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Jet mass and substructure of inclusive jets in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS experiment

Aad, G.; et al., [Unknown]; Bentvelsen, S.; Berglund, E.; Bobbink, G.J.; Bos, K.; Boterenbrood, H.; Colijn, A.P.; de Jong, P.; de Nooij, L.; Deviveiros, P.O.; Doxiadis, A.D.; Ferrari, P.; Garitaonandia, H.; Geerts, D.A.A.; Gosselink, M.; Hartjes, F.; Hessey, N.P.; Igonkina, O.; Kayl, M.S.; Klous, S.; Kluit, P.; Koffeman, E.; Lee, H.; Lenz, T.; Linde, F.; Luijckx, G.; Massaro, G.; Mechnich, J.; Mussche, I.; Ottersbach, J.P.; Reichold, A.; Rijpstra, M.; Ruckstuhl, N.; Snuverink, J.; Ta, D.; Tsiakiris, M.; Turlay, E.; van der Graaf, H.; van der Kraaij, E.; van der Leeuw, R.; van der Poel, E.; van Kesteren, Z.; van Vulpen, I.; Verkerke, W.; Vermeulen, J.C.; Vranjes Milosavljevic, M.; Vreeswijk, M.

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Jet mass and substructure of inclusive jets in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS experiment

The ATLAS collaboration

ABSTRACT: Recent studies have highlighted the potential of jet substructure techniques to identify the hadronic decays of boosted heavy particles. These studies all rely upon the assumption that the internal substructure of jets generated by QCD radiation is well understood. In this article, this assumption is tested on an inclusive sample of jets recorded with the ATLAS detector in 2010, which corresponds to 35 pb^{-1} of pp collisions delivered by the LHC at $\sqrt{s} = 7$ TeV. In a subsample of events with single pp collisions, measurements corrected for detector efficiency and resolution are presented with full systematic uncertainties. Jet invariant mass, k_t splitting scales and N -subjettiness variables are presented for anti- k_t $R = 1.0$ jets and Cambridge-Aachen $R = 1.2$ jets. Jet invariant-mass spectra for Cambridge-Aachen $R = 1.2$ jets after a splitting and filtering procedure are also presented. Leading-order parton-shower Monte Carlo predictions for these variables are found to be broadly in agreement with data. The dependence of mean jet mass on additional pp interactions is also explored.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

The ATLAS experiment observes proton-proton (pp) collisions provided by the Large Hadron Collider (LHC). The outcome of these collisions is frequently the production of large numbers of hadrons. In order to understand these collisions, studies usually group hadrons into jets defined by one of a number of standard algorithms [1–7]. The variables most often used in analyses are the jet direction and momentum transverse to the beam (p_T). However the jets remain composite objects and their masses and internal substructure contain additional information.

One strong motivation for studies of the internal substructure of jets is that at the LHC particles such as W and Z bosons and top quarks are produced abundantly with significant Lorentz boosts. The same may also be true for new particles produced at the LHC. When

such particles decay hadronically, the products tend to be collimated in a small area of the detector. For sufficiently large boosts, the resulting hadrons can be clustered into a single jet. Substructure studies offer a technique to extract these single jets of interest from the overall jet background. Such techniques have been found promising for boosted W decay identification, Higgs searches and boosted top identification amongst others [8]. However, many of these promising approaches have never been tested with collision data and rely on the assumption that the internal structure of jets is well modelled by parton-shower Monte Carlo approaches. It is therefore important to measure some of the relevant variables in a sample of jets to verify the expected features.

In this paper, measurements are made with an inclusive sample of high-transverse momentum jets produced in proton-proton collisions with a centre-of-mass energy (\sqrt{s}) of 7 TeV. This is a natural continuation of the studies in previous experiments [9–13]. It also complements previous ATLAS studies [14] probing the shape of jets reconstructed with the anti- k_t algorithm [5] with smaller radius parameters $R = 0.4$ and 0.6 .

This study focuses on two specific jet algorithms that are likely to be of interest for future searches: anti- k_t jets with an R -parameter of 1.0 and Cambridge-Aachen [3, 4] jets with $R = 1.2$. Jets are required to be at high-transverse momentum ($p_T > 200$ GeV) and central in rapidity¹ ($|y| < 2$). The normalised cross-section as a function of jet mass, taken from the jet four-momentum, is measured for both these algorithms. In addition to the mass, two sets of substructure variables, k_t splitting scales [15] and N -subjettiness ratios [16], are measured. For the Cambridge-Aachen jets, the mass distribution after a substructure splitting and filtering procedure [17] is also presented.

2 Definitions

2.1 Jet algorithms

Jets are constructed using two infrared and collinear-safe recombination jet algorithms, anti- k_t and Cambridge-Aachen, as implemented in the FASTJET package [18]. Both act by iteratively merging the nearest objects in the event but with different definitions of “distance”. The anti- k_t jet algorithm builds jets with a very regular shape, while the Cambridge-Aachen algorithm builds less regular jets. This analysis uses R -parameters of 1.0 and 1.2, for anti- k_t and Cambridge-Aachen jets respectively, in line with recent studies of heavy boosted objects. All discussion of jet algorithms in this paper assumes that the constituents from which the jet is composed are recombined using four-vector addition. Jets in the real or simulated detector are constructed from clusters of energy deposited in the calorimeter (see section 4). Jets in the “true” final state, or “hadron level”, are defined as jets made from all particles with a proper lifetime longer than 10 ps, including neutrinos.

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

2.2 The splitting and filtering procedure

The “splitting and filtering” procedure aims to identify relatively hard, symmetric splittings in a jet that contribute significantly to the jet’s invariant mass. This procedure is taken from recent Higgs search studies [17, 19]. The parameters are tuned to maximise sensitivity to a Standard Model Higgs boson decaying to $b\bar{b}$, but this procedure is suitable generally for identifying two-body decay processes. The effect of the procedure is to search for jets where clustering the constituents with Cambridge-Aachen combines two relatively low mass objects to make a much more massive object. This indicates the presence of a heavy particle decay. The procedure then attempts to retain only the constituents believed to be related to the decay of this particle. Because the procedure itself uses the Cambridge-Aachen algorithm, it is most natural to apply it to jets originally found with this algorithm.

Each stage in the clustering combines two objects j_1 and j_2 to make another object j . Use definitions $v = \frac{\min(p_{Tj_1}^2, p_{Tj_2}^2)}{m_j^2} \delta R_{j_1, j_2}^2$ and $\delta R_{j_1, j_2} = \sqrt{\delta y_{j_1, j_2}^2 + \delta \phi_{j_1, j_2}^2}$, where δy and $\delta \phi$ are the differences in rapidities and azimuthal angles respectively. The procedure takes a jet to be the object j and applies the following:

1. Undo the last clustering step of j to get j_1 and j_2 . These are ordered such that their mass has the property $m_{j_1} > m_{j_2}$. If j cannot be unclustered (i.e. it is a single particle) or $\delta R_{j_1, j_2} < 0.3$ then it is not a suitable candidate, so discard this jet.
2. If the splitting has $m_{j_1}/m_j < \mu$ (large change in jet mass) and $v > v_{\text{cut}}$ (fairly symmetric) then continue, otherwise redefine j as j_1 and go back to step 1. Both μ and v are parameters of the algorithm.
3. Recluster the constituents of the jet with the Cambridge-Aachen algorithm with an R -parameter of $R_{\text{filt}} = \min(0.3, \delta R_{j_1, j_2}/2)$ finding n new subjets $s_1, s_2 \dots s_n$ ordered in descending p_T .
4. Redefine the jet as the sum of subjet four-momenta $\sum_{i=1}^{\min(n,3)} s_i$.

The algorithm parameters μ and v_{cut} are taken as 0.67 and 0.09 respectively [19].

The μ cut attempts to identify a hard structure in the distribution of energy in the jet, which would imply the decay of a heavy particle. The cut on v further helps by suppressing very asymmetric decays of the type favoured by splittings of quarks and gluons. A notable modification of the original procedure [17] in this paper is the addition of the $\delta R_{j_1, j_2}$ cut in step 1. This cut is applied because with current techniques the correction for detector resolution at angular scales below 0.3 is not well controlled. Steps 3 and 4 filter out some of the particles in the candidate jet, the aim being to retain particles relevant to the hard process while reducing the contribution from effects like underlying event and pile-up. The 4-vector after step 4 can be treated like a new jet. This new jet has a p_T and mass less than or equal to those of the original jet.

2.3 k_t splitting scales, $\sqrt{d_{ij}}$

The k_t splitting scales are defined by reclustering the constituents of the jet with the k_t recombination algorithm [1, 2]. The k_t -distance of the final clustering step can be used to define a splitting scale variable $\sqrt{d_{12}}$:

$$\sqrt{d_{12}} = \min(p_{Tj1}, p_{Tj2}) \times \delta R_{j1,j2},$$

where 1 and 2 are the two jets before the final clustering step [15]. The ordering of clustering in the k_t algorithm means that in the presence of a two-body heavy particle decay the final clustering step will usually be to combine the two decay products. The parameter $\sqrt{d_{12}}$ can therefore be used to distinguish heavy particle decays, which tend to be more symmetric, from the largely asymmetric splittings of quarks and gluons. The expected value for a heavy particle decay is approximately $m/2$, whereas inclusive jets will tend to have values $\sim p_T/10$, although with a tail extending to high values. The variable $\sqrt{d_{23}}$ is defined analogously but for the two objects combined in the penultimate clustering step.

2.4 N -subjettiness

The N -subjettiness variables τ_N [16] are designed to be smooth, continuous observables related to the subjet multiplicity. Intuitively, the variables can be thought of as answering the question: ‘‘How much does this jet look like N different subjets?’’ The variable τ_N is calculated by clustering the constituents of the jet with the k_t algorithm and requiring N subjets to be found. These N subjets define axes within the jet around which the jet constituents may be concentrated. The variables τ_N are then defined as the following sum over all constituents k of the jet:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \times \min(\delta R_{1,k}, \delta R_{2,k}, \dots, \delta R_{N,k}) \tag{2.1}$$

$$d_0 = \sum_k p_{T,k} R, \tag{2.2}$$

where $\delta R_{i,k}$ is the distance from the subjet i to the constituent k and R is the R -parameter of the original jet algorithm.

Using this definition, τ_N describes how well the substructure of the jet is described by N subjets by assessing the degree to which constituents are localized near the axes defined by the k_t subjets. For two- and three-body decays, respectively, the ratios τ_2/τ_1 and τ_3/τ_2 have been shown to provide excellent discrimination for hadronic decays of W -bosons and boosted top quarks [20]. These ratios will be referred to as τ_{21} and τ_{32} respectively. These variables mostly fall within the range 0 to 1. As an example, $\tau_{21} \simeq 1$ corresponds to a jet which is narrow and without substructure; $\tau_{21} \simeq 0$ implies a jet which is much better described by two subjets than one. Similarly low values of τ_{32} imply a jet which is much better described by three subjets than two. However, as can be seen from the definition, adding an additional subjet axis will tend to reduce the value of τ_N and therefore even narrow jets tend to have values of τ_{21} and τ_{32} slightly less than 1.

3 The ATLAS detector

The ATLAS detector [21] provides nearly full solid angle coverage around the collision point with tracking detectors, calorimeters and muon chambers. Of these subsystems the most relevant to this study are the inner detector, the barrel and endcap calorimeters, and the trigger system.

The inner detector is a tracking detector covering the range $|\eta| < 2.5$ and with full coverage in ϕ . It is composed of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The whole system is immersed in a 2 T magnetic field. The information from the inner detector is used to reconstruct tracks and vertices.

The barrel and endcap calorimeters cover the regions $|\eta| \lesssim 1.5$ and $1.5 \lesssim |\eta| < 3.2$, respectively. Electromagnetic measurements are provided by a liquid-argon (LAr) sampling calorimeter. The granularity of this detector ranges from $\delta\eta \times \delta\phi = 0.025 \times 0.025$ to 0.1×0.1 . Hadronic calorimetry in $|\eta| < 1.7$ is provided by a scintillating-tile detector, while in the endcaps, coverage is provided by a second LAr system. The granularity of the hadronic calorimetry ranges from 0.1×0.1 to 0.2×0.2 .

The trigger system [22] is composed of three consecutive levels. Only the Level-1 (L1) trigger is used in this study, with higher levels not rejecting any events. The L1 trigger is based on custom-built hardware that processes events with a fixed latency of $2.5 \mu\text{s}$. Events in this analysis are selected based on their L1 calorimeter signature. The L1 calorimeter trigger uses coarse detector information to identify interesting physics objects above a given transverse energy (E_T) threshold. The jet triggers use a sliding window algorithm taking square $\delta\eta \times \delta\phi = 0.2 \times 0.2$ jet elements as input. The window size is 0.8×0.8 .

4 Dataset and reconstruction

The data analysed here come from the 2010 $\sqrt{s} = 7 \text{ TeV}$ pp dataset. Data are used in this study only if the detector conditions were stable, there was a stable beam present in the LHC, the luminosity was reliably monitored and the trigger was operational. The selected data set corresponds to an integrated luminosity of $35.0 \pm 1.1 \text{ pb}^{-1}$ [23, 24].

Events in this analysis are first selected by the L1 calorimeter trigger system. The efficiency of this trigger was evaluated in data and found to contain no significant biases for the selection used here. For the lowest p_T bin (200–300 GeV) a trigger is used which was only available for part of the dataset. As a result some plots are presented with the lower integrated luminosity of $2.0 \pm 0.1 \text{ pb}^{-1}$.

To reject events that are dominated by detector noise or non-collision backgrounds, events are required to contain a primary vertex consistent with the LHC beamspot, reconstructed from at least five tracks with $p_T > 150 \text{ MeV}$. Additionally, jets are reconstructed with the anti- k_t algorithm using an R -parameter of 0.6. Events are discarded if any such jet with transverse momentum greater than 30 GeV fails to satisfy a number of quality criteria, including requirements on timing and calorimeter noise [25]. This selection removes approximately 3% of events in this dataset.

Additional proton-proton collisions (pile-up) can have a significant impact on quantities like jet mass and substructure [8]. The primary results in this paper are therefore presented only in events where the number of reconstructed primary vertices (N_{PV}) composed of at least five tracks is exactly one. This requirement selects approximately 22% of events in the 2010 dataset. As vertex finding is highly efficient, this approach is expected to be very good at rejecting pile-up, and no additional systematic uncertainties as a result of this requirement are considered. The effects of pile-up are discussed in more detail in section 10.

Calorimeter cells are clustered using a three-dimensional topological algorithm. These clusters provide a three-dimensional representation of energy depositions in the calorimeter with a nearest neighbour noise suppression algorithm [26]. The resulting clusters are made massless and then classified as either electromagnetic or hadronic in origin based on their shape, depth and energy density. Cluster energies are corrected with calibration constants, which depend on the cluster classification to account for calorimeter non-compensation [25]. The clusters are then used as input to a jet algorithm.

As part of this study, specific calibrations for these jet algorithms have been devised. Calibrations for the mass, energy and η of jets are derived from Monte Carlo (specifically PYTHIA [27]). Hadron-level jets (excluding muons and neutrinos) are matched to jets reconstructed in the simulated calorimeter. The matched pairs are used to define functions for these three variables, dependent on energy and η , which on average correct the reconstructed quantities back to the true scale. This correction is of the order 10-20% for mass and energy and 0.01 for η .

Jets constructed from tracks are used for systematic studies in this paper. These track-jets are constructed using the same algorithms as calorimeter jets. The input constituents are inner-detector tracks originating only from the selected pp collision of interest as selected by the criteria $p_T > 500$ MeV, $|\eta| < 2.5$, $|z_0| < 5$ mm and $|d_0| < 1.5$ mm [28]. Here z_0 and d_0 are the longitudinal and transverse impact parameter of the track at closest approach to the z -axis, relative to the primary vertex.

The measurements presented in this paper are for jets that have $|y| < 2$ in four 100 GeV p_T bins spanning 200 to 600 GeV. This selection is not biased by trigger effects and the jets it selects are contained entirely within the barrel and end-cap subdetectors.

5 Monte Carlo samples

Samples of inclusive jet events were produced using several Monte Carlo (MC) generators including PYTHIA 6.423 [27] and HERWIG++ 2.4 [29]. These programs implement leading-order (LO) perturbative QCD (pQCD) matrix elements for $2 \rightarrow 2$ processes. Additionally, ALPGEN 2.13 [30] and SHERPA 1.2.3 [31] are used for some cross-checks. SHERPA and ALPGEN implement $2 \rightarrow n$ processes such as explicit QCD multijet production. Parton-showers are calculated in a leading-logarithm approximation. Showers are p_T ordered in PYTHIA and angular ordered in HERWIG++. Fragmentation into particles is implemented in PYTHIA following the string model [32] and in HERWIG++ the cluster [33] model. ALPGEN is interfaced with HERWIG [34, 35] for parton-shower and fragmentation and JIMMY [36] for an underlying event model. Unless otherwise specified, PYTHIA samples

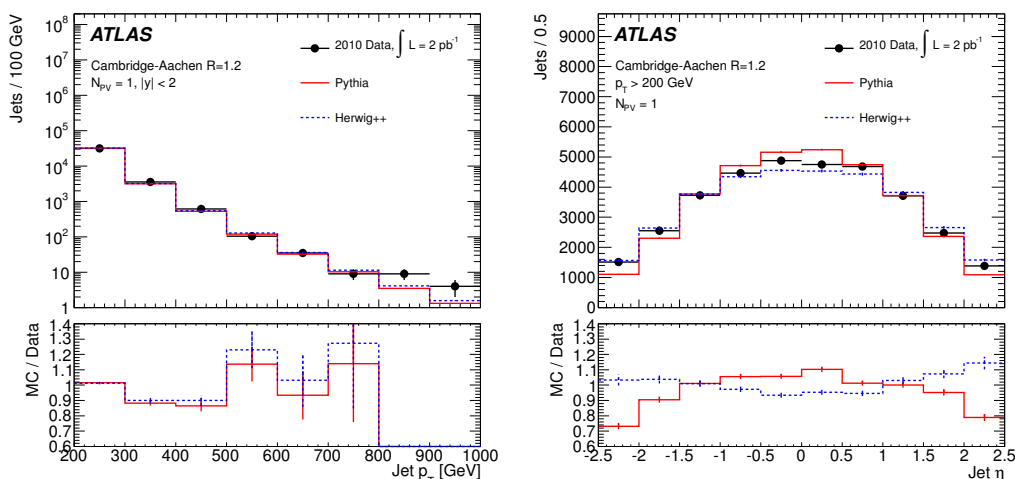


Figure 1. p_T (left) and η distribution (right) of Cambridge-Aachen $R = 1.2$ jets with $p_T > 200$ GeV.

use the AMBT1 tune [28]. In some figures the Perugia2010 PYTHIA tune is used [37], which has been found to describe jet shapes more accurately at ATLAS [14]. Leading-order parton density functions are taken from the MRST2007 LO* set [38, 39], unless stated otherwise. No pile-up was included in any of these samples.

The MC generated samples are passed through a full simulation [40] of the ATLAS detector and trigger, based on GEANT4 [41]. The Quark Gluon String Precompound (QGSP) model is used for the fragmentation of nuclei, and the Bertini cascade (BERT) model for the description of the interactions of the hadrons in the medium of the nucleus [42].

6 Detector-level distributions

Detector-level distributions for jet p_T , η , mass, $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, τ_{21} and τ_{32} are shown in figures 1–6. The statistical uncertainty represented in ratios is that from Monte Carlo and data added in quadrature. Representative distributions of the substructure variables are shown for the 300–400 GeV bin only. The Monte Carlo is normalised to the data separately in each plot. The properties of these jets are observed to be reasonably well modelled by leading-order parton-shower Monte Carlo. There are approximately four times fewer split and filtered jets (e.g. figure 3) because many jets fail the splitting criteria described above.

7 Systematic uncertainties

The modelling of the calorimeter response is the biggest systematic uncertainty for this analysis. The key issue therefore is to validate the Monte Carlo-based jet calibration described in section 4. As the results here use jet algorithms with larger R -parameters, the ATLAS jet energy scale uncertainty [25] for anti- k_t $R = 0.4$ and 0.6 jets cannot be applied.

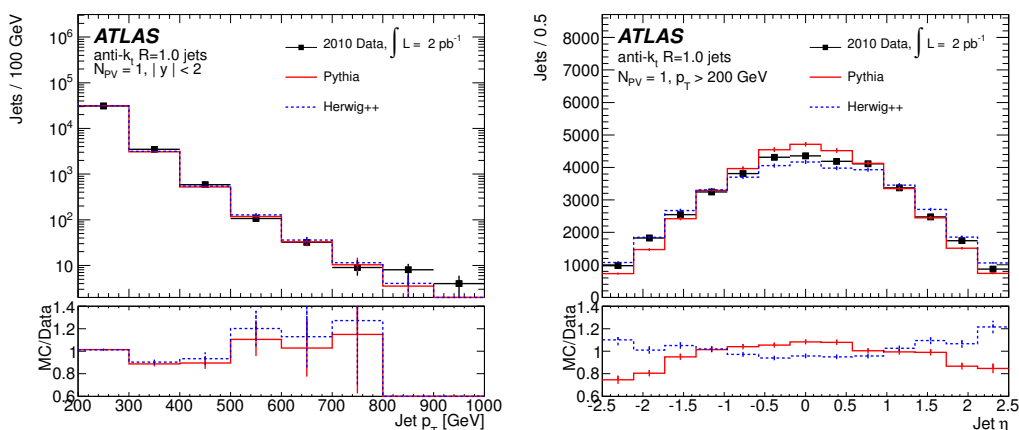


Figure 2. p_T (left) and η distribution (right) of anti- k_t $R = 1.0$ jets with $p_T > 200$ GeV.

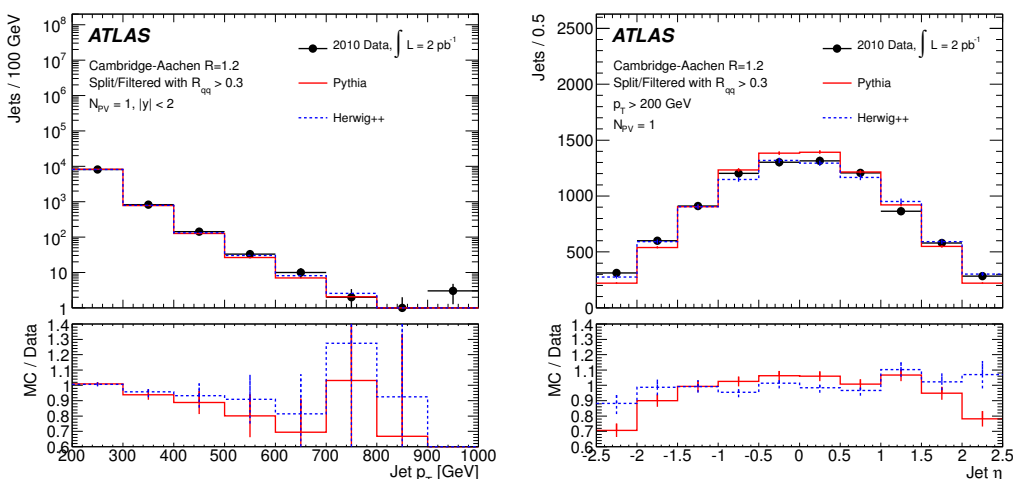


Figure 3. p_T (left) and η distribution (right) of Cambridge-Aachen $R = 1.2$ jets after splitting and filtering with $p_T > 200$ GeV.

The primary systematic uncertainties considered in the present study are those relating to scales and resolutions, such as jet p_T scale (JES) and jet p_T resolution (JER). For each substructure variable, the scale and resolution of the variable itself are also considered, for example the jet mass scale (JMS) and jet mass resolution (JMR). The scale uncertainties are primarily constrained by in-situ validation using track-jets. The inner detector and calorimeter have largely uncorrelated systematic effects, therefore comparison of variables such as jet mass and energy between the two sub-detectors allows for some separation of physics and detector effects. This technique is limited to a precision of around 3-5% by systematic uncertainties arising from the inner-detector tracking efficiency and confidence in Monte Carlo modelling of the relative behaviour of the charged and neutral components of jets.

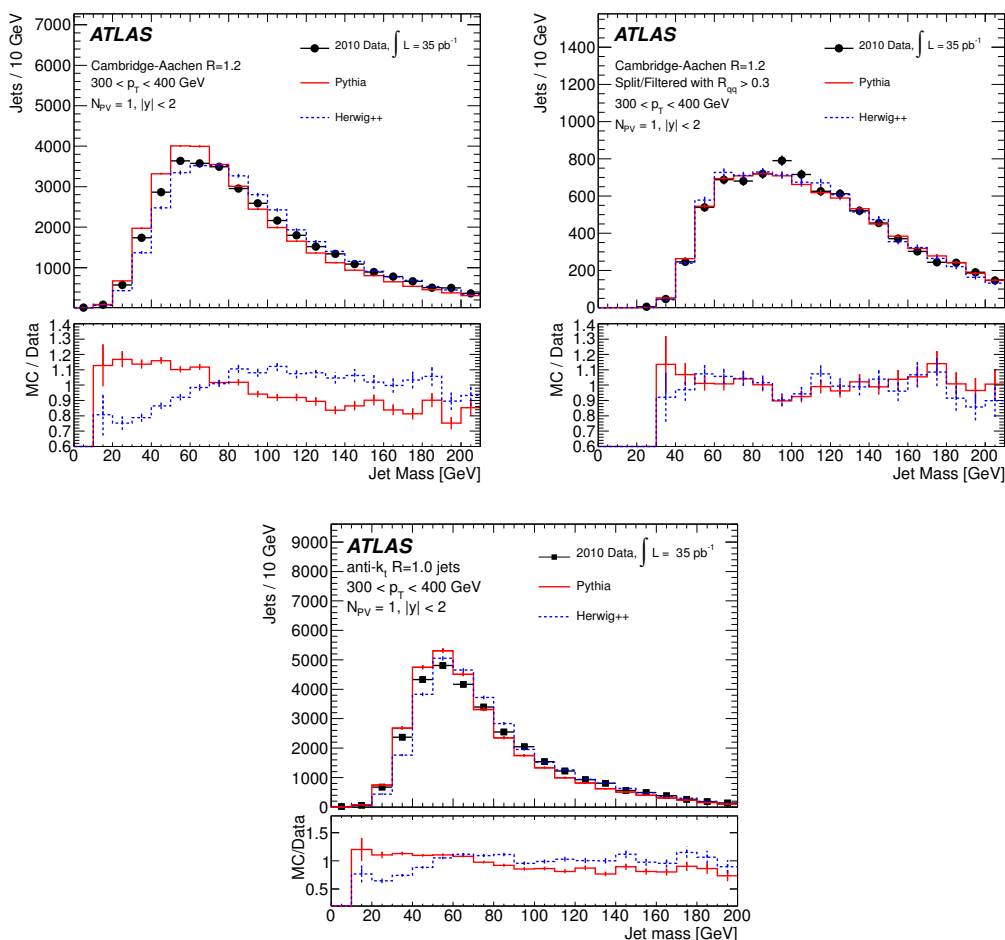


Figure 4. Mass distributions for jets with $|y| < 2.0$ in the 300–400 GeV p_T bin. Jets shown are Cambridge-Aachen (top left), Cambridge-Aachen after splitting and filtering (top right) and anti- k_t (bottom).

Jets composed from tracks are matched to calorimeter-jets if they are within $\delta R < 0.3$ of each other. The split and filtered calorimeter-jets are matched to Cambridge-Aachen $R = 1.2$ track-jets. Ratios are defined between track- and calorimeter-jets for each variable X (p_T , mass, $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, τ_{21} , τ_{32}):

$$r^X = \frac{X_{\text{calorimeter-jet}}}{X_{\text{track-jet}}} \quad (7.1)$$

Example distributions of some of the ratio variables are shown in figure 7. It can be seen that the ratios are in broad agreement between data and Monte Carlo. To quantify the level of agreement, double ratios are defined:

$$\rho^X = \frac{r_{\text{data}}^X}{r_{\text{MC}}^X}, \quad (7.2)$$

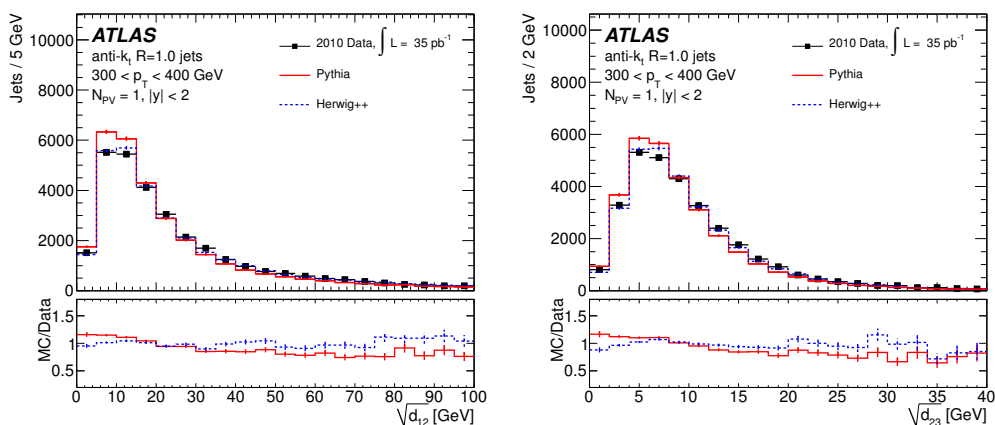


Figure 5. Distributions for $\sqrt{d_{12}}$ (left) and $\sqrt{d_{23}}$ (right) of anti- k_t $R = 1.0$ jets with $|y| < 2.0$ in the 300–400 GeV p_T bin.

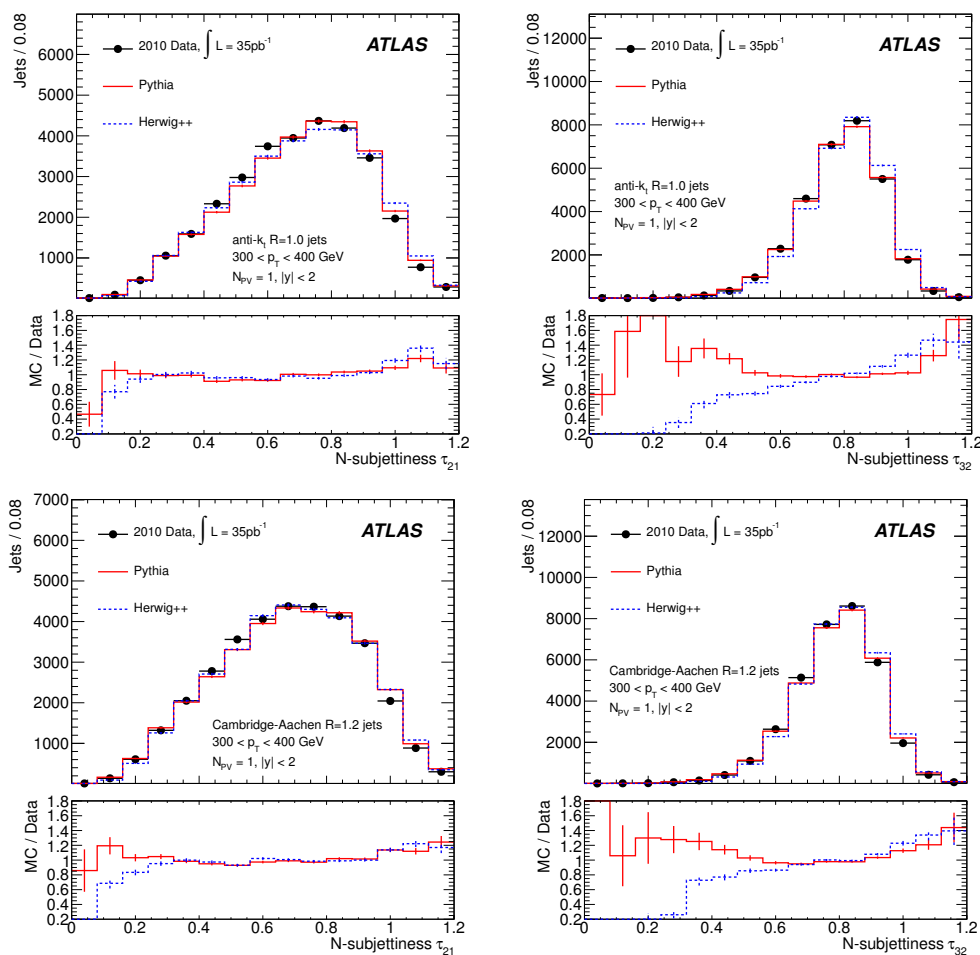


Figure 6. Distributions for τ_{21} (left) and τ_{32} (right) of jets with $|y| < 2.0$ in the 300–400 GeV p_T bin for anti- k_t (top) and Cambridge-Aachen jets (bottom).

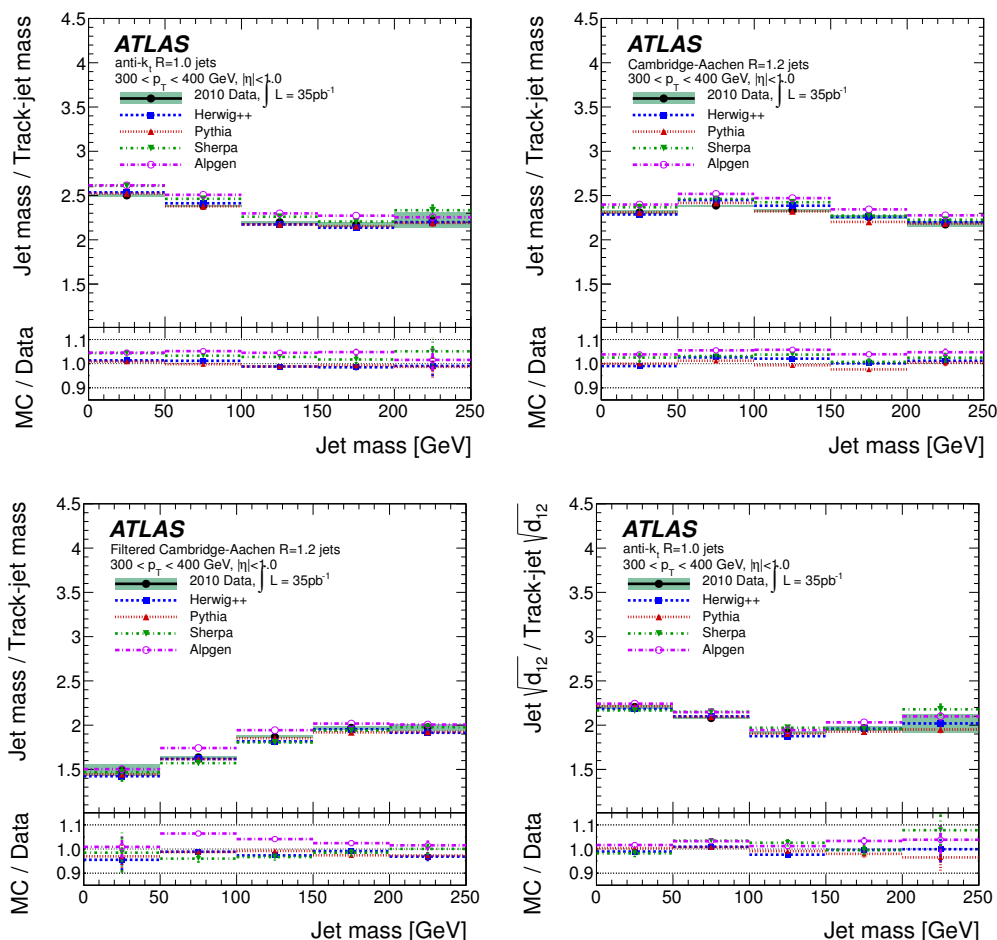


Figure 7. The ratio of a jet property determined by the calorimeter to that determined by tracks versus the calorimeter jet mass for jets with 300–400 GeV in p_T . Shown are the data and a variety of Monte Carlo models. The bottom frame shows the ratio of the Monte Carlo models to data. The top left, top right and bottom left figures show the ratio for jet mass for three different jet algorithms. The bottom-right figure shows the ratios for $\sqrt{d_{12}}$ in anti- k_t jets.

where again, X can be p_T , mass or any of the substructure variables. The distributions of the variables $X_{\text{calorimeter-jet}}$ themselves are not necessarily expected to be correctly modelled by Monte Carlo. However, if the simulation correctly models the effect of the detector on these variables, the double ratios ρ^X , are expected to be consistent with unity. Figure 7 also shows below each plot the corresponding double ratio. In order to account for possible uncertainties due to different fragmentation and hadronisation models, these double ratios are also calculated with a variety of Monte Carlo programs.

Final scale uncertainties are determined by adding in quadrature the estimated uncertainty on the inner-detector measurement with the deviation from unity observed in the double ratios. The resulting scale uncertainties on p_T , mass and substructure variables are in the range 3-6%. The highest p_T bins contain fewer events and therefore suffer from sta-

tistical fluctuations when calculating the double ratio deviation. These scale uncertainties tend to dominate the systematic uncertainties on the final measurements.

As an additional cross-check, Monte Carlo-based tests are used to determine the dependence of the detector response on a number of different variables. These include samples produced with modified detector geometry, different GEANT hadronic physics models and different Monte Carlo generators. These tests indicate variations of a similar order of magnitude to those observed in the in-situ studies. The in-situ track-jet study is limited by inner-detector acceptance and only extends as far as $|\eta| < 1.0$, which corresponds to $\simeq 75\%$ of the jets in the measured distributions. However, the Monte Carlo-based tests also indicate no strong η -dependence from any of the different possible types of mismodelling examined. Based on this, the systematic uncertainty is applied to the entire sample.

In-situ tests of the JER [43] for anti- k_t jets with $R = 0.4$ and 0.6 indicate that the jet p_T resolution predicted by simulation is in good agreement with that observed in the data. Here, the resolution uncertainties are taken from the Monte Carlo tests described above only, primarily because the mass and substructure variable resolutions are difficult to validate in-situ with this dataset. From studying the variations in resolution created by varying the detector geometry, GEANT hadronic physics model and Monte Carlo generator, resolution uncertainties of around 20% are conservatively estimated, except for τ_{21} and τ_{32} where they are around 10%.

8 Data correction

To compare the measurements directly to theoretical predictions the final distributions in this study are corrected for detector resolution and acceptance effects. The procedure here is a matrix-based unfolding technique called Iterative Dynamically Stabilised (IDS) unfolding [44, 45].

In this procedure truth jets and reconstructed jets in Monte Carlo simulated events are matched using the criterion $\delta R < 0.2$, which leads to a match for $> 99\%$ of jets. Matched pairs of jets are used to construct a transfer matrix corresponding to the effect of the detector. A true jet can be matched with a reconstructed jet that fails the p_T cut and vice-versa. As such, the efficiency for matching a true jet to a reconstructed jet in the same p_T bin is recorded as a function of the variable of interest. The reverse quantity is also defined for reconstructed jets. The data are then scaled by the reconstructed matching efficiency, multiplied by the transfer matrix and finally divided by the truth matching efficiency. There is also an iterative optimisation step, where the rows of the matrix are scaled to match the corrected result. PYTHIA is used to provide the central value. Each p_T bin is unfolded independently. The systematic uncertainty is assessed by repeating the procedure using SHERPA samples.

9 Results

Using the analysis techniques outlined above, measured normalised cross-sections are shown in figures 8–16. In ratio plots, the statistical uncertainty on Monte Carlo predictions does

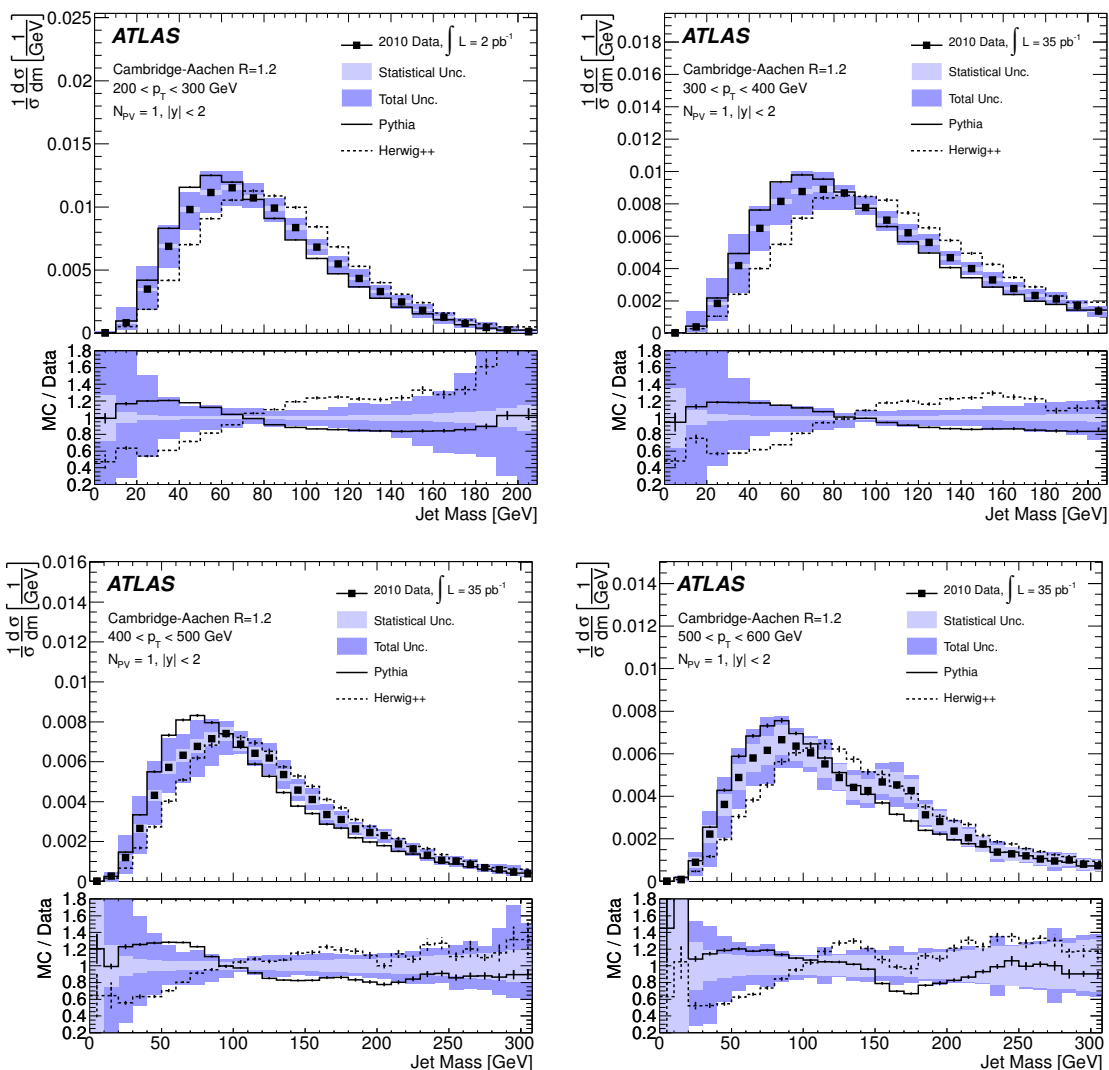


Figure 8. Normalised cross-sections as functions of mass of Cambridge-Aachen jets with $R = 1.2$ in four different p_T bins.

not include the data statistical uncertainty. Although in some cases the Monte Carlo predictions are not in agreement with the data, the shapes of the distributions are correctly reproduced. For jet mass the distributions produced by PYTHIA tend to be too soft, while those from HERWIG++ are too hard. Notably, the Cambridge-Aachen jet mass after splitting and filtering, as shown in figure 9, is the only variable for which the Monte Carlo predictions are in agreement to within statistical uncertainties, both with each other and the data. The substructure variables exhibit generally better agreement with Monte Carlo predictions than mass, with all but a few bins correctly described by both PYTHIA and HERWIG++. In the higher p_T bins statistical fluctuations begin to limit the precision of the measurements, but the level of agreement in all variables appears to remain approximately constant between p_T bins.

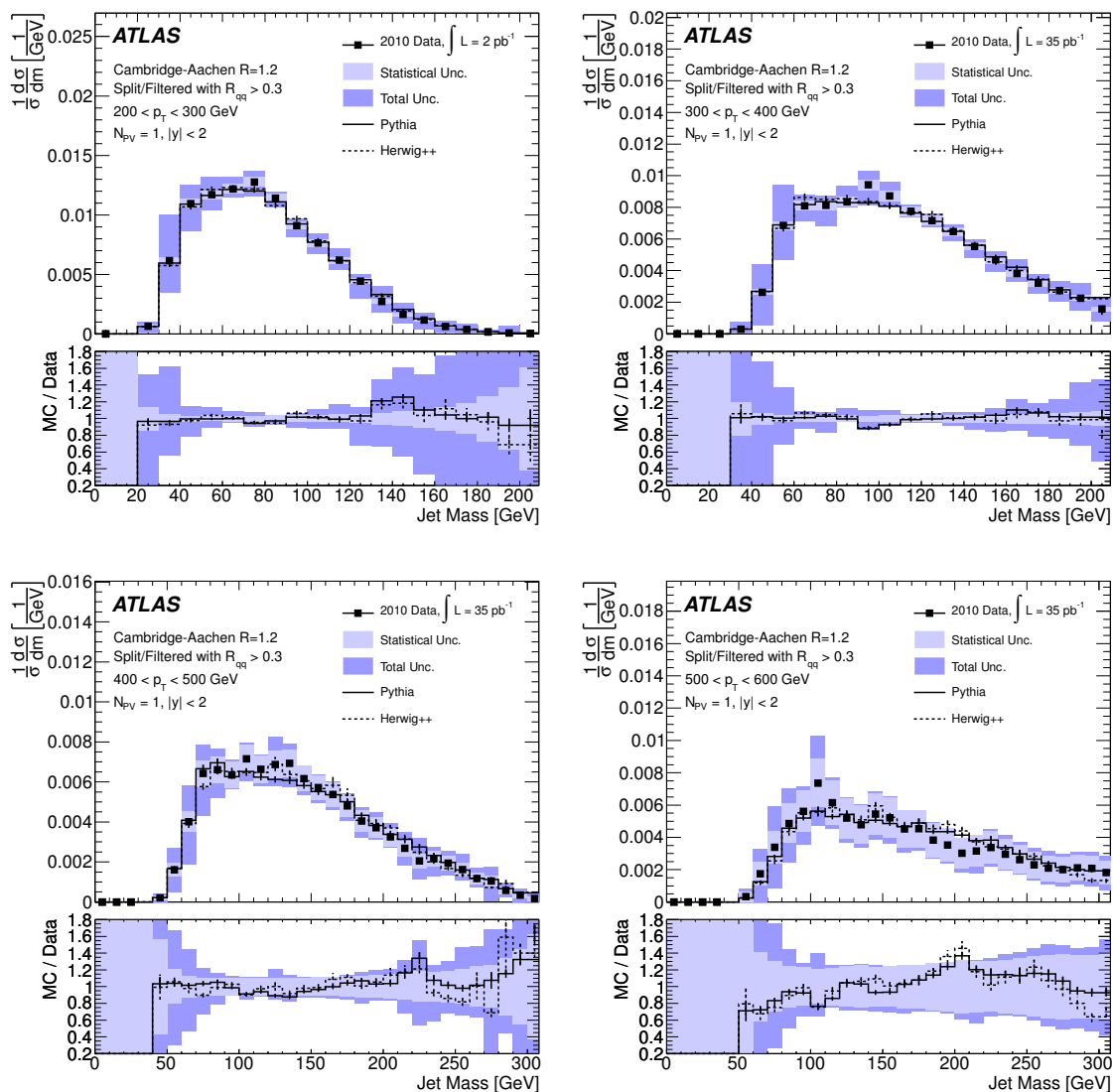


Figure 9. Normalised cross-sections as functions of mass of Cambridge-Aachen jets with $R = 1.2$ after splitting and filtering in four different p_T bins.

The unfolding technique used introduces correlations between the bins. The statistical uncertainty in these results represents the diagonal element of the covariance matrix only; therefore, comparison to alternative predictions requires use of the full covariance matrices. These matrices are available, along with the full results presented here, in HEPDATA [46]. In particular the structure at a jet mass of 150–180 GeV in the 500–600 GeV bin of figures 8 and 10 is consistent with statistical fluctuations.

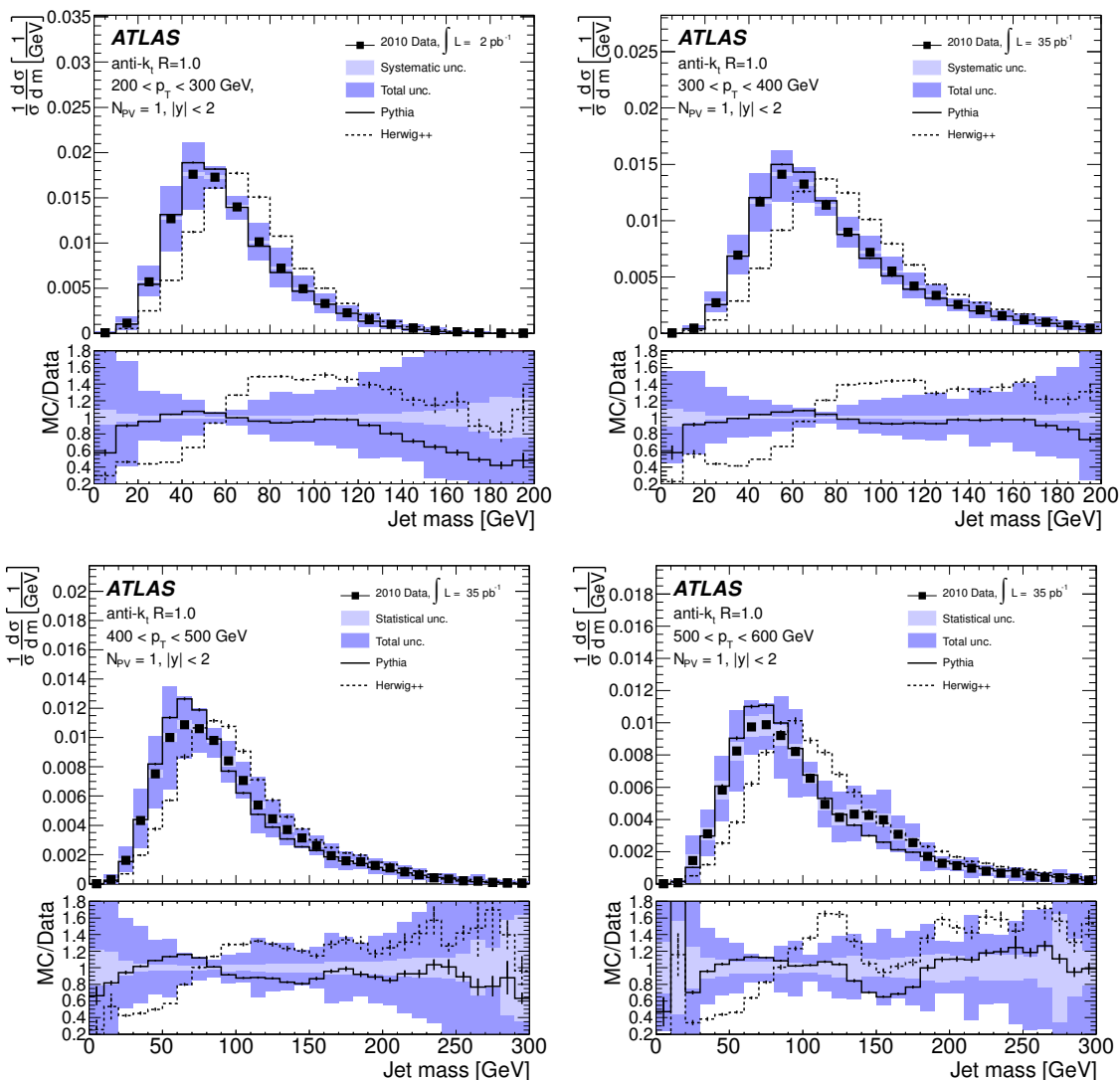


Figure 10. Normalised cross-sections as functions of mass of anti- k_t jets with $R = 1.0$ in four different p_T bins.

10 Mean mass with multiple proton-proton interactions

The results presented so far have been for events containing only one pp interaction; however even in this early period of running, the data contain events with multiple simultaneous pp interactions (pile-up) [47]. These additional collisions are uncorrelated with the hard-scattering process that typically triggers the event. They therefore present a background of soft, diffuse radiation that offsets the energy measurement of jets and will impact jet-shape and substructure measurements. It is essential that future studies involving jet-substructure variables, such as those investigated here, be able to understand and correct for the effects of pile-up. Methods to mitigate these effects will be essential for jet multiplicity and energy scale measurements.

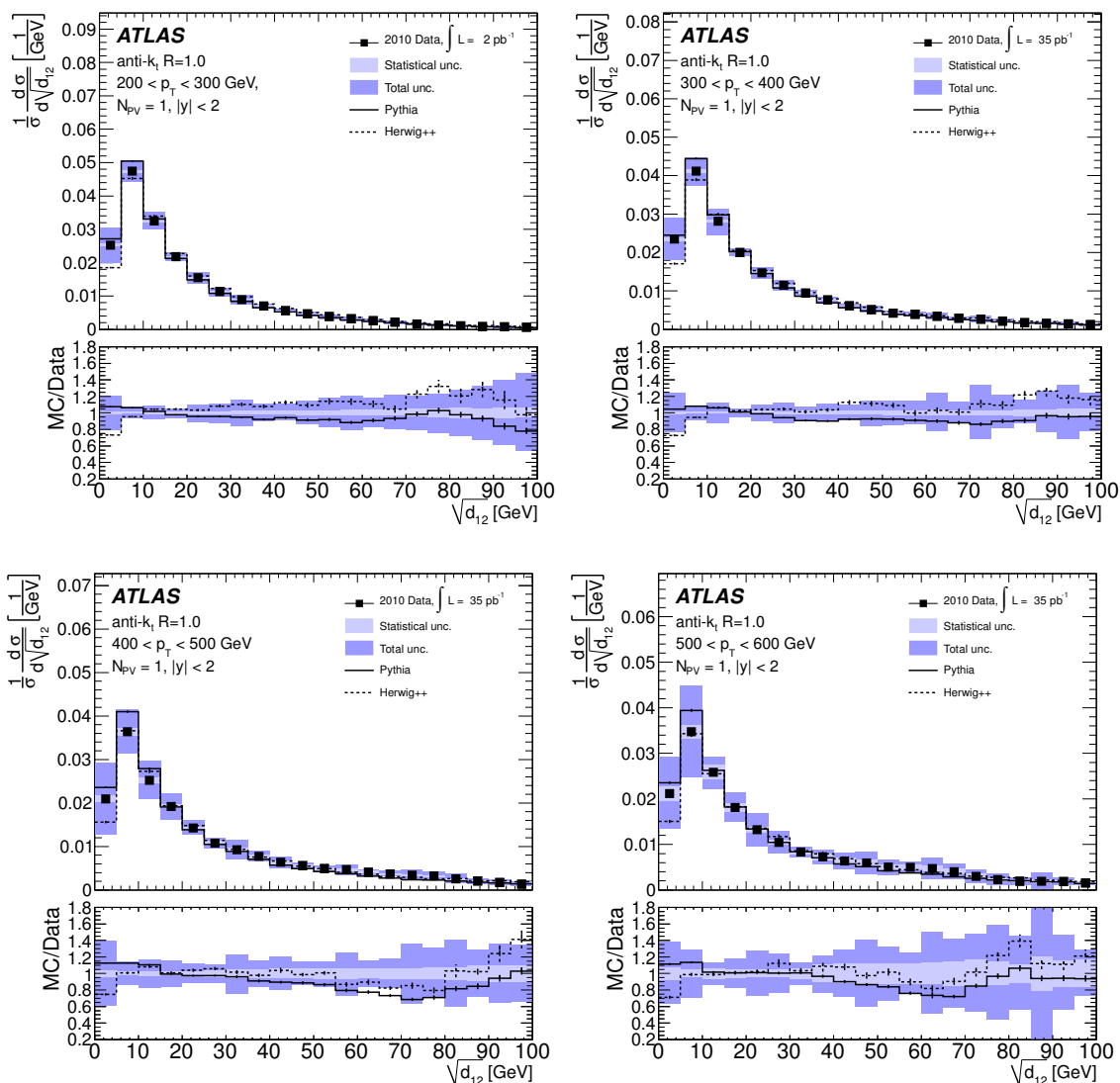


Figure 11. Normalised cross-sections as functions of $\sqrt{d_{12}}$ of anti- k_t jets with $R = 1.0$ in four different p_T bins.

Substructure observables are expected to be especially sensitive to pile-up [8]. This is true in particular for the invariant mass of large-size jets. Techniques such as the splitting and filtering procedure used in this study reduce the effective area of large jets and are therefore expected to reduce sensitivity to pile-up.

The sensitivity of mean jet mass to pile-up is tested in this dataset. The correlation of the mean jet mass of anti- k_t jets with the number of reconstructed primary vertices is presented in figure 17 (left). All jets with a p_T of at least 300 GeV in the rapidity range $|y| < 2$ are considered. The mean mass of jets in the absence of pile-up and the variation with pile-up activity show the expected dependence on the jet size. The mean mass in the

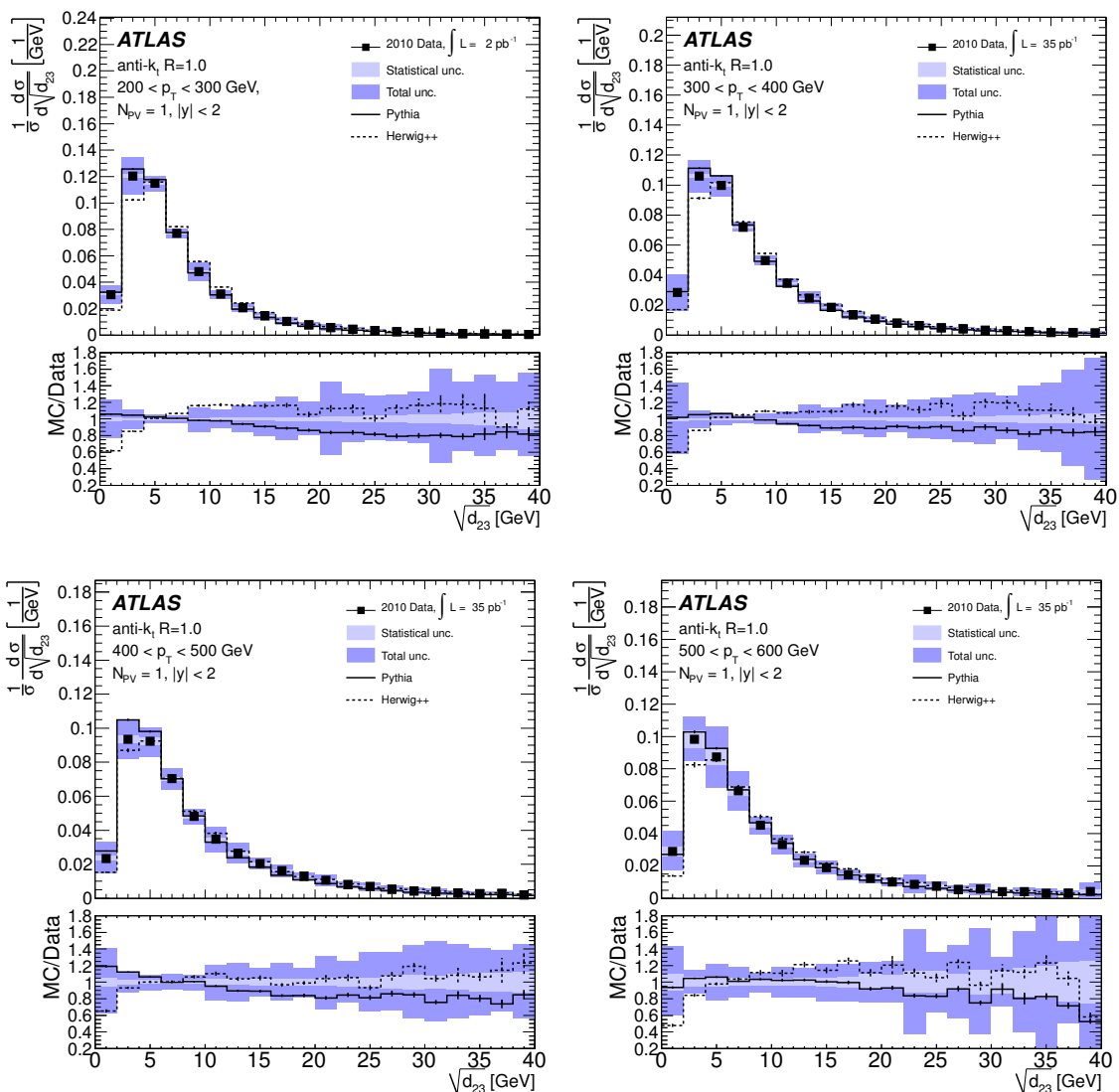


Figure 12. Normalised cross-sections as functions of $\sqrt{d_{23}}$ of anti- k_t jets with $R = 1.0$ in four different p_T bins.

$N_{PV} = 1$ bin increases linearly with R . The ratios of the fitted slopes s_R are found to be:

$$s_{1.0}/s_{0.6} = 4.3 \pm 0.5 \quad ((1.0/0.6)^3 = 4.6), \quad (10.1)$$

$$s_{1.0}/s_{0.4} = 13 \pm 3 \quad ((1.0/0.4)^3 = 15.6), \quad (10.2)$$

$$s_{0.6}/s_{0.4} = 3.0 \pm 0.8 \quad ((0.6/0.4)^3 = 3.4), \quad (10.3)$$

in good agreement with the ratio of the third power of the jet R -parameter. This is in agreement with predictions of scaling of the mean mass [48, 49]. This behaviour can also be qualitatively explained by two factors. Firstly the jet area in the $y - \phi$ plane grows roughly as R^2 . Moreover, the contribution of these particles to the jet mass scales with the distance between them approximately as $R/2$, giving another power of R .

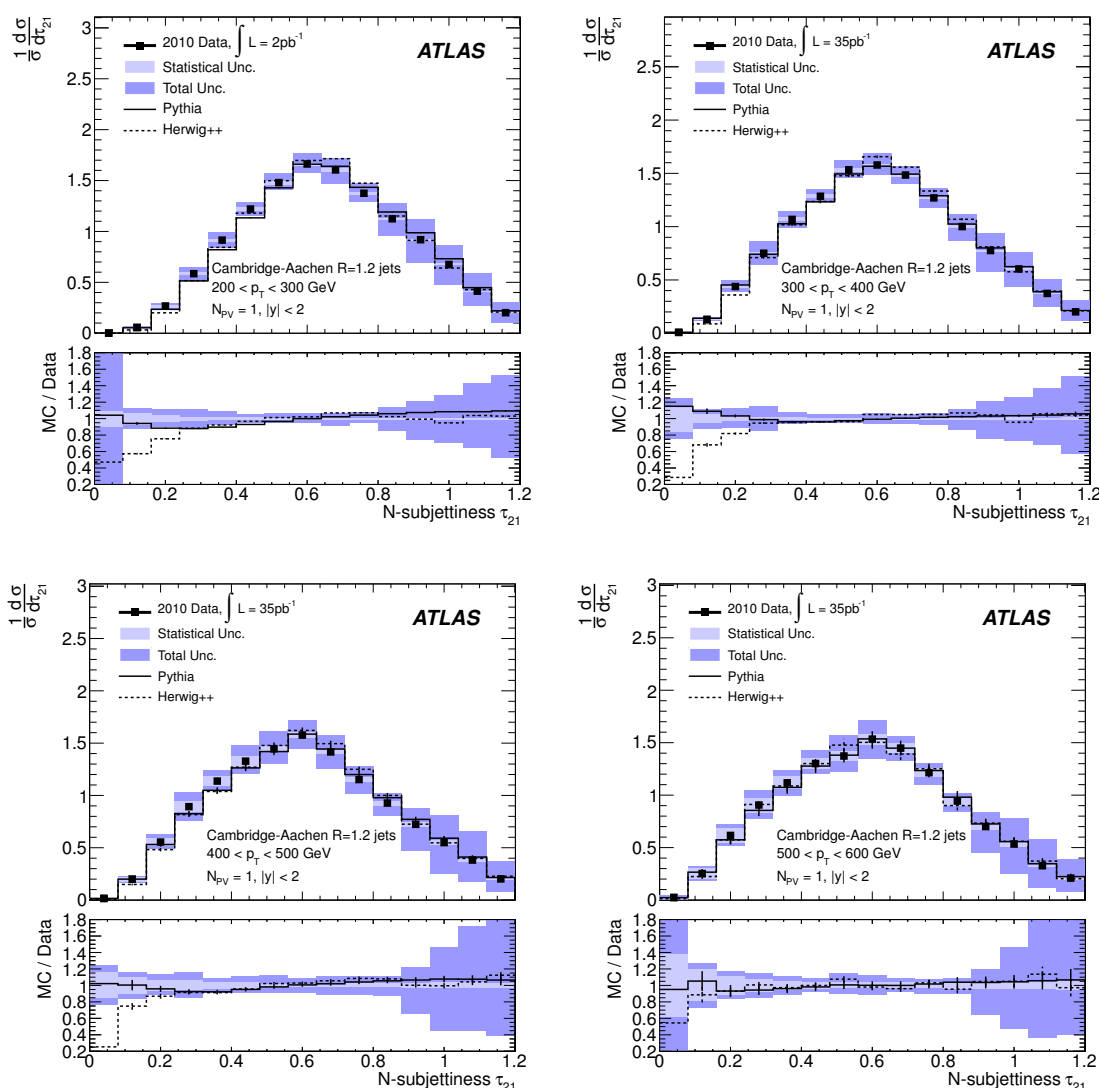


Figure 13. Normalised cross-sections as functions of τ_{21} of Cambridge-Aachen jets with $R = 1.2$ in four different p_T bins.

Figure 17 (right) shows the dependence on N_{PV} of the mean jet mass before and after the splitting and filtering procedure for Cambridge-Aachen jets. Since the angular requirement $R_{jj} > 0.3$ is imposed, the splitting steps of this procedure naturally select more massive jets. Since the splitting procedure selects a kinematically biased subset of jets, a third line shows the mean mass prior to filtering of jets that pass the splitting. The filtering step significantly reduces the impact of pile-up on mean jet mass. In fact, the slope of the straight line fitted to the filtered jet data points is statistically consistent with zero.

Altogether, this demonstrates that the pile-up dependence of mean jet mass in real LHC conditions matches expectations. Additionally, jet substructure techniques that reduce the area of jets are promising for suppressing the effects of pile-up.

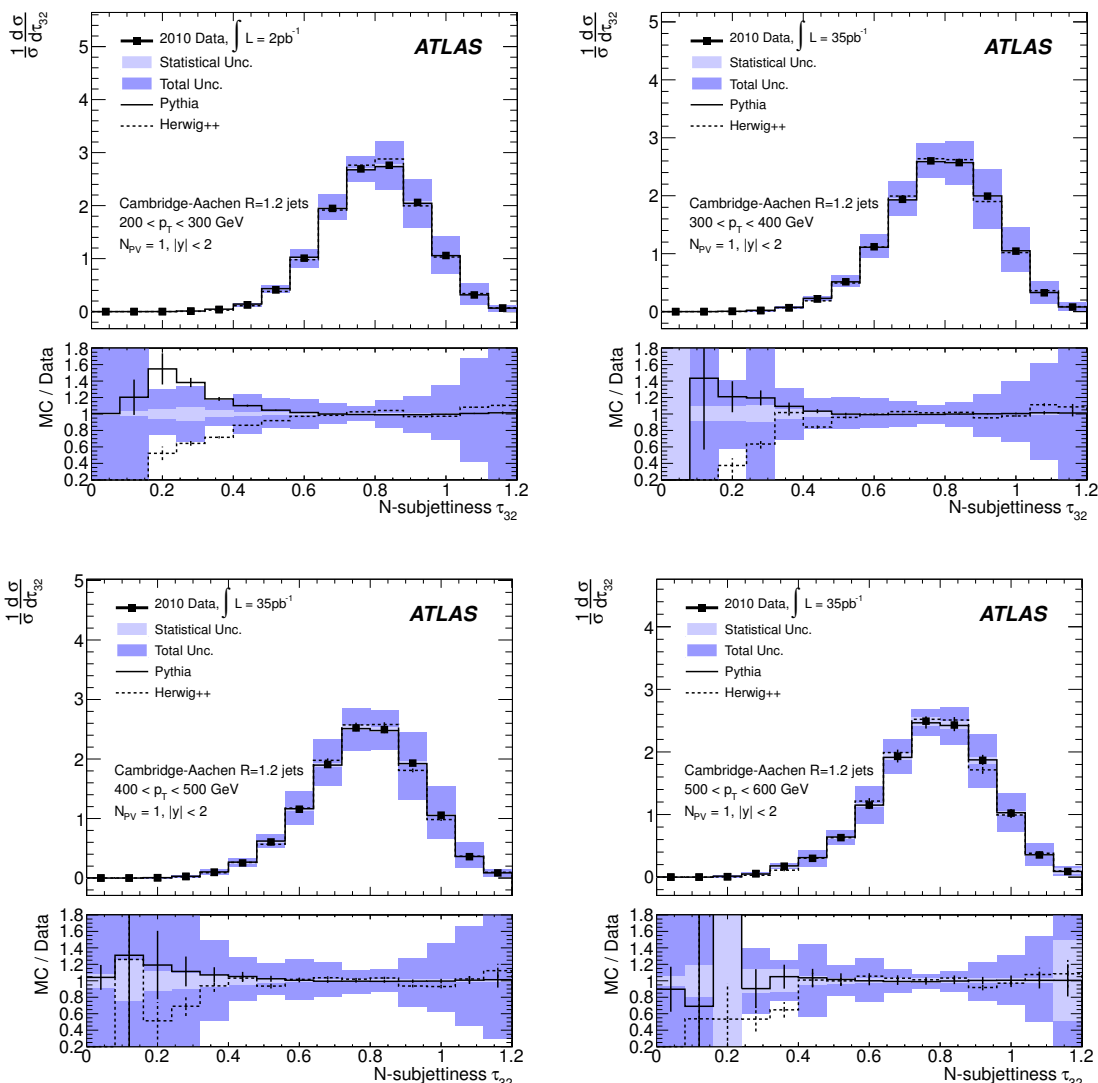


Figure 14. Normalised cross-sections as functions of τ_{32} of Cambridge-Aachen jets with $R = 1.2$ in four different p_T bins.

11 Conclusions

Jet mass and several jet substructure variables have been measured. This is the first particle-level measurement of these variables at the LHC and in many cases the first at any experiment. There is broad agreement between data and leading-order parton-shower Monte Carlo predictions from PYTHIA and HERWIG++, although there is some scope to improve this. Jet mass has generally been found to exhibit the largest disagreements with Monte Carlo simulations. However, in contrast to this, the masses of jets after the Cambridge-Aachen splitting and filtering procedure display good agreement both with and

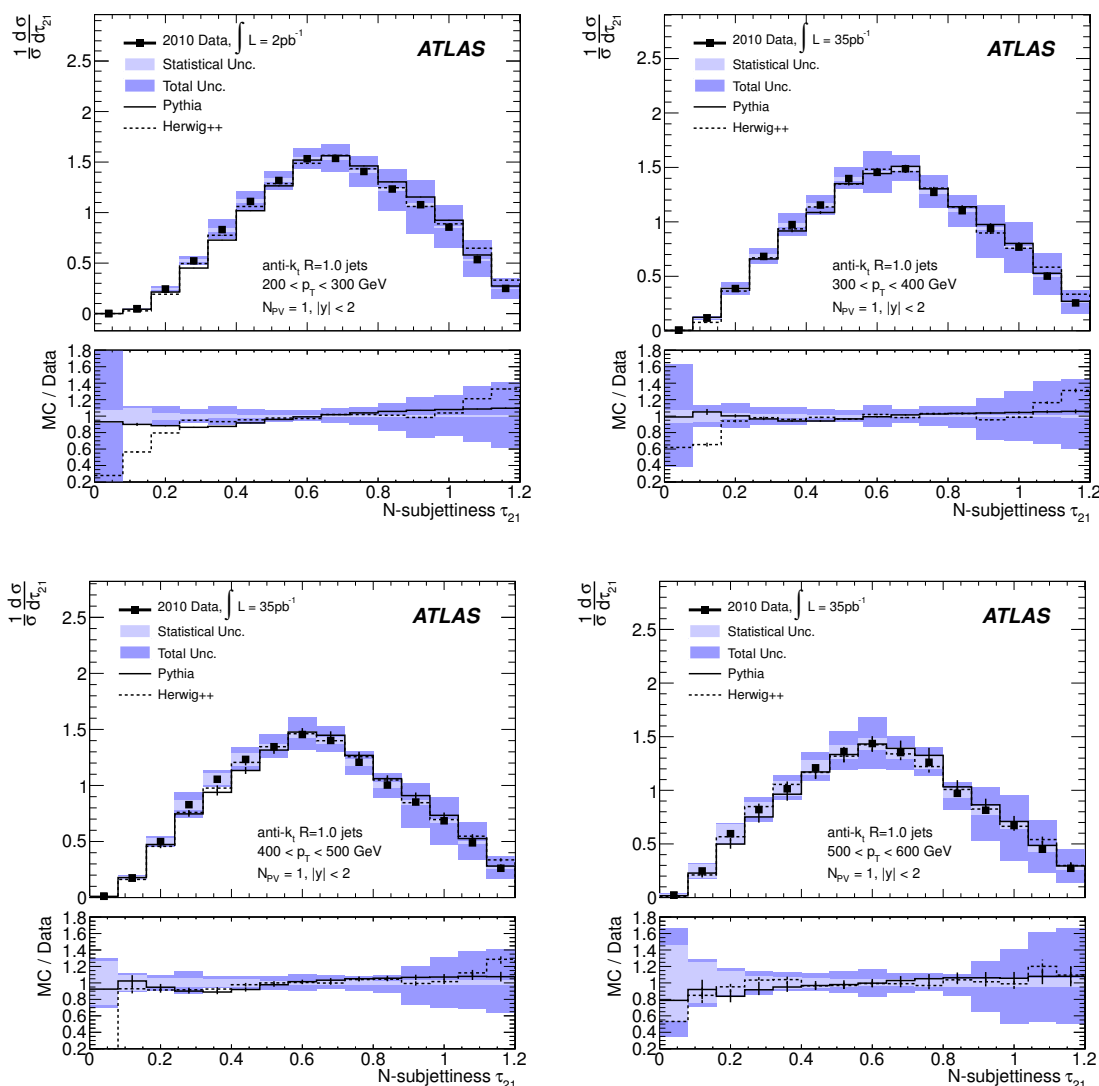


Figure 15. Normalised cross-sections as functions of τ_{21} of anti- k_t jets with $R = 1.0$ in four different p_T bins.

between Monte Carlo simulations. The substructure variables $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, τ_{21} and τ_{32} are all reasonably well reproduced by Monte Carlo predictions. Additionally, the effects of pile-up on mean jet mass have been found to match phenomenological expectations for R -parameter dependence. Splitting and filtering has also been found to reduce the impact of pile-up significantly.

Generally these results show that jet mass and substructure quantities can be successfully reproduced by leading-order parton-shower Monte Carlo. This result bodes well for future analyses aiming to make use of jet substructure techniques.

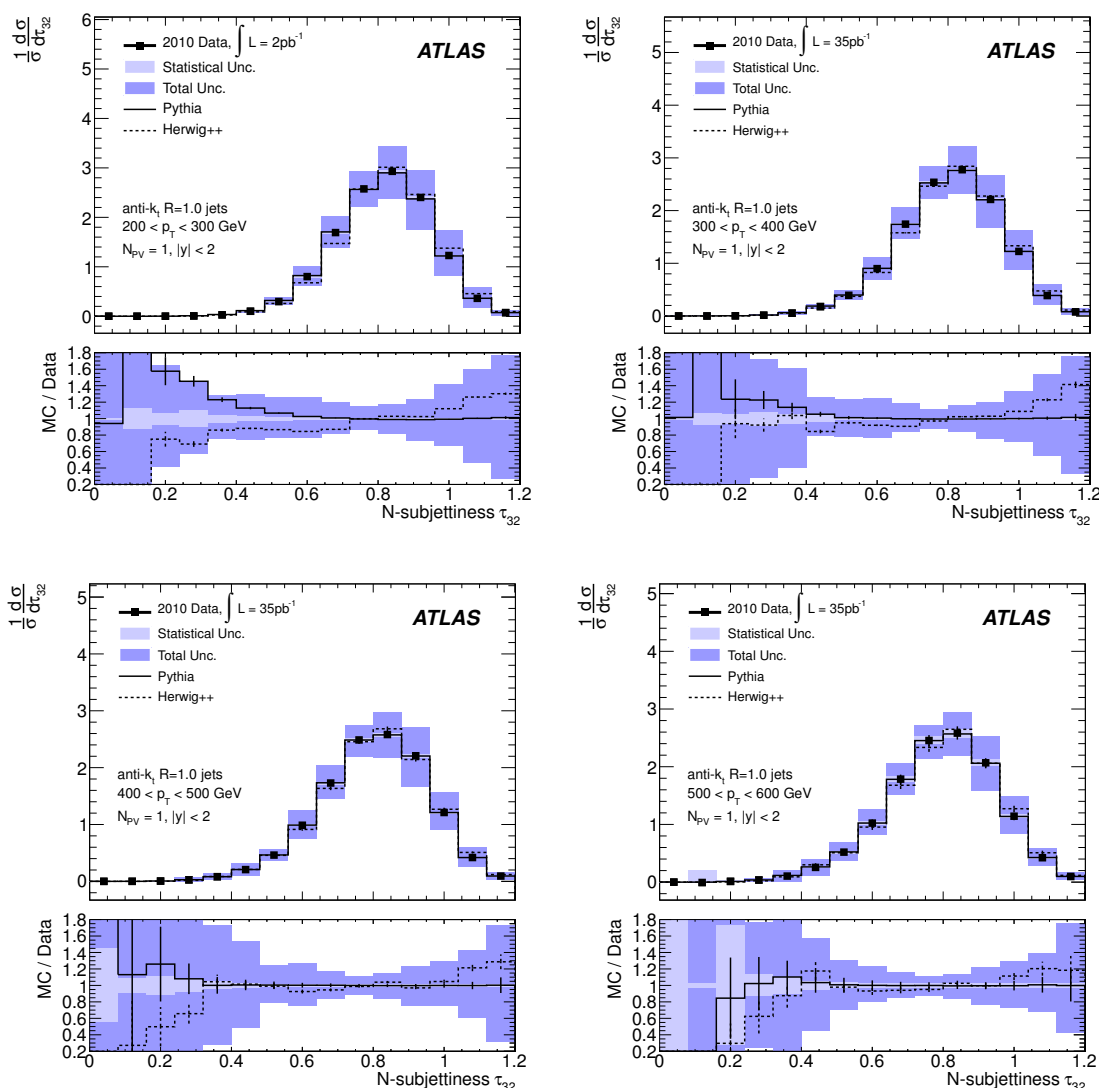


Figure 16. Normalised cross-sections as functions of τ_{32} of anti- k_t jets with $R = 1.0$ in four different p_T bins.

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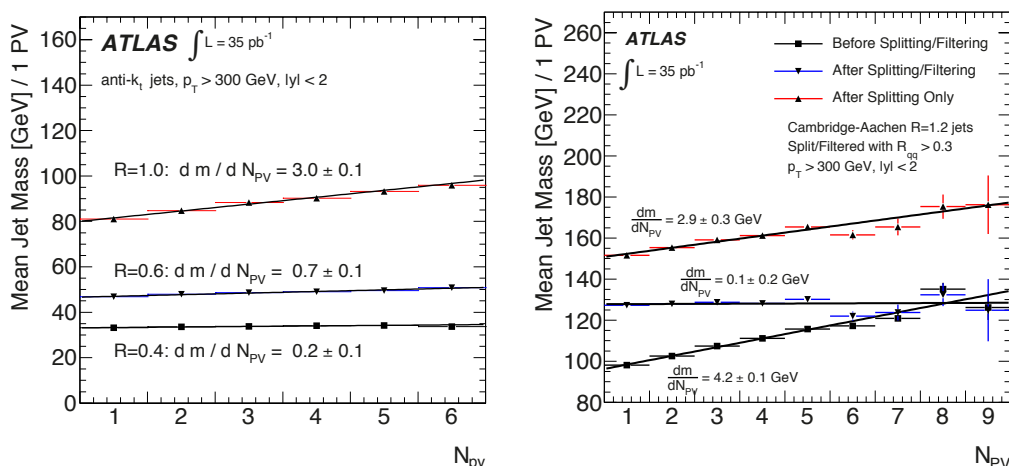


Figure 17. The mean mass for jets with $p_T > 300 \text{ GeV}$ as a function of the number of primary vertices identified in the event. Comparisons show the effect for anti- k_t jets with different R -parameters (left) and Cambridge-Aachen $R = 1.2$ jets with and without splitting and filtering procedure (right). Each set of points is fitted with a straight line.

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The ATLAS collaboration

G. Aad⁴⁸, B. Abbott¹¹⁰, J. Abdallah¹¹, S. Abdel Khalek¹¹⁴, A.A. Abdelalim⁴⁹, A. Abdesselam¹¹⁷, O. Abdinov¹⁰, B. Abi¹¹¹, M. Abolins⁸⁷, O.S. AbouZeid¹⁵⁷, H. Abramowicz¹⁵², H. Abreu¹¹⁴, E. Acerbi^{88a,88b}, B.S. Acharya^{163a,163b}, L. Adamczyk³⁷, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁴, M. Aderholz⁹⁸, S. Adomeit⁹⁷, P. Adragna⁷⁴, T. Adye¹²⁸, S. Aefsky²², J.A. Aguilar-Saavedra^{123b,a}, M. Aharrouche⁸⁰, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁷, M. Ahsan⁴⁰, G. Aielli^{132a,132b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁸, G. Akimoto¹⁵⁴, A.V. Akimov⁹³, A. Akiyama⁶⁶, M.S. Alam¹, M.A. Alam⁷⁵, J. Albert¹⁶⁸, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁴, F. Alessandria^{88a}, C. Alexa^{25a}, G. Alexander¹⁵², G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob²⁰, M. Aliev¹⁵, G. Alimonti^{88a}, J. Alison¹¹⁹, M. Aliyev¹⁰, B.M.M. Allbrooke¹⁷, P.P. Allport⁷², S.E. Allwood-Spiers⁵³, J. Almond⁸¹, A. Aloisio^{101a,101b}, R. Alon¹⁷⁰, A. Alonso⁷⁸, B. Alvarez Gonzalez⁸⁷, M.G. Alviggi^{101a,101b}, K. Amako⁶⁵, P. Amaral²⁹, C. Amelung²², V.V. Ammosov¹²⁷, A. Amorim^{123a,b}, G. Amorós¹⁶⁶, N. Amram¹⁵², C. Anastopoulos²⁹, L.S. Ancu¹⁶, N. Andari¹¹⁴, T. Andeen³⁴, C.F. Anders²⁰, G. Anders^{58a}, K.J. Anderson³⁰, A. Andreazza^{88a,88b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁶⁹, A. Angerami³⁴, F. Anghinolfi²⁹, A. Anisenkov¹⁰⁶, N. Anjos^{123a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, A. Antonov⁹⁵, J. Antos^{143b}, F. Anulli^{131a}, S. Aoun⁸², L. Aperio Bella⁴, R. Apolle^{117,c}, G. Arabidze⁸⁷, I. Aracena¹⁴², Y. Arai⁶⁵, A.T.H. Arce⁴⁴, S. Arfaoui¹⁴⁷, J-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁶,

O. Arnaez⁸⁰, V. Arnal⁷⁹, C. Arnault¹¹⁴, A. Artamonov⁹⁴, G. Artoni^{131a,131b},
 D. Arutinov²⁰, S. Asai¹⁵⁴, R. Asfandiyarov¹⁷¹, S. Ask²⁷, B. Åsman^{145a,145b}, L. Asquith⁵,
 K. Assamagan²⁴, A. Astbury¹⁶⁸, A. Astvatsatourov⁵², B. Aubert⁴, E. Auge¹¹⁴,
 K. Augsten¹²⁶, M. Auresseau^{144a}, G. Avolio¹⁶², R. Avramidou⁹, D. Axen¹⁶⁷, C. Ay⁵⁴,
 G. Azuelos^{92,d}, Y. Azuma¹⁵⁴, M.A. Baak²⁹, G. Baccaglioni^{88a}, C. Bacci^{133a,133b},
 A.M. Bach¹⁴, H. Bachacou¹³⁵, K. Bachas²⁹, M. Backes⁴⁹, M. Backhaus²⁰, E. Badescu^{25a},
 P. Bagnaia^{131a,131b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁷, T. Bain¹⁵⁷, J.T. Baines¹²⁸,
 O.K. Baker¹⁷⁴, M.D. Baker²⁴, S. Baker⁷⁶, E. Banas³⁸, P. Banerjee⁹², Sw. Banerjee¹⁷¹,
 D. Banfi²⁹, A. Bangert¹⁴⁹, V. Bansal¹⁶⁸, H.S. Bansil¹⁷, L. Barak¹⁷⁰, S.P. Baranov⁹³,
 A. Barashkou⁶⁴, A. Barbaro Galtieri¹⁴, T. Barber⁴⁸, E.L. Barberio⁸⁵, D. Barberis^{50a,50b},
 M. Barbero²⁰, D.Y. Bardin⁶⁴, T. Barillari⁹⁸, M. Barisonzi¹⁷³, T. Barklow¹⁴², N. Barlow²⁷,
 B.M. Barnett¹²⁸, R.M. Barnett¹⁴, A. Baroncelli^{133a}, G. Barone⁴⁹, A.J. Barr¹¹⁷,
 F. Barreiro⁷⁹, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁴, R. Bartoldus¹⁴²,
 A.E. Barton⁷⁰, V. Bartsch¹⁴⁸, R.L. Bates⁵³, L. Batkova^{143a}, J.R. Batley²⁷, A. Battaglia¹⁶,
 M. Battistin²⁹, F. Bauer¹³⁵, H.S. Bawa^{142,e}, S. Beale⁹⁷, T. Beau⁷⁷, P.H. Beauchemin¹⁶⁰,
 R. Beccherle^{50a}, P. Bechtel²⁰, H.P. Beck¹⁶, S. Becker⁹⁷, M. Beckingham¹³⁷,
 K.H. Becks¹⁷³, A.J. Beddall^{18c}, A. Beddall^{18c}, S. Bedikian¹⁷⁴, V.A. Bednyakov⁶⁴,
 C.P. Bee⁸², M. Begel²⁴, S. Behar Harpaz¹⁵¹, P.K. Behera⁶², M. Beimforde⁹⁸,
 C. Belanger-Champagne⁸⁴, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵², L. Bellagamba^{19a},
 F. Bellina²⁹, M. Bellomo²⁹, A. Belloni⁵⁷, O. Beloborodova^{106,f}, K. Belotskiy⁹⁵,
 O. Beltramello²⁹, O. Benary¹⁵², D. Bencheekroun^{134a}, C. Benchouk⁸², M. Bendel⁸⁰,
 N. Benekos¹⁶⁴, Y. Benhammou¹⁵², E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{158b},
 D.P. Benjamin⁴⁴, M. Benoit¹¹⁴, J.R. Bensinger²², K. Benslama¹²⁹, S. Bentvelsen¹⁰⁴,
 D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁸, E. Berglund¹⁰⁴,
 J. Beringer¹⁴, P. Bernat⁷⁶, R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁵, C. Bertella⁸²,
 A. Bertin^{19a,19b}, F. Bertinelli²⁹, F. Bertolucci^{121a,121b}, M.I. Besana^{88a,88b}, N. Besson¹³⁵,
 S. Bethke⁹⁸, W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{71a,71b}, O. Biebel⁹⁷, S.P. Bieniek⁷⁶,
 K. Bierwagen⁵⁴, J. Biesiada¹⁴, M. Biglietti^{133a}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁴,
 A. Bingul^{18c}, C. Bini^{131a,131b}, C. Biscarat¹⁷⁶, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵,
 J.-B. Blanchard¹³⁵, G. Blanchot²⁹, T. Blazek^{143a}, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹,
 W. Blum⁸⁰, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁴, V.B. Bobrovnikov¹⁰⁶, S.S. Bocchetta⁷⁸,
 A. Bocci⁴⁴, C.R. Boddy¹¹⁷, M. Boehler⁴¹, J. Boek¹⁷³, N. Boelaert³⁵, J.A. Bogaerts²⁹,
 A. Bogdanchikov¹⁰⁶, A. Bogouch^{89,*}, C. Bohm^{145a}, J. Bohm¹²⁴, V. Boisvert⁷⁵, T. Bold³⁷,
 V. Boldea^{25a}, N.M. Bolnet¹³⁵, M. Bomben⁷⁷, M. Bona⁷⁴, V.G. Bondarenko⁹⁵,
 M. Bondioli¹⁶², M. Boonekamp¹³⁵, C.N. Booth¹³⁸, S. Bordini⁷⁷, C. Borer¹⁶,
 A. Borisov¹²⁷, G. Borissov⁷⁰, I. Borjanovic^{12a}, M. Borri⁸¹, S. Borroni⁸⁶,
 V. Bortolotto^{133a,133b}, K. Bos¹⁰⁴, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁴,
 D. Botterill¹²⁸, J. Bouchami⁹², J. Boudreau¹²², E.V. Bouhova-Thacker⁷⁰,
 D. Boumediene³³, C. Bourdarios¹¹⁴, N. Bousson⁸², A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁴,
 N.I. Bozhko¹²⁷, I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, A. Braem²⁹, P. Branchini^{133a},
 G.W. Brandenburg⁵⁷, A. Brandt⁷, G. Brandt¹¹⁷, O. Brandt⁵⁴, U. Bratzler¹⁵⁵, B. Brau⁸³,
 J.E. Brau¹¹³, H.M. Braun¹⁷³, B. Brelief¹⁵⁷, J. Bremer²⁹, K. Brendlinger¹¹⁹,
 R. Brenner¹⁶⁵, S. Bressler¹⁷⁰, D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁷,

T.J. Brodbeck⁷⁰, E. Brodet¹⁵², F. Broggi^{88a}, C. Bromberg⁸⁷, J. Bronner⁹⁸,
 G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸¹, H. Brown⁷,
 P.A. Bruckman de Renstrom³⁸, D. Bruncko^{143b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰,
 A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³, Q. Buat⁵⁵, F. Bucci⁴⁹,
 J. Buchanan¹¹⁷, N.J. Buchanan², P. Buchholz¹⁴⁰, R.M. Buckingham¹¹⁷, A.G. Buckley⁴⁵,
 S.I. Buda^{25a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁷, V. Büscher⁸⁰, L. Bugge¹¹⁶, O. Bulekov⁹⁵,
 M. Bunse⁴², T. Buran¹¹⁶, H. Burckhart²⁹, S. Burdin⁷², T. Burgess¹³, S. Burke¹²⁸,
 E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁵, F. Butin²⁹, B. Butler¹⁴², J.M. Butler²¹,
 C.M. Buttar⁵³, J.M. Butterworth⁷⁶, W. Buttinger²⁷, S. Cabrera Urbán¹⁶⁶,
 D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁷, P. Calfayan⁹⁷, R. Calkins¹⁰⁵,
 L.P. Caloba^{23a}, R. Caloi^{131a,131b}, D. Calvet³³, S. Calvet³³, R. Camacho Toro³³,
 P. Camarri^{132a,132b}, M. Cambiaghi^{118a,118b}, D. Cameron¹¹⁶, L.M. Caminada¹⁴,
 S. Campana²⁹, M. Campanelli⁷⁶, V. Canale^{101a,101b}, F. Canelli^{30,g}, A. Canepa^{158a},
 J. Cantero⁷⁹, L. Capasso^{101a,101b}, M.D.M. Capeans Garrido²⁹, I. Caprini^{25a},
 M. Caprini^{25a}, D. Capriotti⁹⁸, M. Capua^{36a,36b}, R. Caputo⁸⁰, R. Cardarelli^{132a},
 T. Carli²⁹, G. Carlino^{101a}, L. Carminati^{88a,88b}, B. Caron⁸⁴, S. Caron¹⁰³, E. Carquin^{31b},
 G.D. Carrillo Montoya¹⁷¹, A.A. Carter⁷⁴, J.R. Carter²⁷, J. Carvalho^{123a,h}, D. Casadei¹⁰⁷,
 M.P. Casado¹¹, M. Cascella^{121a,121b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷¹,
 E. Castaneda-Miranda¹⁷¹, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{123a}, G. Cataldi^{71a},
 F. Cataneo²⁹, A. Catinaccio²⁹, J.R. Catmore²⁹, A. Cattai²⁹, G. Cattani^{132a,132b},
 S. Caughron⁸⁷, D. Cauz^{163a,163c}, P. Cavalleri⁷⁷, D. Cavalli^{88a}, M. Cavalli-Sforza¹¹,
 V. Cavasinni^{121a,121b}, F. Ceradini^{133a,133b}, A.S. Cerqueira^{23b}, A. Cerri²⁹, L. Cerrito⁷⁴,
 F. Cerutti⁴⁷, S.A. Cetin^{18b}, F. Cevenini^{101a,101b}, A. Chafaq^{134a}, D. Chakraborty¹⁰⁵,
 K. Chan², B. Chapleau⁸⁴, J.D. Chapman²⁷, J.W. Chapman⁸⁶, E. Chareyre⁷⁷,
 D.G. Charlton¹⁷, V. Chavda⁸¹, C.A. Chavez Barajas²⁹, S. Cheatham⁸⁴, S. Chekanov⁵,
 S.V. Chekulaev^{158a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰³, C. Chen⁶³, H. Chen²⁴,
 S. Chen^{32c}, T. Chen^{32c}, X. Chen¹⁷¹, S. Cheng^{32a}, A. Cheplakov⁶⁴, V.F. Chepurinov⁶⁴,
 R. Cherkaoui El Moursli^{134e}, V. Chernyatin²⁴, E. Cheu⁶, S.L. Cheung¹⁵⁷, L. Chevalier¹³⁵,
 G. Chiefari^{101a,101b}, L. Chikovani^{51a}, J.T. Childers²⁹, A. Chilingarov⁷⁰, G. Chiodini^{71a},
 A.S. Chisholm¹⁷, R.T. Chislett⁷⁶, M.V. Chizhov⁶⁴, G. Choudalakis³⁰, S. Chouridou¹³⁶,
 I.A. Christidi⁷⁶, A. Christov⁴⁸, D. Chromek-Burckhart²⁹, M.L. Chu¹⁵⁰, J. Chudoba¹²⁴,
 G. Ciapetti^{131a,131b}, A.K. Ciftci^{3a}, R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷³,
 M.D. Ciobotaru¹⁶², C. Ciocca^{19a}, A. Cicio¹⁴, M. Cirilli⁸⁶, M. Citterio^{88a},
 M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²², J.C. Clemens⁸², B. Clement⁵⁵,
 C. Clement^{145a,145b}, R.W. Clift¹²⁸, Y. Coadou⁸², M. Cokal^{163a,163c}, A. Coccaro¹⁷¹,
 J. Cochran⁶³, P. Coe¹¹⁷, J.G. Cogan¹⁴², J. Coggeshall¹⁶⁴, E. Cogneras¹⁷⁶, J. Colas⁴,
 A.P. Colijn¹⁰⁴, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵, G. Colon⁸³, P. Conde
 Muiño^{123a}, E. Coniavitis¹¹⁷, M.C. Conidi¹¹, M. Consonni¹⁰³, S.M. Consonni^{88a,88b},
 V. Consorti⁴⁸, S. Constantinescu^{25a}, C. Conta^{118a,118b}, G. Conti⁵⁷, F. Conventi^{101a,i},
 J. Cook²⁹, M. Cooke¹⁴, B.D. Cooper⁷⁶, A.M. Cooper-Sarkar¹¹⁷, K. Copic¹⁴,
 T. Cornelissen¹⁷³, M. Corradi^{19a}, F. Corriveau^{84,j}, A. Cortes-Gonzalez¹⁶⁴, G. Cortiana⁹⁸,
 G. Costa^{88a}, M.J. Costa¹⁶⁶, D. Costanzo¹³⁸, T. Costin³⁰, D. Côté²⁹, R. Coura Torres^{23a},
 L. Courneyea¹⁶⁸, G. Cowan⁷⁵, C. Cowden²⁷, B.E. Cox⁸¹, K. Cranmer¹⁰⁷,

F. Crescioli^{121a,121b}, M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{71a,71b},
S. Crépé-Renaudin⁵⁵, C.-M. Cuciuc^{25a}, C. Cuenca Almenar¹⁷⁴,
T. Cuhadar Donszelmann¹³⁸, M. Curatolo⁴⁷, C.J. Curtis¹⁷, C. Cuthbert¹⁴⁹,
P. Cwetanski⁶⁰, H. Czirr¹⁴⁰, P. Czodrowski⁴³, Z. Czyczula¹⁷⁴, S. D'Auria⁵³,
M. D'Onofrio⁷², A. D'Orazio^{131a,131b}, P.V.M. Da Silva^{23a}, C. Da Via⁸¹, W. Dabrowski³⁷,
A. Dafinca¹¹⁷, T. Dai⁸⁶, C. Dallapiccola⁸³, M. Dam³⁵, M. Dameri^{50a,50b}, D.S. Damiani¹³⁶,
H.O. Danielsson²⁹, D. Dannheim⁹⁸, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b}, W. Davey²⁰,
T. Davidek¹²⁵, N. Davidson⁸⁵, R. Davidson⁷⁰, E. Davies^{117,c}, M. Davies⁹²,
A.R. Davison⁷⁶, Y. Davygora^{58a}, E. Dawe¹⁴¹, I. Dawson¹³⁸, J.W. Dawson^{5,*},
R.K. Daya-Ishmukhametova²², K. De⁷, R. de Asmundis^{101a}, S. De Castro^{19a,19b},
P.E. De Castro Faria Salgado²⁴, S. De Cecco⁷⁷, J. de Graat⁹⁷, N. De Groot¹⁰³,
P. de Jong¹⁰⁴, C. De La Taille¹¹⁴, H. De la Torre⁷⁹, B. De Lotto^{163a,163c}, L. de Mora⁷⁰,
L. De Nooij¹⁰⁴, D. De Pedis^{131a}, A. De Salvo^{131a}, U. De Sanctis^{163a,163c}, A. De Santo¹⁴⁸,
J.B. De Vivie De Regie¹¹⁴, G. De Zorzi^{131a,131b}, S. Dean⁷⁶, W.J. Dearnaley⁷⁰,
R. Debbè²⁴, C. Debenedetti⁴⁵, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹¹⁹,
M. Dehchar¹¹⁷, C. Del Papa^{163a,163c}, J. Del Peso⁷⁹, T. Del Prete^{121a,121b},
T. Delemontex⁵⁵, M. Deliyergiyev⁷³, A. Dell'Acqua²⁹, L. Dell'Asta²¹,
M. Della Pietra^{101a,i}, D. della Volpe^{101a,101b}, M. Delmastro⁴, N. Delruelle²⁹,
P.A. Delsart⁵⁵, C. Deluca¹⁴⁷, S. Demers¹⁷⁴, M. Demichev⁶⁴, B. Demirköz^{11,k}, J. Deng¹⁶²,
S.P. Denisov¹²⁷, D. Derendarz³⁸, J.E. Derkaoui^{134d}, F. Derue⁷⁷, P. Dervan⁷², K. Desch²⁰,
E. Devetak¹⁴⁷, P.O. Deviveiros¹⁰⁴, A. Dewhurst¹²⁸, B. DeWilde¹⁴⁷, S. Dhaliwal¹⁵⁷,
R. Dhullipudi^{24,l}, A. Di Ciaccio^{132a,132b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹,
B. Di Girolamo²⁹, S. Di Luise^{133a,133b}, A. Di Mattia¹⁷¹, B. Di Micco²⁹, R. Di Nardo⁴⁷,
A. Di Simone^{132a,132b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c}, E.B. Diehl⁸⁶,
J. Dietrich⁴¹, T.A. Dietzsch^{58a}, S. Diglio⁸⁵, K. Dindar Yagci³⁹, J. Dingfelder²⁰,
C. Dionisi^{131a,131b}, P. Dita^{25a}, S. Dita^{25a}, F. Dittus²⁹, F. Djama⁸², T. Djobava^{51b},
M.A.B. do Vale^{23c}, A. Do Valle Wemans^{123a}, T.K.O. Doan⁴, M. Dobbs⁸⁴,
R. Dobinson^{29,*}, D. Dobos²⁹, E. Dobson^{29,m}, J. Dodd³⁴, C. Doglioni⁴⁹, T. Doherty⁵³,
Y. Doi^{65,*}, J. Dolejsi¹²⁵, I. Dolenc⁷³, Z. Dolezal¹²⁵, B.A. Dolgoshein^{95,*}, T. Dohmae¹⁵⁴,
M. Donadelli^{23d}, M. Donega¹¹⁹, J. Donini³³, J. Dopke²⁹, A. Doria^{101a}, A. Dos Anjos¹⁷¹,
M. Dosit¹¹, A. Dotti^{121a,121b}, M.T. Dova⁶⁹, J.D. Dowell¹⁷, A.D. Doxiadis¹⁰⁴,
A.T. Doyle⁵³, Z. Drasal¹²⁵, J. Drees¹⁷³, N. Dressnandt¹¹⁹, H. Drevermann²⁹,
C. Driouichi³⁵, M. Dris⁹, J. Dubbert⁹⁸, S. Dube¹⁴, E. Duchovni¹⁷⁰, G. Duckeck⁹⁷,
A. Dudarev²⁹, F. Dudziak⁶³, M. Dührssen²⁹, I.P. Duerdoth⁸¹, L. Duflo¹¹⁴,
M-A. Dufour⁸⁴, M. Dunford²⁹, H. Duran Yildiz^{3a}, R. Duxfield¹³⁸, M. Dwuznik³⁷,
F. Dydak²⁹, M. Düren⁵², W.L. Ebenstein⁴⁴, J. Ebke⁹⁷, S. Eckweiler⁸⁰, K. Edmonds⁸⁰,
C.A. Edwards⁷⁵, N.C. Edwards⁵³, W. Ehrenfeld⁴¹, T. Ehrich⁹⁸, T. Eifert¹⁴², G. Eigen¹³,
K. Einsweiler¹⁴, E. Eisenhandler⁷⁴, T. Ekelof¹⁶⁵, M. El Kacimi^{134c}, M. Ellert¹⁶⁵, S. Elles⁴,
F. Ellinghaus⁸⁰, K. Ellis⁷⁴, N. Ellis²⁹, J. Elmsheuser⁹⁷, M. Elsing²⁹, D. Emeliyanov¹²⁸,
R. Engelmann¹⁴⁷, A. Engl⁹⁷, B. Epp⁶¹, A. Eppig⁸⁶, J. Erdmann⁵⁴, A. Ereditato¹⁶,
D. Eriksson^{145a}, J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁵, D. Errede¹⁶⁴, S. Errede¹⁶⁴,
E. Ertel⁸⁰, M. Escalier¹¹⁴, C. Escobar¹²², X. Espinal Curull¹¹, B. Esposito⁴⁷,
F. Etienne⁸², A.I. Etienvre¹³⁵, E. Etzion¹⁵², D. Evangelakou⁵⁴, H. Evans⁶⁰,

L. Fabbri^{19a,19b}, C. Fabre²⁹, R.M. Fakhruddinov¹²⁷, S. Falciano^{131a}, Y. Fang¹⁷¹,
 M. Fanti^{88a,88b}, A. Farbin⁷, A. Farilla^{133a}, J. Farley¹⁴⁷, T. Farooque¹⁵⁷, S. Farrell¹⁶²,
 S.M. Farrington¹¹⁷, P. Farthouat²⁹, P. Fassnacht²⁹, D. Fassouliotis⁸, B. Fatholahzadeh¹⁵⁷,
 A. Favareto^{88a,88b}, L. Fayard¹¹⁴, S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{143a},
 O.L. Fedin¹²⁰, W. Fedorko⁸⁷, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸², D. Fellmann⁵,
 C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁷, J. Ferencei^{143b}, J. Ferland⁹², W. Fernando¹⁰⁸,
 S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴¹, A. Ferrari¹⁶⁵, P. Ferrari¹⁰⁴, R. Ferrari^{118a},
 D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁶, M.L. Ferrer⁴⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁶,
 A. Ferretto Parodi^{50a,50b}, M. Fiascaris³⁰, F. Fiedler⁸⁰, A. Filipčić⁷³, A. Filippas⁹,
 F. Filthaut¹⁰³, M. Fincke-Keeler¹⁶⁸, M.C.N. Fiolhais^{123a,h}, L. Fiorini¹⁶⁶, A. Firan³⁹,
 G. Fischer⁴¹, P. Fischer²⁰, M.J. Fisher¹⁰⁸, M. Flechl⁴⁸, I. Fleck¹⁴⁰, J. Fleckner⁸⁰,
 P. Fleischmann¹⁷², S. Fleischmann¹⁷³, T. Flick¹⁷³, A. Floderus⁷⁸, L.R. Flores Castillo¹⁷¹,
 M.J. Flowerdew⁹⁸, M. Fokitis⁹, T. Fonseca Martin¹⁶, D.A. Forbush¹³⁷, A. Formica¹³⁵,
 A. Forti⁸¹, D. Fortin^{158a}, J.M. Foster⁸¹, D. Fournier¹¹⁴, A. Foussat²⁹, A.J. Fowler⁴⁴,
 K. Fowler¹³⁶, H. Fox⁷⁰, P. Francavilla¹¹, S. Franchino^{118a,118b}, D. Francis²⁹, T. Frank¹⁷⁰,
 M. Franklin⁵⁷, S. Franz²⁹, M. Fraternali^{118a,118b}, S. Fratina¹¹⁹, S.T. French²⁷,
 F. Friedrich⁴³, R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁵,
 E. Fullana Torregrosa²⁹, J. Fuster¹⁶⁶, C. Gabaldon²⁹, O. Gabizon¹⁷⁰, T. Gadfort²⁴,
 S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁷, E.J. Gallas¹¹⁷, V. Gallo¹⁶,
 B.J. Gallop¹²⁸, P. Gallus¹²⁴, K.K. Gan¹⁰⁸, Y.S. Gao^{142,e}, V.A. Gapienko¹²⁷,
 A. Gaponenko¹⁴, F. Garbersen¹⁷⁴, M. Garcia-Sciveres¹⁴, C. García¹⁶⁶, J.E. García
 Navarro¹⁶⁶, R.W. Gardner³⁰, N. Garelli²⁹, H. Garitaonandia¹⁰⁴, V. Garonne²⁹,
 J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{118a}, B. Gaur¹⁴⁰, L. Gauthier¹³⁵, P. Gauzzi^{131a,131b},
 I.L. Gavrilenko⁹³, C. Gay¹⁶⁷, G. Gaycken²⁰, J.-C. Gayde²⁹, E.N. Gazis⁹, P. Ge^{32d},
 C.N.P. Gee¹²⁸, D.A.A. Geerts¹⁰⁴, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{145a,145b},
 C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{131a,131b}, M. George⁵⁴,
 S. George⁷⁵, P. Gerlach¹⁷³, A. Gershon¹⁵², C. Geweniger^{58a}, H. Ghazlane^{134b},
 N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{131a,131b}, V. Giakoumopoulou⁸,
 V. Giangiobbe¹¹, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁷, S.M. Gibson²⁹,
 L.M. Gilbert¹¹⁷, V. Gilevsky⁹⁰, D. Gillberg²⁸, A.R. Gillman¹²⁸, D.M. Gingrich^{2,d},
 J. Ginzburg¹⁵², N. Giokaris⁸, M.P. Giordani^{163c}, R. Giordano^{101a,101b}, F.M. Giorgi¹⁵,
 P. Giovannini⁹⁸, P.F. Giraud¹³⁵, D. Giugni^{88a}, M. Giunta⁹², P. Giusti^{19a},
 B.K. Gjelsten¹¹⁶, L.K. Gladilin⁹⁶, C. Glasman⁷⁹, J. Glatzer⁴⁸, A. Glazov⁴¹,
 K.W. Glitza¹⁷³, G.L. Glonti⁶⁴, J.R. Goddard⁷⁴, J. Godfrey¹⁴¹, J. Godlewski²⁹,
 M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸⁰, C. Gössling⁴², T. Göttfert⁹⁸, S. Goldfarb⁸⁶,
 T. Golling¹⁷⁴, A. Gomes^{123a,b}, L.S. Gomez Fajardo⁴¹, R. Gonçalo⁷⁵,
 J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰, A. Gonidec²⁹, S. Gonzalez¹⁷¹,
 S. González de la Hoz¹⁶⁶, G. Gonzalez Parra¹¹, M.L. Gonzalez Silva²⁶,
 S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁷, L. Goossens²⁹, P.A. Gorbounov⁹⁴, H.A. Gordon²⁴,
 I. Gorelov¹⁰², G. Gorfine¹⁷³, B. Gorini²⁹, E. Gorini^{71a,71b}, A. Gorišek⁷³, E. Gornicki³⁸,
 S.A. Gorokhov¹²⁷, V.N. Goryachev¹²⁷, B. Gosdzik⁴¹, M. Gosselink¹⁰⁴, M.I. Gostkin⁶⁴,
 I. Gough Eschrich¹⁶², M. Gouighri^{134a}, D. Goujdami^{134c}, M.P. Goulette⁴⁹,
 A.G. Goussiou¹³⁷, C. Goy⁴, S. Gozpinar²², I. Grabowska-Bold³⁷, P. Grafström²⁹,

K.-J. Grahn⁴¹, F. Grancagnolo^{71a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁷, V. Gratchev¹²⁰,
 N. Grau³⁴, H.M. Gray²⁹, J.A. Gray¹⁴⁷, E. Graziani^{133a}, O.G. Grebenyuk¹²⁰,
 T. Greenshaw⁷², Z.D. Greenwood^{24,l}, K. Gregersen³⁵, I.M. Gregor⁴¹, P. Grenier¹⁴²,
 J. Griffiths¹³⁷, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁶, S. Grinstein¹¹, Y.V. Grishkevich⁹⁶,
 J.-F. Grivaz¹¹⁴, M. Groh⁹⁸, E. Gross¹⁷⁰, J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷⁰,
 K. Grybel¹⁴⁰, V.J. Guarino⁵, D. Guest¹⁷⁴, C. Guicheney³³, A. Guida^{71a,71b}, S. Guindon⁵⁴,
 H. Guler^{84,n}, J. Gunther¹²⁴, B. Guo¹⁵⁷, J. Guo³⁴, A. Gupta³⁰, Y. Gusakov⁶⁴,
 V.N. Gushchin¹²⁷, P. Gutierrez¹¹⁰, N. Guttman¹⁵², O. Gutzwiller¹⁷¹, C. Guyot¹³⁵,
 C. Gwenlan¹¹⁷, C.B. Gwilliam⁷², A. Haas¹⁴², S. Haas²⁹, C. Haber¹⁴, H.K. Hadavand³⁹,
 D.R. Hadley¹⁷, P. Haefner⁹⁸, F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁵,
 D. Hall¹¹⁷, J. Haller⁵⁴, K. Hamacher¹⁷³, P. Hamal¹¹², M. Hamer⁵⁴, A. Hamilton^{144b,o},
 S. Hamilton¹⁶⁰, H. Han^{32a}, L. Han^{32b}, K. Hanagaki¹¹⁵, K. Hanawa¹⁵⁹, M. Hance¹⁴,
 C. Handel⁸⁰, P. Hanke^{58a}, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵,
 P. Hansson¹⁴², K. Hara¹⁵⁹, G.A. Hare¹³⁶, T. Harenberg¹⁷³, S. Harkusha⁸⁹, D. Harper⁸⁶,
 R.D. Harrington⁴⁵, O.M. Harris¹³⁷, K. Harrison¹⁷, J. Hartert⁴⁸, F. Hartjes¹⁰⁴,
 T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰⁰, Y. Hasegawa¹³⁹, S. Hassani¹³⁵, M. Hatch²⁹,
 D. Hauff⁹⁸, S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁷, M. Havranek²⁰, B.M. Hawes¹¹⁷,
 C.M. Hawkes¹⁷, R.J. Hawkings²⁹, A.D. Hawkins⁷⁸, D. Hawkins¹⁶², T. Hayakawa⁶⁶,
 T. Hayashi¹⁵⁹, D. Hayden⁷⁵, H.S. Hayward⁷², S.J. Haywood¹²⁸, E. Hazen²¹, M. He^{32d},
 S.J. Head¹⁷, V. Hedberg⁷⁸, L. Heelan⁷, S. Heim⁸⁷, B. Heinemann¹⁴, S. Heisterkamp³⁵,
 L. Helary⁴, C. Heller⁹⁷, M. Heller²⁹, S. Hellman^{145a,145b}, D. Hellmich²⁰, C. Helsens¹¹,
 R.C.W. Henderson⁷⁰, M. Henke^{58a}, A. Henrichs⁵⁴, A.M. Henriques Correia²⁹,
 S. Henrot-Versille¹¹⁴, F. Henry-Couannier⁸², C. Hensel⁵⁴, T. Henß¹⁷³, C.M. Hernandez⁷,
 Y. Hernández Jiménez¹⁶⁶, R. Herrberg¹⁵, A.D. Hershenhorn¹⁵¹, G. Herten⁴⁸,
 R. Hertenberger⁹⁷, L. Hervas²⁹, G.G. Hesketh⁷⁶, N.P. Hessey¹⁰⁴, E. Higón-Rodríguez¹⁶⁶,
 D. Hill^{5,*}, J.C. Hill²⁷, N. Hill⁵, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴,
 E. Hines¹¹⁹, M. Hirose¹¹⁵, F. Hirsch⁴², D. Hirschbuehl¹⁷³, J. Hobbs¹⁴⁷, N. Hod¹⁵²,
 M.C. Hodgkinson¹³⁸, P. Hodgson¹³⁸, A. Hoecker²⁹, M.R. Hoferkamp¹⁰², J. Hoffman³⁹,
 D. Hoffmann⁸², M. Hohlfeld⁸⁰, M. Holder¹⁴⁰, S.O. Holmgren^{145a}, T. Holy¹²⁶,
 J.L. Holzbauer⁸⁷, Y. Homma⁶⁶, T.M. Hong¹¹⁹, L. Hooft van Huysduynen¹⁰⁷,
 T. Horazdovsky¹²⁶, C. Horn¹⁴², S. Horner⁴⁸, J.-Y. Hostachy⁵⁵, S. Hou¹⁵⁰, M.A. Houlden⁷²,
 A. Houmada^{134a}, J. Howarth⁸¹, D.F. Howell¹¹⁷, I. Hristova¹⁵, J. Hrivnac¹¹⁴,
 I. Hruska¹²⁴, T. Hryn'ova⁴, P.J. Hsu⁸⁰, S.-C. Hsu¹⁴, G.S. Huang¹¹⁰, Z. Hubacek¹²⁶,
 F. Hubaut⁸², F. Huegging²⁰, A. Huettmann⁴¹, T.B. Huffman¹¹⁷, E.W. Hughes³⁴,
 G. Hughes⁷⁰, R.E. Hughes-Jones⁸¹, M. Huhtinen²⁹, P. Hurst⁵⁷, M. Hurwitz¹⁴,
 U. Husemann⁴¹, N. Huseynov^{64,p}, J. Huston⁸⁷, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹,
 M. Ibbotson⁸¹, I. Ibragimov¹⁴⁰, R. Ichimiya⁶⁶, L. Iconomidou-Fayard¹¹⁴, J. Idarraga¹¹⁴,
 P. Iengo^{101a}, O. Igonkina¹⁰⁴, Y. Ikegami⁶⁵, M. Ikeno⁶⁵, Y. Ilchenko³⁹, D. Iliadis¹⁵³,
 N. Ilic¹⁵⁷, M. Imori¹⁵⁴, T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{133a},
 V. Ippolito^{131a,131b}, A. Irls Quiles¹⁶⁶, C. Isaksson¹⁶⁵, A. Ishikawa⁶⁶, M. Ishino⁶⁷,
 R. Ishmukhametov³⁹, C. Issever¹¹⁷, S. Istin^{18a}, A.V. Ivashin¹²⁷, W. Iwanski³⁸,
 H. Iwasaki⁶⁵, J.M. Izen⁴⁰, V. Izzo^{101a}, B. Jackson¹¹⁹, J.N. Jackson⁷², P. Jackson¹⁴²,
 M.R. Jaekel²⁹, V. Jain⁶⁰, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁶, D.K. Jana¹¹⁰,

E. Jankowski¹⁵⁷, E. Jansen⁷⁶, H. Jansen²⁹, A. Jantsch⁹⁸, M. Janus⁴⁸, G. Jarlskog⁷⁸,
 L. Jeanty⁵⁷, K. Jelen³⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴,
 M.K. Jha^{19a}, H. Ji¹⁷¹, W. Ji⁸⁰, J. Jia¹⁴⁷, Y. Jiang^{32b}, M. Jimenez Belenguer⁴¹, G. Jin^{32b},
 S. Jin^{32a}, O. Jinnouchi¹⁵⁶, M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³,
 M. Johansen^{145a,145b}, K.E. Johansson^{145a}, P. Johansson¹³⁸, S. Johnert⁴¹, K.A. Johns⁶,
 K. Jon-And^{145a,145b}, G. Jones¹¹⁷, R.W.L. Jones⁷⁰, T.W. Jones⁷⁶, T.J. Jones⁷²,
 O. Jonsson²⁹, C. Joram²⁹, P.M. Jorge^{123a}, J. Joseph¹⁴, K.D. Joshi⁸¹, J. Jovicevic¹⁴⁶,
 T. Jovin^{12b}, X. Ju¹⁷¹, C.A. Jung⁴², R.M. Jungst²⁹, V. Juranek¹²⁴, P. Jussel⁶¹,
 A. Juste Rozas¹¹, V.V. Kabachenko¹²⁷, S. Kabana¹⁶, M. Kaci¹⁶⁶, A. Kaczmarska³⁸,
 P. Kadlecik³⁵, M. Kado¹¹⁴, H. Kagan¹⁰⁸, M. Kagan⁵⁷, S. Kaiser⁹⁸, E. Kajomovitz¹⁵¹,
 S. Kalinin¹⁷³, L.V. Kalinovskaya⁶⁴, S. Kama³⁹, N. Kanaya¹⁵⁴, M. Kaneda²⁹, S. Kaneti²⁷,
 T. Kanno¹⁵⁶, V.A. Kantserov⁹⁵, J. Kanzaki⁶⁵, B. Kaplan¹⁷⁴, A. Kapliy³⁰, J. Kaplon²⁹,
 D. Kar⁴³, M. Karagounis²⁰, M. Karagoz¹¹⁷, M. Karnevskiy⁴¹, K. Karr⁵,
 V. Kartvelishvili⁷⁰, A.N. Karyukhin¹²⁷, L. Kashif¹⁷¹, G. Kasieczka^{58b}, R.D. Kass¹⁰⁸,
 A. Kastanas¹³, M. Kataoka⁴, Y. Kataoka¹⁵⁴, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶,
 K. Kawagoe⁶⁶, T. Kawamoto¹⁵⁴, G. Kawamura⁸⁰, M.S. Kayl¹⁰⁴, V.A. Kazanin¹⁰⁶,
 M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁸, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁴, J.S. Keller¹³⁷,
 J. Kennedy⁹⁷, M. Kenyon⁵³, O. Kepka¹²⁴, N. Kerschen²⁹, B.P. Kerševan⁷³, S. Kersten¹⁷³,
 K. Kessoku¹⁵⁴, J. Keung¹⁵⁷, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁴, A. Khanov¹¹¹,
 D. Kharchenko⁶⁴, A. Khodinov⁹⁵, A.G. Kholodenko¹²⁷, A. Khomich^{58a}, T.J. Khoo²⁷,
 G. Khoriauli²⁰, A. Khoroshilov¹⁷³, N. Khovanskiy⁶⁴, V. Khovanskiy⁹⁴, E. Khramov⁶⁴,
 J. Khubua^{51b}, H. Kim^{145a,145b}, M.S. Kim², S.H. Kim¹⁵⁹, N. Kimura¹⁶⁹, O. Kind¹⁵,
 B.T. King⁷², M. King⁶⁶, R.S.B. King¹¹⁷, J. Kirk¹²⁸, L.E. Kirsch²², A.E. Kiryunin⁹⁸,
 T. Kishimoto⁶⁶, D. Kisielewska³⁷, T. Kittelmann¹²², A.M. Kiver¹²⁷, E. Kladiva^{143b},
 J. Klaiber-Lodewigs⁴², M. Klein⁷², U. Klein⁷², K. Kleinknecht⁸⁰, M. Klemetti⁸⁴,
 A. Klier¹⁷⁰, P. Klimek^{145a,145b}, A. Klimentov²⁴, R. Klingenberg⁴², J.A. Klinger⁸¹,
 E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰³, S. Klous¹⁰⁴, E.-E. Kluge^{58a},
 T. Kluge⁷², P. Kluit¹⁰⁴, S. Kluth⁹⁸, N.S. Knecht¹⁵⁷, E. Kneringer⁶¹, J. Knobloch²⁹,
 E.B.F.G. Knoop⁸², A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁴, M. Kobel⁴³, M. Kocian¹⁴²,
 P. Kodys¹²⁵, K. Köneke²⁹, A.C. König¹⁰³, S. Koenig⁸⁰, L. Köpke⁸⁰, F. Koetsveld¹⁰³,
 P. Koevesarki²⁰, T. Koffas²⁸, E. Koffeman¹⁰⁴, L.A. Kogan¹¹⁷, F. Kohn⁵⁴, Z. Kohout¹²⁶,
 T. Kohriki⁶⁵, T. Koi¹⁴², T. Kokott²⁰, G.M. Kolachev¹⁰⁶, H. Kolanoski¹⁵, V. Kolesnikov⁶⁴,
 I. Koletsou^{88a}, J. Koll⁸⁷, M. Kollefrath⁴⁸, S.D. Kolya⁸¹, A.A. Komar⁹³, Y. Komori¹⁵⁴,
 T. Kondo⁶⁵, T. Kono^{41,q}, A.I. Kononov⁴⁸, R. Konoplich^{107,r}, N. Konstantinidis⁷⁶,
 A. Kootz¹⁷³, S. Koperny³⁷, K. Korcyl³⁸, K. Kordas¹⁵³, V. Koreshev¹²⁷, A. Korn¹¹⁷,
 A. Korol¹⁰⁶, I. Korolkov¹¹, E.V. Korolkova¹³⁸, V.A. Korotkov¹²⁷, O. Kortner⁹⁸,
 S. Kortner⁹⁸, V.V. Kostyukhin²⁰, M.J. Kotamäki²⁹, S. Kotov⁹⁸, V.M. Kotov⁶⁴,
 A. Kotwal⁴⁴, C. Kourkoumelis⁸, V. Kouskoura¹⁵³, A. Koutsman^{158a}, R. Kowalewski¹⁶⁸,
 T.Z. Kowalski³⁷, W. Kozanecki¹³⁵, A.S. Kozhin¹²⁷, V. Kral¹²⁶, V.A. Kramarenko⁹⁶,
 G. Kramberger⁷³, M.W. Krasny⁷⁷, A. Krasznahorkay¹⁰⁷, J. Kraus⁸⁷, J.K. Kraus²⁰,
 A. Kreisel¹⁵², F. Krejci¹²⁶, J. Kretzschmar⁷², N. Krieger⁵⁴, P. Krieger¹⁵⁷,
 K. Kroeninger⁵⁴, H. Kroha⁹⁸, J. Kroll¹¹⁹, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁴,
 H. Krüger²⁰, T. Kruker¹⁶, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruth²⁰, T. Kubota⁸⁵,

S. Kuday^{3a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹, D. Kuhn⁶¹, V. Kukhtin⁶⁴,
 Y. Kulchitsky⁸⁹, S. Kuleshov^{31b}, C. Kummer⁹⁷, M. Kuna⁷⁷, N. Kundu¹¹⁷, J. Kunkle¹¹⁹,
 A. Kupco¹²⁴, H. Kurashige⁶⁶, M. Kurata¹⁵⁹, Y.A. Kurochkin⁸⁹, V. Kus¹²⁴,
 E.S. Kuwertz¹⁴⁶, M. Kuze¹⁵⁶, J. Kvita¹⁴¹, R. Kwee¹⁵, A. La Rosa⁴⁹, L. La Rotonda^{36a,36b},
 L. Labarga⁷⁹, J. Labbe⁴, S. Lablak^{134a}, C. Lacasta¹⁶⁶, F. Lacava^{131a,131b}, H. Lacker¹⁵,
 D. Lacour⁷⁷, V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁴, R. Lafaye⁴, B. Laforge⁷⁷, T. Lagouri⁷⁹,
 S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna²⁹, L. Lambourne⁷⁶, C.L. Lampen⁶, W. Lampl⁶,
 E. Lancon¹³⁵, U. Landgraf⁴⁸, M.P.J. Landon⁷⁴, J.L. Lane⁸¹, C. Lange⁴¹,
 A.J. Lankford¹⁶², F. Lanni²⁴, K. Lantzschi¹⁷³, S. Laplace⁷⁷, C. Lapoire²⁰, J.F. Laporte¹³⁵,
 T. Lari^{88a}, A.V. Larionov¹²⁷, A. Larner¹¹⁷, C. Lasseur²⁹, M. Lassnig²⁹, P. Laurelli⁴⁷,
 V. Lavorini^{36a,36b}, W. Lavrijsen¹⁴, P. Laycock⁷², A.B. Lazarev⁶⁴, O. Le Dortz⁷⁷,
 E. Le Guirriec⁸², C. Le Maner¹⁵⁷, E. Le Menedeu⁹, C. Lebel⁹², T. LeCompte⁵,
 F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁴, J.S.H. Lee¹¹⁵, S.C. Lee¹⁵⁰, L. Lee¹⁷⁴, M. Lefebvre¹⁶⁸,
 M. Legendre¹³⁵, A. Leger⁴⁹, B.C. LeGeyt¹¹⁹, F. Legger⁹⁷, C. Leggett¹⁴, M. Lehmacher²⁰,
 G. Lehmann Miotto²⁹, X. Lei⁶, M.A.L. Leite^{23d}, R. Leitner¹²⁵, D. Lellouch¹⁷⁰,
 M. Leltchouk³⁴, B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{144b}, T. Lenz¹⁰⁴,
 G. Lenzen¹⁷³, B. Lenzi²⁹, K. Leonhardt⁴³, S. Leontsinis⁹, C. Leroy⁹², J-R. Lessard¹⁶⁸,
 J. Lesser^{145a}, C.G. Lester²⁷, A. Leung Fook Cheong¹⁷¹, J. Levêque⁴, D. Levin⁸⁶,
 L.J. Levinson¹⁷⁰, M.S. Levitski¹²⁷, A. Lewis¹¹⁷, G.H. Lewis¹⁰⁷, A.M. Leyko²⁰,
 M. Leyton¹⁵, B. Li⁸², H. Li^{171,s}, S. Li^{32b,t}, X. Li⁸⁶, Z. Liang^{117,u}, H. Liao³³, B. Liberti^{132a},
 P. Lichard²⁹, M. Lichtnecker⁹⁷, K. Lie¹⁶⁴, W. Liebig¹³, R. Lifshitz¹⁵¹, C. Limbach²⁰,
 A. Limosani⁸⁵, M. Limper⁶², S.C. Lin^{150,v}, F. Linde¹⁰⁴, J.T. Linnemann⁸⁷, E. Lipeles¹¹⁹,
 L. Lipinsky¹²⁴, A. Lipniacka¹³, T.M. Liss¹⁶⁴, D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁶,
 C. Liu²⁸, D. Liu¹⁵⁰, H. Liu⁸⁶, J.B. Liu⁸⁶, M. Liu^{32b}, Y. Liu^{32b}, M. Livan^{118a,118b},
 S.S.A. Livermore¹¹⁷, A. Lleres⁵⁵, J. Llorente Merino⁷⁹, S.L. Lloyd⁷⁴, E. Lobodzinska⁴¹,
 P. Loch⁶, W.S. Lockman¹³⁶, T. Loddenkoetter²⁰, F.K. Loebinger⁸¹, A. Loginov¹⁷⁴,
 C.W. Loh¹⁶⁷, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁴, J. Loken¹¹⁷, V.P. Lombardo⁴,
 R.E. Long⁷⁰, L. Lopes^{123a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁷, N. Lorenzo Martinez¹¹⁴,
 M. Losada¹⁶¹, P. Loscutoff¹⁴, F. Lo Sterzo^{131a,131b}, M.J. Losty^{158a}, X. Lou⁴⁰,
 A. Lounis¹¹⁴, K.F. Loureiro¹⁶¹, J. Love²¹, P.A. Love⁷⁰, A.J. Lowe^{142,e}, F. Lu^{32a},
 H.J. Lubatti¹³⁷, C. Luci^{131a,131b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸,
 J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁴, W. Lukas⁶¹, D. Lumb⁴⁸, L. Luminari^{131a},
 E. Lund¹¹⁶, B. Lund-Jensen¹⁴⁶, B. Lundberg⁷⁸, J. Lundberg^{145a,145b}, J. Lundquist³⁵,
 M. Lungwitz⁸⁰, G. Lutz⁹⁸, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁸, H. Ma²⁴, L.L. Ma¹⁷¹,
 J.A. Macana Goia⁹², G. Maccarrone⁴⁷, A. Macchiolo⁹⁸, B. Maček⁷³,
 J. Machado Miguens^{123a}, R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³,
 R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷³, S. Mättig⁴¹, L. Magnoni²⁹, E. Magradze⁵⁴,
 Y. Mahalalel¹⁵², K. Mahboubi⁴⁸, S. Mahmoud⁷², G. Mahout¹⁷, C. Maiani^{131a,131b},
 C. Maidantchik^{23a}, A. Maio^{123a,b}, S. Majewski²⁴, Y. Makida⁶⁵, N. Makovec¹¹⁴, P. Mal¹³⁵,
 B. Malaescu²⁹, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²⁰, F. Malek⁵⁵, U. Mallik⁶²,
 D. Malon⁵, C. Malone¹⁴², S. Maltezos⁹, V. Malyshev¹⁰⁶, S. Malyukov²⁹, R. Mameghani⁹⁷,
 J. Mamuzic^{12b}, A. Manabe⁶⁵, L. Mandelli^{88a}, I. Mandić⁷³, R. Mandrysch¹⁵,
 J. Maneira^{123a}, P.S. Mangear⁸⁷, L. Manhaes de Andrade Filho^{23a}, I.D. Manjavidze⁶⁴,

A. Mann⁵⁴, P.M. Manning¹³⁶, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁵, A. Manz⁹⁸,
 A. Mapelli²⁹, L. Mapelli²⁹, L. March⁷⁹, J.F. Marchand²⁸, F. Marchese^{132a,132b},
 G. Marchiori⁷⁷, M. Marcisovsky¹²⁴, C.P. Marino¹⁶⁸, F. Marroquin^{23a}, R. Marshall⁸¹,
 Z. Marshall²⁹, F.K. Martens¹⁵⁷, S. Marti-Garcia¹⁶⁶, A.J. Martin¹⁷⁴, B. Martin²⁹,
 B. Martin⁸⁷, F.F. Martin¹¹⁹, J.P. Martin⁹², Ph. Martin⁵⁵, T.A. Martin¹⁷, V.J. Martin⁴⁵,
 B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁸, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷,
 A.C. Martyniuk¹⁶⁸, M. Marx⁸¹, F. Marzano^{131a}, A. Marzin¹¹⁰, L. Masetti⁸⁰,
 T. Mashimo¹⁵⁴, R. Mashinistov⁹³, J. Masik⁸¹, A.L. Maslennikov¹⁰⁶, I. Massa^{19a,19b},
 G. Massaro¹⁰⁴, N. Massol⁴, P. Mastrandrea^{131a,131b}, A. Mastroberardino^{36a,36b},
 T. Masubuchi¹⁵⁴, P. Matricon¹¹⁴, H. Matsumoto¹⁵⁴, H. Matsunaga¹⁵⁴, T. Matsushita⁶⁶,
 C. Mattravers^{117,c}, J.M. Maugain²⁹, J. Maurer⁸², S.J. Maxfield⁷², D.A. Maximov^{106,f},
 E.N. May⁵, A. Mayne¹³⁸, R. Mazini¹⁵⁰, M. Mazur²⁰, M. Mazzanti^{88a}, S.P. Mc Kee⁸⁶,
 A. McCarn¹⁶⁴, R.L. McCarthy¹⁴⁷, T.G. McCarthy²⁸, N.A. McCubbin¹²⁸,
 K.W. McFarlane⁵⁶, J.A. Mcfayden¹³⁸, H. McGlone⁵³, G. Mchedlidze^{51b}, R.A. McLaren²⁹,
 T. Mclaughlan¹⁷, S.J. McMahan¹²⁸, R.A. McPherson^{168,j}, A. Meade⁸³, J. Mechnich¹⁰⁴,
 M. Mechtel¹⁷³, M. Medinnis⁴¹, R. Meera-Lebbai¹¹⁰, T. Meguro¹¹⁵, R. Mehdiyev⁹²,
 S. Mehlhase³⁵, A. Mehta⁷², K. Meier^{58a}, B. Meirose⁷⁸, C. Melachrinos³⁰,
 B.R. Mellado Garcia¹⁷¹, L. Mendoza Navas¹⁶¹, Z. Meng^{150,s}, A. Mengarelli^{19a,19b},
 S. Menke⁹⁸, C. Menot²⁹, E. Meoni¹¹, K.M. Mercurio⁵⁷, P. Mermod⁴⁹, L. Merola^{101a,101b},
 C. Meroni^{88a}, F.S. Merritt³⁰, H. Merritt¹⁰⁸, A. Messina²⁹, J. Metcalfe¹⁰², A.S. Mete⁶³,
 C. Meyer⁸⁰, C. Meyer³⁰, J-P. Meyer¹³⁵, J. Meyer¹⁷², J. Meyer⁵⁴, T.C. Meyer²⁹,
 W.T. Meyer⁶³, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁸, S. Migas⁷²,
 L. Mijović⁴¹, G. Mikenberg¹⁷⁰, M. Mikestikova¹²⁴, M. Mikuz⁷³, D.W. Miller³⁰,
 R.J. Miller⁸⁷, W.J. Mills¹⁶⁷, C. Mills⁵⁷, A. Milov¹⁷⁰, D.A. Milstead^{145a,145b},
 D. Milstein¹⁷⁰, A.A. Minaenko¹²⁷, M. Miñano Moya¹⁶⁶, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁷,
 B. Mindur³⁷, M. Mineev⁶⁴, Y. Ming¹⁷¹, L.M. Mir¹¹, G. Mirabelli^{131a}, L. Miralles Verge¹¹,
 A. Misiejuk⁷⁵, J. Mitrevski¹³⁶, G.Y. Mitrofanov¹²⁷, V.A. Mitsou¹⁶⁶, S. Mitsui⁶⁵,
 P.S. Miyagawa¹³⁸, K. Miyazaki⁶⁶, J.U. Mjörnmark⁷⁸, T. Moa^{145a,145b}, P. Mockett¹³⁷,
 S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁷, W. Mohr⁴⁸,
 S. Mohrdieck-Möck⁹⁸, A.M. Moisseev^{127,*}, R. Moles-Valls¹⁶⁶, J. Molina-Perez²⁹,
 J. Monk⁷⁶, E. Monnier⁸², S. Montesano^{88a,88b}, F. Monticelli⁶⁹, S. Monzani^{19a,19b},
 R.W. Moore², G.F. Moorhead⁸⁵, C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁵,
 J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸⁰, M. Moreno Llácer¹⁶⁶, P. Morettini^{50a},
 M. Morgenstern⁴³, M. Morii⁵⁷, J. Morin⁷⁴, A.K. Morley²⁹, G. Mornacchi²⁹,
 S.V. Morozov⁹⁵, J.D. Morris⁷⁴, L. Morvaj¹⁰⁰, H.G. Moser⁹⁸, M. Mosidze^{51b}, J. Moss¹⁰⁸,
 R. Mount¹⁴², E. Mountricha^{9,w}, S.V. Mouraviev⁹³, E.J.W. Moyse⁸³, M. Mudrinic^{12b},
 F. Mueller^{58a}, J. Mueller¹²², K. Mueller²⁰, T.A. Müller⁹⁷, T. Mueller⁸⁰,
 D. Muenstermann²⁹, A. Muir¹⁶⁷, Y. Munwes¹⁵², W.J. Murray¹²⁸, I. Mussche¹⁰⁴,
 E. Musto^{101a,101b}, A.G. Myagkov¹²⁷, M. Myska¹²⁴, J. Nadal¹¹, K. Nagai¹⁵⁹, K. Nagano⁶⁵,
 A. Nagarkar¹⁰⁸, Y. Nagasaka⁵⁹, M. Nagel⁹⁸, A.M. Nairz²⁹, Y. Nakahama²⁹,
 K. Nakamura¹⁵⁴, T. Nakamura¹⁵⁴, I. Nakano¹⁰⁹, G. Nanava²⁰, A. Napier¹⁶⁰,
 R. Narayan^{58b}, M. Nash^{76,c}, N.R. Nation²¹, T. Nattermann²⁰, T. Naumann⁴¹,
 G. Navarro¹⁶¹, H.A. Neal⁸⁶, E. Nebot⁷⁹, P.Yu. Nechaeva⁹³, T.J. Neep⁸¹, A. Negri^{118a,118b},

G. Negri²⁹, S. Nektarijevic⁴⁹, A. Nelson¹⁶², T.K. Nelson¹⁴², S. Nemecek¹²⁴,
P. Nemethy¹⁰⁷, A.A. Nepomuceno^{23a}, M. Nessi^{29,x}, M.S. Neubauer¹⁶⁴, A. Neusiedl⁸⁰,
R.M. Neves¹⁰⁷, P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁵, R.B. Nickerson¹¹⁷,
R. Nicolaidou¹³⁵, L. Nicolas¹³⁸, B. Nicquevert²⁹, F. Niedercorn¹¹⁴, J. Nielsen¹³⁶,
T. Niinikoski²⁹, N. Nikiforou³⁴, A. Nikiforov¹⁵, V. Nikolaenko¹²⁷, K. Nikolaev⁶⁴,
I. Nikolic-Audit⁷⁷, K. Nikolics⁴⁹, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷,
Y. Ninomiya¹⁵⁴, A. Nisati^{131a}, T. Nishiyama⁶⁶, R. Nisius⁹⁸, L. Nodulman⁵,
M. Nomachi¹¹⁵, I. Nomidis¹⁵³, M. Nordberg²⁹, B. Nordkvist^{145a,145b}, P.R. Norton¹²⁸,
J. Novakova¹²⁵, M. Nozaki⁶⁵, L. Nozka¹¹², I.M. Nugent^{158a}, A.-E. Nuncio-Quiroz²⁰,
G. Nunes Hanninger⁸⁵, T. Nunnemann⁹⁷, E. Nurse⁷⁶, B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*},
D.C. O'Neil¹⁴¹, V. O'Shea⁵³, L.B. Oakes⁹⁷, F.G. Oakham^{28,d}, H. Oberlack⁹⁸, J. Ocariz⁷⁷,
A. Ochi⁶⁶, S. Oda¹⁵⁴, S. Odaka⁶⁵, J. Odier⁸², H. Ogren⁶⁰, A. Oh⁸¹, S.H. Oh⁴⁴,
C.C. Ohm^{145a,145b}, T. Ohshima¹⁰⁰, H. Ohshita¹³⁹, S. Okada⁶⁶, H. Okawa¹⁶²,
Y. Okumura¹⁰⁰, T. Okuyama¹⁵⁴, A. Olariu^{25a}, M. Olcese^{50a}, A.G. Olchevski⁶⁴,
S.A. Olivares Pino^{31a}, M. Oliveira^{123a,h}, D. Oliveira Damazio²⁴, E. Oliver Garcia¹⁶⁶,
D. Olivito¹¹⁹, A. Olszewski³⁸, J. Olszowska³⁸, C. Omachi⁶⁶, A. Onofre^{123a,y},
P.U.E. Onyisi³⁰, C.J. Oram^{158a}, M.J. Oreglia³⁰, Y. Oren¹⁵², D. Orestano^{133a,133b},
N. Orlando^{71a,71b}, I. Orlov¹⁰⁶, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁷, B. Osculati^{50a,50b},
R. Ospanov¹¹⁹, C. Osuna¹¹, G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁴, M. Ouchrif^{134d},
E.A. Ouellette¹⁶⁸, F. Ould-Saada¹¹⁶, A. Ouraou¹³⁵, Q. Ouyang^{32a}, A. Ovcharova¹⁴,
M. Owen⁸¹, S. Owen¹³⁸, V.E. Ozcan^{18a}, N. Ozturk⁷, A. Pacheco Pages¹¹,
C. Padilla Aranda¹¹, S. Pagan Griso¹⁴, E. Paganis¹³⁸, F. Paige²⁴, P. Pais⁸³, K. Pajchel¹¹⁶,
G. Palacino^{158b}, C.P. Paleari⁶, S. Palestini²⁹, D. Pallin³³, A. Palma^{123a}, J.D. Palmer¹⁷,
Y.B. Pan¹⁷¹, E. Panagiotopoulou⁹, B. Panes^{31a}, N. Panikashvili⁸⁶, S. Panitkin²⁴,
D. Pantea^{25a}, M. Panuskova¹²⁴, V. Paolone¹²², A. Papadelis^{145a}, Th.D. Papadopoulou⁹,
A. Paramonov⁵, D. Paredes Hernandez³³, W. Park^{24,z}, M.A. Parker²⁷, F. Parodi^{50a,50b},
J.A. Parsons³⁴, U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{131a}, S. Passaggio^{50a},
A. Passeri^{133a}, F. Pastore^{133a,133b}, Fr. Pastore⁷⁵, G. Pásztor^{49,aa}, S. Patariaia¹⁷³,
N. Patel¹⁴⁹, J.R. Pater⁸¹, S. Patricelli^{101a,101b}, T. Pauly²⁹, M. Pecsny^{143a},
M.I. Pedraza Morales¹⁷¹, S.V. Peleganchuk¹⁰⁶, H. Peng^{32b}, R. Pengo²⁹, B. Penning³⁰,
A. Penson³⁴, J. Penwell⁶⁰, M. Perantoni^{23a}, K. Perez^{34,ab}, T. Perez Cavalcanti⁴¹,
E. Perez Codina¹¹, M.T. Pérez García-Estañ¹⁶⁶, V. Perez Reale³⁴, L. Perini^{88a,88b},
H. Pernegger²⁹, R. Perrino^{71a}, P. Perrodo⁴, S. Persebe^{3a}, V.D. Peshekhonov⁶⁴,
K. Peters²⁹, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁴, A. Petridis¹⁵³,
C. Petridou¹⁵³, E. Petrolo^{131a}, F. Petrucci^{133a,133b}, D. Petschull⁴¹, M. Petteni¹⁴¹,
R. Pezoa^{31b}, A. Phan⁸⁵, P.W. Phillips¹²⁸, G. Piacquadio²⁹, A. Picazio⁴⁹, E. Piccaro⁷⁴,
M. Piccinini^{19a,19b}, S.M. Piec⁴¹, R. Piegai²⁶, D.T. Pignotti¹⁰⁸, J.E. Pilcher³⁰,
A.D. Pilkington⁸¹, J. Pina^{123a,b}, M. Pinamonti^{163a,163c}, A. Pinder¹¹⁷, J.L. Pinfold²,
J. Ping^{32c}, B. Pinto^{123a}, O. Pirotte²⁹, C. Pizio^{88a,88b}, M. Plamondon¹⁶⁸, M.-A. Pleier²⁴,
A.V. Pleskach¹²⁷, E. Plotnikova⁶⁴, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³,
L. Poggioli¹¹⁴, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{118a},
A. Policicchio^{36a,36b}, A. Polini^{19a}, J. Poll⁷⁴, V. Polychronakos²⁴, D.M. Pomarede¹³⁵,
D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{131a}, B.G. Pope⁸⁷, G.A. Popeneciu^{25a},

D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso²⁹, C. Posch²¹, G.E. Pospelov⁹⁸, S. Pospisil¹²⁶, I.N. Potrap⁹⁸, C.J. Potter¹⁴⁸, C.T. Potter¹¹³, G. Poulard²⁹, J. Poveda¹⁷¹, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁶, P. Pralavorio⁸², A. Pranko¹⁴, S. Prasad²⁹, R. Pravahan⁷, S. Prell⁶³, K. Pretzl¹⁶, L. Pribyl²⁹, D. Price⁶⁰, J. Price⁷², L.E. Price⁵, M.J. Price²⁹, D. Prieur¹²², M. Primavera^{71a}, K. Prokofiev¹⁰⁷, F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³, M. Przybycien³⁷, H. Przysiezniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹³, E. Pueschel⁸³, J. Purdham⁸⁶, M. Purohit^{24,z}, P. Puzo¹¹⁴, Y. Pylypchenko⁶², J. Qian⁸⁶, Z. Qian⁸², Z. Qin⁴¹, A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷¹, F. Quinonez^{31a}, M. Raas¹⁰³, V. Radescu⁴¹, B. Radics²⁰, P. Radloff¹¹³, T. Rador^{18a}, F. Ragusa^{88a,88b}, G. Rahal¹⁷⁶, A.M. Rahimi¹⁰⁸, D. Rahm²⁴, S. Rajagopalan²⁴, M. Rammensee⁴⁸, M. Rammes¹⁴⁰, A.S. Randle-Conde³⁹, K. Randrianarivony²⁸, P.N. Ratoff⁷⁰, F. Rauscher⁹⁷, T.C. Rave⁴⁸, M. Raymond²⁹, A.L. Read¹¹⁶, D.M. Rebuffi^{118a,118b}, A. Redelbach¹⁷², G. Redlinger²⁴, R. Reece¹¹⁹, K. Reeves⁴⁰, A. Reichold¹⁰⁴, E. Reinherz-Aronis¹⁵², A. Reinsch¹¹³, I. Reisinger⁴², C. Rembser²⁹, Z.L. Ren¹⁵⁰, A. Renaud¹¹⁴, M. Rescigno^{131a}, S. Resconi^{88a}, B. Resende¹³⁵, P. Reznicek⁹⁷, R. Rezvani¹⁵⁷, A. Richards⁷⁶, R. Richter⁹⁸, E. Richter-Was^{4,ac}, M. Ridel⁷⁷, M. Rijpstra¹⁰⁴, M. Rijssenbeek¹⁴⁷, A. Rimoldi^{118a,118b}, L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{88a,88b}, F. Rizatdinova¹¹¹, E. Rizvi⁷⁴, S.H. Robertson^{84,j}, A. Robichaud-Veronneau¹¹⁷, D. Robinson²⁷, J.E.M. Robinson⁷⁶, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁵, C. Roda^{121a,121b}, D. Roda Dos Santos²⁹, D. Rodriguez¹⁶¹, A. Roe⁵⁴, S. Roe²⁹, O. Røhne¹¹⁶, V. Rojo¹, S. Rolli¹⁶⁰, A. Romaniouk⁹⁵, M. Romano^{19a,19b}, V.M. Romanov⁶⁴, G. Romeo²⁶, E. Romero Adam¹⁶⁶, L. Roos⁷⁷, E. Ros¹⁶⁶, S. Rosati^{131a}, K. Rosbach⁴⁹, A. Rose¹⁴⁸, M. Rose⁷⁵, G.A. Rosenbaum¹⁵⁷, E.I. Rosenberg⁶³, P.L. Rosendahl¹³, O. Rosenthal¹⁴⁰, L. Rossetlet⁴⁹, V. Rossetti¹¹, E. Rossi^{131a,131b}, L.P. Rossi^{50a}, M. Rotaru^{25a}, I. Roth¹⁷⁰, J. Rothberg¹³⁷, D. Rousseau¹¹⁴, C.R. Royon¹³⁵, A. Rozanov⁸², Y. Rozen¹⁵¹, X. Ruan^{32a,ad}, I. Rubinskiy⁴¹, B. Ruckert⁹⁷, N. Ruckstuhl¹⁰⁴, V.I. Rud⁹⁶, C. Rudolph⁴³, G. Rudolph⁶¹, F. Rühr⁶, F. Ruggieri^{133a,133b}, A. Ruiz-Martinez⁶³, V. Rumiantsev^{90,*}, L. Rumyantsev⁶⁴, K. Runge⁴⁸, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁴, Y.F. Ryabov¹²⁰, V. Ryadovikov¹²⁷, P. Ryan⁸⁷, M. Rybar¹²⁵, G. Rybkin¹¹⁴, N.C. Ryder¹¹⁷, S. Rzaeva¹⁰, A.F. Saavedra¹⁴⁹, I. Sadeh¹⁵², H.F-W. Sadrozinski¹³⁶, R. Sadykov⁶⁴, F. Safai Tehrani^{131a}, H. Sakamoto¹⁵⁴, G. Salamanna⁷⁴, A. Salamon^{132a}, M. Saleem¹¹⁰, D. Salihagic⁹⁸, A. Salnikov¹⁴², J. Salt¹⁶⁶, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁸, A. Salvucci¹⁰³, A. Salzburger²⁹, D. Sampsonidis¹⁵³, B.H. Samset¹¹⁶, A. Sanchez^{101a,101b}, V. Sanchez Martinez¹⁶⁶, H. Sandaker¹³, H.G. Sander⁸⁰, M.P. Sanders⁹⁷, M. Sandhoff¹⁷³, T. Sandoval²⁷, C. Sandoval¹⁶¹, R. Sandstroem⁹⁸, S. Sandvoss¹⁷³, D.P.C. Sankey¹²⁸, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁴, C. Santoni³³, R. Santonico^{132a,132b}, H. Santos^{123a}, J.G. Saraiva^{123a}, T. Sarangi¹⁷¹, E. Sarkisyan-Grinbaum⁷, F. Sarri^{121a,121b}, G. Sartisohn¹⁷³, O. Sasaki⁶⁵, N. Sasao⁶⁷, I. Satsounkevitch⁸⁹, G. Sauvage⁴, E. Sauvan⁴, J.B. Sauvan¹¹⁴, P. Savard^{157,d}, V. Savinov¹²², D.O. Savu²⁹, L. Sawyer^{24,l}, D.H. Saxon⁵³, J. Saxon¹¹⁹, L.P. SAYS³³, C. Sbarra^{19a}, A. Sbrizzi^{19a,19b}, O. Scallan⁹², D.A. Scannicchio¹⁶², M. Scarcella¹⁴⁹, J. Schaarschmidt¹¹⁴, P. Schacht⁹⁸, D. Schaefer¹¹⁹, U. Schäfer⁸⁰, S. Schaepe²⁰, S. Schaezel^{158b}, A.C. Schaffer¹¹⁴, D. Schaile⁹⁷,

R.D. Schamberger¹⁴⁷, A.G. Schamov¹⁰⁶, V. Scharf^{58a}, V.A. Schegelsky¹²⁰, D. Scheirich⁸⁶, M. Schernau¹⁶², M.I. Scherzer³⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁷, M. Schioppa^{36a,36b}, S. Schlenker²⁹, J.L. Schlereth⁵, E. Schmidt⁴⁸, K. Schmieden²⁰, C. Schmitt⁸⁰, S. Schmitt^{58b}, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹, D. Schouten^{158a}, J. Schovancova¹²⁴, M. Schram⁸⁴, C. Schroeder⁸⁰, N. Schroer^{58c}, G. Schuler²⁹, M.J. Schultens²⁰, J. Schultes¹⁷³, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸, B.A. Schumm¹³⁶, Ph. Schune¹³⁵, C. Schwanenberger⁸¹, A. Schwartzman¹⁴², Ph. Schwemling⁷⁷, R. Schwienhorst⁸⁷, R. Schwierz⁴³, J. Schwindling¹³⁵, T. Schwindt²⁰, M. Schwoerer⁴, G. Sciolla²², W.G. Scott¹²⁸, J. Searcy¹¹³, G. Sedov⁴¹, E. Sedykh¹²⁰, E. Segura¹¹, S.C. Seidel¹⁰², A. Seiden¹³⁶, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{101a}, S.J. Sekula³⁹, K.E. Selbach⁴⁵, D.M. Seliverstov¹²⁰, B. Sellden^{145a}, G. Sellers⁷², M. Seman^{143b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁷, L. Serin¹¹⁴, L. Serkin⁵⁴, R. Seuster⁹⁸, H. Severini¹¹⁰, M.E. Sevior⁸⁵, A. Sfyrila²⁹, E. Shabalina⁵⁴, M. Shamim¹¹³, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁵, M. Shapiro¹⁴, P.B. Shatalov⁹⁴, L. Shaver⁶, K. Shaw^{163a,163c}, D. Sherman¹⁷⁴, P. Sherwood⁷⁶, A. Shibata¹⁰⁷, H. Shichi¹⁰⁰, S. Shimizu²⁹, M. Shimojima⁹⁹, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹³, M.J. Shochet³⁰, D. Short¹¹⁷, S. Shrestha⁶³, E. Shulga⁹⁵, M.A. Shupe⁶, P. Sicho¹²⁴, A. Sidoti^{131a}, F. Siegert⁴⁸, Dj. Sijacki^{12a}, O. Silbert¹⁷⁰, J. Silva^{123a}, Y. Silver¹⁵², D. Silverstein¹⁴², S.B. Silverstein^{145a}, V. Simak¹²⁶, O. Simard¹³⁵, Lj. Simic^{12a}, S. Simion¹¹⁴, B. Simmons⁷⁶, R. Simoniello^{88a,88b}, M. Simonyan³⁵, P. Sinervo¹⁵⁷, N.B. Sinev¹¹³, V. Sipica¹⁴⁰, G. Siragusa¹⁷², A. Sircar²⁴, A.N. Sisakyan⁶⁴, S.Yu. Sivoklov⁹⁶, J. Sjölin^{145a,145b}, T.B. Sjørnsen¹³, L.A. Skinnari¹⁴, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁶, P. Skubic¹¹⁰, N. Skvorodnev²², M. Slater¹⁷, T. Slavicek¹²⁶, K. Sliwa¹⁶⁰, J. Sloper²⁹, V. Smakhtin¹⁷⁰, B.H. Smart⁴⁵, S.Yu. Smirnov⁹⁵, Y. Smirnov⁹⁵, L.N. Smirnova⁹⁶, O. Smirnova⁷⁸, B.C. Smith⁵⁷, D. Smith¹⁴², K.M. Smith⁵³, M. Smizanska⁷⁰, K. Smolek¹²⁶, A.A. Snesarev⁹³, S.W. Snow⁸¹, J. Snow¹¹⁰, J. Snuverink¹⁰⁴, S. Snyder²⁴, M. Soares^{123a}, R. Sobie^{168,j}, J. Sodomka¹²⁶, A. Soffer¹⁵², C.A. Solans¹⁶⁶, M. Solar¹²⁶, J. Solc¹²⁶, E. Soldatov⁹⁵, U. Soldevila¹⁶⁶, E. Solfaroli Camillocci^{131a,131b}, A.A. Solodkov¹²⁷, O.V. Solovyanov¹²⁷, N. Soni², V. Sopko¹²⁶, B. Sopko¹²⁶, M. Sosebee⁷, R. Soualah^{163a,163c}, A. Soukharev¹⁰⁶, S. Spagnolo^{71a,71b}, F. Spanò⁷⁵, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{131a,131b}, R. Spiwoks²⁹, M. Spousta¹²⁵, T. Spreitzer¹⁵⁷, B. Spurlock⁷, R.D. St. Denis⁵³, J. Stahlman¹¹⁹, R. Stamen^{58a}, E. Stanecka³⁸, R.W. Stanek⁵, C. Stanescu^{133a}, M. Stanescu-Bellu⁴¹, S. Stapnes¹¹⁶, E.A. Starchenko¹²⁷, J. Stark⁵⁵, P. Staroba¹²⁴, P. Starovoitov⁹⁰, A. Staude⁹⁷, P. Stavina^{143a}, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁶, B. Stelzer¹⁴¹, H.J. Stelzer⁸⁷, O. Stelzer-Chilton^{158a}, H. Stenzel⁵², S. Stern⁹⁸, K. Stevenson⁷⁴, G.A. Stewart²⁹, J.A. Stillings²⁰, M.C. Stockton⁸⁴, K. Stoerig⁴⁸, G. Stoicea^{25a}, S. Stonjek⁹⁸, P. Strachota¹²⁵, A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg¹⁴⁶, S. Strandberg^{145a,145b}, A. Strandlie¹¹⁶, M. Strang¹⁰⁸, E. Strauss¹⁴², M. Strauss¹¹⁰, P. Strizeneč^{143b}, R. Ströhmer¹⁷², D.M. Strom¹¹³, J.A. Strong^{75,*}, R. Stroynowski³⁹, J. Strube¹²⁸, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁷, P. Sturm¹⁷³, N.A. Styles⁴¹, D.A. Soh^{150,u}, D. Su¹⁴², HS. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁵, T. Sugimoto¹⁰⁰, C. Suhr¹⁰⁵, K. Suita⁶⁶, M. Suk¹²⁵,

V.V. Sulin⁹³, S. Sultansoy^{3d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁸, S. Sushkov¹¹, G. Susinno^{36a,36b}, M.R. Sutton¹⁴⁸, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁴, Yu.M. Sviridov¹²⁷, S. Swedish¹⁶⁷, I. Sykora^{143a}, T. Sykora¹²⁵, B. Szeless²⁹, J. Sánchez¹⁶⁶, D. Ta¹⁰⁴, K. Tackmann⁴¹, A. Taffard¹⁶², R. Tafirout^{158a}, N. Taiblum¹⁵², Y. Takahashi¹⁰⁰, H. Takai²⁴, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹³⁹, Y. Takubo⁶⁵, M. Talby⁸², A. Talyshev^{106,f}, M.C. Tamsett²⁴, J. Tanaka¹⁵⁴, R. Tanaka¹¹⁴, S. Tanaka¹³⁰, S. Tanaka⁶⁵, Y. Tanaka⁹⁹, A.J. Tanasijczuk¹⁴¹, K. Tani⁶⁶, N. Tannoury⁸², G.P. Tappern²⁹, S. Tapprogge⁸⁰, D. Tardif¹⁵⁷, S. Tarem¹⁵¹, F. Tarrade²⁸, G.F. Tartarelli^{88a}, P. Tas¹²⁵, M. Tasevsky¹²⁴, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, Y. Tayalati^{134d}, C. Taylor⁷⁶, F.E. Taylor⁹¹, G.N. Taylor⁸⁵, W. Taylor^{158b}, M. Teinturier¹¹⁴, M. Teixeira Dias Castanheira⁷⁴, P. Teixeira-Dias⁷⁵, K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵⁰, S. Terada⁶⁵, K. Terashi¹⁵⁴, J. Terron⁷⁹, M. Testa⁴⁷, R.J. Teuscher^{157,j}, J. Thadome¹⁷³, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁷, M. Thioye¹⁷⁴, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson³⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁷, A.S. Thompson⁵³, L.A. Thomsen³⁵, E. Thomson¹¹⁹, M. Thomson²⁷, R.P. Thun⁸⁶, F. Tian³⁴, M.J. Tibbetts¹⁴, T. Tic¹²⁴, V.O. Tikhomirov⁹³, Y.A. Tikhonov^{106,f}, S. Timoshenko⁹⁵, P. Tipton¹⁷⁴, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸², B. Toczek³⁷, T. Todorov⁴, S. Todorova-Nova¹⁶⁰, B. Toggerson¹⁶², J. Tojo⁶⁵, S. Tokár^{143a}, K. Tokunaga⁶⁶, K. Tokushuku⁶⁵, K. Tollefson⁸⁷, M. Tomoto¹⁰⁰, L. Tompkins³⁰, K. Toms¹⁰², G. Tong^{32a}, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁴, I. Torchiani²⁹, E. Torrence¹¹³, H. Torres⁷⁷, E. Torró Pastor¹⁶⁶, J. Toth^{82,aa}, F. Touchard⁸², D.R. Tovey¹³⁸, T. Trefzger¹⁷², L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{158a}, S. Trincas-Duvoid⁷⁷, T.N. Trinh⁷⁷, M.F. Tripiana⁶⁹, W. Trischuk¹⁵⁷, A. Trivedi^{24,z}, B. Trocme⁵⁵, C. Troncon^{88a}, M. Trotter-McDonald¹⁴¹, M. Trzebinski³⁸, A. Trzupek³⁸, C. Tsarouchas²⁹, J.C.-L. Tseng¹¹⁷, M. Tsiakiris¹⁰⁴, P.V. Tsiarehka⁸⁹, D. Tsiou^{4,ae}, G. Tsipolitis⁹, V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁴, V. Tsulaia¹⁴, J.-W. Tsung²⁰, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁷, A. Tua¹³⁸, A. Tudorache^{25a}, V. Tudorache^{25a}, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁶, I. Turk Cakir^{3e}, E. Turlay¹⁰⁴, R. Turra^{88a,88b}, P.M. Tuts³⁴, A. Tykhonov⁷³, M. Tylmad^{145a,145b}, M. Tyndel¹²⁸, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁴, R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁵⁹, G. Unal²⁹, D.G. Underwood⁵, A. Undrus²⁴, G. Unel¹⁶², Y. Unno⁶⁵, D. Urbaniec³⁴, G. Usai⁷, M. Uslenghi^{118a,118b}, L. Vacavant⁸², V. Vacek¹²⁶, B. Vachon⁸⁴, S. Vahsen¹⁴, J. Valenta¹²⁴, P. Valente^{131a}, S. Valentineti^{19a,19b}, S. Valkar¹²⁵, E. Valladolid Gallego¹⁶⁶, S. Vallecorsa¹⁵¹, J.A. Valls Ferrer¹⁶⁶, H. van der Graaf¹⁰⁴, E. van der Kraaij¹⁰⁴, R. Van Der Leeuw¹⁰⁴, E. van der Poel¹⁰⁴, D. van der Ster²⁹, N. van Eldik⁸³, P. van Gemmeren⁵, Z. van Kesteren¹⁰⁴, I. van Vulpen¹⁰⁴, M. Vanadia⁹⁸, W. Vandelli²⁹, G. Vandoni²⁹, A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁷, F. Varela Rodriguez²⁹, R. Vari^{131a}, E.W. Varnes⁶, T. Varol⁸³, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁴⁹, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, T. Vazquez Schroeder⁵⁴, G. Vegni^{88a,88b}, J.J. Veillet¹¹⁴, C. Vellidis⁸, F. Veloso^{123a}, R. Veness²⁹, S. Veneziano^{131a}, A. Ventura^{71a,71b}, D. Ventura¹³⁷, M. Venturi⁴⁸, N. Venturi¹⁵⁷, V. Vercesi^{118a}, M. Verducci¹³⁷, W. Verkerke¹⁰⁴, J.C. Vermeulen¹⁰⁴, A. Vest⁴³, M.C. Vetterli^{141,d},

I. Vichou¹⁶⁴, T. Vickey^{144b,af}, O.E. Vickey Boeriu^{144b}, G.H.A. Viehhauser¹¹⁷, S. Viel¹⁶⁷,
 M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁶, E. Vilucchi⁴⁷, M.G. Vincter²⁸, E. Vinek²⁹,
 V.B. Vinogradov⁶⁴, M. Virchaux^{135,*}, J. Virzi¹⁴, O. Vitells¹⁷⁰, M. Viti⁴¹, I. Vivarelli⁴⁸,
 F. Vives Vaque², S. Vlachos⁹, D. Vladoiu⁹⁷, M. Vlasak¹²⁶, N. Vlasov²⁰, A. Vogel²⁰,
 P. Vokac¹²⁶, G. Volpi⁴⁷, M. Volpi⁸⁵, G. Volpini^{88a}, H. von der Schmitt⁹⁸, J. von Loeben⁹⁸,
 H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁵, A.P. Vorobiev¹²⁷, V. Vorwerk¹¹,
 M. Vos¹⁶⁶, R. Voss²⁹, T.T. Voss¹⁷³, J.H. Vosseveld⁷², N. Vranjes¹³⁵,
 M. Vranjes Milosavljevic¹⁰⁴, V. Vrba¹²⁴, M. Vreeswijk¹⁰⁴, T. Vu Anh⁴⁸, R. Vuillermet²⁹,
 I. Vukotic¹¹⁴, W. Wagner¹⁷³, P. Wagner¹¹⁹, H. Wahlen¹⁷³, J. Wakabayashi¹⁰⁰, S. Walch⁸⁶,
 J. Walder⁷⁰, R. Walker⁹⁷, W. Walkowiak¹⁴⁰, R. Wall¹⁷⁴, P. Waller⁷², C. Wang⁴⁴,
 H. Wang¹⁷¹, H. Wang^{32b,ag}, J. Wang¹⁵⁰, J. Wang⁵⁵, J.C. Wang¹³⁷, R. Wang¹⁰²,
 S.M. Wang¹⁵⁰, T. Wang²⁰, A. Warburton⁸⁴, C.P. Ward²⁷, M. Warsinsky⁴⁸, C. Wasicki⁴¹,
 P.M. Watkins¹⁷, A.T. Watson¹⁷, I.J. Watson¹⁴⁹, M.F. Watson¹⁷, G. Watts¹³⁷, S. Watts⁸¹,
 A.T. Waugh¹⁴⁹, B.M. Waugh⁷⁶, M. Weber¹²⁸, M.S. Weber¹⁶, P. Weber⁵⁴,
 A.R. Weidberg¹¹⁷, P. Weigell⁹⁸, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²²,
 P.S. Wells²⁹, T. Wenaus²⁴, D. Wendland¹⁵, S. Wandler¹²², Z. Weng^{150,u}, T. Wengler²⁹,
 S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶², M. Wessels^{58a},
 J. Wetter¹⁶⁰, C. Weydert⁵⁵, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶², S.P. Whitaker²¹,
 A. White⁷, M.J. White⁸⁵, S.R. Whitehead¹¹⁷, D. Whiteson¹⁶², D. Whittington⁶⁰,
 F. Wicke¹¹⁴, D. Wicke¹⁷³, F.J. Wickens¹²⁸, W. Wiedenmann¹⁷¹, M. Wielers¹²⁸,
 P. Wienemann²⁰, C. Wiglesworth⁷⁴, L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁶,
 A. Wildauer¹⁶⁶, M.A. Wildt^{41,q}, I. Wilhelm¹²⁵, H.G. Wilkens²⁹, J.Z. Will⁹⁷,
 E. Williams³⁴, H.H. Williams¹¹⁹, W. Willis³⁴, S. Willocq⁸³, J.A. Wilson¹⁷,
 M.G. Wilson¹⁴², A. Wilson⁸⁶, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹,
 M. Wittgen¹⁴², M.W. Wolter³⁸, H. Wolters^{123a,h}, W.C. Wong⁴⁰, G. Wooden⁸⁶,
 B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸³, K.W. Wozniak³⁸, K. Wraight⁵³,
 C. Wright⁵³, M. Wright⁵³, B. Wrona⁷², S.L. Wu¹⁷¹, X. Wu⁴⁹, Y. Wu^{32b,ah}, E. Wulf³⁴,
 R. Wunstorff⁴², B.M. Wynne⁴⁵, S. Xella³⁵, M. Xiao¹³⁵, S. Xie⁴⁸, Y. Xie^{32a}, C. Xu^{32b,w},
 D. Xu¹³⁸, G. Xu^{32a}, B. Yabsley¹⁴⁹, S. Yacoob^{144b}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁴,
 A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁴, T. Yamamura¹⁵⁴, T. Yamanaka¹⁵⁴,
 J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁴, Y. Yamazaki⁶⁶, Z. Yan²¹, H. Yang⁸⁶, U.K. Yang⁸¹,
 Y. Yang⁶⁰, Y. Yang^{32a}, Z. Yang^{145a,145b}, S. Yanush⁹⁰, Y. Yao¹⁴, Y. Yasu⁶⁵,
 G.V. Ybeles Smit¹²⁹, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosoofmiya¹²², K. Yorita¹⁶⁹,
 R. Yoshida⁵, C. Young¹⁴², S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu¹¹¹, L. Yuan^{32a,ai},
 A. Yurkewicz¹⁰⁵, B. Zabinski³⁸, V.G. Zaets¹²⁷, R. Zaidan⁶², A.M. Zaitsev¹²⁷,
 Z. Zajacova²⁹, L. Zanello^{131a,131b}, A. Zaytsev¹⁰⁶, C. Zeitnitz¹⁷³, M. Zeller¹⁷⁴,
 M. Zeman¹²⁴, A. Zemla³⁸, C. Zendler²⁰, O. Zenin¹²⁷, T. Ženiš^{143a}, Z. Zinonos^{121a,121b},
 S. Zenz¹⁴, D. Zerwas¹¹⁴, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b,ag}, H. Zhang⁸⁷,
 J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁴, L. Zhao¹⁰⁷, T. Zhao¹³⁷, Z. Zhao^{32b},
 A. Zhemchugov⁶⁴, S. Zheng^{32a}, J. Zhong¹¹⁷, B. Zhou⁸⁶, N. Zhou¹⁶², Y. Zhou¹⁵⁰,
 C.G. Zhu^{32d}, H. Zhu⁴¹, J. Zhu⁸⁶, Y. Zhu^{32b}, X. Zhuang⁹⁷, V. Zhuravlov⁹⁸, D. Zieminska⁶⁰,
 R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴⁰, R. Zitoun⁴,
 L. Živković³⁴, V.V. Zmouchko^{127,*}, G. Zobernig¹⁷¹, A. Zoccoli^{19a,19b}, Y. Zolnierowski⁴,
 A. Zsenei²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁵, L. Zwalinski²⁹.

- ¹ University at Albany, Albany NY, U.S.A.
- ² Department of Physics, University of Alberta, Edmonton AB, Canada
- ³ (a) Department of Physics, Ankara University, Ankara, Turkey
 (b) Department of Physics, Dumlupinar University, Kutahya, Turkey
 (c) Department of Physics, Gazi University, Ankara, Turkey
 (d) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
 (e) Turkish Atomic Energy Authority, Ankara, Turkey
- ⁴ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
- ⁵ High Energy Physics Division, Argonne National Laboratory, Argonne IL, U.S.A.
- ⁶ Department of Physics, University of Arizona, Tucson AZ, U.S.A.
- ⁷ Department of Physics, The University of Texas at Arlington, Arlington TX, U.S.A.
- ⁸ Physics Department, University of Athens, Athens, Greece
- ⁹ Physics Department, National Technical University of Athens, Zografou, Greece
- ¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹¹ Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
- ¹² (a) Institute of Physics, University of Belgrade, Belgrade, Serbia
 (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
- ¹³ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁴ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, U.S.A.
- ¹⁵ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁶ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁷ School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.
- ¹⁸ (a) Department of Physics, Bogazici University, Istanbul, Turkey
 (b) Division of Physics, Dogus University, Istanbul, Turkey
 (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
 (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
- ¹⁹ (a) INFN Sezione di Bologna, Italy
 (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
- ²⁰ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²¹ Department of Physics, Boston University, Boston MA, U.S.A.
- ²² Department of Physics, Brandeis University, Waltham MA, U.S.A.
- ²³ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
 (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
 (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
 (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁴ Physics Department, Brookhaven National Laboratory, Upton NY, U.S.A.
- ²⁵ (a) National Institute of Physics and Nuclear Engineering, Bucharest, Romania
 (b) University Politehnica Bucharest, Bucharest, Romania
 (c) West University in Timisoara, Timisoara, Romania
- ²⁶ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

- ²⁷ Cavendish Laboratory, University of Cambridge, Cambridge, U.K.
- ²⁸ Department of Physics, Carleton University, Ottawa ON, Canada
- ²⁹ CERN, Geneva, Switzerland
- ³⁰ Enrico Fermi Institute, University of Chicago, Chicago IL, U.S.A.
- ³¹ ^(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
^(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³² ^(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
^(b)Department of Modern Physics, University of Science and Technology of China, Anhui, China
^(c)Department of Physics, Nanjing University, Jiangsu, China
^(d)School of Physics, Shandong University, Shandong, China
- ³³ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
- ³⁴ Nevis Laboratory, Columbia University, Irvington NY, U.S.A.
- ³⁵ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁶ ^(a)INFN Gruppo Collegato di Cosenza, Italy
^(b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁷ AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ³⁹ Physics Department, Southern Methodist University, Dallas TX, U.S.A.
- ⁴⁰ Physics Department, University of Texas at Dallas, Richardson TX, U.S.A.
- ⁴¹ DESY, Hamburg and Zeuthen, Germany
- ⁴² Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴³ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁴ Department of Physics, Duke University, Durham NC, U.S.A.
- ⁴⁵ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, U.K.
- ⁴⁶ Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a)INFN Sezione di Genova; ^(b)Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a)E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi, Georgia
^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, U.K.

- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton VA, U.S.A.
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, U.S.A.
- ⁵⁸ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington IN, U.S.A.
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City IA, U.S.A.
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames IA, U.S.A.
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁰ Physics Department, Lancaster University, Lancaster, U.K.
- ⁷¹ (a) INFN Sezione di Lecce, Italy
(b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
- ⁷² Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.
- ⁷³ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁴ School of Physics and Astronomy, Queen Mary University of London, London, U.K.
- ⁷⁵ Department of Physics, Royal Holloway University of London, Surrey, U.K.
- ⁷⁶ Department of Physics and Astronomy, University College London, London, U.K.
- ⁷⁷ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁸ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁷⁹ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁰ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸¹ School of Physics and Astronomy, University of Manchester, Manchester, U.K.
- ⁸² CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

- ⁸³ Department of Physics, University of Massachusetts, Amherst MA, U.S.A.
- ⁸⁴ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁵ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁶ Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
- ⁸⁷ Department of Physics and Astronomy, Michigan State University, East Lansing MI, U.S.A.
- ⁸⁸ *(a)* INFN Sezione di Milano, Italy
(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁸⁹ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹⁰ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹¹ Department of Physics, Massachusetts Institute of Technology, Cambridge MA, U.S.A.
- ⁹² Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹³ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁴ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁵ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁶ Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁷ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁸ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ⁹⁹ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁰ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰¹ *(a)* INFN Sezione di Napoli, Italy
(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰² Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, U.S.A.
- ¹⁰³ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁴ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁵ Department of Physics, Northern Illinois University, DeKalb IL, U.S.A.
- ¹⁰⁶ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁷ Department of Physics, New York University, New York NY, U.S.A.
- ¹⁰⁸ Ohio State University, Columbus OH, U.S.A.
- ¹⁰⁹ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁰ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, U.S.A.
- ¹¹¹ Department of Physics, Oklahoma State University, Stillwater OK, U.S.A.
- ¹¹² Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹³ Center for High Energy Physics, University of Oregon, Eugene OR, U.S.A.
- ¹¹⁴ LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁵ Graduate School of Science, Osaka University, Osaka, Japan

- 116 Department of Physics, University of Oslo, Oslo, Norway
- 117 Department of Physics, Oxford University, Oxford, U.K.
- 118 ^(a)INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 119 Department of Physics, University of Pennsylvania, Philadelphia PA, U.S.A.
- 120 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 121 ^(a)INFN Sezione di Pisa, Pisa, Italy
^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, U.S.A.
- 123 ^(a)Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
^(b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 124 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 125 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 126 Czech Technical University in Prague, Praha, Czech Republic
- 127 State Research Center Institute for High Energy Physics, Protvino, Russia
- 128 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.
- 129 Physics Department, University of Regina, Regina SK, Canada
- 130 Ritsumeikan University, Kusatsu, Shiga, Japan
- 131 ^(a)INFN Sezione di Roma I, Roma, Italy
^(b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 132 ^(a)INFN Sezione di Roma Tor Vergata, Roma, Italy
^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 133 ^(a)INFN Sezione di Roma Tre, Roma, Italy
^(b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- 134 ^(a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
^(b)Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco
^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
^(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
^(e)Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco
- 135 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- 136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, U.S.A.
- 137 Department of Physics, University of Washington, Seattle WA, U.S.A.
- 138 Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.
- 139 Department of Physics, Shinshu University, Nagano, Japan
- 140 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 141 Department of Physics, Simon Fraser University, Burnaby BC, Canada

- 142 SLAC National Accelerator Laboratory, Stanford CA, U.S.A.
- 143 ^(a)Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 144 ^(a)Department of Physics, University of Johannesburg, Johannesburg, South Africa
^(b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 145 ^(a)Department of Physics, Stockholm University, Stockholm, Sweden
^(b)The Oskar Klein Centre, Stockholm, Sweden
- 146 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 147 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, U.S.A.
- 148 Department of Physics and Astronomy, University of Sussex, Brighton, U.K.
- 149 School of Physics, University of Sydney, Sydney, Australia
- 150 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 151 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
- 152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 157 Department of Physics, University of Toronto, Toronto ON, Canada
- 158 ^(a)TRIUMF, Vancouver BC, Vancouver, Canada
^(b)Department of Physics and Astronomy, York University, Toronto ON, Canada
- 159 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
- 160 Science and Technology Center, Tufts University, Medford MA, U.S.A.
- 161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 162 Department of Physics and Astronomy, University of California Irvine, Irvine CA, U.S.A.
- 163 ^(a)INFN Gruppo Collegato di Udine, Udine, Italy
^(b)ICTP, Trieste, Italy
^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 164 Department of Physics, University of Illinois, Urbana IL, U.S.A.
- 165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- 167 Department of Physics, University of British Columbia, Vancouver BC, Canada

- ¹⁶⁸ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁶⁹ Waseda University, Tokyo, Japan
- ¹⁷⁰ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷¹ Department of Physics, University of Wisconsin, Madison WI, U.S.A.
- ¹⁷² Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷³ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁴ Department of Physics, Yale University, New Haven CT, U.S.A.
- ¹⁷⁵ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁶ Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
- ^a Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ^b Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- ^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.
- ^d Also at TRIUMF, Vancouver BC, Canada
- ^e Also at Department of Physics, California State University, Fresno CA, U.S.A.
- ^f Also at Novosibirsk State University, Novosibirsk, Russia
- ^g Also at Fermilab, Batavia IL, U.S.A.
- ^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy
- ^j Also at Institute of Particle Physics (IPP), Canada
- ^k Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- ^l Also at Louisiana Tech University, Ruston LA, U.S.A.
- ^m Also at Department of Physics and Astronomy, University College London, London, U.K.
- ⁿ Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ^o Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- ^p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^r Also at Manhattan College, New York NY, U.S.A.
- ^s Also at School of Physics, Shandong University, Shandong, China
- ^t Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^u Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- ^v Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^w Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique), Gif-sur-Yvette, France
- ^x Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ^y Also at Departamento de Física, Universidade de Minho, Braga, Portugal
- ^z Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, U.S.A.

- aa* Also at Institute for Particle and Nuclear Physics,
Wigner Research Centre for Physics, Budapest, Hungary
- ab* Also at California Institute of Technology, Pasadena CA, U.S.A.
- ac* Also at Institute of Physics, Jagiellonian University, Krakow, Poland
- ad* Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- ae* Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.
- af* Also at Department of Physics, Oxford University, Oxford, U.K.
- ag* Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ah* Also at Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
- ai* Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and
Université Paris-Diderot and CNRS/IN2P3, Paris, France
- * Deceased