



Measurement of the top quark mass in the $t\bar{t} \rightarrow$ dilepton channel from $\sqrt{s} = 8$ TeV ATLAS data



The ATLAS Collaboration*

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ABSTRACT

The top quark mass is measured in the $t\bar{t} \rightarrow$ dilepton channel (lepton = e, μ) using ATLAS data recorded in the year 2012 at the LHC. The data were taken at a proton–proton centre-of-mass energy of $\sqrt{s} = 8$ TeV and correspond to an integrated luminosity of about 20.2 fb^{-1} . Exploiting the template method, and using the distribution of invariant masses of lepton– b -jet pairs, the top quark mass is measured to be $m_{\text{top}} = 172.99 \pm 0.41$ (stat) ± 0.74 (syst) GeV, with a total uncertainty of 0.84 GeV. Finally, a combination with previous ATLAS m_{top} measurements from $\sqrt{s} = 7$ TeV data in the $t\bar{t} \rightarrow$ dilepton and $t\bar{t} \rightarrow$ lepton + jets channels results in $m_{\text{top}} = 172.84 \pm 0.34$ (stat) ± 0.61 (syst) GeV, with a total uncertainty of 0.70 GeV.

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1. Introduction

The mass of the top quark (m_{top}) is an important parameter of the Standard Model (SM) of particle physics. Precise measurements of m_{top} provide crucial information for global fits of electroweak parameters [1–3] which help assess the internal consistency of the SM and to probe its extensions. In addition, the value of m_{top} affects the stability of the SM Higgs potential, which has cosmological implications [4–6]. Many measurements of m_{top} have been performed by the Tevatron and LHC Collaborations. Combining a selection of those, the first Tevatron+LHC m_{top} result is $m_{\text{top}} = 173.34 \pm 0.27$ (stat) ± 0.71 (syst) GeV, with a total uncertainty of 0.76 GeV [7]. Meanwhile, a number of new results have become available [8–13], some of which are more precise than the above combination. The latest ATLAS results in the $t\bar{t} \rightarrow$ lepton + jets and $t\bar{t} \rightarrow$ dilepton decay channels, both with electrons (e) and muons (μ) in the final state [14], are $m_{\text{top}} = 172.33 \pm 0.75$ (stat) ± 1.02 (syst) GeV and $m_{\text{top}} = 173.79 \pm 0.54$ (stat) ± 1.30 (syst) GeV, respectively.

This Letter presents a new measurement of m_{top} obtained in the $t\bar{t} \rightarrow$ dilepton decay channel using 2012 data taken at a proton–proton (pp) centre-of-mass energy of $\sqrt{s} = 8$ TeV, with an integrated luminosity of about 20.2 fb^{-1} . The analysis exploits the decay $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$, which is realised when both W bosons decay into a charged lepton and its corresponding neutrino. In the analysis, the $t\bar{t}$ decay channels ee , $e\mu$ and $\mu\mu$ (including $\tau \rightarrow e, \mu$) are combined and referred to as the dilepton channel. Single-top-quark events with the same lepton final states are in-

cluded in the signal. Given the larger data sample compared to Ref. [14], the event selection was optimised to achieve the smallest total uncertainty. The measurement is based on the implementation of the template method described in Ref. [14], which is calibrated using signal Monte Carlo (MC) samples. Consequently, the top quark mass measured in this way corresponds to the mass definition used in the MC program.

2. ATLAS detector

The ATLAS experiment [15] at the LHC is a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy mea-

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

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

measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each. Its bending power is in the range from 2.0 to 7.5 Tm. It includes a system of precision tracking chambers and fast detectors for triggering. A three-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted event rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted rate to 400 Hz on average depending on the data-taking conditions during 2012.

3. Data and MC samples

This analysis is based on pp collision data recorded in 2012 at $\sqrt{s} = 8$ TeV. The integrated data luminosity amounts to 20.2 fb^{-1} with an uncertainty of 1.9% determined with the procedures described in Ref. [16].

The modelling of $t\bar{t}$ and single-top-quark signal events and of most background processes relies on MC simulations. For the simulation of signal events the POWHEG-Box program [17–19] is used. The simulation of the top quark pair [20] and single-top-quark production in the Wt -channel [21] uses matrix elements at next-to-leading order (NLO) in the strong coupling constant α_s , with the NLO CT10 [22] parton distribution function (PDF) and the parameter $h_{\text{damp}} = \infty$. The h_{damp} parameter sets the resummation scale, which controls the transition from the matrix element to the parton shower (PS) simulation. Given that the event selection described below requires leptonic decay products of two W bosons, single-top-quark events in the s -channel and t -channel are found not to contribute to the sample.

The PYTHIA (v6.425) program [23] with the P2011C [24] set of tuned parameters (tune) and the corresponding CTEQ6L1 PDF [25] are employed to provide the parton shower, hadronisation and underlying-event modelling. The uncertainties due to QCD initial- and final-state radiation (ISR/FSR) modelling are estimated with samples generated with the POWHEG-Box program interfaced to the PYTHIA program for which the parameters of the generation are varied to span the ranges compatible with the results of measurements of $t\bar{t}$ production in association with jets [26–28].

For m_{top} hypothesis testing, the $t\bar{t}$ and single-top-quark event samples are generated for five values of m_{top} in the range 167.5 to 177.5 GeV in steps of 2.5 GeV. For each m_{top} value, the MC samples are normalised according to the best available cross-section calculations, which for $m_{\text{top}} = 172.5$ GeV are $\sigma_{t\bar{t}} = 253_{-15}^{+13} \text{ pb}$ [29–34] for $t\bar{t}$ production and $\sigma_{Wt} = 22.4 \pm 1.5 \text{ pb}$ [35] for single-top-quark production in the Wt -channel. The PDF + α_s -induced uncertainties in these cross-sections are calculated using the PDF4LHC prescription [36] with the MSTW2008 68% CL NNLO PDF [37,38], CT10 NNLO PDF [22,39] and NNPDF2.3 5f FFN PDF [40], and are added in quadrature with the uncertainties due to the choices of the factorisation and renormalisation scales.

The simulation of W^\pm or Z boson production in association with jets is performed with the ALPGEN (v2.13) program [41] interfaced to the PYTHIA6 program using the CTEQ6L1 PDF and the corresponding AUET2 tune [42]. Diboson production processes (WW , WZ and ZZ) are simulated using the ALPGEN program interfaced to the HERWIG (v6.520) program [43] with the AUET2 tune and to the JIMMY (v4.31) program [44]. All samples are simulated taking into account the effects of multiple soft pp interactions (pile-up) registered in the 2012 data. These interactions are modelled by overlaying simulated hits from events with exactly one inelastic (signal) collision per bunch crossing with hits from minimum-bias events that are produced with the PYTHIA (v8.160) program [45]

using the A2M tune [46] and the MSTW2008 LO PDF. For this analysis, the observed values of the pile-up-related quantities $\langle\mu\rangle$, the mean number of interactions per bunch crossing, and n_{vtx} , the average number of vertices per event, are $\langle\mu\rangle = 20.7$ and $n_{\text{vtx}} = 9.2$.

Finally, the samples undergo a simulation of the ATLAS detector [47] based on GEANT4 [48], and are then processed through the same reconstruction software as the data. A number of samples used to assess systematic uncertainties are produced with a faster version of the simulation which, in addition to the full simulation of the tracking, uses smearing functions and interpolates particle behaviour and calorimeter response, based on resolution functions measured in full-simulation studies, to approximate the results of the full simulation.

4. Data selection and event reconstruction

Triggers based on isolated single electrons or muons with energy or momentum thresholds of 24 GeV are used. The detector objects resulting from the top quark pair decay are electron and muon candidates, jets and missing transverse momentum ($E_{\text{T}}^{\text{miss}}$). In the following, the term lepton is used for charged leptons (excluding τ leptons) exclusively.

Electron candidates [49] are required to have a transverse energy of $E_{\text{T}} > 25$ GeV, a pseudorapidity of the corresponding EM cluster of $|\eta_{\text{cluster}}| < 2.47$, with the transition region $1.37 < |\eta_{\text{cluster}}| < 1.52$ between the barrel and the end-cap calorimeter excluded. The muon candidates [50] are required to have transverse momentum $p_{\text{T}} > 25$ GeV and $|\eta| < 2.5$. To reduce the contamination by leptons from heavy-flavour decays inside jets or from photon conversions, referred to as non-prompt (NP) leptons, strict isolation criteria are applied to the amount of activity in the vicinity of the lepton candidate [49,50].

Jets are built from topological clusters of calorimeter cells [51] with the anti- k_t jet clustering algorithm [52] using a radius parameter of $R = 0.4$. Jets are reconstructed using the local cluster weighting (LCW) and global sequential calibration (GSC) algorithms [53–55] and required to satisfy $p_{\text{T}} > 25$ GeV and $|\eta| < 2.5$. Muons reconstructed within a $\Delta R = 0.4$ cone around the axis of a jet with $p_{\text{T}} > 25$ GeV are not considered as charged-lepton candidates. In addition, jets within a $\Delta R = 0.2$ cone around an electron candidate are removed and finally electrons within a $\Delta R = 0.4$ cone around any of the remaining jets are discarded. The identification of jets containing b -hadrons, b -tagging, is used for event reconstruction and background suppression. In the following, irrespective of their origin, jets tagged by the b -tagging algorithm are referred to as b -tagged jets, whereas those not tagged are referred to as untagged jets. Similarly, whether they are tagged or not, jets originating from bottom quarks are referred to as b -jets and those from (u, d, c, s)-quarks or gluons as light jets. The working point of the neural-network-based MV1 b -tagging algorithm [56] corresponds to an average b -tagging efficiency of 70% for b -jets in simulated $t\bar{t}$ events and rejection factors of 5 for jets containing a c -hadron and 137 for jets containing only lighter-flavour hadrons. To match the b -tagging performance in the data, p_{T} - and η -dependent scale factors [56], obtained from dijet and $t\bar{t} \rightarrow$ dilepton events, are applied to MC jets depending on their true flavour. The reconstruction of the $E_{\text{T}}^{\text{miss}}$ is based on the vector sum of energy deposits in the calorimeters, projected onto the transverse plane. Muons are included in the $E_{\text{T}}^{\text{miss}}$ using their reconstructed momentum in the tracking detectors [57].

The contribution of events wrongly reconstructed as $t\bar{t} \rightarrow$ dilepton events due to the presence of objects misidentified as leptons (fake leptons), is estimated from data [58]. The technique employed uses fake-lepton and real-lepton efficiencies that depend on η and p_{T} , measured in a background-enhanced control region

Table 1

The observed numbers of events in data after the pre-selection and the final selection. In addition, the expected numbers of signal events for $m_{\text{top}} = 172.5$ GeV and background events corresponding to the integrated data luminosity are given. Two significant digits are used for the uncertainties of the predicted numbers of events explained in the text. The lower rows report the matching performance evaluated for $m_{\text{top}} = 172.5$ GeV, using one significant digit for the statistical uncertainties.

Selection	Pre-selection	Final selection
Data	36 359	9426
$t\bar{t}$ signal	$34\,300 \pm 2700$	9670 ± 770
Single-top-quark signal	1690 ± 110	363 ± 23
Fake leptons	240 ± 240	31 ± 31
$Z + \text{jets}$	212 ± 83	20.6 ± 8.5
$WW/WZ/ZZ$	57 ± 21	10.2 ± 3.8
Signal + background	$36\,600 \pm 2800$	$10\,100 \pm 770$
Expected background fraction	0.01 ± 0.01	0.01 ± 0.00
Data/(Signal + background)	0.99 ± 0.07	0.93 ± 0.07
Matching efficiency [%]	78.4 ± 0.2	95.3 ± 0.4
Selection purity [%]	51.6 ± 0.1	69.8 ± 0.3
Unmatched events [%]	34.2 ± 0.1	26.7 ± 0.1
Wrongly matched events [%]	14.2 ± 0.1	3.4 ± 0.0

with low $E_{\text{T}}^{\text{miss}}$ and from events with dilepton masses around the Z peak [59].

The selection from Ref. [14] is applied as a pre-selection as follows:

1. Events are required to have a signal from the single-electron or single-muon trigger and at least one primary vertex with at least five associated tracks.
2. Exactly two oppositely charged leptons are required, with at least one of them matching the reconstructed object that fired the corresponding trigger.
3. In the same-lepton-flavour channels, ee and $\mu\mu$, $E_{\text{T}}^{\text{miss}} > 60$ GeV is required. In addition, the invariant mass of the lepton pair must satisfy $m_{\ell\ell} > 15$ GeV, and must not be compatible with the Z mass within 10 GeV.
4. In the $e\mu$ channel the scalar sum of p_{T} of the two selected leptons and all jets is required to be larger than 130 GeV.
5. The presence of at least two jets with $p_{\text{T}} > 25$ GeV and $|\eta| < 2.5$ is required, and at least one of these jets has to be b -tagged.

The observed numbers of events in the data after this pre-selection, together with the expected numbers of signal and background events corresponding to the integrated data luminosity, are given in Table 1. Assuming a top quark mass of $m_{\text{top}} = 172.5$ GeV, the predicted number of events is consistent with the one observed in the data within uncertainties. For all predictions, the uncertainties are estimated as the sum in quadrature of the statistical uncertainty, a 1.9% uncertainty in the integrated luminosity, and a number of additional components. For the signal, these are a 5.4% uncertainty in the $t\bar{t}$ cross-section, or a 6.0% uncertainty in the single-top-quark cross-section, as given in Sect. 3. Finally, global 4.1%, 2.2% and 2.8% uncertainties are added, corresponding to the envelopes of the results from the eigenvector variations of the jet energy scale (JES), the relative b -to-light-jet energy scale (bJES) and the b -tagging scale factors, respectively. The background uncertainties contain jet-multiplicity-dependent uncertainties of about 40% in the normalisation of the $Z + \text{jets}$ background and a 100% uncertainty in the normalisation of fake-lepton background.

The two jets carrying the highest MV1 weight are taken as the two b -jets originating from the decays of the two top quarks, and the two leptons are taken as the leptons from the leptonic W de-

cays. From the two possible assignments of the two pairs, the combination leading to the lowest average invariant mass of the two lepton- b -jet pairs ($m_{\ell b}$) is retained. To estimate the performance of this algorithm in MC simulated samples, the reconstruction-level objects are matched to the closest generator-level object based on a maximum allowed ΔR , being 0.1 for leptons and 0.3 for jets. A matched object is defined as a reconstruction-level object that falls within ΔR of any generator-level object of that type, and a correct match means that this generator-level object is the one it originated from. Due to acceptance losses and reconstruction inefficiency, not all reconstruction-level objects can successfully be matched to their generator-level counterparts, resulting in unmatched events. The matching efficiency is the fraction of correctly matched events among all the matched events, and the selection purity is the fraction of correctly matched events among all events, regardless of whether they could be matched or not. The corresponding numbers for $m_{\text{top}} = 172.5$ GeV are reported in Table 1.

Starting from this pre-selection, an optimisation of the total uncertainty in m_{top} is performed. A phase-space restriction based on the average p_{T} of the two lepton- b -jet pairs ($p_{\text{T},\ell b}$) is used to obtain the smallest total uncertainty in m_{top} . The corresponding $p_{\text{T},\ell b}$ distribution is shown in Fig. 1(a). The smallest uncertainty in m_{top} corresponds to $p_{\text{T},\ell b} > 120$ GeV. The difference in shape between data and prediction is covered by the systematic uncertainty as detailed in Sect. 6. This restriction is found to also increase the fraction of correctly matched events in the $t\bar{t}$ sample, and reduces the number of unmatched or wrongly matched events.

To perform the template parameterisation described in Sect. 5, an additional selection criterion is applied, restricting the reconstructed $m_{\ell b}$ value ($m_{\ell b}^{\text{reco}}$) to the range $30 \text{ GeV} < m_{\ell b}^{\text{reco}} < 170 \text{ GeV}$. Applying both restrictions, the numbers of predicted and observed events resulting from the final selection are reported in Table 1. Using this optimisation, the matching efficiency and the sample purity are much improved as reported in the bottom rows of Table 1, while retaining about 26% of the events. Using this selection, and the objects assigned to the two lepton- b -jet pairs, the kinematic distributions in the data are well described by the predictions, as shown in Fig. 1 for the transverse momenta of b -jets and leptons, and for the $\Delta R_{\ell b}$ of the two lepton- b -jet pairs.

5. Template fit and results in the data

The implementation of the template method used in this analysis is described in Ref. [14]. For this analysis, the templates are simulated distributions of $m_{\ell b}^{\text{reco}}$, constructed for a number of discrete values of m_{top} . Appropriate functions are fitted to these templates, interpolating between different input m_{top} . The remaining parameters of the functions are fixed by a simultaneous fit to all templates, imposing linear dependences of the parameters on m_{top} . The resulting template fit function has m_{top} as the only free parameter and an unbinned likelihood maximisation gives the value of m_{top} that best describes the data. Statistically independent signal templates, comprising $t\bar{t}$ and single-top-quark events, are constructed as a function of the top quark mass used in the MC generator. Within the statistical uncertainties, the sum of a Gaussian distribution and a Landau function gives a good description of the shape of the $m_{\ell b}^{\text{reco}}$ distribution as shown in Fig. 2(a) for three values of m_{top} . With this signal choice, the background distribution is independent of m_{top} , and a Landau function is fitted to it. The sum of the signal template at $m_{\text{top}} = 172.5$ GeV and the background is compared to data in Fig. 2(b). It gives a good description of the data except for differences that can be accounted for by a different

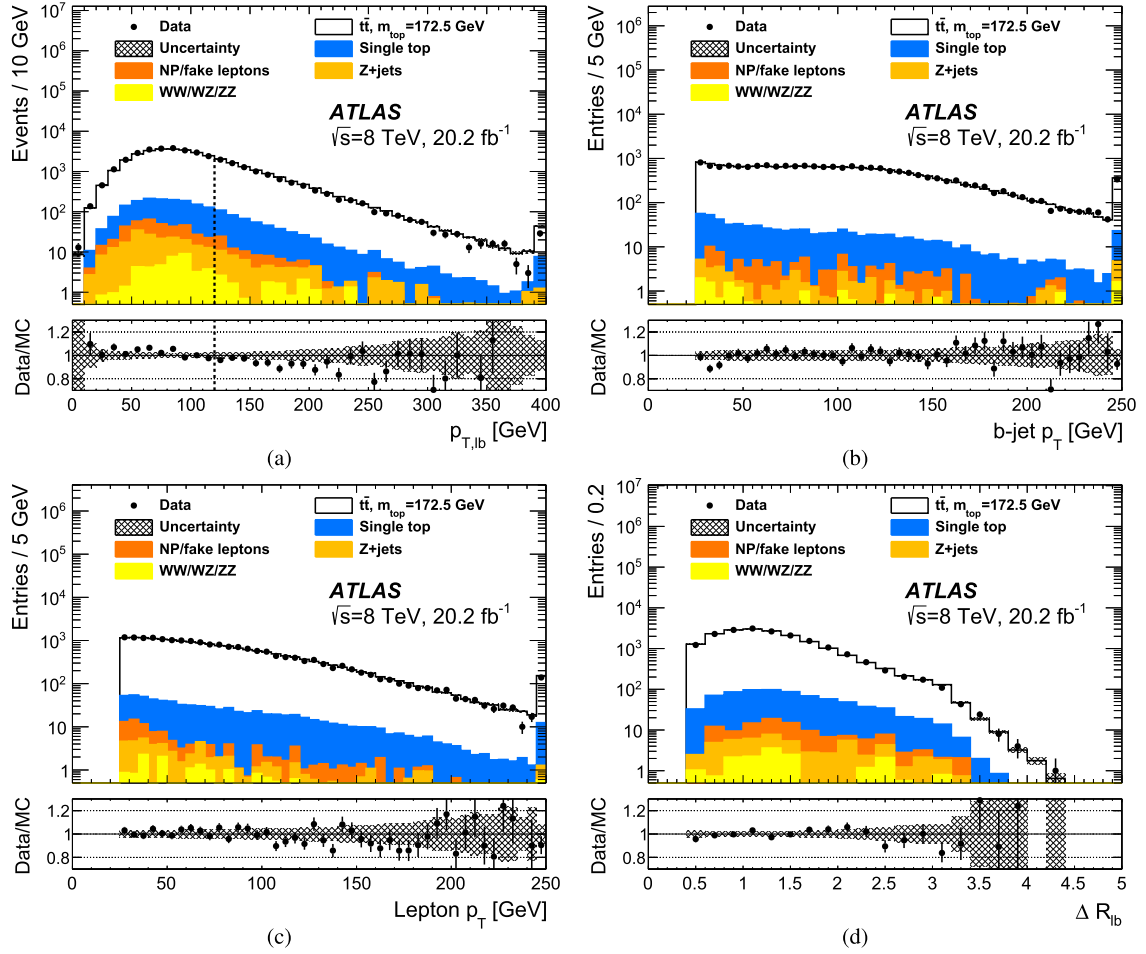


Fig. 1. Kinematic distributions obtained from the objects assigned to the two lepton– b -jet pairs for (a) the pre-selection, or (b)–(d) the final selection. The average $p_{T,lb}$ of the two lepton– b -jet pairs, denoted by $p_{T,lb}$, is shown in (a). The $p_{T,lb}$ requirement for the final selection is indicated by the vertical dashed line. The remaining distributions show the p_T of the b -jets in (b), the p_T of the leptons in (c), and the ΔR_{lb} of the lepton and the b -jet for the two lepton– b -jet pairs in (d). The rightmost bin contains the overflow, if present. For all distributions, the number of predicted events is normalised to the one observed in the data. The hatched area corresponds to the statistical uncertainties in the prediction, the uncertainty bars to the statistical uncertainties in the data. For each figure, the ratio of data and prediction is also presented.

top quark mass. In this distribution, the correctly matched events are concentrated in the central part, whereas the remainder is less peaked and accounts for most of the tails.

In this analysis the expected statistical precision as well as all systematic uncertainties are obtained from pseudo-experiments generated from MC simulated samples mimicking ATLAS data. To verify the internal consistency of the method, 1000 pseudo-experiments per mass point are performed, correcting for oversampling [60]. Within uncertainties, and for all m_{top} values, the residuals and pull means are consistent with zero and the pull widths are consistent with unity, i.e. the estimator is unbiased and uncertainties are calculated properly. The expected statistical uncertainty is obtained from the distribution of the statistical uncertainty in the fitted m_{top} of the pseudo-experiments. For $m_{top} = 172.5$ GeV and the data luminosity it amounts to 0.41 ± 0.03 GeV, where the quoted precision is statistical. The m_{lb}^{reco} distribution in the data is shown in Fig. 2(c) together with the corresponding fitted probability density functions for the background alone and for the sum of signal and background. The value obtained fixing the background contribution to its prediction is $m_{top} = 172.99 \pm 0.41$ (stat) GeV. The statistical uncertainty in m_{top} is taken from the parabolic approximation of the logarithm of the likelihood as shown in Fig. 2(d). The observed and predicted values of the statistical uncertainty agree.

6. Uncertainties affecting the m_{top} determination

The same systematic uncertainty sources as in Ref. [14] are investigated. Their impact on the analysis is mostly evaluated from pairs of samples expressing a particular systematic uncertainty, by constructing the corresponding templates and measuring the average difference in m_{top} of the pair from 1000 pseudo-experiments. To facilitate a combination with other results, every systematic uncertainty is assigned a statistical uncertainty, taking into account the statistical correlation of the considered samples. Following Ref. [61], the resulting uncertainty components are given in Table 2 irrespective of their statistical significance. The uncertainty sources are constructed so as to be uncorrelated with each another and thus the total uncertainty squared is calculated as the sum in quadrature of all components. The various sources of systematic uncertainties and the evaluation of their effect on m_{top} are briefly described in the following. The values are given in Table 2.

Method: The mean value of the differences between the fitted and generated m_{top} for the MC samples at various input top quark masses is assigned as the method calibration uncertainty. This also covers effects from limited numbers of MC simulated events in the templates.

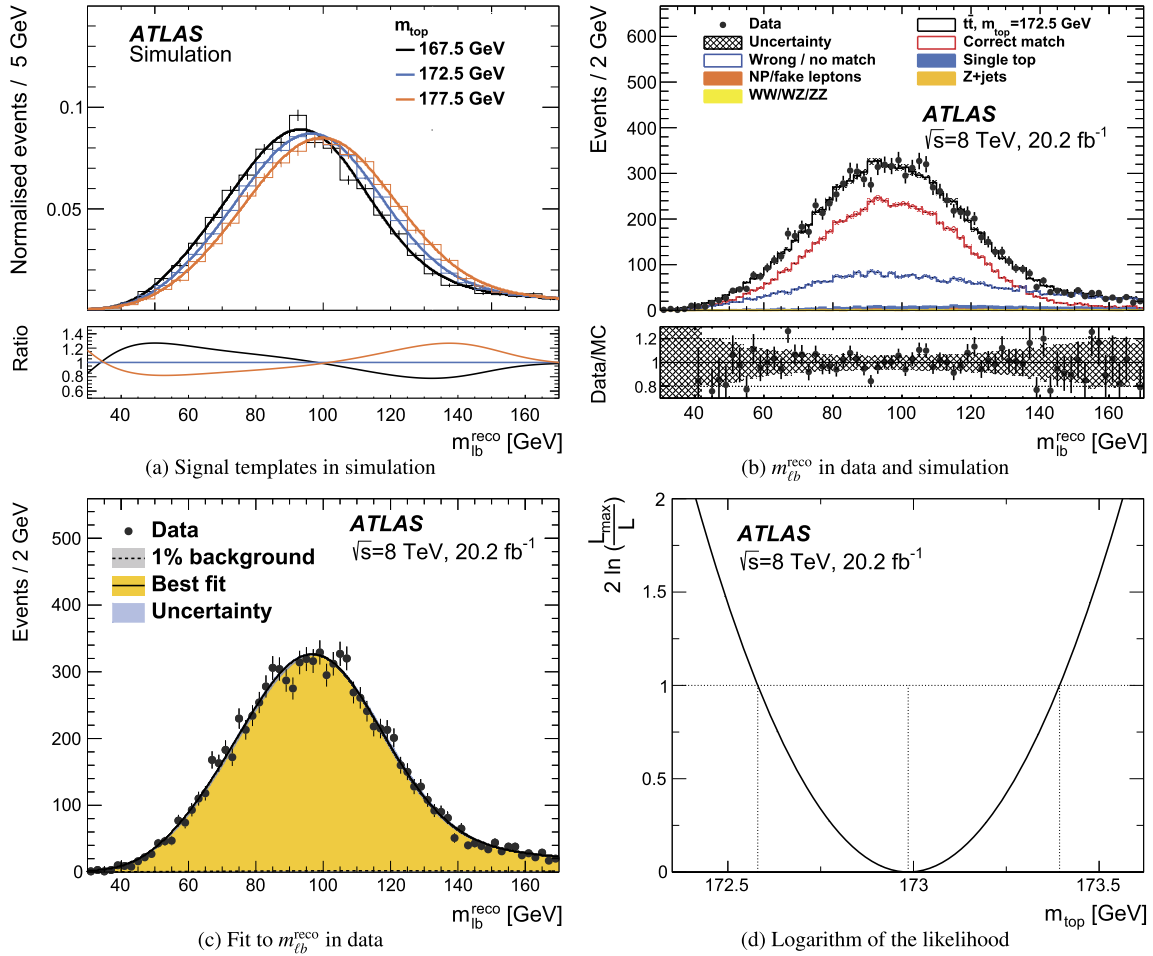


Fig. 2. Simulated signal templates (histograms) for different values of m_{top} together with the template fits (curves) are given in (a). The $m_{\text{lb}}^{\text{reco}}$ distribution observed in data in comparison to the prediction is shown in (b). Both figures show statistical uncertainties only. In (b) the background contributions are too small to be distinguished. The $m_{\text{lb}}^{\text{reco}}$ distribution is shown in (c) for data with statistical uncertainties together with the fitted probability density functions for the background alone (barely visible at the bottom of the figure) and for the sum of signal and background. The uncertainty band corresponds to the total uncertainty in m_{top} . Finally, the corresponding logarithm of the likelihood as a function of m_{top} is displayed in (d).

Signal Monte Carlo generator: The difference in m_{top} between the event sample produced with the MC@NLO program [62,63] and the default POWHEG sample, both generated at $m_{\text{top}} = 172.5$ GeV and using the HERWIG program for parton shower, hadronisation and underlying event, is quoted as a systematic uncertainty.

Hadronisation: The difference in m_{top} between samples produced with the POWHEG-Box program and showered with either the PYTHIA6 program using the P2011C tune or the HERWIG and JIMMY programs using the ATLAS AUET2 tune [42] is quoted as a systematic uncertainty. This includes different approaches in parton-shower modelling and hadronisation, namely the Lund string model [64,65] and the cluster model [66]. The difference in shape between data and prediction observed for the $p_{\text{T},\text{lb}}$ distribution shown in Fig. 1(a) is much reduced when using the POWHEG+HERWIG sample and therefore covered by this uncertainty. As a check to assess the maximum possible difference in m_{top} caused by the mismodelling of the $p_{\text{T},\text{lb}}$ distribution, the predicted distribution is reweighted to the data distribution and the fit is repeated. The observed difference in m_{top} from the nominal sample is about 0.2 GeV, well below the statistical uncertainty in the data. Consequently, no additional uncertainty is applied. Finally, the calibration of the JES and bJES, discussed below, is also partially based on a comparison of jet energy responses in event samples produced with the Herwig++ [67] and PYTHIA6 programs. However, it

was verified [68] that the amount of double-counting of JES and hadronisation effects for the $t\bar{t} \rightarrow \text{lepton} + \text{jets}$ channel is small.

Initial- and final-state QCD radiation (ISR/FSR): The uncertainty due to this effect is evaluated by comparing two dedicated samples generated with the POWHEG-Box and PYTHIA6 programs that differ in several parameters, namely: the QCD scale Λ_{QCD} , the transverse momentum scale for space-like parton-shower evolution Q_{max}^2 and the h_{damp} parameter [69]. Half the observed difference between the up variation and the down variation is quoted as a systematic uncertainty. For comparison, using the signal samples generated at $m_{\text{top}} = 172.5$ GeV, and only changing the h_{damp} parameter but using a much larger range, i.e. from ∞ to m_{top} , the measured m_{top} is lowered by 0.23 ± 0.13 GeV, where the uncertainty is statistical.

Underlying event (UE): The difference in UE modelling is assessed by comparing POWHEG samples based on the same partonic events generated with the CT10 PDFs. The difference in m_{top} for a sample with the Perugia 2012 tune (P2012) and a sample with the P2012 mpiHi tune [24] is assigned as a systematic uncertainty.

Colour reconnection (CR): This systematic uncertainty is estimated using samples with the same partonic events as for the UE uncertainty evaluation, but with the P2012 tune and the P2012 loCR tune [24] for PS and hadronisation. The difference in m_{top} is quoted as a systematic uncertainty.

Parton distribution function (PDF): The PDF systematic uncertainty is the sum in quadrature of three contributions. These are:

Table 2

The three measured values of m_{top} together with their statistical and systematic uncertainty components are shown on the left. The middle part reports the estimated correlations ρ_{ij} per pair of measurements, with 0, 1 and 2 denoting the $\ell + \text{jets}$ and dilepton measurements at $\sqrt{s} = 7$ TeV (from Ref. [14]) and the dilepton measurement at $\sqrt{s} = 8$ TeV, respectively. Finally, the right part lists the m_{top} results for the combinations of the two measurements at $\sqrt{s} = 7$ TeV, the two measurements in the dilepton channel and all measurements. For the individual measurements, the systematic uncertainty in m_{top} and its associated statistical uncertainty is given for each source of uncertainty. Assigned correlations are given as integer values, determined correlations as real values. The last line refers to the sum in quadrature of the statistical and systematic uncertainty components or the total correlations, respectively.

	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	Correlations			Combinations		
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	ρ_{01}	ρ_{02}	ρ_{12}	$m_{\text{top}}^{7\text{TeV}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{all}}$ [GeV]
Results	172.33	173.79	172.99				172.99	173.04	172.84
Statistics	0.75	0.54	0.41	0	0	0	0.48	0.38	0.34
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07	0	0	0	0.07	0.05	0.05
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15	+1.00	+1.00	+1.00	0.24	0.10	0.14
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09	+1.00	+1.00	+1.00	0.34	0.24	0.23
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07	-1.00	-1.00	+1.00	0.04	0.24	0.08
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14	-1.00	-1.00	+1.00	0.06	0.10	0.02
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14	-1.00	-1.00	+1.00	0.01	0.03	0.01
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00	+0.57	-0.29	+0.03	0.17	0.04	0.08
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	+1.00	+0.23	+0.23	0.07	0.03	0.04
$W/Z + \text{jets}$ shape	0.29 ± 0.00	0.00 ± 0.00	0	0			0.16	0.00	0.09
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00	+0.23	+0.20	-0.08	0.03	0.07	0.05
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04	-0.23	+0.06	+0.35	0.41	0.52	0.41
Relative b -to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01	+1.00	+1.00	+1.00	0.34	0.32	0.25
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05	-1.00	0	0	0.03	0.08	0.08
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00	+1.00	+1.00	+1.00	0.10	0.01	0.04
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	-1.00	+1.00	-1.00	0.00	0.02	0.02
b -tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02	-0.77	0	0	0.25	0.03	0.15
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01	-0.34	-0.52	+0.96	0.05	0.14	0.09
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01	-0.15	+0.25	-0.24	0.08	0.01	0.05
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01	0	0	0	0.01	0.05	0.03
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29				0.77	0.74	0.61
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29	-0.07	0.00	0.51	0.91	0.84	0.70

the sum in quadrature of the differences in m_{top} for the 26 eigenvector variations of the CTEQ PDF [25] and two differences in m_{top} obtained from reweighting the central CT10 PDF set to the MSTW2008 PDF [37] and the NNPDF23 PDF [40].

Background normalisation: The normalisations are varied simultaneously for the MC-based and the data-driven background estimates according to the above mentioned uncertainties.

Background shapes: Given the negligible uncertainty in the dilepton channel observed in Ref. [14], no shape uncertainty is evaluated for the MC-based background. For the data-driven background the shape uncertainty is obtained from the estimate of fake-lepton events using the matrix method [58].

Jet energy scale (JES): Mean jet energies are measured with a relative precision of about 1% to 4%, typically falling with jet p_T and rising with jet $|\eta|$ [70,71]. The large number of subcomponents of the total JES uncertainty are reduced by a matrix diagonalisation of the full JES covariance matrix. For each of the resulting 25 significant nuisance parameters [54] the corresponding uncertainty in m_{top} is calculated. The total JES-induced uncertainty in m_{top} is obtained by the sum in quadrature of the results for the subcomponents.

Relative b -to-light-jet energy scale (bJES): The bJES is an additional uncertainty for the remaining differences between b -jets and light jets after the global JES is applied and therefore the corresponding uncertainty is uncorrelated with the JES uncertainty. Jets containing b -hadrons are assigned an additional uncertainty of 0.2% to 1.2%, with lowest uncertainties for high- p_T b -jets [54].

Jet energy resolution (JER): The JER uncertainty is determined by the sum in quadrature of the m_{top} differences between the varied samples and the nominal sample or, where applicable, half the fitted difference between the up variation and the down variation of the components of the eigenvector decomposition.

Jet reconstruction efficiency (JRE): The JRE uncertainty is evaluated by randomly removing 2% of the jets with $p_T < 30$ GeV from the MC simulated events prior to the event selection to reflect the precision with which the data-to-MC JRE ratio is known [53]. The m_{top} difference with respect to the nominal sample is taken as a systematic uncertainty.

Jet vertex fraction (JVF): When summing the scalar p_T of all tracks in a jet, the JVF is the fraction contributed by tracks originating at the primary vertex. The uncertainty is evaluated by varying the requirement on the JVF within its uncertainty [72].

b -tagging: Mismodelling of the b -tagging efficiency and mistag rate is accounted for by the application of scale factors which depend on jet p_T and jet η to MC simulated events [56]. The eigenvector decomposition [56,73] accounts for the uncertainties in the b -tagging, c/τ -tagging and mistagging scale factors. The final b -tagging uncertainty is the sum in quadrature of these uncorrelated components.

Lepton uncertainties: The lepton uncertainties measured in $J/\psi \rightarrow \ell\ell$ and $Z \rightarrow \ell\ell$ events are related to the electron energy or muon momentum scales and resolutions, and the trigger and identification efficiencies [49,50,74]. For each component, the corresponding uncertainty is propagated to the analysis including the recalculation of the E_T^{miss} .

Missing transverse momentum (E_T^{miss}): The remaining contribution to the E_T^{miss} uncertainty stems from the uncertainties in calorimeter cell energies associated with low- p_T jets ($7 \text{ GeV} < p_T < 20 \text{ GeV}$), without any corresponding reconstructed physics object or from pile-up interactions. Their impact is accounted for as described in Ref. [57].

Pile-up: Besides the component treated in the JES, the residual dependence of the fitted m_{top} on the amount of pile-up activity and a possible MC mismodelling is determined. The m_{top} dependence as functions of n_{vtx} and $\langle\mu\rangle$ is found to be consistent in data and

simulation. The corresponding uncertainty evaluated from the remaining difference is small.

The systematic uncertainties quoted in Table 2 carry statistical uncertainties. The statistical precision of a single sample fit is about 100 MeV. The statistical correlation of the samples is calculated from the fraction of shared events. Pairs of samples with only a change in a single parameter have high correlation and correspondingly low statistical uncertainty in the difference in m_{top} , while a pair of statistically independent samples results in a larger uncertainty.

In summary, the result in the dilepton channel at $\sqrt{s} = 8 \text{ TeV}$ of $m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst)} \text{ GeV}$ is about 40% more precise than the one obtained from the $\sqrt{s} = 7 \text{ TeV}$ data and the most precise single result in this decay channel to date. The increased precision is partly driven by a better knowledge of the JES and bJES. In addition, the applied optimisation procedure significantly reduces the total systematic uncertainty, mostly due to a lower impact of the JES and theory modelling uncertainties.

7. Combination with previous ATLAS measurements

The combination of the m_{top} results follows the approach developed for the combination of the $\sqrt{s} = 7 \text{ TeV}$ measurements in Ref. [14] including the evaluation of the correlations. For combining the measurements from data at different centre-of-mass energies a mapping of uncertainty categories is performed. Complex cases are the uncertainty components involving eigenvector decompositions such as the JES, the JER and the b -tagging scale factor uncertainties. The $\sqrt{s} = 7$ and 8 TeV measurements are treated as uncorrelated for the nuisance parameters of the JER and the b -tagging, c/τ -tagging and mistagging uncertainties. A correlated treatment of the estimators for the flavour-tagging nuisance parameters results in an insignificant change in the combination. The total JES uncertainty consists of about 20 eigenvector components, which partly differ for the analyses of $\sqrt{s} = 7$ and 8 TeV data, which make use of the EM+JES and the LCW+GSC [70] jet calibrations, respectively. For the combination, a mapping between uncertainty components at the different centre-of-mass energies is employed to identify the corresponding ones. The combination was found to be stable against variations of the assumptions for ambiguous cases.

The combination is performed using the best linear unbiased estimate (BLUE) method [75,76], implying Gaussian probability density functions for all uncertainties, using the implementation described in Ref. [77]. The central values, the list of uncertainty components and the correlations ρ of the estimators for each uncertainty component have to be provided. For the statistical, method calibration, MC-based background shape at $\sqrt{s} = 7 \text{ TeV}$, and pile-up uncertainties in m_{top} the measurements are assumed to be uncorrelated. For the remaining uncertainties in m_{top} , when using $\pm 1\sigma$ variations of a systematic effect, e.g. when changing the bJES by $\pm 1\sigma$, there are two possibilities. When simultaneously applying a variation for a systematic uncertainty, e.g. $+1\sigma$ for the bJES to a pair of analyses, e.g. the dilepton measurements at $\sqrt{s} = 7$ and 8 TeV, both analyses can result in a larger or smaller m_{top} value than what is obtained for the nominal case (full correlation, $\rho = +1$), or one analysis can obtain a larger and the other a smaller value (full anti-correlation, $\rho = -1$). Consequently, an uncertainty from a source only consisting of a single variation, such as the uncertainty related to the choice of MC generator for signal events, results in a correlation of $\rho = \pm 1$. The estimator correlations for composite uncertainties are evaluated by adding the covariance terms of the subcomponents i with $\rho_i = \pm 1$ and dividing by the total uncertainties for that source. The resulting estimator

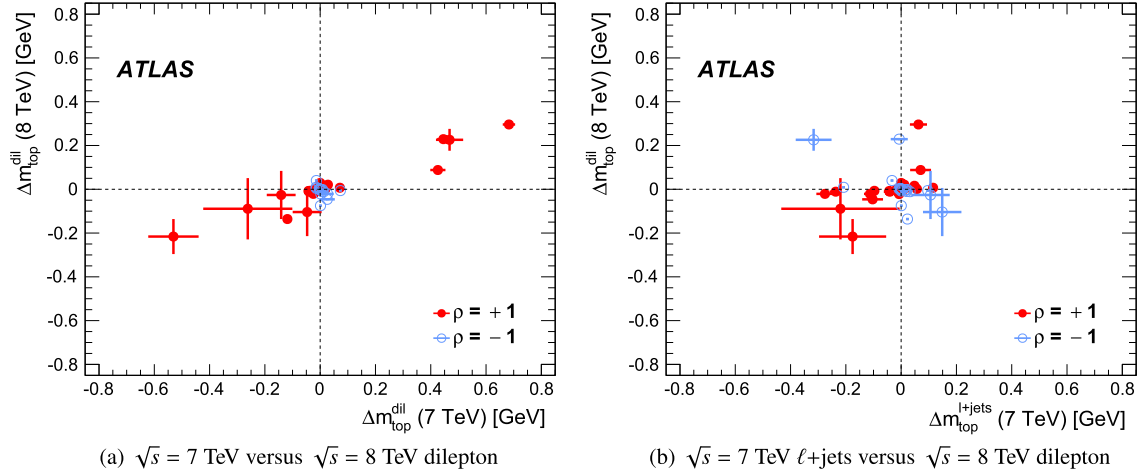


Fig. 3. The pairwise differences in m_{top} when simultaneously varying both analyses for a systematic uncertainty. Each cross indicates the statistical precisions of the systematic uncertainty. The red full points indicate $\rho = 1$, the blue open points $\rho = -1$.

correlation per uncertainty is quoted in Table 2 and used in the combination.

The evaluated uncertainties in m_{top} for the uncertainty components for the two dilepton analyses, denoted by $\Delta m_{\text{top}}^{\text{dilepton}}$, are shown in Fig. 3(a). Each point represents a systematic uncertainty together with a cross, indicating the respective statistical precision of the systematic uncertainty in the two analyses. The red full points indicate $\rho = 1$, the blue open points $\rho = -1$. Given the similarity of the analyses, a positive estimator correlation is observed for most uncertainty components of the two measurements in the dilepton channel. The corresponding distribution for the $\ell + \text{jets}$ measurement at $\sqrt{s} = 7$ TeV and the dilepton measurement at $\sqrt{s} = 8$ TeV is given in Fig. 3(b). In this figure, the estimates are anti-correlated for several significant uncertainties. This is caused by the in-situ measurement of the jet energy scale factor (JSF) and relative b -to-light-jet energy scale factor (bJSF) in the three-dimensional $\ell + \text{jets}$ analysis, detailed in Ref. [14]. The resulting total correlation for this pair is very low as shown in Table 2. The combination strongly profits from this.

The central values of the three measurements, their uncertainty components, the determined correlations per pair of measurements and the results of the combinations are given in Table 2. The pairwise differences in the three measurements are 0.75σ for the $\sqrt{s} = 7$ TeV measurements, 0.43σ for the $\ell + \text{jets}$ measurement at $\sqrt{s} = 7$ TeV and the dilepton measurement at $\sqrt{s} = 8$ TeV and 0.66σ for the two dilepton measurements. For all three cases σ denotes the one standard deviation of the respective m_{top} difference. The combined result in the dilepton channel alone is $m_{\text{top}}^{\text{dilepton}} = 173.04 \pm 0.38$ (stat) ± 0.74 (syst) GeV = 173.04 ± 0.84 GeV, providing no significant improvement with respect to the more precise result at $\sqrt{s} = 8$ TeV which carries a BLUE combination weight of 0.94. This is a mere consequence of the measurement correlation of 0.51, which is close to the ratio of uncertainties (see Ref. [76]). The χ^2 probability of the combination is 51%. The stability of the combination is assessed from the results of 1000 combinations for which all input uncertainties are varied within their statistical uncertainties, which for some cases also result in different correlations (see Fig. 3). The corresponding distributions of the central values and uncertainties of the combinations are approximately Gaussian, with a width of 0.03 GeV and of 0.04 GeV, respectively.

The combination of all three measurements provides a 17% improvement with respect to the most precise single input measurement. The combined result is $m_{\text{top}}^{\text{all}} = 172.84 \pm 0.34$ (stat) \pm

0.61 (syst) GeV = 172.84 ± 0.70 GeV. The χ^2 probability of the combination is 73% and the BLUE combination weights of the $\ell + \text{jets}$ and dilepton measurements at $\sqrt{s} = 7$ TeV and the dilepton measurement at $\sqrt{s} = 8$ TeV are 0.30, 0.07 and 0.63, respectively. Again, the central value and the combined total uncertainty are both stable at the level of 0.03 GeV.

8. Conclusion

The top quark mass is measured in the $t\bar{t} \rightarrow \text{dilepton}$ channel from about 20.2 fb^{-1} of $\sqrt{s} = 8$ TeV proton–proton collision data recorded by the ATLAS detector at the LHC. Compared to the latest ATLAS measurement in this decay channel, the event selection is refined exploiting the average p_T of the lepton– b -jet pairs to enhance the fraction of correctly reconstructed events, thereby reducing the systematic uncertainties. Using the optimal point in terms of total uncertainty observed in a phase-space scan of this variable as an additional event selection criterion, the measured value of m_{top} is

$$m_{\text{top}} = 172.99 \pm 0.41$$
 (stat) ± 0.74 (syst) GeV,

with a total uncertainty of 0.84 GeV. The precision is mainly limited by systematic uncertainties, mostly by the calibration of the jet energy scale, and to a lesser extent by the calibration of the relative b -to-light-jet energy scale and by the Monte Carlo modelling of signal events.

This measurement is combined with the ATLAS measurements in the $t\bar{t} \rightarrow \text{lepton} + \text{jets}$ and $t\bar{t} \rightarrow \text{dilepton}$ decay channels from $\sqrt{s} = 7$ TeV data. The correlations of the measurements are evaluated for all sources of the systematic uncertainty. Using a dedicated mapping of uncertainty categories, the combination of the three measurements results in

$$m_{\text{top}} = 172.84 \pm 0.34$$
 (stat) ± 0.61 (syst) GeV,

with a total uncertainty of 0.70 GeV, i.e. a relative precision of 0.4%. The result is mostly limited by the calibration of the jet energy scales and by the Monte Carlo modelling of signal events.

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ATLAS Collaboration

M. Aaboud^{135d}, G. Aad⁸⁶, B. Abbott¹¹³, J. Abdallah⁶⁴, O. Abdinov¹², B. Abeloos¹¹⁷, R. Aben¹⁰⁷, O.S. AbouZeid¹³⁷, N.L. Abraham¹⁴⁹, H. Abramowicz¹⁵³, H. Abreu¹⁵², R. Abreu¹¹⁶, Y. Abulaiti^{146a,146b}, B.S. Acharya^{163a,163b,a}, L. Adamczyk^{40a}, D.L. Adams²⁷, J. Adelman¹⁰⁸, S. Adomeit¹⁰⁰, T. Adye¹³¹, A.A. Affolder⁷⁵, T. Agatonovic-Jovin¹⁴, J. Agricola⁵⁶, J.A. Aguilar-Saavedra^{126a,126f}, S.P. Ahlen²⁴, F. Ahmadov^{66,b}, G. Aielli^{133a,133b}, H. Akerstedt^{146a,146b}, T.P.A. Åkesson⁸², A.V. Akimov⁹⁶, G.L. Alberghi^{22a,22b}, J. Albert¹⁶⁸, S. Albrand⁵⁷, M.J. Alconada Verzini⁷², M. Aleksa³², I.N. Aleksandrov⁶⁶, C. Alexa^{28b}, G. Alexander¹⁵³, T. Alexopoulos¹⁰, M. Alhroob¹¹³, B. Ali¹²⁸, M. Aliev^{74a,74b}, G. Alimonti^{92a}, J. Alison³³, S.P. Alkire³⁷, B.M.M. Allbrooke¹⁴⁹, B.W. Allen¹¹⁶, P.P. Allport¹⁹, A. Aloisio^{104a,104b}, A. Alonso³⁸, F. Alonso⁷², C. Alpigiani¹³⁸, M. Alstaty⁸⁶, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁶⁶, M.G. Alviggi^{104a,104b}, B.T. Amadio¹⁶, K. Amako⁶⁷, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹⁰, S.P. Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso³², G. Amundsen²⁵, C. Anastopoulos¹³⁹, L.S. Ancu⁵¹, N. Andari¹⁹, T. Andeen¹¹, C.F. Anders^{59b}, G. Anders³², J.K. Anders⁷⁵, K.J. Anderson³³, A. Andreazza^{92a,92b}, V. Andrei^{59a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁶, A. Angerami³⁷, F. Anghinolfi³², A.V. Anisenkov^{109,c}, N. Anjos¹³, A. Annovi^{124a,124b}, C. Antel^{59a}, M. Antonelli⁴⁹, A. Antonov^{98,*}, F. Anulli^{132a}, M. Aoki⁶⁷, L. Aperio Bella¹⁹, G. Arabidze⁹¹, Y. Arai⁶⁷, J.P. Araque^{126a}, A.T.H. Arce⁴⁷, F.A. Arduh⁷², J-F. Arguin⁹⁵, S. Argyropoulos⁶⁴, M. Arik^{20a}, A.J. Armbruster¹⁴³, L.J. Armitage⁷⁷, O. Arnaez³², H. Arnold⁵⁰, M. Arratia³⁰, O. Arslan²³, A. Artamonov⁹⁷, G. Artoni¹²⁰, S. Artz⁸⁴, S. Asai¹⁵⁵, N. Asbah⁴⁴, A. Ashkenazi¹⁵³, B. Åsman^{146a,146b}, L. Asquith¹⁴⁹, K. Assamagan²⁷, R. Astalos^{144a}, M. Atkinson¹⁶⁵, N.B. Atlay¹⁴¹, K. Augsten¹²⁸, G. Avolio³², B. Axen¹⁶, M.K. Ayoub¹¹⁷, G. Azuelos^{95,d}, M.A. Baak³², A.E. Baas^{59a}, M.J. Baca¹⁹, H. Bachacou¹³⁶, K. Bachas^{74a,74b}, M. Backes¹⁴⁸, M. Backhaus³², P. Bagiachi^{132a,132b}, P. Bagnaia^{132a,132b}, Y. Bai^{35a}, J.T. Baines¹³¹, O.K. Baker¹⁷⁵, E.M. Baldin^{109,c}, P. Balek¹⁷¹, T. Balestri¹⁴⁸, F. Balli¹³⁶, W.K. Balunas¹²², E. Banas⁴¹, Sw. Banerjee^{172,e}, A.A.E. Bannoura¹⁷⁴, L. Barak³², E.L. Barberio⁸⁹, D. Barberis^{52a,52b}, M. Barbero⁸⁶, T. Barillari¹⁰¹, M-S Barisits³², T. Barklow¹⁴³, N. Barlow³⁰, S.L. Barnes⁸⁵, B.M. Barnett¹³¹, R.M. Barnett¹⁶, Z. Barnovska⁵, A. Baroncelli^{134a}, G. Barone²⁵, A.J. Barr¹²⁰, L. Barranco Navarro¹⁶⁶, F. Barreiro⁸³, J. Barreiro Guimarães da Costa^{35a}, R. Bartoldus¹⁴³, A.E. Barton⁷³, P. Bartos^{144a}, A. Basalae¹²³, A. Bassalat¹¹⁷, R.L. Bates⁵⁵, S.J. Batista¹⁵⁸, J.R. Batley³⁰, M. Battaglia¹³⁷, M. Bauce^{132a,132b}, F. Bauer¹³⁶, H.S. Bawa^{143,f}, J.B. Beacham¹¹¹, M.D. Beattie⁷³, T. Beau⁸¹, P.H. Beauchemin¹⁶¹, P. Bechtel²³,

H.P. Beck^{18,g}, K. Becker¹²⁰, M. Becker⁸⁴, M. Beckingham¹⁶⁹, C. Becot¹¹⁰, A.J. Beddall^{20e}, A. Beddall^{20b}, V.A. Bednyakov⁶⁶, M. Bedognetti¹⁰⁷, C.P. Bee¹⁴⁸, L.J. Beemster¹⁰⁷, T.A. Beermann³², M. Begel²⁷, J.K. Behr⁴⁴, C. Belanger-Champagne⁸⁸, A.S. Bell⁷⁹, G. Bella¹⁵³, L. Bellagamba^{22a}, A. Bellerive³¹, M. Bellomo⁸⁷, K. Belotskiy⁹⁸, O. Beltramello³², N.L. Belyaev⁹⁸, O. Benary¹⁵³, D. Benckekroun^{135a}, M. Bender¹⁰⁰, K. Bendtz^{146a,146b}, N. Benekos¹⁰, Y. Benhammou¹⁵³, E. Benhar Noccioli¹⁷⁵, J. Benitez⁶⁴, D.P. Benjamin⁴⁷, J.R. Bensinger²⁵, S. Bentvelsen¹⁰⁷, L. Beresford¹²⁰, M. Beretta⁴⁹, D. Berge¹⁰⁷, E. Bergeaas Kuutmann¹⁶⁴, N. Berger⁵, J. Beringer¹⁶, S. Berlendis⁵⁷, N.R. Bernard⁸⁷, C. Bernius¹¹⁰, F.U. Bernlochner²³, T. Berry⁷⁸, P. Berta¹²⁹, C. Bertella⁸⁴, G. Bertoli^{146a,146b}, F. Bertolucci^{124a,124b}, I.A. Bertram⁷³, C. Bertsche⁴⁴, D. Bertsche¹¹³, G.J. Besjes³⁸, O. Bessidskaia Bylund^{146a,146b}, M. Bessner⁴⁴, N. Besson¹³⁶, C. Betancourt⁵⁰, A. Bethani⁵⁷, S. Bethke¹⁰¹, A.J. Bevan⁷⁷, R.M. Bianchi¹²⁵, L. Bianchini²⁵, M. Bianco³², O. Biebel¹⁰⁰, D. Biedermann¹⁷, R. Bielski⁸⁵, N.V. Biesuz^{124a,124b}, M. Biglietti^{134a}, J. Bilbao De Mendizabal⁵¹, T.R.V. Billoud⁹⁵, H. Bilokon⁴⁹, M. Bindi⁵⁶, S. Binet¹¹⁷, A. Bingul^{20b}, C. Bini^{132a,132b}, S. Biondi^{22a,22b}, D.M. Bjergaard⁴⁷, C.W. Black¹⁵⁰, J.E. Black¹⁴³, K.M. Black²⁴, D. Blackburn¹³⁸, R.E. Blair⁶, J.-B. Blanchard¹³⁶, T. Blazek^{144a}, I. Bloch⁴⁴, C. Blocker²⁵, W. Blum^{84,*}, U. Blumenschein⁵⁶, S. Blunier^{34a}, G.J. Bobbink¹⁰⁷, V.S. Bobrovnikov^{109,c}, S.S. Bocchetta⁸², A. Bocci⁴⁷, C. Bock¹⁰⁰, M. Boehler⁵⁰, D. Boerner¹⁷⁴, J.A. Bogaerts³², D. Bogavac¹⁴, A.G. Bogdanchikov¹⁰⁹, C. Bohm^{146a}, V. Boisvert⁷⁸, P. Bokan¹⁴, T. Bold^{40a}, A.S. Boldyrev^{163a,163c}, M. Bomben⁸¹, M. Bona⁷⁷, M. Boonekamp¹³⁶, A. Borisov¹³⁰, G. Borissov⁷³, J. Bortfeldt³², D. Bortoletto¹²⁰, V. Bortolotto^{61a,61b,61c}, K. Bos¹⁰⁷, D. Boscherini^{22a}, M. Bosman¹³, J.D. Bossio Sola²⁹, J. Boudreau¹²⁵, J. Bouffard², E.V. Bouhova-Thacker⁷³, D. Boumediene³⁶, C. Bourdarios¹¹⁷, S.K. Boutle⁵⁵, A. Boveia³², J. Boyd³², I.R. Boyko⁶⁶, J. Bracinik¹⁹, A. Brandt⁸, G. Brandt⁵⁶, O. Brandt^{59a}, U. Bratzler¹⁵⁶, B. Brau⁸⁷, J.E. Brau¹¹⁶, H.M. Braun^{174,*}, W.D. Breaden Madden⁵⁵, K. Brendlinger¹²², A.J. Brennan⁸⁹, L. Brenner¹⁰⁷, R. Brenner¹⁶⁴, S. Bressler¹⁷¹, T.M. Bristow⁴⁸, D. Britton⁵⁵, D. Britzger⁴⁴, F.M. Brochu³⁰, I. Brock²³, R. Brock⁹¹, G. Brooijmans³⁷, T. Brooks⁷⁸, W.K. Brooks^{34b}, J. Brosamer¹⁶, E. Brost¹⁰⁸, J.H. Broughton¹⁹, P.A. Bruckman de Renstrom⁴¹, D. Bruncko^{144b}, R. Bruneliere⁵⁰, A. Bruni^{22a}, G. Bruni^{22a}, L.S. Bruni¹⁰⁷, B.H. Brunt³⁰, M. Bruschi^{22a}, N. Bruscino²³, P. Bryant³³, L. Bryngemark⁸², T. Buanes¹⁵, Q. Buat¹⁴², P. Buchholz¹⁴¹, A.G. Buckley⁵⁵, I.A. Budagov⁶⁶, F. Buehrer⁵⁰, M.K. Bugge¹¹⁹, O. Bulekov⁹⁸, D. Bullock⁸, H. Burckhart³², S. Burdin⁷⁵, C.D. Burgard⁵⁰, B. Burghgrave¹⁰⁸, K. Burka⁴¹, S. Burke¹³¹, I. Burmeister⁴⁵, J.T.P. Burr¹²⁰, E. Busato³⁶, D. Büscher⁵⁰, V. Büscher⁸⁴, P. Bussey⁵⁵, J.M. Butler²⁴, C.M. Buttar⁵⁵, J.M. Butterworth⁷⁹, P. Butti¹⁰⁷, W. Buttinger²⁷, A. Buzatu⁵⁵, A.R. Buzykaev^{109,c}, S. Cabrera Urbán¹⁶⁶, D. Caforio¹²⁸, V.M. Cairo^{39a,39b}, O. Cakir^{4a}, N. Calace⁵¹, P. Calafiura¹⁶, A. Calandri⁸⁶, G. Calderini⁸¹, P. Calfayan¹⁰⁰, G. Callea^{39a,39b}, L.P. Caloba^{26a}, S. Calvente Lopez⁸³, D. Calvet³⁶, S. Calvet³⁶, T.P. Calvet⁸⁶, R. Camacho Toro³³, S. Camarda³², P. Camarri^{133a,133b}, D. Cameron¹¹⁹, R. Caminal Armadans¹⁶⁵, C. Camincher⁵⁷, S. Campana³², M. Campanelli⁷⁹, A. Camplani^{92a,92b}, A. Campoverde¹⁴¹, V. Canale^{104a,104b}, A. Canepa^{159a}, M. Cano Bret^{35e}, J. Cantero¹¹⁴, R. Cantrill^{126a}, T. Cao⁴², M.D.M. Capeans Garrido³², I. Caprini^{28b}, M. Caprini^{28b}, M. Capua^{39a,39b}, R. Caputo⁸⁴, R.M. Carbone³⁷, R. Cardarelli^{133a}, F. Cardillo⁵⁰, I. Carli¹²⁹, T. Carli³², G. Carlino^{104a}, L. Carminati^{92a,92b}, S. Caron¹⁰⁶, E. Carquin^{34b}, G.D. Carrillo-Montoya³², J.R. Carter³⁰, J. Carvalho^{126a,126c}, D. Casadei¹⁹, M.P. Casado^{13,h}, M. Casolino¹³, D.W. Casper¹⁶², E. Castaneda-Miranda^{145a}, R. Castelijm¹⁰⁷, A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{126a,i}, A. Catinaccio³², J.R. Catmore¹¹⁹, A. Cattai³², J. Caudron²³, V. Cavaliere¹⁶⁵, E. Cavallaro¹³, D. Cavalli^{92a}, M. Cavalli-Sforza¹³, V. Cavasinni^{124a,124b}, F. Ceradini^{134a,134b}, L. Cerda Alberich¹⁶⁶, B.C. Cerio⁴⁷, A.S. Cerqueira^{26b}, A. Cerri¹⁴⁹, L. Cerrito^{133a,133b}, F. Cerutti¹⁶, M. Cerv³², A. Cervelli¹⁸, S.A. Cetin^{20d}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁸, S.K. Chan⁵⁸, Y.L. Chan^{61a}, P. Chang¹⁶⁵, J.D. Chapman³⁰, D.G. Charlton¹⁹, A. Chatterjee⁵¹, C.C. Chau¹⁵⁸, C.A. Chavez Barajas¹⁴⁹, S. Che¹¹¹, S. Cheatham⁷³, A. Chegwiddden⁹¹, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov^{66,j}, M.A. Chelstowska⁹⁰, C. Chen⁶⁵, H. Chen²⁷, K. Chen¹⁴⁸, S. Chen^{35c}, S. Chen¹⁵⁵, X. Chen^{35f}, Y. Chen⁶⁸, H.C. Cheng⁹⁰, H.J. Cheng^{35a}, Y. Cheng³³, A. Cheplakov⁶⁶, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{135e}, V. Chernyatin^{27,*}, E. Cheu⁷, L. Chevalier¹³⁶, V. Chiarella⁴⁹, G. Chiarelli^{124a,124b}, G. Chiodini^{74a}, A.S. Chisholm¹⁹, A. Chitan^{28b}, M.V. Chizhov⁶⁶, K. Choi⁶², A.R. Chomont³⁶, S. Chouridou⁹, B.K.B. Chow¹⁰⁰, V. Christodoulou⁷⁹, D. Chromek-Burckhart³², J. Chudoba¹²⁷, A.J. Chuinard⁸⁸, J.J. Chwastowski⁴¹, L. Chytka¹¹⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, D. Cinca⁴⁵, V. Cindro⁷⁶, I.A. Cioara²³, C. Ciocca^{22a,22b}, A. Ciochio¹⁶, F. Ciotto^{104a,104b}, Z.H. Citron¹⁷¹,

M. Citterio^{92a}, M. Ciubancan^{28b}, A. Clark⁵¹, B.L. Clark⁵⁸, M.R. Clark³⁷, P.J. Clark⁴⁸, R.N. Clarke¹⁶,
 C. Clement^{146a,146b}, Y. Coadou⁸⁶, M. Cobal^{163a,163c}, A. Coccaro⁵¹, J. Cochran⁶⁵, L. Colasurdo¹⁰⁶,
 B. Cole³⁷, A.P. Colijn¹⁰⁷, J. Collot⁵⁷, T. Colombo³², G. Compostella¹⁰¹, P. Conde Muño^{126a,126b},
 E. Coniavitis⁵⁰, S.H. Connell^{145b}, I.A. Connelly⁷⁸, V. Consorti⁵⁰, S. Constantinescu^{28b}, G. Conti³²,
 F. Conventi^{104a,k}, M. Cooke¹⁶, B.D. Cooper⁷⁹, A.M. Cooper-Sarkar¹²⁰, K.J.R. Cormier¹⁵⁸,
 T. Cornelissen¹⁷⁴, M. Corradi^{132a,132b}, F. Corriveau^{88,l}, A. Corso-Radu¹⁶², A. Cortes-Gonzalez³²,
 G. Cortiana¹⁰¹, G. Costa^{92a}, M.J. Costa¹⁶⁶, D. Costanzo¹³⁹, G. Cottin³⁰, G. Cowan⁷⁸, B.E. Cox⁸⁵,
 K. Cranmer¹¹⁰, S.J. Crawley⁵⁵, G. Cree³¹, S. Crépé-Renaudin⁵⁷, F. Crescioli⁸¹, W.A. Cribbs^{146a,146b},
 M. Crispin Ortuzar¹²⁰, M. Cristinziani²³, V. Croft¹⁰⁶, G. Crosetti^{39a,39b}, A. Cueto⁸³,
 T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁵, M. Curatolo⁴⁹, J. Cúth⁸⁴, H. Czirr¹⁴¹, P. Czodrowski³,
 G. D'amen^{22a,22b}, S. D'Auria⁵⁵, M. D'Onofrio⁷⁵, M.J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁵,
 W. Dabrowski^{40a}, T. Dado^{144a}, T. Dai⁹⁰, O. Dale¹⁵, F. Dallaire⁹⁵, C. Dallapiccola⁸⁷, M. Dam³⁸,
 J.R. Dandoy³³, N.P. Dang⁵⁰, A.C. Daniells¹⁹, N.S. Dann⁸⁵, M. Danninger¹⁶⁷, M. Dano Hoffmann¹³⁶,
 V. Dao⁵⁰, G. Darbo^{52a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶², W. Davey²³, C. David¹⁶⁸,
 T. Davidek¹²⁹, M. Davies¹⁵³, P. Davison⁷⁹, E. Dawe⁸⁹, I. Dawson¹³⁹, R.K. Daya-Ishmukhametova⁸⁷,
 K. De⁸, R. de Asmundis^{104a}, A. De Benedetti¹¹³, S. De Castro^{22a,22b}, S. De Cecco⁸¹, N. De Groot¹⁰⁶,
 P. de Jong¹⁰⁷, H. De la Torre⁸³, F. De Lorenzi⁶⁵, A. De Maria⁵⁶, D. De Pedis^{132a}, A. De Salvo^{132a},
 U. De Sanctis¹⁴⁹, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁷, W.J. Dearnaley⁷³, R. Debbe²⁷,
 C. Debenedetti¹³⁷, D.V. Dedovich⁶⁶, N. Dehghanian³, I. Deigaard¹⁰⁷, M. Del Gaudio^{39a,39b}, J. Del Peso⁸³,
 T. Del Prete^{124a,124b}, D. Delgove¹¹⁷, F. Deliot¹³⁶, C.M. Delitzsch⁵¹, M. Deliyergiyev⁷⁶, A. Dell'Acqua³²,
 L. Dell'Asta²⁴, M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,k}, D. della Volpe⁵¹, M. Delmastro⁵,
 P.A. Delsart⁵⁷, D.A. DeMarco¹⁵⁸, S. Demers¹⁷⁵, M. Demichev⁶⁶, A. Demilly⁸¹, S.P. Denisov¹³⁰,
 D. Denysiuk¹³⁶, D. Derendarz⁴¹, J.E. Derkaoui^{135d}, F. Derue⁸¹, P. Dervan⁷⁵, K. Desch²³, C. Deterre⁴⁴,
 K. Dette⁴⁵, P.O. Deviveiros³², A. Dewhurst¹³¹, S. Dhaliwal²⁵, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵,
 W.K. Di Clemente¹²², C. Di Donato^{132a,132b}, A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{134a,134b},
 R. Di Nardo³², A. Di Simone⁵⁰, R. Di Sipio¹⁵⁸, D. Di Valentino³¹, C. Diaconu⁸⁶, M. Diamond¹⁵⁸,
 F.A. Dias⁴⁸, M.A. Diaz^{34a}, E.B. Diehl⁹⁰, J. Dietrich¹⁷, S. Diglio⁸⁶, A. Dimitrievska¹⁴, J. Dingfelder²³,
 P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁶, T. Djobava^{53b}, J.I. Djuvsland^{59a}, M.A.B. do Vale^{26c},
 D. Dobos³², M. Dobre^{28b}, C. Doglioni⁸², J. Dolejsi¹²⁹, Z. Dolezal¹²⁹, M. Donadelli^{26d}, S. Donati^{124a,124b},
 P. Dondero^{121a,121b}, J. Donini³⁶, J. Dopke¹³¹, A. Doria^{104a}, M.T. Dova⁷², A.T. Doyle⁵⁵, E. Drechsler⁵⁶,
 M. Dris¹⁰, Y. Du^{35d}, J. Duarte-Campderros¹⁵³, E. Duchovni¹⁷¹, G. Duckeck¹⁰⁰, O.A. Ducu^{95,m},
 D. Duda¹⁰⁷, A. Dudarev³², A.Ch. Dudder⁸⁴, E.M. Duffield¹⁶, L. Dufлот¹¹⁷, M. Dührssen³²,
 M. Dumancic¹⁷¹, M. Dunford^{59a}, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{53b}, D. Duschinger⁴⁶,
 B. Dutta⁴⁴, M. Dyndal⁴⁴, C. Eckardt⁴⁴, K.M. Ecker¹⁰¹, R.C. Edgar⁹⁰, N.C. Edwards⁴⁸, T. Eifert³²,
 G. Eigen¹⁵, K. Einsweiler¹⁶, T. Ekelof¹⁶⁴, M. El Kacimi^{135c}, V. Ellajosyula⁸⁶, M. Ellert¹⁶⁴, S. Elles⁵,
 F. Ellinghaus¹⁷⁴, A.A. Elliot¹⁶⁸, N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emeliyanov¹³¹, Y. Enari¹⁵⁵,
 O.C. Endner⁸⁴, J.S. Ennis¹⁶⁹, J. Erdmann⁴⁵, A. Ereditato¹⁸, G. Ernis¹⁷⁴, J. Ernst², M. Ernst²⁷, S. Errede¹⁶⁵,
 E. Ertel⁸⁴, M. Escalier¹¹⁷, H. Esch⁴⁵, C. Escobar¹²⁵, B. Esposito⁴⁹, A.I. Etienne¹³⁶, E. Etzion¹⁵³,
 H. Evans⁶², A. Ezhilov¹²³, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, G. Facini³³, R.M. Fakhruddinov¹³⁰,
 S. Falciano^{132a}, R.J. Falla⁷⁹, J. Faltova¹²⁹, Y. Fang^{35a}, M. Fanti^{92a,92b}, A. Farbin⁸, A. Farilla^{134a},
 C. Farina¹²⁵, E.M. Farina^{121a,121b}, T. Farooque¹³, S. Farrell¹⁶, S.M. Farrington¹⁶⁹, P. Farthouat³²,
 F. Fassi^{135e}, P. Fassnacht³², D. Fassouliotis⁹, M. Fauci Giannelli⁷⁸, A. Favareto^{52a,52b}, W.J. Fawcett¹²⁰,
 L. Fayard¹¹⁷, O.L. Fedin^{123,n}, W. Fedorko¹⁶⁷, S. Feigl¹¹⁹, L. Feligioni⁸⁶, C. Feng^{35d}, E.J. Feng³², H. Feng⁹⁰,
 A.B. Fenyuk¹³⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁶, S. Fernandez Perez¹³, J. Ferrando⁵⁵,
 A. Ferrari¹⁶⁴, P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁶⁶, D. Ferrere⁵¹,
 C. Ferretti⁹⁰, A. Ferretto Parodi^{52a,52b}, F. Fiedler⁸⁴, A. Filipčič⁷⁶, M. Filipuzzi⁴⁴, F. Filthaut¹⁰⁶,
 M. Fincke-Keeler¹⁶⁸, K.D. Finelli¹⁵⁰, M.C.N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁶, A. Firan⁴², A. Fischer²,
 C. Fischer¹³, J. Fischer¹⁷⁴, W.C. Fisher⁹¹, N. Flaschel⁴⁴, I. Fleck¹⁴¹, P. Fleischmann⁹⁰, G.T. Fletcher¹³⁹,
 R.R.M. Fletcher¹²², T. Flick¹⁷⁴, A. Floderus⁸², L.R. Flores Castillo^{61a}, M.J. Flowerdew¹⁰¹, G.T. Forcolin⁸⁵,
 A. Formica¹³⁶, A. Forti⁸⁵, A.G. Foster¹⁹, D. Fournier¹¹⁷, H. Fox⁷³, S. Fracchia¹³, P. Francavilla⁸¹,
 M. Franchini^{22a,22b}, D. Francis³², L. Franconi¹¹⁹, M. Franklin⁵⁸, M. Frate¹⁶², M. Fraternali^{121a,121b},
 D. Freeborn⁷⁹, S.M. Fressard-Batraneanu³², F. Friedrich⁴⁶, D. Froidevaux³², J.A. Frost¹²⁰, C. Fukunaga¹⁵⁶,

E. Fullana Torregrosa ⁸⁴, T. Fusayasu ¹⁰², J. Fuster ¹⁶⁶, C. Gabaldon ⁵⁷, O. Gabizon ¹⁷⁴, A. Gabrielli ^{22a,22b},
 A. Gabrielli ¹⁶, G.P. Gach ^{40a}, S. Gadatsch ³², S. Gadomski ⁵¹, G. Gagliardi ^{52a,52b}, L.G. Gagnon ⁹⁵,
 P. Gagnon ⁶², C. Galea ¹⁰⁶, B. Galhardo ^{126a,126c}, E.J. Gallas ¹²⁰, B.J. Gallop ¹³¹, P. Gallus ¹²⁸, G. Galster ³⁸,
 K.K. Gan ¹¹¹, J. Gao ^{35b,86}, Y. Gao ⁴⁸, Y.S. Gao ^{143,f}, F.M. Garay Walls ⁴⁸, C. García ¹⁶⁶, J.E. García Navarro ¹⁶⁶,
 M. Garcia-Sciveres ¹⁶, R.W. Gardner ³³, N. Garelli ¹⁴³, V. Garonne ¹¹⁹, A. Gascon Bravo ⁴⁴, K. Gasnikova ⁴⁴,
 C. Gatti ⁴⁹, A. Gaudiello ^{52a,52b}, G. Gaudio ^{121a}, L. Gauthier ⁹⁵, I.L. Gavrilenko ⁹⁶, C. Gay ¹⁶⁷, G. Gaycken ²³,
 E.N. Gazis ¹⁰, Z. Gece ¹⁶⁷, C.N.P. Gee ¹³¹, Ch. Geich-Gimbel ²³, M. Geisen ⁸⁴, M.P. Geisler ^{59a},
 C. Gemme ^{52a}, M.H. Genest ⁵⁷, C. Geng ^{35b,o}, S. Gentile ^{132a,132b}, C. Gentsos ¹⁵⁴, S. George ⁷⁸,
 D. Gerbaudo ¹³, A. Gershon ¹⁵³, S. Ghasemi ¹⁴¹, H. Ghazlane ^{135b}, M. Ghneimat ²³, B. Giacobbe ^{22a},
 S. Giagu ^{132a,132b}, P. Giannetti ^{124a,124b}, B. Gibbard ²⁷, S.M. Gibson ⁷⁸, M. Gignac ¹⁶⁷, M. Gilchriese ¹⁶,
 T.P.S. Gillam ³⁰, D. Gillberg ³¹, G. Gilles ¹⁷⁴, D.M. Gingrich ^{3,d}, N. Giokaris ⁹, M.P. Giordani ^{163a,163c},
 F.M. Giorgi ^{22a}, F.M. Giorgi ¹⁷, P.F. Giraud ¹³⁶, P. Giromini ⁵⁸, D. Giugni ^{92a}, F. Giuli ¹²⁰, C. Giuliani ¹⁰¹,
 M. Giulini ^{59b}, B.K. Gjelsten ¹¹⁹, S. Gkaitatzis ¹⁵⁴, I. Gkialas ¹⁵⁴, E.L. Gkoukousis ¹¹⁷, L.K. Gladilin ⁹⁹,
 C. Glasman ⁸³, J. Glatzer ³², P.C.F. Glaysher ⁴⁸, A. Glazov ⁴⁴, M. Goblirsch-Kolb ²⁵, J. Godlewski ⁴¹,
 S. Goldfarb ⁸⁹, T. Golling ⁵¹, D. Golubkov ¹³⁰, A. Gomes ^{126a,126b,126d}, R. Gonçalo ^{126a},
 J. Goncalves Pinto Firmino Da Costa ¹³⁶, G. Gonella ⁵⁰, L. Gonella ¹⁹, A. Gongadze ⁶⁶,
 S. González de la Hoz ¹⁶⁶, G. Gonzalez Parra ¹³, S. Gonzalez-Sevilla ⁵¹, L. Goossens ³², P.A. Gorbounov ⁹⁷,
 H.A. Gordon ²⁷, I. Gorelov ¹⁰⁵, B. Gorini ³², E. Gorini ^{74a,74b}, A. Gorišek ⁷⁶, E. Gornicki ⁴¹, A.T. Goshaw ⁴⁷,
 C. Gössling ⁴⁵, M.I. Gostkin ⁶⁶, C.R. Goudet ¹¹⁷, D. Goujdami ^{135c}, A.G. Goussiou ¹³⁸, N. Govender ^{145b,p},
 E. Gozani ¹⁵², L. Graber ⁵⁶, I. Grabowska-Bold ^{40a}, P.O.J. Gradin ⁵⁷, P. Grafström ^{22a,22b}, J. Gramling ⁵¹,
 E. Gramstad ¹¹⁹, S. Grancagnolo ¹⁷, V. Gratchev ¹²³, P.M. Gravila ^{28e}, H.M. Gray ³², E. Graziani ^{134a},
 Z.D. Greenwood ^{80,q}, C. Grefe ²³, K. Gregersen ⁷⁹, I.M. Gregor ⁴⁴, P. Grenier ¹⁴³, K. Grevtsov ⁵, J. Griffiths ⁸,
 A.A. Grillo ¹³⁷, K. Grimm ⁷³, S. Grinstein ^{13,r}, Ph. Gris ³⁶, J.-F. Grivaz ¹¹⁷, S. Groh ⁸⁴, J.P. Grohs ⁴⁶,
 E. Gross ¹⁷¹, J. Grosse-Knetter ⁵⁶, G.C. Grossi ⁸⁰, Z.J. Grout ¹⁴⁹, L. Guan ⁹⁰, W. Guan ¹⁷², J. Guenther ⁶³,
 F. Guescini ⁵¹, D. Guest ¹⁶², O. Gueta ¹⁵³, E. Guido ^{52a,52b}, T. Guillemin ⁵, S. Guindon ², U. Gul ⁵⁵,
 C. Gumpert ³², J. Guo ^{35e}, Y. Guo ^{35b,o}, R. Gupta ⁴², S. Gupta ¹²⁰, G. Gustavino ^{132a,132b}, P. Gutierrez ¹¹³,
 N.G. Gutierrez Ortiz ⁷⁹, C. Gutsche ⁴⁶, C. Guyot ¹³⁶, C. Gwenlan ¹²⁰, C.B. Gwilliam ⁷⁵, A. Haas ¹¹⁰,
 C. Haber ¹⁶, H.K. Hadavand ⁸, N. Haddad ^{135e}, A. Hadeef ⁸⁶, S. Hageböck ²³, Z. Hajduk ⁴¹, H. Hakobyan ^{176,*},
 M. Haleem ⁴⁴, J. Haley ¹¹⁴, G. Halladjian ⁹¹, G.D. Hallewell ⁸⁶, K. Hamacher ¹⁷⁴, P. Hamal ¹¹⁵,
 K. Hamano ¹⁶⁸, A. Hamilton ^{145a}, G.N. Hamity ¹³⁹, P.G. Hamnett ⁴⁴, L. Han ^{35b}, K. Hanagaki ^{67,s},
 K. Hanawa ¹⁵⁵, M. Hance ¹³⁷, B. Haney ¹²², S. Hanisch ³², P. Hanke ^{59a}, R. Hanna ¹³⁶, J.B. Hansen ³⁸,
 J.D. Hansen ³⁸, M.C. Hansen ²³, P.H. Hansen ³⁸, K. Hara ¹⁶⁰, A.S. Hard ¹⁷², T. Harenberg ¹⁷⁴, F. Hariri ¹¹⁷,
 S. Harkusha ⁹³, R.D. Harrington ⁴⁸, P.F. Harrison ¹⁶⁹, F. Hartjes ¹⁰⁷, N.M. Hartmann ¹⁰⁰, M. Hasegawa ⁶⁸,
 Y. Hasegawa ¹⁴⁰, A. Hasib ¹¹³, S. Hassani ¹³⁶, S. Haug ¹⁸, R. Hauser ⁹¹, L. Hauswald ⁴⁶, M. Havranek ¹²⁷,
 C.M. Hawkes ¹⁹, R.J. Hawkins ³², D. Hayakawa ¹⁵⁷, D. Hayden ⁹¹, C.P. Hays ¹²⁰, J.M. Hays ⁷⁷,
 H.S. Hayward ⁷⁵, S.J. Haywood ¹³¹, S.J. Head ¹⁹, T. Heck ⁸⁴, V. Hedberg ⁸², L. Heelan ⁸, S. Heim ¹²²,
 T. Heim ¹⁶, B. Heinemann ¹⁶, J.J. Heinrich ¹⁰⁰, L. Heinrich ¹¹⁰, C. Heinz ⁵⁴, J. Hejbal ¹²⁷, L. Helary ³²,
 S. Hellman ^{146a,146b}, C. Hensens ³², J. Henderson ¹²⁰, R.C.W. Henderson ⁷³, Y. Heng ¹⁷², S. Henkelmann ¹⁶⁷,
 A.M. Henriques Correia ³², S. Henrot-Versille ¹¹⁷, G.H. Herbert ¹⁷, V. Herget ¹⁷³, Y. Hernández Jiménez ¹⁶⁶,
 G. Herten ⁵⁰, R. Hertenberger ¹⁰⁰, L. Hervas ³², G.G. Hesketh ⁷⁹, N.P. Hessey ¹⁰⁷, J.W. Hetherly ⁴²,
 R. Hickling ⁷⁷, E. Higón-Rodríguez ¹⁶⁶, E. Hill ¹⁶⁸, J.C. Hill ³⁰, K.H. Hiller ⁴⁴, S.J. Hillier ¹⁹, I. Hincliffe ¹⁶,
 E. Hines ¹²², R.R. Hinman ¹⁶, M. Hirose ⁵⁰, D. Hirschbuehl ¹⁷⁴, J. Hobbs ¹⁴⁸, N. Hod ^{159a},
 M.C. Hodgkinson ¹³⁹, P. Hodgson ¹³⁹, A. Hoecker ³², M.R. Hoferkamp ¹⁰⁵, F. Hoenig ¹⁰⁰, D. Hohn ²³,
 T.R. Holmes ¹⁶, M. Homann ⁴⁵, T.M. Hong ¹²⁵, B.H. Hooberman ¹⁶⁵, W.H. Hopkins ¹¹⁶, Y. Horii ¹⁰³,
 A.J. Horton ¹⁴², J.-Y. Hostachy ⁵⁷, S. Hou ¹⁵¹, A. Hoummada ^{135a}, J. Howarth ⁴⁴, M. Hrabovsky ¹¹⁵,
 I. Hristova ¹⁷, J. Hrivnac ¹¹⁷, T. Hryn'ova ⁵, A. Hrynevich ⁹⁴, C. Hsu ^{145c}, P.J. Hsu ^{151,t}, S.-C. Hsu ¹³⁸, D. Hu ³⁷,
 Q. Hu ^{35b}, S. Hu ^{35e}, Y. Huang ⁴⁴, Z. Hubacek ¹²⁸, F. Hubaut ⁸⁶, F. Huegging ²³, T.B. Huffman ¹²⁰,
 E.W. Hughes ³⁷, G. Hughes ⁷³, M. Huhtinen ³², P. Huo ¹⁴⁸, N. Huseynov ^{66,b}, J. Huston ⁹¹, J. Huth ⁵⁸,
 G. Iacobucci ⁵¹, G. Iakovidis ²⁷, I. Ibragimov ¹⁴¹, L. Iconomidou-Fayard ¹¹⁷, E. Ideal ¹⁷⁵, Z. Idrissi ^{135e},
 P. Iengo ³², O. Igonkina ^{107,u}, T. Iizawa ¹⁷⁰, Y. Ikegami ⁶⁷, M. Ikeno ⁶⁷, Y. Ilchenko ^{11,v}, D. Iliadis ¹⁵⁴,
 N. Ilic ¹⁴³, T. Ince ¹⁰¹, G. Introzzi ^{121a,121b}, P. Ioannou ^{9,*}, M. Iodice ^{134a}, K. Iordanidou ³⁷, V. Ippolito ⁵⁸,
 N. Ishijima ¹¹⁸, M. Ishino ¹⁵⁵, M. Ishitsuka ¹⁵⁷, R. Ishmukhametov ¹¹¹, C. Issever ¹²⁰, S. Istin ^{20a}, F. Ito ¹⁶⁰,

J.M. Iturbe Ponce⁸⁵, R. Iuppa^{133a,133b}, W. Iwanski⁴¹, H. Iwasaki⁶⁷, J.M. Izen⁴³, V. Izzo^{104a}, S. Jabbar³, B. Jackson¹²², P. Jackson¹, V. Jain², K.B. Jakobi⁸⁴, K. Jakobs⁵⁰, S. Jakobsen³², T. Jakoubek¹²⁷, D.O. Jamin¹¹⁴, D.K. Jana⁸⁰, E. Jansen⁷⁹, R. Jansky⁶³, J. Janssen²³, M. Janus⁵⁶, G. Jarlskog⁸², N. Javadov^{66,b}, T. Javůrek⁵⁰, F. Jeanneau¹³⁶, L. Jeanty¹⁶, J. Jejelava^{53a,w}, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁹, P. Jenni^{50,x}, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁸, H. Jiang⁶⁵, Y. Jiang^{35b}, S. Jiggins⁷⁹, J. Jimenez Pena¹⁶⁶, S. Jin^{35a}, A. Jinaru^{28b}, O. Jinnouchi¹⁵⁷, P. Johansson¹³⁹, K.A. Johns⁷, W.J. Johnson¹³⁸, K. Jon-And^{146a,146b}, G. Jones¹⁶⁹, R.W.L. Jones⁷³, S. Jones⁷, T.J. Jones⁷⁵, J. Jongmanns^{59a}, P.M. Jorge^{126a,126b}, J. Jovicevic^{159a}, X. Ju¹⁷², A. Juste Rozas^{13,r}, M.K. Köhler¹⁷¹, A. Kaczmarska⁴¹, M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴³, S.J. Kahn⁸⁶, T. Kaji¹⁷⁰, E. Kajomovitz⁴⁷, C.W. Kalderon¹²⁰, A. Kaluza⁸⁴, S. Kama⁴², A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁵, S. Kaneti³⁰, L. Kanjir⁷⁶, V.A. Kantserov⁹⁸, J. Kanzaki⁶⁷, B. Kaplan¹¹⁰, L.S. Kaplan¹⁷², A. Kapliy³³, D. Kar^{145c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M.J. Kareem⁵⁶, E. Karentzos¹⁰, M. Karnevskiy⁸⁴, S.N. Karpov⁶⁶, Z.M. Karpova⁶⁶, K. Karthik¹¹⁰, V. Kartvelishvili⁷³, A.N. Karyukhin¹³⁰, K. Kasahara¹⁶⁰, L. Kashif¹⁷², R.D. Kass¹¹¹, A. Kastanas¹⁵, Y. Kataoka¹⁵⁵, C. Kato¹⁵⁵, A. Katre⁵¹, J. Katzy⁴⁴, K. Kawagoe⁷¹, T. Kawamoto¹⁵⁵, G. Kawamura⁵⁶, V.F. Kazanin^{109,c}, R. Keeler¹⁶⁸, R. Kehoe⁴², J.S. Keller⁴⁴, J.J. Kempster⁷⁸, K. Kentaro¹⁰³, H. Keoshkerian¹⁵⁸, O. Kepka¹²⁷, B.P. Kerševan⁷⁶, S. Kersten¹⁷⁴, R.A. Keyes⁸⁸, M. Khader¹⁶⁵, F. Khalil-zada¹², A. Khanov¹¹⁴, A.G. Kharlamov^{109,c}, T.J. Khoo⁵¹, V. Khovanskiy⁹⁷, E. Khramov⁶⁶, J. Khubua^{53b,y}, S. Kido⁶⁸, C.R. Kilby⁷⁸, H.Y. Kim⁸, S.H. Kim¹⁶⁰, Y.K. Kim³³, N. Kimura¹⁵⁴, O.M. Kind¹⁷, B.T. King⁷⁵, M. King¹⁶⁶, S.B. King¹⁶⁷, J. Kirk¹³¹, A.E. Kiryunin¹⁰¹, T. Kishimoto¹⁵⁵, D. Kisielewska^{40a}, F. Kiss⁵⁰, K. Kiuchi¹⁶⁰, O. Kivernyk¹³⁶, E. Kladiva^{144b}, M.H. Klein³⁷, M. Klein⁷⁵, U. Klein⁷⁵, K. Kleinknecht⁸⁴, P. Klimek¹⁰⁸, A. Klimentov²⁷, R. Klingenberg⁴⁵, J.A. Klinger¹³⁹, T. Klioutchnikova³², E.-E. Kluge^{59a}, P. Kluit¹⁰⁷, S. Kluth¹⁰¹, J. Knapik⁴¹, E. Kneringer⁶³, E.B.F.G. Knoops⁸⁶, A. Knue⁵⁵, A. Kobayashi¹⁵⁵, D. Kobayashi¹⁵⁷, T. Kobayashi¹⁵⁵, M. Kobel⁴⁶, M. Kocian¹⁴³, P. Kodys¹²⁹, N.M. Koehler¹⁰¹, T. Koffas³¹, E. Koffeman¹⁰⁷, T. Koi¹⁴³, H. Kolanoski¹⁷, M. Kolb^{59b}, I. Koletsou⁵, A.A. Komar^{96,*}, Y. Komori¹⁵⁵, T. Kondo⁶⁷, N. Kondrashova⁴⁴, K. Köneke⁵⁰, A.C. König¹⁰⁶, T. Kono^{67,z}, R. Konoplich^{110,aa}, N. Konstantinidis⁷⁹, R. Kopeliansky⁶², S. Koperny^{40a}, L. Köpke⁸⁴, A.K. Kopp⁵⁰, K. Korcyl⁴¹, K. Kordas¹⁵⁴, A. Korn⁷⁹, A.A. Korol^{109,c}, I. Korolkov¹³, E.V. Korolkova¹³⁹, O. Kortner¹⁰¹, S. Kortner¹⁰¹, T. Kosek¹²⁹, V.V. Kostyukhin²³, A. Kotwal⁴⁷, A. Kourkoumeli-Charalampidi¹⁵⁴, C. Kourkoumelis⁹, V. Kouskoura²⁷, A.B. Kowalewska⁴¹, R. Kowalewski¹⁶⁸, T.Z. Kowalski^{40a}, C. Kozakai¹⁵⁵, W. Kozanecki¹³⁶, A.S. Kozhin¹³⁰, V.A. Kramarenko⁹⁹, G. Kramberger⁷⁶, D. Krasnopevtsev⁹⁸, M.W. Krasny⁸¹, A. Krasznahorkay³², A. Kravchenko²⁷, M. Kretz^{59c}, J. Kretzschmar⁷⁵, K. Kreutzfeldt⁵⁴, P. Krieger¹⁵⁸, K. Krizka³³, K. Kroeninger⁴⁵, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²³, J. Krstic¹⁴, U. Kruchonak⁶⁶, H. Krüger²³, N. Krumnack⁶⁵, A. Kruse¹⁷², M.C. Kruse⁴⁷, M. Kruskal²⁴, T. Kubota⁸⁹, H. Kucuk⁷⁹, S. Kuday^{4b}, J.T. Kuechler¹⁷⁴, S. Kuehn⁵⁰, A. Kugel^{59c}, F. Kuger¹⁷³, A. Kuhl¹³⁷, T. Kuhl⁴⁴, V. Kukhtin⁶⁶, R. Kukla¹³⁶, Y. Kulchitsky⁹³, S. Kuleshov^{34b}, M. Kuna^{132a,132b}, T. Kunigo⁶⁹, A. Kupco¹²⁷, H. Kurashige⁶⁸, Y.A. Kurochkin⁹³, V. Kus¹²⁷, E.S. Kuwertz¹⁶⁸, M. Kuze¹⁵⁷, J. Kvita¹¹⁵, T. Kwan¹⁶⁸, D. Kyriazopoulos¹³⁹, A. La Rosa¹⁰¹, J.L. La Rosa Navarro^{26d}, L. La Rotonda^{39a,39b}, C. Lacasta¹⁶⁶, F. Lacava^{132a,132b}, J. Lacey³¹, H. Lacker¹⁷, D. Lacour⁸¹, V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁶, R. Lafaye⁵, B. Laforge⁸¹, T. Lagouri¹⁷⁵, S. Lai⁵⁶, S. Lammers⁶², W. Lampl⁷, E. Lançon¹³⁶, U. Landgraf⁵⁰, M.P.J. Landon⁷⁷, M.C. Lanfermann⁵¹, V.S. Lang^{59a}, J.C. Lange¹³, A.J. Lankford¹⁶², F. Lanni²⁷, K. Lantsch²³, A. Lanza^{121a}, S. Laplace⁸¹, C. Lapoire³², J.F. Laporte¹³⁶, T. Lari^{92a}, F. Lasagni Manghi^{22a,22b}, M. Lassnig³², P. Laurelli⁴⁹, W. Lavrijsen¹⁶, A.T. Law¹³⁷, P. Laycock⁷⁵, T. Lazovich⁵⁸, M. Lazzaroni^{92a,92b}, B. Le⁸⁹, O. Le Dortz⁸¹, E. Le Guirriec⁸⁶, E.P. Le Quilleuc¹³⁶, M. LeBlanc¹⁶⁸, T. LeCompte⁶, F. Ledroit-Guillon⁵⁷, C.A. Lee²⁷, S.C. Lee¹⁵¹, L. Lee¹, B. Lefebvre⁸⁸, G. Lefebvre⁸¹, M. Lefebvre¹⁶⁸, F. Legger¹⁰⁰, C. Leggett¹⁶, A. Lehan⁷⁵, G. Lehmann Miotto³², X. Lei⁷, W.A. Leight³¹, A. Leisos^{154,ab}, A.G. Leister¹⁷⁵, M.A.L. Leite^{26d}, R. Leitner¹²⁹, D. Lellouch¹⁷¹, B. Lemmer⁵⁶, K.J.C. Leney⁷⁹, T. Lenz²³, B. Lenzi³², R. Leone⁷, S. Leone^{124a,124b}, C. Leonidopoulos⁴⁸, S. Leontsinis¹⁰, G. Lerner¹⁴⁹, C. Leroy⁹⁵, A.A.J. Lesage¹³⁶, C.G. Lester³⁰, M. Levchenko¹²³, J. Levêque⁵, D. Levin⁹⁰, L.J. Levinson¹⁷¹, M. Levy¹⁹, D. Lewis⁷⁷, A.M. Leyko²³, M. Leyton⁴³, B. Li^{35b,o}, C. Li^{35b}, H. Li¹⁴⁸, H.L. Li³³, L. Li⁴⁷, L. Li^{35e}, Q. Li^{35a}, S. Li⁴⁷, X. Li⁸⁵, Y. Li¹⁴¹, Z. Liang^{35a}, B. Liberti^{133a}, A. Liblong¹⁵⁸, P. Lichard³², K. Lie¹⁶⁵, J. Liebal²³, W. Liebig¹⁵, A. Limosani¹⁵⁰, S.C. Lin^{151,ac}, T.H. Lin⁸⁴, B.E. Lindquist¹⁴⁸, A.E. Lioni⁵¹, E. Lipeles¹²², A. Lipniacka¹⁵, M. Lisovsky^{59b}, T.M. Liss¹⁶⁵, A. Lister¹⁶⁷,

A.M. Litke¹³⁷, B. Liu^{151,ad}, D. Liu¹⁵¹, H. Liu⁹⁰, H. Liu²⁷, J. Liu⁸⁶, J.B. Liu^{35b}, K. Liu⁸⁶, L. Liu¹⁶⁵, M. Liu⁴⁷,
 M. Liu^{35b}, Y.L. Liu^{35b}, Y. Liu^{35b}, M. Livan^{121a,121b}, A. Lleres⁵⁷, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁷,
 F. Lo Sterzo¹⁵¹, E. Lobodzinska⁴⁴, P. Loch⁷, W.S. Lockman¹³⁷, F.K. Loebinger⁸⁵, A.E. Loevschall-Jensen³⁸,
 K.M. Loew²⁵, A. Loginov¹⁷⁵, T. Lohse¹⁷, K. Lohwasser⁴⁴, M. Lokajicek¹²⁷, B.A. Long²⁴, J.D. Long¹⁶⁵,
 R.E. Long⁷³, L. Longo^{74a,74b}, K.A. Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹³⁹,
 I. Lopez Paz¹³, A. Lopez Solis⁸¹, J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶², M. Losada²¹, P.J. Lösel¹⁰⁰,
 X. Lou^{35a}, A. Lounis¹¹⁷, J. Love⁶, P.A. Love⁷³, H. Lu^{61a}, N. Lu⁹⁰, H.J. Lubatti¹³⁸, C. Luci^{132a,132b},
 A. Lucotte⁵⁷, C. Luedtke⁵⁰, F. Luehring⁶², W. Lukas⁶³, L. Luminari^{132a}, O. Lundberg^{146a,146b},
 B. Lund-Jensen¹⁴⁷, P.M. Luzi⁸¹, D. Lynn²⁷, R. Lysak¹²⁷, E. Lytken⁸², V. Lyubushkin⁶⁶, H. Ma²⁷,
 L.L. Ma^{35d}, Y. Ma^{35d}, G. Maccarrone⁴⁹, A. Macchiolo¹⁰¹, C.M. Macdonald¹³⁹, B. Maček⁷⁶,
 J. Machado Miguens^{122,126b}, D. Madaffari⁸⁶, R. Madar³⁶, H.J. Maddocks¹⁶⁴, W.F. Mader⁴⁶, A. Madsen⁴⁴,
 J. Maeda⁶⁸, S. Maeland¹⁵, T. Maeno²⁷, A. Maevskiy⁹⁹, E. Magradze⁵⁶, J. Mahlstedt¹⁰⁷, C. Maiani¹¹⁷,
 C. Maidantchik^{26a}, A.A. Maier¹⁰¹, T. Maier¹⁰⁰, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁷,
 N. Makovec¹¹⁷, B. Malaescu⁸¹, Pa. Malecki⁴¹, V.P. Maleev¹²³, F. Malek⁵⁷, U. Mallik⁶⁴, D. Malon⁶,
 C. Malone¹⁴³, S. Maltezos¹⁰, S. Malyukov³², J. Mamuzic¹⁶⁶, G. Mancini⁴⁹, B. Mandelli³², L. Mandelli^{92a},
 I. Mandić⁷⁶, J. Maneira^{126a,126b}, L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos^{159b}, A. Mann¹⁰⁰,
 A. Manousos³², B. Mansoulie¹³⁶, J.D. Mansour^{35a}, R. Mantifel⁸⁸, M. Mantoani⁵⁶, S. Manzoni^{92a,92b},
 L. Mapelli³², G. Marceca²⁹, L. March⁵¹, G. Marchiori⁸¹, M. Marcisovsky¹²⁷, M. Marjanovic¹⁴,
 D.E. Marley⁹⁰, F. Marroquim^{26a}, S.P. Marsden⁸⁵, Z. Marshall¹⁶, S. Marti-Garcia¹⁶⁶, B. Martin⁹¹,
 T.A. Martin¹⁶⁹, V.J. Martin⁴⁸, B. Martin dit Latour¹⁵, M. Martinez^{13,r}, V.I. Martinez Outschoorn¹⁶⁵,
 S. Martin-Haugh¹³¹, V.S. Martoiu^{28b}, A.C. Martyniuk⁷⁹, M. Marx¹³⁸, A. Marzin³², L. Masetti⁸⁴,
 T. Mashimo¹⁵⁵, R. Mashinistov⁹⁶, J. Masik⁸⁵, A.L. Maslennikov^{109,c}, I. Massa^{22a,22b}, L. Massa^{22a,22b},
 P. Mastrandrea⁵, A. Mastroberardino^{39a,39b}, T. Masubuchi¹⁵⁵, P. Mättig¹⁷⁴, J. Mattmann⁸⁴, J. Maurer^{28b},
 S.J. Maxfield⁷⁵, D.A. Maximov^{109,c}, R. Mazini¹⁵¹, S.M. Mazza^{92a,92b}, N.C. Mc Fadden¹⁰⁵,
 G. Mc Goldrick¹⁵⁸, S.P. Mc Kee⁹⁰, A. McCarn⁹⁰, R.L. McCarthy¹⁴⁸, T.G. McCarthy¹⁰¹, L.I. McClymont⁷⁹,
 E.F. McDonald⁸⁹, J.A. MCFayden⁷⁹, G. Mchedlidze⁵⁶, S.J. McMahon¹³¹, R.A. McPherson^{168,l},
 M. Medinnis⁴⁴, S. Meehan¹³⁸, S. Mehlhase¹⁰⁰, A. Mehta⁷⁵, K. Meier^{59a}, C. Meineck¹⁰⁰, B. Meirose⁴³,
 D. Melini¹⁶⁶, B.R. Mellado Garcia^{145c}, M. Melo^{144a}, F. Meloni¹⁸, A. Mengarelli^{22a,22b}, S. Menke¹⁰¹,
 E. Meoni¹⁶¹, S. Mergelmeyer¹⁷, P. Mermod⁵¹, L. Merola^{104a,104b}, C. Meroni^{92a}, F.S. Merritt³³,
 A. Messina^{132a,132b}, J. Metcalfe⁶, A.S. Mete¹⁶², C. Meyer⁸⁴, C. Meyer¹²², J-P. Meyer¹³⁶, J. Meyer¹⁰⁷,
 H. Meyer Zu Theenhausen^{59a}, F. Miano¹⁴⁹, R.P. Middleton¹³¹, S. Miglioranza^{52a,52b}, L. Mijović⁴⁸,
 G. Mikenberg¹⁷¹, M. Mikestikova¹²⁷, M. Mikuž⁷⁶, M. Milesi⁸⁹, A. Milic⁶³, D.W. Miller³³, C. Mills⁴⁸,
 A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, A.A. Minaenko¹³⁰, Y. Minami¹⁵⁵, I.A. Minashvili⁶⁶, A.I. Mincer¹¹⁰,
 B. Mindur^{40a}, M. Mineev⁶⁶, Y. Ming¹⁷², L.M. Mir¹³, K.P. Mistry¹²², T. Mitani¹⁷⁰, J. Mitrevski¹⁰⁰,
 V.A. Mitsou¹⁶⁶, A. Miucci⁵¹, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁸², T. Moa^{146a,146b}, K. Mochizuki⁹⁵,
 S. Mohapatra³⁷, S. Molander^{146a,146b}, R. Moles-Valls²³, R. Monden⁶⁹, M.C. Mondragon⁹¹, K. Mönig⁴⁴,
 J. Monk³⁸, E. Monnier⁸⁶, A. Montalbano¹⁴⁸, J. Montejo Berlingen³², F. Monticelli⁷², S. Monzani^{92a,92b},
 R.W. Moore³, N. Morange¹¹⁷, D. Moreno²¹, M. Moreno Llácer⁵⁶, P. Morettini^{52a}, D. Mori¹⁴², T. Mori¹⁵⁵,
 M. Morii⁵⁸, M. Morinaga¹⁵⁵, V. Morisbak¹¹⁹, S. Moritz⁸⁴, A.K. Morley¹⁵⁰, G. Mornacchi³², J.D. Morris⁷⁷,
 S.S. Mortensen³⁸, L. Morvaj¹⁴⁸, M. Mosidze^{53b}, J. Moss¹⁴³, K. Motohashi¹⁵⁷, R. Mount¹⁴³,
 E. Mountricha²⁷, S.V. Mouraviev^{96,*}, E.J.W. Moyses⁸⁷, S. Muanza⁸⁶, R.D. Mudd¹⁹, F. Mueller¹⁰¹,
 J. Mueller¹²⁵, R.S.P. Mueller¹⁰⁰, T. Mueller³⁰, D. Muenstermann⁷³, P. Mullen⁵⁵, G.A. Mullier¹⁸,
 F.J. Munoz Sanchez⁸⁵, J.A. Murillo Quijada¹⁹, W.J. Murray^{169,131}, H. Musheghyan⁵⁶, M. Muškinja⁷⁶,
 A.G. Myagkov^{130,ae}, M. Myska¹²⁸, B.P. Nachman¹⁴³, O. Nackenhorst⁵¹, K. Nagai¹²⁰, R. Nagai^{67,z},
 K. Nagano⁶⁷, Y. Nagasaka⁶⁰, K. Nagata¹⁶⁰, M. Nagel⁵⁰, E. Nagy⁸⁶, A.M. Nairz³², Y. Nakahama¹⁰³,
 K. Nakamura⁶⁷, T. Nakamura¹⁵⁵, I. Nakano¹¹², H. Namasivayam⁴³, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹,
 D.I. Narrias Villar^{59a}, I. Naryshkin¹²³, T. Naumann⁴⁴, G. Navarro²¹, R. Nayyar⁷, H.A. Neal⁹⁰,
 P.Yu. Nechaeva⁹⁶, T.J. Neep⁸⁵, A. Negri^{121a,121b}, M. Negrini^{22a}, S. Nektarijevic¹⁰⁶, C. Nellist¹¹⁷,
 A. Nelson¹⁶², S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A.A. Nepomuceno^{26a}, M. Nessi^{32,af}, M.S. Neubauer¹⁶⁵,
 M. Neumann¹⁷⁴, R.M. Neves¹¹⁰, P. Nevski²⁷, P.R. Newman¹⁹, D.H. Nguyen⁶, T. Nguyen Manh⁹⁵,
 R.B. Nickerson¹²⁰, R. Nicolaidou¹³⁶, J. Nielsen¹³⁷, A. Nikiforov¹⁷, V. Nikolaenko^{130,ae}, I. Nikolic-Audit⁸¹,
 K. Nikolopoulos¹⁹, J.K. Nilsen¹¹⁹, P. Nilsson²⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁵,

M. Nomachi¹¹⁸, I. Nomidis³¹, T. Nooney⁷⁷, S. Norberg¹¹³, M. Nordberg³², N. Norjoharuddeen¹²⁰,
 O. Novgorodova⁴⁶, S. Nowak¹⁰¹, M. Nozaki⁶⁷, L. Nozka¹¹⁵, K. Ntekas¹⁰, E. Nurse⁷⁹, F. Nuti⁸⁹,
 F. O'grady⁷, D.C. O'Neil¹⁴², A.A. O'Rourke⁴⁴, V. O'Shea⁵⁵, F.G. Oakham^{31,d}, H. Oberlack¹⁰¹,
 T. Obermann²³, J. Ocariz⁸¹, A. Ochi⁶⁸, I. Ochoa³⁷, J.P. Ochoa-Ricoux^{34a}, S. Oda⁷¹, S. Odaka⁶⁷,
 H. Ogren⁶², A. Oh⁸⁵, S.H. Oh⁴⁷, C.C. Ohm¹⁶, H. Ohman¹⁶⁴, H. Oide³², H. Okawa¹⁶⁰, Y. Okumura¹⁵⁵,
 T. Okuyama⁶⁷, A. Olariu^{28b}, L.F. Oleiro Seabra^{126a}, S.A. Olivares Pino⁴⁸, D. Oliveira Damazio²⁷,
 A. Olszewski⁴¹, J. Olszowska⁴¹, A. Onofre^{126a,126e}, K. Onogi¹⁰³, P.U.E. Onyisi^{11,v}, M.J. Oreglia³³,
 Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{61b}, R.S. Orr¹⁵⁸, B. Osculati^{52a,52b}, R. Ospanov⁸⁵,
 G. Otero y Garzon²⁹, H. Otono⁷¹, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁶, K.P. Oussoren¹⁰⁷,
 Q. Ouyang^{35a}, M. Owen⁵⁵, R.E. Owen¹⁹, V.E. Ozcan^{20a}, N. Ozturk⁸, K. Pachal¹⁴², A. Pacheco Pages¹³,
 L. Pacheco Rodriguez¹³⁶, C. Padilla Aranda¹³, M. Pagáčová⁵⁰, S. Pagan Griso¹⁶, F. Paige²⁷, P. Pais⁸⁷,
 K. Pajchel¹¹⁹, G. Palacino^{159b}, S. Palestini³², M. Palka^{40b}, D. Pallin³⁶, E.St. Panagiotopoulou¹⁰,
 C.E. Pandini⁸¹, J.G. Panduro Vazquez⁷⁸, P. Pani^{146a,146b}, S. Panitkin²⁷, D. Pantea^{28b}, L. Paolozzi⁵¹,
 Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁴, A. Paramonov⁶, D. Paredes Hernandez¹⁷⁵, A.J. Parker⁷³,
 M.A. Parker³⁰, K.A. Parker¹³⁹, F. Parodi^{52a,52b}, J.A. Parsons³⁷, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁵⁸,
 E. Pasqualucci^{132a}, S. Passaggio^{52a}, Fr. Pastore⁷⁸, G. Pásztor^{31,ag}, S. Patariaia¹⁷⁴, J.R. Pater⁸⁵, T. Pauly³²,
 J. Pearce¹⁶⁸, B. Pearson¹¹³, L.E. Pedersen³⁸, M. Pedersen¹¹⁹, S. Pedraza Lopez¹⁶⁶, R. Pedro^{126a,126b},
 S.V. Peleganchuk^{109,c}, O. Penc¹²⁷, C. Peng^{35a}, H. Peng^{35b}, J. Penwell⁶², B.S. Peralva^{26b}, M.M. Perego¹³⁶,
 D.V. Perepelitsa²⁷, E. Perez Codina^{159a}, L. Perini^{92a,92b}, H. Pernegger³², S. Perrella^{104a,104b}, R. Peschke⁴⁴,
 V.D. Peshekhonov⁶⁶, K. Peters⁴⁴, R.F.Y. Peters⁸⁵, B.A. Petersen³², T.C. Petersen³⁸, E. Petit⁵⁷, A. Petridis¹,
 C. Petridou¹⁵⁴, P. Petroff¹¹⁷, E. Petrolo^{132a}, M. Petrov¹²⁰, F. Petrucci^{134a,134b}, N.E. Pettersson⁸⁷,
 A. Peyaud¹³⁶, R. Pezoa^{34b}, P.W. Phillips¹³¹, G. Piacquadio¹⁴³, E. Pianori¹⁶⁹, A. Picazio⁸⁷, E. Piccaro⁷⁷,
 M. Piccinini^{22a,22b}, M.A. Pickering¹²⁰, R. Piegaia²⁹, J.E. Pilcher³³, A.D. Pilkington⁸⁵, A.W.J. Pin⁸⁵,
 M. Pinamonti^{163a,163c,ah}, J.L. Pinfold³, A. Pingel³⁸, S. Pires⁸¹, H. Pirumov⁴⁴, M. Pitt¹⁷¹, L. Plazak^{144a},
 M.-A. Pleier²⁷, V. Pleskot⁸⁴, E. Plotnikova⁶⁶, P. Plucinski⁹¹, D. Pluth⁶⁵, R. Poettgen^{146a,146b},
 L. Poggioli¹¹⁷, D. Pohl²³, G. Polesello^{121a}, A. Poley⁴⁴, A. Policicchio^{39a,39b}, R. Polifka¹⁵⁸, A. Polini^{22a},
 C.S. Pollard⁵⁵, V. Polychronakos²⁷, K. Pommès³², L. Pontecorvo^{132a}, B.G. Pope⁹¹, G.A. Popeneciu^{28c},
 D.S. Popovic¹⁴, A. Poppleton³², S. Pospisil¹²⁸, K. Potamianos¹⁶, I.N. Potrap⁶⁶, C.J. Potter³⁰,
 C.T. Potter¹¹⁶, G. Poulard³², J. Poveda³², V. Pozdnyakov⁶⁶, M.E. Pozo Astigarraga³², P. Pralavorio⁸⁶,
 A. Pranko¹⁶, S. Prell⁶⁵, D. Price⁸⁵, L.E. Price⁶, M. Primavera^{74a}, S. Prince⁸⁸, K. Prokofiev^{61c},
 F. Prokoshin^{34b}, S. Protopopescu²⁷, J. Proudfoot⁶, M. Przybycien^{40a}, D. Puddu^{134a,134b}, M. Purohit^{27,ai},
 P. Puzo¹¹⁷, J. Qian⁹⁰, G. Qin⁵⁵, Y. Qin⁸⁵, A. Quadt⁵⁶, W.B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸⁵,
 D. Quilty⁵⁵, S. Raddum¹¹⁹, V. Radeka²⁷, V. Radescu^{59b}, S.K. Radhakrishnan¹⁴⁸, P. Radloff¹¹⁶, P. Rados⁸⁹,
 F. Ragusa^{92a,92b}, G. Rahal¹⁷⁷, J.A. Raine⁸⁵, S. Rajagopalan²⁷, M. Rammensee³², C. Rangel-Smith¹⁶⁴,
 M.G. Ratti^{92a,92b}, F. Rauscher¹⁰⁰, S. Rave⁸⁴, T. Ravenscroft⁵⁵, I. Ravinovich¹⁷¹, M. Raymond³²,
 A.L. Read¹¹⁹, N.P. Readioff⁷⁵, M. Reale^{74a,74b}, D.M. Rebuzzi^{121a,121b}, A. Redelbach¹⁷³, G. Redlinger²⁷,
 R. Reece¹³⁷, K. Reeves⁴³, L. Rehnisch¹⁷, J. Reichert¹²², H. Reisin²⁹, C. Rembser³², H. Ren^{35a},
 M. Rescigno^{132a}, S. Resconi^{92a}, O.L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹,
 S. Richter⁷⁹, E. Richter-Was^{40b}, O. Ricken²³, M. Ridel⁸¹, P. Rieck¹⁷, C.J. Riegel¹⁷⁴, J. Rieger⁵⁶, O. Rifki¹¹³,
 M. Rijssenbeek¹⁴⁸, A. Rimoldi^{121a,121b}, M. Rimoldi¹⁸, L. Rinaldi^{22a}, B. Ristić⁵¹, E. Ritsch³², I. Riu¹³,
 F. Rizatdinova¹¹⁴, E. Rizvi⁷⁷, C. Rizzi¹³, S.H. Robertson^{88,l}, A. Robichaud-Veronneau⁸⁸, D. Robinson³⁰,
 J.E.M. Robinson⁴⁴, A. Robson⁵⁵, C. Roda^{124a,124b}, Y. Rodina⁸⁶, A. Rodriguez Perez¹³,
 D. Rodriguez Rodriguez¹⁶⁶, S. Roe³², C.S. Rogan⁵⁸, O. Røhne¹¹⁹, A. Romaniouk⁹⁸, M. Romano^{22a,22b},
 S.M. Romano Saez³⁶, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁸, M. Ronzani⁵⁰, L. Roos⁸¹, E. Ros¹⁶⁶,
 S. Rosati^{132a}, K. Rosbach⁵⁰, P. Rose¹³⁷, O. Rosenthal¹⁴¹, N.-A. Rosien⁵⁶, V. Rossetti^{146a,146b},
 E. Rossi^{104a,104b}, L.P. Rossi^{52a}, J.H.N. Rosten³⁰, R. Rosten¹³⁸, M. Rotaru^{28b}, I. Roth¹⁷¹, J. Rothberg¹³⁸,
 D. Rousseau¹¹⁷, C.R. Royon¹³⁶, A. Rozanov⁸⁶, Y. Rozen¹⁵², X. Ruan^{145c}, F. Rubbo¹⁴³, M.S. Rudolph¹⁵⁸,
 F. Rühr⁵⁰, A. Ruiz-Martinez³¹, Z. Rurikova⁵⁰, N.A. Rusakovich⁶⁶, A. Ruschke¹⁰⁰, H.L. Russell¹³⁸,
 J.P. Rutherford⁷, N. Ruthmann³², Y.F. Ryabov¹²³, M. Rybar¹⁶⁵, G. Rybkin¹¹⁷, S. Ryu⁶, A. Ryzhov¹³⁰,
 G.F. Rzehorz⁵⁶, A.F. Saavedra¹⁵⁰, G. Sabato¹⁰⁷, S. Sacerdoti²⁹, H.F.W. Sadrozinski¹³⁷, R. Sadykov⁶⁶,
 F. Safai Tehrani^{132a}, P. Saha¹⁰⁸, M. Sahinsoy^{59a}, M. Saimpert¹³⁶, T. Saito¹⁵⁵, H. Sakamoto¹⁵⁵,
 Y. Sakurai¹⁷⁰, G. Salamanna^{134a,134b}, A. Salamon^{133a,133b}, J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁷,

P.H. Sales De Bruin ¹³⁸, D. Salihagic ¹⁰¹, A. Salnikov ¹⁴³, J. Salt ¹⁶⁶, D. Salvatore ^{39a,39b}, F. Salvatore ¹⁴⁹, A. Salvucci ^{61a}, A. Salzburger ³², D. Sammel ⁵⁰, D. Sampsonidis ¹⁵⁴, A. Sanchez ^{104a,104b}, J. Sánchez ¹⁶⁶, V. Sanchez Martinez ¹⁶⁶, H. Sandaker ¹¹⁹, R.L. Sandbach ⁷⁷, H.G. Sander ⁸⁴, M. Sandhoff ¹⁷⁴, C. Sandoval ²¹, R. Sandstroem ¹⁰¹, D.P.C. Sankey ¹³¹, M. Sannino ^{52a,52b}, A. Sansoni ⁴⁹, C. Santoni ³⁶, R. Santonico ^{133a,133b}, H. Santos ^{126a}, I. Santoyo Castillo ¹⁴⁹, K. Sapp ¹²⁵, A. Saprionov ⁶⁶, J.G. Saraiva ^{126a,126d}, B. Sarrazin ²³, O. Sasaki ⁶⁷, Y. Sasaki ¹⁵⁵, K. Sato ¹⁶⁰, G. Sauvage ^{5,*}, E. Sauvan ⁵, G. Savage ⁷⁸, P. Savard ^{158,d}, N. Savic ¹⁰¹, C. Sawyer ¹³¹, L. Sawyer ^{80,q}, J. Saxon ³³, C. Sbarra ^{22a}, A. Sbrizzi ^{22a,22b}, T. Scanlon ⁷⁹, D.A. Scannicchio ¹⁶², M. Scarcella ¹⁵⁰, V. Scarfone ^{39a,39b}, J. Schaarschmidt ¹⁷¹, P. Schacht ¹⁰¹, B.M. Schachtner ¹⁰⁰, D. Schaefer ³², R. Schaefer ⁴⁴, J. Schaeffer ⁸⁴, S. Schaepe ²³, S. Schaezel ^{59b}, U. Schäfer ⁸⁴, A.C. Schaffer ¹¹⁷, D. Schaile ¹⁰⁰, R.D. Schamberger ¹⁴⁸, V. Scharf ^{59a}, V.A. Schegelsky ¹²³, D. Scheirich ¹²⁹, M. Schernau ¹⁶², C. Schiavi ^{52a,52b}, S. Schier ¹³⁷, C. Schillo ⁵⁰, M. Schioppa ^{39a,39b}, S. Schlenker ³², K.R. Schmidt-Sommerfeld ¹⁰¹, K. Schmieden ³², C. Schmitt ⁸⁴, S. Schmitt ⁴⁴, S. Schmitz ⁸⁴, B. Schneider ^{159a}, U. Schnoor ⁵⁰, L. Schoeffel ¹³⁶, A. Schoening ^{59b}, B.D. Schoenrock ⁹¹, E. Schopf ²³, M. Schott ⁸⁴, J. Schovancova ⁸, S. Schramm ⁵¹, M. Schreyer ¹⁷³, N. Schuh ⁸⁴, A. Schulte ⁸⁴, M.J. Schultens ²³, H.-C. Schultz-Coulon ^{59a}, H. Schulz ¹⁷, M. Schumacher ⁵⁰, B.A. Schumm ¹³⁷, Ph. Schune ¹³⁶, A. Schwartzman ¹⁴³, T.A. Schwarz ⁹⁰, H. Schweiger ⁸⁵, Ph. Schwemling ¹³⁶, R. Schwienhorst ⁹¹, J. Schwindling ¹³⁶, T. Schwindt ²³, G. Sciolla ²⁵, F. Scuri ^{124a,124b}, F. Scutti ⁸⁹, J. Searcy ⁹⁰, P. Seema ²³, S.C. Seidel ¹⁰⁵, A. Seiden ¹³⁷, F. Seifert ¹²⁸, J.M. Seixas ^{26a}, G. Sekhniaidze ^{104a}, K. Sekhon ⁹⁰, S.J. Sekula ⁴², D.M. Seliverstov ^{123,*}, N. Semprini-Cesari ^{22a,22b}, C. Serfon ¹¹⁹, L. Serin ¹¹⁷, L. Serkin ^{163a,163b}, M. Sessa ^{134a,134b}, R. Seuster ¹⁶⁸, H. Severini ¹¹³, T. Sfiligoj ⁷⁶, F. Sforza ³², A. Sfyrla ⁵¹, E. Shabalina ⁵⁶, N.W. Shaikh ^{146a,146b}, L.Y. Shan ^{35a}, R. Shang ¹⁶⁵, J.T. Shank ²⁴, M. Shapiro ¹⁶, P.B. Shatalov ⁹⁷, K. Shaw ^{163a,163b}, S.M. Shaw ⁸⁵, A. Shcherbakova ^{146a,146b}, C.Y. Shehu ¹⁴⁹, P. Sherwood ⁷⁹, L. Shi ^{151,qj}, S. Shimizu ⁶⁸, C.O. Shimmin ¹⁶², M. Shimojima ¹⁰², M. Shiyakova ^{66,ak}, A. Shmeleva ⁹⁶, D. Shoaleh Saadi ⁹⁵, M.J. Shochet ³³, S. Shojaii ^{92a,92b}, S. Shrestha ¹¹¹, E. Shulga ⁹⁸, M.A. Shupe ⁷, P. Sicho ¹²⁷, A.M. Sickles ¹⁶⁵, P.E. Sidebo ¹⁴⁷, O. Sidiropoulou ¹⁷³, D. Sidorov ¹¹⁴, A. Sidoti ^{22a,22b}, F. Siegert ⁴⁶, Dj. Sijacki ¹⁴, J. Silva ^{126a,126d}, S.B. Silverstein ^{146a}, V. Simak ¹²⁸, Lj. Simic ¹⁴, S. Simion ¹¹⁷, E. Simioni ⁸⁴, B. Simmons ⁷⁹, D. Simon ³⁶, M. Simon ⁸⁴, P. Sinervo ¹⁵⁸, N.B. Sinev ¹¹⁶, M. Sioli ^{22a,22b}, G. Siragusa ¹⁷³, S.Yu. Sivoklov ⁹⁹, J. Sjölin ^{146a,146b}, M.B. Skinner ⁷³, H.P. Skottowe ⁵⁸, P. Skubic ¹¹³, M. Slater ¹⁹, T. Slavicek ¹²⁸, M. Slawinska ¹⁰⁷, K. Sliwa ¹⁶¹, R. Slovak ¹²⁹, V. Smakhtin ¹⁷¹, B.H. Smart ⁵, L. Smestad ¹⁵, J. Smiesko ^{144a}, S.Yu. Smirnov ⁹⁸, Y. Smirnov ⁹⁸, L.N. Smirnova ^{99,al}, O. Smirnova ⁸², M.N.K. Smith ³⁷, R.W. Smith ³⁷, M. Smizanska ⁷³, K. Smolek ¹²⁸, A.A. Snesarev ⁹⁶, S. Snyder ²⁷, R. Sobie ^{168,l}, F. Socher ⁴⁶, A. Soffer ¹⁵³, D.A. Soh ¹⁵¹, G. Sokhrannyi ⁷⁶, C.A. Solans Sanchez ³², M. Solar ¹²⁸, E.Yu. Soldatov ⁹⁸, U. Soldevila ¹⁶⁶, A.A. Solodkov ¹³⁰, A. Soloshenko ⁶⁶, O.V. Solovyanov ¹³⁰, V. Solovyev ¹²³, P. Sommer ⁵⁰, H. Son ¹⁶¹, H.Y. Song ^{35b,am}, A. Sood ¹⁶, A. Sopczak ¹²⁸, V. Sopko ¹²⁸, V. Sorin ¹³, D. Sosa ^{59b}, C.L. Sotiropoulou ^{124a,124b}, R. Soualah ^{163a,163c}, A.M. Soukharev ^{109,c}, D. South ⁴⁴, B.C. Sowden ⁷⁸, S. Spagnolo ^{74a,74b}, M. Spalla ^{124a,124b}, M. Spangenberg ¹⁶⁹, F. Spanò ⁷⁸, D. Sperlich ¹⁷, F. Spettel ¹⁰¹, R. Spighi ^{22a}, G. Spigo ³², L.A. Spiller ⁸⁹, M. Spousta ¹²⁹, R.D. St. Denis ^{55,*}, A. Stabile ^{92a}, R. Stamen ^{59a}, S. Stamm ¹⁷, E. Stanecka ⁴¹, R.W. Stanek ⁶, C. Stanescu ^{134a}, M. Stanescu-Bellu ⁴⁴, M.M. Stanitzki ⁴⁴, S. Stapnes ¹¹⁹, E.A. Starchenko ¹³⁰, G.H. Stark ³³, J. Stark ⁵⁷, P. Staroba ¹²⁷, P. Starovoitov ^{59a}, S. Stärz ³², R. Staszewski ⁴¹, P. Steinberg ²⁷, B. Stelzer ¹⁴², H.J. Stelzer ³², O. Stelzer-Chilton ^{159a}, H. Stenzel ⁵⁴, G.A. Stewart ⁵⁵, J.A. Stillings ²³, M.C. Stockton ⁸⁸, M. Stoebe ⁸⁸, G. Stoica ^{28b}, P. Stolte ⁵⁶, S. Stonjek ¹⁰¹, A.R. Stradling ⁸, A. Straessner ⁴⁶, M.E. Stramaglia ¹⁸, J. Strandberg ¹⁴⁷, S. Strandberg ^{146a,146b}, A. Strandlie ¹¹⁹, M. Strauss ¹¹³, P. Strizenec ^{144b}, R. Ströhmer ¹⁷³, D.M. Strom ¹¹⁶, R. Stroynowski ⁴², A. Strubig ¹⁰⁶, S.A. Stucci ¹⁸, B. Stugu ¹⁵, N.A. Styles ⁴⁴, D. Su ¹⁴³, J. Su ¹²⁵, S. Suchek ^{59a}, Y. Sugaya ¹¹⁸, M. Suk ¹²⁸, V.V. Sulin ⁹⁶, S. Sultansoy ^{4c}, T. Sumida ⁶⁹, S. Sun ⁵⁸, X. Sun ^{35a}, J.E. Sundermann ⁵⁰, K. Suruliz ¹⁴⁹, G. Susinno ^{39a,39b}, M.R. Sutton ¹⁴⁹, S. Suzuki ⁶⁷, M. Svatos ¹²⁷, M. Swiatlowski ³³, I. Sykora ^{144a}, T. Sykora ¹²⁹, D. Ta ⁵⁰, C. Taccini ^{134a,134b}, K. Tackmann ⁴⁴, J. Taenzer ¹⁵⁸, A. Taffard ¹⁶², R. Tafirout ^{159a}, N. Taiblum ¹⁵³, H. Takai ²⁷, R. Takashima ⁷⁰, T. Takeshita ¹⁴⁰, Y. Takubo ⁶⁷, M. Talby ⁸⁶, A.A. Talyshv ^{109,c}, K.G. Tan ⁸⁹, J. Tanaka ¹⁵⁵, M. Tanaka ¹⁵⁷, R. Tanaka ¹¹⁷, S. Tanaka ⁶⁷, B.B. Tannenwald ¹¹¹, S. Tapia Araya ^{34b}, S. Tapprogge ⁸⁴, S. Tarem ¹⁵², G.F. Tartarelli ^{92a}, P. Tas ¹²⁹, M. Tasevsky ¹²⁷, T. Tashiro ⁶⁹, E. Tassi ^{39a,39b}, A. Tavares Delgado ^{126a,126b}, Y. Tayalati ^{135e}, A.C. Taylor ¹⁰⁵, G.N. Taylor ⁸⁹, P.T.E. Taylor ⁸⁹, W. Taylor ^{159b}, F.A. Teischinger ³², P. Teixeira-Dias ⁷⁸, K.K. Temming ⁵⁰,

D. Temple ¹⁴², H. Ten Kate ³², P.K. Teng ¹⁵¹, J.J. Teoh ¹¹⁸, F. Tepel ¹⁷⁴, S. Terada ⁶⁷, K. Terashi ¹⁵⁵, J. Terron ⁸³, S. Terzo ¹⁰¹, M. Testa ⁴⁹, R.J. Teuscher ^{158,l}, T. Theveneaux-Pelzer ⁸⁶, J.P. Thomas ¹⁹, J. Thomas-Wilsker ⁷⁸, E.N. Thompson ³⁷, P.D. Thompson ¹⁹, A.S. Thompson ⁵⁵, L.A. Thomsen ¹⁷⁵, E. Thomson ¹²², M. Thomson ³⁰, M.J. Tibbetts ¹⁶, R.E. Tisce Torres ⁸⁶, V.O. Tikhomirov ^{96,an}, Yu.A. Tikhonov ^{109,c}, S. Timoshenko ⁹⁸, P. Tipton ¹⁷⁵, S. Tisserant ⁸⁶, K. Todome ¹⁵⁷, T. Todorov ^{5,*}, S. Todorova-Nova ¹²⁹, J. Tojo ⁷¹, S. Tokár ^{144a}, K. Tokushuku ⁶⁷, E. Tolley ⁵⁸, L. Tomlinson ⁸⁵, M. Tomoto ¹⁰³, L. Tompkins ^{143,ao}, K. Toms ¹⁰⁵, B. Tong ⁵⁸, E. Torrence ¹¹⁶, H. Torres ¹⁴², E. Torr o Pastor ¹³⁸, J. Toth ^{86,ap}, F. Touchard ⁸⁶, D.R. Tovey ¹³⁹, T. Trefzger ¹⁷³, A. Tricoli ²⁷, I.M. Trigger ^{159a}, S. Trincaz-Duvoid ⁸¹, M.F. Tripiana ¹³, W. Trischuk ¹⁵⁸, B. Trocm e ⁵⁷, A. Trofymov ⁴⁴, C. Troncon ^{92a}, M. Trottier-McDonald ¹⁶, M. Trovatelli ¹⁶⁸, L. Truong ^{163a,163c}, M. Trzebinski ⁴¹, A. Trzupek ⁴¹, J.C-L. Tseng ¹²⁰, P.V. Tsiareshka ⁹³, G. Tsipolitis ¹⁰, N. Tsirintanis ⁹, S. Tsiskaridze ¹³, V. Tsiskaridze ⁵⁰, E.G. Tskhadadze ^{53a}, K.M. Tsui ^{61a}, I.I. Tsukerman ⁹⁷, V. Tsulaia ¹⁶, S. Tsuno ⁶⁷, D. Tsybychev ¹⁴⁸, Y. Tu ^{61b}, A. Tudorache ^{28b}, V. Tudorache ^{28b}, A.N. Tuna ⁵⁸, S.A. Tuppiti ^{22a,22b}, S. Turchikhin ⁶⁶, D. Turecek ¹²⁸, D. Turgeman ¹⁷¹, R. Turra ^{92a,92b}, A.J. Turvey ⁴², P.M. Tuts ³⁷, M. Tyndel ¹³¹, G. Uccielli ^{22a,22b}, I. Ueda ¹⁵⁵, M. Ughetto ^{146a,146b}, F. Ukegawa ¹⁶⁰, G. Unal ³², A. Undrus ²⁷, G. Unel ¹⁶², F.C. Ungaro ⁸⁹, Y. Unno ⁶⁷, C. Unverdorben ¹⁰⁰, J. Urban ^{144b}, P. Urquijo ⁸⁹, P. Urrejola ⁸⁴, G. Usai ⁸, A. Usanova ⁶³, L. Vacavant ⁸⁶, V. Vacek ¹²⁸, B. Vachon ⁸⁸, C. Valderanis ¹⁰⁰, E. Valdes Santurio ^{146a,146b}, N. Valencic ¹⁰⁷, S. Valentini ^{22a,22b}, A. Valero ¹⁶⁶, L. Valery ¹³, S. Valkar ¹²⁹, J.A. Valls Ferrer ¹⁶⁶, W. Van Den Wollenberg ¹⁰⁷, P.C. Van Der Deijl ¹⁰⁷, H. van der Graaf ¹⁰⁷, N. van Eldik ¹⁵², P. van Gemmeren ⁶, J. Van Nieuwkoop ¹⁴², I. van Vulpen ¹⁰⁷, M.C. van Woerden ³², M. Vanadia ^{132a,132b}, W. Vandelli ³², R. Vanguri ¹²², A. Vaniachine ¹³⁰, P. Vankov ¹⁰⁷, G. Vardanyan ¹⁷⁶, R. Vari ^{132a}, E.W. Varnes ⁷, T. Varol ⁴², D. Varouchas ⁸¹, A. Vartapetian ⁸, K.E. Varvell ¹⁵⁰, J.G. Vasquez ¹⁷⁵, F. Vazeille ³⁶, T. Vazquez Schroeder ⁸⁸, J. Veatch ⁵⁶, V. Veeraraghavan ⁷, L.M. Veloce ¹⁵⁸, F. Veloso ^{126a,126c}, S. Veneziano ^{132a}, A. Ventura ^{74a,74b}, M. Venturi ¹⁶⁸, N. Venturi ¹⁵⁸, A. Venturini ²⁵, V. Vercesi ^{121a}, M. Verducci ^{132a,132b}, W. Verkerke ¹⁰⁷, J.C. Vermeulen ¹⁰⁷, A. Vest ^{46,aq}, M.C. Vetterli ^{142,d}, O. Viazlo ⁸², I. Vichou ¹⁶⁵, T. Vickey ¹³⁹, O.E. Vickey Boeriu ¹³⁹, G.H.A. Viehhauser ¹²⁰, S. Viel ¹⁶, L. Vignani ¹²⁰, M. Villa ^{22a,22b}, M. Villaplana Perez ^{92a,92b}, E. Vilucchi ⁴⁹, M.G. Vincter ³¹, V.B. Vinogradov ⁶⁶, C. Vittori ^{22a,22b}, I. Vivarelli ¹⁴⁹, S. Vlachos ¹⁰, M. Vlasak ¹²⁸, M. Vogel ¹⁷⁴, P. Vokac ¹²⁸, G. Volpi ^{124a,124b}, M. Volpi ⁸⁹, H. von der Schmitt ¹⁰¹, E. von Toerne ²³, V. Vorobel ¹²⁹, K. Vorobev ⁹⁸, M. Vos ¹⁶⁶, R. Voss ³², J.H. Vossebeld ⁷⁵, N. Vranjes ¹⁴, M. Vranjes Milosavljevic ¹⁴, V. Vrba ¹²⁷, M. Vreeswijk ¹⁰⁷, R. Vuillermet ³², I. Vukotic ³³, Z. Vykydal ¹²⁸, P. Wagner ²³, W. Wagner ¹⁷⁴, H. Wahlberg ⁷², S. Wahrmund ⁴⁶, J. Wakabayashi ¹⁰³, J. Walder ⁷³, R. Walker ¹⁰⁰, W. Walkowiak ¹⁴¹, V. Wallangen ^{146a,146b}, C. Wang ^{35c}, C. Wang ^{35d,86}, F. Wang ¹⁷², H. Wang ¹⁶, H. Wang ⁴², J. Wang ⁴⁴, J. Wang ¹⁵⁰, K. Wang ⁸⁸, R. Wang ⁶, S.M. Wang ¹⁵¹, T. Wang ²³, T. Wang ³⁷, W. Wang ^{35b}, X. Wang ¹⁷⁵, C. Wanotayaroj ¹¹⁶, A. Warburton ⁸⁸, C.P. Ward ³⁰, D.R. Wardrope ⁷⁹, A. Washbrook ⁴⁸, P.M. Watkins ¹⁹, A.T. Watson ¹⁹, M.F. Watson ¹⁹, G. Watts ¹³⁸, S. Watts ⁸⁵, B.M. Waugh ⁷⁹, S. Webb ⁸⁴, M.S. Weber ¹⁸, S.W. Weber ¹⁷³, J.S. Webster ⁶, A.R. Weidberg ¹²⁰, B. Weinert ⁶², J. Weingarten ⁵⁶, C. Weiser ⁵⁰, H. Weits ¹⁰⁷, P.S. Wells ³², T. Wenaus ²⁷, T. Wengler ³², S. Wenig ³², N. Wermes ²³, M. Werner ⁵⁰, M.D. Werner ⁶⁵, P. Werner ³², M. Wessels ^{59a}, J. Wetter ¹⁶¹, K. Whalen ¹¹⁶, N.L. Whallon ¹³⁸, A.M. Wharton ⁷³, A. White ⁸, M.J. White ¹, R. White ^{34b}, D. Whiteson ¹⁶², F.J. Wickens ¹³¹, W. Wiedenmann ¹⁷², M. Wielers ¹³¹, P. Wienemann ²³, C. Wiglesworth ³⁸, L.A.M. Wiik-Fuchs ²³, A. Wildauer ¹⁰¹, F. Wilk ⁸⁵, H.G. Wilkens ³², H.H. Williams ¹²², S. Williams ¹⁰⁷, C. Willis ⁹¹, S. Willocq ⁸⁷, J.A. Wilson ¹⁹, I. Wingerter-Seez ⁵, F. Winklmeier ¹¹⁶, O.J. Winston ¹⁴⁹, B.T. Winter ²³, M. Wittgen ¹⁴³, J. Wittkowski ¹⁰⁰, T.M.H. Wolf ¹⁰⁷, M.W. Wolter ⁴¹, H. Wolters ^{126a,126c}, S.D. Worm ¹³¹, B.K. Wosiek ⁴¹, J. Wotschack ³², M.J. Woudstra ⁸⁵, K.W. Wozniak ⁴¹, M. Wu ⁵⁷, M. Wu ³³, S.L. Wu ¹⁷², X. Wu ⁵¹, Y. Wu ⁹⁰, T.R. Wyatt ⁸⁵, B.M. Wynne ⁴⁸, S. Xella ³⁸, D. Xu ^{35a}, L. Xu ²⁷, B. Yabsley ¹⁵⁰, S. Yacoub ^{145a}, D. Yamaguchi ¹⁵⁷, Y. Yamaguchi ¹¹⁸, A. Yamamoto ⁶⁷, S. Yamamoto ¹⁵⁵, T. Yamanaka ¹⁵⁵, K. Yamauchi ¹⁰³, Y. Yamazaki ⁶⁸, Z. Yan ²⁴, H. Yang ^{35e}, H. Yang ¹⁷², Y. Yang ¹⁵¹, Z. Yang ¹⁵, W-M. Yao ¹⁶, Y.C. Yap ⁸¹, Y. Yasu ⁶⁷, E. Yatsenko ⁵, K.H. Yau Wong ²³, J. Ye ⁴², S. Ye ²⁷, I. Yeletsikh ⁶⁶, A.L. Yen ⁵⁸, E. Yildirim ⁸⁴, K. Yorita ¹⁷⁰, R. Yoshida ⁶, K. Yoshihara ¹²², C. Young ¹⁴³, C.J.S. Young ³², S. Youssef ²⁴, D.R. Yu ¹⁶, J. Yu ⁸, J.M. Yu ⁹⁰, J. Yu ⁶⁵, L. Yuan ⁶⁸, S.P.Y. Yuen ²³, I. Yusuff ^{30,ar}, B. Zabinski ⁴¹, R. Zaidan ^{35d}, A.M. Zaitsev ^{130,ae}, N. Zakharchuk ⁴⁴, J. Zalieckas ¹⁵, A. Zaman ¹⁴⁸, S. Zambito ⁵⁸, L. Zanello ^{132a,132b}, D. Zanzi ⁸⁹, C. Zeitnitz ¹⁷⁴, M. Zeman ¹²⁸, A. Zemla ^{40a}, J.C. Zeng ¹⁶⁵, Q. Zeng ¹⁴³, K. Zengel ²⁵, O. Zenin ¹³⁰, T. Zeniř ^{144a}, D. Zerwas ¹¹⁷, D. Zhang ⁹⁰, F. Zhang ¹⁷²,

G. Zhang^{35b,am}, H. Zhang^{35c}, J. Zhang⁶, L. Zhang⁵⁰, R. Zhang²³, R. Zhang^{35b,as}, X. Zhang^{35d}, Z. Zhang¹¹⁷, X. Zhao⁴², Y. Zhao^{35d}, Z. Zhao^{35b}, A. Zhemchugov⁶⁶, J. Zhong¹²⁰, B. Zhou⁹⁰, C. Zhou⁴⁷, L. Zhou³⁷, L. Zhou⁴², M. Zhou¹⁴⁸, N. Zhou^{35f}, C.G. Zhu^{35d}, H. Zhu^{35a}, J. Zhu⁹⁰, Y. Zhu^{35b}, X. Zhuang^{35a}, K. Zhukov⁹⁶, A. Zibell¹⁷³, D. Zieminska⁶², N.I. Zimine⁶⁶, C. Zimmermann⁸⁴, S. Zimmermann⁵⁰, Z. Zinonos⁵⁶, M. Zinser⁸⁴, M. Ziolkowski¹⁴¹, L. Živković¹⁴, G. Zobernig¹⁷², A. Zoccoli^{22a,22b}, M. zur Nedden¹⁷, L. Zwalinski³²

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

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

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

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

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

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

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

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

⁹ Physics Department, University of Athens, Athens, Greece

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

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

¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹³ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹⁴ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁵ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States

¹⁷ Department of Physics, Humboldt University, Berlin, Germany

¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²⁰ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; ^(e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

²¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

²² ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²³ Physikalisches Institut, University of Bonn, Bonn, Germany

²⁴ Department of Physics, Boston University, Boston MA, United States

²⁵ Department of Physics, Brandeis University, Waltham MA, United States

²⁶ ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁷ Physics Department, Brookhaven National Laboratory, Upton NY, United States

²⁸ ^(a) Transilvania University of Brasov, Brasov; ^(b) National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(d) University Politehnica Bucharest, Bucharest; ^(e) West University in Timisoara, Timisoara, Romania

²⁹ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

³⁰ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³¹ Department of Physics, Carleton University, Ottawa ON, Canada

³² CERN, Geneva, Switzerland

³³ Enrico Fermi Institute, University of Chicago, Chicago IL, United States

³⁴ ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³⁵ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c) Department of Physics, Nanjing University, Jiangsu; ^(d) School of Physics, Shandong University, Shandong; ^(e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; ^(f) Physics Department, Tsinghua University, Beijing 100084, China

³⁶ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁷ Nevis Laboratory, Columbia University, Irvington NY, United States

³⁸ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

³⁹ ^(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

⁴⁰ ^(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

⁴¹ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

⁴² Physics Department, Southern Methodist University, Dallas TX, United States

⁴³ Physics Department, University of Texas at Dallas, Richardson TX, United States

⁴⁴ DESY, Hamburg and Zeuthen, Germany

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

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

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

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

⁴⁹ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁵⁰ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁵¹ Section de Physique, Université de Genève, Geneva, Switzerland

⁵² ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy

⁵³ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

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

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

⁵⁶ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

⁵⁷ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

⁵⁸ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States

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

technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

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

- 61 ^(a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, The University of Hong Kong, Hong Kong; ^(c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- 62 Department of Physics, Indiana University, Bloomington IN, United States
- 63 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 64 University of Iowa, Iowa City IA, United States
- 65 Department of Physics and Astronomy, Iowa State University, Ames IA, United States
- 66 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 67 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 68 Graduate School of Science, Kobe University, Kobe, Japan
- 69 Faculty of Science, Kyoto University, Kyoto, Japan
- 70 Kyoto University of Education, Kyoto, Japan
- 71 Department of Physics, Kyushu University, Fukuoka, Japan
- 72 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 73 Physics Department, Lancaster University, Lancaster, United Kingdom
- 74 ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 75 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 76 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 77 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 78 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 79 Department of Physics and Astronomy, University College London, London, United Kingdom
- 80 Louisiana Tech University, Ruston LA, United States
- 81 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 82 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 83 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 84 Institut für Physik, Universität Mainz, Mainz, Germany
- 85 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 86 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 87 Department of Physics, University of Massachusetts, Amherst MA, United States
- 88 Department of Physics, McGill University, Montreal QC, Canada
- 89 School of Physics, University of Melbourne, Victoria, Australia
- 90 Department of Physics, The University of Michigan, Ann Arbor MI, United States
- 91 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
- 92 ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- 93 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 94 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- 95 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 96 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 98 National Research Nuclear University MEPhI, Moscow, Russia
- 99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 100 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 102 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 104 ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
- 106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 108 Department of Physics, Northern Illinois University, DeKalb IL, United States
- 109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 110 Department of Physics, New York University, New York NY, United States
- 111 Ohio State University, Columbus OH, United States
- 112 Faculty of Science, Okayama University, Okayama, Japan
- 113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States
- 114 Department of Physics, Oklahoma State University, Stillwater OK, United States
- 115 Palacký University, RCPTM, Olomouc, Czech Republic
- 116 Center for High Energy Physics, University of Oregon, Eugene OR, United States
- 117 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 118 Graduate School of Science, Osaka University, Osaka, Japan
- 119 Department of Physics, University of Oslo, Oslo, Norway
- 120 Department of Physics, Oxford University, Oxford, United Kingdom
- 121 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States
- 123 National Research Centre "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- 124 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States
- 126 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of 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 and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 128 Czech Technical University in Prague, Praha, Czech Republic
- 129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 130 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- 131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 132 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 133 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 134 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

- ¹³⁵ ^(a) *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca*; ^(b) *Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat*; ^(c) *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech*; ^(d) *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda*; ^(e) *Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ¹³⁶ *DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
- ¹³⁷ *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States*
- ¹³⁸ *Department of Physics, University of Washington, Seattle WA, United States*
- ¹³⁹ *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁰ *Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴¹ *Fachbereich Physik, Universität Siegen, Siegen, Germany*
- ¹⁴² *Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- ¹⁴³ *SLAC National Accelerator Laboratory, Stanford CA, United States*
- ¹⁴⁴ ^(a) *Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava*; ^(b) *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ¹⁴⁵ ^(a) *Department of Physics, University of Cape Town, Cape Town*; ^(b) *Department of Physics, University of Johannesburg, Johannesburg*; ^(c) *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ¹⁴⁶ ^(a) *Department of Physics, Stockholm University*; ^(b) *The Oskar Klein Centre, Stockholm, Sweden*
- ¹⁴⁷ *Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁸ *Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States*
- ¹⁴⁹ *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵⁰ *School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵¹ *Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ¹⁵² *Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
- ¹⁵³ *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁴ *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁵ *International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁶ *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁷ *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁸ *Department of Physics, University of Toronto, Toronto ON, Canada*
- ¹⁵⁹ ^(a) *TRIUMF, Vancouver BC*; ^(b) *Department of Physics and Astronomy, York University, Toronto ON, Canada*
- ¹⁶⁰ *Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*
- ¹⁶¹ *Department of Physics and Astronomy, Tufts University, Medford MA, United States*
- ¹⁶² *Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States*
- ¹⁶³ ^(a) *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine*; ^(b) *ICTP, Trieste*; ^(c) *Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ¹⁶⁴ *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁵ *Department of Physics, University of Illinois, Urbana IL, United States*
- ¹⁶⁶ *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
- ¹⁶⁷ *Department of Physics, University of British Columbia, Vancouver BC, Canada*
- ¹⁶⁸ *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
- ¹⁶⁹ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ¹⁷⁰ *Waseda University, Tokyo, Japan*
- ¹⁷¹ *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷² *Department of Physics, University of Wisconsin, Madison WI, United States*
- ¹⁷³ *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
- ¹⁷⁴ *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷⁵ *Department of Physics, Yale University, New Haven CT, United States*
- ¹⁷⁶ *Yerevan Physics Institute, Yerevan, Armenia*
- ¹⁷⁷ *Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

^a Also at Department of Physics, King’s College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

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

^d Also at TRIUMF, Vancouver BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America.

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

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

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

ⁱ Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^j Also at Tomsk State University, Tomsk, Russia.

^k Also at Università di Napoli Parthenope, Napoli, Italy.

^l Also at Institute of Particle Physics (IPP), Canada.

^m Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

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

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

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

^q Also at Louisiana Tech University, Ruston LA, United States of America.

^r Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

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

^t Also at Department of Physics, National Tsing Hua University, Taiwan.

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

^v Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.

^w Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^x Also at CERN, Geneva, Switzerland.

^y Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^z Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

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

^{ab} Also at Hellenic Open University, Patras, Greece.

- ^{ac} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ad} Also at School of Physics, Shandong University, Shandong, China.
- ^{ae} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{af} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ag} Also at Eotvos Lorand University, Budapest, Hungary.
- ^{ah} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{ai} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
- ^{aj} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^{ak} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{al} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{am} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{an} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{ao} Also at Department of Physics, Stanford University, Stanford CA, United States of America.
- ^{ap} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{aq} Also at Flensburg University of Applied Sciences, Flensburg, Germany.
- ^{ar} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- ^{as} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^{at} Also affiliated with PKU-CHEP.
- * Deceased.