, G. Brooijmans³⁸, T. Brooks⁹¹, W.K. Brooks^{144b}, E. Brost¹¹⁹, J.H. Broughton²¹, P.A. Bruckman de Renstrom⁸², D. Bruncko^{28b}, A. Bruni^{23b}, G. Bruni^{23b}, L.S. Bruni¹¹⁸, S. Bruno^{71a,71b}, B.H. Brunt³¹, M. Bruschi^{23b}, N. Bruscino¹³⁵, P. Bryant³⁶, L. Bryngemark⁴⁴, T. Buanes¹⁷, Q. Buat³⁵, P. Buchholz¹⁴⁸, A.G. Buckley⁵⁵, I.A. Budagov⁷⁷, F. Buehrer⁵⁰, M.K. Bugge¹³⁰, O. Bulekov¹¹⁰, D. Bullock⁸, T.J. Burch¹¹⁹, S. Burdin⁸⁸, C.D. Burgard¹¹⁸, A.M. Burger⁵, B. Burghgrave¹¹⁹, K. Burka⁸², S. Burke¹⁴¹, I. Burmeister⁴⁵, J.T.P. Burr¹³¹, D. Büscher⁵⁰, V. Büscher⁹⁷, E. Buschmann⁵¹, P. Bussey⁵⁵, J.M. Butler²⁵, C.M. Buttar⁵⁵, J.M. Butterworth⁹², P. Butti³⁵, W. Buttinger³⁵, A. Buzatu¹⁵⁵, A.R. Buzykaev^{120b,120a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷¹, D. Caforio¹³⁸, H. Cai¹⁷⁰, V.M.M. Cairo², O. Cakir^{4a}, N. Calace⁵², P. Calafiura¹⁸, A. Calandri⁹⁹, G. Calderini¹³², P. Calfayan⁶³, G. Callea^{40b,40a}, L.P. Caloba^{78b}, S. Calvente Lopez⁹⁶, D. Calvet³⁷, S. Calvet³⁷, T.P. Calvet¹⁵², M. Calvetti^{69a,69b}, R. Camacho Toro¹³², S. Camarda³⁵, P. Camarri^{71a,71b}, D. Cameron¹³⁰, R. Caminal Armadans¹⁰⁰, C. Camincher³⁵, S. Campana³⁵, M. Campanelli⁹², A. Camplani³⁹, A. Campoverde¹⁴⁸, V. Canale^{67a,67b}, M. Cano Bret^{58c}, J. Cantero¹²⁵, T. Cao¹⁵⁸, Y. Cao¹⁷⁰, M.D.M. Capeans Garrido³⁵, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{40b,40a}, R.M. Carbone³⁸, R. Cardarelli^{71a}, F.C. Cardillo¹⁴⁶, I. Carli¹³⁹, T. Carli³⁵, G. Carlino^{67a}, B.T. Carlson¹³⁵, L. Carminati^{66a,66b}, R.M.D. Carney^{43a,43b}, S. Caron¹¹⁷, E. Carquin^{144b}, S. Carrá^{66a,66b}, G.D. Carrillo-Montoya³⁵, D. Casadei^{32b}, M.P. Casado^{14,g}, A.F. Casha¹⁶⁴, D.W. Casper¹⁶⁸, R. Castelijns¹¹⁸, F.L. Castillo¹⁷¹, V. Castillo Gimenez¹⁷¹, N.F. Castro^{136a,136e}, A. Catinaccio³⁵, J.R. Catmore¹³⁰, A. Cattai³⁵, J. Caudron²⁴, V. Cavaliere²⁹, E. Cavallaro¹⁴, D. Cavalli^{66a}, M. Cavalli-Sforza¹⁴, V. Cavasinni^{69a,69b}, E. Celebi^{12b}, F. Ceradini^{72a,72b}, L. Cerda Alberich¹⁷¹, A.S. Cerqueira^{78a}, A. Cerri¹⁵³, L. Cerrito^{71a,71b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a},

S.A. Cetin^{12b}, A. Chafaq^{34a}, D. Chakraborty¹¹⁹, S.K. Chan⁵⁷, W.S. Chan¹¹⁸, Y.L. Chan^{61a}, J.D. Chapman³¹, B. Chargeishvili^{156b}, D.G. Charlton²¹, C.C. Chau³³, C.A. Chavez Barajas¹⁵³, S. Che¹²², A. Chegwidzen¹⁰⁴, S. Chekanov⁶, S.V. Chekulaev^{165a}, G.A. Chelkov^{77,at}, M.A. Chelstowska³⁵, C. Chen^{58a}, C.H. Chen⁷⁶, H. Chen²⁹, J. Chen^{58a}, J. Chen³⁸, S. Chen¹³³, S.J. Chen^{15c}, X. Chen^{15b,as}, Y. Chen⁸⁰, Y.-H. Chen⁴⁴, H.C. Cheng¹⁰³, H.J. Cheng^{15d}, A. Cheplakov⁷⁷, E. Cheremushkina¹⁴⁰, R. Cherkaoui El Moursli^{34e}, E. Cheu⁷, K. Cheung⁶², L. Chevalier¹⁴², V. Chiarella⁴⁹, G. Chiarelli^{69a}, G. Chiodini^{65a}, A.S. Chisholm³⁵, A. Chitan^{27b}, I. Chiu¹⁶⁰, Y.H. Chiu¹⁷³, M.V. Chizhov⁷⁷, K. Choi⁶³, A.R. Chomont¹²⁸, S. Chouridou¹⁵⁹, Y.S. Chow¹¹⁸, V. Christodoulou⁹², M.C. Chu^{61a}, J. Chudoba¹³⁷, A.J. Chuinard¹⁰¹, J.J. Chwastowski⁸², L. Chytka¹²⁶, D. Cinca⁴⁵, V. Cindro⁸⁹, I.A. Cioară²⁴, A. Ciochio¹⁸, F. Ciotto^{67a,67b}, Z.H. Citron¹⁷⁷, M. Citterio^{66a}, A. Clark⁵², M.R. Clark³⁸, P.J. Clark⁴⁸, C. Clement^{43a,43b}, Y. Coadou⁹⁹, M. Cobal^{64a,64c}, A. Coccaro^{53b,53a}, J. Cochran⁷⁶, A.E.C. Coimbra¹⁷⁷, L. Colasurdo¹¹⁷, B. Cole³⁸, A.P. Colijn¹¹⁸, J. Collot⁵⁶, P. Conde Muiño^{136a,136b}, E. Coniavitis⁵⁰, S.H. Connell^{32b}, I.A. Connelly⁹⁸, S. Constantinescu^{27b}, F. Conventi^{67a,av}, A.M. Cooper-Sarkar¹³¹, F. Cormier¹⁷², K.J.R. Cormier¹⁶⁴, M. Corradi^{70a,70b}, E.E. Corrigan⁹⁴, F. Corriveau^{101,ad}, A. Cortes-Gonzalez³⁵, M.J. Costa¹⁷¹, D. Costanzo¹⁴⁶, G. Cottin³¹, G. Cowan⁹¹, B.E. Cox⁹⁸, J. Crane⁹⁸, K. Cranmer¹²¹, S.J. Crawley⁵⁵, R.A. Creager¹³³, G. Cree³³, S. Crépé-Renaudin⁵⁶, F. Crescioli¹³², M. Cristinziani²⁴, V. Croft¹²¹, G. Crosetti^{40b,40a}, A. Cueto⁹⁶, T. Cuhadar Donszelmann¹⁴⁶, A.R. Cukierman¹⁵⁰, J. Cúth⁹⁷, S. Czekierda⁸², P. Czodrowski³⁵, M.J. Da Cunha Sargedas De Sousa^{58b,136b}, C. Da Via⁹⁸, W. Dabrowski^{81a}, T. Dado^{28a,y}, S. Dahbi^{34e}, T. Dai¹⁰³, F. Dallaire¹⁰⁷, C. Dallapiccola¹⁰⁰, M. Dam³⁹, G. D'amen^{23b,23a}, J. Damp⁹⁷, J.R. Dandoy¹³³, M.F. Daneri³⁰, N.P. Dang^{178,k}, N.D. Dann⁹⁸, M. Danninger¹⁷², V. Dao³⁵, G. Darbo^{53b}, S. Darmora⁸, O. Dartsis⁵, A. Dattagupta¹²⁷, T. Daubney⁴⁴, S. D'Auria⁵⁵, W. Davey²⁴, C. David⁴⁴, T. Davidek¹³⁹, D.R. Davis⁴⁷, E. Dawe¹⁰², I. Dawson¹⁴⁶, K. De⁸, R. De Asmundis^{67a}, A. De Benedetti¹²⁴, M. De Beurs¹¹⁸, S. De Castro^{23b,23a}, S. De Cecco^{70a,70b}, N. De Groot¹¹⁷, P. de Jong¹¹⁸, H. De la Torre¹⁰⁴, F. De Lorenzi⁷⁶, A. De Maria^{51,t}, D. De Pedis^{70a}, A. De Salvo^{70a}, U. De Sanctis^{71a,71b}, A. De Santo¹⁵³, K. De Vasconcelos Corga⁹⁹, J.B. De Vivie De Regie¹²⁸, C. Debenedetti¹⁴³, D.V. Dedovich⁷⁷, N. Dehghanian³, M. Del Gaudio^{40b,40a}, J. Del Peso⁹⁶, Y. Delabat Diaz⁴⁴, D. Delgove¹²⁸, F. Deliot¹⁴², C.M. Delitzsch⁷, M. Della Pietra^{67a,67b}, D. Della Volpe⁵², A. Dell'Acqua³⁵, L. Dell'Asta²⁵, M. Delmastro⁵, C. Delporte¹²⁸, P.A. Delsart⁵⁶, D.A. DeMarco¹⁶⁴, S. Demers¹⁸⁰, M. Demichev⁷⁷, S.P. Denisov¹⁴⁰, D. Denysiuk¹¹⁸, L. D'Eramo¹³², D. Derendarz⁸², J.E. Derkaoui^{34d}, F. Derue¹³², P. Dervan⁸⁸, K. Desch²⁴, C. Deterre⁴⁴, K. Dette¹⁶⁴, M.R. Devesa³⁰, P.O. Deviveiros³⁵, A. Dewhurst¹⁴¹, S. Dhaliwal²⁶, F.A. Di Bello⁵², A. Di Ciaccio^{71a,71b}, L. Di Ciaccio⁵, W.K. Di Clemente¹³³, C. Di Donato^{67a,67b}, A. Di Girolamo³⁵, B. Di Micco^{72a,72b}, R. Di Nardo¹⁰⁰, K.F. Di Petrillo⁵⁷, R. Di Sipio¹⁶⁴, D. Di Valentino³³, C. Diaconu⁹⁹, M. Diamond¹⁶⁴, F.A. Dias³⁹, T. Dias Do Vale^{136a}, M.A. Diaz^{144a}, J. Dickinson¹⁸, E.B. Diehl¹⁰³, J. Dietrich¹⁹, S. Díez Cornell⁴⁴, A. Dimitrievska¹⁸, J. Dingfelder²⁴, F. Dittus³⁵, F. Djama⁹⁹, T. Djobava^{156b}, J.I. Djuvsland^{59a}, M.A.B. Do Vale^{78c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁴, J. Dolejsi¹³⁹, Z. Dolezal¹³⁹, M. Donadelli^{78d}, J. Donini³⁷, A. D'Onofrio⁹⁰, M. D'Onofrio⁸⁸, J. Dopke¹⁴¹, A. Doria^{67a}, M.T. Dova⁸⁶, A.T. Doyle⁵⁵, E. Drechsler⁵¹, E. Dreyer¹⁴⁹, T. Dreyer⁵¹, Y. Du^{58b}, J. Duarte-Camperderros¹⁵⁸, F. Dubinin¹⁰⁸, M. Dubovsky^{28a}, A. Dubreuil⁵², E. Duchovni¹⁷⁷, G. Duckeck¹¹², A. Ducourthial¹³², O.A. Ducu^{107,x}, D. Duda¹¹³, A. Dudarev³⁵, A.C. Dudder⁹⁷, E.M. Duffield¹⁸, L. Duflo¹²⁸, M. Dührssen³⁵, C. Dülse¹⁷⁹, M. Dumancic¹⁷⁷, A.E. Dumitriu^{27b,e}, A.K. Duncan⁵⁵, M. Dunford^{59a}, A. Duperrin⁹⁹, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{156b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, D. Duvnjak¹, M. Dyndal⁴⁴, S. Dysch⁹⁸, B.S. Dziedzic⁸², C. Eckardt⁴⁴, K.M. Ecker¹¹³, R.C. Edgar¹⁰³, T. Eifert³⁵, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof¹⁶⁹, M. El Kacimi^{34c}, R. El Kosseifi⁹⁹, V. Ellajosyula⁹⁹, M. Ellert¹⁶⁹, F. Ellinghaus¹⁷⁹, A.A. Elliot⁹⁰, N. Ellis³⁵, J. Elmsheuser²⁹, M. Elsing³⁵, D. Emeliyanov¹⁴¹, Y. Enari¹⁶⁰, J.S. Ennis¹⁷⁵, M.B. Epland⁴⁷, J. Erdmann⁴⁵, A. Ereditato²⁰, S. Errede¹⁷⁰, M. Escalier¹²⁸, C. Escobar¹⁷¹, O. Estrada Pastor¹⁷¹, A.I. Etievre¹⁴², E. Etzion¹⁵⁸, H. Evans⁶³, A. Ezhilov¹³⁴, M. Ezzi^{34e}, F. Fabbri⁵⁵, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁷, G. Facini⁹², R.M. Faisca Rodrigues Pereira^{136a}, R.M. Fakhrutdinov¹⁴⁰, S. Falciano^{70a}, P.J. Falke⁵, S. Falke⁵, J. Faltova¹³⁹, Y. Fang^{15a}, M. Fanti^{66a,66b}, A. Farbin⁸, A. Farilla^{72a}, E.M. Farina^{68a,68b}, T. Farooque¹⁰⁴, S. Farrell¹⁸, S.M. Farrington¹⁷⁵, P. Farthouat³⁵, F. Fassi^{34e}, P. Fassnacht³⁵, D. Fassouliotis⁹, M. Faucci Giannelli⁴⁸, A. Favareto^{53b,53a}, W.J. Fawcett⁵², L. Fayard¹²⁸, O.L. Fedin^{134,p}, W. Fedorko¹⁷², M. Feickert⁴¹, S. Feigl¹³⁰, L. Feligioni⁹⁹, C. Feng^{58b}, E.J. Feng³⁵, M. Feng⁴⁷, M.J. Fenton⁵⁵,

A.B. Fenyuk¹⁴⁰, L. Feremenga⁸, J. Ferrando⁴⁴, A. Ferrari¹⁶⁹, P. Ferrari¹¹⁸, R. Ferrari^{68a},
D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁷¹, D. Ferrere⁵², C. Ferretti¹⁰³, F. Fiedler⁹⁷, A. Filipčič⁸⁹,
F. Filthaut¹¹⁷, K.D. Finelli²⁵, M.C.N. Fiolhais^{136a,136c,a}, L. Fiorini¹⁷¹, C. Fischer¹⁴, W.C. Fisher¹⁰⁴,
N. Flaschel⁴⁴, I. Fleck¹⁴⁸, P. Fleischmann¹⁰³, R.R.M. Fletcher¹³³, T. Flick¹⁷⁹, B.M. Flierl¹¹², L.M. Flores¹³³,
L.R. Flores Castillo^{61a}, F.M. Follega^{73a,73b}, N. Fomin¹⁷, G.T. Forcolin⁹⁸, A. Formica¹⁴², F.A. Förster¹⁴,
A.C. Forti⁹⁸, A.G. Foster²¹, D. Fournier¹²⁸, H. Fox⁸⁷, S. Fracchia¹⁴⁶, P. Francavilla^{69a,69b},
M. Franchini^{23b,23a}, S. Franchino^{59a}, D. Francis³⁵, L. Franconi¹³⁰, M. Franklin⁵⁷, M. Frate¹⁶⁸,
M. Fraternali^{68a,68b}, D. Freeborn⁹², S.M. Fressard-Batraneanu³⁵, B. Freund¹⁰⁷, W.S. Freund^{78b},
D. Froidevaux³⁵, J.A. Frost¹³¹, C. Fukunaga¹⁶¹, E. Fullana Torregrosa¹⁷¹, T. Fusayasu¹¹⁴, J. Fuster¹⁷¹,
O. Gabizon¹⁵⁷, A. Gabrielli^{23b,23a}, A. Gabrielli¹⁸, G.P. Gach^{81a}, S. Gadatsch⁵², P. Gadow¹¹³,
G. Gagliardi^{53b,53a}, L.G. Gagnon¹⁰⁷, C. Galea^{27b}, B. Galhardo^{136a,136c}, E.J. Gallas¹³¹, B.J. Gallop¹⁴¹,
P. Gallus¹³⁸, G. Galster³⁹, R. Gamboa Goni⁹⁰, K.K. Gan¹²², S. Ganguly¹⁷⁷, J. Gao^{58a}, Y. Gao⁸⁸,
Y.S. Gao^{150,m}, C. García¹⁷¹, J.E. García Navarro¹⁷¹, J.A. García Pascual^{15a}, M. Garcia-Sciveres¹⁸,
R.W. Gardner³⁶, N. Garelli¹⁵⁰, V. Garonne¹³⁰, K. Gasnikova⁴⁴, A. Gaudiello^{53b,53a}, G. Gaudio^{68a},
I.L. Gavrilenko¹⁰⁸, A. Gavrilyuk¹⁰⁹, C. Gay¹⁷², G. Gaycken²⁴, E.N. Gazis¹⁰, C.N.P. Gee¹⁴¹, J. Geisen⁵¹,
M. Geisen⁹⁷, M.P. Geisler^{59a}, K. Gellerstedt^{43a,43b}, C. Gemme^{53b}, M.H. Genest⁵⁶, C. Geng¹⁰³,
S. Gentile^{70a,70b}, S. George⁹¹, D. Gerbaudo¹⁴, G. Gessner⁴⁵, S. Ghasemi¹⁴⁸, M. Ghasemi Bostanabad¹⁷³,
M. Ghneimat²⁴, B. Giacobbe^{23b}, S. Giagu^{70a,70b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{69a},
A. Giannini^{67a,67b}, S.M. Gibson⁹¹, M. Gignac¹⁴³, D. Gillberg³³, G. Gilles¹⁷⁹, D.M. Gingrich^{3,au},
M.P. Giordani^{64a,64c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴², P. Giromini⁵⁷, G. Giugliarelli^{64a,64c}, D. Giugni^{66a},
F. Giulì¹³¹, M. Giulini^{59b}, S. Gkaitatzis¹⁵⁹, I. Gkialas^{9,j}, E.L. Gkoukousis¹⁴, P. Gkoutoumis¹⁰,
L.K. Gladilin¹¹¹, C. Glasman⁹⁶, J. Glatzer¹⁴, P.C.F. Glashier⁴⁴, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁶,
J. Godlewski⁸², S. Goldfarb¹⁰², T. Golling⁵², D. Golubkov¹⁴⁰, A. Gomes^{136a,136b,136d},
R. Goncalves Gama^{78a}, R. Gonçalves^{136a}, G. Gonella⁵⁰, L. Gonella²¹, A. Gongadze⁷⁷, F. Gonnella²¹,
J.L. Gonski⁵⁷, S. González de la Hoz¹⁷¹, S. Gonzalez-Sevilla⁵², L. Goossens³⁵, P.A. Gorbounov¹⁰⁹,
H.A. Gordon²⁹, B. Gorini³⁵, E. Gorini^{65a,65b}, A. Gorišek⁸⁹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁷⁷,
C.A. Gottardo²⁴, C.R. Goudet¹²⁸, D. Goujdami^{34c}, A.G. Goussiou¹⁴⁵, N. Govender^{32b,c}, C. Goy⁵,
E. Gozani¹⁵⁷, I. Grabowska-Bold^{81a}, P.O.J. Gradin¹⁶⁹, E.C. Graham⁸⁸, J. Gramling¹⁶⁸, E. Gramstad¹³⁰,
S. Grancagnolo¹⁹, V. Gratchev¹³⁴, P.M. Gravila^{27f}, F.G. Gravili^{65a,65b}, C. Gray⁵⁵, H.M. Gray¹⁸,
Z.D. Greenwood^{93,aj}, C. Grefe²⁴, K. Gregersen⁹⁴, I.M. Gregor⁴⁴, P. Grenier¹⁵⁰, K. Grevtsov⁴⁴, J. Griffiths⁸,
A.A. Grillo¹⁴³, K. Grimm^{150,b}, S. Grinstein^{14,z}, Ph. Gris³⁷, J.-F. Grivaz¹²⁸, S. Groh⁹⁷, E. Gross¹⁷⁷,
J. Grosse-Knetter⁵¹, G.C. Grossi⁹³, Z.J. Grout⁹², C. Grud¹⁰³, A. Grummer¹¹⁶, L. Guan¹⁰³, W. Guan¹⁷⁸,
J. Guenther³⁵, A. Guerguichon¹²⁸, F. Guescini^{165a}, D. Guest¹⁶⁸, R. Gugel⁵⁰, B. Gui¹²², T. Guillemain⁵,
S. Guindon³⁵, U. Gul⁵⁵, C. Gumpert³⁵, J. Guo^{58c}, W. Guo¹⁰³, Y. Guo^{58a,s}, Z. Guo⁹⁹, R. Gupta⁴¹,
S. Gurbuz^{12c}, G. Gustavino¹²⁴, B.J. Gutelman¹⁵⁷, P. Gutierrez¹²⁴, C. Gutsche⁹², C. Guyot¹⁴²,
M.P. Guzik^{81a}, C. Gwenlan¹³¹, C.B. Gwilliam⁸⁸, A. Haas¹²¹, C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{34e},
A. Hadeef^{58a}, S. Hageböck²⁴, M. Hagihara¹⁶⁶, H. Hakobyan^{181,*}, M. Haleem¹⁷⁴, J. Haley¹²⁵,
G. Halladjian¹⁰⁴, G.D. Hallowell⁹⁹, K. Hamacher¹⁷⁹, P. Hamal¹²⁶, K. Hamano¹⁷³, A. Hamilton^{32a},
G.N. Hamity¹⁴⁶, K. Han^{58a,ai}, L. Han^{58a}, S. Han^{15d}, K. Hanagaki^{79,v}, M. Hance¹⁴³, D.M. Handl¹¹²,
B. Haney¹³³, R. Hankache¹³², P. Hanke^{59a}, E. Hansen⁹⁴, J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²⁴,
P.H. Hansen³⁹, K. Hara¹⁶⁶, A.S. Hard¹⁷⁸, T. Harenberg¹⁷⁹, S. Harkusha¹⁰⁵, P.F. Harrison¹⁷⁵,
N.M. Hartmann¹¹², Y. Hasegawa¹⁴⁷, A. Hasib⁴⁸, S. Hassani¹⁴², S. Haug²⁰, R. Hauser¹⁰⁴, L. Hauswald⁴⁶,
L.B. Havener³⁸, M. Havranek¹³⁸, C.M. Hawkes²¹, R.J. Hawking³⁵, D. Hayden¹⁰⁴, C. Hayes¹⁵²,
C.P. Hays¹³¹, J.M. Hays⁹⁰, H.S. Hayward⁸⁸, S.J. Haywood¹⁴¹, M.P. Heath⁴⁸, V. Hedberg⁹⁴, L. Heelan⁸,
S. Heer²⁴, K.K. Heidegger⁵⁰, J. Heilman³³, S. Heim⁴⁴, T. Heim¹⁸, B. Heinemann^{44,ap}, J.J. Heinrich¹¹²,
L. Heinrich¹²¹, C. Heinz⁵⁴, J. Hejbal¹³⁷, L. Helary³⁵, A. Held¹⁷², S. Hellesund¹³⁰, S. Hellman^{43a,43b},
C. Helsens³⁵, R.C.W. Henderson⁸⁷, Y. Heng¹⁷⁸, S. Henkelmann¹⁷², A.M. Henriques Correia³⁵,
G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁴, Y. Hernández Jiménez^{32c}, H. Herr⁹⁷, M.G. Herrmann¹¹²,
G. Herten⁵⁰, R. Hertenberger¹¹², L. Hervas³⁵, T.C. Herwig¹³³, G.G. Hesketh⁹², N.P. Hessey^{165a},
J.W. Hetherly⁴¹, S. Higashino⁷⁹, E. Higón-Rodríguez¹⁷¹, K. Hildebrand³⁶, E. Hill¹⁷³, J.C. Hill³¹,
K.K. Hill²⁹, K.H. Hiller⁴⁴, S.J. Hillier²¹, M. Hils⁴⁶, I. Hinchliffe¹⁸, M. Hirose¹²⁹, D. Hirschbuehl¹⁷⁹,
B. Hiti⁸⁹, O. Hladik¹³⁷, D.R. Hlaluku^{32c}, X. Hoad⁴⁸, J. Hobbs¹⁵², N. Hod^{165a}, M.C. Hodgkinson¹⁴⁶,

A. Hoecker³⁵, M.R. Hoferkamp¹¹⁶, F. Hoenig¹¹², D. Hohn²⁴, D. Hohov¹²⁸, T.R. Holmes³⁶, M. Holzbock¹¹², M. Homann⁴⁵, S. Honda¹⁶⁶, T. Honda⁷⁹, T.M. Hong¹³⁵, A. Hönle¹¹³, B.H. Hooberman¹⁷⁰, W.H. Hopkins¹²⁷, Y. Horii¹¹⁵, P. Horn⁴⁶, A.J. Horton¹⁴⁹, L.A. Horyn³⁶, J.-Y. Hostachy⁵⁶, A. Hostiuc¹⁴⁵, S. Hou¹⁵⁵, A. Hoummada^{34a}, J. Howarth⁹⁸, J. Hoya⁸⁶, M. Hrabovsky¹²⁶, J. Hrdinka³⁵, I. Hristova¹⁹, J. Hrivnac¹²⁸, A. Hrynevich¹⁰⁶, T. Hryn'ova⁵, P.J. Hsu⁶², S.-C. Hsu¹⁴⁵, Q. Hu²⁹, S. Hu^{58c}, Y. Huang^{15a}, Z. Hubacek¹³⁸, F. Hubaut⁹⁹, M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³¹, E.W. Hughes³⁸, M. Huhtinen³⁵, R.F.H. Hunter³³, P. Huo¹⁵², A.M. Hupe³³, N. Huseynov^{77,af}, J. Huston¹⁰⁴, J. Huth⁵⁷, R. Hyneman¹⁰³, G. Iacobucci⁵², G. Iakovidis²⁹, I. Ibragimov¹⁴⁸, L. Iconomidou-Fayard¹²⁸, Z. Idrissi^{34e}, P. Iengo³⁵, R. Ignazzi³⁹, O. Igonkina^{118,ab}, R. Iguchi¹⁶⁰, T. Iizawa⁵², Y. Ikegami⁷⁹, M. Ikeno⁷⁹, D. Iliadis¹⁵⁹, N. Ilic¹⁵⁰, F. Iltzsche⁴⁶, G. Introzzi^{68a,68b}, M. Iodice^{72a}, K. Iordanidou³⁸, V. Ippolito^{70a,70b}, M.F. Isacson¹⁶⁹, N. Ishijima¹²⁹, M. Ishino¹⁶⁰, M. Ishitsuka¹⁶², W. Islam¹²⁵, C. Issever¹³¹, S. Istin^{12c,ao}, F. Ito¹⁶⁶, J.M. Iturbe Ponce^{61a}, R. Iuppa^{73a,73b}, A. Ivina¹⁷⁷, H. Iwasaki⁷⁹, J.M. Izen⁴², V. Izzo^{67a}, P. Jacka¹³⁷, P. Jackson¹, R.M. Jacobs²⁴, V. Jain², G. Jäkel¹⁷⁹, K.B. Jakobi⁹⁷, K. Jakobs⁵⁰, S. Jakobsen⁷⁴, T. Jakoubek¹³⁷, D.O. Jamin¹²⁵, D.K. Jana⁹³, R. Jansky⁵², J. Janssen²⁴, M. Janus⁵¹, P.A. Janus^{81a}, G. Jarlskog⁹⁴, N. Javadov^{77,af}, T. Javůrek³⁵, M. Javurkova⁵⁰, F. Jeanneau¹⁴², L. Jeanty¹⁸, J. Jejelava^{156a,ag}, A. Jelinskas¹⁷⁵, P. Jenni^{50,d}, J. Jeong⁴⁴, S. Jézéquel⁵, H. Ji¹⁷⁸, J. Jia¹⁵², H. Jiang⁷⁶, Y. Jiang^{58a}, Z. Jiang^{150,q}, S. Jiggins⁵⁰, F.A. Jimenez Morales³⁷, J. Jimenez Pena¹⁷¹, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶², H. Jivan^{32c}, P. Johansson¹⁴⁶, K.A. Johns⁷, C.A. Johnson⁶³, W.J. Johnson¹⁴⁵, K. Jon-And^{43a,43b}, R.W.L. Jones⁸⁷, S.D. Jones¹⁵³, S. Jones⁷, T.J. Jones⁸⁸, J. Jongmanns^{59a}, P.M. Jorge^{136a,136b}, J. Jovicevic^{165a}, X. Ju¹⁷⁸, J.J. Junggeburth¹¹³, A. Juste Rozas^{14,z}, A. Kaczmarska⁸², M. Kado¹²⁸, H. Kagan¹²², M. Kagan¹⁵⁰, T. Kaji¹⁷⁶, E. Kajomovitz¹⁵⁷, C.W. Kalderon⁹⁴, A. Kaluza⁹⁷, S. Kama⁴¹, A. Kamenshchikov¹⁴⁰, L. Kanjir⁸⁹, Y. Kano¹⁶⁰, V.A. Kantserov¹¹⁰, J. Kanzaki⁷⁹, B. Kaplan¹²¹, L.S. Kaplan¹⁷⁸, D. Kar^{32c}, M.J. Kareem^{165b}, E. Karentzos¹⁰, S.N. Karpov⁷⁷, Z.M. Karpova⁷⁷, V. Kartvelishvili⁸⁷, A.N. Karyukhin¹⁴⁰, L. Kashif¹⁷⁸, R.D. Kass¹²², A. Kastanas¹⁵¹, Y. Kataoka¹⁶⁰, C. Kato^{58d,58c}, J. Katzy⁴⁴, K. Kawade⁸⁰, K. Kawagoe⁸⁵, T. Kawamoto¹⁶⁰, G. Kawamura⁵¹, E.F. Kay⁸⁸, V.F. Kazanin^{120b,120a}, R. Keeler¹⁷³, R. Kehoe⁴¹, J.S. Keller³³, E. Kellermann⁹⁴, J.J. Kempster²¹, J. Kendrick²¹, O. Kepka¹³⁷, S. Kersten¹⁷⁹, B.P. Kerševan⁸⁹, R.A. Keyes¹⁰¹, M. Khader¹⁷⁰, F. Khalil-Zada¹³, A. Khanov¹²⁵, A.G. Kharlamov^{120b,120a}, T. Kharlamova^{120b,120a}, A. Khodinov¹⁶³, T.J. Khoo⁵², E. Khramov⁷⁷, J. Khubua^{156b}, S. Kido⁸⁰, M. Kiehn⁵², C.R. Kilby⁹¹, Y.K. Kim³⁶, N. Kimura^{64a,64c}, O.M. Kind¹⁹, B.T. King⁸⁸, D. Kirchmeier⁴⁶, J. Kirk¹⁴¹, A.E. Kiryunin¹¹³, T. Kishimoto¹⁶⁰, D. Kisieleska^{81a}, V. Kitali⁴⁴, O. Kivernyk⁵, E. Kladiva^{28b,*}, T. Klapdor-Kleingrothaus⁵⁰, M.H. Klein¹⁰³, M. Klein⁸⁸, U. Klein⁸⁸, K. Kleinknecht⁹⁷, P. Klimek¹¹⁹, A. Klimentov²⁹, R. Klingenberg^{45,*}, T. Klingl²⁴, T. Klioutchnikova³⁵, F.F. Klitzner¹¹², P. Kluit¹¹⁸, S. Kluth¹¹³, E. Kneringer⁷⁴, E.B.F.G. Knoop⁹⁹, A. Knue⁵⁰, A. Kobayashi¹⁶⁰, D. Kobayashi⁸⁵, T. Kobayashi¹⁶⁰, M. Kobel⁴⁶, M. Kocian¹⁵⁰, P. Kodys¹³⁹, T. Koffas³³, E. Koffeman¹¹⁸, N.M. Köhler¹¹³, T. Koi¹⁵⁰, M. Kolb^{59b}, I. Koletsou⁵, T. Kondo⁷⁹, N. Kondrashova^{58c}, K. Köneke⁵⁰, A.C. König¹¹⁷, T. Kono⁷⁹, R. Konoplich^{121,al}, V. Konstantinides⁹², N. Konstantinidis⁹², B. Konya⁹⁴, R. Kopeliansky⁶³, S. Koperny^{81a}, K. Korcyl⁸², K. Kordas¹⁵⁹, A. Korn⁹², I. Korolkov¹⁴, E.V. Korolkova¹⁴⁶, O. Kortner¹¹³, S. Kortner¹¹³, T. Kosek¹³⁹, V.V. Kostyukhin²⁴, A. Kotwal⁴⁷, A. Koulouris¹⁰, A. Kourkouloumeli-Charalampidi^{68a,68b}, C. Kourkouloumelis⁹, E. Kourlitis¹⁴⁶, V. Kouskoura²⁹, A.B. Kowalewska⁸², R. Kowalewski¹⁷³, T.Z. Kowalski^{81a}, C. Kozakai¹⁶⁰, W. Kozanecki¹⁴², A.S. Kozhin¹⁴⁰, V.A. Kramarenko¹¹¹, G. Kramberger⁸⁹, D. Krasnopevtsev^{58a}, M.W. Krasny¹³², A. Krasznahorkay³⁵, D. Krauss¹¹³, J.A. Kremer^{81a}, J. Kretzschmar⁸⁸, P. Krieger¹⁶⁴, K. Krizka¹⁸, K. Kroeninger⁴⁵, H. Kroha¹¹³, J. Kroll¹³⁷, J. Kroll¹³³, J. Krstic¹⁶, U. Kruchonak⁷⁷, H. Krüger²⁴, N. Krumnack⁷⁶, M.C. Kruse⁴⁷, T. Kubota¹⁰², S. Kудay^{4b}, J.T. Kuechler¹⁷⁹, S. Kuehn³⁵, A. Kugel^{59a}, F. Kuger¹⁷⁴, T. Kuhl⁴⁴, V. Kukhtin⁷⁷, R. Kukla⁹⁹, Y. Kulchitsky¹⁰⁵, S. Kuleshov^{144b}, Y.P. Kulinich¹⁷⁰, M. Kuna⁵⁶, T. Kunigo⁸³, A. Kupco¹³⁷, T. Kupfer⁴⁵, O. Kuprash¹⁵⁸, H. Kurashige⁸⁰, L.L. Kurchaninov^{165a}, Y.A. Kurochkin¹⁰⁵, M.G. Kurth^{15d}, E.S. Kuwertz³⁵, M. Kuze¹⁶², J. Kvita¹²⁶, T. Kwan¹⁰¹, A. La Rosa¹¹³, J.L. La Rosa Navarro^{78d}, L. La Rotonda^{40b,40a}, F. La Ruffa^{40b,40a}, C. Lacasta¹⁷¹, F. Lacava^{70a,70b}, J. Lacey⁴⁴, D.P.J. Lack⁹⁸, H. Lacker¹⁹, D. Lacour¹³², E. Ladygin⁷⁷, R. Lafaye⁵, B. Laforge¹³², T. Lagouri^{32c}, S. Lai⁵¹, S. Lammers⁶³, W. Lampl⁷, E. Lançon²⁹, U. Landgraf⁵⁰, M.P.J. Landon⁹⁰, M.C. Lanfermann⁵², V.S. Lang⁴⁴, J.C. Lange¹⁴, R.J. Langenberg³⁵, A.J. Lankford¹⁶⁸, F. Lanni²⁹, K. Lantzsche²⁴, A. Lanza^{68a}, A. Lapertosa^{53b,53a}, S. Laplace¹³², J.F. Laporte¹⁴², T. Lari^{66a}, F. Lasagni Manghi^{23b,23a}, M. Lassnig³⁵,

T.S. Lau^{61a}, A. Laudrain¹²⁸, M. Lavorgna^{67a,67b}, A.T. Law¹⁴³, P. Laycock⁸⁸, M. Lazzaroni^{66a,66b}, B. Le¹⁰², O. Le Dortz¹³², E. Le Guirriec⁹⁹, E.P. Le Quilleuc¹⁴², M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁹, G.R. Lee^{144a}, L. Lee⁵⁷, S.C. Lee¹⁵⁵, B. Lefebvre¹⁰¹, M. Lefebvre¹⁷³, F. Legger¹¹², C. Leggett¹⁸, N. Lehmann¹⁷⁹, G. Lehmann Miotto³⁵, W.A. Leight⁴⁴, A. Leisos^{159,w}, M.A.L. Leite^{78d}, R. Leitner¹³⁹, D. Lellouch¹⁷⁷, B. Lemmer⁵¹, K.J.C. Leney⁹², T. Lenz²⁴, B. Lenzi³⁵, R. Leone⁷, S. Leone^{69a}, C. Leonidopoulos⁴⁸, G. Lerner¹⁵³, C. Leroy¹⁰⁷, R. Les¹⁶⁴, A.A.J. Lesage¹⁴², C.G. Lester³¹, M. Levchenko¹³⁴, J. Levêque⁵, D. Levin¹⁰³, L.J. Levinson¹⁷⁷, D. Lewis⁹⁰, B. Li¹⁰³, C-Q. Li^{58a,ak}, H. Li^{58b}, L. Li^{58c}, Q. Li^{15d}, Q.Y. Li^{58a}, S. Li^{58d,58c}, X. Li^{58c}, Y. Li¹⁴⁸, Z. Liang^{15a}, B. Liberti^{71a}, A. Liblong¹⁶⁴, K. Lie^{61c}, S. Liem¹¹⁸, A. Limosani¹⁵⁴, C.Y. Lin³¹, K. Lin¹⁰⁴, T.H. Lin⁹⁷, R.A. Linck⁶³, J.H. Lindon²¹, B.E. Lindquist¹⁵², A.L. Lioni⁵², E. Lipeles¹³³, A. Lipniacka¹⁷, M. Lisovyi^{59b}, T.M. Liss^{170,ar}, A. Lister¹⁷², A.M. Litke¹⁴³, J.D. Little⁸, B. Liu⁷⁶, B.L. Liu⁶, H.B. Liu²⁹, H. Liu¹⁰³, J.B. Liu^{58a}, J.K.K. Liu¹³¹, K. Liu¹³², M. Liu^{58a}, P. Liu¹⁸, Y. Liu^{15a}, Y.L. Liu^{58a}, Y.W. Liu^{58a}, M. Livan^{68a,68b}, A. Lleres⁵⁶, J. Llorente Merino^{15a}, S.L. Lloyd⁹⁰, C.Y. Lo^{61b}, F. Lo Sterzo⁴¹, E.M. Lobodzinska⁴⁴, P. Loch⁷, T. Lohse¹⁹, K. Lohwasser¹⁴⁶, M. Lokajicek¹³⁷, B.A. Long²⁵, J.D. Long¹⁷⁰, R.E. Long⁸⁷, L. Longo^{65a,65b}, K.A. Looper¹²², J.A. Lopez^{144b}, I. Lopez Paz¹⁴, A. Lopez Solis¹⁴⁶, J. Lorenz¹¹², N. Lorenzo Martinez⁵, M. Losada²², P.J. Lösel¹¹², A. Lösle⁵⁰, X. Lou⁴⁴, X. Lou^{15a}, A. Lounis¹²⁸, J. Love⁶, P.A. Love⁸⁷, J.J. Lozano Bahilo¹⁷¹, H. Lu^{61a}, M. Lu^{58a}, N. Lu¹⁰³, Y.J. Lu⁶², H.J. Lubatti¹⁴⁵, C. Luci^{70a,70b}, A. Lucotte⁵⁶, C. Luedtke⁵⁰, F. Luehring⁶³, I. Luise¹³², L. Luminari^{70a}, B. Lund-Jensen¹⁵¹, M.S. Lutz¹⁰⁰, P.M. Luzi¹³², D. Lynn²⁹, R. Lysak¹³⁷, E. Lytken⁹⁴, F. Lyu^{15a}, V. Lyubushkin⁷⁷, H. Ma²⁹, L.L. Ma^{58b}, Y. Ma^{58b}, G. Maccarrone⁴⁹, A. Macchiolo¹¹³, C.M. Macdonald¹⁴⁶, J. Machado Miguens^{133,136b}, D. Madaffari¹⁷¹, R. Madar³⁷, W.F. Mader⁴⁶, A. Madsen⁴⁴, N. Madysa⁴⁶, J. Maeda⁸⁰, K. Maekawa¹⁶⁰, S. Maeland¹⁷, T. Maeno²⁹, A.S. Maevskiy¹¹¹, V. Magerl⁵⁰, C. Maidantchik^{78b}, T. Maier¹¹², A. Maio^{136a,136b,136d}, O. Majersky^{28a}, S. Majewski¹²⁷, Y. Makida⁷⁹, N. Makovec¹²⁸, B. Malaescu¹³², Pa. Malecki⁸², V.P. Maleev¹³⁴, F. Malek⁵⁶, U. Mallik⁷⁵, D. Malon⁶, C. Malone³¹, S. Maltezos¹⁰, S. Malyukov³⁵, J. Mamuzic¹⁷¹, G. Mancini⁴⁹, I. Mandić⁸⁹, J. Maneira^{136a}, L. Manhaes de Andrade Filho^{78a}, J. Manjarres Ramos⁴⁶, K.H. Mankinen⁹⁴, A. Mann¹¹², A. Manousos⁷⁴, B. Mansoulie¹⁴², J.D. Mansour^{15a}, M. Mantoani⁵¹, S. Manzoni^{66a,66b}, G. Marceca³⁰, L. March⁵², L. Marchese¹³¹, G. Marchiori¹³², M. Marcisovsky¹³⁷, C.A. Marin Tobon³⁵, M. Marjanovic³⁷, D.E. Marley¹⁰³, F. Marroquim^{78b}, Z. Marshall¹⁸, M.U.F. Martensson¹⁶⁹, S. Marti-Garcia¹⁷¹, C.B. Martin¹²², T.A. Martin¹⁷⁵, V.J. Martin⁴⁸, B. Martin dit Latour¹⁷, M. Martinez^{14,z}, V.I. Martinez Outschoorn¹⁰⁰, S. Martin-Haugh¹⁴¹, V.S. Martoiu^{27b}, A.C. Martyniuk⁹², A. Marzin³⁵, L. Masetti⁹⁷, T. Mashimo¹⁶⁰, R. Mashinistov¹⁰⁸, J. Masik⁹⁸, A.L. Maslennikov^{120b,120a}, L.H. Mason¹⁰², L. Massa^{71a,71b}, P. Massarotti^{67a,67b}, P. Mastrandrea⁵, A. Mastroberardino^{40b,40a}, T. Masubuchi¹⁶⁰, P. Mättig¹⁷⁹, J. Maurer^{27b}, B. Maček⁸⁹, S.J. Maxfield⁸⁸, D.A. Maximov^{120b,120a}, R. Mazini¹⁵⁵, I. Maznas¹⁵⁹, S.M. Mazza¹⁴³, N.C. Mc Fadden¹¹⁶, G. Mc Goldrick¹⁶⁴, S.P. Mc Kee¹⁰³, A. McCarn¹⁰³, T.G. McCarthy¹¹³, L.I. McClymont⁹², E.F. McDonald¹⁰², J.A. Mcfayden³⁵, G. Mchedlidze⁵¹, M.A. McKay⁴¹, K.D. McLean¹⁷³, S.J. McMahon¹⁴¹, P.C. McNamara¹⁰², C.J. McNicol¹⁷⁵, R.A. McPherson^{173,ad}, J.E. Mdhluli^{32c}, Z.A. Meadows¹⁰⁰, S. Meehan¹⁴⁵, T.M. Megy⁵⁰, S. Mehlhase¹¹², A. Mehta⁸⁸, T. Meideck⁵⁶, B. Meirose⁴², D. Melini^{171,h}, B.R. Mellado Garcia^{32c}, J.D. Mellenthin⁵¹, M. Melo^{28a}, F. Meloni⁴⁴, A. Melzer²⁴, S.B. Menary⁹⁸, E.D. Mendes Gouveia^{136a}, L. Meng⁸⁸, X.T. Meng¹⁰³, A. Mengarelli^{23b,23a}, S. Menke¹¹³, E. Meoni^{40b,40a}, S. Mergelmeyer¹⁹, C. Merlassino²⁰, P. Mermod⁵², L. Merola^{67a,67b}, C. Meroni^{66a}, F.S. Merritt³⁶, A. Messina^{70a,70b}, J. Metcalfe⁶, A.S. Mete¹⁶⁸, C. Meyer¹³³, J. Meyer¹⁵⁷, J-P. Meyer¹⁴², H. Meyer Zu Theenhausen^{59a}, F. Miano¹⁵³, R.P. Middleton¹⁴¹, L. Mijović⁴⁸, G. Mikenberg¹⁷⁷, M. Mikestikova¹³⁷, M. Mikuž⁸⁹, M. Milesi¹⁰², A. Milic¹⁶⁴, D.A. Millar⁹⁰, D.W. Miller³⁶, A. Milov¹⁷⁷, D.A. Milstead^{43a,43b}, A.A. Minaenko¹⁴⁰, M. Miñano Moya¹⁷¹, I.A. Minashvili^{156b}, A.I. Mincer¹²¹, B. Mindur^{81a}, M. Mineev⁷⁷, Y. Minegishi¹⁶⁰, Y. Ming¹⁷⁸, L.M. Mir¹⁴, A. Mirto^{65a,65b}, K.P. Mistry¹³³, T. Mitani¹⁷⁶, J. Mitrevski¹¹², V.A. Mitsou¹⁷¹, A. Miucci²⁰, P.S. Miyagawa¹⁴⁶, A. Mizukami⁷⁹, J.U. Mjörnmark⁹⁴, T. Mkrtchyan¹⁸¹, M. Mlynarikova¹³⁹, T. Moa^{43a,43b}, K. Mochizuki¹⁰⁷, P. Mogg⁵⁰, S. Mohapatra³⁸, S. Molander^{43a,43b}, R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁴, K. Mönig⁴⁴, J. Monk³⁹, E. Monnier⁹⁹, A. Montalbano¹⁴⁹, J. Montejo Berlingen³⁵, F. Monticelli⁸⁶, S. Monzani^{66a}, N. Morange¹²⁸, D. Moreno²², M. Moreno Llácer³⁵, P. Morettini^{53b}, M. Morgenstern¹¹⁸, S. Morgenstern⁴⁶, D. Mori¹⁴⁹, M. Morii⁵⁷, M. Morinaga¹⁷⁶, V. Morisbak¹³⁰, A.K. Morley³⁵, G. Mornacchi³⁵, A.P. Morris⁹², J.D. Morris⁹⁰, L. Morvaj¹⁵², P. Moschovakos¹⁰, M. Mosidze^{156b},

H.J. Moss¹⁴⁶, J. Moss^{150,n}, K. Motohashi¹⁶², R. Mount¹⁵⁰, E. Mountricha³⁵, E.J.W. Moyse¹⁰⁰, S. Muanza⁹⁹, F. Mueller¹¹³, J. Mueller¹³⁵, R.S.P. Mueller¹¹², D. Muenstermann⁸⁷, G.A. Mullier²⁰, F.J. Munoz Sanchez⁹⁸, P. Murin^{28b}, W.J. Murray^{175,141}, A. Murrone^{66a,66b}, M. Muškinja⁸⁹, C. Mwewa^{32a}, A.G. Myagkov^{140,am}, J. Myers¹²⁷, M. Myska¹³⁸, B.P. Nachman¹⁸, O. Nackenhorst⁴⁵, K. Nagai¹³¹, K. Nagano⁷⁹, Y. Nagasaka⁶⁰, M. Nagel⁵⁰, E. Nagy⁹⁹, A.M. Nairz³⁵, Y. Nakahama¹¹⁵, K. Nakamura⁷⁹, T. Nakamura¹⁶⁰, I. Nakano¹²³, H. Nanjo¹²⁹, F. Napolitano^{59a}, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{59a}, I. Naryshkin¹³⁴, T. Naumann⁴⁴, G. Navarro²², R. Nayyar⁷, H.A. Neal^{103,*}, P.Y. Nechaeva¹⁰⁸, T.J. Neep¹⁴², A. Negri^{68a,68b}, M. Negrini^{23b}, S. Nektarijevic¹¹⁷, C. Nellist⁵¹, M.E. Nelson¹³¹, S. Nemecek¹³⁷, P. Nemethy¹²¹, M. Nessi^{35,f}, M.S. Neubauer¹⁷⁰, M. Neumann¹⁷⁹, P.R. Newman²¹, T.Y. Ng^{61c}, Y.S. Ng¹⁹, H.D.N. Nguyen⁹⁹, T. Nguyen Manh¹⁰⁷, E. Nibigira³⁷, R.B. Nickerson¹³¹, R. Nicolaïdou¹⁴², J. Nielsen¹⁴³, N. Nikiforou¹¹, V. Nikolaenko^{140,am}, I. Nikolic-Audit¹³², K. Nikolopoulos²¹, P. Nilsson²⁹, Y. Ninomiya⁷⁹, A. Nisati^{70a}, N. Nishu^{58c}, R. Nisius¹¹³, I. Nitsche⁴⁵, T. Nitta¹⁷⁶, T. Nobe¹⁶⁰, Y. Noguchi⁸³, M. Nomachi¹²⁹, I. Nomidis¹³², M.A. Nomura²⁹, T. Nooney⁹⁰, M. Nordberg³⁵, N. Norjoharuddeen¹³¹, T. Novak⁸⁹, O. Novgorodova⁴⁶, R. Novotny¹³⁸, L. Nozka¹²⁶, K. Ntekas¹⁶⁸, E. Nurse⁹², F. Nuti¹⁰², F.G. Oakham^{33,au}, H. Oberlack¹¹³, T. Obermann²⁴, J. Ocariz¹³², A. Ochi⁸⁰, I. Ochoa³⁸, J.P. Ochoa-Ricoux^{144a}, K. O'Connor²⁶, S. Oda⁸⁵, S. Odaka⁷⁹, S. Oerdek⁵¹, A. Oh⁹⁸, S.H. Oh⁴⁷, C.C. Ohm¹⁵¹, H. Oide^{53b,53a}, M.L. Ojeda¹⁶⁴, H. Okawa¹⁶⁶, Y. Okazaki⁸³, Y. Okumura¹⁶⁰, T. Okuyama⁷⁹, A. Olariu^{27b}, L.F. Oleiro Seabra^{136a}, S.A. Olivares Pino^{144a}, D. Oliveira Damazio²⁹, J.L. Oliver¹, M.J.R. Olsson³⁶, A. Olszewski⁸², J. Olszowska⁸², D.C. O'Neil¹⁴⁹, A. Onofre^{136a,136e}, K. Onogi¹¹⁵, P.U.E. Onyisi¹¹, H. Oppen¹³⁰, M.J. Oreglia³⁶, Y. Oren¹⁵⁸, D. Orestano^{72a,72b}, E.C. Orgill⁹⁸, N. Orlando^{61b}, A.A. O'Rourke⁴⁴, R.S. Orr¹⁶⁴, B. Osculati^{53b,53a,*}, V. O'Shea⁵⁵, R. Ospanov^{58a}, G. Otero y Garzon³⁰, H. Otono⁸⁵, M. Ouchrif^{34d}, F. Ould-Saada¹³⁰, A. Ouraou¹⁴², Q. Ouyang^{15a}, M. Owen⁵⁵, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, J. Pacalt¹²⁶, H.A. Pacey³¹, K. Pachal¹⁴⁹, A. Pacheco Pages¹⁴, L. Pacheco Rodriguez¹⁴², C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸⁰, G. Palacino⁶³, S. Palazzo^{40b,40a}, S. Palestini³⁵, M. Palka^{81b}, D. Pallin³⁷, I. Panagoulas¹⁰, C.E. Pandini³⁵, J.G. Panduro Vazquez⁹¹, P. Pani³⁵, G. Panizzo^{64a,64c}, L. Paolozzi⁵², T.D. Papadopoulou¹⁰, K. Papageorgiou^{9,j}, A. Paramonov⁶, D. Paredes Hernandez^{61b}, S.R. Paredes Saenz¹³¹, B. Parida^{58c}, A.J. Parker⁸⁷, K.A. Parker⁴⁴, M.A. Parker³¹, F. Parodi^{53b,53a}, J.A. Parsons³⁸, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁶⁴, J.M.P. Pasner¹⁴³, E. Pasqualucci^{70a}, S. Passaggio^{53b}, F. Pastore⁹¹, P. Pasuwan^{43a,43b}, S. Pataria⁹⁷, J.R. Pater⁹⁸, A. Pathak^{178,k}, T. Pauly³⁵, B. Pearson¹¹³, M. Pedersen¹³⁰, L. Pedraza Diaz¹¹⁷, R. Pedro^{136a,136b}, S.V. Peleganchuk^{120b,120a}, O. Penc¹³⁷, C. Peng^{15d}, H. Peng^{58a}, B.S. Peralva^{78a}, M.M. Perego¹⁴², A.P. Pereira Peixoto^{136a}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{66a,66b}, H. Pernegger³⁵, S. Perrella^{67a,67b}, V.D. Peshekhonov^{77,*}, K. Peters⁴⁴, R.F.Y. Peters⁹⁸, B.A. Petersen³⁵, T.C. Petersen³⁹, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁹, P. Petroff¹²⁸, M. Petrov¹³¹, F. Petrucci^{72a,72b}, M. Pettee¹⁸⁰, N.E. Pettersson¹⁰⁰, A. Peyaud¹⁴², R. Pezoa^{144b}, T. Pham¹⁰², F.H. Phillips¹⁰⁴, P.W. Phillips¹⁴¹, G. Piacquadio¹⁵², E. Pianori¹⁸, A. Picazio¹⁰⁰, M.A. Pickering¹³¹, R.H. Pickles⁹⁸, R. Piegaia³⁰, J.E. Pilcher³⁶, A.D. Pilkington⁹⁸, M. Pinamonti^{71a,71b}, J.L. Pinfold³, M. Pitt¹⁷⁷, M.-A. Pleier²⁹, V. Pleskot¹³⁹, E. Plotnikova⁷⁷, D. Pluth⁷⁶, P. Podberezko^{120b,120a}, R. Poettgen⁹⁴, R. Poggi⁵², L. Poggioli¹²⁸, I. Pogrebnyak¹⁰⁴, D. Pohl²⁴, I. Pokharel⁵¹, G. Polesello^{68a}, A. Poley⁴⁴, A. Policicchio^{70a,70b}, R. Polifka³⁵, A. Polini^{23b}, C.S. Pollard⁴⁴, V. Polychronakos²⁹, D. Ponomarenko¹¹⁰, L. Pontecorvo^{70a}, G.A. Popeneciu^{27d}, D.M. Portillo Quintero¹³², S. Pospisil¹³⁸, K. Potamianos⁴⁴, I.N. Potrap⁷⁷, C.J. Potter³¹, H. Potti¹¹, T. Poulsen⁹⁴, J. Poveda³⁵, T.D. Powell¹⁴⁶, M.E. Pozo Astigarraga³⁵, P. Pralavorio⁹⁹, S. Prell⁷⁶, D. Price⁹⁸, M. Primavera^{65a}, S. Prince¹⁰¹, N. Proklova¹¹⁰, K. Prokofiev^{61c}, F. Prokoshin^{144b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{81a}, A. Puri¹⁷⁰, P. Puzo¹²⁸, J. Qian¹⁰³, Y. Qin⁹⁸, A. Quadt⁵¹, M. Queitsch-Maitland⁴⁴, A. Qureshi¹, P. Rados¹⁰², F. Ragusa^{66a,66b}, G. Rahal⁹⁵, J.A. Raine⁵², S. Rajagopalan²⁹, A. Ramirez Morales⁹⁰, T. Rashid¹²⁸, S. Raspopov⁵, M.G. Ratti^{66a,66b}, D.M. Rauch⁴⁴, F. Rauscher¹¹², S. Rave⁹⁷, B. Ravina¹⁴⁶, I. Ravinovich¹⁷⁷, J.H. Rawling⁹⁸, M. Raymond³⁵, A.L. Read¹³⁰, N.P. Readioff⁵⁶, M. Reale^{65a,65b}, D.M. Rebuzzi^{68a,68b}, A. Redelbach¹⁷⁴, G. Redlinger²⁹, R. Reece¹⁴³, R.G. Reed^{32c}, K. Reeves⁴², L. Rehnisch¹⁹, J. Reichert¹³³, A. Reiss⁹⁷, C. Rembser³⁵, H. Ren^{15d}, M. Rescigno^{70a}, S. Resconi^{66a}, E.D. Resseguie¹³³, S. Rettie¹⁷², E. Reynolds²¹, O.L. Rezanova^{120b,120a}, P. Reznicek¹³⁹, E. Ricci^{73a,73b}, R. Richter¹¹³, S. Richter⁹², E. Richter-Was^{81b}, O. Ricken²⁴, M. Ridel¹³², P. Rieck¹¹³, C.J. Riegel¹⁷⁹,

O. Rifki ⁴⁴, M. Rijssenbeek ¹⁵², A. Rimoldi ^{68a,68b}, M. Rimoldi ²⁰, L. Rinaldi ^{23b}, G. Ripellino ¹⁵¹, B. Ristić ⁸⁷, E. Ritsch ³⁵, I. Riu ¹⁴, J.C. Rivera Vergara ^{144a}, F. Rizatdinova ¹²⁵, E. Rizvi ⁹⁰, C. Rizzi ¹⁴, R.T. Roberts ⁹⁸, S.H. Robertson ^{101,ad}, D. Robinson ³¹, J.E.M. Robinson ⁴⁴, A. Robson ⁵⁵, E. Rocco ⁹⁷, C. Roda ^{69a,69b}, Y. Rodina ⁹⁹, S. Rodriguez Bosca ¹⁷¹, A. Rodriguez Perez ¹⁴, D. Rodriguez Rodriguez ¹⁷¹, A.M. Rodriguez Vera ^{165b}, S. Roe ³⁵, C.S. Rogan ⁵⁷, O. Røhne ¹³⁰, R. Röhrig ¹¹³, C.P.A. Roland ⁶³, J. Roloff ⁵⁷, A. Romaniouk ¹¹⁰, M. Romano ^{23b,23a}, N. Rompotis ⁸⁸, M. Ronzani ¹²¹, L. Roos ¹³², S. Rosati ^{70a}, K. Rosbach ⁵⁰, P. Rose ¹⁴³, N.-A. Rosien ⁵¹, E. Rossi ⁴⁴, E. Rossi ^{67a,67b}, L.P. Rossi ^{53b}, L. Rossini ^{66a,66b}, J.H.N. Rosten ³¹, R. Rosten ¹⁴, M. Rotaru ^{27b}, J. Rothberg ¹⁴⁵, D. Rousseau ¹²⁸, D. Roy ^{32c}, A. Rozanov ⁹⁹, Y. Rozen ¹⁵⁷, X. Ruan ^{32c}, F. Rubbo ¹⁵⁰, F. Rühr ⁵⁰, A. Ruiz-Martinez ¹⁷¹, Z. Rurikova ⁵⁰, N.A. Rusakovich ⁷⁷, H.L. Russell ¹⁰¹, J.P. Rutherford ⁷, E.M. Rüttinger ^{44,1}, Y.F. Ryabov ¹³⁴, M. Rybar ¹⁷⁰, G. Rybkin ¹²⁸, S. Ryu ⁶, A. Ryzhov ¹⁴⁰, G.F. Rzehorz ⁵¹, P. Sabatini ⁵¹, G. Sabato ¹¹⁸, S. Sacerdoti ¹²⁸, H.F.-W. Sadrozinski ¹⁴³, R. Sadykov ⁷⁷, F. Safai Tehrani ^{70a}, P. Saha ¹¹⁹, M. Sahinsoy ^{59a}, A. Sahu ¹⁷⁹, M. Saimpert ⁴⁴, M. Saito ¹⁶⁰, T. Saito ¹⁶⁰, H. Sakamoto ¹⁶⁰, A. Sakharov ^{121,al}, D. Salamani ⁵², G. Salamanna ^{72a,72b}, J.E. Salazar Loyola ^{144b}, D. Salek ¹¹⁸, P.H. Sales De Bruin ¹⁶⁹, D. Salihagic ¹¹³, A. Salnikov ¹⁵⁰, J. Salt ¹⁷¹, D. Salvatore ^{40b,40a}, F. Salvatore ¹⁵³, A. Salvucci ^{61a,61b,61c}, A. Salzburger ³⁵, J. Samarati ³⁵, D. Sammel ⁵⁰, D. Sampsonidis ¹⁵⁹, D. Sampsonidou ¹⁵⁹, J. Sánchez ¹⁷¹, A. Sanchez Pineda ^{64a,64c}, H. Sandaker ¹³⁰, C.O. Sander ⁴⁴, M. Sandhoff ¹⁷⁹, C. Sandoval ²², D.P.C. Sankey ¹⁴¹, M. Sannino ^{53b,53a}, Y. Sano ¹¹⁵, A. Sansoni ⁴⁹, C. Santoni ³⁷, H. Santos ^{136a}, I. Santoyo Castillo ¹⁵³, A. Santra ¹⁷¹, A. Saponov ⁷⁷, J.G. Saraiva ^{136a,136d}, O. Sasaki ⁷⁹, K. Sato ¹⁶⁶, E. Sauvan ⁵, P. Savard ^{164,au}, N. Savic ¹¹³, R. Sawada ¹⁶⁰, C. Sawyer ¹⁴¹, L. Sawyer ^{93,aj}, C. Sbarra ^{23b}, A. Sbrizzi ^{23b,23a}, T. Scanlon ⁹², J. Schaarschmidt ¹⁴⁵, P. Schacht ¹¹³, B.M. Schachtner ¹¹², D. Schaefer ³⁶, L. Schaefer ¹³³, J. Schaeffer ⁹⁷, S. Schaepe ³⁵, U. Schäfer ⁹⁷, A.C. Schaffer ¹²⁸, D. Schaile ¹¹², R.D. Schamberger ¹⁵², N. Scharmberg ⁹⁸, V.A. Schegelsky ¹³⁴, D. Scheirich ¹³⁹, F. Schenck ¹⁹, M. Schernau ¹⁶⁸, C. Schiavi ^{53b,53a}, S. Schier ¹⁴³, L.K. Schildgen ²⁴, Z.M. Schillaci ²⁶, E.J. Schioppa ³⁵, M. Schioppa ^{40b,40a}, K.E. Schleicher ⁵⁰, S. Schlenker ³⁵, K.R. Schmidt-Sommerfeld ¹¹³, K. Schmieden ³⁵, C. Schmitt ⁹⁷, S. Schmitt ⁴⁴, S. Schmitz ⁹⁷, J.C. Schmoeckel ⁴⁴, U. Schnoor ⁵⁰, L. Schoeffel ¹⁴², A. Schoening ^{59b}, E. Schopf ²⁴, M. Schott ⁹⁷, J.F.P. Schouwenberg ¹¹⁷, J. Schovancova ³⁵, S. Schramm ⁵², A. Schulte ⁹⁷, H.-C. Schultz-Coulon ^{59a}, M. Schumacher ⁵⁰, B.A. Schumm ¹⁴³, Ph. Schune ¹⁴², A. Schwartzman ¹⁵⁰, T.A. Schwarz ¹⁰³, H. Schweiger ⁹⁸, Ph. Schwemling ¹⁴², R. Schwienhorst ¹⁰⁴, A. Sciandra ²⁴, G. Sciolla ²⁶, M. Scornajenghi ^{40b,40a}, F. Scuri ^{69a}, F. Scutti ¹⁰², L.M. Scyboz ¹¹³, J. Searcy ¹⁰³, C.D. Sebastiani ^{70a,70b}, P. Seema ²⁴, S.C. Seidel ¹¹⁶, A. Seiden ¹⁴³, T. Seiss ³⁶, J.M. Seixas ^{78b}, G. Sekhniaidze ^{67a}, K. Sekhon ¹⁰³, S.J. Sekula ⁴¹, N. Semprini-Cesari ^{23b,23a}, S. Sen ⁴⁷, S. Senkin ³⁷, C. Serfon ¹³⁰, L. Serin ¹²⁸, L. Serkin ^{64a,64b}, M. Sessa ^{72a,72b}, H. Severini ¹²⁴, F. Sforza ¹⁶⁷, A. Sfyrila ⁵², E. Shabalina ⁵¹, J.D. Shahinian ¹⁴³, N.W. Shaikh ^{43a,43b}, L.Y. Shan ^{15a}, R. Shang ¹⁷⁰, J.T. Shank ²⁵, M. Shapiro ¹⁸, A.S. Sharma ¹, A. Sharma ¹³¹, P.B. Shatalov ¹⁰⁹, K. Shaw ¹⁵³, S.M. Shaw ⁹⁸, A. Shcherbakova ¹³⁴, Y. Shen ¹²⁴, N. Sherafati ³³, A.D. Sherman ²⁵, P. Sherwood ⁹², L. Shi ^{155,aq}, S. Shimizu ⁷⁹, C.O. Shimmin ¹⁸⁰, M. Shimojima ¹¹⁴, I.P.J. Shipsey ¹³¹, S. Shirabe ⁸⁵, M. Shiyakova ⁷⁷, J. Shlomi ¹⁷⁷, A. Shmeleva ¹⁰⁸, D. Shoaleh Saadi ¹⁰⁷, M.J. Shochet ³⁶, S. Shojaii ¹⁰², D.R. Shope ¹²⁴, S. Shrestha ¹²², E. Shulga ¹¹⁰, P. Sicho ¹³⁷, A.M. Sickles ¹⁷⁰, P.E. Sidebo ¹⁵¹, E. Sideras Haddad ^{32c}, O. Sidiropoulou ³⁵, A. Sidoti ^{23b,23a}, F. Siegert ⁴⁶, Dj. Sijacki ¹⁶, J. Silva ^{136a}, M. Silva Jr. ¹⁷⁸, M.V. Silva Oliveira ^{78a}, S.B. Silverstein ^{43a}, L. Simic ⁷⁷, S. Simion ¹²⁸, E. Simioni ⁹⁷, M. Simon ⁹⁷, R. Simoniello ⁹⁷, P. Sinervo ¹⁶⁴, N.B. Sinev ¹²⁷, M. Sioli ^{23b,23a}, G. Siragusa ¹⁷⁴, I. Siral ¹⁰³, S.Yu. Sivoklov ¹¹¹, J. Sjölin ^{43a,43b}, P. Skubic ¹²⁴, M. Slater ²¹, T. Slavicek ¹³⁸, M. Slawinska ⁸², K. Sliwa ¹⁶⁷, R. Slovak ¹³⁹, V. Smakhtin ¹⁷⁷, B.H. Smart ⁵, J. Smiesko ^{28a}, N. Smirnov ¹¹⁰, S.Yu. Smirnov ¹¹⁰, Y. Smirnov ¹¹⁰, L.N. Smirnova ¹¹¹, O. Smirnova ⁹⁴, J.W. Smith ⁵¹, M.N.K. Smith ³⁸, M. Smizanska ⁸⁷, K. Smolek ¹³⁸, A. Smykiewicz ⁸², A.A. Snesarev ¹⁰⁸, I.M. Snyder ¹²⁷, S. Snyder ²⁹, R. Sobie ^{173,ad}, A.M. Soffa ¹⁶⁸, A. Soffer ¹⁵⁸, A. Søgaard ⁴⁸, D.A. Soh ¹⁵⁵, G. Sokhrannyi ⁸⁹, C.A. Solans Sanchez ³⁵, M. Solar ¹³⁸, E.Yu. Soldatov ¹¹⁰, U. Soldevila ¹⁷¹, A.A. Solodkov ¹⁴⁰, A. Soloshenko ⁷⁷, O.V. Solovyanov ¹⁴⁰, V. Solovyev ¹³⁴, P. Sommer ¹⁴⁶, H. Son ¹⁶⁷, W. Song ¹⁴¹, W.Y. Song ^{165b}, A. Sopczak ¹³⁸, F. Sopkova ^{28b}, D. Sosa ^{59b}, C.L. Sotiropoulou ^{69a,69b}, S. Sottocornola ^{68a,68b}, R. Soualah ^{64a,64c,i}, A.M. Soukharev ^{120b,120a}, D. South ⁴⁴, B.C. Sowden ⁹¹, S. Spagnolo ^{65a,65b}, M. Spalla ¹¹³, M. Spangenberg ¹⁷⁵, F. Spanò ⁹¹, D. Sperlich ¹⁹, F. Spettel ¹¹³, T.M. Spieker ^{59a}, R. Spighi ^{23b}, G. Spigo ³⁵, L.A. Spiller ¹⁰², D.P. Spiteri ⁵⁵, M. Spousta ¹³⁹, A. Stabile ^{66a,66b}, R. Stamen ^{59a}, S. Stamm ¹⁹, E. Stanecka ⁸², R.W. Stanek ⁶, C. Stancescu ^{72a},

B. Stanislaus¹³¹, M.M. Stanitzki⁴⁴, B. Stapf¹¹⁸, S. Stapnes¹³⁰, E.A. Starchenko¹⁴⁰, G.H. Stark³⁶, J. Stark⁵⁶, S.H. Stark³⁹, P. Staroba¹³⁷, P. Starovoitov^{59a}, S. Stärz³⁵, R. Staszewski⁸², M. Stegler⁴⁴, P. Steinberg²⁹, B. Stelzer¹⁴⁹, H.J. Stelzer³⁵, O. Stelzer-Chilton^{165a}, H. Stenzel⁵⁴, T.J. Stevenson⁹⁰, G.A. Stewart⁵⁵, M.C. Stockton¹²⁷, G. Stoicea^{27b}, P. Stolte⁵¹, S. Stonjek¹¹³, A. Straessner⁴⁶, J. Strandberg¹⁵¹, S. Strandberg^{43a,43b}, M. Strauss¹²⁴, P. Strizenec^{28b}, R. Ströhmer¹⁷⁴, D.M. Strom¹²⁷, R. Stroynowski⁴¹, A. Strubig⁴⁸, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁴, N.A. Styles⁴⁴, D. Su¹⁵⁰, J. Su¹³⁵, S. Suchek^{59a}, Y. Sugaya¹²⁹, M. Suk¹³⁸, V.V. Sulin¹⁰⁸, D.M.S. Sultan⁵², S. Sultansoy^{4c}, T. Sumida⁸³, S. Sun¹⁰³, X. Sun³, K. Suruliz¹⁵³, C.J.E. Suster¹⁵⁴, M.R. Sutton¹⁵³, S. Suzuki⁷⁹, M. Svatos¹³⁷, M. Swiatlowski³⁶, S.P. Swift², A. Sydorenko⁹⁷, I. Sykora^{28a}, T. Sykora¹³⁹, D. Ta⁹⁷, K. Tackmann^{44,aa}, J. Taenzer¹⁵⁸, A. Taffard¹⁶⁸, R. Tafirout^{165a}, E. Tahirovic⁹⁰, N. Taiblum¹⁵⁸, H. Takai²⁹, R. Takashima⁸⁴, E.H. Takasugi¹¹³, K. Takeda⁸⁰, T. Takeshita¹⁴⁷, Y. Takubo⁷⁹, M. Talby⁹⁹, A.A. Talyshev^{120b,120a}, J. Tanaka¹⁶⁰, M. Tanaka¹⁶², R. Tanaka¹²⁸, B.B. Tannenwald¹²², S. Tapia Araya^{144b}, S. Tapprogge⁹⁷, A. Tarek Abouelfadl Mohamed¹³², S. Tarem¹⁵⁷, G. Tarna^{27b,e}, G.F. Tartarelli^{66a}, P. Tas¹³⁹, M. Tasevsky¹³⁷, T. Tashiro⁸³, E. Tassi^{40b,40a}, A. Tavares Delgado^{136a,136b}, Y. Tayalati^{34e}, A.C. Taylor¹¹⁶, A.J. Taylor⁴⁸, G.N. Taylor¹⁰², P.T.E. Taylor¹⁰², W. Taylor^{165b}, A.S. Tee⁸⁷, P. Teixeira-Dias⁹¹, H. Ten Kate³⁵, P.K. Teng¹⁵⁵, J.J. Teoh¹¹⁸, F. Tepel¹⁷⁹, S. Terada⁷⁹, K. Terashi¹⁶⁰, J. Terron⁹⁶, S. Terzo¹⁴, M. Testa⁴⁹, R.J. Teuscher^{164,ad}, S.J. Thais¹⁸⁰, T. Theveniaux-Pelzer⁴⁴, F. Thiele³⁹, D.W. Thomas⁹¹, J.P. Thomas²¹, A.S. Thompson⁵⁵, P.D. Thompson²¹, L.A. Thomsen¹⁸⁰, E. Thomson¹³³, Y. Tian³⁸, R.E. Ticse Torres⁵¹, V.O. Tikhomirov^{108,an}, Yu.A. Tikhonov^{120b,120a}, S. Timoshenko¹¹⁰, P. Tipton¹⁸⁰, S. Tisserant⁹⁹, K. Todome¹⁶², S. Todorova-Nova⁵, S. Todt⁴⁶, J. Tojo⁸⁵, S. Tokár^{28a}, K. Tokushuku⁷⁹, E. Tolley¹²², K.G. Tomiwa^{32c}, M. Tomoto¹¹⁵, L. Tompkins^{150,q}, K. Toms¹¹⁶, B. Tong⁵⁷, P. Tornambe⁵⁰, E. Torrence¹²⁷, H. Torres⁴⁶, E. Torró Pastor¹⁴⁵, C. Toscirci¹³¹, J. Toth^{99,ac}, F. Touchard⁹⁹, D.R. Tovey¹⁴⁶, C.J. Treado¹²¹, T. Trefzger¹⁷⁴, F. Tresoldi¹⁵³, A. Tricoli²⁹, I.M. Trigger^{165a}, S. Trincaz-Duvold¹³², M.F. Tripiana¹⁴, W. Trischuk¹⁶⁴, B. Trocmé⁵⁶, A. Trofymov¹²⁸, C. Troncon^{66a}, M. Trovatielli¹⁷³, F. Trovato¹⁵³, L. Truong^{32b}, M. Trzebinski⁸², A. Trzupek⁸², F. Tsai⁴⁴, J.C.-L. Tseng¹³¹, P.V. Tsiarashka¹⁰⁵, A. Tsigotis¹⁵⁹, N. Tsirintanis⁹, V. Tsiskaridze¹⁵², E.G. Tskhadadze^{156a}, I.I. Tsukerman¹⁰⁹, V. Tsulaia¹⁸, S. Tsuno⁷⁹, D. Tsybychev¹⁵², Y. Tu^{61b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tulbure^{27a}, A.N. Tuna⁵⁷, S. Turchikhin⁷⁷, D. Turgeman¹⁷⁷, I. Turk Cakir^{4b,u}, R. Turra^{66a}, P.M. Tuts³⁸, E. Tzovara⁹⁷, G. Ucchielli^{23b,23a}, I. Ueda⁷⁹, M. Ughetto^{43a,43b}, F. Ukegawa¹⁶⁶, G. Unal³⁵, A. Undrus²⁹, G. Unel¹⁶⁸, F.C. Ungaro¹⁰², Y. Unno⁷⁹, K. Uno¹⁶⁰, J. Urban^{28b}, P. Urquijo¹⁰², P. Urrejola⁹⁷, G. Usai⁸, J. Usui⁷⁹, L. Vacavant⁹⁹, V. Vacek¹³⁸, B. Vachon¹⁰¹, K.O.H. Vadla¹³⁰, A. Vaidya⁹², C. Valderanis¹¹², E. Valdes Santurio^{43a,43b}, M. Valente⁵², S. Valentinetti^{23b,23a}, A. Valero¹⁷¹, L. Valéry⁴⁴, R.A. Vallance²¹, A. Vallier⁵, J.A. Valls Ferrer¹⁷¹, T.R. Van Daalen¹⁴, W. Van Den Wollenberg¹¹⁸, H. Van der Graaf¹¹⁸, P. Van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁹, I. Van Vulpen¹¹⁸, M. Vanadia^{71a,71b}, W. Vandelli³⁵, A. Vaniachine¹⁶³, P. Vankov¹¹⁸, R. Vari^{70a}, E.W. Varnes⁷, C. Varni^{53b,53a}, T. Varol⁴¹, D. Varouchas¹²⁸, K.E. Varvell¹⁵⁴, G.A. Vasquez^{144b}, J.G. Vasquez¹⁸⁰, F. Vazeille³⁷, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder¹⁰¹, J. Veatch⁵¹, V. Vecchio^{72a,72b}, L.M. Veloce¹⁶⁴, F. Veloso^{136a,136c}, S. Veneziano^{70a}, A. Ventura^{65a,65b}, M. Venturi¹⁷³, N. Venturi³⁵, V. Vercesi^{68a}, M. Verducci^{72a,72b}, C.M. Vergel Infante⁷⁶, W. Verkerke¹¹⁸, A.T. Vermeulen¹¹⁸, J.C. Vermeulen¹¹⁸, M.C. Vetterli^{149,au}, N. Viaux Maira^{144b}, M. Vicente Barreto Pinto⁵², I. Vichou^{170,*}, T. Vickey¹⁴⁶, O.E. Vickey Boeriu¹⁴⁶, G.H.A. Viehhauser¹³¹, S. Viel¹⁸, L. Viganì¹³¹, M. Villa^{23b,23a}, M. Villaplana Perez^{66a,66b}, E. Vilucchi⁴⁹, M.G. Vinciter³³, V.B. Vinogradov⁷⁷, A. Vishwakarma⁴⁴, C. Vittori^{23b,23a}, I. Vivarelli¹⁵³, S. Vlachos¹⁰, M. Vogel¹⁷⁹, P. Vokac¹³⁸, G. Volpi¹⁴, S.E. von Buddenbrock^{32c}, E. Von Toerne²⁴, V. Vorobel¹³⁹, K. Vorobev¹¹⁰, M. Vos¹⁷¹, J.H. Vosseveld⁸⁸, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹³⁸, M. Vreeswijk¹¹⁸, T. Šfiligoj⁸⁹, R. Vuillermet³⁵, I. Vukotic³⁶, T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁷⁹, J. Wagner-Kuhr¹¹², H. Wahlberg⁸⁶, S. Wahrmond⁴⁶, K. Wakamiya⁸⁰, V.M. Walbrecht¹¹³, J. Walder⁸⁷, R. Walker¹¹², S.D. Walker⁹¹, W. Walkowiak¹⁴⁸, V. Wallangen^{43a,43b}, A.M. Wang⁵⁷, C. Wang^{58b,e}, F. Wang¹⁷⁸, H. Wang¹⁸, H. Wang³, J. Wang¹⁵⁴, J. Wang^{59b}, P. Wang⁴¹, Q. Wang¹²⁴, R.-J. Wang¹³², R. Wang^{58a}, R. Wang⁶, S.M. Wang¹⁵⁵, W.T. Wang^{58a}, W. Wang^{15c,ae}, W.X. Wang^{58a,ae}, Y. Wang^{58a,ak}, Z. Wang^{58c}, C. Wanotayaroj⁴⁴, A. Warburton¹⁰¹, C.P. Ward³¹, D.R. Wardrope⁹², A. Washbrook⁴⁸, P.M. Watkins²¹, A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁵, S. Watts⁹⁸, B.M. Waugh⁹², A.F. Webb¹¹, S. Webb⁹⁷, C. Weber¹⁸⁰, M.S. Weber²⁰, S.A. Weber³³, S.M. Weber^{59a}, A.R. Weidberg¹³¹,

B. Weinert⁶³, J. Weingarten⁴⁵, M. Weirich⁹⁷, C. Weiser⁵⁰, P.S. Wells³⁵, T. Wenaus²⁹, T. Wengler³⁵, S. Wenig³⁵, N. Wermes²⁴, M.D. Werner⁷⁶, P. Werner³⁵, M. Wessels^{59a}, T.D. Weston²⁰, K. Whalen¹²⁷, N.L. Whallon¹⁴⁵, A.M. Wharton⁸⁷, A.S. White¹⁰³, A. White⁸, M.J. White¹, R. White^{144b}, D. Whiteson¹⁶⁸, B.W. Whitmore⁸⁷, F.J. Wickens¹⁴¹, W. Wiedenmann¹⁷⁸, M. Wielers¹⁴¹, C. Wiglesworth³⁹, L.A.M. Wiik-Fuchs⁵⁰, A. Wildauer¹¹³, F. Wilk⁹⁸, H.G. Wilkens³⁵, L.J. Wilkins⁹¹, H.H. Williams¹³³, S. Williams³¹, C. Willis¹⁰⁴, S. Willocq¹⁰⁰, J.A. Wilson²¹, I. Wingerter-Seetz⁵, E. Winkels¹⁵³, F. Winklmeier¹²⁷, O.J. Winston¹⁵³, B.T. Winter²⁴, M. Wittgen¹⁵⁰, M. Wobisch⁹³, A. Wolf⁹⁷, T.M.H. Wolf¹¹⁸, R. Wolff⁹⁹, M.W. Wolter⁸², H. Wolters^{136a,136c}, V.W.S. Wong¹⁷², N.L. Woods¹⁴³, S.D. Worm²¹, B.K. Wosiek⁸², K.W. Woźniak⁸², K. Wraight⁵⁵, M. Wu³⁶, S.L. Wu¹⁷⁸, X. Wu⁵², Y. Wu^{58a}, T.R. Wyatt⁹⁸, B.M. Wynne⁴⁸, S. Xella³⁹, Z. Xi¹⁰³, L. Xia¹⁷⁵, D. Xu^{15a}, H. Xu^{58a,e}, L. Xu²⁹, T. Xu¹⁴², W. Xu¹⁰³, B. Yabsley¹⁵⁴, S. Yacoub^{32a}, K. Yajima¹²⁹, D.P. Yallup⁹², D. Yamaguchi¹⁶², Y. Yamaguchi¹⁶², A. Yamamoto⁷⁹, T. Yamanaka¹⁶⁰, F. Yamane⁸⁰, M. Yamatani¹⁶⁰, T. Yamazaki¹⁶⁰, Y. Yamazaki⁸⁰, Z. Yan²⁵, H.J. Yang^{58c,58d}, H.T. Yang¹⁸, S. Yang⁷⁵, Y. Yang¹⁶⁰, Z. Yang¹⁷, W.-M. Yao¹⁸, Y.C. Yap⁴⁴, Y. Yasu⁷⁹, E. Yatsenko^{58c,58d}, J. Ye⁴¹, S. Ye²⁹, I. Yeletsikh⁷⁷, E. Yigitbasi²⁵, E. Yildirim⁹⁷, K. Yorita¹⁷⁶, K. Yoshihara¹³³, C.J.S. Young³⁵, C. Young¹⁵⁰, J. Yu⁸, J. Yu⁷⁶, X. Yue^{59a}, S.P.Y. Yuen²⁴, B. Zabinski⁸², G. Zacharis¹⁰, E. Zaffaroni⁵², R. Zaidan¹⁴, A.M. Zaitsev^{140,am}, T. Zakareishvili^{156b}, N. Zakharchuk⁴⁴, J. Zalieckas¹⁷, S. Zambito⁵⁷, D. Zanzi³⁵, D.R. Zaripovas⁵⁵, S.V. Zeiřner⁴⁵, C. Zeitnitz¹⁷⁹, G. Zemaityte¹³¹, J.C. Zeng¹⁷⁰, Q. Zeng¹⁵⁰, O. Zenin¹⁴⁰, D. Zerwas¹²⁸, M. Zgubić¹³¹, D.F. Zhang^{58b}, D. Zhang¹⁰³, F. Zhang¹⁷⁸, G. Zhang^{58a}, H. Zhang^{15c}, J. Zhang⁶, L. Zhang^{15c}, L. Zhang^{58a}, M. Zhang¹⁷⁰, P. Zhang^{15c}, R. Zhang^{58a}, R. Zhang²⁴, X. Zhang^{58b}, Y. Zhang^{15d}, Z. Zhang¹²⁸, P. Zhao⁴⁷, X. Zhao⁴¹, Y. Zhao^{58b,128,ai}, Z. Zhao^{58a}, A. Zhemchugov⁷⁷, B. Zhou¹⁰³, C. Zhou¹⁷⁸, L. Zhou⁴¹, M.S. Zhou^{15d}, M. Zhou¹⁵², N. Zhou^{58c}, Y. Zhou⁷, C.G. Zhu^{58b}, H.L. Zhu^{58a}, H. Zhu^{15a}, J. Zhu¹⁰³, Y. Zhu^{58a}, X. Zhuang^{15a}, K. Zhukov¹⁰⁸, V. Zhulanov^{120b,120a}, A. Zibell¹⁷⁴, D. Zieminska⁶³, N.I. Zimine⁷⁷, S. Zimmermann⁵⁰, Z. Zinonos¹¹³, M. Zinser⁹⁷, M. Ziolkowski¹⁴⁸, G. Zobernig¹⁷⁸, A. Zoccoli^{23b,23a}, K. Zoch⁵¹, T.G. Zorbas¹⁴⁶, R. Zou³⁶, M. Zur Nedden¹⁹, L. Zwalinski³⁵

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany, NY, United States of America

³ Department of Physics, University of Alberta, Edmonton, AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America

⁷ Department of Physics, University of Arizona, Tucson, AZ, United States of America

⁸ Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America

⁹ Physics Department, National and Kapodistrian University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Department of Physics, University of Texas at Austin, Austin, TX, United States of America

¹² (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

¹³ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹⁴ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

¹⁵ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing;

¹⁶ University of Chinese Academy of Science (UCAS), Beijing, China

¹⁷ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁸ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁹ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America

²⁰ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

²¹ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

²² School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²³ Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

²⁴ (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (b) INFN Sezione di Bologna, Italy

²⁵ Physikalisches Institut, Universität Bonn, Bonn, Germany

²⁶ Department of Physics, Boston University, Boston, MA, United States of America

²⁷ Department of Physics, Brandeis University, Waltham, MA, United States of America

²⁸ (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara, Romania

²⁹ (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

³⁰ Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America

³¹ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

³² Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³³ (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

³⁴ Department of Physics, Carleton University, Ottawa, ON, Canada

- ³⁴ (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 (CNESTEN), Rabat*; (c) *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech*; (d) *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda*;
- ³⁵ *Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ³⁶ *CERN, Geneva, Switzerland*
- ³⁷ *Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America*
- ³⁸ *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- ³⁹ *Nevis Laboratory, Columbia University, Irvington, NY, United States of America*
- ⁴⁰ *Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ⁴¹ (a) *Dipartimento di Fisica, Università della Calabria, Rende*; (b) *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴² *Physics Department, Southern Methodist University, Dallas, TX, United States of America*
- ⁴³ *Physics Department, University of Texas at Dallas, Richardson, TX, United States of America*
- ⁴⁴ (a) *Department of Physics, Stockholm University*; (b) *Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁵ *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁶ *Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁷ *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁸ *Department of Physics, Duke University, Durham, NC, United States of America*
- ⁴⁹ *SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁰ *INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵¹ *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵² *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵³ *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ⁵⁴ (a) *Dipartimento di Fisica, Università di Genova, Genova*; (b) *INFN Sezione di Genova, Italy*
- ⁵⁵ *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁶ *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁷ *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁸ *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America*
- ⁵⁹ (a) *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei*; (b) *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao*; (c) *School of Physics and Astronomy, Shanghai Jiao Tong University, KLPAC-MoE, SKLPPC, Shanghai*; (d) *Tsung-Dao Lee Institute, Shanghai, China*
- ⁶⁰ (a) *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg*; (b) *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶¹ *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ⁶² (a) *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong*; (b) *Department of Physics, University of Hong Kong, Hong Kong*; (c) *Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶³ *Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁴ *Department of Physics, Indiana University, Bloomington, IN, United States of America*
- ⁶⁵ (a) *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine*; (b) *ICTP, Trieste*; (c) *Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ⁶⁶ (a) *INFN Sezione di Lecce*; (b) *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ⁶⁷ (a) *INFN Sezione di Milano*; (b) *Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁶⁸ (a) *INFN Sezione di Napoli*; (b) *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ⁶⁹ (a) *INFN Sezione di Pavia*; (b) *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ⁷⁰ (a) *INFN Sezione di Pisa*; (b) *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ⁷¹ (a) *INFN Sezione di Roma*; (b) *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ⁷² (a) *INFN Sezione di Roma Tor Vergata*; (b) *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ⁷³ (a) *INFN Sezione di Roma Tre*; (b) *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ⁷⁴ (a) *INFN-TIFPA*; (b) *Università degli Studi di Trento, Trento, Italy*
- ⁷⁵ *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- ⁷⁶ *University of Iowa, Iowa City, IA, United States of America*
- ⁷⁷ *Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America*
- ⁷⁸ *Joint Institute for Nuclear Research, Dubna, Russia*
- ⁷⁹ (a) *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora*; (b) *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro*;
- ⁸⁰ (c) *Universidade Federal de São João del Rei (UFSJ), São João del Rei*; (d) *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ⁸¹ *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ⁸² *Graduate School of Science, Kobe University, Kobe, Japan*
- ⁸³ (a) *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow*; (b) *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁸⁴ *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- ⁸⁵ *Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁸⁶ *Kyoto University of Education, Kyoto, Japan*
- ⁸⁷ *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁸⁸ *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁸⁹ *Physics Department, Lancaster University, Lancaster, United Kingdom*
- ⁹⁰ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁹¹ *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁹² *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁹³ *Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- ⁹⁴ *Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁹⁵ *Louisiana Tech University, Ruston, LA, United States of America*
- ⁹⁶ *Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁷ *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- ⁹⁸ *Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁹⁹ *Institut für Physik, Universität Mainz, Mainz, Germany*
- ¹⁰⁰ *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ¹⁰¹ *CPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ¹⁰² *Department of Physics, University of Massachusetts, Amherst, MA, United States of America*
- ¹⁰³ *Department of Physics, McGill University, Montreal, QC, Canada*
- ¹⁰⁴ *School of Physics, University of Melbourne, Victoria, Australia*
- ¹⁰⁵ *Department of Physics, University of Michigan, Ann Arbor, MI, United States of America*
- ¹⁰⁶ *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America*
- ¹⁰⁷ *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*

- 106 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- 107 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 108 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 109 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 110 National Research Nuclear University MEPhI, Moscow, Russia
- 111 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 112 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 114 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 115 Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
- 116 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- 117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 119 Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- 120 ^(a) Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; ^(b) Novosibirsk State University Novosibirsk, Russia
- 121 Department of Physics, New York University, New York, NY, United States of America
- 122 Ohio State University, Columbus, OH, United States of America
- 123 Faculty of Science, Okayama University, Okayama, Japan
- 124 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- 125 Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- 126 Palacký University, RPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- 127 Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- 128 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 129 Graduate School of Science, Osaka University, Osaka, Japan
- 130 Department of Physics, University of Oslo, Oslo, Norway
- 131 Department of Physics, Oxford University, Oxford, United Kingdom
- 132 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- 133 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- 134 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
- 135 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- 136 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 137 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- 138 Czech Technical University in Prague, Prague, Czech Republic
- 139 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- 140 State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia
- 141 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 142 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 143 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
- 144 ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- 145 Department of Physics, University of Washington, Seattle, WA, United States of America
- 146 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 147 Department of Physics, Shinshu University, Nagano, Japan
- 148 Department Physik, Universität Siegen, Siegen, Germany
- 149 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- 150 SLAC National Accelerator Laboratory, Stanford, CA, United States of America
- 151 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 152 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America
- 153 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 154 School of Physics, University of Sydney, Sydney, Australia
- 155 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 156 ^(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 157 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
- 158 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 159 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 160 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
- 161 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 162 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 163 Tomsk State University, Tomsk, Russia
- 164 Department of Physics, University of Toronto, Toronto, ON, Canada
- 165 ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- 166 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- 167 Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America
- 168 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America
- 169 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 170 Department of Physics, University of Illinois, Urbana, IL, United States of America
- 171 Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain
- 172 Department of Physics, University of British Columbia, Vancouver, BC, Canada
- 173 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- 174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
- 175 Department of Physics, University of Warwick, Coventry, United Kingdom
- 176 Waseda University, Tokyo, Japan
- 177 Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
- 178 Department of Physics, University of Wisconsin, Madison, WI, United States of America
- 179 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- 180 Department of Physics, Yale University, New Haven, CT, United States of America
- 181 Yerevan Physics Institute, Yerevan, Armenia

- ^a Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.
- ^b Also at California State University, East Bay; United States of America.
- ^c Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.
- ^d Also at CERN, Geneva; Switzerland.
- ^e Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ^f Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^g Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ^h Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.
- ⁱ Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
- ^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^k Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
- ^l Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ^m Also at Department of Physics, California State University, Fresno CA; United States of America.
- ⁿ Also at Department of Physics, California State University, Sacramento CA; United States of America.
- ^o Also at Department of Physics, King's College London, London; United Kingdom.
- ^p Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
- ^q Also at Department of Physics, Stanford University; United States of America.
- ^r Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^s Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ^t Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ^u Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
- ^v Also at Graduate School of Science, Osaka University, Osaka; Japan.
- ^w Also at Hellenic Open University, Patras; Greece.
- ^x Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.
- ^y Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ^z Also at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona; Spain.
- ^{aa} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^{ab} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ^{ac} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
- ^{ad} Also at Institute of Particle Physics (IPP); Canada.
- ^{ae} Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ^{af} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{ag} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ah} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
- ^{ai} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
- ^{aj} Also at Louisiana Tech University, Ruston LA; United States of America.
- ^{ak} Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
- ^{al} Also at Manhattan College, New York NY; United States of America.
- ^{am} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{an} Also at National Research Nuclear University MEPhI, Moscow; Russia.
- ^{ao} Also at Near East University, Nicosia, North Cyprus, Mersin; Turkey.
- ^{ap} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ^{aq} Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
- ^{ar} Also at The City College of New York, New York NY; United States of America.
- ^{as} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{at} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{au} Also at TRIUMF, Vancouver BC; Canada.
- ^{av} Also at Università di Napoli Parthenope, Napoli; Italy.
- * Deceased.