



Azimuthal correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Azimuthal correlations between the two jets with the largest transverse momenta p_T in inclusive 2-, 3-, and 4-jet events are presented for several regions of the leading jet p_T up to 4 TeV. For 3- and 4-jet scenarios, measurements of the minimum azimuthal angles between any two of the three or four leading p_T jets are also presented. The analysis is based on data from proton-proton collisions collected by the CMS Collaboration at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} . Calculations based on leading-order matrix elements supplemented with parton showering and hadronization do not fully describe the data, so next-to-leading-order calculations matched with parton shower and hadronization models are needed to better describe the measured distributions. Furthermore, we show that azimuthal jet correlations are sensitive to details of the parton showering, hadronization, and multiparton interactions. A next-to-leading-order calculation matched with parton showers in the MC@NLO method, as implemented in HERWIG 7, gives a better overall description of the measurements than the POWHEG method.

Published in the European Physical Journal C as doi:10.1140/epjc/s10052-018-6033-4.

1 Introduction

Particle jets with large transverse momenta p_T are abundantly produced in proton-proton collisions at the CERN LHC through the strong interactions of quantum chromodynamics (QCD) between the incoming partons. When the momentum transfer is large, the dynamics can be predicted using perturbative techniques (pQCD). The two final-state partons at leading order (LO) in pQCD are produced back-to-back in the transverse plane, and thus the azimuthal angular separation between the two highest- p_T jets, $\Delta\phi_{1,2} = |\phi_{\text{jet1}} - \phi_{\text{jet2}}|$, equals π . The production of additional high- p_T jets leads to a deviation of the azimuthal angle from π . The measurement of azimuthal angular correlations (or decorrelation from π) in inclusive 2-jet topologies is a useful tool to test theoretical predictions of multijet production processes. Previous measurements of azimuthal correlation in inclusive 2-jet events were reported by the D0 Collaboration in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron [1, 2], and by the ATLAS Collaboration in pp collisions at $\sqrt{s} = 7$ TeV [3] and the CMS Collaboration in pp collisions at $\sqrt{s} = 7$ and 8 TeV [4, 5] at the LHC. Multijet correlations have been measured by the ATLAS Collaboration at $\sqrt{s} = 8$ TeV [6, 7].

This paper reports measurements of the normalized inclusive 2-, 3-, and 4-jet cross sections as a function of the azimuthal angular separation between the two highest p_T (leading) jets, $\Delta\phi_{1,2}$,

$$\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi_{1,2}},$$

for several regions of the leading jet p_T , p_T^{max} , for the rapidity region $|y| < 2.5$. The measurements cover the region $\pi/2 < \Delta\phi_{1,2} \leq \pi$; the region $\Delta\phi_{1,2} \leq \pi/2$ includes large backgrounds due to $t\bar{t}$ and $Z/W+\text{jet}(s)$ events. Experimental and theoretical uncertainties are reduced by normalizing the $\Delta\phi_{1,2}$ distribution to the total dijet cross section within each region of p_T^{max} .

For 3- and 4-jet topologies, measurements of the normalized inclusive 3- and 4-jet cross sections are also presented as a function of the minimum azimuthal angular separation between any two of the three or four highest p_T jets, $\Delta\phi_{2j}^{\text{min}}$,

$$\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi_{2j}^{\text{min}}},$$

for several regions of p_T^{max} , for $|y| < 2.5$. This observable, which is infrared safe (independent of additional soft radiation), is especially suited for studying correlations amongst the jets in multijet events: the maximum value of $\Delta\phi_{2j}^{\text{min}}$ is $2\pi/3$ for 3-jet events (the ‘‘Mercedes star’’ configuration), while it is $\pi/2$ in the 4-jet case (corresponding to the ‘‘cross’’ configuration). The cross section for small angular separations is suppressed because of the finite jet sizes for a particular jet algorithm. The observable $\Delta\phi_{2j}^{\text{min}}$ is sensitive to the contributions of jets with lower p_T than the leading jet, i.e. the subleading jets, and one can distinguish nearby (nearly collinear) jets (at large $\Delta\phi_{2j}^{\text{min}}$) from other additional high p_T jets (small $\Delta\phi_{2j}^{\text{min}}$), yielding information additional to that of the $\Delta\phi_{1,2}$ observable. The 4-jet cross section differential in $\Delta\phi_{2j}^{\text{min}}$ has also been measured by the ATLAS Collaboration [7].

The measurements are performed using data collected during 2016 with the CMS experiment at the LHC, and the event sample corresponds to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid, 13 m in length and 6 m in inner diameter, providing an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Charged-particle trajectories are measured by the tracker with full azimuthal coverage within pseudorapidities $|\eta| < 2.5$. The ECAL, which is equipped with a preshower detector in the endcaps, and the HCAL cover the region $|\eta| < 3.0$. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Finally, muons are measured up to $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector together with a definition of the coordinate system used and the relevant kinematic variables can be found in Ref. [8].

3 Theoretical predictions

Predictions from five different Monte Carlo (MC) event generators are compared with data. The PYTHIA 8 [9] and HERWIG++ [10] event generators are used, both based on LO $2 \rightarrow 2$ matrix element calculations. The PYTHIA 8 event generator simulates parton showers ordered in p_T and uses the Lund string model [11] for hadronization, while HERWIG++ generates parton showers through angular-ordered emissions and uses a cluster fragmentation model [12] for hadronization. The contribution of multiparton interactions (MPI) is simulated in both PYTHIA 8 and HERWIG++, but the number of generated MPI varies between PYTHIA 8 and HERWIG++ MPI simulations. The MPI parameters of both generators are tuned to measurements in proton-proton collisions at the LHC and proton-antiproton collisions at the Tevatron [13], while the hadronization parameters are determined from fits to LEP data. For PYTHIA 8 the CUETP8M1 [13] tune, which is based on the NNPDF2.3LO PDF set [14, 15], is employed, while for HERWIG++ the CUETHppS1 tune [13], based on the CTEQ6L1 PDF set [16], is used.

The MADGRAPH [17, 18] event generator provides LO matrix element calculations with up to four outgoing partons, i.e. $2 \rightarrow 2$, $2 \rightarrow 3$, and $2 \rightarrow 4$ diagrams. It is interfaced to PYTHIA 8 with tune CUETP8M1 for the implementation of parton showers, hadronization, and MPI. In order to match with PYTHIA 8 the k_T -MLM matching procedure [19] with a matching scale of 14 GeV is used to avoid any double counting of the parton configurations generated within the matrix element calculation and the ones simulated by the parton shower. The NNPDF2.3LO PDF set is used for the hard-process calculation.

Predictions based on next-to-leading-order (NLO) pQCD are obtained with the POWHEGBOX library [20–22] and the HERWIG 7 [23] event generator. The events simulated with POWHEG are matched to PYTHIA 8 or to HERWIG++ parton showers and MPI, while HERWIG 7 uses similar parton shower and MPI models as HERWIG++, and the MC@NLO [24, 25] method is applied to combine the parton shower with the NLO calculation. The POWHEG generator is used in the NLO dijet mode [26], referred to as PH-2J, as well as in the NLO three-jet mode [27], referred to as PH-3J, both using the NNPDF3.0NLO PDF set [28]. The POWHEG generator, referred to as PH-2J-LHE, is also used in the NLO dijet mode without parton showers and MPI. A minimum p_T for real parton emission of 10 GeV is required for the PH-2J predictions, and similarly for the PH-3J predictions a minimum p_T for the three final-state partons of 10 GeV is imposed. To simulate the contributions due to parton showers, hadronization, and MPIs, the PH-2J is matched to PYTHIA 8 with tune CUETP8M1 and HERWIG++ with tune CUETHppS1, while the PH-3J is

matched only to PYTHIA 8 with tune CUETP8M1. The matching between the POWHEG matrix element calculations and the PYTHIA 8 underlying event (UE) simulation is performed using the shower-veto procedure, which rejects showers if their transverse momentum is greater than the minimal p_T of all final-state partons simulated in the matrix element (parameter PTHARD = 2 [26]). Predictions from the HERWIG 7 event generator are based on the MMHT2014 PDF set [29] and the default tune H7-UE-MMHT [23] for the UE simulation. A summary of the details of the MC event generators used for comparisons with the experimental data is shown in Table 1.

Table 1: Monte Carlo event generators used for comparison in this analysis. Version of the generators, PDF set, underlying event tune, and corresponding references are listed.

Matrix element generator	Simulated diagrams	PDF set	Tune
PYTHIA 8.219 [9]	2→2 (LO)	NNPDF2.3LO [14, 15]	CUETP8M1 [13]
HERWIG++ 2.7.1 [10]	2→2 (LO)	CTEQ6L1 [16]	CUETHppS1 [13]
MADGRAPH5_AMC@NLO 2.3.3 [17, 18] + PYTHIA 8.219 [9]	2→2, 2→3, 2→4 (LO)	NNPDF2.3LO [14, 15]	CUETP8M1 [13]
PH-2J V2.Sep2016 [20–22] + PYTHIA 8.219 [9]	2→2 (NLO), 2→3 (LO)	NNPDF3.0NLO [28]	CUETP8M1 [13]
PH-2J-LHE V2.Sep2016 [20–22]	2→2 (NLO), 2→3 (LO)	NNPDF3.0NLO [28]	
PH-3J V2.Sep2016 [20–22] + PYTHIA 8.219 [9]	2→3 (NLO), 2→4 (LO)	NNPDF3.0NLO [28]	CUETP8M1 [13]
PH-2J V2.Sep2016 [20–22] + HERWIG++ 2.7.1 [10]	2→2 (NLO), 2→3 (LO)	NNPDF3.0NLO [28]	CUETHppS1 [13]
HERWIG 7.0.4 [23]	2→2 (NLO), 2→3 (LO)	MMHT2014 [29]	H7-UE-MMHT [23]

Uncertainties in the theoretical predictions of the parton shower simulation are illustrated using the PYTHIA 8 event generator. Choices of scale for the parton shower are expected to have the largest impact on the azimuthal distributions. The parton shower uncertainty is calculated by independently varying the renormalization scales (μ_r) for initial- and final-state radiation by a factor 2 in units of the p_T of the emitted partons of the hard scattering. The maximum deviation found is considered a theoretical uncertainty in the event generator predictions.

4 Jet reconstruction and event selection

The measurements are based on data samples collected with single-jet high-level triggers (HLT) [30, 31]. Five such triggers are considered that require at least one jet in an event with $p_T > 140, 200, 320, 400, \text{ or } 450 \text{ GeV}$ in the full rapidity coverage of the CMS detector. All triggers are prescaled except the one with the highest threshold. Table 2 shows the integrated luminosity \mathcal{L} for the five trigger samples. The relative efficiency of each trigger is estimated using triggers with lower p_T thresholds. Using these five jet energy thresholds, a 100% trigger efficiency is achieved in the region of $p_T^{\text{max}} > 200 \text{ GeV}$.

Table 2: The integrated luminosity for each trigger sample considered in this analysis.

HLT p_T threshold (GeV)	140	200	320	400	450
p_T^{max} region (GeV)	200–300	300–400	400–500	500–600	>600
\mathcal{L} (fb^{-1})	0.024	0.11	1.77	5.2	36

Particles are reconstructed and identified using a particle-flow (PF) algorithm [32], which uses an optimized combination of information from the various elements of the CMS detector. Jets are reconstructed by clustering the Lorentz vectors of the PF candidates with the infrared- and collinear-safe anti- k_T clustering algorithm [33] with a distance parameter $R = 0.4$. The clustering is performed with the FASTJET package [34]. The technique of charged-hadron subtraction [35] is used to remove tracks identified as originating from additional pp interactions within the same or neighbouring bunch crossings (pileup). The average number of pileup interactions observed in the data is about 27.

The reconstructed jets require energy corrections to account for residual nonuniformities and nonlinearities in the detector response. These jet energy scale (JES) corrections [35] are derived using simulated events that are generated with PYTHIA 8.219 [9] using tune CUETP8M1 [13] and processed through the CMS detector simulation based on GEANT4 [36]; they are confirmed with in situ measurements with dijet, multijet, photon+jet, and leptonic Z+jet events. An offset correction is required to account for the extra energy clustered into jets due to pileup. The JES corrections, which depend on the η and p_T of the jet, are applied as multiplicative factors to the jet four-momentum vectors. The typical overall correction is about 10% for central jets having $p_T = 100$ GeV and decreases with increasing p_T .

Resolution studies on the measurements of $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{\min}$ are performed using PYTHIA 8.219 with tune CUETP8M1 processed through the CMS detector simulation. The azimuthal angular separation is determined with an accuracy from 1° to 0.5° (0.017 to 0.0087 in radians) for $p_T^{\max} = 200$ GeV to 1 TeV, respectively.

Events are required to have at least one primary vertex candidate [37] reconstructed offline from at least five charged-particle tracks and lies along the beam line within 24 cm of the nominal interaction point. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the objects determined by a jet finding algorithm [33, 34] applied to all charged tracks associated with the vertex plus the corresponding associated missing transverse momentum. Additional selection criteria are applied to each event to remove spurious jet-like signatures originating from isolated noise patterns in certain HCAL regions. Stringent criteria [38] are applied to suppress these nonphysical signatures; each jet should contain at least two particles, one of which is a charged hadron, and the jet energy fraction carried by neutral hadrons and photons should be less than 90%. These criteria have a jet selection efficiency greater than 99% for genuine jets.

For the measurements of the normalized inclusive 2-, 3-, and 4-jet cross sections as a function of $\Delta\phi_{1,2}$ or $\Delta\phi_{2j}^{\min}$ all jets in the event with $p_T > 100$ GeV and a rapidity $|y| < 5$ are considered and ordered in p_T . Events are selected where the two highest- p_T jets have $|y| < 2.5$, (i.e. events are not counted where one of the leading jets has $|y| > 2.5$). Also, events are only selected in which the highest- p_T jet has $|y| < 2.5$ and exceeds 200 GeV. The inclusive 2-jet event sample includes events where the two leading jets lie within the tracker coverage of $|y| < 2.5$. Similarly the 3-jet (4-jet) event sample includes those events where the three (four) leading jets lie within $|y| < 2.5$, respectively. In this paper results are presented in bins of p_T^{\max} , corresponding to the p_T of the leading jet, which is always within $|y| < 2.5$.

5 Measurements of the normalized inclusive 2-, 3-, and 4-jet cross sections in $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{\min}$

The normalized inclusive 2-, 3-, and 4-jet cross sections differential in $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{\min}$ are corrected for the finite detector resolution to better approximate the final-state particles, a procedure called "unfolding". In this way, a direct comparison of this measurement to results from other experiments and to QCD predictions is possible. Particles are considered stable if their mean decay length is $c\tau > 1$ cm.

The bin width used in the measurements of $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{\min}$ is set to $\pi/36 = 0.087$ rads (5°), which is five to ten times larger than the azimuthal angular separation resolution. The corrections due to the unfolding are approximately a few per cent.

The unfolding procedure is based on the matrix inversion algorithm implemented in the software package ROOUNFOLD [39] using a 2-dimensional response matrix that correlates the modeled distribution with the reconstructed one. The response matrix is created by the convolution of the $\Delta\phi$ resolution with the generator-level inclusive 2-, 3-, and 4- cross section distributions from PYTHIA 8 with tune CUETP8M1. The unfolded distributions differ from the distributions at detector level by 1 to 4%. As a cross-check, the above procedure was repeated by creating the response matrix with event samples obtained with the full GEANT4 detector simulation, and no significant difference was observed.

We consider three main sources of systematic uncertainties that arise from the estimation of the JES calibration, the jet energy resolution (JER), and the unfolding correction. The relative JES uncertainty is estimated to be 1–2% for PF jets using charged-hadron subtraction [35]. The resulting uncertainties in the normalized 2-, 3-, and 4-jet cross sections differential in $\Delta\phi_{1,2}$ range from 3% at $\pi/2$ to 0.1% at π . For the normalized 3- and 4-jet cross sections differential in $\Delta\phi_{2j}^{\min}$ the resulting uncertainties range from 0.1 to 1%, and 0.1 to 2%, respectively.

The JER [35] is responsible for migration of events among the p_T^{\max} regions, and its parametrization is determined from a full detector simulation using events generated by PYTHIA 8 with tune CUETP8M1. The effect of the JER uncertainty is estimated by varying its parameters within their uncertainties [35] and comparing the normalized inclusive 2-, 3-, and 4-jet cross sections before and after the changes. The JER-induced uncertainty ranges from 1% at $\pi/2$ to 0.1% at π for the normalized 2-, 3-, and 4-jet cross sections differential in $\Delta\phi_{1,2}$ and is less than 0.5% for the normalized 3- and 4-jet cross sections differential in $\Delta\phi_{2j}^{\min}$.

The above systematic uncertainties in the JES calibration and the JER cover the effects from migrations due to the p_T thresholds, i.e. migrations between the 2-, 3-, and 4-jet samples and migrations between the various p_T^{\max} regions of the measurements.

The unfolding procedure is affected by uncertainties in the parametrization of the $\Delta\phi$ resolution. Alternative response matrices, generated by varying the $\Delta\phi$ resolution by $\pm 10\%$, are used to unfold the measured spectra. This variation is motivated by studies on the $\Delta\phi$ resolution for simulated di-jet events [32]. The uncertainty in the unfolding correction factors is estimated to be about 0.2%. An additional systematic uncertainty is obtained by examining the dependence of the response matrix on the choice of the MC generator. Alternative response matrices are constructed using the HERWIG++ event generator [10] with tune EE5C [40]; the effect is $< 0.1\%$. A total systematic unfolding uncertainty of 0.2% is considered, which accounts for all these various uncertainty sources.

6 Comparison with theoretical predictions

6.1 The $\Delta\phi_{1,2}$ measurements

The unfolded, normalized, inclusive 2-, 3-, and 4-jet cross sections differential in $\Delta\phi_{1,2}$ are shown in Figs. 1-3 for the various p_T^{\max} regions considered in this analysis. In the 2-jet case the $\Delta\phi_{1,2}$ distributions are strongly peaked at π and become steeper with increasing p_T^{\max} . In the 3-jet case, the $\Delta\phi_{1,2}$ distributions become flatter at π , since by definition dijet events do not contribute, and in the 4-jet case they become even flatter. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

The ratios of the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 event generator predictions to the normalized inclusive 2-, 3-, and 4-jet cross section differential in $\Delta\phi_{1,2}$ are shown in Figs. 4, 5, and 6, respectively, for all p_T^{\max} regions. The solid band around unity represents the total experimental uncertainty and the error bars on the points represent the statistical uncertainties in the simulated data. Among the LO dijet event generators, HERWIG++ exhibits the largest deviations from the experimental measurements, whereas PYTHIA 8 behaves much better than HERWIG++, although with deviations of up to 30-40%, in particular around $\Delta\phi_{1,2} = 5\pi/6$ in the 2-jet case and around $\Delta\phi_{1,2} < 2\pi/3$ in the 3- and 4-jet case. Predictions from HERWIG++ tend to overestimate the measurements as a function of $\Delta\phi_{1,2}$ in the 2-, 3-, and 4-jet cases, especially at $\Delta\phi_{1,2} < 5\pi/6$ for $p_T^{\max} > 400$ GeV. However, it is remarkable that predictions based on the $2 \rightarrow 2$ matrix element calculations supplemented with parton showers, MPI, and hadronization describe the $\Delta\phi_{1,2}$ distributions rather well, even in regions that are sensitive to hard jets not included in the matrix element calculations. The MADGRAPH + PYTHIA 8 calculation using up to 4 partons in the matrix element calculations provides the best description of the measurements.

Figures 7-9 show the ratios of the PH-2J matched to PYTHIA 8 and HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 event generators predictions to the normalized inclusive 2-, 3-, and 4-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band around unity represents the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data. The predictions of PH-2J and PH-3J exhibit deviations from the measurement, increasing towards small $\Delta\phi_{1,2}$. While PH-2J is above the data, PH-3J predicts too few events at small $\Delta\phi_{1,2}$. These deviations were investigated in a dedicated study with parton showers and MPI switched off. Because of the kinematic restriction of a 3-parton state, PH-2J without parton showers cannot fill the region $\Delta\phi_{1,2} < 2\pi/3$, shown as PH-2J-LHE with the dashed line in Fig. 7, whereas for PH-3J the parton showers have little impact. Thus, the events at low $\Delta\phi_{1,2}$ observed for PH-2J originate from leading-log parton showers, and there are too many of these. In contrast, the PH-3J prediction, which provides $2 \rightarrow 3$ jet calculations at NLO QCD, is below the measurement. The NLO PH-2J calculation and the LO POWHEG three-jet calculation are equivalent when initial- and final-state radiation are not allowed to occur.

The predictions from PH-2J matched to PYTHIA 8 describe the normalized cross sections better than those where PH-2J is matched to HERWIG++. Since the hard process calculation is the same, the difference between the two predictions might be due to the treatment of parton showers in PYTHIA 8 and HERWIG++ and to the matching to the matrix element calculation. The PYTHIA 8 and HERWIG++ parton shower calculations use different α_s values for initial- and final-state emissions, in addition to a different upper scale for the parton shower simulation, which is higher in PYTHIA 8 than in HERWIG++. The dijet NLO calculation of HERWIG 7 provides the best description of the measurements, indicating that the MC@NLO method of combining parton showers with the NLO parton level calculations has advantages compared

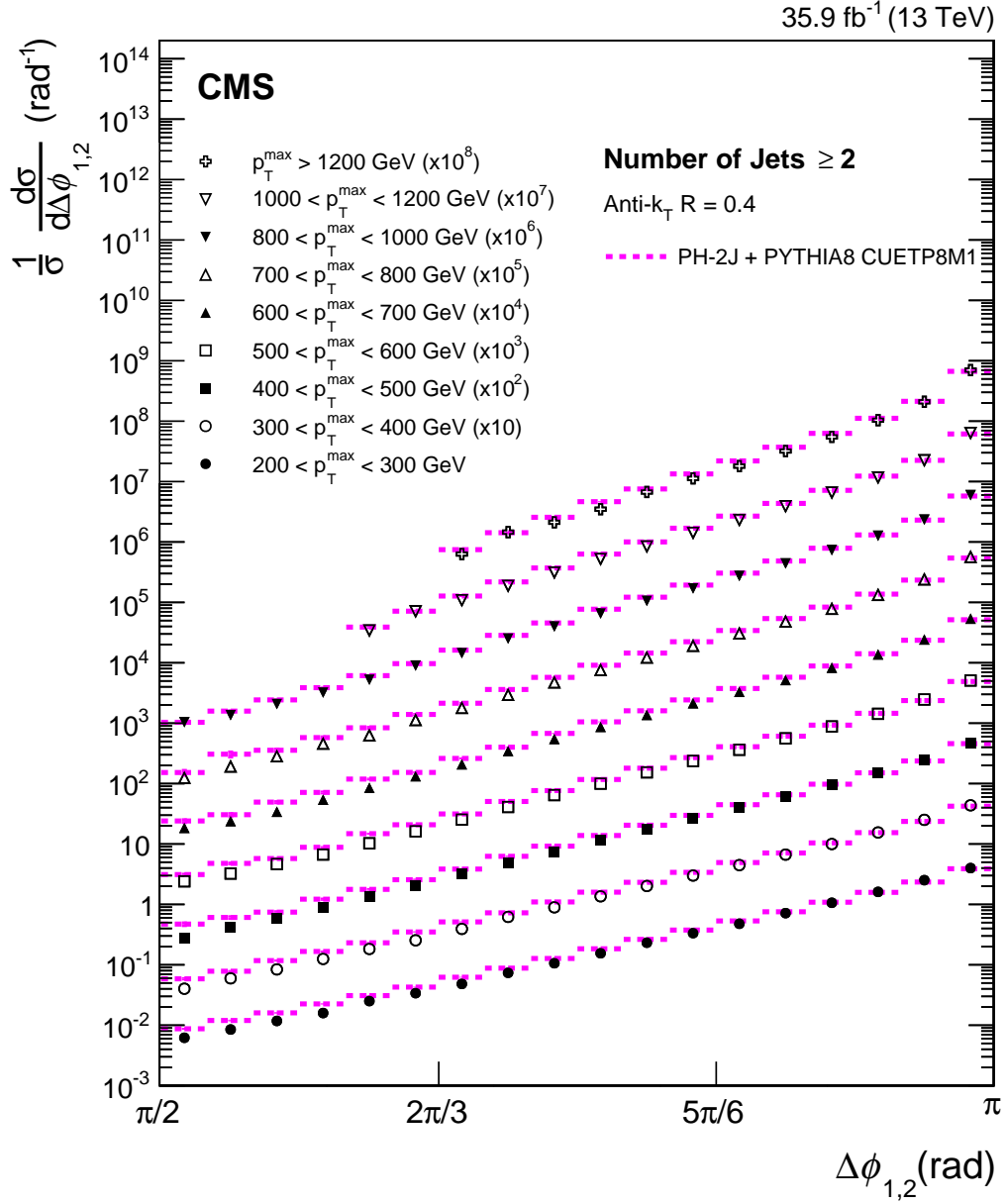


Figure 1: Normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$ for nine p_T^{\max} regions, scaled by multiplicative factors for presentation purposes. The size of the data symbol includes both statistical and systematic uncertainties. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

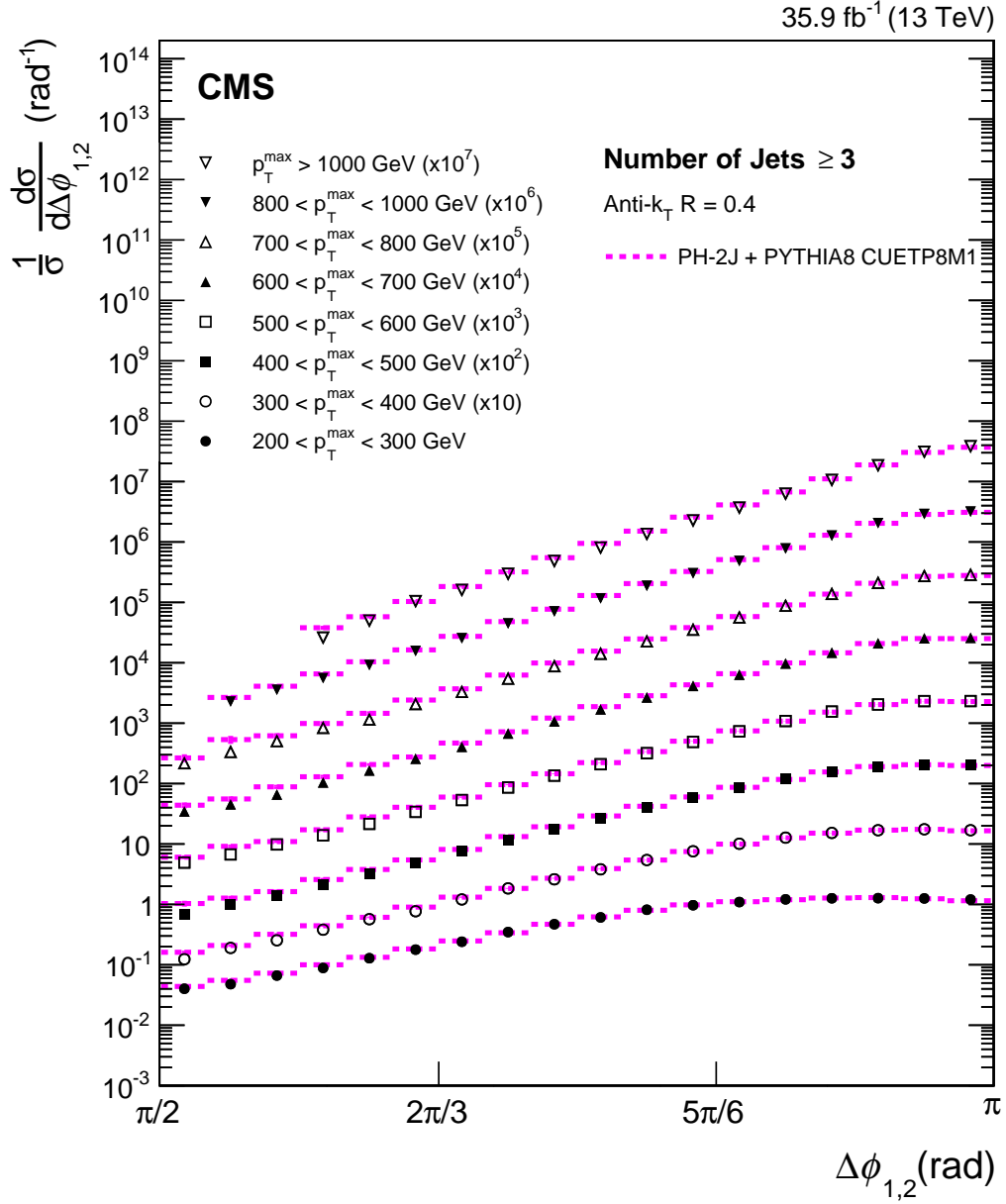


Figure 2: Normalized inclusive 3-jet cross section differential in $\Delta\phi_{1,2}$ for eight p_T^{\max} regions, scaled by multiplicative factors for presentation purposes. The size of the data symbol includes both statistical and systematic uncertainties. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

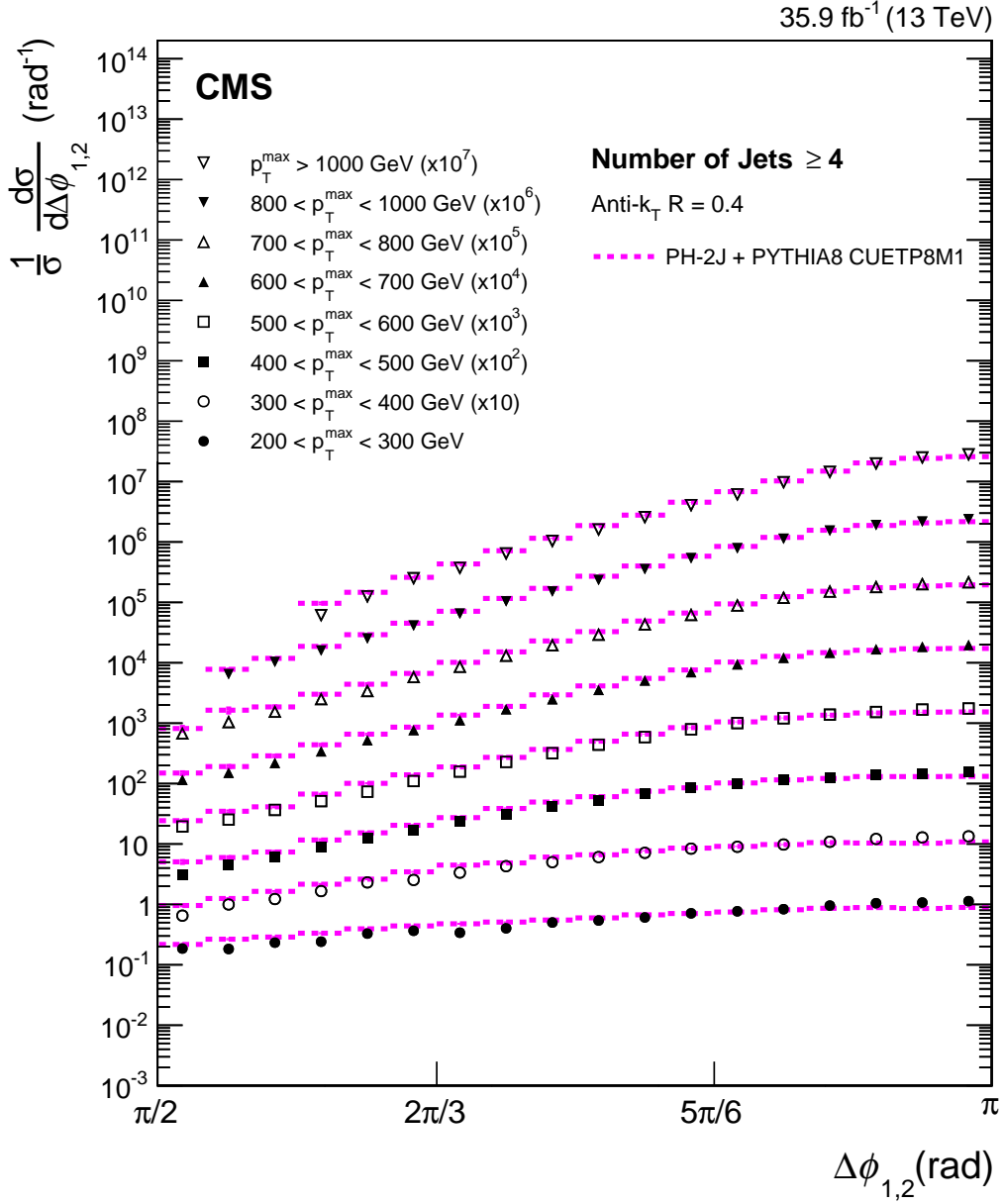


Figure 3: Normalized inclusive 4-jet cross section differential in $\Delta\phi_{1,2}$ for eight p_T^{\max} regions, scaled by multiplicative factors for presentation purposes. The size of the data symbol includes both statistical and systematic uncertainties. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

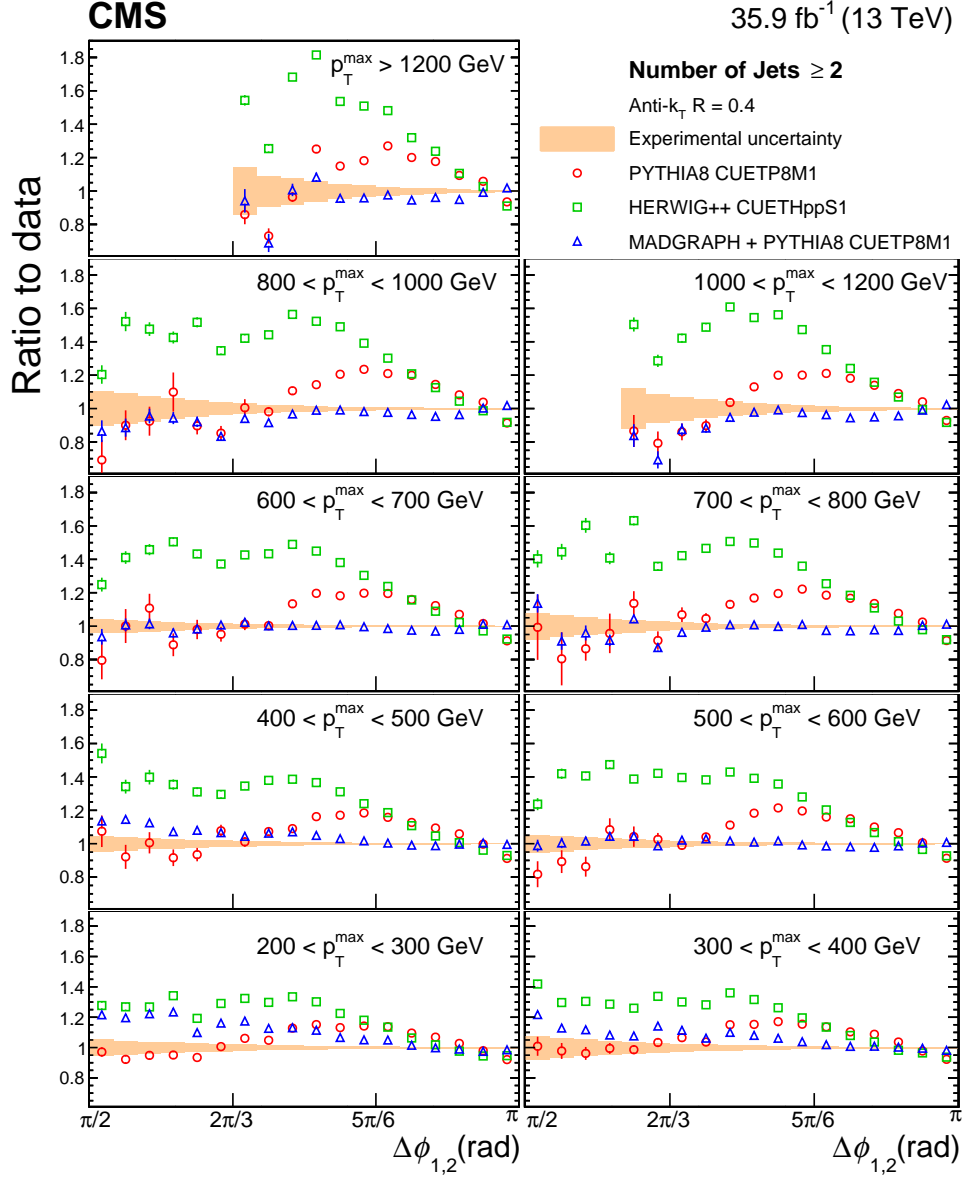


Figure 4: Ratios of PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to the normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

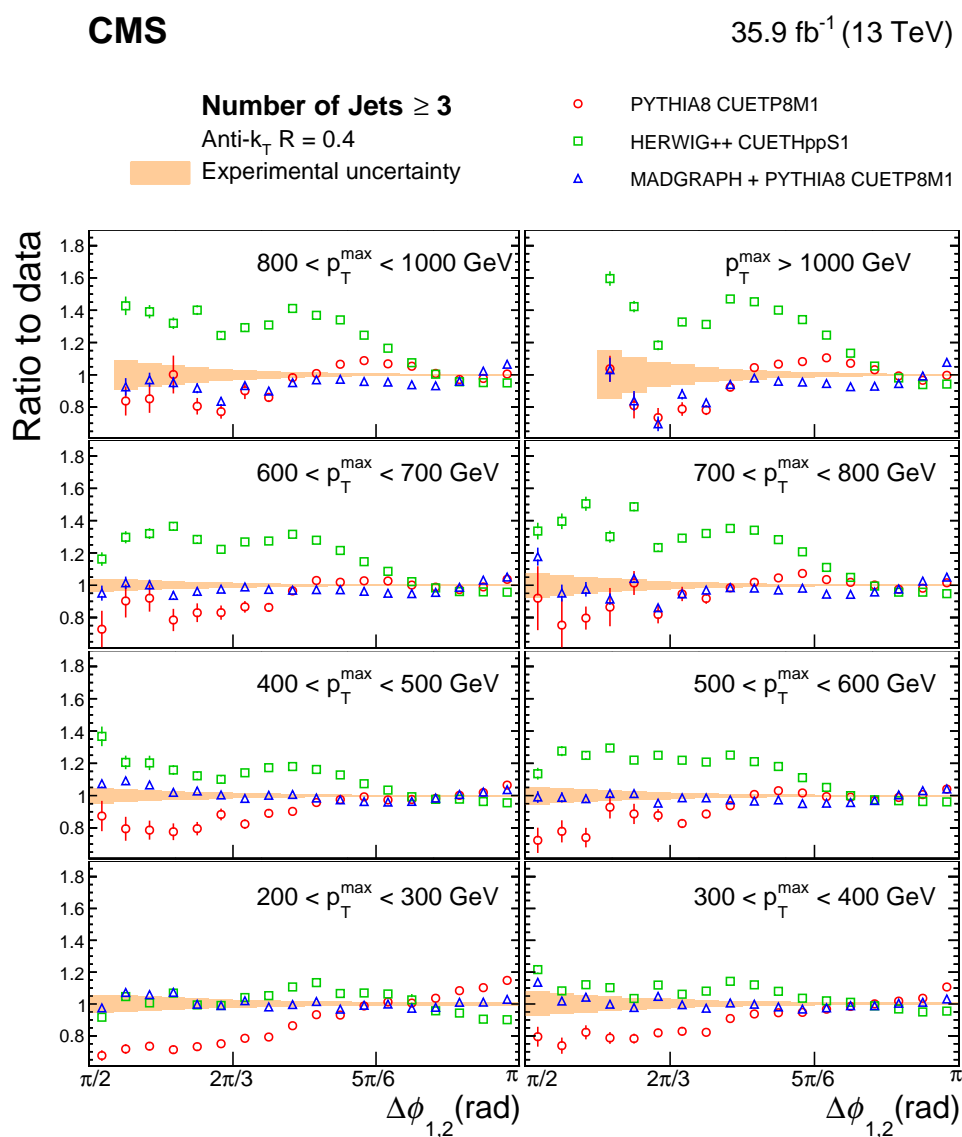


Figure 5: Ratios of PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to the normalized inclusive 3-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

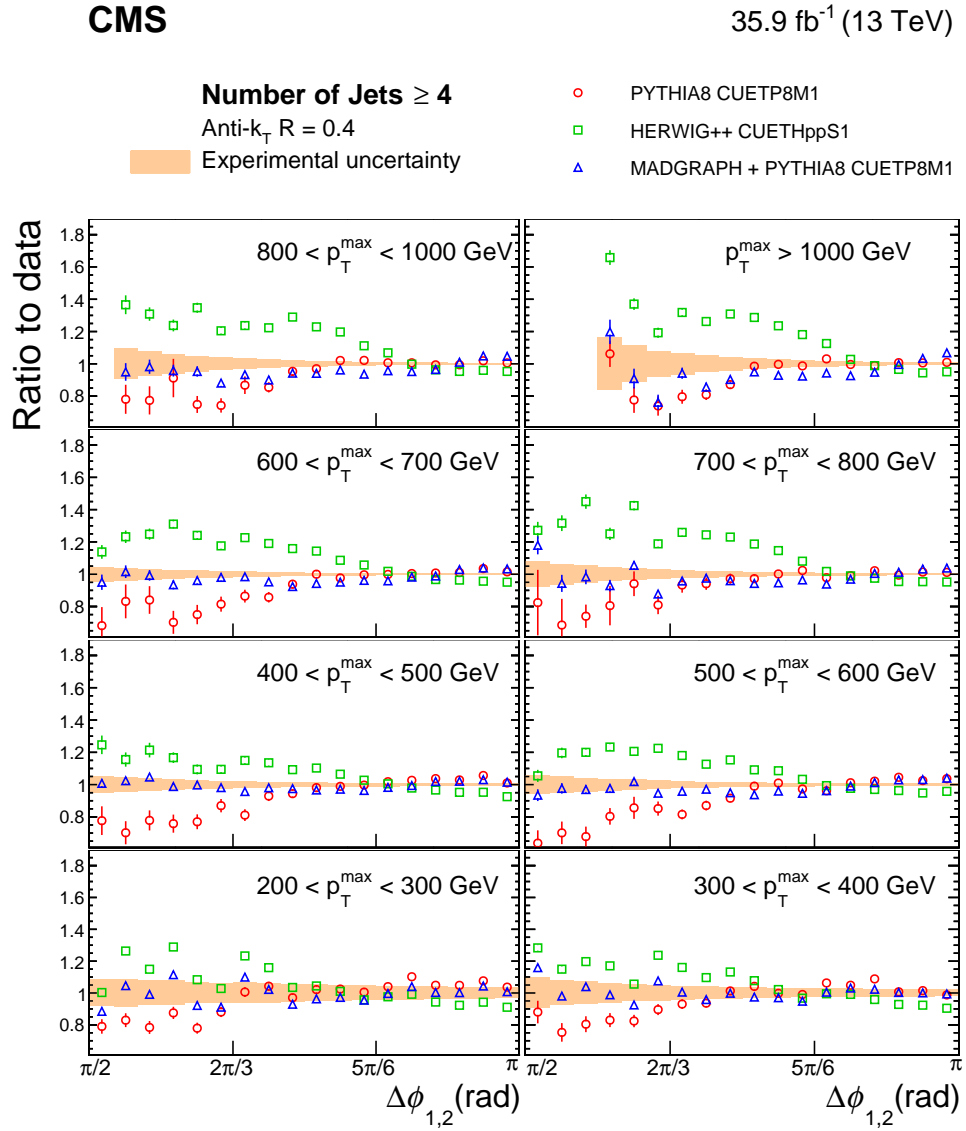


Figure 6: Ratios of PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to the normalized inclusive 4-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

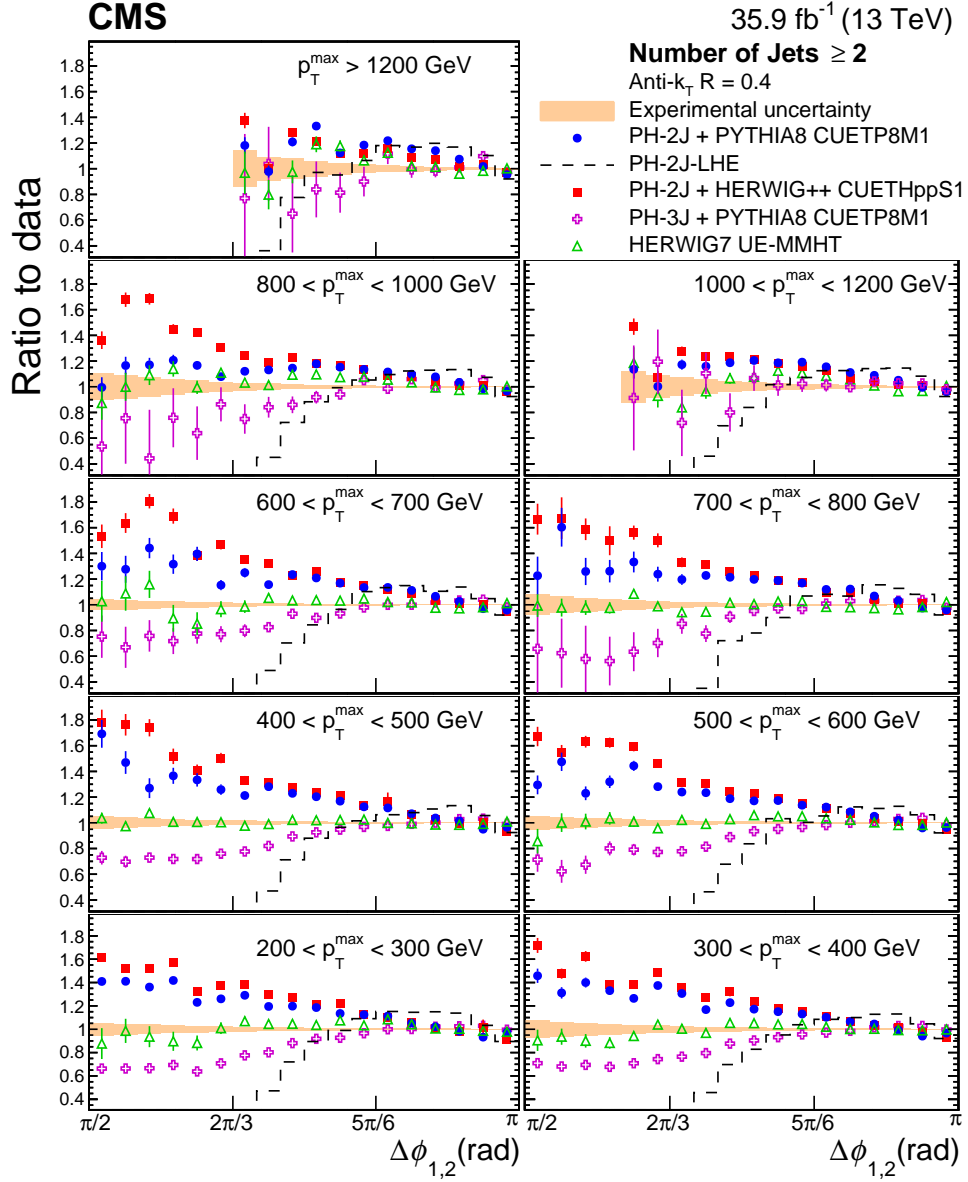


Figure 7: Ratios of PH-2J + PYTHIA 8, PH-2J-LHE, PH-2J + HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 predictions to the normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

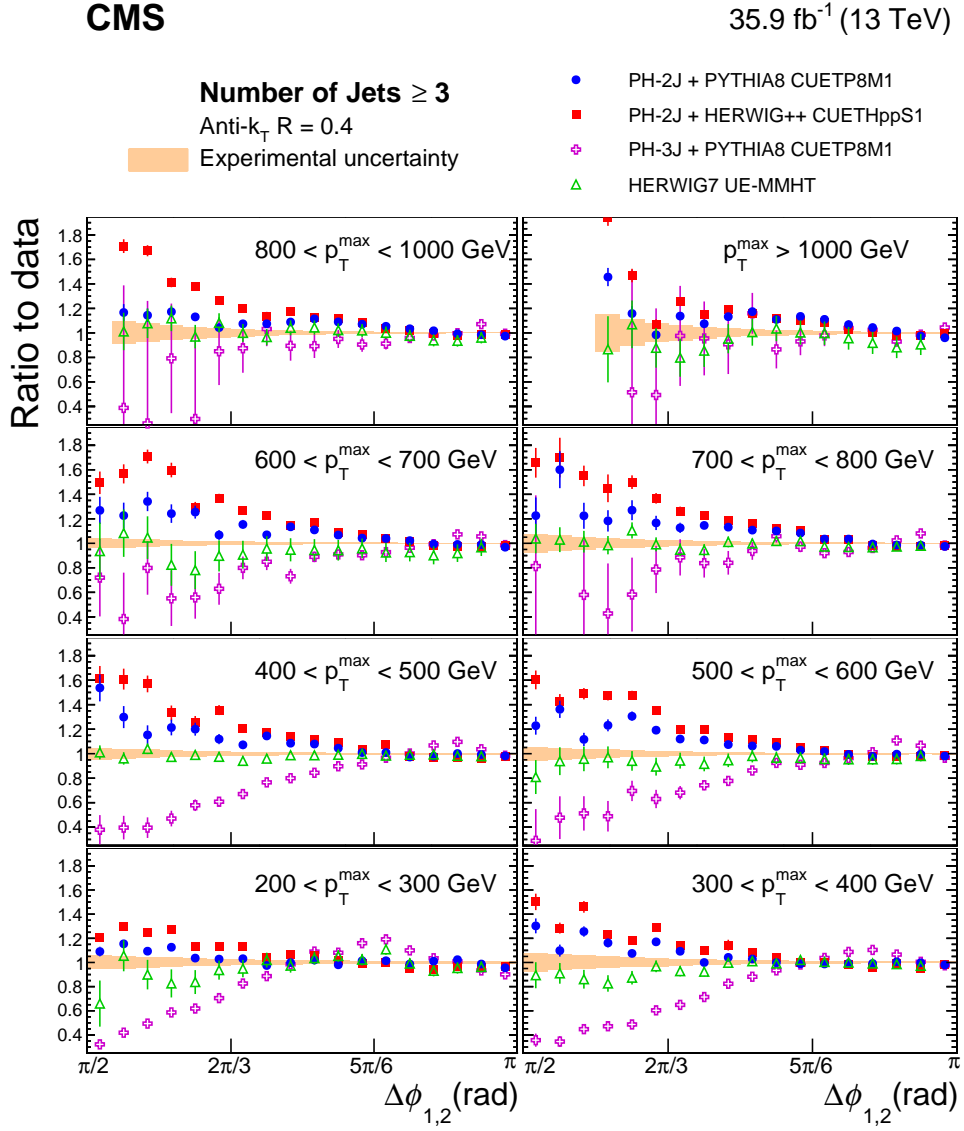


Figure 8: Ratios of PH-2J + PYTHIA 8, PH-2J + HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 predictions to the normalized inclusive 3-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

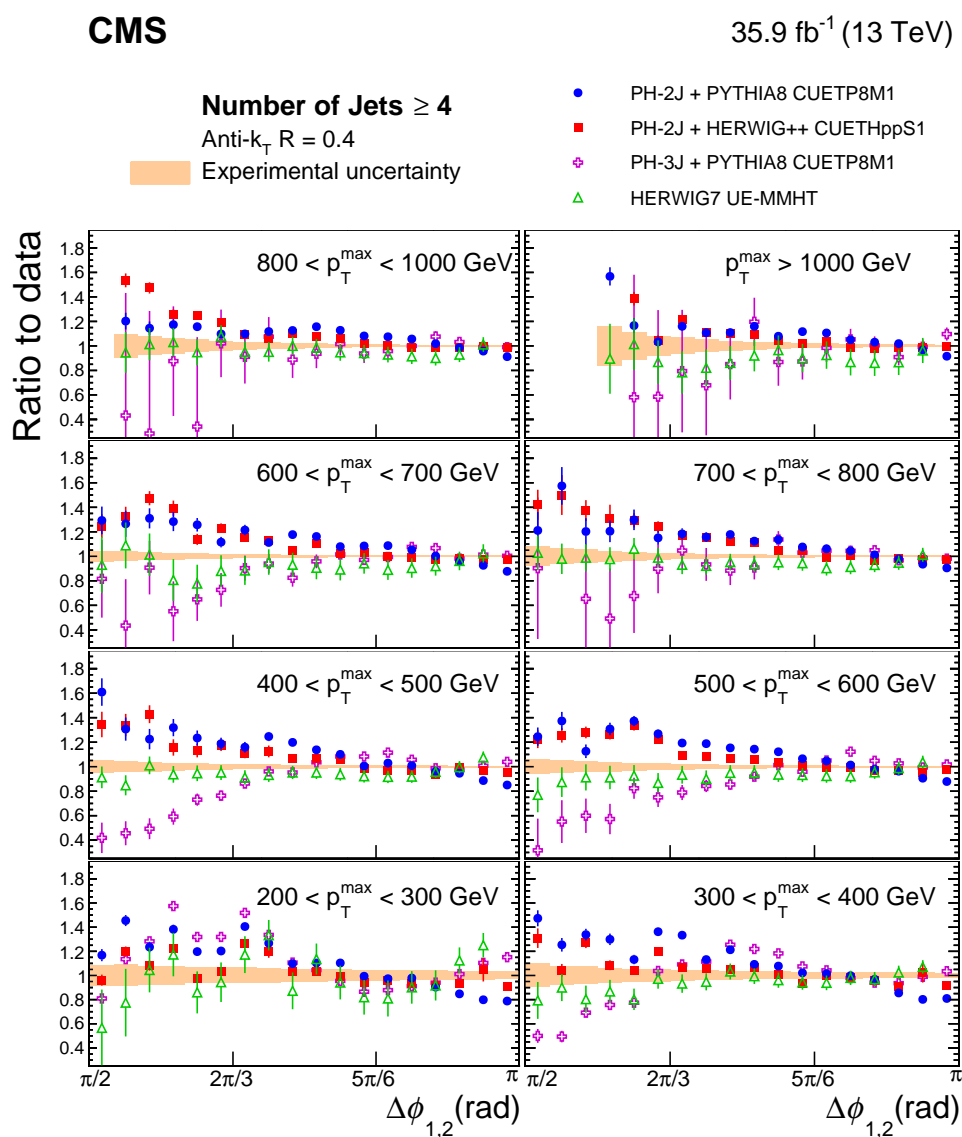


Figure 9: Ratios of PH-2J + PYTHIA 8, PH-2J + HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 predictions to the normalized inclusive 4-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

to the POWHEG method in this context.

For $\Delta\phi_{1,2}$ generator-level predictions in the 2-jet case, parton shower uncertainties have a very small impact ($<5\%$) at values close to π and go up to 40–60% for increasing p_T^{\max} at $\Delta\phi_{1,2} \sim \pi/2$. For the 3- and 4-jet scenarios, parton shower uncertainties are less relevant, not exceeding $\sim 20\%$ for $\Delta\phi_{1,2}$.

6.2 The $\Delta\phi_{2j}^{\min}$ measurements

The unfolded, normalized, inclusive 3- and 4-jet cross sections differential in $\Delta\phi_{2j}^{\min}$ are shown in Figs. 10 and 11, respectively, for eight p_T^{\max} regions. The measured distributions decrease towards the kinematic limit of $\Delta\phi_{2j}^{\min} \rightarrow 2\pi/3(\pi/2)$ for the 3-jet and 4-jet case, respectively. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator. The size of the data symbol includes both statistical and systematic uncertainties.

Figures 12 and 13 show, respectively, the ratios of the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 event generators predictions to the normalized inclusive 3- and 4-jet cross sections differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. The PYTHIA 8 event generator shows larger deviations from the measured $\Delta\phi_{2j}^{\min}$ distributions in comparison to HERWIG++, which provides a reasonable description of the measurement. The MADGRAPH generator matched to PYTHIA 8 provides a reasonable description of the measurements in the 3-jet case, but shows deviations in the 4-jet case.

The predictions from MADGRAPH + PYTHIA 8 and PYTHIA 8 are very similar for the normalized cross sections as a function of $\Delta\phi_{2j}^{\min}$ in the four-jet case. It has been checked that predictions obtained with the MADGRAPH matrix element with up to 4 partons included in the calculation without contribution of the parton shower are able to reproduce the data very well. Parton shower effects increase the number of events with low values of $\Delta\phi_{2j}^{\min}$.

Figures 14 and 15 illustrate the ratios of predictions from PH-2J matched to PYTHIA 8 and HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 to the normalized inclusive 3- and 4-jet cross sections differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. Due to an unphysical behavior of the HERWIG 7 prediction (which has been confirmed by the HERWIG 7 authors), the first $\Delta\phi_{2j}^{\min}$ and last $\Delta\phi_{1,2}$ bins are not shown in Figs. 8, 9, 14, and 15. An additional uncertainty is introduced to the prediction of HERWIG 7, that is evaluated as the difference between this prediction and the prediction when the first bin is replaced with the result from HERWIG++. The additional uncertainty ranges from 2 to 10%. Among the three NLO dijet calculations PH-2J matched to PYTHIA 8 or to HERWIG++ provides the best description of the measurements.

For the two lowest p_T^{\max} regions in Figs 13 and 15, which correspond to the 4-jet case, the measurements become statistically limited because the data used for these two regions were collected with highly prescaled triggers with p_T thresholds of 140 and 200 GeV (c.f. Table 2).

The PH-3J predictions suffer from low statistical accuracy, especially in the highest interval of p_T^{\max} , because the same p_T threshold is applied to all 3 jets resulting in low efficiency at large p_T . Nevertheless, the performance of the PH-3J simulation on multijet observables can already be inferred by the presented predictions, especially in the low p_T region.

The effect of parton shower uncertainties in the event generator predictions of $\Delta\phi_{2j}^{\min}$ is estimated to be less than 10% over the entire phase space.

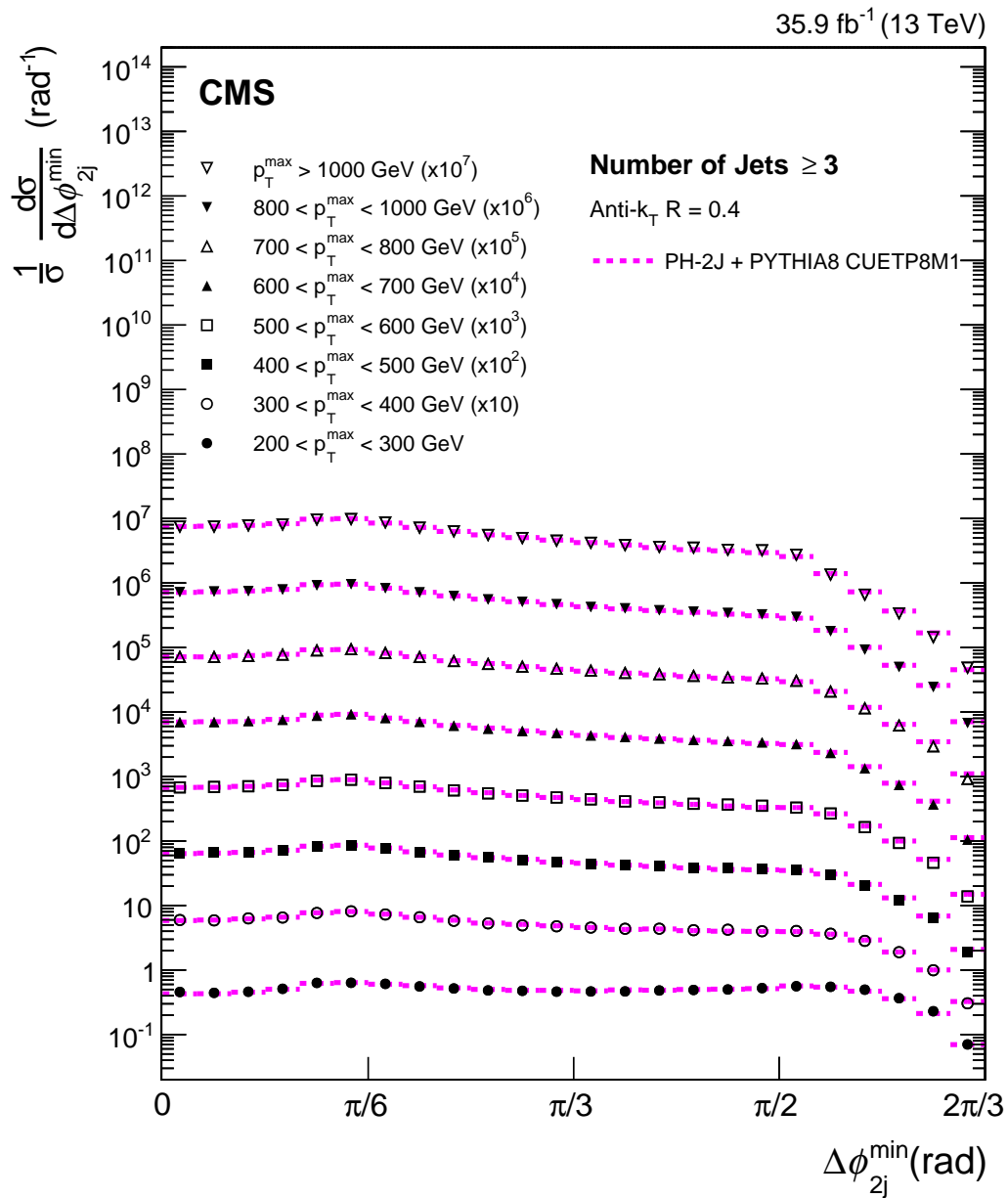


Figure 10: Normalized inclusive 3-jet cross section differential in $\Delta\phi_{2j}^{\min}$ for eight p_T^{\max} regions, scaled by multiplicative factors for presentation purposes. The size of the data symbol includes both statistical and systematic uncertainties. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

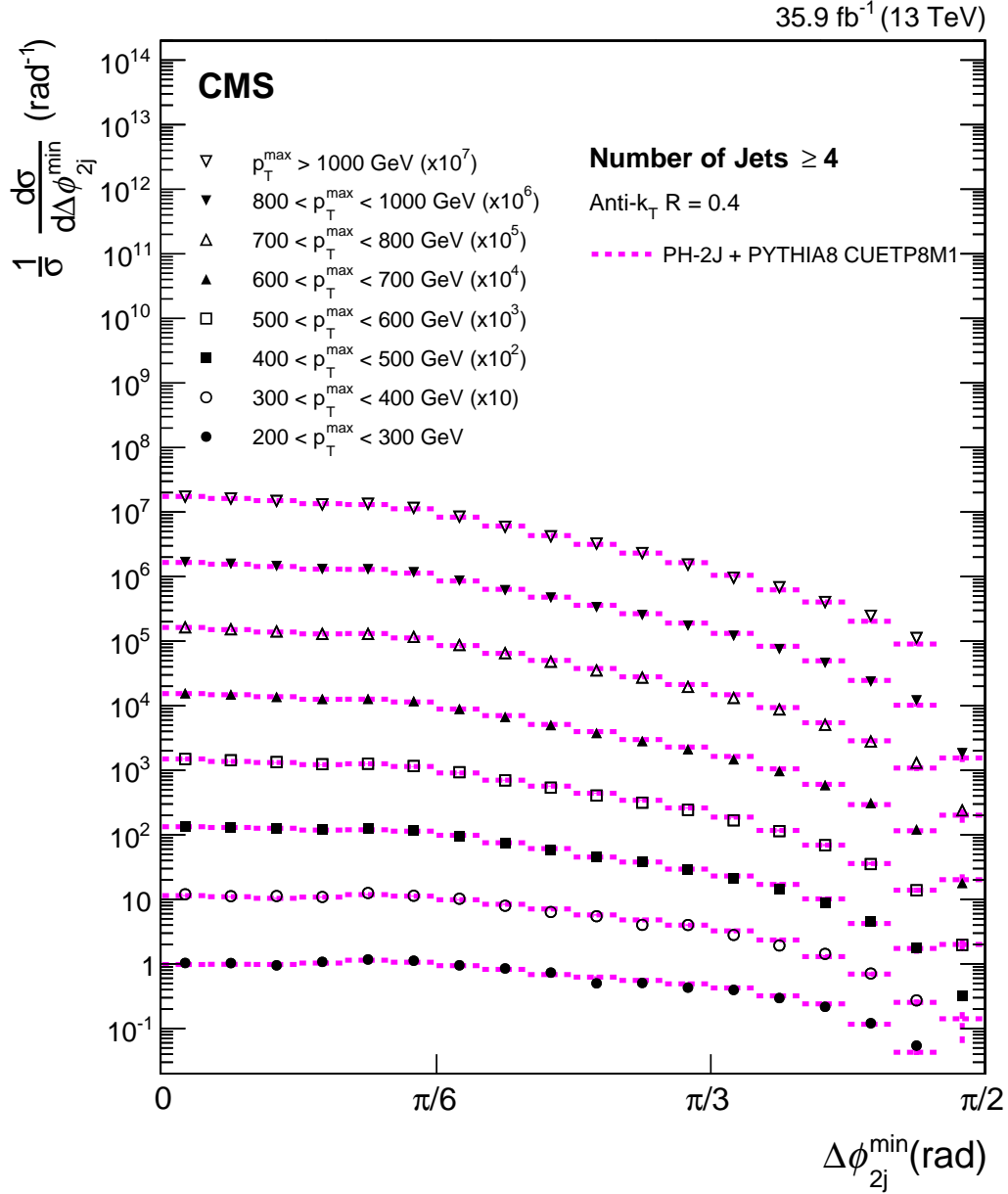


Figure 11: Normalized inclusive 4-jet cross section differential in $\Delta\phi_{2j}^{\min}$ for eight p_T^{\max} regions, scaled by multiplicative factors for presentation purposes. The size of the data symbol includes both statistical and systematic uncertainties. The data points are overlaid with the predictions from the PH-2J + PYTHIA 8 event generator.

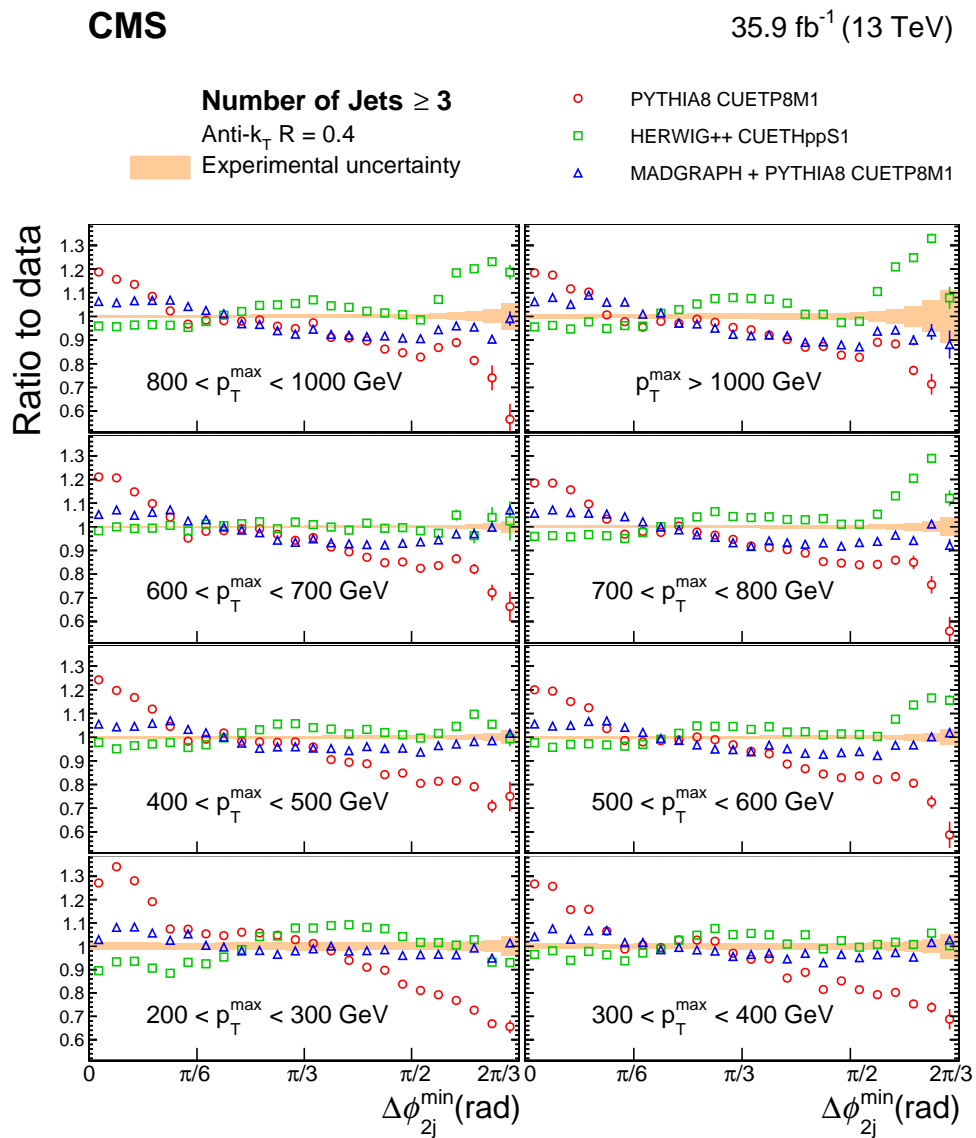


Figure 12: Ratios of PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to the normalized inclusive 3-jet cross section differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

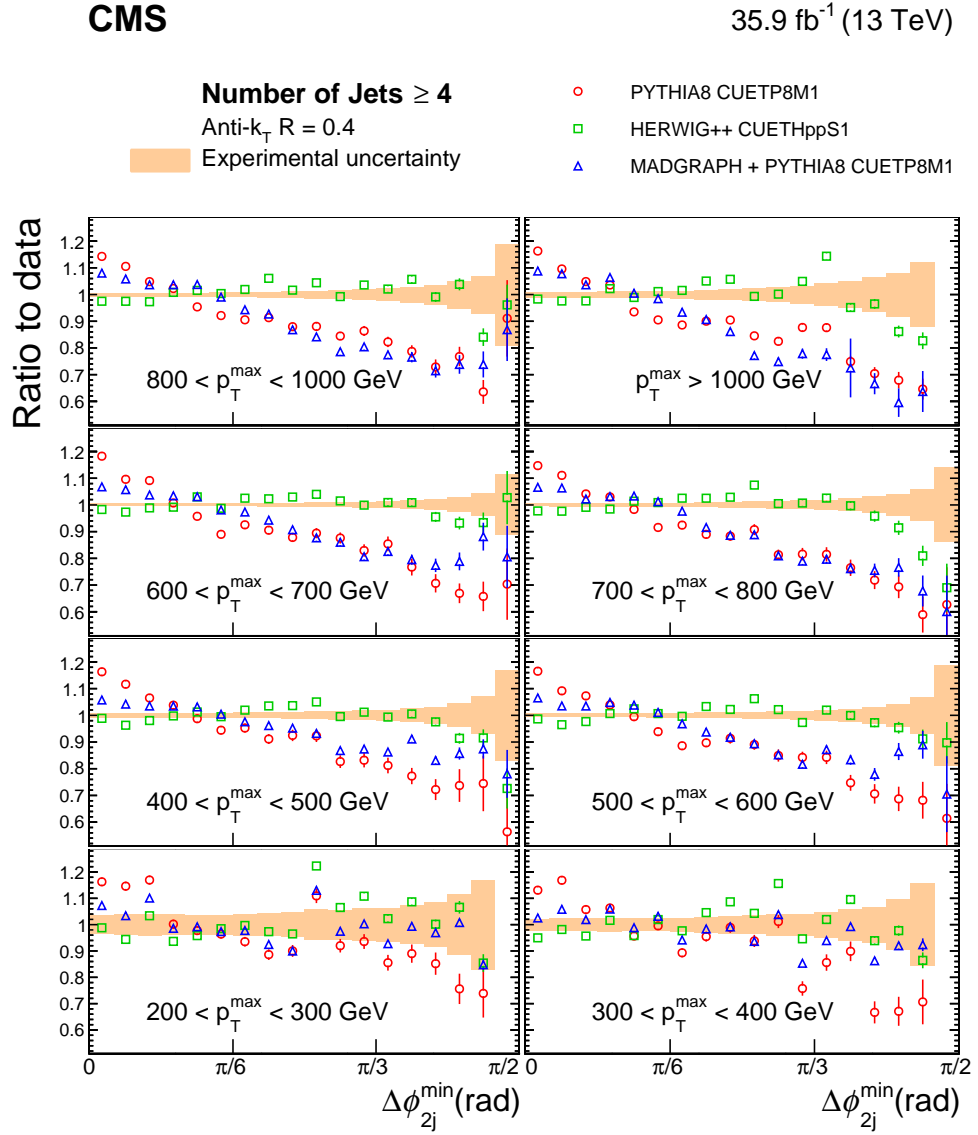


Figure 13: Ratios of PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to the normalized inclusive 4-jet cross section differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties in the simulated data.

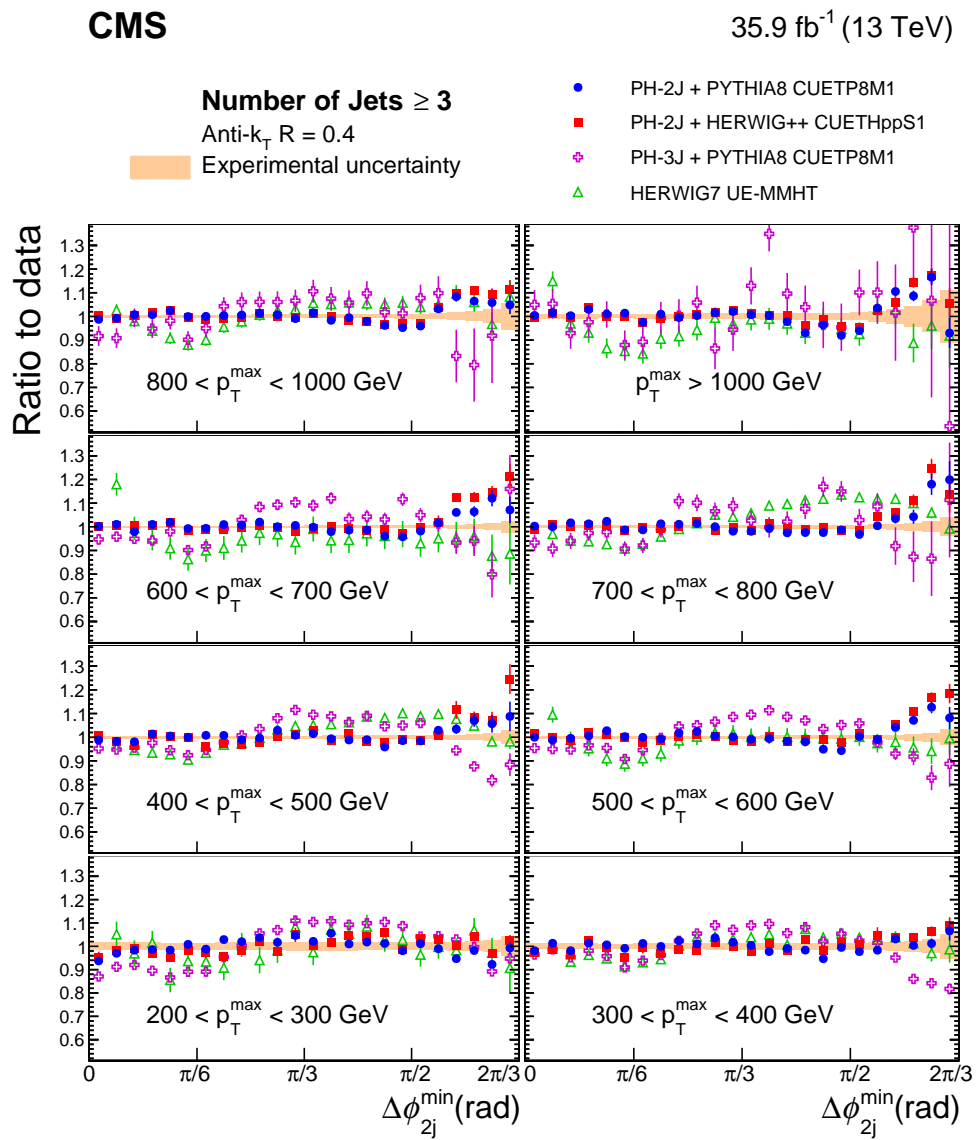


Figure 14: Ratios of PH-2J + PYTHIA 8, PH-2J + HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 predictions to the normalized inclusive 3-jet cross section differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties of the simulated data.

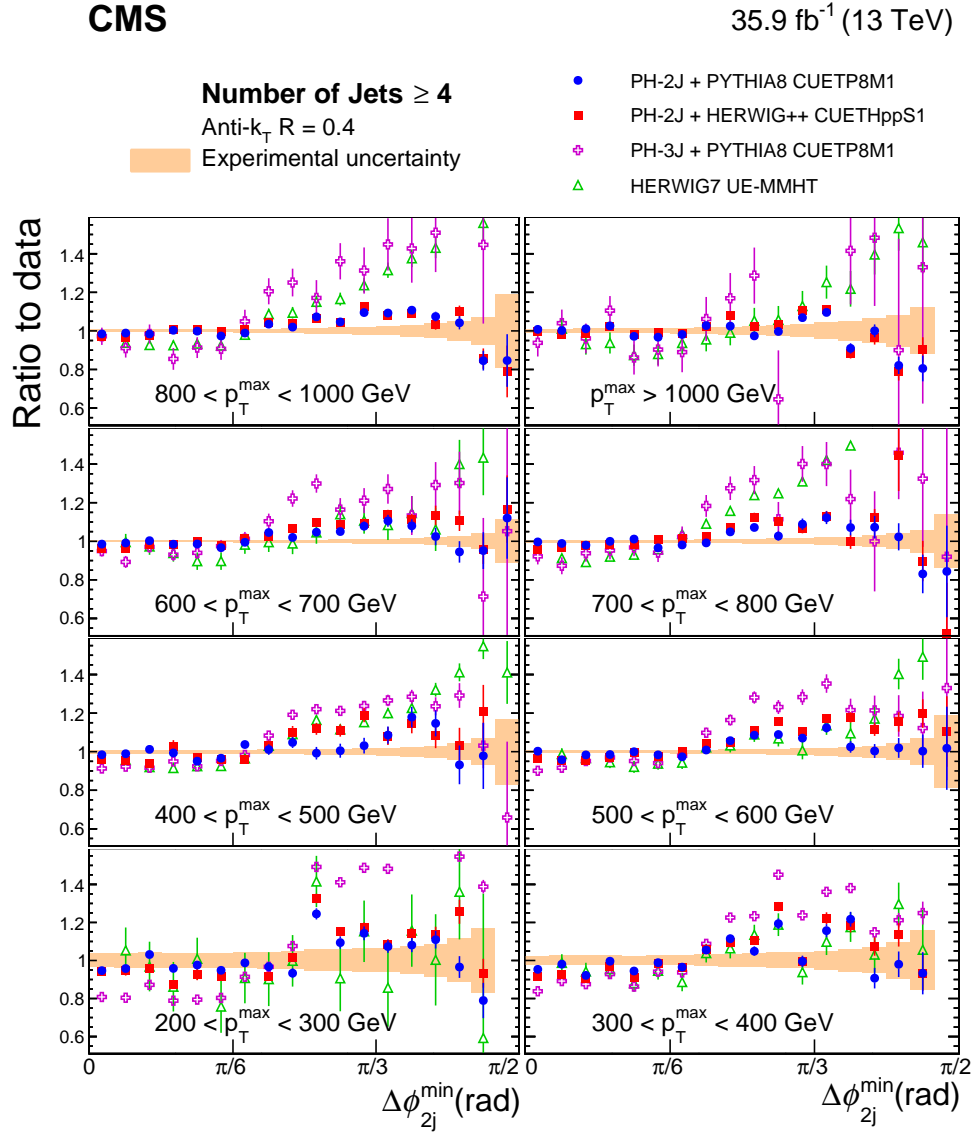


Figure 15: Ratios of PH-2J + PYTHIA 8, PH-2J + HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 predictions to the normalized inclusive 4-jet cross section differential in $\Delta\phi_{2j}^{\min}$, for all p_T^{\max} regions. The solid band indicates the total experimental uncertainty and the vertical bars on the points represent the statistical uncertainties of the simulated data.

7 Summary

Measurements of the normalized inclusive 2-, 3-, and 4-jet cross sections differential in the azimuthal angular separation $\Delta\phi_{1,2}$ and of the normalized inclusive 3- and 4-jet cross sections differential in the minimum azimuthal angular separation between any two jets $\Delta\phi_{2j}^{\min}$ are presented for several regions of the leading-jet transverse momentum p_T^{\max} . The measurements are performed using data collected during 2016 with the CMS detector at the CERN LHC corresponding to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$.

The measured distributions in $\Delta\phi_{1,2}$ and $\Delta\phi_{2j}^{\min}$ are compared with predictions from PYTHIA 8, HERWIG++, MADGRAPH + PYTHIA 8, PH-2J matched to PYTHIA 8 and HERWIG++, PH-3J + PYTHIA 8, and HERWIG 7 event generators.

The leading order (LO) PYTHIA 8 dijet event generator exhibits small deviations from the $\Delta\phi_{1,2}$ measurements but shows significant deviations at low- p_T in the $\Delta\phi_{2j}^{\min}$ distributions. The HERWIG++ event generator exhibits the largest deviations of any of the generators for the $\Delta\phi_{1,2}$ measurements, but provides a reasonable description of the $\Delta\phi_{2j}^{\min}$ distributions. The tree-level multijet event generator MADGRAPH in combination with PYTHIA 8 for showering, hadronization, and multiparton interactions provides a good overall description of the measurements, except for the $\Delta\phi_{2j}^{\min}$ distributions in the 4-jet case, where the generator deviates from the measurement mainly at high p_T^{\max} .

The dijet next-to-leading order (NLO) PH-2J event generator deviates from the $\Delta\phi_{1,2}$ measurements, but provides a good description of the $\Delta\phi_{2j}^{\min}$ observable. The predictions from the three-jet NLO PH-3J event generator exhibit large deviations from the measurements and describe the considered multijet observables in a less accurate way than the predictions from PH-2J. Parton shower contributions are responsible for the different behaviour of the PH-2J and PH-3J predictions. Finally, predictions from the dijet NLO HERWIG 7 event generator matched to parton shower contributions with the MC@NLO method provide a very good description of the $\Delta\phi_{1,2}$ measurements, showing improvement in comparison to HERWIG++.

All these observations emphasize the need to improve predictions for multijet production. Similar observations, for the inclusive 2-jet cross sections differential in $\Delta\phi_{1,2}$, were reported previously by CMS [5] at a different centre-of-mass energy of 8 TeV. The extension of $\Delta\phi_{1,2}$ correlations, and the measurement of the $\Delta\phi_{2j}^{\min}$ distributions in inclusive 3- and 4-jet topologies are novel measurements of the present analysis.

Acknowledgments

We thank Simon Plätzer and Simone Alioli for discussion and great help on setting up, respectively, the HERWIG 7 and the PH-3J simulation.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia);

RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] D0 Collaboration, "Measurement of dijet azimuthal decorrelations at central rapidities in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. Lett.* **94** (2005) 221801, doi:10.1103/PhysRevLett.94.221801, arXiv:hep-ex/0409040.
- [2] D0 Collaboration, "Measurement of the combined rapidity and p_T dependence of dijet azimuthal decorrelations in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Lett. B* **721** (2013) 212, doi:10.1016/j.physletb.2013.03.029, arXiv:1212.1842.
- [3] ATLAS Collaboration, "Measurement of dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **106** (2011) 172002, doi:10.1103/PhysRevLett.106.172002, arXiv:1102.2696.
- [4] CMS Collaboration, "Dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **106** (2011) 122003, doi:10.1103/PhysRevLett.106.122003, arXiv:1101.5029.
- [5] CMS Collaboration, "Measurement of dijet azimuthal decorrelation in pp collisions at $\sqrt{s} = 8$ TeV", *Eur. Phys. J. C* **76** (2016) 536, doi:10.1140/epjc/s10052-016-4346-8, arXiv:1602.04384.
- [6] ATLAS Collaboration, "Measurement of three-jet production cross-sections in pp collisions at 7 TeV centre-of-mass energy using the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 228, doi:10.1140/epjc/s10052-015-3363-3, arXiv:1411.1855.
- [7] ATLAS Collaboration, "Measurement of four-jet differential cross sections in $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS detector", *JHEP* **12** (2015) 105, doi:10.1007/JHEP12(2015)105, arXiv:1509.07335.
- [8] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [9] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [10] M. Bähr et al., "Herwig++ physics and manual", *Eur. Phys. J. C* **58** (2008) 639, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.
- [11] B. Andersson, "The Lund model", *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **7** (1997) 1, doi:10.1016/0375-9474(87)90510-0.
- [12] B. R. Webber, "A QCD model for jet fragmentation including soft gluon interference", *Nucl. Phys. B* **238** (1984) 492, doi:10.1016/0550-3213(84)90333-X.
- [13] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [14] NNPDF Collaboration, "Parton distributions with QED corrections", *Nucl. Phys. B* **877** (2013) 290, doi:10.1016/j.nuclphysb.2013.10.010, arXiv:1308.0598.
- [15] NNPDF Collaboration, "Unbiased global determination of parton distributions and their uncertainties at NNLO and at LO", *Nucl. Phys. B* **855** (2012) 153, doi:10.1016/j.nuclphysb.2011.09.024, arXiv:1107.2652.

-
- [16] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.
- [17] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [18] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [19] S. Mrenna and P. Richardson, “Matching matrix elements and parton showers with HERWIG and PYTHIA”, *JHEP* **05** (2004) 040, doi:10.1088/1126-6708/2004/05/040, arXiv:hep-ph/0312274.
- [20] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [21] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [22] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [23] J. Bellm et al., “Herwig 7.0/Herwig++ 3.0 release note”, *Eur. Phys. J. C* **76** (2016) 196, doi:10.1140/epjc/s10052-016-4018-8, arXiv:1512.01178.
- [24] S. Frixione and B. R. Webber, “Matching NLO QCD computations and parton shower simulations”, *JHEP* **06** (2002) 029, doi:10.1088/1126-6708/2002/06/029, arXiv:hep-ph/0204244.
- [25] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [26] S. Alioli et al., “Jet pair production in POWHEG”, *JHEP* **11** (2011) 081, doi:10.1007/JHEP04(2011)081, arXiv:1012.3380.
- [27] A. Kardos, P. Nason, and C. Oleari, “Three-jet production in POWHEG”, *JHEP* **04** (2014) 043, doi:10.1007/JHEP04(2014)043, arXiv:1402.4001.
- [28] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [29] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, “Parton distributions in the LHC era: MMHT 2014 PDFs”, *Eur. Phys. J. C* **75** (2015) 204, doi:10.1140/epjc/s10052-015-3397-6, arXiv:1412.3989.
- [30] CMS Collaboration, “The CMS high level trigger”, *Eur. Phys. J. C* **46** (2006) 605, doi:10.1140/epjc/s2006-02495-8, arXiv:hep-ex/0512077.

- [31] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [32] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [33] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [34] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [35] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) 02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [36] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [37] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [38] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.
- [39] T. Auye, “Unfolding algorithms and tests using RooUnfold”, in *PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding*, H. Prosper and L. Lyons, eds., p. 313. Geneva, Switzerland, 2011. arXiv:1105.1160. doi:10.5170/CERN-2011-006.313.
- [40] M. H. Seymour and A. Siodmok, “Constraining MPI models using σ_{eff} and recent Tevatron and LHC underlying event data”, *JHEP* **10** (2013) 113, doi:10.1007/JHEP10(2013)113, arXiv:1307.5015.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haeuvermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov³, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, M. Komm, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁶, X. Gao⁶, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, S. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

A.A. Abdelalim^{9,10}, Y. Mohammed¹¹, E. Salama^{12,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

A. Abdulsalam, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, FranceJ.-L. Agram¹⁴, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁴, X. Coubez, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁵, V. Sordini, M. Vander Donckt, S. Viret**Georgian Technical University, Tbilisi, Georgia**A. Khvedelidze⁸**Tbilisi State University, Tbilisi, Georgia**

D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, GermanyC. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, V. Zhukov¹⁵**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyG. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁶**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁷, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn,

E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinemann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁶, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, F. Kassel¹⁶, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

National Technical University of Athens, Athens, Greece

K. Kousouris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres²⁰

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, Á. Hunyadi, F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók²⁰, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²³, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo²³, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁶, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁸, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,16}, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,30}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,16}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

V. Calvelli^{a,b}, F. Ferro^a, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,16}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,31}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,16}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen^a

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^{a,16}, G. Bagliesi^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedì^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,30}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a

M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea

A. Lee

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³³, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, PolandK. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

Joint Institute for Nuclear Research, Dubna, RussiaI. Golutvin, V. Karjavin, I. Kashunin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev^{37,38}, V.V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, V. Trofimov, N. Voytishin, B.S. Yuldashev³⁹, A. Zarubin, V. Zhiltsov**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**Y. Ivanov, V. Kim⁴⁰, E. Kuznetsova⁴¹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, RussiaT. Aushev, A. Bylinkin³⁸**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**M. Chadeeva⁴², O. Markin, P. Parygin, D. Philippov, S. Polikarpov, V. Rusinov**P.N. Lebedev Physical Institute, Moscow, Russia**V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan³⁸, A. Terkulov**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴³, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴⁴, D. Shtol⁴⁴, Y. Skovpen⁴⁴

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁴⁵, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁹, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁶, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabaday, A. Racz, T. Reis, G. Rolandi⁴⁷, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁸, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁹, M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁵⁰, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà,

C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijsma, W. Lustermaun, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D.A. Sanz Becerra, M. Schönerberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵¹, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁵², S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵³, E.E. Kangal⁵⁴, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁵, K. Ozdemir⁵⁶, D. Sunar Cerci⁵², B. Tali⁵², U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, G. Karapinar⁵⁷, K. Ocalan⁵⁸, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, S. Tekten, E.A. Yetkin⁶¹

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, I. Köseoglu

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶², S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶³, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria,

A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁴, T. Virdee¹⁶, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, M. Turner, S. Zahid

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, D. Cutts, A. Garabedian, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁵, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, F. Golf, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA

B. Bilki⁶⁶, W. Clarida, K. Dilsiz⁶⁷, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁸, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁹, Y. Onel, F. Ozok⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA

R. Ciesielski, K. Goulianos, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷¹, A. Castaneda Hernandez⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷², R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderø, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Universidade Federal de Pelotas, Pelotas, Brazil

6: Also at Université Libre de Bruxelles, Bruxelles, Belgium

7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Helwan University, Cairo, Egypt

10: Now at Zewail City of Science and Technology, Zewail, Egypt

11: Now at Fayoum University, El-Fayoum, Egypt

12: Also at British University in Egypt, Cairo, Egypt

13: Now at Ain Shams University, Cairo, Egypt

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

18: Also at University of Hamburg, Hamburg, Germany

19: Also at Brandenburg University of Technology, Cottbus, Germany

20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

24: Also at Institute of Physics, Bhubaneswar, India

25: Also at University of Visva-Bharati, Santiniketan, India

26: Also at University of Ruhuna, Matara, Sri Lanka

27: Also at Isfahan University of Technology, Isfahan, Iran

28: Also at Yazd University, Yazd, Iran

29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

30: Also at Università degli Studi di Siena, Siena, Italy

31: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy

32: Also at Purdue University, West Lafayette, USA

33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico

36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

37: Also at Institute for Nuclear Research, Moscow, Russia

- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 41: Also at University of Florida, Gainesville, USA
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at California Institute of Technology, Pasadena, USA
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 47: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Riga Technical University, Riga, Latvia
- 50: Also at Universität Zürich, Zurich, Switzerland
- 51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 52: Also at Adiyaman University, Adiyaman, Turkey
- 53: Also at Istanbul Aydin University, Istanbul, Turkey
- 54: Also at Mersin University, Mersin, Turkey
- 55: Also at Cag University, Mersin, Turkey
- 56: Also at Piri Reis University, Istanbul, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Necmettin Erbakan University, Konya, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 65: Also at Utah Valley University, Orem, USA
- 66: Also at Beykent University, Istanbul, Turkey
- 67: Also at Bingol University, Bingol, Turkey
- 68: Also at Erzincan University, Erzincan, Turkey
- 69: Also at Sinop University, Sinop, Turkey
- 70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 71: Also at Texas A&M University at Qatar, Doha, Qatar
- 72: Also at Kyungpook National University, Daegu, Korea