



Measurement of the charge asymmetry in top-quark pair production in association with a photon with the ATLAS experiment

The ATLAS Collaboration*

ARTICLE INFO

Article history:

Received 21 December 2022
Received in revised form 17 February 2023
Accepted 14 March 2023
Available online 20 June 2023
Editor: M. Doser

ABSTRACT

A measurement of the charge asymmetry in top-quark pair ($t\bar{t}$) production in association with a photon is presented. The measurement is performed in the single-lepton $t\bar{t}$ decay channel using *proton–proton* collision data collected with the ATLAS detector at the Large Hadron Collider at CERN at a centre-of-mass energy of 13 TeV during the years 2015–2018, corresponding to an integrated luminosity of 139 fb^{−1}. The charge asymmetry is obtained from the distribution of the difference of the absolute rapidities of the top quark and antiquark using a profile likelihood unfolding approach. It is measured to be $A_C = -0.003 \pm 0.029$ in agreement with the Standard Model expectation.

© 2023 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 top quark is the heaviest known elementary particle and the only quark that decays before hadronisation, which allows direct access to its properties in production and decay. Measurements of top-quark properties, predicted by the Standard Model (SM), provide important input to test theoretical calculations and have the potential to reveal deviations from the SM predictions. One of the relevant properties is related to the slight difference between the rapidity distributions of top quarks and top antiquarks produced in pairs ($t\bar{t}$). This asymmetry, referred to as charge asymmetry, is defined in *proton–proton* collisions as follows [1–4]:

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)},$$

where N is the number of events and y_t ($y_{\bar{t}}$) the rapidity of the top quark (top antiquark). The production of $t\bar{t}$ events is predicted to be symmetric under the exchange of top quark and antiquark, i.e. $A_C = 0$, at leading-order (LO) accuracy in perturbative QCD. However, at next-to-leading order (NLO), quark–antiquark-initiated $t\bar{t}$ production is asymmetric in the top-quark rapidity distribution, owing to interference between processes with initial- and final-state gluon emission and between the Born diagram and the box diagram at $O(\alpha_s^4)$. The total asymmetry from the sum of all effects is expected to be positive [5].

Previous measurements of the asymmetry in $t\bar{t}$ production by the ATLAS and CMS Collaborations at centre-of-mass energies ($\sqrt{s}$) of 7, 8 and 13 TeV [6–16] agree with the SM expectation. The most

recent measurement of the inclusive and differential charge asymmetry at 13 TeV by the ATLAS Collaboration [17] reported evidence for a non-zero asymmetry in $t\bar{t}$ production (measured as $A_C = 0.0068 \pm 0.0015$ and in agreement with the SM prediction [17,18]). While A_C at the LHC corresponds to a central–forward asymmetry, the $t\bar{t}$ production asymmetry manifests itself as a forward–backward asymmetry at the Tevatron. Early measurements of this asymmetry showed deviations from NLO QCD predictions, particularly at large values of the $t\bar{t}$ invariant mass [19]. However, more recent results by the CDF and D0 Collaborations [20–22] are compatible with the improved SM predictions including NLO electroweak (EW) and higher-order QCD corrections [23,24].

The $t\bar{t}$ charge asymmetry is diluted at the LHC owing to the large fraction of gluon–gluon-initiated $t\bar{t}$ events, which are symmetric under the exchange of the top quark and antiquark. However, it is enhanced in other topologies where the fraction of quark–antiquark-initiated production is larger, such as in associated production of $t\bar{t}$ with a photon ($t\bar{t}\gamma$) [1,2]. Interference effects among QCD diagrams at NLO, similar to those in $t\bar{t}$ events, are predicted in $t\bar{t}\gamma$ production. However, the dominant contribution to the asymmetry in $t\bar{t}\gamma$ arises from interference between QED initial-state radiation, Fig. 1(left), and final-state radiation, Fig. 1(right), which yields a larger asymmetry of negative sign. In addition, other QCD–EW higher-order contributions can have a sizeable effect on the observed asymmetry [25]. The overall asymmetry in $t\bar{t}\gamma$ at $\sqrt{s} = 13$ TeV is expected to have a negative value, of 1%–2% depending on the phase space, according to SM predictions [25,26] and can be modified by ‘beyond-the-SM’ contributions. Contributions from an s -channel colour octet or a Z' boson would, for instance, result in a smaller A_C absolute value [1].

These sources of asymmetry are only present in the $t\bar{t}\gamma$ events where the photon is radiated from an initial-state parton or one of

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

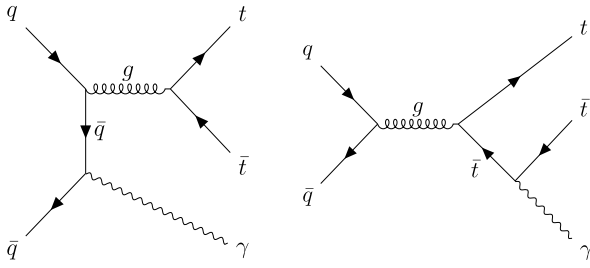


Fig. 1. Example Feynman diagrams of $t\bar{t}\gamma$ production contributing to the charge asymmetry.

the top quarks (hereafter referred to as $t\bar{t}\gamma$ production). The asymmetry is diluted by $t\bar{t}\gamma$ events where the photon arises from any of the charged decay products of the $t\bar{t}$ system ($t\bar{t}\gamma$ decay in the following). Therefore, only $t\bar{t}\gamma$ production events are considered as signal in this analysis.

This paper presents the first measurement of the charge asymmetry of the top-quark pairs in $t\bar{t}\gamma$ production in $t\bar{t}$ single-lepton final states, which have one high- p_T lepton and at least four jets, two of which arise from b -quarks. It is performed using the full 139 fb^{-1} data set recorded with the ATLAS detector between 2015 and 2018 at $\sqrt{s} = 13\text{ TeV}$, referred to as Run 2. In order to extract the asymmetry, the top quarks are reconstructed using a kinematic likelihood fit. The separation between signal and background processes is enhanced using a neural network (NN) approach. The output distribution of the NN is used to define two regions, one enriched in background events and one in signal events. The A_C value is determined by means of a maximum-likelihood fit to the distribution of the difference of absolute rapidities of the top quark and antiquark. This is also referred to as ‘maximum-likelihood unfolding’.

The paper is organised as follows. The ATLAS detector is briefly introduced in Section 2. The simulation of signal and background processes is summarised in Section 3. The event reconstruction, selection, and estimation of the background processes are presented in Sections 4 and 5. The systematic uncertainties are described in Section 6. The analysis strategy is discussed in Section 7, followed by the result in Section 8. Finally, a summary is given in Section 9.

2. ATLAS detector

The ATLAS [27–29] detector is a multipurpose detector with a forward-backward symmetric cylindrical geometry with respect to the LHC beam axis.¹ The innermost layers consist of tracking detectors in the pseudorapidity range $|\eta| < 2.5$. This inner detector (ID) is surrounded by a thin superconducting solenoid that provides a 2 T axial magnetic field. It is enclosed by the electromagnetic and hadronic calorimeters, which cover $|\eta| < 4.9$. The outermost layers of ATLAS consist of an external muon spectrometer within $|\eta| < 2.7$, incorporating three large toroidal magnetic assemblies with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm for most of the acceptance. The muon spectrometer includes precision tracking chambers and fast detectors for triggering. A two-level trigger system [30] reduces the recorded event rate to an average of 1 kHz. An extensive software suite [31] is used in data simulation, in the reconstruction

and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Simulation of signal and background processes

Monte Carlo (MC) event generators were used to estimate the contributions from the expected signal and background processes. The response of the ATLAS detector was simulated [32] with GEANT4 [33]. A fast simulation (ATLFAST-II), which relies on a parameterisation of the calorimeter response [34], was used in samples employed to estimate uncertainties related to the $t\bar{t}$ and $tW\gamma$ modelling. The additional pp collisions in the same or neighbouring bunch crossings, referred to as pile-up, were generated with PYTHIA 8.186 [35] using a set of tuned parameters called the A3 tune [36] and the NNPDF2.3LO parton distribution function (PDF) set [37].

The signal $t\bar{t}\gamma$ production events were simulated with MADGRAPH5_AMC@NLO 2.7.3 [38] as a $2 \rightarrow 3$ process at NLO accuracy in QCD. The interference effects between initial-state and final-state photon radiation were considered in this process. The final-state top quarks in the $t\bar{t}\gamma$ production sample are on-shell and were decayed at LO using MADSPIN [39,40] to preserve spin correlations.

The background $t\bar{t}\gamma$ decay events, where the photon arises from any of the decay products of the top quarks or one of the on-shell top quarks, were simulated with the same version of MADGRAPH5_AMC@NLO but at LO precision as a $2 \rightarrow 2$ process followed by the decay of the top quarks, also simulated at LO precision. Both samples were generated using the NNPDF3.0NLO [41] PDF set and interfaced to PYTHIA 8.240 [42], which used the A14 tune [43] and the NNPDF2.3LO PDF set to model the parton shower, hadronisation, fragmentation and underlying event. The renormalisation and factorisation scales were set to $0.5 \times \sum_i \sqrt{m_i^2 + p_{T,i}^2}$, where m_i and $p_{T,i}$ are the masses and transverse momenta of the particles generated from the matrix element (ME) calculation. Photons are required to have $p_T > 15\text{ GeV}$ and to be isolated according to a smooth-cone hadronic isolation criterion with $\delta_0 = 0.1$, $\epsilon_\gamma = 0.1$ and $n = 2$, defined in Ref. [44], which avoids infrared divergences. The top-quark mass in the $t\bar{t}\gamma$ sample and all other samples involving top quarks was set to 172.5 GeV and the decays of bottom and charm hadrons were simulated using the EVTGEN 1.6.0 program [45].

The $t\bar{t}\gamma$ production sample is normalised to the NLO cross section given by the MC simulation, while the normalisation of the $t\bar{t}\gamma$ decay sample is corrected by a NLO/LO inclusive K -factor of 1.5. This K -factor was derived by comparing the normalisation of the sum of the NLO $t\bar{t}\gamma$ production sample and the LO $t\bar{t}\gamma$ decay sample with the normalisation of a LO inclusive $2 \rightarrow 7$ $t\bar{t}\gamma$ sample corrected with the K -factor obtained in Ref. [46] using the calculation described in Ref. [47].

The $t\bar{t}$ events were simulated at NLO accuracy in QCD using POWHEG Box v2 [48–50] and the NNPDF3.0NLO PDF set. The parton shower was generated with PYTHIA 8.230 using the A14 tune [51]. The $t\bar{t}$ events are normalised to a cross-section value calculated with the TOP++ 2.0 program at next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-logarithm order (see Ref. [52] and references therein).

The $tW\gamma$ events were generated at LO accuracy with the MADGRAPH5_AMC@NLO 2.7.3 generator in the five-flavour scheme. To simulate this process, two complementary samples were generated; one as a $2 \rightarrow 3$ process assuming a stable top quark and the other as a $2 \rightarrow 2$ process, where the photon is radiated from any other charged final-state particle. To avoid infrared divergences, the photon was required to have $p_T > 15\text{ GeV}$ and $|\eta| < 5.0$ and to be

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 $\eta = -\ln \tan(\theta/2)$, and the rapidity as $y = (1/2) \ln[(E + p_z)/(E - p_z)]$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

separated by $\Delta R > 0.2$ from any parton. Both samples make use of the NNPDF2.3LO PDF set and were interfaced to PYTHIA 8.212 for parton showering using the A14 tune.

Single-top-quark s - and t -channel production and inclusive tW production were simulated at ME level at NLO in QCD with POWHEGBox v2 and the NNPDF2.3LO PDF set. The event generator was interfaced to PYTHIA 8.230, which used the A14 tune. The events are normalised to the NNLO cross section [53–55].

Events with $W\gamma$ and $Z\gamma$ final states (with additional jets) were simulated with SHERPA 2.2.8 [56] at NLO in QCD using the NNPDF3.0NNLO PDF set. The samples are normalised to the cross sections given by the MC simulation. The SHERPA generator performs all steps of the event generation, from the hard process to the observable particles. Events with inclusive W - and Z -boson production in association with additional jets were simulated with SHERPA 2.2.1 [56,57] at NLO in QCD. The NNPDF3.0NNLO PDF set was used together with a dedicated tune provided by the SHERPA authors. The samples are normalised to the NNLO cross section in QCD [58].

Diboson processes, WW , WZ and ZZ , were generated with SHERPA 2.2.2 (leptonic decays) and 2.2.1 (non-leptonic final states) at LO in QCD. The NNPDF3.0NNLO PDF set was used with a dedicated tune provided by the SHERPA authors. The samples are normalised to NLO cross sections in QCD [59].

Events with a $t\bar{t}$ pair and an associated W or Z boson ($t\bar{t}V$) were simulated at NLO at the ME level with MADGRAPH5_AMC@NLO using the NNPDF3.0NNLO PDF set. The ME generator was interfaced to PYTHIA 8.210, for which the A14 tune was used in conjunction with the NNPDF2.3LO PDF set. The samples are normalised to NLO in QCD and electroweak theory [60].

A procedure was applied to remove the overlap between the samples in which events were generated at ME level without explicitly including a photon in the final state and the dedicated samples where photons were included in the ME-level event-generation step ($t\bar{t}\gamma$ and $tW\gamma$ final states, as well as $W\gamma$ and $Z\gamma$ final states with additional jets). Events in the inclusive samples are discarded if they contain a parton-level photon that fulfils $p_T(\gamma) > 15$ GeV and $\Delta R(\gamma, \ell) > 0.2$, where $p_T(\gamma)$ is the transverse momentum of the photon and $\Delta R(\gamma, \ell)$ is the angular distance between the photon and any charged lepton.

Corrections to the pile-up profile, the trigger, reconstruction and selection efficiencies, and the energy scales and resolutions, are applied to the MC simulation samples to improve the description of the data.

4. Event reconstruction and selection

The analysis uses a data set that passes stringent quality requirements and corresponds to an integrated luminosity of 139 fb^{-1} collected with the ATLAS detector during Run 2 of the LHC. Events are required to have at least one primary vertex reconstructed from at least two associated tracks, and only events where at least one single-electron [61] or single-muon [62] trigger was fired are selected.

Muons are reconstructed by combining a track in the muon spectrometer with a track in the ID system. The reconstruction, identification and calibration methods are described in Ref. [63]. The muon track is also required to originate from the primary collision vertex. Muons are required to be isolated according to measurements of nearby track p_T and calorimeter energy. Only muons with calibrated $p_T > 25$ GeV and $|\eta| < 2.5$ and passing ‘medium’ quality requirements are considered.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter (ECAL) associated with reconstructed tracks in the ID system. The origin of the electron track also has to be compatible with the primary vertex. Electrons are identified

with a combined likelihood technique [64] using a ‘tight’ working point, and are required to be isolated according to measurements of nearby calorimeter energy and track p_T . Electrons are calibrated with the method described in Ref. [64] and are selected if they fulfil $p_T > 25$ GeV and $|\eta_{\text{clus}}| < 2.47$, excluding the ECAL barrel/end-cap transition region $1.37 < |\eta_{\text{clus}}| < 1.52$, where η_{clus} refers to the pseudorapidity of the calorimeter energy cluster associated with the electron.

Photons are reconstructed from energy deposits in the central region of the ECAL [64]. Photons are required to fulfil tight identification and isolation requirements. The latter is defined as $E_T^{\text{iso}}|_{\Delta R < 0.4} < 0.022 \cdot E_T(\gamma) + 2.45$ GeV in conjunction with $p_T^{\text{iso}}|_{\Delta R < 0.2} < 0.05 \cdot E_T(\gamma)$, where E_T^{iso} refers to the calorimeter isolation within a cone of size $\Delta R = 0.4$ around the direction of the photon candidate and p_T^{iso} is the track isolation within a $\Delta R = 0.2$ cone [65]. Photons are required to have transverse energy $E_T > 20$ GeV and $|\eta_{\text{clus}}| < 2.37$, excluding the calorimeter transition region. They are separated into two categories, one where the cluster is not matched to any reconstructed track in the ID system (unconverted photons) and the other where the cluster is matched to one or two reconstructed tracks that are consistent with originating from a photon conversion and, in addition, a conversion vertex can be found (converted photons).

Jets are reconstructed using the anti- k_t algorithm [66] in the FASTJET implementation [67] with a distance parameter $R = 0.4$. Their reconstruction is performed on particle-flow objects [68]. The jet energy scale and jet energy resolution are calibrated using an energy- and η -dependent calibration scheme based on simulation with in situ corrections obtained from data [69]. Only jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered in the analysis. Jets with a large contribution from pile-up vertices are identified with the *jet vertex tagger* (JVT) [70] and rejected.

Jets arising from b -quark hadronisation, referred to as b -jets, are identified using the DL1r b -tagging algorithm [71], which is based on an artificial deep neural network combining information from other algorithms using track impact parameters and secondary vertices, and a multi-vertex reconstruction algorithm. The flavour-tagging efficiency for b -jets, as well as for c -jets and light-flavour jets, is calibrated as described in Ref. [72]. The working point used to select the b -jets corresponds to a selection efficiency of 77% in simulated $t\bar{t}$ events.

The magnitude of the reconstructed missing transverse momentum (E_T^{miss}) [73,74] is calculated from the negative vector sum of the p_T of all calibrated physics objects and the remaining unclustered energy, also called the *soft term*. This term is estimated from low- p_T tracks associated with the primary vertex but not with any reconstructed object.

An overlap removal procedure is implemented to avoid the reconstruction of the same energy clusters or tracks as different objects. Electron candidates that share their track with a muon candidate are removed and jets within a $\Delta R = 0.2$ cone around any of the remaining electrons are excluded. If the distance between an electron and any remaining jet is $\Delta R < 0.4$, the electron is subsequently removed. In the next step, muon candidates within $\Delta R = 0.4$ of a jet are removed if the jet has more than two associated tracks, otherwise the jet is discarded. In the final step, photons within a $\Delta R = 0.4$ cone around any remaining electron or muon are excluded and then jets within a $\Delta R = 0.4$ cone around any remaining photon are removed.

Events are selected if they have exactly one electron or one muon that is matched to the corresponding trigger-level object. The p_T thresholds for the leptons are 25 GeV in 2015 data, 27 GeV in 2016 data, and 28 GeV in 2017 and 2018 data, which are at least 1 GeV above the p_T thresholds of the single-lepton triggers. This is done to avoid differences due to the calibration of the objects used in the trigger logic, and objects used in the physics analysis. Only

events containing exactly one reconstructed photon fulfilling the condition $\Delta R(\ell, \gamma) > 0.4$ are considered in the measurement. Additionally, events where the invariant mass of the electron–photon system is within 5 GeV of the Z-boson mass are rejected. The event is also required to have at least four jets and at least one of them must be *b*-tagged.

The kinematic properties, in particular the rapidities of the top quark and antiquark, are determined by means of a constrained kinematic fitting algorithm, KLFitter [75], based on a maximum-likelihood approach applied to the four-momenta of the selected lepton and up to five leading jets (p_T -ordered) and E_T^{miss} , representing the transverse momentum of the neutrino. The likelihood is constructed as the product of transfer functions that relate the energies of the reconstructed objects and parton-level objects and Breit–Wigner distributions that match the selected objects to the *W* bosons and the top quarks. The fit is constrained to reconstruct two *W* bosons, each with a mass of 80.4 GeV. In addition, the reconstructed masses of the top quark and antiquark are constrained to 172.5 GeV. The combination of jets that gives the highest likelihood is selected and the jets are used to reconstruct the hadronically and leptonically decaying top quark or antiquark. In the case of leptonic top-quark decay, the invariant mass of the lepton–neutrino system is constrained to be the *W*-boson mass and a quadratic equation for the neutrino’s longitudinal momentum is obtained. For real solutions of the equation, the solution that results in the top-quark mass closer to 172.5 GeV is chosen, while in the case of complex solutions, the real part of the solution is considered. The fraction of top quarks that are reconstructed within $\Delta R = 1.0$ of the parton-level top quarks is about 64% for hadronically decaying top quarks and 72% for leptonically decaying top quarks.

5. Background estimation

Each background process is assigned to one of several categories depending on the origin of the reconstructed photon, whether it is a prompt photon or whether another object mimics a photon signature. The estimation of background events from different sources closely follows the methods employed in Ref. [46].

After the event selection, the largest background contribution is that of $t\bar{t}\gamma$ decay events (about 30% of the total number of events). The *prompt γ background* category, which contains any other type of background process with a prompt photon, constitutes about 15% of the selected events. Both contributions are estimated using MC simulation. Agreement between data and simulation of the prompt γ background was validated in dedicated regions. A validation region enriched in the $Z\gamma$ process is defined by selecting events with exactly one photon, two same-flavour opposite-sign leptons, fewer than four jets and no *b*-tagged jets. Events in the $W\gamma$ validation region fulfil the same lepton and photon requirements as in the signal region. The simulation of $W\gamma$ is known to underestimate the number of events with heavy-flavour jets in data. Thus, to define a region orthogonal to the signal region while selecting events with heavy-flavour content, the events in the validation region are additionally required to have fewer than four jets and at least one must pass the *b*-tagging working point with a selection efficiency of 85% but fail the one with 70% efficiency in simulated $t\bar{t}$ events. The expected fractions of $Z\gamma$ and $W\gamma$ events in the corresponding control regions are about 95% and 50%, respectively.

Another significant contribution arises from processes with an electron mimicking a photon signature in the detector, referred to as *e-fake*. This background contribution amounts to 16% of the total number of selected events and it is estimated from data by applying a tag-and-probe method to $Z \rightarrow e^+e^-$ events [65]. Two control regions are defined in order to determine the *e-fake* pho-

ton rate in data and simulation: one region contains events with an electron–positron pair and the other, enriched in *e-fake* photon events, contains events with an electron and a photon satisfying the object selection criteria described in Section 4. Additionally, the invariant mass of the pair of objects is required to be in the range [40, 140] GeV, and their angular separation in ϕ must exceed 2.62 rad to suppress the contributions from events where the photon is radiated from the electron. Background contributions not originating from Z-boson events are subtracted in data with a fit of the invariant mass distribution. The $Z \rightarrow e^+e^-\gamma$ contribution with prompt photons where one of the electrons is not reconstructed or identified is subtracted using simulation. The *e-fake* photon rate is obtained as the ratio of the event yield after background subtraction in the *e-fake*-enriched control region to the yield in the electron–positron control region. The calculated ratio is binned in the p_T (three bins) and $|\eta|$ (four bins) of the photon in the $e\gamma$ events and either the electron or the positron in the e^+e^- events, selected randomly to avoid biasing the selection, and separately for converted and unconverted photons. Scale factors are calculated to correct the *e-fake* background estimate in the signal region, based on a comparison between the *e-fake* photon rates obtained using either data or simulation. The systematic uncertainties in the scale factors account for possible mismodelling of the signal and background processes in the fit. The values of the scale factors vary from 0.8 to 1.4 with uncertainties between 5% and 20%.

The background contribution from events where the photon signature arises from hadronic energy depositions in the ECAL or from hadron decays such as $\pi^0 \rightarrow \gamma\gamma$, generically referred to as *h-fake*, constitutes about 7% of the events. The *h-fake* background is estimated from data by using the so-called ABCD method. Three orthogonal regions enriched with *h-fake* photon events are defined by inverting the photon isolation selection and the requirements on four variables related to the shower shape in the first layer of the ECAL, which are part of the photon tight identification criteria. They are chosen because of their small correlation with the photon isolation and their power to discriminate between prompt and *h-fake* photons. Events are selected for regions A and B if their photon fails at least two out of four identification requirements, while satisfying all other identification criteria, and pass or fail the isolation requirements, respectively. Region C contains events where the photons fail the isolation requirements but satisfy the tight identification criteria. Additionally, the sum of the p_T of all tracks within $\Delta R = 0.2$ of the photon is required to be larger than 3 GeV to further suppress the prompt-photon contribution in regions B and C. The *h-fake* background contribution in the signal region is measured as the product of the numbers of events in regions A and C divided by the number of events in region B. The estimate is corrected for the correlation between the criteria, which is obtained using MC simulations. The scale factors are obtained separately for converted and unconverted photons and as a function of the photon p_T (two bins) and $|\eta|$ (four bins). The considered sources of systematic uncertainty in the *h-fake* background contribution include the modelling of the $t\bar{t}$ process, which contributes about 90% of the *h-fake* events, the shower shapes, and the normalisation uncertainties of the background processes. The scale factors range from 0.6 to 1.5, with uncertainties of 30%–60%.

The contribution from events with a non-prompt or misidentified lepton, referred to as *lepton fake*, is obtained using the data-driven approach referred to as the matrix method [76]. Events are separated into two categories that are based on tighter or looser lepton identification and isolation requirements, and thus enriched in events with real leptons or non-prompt/fake leptons, respectively. The contribution in the signal region is estimated from the data events passing loose lepton selection requirements, corrected by a weight that depends on the real- and fake-lepton efficiencies obtained from the two event categories described above. The *e-fake*

iciencies are parameterised as a function of the lepton kinematic properties. The uncertainties are estimated by using different parameterisations and tighter control regions, and by including the normalisation uncertainty of the prompt-lepton background. This background contribution amounts to around 1% of all selected events, dominated by events with a misidentified electron.

6. Systematic uncertainties

The precision of the obtained asymmetry A_C is affected by several sources of systematic uncertainty, arising from detector effects or theoretical assumptions, as well as uncertainties due to the limited number of events in the MC simulations. The different sources of systematic uncertainty, discussed in the following, affect the event yields, the distribution shape of the observable of interest, or both. The sources of systematic uncertainty affecting the shape of the distribution typically have a larger impact on the precision of the result because global normalisation uncertainties cancel out in the ratio of event yields that defines A_C .

The experimental systematic effects include uncertainties in the integrated luminosity and the simulation of pile-up events, as well as effects related to the reconstruction and identification of the physics objects in the analysis.

The uncertainty in the total integrated luminosity is estimated to be 1.7% [77], using the LUCID-2 detector [78] for the primary luminosity measurements. The uncertainty associated with the modelling of pile-up is determined by varying the pile-up reweighting in the simulation within its uncertainties.

The photon and lepton identification and isolation efficiencies, momentum scale and resolution [79,80], and lepton trigger efficiencies in simulation are corrected using scale factors to better describe the corresponding values in data. These corrections, which typically depend on p_T and η , are varied within their uncertainties to estimate the corresponding systematic uncertainty.

The jet energy scale (JES) uncertainty is derived from a combination of simulations, test-beam data and in situ measurements [69]. Contributions from jet-flavour composition, η -intercalibration, punch-through, single-particle response, calorimeter response to different jet flavours, and pile-up are also taken into account, yielding a total of 30 uncorrelated JES uncertainty subcomponents, of which 29 are non-zero in a given event depending on the type of simulation used. The jet energy resolution in simulation is smeared by its corresponding uncertainty [81] split into eight uncorrelated sources. The uncertainty associated with the JVT discriminant for pile-up jet rejection is obtained by varying the efficiency correction factors.

The uncertainties in the b -jet tagging calibration are determined separately for b -jets, c -jets and light-flavour jets [82–84]. For each jet category, the uncertainties are decomposed into several uncorrelated components.

The uncertainty in E_T^{miss} arises from the propagation of the energy scales and resolutions of photons, leptons and jets, and the modelling of its soft term [74].

The signal and background modelling uncertainties include those owing to the choice of QCD scales, parton shower, amount of QCD initial-state radiation (ISR), and PDF set.

The effect of the QCD scale uncertainty for each of the $t\bar{t}\gamma$, $tW\gamma$ and $t\bar{t}$ processes is evaluated independently by separately halving and doubling the renormalisation and factorisation scales relative to the default scale choice. The uncertainty from the parton shower and hadronisation for those processes is estimated by comparing the nominal simulated samples interfaced with PYTHIA 8 with alternative samples interfaced to HERWIG 7 [85,86]. Uncertainties due to the value of α_s used in the ISR parton shower modelling are estimated by comparing the nominal $t\bar{t}\gamma$, $tW\gamma$ and $t\bar{t}$ simulations with alternative samples simulated with higher or

lower radiation parameter settings in the A14 tune, controlled by the *var3c* parameter implemented in PYTHIA 8. An additional ISR uncertainty is obtained for the $t\bar{t}$ process by comparing the nominal sample with an additional one with the h_{damp} parameter, which controls the p_T of the first additional emission, varied by a factor of two [87]. The uncertainty in the PDFs for the signal and background $t\bar{t}\gamma$ processes is estimated using the 30 PDF variations of the PDF4LHC15 prescription [88]. The PDF variations are propagated by using alternative generator weights and each of them is considered as a separate nuisance parameter in the fit.

For the e-fake, h-fake, and lepton-fake background contributions, the total uncertainties associated with the corrections obtained using data are propagated to the final result. A normalisation uncertainty of 20% is assigned to the $t\bar{t}\gamma$ decay process, based on the estimated uncertainty in the NLO K -factor [46], and a 50% normalisation uncertainty is assigned to $W\gamma$, based on the differences between data and simulation observed in the dedicated control region, and to the minor background processes contributing to the prompt-photon category, i.e. single top quark, $t\bar{t}V$, diboson, and $Z\gamma$.

7. Signal discrimination

A multivariate analysis using a neural network is performed to further separate the $t\bar{t}\gamma$ signal from the background processes. The NN is fully connected and consists of three hidden layers. The first two layers consist of 96 nodes and are followed by a batch normalisation layer. The third layer has 16 nodes. The hidden layers use a parametric ReLU activation function, while the output node uses a sigmoid activation function. The training is performed with Keras [89] with the TensorFlow [90] backend with binary cross-entropy as a loss function. The overall events are split into a training and validation set (85%) and a testing set (15%). The first set of events is used in a 5-fold cross-validation: Events are split randomly into 5 folds, the model is trained on 4 folds and one fold is used for validation of the NN configuration. This procedure is repeated 5 times. The event weights are applied to the events in the training, testing and validation samples. The NN uses a total of 21 variables related to the kinematic properties of individual objects, such as the photon p_T and η , event shape variables (e.g. E_T^{miss} and the scalar sum of the p_T of the jets in the event), the number of b -tagged jets, the pseudo-continuous binned b -tagging discriminant [72], the photon conversion type, and invariant masses and angular separations of different objects in the event (e.g. the invariant mass and ΔR of the lepton or the photon and the closest b -tagged jet). Example variables from among those with the most discriminating power are shown in Fig. 2. The MC simulation describes the data within the uncertainties. The largest contributions to the MC uncertainty band are the normalisation uncertainties associated with the backgrounds with prompt photons.

The resulting NN discriminant output, O_{NN} , shown in Fig. 3, is used to divide the events into a background-enriched region and a signal-enriched region, defined by $O_{\text{NN}} < 0.6$ and $O_{\text{NN}} \geq 0.6$, respectively. This threshold was optimised to give the smallest expected uncertainty in A_C . The observed and expected signal and background event yields in the two regions are summarised in Table 1. The slight underestimate of the data by the SM prediction, observed in Fig. 2, is reflected in Fig. 3 at large values of O_{NN} because it is expected to partially come from the normalisation of the $t\bar{t}\gamma$ production simulation, which is a free parameter in the profile likelihood unfolding described in the following.

8. Results

The value of A_C is extracted from the $|y_t| - |y_{\bar{t}}|$ distribution in a fiducial region defined at particle level. The top quark and

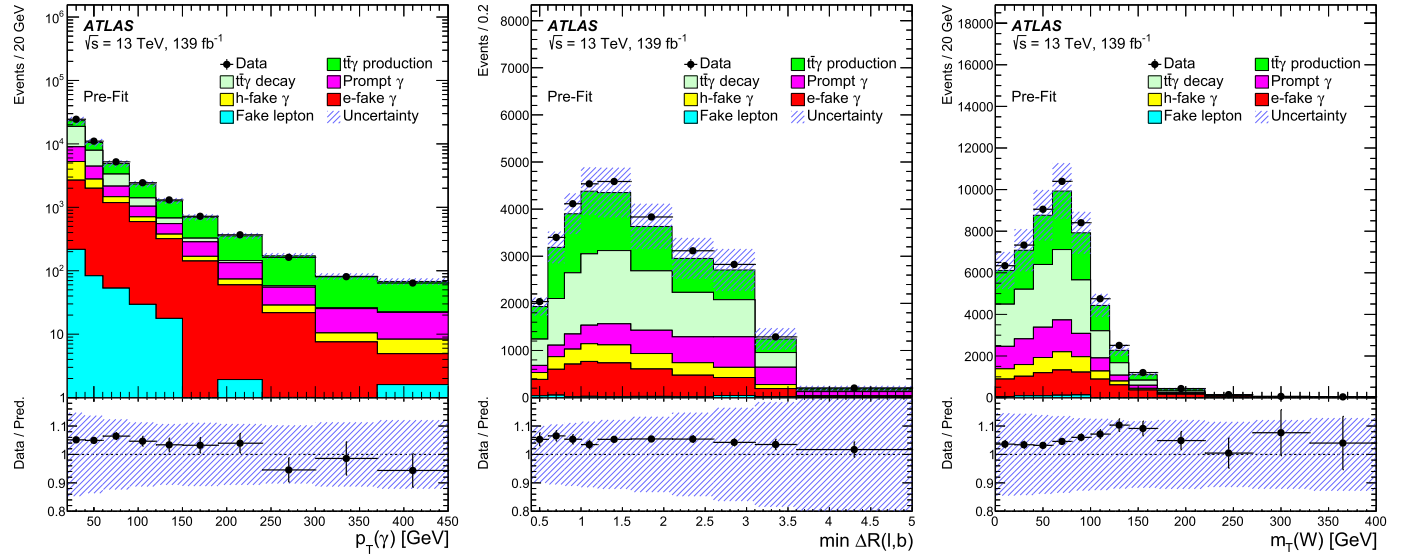


Fig. 2. Distributions of photon p_T (left), angular separation of the lepton and the closest b -tagged jet (middle), and transverse mass of the leptonically decaying W boson (right) before the fit. The uncertainty band includes all experimental and modelling systematic uncertainties (cf. Section 6) added in quadrature. Overflow events are included in the last bin of each distribution. The lower part of the plot shows the ratio of the data to the prediction.

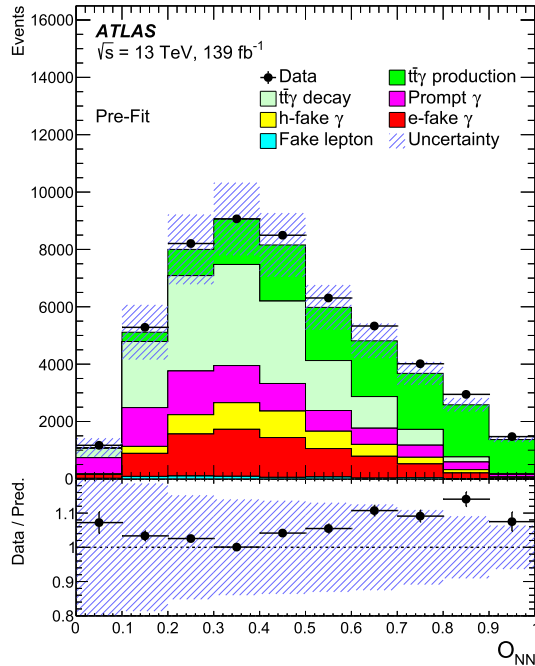


Fig. 3. Distribution of the NN output discriminant before the fit. The uncertainty band includes all experimental and modelling systematic uncertainties (cf. Section 6) added in quadrature. The lower part of the plot shows the ratio of the data to the prediction.

antiquark are defined at parton level in the MC simulation after final-state radiation but before decay. The fiducial region at particle level is defined by applying selection requirements similar to those at reconstruction level to the stable particles after the event generation and before the detector simulation. The fiducial phase space is defined by requiring exactly one photon, exactly one electron or muon, and at least four jets, of which at least one must be a b -jet, defined as follows. Photons are required to not originate from a hadron decay, to have $E_T > 20$ GeV and $|\eta| < 2.37$, and to be isolated such that the sum of transverse momenta of all charged particles surrounding the photon within $\Delta R \leq 0.2$ must be less than 5% of its own p_T . Muons and elec-

Table 1

Event yields before the profile likelihood unfolding after the full selection in the two regions defined by the NN discriminant value. The quoted uncertainties correspond to all statistical and systematic uncertainties (cf. Section 6) added in quadrature.

	$O_{NN} < 0.6$	$O_{NN} \geq 0.6$
$t\bar{t}\gamma$ prod (signal)	6660 ± 350	6910 ± 340
$t\bar{t}\gamma$ decay	14100 ± 3100	1900 ± 560
h-fake γ	3400 ± 1400	790 ± 360
e-fake γ	6420 ± 860	1480 ± 260
Prompt γ	6400 ± 2000	1300 ± 400
Lepton fake	410 ± 110	57 ± 35
Total	37400 ± 4500	12400 ± 1100
Data	38 527	13 763

trons must have $p_T > 25$ GeV and $|\eta| < 2.5$, and must not originate from hadron decays. The momenta of nearby photons, within a $\Delta R = 0.1$ cone, are added to the lepton before applying the selection. Jets are clustered with the anti- k_t algorithm with a radius parameter of $R = 0.4$. All stable particles are considered in the clustering, except for the selected electrons, muons and photons, and the neutrinos originating from the top quarks. Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. A particle-level jet is identified as a b -jet if a hadron with $p_T > 5$ GeV containing a b -quark is matched to the jet through a ghost-matching method [91]. Jets within $\Delta R = 0.4$ of lepton or isolated photon candidates are removed.

The A_C value is obtained by means of a simultaneous maximum-likelihood unfolding of the $|y_t| - |y_{\bar{t}}|$ distributions in the two regions defined by the NN output discriminant. The efficiency of selecting and reconstructing an event that is generated in the fiducial phase space is about 30% in the two regions, while the fraction of events that fulfil the selection at reconstruction level but fail the particle-level requirements is about 20%. The fraction of events that are reconstructed in the $|y_t| - |y_{\bar{t}}|$ bin where they were generated is approximately 75%. The parameters of interest, which float freely in the fit, are the signal strength of the bin $|y_t| - |y_{\bar{t}}| > 0$ and A_C , which replaces the signal strength of the other bin, using the following expression: $A_C = (\mu_+ T_+ - \mu_- T_-) / (\mu_+ T_+ + \mu_- T_-)$. The signal strength μ_+ (μ_-) is defined as the ratio of the measured cross section to the expected value given by the SM simulation in

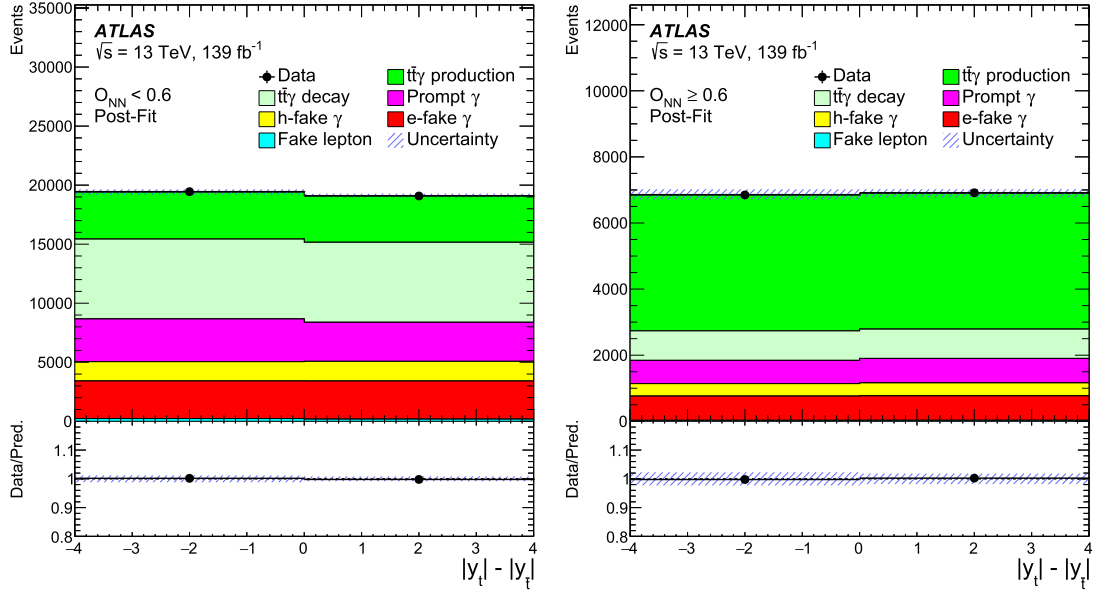


Fig. 4. The distributions of $|y_t| - |y_{\bar{t}}|$ after the fit in the two regions defined by the NN output. Underflow and overflow events are included in corresponding bins of the distributions. The uncertainty band represents the total post-fit uncertainties. Correlations among uncertainties are taken into account as determined in the fit. The lower part of the plot shows the ratio of the data to the prediction.

the bin $|y_t| - |y_{\bar{t}}| > 0$ (< 0) at generator level. The variable $T_{+/-}$ represents the number of $t\bar{t}\gamma$ production events at particle level in the corresponding bin. No regularisation is applied. The systematic uncertainties are taken into account via nuisance parameters in the likelihood function. They are symmetrised, taking half of the difference between the upward and downward variations as the uncertainty. If both variations have the same sign, the average of the difference between each variation and the nominal value is chosen as the two-sided uncertainty. If only one variation is available (e.g. the uncertainty from the parton shower or the PDF uncertainties) the difference from the nominal value is taken as both the upward and downward variations for the corresponding source. In addition, a pruning procedure is implemented in order to remove the smallest systematic uncertainties.

In addition to the NLO/LO K -factor applied to correct the normalisation of the $t\bar{t}\gamma$ decay process, the $|y_t| - |y_{\bar{t}}|$ template is reweighted to account for the asymmetry in $t\bar{t}$ production. The weight is obtained at parton level by considering the central value of the prediction for the inclusive $t\bar{t}$ asymmetry, $A_C^{t\bar{t}} = 0.0064^{+0.0005}_{-0.0006}$, calculated at NNLO accuracy in QCD with EW corrections at NLO [17,18]. The weight is then propagated to the distribution at reconstruction level. For consistency, the MC templates obtained with the NLO $t\bar{t}$ samples are also reweighted to match that asymmetry value. To probe the robustness of the method, and in particular to verify that the unfolding procedure does not bias the result towards the asymmetry in the signal MC simulation, the measurement was repeated with pseudodata. Several pseudodata sets were obtained by reweighting the $|y_t| - |y_{\bar{t}}|$ distribution of the signal $t\bar{t}\gamma$ production sample to correspond to different A_C values and by adding the background contributions. The unfolding procedure was repeated using the nominal simulation. The resulting values of the asymmetry are in agreement with the true A_C asymmetry of each pseudodata set within the statistical precision and do not indicate any bias.

The post-fit $|y_t| - |y_{\bar{t}}|$ distributions in the two regions are shown in Fig. 4. The A_C of the $t\bar{t}\gamma$ production process is expected to have a negative sign, while the asymmetry of the background contributions with a top-quark pair, i.e. $t\bar{t}\gamma$ decay and $t\bar{t}$, is expected to be positive as discussed in Section 1. Good agreement is observed between the data and the prediction after the fit. As a re-

Table 2

Summary of the impact of the systematic uncertainties on A_C grouped into different categories. The quoted uncertainties are obtained by repeating the fit with certain sets of nuisance parameters fixed to their post-fit values, and calculating the squared uncertainties as the difference of the squares of the full-fit and repeated-fit uncertainties. The category *Other experimental* includes uncertainties associated with leptons, pile-up and luminosity.

Total uncertainty	0.029
Statistical uncertainty	0.024
MC statistical uncertainties	
Background processes	0.008
$t\bar{t}\gamma$ production	0.004
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.002
Experimental uncertainties	
Jet	0.009
Fake-lepton background estimate	0.005
E_T^{miss}	0.005
Fake-photon background estimates	0.003
Photon	0.001
b -tagging	0.001
Other experimental	0.004

sult of the fit, a few nuisance parameters are slightly constrained: the uncertainties in the normalisation of the $t\bar{t}\gamma$ decay and $W\gamma$ backgrounds are reduced by 30% and 15%, respectively. In all cases, the best-fit values of the nuisance parameters are well within one standard deviation of their initial values.

The asymmetry is found to be $A_C = -0.003 \pm 0.029 = -0.003 \pm 0.024(\text{stat}) \pm 0.017(\text{syst})$, assuming the SM $t\bar{t}$ charge asymmetry of $A_C^{t\bar{t}} = 0.0064$ [18]. The systematic uncertainty is derived from its squared value, calculated as the difference of the squares of the total uncertainty and the statistical uncertainty, obtained from a fit without systematic uncertainties. The A_C value is compatible with the value obtained from the MADGRAPH5_AMC@NLO MC sim-

ulation in the same phase space, $A_C = -0.014 \pm 0.001(\text{scale})$. The precision of the result is limited by the statistical uncertainty. The impact of the different sources of systematic uncertainty, grouped in categories, is summarised in Table 2. The most relevant sources of systematic uncertainty are the MC statistical uncertainty of the prompt-photon background and the experimental systematic sources related to jets and E_T^{miss} . The dependence of the measured $t\bar{t}\gamma$ A_C on A_C^{MC} is estimated by repeating the measurement for different values of the $t\bar{t}$ asymmetry in the range between 0 and $2 \times A_C^{\text{MC}}$. The dependence is found to be linear and can be parameterised as $A_C = -0.57 \times A_C^{\text{MC}} + 0.0005$.

9. Conclusion

This paper presents a measurement of the top-quark pair charge asymmetry in $t\bar{t}\gamma$ events using 139fb^{-1} of pp collision data at a centre-of-mass energy of 13 TeV collected by the ATLAS experiment at the LHC. The selected events have exactly one photon, one lepton, and at least four jets, of which at least one is b -tagged. The inclusive charge asymmetry yields $A_C = -0.003 \pm 0.029 = -0.003 \pm 0.024(\text{stat}) \pm 0.017(\text{syst})$, which is compatible with the Standard Model prediction within the uncertainties. The precision is limited by the statistical uncertainty.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNR and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MeIn, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST/ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014–2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stift-

telse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [92].

References

- [1] J.A. Aguilar-Saavedra, E. Álvarez, A. Juste, F. Rubbo, Shedding light on the $t\bar{t}$ asymmetry: the photon handle, *J. High Energy Phys.* 04 (2014) 188, arXiv:1402.3598 [hep-ph].
- [2] J.A. Aguilar-Saavedra, D. Amidei, A. Juste, M. Perez-Victoria, Asymmetries in top quark pair production at hadron colliders, *Rev. Mod. Phys.* 87 (2015) 421, arXiv:1406.1798 [hep-ph].
- [3] S. Jung, A. Pierce, J.D. Wells, Top quark asymmetry from a non-Abelian horizontal symmetry, *Phys. Rev. D* 83 (2011) 114039, arXiv:1103.4835 [hep-ph].
- [4] R. Diener, S. Godfrey, T.A.W. Martin, Using final state pseudorapidities to improve s-channel resonance observables at the LHC, *Phys. Rev. D* 80 (2009) 075014, arXiv:0909.2022 [hep-ph].
- [5] W. Bernreuther, Z.-G. Si, Top quark and leptonic charge asymmetries for the Tevatron and LHC, *Phys. Rev. D* 86 (2012) 034026, arXiv:1205.6580 [hep-ph].
- [6] ATLAS Collaboration, Measurement of the top quark pair production charge asymmetry in proton–proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, *J. High Energy Phys.* 02 (2014) 107, arXiv:1311.6724 [hep-ex].
- [7] ATLAS Collaboration, Measurement of the charge asymmetry in top-quark pair production in the lepton-plus-jets final state in pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C* 76 (2016) 87, arXiv:1509.02358 [hep-ex], Erratum: *Eur. Phys. J. C* 77 (2017) 564.
- [8] CMS Collaboration, Inclusive and differential measurements of the $t\bar{t}$ charge asymmetry in proton–proton collisions at $\sqrt{s} = 7$ TeV, *Phys. Lett. B* 717 (2012) 129, arXiv:1207.0065 [hep-ex].
- [9] CMS Collaboration, Inclusive and differential measurements of the $t\bar{t}$ charge asymmetry in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Lett. B* 757 (2016) 154, arXiv:1507.03119 [hep-ex].
- [10] ATLAS Collaboration, Measurement of the charge asymmetry in dileptonic decays of top quark pairs in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, *J. High Energy Phys.* 05 (2015) 061, arXiv:1501.07383 [hep-ex].
- [11] ATLAS Collaboration, Measurements of the charge asymmetry in top-quark pair production in the dilepton final state at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Rev. D* 94 (2016) 032006, arXiv:1604.05538 [hep-ex].
- [12] CMS Collaboration, Measurements of the $t\bar{t}$ charge asymmetry using the dilepton decay channel in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 04 (2014) 191, arXiv:1402.3803 [hep-ex].
- [13] CMS Collaboration, Measurements of $t\bar{t}$ charge asymmetry using dilepton final states in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Lett. B* 760 (2016) 365, arXiv:1603.06221 [hep-ex].
- [14] ATLAS Collaboration, Measurement of the charge asymmetry in highly boosted top-quark pair production in $\sqrt{s} = 8$ TeV pp collision data collected by the ATLAS experiment, *Phys. Lett. B* 756 (2016) 52, arXiv:1512.06092 [hep-ex].
- [15] CMS Collaboration, Measurement of the charge asymmetry in top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV using a template method, *Phys. Rev. D* 93 (2016) 034014, arXiv:1508.03862 [hep-ex].
- [16] CMS Collaboration, Measurements of $t\bar{t}$ differential cross sections in proton–proton collisions at $\sqrt{s} = 13$ TeV using events containing two leptons, *J. High Energy Phys.* 02 (2019) 149, arXiv:1811.06625 [hep-ex].
- [17] ATLAS Collaboration, Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$ production at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:2208.12095, 2022, <https://cds.cern.ch/record/2825632>.
- [18] M. Czakon, et al., Top-quark charge asymmetry at the LHC and Tevatron through NNLO QCD and NLO EW, *Phys. Rev. D* 98 (2018) 014003, arXiv:1711.03945 [hep-ph].
- [19] CDF Collaboration, Evidence for a mass dependent forward-backward asymmetry in top quark pair production, *Phys. Rev. D* 83 (2011) 112003, arXiv:1101.0034 [hep-ex].
- [20] D0 Collaboration, Simultaneous measurement of forward-backward asymmetry and top polarization in dilepton final states from $t\bar{t}$ production at the Tevatron, *Phys. Rev. D* 92 (2015) 052007, arXiv:1507.05666 [hep-ex].
- [21] CDF Collaboration, Measurement of the top quark forward-backward production asymmetry and its dependence on event kinematic properties, *Phys. Rev. D* 87 (2013) 092002, arXiv:1211.1003 [hep-ex].
- [22] D0 Collaboration, Measurement of the forward-backward asymmetry in top quark-antiquark production in $p\bar{p}$ collisions using the lepton+jets channel, *Phys. Rev. D* 90 (2014) 072011, arXiv:1405.0421 [hep-ex].

- [23] M. Czakon, P. Fiedler, A. Mitov, Resolving the Tevatron top quark forward-backward asymmetry puzzle: fully differential next-to-next-to-leading-order calculation, *Phys. Rev. Lett.* 115 (2015) 052001, arXiv:1411.3007 [hep-ph].
- [24] N. Kidonakis, The top quark forward-backward asymmetry at approximate $N^3\text{LO}$, *Phys. Rev. D* 91 (2015) 071502, arXiv:1501.01581 [hep-ph].
- [25] D. Pagani, H.-S. Shao, I. Tsiniikos, M. Zaro, Automated EW corrections with isolated photons: $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$ and $t\gamma j$ as case studies, *J. High Energy Phys.* 09 (2021) 155, arXiv:2106.02059 [hep-ph].
- [26] J. Bergner, M. Schulze, The top quark charge asymmetry in $t\bar{t}\gamma$ production at the LHC, *Eur. Phys. J. C* 79 (2019) 189, arXiv:1812.10535 [hep-ph].
- [27] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, *J. Instrum.* 3 (2008) S08003.
- [28] ATLAS Collaboration, ATLAS insertable B-layer: Technical design report, ATLAS-TDR-19, CERN-LHCC-2010-013, <https://cds.cern.ch/record/1291633>, 2010, Addendum: ATLAS-TDR-19-ADD-1, CERN-LHCC-2012-009, <https://cds.cern.ch/record/1451888>, 2012.
- [29] B. Abbott, et al., Production and integration of the ATLAS Insertable B-Layer, *J. Instrum.* 13 (2018) T05008, arXiv:1803.00844 [physics.ins-det].
- [30] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, *Eur. Phys. J. C* 77 (2017) 317, arXiv:1611.09661 [hep-ex].
- [31] ATLAS Collaboration, The ATLAS Collaboration software and firmware, ATLAS-PUB-2021-001, <https://cds.cern.ch/record/2767187>, 2021.
- [32] ATLAS Collaboration, The ATLAS simulation infrastructure, *Eur. Phys. J. C* 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].
- [33] GEANT4 Collaboration, S. Agostinelli, et al., Geant4 – a simulation toolkit, *Nucl. Instrum. Methods A* 506 (2003) 250.
- [34] ATLAS Collaboration, The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim, ATLAS-PUB-2010-013, <https://cds.cern.ch/record/1300517>, 2010.
- [35] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* 178 (2008) 852, arXiv:0710.3820 [hep-ph].
- [36] ATLAS Collaboration, The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, ATLAS-PUB-2016-017, <https://cds.cern.ch/record/2206965>, 2016.
- [37] J. Pumplin, et al., New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* 07 (2002) 012, arXiv:hep-ph/0201195.
- [38] J. Alwall, et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, arXiv:1405.0301 [hep-ph].
- [39] S. Frixione, E. Laenen, P. Motylinski, B.R. Webber, Angular correlations of lepton pairs from vector boson and top quark decays in Monte Carlo simulations, *J. High Energy Phys.* 04 (2007) 081, arXiv:hep-ph/0702198.
- [40] P. Artoisenet, R. Frederix, O. Mattelaer, R. Rietkerk, Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations, *J. High Energy Phys.* 03 (2013) 015, arXiv:1212.3460 [hep-ph].
- [41] R.D. Ball, et al., Parton distributions for the LHC run II, *J. High Energy Phys.* 04 (2015) 040, arXiv:1410.8849 [hep-ph].
- [42] T. Sjöstrand, et al., An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* 191 (2015) 159, arXiv:1410.3012 [hep-ph].
- [43] ATLAS Collaboration, ATLAS Pythia 8 tunes to 7 TeV data, ATLAS-PUB-2014-021, <https://cds.cern.ch/record/1966419>, 2014.
- [44] S. Frixione, Isolated photons in perturbative QCD, *Phys. Lett. B* 429 (1998) 369, arXiv:hep-ph/9801442.
- [45] D.J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods* 462 (2001) 152.
- [46] ATLAS Collaboration, Measurements of inclusive and differential fiducial cross-sections of $t\bar{t}\gamma$ production in leptonic final states at $\sqrt{s} = 13\text{ TeV}$ in ATLAS, *Eur. Phys. J. C* 79 (2019) 382, arXiv:1812.01697 [hep-ex].
- [47] K. Melnikov, M. Schulze, A. Scharf, QCD corrections to top quark pair production in association with a photon at hadron colliders, *Phys. Rev. D* 83 (2011) 074013, arXiv:1102.1967 [hep-ph].
- [48] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2004) 040, arXiv:hep-ph/0409146.
- [49] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, arXiv:0709.2092 [hep-ph].
- [50] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, arXiv:1002.2581 [hep-ph].
- [51] ATLAS Collaboration, Summary of ATLAS Pythia 8 tunes, ATLAS-PUB-2012-003, <https://cds.cern.ch/record/1474107>, 2012.
- [52] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, *Comput. Phys. Commun.* 185 (2014) 2930, arXiv:1112.5675 [hep-ph].
- [53] N. Kidonakis, Next-to-next-to-leading logarithm resummation for s-channel single top quark production, *Phys. Rev. D* 81 (2010) 054028, arXiv:1001.5034 [hep-ph].
- [54] N. Kidonakis, Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^- , *Phys. Rev. D* 82 (2010) 054018, arXiv:1005.4451 [hep-ph].
- [55] N. Kidonakis, Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production, *Phys. Rev. D* 83 (2011) 091503, arXiv:1103.2792 [hep-ph].
- [56] E. Bothmann, et al., Event generation with Sherpa 2.2, *SciPost Phys.* 7 (2019) 034, arXiv:1905.09127 [hep-ph].
- [57] S. Höche, F. Krauss, S. Schumann, F. Siegert, QCD matrix elements and truncated showers, *J. High Energy Phys.* 05 (2009) 053, arXiv:0903.1219 [hep-ph].
- [58] ATLAS Collaboration, Measurement of $W^\pm$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector, *Phys. Lett. B* 759 (2016) 601, arXiv:1603.09222 [hep-ex].
- [59] J.M. Campbell, R.K. Ellis, Update on vector boson pair production at hadron colliders, *Phys. Rev. D* 60 (1999) 113006, arXiv:hep-ph/9905386.
- [60] D. de Florian, et al., Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, arXiv:1610.07922 [hep-ph], 2016.
- [61] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, *Eur. Phys. J. C* 80 (2020) 47, arXiv:1909.00761 [hep-ex].
- [62] ATLAS Collaboration, Performance of the ATLAS muon triggers in Run 2, *J. Instrum.* 15 (2020) P09015, arXiv:2004.13447 [hep-ex].
- [63] ATLAS Collaboration, Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13\text{ TeV}$, *Eur. Phys. J. C* 81 (2021) 578, arXiv:2012.00578 [hep-ex].
- [64] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, *J. Instrum.* 14 (2019) P12006, arXiv:1908.00005 [hep-ex].
- [65] ATLAS Collaboration, Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016, *Eur. Phys. J. C* 79 (2019) 205, arXiv:1810.05087 [hep-ex].
- [66] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, arXiv:0802.1189 [hep-ph].
- [67] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012) 1896, arXiv:1111.6097 [hep-ph].
- [68] ATLAS Collaboration, Jet reconstruction and performance using particle flow with the ATLAS Detector, *Eur. Phys. J. C* 77 (2017) 466, arXiv:1703.10485 [hep-ex].
- [69] ATLAS Collaboration, Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector, *Phys. Rev. D* 96 (2017) 072002, arXiv:1703.09665 [hep-ex].
- [70] ATLAS Collaboration, Tagging and suppression of pileup jets with the ATLAS detector, ATLAS-CONF-2014-018, <https://cds.cern.ch/record/1700870>, 2014.
- [71] ATLAS Collaboration, ATLAS flavour-tagging algorithms for the LHC Run 2 pp collision dataset, arXiv:2211.16345 [physics.data-an], 2022.
- [72] ATLAS Collaboration, ATLAS b -jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13\text{ TeV}$, *Eur. Phys. J. C* 79 (2019) 970, arXiv:1907.05120 [hep-ex].
- [73] ATLAS Collaboration, E_T^{miss} performance in the ATLAS detector using 2015–2016 LHC pp collisions, ATLAS-CONF-2018-023, <https://cds.cern.ch/record/2625233>, 2018.
- [74] ATLAS Collaboration, Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13\text{ TeV}$, *Eur. Phys. J. C* 78 (2018) 903, arXiv:1802.08168 [hep-ex].
- [75] J. Erdmann, et al., A likelihood-based reconstruction algorithm for top-quark pairs and the KLfitter framework, *Nucl. Instrum. Methods* 748 (2014) 18, arXiv:1312.5595 [hep-ex].
- [76] ATLAS Collaboration, Tools for estimating fake/non-prompt lepton backgrounds with the ATLAS detector at the LHC, arXiv:2211.16178 [hep-ex], 2022.
- [77] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 13\text{ TeV}$ using the ATLAS detector at the LHC, ATLAS-CONF-2019-021, <https://cds.cern.ch/record/2677054>, 2019.
- [78] G. Avoni, et al., The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, *J. Instrum.* 13 (2018) P07017.
- [79] ATLAS Collaboration, Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton–proton collision data, *J. Instrum.* 14 (2019) P03017, arXiv:1812.03848 [hep-ex].
- [80] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13\text{ TeV}$, *Eur. Phys. J. C* 76 (2016) 292, arXiv:1603.05598 [hep-ex].
- [81] ATLAS Collaboration, Jet calibration and systematic uncertainties for jets reconstructed in the ATLAS detector at $\sqrt{s} = 13\text{ TeV}$, ATLAS-PUB-2015-015, <https://cds.cern.ch/record/2037613>, 2015.
- [82] ATLAS Collaboration, Measurements of b -jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13\text{ TeV}$, *J. High Energy Phys.* 08 (2018) 089, arXiv:1805.01845 [hep-ex].
- [83] ATLAS Collaboration, Measurement of the c -jet mistagging efficiency in $t\bar{t}$ events using pp collision data at $\sqrt{s} = 13\text{ TeV}$ collected with the ATLAS detector, *Eur. Phys. J. C* 82 (2021) 95, arXiv:2109.10627 [hep-ex].

- [84] ATLAS Collaboration, Calibration of light-flavour b -jet mistagging rates using ATLAS proton-proton collision data at $\sqrt{s} = 13$ TeV, ATLAS-CONF-2018-006, <https://cds.cern.ch/record/2314418>, 2018.
- [85] M. Bähr, et al., Herwig++ physics and manual, *Eur. Phys. J. C* **58** (2008) 639, [arXiv:0803.0883](https://arxiv.org/abs/0803.0883) [hep-ph].
- [86] J. Bellm, et al., Herwig 7.0/Herwig++ 3.0 release note, *Eur. Phys. J. C* **76** (2016) 196, [arXiv:1512.01178](https://arxiv.org/abs/1512.01178) [hep-ph].
- [87] ATLAS Collaboration, Improvements in $t\bar{t}$ modelling using NLO+PS Monte Carlo generators for Run 2, ATL-PHYS-PUB-2018-009, <https://cds.cern.ch/record/2630327>, 2018.
- [88] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, *J. Phys. G* **43** (2016) 023001, [arXiv:1510.03865](https://arxiv.org/abs/1510.03865) [hep-ph].
- [89] F. Chollet, et al., <https://keras.io>, 2015.
- [90] M. Abadi, et al., TensorFlow: Large-Scale Machine Learning on Heterogeneous Systems, <https://www.tensorflow.org/>, 2015.
- [91] M. Cacciari, G.P. Salam, G. Soyez, The catchment area of jets, *J. High Energy Phys.* **04** (2008) 005, [arXiv:0802.1188](https://arxiv.org/abs/0802.1188) [hep-ph].
- [92] ATLAS Collaboration, ATLAS Computing Acknowledgements, ATL-SOFT-PUB-2021-003, <https://cds.cern.ch/record/2776662>, 2021.

The ATLAS Collaboration

G. Aad¹⁰¹, B. Abbott¹¹⁹, D.C. Abbott¹⁰², K. Abeling⁵⁵, S.H. Abidi²⁹, A. Aboulhorma^{35e}, H. Abramowicz¹⁵⁰, H. Abreu¹⁴⁹, Y. Abulaiti¹¹⁶, A.C. Abusleme Hoffman^{136a}, B.S. Acharya^{68a,68b,q}, B. Achkar⁵⁵, C. Adam Bourdarios⁴, L. Adamczyk^{84a}, L. Adamek¹⁵⁴, S.V. Addepalli²⁶, J. Adelman¹¹⁴, A. Adiguzel^{21c}, S. Adorni⁵⁶, T. Adye¹³³, A.A. Affolder¹³⁵, Y. Afik³⁶, M.N. Agaras¹³, J. Agarwala^{72a,72b}, A. Aggarwal⁹⁹, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{129f}, A. Ahmad³⁶, F. Ahmadov^{38,aa}, W.S. Ahmed¹⁰³, S. Ahuja⁹⁴, X. Ai⁴⁸, G. Aielli^{75a,75b}, I. Aizenberg¹⁶⁸, M. Akbiyik⁹⁹, T.P.A. Åkesson⁹⁷, A.V. Akimov³⁷, K. Al Khoury⁴¹, G.L. Alberghi^{23b}, J. Albert¹⁶⁴, P. Albicocco⁵³, S. Alderweireldt⁵², M. Aleksa³⁶, I.N. Aleksandrov³⁸, C. Alexa^{27b}, T. Alexopoulos¹⁰, A. Alfonsi¹¹³, F. Alfonsi^{23b}, M. Alhroob¹¹⁹, B. Ali¹³¹, S. Ali¹⁴⁷, M. Aliev³⁷, G. Alimonti^{70a}, W. Alkakh⁵⁵, C. Allaire⁶⁶, B.M.M. Allbrooke¹⁴⁵, P.P. Allport²⁰, A. Aloisio^{71a,71b}, F. Alonso⁸⁹, C. Alpigiani¹³⁷, E. Alunno Camelia^{75a,75b}, M. Alvarez Estevez⁹⁸, M.G. Alviggi^{71a,71b}, M. Aly¹⁰⁰, Y. Amaral Coutinho^{81b}, A. Ambler¹⁰³, C. Amelung³⁶, M. Amerl¹, C.G. Ames¹⁰⁸, D. Amidei¹⁰⁵, S.P. Amor Dos Santos^{129a}, S. Amoroso⁴⁸, K.R. Amos¹⁶², V. Ananiev¹²⁴, C. Anastopoulos¹³⁸, T. Andeen¹¹, J.K. Anders³⁶, S.Y. Andrean^{47a,47b}, A. Andreazza^{70a,70b}, S. Angelidakis⁹, A. Angerami^{41,ad}, A.V. Anisenkov³⁷, A. Annovi^{73a}, C. Antel⁵⁶, M.T. Anthony¹³⁸, E. Antipov¹²⁰, M. Antonelli⁵³, D.J.A. Antrim^{17a}, F. Anulli^{74a}, M. Aoki⁸², T. Aoki¹⁵², J.A. Aparisi Pozo¹⁶², M.A. Aparo¹⁴⁵, L. Aperio Bella⁴⁸, C. Appelt¹⁸, N. Aranzabal³⁶, V. Araujo Ferraz^{81a}, C. Arcangeletti⁵³, A.T.H. Arce⁵¹, E. Arena⁹¹, J-F. Arguin¹⁰⁷, S. Argyropoulos⁵⁴, J.-H. Arling⁴⁸, A.J. Armbruster³⁶, O. Arnaez¹⁵⁴, H. Arnold¹¹³, Z.P. Arrubarrena Tame¹⁰⁸, G. Artoni^{74a,74b}, H. Asada¹¹⁰, K. Asai¹¹⁷, S. Asai¹⁵², N.A. Asbah⁶¹, J. Assahsah^{35d}, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{33a}, M. Atkinson¹⁶¹, N.B. Atlay¹⁸, H. Atmani^{62b}, P.A. Atmasiddha¹⁰⁵, K. Augsten¹³¹, S. Auricchio^{71a,71b}, A.D. Auriol²⁰, V.A. Austrup¹⁷⁰, G. Avner¹⁴⁹, G. Avolio³⁶, K. Axiotis⁵⁶, M.K. Ayoub^{14c}, G. Azuelos^{107,ai}, D. Babal^{28a}, H. Bachacou¹³⁴, K. Bachas^{151,t}, A. Bachiou³⁴, F. Backman^{47a,47b}, A. Badea⁶¹, P. Bagnaia^{74a,74b}, M. Bahmani¹⁸, A.J. Bailey¹⁶², V.R. Bailey¹⁶¹, J.T. Baines¹³³, C. Bakalis¹⁰, O.K. Baker¹⁷¹, P.J. Bakker¹¹³, E. Bakos¹⁵, D. Bakshi Gupta⁸, S. Balaji¹⁴⁶, R. Balasubramanian¹¹³, E.M. Baldin³⁷, P. Balek¹³², E. Ballabene^{70a,70b}, F. Balli¹³⁴, L.M. Baltes^{63a}, W.K. Balunas³², J. Balz⁹⁹, E. Banas⁸⁵, M. Bandieramonte¹²⁸, A. Bandyopadhyay²⁴, S. Bansal²⁴, L. Barak¹⁵⁰, E.L. Barberio¹⁰⁴, D. Barberis^{57b,57a}, M. Barbero¹⁰¹, G. Barbour⁹⁵, K.N. Barends^{33a}, T. Barillari¹⁰⁹, M-S. Barisits³⁶, T. Barklow¹⁴², R.M. Barnett^{17a}, P. Baron¹²¹, D.A. Baron Moreno¹⁰⁰, A. Baroncelli^{62a}, G. Barone²⁹, A.J. Barr¹²⁵, L. Barranco Navarro^{47a,47b}, F. Barreiro⁹⁸, J. Barreiro Guimarães da Costa^{14a}, U. Barron¹⁵⁰, M.G. Barros Teixeira^{129a}, S. Barsov³⁷, F. Bartels^{63a}, R. Bartoldus¹⁴², A.E. Barton⁹⁰, P. Bartos^{28a}, A. Basalae⁴⁸, A. Basan⁹⁹, M. Baselga⁴⁹, I. Bashta^{76a,76b}, A. Bassalat^{66,b}, M.J. Basso¹⁵⁴, C.R. Basson¹⁰⁰, R.L. Bates⁵⁹, S. Batlamous^{35e}, J.R. Batley³², B. Batool¹⁴⁰, M. Battaglia¹³⁵, D. Battulga¹⁸, M. Bauce^{74a,74b}, P. Bauer²⁴, A. Bayirli^{21a}, J.B. Beacham⁵¹, T. Beau¹²⁶, P.H. Beauchemin¹⁵⁷, F. Becherer⁵⁴, P. Bechtel²⁴, H.P. Beck^{19,s}, K. Becker¹⁶⁶, A.J. Beddall^{21d}, V.A. Bednyakov³⁸, C.P. Bee¹⁴⁴, L.J. Beemster¹⁵, T.A. Beermann³⁶, M. Begalli^{81d}, M. Begel²⁹, A. Behera¹⁴⁴, J.K. Behr⁴⁸, C. Beirao Da Cruz E Silva³⁶, J.F. Beirer^{55,36}, F. Beisiegel²⁴, M. Belfkir¹⁵⁸, G. Bella¹⁵⁰, L. Bellagamba^{23b}, A. Bellerive³⁴, P. Bellos²⁰, K. Beloborodov³⁷, K. Belotskiy³⁷, N.L. Belyaev³⁷, D. Benchekroun^{35a}, F. Bendebba^{35a}, Y. Benhammou¹⁵⁰, D.P. Benjamin²⁹, M. Benoit²⁹, J.R. Bensinger²⁶, S. Bentvelsen¹¹³, L. Beresford³⁶, M. Beretta⁵³, D. Berge¹⁸, E. Bergeaas Kuutmann¹⁶⁰, N. Berger⁴, B. Bergmann¹³¹, J. Beringer^{17a}, S. Berlendis⁷, G. Bernardi⁵, C. Bernius¹⁴², F.U. Bernlochner²⁴, T. Berry⁹⁴, P. Berta¹³², A. Berthold⁵⁰, I.A. Bertram⁹⁰, S. Bethke¹⁰⁹, A. Betti^{74a,74b}, A.J. Bevan⁹³, M. Bhamjee^{33c}, S. Bhatta¹⁴⁴, D.S. Bhattacharya¹⁶⁵, P. Bhattarai²⁶, V.S. Bhopatkar¹²⁰, R. Bi^{29,al}, R.M. Bianchi¹²⁸, O. Biebel¹⁰⁸, R. Bielski¹²², M. Biglietti^{76a}, T.R.V. Billoud¹³¹, M. Bindi⁵⁵, A. Bingul^{21b}, C. Bini^{74a,74b}, S. Biondi^{23b,23a}, A. Biondini⁹¹,

C.J. Birch-sykes¹⁰⁰, G.A. Bird^{20,133}, M. Birman¹⁶⁸, T. Bisanz³⁶, E. Bisceglie^{43b,43a}, D. Biswas^{169,m}, A. Bitadze¹⁰⁰, K. Bjørke¹²⁴, I. Bloch⁴⁸, C. Blocker²⁶, A. Blue⁵⁹, U. Blumenschein⁹³, J. Blumenthal⁹⁹, G.J. Bobbink¹¹³, V.S. Bobrovnikov³⁷, M. Boehler⁵⁴, D. Bogavac³⁶, A.G. Bogdanchikov³⁷, C. Boehm^{47a}, V. Boisvert⁹⁴, P. Bokan⁴⁸, T. Bold^{84a}, M. Bomben⁵, M. Bona⁹³, M. Boonekamp¹³⁴, C.D. Booth⁹⁴, A.G. Borbély⁵⁹, H.M. Borecka-Bielska¹⁰⁷, L.S. Borgna⁹⁵, G. Borissov⁹⁰, D. Bortoletto¹²⁵, D. Boscherini^{23b}, M. Bosman¹³, J.D. Bossio Sola³⁶, K. Bouaouda^{35a}, N. Bouchhar¹⁶², J. Boudreau¹²⁸, E.V. Bouhova-Thacker⁹⁰, D. Boumediene⁴⁰, R. Bouquet⁵, A. Boveia¹¹⁸, J. Boyd³⁶, D. Boye²⁹, I.R. Boyko³⁸, J. Bracinik²⁰, N. Brahimi^{62d}, G. Brandt¹⁷⁰, O. Brandt³², F. Braren⁴⁸, B. Brau¹⁰², J.E. Brau¹²², K. Brendlinger⁴⁸, R. Brenner¹⁶⁸, L. Brenner¹¹³, R. Brenner¹⁶⁰, S. Bressler¹⁶⁸, B. Brickwedde⁹⁹, D. Britton⁵⁹, D. Britzger¹⁰⁹, I. Brock²⁴, G. Brooijmans⁴¹, W.K. Brooks^{136f}, E. Brost²⁹, T.L. Bruckler¹²⁵, P.A. Bruckman de Renstrom⁸⁵, B. Brüers⁴⁸, D. Bruncko^{28b,*}, A. Bruni^{23b}, G. Bruni^{23b}, M. Bruschi^{23b}, N. Bruscino^{74a,74b}, L. Bryngemark¹⁴², T. Buanes¹⁶, Q. Buat¹³⁷, P. Buchholz¹⁴⁰, A.G. Buckley⁵⁹, I.A. Budagov^{38,*}, M.K. Bugge¹²⁴, O. Bulekov³⁷, B.A. Bullard⁶¹, S. Burdin⁹¹, C.D. Burgard⁴⁸, A.M. Burger⁴⁰, B. Burghgrave⁸, J.T.P. Burr³², C.D. Burton¹¹, J.C. Burzynski¹⁴¹, E.L. Busch⁴¹, V. Büscher⁹⁹, P.J. Bussey⁵⁹, J.M. Butler²⁵, C.M. Buttar⁵⁹, J.M. Butterworth⁹⁵, W. Buttinger¹³³, C.J. Buxo Vazquez¹⁰⁶, A.R. Buzykaev³⁷, G. Cabras^{23b}, S. Cabrera Urbán¹⁶², D. Caforio⁵⁸, H. Cai¹²⁸, Y. Cai^{14a,14d}, V.M.M. Cairo³⁶, O. Cakir^{3a}, N. Calace³⁶, P. Calafiura^{17a}, G. Calderini¹²⁶, P. Calfayan⁶⁷, G. Callea⁵⁹, L.P. Caloba^{81b}, D. Calvet⁴⁰, S. Calvet⁴⁰, T.P. Calvet¹⁰¹, M. Calvetti^{73a,73b}, R. Camacho Toro¹²⁶, S. Camarda³⁶, D. Camarero Munoz²⁶, P. Camarri^{75a,75b}, M.T. Camerlingo^{76a,76b}, D. Cameron¹²⁴, C. Camincher¹⁶⁴, M. Campanelli⁹⁵, A. Camplani⁴², V. Canale^{71a,71b}, A. Canesse¹⁰³, M. Cano Bret⁷⁹, J. Cantero¹⁶², Y. Cao¹⁶¹, F. Capocasa²⁶, M. Capua^{43b,43a}, A. Carbone^{70a,70b}, R. Cardarelli^{75a}, J.C.J. Cardenas⁸, F. Cardillo¹⁶², T. Carli³⁶, G. Carlino^{71a}, J.I. Carlotto¹³, B.T. Carlson^{128,u}, E.M. Carlson^{164,155a}, L. Carminati^{70a,70b}, M. Carnesale^{74a,74b}, S. Caron¹¹², E. Carquin^{136f}, S. Carrá^{70a,70b}, G. Carratta^{23b,23a}, F. Carrio Argos^{33g}, J.W.S. Carter¹⁵⁴, T.M. Carter⁵², M.P. Casado^{13,j}, A.F. Casha¹⁵⁴, E.G. Castiglia¹⁷¹, F.L. Castillo^{63a}, L. Castillo Garcia¹³, V. Castillo Gimenez¹⁶², N.F. Castro^{129a,129e}, A. Catinaccio³⁶, J.R. Catmore¹²⁴, V. Cavaliere²⁹, N. Cavalli^{23b,23a}, V. Cavasinni^{73a,73b}, E. Celebi^{21a}, F. Celli¹²⁵, M.S. Centonze^{69a,69b}, K. Cerny¹²¹, A.S. Cerqueira^{81a}, A. Cerri¹⁴⁵, L. Cerrito^{75a,75b}, F. Cerutti^{17a}, A. Cervelli^{23b}, S.A. Cetin^{21d}, Z. Chadi^{35a}, D. Chakraborty¹¹⁴, M. Chala^{129f}, J. Chan¹⁶⁹, W.Y. Chan¹⁵², J.D. Chapman³², B. Chargeishvili^{148b}, D.G. Charlton²⁰, T.P. Charman⁹³, M. Chatterjee¹⁹, S. Chekanov⁶, S.V. Chekulaev^{155a}, G.A. Chelkov^{38,a}, A. Chen¹⁰⁵, B. Chen¹⁵⁰, B. Chen¹⁶⁴, H. Chen^{14c}, H. Chen²⁹, J. Chen^{62c}, J. Chen²⁶, S. Chen¹⁵², S.J. Chen^{14c}, X. Chen^{62c}, X. Chen^{14b,ah}, Y. Chen^{62a}, C.L. Cheng¹⁶⁹, H.C. Cheng^{64a}, S. Cheong¹⁴², A. Cheplakov³⁸, E. Cheremushkina⁴⁸, E. Cherepanova¹¹³, R. Cherkaoui El Moursli^{35e}, E. Cheu⁷, K. Cheung⁶⁵, L. Chevalier¹³⁴, V. Chiarella⁵³, G. Chiarelli^{73a}, N. Chiedde¹⁰¹, G. Chiodini^{69a}, A.S. Chisholm²⁰, A. Chitan^{27b}, M. Chitishvili¹⁶², Y.H. Chiu¹⁶⁴, M.V. Chizhov³⁸, K. Choi¹¹, A.R. Chomont^{74a,74b}, Y. Chou¹⁰², E.Y.S. Chow¹¹³, T. Chowdhury^{33g}, L.D. Christopher^{33g}, K.L. Chu^{64a}, M.C. Chu^{64a}, X. Chu^{14a,14d}, J. Chudoba¹³⁰, J.J. Chwastowski⁸⁵, D. Cieri¹⁰⁹, K.M. Ciesla^{84a}, V. Cindro⁹², A. Ciochio^{17a}, F. Ciotto^{71a,71b}, Z.H. Citron^{168,n}, M. Citterio^{70a}, D.A. Ciubotaru^{27b}, B.M. Ciungu¹⁵⁴, A. Clark⁵⁶, P.J. Clark⁵², J.M. Clavijo Columbie⁴⁸, S.E. Clawson¹⁰⁰, C. Clement^{47a,47b}, J. Clercx⁴⁸, L. Clissa^{23b,23a}, Y. Coadou¹⁰¹, M. Cobal^{68a,68c}, A. Coccaro^{57b}, R.F. Coelho Barrue^{129a}, R. Coelho Lopes De Sa¹⁰², S. Coelli^{70a}, H. Cohen¹⁵⁰, A.E.C. Coimbra^{70a,70b}, B. Cole⁴¹, J. Collot⁶⁰, P. Conde Muiño^{129a,129g}, M.P. Connell^{33c}, S.H. Connell^{33c}, I.A. Connelly⁵⁹, E.I. Conroy¹²⁵, F. Conventi^{71a,aj}, H.G. Cooke²⁰, A.M. Cooper-Sarkar¹²⁵, F. Cormier¹⁶³, L.D. Corpe³⁶, M. Corradi^{74a,74b}, E.E. Corrigan⁹⁷, F. Corriveau^{103,y}, A. Cortes-Gonzalez¹⁸, M.J. Costa¹⁶², F. Costanza⁴, D. Costanzo¹³⁸, B.M. Cote¹¹⁸, G. Cowan⁹⁴, J.W. Cowley³², K. Cranmer¹¹⁶, S. Crépe-Renaudin⁶⁰, F. Crescioli¹²⁶, M. Cristinziani¹⁴⁰, M. Cristoforetti^{77a,77b,d}, V. Croft¹⁵⁷, G. Crosetti^{43b,43a}, A. Cueto³⁶, T. Cuhadar Donszelmann¹⁵⁹, H. Cui^{14a,14d}, Z. Cui⁷, A.R. Cukierman¹⁴², W.R. Cunningham⁵⁹, F. Curcio^{43b,43a}, P. Czodrowski³⁶, M.M. Czurylo^{63b}, M.J. Da Cunha Sargedas De Sousa^{62a}, J.V. Da Fonseca Pinto^{81b}, C. Da Via¹⁰⁰, W. Dabrowski^{84a}, T. Dado⁴⁹, S. Dahbi^{33g}, T. Dai¹⁰⁵, C. Dallapiccola¹⁰², M. Dam⁴², G. D'amen²⁹, V. D'Amico¹⁰⁸, J. Damp⁹⁹, J.R. Dandoy¹²⁷, M.F. Daneri³⁰, M. Danninger¹⁴¹, V. Dao³⁶, G. Darbo^{57b}, S. Darmora⁶, S.J. Das^{29,al}, S. D'Auria^{70a,70b}, C. David^{155b}, T. Davidek¹³², D.R. Davis⁵¹, B. Davis-Purcell³⁴, I. Dawson⁹³, K. De⁸, R. De Asmundis^{71a}, M. De Beurs¹¹³, N. De Biase⁴⁸, S. De Castro^{23b,23a}, N. De Groot¹¹², P. de Jong¹¹³, H. De la Torre¹⁰⁶, A. De Maria^{14c}, A. De Salvo^{74a}, U. De Sanctis^{75a,75b}, A. De Santo¹⁴⁵, J.B. De Vivie De Regie⁶⁰, D.V. Dedovich³⁸,

J. Degens¹¹³, A.M. Deiana⁴⁴, F. Del Corso^{23b,23a}, J. Del Peso⁹⁸, F. Del Rio^{63a}, F. Deliot¹³⁴, C.M. Delitzsch⁴⁹, M. Della Pietra^{71a,71b}, D. Della Volpe⁵⁶, A. Dell'Acqua³⁶, L. Dell'Asta^{70a,70b}, M. Delmastro⁴, P.A. Delsart⁶⁰, S. Demers¹⁷¹, M. Demichev³⁸, S.P. Denisov³⁷, L. D'Eramo¹¹⁴, D. Derendarz⁸⁵, F. Derue¹²⁶, P. Dervan⁹¹, K. Desch²⁴, K. Dette¹⁵⁴, C. Deutsch²⁴, P.O. Deviveiros³⁶, F.A. Di Bello^{57b,57a}, A. Di Ciaccio^{75a,75b}, L. Di Ciaccio⁴, A. Di Domenico^{74a,74b}, C. Di Donato^{71a,71b}, A. Di Girolamo³⁶, G. Di Gregorio⁵, A. Di Luca^{77a,77b}, B. Di Micco^{76a,76b}, R. Di Nardo^{76a,76b}, C. Diaconu¹⁰¹, F.A. Dias¹¹³, T. Dias Do Vale¹⁴¹, M.A. Diaz^{136a,136b}, F.G. Diaz Capriles²⁴, M. Didenko¹⁶², E.B. Diehl¹⁰⁵, L. Diehl⁵⁴, S. Díez Cornell⁴⁸, C. Díez Pardos¹⁴⁰, C. Dimitriadi^{24,160}, A. Dimitrievska^{17a}, W. Ding^{14b}, J. Dingfelder²⁴, I.-M. Dinu^{27b}, S.J. Dittmeier^{63b}, F. Dittus³⁶, F. Djama¹⁰¹, T. Djobava^{148b}, J.I. Djuvsland¹⁶, C. Doglioni^{100,97}, J. Dolejsi¹³², Z. Dolezal¹³², M. Donadelli^{81c}, B. Dong^{62c}, J. Donini⁴⁰, A. D'Onofrio^{14c}, M. D'Onofrio⁹¹, J. Dopke¹³³, A. Doria^{71a}, M.T. Dova⁸⁹, A.T. Doyle⁵⁹, M.A. Draguet¹²⁵, E. Drechsler¹⁴¹, E. Dreyer¹⁶⁸, I. Drivas-koulouris¹⁰, A.S. Drobac¹⁵⁷, M. Drozdova⁵⁶, D. Du^{62a}, T.A. du Pree¹¹³, F. Dubinin³⁷, M. Dubovsky^{28a}, E. Duchovni¹⁶⁸, G. Duckeck¹⁰⁸, O.A. Ducu^{27b}, D. Duda¹⁰⁹, A. Dudarev³⁶, M. D'uffizi¹⁰⁰, L. Dufлот⁶⁶, M. Dührssen³⁶, C. Dülse¹⁷⁰, A.E. Dumitriu^{27b}, M. Dunford^{63a}, S. Dungs⁴⁹, K. Dunne^{47a,47b}, A. Duperrin¹⁰¹, H. Duran Yildiz^{3a}, M. Düren⁵⁸, A. Durglishvili^{148b}, B.L. Dwyer¹¹⁴, G.I. Dyckes^{17a}, M. Dyndal^{84a}, S. Dysch¹⁰⁰, B.S. Dziedzic⁸⁵, Z.O. Earnshaw¹⁴⁵, B. Eckerova^{28a}, M.G. Eggleston⁵¹, E. Egidio Purcino De Souza^{81b}, L.F. Ehrke⁵⁶, G. Eigen¹⁶, K. Einsweiler^{17a}, T. Ekelof¹⁶⁰, P.A. Ekman⁹⁷, Y. El Ghazali^{35b}, H. El Jarrari^{35e,147}, A. El Moussaouy^{35a}, V. Ellajosyula¹⁶⁰, M. Ellert¹⁶⁰, F. Ellinghaus¹⁷⁰, A.A. Elliot⁹³, N. Ellis³⁶, J. Elmsheuser²⁹, M. Elsing³⁶, D. Emeliyanov¹³³, A. Emerman⁴¹, Y. Enari¹⁵², I. Ene^{17a}, S. Epari¹³, J. Erdmann^{49,af}, A. Ereditato¹⁹, P.A. Erland⁸⁵, M. Errenst¹⁷⁰, M. Escalier⁶⁶, C. Escobar¹⁶², E. Etzion¹⁵⁰, G. Evans^{129a}, H. Evans⁶⁷, M.O. Evans¹⁴⁵, A. Ezhilov³⁷, S. Ezzarqtouni^{35a}, F. Fabbri⁵⁹, L. Fabbri^{23b,23a}, G. Facini⁹⁵, V. Fadeyev¹³⁵, R.M. Fakhruddinov³⁷, S. Falciano^{74a}, P.J. Falke²⁴, S. Falke³⁶, J. Faltova¹³², Y. Fan^{14a}, Y. Fang^{14a,14d}, G. Fanourakis⁴⁶, M. Fanti^{70a,70b}, M. Faraj^{68a,68b}, Z. Farazpay⁹⁶, A. Farbin⁸, A. Farilla^{76a}, T. Farooque¹⁰⁶, S.M. Farrington⁵², F. Fassi^{35e}, D. Fassouliotis⁹, M. Fauci Giannelli^{75a,75b}, W.J. Fawcett³², L. Fayard⁶⁶, P. Federicova¹³⁰, O.L. Fedin^{37,a}, G. Fedotov³⁷, M. Feickert¹⁶⁹, L. Feligioni¹⁰¹, A. Fell¹³⁸, D.E. Fellers¹²², C. Feng^{62b}, M. Feng^{14b}, Z. Feng¹¹³, M.J. Fenton¹⁵⁹, A.B. Fenyuk³⁷, L. Ferencz⁴⁸, J. Ferrando⁴⁸, A. Ferrari¹⁶⁰, P. Ferrari^{113,112}, R. Ferrari^{72a}, D. Ferrere⁵⁶, C. Ferretti¹⁰⁵, F. Fiedler⁹⁹, A. Filipčič⁹², E.K. Filmer¹, F. Filthaut¹¹², M.C.N. Fiolhais^{129a,129c,c}, L. Fiorini¹⁶², F. Fischer¹⁴⁰, W.C. Fisher¹⁰⁶, T. Fitschen¹⁰⁰, I. Fleck¹⁴⁰, P. Fleischmann¹⁰⁵, T. Flick¹⁷⁰, L. Flores¹²⁷, M. Flores^{33d,ae}, L.R. Flores Castillo^{64a}, F.M. Follega^{77a,77b}, N. Fomin¹⁶, J.H. Foo¹⁵⁴, B.C. Forland⁶⁷, A. Formica¹³⁴, A.C. Forti¹⁰⁰, E. Fortin¹⁰¹, A.W. Fortman⁶¹, M.G. Foti^{17a}, L. Fountas^{9,k}, D. Fournier⁶⁶, H. Fox⁹⁰, P. Francavilla^{73a,73b}, S. Francescato⁶¹, S. Franchellucci⁵⁶, M. Franchini^{23b,23a}, S. Franchino^{63a}, D. Francis³⁶, L. Franco¹¹², L. Franconi¹⁹, M. Franklin⁶¹, G. Frattari²⁶, A.C. Freegard⁹³, P.M. Freeman²⁰, W.S. Freund^{81b}, N. Fritzsche⁵⁰, A. Froch⁵⁴, D. Froidevaux³⁶, J.A. Frost¹²⁵, Y. Fu^{62a}, M. Fujimoto¹¹⁷, E. Fullana Torregrosa^{162,*}, J. Fuster¹⁶², A. Gabrielli^{23b,23a}, A. Gabrielli¹⁵⁴, P. Gadow⁴⁸, G. Gagliardi^{57b,57a}, L.G. Gagnon^{17a}, G.E. Gallardo¹²⁵, E.J. Gallas¹²⁵, B.J. Gallop¹³³, R. Gamboa Goni⁹³, K.K. Gan¹¹⁸, S. Ganguly¹⁵², J. Gao^{62a}, Y. Gao⁵², F.M. Garay Walls^{136a,136b}, B. Garcia^{29,al}, C. García¹⁶², J.E. García Navarro¹⁶², J.A. García Pascual^{14a}, M. Garcia-Sciveres^{17a}, R.W. Gardner³⁹, D. Garg⁷⁹, R.B. Garg^{142,r}, S. Gargiulo⁵⁴, C.A. Garner¹⁵⁴, V. Garonne²⁹, S.J. Gasiorowski¹³⁷, P. Gaspar^{81b}, G. Gaudio^{72a}, V. Gautam¹³, P. Gauzzi^{74a,74b}, I.L. Gavrilenko³⁷, A. Gavrilyuk³⁷, C. Gay¹⁶³, G. Gaycken⁴⁸, E.N. Gazis¹⁰, A.A. Geanta^{27b,27e}, C.M. Gee¹³⁵, J. Geisen⁹⁷, M. Geisen⁹⁹, C. Gemme^{57b}, M.H. Genest⁶⁰, S. Gentile^{74a,74b}, S. George⁹⁴, W.F. George²⁰, T. Geralis⁴⁶, L.O. Gerlach⁵⁵, P. Gessinger-Befurt³⁶, M. Ghasemi Bostanabad¹⁶⁴, M. Ghneimat¹⁴⁰, K. Ghorbanian⁹³, A. Ghosal¹⁴⁰, A. Ghosh¹⁵⁹, A. Ghosh⁷, B. Giacobbe^{23b}, S. Giagu^{74a,74b}, N. Giangiacomi¹⁵⁴, P. Giannetti^{73a}, A. Giannini^{62a}, S.M. Gibson⁹⁴, M. Gignac¹³⁵, D.T. Gil^{84b}, A.K. Gilbert^{84a}, B.J. Gilbert⁴¹, D. Gillberg³⁴, G. Gilles¹¹³, N.E.K. Gillwald⁴⁸, L. Ginabat¹²⁶, D.M. Gingrich^{2,ai}, M.P. Giordani^{68a,68c}, P.F. Giraud¹³⁴, G. Giugliarelli^{68a,68c}, D. Giugni^{70a}, F. Giuli³⁶, I. Gkialas^{9,k}, L.K. Gladilin³⁷, C. Glasman⁹⁸, G.R. Gledhill¹²², M. Glisic¹²², I. Gnesi^{43b,g}, Y. Go^{29,al}, M. Goblirsch-Kolb²⁶, B. Gocke⁴⁹, D. Godin¹⁰⁷, S. Goldfarb¹⁰⁴, T. Golling⁵⁶, M.G.D. Gololo^{33g}, D. Golubkov³⁷, J.P. Gombas¹⁰⁶, A. Gomes^{129a,129b}, G. Gomes Da Silva¹⁴⁰, A.J. Gomez Delegido¹⁶², R. Goncalves Gama⁵⁵, R. Gonçalves^{129a,129c}, G. Gonella¹²², L. Gonella²⁰, A. Gongadze³⁸, F. Gonnella²⁰, J.L. Gonski⁴¹, R.Y. González Andana⁵², S. González de la Hoz¹⁶², S. Gonzalez Fernandez¹³, R. Gonzalez Lopez⁹¹, C. Gonzalez Renteria^{17a}, R. Gonzalez Suarez¹⁶⁰, S. Gonzalez-Sevilla⁵⁶,

G.R. Gonzalvo Rodriguez ¹⁶², L. Goossens ³⁶, N.A. Gorasia ²⁰, P.A. Gorbounov ³⁷, B. Gorini ³⁶, E. Gorini ^{69a,69b}, A. Gorišek ⁹², A.T. Goshaw ⁵¹, M.I. Gostkin ³⁸, C.A. Gottardo ³⁶, M. Goughri ^{35b}, V. Goumarre ⁴⁸, A.G. Goussiou ¹³⁷, N. Govender ^{33c}, C. Goy ⁴, I. Grabowska-Bold ^{84a}, K. Graham ³⁴, E. Gramstad ¹²⁴, S. Grancagnolo ¹⁸, M. Grandi ¹⁴⁵, V. Gratchev ^{37,*}, P.M. Gravila ^{27f}, F.G. Gravili ^{69a,69b}, H.M. Gray ^{17a}, M. Greco ^{69a,69b}, C. Grefe ²⁴, I.M. Gregor ⁴⁸, P. Grenier ¹⁴², C. Grieco ¹³, A.A. Grillo ¹³⁵, K. Grimm ^{31,o}, S. Grinstein ^{13,w}, J.-F. Grivaz ⁶⁶, E. Gross ¹⁶⁸, J. Grosse-Knetter ⁵⁵, C. Grud ¹⁰⁵, A. Grummer ¹¹¹, J.C. Grundy ¹²⁵, L. Guan ¹⁰⁵, W. Guan ¹⁶⁹, C. Gubbels ¹⁶³, J.G.R. Guerrero Rojas ¹⁶², G. Guerrieri ^{68a,68b}, F. Guescini ¹⁰⁹, R. Gugel ⁹⁹, J.A.M. Guhit ¹⁰⁵, A. Guida ⁴⁸, T. Guillemain ⁴, E. Guillon ^{166,133}, S. Guindon ³⁶, F. Guo ^{14a,14d}, J. Guo ^{62c}, L. Guo ⁶⁶, Y. Guo ¹⁰⁵, R. Gupta ⁴⁸, S. Gurbuz ²⁴, S.S. Gurdasani ⁵⁴, G. Gustavino ³⁶, M. Guth ⁵⁶, P. Gutierrez ¹¹⁹, L.F. Gutierrez Zagazeta ¹²⁷, C. Gutsche ⁹⁵, C. Guyot ¹³⁴, C. Gwenlan ¹²⁵, C.B. Gwilliam ⁹¹, E.S. Haaland ¹²⁴, A. Haas ¹¹⁶, M. Habedank ⁴⁸, C. Haber ^{17a}, H.K. Hadavand ⁸, A. Hadeef ⁹⁹, S. Hadzic ¹⁰⁹, E.H. Haines ⁹⁵, M. Haleem ¹⁶⁵, J. Haley ¹²⁰, J.J. Hall ¹³⁸, G.D. Hallewell ¹⁰¹, L. Halser ¹⁹, K. Hamano ¹⁶⁴, H. Hamdaoui ^{35e}, M. Hamer ²⁴, G.N. Hamity ⁵², J. Han ^{62b}, K. Han ^{62a}, L. Han ^{14c}, L. Han ^{62a}, S. Han ^{17a}, Y.F. Han ¹⁵⁴, K. Hanagaki ⁸², M. Hance ¹³⁵, D.A. Hangal ^{41,ad}, H. Hanif ¹⁴¹, M.D. Hank ³⁹, R. Hankache ¹⁰⁰, J.B. Hansen ⁴², J.D. Hansen ⁴², P.H. Hansen ⁴², K. Hara ¹⁵⁶, D. Harada ⁵⁶, T. Harenberg ¹⁷⁰, S. Harkusha ³⁷, Y.T. Harris ¹²⁵, N.M. Harrison ¹¹⁸, P.F. Harrison ¹⁶⁶, N.M. Hartman ¹⁴², N.M. Hartmann ¹⁰⁸, Y. Hasegawa ¹³⁹, A. Hasib ⁵², S. Haug ¹⁹, R. Hauser ¹⁰⁶, M. Havranek ¹³¹, C.M. Hawkes ²⁰, R.J. Hawkings ³⁶, S. Hayashida ¹¹⁰, D. Hayden ¹⁰⁶, C. Hayes ¹⁰⁵, R.L. Hayes ¹⁶³, C.P. Hays ¹²⁵, J.M. Hays ⁹³, H.S. Hayward ⁹¹, F. He ^{62a}, Y. He ¹⁵³, Y. He ¹²⁶, M.P. Heath ⁵², V. Hedberg ⁹⁷, A.L. Heggelund ¹²⁴, N.D. Hehir ⁹³, C. Heidegger ⁵⁴, K.K. Heidegger ⁵⁴, W.D. Heidorn ⁸⁰, J. Heilman ³⁴, S. Heim ⁴⁸, T. Heim ^{17a}, J.G. Heinlein ¹²⁷, J.J. Heinrich ¹²², L. Heinrich ^{109,ag}, J. Hejbal ¹³⁰, L. Helary ⁴⁸, A. Held ¹⁶⁹, S. Hellesund ¹²⁴, C.M. Helling ¹⁶³, S. Hellman ^{47a,47b}, C. Helsens ³⁶, R.C.W. Henderson ⁹⁰, L. Henkelmann ³², A.M. Henriques Correia ³⁶, H. Herde ⁹⁷, Y. Hernández Jiménez ¹⁴⁴, L.M. Herrmann ²⁴, M.G. Herrmann ¹⁰⁸, T. Herrmann ⁵⁰, G. Herten ⁵⁴, R. Hertenberger ¹⁰⁸, L. Hervas ³⁶, N.P. Hessey ^{155a}, H. Hibi ⁸³, E. Higón-Rodríguez ¹⁶², S.J. Hillier ²⁰, I. Hinchliffe ^{17a}, F. Hinterkeuser ²⁴, M. Hirose ¹²³, S. Hirose ¹⁵⁶, D. Hirschbuehl ¹⁷⁰, T.G. Hitchings ¹⁰⁰, B. Hiti ⁹², J. Hobbs ¹⁴⁴, R. Hobincu ^{27e}, N. Hod ¹⁶⁸, M.C. Hodgkinson ¹³⁸, B.H. Hodgkinson ³², A. Hoecker ³⁶, J. Hofer ⁴⁸, D. Hohn ⁵⁴, T. Holm ²⁴, M. Holzbock ¹⁰⁹, L.B.A.H. Hommels ³², B.P. Honan ¹⁰⁰, J. Hong ^{62c}, T.M. Hong ¹²⁸, J.C. Honig ⁵⁴, A. Hönle ¹⁰⁹, B.H. Hooberman ¹⁶¹, W.H. Hopkins ⁶, Y. Horii ¹¹⁰, S. Hou ¹⁴⁷, A.S. Howard ⁹², J. Howarth ⁵⁹, J. Hoya ⁶, M. Hrabovsky ¹²¹, A. Hrynevich ⁴⁸, T. Hryn'ova ⁴, P.J. Hsu ⁶⁵, S.-C. Hsu ¹³⁷, Q. Hu ⁴¹, Y.F. Hu ^{14a,14d,ak}, D.P. Huang ⁹⁵, S. Huang ^{64b}, X. Huang ^{14c}, Y. Huang ^{62a}, Y. Huang ^{14a}, Z. Huang ¹⁰⁰, Z. Hubacek ¹³¹, M. Huebner ²⁴, F. Huegging ²⁴, T.B. Huffman ¹²⁵, M. Huhtinen ³⁶, S.K. Huiberts ¹⁶, R. Hulsken ¹⁰³, N. Huseynov ^{12,a}, J. Huston ¹⁰⁶, J. Huth ⁶¹, R. Hyneman ¹⁴², S. Hyrych ^{28a}, G. Iacobucci ⁵⁶, G. Iakovidis ²⁹, I. Ibragimov ¹⁴⁰, L. Iconomidou-Fayard ⁶⁶, P. Iengo ^{71a,71b}, R. Iguchi ¹⁵², T. Iizawa ⁵⁶, Y. Ikegami ⁸², A. Ilg ¹⁹, N. Ilic ¹⁵⁴, H. Imam ^{35a}, T. Ingebrechtsen Carlson ^{47a,47b}, G. Introzzi ^{72a,72b}, M. Iodice ^{76a}, V. Ippolito ^{74a,74b}, M. Ishino ¹⁵², W. Islam ¹⁶⁹, C. Issever ^{18,48}, S. Istin ^{21a,an}, H. Ito ¹⁶⁷, J.M. Iturbe Ponce ^{64a}, R. Iuppa ^{77a,77b}, A. Ivina ¹⁶⁸, J.M. Izen ⁴⁵, V. Izzo ^{71a}, P. Jacka ^{130,131}, P. Jackson ¹, R.M. Jacobs ⁴⁸, B.P. Jaeger ¹⁴¹, C.S. Jagfeld ¹⁰⁸, G. Jäkel ¹⁷⁰, K. Jakobs ⁵⁴, T. Jakoubek ¹⁶⁸, J. Jamieson ⁵⁹, K.W. Janas ^{84a}, G. Jarlskog ⁹⁷, A.E. Jaspan ⁹¹, M. Javurkova ¹⁰², F. Jeanneau ¹³⁴, L. Jeanty ¹²², J. Jejelava ^{148a,ab}, P. Jenni ^{54,h}, C.E. Jessiman ³⁴, S. Jézéquel ⁴, J. Jia ¹⁴⁴, X. Jia ⁶¹, X. Jia ^{14a,14d}, Z. Jia ^{14c}, Y. Jiang ^{62a}, S. Jiggins ⁵², J. Jimenez Pena ¹⁰⁹, S. Jin ^{14c}, A. Jinaru ^{27b}, O. Jinnouchi ¹⁵³, P. Johansson ¹³⁸, K.A. Johns ⁷, D.M. Jones ³², E. Jones ¹⁶⁶, P. Jones ³², R.W.L. Jones ⁹⁰, T.J. Jones ⁹¹, R. Joshi ¹¹⁸, J. Jovicevic ¹⁵, X. Ju ^{17a}, J.J. Junggeburth ³⁶, A. Juste Rozas ^{13,w}, S. Kabana ^{136e}, A. Kaczmarska ⁸⁵, M. Kado ^{74a,74b}, H. Kagan ¹¹⁸, M. Kagan ¹⁴², A. Kahn ⁴¹, A. Kahn ¹²⁷, C. Kahra ⁹⁹, T. Kaji ¹⁶⁷, E. Kajomovitz ¹⁴⁹, N. Kakati ¹⁶⁸, C.W. Kalderon ²⁹, A. Kamenshchikov ¹⁵⁴, S. Kanayama ¹⁵³, N.J. Kang ¹³⁵, Y. Kano ¹¹⁰, D. Kar ^{33g}, K. Karava ¹²⁵, M.J. Kareem ^{155b}, E. Karentzos ⁵⁴, I. Karkanas ^{151,f}, S.N. Karpov ³⁸, Z.M. Karpova ³⁸, V. Kartvelishvili ⁹⁰, A.N. Karyukhin ³⁷, E. Kasimi ^{151,f}, C. Kato ^{62d}, J. Katzy ⁴⁸, S. Kaur ³⁴, K. Kawade ¹³⁹, K. Kawagoe ⁸⁸, T. Kawamoto ¹³⁴, G. Kawamura ⁵⁵, E.F. Kay ¹⁶⁴, F.I. Kaya ¹⁵⁷, S. Kazakos ¹³, V.F. Kazanin ³⁷, Y. Ke ¹⁴⁴, J.M. Keaveney ^{33a}, R. Keeler ¹⁶⁴, G.V. Kehris ⁶¹, J.S. Keller ³⁴, A.S. Kelly ⁹⁵, D. Kelsey ¹⁴⁵, J.J. Kempster ²⁰, K.E. Kennedy ⁴¹, P.D. Kennedy ⁹⁹, O. Kepka ¹³⁰, B.P. Kerridge ¹⁶⁶, S. Kersten ¹⁷⁰, B.P. Kerševan ⁹², S. Keshri ⁶⁶, L. Keszeghova ^{28a}, S. Ketabchi Haghighat ¹⁵⁴, M. Khandoga ¹²⁶, A. Khanov ¹²⁰, A.G. Kharlamov ³⁷, T. Kharlamova ³⁷, E.E. Khoda ¹³⁷, T.J. Khoo ¹⁸, G. Khoraiuli ¹⁶⁵, J. Khubua ^{148b}, Y.A.R. Khwaira ⁶⁶, M. Kiehn ³⁶, A. Kilgallon ¹²², D.W. Kim ^{47a,47b}, E. Kim ¹⁵³, Y.K. Kim ³⁹, N. Kimura ⁹⁵,

A. Kirchhoff⁵⁵, D. Kirchmeier⁵⁰, C. Kirfel²⁴, J. Kirk¹³³, A.E. Kiryunin¹⁰⁹, T. Kishimoto¹⁵², D.P. Kisliuk¹⁵⁴, C. Kitsaki¹⁰, O. Kivernyk²⁴, M. Klassen^{63a}, C. Klein³⁴, L. Klein¹⁶⁵, M.H. Klein¹⁰⁵, M. Klein⁹¹, S.B. Klein⁵⁶, U. Klein⁹¹, P. Klimek³⁶, A. Klimentov²⁹, F. Klimpel¹⁰⁹, T. Klingl²⁴, T. Klioutchnikova³⁶, F.F. Klitzner¹⁰⁸, P. Kluit¹¹³, S. Kluth¹⁰⁹, E. Kneringer⁷⁸, T.M. Knight¹⁵⁴, A. Knue⁵⁴, D. Kobayashi⁸⁸, R. Kobayashi⁸⁶, M. Kocian¹⁴², P. Kodyš¹³², D.M. Koeck¹⁴⁵, P.T. Koenig²⁴, T. Koffas³⁴, M. Kolb¹³⁴, I. Koletsou⁴, T. Komarek¹²¹, K. Köneke⁵⁴, A.X.Y. Kong¹, T. Kono¹¹⁷, N. Konstantinidis⁹⁵, B. Konya⁹⁷, R. Kopeliansky⁶⁷, S. Koperny^{84a}, K. Korcyl⁸⁵, K. Kordas^{151f}, G. Koren¹⁵⁰, A. Korn⁹⁵, S. Korn⁵⁵, I. Korolkov¹³, N. Korotkova³⁷, B. Kortman¹¹³, O. Kortner¹⁰⁹, S. Kortner¹⁰⁹, W.H. Kostecka¹¹⁴, V.V. Kostyukhin¹⁴⁰, A. Kotsokechagia¹³⁴, A. Kotwal⁵¹, A. Koulouris³⁶, A. Kourkoumeli-Charalampidi^{72a,72b}, C. Kourkoumelis⁹, E. Kourlitis⁶, O. Kovanda¹⁴⁵, R. Kowalewski¹⁶⁴, W. Kozanecki¹³⁴, A.S. Kozhin³⁷, V.A. Kramarenko³⁷, G. Kramberger⁹², P. Kramer⁹⁹, M.W. Krasny¹²⁶, A. Krasznahorkay³⁶, J.A. Kremer⁹⁹, T. Kresse⁵⁰, J. Kretzschmar⁹¹, K. Kreul¹⁸, P. Krieger¹⁵⁴, F. Krieter¹⁰⁸, S. Krishnamurthy¹⁰², A. Krishnan^{63b}, M. Krivos¹³², K. Krizka^{17a}, K. Kroeninger⁴⁹, H. Kroha¹⁰⁹, J. Kroll¹³⁰, J. Kroll¹²⁷, K.S. Krowpman¹⁰⁶, U. Kruchonak³⁸, H. Krüger²⁴, N. Krumnack⁸⁰, M.C. Kruse⁵¹, J.A. Krzysiak⁸⁵, O. Kuchinskaia³⁷, S. Kuday^{3a}, D. Kuechler⁴⁸, J.T. Kuechler⁴⁸, S. Kuehn³⁶, T. Kuhl⁴⁸, V. Kukhtin³⁸, Y. Kulchitsky^{37a}, S. Kuleshov^{136d,136b}, M. Kumar^{33g}, N. Kumari¹⁰¹, A. Kupco¹³⁰, T. Kupfer⁴⁹, A. Kupich³⁷, O. Kuprash⁵⁴, H. Kurashige⁸³, L.L. Kurchaninov^{155a}, Y.A. Kurochkin³⁷, A. Kurova³⁷, M. Kuze¹⁵³, A.K. Kvam¹⁰², J. Kvita¹²¹, T. Kwan¹⁰³, K.W. Kwok^{64a}, N.G. Kyriacou¹⁰⁵, L.A.O. Laatu¹⁰¹, C. Lacasta¹⁶², F. Lacava^{74a,74b}, H. Lacker¹⁸, D. Lacour¹²⁶, N.N. Lad⁹⁵, E. Ladygin³⁸, B. Laforge¹²⁶, T. Lagouri^{136e}, S. Lai⁵⁵, I.K. Lakomic^{84a}, N. Lalloue⁶⁰, J.E. Lambert¹¹⁹, S. Lammers⁶⁷, W. Lamp⁷, C. Lampoudis^{151f}, A.N. Lancaster¹¹⁴, E. Lançon²⁹, U. Landgraf⁵⁴, M.P.J. Landon⁹³, V.S. Lang⁵⁴, R.J. Langenberg¹⁰², A.J. Lankford¹⁵⁹, F. Lanni³⁶, K. Lantzs²⁴, A. Lanza^{72a}, A. Lapertosa^{57b,57a}, J.F. Laporte¹³⁴, T. Lari^{70a}, F. Lasagni Manghi^{23b}, M. Lassnig³⁶, V. Latonova¹³⁰, T.S. Lau^{64a}, A. Laudrain⁹⁹, A. Laurier³⁴, S.D. Lawlor⁹⁴, Z. Lawrence¹⁰⁰, M. Lazzaroni^{70a,70b}, B. Le¹⁰⁰, B. Leban⁹², A. Lebedev⁸⁰, M. LeBlanc³⁶, T. LeCompte⁶, F. Ledroit-Guillon⁶⁰, A.C.A. Lee⁹⁵, G.R. Lee¹⁶, L. Lee⁶¹, S.C. Lee¹⁴⁷, S. Lee^{47a,47b}, T.F. Lee⁹¹, L.L. Leeuw^{33c}, H.P. Lefebvre⁹⁴, M. Lefebvre¹⁶⁴, C. Leggett^{17a}, K. Lehmann¹⁴¹, G. Lehmann Miotto³⁶, M. Leigh⁵⁶, W.A. Leight¹⁰², A. Leisos^{151v}, M.A.L. Leite^{81c}, C.E. Leitgeb⁴⁸, R. Leitner¹³², K.J.C. Leney⁴⁴, T. Lenz²⁴, S. Leone^{73a}, C. Leonidopoulos⁵², A. Leopold¹⁴³, C. Leroy¹⁰⁷, R. Les¹⁰⁶, C.G. Lester³², M. Levchenko³⁷, J. Levêque⁴, D. Levin¹⁰⁵, L.J. Levinson¹⁶⁸, M.P. Lewicki⁸⁵, D.J. Lewis⁴, A. Li⁵, B. Li^{14b}, B. Li^{62b}, C. Li^{62a}, C-Q. Li^{62c}, H. Li^{62a}, H. Li^{62b}, H. Li^{14c}, H. Li^{62b}, J. Li^{62c}, K. Li¹³⁷, L. Li^{62c}, M. Li^{14a,14d}, Q.Y. Li^{62a}, S. Li^{14a,14d}, S. Li^{62d,62c,e}, T. Li^{62b}, X. Li¹⁰³, Z. Li^{62b}, Z. Li¹²⁵, Z. Li¹⁰³, Z. Li⁹¹, Z. Li^{14a,14d}, Z. Liang^{14a}, M. Liberatore⁴⁸, B. Liberti^{75a}, K. Lie^{64c}, J. Lieber Marin^{81b}, K. Lin¹⁰⁶, R.A. Linck⁶⁷, R.E. Lindley⁷, J.H. Lindon², A. Linss⁴⁸, E. Lipeles¹²⁷, A. Lipniacka¹⁶, A. Lister¹⁶³, J.D. Little⁴, B. Liu^{14a}, B.X. Liu¹⁴¹, D. Liu^{62d,62c}, J.B. Liu^{62a}, J.K.K. Liu³², K. Liu^{62d,62c}, M. Liu^{62a}, M.Y. Liu^{62a}, P. Liu^{14a}, Q. Liu^{62d,137,62c}, X. Liu^{62a}, Y. Liu⁴⁸, Y. Liu^{14c,14d}, Y.L. Liu¹⁰⁵, Y.W. Liu^{62a}, M. Livan^{72a,72b}, J. Llorente Merino¹⁴¹, S.L. Lloyd⁹³, E.M. Lobodzinska⁴⁸, P. Loch⁷, S. Loffredo^{75a,75b}, T. Lohse¹⁸, K. Lohwasser¹³⁸, M. Lokajicek¹³⁰, J.D. Long¹⁶¹, I. Longarini^{74a,74b}, L. Longo^{69a,69b}, R. Longo¹⁶¹, I. Lopez Paz³⁶, A. Lopez Solis⁴⁸, J. Lorenz¹⁰⁸, N. Lorenzo Martinez⁴, A.M. Lory¹⁰⁸, A. Lösle⁵⁴, X. Lou^{47a,47b}, X. Lou^{14a,14d}, A. Lounis⁶⁶, J. Love⁶, P.A. Love⁹⁰, J.J. Lozano Bahilo¹⁶², G. Lu^{14a,14d}, M. Lu⁷⁹, S. Lu¹²⁷, Y.J. Lu⁶⁵, H.J. Lubatti¹³⁷, C. Luci^{74a,74b}, F.L. Lucio Alves^{14c}, A. Lucotte⁶⁰, F. Luehring⁶⁷, I. Luise¹⁴⁴, O. Lukianchuk⁶⁶, O. Lundberg¹⁴³, B. Lund-Jensen¹⁴³, N.A. Luongo¹²², M.S. Lutz¹⁵⁰, D. Lynn²⁹, H. Lyons⁹¹, R. Lysak¹³⁰, E. Lytken⁹⁷, F. Lyu^{14a}, V. Lyubushkin³⁸, T. Lyubushkina³⁸, H. Ma²⁹, L.L. Ma^{62b}, Y. Ma⁹⁵, D.M. Mac Donell¹⁶⁴, G. Maccarrone⁵³, J.C. MacDonald¹³⁸, R. Madar⁴⁰, W.F. Mader⁵⁰, J. Maeda⁸³, T. Maeno²⁹, M. Maerker⁵⁰, V. Magerl⁵⁴, H. Maguire¹³⁸, D.J. Mahon⁴¹, C. Maidantchik^{81b}, A. Maio^{129a,129b,129d}, K. Maj^{84a}, O. Majersky^{28a}, S. Majewski¹²², N. Makovec⁶⁶, V. Maksimovic¹⁵, B. Malaescu¹²⁶, Pa. Malecki⁸⁵, V.P. Maleev³⁷, F. Malek⁶⁰, D. Malito^{43b,43a}, U. Mallik⁷⁹, C. Malone³², S. Maltezos¹⁰, S. Malyukov³⁸, J. Mamuzic¹³, G. Mancini⁵³, G. Manco^{72a,72b}, J.P. Mandalia⁹³, I. Mandić⁹², L. Manhaes de Andrade Filho^{81a}, I.M. Maniatis^{151f}, M. Manisha¹³⁴, J. Manjarres Ramos⁵⁰, D.C. Mankad¹⁶⁸, A. Mann¹⁰⁸, B. Mansoulie¹³⁴, S. Manzoni³⁶, A. Marantis^{151v}, G. Marchiori⁵, M. Marcisovsky¹³⁰, L. Marcoccia^{75a,75b}, C. Marcon^{70a,70b}, M. Marinescu²⁰, M. Marjanovic¹¹⁹, E.J. Marshall⁹⁰, Z. Marshall^{17a}, S. Marti-Garcia¹⁶², T.A. Martin¹⁶⁶, V.J. Martin⁵², B. Martin dit Latour¹⁶, L. Martinelli^{74a,74b}, M. Martinez^{13,w}, P. Martinez Agullo¹⁶², V.I. Martinez Outschoorn¹⁰²,

P. Martinez Suarez ¹³, S. Martin-Haugh ¹³³, V.S. Martoiu ^{27b}, A.C. Martyniuk ⁹⁵, A. Marzin ³⁶, S.R. Maschek ¹⁰⁹, L. Masetti ⁹⁹, T. Mashimo ¹⁵², J. Masik ¹⁰⁰, A.L. Maslennikov ³⁷, L. Massa ^{23b}, P. Massarotti ^{71a,71b}, P. Mastrandrea ^{73a,73b}, A. Mastroberardino ^{43b,43a}, T. Masubuchi ¹⁵², T. Mathisen ¹⁶⁰, N. Matsuzawa ¹⁵², J. Maurer ^{27b}, B. Maček ⁹², D.A. Maximov ³⁷, R. Mazini ¹⁴⁷, I. Maznas ^{151f}, M. Mazza ¹⁰⁶, S.M. Mazza ¹³⁵, C. Mc Ginn ^{29,al}, J.P. Mc Gowan ¹⁰³, S.P. Mc Kee ¹⁰⁵, W.P. McCormack ^{17a}, E.F. McDonald ¹⁰⁴, A.E. McDougall ¹¹³, J.A. Mcfayden ¹⁴⁵, G. Mchedlidze ^{148b}, R.P. Mckenzie ^{33g}, T.C. McLachlan ⁴⁸, D.J. McLaughlin ⁹⁵, K.D. McLean ¹⁶⁴, S.J. McMahon ¹³³, P.C. McNamara ¹⁰⁴, C.M. Mcpartland ⁹¹, R.A. McPherson ^{164,y}, T. Megy ⁴⁰, S. Mehlhase ¹⁰⁸, A. Mehta ⁹¹, B. Meirose ⁴⁵, D. Melini ¹⁴⁹, B.R. Mellado Garcia ^{33g}, A.H. Melo ⁵⁵, F. Meloni ⁴⁸, E.D. Mendes Gouveia ^{129a}, A.M. Mendes Jacques Da Costa ²⁰, H.Y. Meng ¹⁵⁴, L. Meng ⁹⁰, S. Menke ¹⁰⁹, M. Mentink ³⁶, E. Meoni ^{43b,43a}, C. Merlassino ¹²⁵, L. Merola ^{71a,71b}, C. Meroni ^{70a}, G. Merz ¹⁰⁵, O. Meshkov ³⁷, J.K.R. Meshreki ¹⁴⁰, J. Metcalfe ⁶, A.S. Mete ⁶, C. Meyer ⁶⁷, J-P. Meyer ¹³⁴, M. Michetti ¹⁸, R.P. Middleton ¹³³, L. Mijović ⁵², G. Mikenberg ¹⁶⁸, M. Mikestikova ¹³⁰, M. Mikuz ⁹², H. Mildner ¹³⁸, A. Milic ³⁶, C.D. Milke ⁴⁴, D.W. Miller ³⁹, L.S. Miller ³⁴, A. Milov ¹⁶⁸, D.A. Milstead ^{47a,47b}, T. Min ^{14c}, A.A. Minaenko ³⁷, I.A. Minashvili ^{148b}, L. Mince ⁵⁹, A.I. Mincer ¹¹⁶, B. Mindur ^{84a}, M. Mineev ³⁸, Y. Mino ⁸⁶, L.M. Mir ¹³, M. Miralles Lopez ¹⁶², M. Mironova ¹²⁵, M.C. Missio ¹¹², T. Mitani ¹⁶⁷, A. Mitra ¹⁶⁶, V.A. Mitsou ¹⁶², O. Miu ¹⁵⁴, P.S. Miyagawa ⁹³, Y. Miyazaki ⁸⁸, A. Mizukami ⁸², J.U. Mjörnmark ⁹⁷, T. Mkrtchyan ^{63a}, T. Mlinarevic ⁹⁵, M. Mlynarikova ³⁶, T. Moa ^{47a,47b}, S. Mobius ⁵⁵, K. Mochizuki ¹⁰⁷, P. Moder ⁴⁸, P. Mogg ¹⁰⁸, A.F. Mohammed ^{14a,14d}, S. Mohapatra ⁴¹, G. Mokgatitwane ^{33g}, B. Mondal ¹⁴⁰, S. Mondal ¹³¹, K. Mönig ⁴⁸, E. Monnier ¹⁰¹, L. Monsonis Romero ¹⁶², J. Montejo Berlingen ³⁶, M. Montella ¹¹⁸, F. Monticelli ⁸⁹, N. Morange ⁶⁶, A.L. Moreira De Carvalho ^{129a}, M. Moreno Llácer ¹⁶², C. Moreno Martinez ⁵⁶, P. Morettini ^{57b}, S. Morgenstern ¹⁶⁶, M. Morii ⁶¹, M. Morinaga ¹⁵², A.K. Morley ³⁶, F. Morodei ^{74a,74b}, L. Morvaj ³⁶, P. Moschovakos ³⁶, B. Moser ³⁶, M. Mosidze ^{148b}, T. Moskalets ⁵⁴, P. Moskvitina ¹¹², J. Moss ^{31,p}, E.J.W. Moyse ¹⁰², O. Mtintsilana ^{33g}, S. Muanza ¹⁰¹, J. Mueller ¹²⁸, D. Muenstermann ⁹⁰, R. Müller ¹⁹, G.A. Mullier ¹⁶⁰, J.J. Mullin ¹²⁷, D.P. Mungo ¹⁵⁴, J.L. Munoz Martinez ¹³, D. Munoz Perez ¹⁶², F.J. Munoz Sanchez ¹⁰⁰, M. Murin ¹⁰⁰, W.J. Murray ^{166,133}, A. Murrone ^{70a,70b}, J.M. Muse ¹¹⁹, M. Muškinja ^{17a}, C. Mwewa ²⁹, A.G. Myagkov ^{37,a}, A.J. Myers ⁸, A.A. Myers ¹²⁸, G. Myers ⁶⁷, M. Myska ¹³¹, B.P. Nachman ^{17a}, O. Nackenhorst ⁴⁹, A. Nag ⁵⁰, K. Nagai ¹²⁵, K. Nagano ⁸², J.L. Nagle ^{29,al}, E. Nagy ¹⁰¹, A.M. Nairz ³⁶, Y. Nakahama ⁸², K. Nakamura ⁸², H. Nanjo ¹²³, R. Narayan ⁴⁴, E.A. Narayanan ¹¹¹, I. Naryshkin ³⁷, M. Naseri ³⁴, C. Nass ²⁴, G. Navarro ^{22a}, J. Navarro-Gonzalez ¹⁶², R. Nayak ¹⁵⁰, A. Nayaz ¹⁸, P.Y. Nechaeva ³⁷, F. Nechansky ⁴⁸, L. Nedic ¹²⁵, T.J. Neep ²⁰, A. Negri ^{72a,72b}, M. Negrini ^{23b}, C. Nellist ¹¹², C. Nelson ¹⁰³, K. Nelson ¹⁰⁵, S. Nemecek ¹³⁰, M. Nessi ^{36,i}, M.S. Neubauer ¹⁶¹, F. Neuhaus ⁹⁹, J. Neundorff ⁴⁸, R. Newhouse ¹⁶³, P.R. Newman ²⁰, C.W. Ng ¹²⁸, Y.S. Ng ¹⁸, Y.W.Y. Ng ⁴⁸, B. Ngair ^{35e}, H.D.N. Nguyen ¹⁰⁷, R.B. Nickerson ¹²⁵, R. Nicolaidou ¹³⁴, J. Nielsen ¹³⁵, M. Niemeyer ⁵⁵, N. Nikiforou ³⁶, V. Nikolaenko ^{37,a}, I. Nikolic-Audit ¹²⁶, K. Nikolopoulos ²⁰, P. Nilsson ²⁹, H.R. Nindhito ⁵⁶, A. Nisati ^{74a}, N. Nishu ², R. Nisius ¹⁰⁹, J-E. Nitschke ⁵⁰, E.K. Nkadimeng ^{33g}, S.J. Noacco Rosende ⁸⁹, T. Nobe ¹⁵², D.L. Noel ³², Y. Noguchi ⁸⁶, T. Nommensen ¹⁴⁶, M.A. Nomura ²⁹, M.B. Norfolk ¹³⁸, R.R.B. Norisam ⁹⁵, B.J. Norman ³⁴, J. Novak ⁹², T. Novak ⁴⁸, O. Novgorodova ⁵⁰, L. Novotny ¹³¹, R. Novotny ¹¹¹, L. Nozka ¹²¹, K. Ntekas ¹⁵⁹, N.M.J. Nunes De Moura Junior ^{81b}, E. Nurse ⁹⁵, F.G. Oakham ^{34,ai}, J. Ocariz ¹²⁶, A. Ochi ⁸³, I. Ochoa ^{129a}, S. Oerdek ¹⁶⁰, A. Ogrodnik ^{84a}, A. Oh ¹⁰⁰, C.C. Ohm ¹⁴³, H. Oide ⁸², R. Oishi ¹⁵², M.L. Ojeda ⁴⁸, Y. Okazaki ⁸⁶, M.W. O'Keefe ⁹¹, Y. Okumura ¹⁵², A. Olariu ^{27b}, L.F. Oleiro Seabra ^{129a}, S.A. Olivares Pino ^{136e}, D. Oliveira Damazio ²⁹, D. Oliveira Goncalves ^{81a}, J.L. Oliver ¹⁵⁹, M.J.R. Olsson ¹⁵⁹, A. Olszewski ⁸⁵, J. Olszowska ^{85,*}, Ö.O. Öncel ⁵⁴, D.C. O'Neil ¹⁴¹, A.P. O'Neill ¹⁹, A. Onofre ^{129a,129e}, P.U.E. Onyisi ¹¹, M.J. Oreglia ³⁹, G.E. Orellana ⁸⁹, D. Orestano ^{76a,76b}, N. Orlando ¹³, R.S. Orr ¹⁵⁴, V. O'Shea ⁵⁹, R. Ospanov ^{62a}, G. Otero y Garzon ³⁰, H. Otono ⁸⁸, P.S. Ott ^{63a}, G.J. Ottino ^{17a}, M. Ouchrif ^{35d}, J. Ouellette ^{29,al}, F. Ould-Saada ¹²⁴, M. Owen ⁵⁹, R.E. Owen ¹³³, K.Y. Oyulmaz ^{21a}, V.E. Ozcan ^{21a}, N. Ozturk ⁸, S. Ozturk ^{21d}, J. Pacalt ¹²¹, H.A. Pacey ³², K. Pachal ⁵¹, A. Pacheco Pages ¹³, C. Padilla Aranda ¹³, G. Padovano ^{74a,74b}, S. Pagan Griso ^{17a}, G. Palacino ⁶⁷, A. Palazzo ^{69a,69b}, S. Palestini ³⁶, M. Palka ^{84b}, J. Pan ¹⁷¹, T. Pan ^{64a}, D.K. Panchal ¹¹, C.E. Pandini ¹¹³, J.G. Panduro Vazquez ⁹⁴, H. Pang ^{14b}, P. Pani ⁴⁸, G. Panizzo ^{68a,68c}, L. Paolozzi ⁵⁶, C. Papadatos ¹⁰⁷, S. Parajuli ⁴⁴, A. Paramonov ⁶, C. Paraskevopoulos ¹⁰, D. Paredes Hernandez ^{64b}, T.H. Park ¹⁵⁴, M.A. Parker ³², F. Parodi ^{57b,57a}, E.W. Parrish ¹¹⁴, V.A. Parrish ⁵², J.A. Parsons ⁴¹, U. Parzefall ⁵⁴, B. Pascual Dias ¹⁰⁷, L. Pascual Dominguez ¹⁵⁰, V.R. Pascuzzi ^{17a}, F. Pasquali ¹¹³, E. Pasqualucci ^{74a}, S. Passaggio ^{57b}, F. Pastore ⁹⁴, P. Pasuwan ^{47a,47b}, P. Patel ⁸⁵, J.R. Pater ¹⁰⁰,

T. Pauly³⁶, J. Pearkes¹⁴², M. Pedersen¹²⁴, R. Pedro^{129a}, S.V. Peleganchuk³⁷, O. Penc³⁶, E.A. Pender⁵², C. Peng^{64b}, H. Peng^{62a}, K.E. Penski¹⁰⁸, M. Penzin³⁷, B.S. Peralva^{81d}, A.P. Pereira Peixoto⁶⁰, L. Pereira Sanchez^{47a,47b}, D.V. Perepelitsa^{29,ai}, E. Perez Codina^{155a}, M. Perganti¹⁰, L. Perini^{70a,70b,*}, H. Pernegger³⁶, S. Perrella³⁶, A. Perrevoort¹¹², O. Perrin⁴⁰, K. Peters⁴⁸, R.F.Y. Peters¹⁰⁰, B.A. Petersen³⁶, T.C. Petersen⁴², E. Petit¹⁰¹, V. Petousis¹³¹, C. Petridou^{151,f}, A. Petrukhin¹⁴⁰, M. Pettee^{17a}, N.E. Pettersson³⁶, A. Petukhov³⁷, K. Petukhova¹³², A. Peyaud¹³⁴, R. Pezoa^{136f}, L. Pezzotti³⁶, G. Pezzullo¹⁷¹, T.M. Pham¹⁶⁹, T. Pham¹⁰⁴, P.W. Phillips¹³³, M.W. Phipps¹⁶¹, G. Piacquadio¹⁴⁴, E. Pianori^{17a}, F. Piazza^{70a,70b}, R. Piegaia³⁰, D. Pietreanu^{27b}, A.D. Pilkington¹⁰⁰, M. Pinamonti^{68a,68c}, J.L. Pinfold², B.C. Pinheiro Pereira^{129a}, C. Pitman Donaldson⁹⁵, D.A. Pizzi³⁴, L. Pizzimento^{75a,75b}, A. Pizzini¹¹³, M.-A. Pleier²⁹, V. Plesanovs⁵⁴, V. Pleskot¹³², E. Plotnikova³⁸, G. Poddar⁴, R. Poettgen⁹⁷, L. Poggioli¹²⁶, I. Pogrebnyak¹⁰⁶, D. Pohl²⁴, I. Pokharel⁵⁵, S. Polacek¹³², G. Polesello^{72a}, A. Poley^{141,155a}, R. Polifka¹³¹, A. Polini^{23b}, C.S. Pollard¹²⁵, Z.B. Pollock¹¹⁸, V. Polychronakos²⁹, E. Pompa Pacchi^{74a,74b}, D. Ponomarenko³⁷, L. Pontecorvo³⁶, S. Popa^{27a}, G.A. Popeneciu^{27d}, D.M. Portillo Quintero^{155a}, S. Pospisil¹³¹, P. Postolache^{27c}, K. Potamianos¹²⁵, I.N. Potrap³⁸, C.J. Potter³², H. Potti¹, T. Poulsen⁴⁸, J. Poveda¹⁶², M.E. Pozo Astigarraga³⁶, A. Prades Ibanez¹⁶², M.M. Prapa⁴⁶, J. Pretel⁵⁴, D. Price¹⁰⁰, M. Primavera^{69a}, M.A. Principe Martin⁹⁸, R. Privara¹²¹, M.L. Proffitt¹³⁷, N. Proklova¹²⁷, K. Prokofiev^{64c}, G. Proto^{75a,75b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{84a}, J.E. Puddefoot¹³⁸, D. Pudzha³⁷, P. Puzo⁶⁶, D. Pyatiizbyantseva³⁷, J. Qian¹⁰⁵, D. Qichen¹⁰⁰, Y. Qin¹⁰⁰, T. Qiu⁹³, A. Quadt⁵⁵, M. Queitsch-Maitland¹⁰⁰, G. Quetant⁵⁶, G. Rabanal Bolanos⁶¹, D. Rafanoharana⁵⁴, F. Ragusa^{70a,70b}, J.L. Rainbolt³⁹, J.A. Raine⁵⁶, S. Rajagopalan²⁹, E. Ramakoti³⁷, K. Ran^{48,14d}, N.P. Rapheeha^{33g}, V. Raskina¹²⁶, D.F. Rassloff^{63a}, S. Rave⁹⁹, B. Ravina⁵⁵, I. Ravinovitch¹⁶⁸, M. Raymond³⁶, A.L. Read¹²⁴, N.P. Readioff¹³⁸, D.M. Rebuffi^{72a,72b}, G. Redlinger²⁹, K. Reeves⁴⁵, J.A. Reidelsturz¹⁷⁰, D. Reikher¹⁵⁰, A. Reiss⁹⁹, A. Rej¹⁴⁰, C. Rembser³⁶, A. Renardi⁴⁸, M. Renda^{27b}, M.B. Rendel¹⁰⁹, F. Renner⁴⁸, A.G. Rennie⁵⁹, S. Resconi^{70a}, M. Ressegotti^{57b,57a}, E.D. Resseguie^{17a}, S. Rettie³⁶, J.G. Reyes Rivera¹⁰⁶, B. Reynolds¹¹⁸, E. Reynolds^{17a}, M. Rezaei Estabragh¹⁷⁰, O.L. Rezanova³⁷, P. Reznicek¹³², E. Ricci^{77a,77b}, R. Richter¹⁰⁹, S. Richter^{47a,47b}, E. Richter-Was^{84b}, M. Ridel¹²⁶, P. Rieck¹¹⁶, P. Riedler³⁶, M. Rijssenbeek¹⁴⁴, A. Rimoldi^{72a,72b}, M. Rimoldi⁴⁸, L. Rinaldi^{23b,23a}, T.T. Rinn²⁹, M.P. Rinnagel¹⁰⁸, G. Ripellino¹⁴³, I. Riu¹³, P. Rivadeneira⁴⁸, J.C. Rivera Vergara¹⁶⁴, F. Rizatdinova¹²⁰, E. Rizvi⁹³, C. Rizzi⁵⁶, B.A. Roberts¹⁶⁶, B.R. Roberts^{17a}, S.H. Robertson^{103,y}, M. Robin⁴⁸, D. Robinson³², C.M. Robles Gajardo^{136f}, M. Robles Manzano⁹⁹, A. Robson⁵⁹, A. Rocchi^{75a,75b}, C. Roda^{73a,73b}, S. Rodriguez Bosca^{63a}, Y. Rodriguez Garcia^{22a}, A. Rodriguez Rodriguez⁵⁴, A.M. Rodríguez Vera^{155b}, S. Roe³⁶, J.T. Roemer¹⁵⁹, A.R. Roepe-Gier¹¹⁹, J. Roggel¹⁷⁰, O. Röhne¹²⁴, R.A. Rojas¹⁶⁴, B. Roland⁵⁴, C.P.A. Roland⁶⁷, J. Roloff²⁹, A. Romaniouk³⁷, E. Romano^{72a,72b}, M. Romano^{23b}, A.C. Romero Hernandez¹⁶¹, N. Rompotis⁹¹, L. Roos¹²⁶, S. Rosati^{74a}, B.J. Rosser³⁹, E. Rossi⁴, E. Rossi^{71a,71b}, L.P. Rossi^{57b}, L. Rossini⁴⁸, R. Rosten¹¹⁸, M. Rotaru^{27b}, B. Rottler⁵⁴, D. Rousseau⁶⁶, D. Rousso³², G. Rovelli^{72a,72b}, A. Roy¹⁶¹, A. Rozanov¹⁰¹, Y. Rozen¹⁴⁹, X. Ruan^{33g}, A. Rubio Jimenez¹⁶², A.J. Ruby⁹¹, V.H. Ruelas Rivera¹⁸, T.A. Ruggeri¹, F. Rühr⁵⁴, A. Ruiz-Martinez¹⁶², A. Rummler³⁶, Z. Rurikova⁵⁴, N.A. Rusakovitch³⁸, H.L. Russell¹⁶⁴, J.P. Rutherford⁷, K. Rybacki⁹⁰, M. Rybar¹³², E.B. Rye¹²⁴, A. Ryzhov³⁷, J.A. Sabater Iglesias⁵⁶, P. Sabatini¹⁶², L. Sabetta^{74a,74b}, H.F-W. Sadrozinski¹³⁵, F. Safai Tehrani^{74a}, B. Safarzadeh Samani¹⁴⁵, M. Safdari¹⁴², S. Saha¹⁰³, M. Sahinsoy¹⁰⁹, M. Saimpert¹³⁴, M. Saito¹⁵², T. Saito¹⁵², D. Salamani³⁶, G. Salamanna^{76a,76b}, A. Salnikov¹⁴², J. Salt¹⁶², A. Salvador Salas¹³, D. Salvatore^{43b,43a}, F. Salvatore¹⁴⁵, A. Salzburger³⁶, D. Sammel⁵⁴, D. Sampsonidis^{151,f}, D. Sampsonidou^{62d,62c}, J. Sánchez¹⁶², A. Sanchez Pineda⁴, V. Sanchez Sebastian¹⁶², H. Sandaker¹²⁴, C.O. Sander⁴⁸, J.A. Sandesara¹⁰², M. Sandhoff¹⁷⁰, C. Sandoval^{22b}, D.P.C. Sankey¹³³, A. Sansoni⁵³, L. Santi^{74a,74b}, C. Santoni⁴⁰, H. Santos^{129a,129b}, S.N. Santpur^{17a}, A. Santra¹⁶⁸, K.A. Saoucha¹³⁸, J.G. Saraiva^{129a,129d}, J. Sardain⁷, O. Sasaki⁸², K. Sato¹⁵⁶, C. Sauer^{63b}, F. Sauerburger⁵⁴, E. Sauvan⁴, P. Savard^{154,ai}, R. Sawada¹⁵², C. Sawyer¹³³, L. Sawyer⁹⁶, I. Sayago Galvan¹⁶², C. Sbarra^{23b}, A. Sbrizzi^{23b,23a}, T. Scanlon⁹⁵, J. Schaarschmidt¹³⁷, P. Schacht¹⁰⁹, D. Schaefer³⁹, U. Schäfer⁹⁹, A.C. Schaffer⁶⁶, D. Schaile¹⁰⁸, R.D. Schamberger¹⁴⁴, E. Schanet¹⁰⁸, C. Scharf¹⁸, M.M. Schefer¹⁹, V.A. Schegelsky³⁷, D. Scheirich¹³², F. Schenck¹⁸, M. Schernau¹⁵⁹, C. Scheulen⁵⁵, C. Schiavi^{57b,57a}, Z.M. Schillaci²⁶, E.J. Schioppa^{69a,69b}, M. Schioppa^{43b,43a}, B. Schlag⁹⁹, K.E. Schleicher⁵⁴, S. Schlenker³⁶, J. Schmeing¹⁷⁰, M.A. Schmidt¹⁷⁰, K. Schmieden⁹⁹, C. Schmitt⁹⁹, S. Schmitt⁴⁸, L. Schoeffel¹³⁴, A. Schoening^{63b}, P.G. Scholer⁵⁴, E. Schopf¹²⁵, M. Schott⁹⁹, J. Schovancova³⁶, S. Schramm⁵⁶,

F. Schroeder¹⁷⁰, H.-C. Schultz-Coulon^{63a}, M. Schumacher⁵⁴, B.A. Schumm¹³⁵, Ph. Schune¹³⁴, A. Schwartzman¹⁴², T.A. Schwarz¹⁰⁵, Ph. Schwemling¹³⁴, R. Schwienhorst¹⁰⁶, A. Sciandra¹³⁵, G. Sciolla²⁶, F. Scuri^{73a}, F. Scutti¹⁰⁴, C.D. Sebastiani⁹¹, K. Sedlaczek⁴⁹, P. Seema¹⁸, S.C. Seidel¹¹¹, A. Seiden¹³⁵, B.D. Seidlitz⁴¹, T. Seiss³⁹, C. Seitz⁴⁸, J.M. Seixas^{81b}, G. Sekhniaidze^{71a}, S.J. Sekula⁴⁴, L. Selem⁴, N. Semprini-Cesari^{23b,23a}, S. Sen⁵¹, D. Sengupta⁵⁶, V. Senthilkumar¹⁶², L. Serin⁶⁶, L. Serkin^{68a,68b}, M. Sessa^{76a,76b}, H. Severini¹¹⁹, S. Sevova¹⁴², F. Sforza^{57b,57a}, A. Sfyrila⁵⁶, E. Shabalina⁵⁵, R. Shaheen¹⁴³, J.D. Shahinian¹²⁷, D. Shaked Renous¹⁶⁸, L.Y. Shan^{14a}, M. Shapiro^{17a}, A. Sharma³⁶, A.S. Sharma¹⁶³, P. Sharma⁷⁹, S. Sharma⁴⁸, P.B. Shatalov³⁷, K. Shaw¹⁴⁵, S.M. Shaw¹⁰⁰, Q. Shen^{62c,5}, P. Sherwood⁹⁵, L. Shi⁹⁵, C.O. Shimmin¹⁷¹, Y. Shimogama¹⁶⁷, J.D. Shinner⁹⁴, I.P.J. Shipsey¹²⁵, S. Shirabe⁶⁰, M. Shiyakova³⁸, J. Shlomi¹⁶⁸, M.J. Shochet³⁹, J. Shojaii¹⁰⁴, D.R. Shope¹²⁴, S. Shrestha^{118,am}, E.M. Shrif^{33g}, M.J. Shroff¹⁶⁴, P. Sicho¹³⁰, A.M. Sickles¹⁶¹, E. Sideras Haddad^{33g}, A. Sidoti^{23b}, F. Siegert⁵⁰, Dj. Sijacki¹⁵, R. Sikora^{84a}, F. Sili⁸⁹, J.M. Silva²⁰, M.V. Silva Oliveira³⁶, S.B. Silverstein^{47a}, S. Simion⁶⁶, R. Simoniello³⁶, E.L. Simpson⁵⁹, N.D. Simpson⁹⁷, S. Simsek^{21d}, S. Sindhu⁵⁵, P. Sinervo¹⁵⁴, V. Sinetckii³⁷, S. Singh¹⁴¹, S. Singh¹⁵⁴, S. Sinha⁴⁸, S. Sinha^{33g}, M. Sioli^{23b,23a}, I. Siral³⁶, S.Yu. Sivoklokov^{37,*}, J. Sjölin^{47a,47b}, A. Skaf⁵⁵, E. Skorda⁹⁷, P. Skubic¹¹⁹, M. Slawinska⁸⁵, V. Smakhtin¹⁶⁸, B.H. Smart¹³³, J. Smiesko³⁶, S.Yu. Smirnov³⁷, Y. Smirnov³⁷, L.N. Smirnova^{37,a}, O. Smirnova⁹⁷, A.C. Smith⁴¹, E.A. Smith³⁹, H.A. Smith¹²⁵, J.L. Smith⁹¹, R. Smith¹⁴², M. Smizanska⁹⁰, K. Smolek¹³¹, A. Smykiewicz⁸⁵, A.A. Snesarev³⁷, H.L. Snoek¹¹³, S. Snyder²⁹, R. Sobie^{164,y}, A. Soffer¹⁵⁰, C.A. Solans Sanchez³⁶, E.Yu. Soldatov³⁷, U. Soldevila¹⁶², A.A. Solodkov³⁷, S. Solomon⁵⁴, A. Soloshenko³⁸, K. Solovieva⁵⁴, O.V. Solovyanov³⁷, V. Solovyev³⁷, P. Sommer³⁶, A. Sonay¹³, W.Y. Song^{155b}, A. Sopczak¹³¹, A.L. Sopio⁹⁵, F. Sopkova^{28b}, V. Sothilingam^{63a}, S. Sottocornola^{72a,72b}, R. Soualah^{115b}, Z. Soumami^{35e}, D. South⁴⁸, S. Spagnolo^{69a,69b}, M. Spalla¹⁰⁹, F. Spanò⁹⁴, D. Sperlich⁵⁴, G. Spigo³⁶, M. Spina¹⁴⁵, S. Spinali⁹⁰, D.P. Spiteri⁵⁹, M. Spousta¹³², E.J. Staats³⁴, A. Stabile^{70a,70b}, R. Stamen^{63a}, M. Stamenkovic¹¹³, A. Stampekis²⁰, M. Standke²⁴, E. Stanecka⁸⁵, M.V. Stange⁵⁰, B. Stanislaus^{17a}, M.M. Stanitzki⁴⁸, M. Stankaityte¹²⁵, B. Stapf⁴⁸, E.A. Starchenko³⁷, G.H. Stark¹³⁵, J. Stark^{101,ac}, D.M. Starko^{155b}, P. Staroba¹³⁰, P. Starovoitov^{63a}, S. Stärz¹⁰³, R. Staszewski⁸⁵, G. Stavropoulos⁴⁶, J. Steentoft¹⁶⁰, P. Steinberg²⁹, A.L. Steinhebel¹²², B. Stelzer^{141,155a}, H.J. Stelzer¹²⁸, O. Stelzer-Chilton^{155a}, H. Stenzel⁵⁸, T.J. Stevenson¹⁴⁵, G.A. Stewart³⁶, M.C. Stockton³⁶, G. Stoica^{27b}, M. Stolarski^{129a}, S. Stonjek¹⁰⁹, A. Straessner⁵⁰, J. Strandberg¹⁴³, S. Strandberg^{47a,47b}, M. Strauss¹¹⁹, T. Strebler¹⁰¹, P. Strizenec^{28b}, R. Ströhmer¹⁶⁵, D.M. Strom¹²², L.R. Strom⁴⁸, R. Stroynowski⁴⁴, A. Strubig^{47a,47b}, S.A. Stucci²⁹, B. Stugu¹⁶, J. Stupak¹¹⁹, N.A. Styles⁴⁸, D. Su¹⁴², S. Su^{62a}, W. Su^{62d,137,62c}, X. Su^{62a,66}, K. Sugizaki¹⁵², V.V. Sulin³⁷, M.J. Sullivan⁹¹, D.M.S. Sultan^{77a,77b}, L. Sultanaliyeva³⁷, S. Sultansoy^{3b}, T. Sumida⁸⁶, S. Sun¹⁰⁵, S. Sun¹⁶⁹, O. Sunneborn Gudnadottir¹⁶⁰, M.R. Sutton¹⁴⁵, M. Svatos¹³⁰, M. Swiatlowski^{155a}, T. Swirski¹⁶⁵, I. Sykora^{28a}, M. Sykora¹³², T. Sykora¹³², D. Ta⁹⁹, K. Tackmann^{48,x}, A. Taffard¹⁵⁹, R. Tafrout^{155a}, J.S. Tafoya Vargas⁶⁶, R.H.M. Taibah¹²⁶, R. Takashima⁸⁷, K. Takeda⁸³, E.P. Takeva⁵², Y. Takubo⁸², M. Talby¹⁰¹, A.A. Talyshv³⁷, K.C. Tam^{64b}, N.M. Tamir¹⁵⁰, A. Tanaka¹⁵², J. Tanaka¹⁵², R. Tanaka⁶⁶, M. Tanasini^{57b,57a}, J. Tang^{62c}, Z. Tao¹⁶³, S. Tapia Araya⁸⁰, S. Tapprogge⁹⁹, A. Tarek Abouelfadl Mohamed¹⁰⁶, S. Tarem¹⁴⁹, K. Tariq^{62b}, G. Tarna^{101,27b}, G.F. Tartarelli^{70a}, P. Tas¹³², M. Tasevsky¹³⁰, E. Tassi^{43b,43a}, A.C. Tate¹⁶¹, G. Tateno¹⁵², Y. Tayalati^{35e}, G.N. Taylor¹⁰⁴, W. Taylor^{155b}, H. Teagle⁹¹, A.S. Tee¹⁶⁹, R. Teixeira De Lima¹⁴², P. Teixeira-Dias⁹⁴, J.J. Teoh¹⁵⁴, K. Terashi¹⁵², J. Terron⁹⁸, S. Terzo¹³, M. Testa⁵³, R.J. Teuscher^{154,y}, A. Thaler⁷⁸, O. Theiner⁵⁶, N. Themistokleous⁵², T. Theveneaux-Pelzer¹⁸, O. Thielmann¹⁷⁰, D.W. Thomas⁹⁴, J.P. Thomas²⁰, E.A. Thompson⁴⁸, P.D. Thompson²⁰, E. Thomson¹²⁷, E.J. Thorpe⁹³, Y. Tian⁵⁵, V. Tikhomirov^{37,a}, Yu.A. Tikhonov³⁷, S. Timoshenko³⁷, E.X.L. Ting¹, P. Tipton¹⁷¹, S. Tisserant¹⁰¹, S.H. Tlou^{33g}, A. Tnourji⁴⁰, K. Todome^{23b,23a}, S. Todorova-Nova¹³², S. Todt⁵⁰, M. Togawa⁸², J. Tojo⁸⁸, S. Tokár^{28a}, K. Tokushuku⁸², R. Tombs³², M. Tomoto^{82,110}, L. Tompkins^{142,r}, K.W. Topolnicki^{84b}, P. Tornambe¹⁰², E. Torrence¹²², H. Torres⁵⁰, E. Torró Pastor¹⁶², M. Toscani³⁰, C. Toscirci³⁹, M. Tost¹¹, D.R. Tovey¹³⁸, A. Traeet¹⁶, I.S. Trandafir^{27b}, T. Trefzger¹⁶⁵, A. Tricoli²⁹, I.M. Trigger^{155a}, S. Trincas-Duvold¹²⁶, D.A. Trischuk²⁶, B. Trocmé⁶⁰, A. Trofymov⁶⁶, C. Troncon^{70a}, L. Truong^{33c}, M. Trzebinski⁸⁵, A. Trzupek⁸⁵, F. Tsai¹⁴⁴, M. Tsai¹⁰⁵, A. Tsiamis^{151,f}, P.V. Tsiareshka³⁷, S. Tsigaridas^{155a}, A. Tsirigotis^{151,v}, V. Tsiskaridze¹⁴⁴, E.G. Tskhadadze^{148a}, M. Tsopoulou^{151,f}, Y. Tsujikawa⁸⁶, I.I. Tsukerman³⁷, V. Tsulaia^{17a}, S. Tsuno⁸², O. Tsur¹⁴⁹, D. Tsybychev¹⁴⁴, Y. Tu^{64b}, A. Tudorache^{27b}, V. Tudorache^{27b}, A.N. Tuna³⁶, S. Turchikhin³⁸, I. Turk Cakir^{3a}, R. Turra^{70a}, T. Turtuvshin^{38,z}, P.M. Tuts⁴¹, S. Tzamarias^{151,f}, P. Tzanis¹⁰, E. Tzovara⁹⁹,

K. Uchida¹⁵², F. Ukegawa¹⁵⁶, P.A. Ulloa Poblete^{136c}, E.N. Umaka⁸⁰, G. Unal³⁶, M. Unal¹¹, A. Undrus²⁹, G. Unel¹⁵⁹, J. Urban^{28b}, P. Urquijo¹⁰⁴, G. Usai⁸, R. Ushioda¹⁵³, M. Usman¹⁰⁷, Z. Uysal^{21b}, L. Vacavant¹⁰¹, V. Vacek¹³¹, B. Vachon¹⁰³, K.O.H. Vadla¹²⁴, T. Vafeiadis³⁶, A. Vaitkus⁹⁵, C. Valderanis¹⁰⁸, E. Valdes Santurio^{47a,47b}, M. Valente^{155a}, S. Valentinetti^{23b,23a}, A. Valero¹⁶², A. Vallier^{101,ac}, J.A. Valls Ferrer¹⁶², T.R. Van Daalen¹³⁷, P. Van Gemmeren⁶, M. Van Rijnbach^{124,36}, S. Van Stroud⁹⁵, I. Van Vulpen¹¹³, M. Vanadia^{75a,75b}, W. Vandelli³⁶, M. Vandenbroucke¹³⁴, E.R. Vandewall¹²⁰, D. Vannicola¹⁵⁰, L. Vannoli^{57b,57a}, R. Vari^{74a}, E.W. Varnes⁷, C. Varni^{17a}, T. Varol¹⁴⁷, D. Varouchas⁶⁶, L. Varriale¹⁶², K.E. Varvell¹⁴⁶, M.E. Vasile^{27b}, L. Vaslin⁴⁰, G.A. Vasquez¹⁶⁴, F. Vazeille⁴⁰, T. Vazquez Schroeder³⁶, J. Veatch³¹, V. Vecchio¹⁰⁰, M.J. Veen¹⁰², I. Veliscek¹²⁵, L.M. Veloce¹⁵⁴, F. Veloso^{129a,129c}, S. Veneziano^{74a}, A. Ventura^{69a,69b}, A. Verbytskyi¹⁰⁹, M. Verducci^{73a,73b}, C. Vergis²⁴, M. Verissimo De Araujo^{81b}, W. Verkerke¹¹³, J.C. Vermeulen¹¹³, C. Vernieri¹⁴², P.J. Verschuuren⁹⁴, M. Vessella¹⁰², M.C. Vetterli^{141,ai}, A. Vgenopoulos^{151,f}, N. Viaux Maira^{136f}, T. Vickey¹³⁸, O.E. Vickey Boeriu¹³⁸, G.H.A. Viehhauser¹²⁵, L. Vigani^{63b}, M. Villa^{23b,23a}, M. Villaplana Perez¹⁶², E.M. Villhauer⁵², E. Vilucchi⁵³, M.G. Vincker³⁴, G.S. Virdee²⁰, A. Vishwakarma⁵², C. Vittori^{23b,23a}, I. Vivarelli¹⁴⁵, V. Vladimirov¹⁶⁶, E. Voevodina¹⁰⁹, F. Vogel¹⁰⁸, P. Vokac¹³¹, J. Von Ahnen⁴⁸, E. Von Toerne²⁴, B. Vormwald³⁶, V. Vorobel¹³², K. Vorobev³⁷, M. Vos¹⁶², J.H. Vosseveld⁹¹, M. Vozak¹¹³, L. Vozdecky⁹³, N. Vranjes¹⁵, M. Vranjes Milosavljevic¹⁵, M. Vreeswijk¹¹³, R. Vuillermet³⁶, O. Vujanovic⁹⁹, I. Vukotic³⁹, S. Wada¹⁵⁶, C. Wagner¹⁰², W. Wagner¹⁷⁰, S. Wahdan¹⁷⁰, H. Wahlberg⁸⁹, R. Wakasa¹⁵⁶, M. Wakida¹¹⁰, V.M. Walbrecht¹⁰⁹, J. Walder¹³³, R. Walker¹⁰⁸, W. Walkowiak¹⁴⁰, A.M. Wang⁶¹, A.Z. Wang¹⁶⁹, C. Wang^{62a}, C. Wang^{62c}, H. Wang^{17a}, J. Wang^{64a}, R.-J. Wang⁹⁹, R. Wang⁶¹, R. Wang⁶, S.M. Wang¹⁴⁷, S. Wang^{62b}, T. Wang^{62a}, W.T. Wang⁷⁹, X. Wang^{14c}, X. Wang¹⁶¹, X. Wang^{62c}, Y. Wang^{62d}, Y. Wang^{14c}, Z. Wang¹⁰⁵, Z. Wang^{62d,51,62c}, Z. Wang¹⁰⁵, A. Warburton¹⁰³, R.J. Ward²⁰, N. Warrack⁵⁹, A.T. Watson²⁰, H. Watson⁵⁹, M.F. Watson²⁰, G. Watts¹³⁷, B.M. Waugh⁹⁵, A.F. Webb¹¹, C. Weber²⁹, H.A. Weber¹⁸, M.S. Weber¹⁹, S.M. Weber^{63a}, C. Wei^{62a}, Y. Wei¹²⁵, A.R. Weidberg¹²⁵, J. Weingarten⁴⁹, M. Weirich⁹⁹, C. Weiser⁵⁴, C.J. Wells⁴⁸, T. Wenaus²⁹, B. Wendland⁴⁹, T. Wengler³⁶, N.S. Wenke¹⁰⁹, N. Wermes²⁴, M. Wessels^{63a}, K. Whalen¹²², A.M. Wharton⁹⁰, A.S. White⁶¹, A. White⁸, M.J. White¹, D. Whiteson¹⁵⁹, L. Wickremasinghe¹²³, W. Wiedenmann¹⁶⁹, C. Wiel⁵⁰, M. Wielers¹³³, N. Wieseotte⁹⁹, C. Wiglesworth⁴², L.A.M. Wiik-Fuchs⁵⁴, D.J. Wilbern¹¹⁹, H.G. Wilkens³⁶, D.M. Williams⁴¹, H.H. Williams¹²⁷, S. Williams³², S. Willocq¹⁰², P.J. Windischhofer¹²⁵, F. Winklmeier¹²², B.T. Winter⁵⁴, J.K. Winter¹⁰⁰, M. Wittgen¹⁴², M. Wobisch⁹⁶, R. Wölker¹²⁵, J. Wollrath¹⁵⁹, M.W. Wolter⁸⁵, H. Wolters^{129a,129c}, V.W.S. Wong¹⁶³, A.F. Wongel⁴⁸, S.D. Worm⁴⁸, B.K. Wosiek⁸⁵, K.W. Woźniak⁸⁵, K. Wraight⁵⁹, J. Wu^{14a,14d}, M. Wu^{64a}, M. Wu¹¹², S.L. Wu¹⁶⁹, X. Wu⁵⁶, Y. Wu^{62a}, Z. Wu^{134,62a}, J. Wuerzinger¹²⁵, T.R. Wyatt¹⁰⁰, B.M. Wynne⁵², S. Xella⁴², L. Xia^{14c}, M. Xia^{14b}, J. Xiang^{64c}, X. Xiao¹⁰⁵, M. Xie^{62a}, X. Xie^{62a}, S. Xin^{14a,14d}, J. Xiong^{17a}, I. Xiotidis¹⁴⁵, D. Xu^{14a}, H. Xu^{62a}, H. Xu^{62a}, L. Xu^{62a}, R. Xu¹²⁷, T. Xu¹⁰⁵, W. Xu¹⁰⁵, Y. Xu^{14b}, Z. Xu^{62b}, Z. Xu^{14a}, B. Yabsley¹⁴⁶, S. Yacoub^{33a}, N. Yamaguchi⁸⁸, Y. Yamaguchi¹⁵³, H. Yamauchi¹⁵⁶, T. Yamazaki^{17a}, Y. Yamazaki⁸³, J. Yan^{62c}, S. Yan¹²⁵, Z. Yan²⁵, H.J. Yang^{62c,62d}, H.T. Yang^{62a}, S. Yang^{62a}, T. Yang^{64c}, X. Yang^{62a}, X. Yang^{14a}, Y. Yang⁴⁴, Z. Yang^{62a,105}, W.-M. Yao^{17a}, Y.C. Yap⁴⁸, H. Ye^{14c}, H. Ye⁵⁵, J. Ye⁴⁴, S. Ye²⁹, X. Ye^{62a}, Y. Yeh⁹⁵, I. Yeletsikh³⁸, B.K. Yeo^{17a}, M.R. Yexley⁹⁰, P. Yin⁴¹, K. Yorita¹⁶⁷, S. Younas^{27b}, C.J.S. Young⁵⁴, C. Young¹⁴², M. Yuan¹⁰⁵, R. Yuan^{62b,l}, L. Yue⁹⁵, X. Yue^{63a}, M. Zaazoua^{35e}, B. Zabinski⁸⁵, E. Zaid⁵², T. Zakareishvili^{148b}, N. Zakharchuk³⁴, S. Zambito⁵⁶, J.A. Zamora Saa^{136d,136b}, J. Zang¹⁵², D. Zanzi⁵⁴, O. Zaplatilek¹³¹, S.V. Zeiβner⁴⁹, C. Zeitnitz¹⁷⁰, J.C. Zeng¹⁶¹, D.T. Zenger Jr²⁶, O. Zenin³⁷, T. Ženiš^{28a}, S. Zenz⁹³, S. Zerradi^{35a}, D. Zerwas⁶⁶, B. Zhang^{14c}, D.F. Zhang¹³⁸, G. Zhang^{14b}, J. Zhang^{62b}, J. Zhang⁶, K. Zhang^{14a,14d}, L. Zhang^{14c}, P. Zhang^{14a,14d}, R. Zhang¹⁶⁹, S. Zhang¹⁰⁵, T. Zhang¹⁵², X. Zhang^{62c}, X. Zhang^{62b}, Y. Zhang^{62c,5}, Z. Zhang^{17a}, Z. Zhang⁶⁶, H. Zhao¹³⁷, P. Zhao⁵¹, T. Zhao^{62b}, Y. Zhao¹³⁵, Z. Zhao^{62a}, A. Zhemchugov³⁸, X. Zheng^{62a}, Z. Zheng¹⁴², D. Zhong¹⁶¹, B. Zhou¹⁰⁵, C. Zhou¹⁶⁹, H. Zhou⁷, N. Zhou^{62c}, Y. Zhou⁷, C.G. Zhu^{62b}, C. Zhu^{14a,14d}, H.L. Zhu^{62a}, H. Zhu^{14a}, J. Zhu¹⁰⁵, Y. Zhu^{62c}, Y. Zhu^{62a}, X. Zhuang^{14a}, K. Zhukov³⁷, V. Zhulanov³⁷, N.I. Zimine³⁸, J. Zinsser^{63b}, M. Ziolkowski¹⁴⁰, L. Živković¹⁵, A. Zoccoli^{23b,23a}, K. Zoch⁵⁶, T.G. Zorbass¹³⁸, O. Zormpa⁴⁶, W. Zou⁴¹, L. Zwalinski³⁶

¹ Department of Physics, University of Adelaide, Adelaide; Australia² Department of Physics, University of Alberta, Edmonton AB; Canada³ (a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye⁴ LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France

- ⁵ APC, Université Paris Cité, CNRS/IN2P3, Paris; 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 Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
- ¹³ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain
- ¹⁴ ^(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
- ¹⁵ Institute of Physics, University of Belgrade, Belgrade; Serbia
- ¹⁶ Department for Physics and Technology, University of Bergen, Bergen; Norway
- ¹⁷ ^(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; ^(b) University of California, Berkeley CA; United States of America
- ¹⁸ Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
- ¹⁹ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
- ²⁰ School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
- ²¹ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(c) Department of Physics, Istanbul University, Istanbul; ^(d) Istinye University, Sariyer, Istanbul; Türkiye
- ²² ^(a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; ^(b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
- ²³ ^(a) Dipartimento di Fisica e Astronomia A. Righi, 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; ^(g) Faculty of Physics, University of Bucharest, Bucharest; 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 Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
- ³¹ California State University, CA; United States of America
- ³² Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- ³³ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) iThemba Labs, Western Cape; ^(c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; ^(d) National Institute of Physics, University of the Philippines Diliman (Philippines); ^(e) University of South Africa, Department of Physics, Pretoria; ^(f) University of Zululand, KwaDlangezwa; ^(g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- ³⁴ Department of Physics, Carleton University, Ottawa ON; Canada
- ³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat; ^(f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
- ³⁶ CERN, Geneva; Switzerland
- ³⁷ Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁸ Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ³⁹ Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- ⁴⁰ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- ⁴¹ Nevis Laboratory, Columbia University, Irvington NY; United States of America
- ⁴² Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- ⁴³ ^(a) Dipartimento di Fisica, Università della Calabria, Rende; ^(b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- ⁴⁴ Physics Department, Southern Methodist University, Dallas TX; United States of America
- ⁴⁵ Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- ⁴⁶ National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
- ⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) Oskar Klein Centre, Stockholm; Sweden
- ⁴⁸ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- ⁴⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- ⁵⁰ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- ⁵¹ Department of Physics, Duke University, Durham NC; United States of America
- ⁵² SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
- ⁵³ INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- ⁵⁴ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- ⁵⁵ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- ⁵⁶ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- ⁵⁷ ^(a) Dipartimento di Fisica, Università di Genova, Genova; ^(b) INFN Sezione di Genova; Italy
- ⁵⁸ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- ⁵⁹ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- ⁶⁰ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- ⁶¹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- ⁶² ^(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, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; ^(d) Tsung-Dao Lee Institute, Shanghai; China
- ⁶³ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- ⁶⁴ ^(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
- ⁶⁵ Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- ⁶⁶ IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- ⁶⁷ Department of Physics, Indiana University, Bloomington IN; United States of America
- ⁶⁸ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- ⁶⁹ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- ⁷⁰ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano; Italy
- ⁷¹ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- ⁷² ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy

- 73 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
 74 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
 75 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
 76 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
 77 (a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento; Italy
 78 Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
 79 University of Iowa, Iowa City IA; United States of America
 80 Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
 81 (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) Instituto de Física, Universidade de São Paulo, São Paulo; (d) Rio de Janeiro State University, Rio de Janeiro; Brazil
 82 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
 83 Graduate School of Science, Kobe University, Kobe; Japan
 84 (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
 85 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
 86 Faculty of Science, Kyoto University, Kyoto; Japan
 87 Kyoto University of Education, Kyoto; Japan
 88 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
 89 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
 90 Physics Department, Lancaster University, Lancaster; United Kingdom
 91 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
 92 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
 93 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
 94 Department of Physics, Royal Holloway University of London, Egham; United Kingdom
 95 Department of Physics and Astronomy, University College London, London; United Kingdom
 96 Louisiana Tech University, Ruston LA; United States of America
 97 Fysiska institutionen, Lunds universitet, Lund; Sweden
 98 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
 99 Institut für Physik, Universität Mainz, Mainz; Germany
 100 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
 101 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
 102 Department of Physics, University of Massachusetts, Amherst MA; United States of America
 103 Department of Physics, McGill University, Montreal QC; Canada
 104 School of Physics, University of Melbourne, Victoria; Australia
 105 Department of Physics, University of Michigan, Ann Arbor MI; United States of America
 106 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
 107 Group of Particle Physics, University of Montreal, Montreal QC; Canada
 108 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
 109 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
 110 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
 111 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
 112 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
 113 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
 114 Department of Physics, Northern Illinois University, DeKalb IL; United States of America
 115 (a) New York University Abu Dhabi, Abu Dhabi; (b) University of Sharjah, Sharjah; United Arab Emirates
 116 Department of Physics, New York University, New York NY; United States of America
 117 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
 118 Ohio State University, Columbus OH; United States of America
 119 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
 120 Department of Physics, Oklahoma State University, Stillwater OK; United States of America
 121 Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
 122 Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
 123 Graduate School of Science, Osaka University, Osaka; Japan
 124 Department of Physics, University of Oslo, Oslo; Norway
 125 Department of Physics, Oxford University, Oxford; United Kingdom
 126 LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
 127 Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
 128 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
 129 (a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (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) Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
 130 Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
 131 Czech Technical University in Prague, Prague; Czech Republic
 132 Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
 133 Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
 134 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
 135 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
 136 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; (c) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; (d) Universidad Andres Bello, Department of Physics, Santiago; (e) Instituto de Alta Investigación, Universidad de Tarapacá, Arica; (f) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
 137 Department of Physics, University of Washington, Seattle WA; United States of America
 138 Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
 139 Department of Physics, Shinshu University, Nagano; Japan
 140 Department Physik, Universität Siegen, Siegen; Germany
 141 Department of Physics, Simon Fraser University, Burnaby BC; Canada
 142 SLAC National Accelerator Laboratory, Stanford CA; United States of America
 143 Department of Physics, Royal Institute of Technology, Stockholm; Sweden
 144 Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
 145 Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
 146 School of Physics, University of Sydney, Sydney; Australia

- ¹⁴⁷ Institute of Physics, Academia Sinica, Taipei; Taiwan
- ¹⁴⁸ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi; ^(c) University of Georgia, Tbilisi; Georgia
- ¹⁴⁹ Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
- ¹⁵⁰ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
- ¹⁵¹ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
- ¹⁵² International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
- ¹⁵³ Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
- ¹⁵⁴ Department of Physics, University of Toronto, Toronto ON; Canada
- ¹⁵⁵ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON; Canada
- ¹⁵⁶ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
- ¹⁵⁷ Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
- ¹⁵⁸ United Arab Emirates University, Al Ain; United Arab Emirates
- ¹⁵⁹ Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
- ¹⁶⁰ Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
- ¹⁶¹ Department of Physics, University of Illinois, Urbana IL; United States of America
- ¹⁶² Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain
- ¹⁶³ Department of Physics, University of British Columbia, Vancouver BC; Canada
- ¹⁶⁴ Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
- ¹⁶⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
- ¹⁶⁶ Department of Physics, University of Warwick, Coventry; United Kingdom
- ¹⁶⁷ Waseda University, Tokyo; Japan
- ¹⁶⁸ Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
- ¹⁶⁹ Department of Physics, University of Wisconsin, Madison WI; United States of America
- ¹⁷⁰ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
- ¹⁷¹ Department of Physics, Yale University, New Haven CT; United States of America
- ^a Also Affiliated with an institute covered by a cooperation agreement with CERN.
- ^b Also at An-Najah National University, Nablus; Palestine.
- ^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
- ^d Also at Bruno Kessler Foundation, Trento; Italy.
- ^e Also at Center for High Energy Physics, Peking University; China.
- ^f Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
- ^g Also at Centro Studi e Ricerche Enrico Fermi; Italy.
- ^h Also at CERN, Geneva; Switzerland.
- ⁱ Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^j Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ^k Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^l Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ^m Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
- ⁿ Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
- ^o Also at Department of Physics, California State University, East Bay; United States of America.
- ^p Also at Department of Physics, California State University, Sacramento; United States of America.
- ^q Also at Department of Physics, King's College London, London; United Kingdom.
- ^r Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ^s Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^t Also at Department of Physics, University of Thessaly; Greece.
- ^u Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^v Also at Hellenic Open University, Patras; Greece.
- ^w Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^x Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^y Also at Institute of Particle Physics (IPP); Canada.
- ^z Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
- ^{aa} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{ab} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ac} Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ^{ad} Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
- ^{ae} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{af} Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen; Germany.
- ^{ag} Also at Technical University of Munich, Munich; Germany.
- ^{ah} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{ai} Also at TRIUMF, Vancouver BC; Canada.
- ^{aj} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{ak} Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
- ^{al} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{am} Also at Washington College, Maryland; United States of America.
- ^{an} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased.