



Study of the hard double-parton scattering contribution to inclusive four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration*

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ABSTRACT

The inclusive production of four isolated charged leptons in pp collisions is analysed for the presence of hard double-parton scattering, using 20.2 fb^{-1} of data recorded in the ATLAS detector at the LHC at centre-of-mass energy $\sqrt{s} = 8$ TeV. In the four-lepton invariant-mass range of $80 < m_{4\ell} < 1000$ GeV, an artificial neural network is used to enhance the separation between single- and double-parton scattering based on the kinematics of the four leptons in the final state. An upper limit on the fraction of events originating from double-parton scattering is determined at 95% confidence level to be $f_{\text{DPS}} = 0.042$, which results in an estimated lower limit on the effective cross section at 95% confidence level of 1.0 mb. © 2019 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The parton–parton scattering at the origin of hard processes in pp interactions is accompanied by proton-remnant fragments that contribute to the hadronic final state through the so-called underlying event. As first pointed out by Sjöstrand and van Zijl [1], one source of the underlying-event activity, particularly in the high-energy regime of the LHC, is multi-parton interactions (MPI): interactions of pairs of partons from the interacting protons which occur simultaneously with the hard process. In high-energy pp interactions, where the density of low- x partons is high, there is enough energy to produce hard multi-parton interactions. The simplest example is hard double-parton scattering (DPS), where two partons from each proton interact with each other leading to perturbative final states.

The interest in studying DPS is twofold. Firstly, the probability of occurrence of DPS and the potential correlations between the products of these two perturbative interactions provide valuable information about the dynamics of the partonic structure of the proton (see Ref. [2] and references therein). Secondly, DPS processes may also constitute a background to reactions proceeding through single-parton scattering (SPS). An example is the production of four charged leptons in the final state, addressed in this Letter. This reaction is dominated by the SPS production of two $Z^{(*)}$ bosons, followed by subsequent leptonic decays. The $Z^{(*)}$ no-

tation indicates the production of on- or off-shell Z bosons (Z and Z^*), or the production of off-shell photons (γ^*). However, the four leptons could also be produced as the result of two Drell–Yan processes occurring simultaneously, potentially distorting the measurements of prompt-lepton production.

For a process $pp \rightarrow A + B + X$, the expected DPS cross section for producing states A and B in two independent scatterings, σ_{DPS}^{AB} , may be estimated from the following formula [3–5] (see also Ref. [6] for a detailed derivation):

$$\sigma_{\text{DPS}}^{AB} = \frac{k}{2} \frac{\sigma_{\text{SPS}}^A \sigma_{\text{SPS}}^B}{\sigma_{\text{eff}}}, \quad (1)$$

where $\sigma_{\text{SPS}}^{A(B)}$ denotes the production cross section of state $A(B)$ in a single-parton scattering, the symmetry factor k depends on whether the two scatterings lead to the same final state ($A = B$, $k = 1$) or different final states ($A \neq B$, $k = 2$), and σ_{eff} represents the effective transverse overlap area containing the interacting partons.

For most of the existing measurements [7–21], σ_{eff} fluctuates around 15 mb. However, for the associated production of quarkonia $J/\psi J/\psi$ or $J/\psi \Upsilon$, σ_{eff} is systematically lower [22–25] than for all other investigated processes. This might indicate that σ_{eff} is not universal and that there are spatial fluctuations of the parton densities in the proton, which may favour certain final states over others [26,27]. The concept of geometric fluctuations in the spatial parton densities has also been invoked [28] to explain the collective phenomena observed in high-multiplicity proton–

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

proton and proton–nucleus interactions [29–32]. In pp interactions at $\sqrt{s} = 8$ TeV [33], the double Drell–Yan contribution may add 0.3% to the yield of four leptons in the invariant-mass range $80 < m_{4\ell} < 1000$ GeV, using Eq. (1) with $\sigma_{\text{eff}} = 15$ mb. The latter is obtained from calculations of the Drell–Yan cross section in the phase space of the measurement in next-to-leading-order (NLO) QCD with POWHEG-Box [34–36].

Since double Drell–Yan production is driven by quark–antiquark annihilation, while most of the previously explored DPS processes are driven by gluon–gluon scattering, and the final state of four charged leptons constitutes the golden channel for the studies of Higgs boson properties, $H \rightarrow Z^{(*)}Z^{(*)} \rightarrow 4\ell$, a study of a possible DPS contribution to the production of four isolated charged leptons at $\sqrt{s} = 8$ TeV is warranted. The analysis presented in this Letter closely follows a previous analysis of this final state [33], but extends it to consider DPS.

2. ATLAS detector

The ATLAS detector [37] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly full coverage in solid angle.¹

It consists of an inner tracking detector (ID) system surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating superconducting toroid magnets. During Run 1 of the LHC the ID consisted of a pixel detector closest to the beam-pipe, followed by a silicon strip detector and a transition radiation tracker. This ID system, operating in a 2 T axial magnetic field, provides the tracking of charged particles within the pseudorapidity range $|\eta| < 2.5$. The calorimeter system, which covers the range $|\eta| < 4.9$, includes in the barrel region a high-granularity lead/liquid-argon (LAr) barrel electromagnetic (EM) calorimeter ($|\eta| < 1.5$) and a steel/scintillator-tile hadronic calorimeter ($|\eta| < 1.7$). In the end-cap ($1.5 < |\eta| < 3.2$) and forward ($3.2 < |\eta| < 4.9$) regions, the EM calorimeter and the hadronic calorimeter are made of LAr active layers with either copper or tungsten as the absorber material. The muon spectrometer constitutes the outermost detector and includes fast trigger chambers covering the region $|\eta| < 2.4$ and high-precision tracking chambers covering $|\eta| < 2.7$. A three-level trigger system [38] was used to select events to be recorded.

3. Monte Carlo event samples

In SPS events, the four-lepton events correspond to the production and subsequent decay of resonant Z or Higgs bosons, or to the production of the continuum $Z^{(*)}Z^{(*)}$ system. In the case of DPS, the four leptons are decay products of two $Z^{(*)}$ bosons that are produced in two distinct parton–parton scatterings within the same pp interaction.

The Monte Carlo samples are unchanged with respect to Ref. [33]. The SPS $q\bar{q} \rightarrow 4\ell$ was simulated with the POWHEG-Box (revision 2330) [34–36] Monte Carlo (MC) program, which is based on perturbative QCD calculations at NLO. The four-lepton production through the qg initial state is included as part of the NLO contributions to the $q\bar{q}$ process. The parton distribution functions (PDFs) of the CT10NLO [39] set were used. The $gg \rightarrow 4\ell$

events corresponding to the continuum $Z^{(*)}Z^{(*)}$ production were generated with MCFM 6.1 [40] at leading order (LO) in QCD, using the CT10NNLO [41] set of PDFs, and the cross sections were corrected for higher-order effects using the ratio of NLO to LO cross sections (the so-called K -factors) [42]. The on-shell Higgs boson production was simulated with POWHEG-Box at NLO QCD, using the CT10NLO PDFs, in the case of gluon–gluon fusion and vector-boson fusion, and with LO PYTHIA 8 [43] in the case of vector-boson associated production (VH) and top-pair associated production ($t\bar{t}H$). The event yield of on-shell Higgs boson was normalised to the higher-order corrected cross section [44]. The events with off-shell Higgs boson production were simulated with the LO MADGRAPH 5.1.5.12 [45] generator via vector-boson fusion and vector-boson scattering processes, including their interference. For the LO PYTHIA 8 and MADGRAPH generators, the LO version of CTEQ6L1 PDFs [46] was used.

The MC generators listed above were interfaced to PYTHIA 8 for parton showering, except MADGRAPH which was interfaced to PYTHIA 6 [47]. The underlying-event parameter values belong to the AU2 [48] tune.

The DPS events that contribute to the 4ℓ production were simulated with PYTHIA 8.175 using the LO version of CTEQ6L1 PDFs.

Background events may originate from Z + jets, $t\bar{t}$, diboson (ZW , $Z\gamma$), triboson VVV ($V = Z, W$), VH , and Z + top ($t\bar{t}$ and t) processes.

The production of Z + jets events, including the light- and heavy-flavour contributions, was simulated with ALPGEN 2.1.4 [49], using the Perugia2011C [50] tune. The $Z\gamma$ production was modelled with SHERPA 1.4.5 [51]. Background $t\bar{t}$ events were generated with POWHEG-Box using the Perugia2011C tune. The ZH events, with subsequent decays $Z \rightarrow \ell\ell$ and $H \rightarrow VV^*$ (with two leptons and two neutrinos or two leptons and two jets in the final state), were generated with PYTHIA 8, using the AU2 tune. The ZW and tZ processes were simulated with SHERPA and MADGRAPH respectively, with the latter using the AUET2B tune [52]. The background contribution from VVV and $t\bar{t}Z$ was modelled with MADGRAPH, using the AUET2B tune. The MC generators for background simulation used the LO version of the CTEQ6L1 PDF set, except SHERPA, which used the CT10 PDF set.

The largest contributions to the background, originating from $Z + b\bar{b}$ jets and $t\bar{t}$ production, were estimated in Ref. [33] from the respective MC samples normalised to the data in selected control regions. The remaining background contributions were directly extracted from the MC expectations.

Additional pp interactions occurring in the same and neighbouring bunch crossings (pile-up) were also simulated, using the PYTHIA 8 MC generator, with the A2 [53] tune and MSTW 2008 LO [54] PDF set. The MC samples were reweighted to reproduce the distribution of the mean number of pp interactions per bunch crossing observed in the data. The estimated number of events with two $Z^{(*)}$ bosons produced in the same bunch crossing with less than 1 cm separation along the beam axis is negligible compared to the DPS expectations.

Monte Carlo events were passed through the ATLAS detector simulation [55], which is based on the GEANT4 [56] framework, and which includes simulation of the trigger selection. The MC events were reconstructed and selected offline using the same software and selections as for the data.

4. Event selection

The dataset and the event selection are unchanged with respect to Ref. [33]. The updated luminosity of the analysed sample is 20.2 fb^{-1} . The events were selected online using single-lepton or dilepton triggers. The single-lepton trigger required the transverse

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

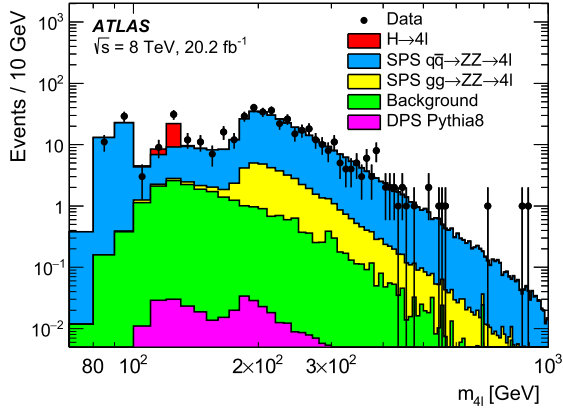


Fig. 1. The distribution of the four-lepton invariant mass, $m_{4\ell}$. The data (black dots) are compared with the sum of signal and background MC expectations (filled coloured histograms). Also shown is the expected contribution of DPS from PYTHIA 8.

energy of the electron candidate or the transverse momentum of the muon candidate to be above 24 GeV. The dielectron trigger had the same threshold of 12 GeV for both electron candidates. The dimuon trigger required either two muons with transverse momentum above 13 GeV or one above 18 GeV and the other above 8 GeV. An electron–muon trigger was also used with thresholds at 12 GeV for electrons and 8 GeV for muons.

The final sample consists of events with at least four leptons, where each lepton is either an electron or a muon. The four leptons are required to form two same-flavour (electrons or muons) opposite-charge (SFOC) lepton pairs. The pair with the invariant mass closer to the mass of the Z boson is called the leading pair, and the other pair is the sub-leading one. The invariant mass of the leading pair is restricted to the range $50 < m_{\text{leading}} < 120$ GeV, while for the sub-leading pair the mass requirement is $12 < m_{\text{sub-leading}} < 120$ GeV. A J/ψ veto is applied such that for any SFOC lepton combination the invariant mass of the dilepton, $m_{2\ell}$, must be greater than 5 GeV. Only events with the four-lepton invariant mass in the range $80 < m_{4\ell} < 1000$ GeV are selected. The transverse momentum of dileptons, $p_T^{\ell+\ell^-}$, is required to be above 2 GeV. Selected leptons, ordered in descending order of transverse momentum, are required to have transverse momenta p_T above 20, 15, 10 (8 if muon), and 7 (6 if muon) GeV. The leptons are selected within the pseudorapidity range $|\eta| < 2.5$ in the case of electrons and $|\eta| < 2.7$ in the case of muons. In order to have well-measured leptons, a lepton separation requirement is imposed, such that the distance between any two leptons in the η – ϕ space, ΔR , is required to fulfil the condition $\Delta R > 0.1$ (0.2) for same-flavour (different-flavour) leptons. Each event is required to have the triggering lepton(s) matched to one or two of the selected leptons.

The data sample, after all selections, contains 476 events. The resulting data and MC distributions of the four-lepton invariant mass are shown in Fig. 1. For completeness, the figure also includes the DPS contribution of 0.4 events predicted by the PYTHIA 8.175 simulation.

5. DPS signal extraction

The assumption that in DPS the two scatters are distinct implies that, in the DPS four-lepton final states, the two leptons of each dilepton will tend to be balanced in p_T and therefore back-to-back in the azimuthal angle ϕ , due to the dominance of low- p_T $Z^{(*)}$ production. In the SPS case, the leading and sub-leading pairs are expected to balance each other in p_T .

Based on the experience gained in the study of four-jet final states [57], in order to distinguish between DPS events and SPS events, the distributions of the following kinematic variables of the four leptons are considered:

$$\begin{aligned} \Delta p_{T,ij} &= \frac{|\vec{p}_{T,i} + \vec{p}_{T,j}|}{p_{T,i} + p_{T,j}}, & \Delta\phi_{ij} &= |\phi_i - \phi_j|, \\ \Delta y_{ij} &= |y_i - y_j|, & i, j &= 1, 2, 3, 4, \quad i \neq j \\ \Delta_{ijklm} &= |\phi_{i+j} - \phi_{k+m}|, & ijkm &= 1234, 1324, 1423. \end{aligned} \quad (2)$$

Here, $\vec{p}_{T,i}$ is the transverse momentum component of the i -th lepton ($i = 1, 2, 3, 4$), and ϕ_i and y_i are the azimuthal angle and the rapidity of the i -th lepton, respectively. The angle ϕ_{i+j} is the azimuthal angle of the momentum vector composed by the sum of momenta of leptons i and j . Leptons 1 and 2 form the leading dilepton. The lepton ordering is chosen such that $p_{T,1} > p_{T,2}$ and $p_{T,3} > p_{T,4}$.

The distributions of the variables $\Delta p_{T,12}$, $\Delta\phi_{13}$, Δy_{13} , and Δ_{1234} are presented in Fig. 2(a)–(d). The distribution of $\Delta p_{T,12}$ peaks around 0.1 for simulated DPS events, while the simulated SPS events are more evenly distributed across the range [0,1]. This demonstrates that, as expected, two leptons coming from the same Z candidate in DPS balance each other in p_T , while in SPS the pairwise p_T balance is not dominant. This is again demonstrated in the $\Delta\phi_{13}$ distribution, where leptons 1 and 3 are decorrelated in $\Delta\phi$ for DPS, while for the SPS events these leading- p_T decay leptons tend to be back-to-back in ϕ , because they originate from the two Z bosons, which themselves are expected to be back-to-back in ϕ . The Δy_{13} distribution shows that leptons associated to different dileptons tend to be more separated in rapidity in DPS than in SPS. The back-to-back configurations of the two Z candidates in the case of SPS, and their decorrelation in the case of DPS is explicitly demonstrated in the distribution of the azimuthal angle between two Z candidates, Δ_{1234} .

The difference between the topologies of SPS and DPS events is used to train an artificial neural network (ANN) to discriminate between the DPS and non-DPS classes, where the latter corresponds to SPS and background events.

The training is performed with the ANN available in the ROOT [58] implementation of a feed-forward multilayer perceptron. The Broyden–Fletcher–Goldfarb–Shanno supervised learning algorithm [59–62] is used in the training. The input layer contains 21 neurons, corresponding to the variables listed in Eq. (2), and the output layer consists of one neuron. As the result of optimising the convergence and the performance of the ANN, a configuration of 30 and 9 neurons is adopted for the first and second hidden layer, respectively. The output of the ANN, ξ_{DPS} , is a number distributed between 0 and 1, which represents the likelihood for an event to belong to the DPS class.

The event weights are chosen such that during the training procedure the effective numbers of SPS $q\bar{q}$ -initiated events, $g\bar{g}$ -initiated events and background $Z + b\bar{b}$ jets events are in the ratio 1 : 1 : 1. The SPS $g\bar{g}$ -initiated events tend to spill over into the DPS signal region, and a better separation between the SPS and DPS classes is achieved by increasing their weight in the minimisation of the error function. Similarly, the effective contribution of $Z + b\bar{b}$ jets events is increased for the ANN training to distinguish them better from the DPS ones, as the kinematics of the $Z + b\bar{b}$ jets background subprocess has features similar to DPS. The effective numbers of events for DPS and non-DPS events are equal. Each MC set is split randomly into two subsets having approximately the same number of events. One subset is used for the ANN training, while the other is used to validate the performance of the ANN and to determine the number of training epochs, so as

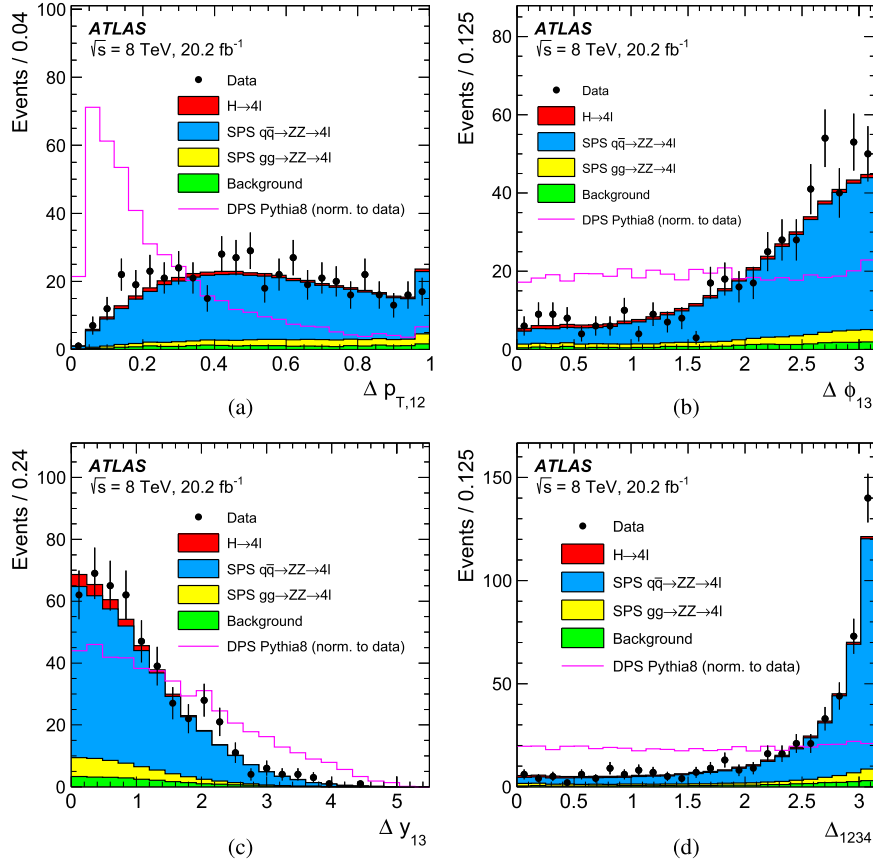


Fig. 2. Distributions of the discriminating variables (a) $\Delta p_{T,12}$, (b) $\Delta\phi_{13}$, (c) Δy_{13} , and (d) Δ_{1234} . The definition of variables is given in Eq. (2). Also plotted are the MC expectations for SPS and DPS, where the latter is normalised to the number of observed data events in order to make it clearly visible.

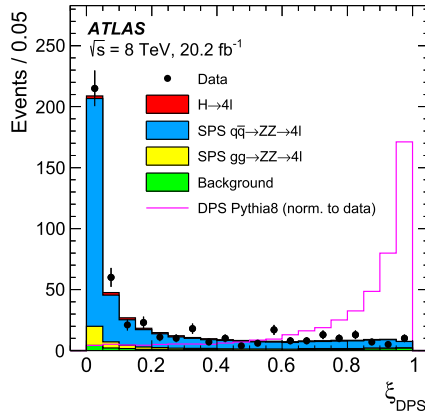


Fig. 3. The distribution of the output variable of the artificial neural network, ξ_{DPS} , shown separately for the data, SPS, background, and DPS distributions.

to reach the best possible level of discrimination while preventing overtraining.

The trained ANN is applied to data events, and the resulting distribution of ξ_{DPS} is shown in Fig. 3, together with the corresponding DPS, SPS and background MC distributions. The DPS MC events form a peak around $\xi_{\text{DPS}} = 1$ and the SPS and background events form a peak at $\xi_{\text{DPS}} = 0$, as expected. A similar peak at $\xi_{\text{DPS}} = 0$ is observed in data events, with no indication of a substantial contribution of double-parton scattering at $\xi_{\text{DPS}} = 1$.

In order to quantify the level of the potential DPS contribution in the data, the variable f_{DPS} is introduced, defined as the ratio of

the number of DPS events, $N_{\text{DPS},4\ell}$, to the sum of the DPS and SPS ($N_{\text{SPS},4\ell}$):

$$f_{\text{DPS}} = \frac{N_{\text{DPS},4\ell}}{N_{\text{SPS},4\ell} + N_{\text{DPS},4\ell}}.$$

The MC template fit of the sum of the DPS, SPS and background contributions to the data yields $f_{\text{DPS}} = -0.009 \pm 0.017$ with a χ^2 per degree of freedom $\chi^2/\text{dof} = 8.6/9$. Since the result is consistent with zero, an upper limit on f_{DPS} is extracted, as described in Section 7.1.

For the ANN performance to be robust and independent of the DPS model, it is best to have a DPS training sample with no inherent correlations between the initial partons or the final states. The DPS model in PYTHIA [63–65] used in the analysis contains some correlations between the initial-state partons, implied by conservation of flavour and by the proton momentum sum-rule, as well as correlations due to inherent primordial transverse momentum of the partons and interleaved initial-state radiation. These effects are expected to be weak in the phase space of the present analysis (low-momentum partons and large transverse momenta of the final-state leptons). No correlations are expected in the production of the Drell–Yan final states.

To test this assumption of a very weak correlation between two subscatterings in the PYTHIA DPS model, the MC training sample was compared with a sample of two randomly overlaid dilepton events, where any correlation is eliminated by construction. Such a sample was made by overlaying dilepton events selected in the data, with the selection driven by the four-lepton phase space. Each dilepton event was required to have two selected leptons forming an SFOC pair with transverse momenta

$p_T^{\ell_1, \ell_2} > 20, 15$ GeV to account for the trigger conditions under which the dilepton data were collected. The same single-lepton, double-electron and double-muon triggers were used as in the selection of the four-lepton sample. An event was rejected if there was a third lepton with $p_T > 7$ GeV (6 GeV for muons). The pairs of events were chosen randomly and overlaid by adding the lepton four-vectors of one event to the other. The distance between the primary vertices along the z -axis for the two events was required to be smaller than 1 cm. After the overlay, the same four-lepton selection was applied as described in Section 4, but the trigger configuration of the available dilepton datasets required an increase in the lepton p_T thresholds. They were chosen to be 20, 20, 15, and 15 GeV for leptons ordered in descending order of p_T . To have a valid comparison within the same phase space between the overlaid dileptons and the PYTHIA 8 sample, the same selection on lepton p_T was also applied to the latter. The distributions of discriminating variables were compared, as were the distributions of ξ_{DPS} , obtained with the ANN trained on PYTHIA 8. Very good agreement between PYTHIA 8 and the overlaid data was observed, confirming the initial assumption of a very weak correlation between the two scatterings in the PYTHIA DPS model with no effect on the analysis.

The value of f_{DPS} is extracted using detector-level distributions. To test how well this result agrees with the parton-level value, $f_{\text{DPS}}^{\text{parton}}$, several pseudo-datasets were constructed by mixing DPS, SPS and background samples with a number of predefined parton-level values of $f_{\text{DPS}}^{\text{parton}} = 0.01, 0.03, 0.05, 0.1, \text{ and } 0.3$. The number of background events in all mixtures was the same as expected in the selected four-lepton data sample. The corresponding value of f_{DPS} at the detector level was then determined by fitting the detector-level distributions and compared with the input $f_{\text{DPS}}^{\text{parton}}$ value. It was found that the fitted value of f_{DPS} is systematically lower than $f_{\text{DPS}}^{\text{parton}}$ due to slightly different detector acceptances for DPS and SPS events. However, the two quantities agree within 2%.

6. Systematic uncertainties

The following sources of systematic uncertainty are considered:

- The experimental systematic uncertainty, which includes the uncertainties of the electron and muon energy scales, the uncertainty of the energy and momentum resolution, and of the trigger, reconstruction and identification efficiencies [66,67].
- The uncertainty due to the model choice for the SPS process, which is evaluated by considering the effect of the variation of the fractions of $q\bar{q}$ - and $g\bar{g}$ -initiated subprocesses, which are modelled with different MC generators, as described in Section 3. For the determination of the range of variation, these fractions are fitted to the $m_{4\ell}$ distribution in the data, keeping the fraction of background events unchanged. The fraction values of $q\bar{q}$ - and $g\bar{g}$ -initiated subprocesses were varied between the nominal values and the values obtained from the fit to the $m_{4\ell}$ distribution.
- The uncertainty in the background modelling, which is estimated by varying the contributions of various background subprocesses according to the uncertainty of their normalisations obtained in Ref. [33].

No uncertainty is assigned to the DPS model, since the kinematic distributions agree well between the PYTHIA 8 DPS model and the assumption of two independent interactions as represented by the overlaid dilepton data.

The combined effect of all systematic uncertainties, of which the variation of the $Z + b\bar{b}$ jets background is the dominant uncertainty, is about 20% of the statistical uncertainty on the fitted

value of f_{DPS} . The effect of systematic uncertainties is therefore neglected when setting the upper limit on f_{DPS} .

The validity of neglecting the systematic uncertainties was also checked with pseudo-experiments: the contents of data bins were varied according to a Poisson distribution and those of MC profile histograms were varied according to the systematic uncertainty, sampling the variations according to Gaussian distribution in the corresponding nuisance parameter, taking into account the correlation between the bins where appropriate. For each set of varied data and MC histograms, the fit of f_{DPS} was performed. The resulting distribution of f_{DPS} was compared with that obtained with systematic uncertainties neglected. The comparison showed no significant difference between the two distributions.

7. Results

7.1. Upper limit on f_{DPS}

The upper limit on f_{DPS} is determined using the distributions of the ξ_{DPS} variable in data, SPS, DPS, and background MC samples. The statistical method to interpret the data uses the test statistic for upper limits, q_μ , based on the profile likelihood ratio as described in Ref. [68],

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu. \end{cases}$$

Here μ is the signal strength and $\lambda(\mu)$ is the profile likelihood ratio,

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})},$$

where θ is the number of non-DPS events and constitutes a nuisance parameter. The values $\hat{\mu}$ and $\hat{\theta}$ are maximum-likelihood estimators. The value of $\hat{\theta}$ maximises L for a given value of μ . The parameter of interest, μ , is defined to be equal to the f_{DPS} variable, $\mu = f_{\text{DPS}}$. Thus $\mu = 0$ corresponds to no DPS contribution, while $\mu = 1$ means that the four-lepton sample consists exclusively of DPS events. The procedure is that the data distribution is fitted with the sum of background, SPS and DPS histograms using the maximum-likelihood method. The upper limit is extracted using the CL_s method [69] from distributions of the test statistic for various hypothesised values of μ . The test-statistic distribution is obtained from an ensemble of pseudo-experiments. The shape of the test-statistic distribution agrees with the asymptotic formulae of Ref. [68]. The value of the CL_s upper limit on f_{DPS} found with this method at 95% confidence level (CL) is 0.042.

7.2. Lower limit on the effective cross section

The upper limit on f_{DPS} can be transformed into a lower limit on σ_{eff} by using Eq. (1). In order to perform this calculation, several inputs to the formula have to be determined.

The fiducial cross section for inclusive four-lepton production [33] is

$$\sigma_{4\ell} = 32.0 \pm 1.6 (\text{stat.}) \pm 0.7 (\text{syst.}) \pm 0.9 (\text{lumi.}) \text{ fb.}$$

The value of the symmetry factor $k/2$ in Eq. (1) is well defined for the case of $2e + 2\mu$ or $2\mu + 2e$ final states, $k/2 = 1$. For the $4e$ or 4μ final states, $k/2$ is well defined only in the case of completely overlapping ($k/2 = 1/2$) or fully exclusive ($k/2 = 1$) dilepton phase spaces. Therefore, the dilepton phase space is divided into 40 mutually exclusive regions. The boundaries of these regions are driven

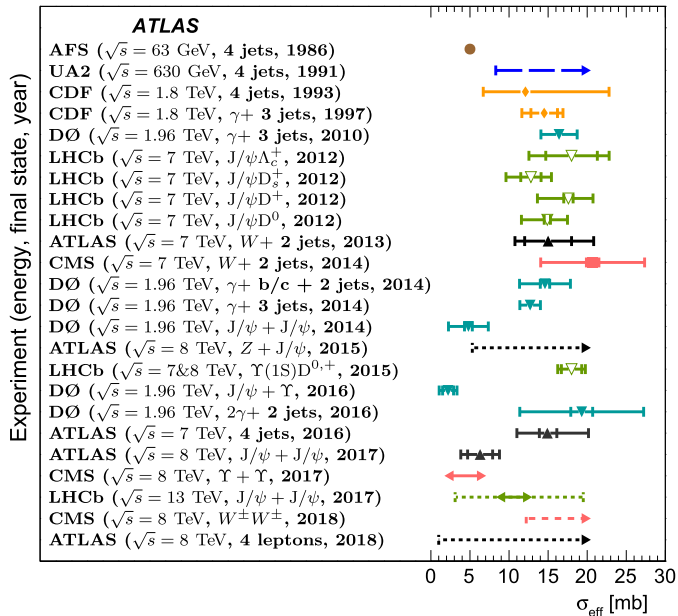


Fig. 4. Summary of measurements and limits on the effective cross section, determined in different experiments [7–25], sorted chronologically. The measurements that were made by different experiments are denoted by different symbols and colours. The inner error bars represent statistical uncertainties and the outer error bars correspond to the total uncertainty. Dashed arrows indicate lower limits. Lines with arrows on both ends represent ranges of the effective cross-section values, determined within a single publication. In the case of the double J/ψ measurement by LHCb, the dashed line denotes the upper and lower uncertainties. The AFS measurement [7], indicated with a dot, was published without uncertainties.

by the lepton- p_T thresholds and by the dilepton invariant-mass ranges for the leading and sub-leading lepton pairs. The product $\frac{k}{2}\sigma_A\sigma_B$ is determined by representing Eq. (1) as the sum over these phase-space regions. In order to determine the Drell–Yan cross section in each of the regions, the POWHEG-Box MC simulation was used, based on NLO QCD calculations with the CT10 NLO set of PDFs. In the most populated region of $p_T > 20$ GeV for each lepton and of $50 < m_{2\ell} < 120$ GeV, the calculated cross section is 0.55 nb for 2μ and 0.49 nb for $2e$ final states. A conservative uncertainty of $\pm 15\%$ is assigned to Drell–Yan cross sections. After summing the contributions from different dilepton phase-space regions, the result is

$$\frac{k}{2}\sigma_A\sigma_B = (13.9 \pm 0.1 \text{ (stat)} \pm 3.6 \text{ (syst)}) \cdot 10^{11} \text{ fb}^2.$$

Here the systematic uncertainty is determined by propagating the assumed Drell–Yan cross-section uncertainty, assuming 100% correlation between various phase-space regions.

From the definition of f_{DPS} , Eq. (1) may be written as:

$$\frac{1}{\sigma_{\text{eff}}} = \frac{f_{\text{DPS}}\sigma^{4\ell}}{\frac{k}{2}\sigma_{\text{SPS}}^A\sigma_{\text{SPS}}^B},$$

and hence an approach similar to that used for the extraction of the upper limit on f_{DPS} can be applied to set the lower limit on σ_{eff} . The lower limit on σ_{eff} at 95% CL is 1.0 mb, consistent with previously measured values of the effective cross section, as shown in Fig. 4.

8. Summary

The production of four-lepton (electrons or muons) final states in pp interactions at 8 TeV is analysed for the presence of double-parton scattering, using 20.2 fb^{-1} of data recorded by the ATLAS

experiment at the LHC. Leptons with transverse momentum above 20, 15, 10 (8 if muon), and 7 (6 if muon) GeV, sorted in descending order of p_T , are selected in the pseudorapidity range $|\eta| < 2.5$ in the case of electrons and $|\eta| < 2.7$ in the case of muons. The four leptons form two same-flavour opposite-charge lepton pairs. The dilepton invariant masses are required to be in the range $50 < m_{\text{leading}} < 120$ GeV for the leading pair and $12 < m_{\text{sub-leading}} < 120$ GeV for the sub-leading pair, where the leading pair is defined as the pair with invariant mass closer to the Z boson mass. The transverse momentum $p_T^{\ell^+\ell^-}$ of the dileptons is required to be above 2 GeV. The events in the four-lepton invariant-mass range of $80 < m_{4\ell} < 1000$ GeV are considered. An artificial neural network is used to discriminate between single- and double-parton scattering events. No signal of double-parton scattering is observed and an upper limit on the fraction of the DPS contribution to the inclusive four-lepton final state of 0.042 is obtained at 95% CL. This upper limit translates, for two independent subscatterings, into a lower limit of 1.0 mb on the effective cross section, consistent with previously measured values in different processes and at different centre-of-mass energies.

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The ATLAS Collaboration

M. Aaboud^{34d}, G. Aad⁹⁹, B. Abbott¹²⁵, O. Abidinov^{13,*}, B. Abeloos¹²⁹, D.K. Abhayasinghe⁹¹, S.H. Abidi¹⁶⁴, O.S. AbouZeid³⁹, N.L. Abraham¹⁵³, H. Abramowicz¹⁵⁸, H. Abreu¹⁵⁷, Y. Abulaiti⁶, B.S. Acharya^{64a,64b,p}, S. Adachi¹⁶⁰, L. Adam⁹⁷, L. Adamczyk^{81a}, J. Adelman¹¹⁹, M. Adersberger¹¹², A. Adiguzel^{12c,ai}, T. Adye¹⁴¹, A.A. Affolder¹⁴³, Y. Afik¹⁵⁷, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{137f,137a,ah}, F. Ahmadov^{77,af}, G. Aielli^{71a,71b}, S. Akatsuka⁸³, T.P.A. Åkesson⁹⁴, E. Akilli⁵², A.V. Akimov¹⁰⁸, G.L. Alberghi^{23b,23a}, J. Albert¹⁷³, P. Albicocco⁴⁹, M.J. Alconada Verzini⁸⁶, S. Alderweireldt¹¹⁷, M. Aleksa³⁵, I.N. Aleksandrov⁷⁷, C. Alexa^{27b}, D. Alexandre¹⁹, T. Alexopoulos¹⁰, M. Alhroob¹²⁵, B. Ali¹³⁹, G. Alimonti^{66a}, J. Alison³⁶, S.P. Alkire¹⁴⁵, C. Allaire¹²⁹, B.M.M. Allbrooke¹⁵³, B.W. Allen¹²⁸, P.P. Allport²¹, A. Aloisio^{67a,67b}, A. Alonso³⁹, F. Alonso⁸⁶, C. Alpigiani¹⁴⁵, A.A. Alshehri⁵⁵, M.I. Alstary⁹⁹, B. Alvarez Gonzalez³⁵, D. Álvarez Piqueras¹⁷¹, M.G. Alvigi^{67a,67b}, B.T. Amadio¹⁸, Y. Amaral Coutinho^{78b}, A. Ambler¹⁰¹, L. Ambroz¹³², C. Amelung²⁶, D. Amidei¹⁰³, S.P. Amor Dos Santos^{137a,137c}, S. Amoroso⁴⁴, C.S. Amrouche⁵², F. An⁷⁶, C. Anastopoulos¹⁴⁶, L.S. Ancu⁵², N. Andari¹⁴², T. Andeen¹¹, C.F. Anders^{59b}, J.K. Anders²⁰, K.J. Anderson³⁶, A. Andreazza^{66a,66b}, V. Andrei^{59a}, C.R. Anelli¹⁷³, S. Angelidakis³⁷, I. Angelozzi¹¹⁸, A. Angerami³⁸, A.V. Anisenkov^{120b,120a}, A. Annovi^{69a}, C. Antel^{59a}, M.T. Anthony¹⁴⁶, M. Antonelli⁴⁹, D.J.A. Antrim¹⁶⁸, F. Anulli^{70a}, M. Aoki⁷⁹, J.A. Aparisi Pozo¹⁷¹, L. Aperio Bella³⁵, G. Arabidze¹⁰⁴, J.P. Araque^{137a}, V. Araujo Ferraz^{78b}, R. Araujo Pereira^{78b}, A.T.H. Arce⁴⁷, R.E. Ardell⁹¹, F.A. Arduh⁸⁶, J-F. Arguin¹⁰⁷, S. Argyropoulos⁷⁵, J.-H. Arling⁴⁴, A.J. Armbruster³⁵, L.J. Armitage⁹⁰, A. Armstrong¹⁶⁸, O. Arnaez¹⁶⁴, H. Arnold¹¹⁸, M. Arratia³¹, O. Arslan²⁴, A. Artamonov^{109,*}, G. Artoni¹³², S. Artz⁹⁷, S. Asai¹⁶⁰, N. Asbah⁵⁷, E.M. Asimakopoulou¹⁶⁹, L. Asquith¹⁵³, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{32a}, M. Atkinson¹⁷⁰, N.B. Atlay¹⁴⁸, K. Augsten¹³⁹, G. Avolio³⁵, R. Avramidou^{58a}, M.K. Ayoub^{15a}, A.M. Azoulay^{165b}, G. Azuelos^{107,av}, A.E. Baas^{59a}, M.J. Baca²¹, H. Bachacou¹⁴², K. Bachas^{65a,65b}, M. Backes¹³², P. Bagnaia^{70a,70b}, M. Bahmani⁸², H. Bahrasemani¹⁴⁹, A.J. Bailey¹⁷¹, J.T. Baines¹⁴¹, M. Bajic³⁹, C. Bakalis¹⁰, O.K. Baker¹⁸⁰, P.J. Bakker¹¹⁸, D. Bakshi Gupta⁸, S. Balaji¹⁵⁴, E.M. Baldin^{120b,120a}, P. Balek¹⁷⁷, F. Balli¹⁴², W.K. Balunas¹³⁴, J. Balz⁹⁷, E. Banas⁸², A. Bandyopadhyay²⁴, S. Banerjee^{178,l}, A.A.E. Bannoura¹⁷⁹, L. Barak¹⁵⁸, W.M. Barbe³⁷, E.L. Barberio¹⁰², D. Barberis^{53b,53a}, M. Barbero⁹⁹, T. Barillari¹¹³, M-S. Barisits³⁵, J. Barkeloo¹²⁸, T. Barklow¹⁵⁰, R. Barnea¹⁵⁷, S.L. Barnes^{58c}, B.M. Barnett¹⁴¹, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{58a}, A. Baroncelli^{72a}, G. Barone²⁹, A.J. Barr¹³², L. Barranco Navarro¹⁷¹, F. Barreiro⁹⁶, J. Barreiro Guimarães da Costa^{15a}, R. Bartoldus¹⁵⁰, A.E. Barton⁸⁷, P. Bartos^{28a}, A. Basalaeu¹³⁵, A. Bassalat¹²⁹, R.L. Bates⁵⁵, S.J. Batista¹⁶⁴, S. Batlamous^{34e}, J.R. Batley³¹, M. Battaglia¹⁴³, M. Bause^{70a,70b}, F. Bauer¹⁴², K.T. Bauer¹⁶⁸, H.S. Bawa^{150,n}, J.B. Beacham¹²³, T. Beau¹³³, P.H. Beauchemin¹⁶⁷, P. Bechtel²⁴, H.C. Beck⁵¹, H.P. Beck^{20,s}, K. Becker⁵⁰, M. Becker⁹⁷, C. Becot⁴⁴, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁷⁷, M. Bedognetti¹¹⁸, C.P. Bee¹⁵², T.A. Beermann⁷⁴, M. Begalli^{78b}, M. Begel²⁹, A. Behera¹⁵², J.K. Behr⁴⁴, F. Beisiegel²⁴, A.S. Bell⁹², G. Bella¹⁵⁸, L. Bellagamba^{23b}, A. Bellerive³³, M. Bellomo¹⁵⁷, P. Bellos⁹, K. Belotskiy¹¹⁰, N.L. Belyaev¹¹⁰, O. Benary^{158,*}, D. Benchekroun^{34a}, M. Bender¹¹², N. Benekos¹⁰, Y. Benhammou¹⁵⁸, E. Benhar Nocchioli¹⁸⁰, J. Benitez⁷⁵, D.P. Benjamin⁶, M. Benoit⁵², J.R. Bensinger²⁶, S. Bentvelsen¹¹⁸, L. Beresford¹³², M. Beretta⁴⁹, D. Berge⁴⁴, E. Bergeaas Kuutmann¹⁶⁹, N. Berger⁵, B. Bergmann¹³⁹, L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁷, N.R. Bernard¹⁰⁰, G. Bernardi¹³³, C. Bernius¹⁵⁰, F.U. Bernlochner²⁴, T. Berry⁹¹, P. Berta⁹⁷, C. Bertella^{15a}, G. Bertoli^{43a,43b}, I.A. Bertram⁸⁷, G.J. Besjes³⁹, O. Bessidskaia Bylund¹⁷⁹, M. Bessner⁴⁴, N. Besson¹⁴², A. Bethani⁹⁸, S. Bethke¹¹³, A. Betti²⁴, A.J. Bevan⁹⁰, J. Beyer¹¹³, R. Bi¹³⁶, R.M. Bianchi¹³⁶, O. Biebel¹¹², D. Biedermann¹⁹, R. Bielski³⁵, K. Bierwagen⁹⁷, N.V. Biesuz^{69a,69b}, M. Biglietti^{72a}, T.R.V. Billoud¹⁰⁷, M. Bindi⁵¹, A. Bingul^{12d}, C. Bini^{70a,70b}, S. Biondi^{23b,23a}, M. Birman¹⁷⁷, T. Bisanz⁵¹, J.P. Biswal¹⁵⁸, C. Bittrich⁴⁶, D.M. Bjergaard⁴⁷,

J.E. Black¹⁵⁰, K.M. Black²⁵, T. Blazek^{28a}, I. Bloch⁴⁴, C. Blocker²⁶, A. Blue⁵⁵, U. Blumenschein⁹⁰, Dr. Blunier^{144a}, G.J. Bobbink¹¹⁸, V.S. Bobrovnikov^{120b,120a}, S.S. Bocchetta⁹⁴, A. Bocci⁴⁷, D. Boerner¹⁷⁹, D. Bogavac¹¹², A.G. Bogdanchikov^{120b,120a}, C. Bohm^{43a}, V. Boisvert⁹¹, P. Bokan¹⁶⁹, T. Bold^{81a}, A.S. Boldyrev¹¹¹, A.E. Bolz^{59b}, M. Bomben¹³³, M. Bona⁹⁰, J.S. Bonilla¹²⁸, M. Boonekamp¹⁴², H.M. Borecka-Bielska⁸⁸, A. Borisov¹²¹, G. Borissov⁸⁷, J. Bortfeldt³⁵, D. Bortoletto¹³², V. Bortolotto^{71a,71b}, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola³⁰, K. Bouaouda^{34a}, J. Boudreau¹³⁶, E.V. Bouhova-Thacker⁸⁷, D. Boumediene³⁷, C. Bourdarios¹²⁹, S.K. Boutle⁵⁵, A. Boveia¹²³, J. Boyd³⁵, D. Boye^{32b}, I.R. Boyko⁷⁷, A.J. Bozson⁹¹, J. Bracinik²¹, N. Brahimi⁹⁹, A. Brandt⁸, G. Brandt¹⁷⁹, O. Brandt^{59a}, F. Braren⁴⁴, U. Bratzler¹⁶¹, B. Brau¹⁰⁰, J.E. Brau¹²⁸, W.D. Breaden Madden⁵⁵, K. Brendlinger⁴⁴, L. Brenner⁴⁴, R. Brenner¹⁶⁹, S. Bressler¹⁷⁷, B. Brickwedde⁹⁷, D.L. Briglin²¹, D. Britton⁵⁵, D. Britzger¹¹³, I. Brock²⁴, R. Brock¹⁰⁴, G. Brooijmans³⁸, T. Brooks⁹¹, W.K. Brooks^{144b}, E. Brost¹¹⁹, J.H. Broughton²¹, P.A. Bruckman de Renstrom⁸², D. Bruncko^{28b}, A. Bruni^{23b}, G. Bruni^{23b}, L.S. Bruni¹¹⁸, S. Bruno^{71a,71b}, B.H. Brunt³¹, M. Bruschi^{23b}, N. Bruscinò¹³⁶, P. Bryant³⁶, L. Bryngemark⁹⁴, T. Buanes¹⁷, Q. Buat³⁵, P. Buchholz¹⁴⁸, A.G. Buckley⁵⁵, I.A. Budagov⁷⁷, M.K. Bugge¹³¹, F. Bühner⁵⁰, O. Bulekov¹¹⁰, D. Bullock⁸, T.J. Burch¹¹⁹, S. Burdina⁸⁸, C.D. Burgard¹¹⁸, A.M. Burger⁵, B. Burghgrave¹¹⁹, K. Burkhardt⁸², S. Burke¹⁴¹, I. Burmeister⁴⁵, J.T.P. Burr¹³², V. Büscher⁹⁷, E. Buschmann⁵¹, P. Bussey⁵⁵, J.M. Butler²⁵, C.M. Buttar⁵⁵, J.M. Butterworth⁹², P. Butti³⁵, W. Buttinger³⁵, A. Buzatu¹⁵⁵, A.R. Buzykaev^{120b,120a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷¹, D. Caforio¹³⁹, H. Cai¹⁷⁰, V.M.M. Cairo², O. Cakir^{4a}, N. Calace⁵², P. Calafiura¹⁸, A. Calandri⁹⁹, G. Calderini¹³³, P. Calfayan⁶³, G. Callea⁵⁵, L.P. Caloba^{78b}, S. Calvente Lopez⁹⁶, D. Calvet³⁷, S. Calvet³⁷, T.P. Calvet¹⁵², M. Calvetti^{69a,69b}, R. Camacho Toro¹³³, S. Camarda³⁵, D. Camarero Munoz⁹⁶, P. Camarri^{71a,71b}, D. Cameron¹³¹, R. Caminal Armadans¹⁰⁰, C. Camincher³⁵, S. Campana³⁵, M. Campanelli⁹², A. Camplani³⁹, A. Campoverde¹⁴⁸, V. Canale^{67a,67b}, M. Cano Bret^{58c}, J. Cantero¹²⁶, T. Cao¹⁵⁸, Y. Cao¹⁷⁰, M.D.M. Capeans Garrido³⁵, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{40b,40a}, R.M. Carbone³⁸, R. Cardarelli^{71a}, F.C. Cardillo¹⁴⁶, I. Carli¹⁴⁰, T. Carli³⁵, G. Carlino^{67a}, B.T. Carlson¹³⁶, L. Carminati^{66a,66b}, R.M.D. Carney^{43a,43b}, S. Caron¹¹⁷, E. Carquin^{144b}, S. Carrá^{66a,66b}, J.W.S. Carter¹⁶⁴, D. Casadei^{32b}, M.P. Casado^{14g}, A.F. Casha¹⁶⁴, D.W. Casper¹⁶⁸, R. Castelijin¹¹⁸, F.L. Castillo¹⁷¹, V. Castillo Gimenez¹⁷¹, N.F. Castro^{137a,137e}, A. Catinaccio³⁵, J.R. Catmore¹³¹, A. Cattai³⁵, J. Caudron²⁴, V. Cavaliere²⁹, E. Cavallaro¹⁴, D. Cavalli^{66a}, M. Cavalli-Sforza¹⁴, V. Cavasinni^{69a,69b}, E. Celebi^{12b}, F. Ceradini^{72a,72b}, L. Cerda Alberich¹⁷¹, A.S. Cerqueira^{78a}, A. Cerri¹⁵³, L. Cerrito^{71a,71b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a}, S.A. Cetin^{12b}, A. Chafaq^{34a}, D. Chakraborty¹¹⁹, S.K. Chan⁵⁷, W.S. Chan¹¹⁸, J.D. Chapman³¹, B. Chargeishvili^{156b}, D.G. Charlton²¹, C.C. Chau³³, C.A. Chavez Barajas¹⁵³, S. Che¹²³, A. Chegwidden¹⁰⁴, S. Chekanov⁶, S.V. Chekulaev^{165a}, G.A. Chelkov^{77,au}, M.A. Chelstowska³⁵, C. Chen^{58a}, C.H. Chen⁷⁶, H. Chen²⁹, J. Chen^{58a}, J. Chen³⁸, S. Chen¹³⁴, S.J. Chen^{15c}, X. Chen^{15b,at}, Y. Chen⁸⁰, Y-H. Chen⁴⁴, H.C. Cheng^{61a}, H.J. Cheng^{15d}, A. Cheplakov⁷⁷, E. Cheremushkina¹²¹, R. Cherkaoui El Moursli^{34e}, E. Cheu⁷, K. Cheung⁶², T.J.A. Chevaléras¹⁴², L. Chevalier¹⁴², V. Chiarella⁴⁹, G. Chiarelli^{69a}, G. Chiodini^{65a}, A.S. Chisholm^{35,21}, A. Chitan^{27b}, I. Chiu¹⁶⁰, Y.H. Chiu¹⁷³, M.V. Chizhov⁷⁷, K. Choi⁶³, A.R. Chomont¹²⁹, S. Chouridou¹⁵⁹, Y.S. Chow¹¹⁸, V. Christodoulou⁹², M.C. Chu^{61a}, J. Chudoba¹³⁸, A.J. Chuinard¹⁰¹, J.J. Chwastowski⁸², L. Chytka¹²⁷, D. Cinca⁴⁵, V. Cindro⁸⁹, I.A. Cioară²⁴, A. Ciochio¹⁸, F. Ciotto^{67a,67b}, Z.H. Citron¹⁷⁷, M. Citterio^{66a}, A. Clark⁵², M.R. Clark³⁸, P.J. Clark⁴⁸, C. Clement^{43a,43b}, Y. Coadou⁹⁹, M. Cobal^{64a,64c}, A. Coccaro^{53b,53a}, J. Cochran⁷⁶, H. Cohen¹⁵⁸, A.E.C. Coimbra¹⁷⁷, L. Colasurdo¹¹⁷, B. Cole³⁸, A.P. Colijn¹¹⁸, J. Collot⁵⁶, P. Conde Muiño^{137a,i}, E. Coniavitis⁵⁰, S.H. Connell^{32b}, I.A. Connelly⁹⁸, S. Constantinescu^{27b}, F. Conventi^{67a,aw}, A.M. Cooper-Sarkar¹³², F. Cormier¹⁷², K.J.R. Cormier¹⁶⁴, L.D. Corpe⁹², M. Corradi^{70a,70b}, E.E. Corrigan⁹⁴, F. Corriveau^{101,ad}, A. Cortes-Gonzalez³⁵, M.J. Costa¹⁷¹, F. Costanza⁵, D. Costanzo¹⁴⁶, G. Cottin³¹, G. Cowan⁹¹, B.E. Cox⁹⁸, J. Crane⁹⁸, K. Cranmer¹²², S.J. Crawley⁵⁵, R.A. Creager¹³⁴, G. Cree³³, S. Crépé-Renaudin⁵⁶, F. Crescioli¹³³, M. Cristinziani²⁴, V. Croft¹²², G. Crosetti^{40b,40a}, A. Cueto⁹⁶, T. Cuhadar Donszelmann¹⁴⁶, A.R. Cukierman¹⁵⁰, S. Czekierda⁸², P. Czodrowski³⁵, M.J. Da Cunha Sargedas De Sousa^{58b}, C. Da Via⁹⁸, W. Dabrowski^{81a}, T. Dado^{28a,y}, S. Dahbi^{34e}, T. Dai¹⁰³, F. Dallaire¹⁰⁷, C. Dallapiccola¹⁰⁰, M. Dam³⁹, G. D'amen^{23b,23a}, J. Damp⁹⁷, J.R. Dandoy¹³⁴, M.F. Daneri³⁰, N.P. Dang^{178,l}, N.D. Dann⁹⁸, M. Danninger¹⁷², V. Dao³⁵, G. Darbo^{53b}, S. Darmora⁸, O. Dartsis⁵, A. Dattagupta¹²⁸, T. Daubney⁴⁴, S. D'Auria^{66a,66b}, W. Davey²⁴, C. David⁴⁴, T. Davidek¹⁴⁰, D.R. Davis⁴⁷, E. Dawe¹⁰², I. Dawson¹⁴⁶, K. De⁸,

R. De Asmundis^{67a}, A. De Benedetti¹²⁵, M. De Beurs¹¹⁸, S. De Castro^{23b,23a}, S. De Cecco^{70a,70b}, N. De Groot¹¹⁷, P. de Jong¹¹⁸, H. De la Torre¹⁰⁴, F. De Lorenzi⁷⁶, A. De Maria^{69a,69b}, D. De Pedis^{70a}, A. De Salvo^{70a}, U. De Sanctis^{71a,71b}, M. De Santis^{71a,71b}, A. De Santo¹⁵³, K. De Vasconcelos Corga⁹⁹, J.B. De Vivie De Regie¹²⁹, C. Debenedetti¹⁴³, D.V. Dedovich⁷⁷, N. Dehghanian³, M. Del Gaudio^{40b,40a}, J. Del Peso⁹⁶, Y. Delabat Diaz⁴⁴, D. Delgove¹²⁹, F. Deliot¹⁴², C.M. Delitzsch⁷, M. Della Pietra^{67a,67b}, D. Della Volpe⁵², A. Dell'Acqua³⁵, L. Dell'Asta²⁵, M. Delmastro⁵, C. Delporte¹²⁹, P.A. Delsart⁵⁶, D.A. DeMarco¹⁶⁴, S. Demers¹⁸⁰, M. Demichev⁷⁷, S.P. Denisov¹²¹, D. Denysiuk¹¹⁸, L. D'Eramo¹³³, D. Derendarz⁸², J.E. Derkaoui^{34d}, F. Derue¹³³, P. Dervan⁸⁸, K. Desch²⁴, C. Deterre⁴⁴, K. Dette¹⁶⁴, M.R. Devesa³⁰, P.O. Deviveiros³⁵, A. Dewhurst¹⁴¹, S. Dhaliwal²⁶, F.A. Di Bello⁵², A. Di Ciaccio^{71a,71b}, L. Di Ciaccio⁵, W.K. Di Clemente¹³⁴, C. Di Donato^{67a,67b}, A. Di Girolamo³⁵, G. Di Gregorio^{69a,69b}, B. Di Micco^{72a,72b}, R. Di Nardo¹⁰⁰, K.F. Di Petrillo⁵⁷, R. Di Sipio¹⁶⁴, D. Di Valentino³³, C. Diaconu⁹⁹, M. Diamond¹⁶⁴, F.A. Dias³⁹, T. Dias Do Vale^{137a}, M.A. Diaz^{144a}, J. Dickinson¹⁸, E.B. Diehl¹⁰³, J. Dietrich¹⁹, S. Díez Cornell⁴⁴, A. Dimitrievska¹⁸, J. Dingfelder²⁴, F. Dittus³⁵, F. Djama⁹⁹, T. Djobava^{156b}, J.I. Djuvsland^{59a}, M.A.B. Do Vale^{78c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁴, J. Dolejsi¹⁴⁰, Z. Dolezal¹⁴⁰, M. Donadelli^{78d}, J. Donini³⁷, A. D'onofrio⁹⁰, M. D'Onofrio⁸⁸, J. Dopke¹⁴¹, A. Doria^{67a}, M.T. Dova⁸⁶, A.T. Doyle⁵⁵, E. Drechsler⁵¹, E. Dreyer¹⁴⁹, T. Dreyer⁵¹, Y. Du^{58b}, F. Dubinin¹⁰⁸, M. Dubovsky^{28a}, A. Dubreuil⁵², E. Duchovni¹⁷⁷, G. Duckeck¹¹², A. Ducourthial¹³³, O.A. Ducu^{107,x}, D. Duda¹¹³, A. Dudarev³⁵, A.C. Dudder⁹⁷, E.M. Duffield¹⁸, L. Duflot¹²⁹, M. Dührssen³⁵, C. Dülse¹⁷⁹, M. Dumancic¹⁷⁷, A.E. Dumitriu^{27b,e}, A.K. Duncan⁵⁵, M. Dunford^{59a}, A. Duperrin⁹⁹, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{156b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, D. Duvnjak¹, M. Dyndal⁴⁴, S. Dych⁹⁸, B.S. Dziedzic⁸², C. Eckardt⁴⁴, K.M. Ecker¹¹³, R.C. Edgar¹⁰³, T. Eifert³⁵, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof¹⁶⁹, M. El Kacimi^{34c}, R. El Kosseifi⁹⁹, V. Ellajosyula⁹⁹, M. Ellert¹⁶⁹, F. Ellinghaus¹⁷⁹, A.A. Elliot⁹⁰, N. Ellis³⁵, J. Elmsheuser²⁹, M. Elsing³⁵, D. Emelianov¹⁴¹, A. Emerman³⁸, Y. Enari¹⁶⁰, J.S. Ennis¹⁷⁵, M.B. Epland⁴⁷, J. Erdmann⁴⁵, A. Ereditato²⁰, S. Errede¹⁷⁰, M. Escalier¹²⁹, C. Escobar¹⁷¹, O. Estrada Pastor¹⁷¹, A.I. Etienne¹⁴², E. Etzion¹⁵⁸, H. Evans⁶³, A. Ezhilov¹³⁵, M. Ezzi^{34e}, F. Fabbri⁵⁵, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁷, G. Facini⁹², R.M. Faisca Rodrigues Pereira^{137a}, R.M. Fakhruddinov¹²¹, S. Falciano^{70a}, P.J. Falke⁵, S. Falke⁵, J. Faltova¹⁴⁰, Y. Fang^{15a}, M. Fanti^{66a,66b}, A. Farbin⁸, A. Farilla^{72a}, E.M. Farina^{68a,68b}, T. Farooque¹⁰⁴, S. Farrell¹⁸, S.M. Farrington¹⁷⁵, P. Farthouat³⁵, F. Fassi^{34e}, P. Fassnacht³⁵, D. Fassouliotis⁹, M. Fauci Giannelli⁴⁸, A. Favareto^{53b,53a}, W.J. Fawcett³¹, L. Fayard¹²⁹, O.L. Fedin^{135,q}, W. Fedorko¹⁷², M. Feickert⁴¹, S. Feigl¹³¹, L. Felgioni⁹⁹, C. Feng^{58b}, E.J. Feng³⁵, M. Feng⁴⁷, M.J. Fenton⁵⁵, A.B. Fenyuk¹²¹, L. Feremenga⁸, J. Ferrando⁴⁴, A. Ferrari¹⁶⁹, P. Ferrari¹¹⁸, R. Ferrari^{68a}, D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁷¹, D. Ferrere⁵², C. Ferretti¹⁰³, F. Fiedler⁹⁷, A. Filipčič⁸⁹, F. Filthaut¹¹⁷, K.D. Finelli²⁵, M.C.N. Fiolhais^{137a,137c,a}, L. Fiorini¹⁷¹, C. Fischer¹⁴, W.C. Fisher¹⁰⁴, N. Flaschel⁴⁴, I. Fleck¹⁴⁸, P. Fleischmann¹⁰³, R.R.M. Fletcher¹³⁴, T. Flick¹⁷⁹, B.M. Flierl¹¹², L.M. Flores¹³⁴, L.R. Flores Castillo^{61a}, F.M. Follega^{73a,73b}, N. Fomin¹⁷, G.T. Forcolin^{73a,73b}, A. Formica¹⁴², F.A. Förster¹⁴, A.C. Forti⁹⁸, A.G. Foster²¹, D. Fournier¹²⁹, H. Fox⁸⁷, S. Fracchia¹⁴⁶, P. Francavilla^{69a,69b}, M. Franchini^{23b,23a}, S. Franchino^{59a}, D. Francis³⁵, L. Franconi¹⁴³, M. Franklin⁵⁷, M. Frate¹⁶⁸, M. Fraternali^{68a,68b}, A.N. Fray⁹⁰, D. Freeborn⁹², B. Freund¹⁰⁷, W.S. Freund^{78b}, E.M. Freundlich⁴⁵, D.C. Frizzell¹²⁵, D. Froidevaux³⁵, J.A. Frost¹³², C. Fukunaga¹⁶¹, E. Fullana Torregrosa¹⁷¹, T. Fusayasu¹¹⁴, J. Fuster¹⁷¹, O. Gabizon¹⁵⁷, A. Gabrielli^{23b,23a}, A. Gabrielli¹⁸, G.P. Gach^{81a}, S. Gadatsch⁵², P. Gadow¹¹³, G. Gagliardi^{53b,53a}, L.G. Gagnon¹⁰⁷, C. Galea^{27b}, B. Galhardo^{137a,137c}, E.J. Gallas¹³², B.J. Gallop¹⁴¹, P. Gallus¹³⁹, G. Galster³⁹, R. Gamboa Goni⁹⁰, K.K. Gan¹²³, S. Ganguly¹⁷⁷, J. Gao^{58a}, Y. Gao⁸⁸, Y.S. Gao^{150,n}, C. García¹⁷¹, J.E. García Navarro¹⁷¹, J.A. García Pascual^{15a}, M. Garcia-Sciveres¹⁸, R.W. Gardner³⁶, N. Garelli¹⁵⁰, S. Gargiulo⁵⁰, V. Garonne¹³¹, K. Gasnikova⁴⁴, A. Gaudiello^{53b,53a}, G. Gaudio^{68a}, I.L. Gavrilenko¹⁰⁸, A. Gavrilyuk¹⁰⁹, C. Gay¹⁷², G. Gaycken²⁴, E.N. Gazis¹⁰, C.N.P. Gee¹⁴¹, J. Geisen⁵¹, M. Geisen⁹⁷, M.P. Geisler^{59a}, C. Gemme^{53b}, M.H. Genest⁵⁶, C. Geng¹⁰³, S. Gentile^{70a,70b}, S. George⁹¹, D. Gerbaudo¹⁴, G. Gessner⁴⁵, S. Ghasemi¹⁴⁸, M. Ghasemi Bostanabad¹⁷³, M. Ghneimat²⁴, B. Giacobbe^{23b}, S. Giagu^{70a,70b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{69a}, A. Giannini^{67a,67b}, S.M. Gibson⁹¹, M. Gignac¹⁴³, D. Gillberg³³, G. Gilles¹⁷⁹, D.M. Gingrich^{3,av}, M.P. Giordani^{64a,64c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴², P. Giromini⁵⁷, G. Giugliarelli^{64a,64c}, D. Giugni^{66a}, F. Giuli¹³², M. Giulini^{59b}, S. Gkaitatzis¹⁵⁹, I. Gkialas^{9,k}, E.L. Gkoukousis¹⁴, P. Gkoutoumis¹⁰, L.K. Gladilin¹¹¹, C. Glasman⁹⁶, J. Glatzer¹⁴, P.C.F. Glaysher⁴⁴, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁶, J. Godlewski⁸², S. Goldfarb¹⁰²,

T. Golling⁵², D. Golubkov¹²¹, A. Gomes^{137a,137b}, R. Goncalves Gama⁵¹, R. Gonçalo^{137a}, G. Gonella⁵⁰, L. Gonella²¹, A. Gongadze⁷⁷, F. Gonnella²¹, J.L. Gonski⁵⁷, S. González de la Hoz¹⁷¹, S. Gonzalez-Sevilla⁵², L. Goossens³⁵, P.A. Gorbounov¹⁰⁹, H.A. Gordon²⁹, B. Gorini³⁵, E. Gorini^{65a,65b}, A. Gorišek⁸⁹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁷⁷, C.A. Gottardo²⁴, C.R. Goudet¹²⁹, D. Goujdami^{34c}, A.G. Goussiou¹⁴⁵, N. Govender^{32b,c}, C. Goy⁵, E. Gozani¹⁵⁷, I. Grabowska-Bold^{81a}, P.O.J. Gradin¹⁶⁹, E.C. Graham⁸⁸, J. Gramling¹⁶⁸, E. Gramstad¹³¹, S. Grancagnolo¹⁹, V. Gratchev¹³⁵, P.M. Gravila^{27f}, F.G. Gravili^{65a,65b}, C. Gray⁵⁵, H.M. Gray¹⁸, Z.D. Greenwood^{93,al}, C. Grefe²⁴, K. Gregersen⁹⁴, I.M. Gregor⁴⁴, P. Grenier¹⁵⁰, K. Grevtsov⁴⁴, N.A. Grieser¹²⁵, J. Griffiths⁸, A.A. Grillo¹⁴³, K. Grimm^{150,b}, S. Grinstein^{14,z}, Ph. Gris³⁷, J.-F. Grivaz¹²⁹, S. Groh⁹⁷, E. Gross¹⁷⁷, J. Grosse-Knetter⁵¹, G.C. Grossi⁹³, Z.J. Grout⁹², C. Grud¹⁰³, A. Grummer¹¹⁶, L. Guan¹⁰³, W. Guan¹⁷⁸, J. Guenther³⁵, A. Guerguichon¹²⁹, F. Guescini^{165a}, D. Guest¹⁶⁸, R. Gugel⁵⁰, B. Gui¹²³, T. Guillemin⁵, S. Guindon³⁵, U. Gul⁵⁵, C. Gumpert³⁵, J. Guo^{58c}, W. Guo¹⁰³, Y. Guo^{58a,t}, Z. Guo⁹⁹, R. Gupta⁴⁴, S. Gurbuz^{12c}, G. Gustavino¹²⁵, B.J. Gutelman¹⁵⁷, P. Gutierrez¹²⁵, C. Gutsche⁹², C. Guyot¹⁴², M.P. Guzik^{81a}, C. Gwenlan¹³², C.B. Gwilliam⁸⁸, A. Haas¹²², C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{34e}, A. Hadeef^{58a}, S. Hageböck²⁴, M. Hagihara¹⁶⁶, H. Hakobyan^{181,*}, M. Haleem¹⁷⁴, J. Haley¹²⁶, G. Halladjian¹⁰⁴, G.D. Hallewell⁹⁹, K. Hamacher¹⁷⁹, P. Hamal¹²⁷, K. Hamano¹⁷³, A. Hamilton^{32a}, G.N. Hamity¹⁴⁶, K. Han^{58a,ak}, L. Han^{58a}, S. Han^{15d}, K. Hanagaki^{79,v}, M. Hance¹⁴³, D.M. Handl¹¹², B. Haney¹³⁴, R. Hankache¹³³, P. Hanke^{59a}, E. Hansen⁹⁴, J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²⁴, P.H. Hansen³⁹, K. Hara¹⁶⁶, A.S. Hard¹⁷⁸, T. Harenberg¹⁷⁹, S. Harkusha¹⁰⁵, P.F. Harrison¹⁷⁵, N.M. Hartmann¹¹², Y. Hasegawa¹⁴⁷, A. Hasib⁴⁸, S. Hassani¹⁴², S. Haug²⁰, R. Hauser¹⁰⁴, L. Hauswald⁴⁶, L.B. Havener³⁸, M. Havranek¹³⁹, C.M. Hawkes²¹, R.J. Hawkins³⁵, D. Hayden¹⁰⁴, C. Hayes¹⁵², C.P. Hays¹³², J.M. Hays⁹⁰, H.S. Hayward⁸⁸, S.J. Haywood¹⁴¹, M.P. Heath⁴⁸, V. Hedberg⁹⁴, L. Heelan⁸, S. Heer²⁴, K.K. Heidegger⁵⁰, J. Heilman³³, S. Heim⁴⁴, T. Heim¹⁸, B. Heinemann^{44,aq}, J.J. Heinrich¹¹², L. Heinrich¹²², C. Heinz⁵⁴, J. Hejbal¹³⁸, L. Helary³⁵, A. Held¹⁷², S. Hellesund¹³¹, C.M. Helling¹⁴³, S. Hellman^{43a,43b}, C. Helsens³⁵, R.C.W. Henderson⁸⁷, Y. Heng¹⁷⁸, S. Henkelmann¹⁷², A.M. Henriques Correia³⁵, G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁴, Y. Hernández Jiménez^{32c}, H. Herr⁹⁷, M.G. Herrmann¹¹², T. Herrmann⁴⁶, G. Herten⁵⁰, R. Hertenberger¹¹², L. Hervas³⁵, T.C. Herwig¹³⁴, G.G. Hesketh⁹², N.P. Hessey^{165a}, A. Higashida¹⁶⁰, S. Higashino⁷⁹, E. Higón-Rodríguez¹⁷¹, K. Hildebrand³⁶, E. Hill¹⁷³, J.C. Hill³¹, K.K. Hill²⁹, K.H. Hiller⁴⁴, S.J. Hillier²¹, M. Hils⁴⁶, I. Hinchliffe¹⁸, F. Hinterkeuser²⁴, M. Hirose¹³⁰, D. Hirschbuehl¹⁷⁹, B. Hiti⁸⁹, O. Hladik¹³⁸, D.R. Hlaluku^{32c}, X. Hoad⁴⁸, J. Hobbs¹⁵², N. Hod^{165a}, M.C. Hodgkinson¹⁴⁶, A. Hoecker³⁵, M.R. Hoefkamp¹¹⁶, F. Hoenig¹¹², D. Hohn⁵⁰, D. Hohov¹²⁹, T.R. Holmes³⁶, M. Holzbock¹¹², M. Homann⁴⁵, B.H. Hommels³¹, S. Honda¹⁶⁶, T. Honda⁷⁹, T.M. Hong¹³⁶, A. Hönle¹¹³, B.H. Hooberman¹⁷⁰, W.H. Hopkins¹²⁸, Y. Horii¹¹⁵, P. Horn⁴⁶, A.J. Horton¹⁴⁹, L.A. Horyn³⁶, J.-Y. Hostachy⁵⁶, A. Hostiuc¹⁴⁵, S. Hou¹⁵⁵, A. Hoummada^{34a}, J. Howarth⁹⁸, J. Hoya⁸⁶, M. Hrabovsky¹²⁷, I. Hristova¹⁹, J. Hrivnac¹²⁹, A. Hrynevich¹⁰⁶, T. Hryn'ova⁵, P.J. Hsu⁶², S.-C. Hsu¹⁴⁵, Q. Hu²⁹, S. Hu^{58c}, Y. Huang^{15a}, Z. Hubacek¹³⁹, F. Hubaut⁹⁹, M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³², M. Huhtinen³⁵, R.F.H. Hunter³³, P. Huo¹⁵², A.M. Hupe³³, N. Huseynov^{77,af}, J. Huston¹⁰⁴, J. Huth⁵⁷, R. Hyneman¹⁰³, G. Iacobucci⁵², G. Iakovidis²⁹, I. Ibragimov¹⁴⁸, L. Iconomidou-Fayard¹²⁹, Z. Idrissi^{34e}, P. Iengo³⁵, R. Ignazzi³⁹, O. Igonkina^{118,ab}, R. Iguchi¹⁶⁰, T. Iizawa⁵², Y. Ikegami⁷⁹, M. Ikeno⁷⁹, D. Iliadis¹⁵⁹, N. Ilic¹¹⁷, F. Iltzsche⁴⁶, G. Introzzi^{68a,68b}, M. Iodice^{72a}, K. Iordanidou³⁸, V. Ippolito^{70a,70b}, M.F. Isacson¹⁶⁹, N. Ishijima¹³⁰, M. Ishino¹⁶⁰, M. Ishitsuka¹⁶², W. Islam¹²⁶, C. Issever¹³², S. Istin¹⁵⁷, F. Ito¹⁶⁶, J.M. Iturbe Ponce^{61a}, R. Iuppa^{73a,73b}, A. Ivina¹⁷⁷, H. Iwasaki⁷⁹, J.M. Izen⁴², V. Izzo^{67a}, P. Jacka¹³⁸, P. Jackson¹, R.M. Jacobs²⁴, V. Jain², G. Jäkel¹⁷⁹, K.B. Jakobi⁹⁷, K. Jakobs⁵⁰, S. Jakobsen⁷⁴, T. Jakoubek¹³⁸, D.O. Jamin¹²⁶, R. Jansky⁵², J. Janssen²⁴, M. Janus⁵¹, P.A. Janus^{81a}, G. Jarlskog⁹⁴, N. Javadov^{77,af}, T. Javůrek³⁵, M. Javurkova⁵⁰, F. Jeanneau¹⁴², L. Jeanty¹⁸, J. Jejelava^{156a,ag}, A. Jelinskas¹⁷⁵, P. Jenni^{50,d}, J. Jeong⁴⁴, N. Jeong⁴⁴, S. Jézéquel⁵, H. Ji¹⁷⁸, J. Jia¹⁵², H. Jiang⁷⁶, Y. Jiang^{58a}, Z. Jiang^{150,r}, S. Jiggins⁵⁰, F.A. Jimenez Morales³⁷, J. Jimenez Pena¹⁷¹, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶², H. Jivan^{32c}, P. Johansson¹⁴⁶, K.A. Johns⁷, C.A. Johnson⁶³, W.J. Johnson¹⁴⁵, K. Jon-And^{43a,43b}, R.W.L. Jones⁸⁷, S.D. Jones¹⁵³, S. Jones⁷, T.J. Jones⁸⁸, J. Jongmanns^{59a}, P.M. Jorge^{137a,137b}, J. Jovicevic^{165a}, X. Ju¹⁸, J.J. Junggeburth¹¹³, A. Juste Rozas^{14,z}, A. Kaczmarska⁸², M. Kado¹²⁹, H. Kagan¹²³, M. Kagan¹⁵⁰, T. Kaji¹⁷⁶, E. Kajomovitz¹⁵⁷, C.W. Kalderon⁹⁴, A. Kaluza⁹⁷, S. Kama⁴¹, A. Kamenshchikov¹²¹, L. Kanjir⁸⁹, Y. Kano¹⁶⁰, V.A. Kantserov¹¹⁰, J. Kanzaki⁷⁹,

L.S. Kaplan ¹⁷⁸, D. Kar ^{32c}, M.J. Kareem ^{165b}, E. Karentzos ¹⁰, S.N. Karpov ⁷⁷, Z.M. Karpova ⁷⁷,
 V. Kartvelishvili ⁸⁷, A.N. Karyukhin ¹²¹, L. Kashif ¹⁷⁸, R.D. Kass ¹²³, A. Kastanas ^{43a,43b}, Y. Kataoka ¹⁶⁰,
 C. Kato ^{58d,58c}, J. Katzy ⁴⁴, K. Kawade ⁸⁰, K. Kawagoe ⁸⁵, T. Kawamoto ¹⁶⁰, G. Kawamura ⁵¹, E.F. Kay ⁸⁸,
 V.F. Kazanin ^{120b,120a}, R. Keeler ¹⁷³, R. Kehoe ⁴¹, J.S. Keller ³³, E. Kellermann ⁹⁴, J.J. Kempster ²¹,
 J. Kendrick ²¹, O. Kepka ¹³⁸, S. Kersten ¹⁷⁹, B.P. Kerševan ⁸⁹, S. Ketabchi Haghighat ¹⁶⁴, R.A. Keyes ¹⁰¹,
 M. Khader ¹⁷⁰, F. Khalil-Zada ¹³, A. Khanov ¹²⁶, A.G. Kharlamov ^{120b,120a}, T. Kharlamova ^{120b,120a},
 E.E. Khoda ¹⁷², A. Khodinov ¹⁶³, T.J. Khoo ⁵², E. Khramov ⁷⁷, J. Khubua ^{156b}, S. Kido ⁸⁰, M. Kiehn ⁵²,
 C.R. Kilby ⁹¹, Y.K. Kim ³⁶, N. Kimura ^{64a,64c}, O.M. Kind ¹⁹, B.T. King ⁸⁸, D. Kirchmeier ⁴⁶, J. Kirk ¹⁴¹,
 A.E. Kiryunin ¹¹³, T. Kishimoto ¹⁶⁰, D. Kisielewska ^{81a}, V. Kitali ⁴⁴, O. Kivernyk ⁵, E. Kladiva ^{28b,*},
 T. Klapdor-Kleingrothaus ⁵⁰, M.H. Klein ¹⁰³, M. Klein ⁸⁸, U. Klein ⁸⁸, K. Kleinknecht ⁹⁷, P. Klimek ¹¹⁹,
 A. Klimentov ²⁹, T. Klingl ²⁴, T. Klioutchnikova ³⁵, F.F. Klitzner ¹¹², P. Kluit ¹¹⁸, S. Kluth ¹¹³, E. Kneringer ⁷⁴,
 E.B.F.G. Knoops ⁹⁹, A. Knue ⁵⁰, A. Kobayashi ¹⁶⁰, D. Kobayashi ⁸⁵, T. Kobayashi ¹⁶⁰, M. Kobel ⁴⁶,
 M. Kocian ¹⁵⁰, P. Kodys ¹⁴⁰, P.T. Koenig ²⁴, T. Koffas ³³, E. Koffeman ¹¹⁸, N.M. Köhler ¹¹³, T. Koi ¹⁵⁰,
 M. Kolb ^{59b}, I. Koletsou ⁵, T. Kondo ⁷⁹, N. Kondrashova ^{58c}, K. Köneke ⁵⁰, A.C. König ¹¹⁷, T. Kono ⁷⁹,
 R. Konoplich ^{122.an}, V. Konstantinides ⁹², N. Konstantinidis ⁹², B. Konya ⁹⁴, R. Kopeliansky ⁶³,
 S. Koperny ^{81a}, K. Korcyl ⁸², K. Kordas ¹⁵⁹, G. Koren ¹⁵⁸, A. Korn ⁹², I. Korolkov ¹⁴, E.V. Korolkova ¹⁴⁶,
 N. Korotkova ¹¹¹, O. Kortner ¹¹³, S. Kortner ¹¹³, T. Kosek ¹⁴⁰, V.V. Kostyukhin ²⁴, A. Kotwal ⁴⁷,
 A. Koulouris ¹⁰, A. Kourkouveli-Charalampidi ^{68a,68b}, C. Kourkouvelis ⁹, E. Kourlitis ¹⁴⁶, V. Kouskoura ²⁹,
 A.B. Kowalewska ⁸², R. Kowalewski ¹⁷³, T.Z. Kowalski ^{81a}, C. Kozakai ¹⁶⁰, W. Kozanecki ¹⁴², A.S. Kozhin ¹²¹,
 V.A. Kramarenko ¹¹¹, G. Kramberger ⁸⁹, D. Krasnopevtsev ^{58a}, M.W. Krasny ¹³³, A. Krasznahorkay ³⁵,
 D. Krauss ¹¹³, J.A. Kremer ^{81a}, J. Kretzschmar ⁸⁸, P. Krieger ¹⁶⁴, K. Krizka ¹⁸, K. Kroeninger ⁴⁵, H. Kroha ¹¹³,
 J. Kroll ¹³⁸, J. Kroll ¹³⁴, J. Krstic ¹⁶, U. Kruchonak ⁷⁷, H. Krüger ²⁴, N. Krumnack ⁷⁶, M.C. Kruse ⁴⁷,
 T. Kubota ¹⁰², S. Kuday ^{4b}, J.T. Kuechler ¹⁷⁹, S. Kuehn ³⁵, A. Kugel ^{59a}, T. Kuhl ⁴⁴, V. Kukhtin ⁷⁷, R. Kukla ⁹⁹,
 Y. Kulchitsky ^{105.aj}, S. Kuleshov ^{144b}, Y.P. Kulinich ¹⁷⁰, M. Kuna ⁵⁶, T. Kunigo ⁸³, A. Kupco ¹³⁸, T. Kupfer ⁴⁵,
 O. Kuprash ¹⁵⁸, H. Kurashige ⁸⁰, L.L. Kurchaninov ^{165a}, Y.A. Kurochkin ¹⁰⁵, A. Kurova ¹¹⁰, M.G. Kurth ^{15d},
 E.S. Kuwertz ³⁵, M. Kuze ¹⁶², J. Kvita ¹²⁷, T. Kwan ¹⁰¹, A. La Rosa ¹¹³, J.L. La Rosa Navarro ^{78d},
 L. La Rotonda ^{40b,40a}, F. La Ruffa ^{40b,40a}, C. Lacasta ¹⁷¹, F. Lacava ^{70a,70b}, J. Lacey ⁴⁴, D.P.J. Lack ⁹⁸,
 H. Lacker ¹⁹, D. Lacour ¹³³, E. Ladygin ⁷⁷, R. Lafaye ⁵, B. Laforge ¹³³, T. Lagouri ^{32c}, S. Lai ⁵¹, S. Lammers ⁶³,
 W. Lampl ⁷, E. Lançon ²⁹, U. Landgraf ⁵⁰, M.P.J. Landon ⁹⁰, M.C. Lanfermann ⁵², V.S. Lang ⁴⁴, J.C. Lange ⁵¹,
 R.J. Langenberg ³⁵, A.J. Lankford ¹⁶⁸, F. Lanni ²⁹, K. Lantsch ²⁴, A. Lanza ^{68a}, A. Lapertosa ^{53b,53a},
 S. Laplace ¹³³, J.F. Laporte ¹⁴², T. Lari ^{66a}, F. Lasagni Manghi ^{23b,23a}, M. Lassnig ³⁵, T.S. Lau ^{61a},
 A. Laudrain ¹²⁹, M. Lavorgna ^{67a,67b}, M. Lazzaroni ^{66a,66b}, B. Le ¹⁰², O. Le Dortz ¹³³, E. Le Guirriec ⁹⁹,
 E.P. Le Quilleuc ¹⁴², M. LeBlanc ⁷, T. LeCompte ⁶, F. Ledroit-Guillon ⁵⁶, C.A. Lee ²⁹, G.R. Lee ^{144a}, L. Lee ⁵⁷,
 S.C. Lee ¹⁵⁵, B. Lefebvre ¹⁰¹, M. Lefebvre ¹⁷³, F. Legger ¹¹², C. Leggett ¹⁸, K. Lehmann ¹⁴⁹, N. Lehmann ¹⁷⁹,
 G. Lehmann Miotto ³⁵, W.A. Light ⁴⁴, A. Leisos ^{159.w}, M.A.L. Leite ^{78d}, R. Leitner ¹⁴⁰, D. Lellouch ¹⁷⁷,
 K.J.C. Leney ⁹², T. Lenz ²⁴, B. Lenzi ³⁵, R. Leone ⁷, S. Leone ^{69a}, C. Leonidopoulos ⁴⁸, G. Lerner ¹⁵³,
 C. Leroy ¹⁰⁷, R. Les ¹⁶⁴, A.A.J. Lesage ¹⁴², C.G. Lester ³¹, M. Levchenko ¹³⁵, J. Levêque ⁵, D. Levin ¹⁰³,
 L.J. Levinson ¹⁷⁷, D. Lewis ⁹⁰, B. Li ^{15b}, B. Li ¹⁰³, C-Q. Li ^{58a.am}, H. Li ^{58a}, H. Li ^{58b}, L. Li ^{58c}, M. Li ^{15a}, Q. Li ^{15d},
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 A. Limosani ¹⁵⁴, C.Y. Lin ³¹, K. Lin ¹⁰⁴, T.H. Lin ⁹⁷, R.A. Linck ⁶³, J.H. Lindon ²¹, B.E. Lindquist ¹⁵²,
 A.L. Lioni ⁵², E. Lipeles ¹³⁴, A. Lipniacka ¹⁷, M. Lisovyi ^{59b}, T.M. Liss ^{170.as}, A. Lister ¹⁷², A.M. Litke ¹⁴³,
 J.D. Little ⁸, B. Liu ⁷⁶, B.L. Liu ⁶, H.B. Liu ²⁹, H. Liu ¹⁰³, J.B. Liu ^{58a}, J.K.K. Liu ¹³², K. Liu ¹³³, M. Liu ^{58a},
 P. Liu ¹⁸, Y. Liu ^{15a}, Y.L. Liu ^{58a}, Y.W. Liu ^{58a}, M. Livan ^{68a,68b}, A. Lleres ⁵⁶, J. Llorente Merino ^{15a},
 S.L. Lloyd ⁹⁰, C.Y. Lo ^{61b}, F. Lo Sterzo ⁴¹, E.M. Lobodzinska ⁴⁴, P. Loch ⁷, T. Lohse ¹⁹, K. Lohwasser ¹⁴⁶,
 M. Lokajicek ¹³⁸, J.D. Long ¹⁷⁰, R.E. Long ⁸⁷, L. Longo ^{65a,65b}, K.A. Looper ¹²³, J.A. Lopez ^{144b}, I. Lopez Paz ⁹⁸,
 A. Lopez Solis ¹⁴⁶, J. Lorenz ¹¹², N. Lorenzo Martinez ⁵, M. Losada ²², P.J. Lösel ¹¹², A. Lösle ⁵⁰, X. Lou ⁴⁴,
 X. Lou ^{15a}, A. Lounis ¹²⁹, J. Love ⁶, P.A. Love ⁸⁷, J.J. Lozano Bahilo ¹⁷¹, H. Lu ^{61a}, M. Lu ^{58a}, Y.J. Lu ⁶²,
 H.J. Lubatti ¹⁴⁵, C. Luci ^{70a,70b}, A. Lucotte ⁵⁶, C. Luedtke ⁵⁰, F. Luehring ⁶³, I. Luise ¹³³, L. Luminari ^{70a},
 B. Lund-Jensen ¹⁵¹, M.S. Lutz ¹⁰⁰, P.M. Luzzi ¹³³, D. Lynn ²⁹, R. Lysak ¹³⁸, E. Lytken ⁹⁴, F. Lyu ^{15a},
 V. Lyubushkin ⁷⁷, T. Lyubushkina ⁷⁷, H. Ma ²⁹, L.L. Ma ^{58b}, Y. Ma ^{58b}, G. Maccarrone ⁴⁹, A. Macchiolo ¹¹³,
 C.M. Macdonald ¹⁴⁶, J. Machado Miguens ^{134,137b}, D. Madaffari ¹⁷¹, R. Madar ³⁷, W.F. Mader ⁴⁶,
 A. Madsen ⁴⁴, N. Madysa ⁴⁶, J. Maeda ⁸⁰, K. Maekawa ¹⁶⁰, S. Maeland ¹⁷, T. Maeno ²⁹, M. Maerker ⁴⁶,

A.S. Maevskiy ¹¹¹, V. Magerl ⁵⁰, D.J. Mahon ³⁸, C. Maidantchik ^{78b}, T. Maier ¹¹², A. Maio ^{137a,137b,137d},
 O. Majersky ^{28a}, S. Majewski ¹²⁸, Y. Makida ⁷⁹, N. Makovec ¹²⁹, B. Malaescu ¹³³, Pa. Malecki ⁸²,
 V.P. Maleev ¹³⁵, F. Malek ⁵⁶, U. Mallik ⁷⁵, D. Malon ⁶, C. Malone ³¹, S. Maltezos ¹⁰, S. Malyukov ³⁵,
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 S. Manzoni ^{66a,66b}, A. Marantis ¹⁵⁹, G. Marceca ³⁰, L. March ⁵², L. Marchese ¹³², G. Marchiori ¹³³,
 M. Marcisovsky ¹³⁸, C. Marcon ⁹⁴, C.A. Marin Tobon ³⁵, M. Marjanovic ³⁷, F. Marroquim ^{78b}, Z. Marshall ¹⁸,
 M.U.F. Martensson ¹⁶⁹, S. Marti-Garcia ¹⁷¹, C.B. Martin ¹²³, T.A. Martin ¹⁷⁵, V.J. Martin ⁴⁸,
 B. Martin dit Latour ¹⁷, M. Martinez ^{14,z}, V.I. Martinez Outschoorn ¹⁰⁰, S. Martin-Haugh ¹⁴¹,
 V.S. Martoiu ^{27b}, A.C. Martyniuk ⁹², A. Marzin ³⁵, L. Masetti ⁹⁷, T. Mashimo ¹⁶⁰, R. Mashinistov ¹⁰⁸,
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 P. Mastrandrea ¹⁵², A. Mastroberardino ^{40b,40a}, T. Masubuchi ¹⁶⁰, P. Mättig ¹⁷⁹, J. Maurer ^{27b}, B. Maček ⁸⁹,
 S.J. Maxfield ⁸⁸, D.A. Maximov ^{120b,120a}, R. Mazini ¹⁵⁵, I. Maznas ¹⁵⁹, S.M. Mazza ¹⁴³, G. Mc Goldrick ¹⁶⁴,
 S.P. Mc Kee ¹⁰³, A. McCarn ⁴¹, T.G. McCarthy ¹¹³, L.I. McClymont ⁹², W.P. McCormack ¹⁸, E.F. McDonald ¹⁰²,
 J.A. MCFayden ³⁵, G. Mchedlize ⁵¹, M.A. McKay ⁴¹, K.D. McLean ¹⁷³, S.J. McMahon ¹⁴¹, P.C. McNamara ¹⁰²,
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 F. Miano ¹⁵³, R.P. Middleton ¹⁴¹, L. Mijović ⁴⁸, G. Mikenberg ¹⁷⁷, M. Mikestikova ¹³⁸, M. Mikuž ⁸⁹,
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 Y. Minegishi ¹⁶⁰, Y. Ming ¹⁷⁸, L.M. Mir ¹⁴, A. Mirto ^{65a,65b}, K.P. Mistry ¹³⁴, T. Mitani ¹⁷⁶, J. Mitrevski ¹¹²,
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 M. Moreno Llácer ³⁵, P. Morettini ^{53b}, M. Morgenstern ¹¹⁸, S. Morgenstern ⁴⁶, D. Mori ¹⁴⁹, M. Morii ⁵⁷,
 M. Morinaga ¹⁷⁶, V. Morisbak ¹³¹, A.K. Morley ³⁵, G. Mornacchi ³⁵, A.P. Morris ⁹², J.D. Morris ⁹⁰,
 L. Morvaj ¹⁵², P. Moschovakos ¹⁰, M. Mosidze ^{156b}, H.J. Moss ¹⁴⁶, J. Moss ^{150,o}, K. Motohashi ¹⁶²,
 R. Mount ¹⁵⁰, E. Mountricha ³⁵, E.J.W. Moyse ¹⁰⁰, S. Muanza ⁹⁹, F. Mueller ¹¹³, J. Mueller ¹³⁶,
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 E. Nagy ⁹⁹, A.M. Nairz ³⁵, Y. Nakahama ¹¹⁵, K. Nakamura ⁷⁹, T. Nakamura ¹⁶⁰, I. Nakano ¹²⁴, H. Nanjo ¹³⁰,
 F. Napolitano ^{59a}, R.F. Naranjo Garcia ⁴⁴, R. Narayan ¹¹, D.I. Narrias Villar ^{59a}, I. Naryshkin ¹³⁵,
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 M. Nessi ^{35,f}, M.S. Neubauer ¹⁷⁰, M. Neumann ¹⁷⁹, P.R. Newman ²¹, T.Y. Ng ^{61c}, Y.S. Ng ¹⁹, Y.W.Y. Ng ¹⁶⁸,
 H.D.N. Nguyen ⁹⁹, T. Nguyen Manh ¹⁰⁷, E. Nibigira ³⁷, R.B. Nickerson ¹³², R. Nicolaidou ¹⁴², D.S. Nielsen ³⁹,
 J. Nielsen ¹⁴³, N. Nikiforou ¹¹, V. Nikolaenko ^{121,ao}, I. Nikolic-Audit ¹³³, K. Nikolopoulos ²¹, P. Nilsson ²⁹,
 Y. Ninomiya ⁷⁹, A. Nisati ^{70a}, N. Nishu ^{58c}, R. Nisius ¹¹³, I. Nitsche ⁴⁵, T. Nitta ¹⁷⁶, T. Nobe ¹⁶⁰, Y. Noguchi ⁸³,
 M. Nomachi ¹³⁰, I. Nomidis ¹³³, M.A. Nomura ²⁹, T. Nooney ⁹⁰, M. Nordberg ³⁵, N. Norjoharuddeen ¹³²,
 T. Novak ⁸⁹, O. Novgorodova ⁴⁶, R. Novotny ¹³⁹, L. Nozka ¹²⁷, K. Ntekas ¹⁶⁸, E. Nurse ⁹², F. Nuti ¹⁰²,
 F.G. Oakham ^{33,av}, H. Oberlack ¹¹³, J. Ocariz ¹³³, A. Ochi ⁸⁰, I. Ochoa ³⁸, J.P. Ochoa-Ricoux ^{144a},
 K. O'Connor ²⁶, S. Oda ⁸⁵, S. Odaka ⁷⁹, S. Oerdek ⁵¹, A. Oh ⁹⁸, S.H. Oh ⁴⁷, C.C. Ohm ¹⁵¹, H. Oide ^{53b,53a},
 M.L. Ojeda ¹⁶⁴, H. Okawa ¹⁶⁶, Y. Okazaki ⁸³, Y. Okumura ¹⁶⁰, T. Okuyama ⁷⁹, A. Olariu ^{27b},
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 H. Oppen ¹³¹, M.J. Oreglia ³⁶, G.E. Orellana ⁸⁶, Y. Oren ¹⁵⁸, D. Orestano ^{72a,72b}, E.C. Orgill ⁹⁸, N. Orlando ^{61b},

A.A. O'Rourke⁴⁴, R.S. Orr¹⁶⁴, B. Osculati^{53b,53a,*}, V. O'Shea⁵⁵, R. Ospanov^{58a}, G. Otero y Garzon³⁰, H. Otono⁸⁵, M. Ouchrif^{34d}, F. Ould-Saada¹³¹, A. Ouraou¹⁴², Q. Ouyang^{15a}, M. Owen⁵⁵, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, J. Pacalt¹²⁷, H.A. Pacey³¹, K. Pachal¹⁴⁹, A. Pacheco Pages¹⁴, L. Pacheco Rodriguez¹⁴², C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸⁰, G. Palacino⁶³, S. Palazzo⁴⁸, S. Palestini³⁵, M. Palka^{81b}, D. Pallin³⁷, I. Panagoulas¹⁰, C.E. Pandini³⁵, J.G. Panduro Vazquez⁹¹, P. Pani³⁵, G. Panizzo^{64a,64c}, L. Paolozzi⁵², T.D. Papadopoulou¹⁰, K. Papageorgiou^{9,k}, A. Paramonov⁶, D. Paredes Hernandez^{61b}, S.R. Paredes Saenz¹³², B. Parida¹⁶³, T.H. Park³³, A.J. Parker⁸⁷, K.A. Parker⁴⁴, M.A. Parker³¹, F. Parodi^{53b,53a}, J.A. Parsons³⁸, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁶⁴, J.M.P. Pasner¹⁴³, E. Pasqualucci^{70a}, S. Passaggio^{53b}, F. Pastore⁹¹, P. Pasuwan^{43a,43b}, S. Pataraiia⁹⁷, J.R. Pater⁹⁸, A. Pathak^{178,l}, T. Pauly³⁵, B. Pearson¹¹³, M. Pedersen¹³¹, L. Pedraza Diaz¹¹⁷, R. Pedro^{137a,137b}, S.V. Peleganchuk^{120b,120a}, O. Penc¹³⁸, C. Peng^{15d}, H. Peng^{58a}, B.S. Peralva^{78a}, M.M. Perego¹²⁹, A.P. Pereira Peixoto^{137a}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{66a,66b}, H. Pernegger³⁵, S. Perrella^{67a,67b}, V.D. Peshekhonov^{77,*}, K. Peters⁴⁴, R.F.Y. Peters⁹⁸, B.A. Petersen³⁵, T.C. Petersen³⁹, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁹, P. Petroff¹²⁹, M. Petrov¹³², F. Petrucci^{72a,72b}, M. Pettee¹⁸⁰, N.E. Pettersson¹⁰⁰, A. Peyaud¹⁴², R. Pezoa^{144b}, T. Pham¹⁰², F.H. Phillips¹⁰⁴, P.W. Phillips¹⁴¹, M.W. Phipps¹⁷⁰, G. Piacquadio¹⁵², E. Pianori¹⁸, A. Picazio¹⁰⁰, R.H. Pickles⁹⁸, R. Piegaiia³⁰, J.E. Pilcher³⁶, A.D. Pilkington⁹⁸, M. Pinamonti^{71a,71b}, J.L. Pinfold³, M. Pitt¹⁷⁷, L. Pizzimento^{71a,71b}, M.-A. Pleier²⁹, V. Pleskot¹⁴⁰, E. Plotnikova⁷⁷, D. Pluth⁷⁶, P. Podberezko^{120b,120a}, R. Poettgen⁹⁴, R. Poggi⁵², L. Poggioli¹²⁹, I. Pogrebnyak¹⁰⁴, D. Pohl²⁴, I. Pokharel⁵¹, G. Polesello^{68a}, A. Poley¹⁸, A. Policicchio^{70a,70b}, R. Polifka³⁵, A. Polini^{23b}, C.S. Pollard⁴⁴, V. Polychronakos²⁹, D. Ponomarenko¹¹⁰, L. Pontecorvo³⁵, G.A. Popeneciu^{27d}, D.M. Portillo Quintero¹³³, S. Pospisil¹³⁹, K. Potamianos⁴⁴, I.N. Potrap⁷⁷, C.J. Potter³¹, H. Potti¹¹, T. Poulsen⁹⁴, J. Poveda³⁵, T.D. Powell¹⁴⁶, M.E. Pozo Astigarraga³⁵, P. Pralavorio⁹⁹, S. Prell⁷⁶, D. Price⁹⁸, M. Primavera^{65a}, S. Prince¹⁰¹, M.L. Proffitt¹⁴⁵, N. Proklova¹¹⁰, K. Prokofiev^{61c}, F. Prokoshin^{144b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{81a}, A. Puri¹⁷⁰, P. Puzo¹²⁹, J. Qian¹⁰³, Y. Qin⁹⁸, A. Quadt⁵¹, M. Queitsch-Maitland⁴⁴, A. Qureshi¹, P. Rados¹⁰², F. Ragusa^{66a,66b}, G. Rahal⁹⁵, J.A. Raine⁵², S. Rajagopalan²⁹, A. Ramirez Morales⁹⁰, T. Rashid¹²⁹, S. Raspopov⁵, M.G. Ratti^{66a,66b}, D.M. Rauch⁴⁴, F. Rauscher¹¹², S. Rave⁹⁷, B. Ravina¹⁴⁶, I. Ravinovich¹⁷⁷, J.H. Rawling⁹⁸, M. Raymond³⁵, A.L. Read¹³¹, N.P. Readioff⁵⁶, M. Reale^{65a,65b}, D.M. Rebuzzi^{68a,68b}, A. Redelbach¹⁷⁴, G. Redlinger²⁹, R. Reece¹⁴³, R.G. Reed^{32c}, K. Reeves⁴², L. Rehnisch¹⁹, J. Reichert¹³⁴, D. Reikher¹⁵⁸, A. Reiss⁹⁷, A. Rej¹⁴⁸, C. Rembser³⁵, H. Ren^{15d}, M. Rescigno^{70a}, S. Resconi^{66a}, E.D. Resseguie¹³⁴, S. Rettie¹⁷², E. Reynolds²¹, O.L. Rezanova^{120b,120a}, P. Reznicek¹⁴⁰, E. Ricci^{73a,73b}, R. Richter¹¹³, S. Richter⁴⁴, E. Richter-Was^{81b}, O. Ricken²⁴, M. Ridel¹³³, P. Rieck¹¹³, C.J. Riegel¹⁷⁹, O. Rifki⁴⁴, M. Rijssenbeek¹⁵², A. Rimoldi^{68a,68b}, M. Rimoldi²⁰, L. Rinaldi^{23b}, G. Ripellino¹⁵¹, B. Ristić⁸⁷, E. Ritsch³⁵, I. Riu¹⁴, J.C. Rivera Vergara^{144a}, F. Rizatdinova¹²⁶, E. Rizvi⁹⁰, C. Rizzi¹⁴, R.T. Roberts⁹⁸, S.H. Robertson^{101,ad}, D. Robinson³¹, J.E.M. Robinson⁴⁴, A. Robson⁵⁵, E. Rocco⁹⁷, C. Roda^{69a,69b}, Y. Rodina⁹⁹, S. Rodriguez Bosca¹⁷¹, A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷¹, A.M. Rodriguez Vera^{165b}, S. Roe³⁵, C.S. Rogan⁵⁷, O. Röhne¹³¹, R. Röhrig¹¹³, C.P.A. Roland⁶³, J. Roloff⁵⁷, A. Romaniouk¹¹⁰, M. Romano^{23b,23a}, N. Rompotis⁸⁸, M. Ronzani¹²², L. Roos¹³³, S. Rosati^{70a}, K. Rosbach⁵⁰, N.-A. Rosien⁵¹, B.J. Rosser¹³⁴, E. Rossi⁴⁴, E. Rossi^{72a,72b}, E. Rossi^{67a,67b}, L.P. Rossi^{53b}, L. Rossini^{66a,66b}, J.H.N. Rosten³¹, R. Rosten¹⁴, M. Rotaru^{27b}, J. Rothberg¹⁴⁵, D. Rousseau¹²⁹, D. Roy^{32c}, A. Rozanov⁹⁹, Y. Rozen¹⁵⁷, X. Ruan^{32c}, F. Rubbo¹⁵⁰, F. Rühr⁵⁰, A. Ruiz-Martinez¹⁷¹, Z. Rurikova⁵⁰, N.A. Rusakovich⁷⁷, H.L. Russell¹⁰¹, J.P. Rutherford⁷, E.M. Rüttinger^{44,m}, Y.F. Ryabov¹³⁵, M. Rybar³⁸, G. Rybkin¹²⁹, S. Ryu⁶, A. Ryzhov¹²¹, G.F. Rzehorz⁵¹, P. Sabatini⁵¹, G. Sabato¹¹⁸, S. Sacerdoti¹²⁹, H.F.-W. Sadrozinski¹⁴³, R. Sadykov⁷⁷, F. Safai Tehrani^{70a}, P. Saha¹¹⁹, M. Sahinsoy^{59a}, A. Sahu¹⁷⁹, M. Saimpert⁴⁴, M. Saito¹⁶⁰, T. Saito¹⁶⁰, H. Sakamoto¹⁶⁰, A. Sakharov^{122,an}, D. Salamani⁵², G. Salamanna^{72a,72b}, J.E. Salazar Loyola^{144b}, P.H. Sales De Bruin¹⁶⁹, D. Salihagic¹¹³, A. Salnikov¹⁵⁰, J. Salt¹⁷¹, D. Salvatore^{40b,40a}, F. Salvatore¹⁵³, A. Salvucci^{61a,61b,61c}, A. Salzburger³⁵, J. Samarati³⁵, D. Sammel⁵⁰, D. Sampsonidis¹⁵⁹, D. Sampsonidou¹⁵⁹, J. Sánchez¹⁷¹, A. Sanchez Pineda^{64a,64c}, H. Sandaker¹³¹, C.O. Sander⁴⁴, M. Sandhoff¹⁷⁹, C. Sandoval²², D.P.C. Sankey¹⁴¹, M. Sannino^{53b,53a}, Y. Sano¹¹⁵, A. Sansoni⁴⁹, C. Santoni³⁷, H. Santos^{137a}, I. Santoyo Castillo¹⁵³, A. Santra¹⁷¹, A. Sapronov⁷⁷, J.G. Saraiva^{137a,137d}, O. Sasaki⁷⁹, K. Sato¹⁶⁶, E. Sauvan⁵, P. Savard^{164,av}, N. Savic¹¹³, R. Sawada¹⁶⁰, C. Sawyer¹⁴¹, L. Sawyer^{93,al}, C. Sbarra^{23b}, A. Sbrizzi^{23a}, T. Scanlon⁹², J. Schaarschmidt¹⁴⁵, P. Schacht¹¹³,

B.M. Schachtner¹¹², D. Schaefer³⁶, L. Schaefer¹³⁴, J. Schaeffer⁹⁷, S. Schaepe³⁵, U. Schäfer⁹⁷,
 A.C. Schaffer¹²⁹, D. Schaile¹¹², R.D. Schamberger¹⁵², N. Scharmberg⁹⁸, V.A. Schegelsky¹³⁵,
 D. Scheirich¹⁴⁰, F. Schenck¹⁹, M. Schernau¹⁶⁸, C. Schiavi^{53b,53a}, S. Schier¹⁴³, L.K. Schildgen²⁴,
 Z.M. Schillaci²⁶, E.J. Schioppa³⁵, M. Schioppa^{40b,40a}, K.E. Schleicher⁵⁰, S. Schlenker³⁵,
 K.R. Schmidt-Sommerfeld¹¹³, K. Schmieden³⁵, C. Schmitt⁹⁷, S. Schmitt⁴⁴, S. Schmitz⁹⁷,
 J.C. Schmoeckel⁴⁴, U. Schnoor⁵⁰, L. Schoeffel¹⁴², A. Schoening^{59b}, E. Schopf¹³², M. Schott⁹⁷,
 J.F.P. Schouwenberg¹¹⁷, J. Schovancova³⁵, S. Schramm⁵², A. Schulte⁹⁷, H-C. Schultz-Coulon^{59a},
 M. Schumacher⁵⁰, B.A. Schumm¹⁴³, Ph. Schune¹⁴², A. Schwartzman¹⁵⁰, T.A. Schwarz¹⁰³,
 Ph. Schwemling¹⁴², R. Schwienhorst¹⁰⁴, A. Sciandra²⁴, G. Sciolla²⁶, M. Scornajenghi^{40b,40a}, F. Scuri^{69a},
 F. Scutti¹⁰², L.M. Scyboz¹¹³, C.D. Sebastiani^{70a,70b}, P. Seema¹⁹, S.C. Seidel¹¹⁶, A. Seiden¹⁴³, T. Seiss³⁶,
 J.M. Seixas^{78b}, G. Sekhniaidze^{67a}, K. Sekhon¹⁰³, S.J. Sekula⁴¹, N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁷,
 S. Senkin³⁷, C. Serfon¹³¹, L. Serin¹²⁹, L. Serkin^{64a,64b}, M. Sessa^{58a}, H. Severini¹²⁵, F. Sforza¹⁶⁷,
 A. Sfyrla⁵², E. Shabalina⁵¹, J.D. Shahinian¹⁴³, N.W. Shaikh^{43a,43b}, D. Shaked Renous¹⁷⁷, L.Y. Shan^{15a},
 R. Shang¹⁷⁰, J.T. Shank²⁵, M. Shapiro¹⁸, A.S. Sharma¹, A. Sharma¹³², P.B. Shatalov¹⁰⁹, K. Shaw¹⁵³,
 S.M. Shaw⁹⁸, A. Shcherbakova¹³⁵, Y. Shen¹²⁵, N. Sherafati³³, A.D. Sherman²⁵, P. Sherwood⁹²,
 L. Shi^{155,ar}, S. Shimizu⁷⁹, C.O. Shimmin¹⁸⁰, Y. Shimogama¹⁷⁶, M. Shimojima¹¹⁴, I.P.J. Shipsey¹³²,
 S. Shirabe⁸⁵, M. Shiyakova⁷⁷, J. Shlomi¹⁷⁷, A. Shmeleva¹⁰⁸, D. Shoaleh Saadi¹⁰⁷, M.J. Shochet³⁶,
 S. Shojaii¹⁰², D.R. Shope¹²⁵, S. Shrestha¹²³, E. Shulga¹¹⁰, P. Sicho¹³⁸, A.M. Sickles¹⁷⁰, P.E. Sidebo¹⁵¹,
 E. Sideras Haddad^{32c}, O. Sidiropoulou³⁵, A. Sidoti^{23b,23a}, F. Siegert⁴⁶, Dj. Sijacki¹⁶, J. Silva^{137a},
 M. Silva Jr.¹⁷⁸, M.V. Silva Oliveira^{78a}, S.B. Silverstein^{43a}, S. Simion¹²⁹, E. Simioni⁹⁷, M. Simon⁹⁷,
 R. Simoniello⁹⁷, P. Sinervo¹⁶⁴, N.B. Sinev¹²⁸, M. Sioli^{23b,23a}, I. Siral¹⁰³, S.Yu. Sivoklov¹¹¹,
 J. Sjölin^{43a,43b}, P. Skubic¹²⁵, M. Slater²¹, T. Slavicek¹³⁹, M. Slawinska⁸², K. Sliwa¹⁶⁷, R. Slovak¹⁴⁰,
 V. Smakhtin¹⁷⁷, B.H. Smart⁵, J. Smiesko^{28a}, N. Smirnov¹¹⁰, S.Yu. Smirnov¹¹⁰, Y. Smirnov¹¹⁰,
 L.N. Smirnova¹¹¹, O. Smirnova⁹⁴, J.W. Smith⁵¹, M. Smizanska⁸⁷, K. Smolek¹³⁹, A. Smykiewicz⁸²,
 A.A. Snesarev¹⁰⁸, I.M. Snyder¹²⁸, S. Snyder²⁹, R. Sobie^{173,ad}, A.M. Soffa¹⁶⁸, A. Soffer¹⁵⁸, A. Søgaard⁴⁸,
 D.A. Soh¹⁵⁵, G. Sokhrannyi⁸⁹, C.A. Solans Sanchez³⁵, M. Solar¹³⁹, E.Yu. Soldatov¹¹⁰, U. Soldevila¹⁷¹,
 A.A. Solodkov¹²¹, A. Soloshenko⁷⁷, O.V. Solovyanov¹²¹, V. Solovyev¹³⁵, P. Sommer¹⁴⁶, H. Son¹⁶⁷,
 W. Song¹⁴¹, W.Y. Song^{165b}, A. Sopczak¹³⁹, F. Sopkova^{28b}, C.L. Sotiropoulou^{69a,69b}, S. Sottocornola^{68a,68b},
 R. Soualah^{64a,64c,j}, A.M. Soukharev^{120b,120a}, D. South⁴⁴, B.C. Sowden⁹¹, S. Spagnolo^{65a,65b}, M. Spalla¹¹³,
 M. Spangenberg¹⁷⁵, F. Spanò⁹¹, D. Sperlich¹⁹, T.M. Spieker^{59a}, R. Spighi^{23b}, G. Spigo³⁵, L.A. Spiller¹⁰²,
 D.P. Spiteri⁵⁵, M. Spousta¹⁴⁰, A. Stabile^{66a,66b}, R. Stamen^{59a}, S. Stamm¹⁹, E. Stanecka⁸², R.W. Stanek⁶,
 C. Stanescu^{72a}, B. Stanislaus¹³², M.M. Stanitzki⁴⁴, B. Stapf¹¹⁸, S. Stapnes¹³¹, E.A. Starchenko¹²¹,
 G.H. Stark³⁶, J. Stark⁵⁶, S.H. Stark³⁹, P. Staroba¹³⁸, P. Starovoitov^{59a}, S. Stärz³⁵, R. Staszewski⁸²,
 M. Stegler⁴⁴, P. Steinberg²⁹, B. Stelzer¹⁴⁹, H.J. Stelzer³⁵, O. Stelzer-Chilton^{165a}, H. Stenzel⁵⁴,
 T.J. Stevenson⁹⁰, G.A. Stewart³⁵, M.C. Stockton³⁵, G. Stoica^{27b}, P. Stolte⁵¹, S. Stonjek¹¹³,
 A. Straessner⁴⁶, J. Strandberg¹⁵¹, S. Strandberg^{43a,43b}, M. Strauss¹²⁵, P. Strizeneč^{28b}, R. Ströhmer¹⁷⁴,
 D.M. Strom¹²⁸, R. Stroynowski⁴¹, A. Strubig⁴⁸, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁵, N.A. Styles⁴⁴,
 D. Su¹⁵⁰, J. Su¹³⁶, S. Suchek^{59a}, Y. Sugaya¹³⁰, M. Suk¹³⁹, V.V. Sulin¹⁰⁸, M.J. Sullivan⁸⁸, D.M.S. Sultan⁵²,
 S. Sultansoy^{4c}, T. Sumida⁸³, S. Sun¹⁰³, X. Sun³, K. Suruliz¹⁵³, C.J.E. Suster¹⁵⁴, M.R. Sutton¹⁵³,
 S. Suzuki⁷⁹, M. Svatos¹³⁸, M. Swiatlowski³⁶, S.P. Swift², A. Sydorenko⁹⁷, I. Sykora^{28a}, T. Sykora¹⁴⁰,
 D. Ta⁹⁷, K. Tackmann^{44,aa}, J. Taenzer¹⁵⁸, A. Taffard¹⁶⁸, R. Tafirout^{165a}, E. Tahirovic⁹⁰, N. Taiblum¹⁵⁸,
 H. Takai²⁹, R. Takashima⁸⁴, E.H. Takasugi¹¹³, K. Takeda⁸⁰, T. Takeshita¹⁴⁷, Y. Takubo⁷⁹, M. Talby⁹⁹,
 A.A. Talyshev^{120b,120a}, J. Tanaka¹⁶⁰, M. Tanaka¹⁶², R. Tanaka¹²⁹, B.B. Tannenwald¹²³, S. Tapia Araya^{144b},
 S. Tapprogge⁹⁷, A. Tarek Abouelfadl Mohamed¹³³, S. Tarem¹⁵⁷, G. Tarna^{27b,e}, G.F. Tartarelli^{66a}, P. Tas¹⁴⁰,
 M. Tasevsky¹³⁸, T. Tashiro⁸³, E. Tassi^{40b,40a}, A. Tavares Delgado^{137a,137b}, Y. Tayalati^{34e}, A.C. Taylor¹¹⁶,
 A.J. Taylor⁴⁸, G.N. Taylor¹⁰², P.T.E. Taylor¹⁰², W. Taylor^{165b}, A.S. Tee⁸⁷, R. Teixeira De Lima¹⁵⁰,
 P. Teixeira-Dias⁹¹, H. Ten Kate³⁵, J.J. Teoh¹¹⁸, S. Terada⁷⁹, K. Terashi¹⁶⁰, J. Terron⁹⁶, S. Terzo¹⁴,
 M. Testa⁴⁹, R.J. Teuscher^{164,ad}, S.J. Thais¹⁸⁰, T. Thevenaux-Pelzer⁴⁴, F. Thiele³⁹, D.W. Thomas⁹¹,
 J.P. Thomas²¹, A.S. Thompson⁵⁵, P.D. Thompson²¹, L.A. Thomsen¹⁸⁰, E. Thomson¹³⁴, Y. Tian³⁸,
 R.E. Ticse Torres⁵¹, V.O. Tikhomirov^{108,ap}, Yu.A. Tikhonov^{120b,120a}, S. Timoshenko¹¹⁰, P. Tipton¹⁸⁰,
 S. Tisserant⁹⁹, K. Todome¹⁶², S. Todorova-Nova⁵, S. Todt⁴⁶, J. Tojo⁸⁵, S. Tokár^{28a}, K. Tokushuku⁷⁹,
 E. Tolley¹²³, K.G. Tomiwa^{32c}, M. Tomoto¹¹⁵, L. Tompkins^{150,r}, K. Toms¹¹⁶, B. Tong⁵⁷, P. Tornambe⁵⁰,

E. Torrence¹²⁸, H. Torres⁴⁶, E. Torró Pastor¹⁴⁵, C. Tosciri¹³², J. Toth^{99,ac}, F. Touchard⁹⁹, D.R. Tovey¹⁴⁶,
 C.J. Treado¹²², T. Trefzger¹⁷⁴, F. Tresoldi¹⁵³, A. Tricoli²⁹, I.M. Trigger^{165a}, S. Trincaz-Duvold¹³³,
 M.F. Tripiana¹⁴, W. Trischuk¹⁶⁴, B. Trocme⁵⁶, A. Trofymov¹²⁹, C. Troncon^{66a}, M. Trovatelli¹⁷³,
 F. Trovato¹⁵³, L. Truong^{32b}, M. Trzebinski⁸², A. Trzupek⁸², F. Tsai⁴⁴, J.C.-L. Tseng¹³², P.V. Tsiarehka^{105,aj},
 A. Tsirigotis¹⁵⁹, N. Tsirintanis⁹, V. Tsiskaridze¹⁵², E.G. Tskhadadze^{156a}, I.I. Tsukerman¹⁰⁹, V. Tsulaia¹⁸,
 S. Tsuno⁷⁹, D. Tsybychev^{152,163}, Y. Tu^{61b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tulbure^{27a},
 A.N. Tuna⁵⁷, S. Turchikhin⁷⁷, D. Turgeman¹⁷⁷, I. Turk Cakir^{4b,u}, R. Turra^{66a}, P.M. Tuts³⁸, E. Tzovara⁹⁷,
 G. Uccielli⁴⁵, I. Ueda⁷⁹, M. Ughetto^{43a,43b}, F. Ukegawa¹⁶⁶, G. Unal³⁵, A. Undrus²⁹, G. Unel¹⁶⁸,
 F.C. Ungaro¹⁰², Y. Unno⁷⁹, K. Uno¹⁶⁰, J. Urban^{28b}, P. Urquijo¹⁰², P. Urrejola⁹⁷, G. Usai⁸, J. Usui⁷⁹,
 L. Vacavant⁹⁹, V. Vacek¹³⁹, B. Vachon¹⁰¹, K.O.H. Vadla¹³¹, A. Vaidya⁹², C. Valderanis¹¹²,
 E. Valdes Santurio^{43a,43b}, M. Valente⁵², S. Valentini^{23b,23a}, A. Valero¹⁷¹, L. Valéry⁴⁴, R.A. Vallance²¹,
 A. Vallier⁵, J.A. Valls Ferrer¹⁷¹, T.R. Van Daalen¹⁴, H. Van der Graaf¹¹⁸, P. Van Gemmeren⁶,
 I. Van Vulpen¹¹⁸, M. Vanadia^{71a,71b}, W. Vandelli³⁵, A. Vaniachine¹⁶³, P. Vankov¹¹⁸, R. Vari^{70a},
 E.W. Varnes⁷, C. Varni^{53b,53a}, T. Varol⁴¹, D. Varouchas¹²⁹, K.E. Varvell¹⁵⁴, G.A. Vasquez^{144b},
 J.G. Vasquez¹⁸⁰, F. Vazeille³⁷, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder³⁵, J. Veatch⁵¹,
 V. Vecchio^{72a,72b}, L.M. Veloce¹⁶⁴, F. Veloso^{137a,137c}, S. Veneziano^{70a}, A. Ventura^{65a,65b}, N. Venturi³⁵,
 V. Vercesi^{68a}, M. Verducci^{72a,72b}, C.M. Vergel Infante⁷⁶, C. Vergis²⁴, W. Verkerke¹¹⁸, A.T. Vermeulen¹¹⁸,
 J.C. Vermeulen¹¹⁸, M.C. Vetterli^{149,av}, N. Viaux Maira^{144b}, M. Vicente Barreto Pinto⁵², I. Vichou^{170,*},
 T. Vickey¹⁴⁶, O.E. Vickey Boeriu¹⁴⁶, G.H.A. Viehhauser¹³², S. Viel¹⁸, L. Vigani¹³², M. Villa^{23b,23a},
 M. Villaplana Perez^{66a,66b}, E. Vilucchi⁴⁹, M.G. Vincter³³, V.B. Vinogradov⁷⁷, A. Vishwakarma⁴⁴,
 C. Vittori^{23b,23a}, I. Vivarelli¹⁵³, S. Vlachos¹⁰, M. Vogel¹⁷⁹, P. Vokac¹³⁹, G. Volpi¹⁴,
 S.E. von Buddenbrock^{32c}, E. Von Toerne²⁴, V. Vorobel¹⁴⁰, K. Vorobev¹¹⁰, M. Vos¹⁷¹, J.H. Vossebeld⁸⁸,
 N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹³⁹, M. Vreeswijk¹¹⁸, T. Šfiligoj⁸⁹, R. Vuillemet³⁵,
 I. Vukotic³⁶, T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁷⁹, J. Wagner-Kuhr¹¹², H. Wahlberg⁸⁶,
 S. Wahrmund⁴⁶, K. Wakamiya⁸⁰, V.M. Walbrecht¹¹³, J. Walder⁸⁷, R. Walker¹¹², S.D. Walker⁹¹,
 W. Walkowiak¹⁴⁸, V. Wallangen^{43a,43b}, A.M. Wang⁵⁷, C. Wang^{58b}, F. Wang¹⁷⁸, H. Wang¹⁸, H. Wang³,
 J. Wang¹⁵⁴, J. Wang^{59b}, P. Wang⁴¹, Q. Wang¹²⁵, R.-J. Wang¹³³, R. Wang^{58a}, R. Wang⁶, S.M. Wang¹⁵⁵,
 W.T. Wang^{58a}, W. Wang^{15c,ae}, W.X. Wang^{58a,ae}, Y. Wang^{58a,am}, Z. Wang^{58c}, C. Wanotayaroj⁴⁴,
 A. Warburton¹⁰¹, C.P. Ward³¹, D.R. Wardrope⁹², A. Washbrook⁴⁸, P.M. Watkins²¹, A.T. Watson²¹,
 M.F. Watson²¹, G. Watts¹⁴⁵, S. Watts⁹⁸, B.M. Waugh⁹², A.F. Webb¹¹, S. Webb⁹⁷, C. Weber¹⁸⁰,
 M.S. Weber²⁰, S.A. Weber³³, S.M. Weber^{59a}, A.R. Weidberg¹³², J. Weingarten⁴⁵, M. Weirich⁹⁷,
 C. Weiser⁵⁰, P.S. Wells³⁵, T. Wenaus²⁹, T. Wengler³⁵, S. Wenig³⁵, N. Vermes²⁴, M.D. Werner⁷⁶,
 P. Werner³⁵, M. Wessels^{59a}, T.D. Weston²⁰, K. Whalen¹²⁸, N.L. Whallon¹⁴⁵, A.M. Wharton⁸⁷,
 A.S. White¹⁰³, A. White⁸, M.J. White¹, R. White^{144b}, D. Whiteson¹⁶⁸, B.W. Whitmore⁸⁷, F.J. Wickens¹⁴¹,
 W. Wiedenmann¹⁷⁸, M. Wielers¹⁴¹, C. Wiglesworth³⁹, L.A.M. Wiik-Fuchs⁵⁰, F. Wilk⁹⁸, H.G. Wilkens³⁵,
 L.J. Wilkins⁹¹, H.H. Williams¹³⁴, S. Williams³¹, C. Willis¹⁰⁴, S. Willocq¹⁰⁰, J.A. Wilson²¹,
 I. Wingerter-Seez⁵, E. Winkels¹⁵³, F. Winklmeier¹²⁸, O.J. Winston¹⁵³, B.T. Winter⁵⁰, M. Wittgen¹⁵⁰,
 M. Wobisch⁹³, A. Wolf⁹⁷, T.M.H. Wolf¹¹⁸, R. Wolff⁹⁹, M.W. Wolter⁸², H. Wolters^{137a,137c},
 V.W.S. Wong¹⁷², N.L. Woods¹⁴³, S.D. Worm²¹, B.K. Wosiek⁸², K.W. Woźniak⁸², K. Wraight⁵⁵, M. Wu³⁶,
 S.L. Wu¹⁷⁸, X. Wu⁵², Y. Wu^{58a}, T.R. Wyatt⁹⁸, B.M. Wynne⁴⁸, S. Xella³⁹, Z. Xi¹⁰³, L. Xia¹⁷⁵, D. Xu^{15a},
 H. Xu^{58a,e}, L. Xu²⁹, T. Xu¹⁴², W. Xu¹⁰³, Z. Xu¹⁵⁰, B. Yabsley¹⁵⁴, S. Yacoob^{32a}, K. Yajima¹³⁰, D.P. Yallup⁹²,
 D. Yamaguchi¹⁶², Y. Yamaguchi¹⁶², A. Yamamoto⁷⁹, T. Yamanaka¹⁶⁰, F. Yamane⁸⁰, M. Yamatani¹⁶⁰,
 T. Yamazaki¹⁶⁰, Y. Yamazaki⁸⁰, Z. Yan²⁵, H.J. Yang^{58c,58d}, H.T. Yang¹⁸, S. Yang⁷⁵, Y. Yang¹⁶⁰, Z. Yang¹⁷,
 W.-M. Yao¹⁸, Y.C. Yap⁴⁴, Y. Yasu⁷⁹, E. Yatsenko^{58c,58d}, J. Ye⁴¹, S. Ye²⁹, I. Yeletsikh⁷⁷, E. Yigitbasi²⁵,
 E. Yildirim⁹⁷, K. Yorita¹⁷⁶, K. Yoshihara¹³⁴, C.J.S. Young³⁵, C. Young¹⁵⁰, J. Yu⁸, J. Yu⁷⁶, X. Yue^{59a},
 S.P.Y. Yuen²⁴, B. Zabinski⁸², G. Zacharis¹⁰, E. Zaffaroni⁵², R. Zaidan¹⁴, A.M. Zaitsev^{121,ao},
 T. Zakareishvili^{156b}, N. Zakharchuk³³, J. Zalieckas¹⁷, S. Zambito⁵⁷, D. Zanzi³⁵, D.R. Zaripovas⁵⁵,
 S.V. Zeiβner⁴⁵, C. Zeitnitz¹⁷⁹, G. Zemaityte¹³², J.C. Zeng¹⁷⁰, Q. Zeng¹⁵⁰, O. Zenin¹²¹, D. Zerwas¹²⁹,
 M. Zgubič¹³², D.F. Zhang^{58b}, D. Zhang¹⁰³, F. Zhang¹⁷⁸, G. Zhang^{58a}, G. Zhang^{15b}, H. Zhang^{15c}, J. Zhang⁶,
 L. Zhang^{15c}, L. Zhang^{58a}, M. Zhang¹⁷⁰, P. Zhang^{15c}, R. Zhang^{58a}, R. Zhang²⁴, X. Zhang^{58b}, Y. Zhang^{15d},
 Z. Zhang¹²⁹, P. Zhao⁴⁷, Y. Zhao^{58b,129,ak}, Z. Zhao^{58a}, A. Zhemchugov⁷⁷, Z. Zheng¹⁰³, D. Zhong¹⁷⁰,
 B. Zhou¹⁰³, C. Zhou¹⁷⁸, L. Zhou⁴¹, M.S. Zhou^{15d}, M. Zhou¹⁵², N. Zhou^{58c}, Y. Zhou⁷, C.G. Zhu^{58b},

H.L. Zhu^{58a}, H. Zhu^{15a}, J. Zhu¹⁰³, Y. Zhu^{58a}, X. Zhuang^{15a}, K. Zhukov¹⁰⁸, V. Zhulanov^{120b,120a},
 A. Zibell¹⁷⁴, D. Zieminska⁶³, N.I. Zimine⁷⁷, S. Zimmermann⁵⁰, Z. Zinonos¹¹³, M. Ziolkowski¹⁴⁸,
 G. Zobernig¹⁷⁸, A. Zoccoli^{23b,23a}, K. Zoch⁵¹, T.G. Zorbas¹⁴⁶, R. Zou³⁶, M. Zur Nedden¹⁹, L. Zwalinski³⁵

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

¹⁶ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁷ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁸ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America

¹⁹ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

²⁰ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

²¹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²² Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

²³ (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (b) INFN Sezione di Bologna, Italy

²⁴ Physikalisches Institut, Universität Bonn, Bonn, Germany

²⁵ Department of Physics, Boston University, Boston, MA, United States of America

²⁶ Department of Physics, Brandeis University, Waltham, MA, United States of America

²⁷ (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara, Romania

²⁸ (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

²⁹ Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America

³⁰ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

³¹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³² (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

³³ Department of Physics, Carleton University, Ottawa, ON, Canada

³⁴ (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;

(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco

³⁵ CERN, Geneva, Switzerland

³⁶ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America

³⁷ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France

³⁸ Nevis Laboratory, Columbia University, Irvington, NY, United States of America

³⁹ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

⁴⁰ (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

⁴¹ Physics Department, Southern Methodist University, Dallas, TX, United States of America

⁴² Physics Department, University of Texas at Dallas, Richardson, TX, United States of America

⁴³ (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm, Sweden

⁴⁴ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany

⁴⁵ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁷ Department of Physics, Duke University, Durham, NC, United States of America

⁴⁸ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁹ INFN e Laboratori Nazionali di Frascati, Frascati, Italy

⁵⁰ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

⁵¹ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany

⁵² Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland

⁵³ (a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova, Italy

⁵⁴ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

⁵⁵ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

⁵⁶ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France

⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America

⁵⁸ (a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (c) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; (d) Tsung-Dao Lee Institute, Shanghai, China

⁵⁹ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

⁶⁰ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

⁶¹ (a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, University of Hong Kong, Hong Kong; (c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

⁶² Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

⁶³ Department of Physics, Indiana University, Bloomington, IN, United States of America

- 64 ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 65 ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 66 ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- 67 ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 68 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 69 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 70 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 71 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 72 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 73 ^(a) INFN-TIFPA; ^(b) Università degli Studi di Trento, Trento, Italy
- 74 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 75 University of Iowa, Iowa City, IA, United States of America
- 76 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America
- 77 Joint Institute for Nuclear Research, Dubna, Russia
- 78 ^(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c) Universidade Federal de São João del Rei (UFSJ), São João del Rei; ^(d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- 79 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 80 Graduate School of Science, Kobe University, Kobe, Japan
- 81 ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 82 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- 83 Faculty of Science, Kyoto University, Kyoto, Japan
- 84 Kyoto University of Education, Kyoto, Japan
- 85 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- 86 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 87 Physics Department, Lancaster University, Lancaster, United Kingdom
- 88 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 89 Department of Experimental Particle Physics, Jozef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- 90 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 91 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- 92 Department of Physics and Astronomy, University College London, London, United Kingdom
- 93 Louisiana Tech University, Ruston, LA, United States of America
- 94 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 95 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- 96 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- 97 Institut für Physik, Universität Mainz, Mainz, Germany
- 98 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 99 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- 100 Department of Physics, University of Massachusetts, Amherst, MA, United States of America
- 101 Department of Physics, McGill University, Montreal, QC, Canada
- 102 School of Physics, University of Melbourne, Victoria, Australia
- 103 Department of Physics, University of Michigan, Ann Arbor, MI, United States of America
- 104 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America
- 105 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 106 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- 107 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 108 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 109 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 110 National Research Nuclear University MEPhI, Moscow, Russia
- 111 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 112 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 114 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 115 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 116 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- 117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 119 Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- 120 ^(a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; ^(b) Novosibirsk State University Novosibirsk, Russia
- 121 Institute for High Energy Physics of the National Research Centre, Kurchatov Institute, Protvino, Russia
- 122 Department of Physics, New York University, New York, NY, United States of America
- 123 Ohio State University, Columbus, OH, United States of America
- 124 Faculty of Science, Okayama University, Okayama, Japan
- 125 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- 126 Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- 127 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- 128 Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- 129 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 130 Graduate School of Science, Osaka University, Osaka, Japan
- 131 Department of Physics, University of Oslo, Oslo, Norway
- 132 Department of Physics, Oxford University, Oxford, United Kingdom
- 133 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- 134 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- 135 Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- 136 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- 137 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 138 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

- ¹³⁹ Czech Technical University in Prague, Prague, Czech Republic
¹⁴⁰ Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
¹⁴¹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
¹⁴² IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
¹⁴³ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
¹⁴⁴ ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
¹⁴⁵ Department of Physics, University of Washington, Seattle, WA, United States of America
¹⁴⁶ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
¹⁴⁷ Department of Physics, Shinshu University, Nagano, Japan
¹⁴⁸ Department Physik, Universität Siegen, Siegen, Germany
¹⁴⁹ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
¹⁵⁰ SLAC National Accelerator Laboratory, Stanford, CA, United States of America
¹⁵¹ Physics Department, Royal Institute of Technology, Stockholm, Sweden
¹⁵² Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America
¹⁵³ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
¹⁵⁴ School of Physics, University of Sydney, Sydney, Australia
¹⁵⁵ Institute of Physics, Academia Sinica, Taipei, Taiwan
¹⁵⁶ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
¹⁵⁷ Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
¹⁵⁸ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
¹⁵⁹ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
¹⁶⁰ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
¹⁶¹ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁶² Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁶³ Tomsk State University, Tomsk, Russia
¹⁶⁴ Department of Physics, University of Toronto, Toronto, ON, Canada
¹⁶⁵ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
¹⁶⁶ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
¹⁶⁷ Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America
¹⁶⁸ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America
¹⁶⁹ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁷⁰ Department of Physics, University of Illinois, Urbana, IL, United States of America
¹⁷¹ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain
¹⁷² Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁷³ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
¹⁷⁵ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁶ Waseda University, Tokyo, Japan
¹⁷⁷ Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
¹⁷⁸ Department of Physics, University of Wisconsin, Madison, WI, United States of America
¹⁷⁹ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁸⁰ Department of Physics, Yale University, New Haven, CT, United States of America
¹⁸¹ Yerevan Physics Institute, Yerevan, Armenia

^a Also at Borough of Manhattan Community College, City University of New York, NY, United States of America.

^b Also at California State University, East Bay, United States of America.

^c Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

^d Also at CERN, Geneva, Switzerland.

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

^f Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

^g Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^h Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.

ⁱ Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

^j Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

^k Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^l Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America.

^m Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

ⁿ Also at Department of Physics, California State University, Fresno, CA, United States of America.

^o Also at Department of Physics, California State University, Sacramento, CA, United States of America.

^p Also at Department of Physics, King's College London, London, United Kingdom.

^q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^r Also at Department of Physics, Stanford University, United States of America.

^s Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^t Also at Department of Physics, University of Michigan, Ann Arbor, MI, United States of America.

^u Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

^v Also at Graduate School of Science, Osaka University, Osaka, Japan.

^w Also at Hellenic Open University, Patras, Greece.

^x Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^y Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.

^z Also at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.

^{aa} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

^{ab} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

^{ac} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{ad} Also at Institute of Particle Physics (IPP), Canada.

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

^{af} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^{ag} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^{ah} Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain.

^{ai} Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.

^{aj} Also at Joint Institute for Nuclear Research, Dubna, Russia.

^{ak} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

^{al} Also at Louisiana Tech University, Ruston, LA, United States of America.

^{am} Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.

^{an} Also at Manhattan College, New York, NY, United States of America.

^{ao} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{ap} Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{aq} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

^{ar} Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

^{as} Also at The City College of New York, New York, NY, United States of America.

^{at} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

^{au} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{av} Also at TRIUMF, Vancouver, BC, Canada.

^{aw} Also at Università di Napoli Parthenope, Napoli, Italy.

* Deceased.