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Measurement of the transverse momentum distribution of Z/γ^* bosons in proton–proton collisions at $\sqrt{s}=7$ TeV with the ATLAS detector

Collaborators: Abdelalim Aly, Ahmed Aly; Alexandre, Gauthier; Backes, Moritz; Barone, Gaetano; Bell, Paul; Bell, William; Berglund, Frida Elina; Blondel, Alain; Bucci, Francesca; Clark, Allan Geoffrey; Dao, Valerio; Ferrere, Didier; Gadomski, Szymon **[and 19 more]**

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Measurement of the transverse momentum distribution of Z/γ^* bosons in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector [☆]

ATLAS Collaboration ^{*}

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ABSTRACT

A measurement of the Z/γ^* transverse momentum (p_T^Z) distribution in proton–proton collisions at $\sqrt{s} = 7$ TeV is presented using $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ decays collected with the ATLAS detector in data sets with integrated luminosities of 35 pb^{-1} and 40 pb^{-1} , respectively. The normalized differential cross sections are measured separately for electron and muon decay channels as well as for their combination up to p_T^Z of 350 GeV for invariant dilepton masses $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$. The measurement is compared to predictions of perturbative QCD and various event generators. The prediction of resummed QCD combined with fixed order perturbative QCD is found to be in good agreement with the data.

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1. Introduction

In hadron collisions, the weak vector bosons W and Z are produced with a momentum component transverse to the beam axis, which is balanced by a recoiling hadronic system mainly arising from initial state QCD radiation of quarks and gluons. The measurement of the boson transverse momentum offers a very sensitive way of studying dynamical effects of the strong interaction, complementary to measurements of the associated production of the bosons with jets [1]. The simple signatures of $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ production, which can be identified with little background, enable a precise measurement of the boson transverse momentum (p_T^Z) and thus provide an ideal testing ground for predictions of QCD and phenomenological models. Moreover, the knowledge of the p_T^Z distribution is crucial to improve the modelling of W boson production needed for a precise measurement of the W mass [2,3], in particular in the low p_T^Z region which dominates the cross section.

This Letter presents a measurement of the Z/γ^* normalized transverse momentum distribution in proton–proton collisions at $\sqrt{s} = 7$ TeV using $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ decays collected in 2010 with the ATLAS detector in data sets with integrated luminosities of 35 pb^{-1} and 40 pb^{-1} , respectively. In the normalized transverse momentum distribution, many systematic uncertainties cancel. In particular, the precision of the measurement

is not impaired by the uncertainty on the integrated luminosity. The normalized transverse momentum distribution is defined in the following way: $1/\sigma^{\text{fid}} \times d\sigma^{\text{fid}}/dp_T^Z$, where σ^{fid} is the measured inclusive cross section of $pp \rightarrow Z/\gamma^* + X$ multiplied by the branching ratio of $Z/\gamma^* \rightarrow \ell^+\ell^-$ within the fiducial acceptance, and X denotes the underlying event and the recoil system. For both the ee and $\mu\mu$ channels, the fiducial acceptance is defined by the lepton transverse momentum and pseudorapidity,¹ and by the invariant mass of the lepton pair $m_{\ell\ell}$: $p_T^\ell > 20 \text{ GeV}$, $|\eta^\ell| < 2.4$ and $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$. The measurements in both decay channels are corrected for detector effects and QED final state radiation (FSR). The combined result is compared to predictions of perturbative QCD calculations and QCD-inspired models implemented in various event generators.

Predictions and previous measurements are discussed in Section 2. The ATLAS detector and trigger are described in Section 3. In Sections 4 and 5 the event simulation and selections are described. Section 6 reports the p_T^Z measurements for different treatments of QED final state radiation. Systematic uncertainties are discussed in Section 7. Section 8 presents the combined result which is compared with various models.

¹ The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive x -axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y -axis pointing upwards. The azimuthal angle φ is measured around the beam axis and the polar angle θ is the angle from the z -axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$.

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

2. QCD predictions and previous measurements

Perturbative QCD (pQCD) calculations have been performed up to $\mathcal{O}(\alpha_s^2)$ in the strong coupling constant α_s [4,5] and are expected to be reliable at large p_T^Z . In this kinematic regime, the cross section is dominated by the radiation of a single parton. Fully differential inclusive boson production cross sections can be obtained at $\mathcal{O}(\alpha_s^2)$ with FEWZ [6,7] and DYNLLO [8]. While the integrated $\mathcal{O}(\alpha_s^2)$ cross section predictions are finite, the fixed order pQCD prediction diverges at vanishing p_T^Z . In this regime, the leading contribution of multiple soft gluon emissions to the inclusive cross section can be resummed to all orders [9–11] up to next-to-next-to-leading logarithms (NNLL) [12] in α_s . The RESBOS generator [13] matches the prediction of soft gluon resummation including a non-perturbative form factor [14] at low p_T^Z with the fixed order pQCD calculation at $\mathcal{O}(\alpha_s)$ at high p_T^Z , which is corrected to $\mathcal{O}(\alpha_s^2)$ using K -factors.

Similar to resummed calculations, parton showers provide an all-order approximation of parton radiation in the soft and collinear region. In order to describe the large p_T^Z region, the parton shower based leading-order event generators PYTHIA [15] and HERWIG [16] apply weights to the first or hardest branching, respectively, to effectively merge the $\mathcal{O}(\alpha_s^0)$ and $\mathcal{O}(\alpha_s)$ pQCD predictions. The next-to-leading order (NLO) Monte Carlo generators MC@NLO [17] and POWHEG [18] incorporate NLO QCD matrix elements consistently into the parton shower frameworks of HERWIG or PYTHIA.

The ALPGEN [19] and SHERPA [20] event generators implement tree-level matrix elements for the generation of multiple hard partons in association with the weak boson. The matrix-element calculations for various parton multiplicities are matched with parton showers (which in the case of ALPGEN are provided by either PYTHIA or HERWIG) such that double counting is explicitly avoided by means of weighting procedures [21] or veto algorithms [19].

As the predictions of these generators differ significantly and show a considerable dependence on adjustable internal parameters [22], a precise measurement of the boson transverse momentum distribution is an important input to validate and tune these models.

The Z/γ^* boson p_T distribution has been measured in proton–antiproton collisions at the Tevatron collider at centre of mass energies of $\sqrt{s} = 1.8$ TeV and 1.96 TeV [23–27]. For $p_T^Z \lesssim 30$ GeV, these measurements found a good agreement with RESBOS and disfavoured models [28] suggesting a broadening of the p_T^Z distribution for small x values [25,27], where x is the fraction of the momentum of one of the two partons with respect to the proton momentum. At large p_T^Z , the $\mathcal{O}(\alpha_s^2)$ pQCD prediction was reported to underestimate the measured cross section by up to about 25% [25,26].

3. The ATLAS detector

The ATLAS detector system [29] comprises an inner tracking detector immersed in a 2 T axial magnetic field, a calorimeter, and a large muon spectrometer with a superconducting toroid magnet system. Charged particle tracks and vertices are reconstructed with silicon pixel and strip detectors covering $|\eta| < 2.5$ and transition radiation detectors covering $|\eta| < 2.0$. These tracking detectors are surrounded by a finely segmented calorimeter system which provides three-dimensional reconstruction of particle showers up to $|\eta| < 4.9$. The electromagnetic compartment uses liquid argon as the active material and is divided into barrel ($|\eta| < 1.5$), end-cap ($1.4 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) components. The hadron calorimeter is based on scintillating tiles in the central re-

gion ($|\eta| < 1.7$). It is extended up to 4.9 in pseudorapidity by end-caps and forward calorimeters which use liquid argon. The muon spectrometer is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, covering a range of $|\eta| < 2.7$ and providing an integral magnetic field varying from about 1 to 8 T m. Three stations of drift tubes and cathode strip chambers enable precise muon track measurements, and resistive-plate and thin-gap chambers provide muon triggering capability and additional measurements of the φ coordinate.

The ATLAS detector has a three-level trigger system which reduces the event rate to approximately 200 Hz before data transfer to mass storage. The triggers employed require the presence of a single electron or muon candidate with $p_T > 15$ GeV or $p_T > 13$ GeV, respectively. Lower thresholds were used for the early data. The trigger efficiencies are defined for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ events as the fraction of triggered electrons or muons with respect to the reconstructed lepton and are studied as a function of their p_T and η . For muons, the efficiencies are also obtained separately in φ regions which match the geometry of the trigger chambers. The efficiency for single leptons is derived from data using $Z/\gamma^* \rightarrow \ell^+\ell^-$ candidate events or using independent triggers by matching reconstructed lepton candidates to trigger signals in the calorimeter (muon spectrometer) in case of the ee ($\mu\mu$) decay channel. For $p_T^\ell > 20$ GeV, the efficiency is 99% for electrons and 77% (93%) for muons in the barrel (end-cap). For signatures with two high- E_T electrons, the trigger is fully efficient. The trigger efficiency for $Z/\gamma^* \rightarrow \mu^+\mu^-$ events is determined to be on average 97.7% and to be constant as a function of p_T^Z within an uncertainty of 0.1–0.7% depending on p_T^Z .

4. Event simulation

The properties, including signal efficiencies and acceptances, of $Z/\gamma^* \rightarrow e^+e^-$, $Z/\gamma^* \rightarrow \mu^+\mu^-$ and background processes are modelled with PYTHIA [15] using the MRST2007LO* [30] parton distribution functions (PDF), MC@NLO [17] and POWHEG using CTEQ6.6 [31] PDFs. MC@NLO uses HERWIG for the parton shower and JIMMY [32] for the underlying event. POWHEG is interfaced to PYTHIA for the underlying event and the parton shower. The event generators are interfaced to PHOTOS [33] to simulate QED FSR. Version 6.4 of PYTHIA is used with the p_T -ordered parton shower and with parameters describing the properties of the underlying event which were tuned to Tevatron measurements [34]. For systematic studies and comparisons, a MC@NLO based signal sample is used with underlying event parameters (JIMMY) tuned to Tevatron and 7 TeV ATLAS pp collision data [35]. The response of the ATLAS detector to the generated particles is modelled using GEANT4 [36], and the fully simulated events [37] are passed through the same reconstruction chain as the data. The Monte Carlo simulation (MC) is corrected for differences with respect to the data in the lepton reconstruction and identification efficiencies as well as in energy (momentum) scale and resolution. The efficiencies are determined from a tag-and-probe method based on reconstructed Z and W events [38,39], while the resolution and scale corrections are obtained from a fit to the observed Z boson line shape. The lepton identification efficiencies can depend on the hadronic activity, which is correlated with the Z/γ^* transverse momentum. Therefore, using the tag-and-probe method, it is verified that the p_T^Z dependence of the single lepton efficiency is correctly modelled after efficiency corrections. Differences between data and simulation are mostly consistent with statistical fluctuations and are considered as systematic uncertainties due to the modelling of the efficiencies as described in Section 7.

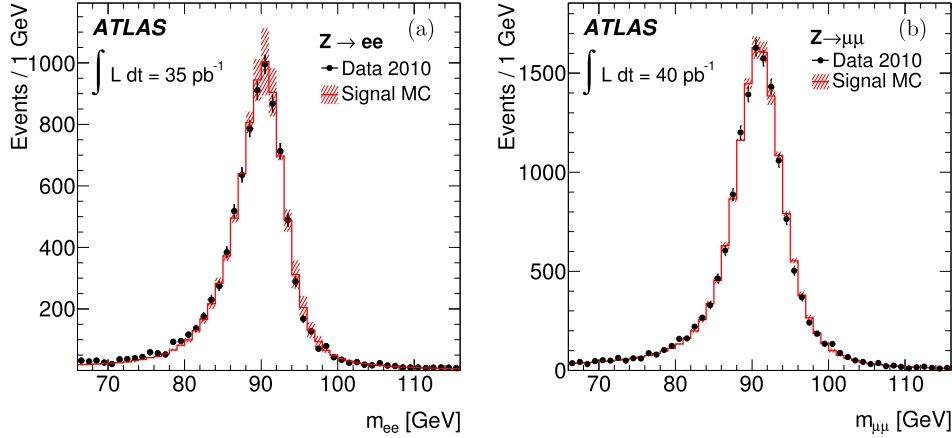


Fig. 1. The observed (a) dielectron and (b) dimuon invariant mass distributions compared to simulation. The shaded bands indicate the systematic uncertainty on the MC prediction due to the lepton momentum resolution correction. The PYTHIA sample, which is normalized to the next-to-next-to-leading order (NNLO) prediction [40,6,7], is used for signal events. The total background, which is invisible on this scale, amounts to only 1.5% and 0.4% in the ee and $\mu\mu$ decay channels, respectively.

Multiple pp interactions per bunch crossing (*pileup*) are accounted for by overlaying simulated minimum bias events. To match the observed instantaneous luminosity profile, the MC events are reweighted to yield the same distribution of the number of primary vertices as measured in the data.

In the following, if not stated otherwise, the generated samples are fully simulated, *pileup* and resolution corrected, and interfaced to PHOTOS, with PYTHIA as the default MC signal sample. The background samples are produced with PYTHIA for $W \rightarrow \ell\nu$, with MC@NLO and POWHEG for $t\bar{t}$, and with PYTHIA and MC@NLO for $Z/\gamma^* \rightarrow \tau^+\tau^-$.

5. Event selection

The analysis uses data taken during stable beam conditions with properly operating inner detector, magnets, and calorimeter or muon spectrometer, in case of the ee or $\mu\mu$ channel, respectively. Events are required to have at least one primary vertex reconstructed from at least three tracks. Z/γ^* events are selected by requiring two oppositely charged electrons or muons, defined below, with an invariant mass $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$.

Electrons are reconstructed from the energy deposits in the calorimeter matched to inner detector tracks. They are required to have a transverse energy $E_T^e > 20 \text{ GeV}$ and pseudorapidity $|\eta^e| < 2.4$, excluding the transition regions between the barrel and end-cap calorimeter components at $1.37 < |\eta^e| < 1.52$. They should pass *medium* identification criteria based on shower shape and track quality variables [38] to provide rejection against hadrons. The single electron selection efficiency varies in the range 90–96% depending on pseudorapidity and azimuthal angle.

Muons are reconstructed from matching tracks in the inner detector and muon spectrometer with $p_T^\mu > 20 \text{ GeV}$ and $|\eta^\mu| < 2.4$ measured using the information from these two detector sub-components. To ensure the compatibility of the muon track with the primary vertex, the corresponding impact parameters in the transverse and longitudinal direction with respect to the beam axis have to be smaller than 1 mm and 5 mm, respectively. The muon candidates are required to be isolated to suppress background from heavy flavour production using the transverse momentum sum of tracks with $p_T > 1 \text{ GeV}$ within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the muon track. This sum has to be smaller than $0.2 \times p_T^\mu$. The single muon selection efficiency is of the order of 87–95% depending on pseudorapidity and azimuthal angle.

After this selection, 8923 $Z/\gamma^* \rightarrow e^+e^-$ and 15060 $Z/\gamma^* \rightarrow \mu^+\mu^-$ candidate events are found in the data. The main reasons for the difference in the number of candidate events in the ee and $\mu\mu$ decay channels are: the integrated luminosity for which all relevant detector components were operating properly; regions in the electromagnetic calorimeter with readout problems; a reduced acceptance for electrons in the transition region between the barrel and end-cap calorimeter. Fig. 1 demonstrates the agreement of the data and the simulation in the dilepton mass spectrum for the selected events including the background, after applying the corrections described in Section 4.

The background contribution from $Z/\gamma^* \rightarrow \tau^+\tau^-$, W boson, and $t\bar{t}$ production is estimated as a function of p_T^Z using simulation, where the cross sections are normalized to next-to-next-to-leading order (NNLO) predictions for Z/γ^* and W and NLL–NLO predictions for $t\bar{t}$ production. The procedure outlined in Ref. [38] is followed here.

For both ee and $\mu\mu$ channels, the main background at high p_T^Z arises from $t\bar{t}$ production. At low p_T^Z the background is dominated by QCD multijet production, where a jet is falsely identified as a primary e or μ . Its contribution is determined from the data as follows.

In the ee channel, the normalization of the multijet contribution is derived from a fit of signal and background templates to the observed dilepton invariant mass distribution with loosened identification requirements for one of the two reconstructed electron candidates. An extended mass range of $50 \text{ GeV} < m_{ee} < 130 \text{ GeV}$ is used which provides a better background constraint in the off-resonance region. The normalization derived from this loosened selection has to be scaled to the Z/γ^* event selection, which requires two reconstructed electron candidates of medium quality. The scaling factor is determined from a QCD multijet enhanced control sample with single electron candidates which fulfil the loosened electron identification requirements. The contamination with other events, in particular the contribution from W production, is suppressed by rejecting events with large missing transverse energy. The remaining contamination is determined using simulated events. The systematic uncertainty of the normalization is determined by varying the background templates and the criteria for the loosened selection. The shape of the multijet background as a function of p_T^Z is determined from a dielectron sample with an invariant mass $66 \text{ GeV} < m_{ee} < 116 \text{ GeV}$ for which exactly one electron passes and one fails the medium identification criteria. The difference between same and opposite sign events is taken as the shape uncertainty.

Table 1
The measured normalized differential cross section $1/\sigma^{\text{fid}} d\sigma^{\text{fid}}/dp_T^Z$ in bins of p_T^Z for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ production. The cross sections, which are to be multiplied by the factor k , are reported with respect to three different treatments of QED final state radiation for the definition of lepton and Z/γ^* momentum at particle level: corresponding to the Z/γ^* propagator (propag.), to dressed leptons (with recombined radiated photons within a cone of $\Delta R = 0.1$), and to bare leptons, respectively. The relative statistical (stat.) and total systematic (syst.) uncertainties are given. The data can be obtained electronically through the HepData repository [43].

p_T^Z bin (GeV)	$1/\sigma^{\text{fid}} d\sigma^{\text{fid}}/dp_T^Z$ (GeV ⁻¹) $Z/\gamma^* \rightarrow e^+e^-$					$Z/\gamma^* \rightarrow \mu^+\mu^-$						
				uncert. (%)					uncert. (%)			
	propag.	dressed	bare	k	stat.	syst.	propag.	dressed	bare	k	stat.	syst.
0–3	3.48	3.40	3.21	$\cdot 10^{-2}$	3.3	4.7	3.75	3.66	3.58	$\cdot 10^{-2}$	2.6	5.0
3–6	5.85	5.78	5.60	$\cdot 10^{-2}$	2.4	3.3	5.81	5.74	5.68	$\cdot 10^{-2}$	2.0	4.0
6–9	4.61	4.62	4.64	$\cdot 10^{-2}$	2.7	2.3	4.67	4.68	4.69	$\cdot 10^{-2}$	2.1	1.6
9–12	3.43	3.46	3.56	$\cdot 10^{-2}$	3.1	2.4	3.50	3.54	3.58	$\cdot 10^{-2}$	2.4	1.6
12–15	2.93	2.97	3.09	$\cdot 10^{-2}$	3.3	2.7	2.67	2.72	2.76	$\cdot 10^{-2}$	2.8	1.7
15–18	2.04	2.08	2.16	$\cdot 10^{-2}$	3.9	3.0	2.13	2.17	2.20	$\cdot 10^{-2}$	3.1	1.7
18–21	1.64	1.67	1.73	$\cdot 10^{-2}$	4.4	3.3	1.69	1.72	1.74	$\cdot 10^{-2}$	3.5	1.8
21–24	1.32	1.33	1.37	$\cdot 10^{-2}$	4.8	3.6	1.35	1.36	1.37	$\cdot 10^{-2}$	4.0	1.8
24–27	1.08	1.08	1.11	$\cdot 10^{-2}$	5.5	3.8	1.15	1.16	1.17	$\cdot 10^{-2}$	4.3	1.9
27–30	1.02	1.03	1.03	$\cdot 10^{-2}$	6.5	4.0	0.87	0.88	0.88	$\cdot 10^{-2}$	5.0	2.0
30–36	7.22	7.24	7.26	$\cdot 10^{-3}$	4.8	4.2	6.45	6.46	6.45	$\cdot 10^{-3}$	4.1	2.1
36–42	4.89	4.88	4.85	$\cdot 10^{-3}$	5.8	4.5	4.63	4.63	4.62	$\cdot 10^{-3}$	4.9	2.2
42–48	3.66	3.64	3.59	$\cdot 10^{-3}$	7.0	4.8	3.97	3.95	3.94	$\cdot 10^{-3}$	5.3	2.4
48–54	3.26	3.25	3.20	$\cdot 10^{-3}$	7.8	5.0	2.90	2.88	2.86	$\cdot 10^{-3}$	6.2	2.6
54–60	2.14	2.13	2.08	$\cdot 10^{-3}$	9.2	5.4	2.14	2.13	2.11	$\cdot 10^{-3}$	7.2	2.7
60–80	1.21	1.20	1.17	$\cdot 10^{-3}$	6.5	5.7	1.31	1.30	1.28	$\cdot 10^{-3}$	5.1	3.0
80–100	5.69	5.63	5.44	$\cdot 10^{-4}$	9.8	5.9	5.52	5.47	5.40	$\cdot 10^{-4}$	7.8	3.5
100–180	1.74	1.73	1.67	$\cdot 10^{-4}$	9.6	6.1	1.52	1.51	1.49	$\cdot 10^{-4}$	7.5	4.4
180–350	0.78	0.77	0.73	$\cdot 10^{-5}$	27.0	7.8	1.14	1.14	1.11	$\cdot 10^{-5}$	18.9	6.6

For the $\mu\mu$ selection, the multijet contribution is estimated from four two-dimensional regions which are obtained by changing the mass window to $40 \text{ GeV} < m_{\mu\mu} < 60 \text{ GeV}$ or by inverting the isolation criterion. The normalization is determined from the number of candidate events in these four regions which is corrected by the expected number of non-QCD multijet background events and number of signal events. The number of signal events is determined from the measurement in the signal region which is corrected for the background including the multijet background, and extrapolated to the other regions using relative efficiencies extracted from the simulation. The resulting equation can be solved for the number of QCD multijet background events. The shape is determined from the control region where both muon candidates are non-isolated and their invariant mass is within $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$. Systematic uncertainties are determined by comparing the results to those of alternative methods which use template fits or same sign and opposite sign events.

The total background contribution, which amounts to $(1.5 \pm 0.6)\%$ and $(0.4 \pm 0.2)\%$ in the ee and $\mu\mu$ channels, respectively, is found to increase from 0.5% (0.2%) to 3.5% (1.5%) as a function of p_T^Z in the ee ($\mu\mu$) analysis.

6. The measured p_T^Z distribution

The Z/γ^* transverse momentum is reconstructed from the measured lepton momenta. The p_T^Z range is divided into 19 bins from 0 GeV to 350 GeV with widths of 3 GeV for $p_T^Z < 30 \text{ GeV}$ and increasing widths at larger transverse momenta as given in Table 1. For this binning, the fraction of simulated events reconstructed in a particular p_T^Z bin which have generator-level p_T^Z in the same bin is always better than 60% and reaches values above 90% in the highest p_T^Z bins for both decay channels. The bin-by-bin efficiency, defined as the ratio between the number of signal events which pass the final selection and the total number of generated events within the fiducial region, are on average about 56% in the ee and 83% in the $\mu\mu$ channel, respectively. Three Z/γ^* candidate events with $p_T^Z > 350 \text{ GeV}$ are found, which are not considered further due to the limited statistical significance.

The observed p_T^Z spectrum is found to be well described by the simulation, using the default MC signal samples and background estimations as described in Sections 4 and 5. A bin-by-bin efficiency correction is used to correct (unfold) the observed data for detector effects and QED FSR, where the correction factors are determined from the default MC signal sample. Alternative matrix unfolding methods [41,42], which explicitly take the bin-to-bin migration into account, yield compatible results. However, these techniques require higher data statistics to fully exploit their advantages. Therefore they are currently used only to estimate the systematic uncertainties due to the unfolding method as discussed in Section 7.

In Table 1, the cross section measurements in the ee and $\mu\mu$ decay channels are reported in the fiducial volume, which is defined by the lepton acceptance $p_T^\ell > 20 \text{ GeV}$ and $|\eta^\ell| < 2.4$, and the invariant mass of the lepton pair $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$. This implies for the ee decay channel a small acceptance correction due to the discarded events, in which one or more electrons are within the calorimeter transition region, $1.37 < |\eta^e| < 1.52$. The resulting correction of the normalized differential cross section is smaller than 0.6%. The measurement is reported with respect to three distinct reference points at particle level regarding QED FSR corrections. The true dilepton mass $m_{\ell\ell}$ and transverse momentum p_T^Z are either defined by the final state leptons after QED FSR (“bare” leptons), or by recombining them with radiated photons within a cone of $\Delta R = 0.1$ (“dressed” leptons), or by the Z/γ^* propagator. The propagator definition corresponds to a full correction for QED FSR effects, allows for a combination of the electron and muon channels, and facilitates a direct comparison of the measurement with QCD calculations. The QED FSR corrections are at most 8% (5%) for the normalized differential cross section in the ee ($\mu\mu$) decay channel.

7. Systematic uncertainties

Systematic uncertainties arise mainly from lepton efficiencies, momentum scale and resolution, and from the unfolding procedure. They are evaluated by varying separately each parameter in question and recalculating the bin-by-bin correction factors used to

unfold the p_T^Z spectrum. The observed deviation in the unfolded distributions is limited by the statistics of the simulated events. The statistical component of these deviations is estimated using a bootstrap method [44] based on multiple resampling of the simulated events. Each sample has the same size and may contain the same events multiple times. Symmetric systematic uncertainties are derived in such a way [45] that the area spanned by these uncertainties covers 68% of the integral over a Gaussian with mean and width equal to the mean and standard deviation of the bootstrap distributions. The resulting uncertainties are equal to the standard deviation if the bootstrap distribution is centred at zero, and approach the mean plus half the standard deviation if the mean deviates from zero.

The following sources of systematic uncertainties on the measured normalized differential cross section are evaluated, where the quoted uncertainties are relative percentages.

Lepton reconstruction and identification: The efficiencies are determined as a function of p_T^Z using a tag-and-probe method. Due to the limited statistics at high p_T^Z , the uncertainties are parametrized by a function which increases with p_T^Z . For the ee analysis, the uncertainty due to the electron reconstruction and identification varies between 1.0% and 3.2%. An additional uncertainty of 0.1% arises from the modelling of local calorimeter read-out problems. In the case of the $\mu\mu$ selection, the uncertainties due to the efficiencies on the trigger, on the muon reconstruction and identification, and on the isolation requirement are evaluated separately and are found to be within 0.4%, 2.3%, and 1.0%, respectively, except for the three highest p_T^Z bins, where they reach 0.8%, 4.9%, and 2.7%.

Lepton energy (momentum) scale and resolution: The scale and resolution corrections of the simulation are varied within their uncertainties estimated from the fit to the observed Z/γ^* line shape. Correlations across p_T^Z bins are taken into account. Due to the normalization to the inclusive cross section, a systematic shift at low p_T^Z is balanced by a shift in the opposite direction at high p_T^Z . In the ee ($\mu\mu$) analysis, the uncertainty due to scale variations is found to be 2.7% (0.2%) for the lowest bin, decreasing down to 0.2% (< 0.1%) at $p_T^Z \sim 10$ GeV, and then increasing up to 4.4% (0.4%) at the highest p_T^Z values. Uncertainties due to resolution are estimated to be 0.5% for the ee channel and between 0.1% and 0.7% for the $\mu\mu$ channel.

Unfolding procedure: The bin-by-bin correction factors depend on the shape of the assumed underlying p_T^Z distribution, which leads to a systematic uncertainty evaluated in the following way. The default MC signal sample (PYTHIA) is reweighted to different true p_T^Z shapes using RESBOS and Mc@NLO. The variance of these generator predictions does not entirely cover the observed difference between simulation and data. Therefore the PYTHIA signal sample is reweighted, in addition, to distributions based on unfolded data. The spectra obtained by unfolding the data either with the bin-by-bin method or alternative matrix unfolding techniques [41,42] are considered. These new corrected spectra feature different uncertainties. The bin-by-bin method suffers a larger systematic uncertainty due to the assumed true p_T^Z shape, whereas matrix-based unfolding is nearly independent of this assumption, but suffers from a larger statistical uncertainty. Each of the reweighted spectra is treated in the same way as the data, and is unfolded with the default bin-by-bin correction factors. The maximum deviation from the respective true p_T^Z spectrum is considered as a systematic uncertainty. A possible influence from the parton shower and hadronization model is estimated by comparing the bin-by-bin correction factors determined from either the default PYTHIA sample or the Mc@NLO sample. Mc@NLO uses HERWIG for the parton shower and JIMMY for the underlying event. To separate these model uncertainties from the uncertainty due

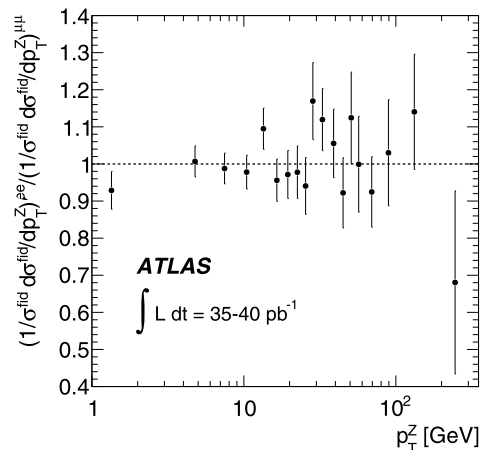


Fig. 2. Ratio of the normalized differential cross section for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ production as a function of p_T^Z at Z/γ^* propagator level using an integrated luminosity of 35 pb^{-1} and 40 pb^{-1} , respectively. The error bars shown include statistical and systematic uncertainties. The systematic uncertainties due to the unfolding procedure and QED FSR, which are correlated between the electron and muon decay channel, are omitted.

to the underlying p_T^Z distribution, which is already accounted for, the Mc@NLO sample is reweighted to the p_T^Z shape of the default MC signal sample. The uncertainties due to the shape of the p_T^Z distribution and due to the modelling of the parton shower and the hadronization are combined to yield the total unfolding uncertainty, which is found to be within 2.0% (1.3%) in the ee ($\mu\mu$) channel for p_T^Z between 6 GeV and 100 GeV. For $p_T^Z < 6$ GeV the uncertainty is as large as 3.6% (4.7%) and for $p_T^Z > 100$ GeV it is as large as 4.2% (2.9%) in the ee ($\mu\mu$) channel. The unfolding uncertainty is dominated by the deviations observed when reweighting the default MC signal sample to the p_T^Z distributions obtained from the data with the matrix unfolding techniques.

Background contamination: Uncertainties in the estimation of the background from QCD multijet, weak boson, and $t\bar{t}$ production yield values of up to 1.4% (0.6%) for the ee ($\mu\mu$) analysis when propagated to the normalized differential cross section.

Modelling of pileup corrections: Pileup has a small influence on this measurement. An uncertainty of 0.3% on the normalized differential cross section is derived.

MC sample statistics: The uncertainties are within 0.4%–1.5% (0.3%–0.8%) in the ee ($\mu\mu$) channel, except for highest p_T^Z values for which the uncertainties reach 3.6% (1.6%).

QED final state radiation: A conservative systematic uncertainty of 0.6% due to the p_T^Z -dependent modelling of QED FSR is assigned. This uncertainty addresses both potential differences between the approximation used in PHOTOS compared to exact second order QED FSR matrix element calculations [46,47] and uncertainties in the simulation of the interaction of the radiated photons with the detector material [38].

The systematic uncertainties listed above are added quadratically to obtain the total systematic uncertainties listed in Table 1.

8. Results and conclusions

The normalized differential cross section measurements for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ production are in good agreement with each other at the Z/γ^* propagator level; see Fig. 2 for the ratio of the measured cross sections. The two decay channels are combined at Z/γ^* propagator level using a χ^2 minimization method which takes into account the correlated systematic uncertainties for the ee and $\mu\mu$ channels [48]. The uncertain-

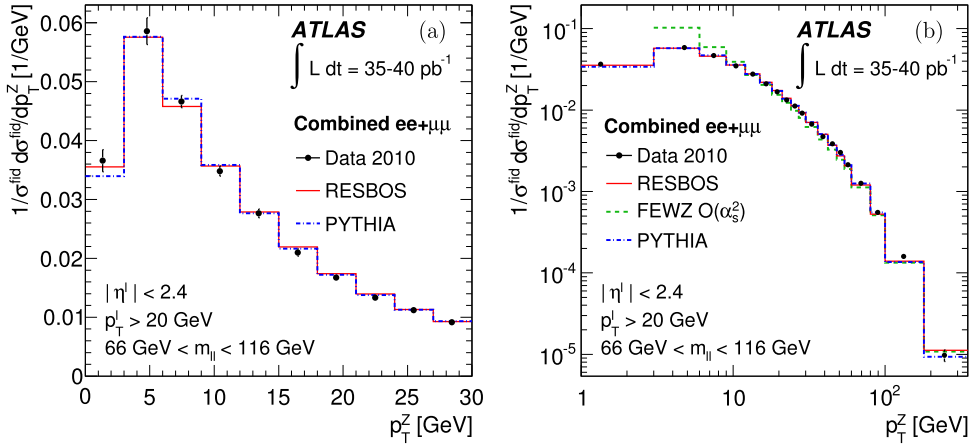


Fig. 3. The combined normalized differential cross section at Z/γ^* propagator level as a function of p_T^Z for (a) the range $p_T^Z < 30$ GeV and (b) the full range compared to the predictions of RESBOS, PYTHIA, and FEWZ at $\mathcal{O}(\alpha_s^2)$. The error bars shown include statistical and systematic uncertainties. For the combination, the ee ($\mu\mu$) channel contributes with an integrated luminosity of 35 pb^{-1} (40 pb^{-1}). At low p_T^Z the FEWZ prediction diverges and is omitted.

Table 2

The combined normalized differential cross section at Z/γ^* propagator level, $1/\sigma^{\text{fid}} d\sigma^{\text{fid}}/dp_T^Z$, as a function of the average Z/γ^* transverse momentum (p_T^Z) with relative statistical and total systematic uncertainties. The multiplication with the inverse acceptance correction A_c^{-1} (given with uncertainties, “unc.”) yields the normalized differential cross section $1/\sigma^{\text{tot}} d\sigma^{\text{tot}}/dp_T^Z$ extrapolated to the full lepton acceptance. The data can be obtained electronically through the HepData repository [43].

$\langle p_T^Z \rangle$ (GeV)	$\frac{1}{\sigma^{\text{fid}}} \frac{d\sigma^{\text{fid}}}{dp_T^Z}$ (GeV^{-1})	stat. (%)	syst. (%)	A_c^{-1}	unc. (%)
1.3	0.0366	2.0	4.7	1.047	3.7
4.8	0.0586	1.5	3.6	1.029	1.8
7.5	0.0466	1.7	1.5	1.014	1.5
10	0.0348	1.9	1.6	0.999	1.5
13	0.0277	2.2	1.7	0.999	1.4
16	0.0210	2.5	1.7	0.990	1.5
19	0.0167	2.8	1.8	0.989	1.5
22	0.0133	3.1	1.9	0.990	1.5
25	0.0112	3.4	2.0	0.994	2.3
28	0.0092	4.0	2.1	0.988	2.3
33	0.0067	3.2	2.1	0.987	3.2
39	0.0047	3.8	2.3	0.979	3.9
45	0.0038	4.2	2.4	0.965	4.3
51	0.0030	4.9	2.5	0.950	4.4
57	0.0021	5.7	2.7	0.938	5.3
69	0.0013	4.0	2.8	0.910	5.3
89	$5.5 \cdot 10^{-4}$	6.1	3.1	0.894	5.3
132	$1.6 \cdot 10^{-4}$	5.9	3.7	0.826	5.4
245	$9.8 \cdot 10^{-6}$	15.6	5.4	0.672	5.6

ties due to the unfolding procedure and QED FSR are considered to be common for the two channels. The minimization yields a $\chi^2/\text{d.o.f.} = 17.0/19$ indicating the excellent compatibility of the electron and muon data.

The combined measurement of the normalized differential cross section within the fiducial lepton acceptance as a function of p_T^Z , $1/\sigma^{\text{fid}} d\sigma^{\text{fid}}/dp_T^Z$, is shown in Fig. 3 and Table 2. In addition, the acceptance corrections A_c needed to extrapolate the measurement to full lepton acceptance, but keeping the mass range $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$, are reported. They are determined using PYTHIA and the MRST2007LO* PDF set. The acceptance for the inclusive fiducial cross section is 0.48. However, the acceptance corrections A_c for the normalized differential cross section are within 10% of 1.0 for the bins with $p_T^Z < 80 \text{ GeV}$. The uncertainty on A_c is estimated by: reweighting the PYTHIA prediction using the HERAPDF1.0 [49] and CTEQ6.6 [31] parton distribution functions; propagating

the CTEQ6.6 PDF error eigenvector sets; and by taking into account the difference to the predictions obtained with MC@NLO, RESBOS, and FEWZ.

In Fig. 4, the measurement within the fiducial acceptance is compared with predictions of pQCD calculations and of various event generators introduced above. The $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ pQCD predictions of the p_T^Z dependent cross section are obtained with FEWZ v2.0 [7] and the MSTW2008 PDF sets [50]. The inclusive cross section, which is used to normalize the prediction, is calculated in the same way. The uncertainties on the normalized predictions are evaluated by variation of the renormalization and factorization scales by factors of two around the nominal scale $\mu_R = \mu_F = M_Z$ with the constraint $0.5 \leq \mu_R/\mu_F \leq 2$, by variation of α_s within a range corresponding to 90% confidence level limits [51], and by using the PDF error eigenvector sets at 90% confidence level. They amount to $\sim 10\%$ and $\sim 8\%$ for the $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ prediction, respectively, with a dominant contribution of 9% and 6.5% from the scale variations. In contrast to the Z/γ^* inclusive cross section, the prediction of the p_T^Z distribution suffers from substantial scale uncertainties indicating non-negligible missing higher order corrections. For $p_T^Z > 18 \text{ GeV}$, the pQCD prediction receives an $\mathcal{O}(\alpha_s^2)$ correction of 26–36%. Despite this correction, the $\mathcal{O}(\alpha_s^2)$ prediction undershoots the data by about 10%, which is comparable to the size of the scale uncertainty. This deficit is smaller compared to the 15–25% difference observed at the Tevatron [25,26]. At low boson transverse momenta, where fixed order pQCD calculations are not expected to give an adequate description of the cross section, the disagreement increases rapidly towards vanishing p_T^Z .

In addition, the measurement is compared to the predictions of RESBOS and various event generators. The consistency with the data is verified with a χ^2 test which uses the χ^2 definition also used for the combination of the ee and $\mu\mu$ decay channels.

The RESBOS [13] prediction, which combines resummed and fixed order pQCD calculations, is based on the CTEQ6.6 [31] PDF set and a resummation scale of m_Z . It is verified that the different PDF sets used for the FEWZ and RESBOS predictions lead to differences below 3%. RESBOS shows good agreement with the measurement over the entire p_T^Z range ($\chi^2/\text{d.o.f.} = 21.7/19$), indicating the importance of resummation even at relatively large p_T^Z . However, its predictions are slightly higher than the data for p_T^Z values in the range of 10 GeV to 40 GeV and slightly lower above 40 GeV.

The ALPGEN [19] and SHERPA [20] generators consider processes with up to five additional hard partons associated with the pro-

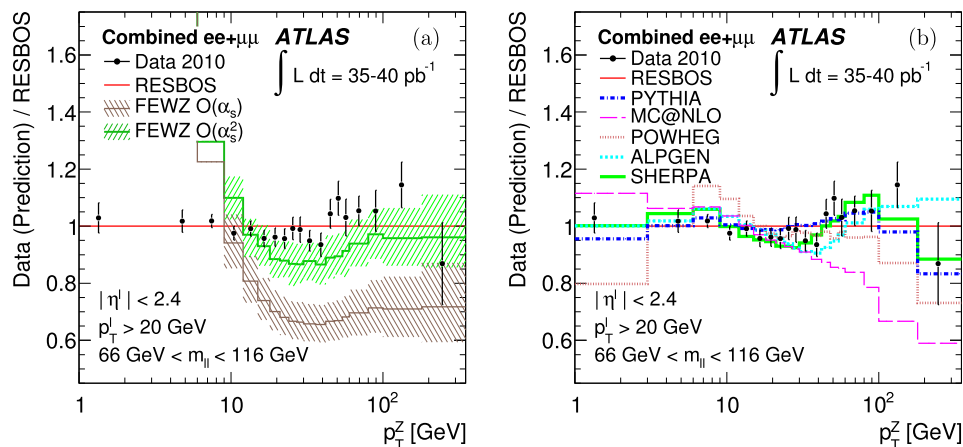


Fig. 4. Ratios of the combined data and various predictions over the RESBOS prediction for the normalized differential cross section as a function of p_T^Z : (a) FEWZ predictions at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$; (b) predictions from the generators PYTHIA, MC@NLO, POWHEG, ALPGEN and SHERPA. The FEWZ predictions are shown with combined scale, α_s , and PDF uncertainties. The data points are shown with combined statistical and systematic uncertainty. At low p_T^Z the $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ predictions of FEWZ diverge and are omitted.

duced boson and give a good description of the entire measured spectrum, up to large p_T^Z , with $\chi^2/\text{d.o.f.}$ of 31.9/19 and 16.8/19, respectively. Here, the enhancement of the cross section compared to the $\mathcal{O}(\alpha_s^2)$ prediction can be attributed to processes with large parton multiplicities [52], which correspond to tree-level diagrams of higher order in the strong coupling. SHERPA v1.2.3 and ALPGEN v2.13 are used, with the latter being interfaced to HERWIG v6.510 [16] for parton shower and fragmentation into particles, and to JIMMY v4.31 [32] to model underlying event contributions. For ALPGEN, the CTEQ6L1 [53] PDF set is employed and the factorization scale is set to $\mu_F^2 = m_{\ell\ell}^2 + \sum p_T^2$, where the sum extends over all associated partons. The SHERPA prediction uses the CTEQ6.6 PDF set and $\mu_F^2 = m_{\ell\ell}^2 + (p_T^Z)^2$.

The predictions of the parton shower event generators PYTHIA and MC@NLO are based on the simulated samples as described above. Fig. 4b also shows the predictions of POWHEG v1.0 [18] interfaced to a PYTHIA version with an underlying event tune to Tevatron and 7 TeV pp collision data [54]. Whereas MC@NLO ($\chi^2/\text{d.o.f.} = 111.6/19$) and POWHEG ($\chi^2/\text{d.o.f.} = 100.4/19$) deviate from the data at low and high p_T^Z , PYTHIA describes the measurement well over the entire range of boson transverse momentum ($\chi^2/\text{d.o.f.} = 17.9/19$).

In summary, the Z/γ^* transverse momentum differential distribution has been measured up to $p_T^Z = 350$ GeV for electron and muon pairs with invariant masses $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$ produced in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ based on integrated luminosities of 35 pb^{-1} and 40 pb^{-1} , respectively, recorded with the ATLAS detector. RESBOS describes the spectrum well for the entire p_T^Z range. At $p_T^Z > 18 \text{ GeV}$, the central FEWZ $\mathcal{O}(\alpha_s^2)$ prediction underestimates the data by about 10%, which is comparable to the size of the combined experimental and theoretical uncertainty. The measurement is compared to predictions of various event generators and a good agreement with SHERPA, ALPGEN, and PYTHIA is found. Except for the lowest p_T^Z values, the measurement is limited by statistics rather than systematic uncertainties. The systematic uncertainties are also mostly limited by the size of the data sample and are expected to improve with increasing integrated luminosity.

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G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, A.A. Abdelalim⁴⁹, A. Abdesselam¹¹⁸, O. Abdinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, H. Abramowicz¹⁵³, H. Abreu¹¹⁵, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁵, M. Aderholz⁹⁹, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, A. Akiyama⁶⁷, M.S. Alam¹, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁵, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob²⁰, M. Aliev¹⁵, G. Alimonti^{89a}, J. Alison¹²⁰, M. Aliyev¹⁰, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷¹, A. Alonso⁷⁹, M.G. Alviggi^{102a,102b}, K. Amako⁶⁶, P. Amaral²⁹, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,b}, G. Amorós¹⁶⁷, N. Amram¹⁵³, C. Anastopoulos²⁹, N. Andari¹¹⁵, T. Andeen³⁴, C.F. Anders²⁰, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M.-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³, L. Aperio Bella⁴, R. Apolle^{118,c}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁶, A.T.H. Arce⁴⁴, J.P. Archambault²⁸, S. Arfaoui^{29,d}, J.-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, O. Arnaez⁸¹, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷², S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵, K. Assamagan²⁴, A. Astbury¹⁶⁹, A. Astvatsatourov⁵², G. Atoian¹⁷⁵, B. Aubert⁴, B. Auerbach¹⁷⁵, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Auresseu^{145a}, N. Austin⁷³, G. Avolio¹⁶³, R. Avramidou⁹, D. Axen¹⁶⁸, C. Ay⁵⁴, G. Azuelos^{93,e}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, G. Bachy²⁹, M. Backes⁴⁹, M. Backhaus²⁰, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁵, M.D. Baker²⁴, S. Baker⁷⁷, F. Baltasar Dos Santos Pedrosa²⁹, E. Banas³⁸, P. Banerjee⁹³, Sw. Banerjee¹⁷², D. Banfi²⁹, A. Bangert¹³⁷, V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷¹, S.P. Baranov⁹⁴, A. Barashkou⁶⁵, A. Barbaro Galtieri¹⁴, T. Barber²⁷, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁵, T. Barillari⁹⁹, M. Barisonzi¹⁷⁴, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, A.E. Barton⁷¹, D. Bartsch²⁰, V. Bartsch¹⁴⁹, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, G. Battistoni^{89a}, F. Bauer¹³⁶, H.S. Bawa^{143,f}, B. Beare¹⁵⁸, T. Beau⁷⁸, P.H. Beauchemin¹¹⁸,

R. Beccherle^{50a}, P. Bechtle⁴¹, H.P. Beck¹⁶, M. Beckingham⁴⁸, K.H. Becks¹⁷⁴, A.J. Beddall^{18c},
 A. Beddall^{18c}, S. Bedikian¹⁷⁵, V.A. Bednyakov⁶⁵, C.P. Bee⁸³, M. Begel²⁴, S. Behar Harpaz¹⁵²,
 P.K. Behera⁶³, M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³,
 L. Bellagamba^{19a}, F. Bellina²⁹, M. Bellomo^{119a}, A. Belloni⁵⁷, O. Beloborodova¹⁰⁷, K. Belotskiy⁹⁶,
 O. Beltramello²⁹, S. Ben Ami¹⁵², O. Benary¹⁵³, D. Bencheekroun^{135a}, C. Benchouk⁸³, M. Bendel⁸¹,
 B.H. Benedict¹⁶³, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²²,
 K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹,
 E. Berglund⁴⁹, J. Beringer¹⁴, K. Bernardet⁸³, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶,
 A. Bertin^{19a,19b}, F. Bertinelli²⁹, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹,
 W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, J. Biesiada¹⁴,
 M. Biglietti^{134a,134b}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁵, A. Bingul^{18c}, C. Bini^{132a,132b},
 C. Biscarat¹⁷⁷, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵, J.-B. Blanchard¹¹⁵, G. Blanchot²⁹, T. Blazek^{144a},
 C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵,
 V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁴, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁴, N. Boelaert³⁵,
 S. Böser⁷⁷, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, V. Boisvert⁷⁶, T. Bold^{163,g},
 V. Boldea^{25a}, N.M. Bolnet¹³⁶, M. Bona⁷⁵, V.G. Bondarenko⁹⁶, M. Boonekamp¹³⁶, G. Boorman⁷⁶,
 C.N. Booth¹³⁹, S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{12a}, S. Borroni^{132a,132b},
 K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³,
 J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, C. Boulahouache¹²³, C. Bourdarios¹¹⁵, N. Bousson⁸³,
 A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁵, N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, A. Braem²⁹,
 P. Branchini^{134a}, G.W. Brandenburg⁵⁷, A. Brandt⁷, G. Brandt¹⁵, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴,
 J.E. Brau¹¹⁴, H.M. Braun¹⁷⁴, B. Brelief¹⁵⁸, J. Bremer²⁹, R. Brenner¹⁶⁶, S. Bressler¹⁵², D. Breton¹¹⁵,
 D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, T.J. Brodbeck⁷¹, E. Brodet¹⁵³, F. Broggi^{89a},
 C. Bromberg⁸⁸, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², H. Brown⁷, P.A. Bruckman de Renstrom³⁸,
 D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶¹, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³,
 F. Bucci⁴⁹, J. Buchanan¹¹⁸, N.J. Buchanan², P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵,
 S.I. Buda^{25a}, I.A. Budagov⁶⁵, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, D. Buira-Clark¹¹⁸, O. Bulekov⁹⁶,
 M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³, T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³,
 C.P. Buszello¹⁶⁶, F. Butin²⁹, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷,
 W. Buttinger²⁷, T. Byatt⁷⁷, S. Cabrera Urbán¹⁶⁷, D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴,
 G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, S. Calvet³³,
 R. Camacho Toro³³, P. Camarri^{133a,133b}, M. Cambiaghi^{119a,119b}, D. Cameron¹¹⁷, S. Campana²⁹,
 M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³⁰, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b},
 M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo¹⁴⁸,
 C. Caramarcu^{25a}, R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron^{159a},
 S. Caron⁴⁸, G.D. Carrillo Montoya¹⁷², A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,h}, D. Casadei¹⁰⁸,
 M.P. Casado¹¹, M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷²,
 E. Castaneda-Miranda¹⁷², V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, F. Cataneo²⁹,
 A. Catinaccio²⁹, J.R. Catmore⁷¹, A. Cattai²⁹, G. Cattani^{133a,133b}, S. Caughron⁸⁸, D. Cauz^{164a,164c},
 P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b},
 A.S. Cerqueira^{23a}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷, S.A. Cetin^{18b}, F. Cevenini^{102a,102b}, A. Chafaq^{135a},
 D. Chakraborty¹⁰⁶, K. Chan², B. Chapleau⁸⁵, J.D. Chapman²⁷, J.W. Chapman⁸⁷, E. Chareyre⁷⁸,
 D.G. Charlton¹⁷, V. Chavda⁸², C.A. Chavez Barajas²⁹, S. Cheatham⁸⁵, S. Chekanov⁵, S.V. Chekulaev^{159a},
 G.A. Chelkov⁶⁵, M.A. Chelstowska¹⁰⁴, C. Chen⁶⁴, H. Chen²⁴, S. Chen^{32c}, T. Chen^{32c}, X. Chen¹⁷²,
 S. Cheng^{32a}, A. Cheplakov⁶⁵, V.F. Chepurinov⁶⁵, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁴, E. Cheu⁶,
 S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani⁵¹, J.T. Childers^{58a}, A. Chilingarov⁷¹,
 G. Chiodini^{72a}, M.V. Chizhov⁶⁵, G. Choudalakis³⁰, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸,
 D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, K. Ciba³⁷, A.K. Ciftci^{3a},
 R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, M.D. Ciobotaru¹⁶³, C. Ciocca^{19a,19b}, A. Ciochio¹⁴, M. Cirilli⁸⁷,
 M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵,
 C. Clement^{146a,146b}, R.W. Clift¹²⁹, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro^{50a,50b}, J. Cochran⁶⁴,
 P. Coe¹¹⁸, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁷, C.D. Cojocaru²⁸, J. Colas⁴, A.P. Colijn¹⁰⁵,

C. Collard ¹¹⁵, N.J. Collins ¹⁷, C. Collins-Tooth ⁵³, J. Collot ⁵⁵, G. Colon ⁸⁴, P. Conde Muiño ^{124a},
 E. Coniavitis ¹¹⁸, M.C. Conidi ¹¹, M. Consonni ¹⁰⁴, V. Consorti ⁴⁸, S. Constantinescu ^{25a}, C. Conta ^{119a,119b},
 F. Conventi ^{102a,i}, J. Cook ²⁹, M. Cooke ¹⁴, B.D. Cooper ⁷⁷, A.M. Cooper-Sarkar ¹¹⁸, N.J. Cooper-Smith ⁷⁶,
 K. Copic ³⁴, T. Cornelissen ^{50a,50b}, M. Corradi ^{19a}, F. Corriveau ^{85,j}, A. Cortes-Gonzalez ¹⁶⁵, G. Cortiana ⁹⁹,
 G. Costa ^{89a}, M.J. Costa ¹⁶⁷, D. Costanzo ¹³⁹, T. Costin ³⁰, D. Côté ²⁹, R. Coura Torres ^{23a}, L. Courneyea ¹⁶⁹,
 G. Cowan ⁷⁶, C. Cowden ²⁷, B.E. Cox ⁸², K. Cranmer ¹⁰⁸, F. Crescioli ^{122a,122b}, M. Cristinziani ²⁰,
 G. Crosetti ^{36a,36b}, R. Crupi ^{72a,72b}, S. Crépé-Renaudin ⁵⁵, C.-M. Cuciuc ^{25a}, C. Cuenca Almenar ¹⁷⁵,
 T. Cuhadar Donszelmann ¹³⁹, S. Cuneo ^{50a,50b}, M. Curatolo ⁴⁷, C.J. Curtis ¹⁷, P. Cwetanski ⁶¹, H. Czirr ¹⁴¹,
 Z. Czyzula ¹¹⁷, S. D'Auria ⁵³, M. D'Onofrio ⁷³, A. D'Orazio ^{132a,132b}, P.V.M. Da Silva ^{23a}, C. Da Via ⁸²,
 W. Dabrowski ³⁷, T. Dai ⁸⁷, C. Dallapiccola ⁸⁴, M. Dam ³⁵, M. Dameri ^{50a,50b}, D.S. Damiani ¹³⁷,
 H.O. Danielsson ²⁹, D. Dannheim ⁹⁹, V. Dao ⁴⁹, G. Darbo ^{50a}, G.L. Darlea ^{25b}, C. Daum ¹⁰⁵, J.P. Dauvergne ²⁹,
 W. Davey ⁸⁶, T. Davidek ¹²⁶, N. Davidson ⁸⁶, R. Davidson ⁷¹, E. Davies ^{118,c}, M. Davies ⁹³, A.R. Davison ⁷⁷,
 Y. Davygora ^{58a}, E. Dawe ¹⁴², I. Dawson ¹³⁹, J.W. Dawson ^{5,*}, R.K. Daya ³⁹, K. De ⁷, R. de Asmundis ^{102a},
 S. De Castro ^{19a,19b}, P.E. De Castro Faria Salgado ²⁴, S. De Cecco ⁷⁸, J. de Graat ⁹⁸, N. De Groot ¹⁰⁴,
 P. de Jong ¹⁰⁵, C. De La Taille ¹¹⁵, H. De la Torre ⁸⁰, B. De Lotto ^{164a,164c}, L. De Mora ⁷¹, L. De Nooij ¹⁰⁵,
 M. De Oliveira Branco ²⁹, D. De Pedis ^{132a}, P. de Saintignon ⁵⁵, A. De Salvo ^{132a}, U. De Sanctis ^{164a,164c},
 A. De Santo ¹⁴⁹, J.B. De Vivie De Regie ¹¹⁵, S. Dean ⁷⁷, D.V. Dedovich ⁶⁵, J. Degenhardt ¹²⁰, M. Dehchar ¹¹⁸,
 M. Deile ⁹⁸, C. Del Papa ^{164a,164c}, J. Del Peso ⁸⁰, T. Del Prete ^{122a,122b}, M. Deliyergiyev ⁷⁴, A. Dell'Acqua ²⁹,
 L. Dell'Asta ^{89a,89b}, M. Della Pietra ^{102a,i}, D. della Volpe ^{102a,102b}, M. Delmastro ²⁹, P. Delpierre ⁸³,
 N. Delruelle ²⁹, P.A. Delsart ⁵⁵, C. Deluca ¹⁴⁸, S. Demers ¹⁷⁵, M. Demichev ⁶⁵, B. Demirkoz ^{11,k},
 J. Deng ¹⁶³, S.P. Denisov ¹²⁸, D. Derendarz ³⁸, J.E. Derkaoui ^{135d}, F. Derue ⁷⁸, P. Dervan ⁷³, K. Desch ²⁰,
 E. Devetak ¹⁴⁸, P.O. Deviveiros ¹⁵⁸, A. Dewhurst ¹²⁹, B. DeWilde ¹⁴⁸, S. Dhaliwal ¹⁵⁸, R. Dhullipudi ^{24,l},
 A. Di Ciaccio ^{133a,133b}, L. Di Ciaccio ⁴, A. Di Girolamo ²⁹, B. Di Girolamo ²⁹, S. Di Luise ^{134a,134b},
 A. Di Mattia ⁸⁸, B. Di Micco ²⁹, R. Di Nardo ^{133a,133b}, A. Di Simone ^{133a,133b}, R. Di Sipio ^{19a,19b},
 M.A. Diaz ^{31a}, F. Diblen ^{18c}, E.B. Diehl ⁸⁷, J. Dietrich ⁴¹, T.A. Dietzsch ^{58a}, S. Diglio ¹¹⁵, K. Dindar Yagci ³⁹,
 J. Dingfelder ²⁰, C. Dionisi ^{132a,132b}, P. Dita ^{25a}, S. Dita ^{25a}, F. Dittus ²⁹, F. Djama ⁸³, T. Djobava ⁵¹,
 M.A.B. do Vale ^{23a}, A. Do Valle Wemans ^{124a}, T.K.O. Doan ⁴, M. Dobbs ⁸⁵, R. Dobinson ^{29,*}, D. Dobos ⁴²,
 E. Dobson ²⁹, M. Dobson ¹⁶³, J. Dodd ³⁴, C. Doglioni ¹¹⁸, T. Doherty ⁵³, Y. Doi ^{66,*}, J. Dolejsi ¹²⁶, I. Dolenc ⁷⁴,
 Z. Dolezal ¹²⁶, B.A. Dolgoshein ^{96,*}, T. Dohmae ¹⁵⁵, M. Donadelli ^{23b}, M. Donega ¹²⁰, J. Donini ⁵⁵,
 J. Dopke ²⁹, A. Doria ^{102a}, A. Dos Anjos ¹⁷², M. Dosil ¹¹, A. Dotti ^{122a,122b}, M.T. Dova ⁷⁰, J.D. Dowell ¹⁷,
 A.D. Doxiadis ¹⁰⁵, A.T. Doyle ⁵³, Z. Drasal ¹²⁶, J. Drees ¹⁷⁴, N. Dressnandt ¹²⁰, H. Drevermann ²⁹,
 C. Driouichi ³⁵, M. Dris ⁹, J. Dubbert ⁹⁹, T. Dubbs ¹³⁷, S. Dube ¹⁴, E. Duchovni ¹⁷¹, G. Duckeck ⁹⁸,
 A. Dudarev ²⁹, F. Dudziak ⁶⁴, M. Dührssen ²⁹, I.P. Duerdoth ⁸², L. Duflot ¹¹⁵, M.-A. Dufour ⁸⁵, M. Dunford ²⁹,
 H. Duran Yildiz ^{3b}, R. Duxfield ¹³⁹, M. Dwuznik ³⁷, F. Dydak ²⁹, D. Dzahini ⁵⁵, M. Düren ⁵²,
 W.L. Ebenstein ⁴⁴, J. Ebke ⁹⁸, S. Eckert ⁴⁸, S. Eckweiler ⁸¹, K. Edmonds ⁸¹, C.A. Edwards ⁷⁶, N.C. Edwards ⁵³,
 W. Ehrenfeld ⁴¹, T. Ehrich ⁹⁹, T. Eifert ²⁹, G. Eigen ¹³, K. Einsweiler ¹⁴, E. Eisenhandler ⁷⁵, T. Ekelof ¹⁶⁶,
 M. El Kacimi ^{135c}, M. Ellert ¹⁶⁶, S. Elles ⁴, F. Ellinghaus ⁸¹, K. Ellis ⁷⁵, N. Ellis ²⁹, J. Elmsheuser ⁹⁸,
 M. Elsing ²⁹, R. Ely ¹⁴, D. Emelianov ¹²⁹, R. Engelmann ¹⁴⁸, A. Engl ⁹⁸, B. Epp ⁶², A. Eppig ⁸⁷,
 J. Erdmann ⁵⁴, A. Ereditato ¹⁶, D. Eriksson ^{146a}, J. Ernst ¹, M. Ernst ²⁴, J. Ernwein ¹³⁶, D. Errede ¹⁶⁵,
 S. Errede ¹⁶⁵, E. Ertel ⁸¹, M. Escalier ¹¹⁵, C. Escobar ¹⁶⁷, X. Espinal Curull ¹¹, B. Esposito ⁴⁷, F. Etienne ⁸³,
 A.I. Etievre ¹³⁶, E. Etzion ¹⁵³, D. Evangelakou ⁵⁴, H. Evans ⁶¹, L. Fabbri ^{19a,19b}, C. Fabre ²⁹,
 R.M. Fakhruddinov ¹²⁸, S. Falciano ^{132a}, Y. Fang ¹⁷², M. Fanti ^{89a,89b}, A. Farbin ⁷, A. Farilla ^{134a}, J. Farley ¹⁴⁸,
 T. Farooque ¹⁵⁸, S.M. Farrington ¹¹⁸, P. Farthouat ²⁹, P. Fassnacht ²⁹, D. Fassouliotis ⁸, B. Fatholahzadeh ¹⁵⁸,
 A. Favareto ^{89a,89b}, L. Fayard ¹¹⁵, S. Fazio ^{36a,36b}, R. Febbraro ³³, P. Federic ^{144a}, O.L. Fedin ¹²¹,
 W. Fedorko ⁸⁸, M. Fehling-Kaschek ⁴⁸, L. Feligioni ⁸³, D. Fellmann ⁵, C.U. Felzmann ⁸⁶, C. Feng ^{32d},
 E.J. Feng ³⁰, A.B. Fenyuk ¹²⁸, J. Ferencei ^{144b}, J. Ferland ⁹³, W. Fernando ¹⁰⁹, S. Ferrag ⁵³, J. Ferrando ⁵³,
 V. Ferrara ⁴¹, A. Ferrari ¹⁶⁶, P. Ferrari ¹⁰⁵, R. Ferrari ^{119a}, A. Ferrer ¹⁶⁷, M.L. Ferrer ⁴⁷, D. Ferrere ⁴⁹,
 C. Ferretti ⁸⁷, A. Ferretto Parodi ^{50a,50b}, M. Fiascaris ³⁰, F. Fiedler ⁸¹, A. Filipčič ⁷⁴, A. Filippas ⁹,
 F. Filthaut ¹⁰⁴, M. Fincke-Keeler ¹⁶⁹, M.C.N. Fiolhais ^{124a,h}, L. Fiorini ¹⁶⁷, A. Firan ³⁹, G. Fischer ⁴¹,
 P. Fischer ²⁰, M.J. Fisher ¹⁰⁹, S.M. Fisher ¹²⁹, M. Flechl ⁴⁸, I. Fleck ¹⁴¹, J. Fleckner ⁸¹, P. Fleischmann ¹⁷³,
 S. Fleischmann ¹⁷⁴, T. Flick ¹⁷⁴, L.R. Flores Castillo ¹⁷², M.J. Flowerdew ⁹⁹, F. Föhlich ^{58a}, M. Fokitis ⁹,
 T. Fonseca Martin ¹⁶, D.A. Forbush ¹³⁸, A. Formica ¹³⁶, A. Forti ⁸², D. Fortin ^{159a}, J.M. Foster ⁸²,

D. Fournier¹¹⁵, A. Foussat²⁹, A.J. Fowler⁴⁴, K. Fowler¹³⁷, H. Fox⁷¹, P. Francavilla^{122a,122b},
 S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷¹, M. Franklin⁵⁷, S. Franz²⁹, M. Fraternali^{119a,119b},
 S. Fratina¹²⁰, S.T. French²⁷, R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶,
 E. Fullana Torregrosa²⁹, J. Fuster¹⁶⁷, C. Gabaldon²⁹, O. Gabizon¹⁷¹, T. Gadfort²⁴, S. Gadomski⁴⁹,
 G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea⁹⁸, E.J. Gallas¹¹⁸, M.V. Gallas²⁹, V. Gallo¹⁶, B.J. Gallop¹²⁹,
 P. Gallus¹²⁵, E. Galyaev⁴⁰, K.K. Gan¹⁰⁹, Y.S. Gao^{143,f}, V.A. Gapienko¹²⁸, A. Gaponenko¹⁴,
 F. Garberon¹⁷⁵, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro⁴⁹, R.W. Gardner³⁰, N. Garelli²⁹,
 H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, O. Gaumer⁴⁹, B. Gaur¹⁴¹,
 L. Gauthier¹³⁶, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, J.-C. Gayde²⁹, E.N. Gazis⁹, P. Ge^{32d},
 C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a},
 A. Gemmell⁵³, M.H. Genest⁹⁸, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, P. Gerlach¹⁷⁴,
 A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, P. Ghez⁴, N. Ghodbane³³, B. Giacobbe^{19a},
 S. Giagu^{132a,132b}, V. Giakoumopoulou⁸, V. Giangiobbe^{122a,122b}, F. Gianotti²⁹, B. Gibbard²⁴,
 A. Gibson¹⁵⁸, S.M. Gibson²⁹, L.M. Gilbert¹¹⁸, M. Gilchriese¹⁴, V. Gilewsky⁹¹, D. Gillberg²⁸,
 A.R. Gillman¹²⁹, D.M. Gingrich^{2,e}, J. Ginzburg¹⁵³, N. Giokaris⁸, R. Giordano^{102a,102b}, F.M. Giorgi¹⁵,
 P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta^{132a,132b}, P. Giusti^{19a}, B.K. Gjelsten¹¹⁷,
 L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁴, G.L. Glonti⁶⁵, J. Godfrey¹⁴²,
 J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷,
 D. Goldin³⁹, T. Golling¹⁷⁵, S.N. Golovnia¹²⁸, A. Gomes^{124a,b}, L.S. Gomez Fajardo⁴¹, R. Gonçalves⁷⁶,
 J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰, A. Gonidec²⁹, S. Gonzalez¹⁷²,
 S. González de la Hoz¹⁶⁷, M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens²⁹,
 P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³, G. Gorfine¹⁷⁴, B. Gorini²⁹, E. Gorini^{72a,72b},
 A. Gorišek⁷⁴, E. Gornicki³⁸, S.A. Gorokhov¹²⁸, V.N. Goryachev¹²⁸, B. Gosdzik⁴¹, M. Gosselink¹⁰⁵,
 M.I. Gostkin⁶⁵, M. Gouanère⁴, I. Gough Eschrich¹⁶³, M. Gouighri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹,
 A.G. Goussiou¹³⁸, C. Goy⁴, I. Grabowska-Bold^{163,g}, V. Grabski¹⁷⁶, P. Grafström²⁹, C. Grah¹⁷⁴,
 K.-J. Grah⁴¹, F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray²⁹,
 J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, D. Greenfield¹²⁹, T. Greenshaw⁷³, Z.D. Greenwood^{24,i},
 I.M. Gregor⁴¹, P. Grenier¹⁴³, J. Griffiths¹³⁸, N. Grigalashvili⁶⁵, A.A. Grillo¹³⁷, S. Grinstein¹¹,
 Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, J. Grognuz²⁹, M. Groh⁹⁹, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁴,
 J. Groth-Jensen¹⁷¹, K. Grybel¹⁴¹, V.J. Guarino⁵, D. Guest¹⁷⁵, C. Guicheney³³, A. Guida^{72a,72b},
 T. Guillemin⁴, S. Guindon⁵⁴, H. Guler^{85,m}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁴, A. Gupta³⁰, Y. Gusakov⁶⁵,
 V.N. Gushchin¹²⁸, A. Gutierrez⁹³, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷², C. Guyot¹³⁶,
 C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴, R. Hackenburg²⁴, H.K. Hadavand³⁹,
 D.R. Hadley¹⁷, P. Haefner⁹⁹, F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁶, J. Haller⁵⁴,
 K. Hamacher¹⁷⁴, P. Hamal¹¹³, A. Hamilton⁴⁹, S. Hamilton¹⁶¹, H. Han^{32a}, L. Han^{32b}, K. Hanagaki¹¹⁶,
 M. Hance¹²⁰, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵,
 P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁴, S. Harkusha⁹⁰, D. Harper⁸⁷,
 R.D. Harrington²¹, O.M. Harris¹³⁸, K. Harrison¹⁷, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁶, A. Harvey⁵⁶,
 S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, M. Hatch²⁹, D. Hauff⁹⁹, S. Haug¹⁶, M. Hauschild²⁹,
 R. Hauser⁸⁸, M. Havranek²⁰, B.M. Hawes¹¹⁸, C.M. Hawkes¹⁷, R.J. Hawkings²⁹, D. Hawkins¹⁶³,
 T. Hayakawa⁶⁷, D. Hayden⁷⁶, H.S. Hayward⁷³, S.J. Haywood¹²⁹, E. Hazen²¹, M. He^{32d}, S.J. Head¹⁷,
 V. Hedberg⁷⁹, L. Heelan⁷, S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵, L. Helary⁴, M. Heller¹¹⁵,
 S. Hellman^{146a,146b}, D. Hellmich²⁰, C. Hensels¹¹, R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴,
 A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³, C. Hensel⁵⁴, T. Henß¹⁷⁴,
 C.M. Hernandez⁷, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, A.D. Hershenhorn¹⁵², G. Herten⁴⁸,
 R. Hertenberger⁹⁸, L. Hervas²⁹, N.P. Hessey¹⁰⁵, A. Hidvegi^{146a}, E. Higón-Rodríguez¹⁶⁷, D. Hill^{5,*},
 J.C. Hill²⁷, N. Hill⁵, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶,
 F. Hirsch⁴², D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹,
 A. Hoecker²⁹, M.R. Hoferkamp¹⁰³, J. Hoffman³⁹, D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹,
 A. Holmes¹¹⁸, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, Y. Homma⁶⁷, T.M. Hong¹²⁰,
 L. Hooft van Huysduynen¹⁰⁸, T. Horazdovsky¹²⁷, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸, J.-Y. Hostachy⁵⁵,
 S. Hou¹⁵¹, M.A. Houlden⁷³, A. Hoummada^{135a}, J. Howarth⁸², D.F. Howell¹¹⁸, I. Hristova¹⁵, J. Hrivnac¹¹⁵,

I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu¹⁷⁵, S.-C. Hsu¹⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰, T.B. Huffman¹¹⁸, E.W. Hughes³⁴, G. Hughes⁷¹, R.E. Hughes-Jones⁸², M. Huhtinen²⁹, P. Hurst⁵⁷, M. Hurwitz¹⁴, U. Husemann⁴¹, N. Huseynov^{65,n}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹, M. Ibbotson⁸², I. Ibragimov¹⁴¹, R. Ichimiya⁶⁷, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, M. Idzik³⁷, P. Iengo^{102a,102b}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁶, M. Ikeno⁶⁶, Y. Ilchenko³⁹, D. Iliadis¹⁵⁴, D. Imbault⁷⁸, M. Imhaeuser¹⁷⁴, M. Imori¹⁵⁵, T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{134a}, G. Ionescu⁴, A. Irles Quiles¹⁶⁷, K. Ishii⁶⁶, A. Ishikawa⁶⁷, M. Ishino⁶⁶, R. Ishmukhametov³⁹, C. Issever¹¹⁸, S. Istin^{18a}, Y. Itoh¹⁰¹, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁶, J.M. Izen⁴⁰, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹, V. Jain⁶¹, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jankowski¹⁵⁸, E. Jansen⁷⁷, A. Jantsch⁹⁹, M. Janus²⁰, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, K. Jelen³⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴, M.K. Jha^{19a}, H. Ji¹⁷², W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b}, M. Jimenez Belenguer⁴¹, G. Jin^{32b}, S. Jin^{32a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶, K. Jon-And^{146a,146b}, G. Jones⁸², R.W.L. Jones⁷¹, T.W. Jones⁷⁷, T.J. Jones⁷³, O. Jonsson²⁹, C. Joram²⁹, P.M. Jorge^{124a,b}, J. Joseph¹⁴, T. Jovin^{12b}, X. Ju¹³⁰, V. Juranek¹²⁵, P. Jussel⁶², V.V. Kabachenko¹²⁸, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarska³⁸, P. Kadlecik³⁵, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, S. Kaiser⁹⁹, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁴, L.V. Kalinovskaya⁶⁵, S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda²⁹, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁶, B. Kaplan¹⁷⁵, A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁴³, M. Karagöz¹¹⁸, M. Karneviy⁴¹, K. Karr⁵, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷², A. Kasmi³⁹, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁷, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁵, J.R. Keates⁸², R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁵, M. Kelly⁸², J. Kennedy⁹⁸, C.J. Kenney¹⁴³, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁴, K. Kessoku¹⁵⁵, C. Ketterer⁴⁸, J. Keung¹⁵⁸, M. Khakzad²⁸, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁵, A. Khodinov⁹⁶, A.G. Kholodenko¹²⁸, A. Khomich^{58a}, T.J. Khoo²⁷, G. Khoraiuli²⁰, A. Khoroshilov¹⁷⁴, N. Khovanskiy⁶⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁵, J. Khubua⁵¹, H. Kim⁷, M.S. Kim², P.C. Kim¹⁴³, S.H. Kim¹⁶⁰, N. Kimura¹⁷⁰, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁷, R.S.B. King¹¹⁸, J. Kirk¹²⁹, G.P. Kirsch¹¹⁸, L.E. Kirsch²², A.E. Kiryunin⁹⁹, D. Kisielewska³⁷, T. Kittelmann¹²³, A.M. Kiver¹²⁸, H. Kiyamura⁶⁷, E. Kladiva^{144b}, J. Klaiber-Lodewigs⁴², M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷¹, A. Klimentov²⁴, R. Klingenberg⁴², E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, E. Kneringer⁶², J. Knobloch²⁹, E.B.F.G. Knoops⁸³, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, M. Kocian¹⁴³, A. Kocnar¹¹³, P. Kodys¹²⁶, K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁹, E. Koffeman¹⁰⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁶, T. Koi¹⁴³, T. Kokott²⁰, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁵, I. Koletsou^{89a}, J. Koll⁸⁸, D. Kollar²⁹, M. Kollefrath⁴⁸, S.D. Kolya⁸², A.A. Komar⁹⁴, J.R. Komaragiri¹⁴², Y. Komori¹⁵⁵, T. Kondo⁶⁶, T. Kono^{41,o}, A.I. Kononov⁴⁸, R. Konoplich^{108,p}, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁴, S. Koperny³⁷, S.V. Kopikov¹²⁸, K. Korcyl³⁸, K. Kordas¹⁵⁴, V. Koreshev¹²⁸, A. Korn¹⁴, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰, M.J. Kotamäki²⁹, S. Kotov⁹⁹, V.M. Kotov⁶⁵, A. Kotwal⁴⁴, C. Kourkoumelis⁸, V. Kouskoura¹⁵⁴, A. Koutsman¹⁰⁵, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, O. Krasel⁴², M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, A. Kreisel¹⁵³, F. Krejci¹²⁷, J. Kretschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁵, H. Krüger²⁰, T. Kruker¹⁶, Z.V. Krumshteyn⁶⁵, A. Kruth²⁰, T. Kubota⁸⁶, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹, D. Kuhn⁶², V. Kukhtin⁶⁵, Y. Kulchitsky⁹⁰, S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁷⁸, N. Kundu¹¹⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁷, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, W. Kuykendall¹³⁸, M. Kuze¹⁵⁷, P. Kuzhir⁹¹, O. Kvasnicka¹²⁵, J. Kvita²⁹, R. Kwee¹⁵, A. La Rosa¹⁷², L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁵, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna²⁹, C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, H. Landsman¹⁵², J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzsich²⁹, S. Laplace⁷⁸, C. Lapoire²⁰, J.F. Laporte¹³⁶, T. Lari^{89a}, A.V. Larionov¹²⁸, A. Larner¹¹⁸,

C. Lasseur²⁹, M. Lassnig²⁹, W. Lau¹¹⁸, P. Laurelli⁴⁷, A. Lavorato¹¹⁸, W. Lavrijsen¹⁴, P. Laycock⁷³, A.B. Lazarev⁶⁵, A. Lazzaro^{89a,89b}, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹³⁶, C. Lebel⁹³, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹⁵⁰, S.C. Lee¹⁵¹, L. Lee¹⁷⁵, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, A. Leger⁴⁹, B.C. LeGeyt¹²⁰, F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, X. Lei⁶, M.A.L. Leite^{23b}, R. Leitner¹²⁶, D. Lellouch¹⁷¹, J. Lellouch⁷⁸, M. Leltchouk³⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁷⁴, G. Lenzen¹⁷⁴, B. Lenzi²⁹, K. Leonhardt⁴³, S. Leontsinis⁹, C. Leroy⁹³, J.-R. Lessard¹⁶⁹, J. Lesser^{146a}, C.G. Lester²⁷, A. Leung Fook Cheong¹⁷², J. Levêque⁴, D. Levin⁸⁷, L.J. Levinson¹⁷¹, M.S. Levitski¹²⁸, M. Lewandowska²¹, A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²⁰, M. Leyton¹⁵, B. Li⁸³, H. Li¹⁷², S. Li^{32b,d}, X. Li⁸⁷, Z. Liang³⁹, Z. Liang^{118,q}, B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, R. Lifshitz¹⁵², J.N. Lilley¹⁷, C. Limbach²⁰, A. Limosani⁸⁶, M. Limper⁶³, S.C. Lin^{151,r}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, L. Lipinsky¹²⁵, A. Lipniacka¹³, T.M. Liss¹⁶⁵, D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu^{151,s}, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, S. Liu², Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, S. Lockwitz¹⁷⁵, T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁵, C.W. Loh¹⁶⁸, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, J. Loken¹¹⁸, V.P. Lombardo⁴, R.E. Long⁷¹, L. Lopes^{124a,b}, D. Lopez Mateos^{34,t}, M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe^{143,f}, F. Lu^{32a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶¹, G. Luijckx¹⁰⁵, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹, A. Lupi^{122a,122b}, G. Lutz⁹⁹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷², J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a}, D. Macina⁴⁹, R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁴, S. Mättig⁴¹, P.J. Magalhaes Martins^{124a,h}, L. Magnoni²⁹, E. Magradze⁵⁴, Y. Mahalalel¹⁵³, K. Mahboubi⁴⁸, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a}, A. Maio^{124a,b}, S. Majewski²⁴, Y. Makida⁶⁶, N. Makovec¹¹⁵, P. Mal⁶, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶³, D. Malon⁵, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov²⁹, R. Mameghani⁹⁸, J. Mamuzic^{12b}, A. Manabe⁶⁶, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangedard⁸⁸, I.D. Manjavidze⁶⁵, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Manz⁹⁹, A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁹, F. Marchese^{133a,133b}, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, A. Marin^{21,*}, C.P. Marino⁶¹, F. Marroquim^{23a}, R. Marshall⁸², Z. Marshall²⁹, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, A.J. Martin¹⁷⁵, B. Martin²⁹, B. Martin⁸⁸, F.F. Martin¹²⁰, J.P. Martin⁹³, Ph. Martin⁵⁵, T.A. Martin¹⁷, B. Martin dit Latour⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷, A.C. Martyniuk⁸², M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, M. Maß⁴², I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴, P. Mastrandrea^{132a,132b}, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, M. Mathes²⁰, P. Matricon¹¹⁵, H. Matsumoto¹⁵⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁷, C. Mattravers^{118,c}, J.M. Maugain²⁹, S.J. Maxfield⁷³, D.A. Maximov¹⁰⁷, E.N. May⁵, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰, M. Mazzanti^{89a}, E. Mazzoni^{122a,122b}, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶, J.A. McFayden¹³⁹, H. McGlone⁵³, G. Mchedlidze⁵¹, R.A. McLaren²⁹, T. Mclaughlan¹⁷, S.J. McMahon¹²⁹, R.A. McPherson^{169,j}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁴, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase³⁵, A. Mehta⁷³, K. Meier^{58a}, J. Meinhardt⁴⁸, B. Meirose⁷⁹, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷², L. Mendoza Navas¹⁶², Z. Meng^{151,s}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹, C. Menot²⁹, E. Meoni¹¹, K.M. Mercurio⁵⁷, P. Mermod¹¹⁸, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰, A. Messina²⁹, J. Metcalfe¹⁰³, A.S. Mete⁶⁴, S. Meuser²⁰, C. Meyer⁸¹, J.-P. Meyer¹³⁶, J. Meyer¹⁷³, J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶⁴, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹, P. Miele²⁹, S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷¹, M. Mikesstikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller¹⁴³, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, D. Milstein¹⁷¹, A.A. Minaenko¹²⁸, M. Miñano¹⁶⁷, I.A. Minashvili⁶⁵, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁵, Y. Ming¹³⁰, L.M. Mir¹¹, G. Mirabelli^{132a}, L. Miralles Verge¹¹, A. Misiejuk⁷⁶, J. Mitrevski¹³⁷, G.Y. Mitrofanov¹²⁸, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁶, P.S. Miyagawa⁸², K. Miyazaki⁶⁷,

J.U. Mjörnmark⁷⁹, T. Moe^{146a,146b}, P. Mockett¹³⁸, S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸, B. Mohn¹³, W. Mohr⁴⁸, S. Mohr dieck-Möck⁹⁹, A.M. Moiseev^{128,*}, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, J. Monk⁷⁷, E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, A. Morais^{124a,b}, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹, M. Moreno Llácer¹⁶⁷, P. Morettini^{50a}, M. Morii⁵⁷, J. Morin⁷⁵, Y. Morita⁶⁶, A.K. Morley²⁹, G. Mornacchi²⁹, M.-C. Morone⁴⁹, S.V. Morozov⁹⁶, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze⁵¹, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha¹³⁶, S.V. Mouraviev⁹⁴, E.J.W. Moyse⁸⁴, M. Mudrinic^{12b}, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰, T.A. Müller⁹⁸, D. Muenstermann²⁹, A. Muijs¹⁰⁵, A. Muir¹⁶⁸, Y. Munwes¹⁵³, K. Murakami⁶⁶, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁶, Y. Nagasaka⁶⁰, A.M. Nairz²⁹, Y. Nakahama²⁹, K. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, M. Nash^{77,c}, N.R. Nation²¹, T. Nattermann²⁰, T. Naumann⁴¹, G. Navarro¹⁶², H.A. Neal⁸⁷, E. Nebot⁸⁰, P.Yu. Nechaeva⁹⁴, A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹, S. Nelson¹⁴³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi^{29,u}, S.Y. Nesterov¹²¹, M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁶, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, T. Niinikoski²⁹, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, K. Nikolaev⁶⁵, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁷, R. Nisius⁹⁹, L. Nodulman⁵, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, M. Nordberg²⁹, B. Nordkvist^{146a,146b}, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁶, M. Nožička⁴¹, L. Nozka¹¹³, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷, T. Nyman²⁹, B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, F.G. Oakham^{28,e}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁷, S. Oda¹⁵⁵, S. Odaka⁶⁶, J. Odier⁸³, H. Ogren⁶¹, A. Oh⁸², S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, H. Ohshita¹⁴⁰, T.K. Ohska⁶⁶, T. Ohsugi⁵⁹, S. Okada⁶⁷, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵, M. Olcese^{50a}, A.G. Olchevski⁶⁵, M. Oliveira^{124a,h}, D. Oliveira Damazio²⁴, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, C. Omachi⁶⁷, A. Onofre^{124a,v}, P.U.E. Onyisi³⁰, C.J. Oram^{159a}, M.J. Oreglia³⁰, Y. Oren¹⁵³, D. Orestano^{134a,134b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶, J. P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a}, M. Owen⁸², S. Owen¹³⁹, O.K. Øye¹³, V.E. Ozcan^{18a}, N. Ozturk⁷, A. Pacheco Pages¹¹, C. Padilla Aranda¹¹, S. Pagan Griso¹⁴, E. Paganis¹³⁹, F. Paige²⁴, K. Pajchel¹¹⁷, S. Palestini²⁹, D. Pallin³³, A. Palma^{124a,b}, J.D. Palmer¹⁷, Y.B. Pan¹⁷², E. Panagiotopoulou⁹, B. Panes^{31a}, N. Panikashvili⁸⁷, S. Panitkin²⁴, D. Pantea^{25a}, M. Panuskova¹²⁵, V. Paolone¹²³, A. Papadelis^{146a}, Th.D. Papadopoulou⁹, A. Paramonov⁵, W. Park^{24,w}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸, E. Pasqualucci^{132a}, A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore²⁹, G. Pásztor^{49,x}, S. Pataria¹⁷², N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsý^{144a}, M.I. Pedraza Morales¹⁷², S.V. Peleganchuk¹⁰⁷, H. Peng¹⁷², R. Pengo²⁹, A. Penson³⁴, J. Penwell⁶¹, M. Perantoni^{23a}, K. Perez^{34,t}, T. Perez Cavalcanti⁴¹, E. Perez Codina¹¹, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴, S. Persema^{3a}, V.D. Peshekhonov⁶⁵, O. Peters¹⁰⁵, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁸³, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolu^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, A. Phan⁸⁶, A.W. Phillips²⁷, P.W. Phillips¹²⁹, G. Piacquadio²⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b}, A. Pickford⁵³, S.M. Piec⁴¹, R. Piegaia²⁶, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,b}, M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold², J. Ping^{32c}, B. Pinto^{124a,b}, O. Pirotte²⁹, C. Pizio^{89a,89b}, R. Placakyte⁴¹, M. Plamondon¹⁶⁹, W.G. Plano⁸², M.-A. Pleier²⁴, A.V. Pleskach¹²⁸, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³, L. Poggioli¹¹⁵, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio¹³⁸, A. Polini^{19a}, J. Poll⁷⁵, V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso⁴⁸, R. Porter¹⁶³, C. Posch²¹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard²⁹, J. Poveda¹⁷², R. Prabhu⁷⁷, P. Pralavorio⁸³, S. Prasad⁵⁷, R. Pravahan⁷, S. Prell⁶⁴, K. Pretzl¹⁶, L. Pribyl²⁹, D. Price⁶¹, L.E. Price⁵, M.J. Price²⁹, P.M. Prichard⁷³, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³, H. Przysiezniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴, J. Purdham⁸⁷, M. Purohit^{24,w}, P. Puzo¹¹⁵, Y. Pylypchenko¹¹⁷, J. Qian⁸⁷, Z. Qian⁸³,

Z. Qin⁴¹, A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷², F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radescu^{58b}, B. Radics²⁰, T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁷, A.M. Rahimi¹⁰⁹, D. Rahm²⁴, S. Rajagopalan²⁴, M. Rammensee⁴⁸, M. Rammes¹⁴¹, M. Ramstedt^{146a,146b}, K. Randrianarivony²⁸, P.N. Ratoff⁷¹, F. Rauscher⁹⁸, E. Rauter⁹⁹, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuffi^{119a,119b}, A. Redelbach¹⁷³, G. Redlinger²⁴, R. Reece¹²⁰, K. Reeves⁴⁰, A. Reichold¹⁰⁵, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², D. Reljic^{12a}, C. Rembser²⁹, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, P. Renkel³⁹, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, A. Richards⁷⁷, R. Richter⁹⁹, E. Richter-Was^{38,y}, M. Ridel⁷⁸, S. Rieke⁸¹, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,j}, A. Robichaud-Veronneau⁴⁹, D. Robinson²⁷, J.E.M. Robinson⁷⁷, M. Robinson¹¹⁴, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, S. Rodier⁸⁰, D. Rodriguez¹⁶², A. Roe⁵⁴, S. Roe²⁹, O. Røhne¹¹⁷, V. Rojo¹, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, V.M. Romanov⁶⁵, G. Romeo²⁶, D. Romero Maltrana^{31a}, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a,132b}, K. Rosbach⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶⁴, P.L. Rosendahl¹³, L. Rossetlet⁴⁹, V. Rossetti¹¹, E. Rossi^{102a,102b}, L.P. Rossi^{50a}, L. Rossi^{89a,89b}, M. Rotaru^{25a}, I. Roth¹⁷¹, J. Rothberg¹³⁸, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan¹¹⁵, I. Rubinskiy⁴¹, B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴³, G. Rudolph⁶², F. Rühr⁶, F. Ruggieri^{134a,134b}, A. Ruiz-Martinez⁶⁴, E. Rulikowska-Zarebska³⁷, V. Rumiantsev^{91,*}, L. Rummyantsev⁶⁵, K. Runge⁴⁸, O. Runolfsson²⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵, D.R. Rust⁶¹, J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, V. Ryadovikov¹²⁸, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, S. Rzaeva¹⁰, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁵, F. Safai Tehrani^{132a,132b}, H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger²⁹, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, A. Sanchez^{102a,102b}, H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁴, T. Sandoval²⁷, R. Sandstroem⁹⁹, S. Sandvoss¹⁷⁴, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a,b}, T. Sarangi¹⁷², E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁴, O. Sasaki⁶⁶, T. Sasaki⁶⁶, N. Sasao⁶⁸, I. Satsounkevitch⁹⁰, G. Sauvage⁴, E. Sauvan⁴, J.B. Sauvan¹¹⁵, P. Savard^{158,e}, V. Savinov¹²³, D.O. Savu²⁹, P. Savva⁹, L. Sawyer^{24,l}, D.H. Saxon⁵³, L.P. Says³³, C. Sbarra^{19a,19b}, A. Sbrizzi^{19a,19b}, O. Scallon⁹³, D.A. Scannicchio¹⁶³, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, U. Schäfer⁸¹, S. Schaepe²⁰, S. Schaezel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer¹⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{36a,36b}, S. Schlenker²⁹, J.L. Schlereth⁵, E. Schmidt⁴⁸, K. Schmieden²⁰, C. Schmitt⁸¹, S. Schmitt^{58b}, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹, D. Schouten¹⁴², J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, S. Schuh²⁹, G. Schuler²⁹, J. Schultes¹⁷⁴, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³, J. Schwindling¹³⁶, W.G. Scott¹²⁹, J. Searcy¹¹⁴, E. Sedykh¹²¹, E. Segura¹¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, R. Seuster⁹⁹, H. Severini¹¹¹, M.E. Sevir⁸⁶, A. Sfyrla²⁹, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵, L. Shaver⁶, C. Shaw⁵³, K. Shaw^{164a,164c}, D. Sherman¹⁷⁵, P. Sherwood⁷⁷, A. Shibata¹⁰⁸, H. Shichi¹⁰¹, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, A. Shmeleva⁹⁴, M.J. Shochet³⁰, D. Short¹¹⁸, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti^{132a,132b}, A. Siebel¹⁷⁴, F. Siegert⁴⁸, J. Siegrist¹⁴, Dj. Sijacki^{12a}, O. Silbert¹⁷¹, J. Silva^{124a,b}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷, O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, M. Simonyan³⁵, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa¹⁷³, A.N. Sisakyan⁶⁵, S.Yu. Sivoklokov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjursten¹³, L.A. Skinnari¹⁴, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, N. Skvorodnev²², M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, T.J. Sloan⁷¹, J. Sloper²⁹, V. Smakhtin¹⁷¹, S.Yu. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, J. Snuverink¹⁰⁵, S. Snyder²⁴, M. Soares^{124a}, R. Sobie^{169,j}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, E. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸,

O.V. Solovyanov¹²⁸, J. Sondericker²⁴, N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sorbi^{89a,89b}, M. Sosebee⁷, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò³⁴, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, E. Spiriti^{134a}, R. Spiwoks²⁹, M. Spousta¹²⁶, T. Spreitzer¹⁵⁸, B. Spurlock⁷, R.D. St. Denis⁵³, T. Stahl¹⁴¹, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka²⁹, R.W. Stanek⁵, C. Stancu^{134a}, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁹¹, A. Staude⁹⁸, P. Stavina^{144a}, G. Stavropoulos¹⁴, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁴¹, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², K. Stevenson⁷⁵, G.A. Stewart²⁹, J.A. Stillings²⁰, T. Stockmanns²⁰, M.C. Stockton²⁹, K. Stoerig⁴⁸, G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷³, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹, J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁴, D.A. Soh^{151,q}, D. Su¹⁴³, H.S. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁶, T. Sugimoto¹⁰¹, C. Suhr¹⁰⁶, K. Suita⁶⁷, M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{3d}, T. Sumida²⁹, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, S. Sushkov¹¹, G. Susinno^{36a,36b}, M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁶, M. Svatos¹²⁵, Yu.M. Sviridov¹²⁸, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶, B. Szeless²⁹, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴¹, A. Taffard¹⁶³, R. Tahirout^{159a}, A. Taga¹¹⁷, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁴, R. Takashima⁶⁹, H. Takeda⁶⁷, T. Takeshita¹⁴⁰, M. Talby⁸³, A. Talyshev¹⁰⁷, M.C. Tamsett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁶, Y. Tanaka¹⁰⁰, K. Tani⁶⁷, N. Tannoury⁸³, G.P. Tappern²⁹, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁴, G.F. Tartarelli^{89a}, P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, C. Taylor⁷⁷, F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, S. Terada⁶⁶, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Terwort^{41,o}, M. Testa⁴⁷, R.J. Teuscher^{158,j}, J. Thadome¹⁷⁴, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸, M. Thioye¹⁷⁵, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson⁸⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, E. Thomson¹²⁰, M. Thomson²⁷, R.P. Thun⁸⁷, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov¹⁰⁷, C.J.W.P. Timmermans¹⁰⁴, P. Tipton¹⁷⁵, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, J. Tobias⁴⁸, B. Toczek³⁷, T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁶, S. Tokár^{144a}, K. Tokunaga⁶⁷, K. Tokushuku⁶⁶, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins¹⁴, K. Toms¹⁰³, G. Tong^{32a}, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁵, I. Torchiani²⁹, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torró Pastor¹⁶⁷, J. Toth^{83,x}, F. Touchard⁸³, D.R. Tovey¹³⁹, D. Traynor⁷⁵, T. Trefzger¹⁷³, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvold⁷⁸, T.N. Trinh⁷⁸, M.F. Tripiana⁷⁰, W. Trischuk¹⁵⁸, A. Trivedi^{24,w}, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trottier-McDonald¹⁴², A. Trzupek³⁸, C. Tsarouchas²⁹, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehka⁹⁰, D. Tsionou⁴, G. Tsiopolitis⁹, V. Tsiskaridze⁴⁸, E.G. Tskhadadze⁵¹, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁴, J.-W. Tsung²⁰, S. Tsuno⁶⁶, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁴, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, H. Tyrvalinen²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, D.G. Underwood⁵, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁶, D. Urbaniec³⁴, E. Urkovsky¹⁵³, P. Urrejola^{31a}, G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, J. Valenta¹²⁵, P. Valente^{132a}, S. Valentinetti^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster²⁹, B. Van Eijk¹⁰⁵, N. van Eldik⁸⁴, P. van Gemmeren⁵, Z. van Kesteren¹⁰⁵, I. van Vulpen¹⁰⁵, W. Vandelli²⁹, G. Vandoni²⁹, A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, F. Varela Rodriguez²⁹, R. Vari^{132a}, E.W. Varnes⁶, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, C. Vellidis⁸, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura¹³⁸, M. Venturi⁴⁸, N. Venturi¹⁶, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴³, M.C. Vetterli^{142,e}, I. Vichou¹⁶⁵, T. Vickey^{145b,z}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincker²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁵, M. Virchaux^{136,*}, J. Virzi¹⁴, O. Vitells¹⁷¹, M. Viti⁴¹, I. Vivarelli⁴⁸, F. Vives Vaque¹¹, S. Vlachos⁹, M. Vlasak¹²⁷, N. Vlasov²⁰, A. Vogel²⁰, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶, A.P. Vorobiev¹²⁸, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁴, J.H. Vosseveld⁷³, N. Vranjes^{12a}, M. Vranjes Milosavljevic^{12a}, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁸¹, R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁴, P. Wagner¹²⁰,

H. Wahlen¹⁷⁴, J. Wakabayashi¹⁰¹, J. Walbersloh⁴², S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸,
W. Walkowiak¹⁴¹, R. Wall¹⁷⁵, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷², H. Wang^{32b,aa}, J. Wang¹⁵¹,
J. Wang^{32d}, J.C. Wang¹³⁸, R. Wang¹⁰³, S.M. Wang¹⁵¹, A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸,
P.M. Watkins¹⁷, A.T. Watson¹⁷, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷,
J. Weber⁴², M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴,
C. Weiser⁴⁸, H. Wellenstein²², P.S. Wells²⁹, M. Wen⁴⁷, T. Wenaus²⁴, S. Wendler¹²³, Z. Weng^{151,q},
T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, M. Wessels^{58a},
C. Weydert⁵⁵, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, S.P. Whitaker²¹, A. White⁷, M.J. White⁸⁶, S. White²⁴,
S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶¹, F. Wicek¹¹⁵, D. Wicke¹⁷⁴, F.J. Wickens¹²⁹,
W. Wiedenmann¹⁷², M. Wielers¹²⁹, P. Wienemann²⁰, C. Wiglesworth⁷⁵, L.A.M. Wiik⁴⁸,
P.A. Wijeratne⁷⁷, A. Wildauer¹⁶⁷, M.A. Wildt^{41,o}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸,
E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷,
I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸, H. Wolters^{124a,h},
G. Wooden¹¹⁸, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸⁴, K. Wraight⁵³, C. Wright⁵³, B. Wrona⁷³,
S.L. Wu¹⁷², X. Wu⁴⁹, Y. Wu^{32b,ab}, E. Wulf³⁴, R. Wunstorff⁴², B.M. Wynne⁴⁵, L. Xaplanteris⁹, S. Xella³⁵,
S. Xie⁴⁸, Y. Xie^{32a}, C. Xu^{32b,ac}, D. Xu¹³⁹, G. Xu^{32a}, B. Yabsley¹⁵⁰, M. Yamada⁶⁶, A. Yamamoto⁶⁶,
K. Yamamoto⁶⁴, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁷,
Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶¹, Y. Yang^{32a}, Z. Yang^{146a,146b}, S. Yanush⁹¹, W.-M. Yao¹⁴,
Y. Yao¹⁴, Y. Yasu⁶⁶, G.V. Ybeles Smit¹³⁰, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosofmiya¹²³, K. Yorita¹⁷⁰,
R. Yoshida⁵, C. Young¹⁴³, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu^{32c,ac}, L. Yuan^{32a,ad}, A. Yurkewicz¹⁴⁸,
V.G. Zaets¹²⁸, R. Zaidan⁶³, A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, Yo.K. Zalite¹²¹, L. Zanello^{132a,132b},
P. Zarzhitsky³⁹, A. Zaytsev¹⁰⁷, C. Zeitnitz¹⁷⁴, M. Zeller¹⁷⁵, A. Zemla³⁸, C. Zender²⁰, A.V. Zenin¹²⁸,
O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zenonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d},
D. Zhang^{32b,aa}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b},
A. Zhemchugov⁶⁵, S. Zheng^{32a}, J. Zhong^{151,ae}, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹,
J. Zhu⁸⁷, Y. Zhu¹⁷², X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶¹, R. Zimmermann²⁰, S. Zimmermann²⁰,
S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷²,
A. Zoccoli^{19a,19b}, Y. Zolnierowski⁴, A. Zsenei²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalinski²⁹

¹ University at Albany, Albany, NY, United States² Department of Physics, University of Alberta, Edmonton, AB, Canada³ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara;^(d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey⁴ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France⁵ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States⁶ Department of Physics, University of Arizona, Tucson, AZ, United States⁷ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States⁸ Physics Department, University of Athens, Athens, Greece⁹ Physics Department, National Technical University of Athens, Zografou, Greece¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan¹¹ Institut de Física d'Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain¹² (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia¹³ Department for Physics and Technology, University of Bergen, Bergen, Norway¹⁴ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States¹⁵ Department of Physics, Humboldt University, Berlin, Germany¹⁶ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland¹⁷ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom¹⁸ (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep;^(d) Department of Physics, Istanbul Technical University, Istanbul, Turkey¹⁹ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy²⁰ Physikalisches Institut, University of Bonn, Bonn, Germany²¹ Department of Physics, Boston University, Boston, MA, United States²² Department of Physics, Brandeis University, Waltham, MA, United States²³ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil²⁴ Physics Department, Brookhaven National Laboratory, Upton, NY, United States²⁵ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania²⁶ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina²⁷ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom²⁸ Department of Physics, Carleton University, Ottawa, ON, Canada²⁹ CERN, Geneva, Switzerland³⁰ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States³¹ (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile³² (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui;^(c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China³³ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

- ³⁴ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁵ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁶ ^(a) INFN Gruppo Collegato di Cosenza; ^(b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁷ Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ³⁹ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴⁰ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴¹ DESY, Hamburg and Zeuthen, Germany
- ⁴² Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴³ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁴ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁵ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁵⁸ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;
- ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Science, Hiroshima University, Hiroshima, Japan
- ⁶⁰ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶¹ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶² Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶³ University of Iowa, Iowa City, IA, United States
- ⁶⁴ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁶ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁷ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁸ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁹ Kyoto University of Education, Kyoto, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ Department of Physics, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹ Fysiska Institutionen, Lunds Universitet, Lund, Sweden
- ⁸⁰ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸¹ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸² School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁵ Department of Physics, McGill University, Montreal, QC, Canada
- ⁸⁶ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁸⁹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹³ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁷ Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York, NY, United States
- ¹⁰⁹ Ohio State University, Columbus, OH, United States
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States

- 112 Department of Physics, Oklahoma State University, Stillwater, OK, United States
 113 Palacký University, RCPTM, Olomouc, Czech Republic
 114 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
 115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
 116 Graduate School of Science, Osaka University, Osaka, Japan
 117 Department of Physics, University of Oslo, Oslo, Norway
 118 Department of Physics, Oxford University, Oxford, United Kingdom
 119 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
 120 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
 121 Petersburg Nuclear Physics Institute, Gatchina, Russia
 122 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
 123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
 124 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; ^(b) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
 125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
 126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
 127 Czech Technical University in Prague, Praha, Czech Republic
 128 State Research Center Institute for High Energy Physics, Protvino, Russia
 129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
 130 Physics Department, University of Regina, Regina, SK, Canada
 131 Ritsumeikan University, Kusatsu, Shiga, Japan
 132 ^(a) INFN Sezione di Roma I; ^(b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
 133 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
 134 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
 135 ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390, Marrakech 40000; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
 138 Department of Physics, University of Washington, Seattle, WA, United States
 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
 140 Department of Physics, Shinshu University, Nagano, Japan
 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
 142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
 143 SLAC National Accelerator Laboratory, Stanford, CA, United States
 144 ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
 145 ^(a) Department of Physics, University of Johannesburg, Johannesburg; ^(b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
 146 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
 148 Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States
 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
 150 School of Physics, University of Sydney, Sydney, Australia
 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
 152 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
 158 Department of Physics, University of Toronto, Toronto, ON, Canada
 159 ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
 160 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
 161 Science and Technology Center, Tufts University, Medford, MA, United States
 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
 163 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
 164 ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Fisica, Università di Udine, Udine, Italy
 165 Department of Physics, University of Illinois, Urbana, IL, United States
 166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
 167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
 168 Department of Physics, University of British Columbia, Vancouver, BC, Canada
 169 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
 170 Waseda University, Tokyo, Japan
 171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
 172 Department of Physics, University of Wisconsin, Madison, WI, United States
 173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
 174 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
 175 Department of Physics, Yale University, New Haven, CT, United States
 176 Yerevan Physics Institute, Yerevan, Armenia
 177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

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

^b Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

^d Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^e Also at TRIUMF, Vancouver, BC, Canada.

^f Also at Department of Physics, California State University, Fresno, CA, United States.

- ^g Also at Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland.
- ^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy.
- ^j Also at Institute of Particle Physics (IPP), Canada.
- ^k Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
- ^l Also at Louisiana Tech University, Ruston, LA, United States.
- ^m Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
- ⁿ Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- ^o Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^p Also at Manhattan College, New York, NY, United States.
- ^q Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
- ^r Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^s Also at High Energy Physics Group, Shandong University, Shandong, China.
- ^t Also at California Institute of Technology, Pasadena, CA, United States.
- ^u Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^v Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
- ^w Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^x Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ^y Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
- ^z Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- ^{aa} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ab} Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- ^{ac} Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France.
- ^{ad} Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
- ^{ae} Also at Department of Physics, Nanjing University, Jiangsu, China.
- * Deceased.