

Measurements of jet multiplicity and differential production cross sections of $Z + \text{jets}$ events in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$

V. Khachatryan *et al.**

(CMS Collaboration)

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Measurements of differential cross sections are presented for the production of a Z boson and at least one hadronic jet in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$, recorded by the CMS detector, using a data sample corresponding to an integrated luminosity of 4.9 fb^{-1} . The jet multiplicity distribution is measured for up to six jets. The differential cross sections are measured as a function of jet transverse momentum and pseudorapidity for the four highest transverse momentum jets. The distribution of the scalar sum of jet transverse momenta is also measured as a function of the jet multiplicity. The measurements are compared with theoretical predictions at leading and next-to-leading order in perturbative QCD.

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I. INTRODUCTION

Measurements of the production cross section of a Z boson with one or more jets in hadron collisions, hereafter $Z + \text{jets}$, can be compared with predictions of perturbative quantum chromodynamics (pQCD). Analyses of data collected during the first run of the CERN LHC have used two main theoretical approaches, developed in the last decade, for the complete description of the associated production of vector bosons and jets up to stable particles in the final state. Multileg matrix elements, computed at leading order (LO) in pQCD, have been combined with parton showers (PS), merging different final jet multiplicities together. Alternatively, next-to-leading order (NLO) matrix elements have been interfaced with parton showers for final states of fixed jet multiplicity. CMS has relied on MADGRAPH [1] and POWHEG-BOX [2–4] as main implementations of the former and latter approaches, respectively. In the last few years, novel techniques have been developed in order to merge NLO calculations for several final-state multiplicities in a theoretically consistent way, and interface them with PS, as formerly done for LO matrix elements. This approach may provide a NLO accuracy for a range of complex topologies, overcoming the limitations of fixed order NLO calculations, which cannot in general describe completely inclusive distributions receiving contributions by final states of different jet multiplicity. Furthermore, a description of these final states up to stable particles is possible, since hadronization models can be used in combination with these calculations. The $Z + \text{jets}$ final state provides jet kinematic distributions that are

ideal for testing these different options for theoretical predictions.

Also, this process contributes a large background to many standard model processes, like top production or diboson final states, e.g., the associated production of a Higgs boson and a Z , where the former decays in $b\bar{b}$ pairs and the second in charged leptons [5,6]. Searches for phenomena beyond the standard model may also be sensitive to this process, which plays a particularly important role as the main background in the study of supersymmetric scenarios with large missing transverse momentum. This has been one of the main motivations for a previous analysis of the angular distributions in $Z + \text{jets}$ events presented by CMS [7], and the study presented in this paper is complementing it with the measurement of jet spectra.

Measurements of $Z + \text{jets}$ production were published by the CDF and D0 collaborations based on a sample of proton-antiproton collisions at $\sqrt{s} = 1.96 \text{ TeV}$ [8,9], and by the ATLAS [10] and CMS [11] collaborations from a sample of proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ collected at the LHC, corresponding to an integrated luminosity of 0.036 fb^{-1} . ATLAS has reported an updated measurement at the same center-of-mass energy with a data set corresponding to an integrated luminosity of 4.6 fb^{-1} [12].

In this paper, we update and expand upon the results obtained by the CMS Collaboration at $\sqrt{s} = 7 \text{ TeV}$ with a data sample corresponding to an integrated luminosity of $4.9 \pm 0.1 \text{ fb}^{-1}$ [13] collected in 2011. We present fiducial cross sections for $Z + \text{jets}$ production as a function of the exclusive and inclusive jet multiplicity, where the Z bosons are identified through their decays into electron or muon pairs. The contribution from Z/γ^* interference is considered to be part of the measured signal. We measure the differential cross sections as a function of the transverse momentum p_T and pseudorapidity η of the four highest- p_T jets in the event. The pseudorapidity is defined as $\eta = -\ln \tan[\theta/2]$, where θ is the polar angle with respect

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to the counterclockwise-rotating proton beam. We also present results for the distribution of H_T , the scalar sum of jet transverse momenta, measured as a function of the inclusive jet multiplicity. The jet p_T and η differential cross sections are sensitive to higher order QCD corrections. H_T is an observable characterizing globally the QCD emission structure of the event, and it is often used as a discriminant variable in searches for supersymmetric scenarios, to which $Z + \text{jets}$ contribute as a background. The measurement of its distribution is therefore of great interest.

The paper is organized as follows. Section II presents a description of the CMS apparatus and its main characteristics. Section III provides details about the simulation used in this analysis. Section IV discusses the event reconstruction and selection. Section V is devoted to the estimation of the signal event selection efficiency and to the subtraction of the background contributions. The procedure used to correct the measurement for detector response and resolution is presented in Sec. VI. Section VII describes the estimation of the systematic uncertainties, and in Sec. VIII the results are presented and theoretical predictions are compared to them.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6m internal diameter that provides a magnetic field of 3.8T. The field volume contains a silicon tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter; each subdetector in the barrel section is enclosed by two end caps. The magnet flux-return yoke is instrumented with gas-ionization tracking devices for muon detection. In addition to the barrel and end cap detectors, CMS has an extensive forward calorimetry system. CMS uses a two-level trigger system. The first level is composed of custom hardware processors, and uses local information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs . The high-level trigger is a processor farm that further decreases the event rate from a maximum of 100 kHz to roughly 300 Hz, before data storage. A detailed description of the CMS detector can be found in Ref. [14].

Here we briefly outline the detector elements and performance characteristics that are most relevant to this measurement. The inner tracker, which consists of silicon pixel and silicon strip detectors, reconstructs charged-particle trajectories within the range $|\eta| < 2.5$. The tracking system provides an impact parameter resolution of 15 μm and a p_T resolution of 1.5% for 100 GeV particles. Energy deposits in the ECAL are matched to tracks in the silicon detector and used to initiate the reconstruction algorithm for electrons. The tracking algorithm takes into account the energy lost by electrons in the detector material through bremsstrahlung. In the energy range relevant for Z -boson decays, the electron energy resolution is below 3%. Muon

trajectories are reconstructed for $|\eta| < 2.4$ using detector planes based on three technologies: drift tubes, cathode-strip chambers, and resistive-plate chambers. Matching outer muon trajectories to tracks measured in the silicon tracker provides an average p_T resolution of 1.6% for the p_T range used in this analysis. For the jets reconstructed in this analysis, the p_T resolution is better than 10% and the energy scale uncertainty is less than 3% [15].

III. PHYSICS PROCESSES AND DETECTOR SIMULATION

Simulated events are used to correct the signal event yield for detector effects and to subtract the contribution from background events. Simulated Drell–Yan Z/γ^* , $t\bar{t}$, and $W + \text{jets}$ events are generated using the MADGRAPH 5.1.1 [1] event generator. The package provides a tree level matrix-element calculation with up to four additional partons in the final state for vector boson production, and three additional partons for $t\bar{t}$ events. The leading-order CTEQ6L1 parton distribution functions (PDF) [16] are used with MADGRAPH. The residual QCD radiation, described by a parton shower algorithm, and the hadronization, which turns the partons into a set of stable particles, are implemented with PYTHIA 6.424 [17] using the Z2 underlying event and fragmentation tune [18]. The default α_s value of the PDF set used is adopted for the event generator. The matrix-element and parton shower calculations are matched using the k_T -MLM algorithm [19]. Decays of the τ lepton are described by the TAUOLA 1.27 [20] package. Diboson events (WW , WZ , ZZ) are modeled entirely with PYTHIA. Single-top events in the Wt channel are simulated using POWHEG-BOX [2–4,21], and followed by PYTHIA to describe QCD radiation beyond NLO and hadronization. An alternative description of the Drell–Yan signal is used for the evaluation of systematic uncertainties that is based on the SHERPA 1.4 [22–25] tree level matrix-element calculation, which has up to four additional partons in the final state, and uses the NLO CTEQ6.6M [26] PDF set.

The total cross sections for the Z signal and the W background are normalized to the next-to-next-to-leading-order (NNLO) predictions that are obtained with FEWZ [27] and the MSTW2008 [28] PDF set. The $t\bar{t}$ cross section is normalized to the NNLO prediction from Ref. [29]. Diboson cross sections are rescaled to the NLO predictions obtained with MCFM [30].

The interaction of the generated particles in the CMS detector is simulated using the GEANT4 toolkit [31,32]. During data collection, an average of nine additional interactions occurred in each bunch crossing (pileup). Pileup events are generated with PYTHIA and added to the generated hard-scattering events. The evolution of beam conditions during data taking is taken into account by reweighting the Monte Carlo (MC) simulation to match the

distribution of the number of pileup interactions observed in data.

IV. EVENT RECONSTRUCTION AND SELECTION

The production of a Z boson is identified through its decay into a pair of isolated leptons (electrons or muons). Trigger selection requires pairs of leptons with p_T exceeding predefined thresholds; these thresholds were changed during the data acquisition period because of the increasing instantaneous luminosity. For both lepton types threshold pairs of 17 and 8 GeV are used for most of the data sample. The electron triggers include isolation requirements in order to reduce the misidentification rate. Triggered events are reconstructed using the particle-flow algorithm [33,34], which combines the information from all CMS subdetectors to reconstruct and classify muons, electrons, photons, charged hadrons, and neutral hadrons.

Electrons are selected with $p_T > 20$ GeV in the fiducial region of pseudorapidity $|\eta| < 2.4$, but excluding the region $1.44 < |\eta| < 1.57$ between the barrel and the end caps of ECAL to ensure uniform quality of reconstruction. The electron identification criteria [35,36] comprise requirements on the distance in $\eta - \phi$ space between the cluster barycenter and the electron track extrapolation, where ϕ is the azimuthal angle measured in the plane transverse to the beams, and the size and the shape of the electromagnetic shower in the calorimeter. Electron-positron pairs consistent with photon conversion are rejected. Electron isolation is evaluated using all particles reconstructed with the particle-flow algorithm within a cone around the electron direction of radius $\Delta R = 0.3$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the distance in the $\eta - \phi$ plane. An isolation variable is defined as $I_{\text{rel}} = (I_{\text{charged}} + I_{\text{photon}} + I_{\text{neutral}}) / p_T^e$, where I_{charged} , I_{photon} , I_{neutral} are respectively the p_T sums of all charged hadrons, photons, and neutral hadrons in the cone of interest, and p_T^e is the electron transverse momentum. The selection requires $I_{\text{rel}} < 0.15$. Isolation variables are sensitive to contamination from pileup events and thus a correction for this effect is necessary for the high pileup environment of the LHC collisions. Only the particles consistent with originating from the reconstructed primary vertex of the event, the vertex with the largest quadratic sum of its constituent tracks' p_T , are included in the calculation of I_{charged} . The I_{photon} and I_{neutral} components are corrected using the jet area subtraction approach [37].

The selected muons must have $p_T > 20$ GeV and $|\eta| < 2.4$. Muon identification criteria are based on the quality of the global track reconstruction, which includes both tracker and muon detectors. Muons from cosmic rays are removed with requirements on the impact parameter with respect to the primary vertex. In order to evaluate the isolation, the variables I_{charged} , I_{photon} , and I_{neutral} are computed within a cone of radius $\Delta R = 0.4$ around the trajectory of the muon candidate, and I_{rel} is required to be

less than 0.2. Charged hadrons from pileup interactions are rejected by requiring their tracks to be associated with the primary vertex. The transverse momentum sum of the charged hadrons that are not associated with the primary vertex is used to estimate the contribution from the neutral particles produced in the pileup interactions; half of this sum is subtracted from the isolation variable.

The two highest- p_T , same-flavor, oppositely charged, and isolated leptons are selected to form the Z-boson candidate if their invariant mass lies between 71 and 111 GeV. The lepton pair is required to be associated with the primary vertex of the event. Leptons associated with the primary vertex and passing the isolation criteria are removed from the collection of particles used for jet clustering.

For jet reconstruction, charged-particle tracks not associated with the primary vertex are removed from the collection of particles used for clustering. In this way, the dominant part of the pileup contamination of the events of interest is suppressed. The remaining particles are used as input to the jet clustering, which is based on the anti- k_T algorithm [38] as implemented in the FASTJET package [39,40], with a distance parameter in the rapidity-azimuth plane of 0.5. In order to reject misreconstructed jets and instrumental noise, identification quality criteria are imposed on the jets based on the energy fraction of the charged, electromagnetic, and neutral hadronic components, and requiring at least one charged particle in the jet.

Several effects contribute to bias the measured jet energy, compared with the value it would acquire by clustering stable particles originating from the fragmented hard-scattered partons and from the underlying event. The sources of energy bias are pileup interactions, detector noise, and detector response nonuniformities in η and nonlinearities in p_T . The jet energy scale (JES) calibration [15] relies on a combination of PYTHIA multijet simulations and measurements of exclusive dijet and photon+jet events from data. The corrections are parametrized in terms of the uncorrected p_T and η of the jet, and applied as multiplicative factors scaling the four-momentum vector of each jet. These factors include the correction for the contribution from neutral pileup particles using the jet area approach [37], and corrections for residual discrepancies between data and simulation. The correction factors range between 1.0 and 1.2, depend mostly on p_T , and are approximately independent of η .

Furthermore, the jet energy resolution (JER) in data is known to be worse than in the simulation; therefore the simulated resolution is degraded to compensate for this effect. The difference between the reconstructed jet transverse momentum and the corresponding generated one is scaled in the simulation so as to reproduce the observed resolution.

A minimum threshold of $p_T > 30$ GeV is required for the jets to reduce contamination from the underlying event. Only jets with $|\eta| < 2.4$ are considered, and jets are

required to be separated from each lepton of the Z candidate by $\Delta R \geq 0.5$ in the $\eta - \phi$ plane.

V. SIGNAL EFFICIENCY AND BACKGROUND

A “tag-and-probe” technique [41] is used to estimate efficiencies for trigger selection, event reconstruction, and the offline selection of the $Z + \text{jets}$ sample. Scaling factors derived from the ratio between the data and simulation efficiencies are used to reweight simulated events in order to compensate for the residual data-simulation differences. The correction is determined as a function of p_T and η of the leptons, and background components are resolved using a binned extended maximum-likelihood fit of the dilepton invariant-mass distribution between 60 and 120 GeV. The signal component of the distribution, which is taken from the Drell-Yan simulated sample, is convolved with a Gaussian function to account for the resolution difference between data and simulation. The background contribution is modeled by an exponential function multiplied by an error function describing the kinematic threshold due to binning of the probe lepton p_T . The combined single-flavor identification efficiency is the product of contributions from the trigger, event reconstruction, and offline selection. The same technique is used on the data and in the simulation. The trigger efficiency of the data ranges between 94 and 99% for electrons and between 82 and 97% for muons. The combined identification and isolation efficiency depends on the p_T and η of the leptons; it ranges between 68 and 91% for electrons and between 86 to 99% for muons.

The fiducial acceptance for muons and electrons is different, since the latter are not well reconstructed in the transition region between the barrel and end cap electromagnetic calorimeters. In order to facilitate the combination of results from the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ final states, this difference is evaluated using the simulation, giving a correction to the e^+e^- cross section, applied within the unfolding procedure described in the next section, that amounts to 8%.

Several background processes can produce or mimic two reconstructed opposite-sign same-flavor leptons. The largest contribution comes from $t\bar{t}$ production, while diboson production contributes near the Z -boson invariant-mass peak. Other minor contributions arise from $Z \rightarrow \tau^+\tau^-$ as well as single-top and $W + \text{jets}$ events. The contamination from multijet events produced through the strong interaction is negligible, as established with a control sample in which the two leptons in each event have the same charge [7]. The total contribution of the backgrounds is approximately 1% of the total yield of the selected events, and it increases as a function of jet multiplicity. At the highest measured jet multiplicities it reaches values up to 10%. The background subtraction procedure is performed after scaling the number of background events to the integrated

luminosity in the data sample using the corresponding cross section for each background process.

The exclusive jet multiplicity in the selected events is shown in Fig. 1. For both leptonic decay channels, the data show overall agreement with combined signal and background samples from the simulation. The ratio between the cross sections as a function of jet multiplicity in data and in

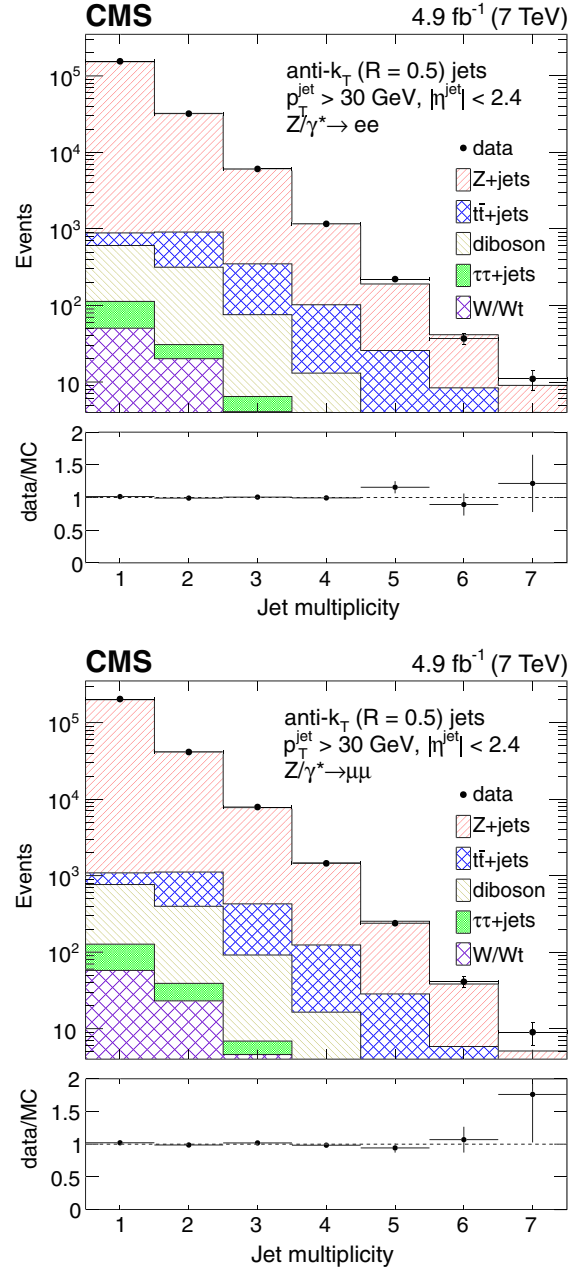


FIG. 1 (color online). Distributions of the exclusive jet multiplicity for the electron channel (upper plot) and muon channel (lower plot). Data are compared to the simulation, which is the sum of signal and background events. Scale factors have been used to correct simulation distributions for residual efficiency differences with respect to data. No unfolding procedure is applied. Only statistical uncertainties are shown.

TABLE I. Sources of uncertainties (in percent) in the differential exclusive cross section and in the differential cross sections as a function of the jet p_T , for each of the four highest p_T jets exclusively. The constant luminosity uncertainty is not included in the total.

Systematic uncertainty (%)	$\sigma(Z/\gamma^* + \text{jets})$	$\frac{d\sigma}{dp_T}$ (1st jet)	$\frac{d\sigma}{dp_T}$ (2nd jet)	$\frac{d\sigma}{dp_T}$ (3rd jet)	$\frac{d\sigma}{dp_T}$ (4th jet)
JES + JER	2.0–18	4.9–8.7	6.3–16	8.8–15	15–23
Unfolding	1.7–9.2	1.3–22	0.5–21	0.8–13	0.3–12
Efficiency	0.3	0.3	0.3	0.3	0.3
Background	0.1–25	0.1–0.4	0.6–1.8	0.6–1.0	0.9–1.5
Pileup	0.3–0.8	0.2–2.7	0.3–0.6	0.2–0.7	0.4–1.0
Total systematic uncertainty (%)	2.7–32	5.1–24	9.0–27	10–20	17–23
Statistical uncertainty (%)	0.7–6.4	0.1–7.2	1.4–12	3.0–13	4.3–19

signal plus background simulation, shown in the bottom part of the figure, is compatible with unity within the uncertainties.

VI. UNFOLDING

The distributions of the observables are corrected for event selection efficiencies and for detector resolution effects back to the stable particle level, in order to compare with predictions from event generators simulating $Z + \text{jets}$ final states. Particles are considered stable if their proper average lifetime τ satisfies $c\tau > 10$ cm. The correction procedure is based on unfolding techniques, as implemented in the ROOUNFOLD toolkit [42], which provides both the “singular value decomposition” (SVD) method [43] and the iterative algorithm based on Bayes’ theorem [44]. Both algorithms use a “response matrix” that correlates the values of the observable with and without detector effects.

The response matrix is evaluated using $Z + \text{jets}$ events, generated by MADGRAPH followed by PYTHIA, with full detector simulation. For generator-level events, leptons and jets are reconstructed from the collection of all stable final-state particles using criteria that mimic the reconstructed data. Electrons and muons with the highest p_T above 20 GeV in the pseudorapidity range $|\eta| < 2.4$ are selected as Z -boson decay products. In order to include the effects of final-state electromagnetic radiation in the generator-level distributions, the electron and muon candidates are reconstructed by clustering the leptons with all photons in a cone of radius $\Delta R = 0.1$ in the $\eta - \phi$ plane. Leptons from Z -boson decay are removed from the particle collection used for the jet clustering at generator level. The remaining particles, excluding neutrinos, are clustered into jets using the anti- k_T algorithm. A generated jet is included in the analysis if it satisfies $p_T > 30$ GeV, $|\eta| < 2.4$; the jet must contain at least one charged particle, to match the jet reconstruction quality requirements used for data analysis, and the distance of the jet from the leptons forming the Z -boson candidate is larger than $\Delta R = 0.5$.

The unfolded distributions are obtained with the SVD algorithm. As a cross check, the unfolding of the

distributions is also performed with the D’Agostini method, which leads to compatible results within statistical uncertainties. The unfolding has a small effect on the jet η distributions, with migrations among the bins of a few percent for central jets and up to 10% in the outer regions. Larger unfolding effects are observed in the other distributions: up to 20% for the jet multiplicity, between 10 and 20% for the jet p_T , and between 10 and 30% for the H_T distribution.

VII. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainties that affect the $Z + \text{jets}$ cross section measurement are divided into the following categories: JES and JER [15], unfolding procedure, efficiency correction and background subtraction, pileup reweighting procedure, and integrated luminosity measurement.

Jet energy scale and resolution uncertainties affect the jet p_T reconstruction and the determination of H_T . Each JES correction factor has an associated uncertainty that is a function of the η and p_T of the jet. The difference in the distribution of an observable, after varying the JES both up and down by one standard deviation, is used as an estimate

TABLE II. Sources of uncertainties (in percent) in the differential cross sections as a function of η , for each of the four highest p_T jets exclusively. The constant luminosity uncertainty is not included in the total.

Systematic uncertainty (%)	$\frac{d\sigma}{d\eta}$ (1st jet)	$\frac{d\sigma}{d\eta}$ (2nd jet)	$\frac{d\sigma}{d\eta}$ (3rd jet)	$\frac{d\sigma}{d\eta}$ (4th jet)
JES + JER	3.5–8.2	7.2–8.9	9.4–12	13–15
Unfolding	6.5–13	8.4–11	5.0–12	6.4–13
Efficiency	0.3	0.3	0.3	0.3
Background	0.2	0.3–0.5	0.6–1.1	0.9–1.0
Pileup	0.2–0.4	0.3–0.5	0.3–0.7	0.5–1.2
Total systematic uncertainty (%)	7.8–17	11–15	11–19	15–23
Statistical uncertainty (%)	0.6–1.0	0.9–1.4	2.4–3.6	7.6–12

TABLE III. Sources of uncertainties (in percent) in the differential cross sections as a function of H_T and inclusive jet multiplicity. The constant luminosity uncertainty is not included in the total.

Systematic uncertainty (%)	$\frac{d\sigma}{dH_T},$	$\frac{d\sigma}{dH_T},$	$\frac{d\sigma}{dH_T},$	$\frac{d\sigma}{dH_T},$
	$N_{\text{jet}} \geq 1$	$N_{\text{jet}} \geq 2$	$N_{\text{jet}} \geq 3$	$N_{\text{jet}} \geq 4$
JES + JER	4.5–9.1	7.0–11	8.6–13	11–17
Unfolding	0.4–17	2.1–18	3.1–22	4.9–23
Efficiency	0.2–0.3	0.3	0.3–0.4	0.3
Background	0.1–0.7	0.3–0.7	0.5–0.8	0.6–1.1
Pileup	0.1–2.3	0.1–2.2	0.3–1.0	0.5–1.0
Total systematic uncertainty (%)	4.6–19	7.8–21	10–26	12–25
Statistical uncertainty (%)	0.6–4.1	0.9–3.3	2.3–5.6	8.6–17

of the JES systematic uncertainty. Similarly, the effect of the systematic uncertainties in the scaling factor used in the JER degradation is estimated by varying its value up and down by one standard deviation.

The uncertainty in the unfolding procedure is due to both the statistical uncertainty in the response matrix from the finite size of the simulated sample and to any dependence on the signal model provided by different event generators.

The statistical uncertainty is computed using a MC simulation, which produces variants of the matrix according to random Poisson fluctuations of the bin contents. The entire unfolding procedure is repeated for each variant, and the standard deviation of the obtained results is used as an estimate of this uncertainty. The systematic uncertainty due to the generator model is estimated from the difference between events simulated with MADGRAPH and SHERPA at detector response level. The overall unfolding uncertainty is taken to be either the statistical uncertainty alone, in the case where the results from the two event generators agree within one standard deviation, or the sum in quadrature of the simulation statistical uncertainty and the difference between the two MC generators.

Additional uncertainty arises from the efficiency corrections and from the background subtraction. The contribution due to efficiency corrections is estimated by adding and subtracting the statistical uncertainties from the tag-and-probe fits. The systematic uncertainty from the background subtraction procedure is small relative to the other sources. For $t\bar{t}$ and diboson processes, the uncertainty in the normalization arises from both the theoretical uncertainty in the inclusive cross section and the difference between the theoretical prediction of the cross section (as in Sec. III) and the corresponding CMS measurement [45–48]. The largest

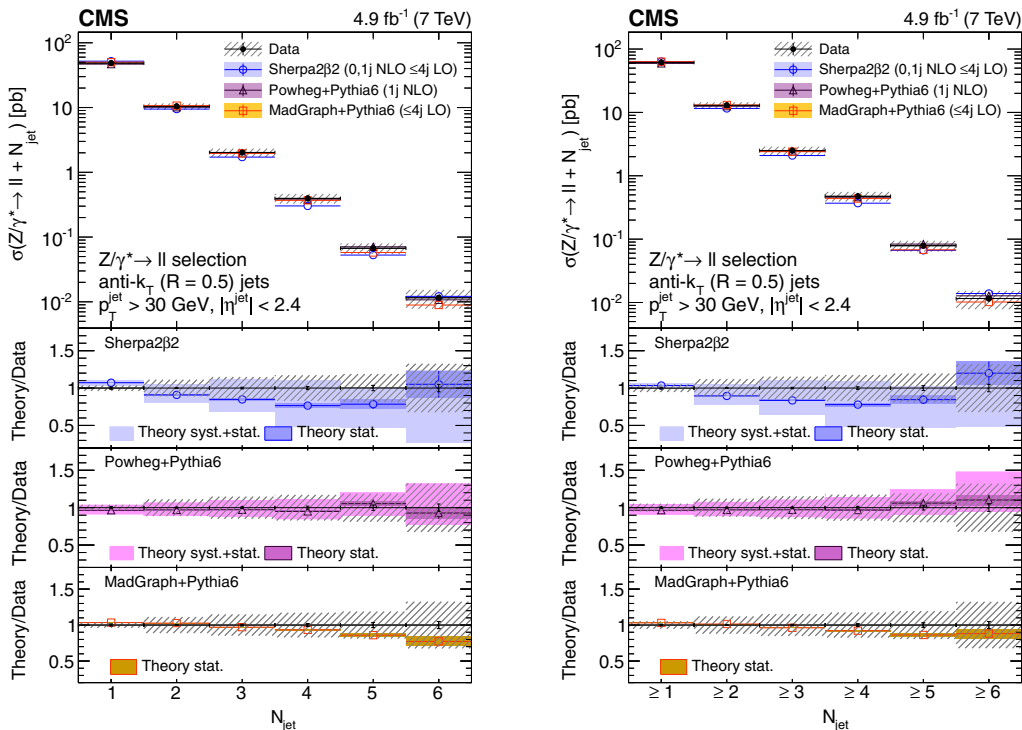


FIG. 2 (color online). Exclusive (left) and inclusive (right) jet multiplicity distributions, after the unfolding procedure, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and, for NLO calculations, to its combination with the systematic uncertainty related to scale variations.

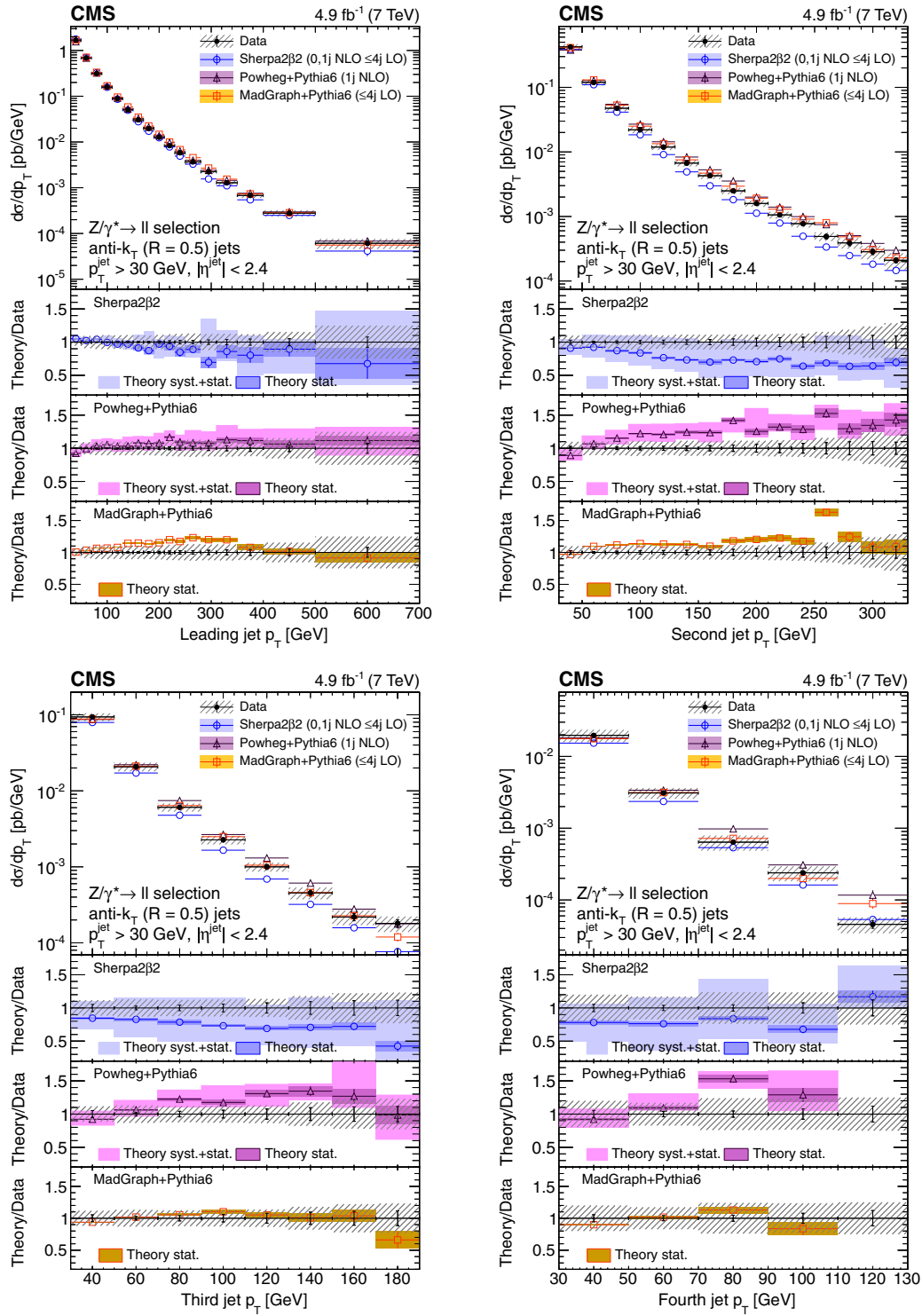


FIG. 3 (color online). Unfolded differential cross section as a function of p_T for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and, for NLO calculations, to its combination with systematic uncertainty related to scale variations.

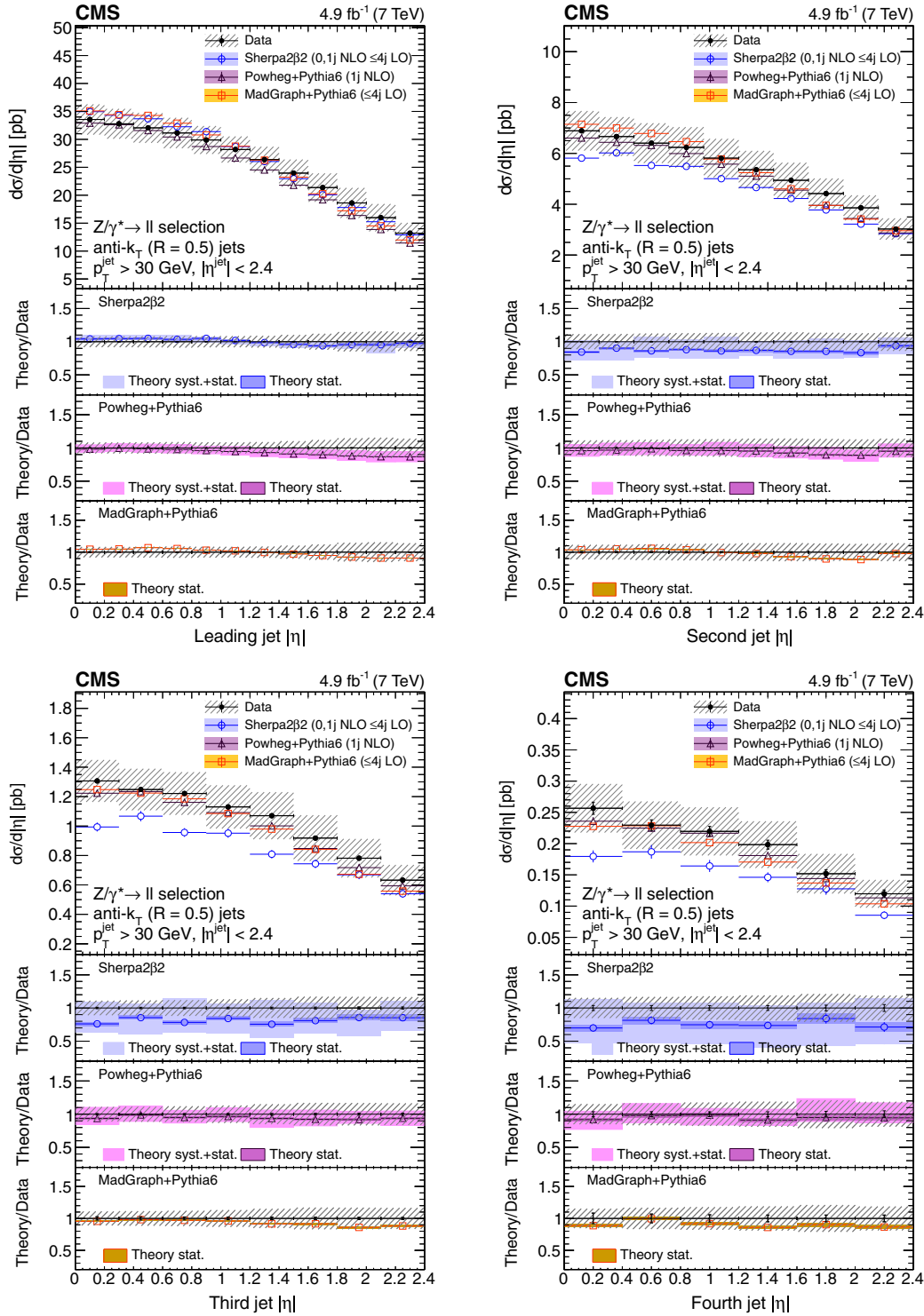


FIG. 4 (color online). Unfolded differential cross section as a function of the jet absolute pseudorapidity $|\eta|$ for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and, for NLO calculations, to its combination with systematic uncertainty related to scale variations.

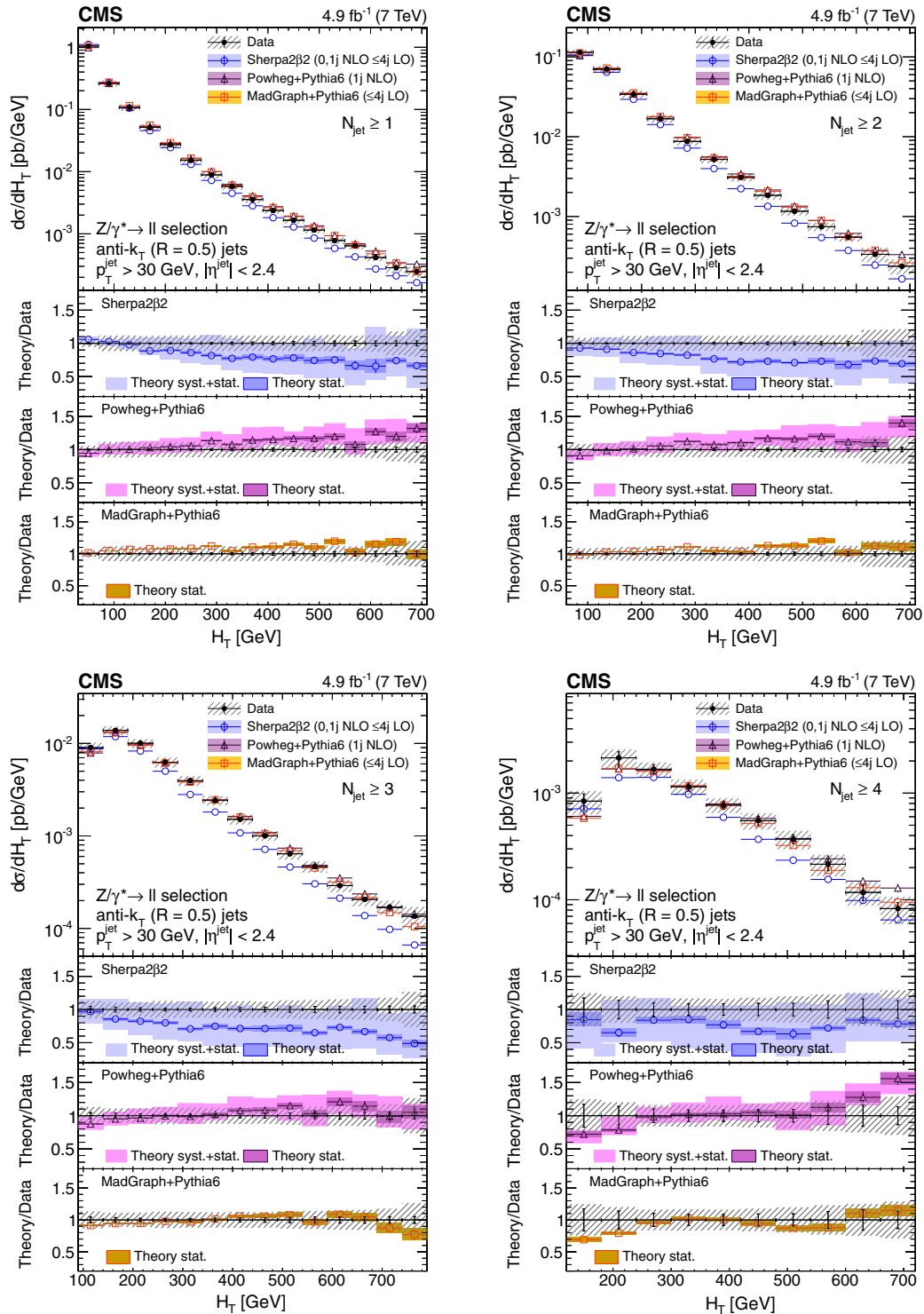


FIG. 5 (color online). Unfolded differential cross section as a function of H_T for events with at least one (top left), two (top right), three (bottom left), and four (bottom right) jets compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and, for NLO calculations, to its combination with systematic uncertainty related to scale variations.

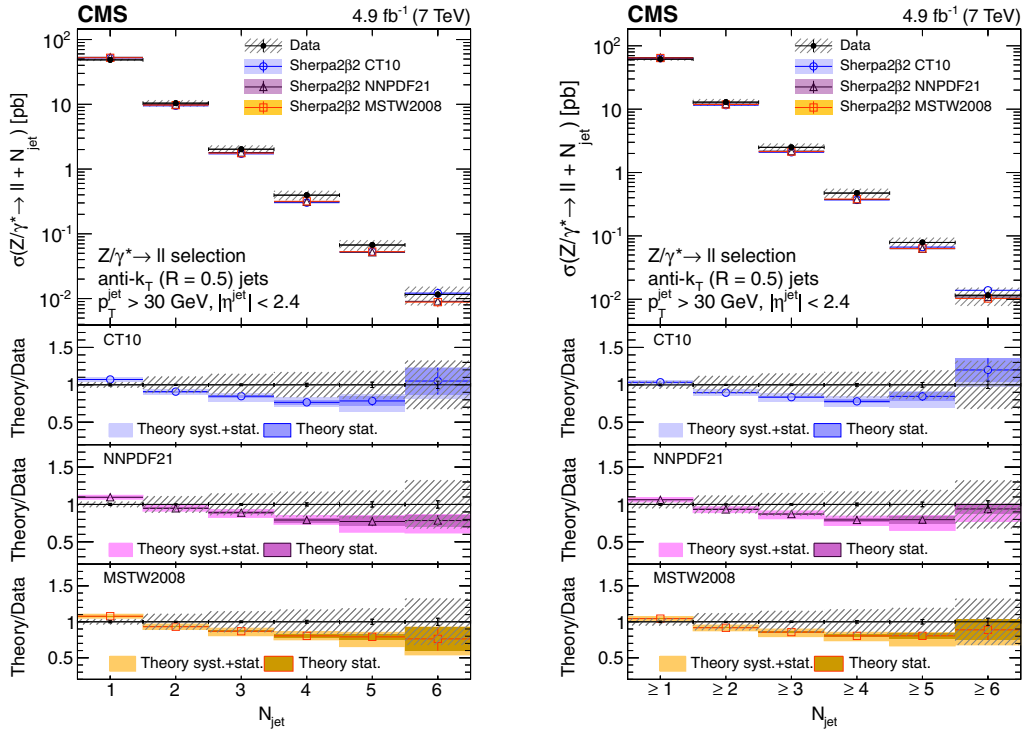


FIG. 6 (color online). Exclusive jet multiplicity distribution (left) and inclusive jet multiplicity distribution (right), after the unfolding procedure, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and to its combination with the theoretical PDF uncertainty.

of these two values is taken as the magnitude of the uncertainty. As observed in previous studies [7], the single-top quark and $W + \text{jets}$ contributions are at the sub-per-mil level, and they are assigned a 100% uncertainty.

Since the background contribution as a function of the jet multiplicity is theoretically less well known than the fully inclusive cross section, control data samples are used to validate the simulation of this dependence. The modeling of the dominant $t\bar{t}$ background as a function of the jet multiplicity is compared with the data using a control sample enriched in $t\bar{t}$ events. This sample is selected by requiring the presence of two leptons of different flavors, i.e., $e\mu$ combinations, and an agreement is found between data and simulation at the 6% level [7]. The CMS measurement of the $t\bar{t}$ differential cross section [49], using an event selection compatible with the study presented in this paper, leads to a production rate for events with six jets in simulation overestimated by about 30%. This difference is used as the estimated uncertainty for the six-jets sub-sample. Variations in the MADGRAPH prediction for $t\bar{t}$ production from a change in the renormalization, factorization, and matching scales, as well as from the PDF choice, show that data and simulation agree within the estimated uncertainties.

The systematic uncertainty of the pileup reweighting procedure in MC simulation is due to the uncertainties in

the minimum-bias cross section and in the instantaneous luminosity of the data sample. This uncertainty is evaluated by varying the number of simulated pileup interactions by $\pm 5\%$. The measurement of the integrated luminosity has an associated uncertainty of 2.2% that directly propagates to any cross section measurement.

The systematic uncertainties (excluding luminosity) used for the combination of the electron and muon samples are summarized in Tables I–III.

VIII. RESULTS AND COMPARISON WITH THEORETICAL PREDICTIONS

The results presented for observable quantities are obtained by combining the unfolded distributions for both leptonic channels into an uncertainty-weighted average for a single lepton flavor. Correlations between systematic uncertainties for the electron and muon channels are taken into account in the combination. Fiducial cross sections are shown, without further corrections for the geometrical acceptance or kinematic selection, for leptons and jets. All the results are compared with theoretical distributions, produced with the RIVET toolkit [50], obtained with the generator-level phase space definition and on final-state stable particles as discussed in Sec. VI. Neutrinos are excluded from the collection of stable particles.

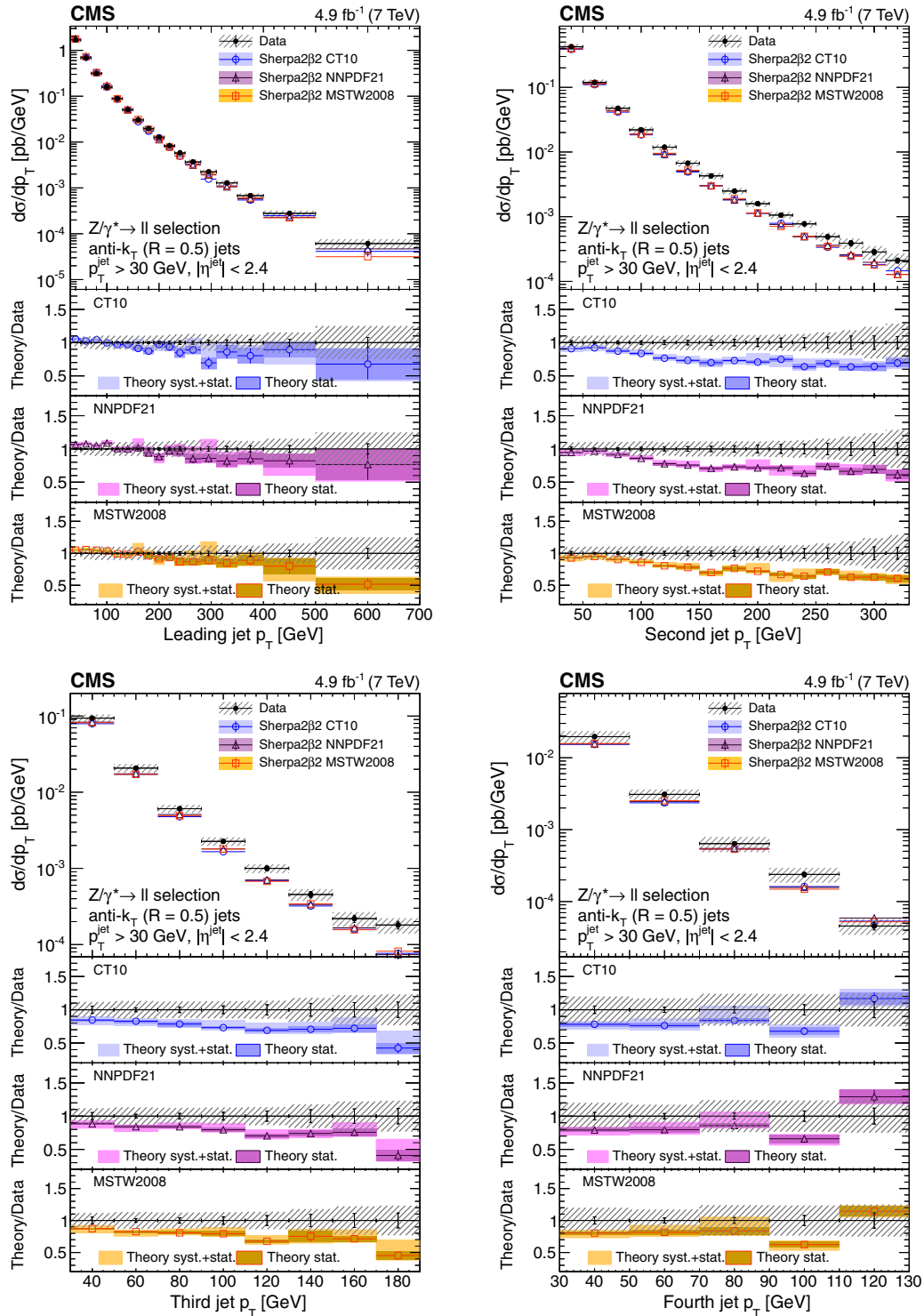


FIG. 7 (color online). Unfolded differential cross section as a function of p_T for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and to its combination with the theoretical PDF uncertainty.

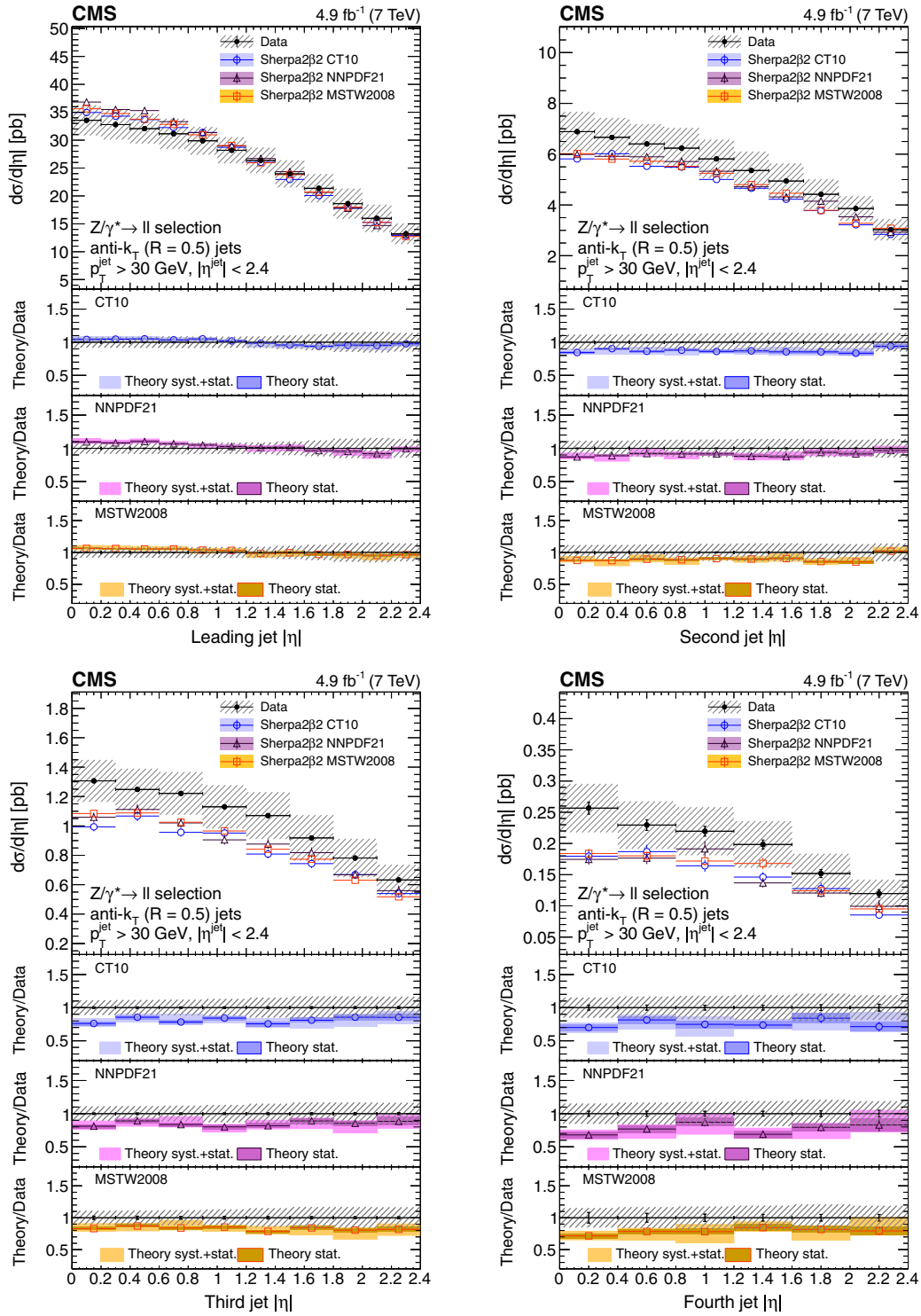


FIG. 8 (color online). Unfolded differential cross section as a function of the jet absolute pseudorapidity $|\eta|$ for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and to its combination with the theoretical PDF uncertainty.

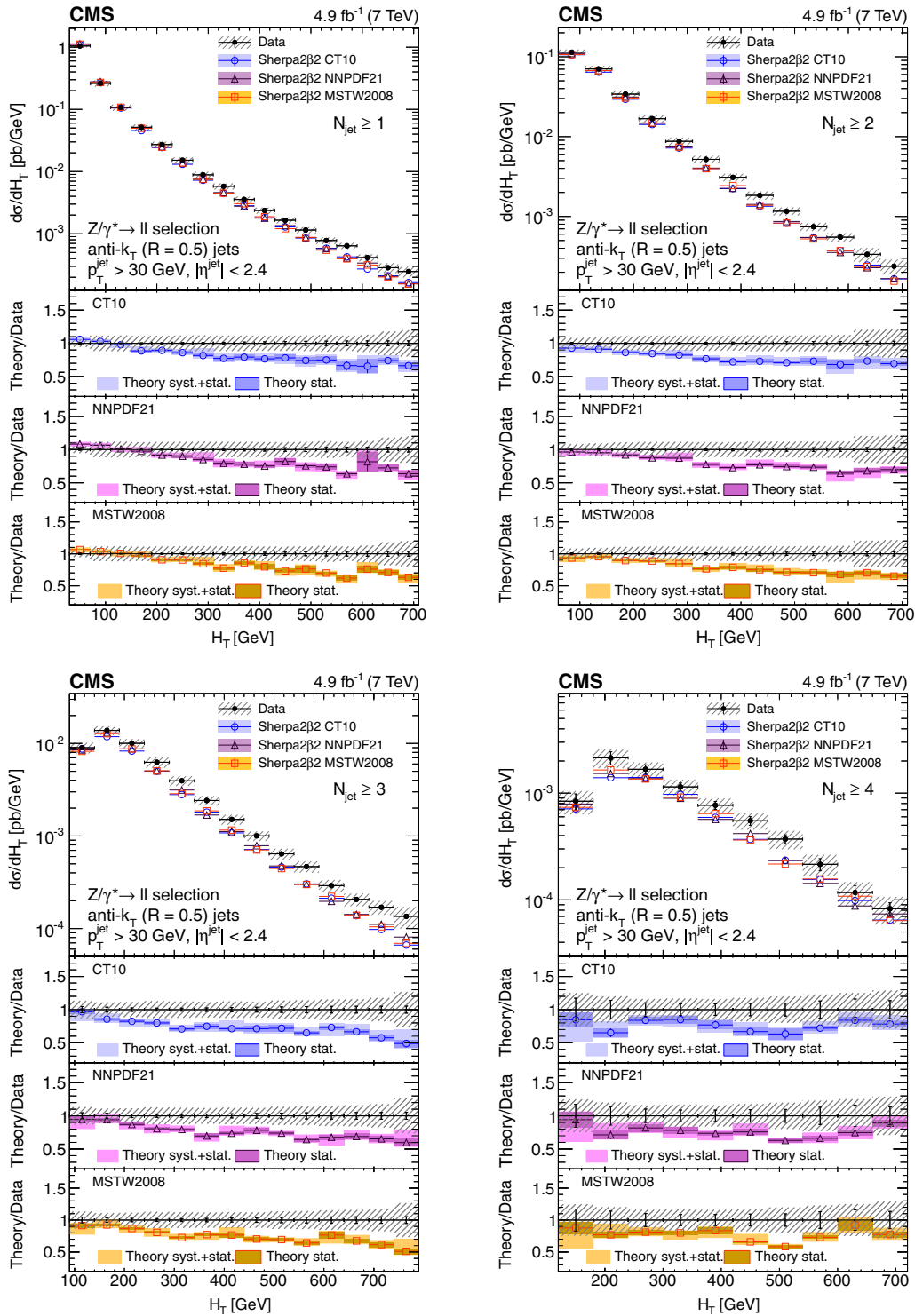


FIG. 9 (color online). Unfolded differential cross section as a function of H_T for events with at least one (top left), two (top right), three (bottom left), and four (bottom right) jets compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus systematic uncertainty. The bands around theory predictions correspond to the statistical uncertainty of the generated sample and to its combination with the theoretical PDF uncertainty.

Theoretical predictions at leading order in pQCD are computed with the MADGRAPH 5.1.1 generator followed by PYTHIA 6.424 with the Z2 tune and CTEQ6L1 PDF set for fragmentation and parton shower simulation. For the MADGRAPH simulation, the factorization and renormalization scales are chosen on an event-by-event basis as the transverse mass of the event, clustered with the k_T algorithm down to a $2 \rightarrow 2$ topology, and k_T at each vertex splitting, respectively [19,51]. The MADGRAPH predictions are rescaled to the available NNLO inclusive cross section [27], which has a uniform associated uncertainty of about 5% that is not propagated into the figures.

Predictions at next-to-leading order in QCD are provided by SHERPA 2.β2 [22–25,52], using the CT10 NLO PDF set [53], in a configuration where NLO calculations for $Z + 0$ and $Z + 1$ jet event topologies are merged with leading-order matrix elements for final states with up to four real emissions and matched to the parton shower. The NLO virtual corrections are computed using the BLACKHAT library [54]. In this calculation, the factorization and renormalization scales are defined for each event by clustering the $2 \rightarrow n$ parton level kinematics onto a core $2 \rightarrow 2$ configuration using a k_T -type algorithm, and using the smallest invariant mass or virtuality in the core configuration as the scale [52]. The default configuration for the underlying event and fragmentation tune is used.

The third theoretical prediction considered is the NLO QCD calculation for the $Z + 1$ jet matrix element as provided by the POWHEG-BOX package [2–4,55], with CT10 NLO PDF set, and matched with the PYTHIA parton shower evolution using the Z2 tune. In this case, the factorization and renormalization scales in the inclusive cross section calculation are defined on an event-by-event basis as the Z -boson p_T , while for the generation of the radiation they are given by the p_T of the produced radiation.

The comparisons of these predictions with the corrected data are presented in Figs. 2–5. The effect of PDF choice is shown in Figs. 6–9. The error bars on the plotted data points represent the statistical uncertainty, while cross-hatched bands represent the total experimental uncertainty (statistical and systematic uncertainties summed in quadrature) after the unfolding procedure. Uncertainties in the theoretical predictions are shown in the ratio of data to simulation only. For the NLO prediction, theoretical uncertainties are evaluated by varying simultaneously the factorization and renormalization scales up and down by a factor of two (for SHERPA and POWHEG). For the SHERPA prediction only, the resummation scale is changed up and down by a factor $\sqrt{2}$ and the parton shower matching scale is changed by 10 GeV in both directions. The effect of the PDF choice is shown for SHERPA, by comparing the results based on CT10 PDF set with those based on the alternative NLO PDFs MSTW2008 and NNPDF2.1 [56]. The theoretical part of the plotted uncertainty band for each PDF choice includes both the intrinsic PDF uncertainty,

evaluated according to the prescriptions of the authors of each PDF set, and the effect of the variation of ± 0.002 in the value of the strong coupling constant α_s around the central value used in the PDF.

A. Jet multiplicity

Figure 2 shows the measured cross sections as a function of the exclusive and inclusive jet multiplicities, for a total number of up to six jets in the final state. Beyond the sixth jet, the measurement is not performed due to the statistical limitation of the data and simulated samples. The trend of the jet multiplicity represents the expectation of the pQCD prediction for a staircaselike scaling, with an approximately constant ratio between cross sections for successive multiplicities [57]. This result confirms the previous observation, which was based on a more statistically limited sample [11]. Within the uncertainties, there is agreement between theory and measurement for both the inclusive and the exclusive distributions.

B. Differential cross sections

The differential cross sections as a function of jet p_T and jet η for the first, second, third, and fourth highest p_T jet in the event are presented in Figs. 3 and 4, respectively. In addition, the differential cross sections as a function of H_T for events with at least one, two, three, or four jets are presented in Fig. 5. The pQCD prediction by MADGRAPH provides a satisfactory description of data for most distributions, but shows an excess in the p_T spectra for the first and second leading jets at $p_T > 100$ GeV. SHERPA tends to underestimate the high p_T and H_T regions in most of the spectra, while remaining compatible with the measurement within the estimated theoretical uncertainty. POWHEG predicts harder p_T spectra than those observed in the data for the events with two or more jets, where the additional hard radiation is described by the parton showers and not by matrix elements. This discrepancy is also reflected in the H_T distribution. Figures 6–9 show no significant dependence of the level of agreement between data and the SHERPA prediction on the PDF set chosen. Hence the PDF choice cannot explain the observed differences with data.

IX. SUMMARY

The fiducial production cross section of a Z boson with at least one hadronic jet has been measured in proton-proton collisions at $\sqrt{s} = 7$ TeV in a sample corresponding to an integrated luminosity of 4.9 fb^{-1} . The measurements comprise inclusive jet multiplicities, exclusive jet multiplicities, and the differential cross sections as a function of jet p_T and η for the four highest p_T jets of the event. In addition, the H_T distribution for events with different minimum numbers of jets has been measured. All measured differential cross sections are corrected for detector effects and compared with theoretical predictions at particle level.

The predictions of calculations combining matrix element and parton shower can describe, within uncertainties, the measured spectra over a wide kinematical range. The measured jet multiplicity distributions and their NLO theoretical predictions from the SHERPA and POWHEG generators are consistent within the experimental and theoretical uncertainties. However, SHERPA predicts softer p_T and H_T spectra than the measured ones, while POWHEG shows an excess compared to data in the high p_T and H_T regions. In particular, the POWHEG spectra are harder for the highest jet multiplicities, which are described only by parton showers. The tree level calculation based on MADGRAPH predicts harder p_T spectra than the measured ones for low jet multiplicities.

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V. Khachatryan,¹ A. M. Sirunyan,¹ A. Tumasyan,¹ W. Adam,² T. Bergauer,² M. Dragicevic,² J. Erö,² C. Fabjan,^{2,b} M. Friedl,² R. Frühwirth,^{2,b} V. M. Ghete,² C. Hartl,² N. Hörmann,² J. Hrubec,² M. Jeitler,^{2,b} W. Kiesenhofer,² V. Knünz,² M. Krammer,^{2,b} I. Krätschmer,² D. Liko,² I. Mikulec,² D. Rabady,^{2,c} B. Rahbaran,² H. Rohringer,² R. Schöfbeck,² J. Strauss,² A. Taurok,² W. Treberer-Treberspurg,² W. Waltenberger,² C.-E. Wulz,^{2,b} V. Mossolov,³ N. Shumeiko,³

J. Suarez Gonzalez,³ S. Alderweireldt,⁴ M. Bansal,⁴ S. Bansal,⁴ T. Cornelis,⁴ E. A. De Wolf,⁴ X. Janssen,⁴ A. Knutsson,⁴ S. Luyckx,⁴ S. Ochesanu,⁴ B. Roland,⁴ R. Rougny,⁴ M. Van De Klundert,⁴ H. Van Haevermaet,⁴ P. Van Mechelen,⁴ N. Van Remortel,⁴ A. Van Spilbeeck,⁴ F. Blekman,⁵ S. Blyweert,⁵ J. D'Hondt,⁵ N. Daci,⁵ N. Heracleous,⁵ J. Keaveney,⁵ S. Lowette,⁵ M. Maes,⁵ A. Olbrechts,⁵ Q. Python,⁵ D. Strom,⁵ S. Tavernier,⁵ W. Van Doninck,⁵ P. Van Mulders,⁵ G. P. Van Onsem,⁵ I. Vilella,⁵ C. Caillol,⁶ B. Clerbaux,⁶ G. De Lentdecker,⁶ D. Dobur,⁶ L. Favart,⁶ A. P. R. Gay,⁶ A. Grebenyuk,⁶ A. Léonard,⁶ A. Mohammadi,⁶ L. Perniè,^{6,c} T. Reis,⁶ T. Seva,⁶ L. Thomas,⁶ C. Vander Velde,⁶ P. Vanlaer,⁶ J. Wang,⁶ V. Adler,⁷ K. Beernaert,⁷ L. Benucci,⁷ A. Cimmino,⁷ S. Costantini,⁷ S. Crucy,⁷ S. Dildick,⁷ A. Fagot,⁷ G. Garcia,⁷ J. Mccartin,⁷ A. A. Ocampo Rios,⁷ D. Ryckbosch,⁷ S. Salva Diblen,⁷ M. Sigamani,⁷ N. Strobbe,⁷ F. Thyssen,⁷ M. Tytgat,⁷ E. Yazgan,⁷ N. Zaganidis,⁷ S. Basegmez,⁸ C. Beluffi,^{8,d} G. Bruno,⁸ R. Castello,⁸ A. Caudron,⁸ L. Ceard,⁸ G. G. Da Silveira,⁸ C. Delaere,⁸ T. du Pree,⁸ D. Favart,⁸ L. Forthomme,⁸ A. Giammanco,^{8,e} J. Hollar,⁸ P. Jez,⁸ M. Komm,⁸ V. Lemaitre,⁸ C. Nuttens,⁸ D. Pagano,⁸ L. Perrini,⁸ A. Pin,⁸ K. Piotrkowski,⁸ A. Popov,^{8,f} L. Quertenmont,⁸ M. Selvaggi,⁸ M. Vidal Marono,⁸ J. M. Vizan Garcia,⁸ N. Beliy,⁹ T. Caeberts,⁹ E. Daubie,⁹ G. H. Hammad,⁹ W. L. Aldá Júnior,¹⁰ G. A. Alves,¹⁰ L. Brito,¹⁰ M. Correa Martins Junior,¹⁰ T. Dos Reis Martins,¹⁰ C. Mora Herrera,¹⁰ M. E. Pol,¹⁰ W. Carvalho,¹¹ J. Chinellato,^{11,g} A. Custódio,¹¹ E. M. Da Costa,¹¹ D. De Jesus Damiao,¹¹ C. De Oliveira Martins,¹¹ S. Fonseca De Souza,¹¹ H. Malbouisson,¹¹ D. Matos Figueiredo,¹¹ L. Mundim,¹¹ H. Nogima,¹¹ W. L. Prado Da Silva,¹¹ J. Santaolalla,¹¹ A. Santoro,¹¹ A. Sznajder,¹¹ E. J. Tonelli Manganote,^{11,g} A. Vilela Pereira,¹¹ C. A. Bernardes,^{12b} S. Dogra,^{12a} T. R. Fernandez Perez Tomei,^{12a} E. M. Gregores,^{12b} P. G. Mercadante,^{12b} S. F. Novaes,^{12a} Sandra S. Padula,^{12a} A. Aleksandrov,¹³ V. Genchev,^{13,c} P. Iaydjiev,¹³ A. Marinov,¹³ S. Piperov,¹³ M. Rodozov,¹³ S. Stoykova,¹³ G. Sultanov,¹³ V. Tcholakov,¹³ M. Vutova,¹³ A. Dimitrov,¹⁴ I. Glushkov,¹⁴ R. Hadjiiska,¹⁴ V. Kozhuharov,¹⁴ L. Litov,¹⁴ B. Pavlov,¹⁴ P. Petkov,¹⁴ J. G. Bian,¹⁵ G. M. Chen,¹⁵ H. S. Chen,¹⁵ M. Chen,¹⁵ R. Du,¹⁵ C. H. Jiang,¹⁵ S. Liang,¹⁵ R. Plestina,^{15,h} J. Tao,¹⁵ X. Wang,¹⁵ Z. Wang,¹⁵ C. Asawatangtrakuldee,¹⁶ Y. Ban,¹⁶ Y. Guo,¹⁶ Q. Li,¹⁶ W. Li,¹⁶ S. Liu,¹⁶ Y. Mao,¹⁶ S. J. Qian,¹⁶ D. Wang,¹⁶ L. Zhang,¹⁶ W. Zou,¹⁶ C. Avila,¹⁷ L. F. Chaparro Sierra,¹⁷ C. Florez,¹⁷ J. P. Gomez,¹⁷ B. Gomez Moreno,¹⁷ J. C. Sanabria,¹⁷ N. Godinovic,¹⁸ D. Lelas,¹⁸ D. Polic,¹⁸ I. Puljak,¹⁸ Z. Antunovic,¹⁹ M. Kovac,¹⁹ V. Brigljevic,²⁰ K. Kadija,²⁰ J. Luetic,²⁰ D. Mekterovic,²⁰ L. Sudic,²⁰ A. Attikis,²¹ G. Mavromanolakis,²¹ J. Mousa,²¹ C. Nicolaou,²¹ F. Ptochos,²¹ P. A. Razis,²¹ M. Bodlak,²² M. Finger,²² M. Finger Jr.,^{22,i} Y. Assran,^{23,j} A. Ellithi Kamel,^{23,k} M. A. Mahmoud,^{23,l} A. Radi,^{23,m,n} M. Kadastik,²⁴ M. Murumaa,²⁴ M. Raidal,²⁴ A. Tiko,²⁴ P. Eerola,²⁵ G. Fedi,²⁵ M. Voutilainen,²⁵ J. Härkönen,²⁶ V. Karimäki,²⁶ R. Kinnunen,²⁶ M. J. Kortelainen,²⁶ T. Lampén,²⁶ K. Lassila-Perini,²⁶ S. Lehti,²⁶ T. Lindén,²⁶ P. Luukka,²⁶ T. Mäenpää,²⁶ T. Peltola,²⁶ E. Tuominen,²⁶ J. Tuominiemi,²⁶ E. Tuovinen,²⁶ L. Wendland,²⁶ T. Tuuva,²⁷ M. Besancon,²⁸ F. Couderc,²⁸ M. Dejardin,²⁸ D. Denegri,²⁸ B. Fabbro,²⁸ J. L. Faure,²⁸ C. Favaro,²⁸ F. Ferri,²⁸ S. Ganjour,²⁸ A. Givernaud,²⁸ P. Gras,²⁸ G. Hamel de Monchenault,²⁸ P. Jarry,²⁸ E. Locci,²⁸ J. Malcles,²⁸ J. Rander,²⁸ A. Rosowsky,²⁸ M. Titov,²⁸ S. Baffioni,²⁹ F. Beaudette,²⁹ P. Busson,²⁹ C. Charlot,²⁹ T. Dahms,²⁹ M. Dalchenko,²⁹ L. Dobrzynski,²⁹ N. Filipovic,²⁹ A. Florent,²⁹ R. Granier de Cassagnac,²⁹ L. Mastrolorenzo,²⁹ P. Miné,²⁹ C. Mironov,²⁹ I. N. Naranjo,²⁹ M. Nguyen,²⁹ C. Ochando,²⁹ P. Paganini,²⁹ S. Regnard,²⁹ R. Salerno,²⁹ J. B. Sauvan,²⁹ Y. Sirois,²⁹ C. Veelken,²⁹ Y. Yilmaz,²⁹ A. Zabi,²⁹ J.-L. Agram,^{30,o} J. Andrea,³⁰ A. Aubin,³⁰ D. Bloch,³⁰ J.-M. Brom,³⁰ E. C. Chabert,³⁰ C. Collard,³⁰ E. Conte,^{30,o} J.-C. Fontaine,^{30,o} D. Gelé,³⁰ U. Goerlach,³⁰ C. Goetzmann,³⁰ A.-C. Le Bihan,³⁰ P. Van Hove,³⁰ S. Gadrat,³¹ S. Beauceron,³² N. Beaupere,³² G. Boudoul,^{32,c} E. Bouvier,³² S. Brochet,³² C. A. Carrillo Montoya,³² J. Chasserat,³² R. Chierici,³² D. Contardo,^{32,c} P. Depasse,³² H. El Mamouni,³² J. Fan,³² J. Fay,³² S. Gascon,³² M. Gouzevitch,³² B. Ille,³² T. Kurca,³² M. Lethuillier,³² L. Mirabito,³² S. Perries,³² J. D. Ruiz Alvarez,³² D. Sabes,³² L. Sgandurra,³² V. Sordini,³² M. Vander Donckt,³² P. Verdier,³² S. Viret,³² H. Xiao,³² Z. Tsamalaidze,^{33,i} C. Autermann,³⁴ S. Beranek,³⁴ M. Bontenackels,³⁴ M. Edelhoff,³⁴ L. Feld,³⁴ O. Hindrichs,³⁴ K. Klein,³⁴ A. Ostapchuk,³⁴ A. Perieanu,³⁴ F. Raupach,³⁴ J. Sammet,³⁴ S. Schael,³⁴ H. Weber,³⁴ B. Wittmer,³⁴ V. Zhukov,^{34,f} M. Ata,³⁵ E. Dietz-Laursonn,³⁵ D. Duchardt,³⁵ M. Erdmann,³⁵ R. Fischer,³⁵ A. Güth,³⁵ T. Hebbeker,³⁵ C. Heidemann,³⁵ K. Hoepfner,³⁵ D. Klingebiel,³⁵ S. Knutzen,³⁵ P. Kreuzer,³⁵ M. Merschmeyer,³⁵ A. Meyer,³⁵ P. Millet,³⁵ M. Olschewski,³⁵ K. Padeken,³⁵ P. Papacz,³⁵ H. Reithler,³⁵ S. A. Schmitz,³⁵ L. Sonnenschein,³⁵ D. Teyssier,³⁵ S. Thüer,³⁵ M. Weber,³⁵ V. Cherepanov,³⁶ Y. Erdogan,³⁶ G. Flügge,³⁶ H. Geenen,³⁶ M. Geisler,³⁶ W. Haj Ahmad,³⁶ A. Heister,³⁶ F. Hoehle,³⁶ B. Kargoll,³⁶ T. Kress,³⁶ Y. Kuessel,³⁶ J. Lingemann,^{36,c} A. Nowack,³⁶ I. M. Nugent,³⁶ L. Perchalla,³⁶ O. Pooth,³⁶ A. Stahl,³⁶ I. Asin,³⁷ N. Bartosik,³⁷ J. Behr,³⁷ W. Behrenhoff,³⁷ U. Behrens,³⁷ A. J. Bell,³⁷ M. Bergholz,^{37,p} A. Bethani,³⁷ K. Borras,³⁷ A. Burgmeier,³⁷ A. Cakir,³⁷ L. Calligaris,³⁷ A. Campbell,³⁷ S. Choudhury,³⁷ F. Costanza,³⁷ C. Diez Pardos,³⁷ S. Dooling,³⁷ T. Dorland,³⁷ G. Eckerlin,³⁷ D. Eckstein,³⁷ T. Eichhorn,³⁷ G. Flucke,³⁷ J. Garay Garcia,³⁷ A. Geiser,³⁷ P. Gunnellini,³⁷ J. Hauk,³⁷ G. Hellwig,³⁷

M. Hempel,³⁷ D. Horton,³⁷ H. Jung,³⁷ A. Kalogeropoulos,³⁷ M. Kasemann,³⁷ P. Katsas,³⁷ J. Kieseler,³⁷ C. Kleinwort,³⁷ D. Krücker,³⁷ W. Lange,³⁷ J. Leonard,³⁷ K. Lipka,³⁷ A. Lobanov,³⁷ W. Lohmann,^{37,p} B. Lutz,³⁷ R. Mankel,³⁷ I. Marfin,³⁷ I.-A. Melzer-Pellmann,³⁷ A. B. Meyer,³⁷ J. Mnich,³⁷ A. Mussgiller,³⁷ S. Naumann-Emme,³⁷ A. Nayak,³⁷ O. Novgorodova,³⁷ F. Nowak,³⁷ E. Ntomari,³⁷ H. Perrey,³⁷ D. Pitzl,³⁷ R. Placakyte,³⁷ A. Raspereza,³⁷ P. M. Ribeiro Cipriano,³⁷ E. Ron,³⁷ M. Ö. Sahin,³⁷ J. Salfeld-Nebgen,³⁷ P. Saxena,³⁷ R. Schmidt,^{37,p} T. Schoerner-Sadenius,³⁷ M. Schröder,³⁷ C. Seitz,³⁷ S. Spannagel,³⁷ A. D. R. Vargas Trevino,³⁷ R. Walsh,³⁷ C. Wissing,³⁷ M. Aldaya Martin,³⁸ V. Blobel,³⁸ M. Centis Vignali,³⁸ A. r. Draeger,³⁸ J. Erfle,³⁸ E. Garutti,³⁸ K. Goebel,³⁸ M. Görner,³⁸ J. Haller,³⁸ M. Hoffmann,³⁸ R. S. Höing,³⁸ H. Kirschenmann,³⁸ R. Klanner,³⁸ R. Kogler,³⁸ J. Lange,³⁸ T. Lapsien,³⁸ T. Lenz,³⁸ I. Marchesini,³⁸ J. Ott,³⁸ T. Peiffer,³⁸ N. Pietsch,³⁸ J. Poehlsen,³⁸ T. Poehlsen,³⁸ D. Rathjens,³⁸ C. Sander,³⁸ H. Schettler,³⁸ P. Schleper,³⁸ E. Schlieckau,³⁸ A. Schmidt,³⁸ M. Seidel,³⁸ V. Sola,³⁸ H. Stadie,³⁸ G. Steinbrück,³⁸ D. Troendle,³⁸ E. Usai,³⁸ L. Vanelderden,³⁸ C. Barth,³⁹ C. Baus,³⁹ J. Berger,³⁹ C. Böser,³⁹ E. Butz,³⁹ T. Chwalek,³⁹ W. De Boer,³⁹ A. Descroix,³⁹ A. Dierlamm,³⁹ M. Feindt,³⁹ F. Frensch,³⁹ M. Giffels,³⁹ F. Hartmann,^{39,c} T. Hauth,^{39,c} U. Husemann,³⁹ I. Katkov,^{39,f} A. Kornmayer,^{39,c} E. Kuznetsova,³⁹ P. Lobelle Pardo,³⁹ M. U. Mozer,³⁹ Th. Müller,³⁹ A. Nürnberg,³⁹ G. Quast,³⁹ K. Rabbertz,³⁹ F. Ratnikov,³⁹ S. Röcker,³⁹ H. J. Simonis,³⁹ F. M. Stober,³⁹ R. Ulrich,³⁹ J. Wagner-Kuhr,³⁹ S. Wayand,³⁹ T. Weiler,³⁹ R. Wolf,³⁹ G. Anagnostou,⁴⁰ G. Daskalakis,⁴⁰ T. Gerasis,⁴⁰ V. A. Giakoumopoulou,⁴⁰ A. Kyriakis,⁴⁰ D. Loukas,⁴⁰ A. Markou,⁴⁰ C. Markou,⁴⁰ A. Psallidas,⁴⁰ I. Topsis-Giotis,⁴⁰ A. Panagiotou,⁴¹ N. Saoulidou,⁴¹ E. Stiliaris,⁴¹ X. Aslanoglou,⁴² I. Evangelou,⁴² G. Flouris,⁴² C. Foudas,⁴² P. Kokkas,⁴² N. Manthos,⁴² I. Papadopoulos,⁴² E. Paradas,⁴² G. Bencze,⁴³ C. Hajdu,⁴³ P. Hidas,⁴³ D. Horvath,^{43,q} F. Sikler,⁴³ V. Veszpremi,⁴³ G. Vesztergombi,^{43,r} A. J. Zsigmond,⁴³ N. Beni,⁴⁴ S. Czellar,⁴⁴ J. Karancsi,^{44,s} J. Molnar,⁴⁴ J. Palinkas,⁴⁴ Z. Szillasi,⁴⁴ P. Raics,⁴⁵ Z. L. Trocsanyi,⁴⁵ B. Ujvari,⁴⁵ S. K. Swain,⁴⁶ S. B. Beri,⁴⁷ V. Bhatnagar,⁴⁷ N. Dhingra,⁴⁷ R. Gupta,⁴⁷ U. Bhawandeep,⁴⁷ A. K. Kalsi,⁴⁷ M. Kaur,⁴⁷ M. Mittal,⁴⁷ N. Nishu,⁴⁷ J. B. Singh,⁴⁷ Ashok Kumar,⁴⁸ Arun Kumar,⁴⁸ S. Ahuja,⁴⁸ A. Bhardwaj,⁴⁸ B. C. Choudhary,⁴⁸ A. Kumar,⁴⁸ S. Malhotra,⁴⁸ M. Naimuddin,⁴⁸ K. Ranjan,⁴⁸ V. Sharma,⁴⁸ S. Banerjee,⁴⁹ S. Bhattacharya,⁴⁹ K. Chatterjee,⁴⁹ S. Dutta,⁴⁹ B. Gomber,⁴⁹ Sa. Jain,⁴⁹ Sh. Jain,⁴⁹ R. Khurana,⁴⁹ A. Modak,⁴⁹ S. Mukherjee,⁴⁹ D. Roy,⁴⁹ S. Sarkar,⁴⁹ M. Sharan,⁴⁹ A. Abdulsalam,⁵⁰ D. Dutta,⁵⁰ S. Kailas,⁵⁰ V. Kumar,⁵⁰ A. K. Mohanty,^{50,c} L. M. Pant,⁵⁰ P. Shukla,⁵⁰ A. Topkar,⁵⁰ T. Aziz,⁵¹ S. Banerjee,⁵¹ S. Bhowmik,^{51,t} R. M. Chatterjee,⁵¹ R. K. Dewanjee,⁵¹ S. Dugad,⁵¹ S. Ganguly,⁵¹ S. Ghosh,⁵¹ M. Guchait,⁵¹ A. Gurtu,^{51,u} G. Kole,⁵¹ S. Kumar,⁵¹ M. Maity,^{51,t} G. Majumder,⁵¹ K. Mazumdar,⁵¹ G. B. Mohanty,⁵¹ B. Parida,⁵¹ K. Sudhakar,⁵¹ N. Wickramage,^{51,v} H. Bakhshiansohi,⁵² H. Behnamian,⁵² S. M. Etesami,^{52,w} A. Fahim,^{52,x} R. Goldouzian,⁵² A. Jafari,⁵² M. Khakzad,⁵² M. Mohammadi Najafabadi,⁵² M. Naseri,⁵² S. Paktinat Mehdiabadi,⁵² B. Safarzadeh,^{52,y} M. Zeinali,⁵² M. Felcini,⁵³ M. Grunewald,⁵³ M. Abbrescia,^{54a,54b} L. Barbone,^{54a,54b} C. Calabria,^{54a,54b} S. S. Chhibra,^{54a,54b} A. Colaleo,^{54a} D. Creanza,^{54a,54c} N. De Filippis,^{54a,54c} M. De Palma,^{54a,54b} L. Fiore,^{54a} G. Iaselli,^{54a,54c} G. Maggi,^{54a,54c} M. Maggi,^{54a} S. My,^{54a,54c} S. Nuzzo,^{54a,54b} A. Pompili,^{54a,54b} G. Pugliese,^{54a,54c} R. Radogna,^{54a,54b,c} G. Selvaggi,^{54a,54b} L. Silvestris,^{54a,c} G. Singh,^{54a,54b} R. Venditti,^{54a,54b} P. Verwilligen,^{54a} G. Zito,^{54a} G. Abbiendi,^{55a} A. C. Benvenuti,^{55a} D. Bonacorsi,^{55a,55b} S. Braibant-Giacomelli,^{55a,55b} L. Brigliadori,^{55a,55b} R. Campanini,^{55a,55b} P. Capiluppi,^{55a,55b} A. Castro,^{55a,55b} F. R. Cavallo,^{55a} G. Codispoti,^{55a,55b} M. Cuffiani,^{55a,55b} G. M. Dallavalle,^{55a} F. Fabbri,^{55a} A. Fanfani,^{55a,55b} D. Fasanella,^{55a,55b} P. Giacomelli,^{55a} C. Grandi,^{55a} L. Guiducci,^{55a,55b} S. Marcellini,^{55a} G. Masetti,^{55a,c} A. Montanari,^{55a} F. L. Navarria,^{55a,55b} A. Perrotta,^{55a} F. Primavera,^{55a,55b} A. M. Rossi,^{55a,55b} T. Rovelli,^{55a,55b} G. P. Siroli,^{55a,55b} N. Tosi,^{55a,55b} R. Travaglini,^{55a,55b} S. Albergo,^{56a,56b} G. Cappello,^{56a} M. Chiorboli,^{56a,56b} S. Costa,^{56a,56b} F. Giordano,^{56a,c} R. Potenza,^{56a,56b} A. Tricomi,^{56a,56b} C. Tuve,^{56a,56b} G. Barbagli,^{57a} V. Ciulli,^{57a,57b} C. Civinini,^{57a} R. D'Alessandro,^{57a,57b} E. Focardi,^{57a,57b} E. Gallo,^{57a} S. Gonzi,^{57a,57b} V. Gori,^{57a,57b,c} P. Lenzi,^{57a,57b} M. Meschini,^{57a} S. Paoletti,^{57a} G. Sguazzoni,^{57a} A. Tropiano,^{57a,57b} L. Benussi,⁵⁸ S. Bianco,⁵⁸ F. Fabbri,⁵⁸ D. Piccolo,⁵⁸ F. Ferro,^{59a} M. Lo Vetere,^{59a,59b} E. Robutti,^{59a} S. Tosi,^{59a,59b} M. E. Dinardo,^{60a,60b} S. Fiorendi,^{60a,60b,c} S. Gennai,^{60a,c} R. Gerosa,^{60a,c} A. Ghezzi,^{60a,60b} P. Govoni,^{60a,60b} M. T. Lucchini,^{60a,60b,c} S. Malvezzi,^{60a} R. A. Manzoni,^{60a,60b} A. Martelli,^{60a,60b} B. Marzocchi,^{60a} D. Menasce,^{60a} L. Moroni,^{60a} M. Paganoni,^{60a,60b} D. Pedrini,^{60a} S. Ragazzi,^{60a,60b} N. Redaelli,^{60a} T. Tabarelli de Fatis,^{60a,60b} S. Buontempo,^{61a} N. Cavallo,^{61a,61c} S. Di Guida,^{61a,61d,c} F. Fabozzi,^{61a,61c} A. O. M. Iorio,^{61a,61b} L. Lista,^{61a} S. Meola,^{61a,61d,c} M. Merola,^{61a} P. Paolucci,^{61a,c} P. Azzi,^{62a} N. Bacchetta,^{62a} M. Bellato,^{62a} M. Biasotto,^{62a,z} A. Branca,^{62a,62b} M. Dall'Osso,^{62a,62b} T. Dorigo,^{62a} F. Fanzago,^{62a} M. Galanti,^{62a,62b} F. Gasparini,^{62a,62b} P. Giubilato,^{62a,62b} A. Gozzelino,^{62a} K. Kanishchev,^{62a,62c} S. Lacaprara,^{62a} M. Margoni,^{62a,62b} A. T. Meneguzzo,^{62a,62b} M. Passaseo,^{62a} J. Pazzini,^{62a,62b} M. Pegoraro,^{62a} N. Pozzobon,^{62a,62b} P. Ronchese,^{62a,62b} F. Simonetto,^{62a,62b} E. Torassa,^{62a} M. Tosi,^{62a,62b} S. Vanini,^{62a,62b} P. Zotto,^{62a,62b} A. Zucchetta,^{62a,62b} M. Gabusi,^{63a,63b} S. P. Ratti,^{63a,63b} C. Riccardi,^{63a,63b} P. Salvini,^{63a} P. Vitulo,^{63a,63b} M. Biasini,^{64a,64b}

G. M. Bilei,^{64a} D. Cianggottini,^{64a,64b} L. Fanò,^{64a,64b} P. Lariccia,^{64a,64b} G. Mantovani,^{64a,64b} M. Menichelli,^{64a} F. Romeo,^{64a,64b}
A. Saha,^{64a} A. Santocchia,^{64a,64b} A. Spiezia,^{64a,64b,c} K. Androsof,^{65a,aa} P. Azzurri,^{65a} G. Bagliesi,^{65a} J. Bernardini,^{65a}
T. Boccali,^{65a} G. Broccolo,^{65a,65c} R. Castaldi,^{65a} M. A. Ciocci,^{65a,aa} R. Dell'Orso,^{65a} S. Donato,^{65a,65c} F. Fiori,^{65a,65c}
L. Foà,^{65a,65c} A. Giassi,^{65a} M. T. Grippo,^{65a,aa} F. Ligabue,^{65a,65c} T. Lomtadze,^{65a} L. Martini,^{65a,65b} A. Messineo,^{65a,65b}
C. S. Moon,^{65a,bb} F. Palla,^{65a,c} A. Rizzi,^{65a,65b} A. Savoy-Navarro,^{65a,cc} A. T. Serban,^{65a} P. Spagnolo,^{65a} P. Squillacioti,^{65a,aa}
R. Tenchini,^{65a} G. Tonelli,^{65a,65b} A. Venturi,^{65a} P. G. Verdini,^{65a} C. Vernieri,^{65a,65c,c} L. Barone,^{66a,66b} F. Cavallari,^{66a}
G. D'imperio,^{66a,66b} D. Del Re,^{66a,66b} M. Diemoz,^{66a} M. Grassi,^{66a,66b} C. Jorda,^{66a} E. Longo,^{66a,66b} F. Margaroli,^{66a,66b}
P. Meridiani,^{66a} F. Micheli,^{66a,66b,c} S. Nourbakhsh,^{66a,66b} G. Organtini,^{66a,66b} R. Paramatti,^{66a} S. Rahatlou,^{66a,66b} C. Rovelli,^{66a}
F. Santanastasio,^{66a,66b} L. Soffi,^{66a,66b,c} P. Traczyk,^{66a,66b} N. Amapane,^{67a,67b} R. Arcidiacono,^{67a,67c} S. Argiro,^{67a,67b,c}
M. Arneodo,^{67a,67c} R. Bellan,^{67a,67b} C. Biino,^{67a} N. Cartiglia,^{67a} S. Casasso,^{67a,67b,c} M. Costa,^{67a,67b} A. Degano,^{67a,67b}
N. Demaria,^{67a} L. Finco,^{67a,67b} C. Mariotti,^{67a} S. Maselli,^{67a} E. Migliore,^{67a,67b} V. Monaco,^{67a,67b} M. Musich,^{67a}
M. M. Obertino,^{67a,67c,c} G. Ortona,^{67a,67b} L. Pacher,^{67a,67b} N. Pastrone,^{67a} M. Pelliccioni,^{67a} G. L. Pinna Angioni,^{67a,67b}
A. Potenza,^{67a,67b} A. Romero,^{67a,67b} M. Ruspa,^{67a,67c} R. Sacchi,^{67a,67b} A. Solano,^{67a,67b} A. Staiano,^{67a} U. Tamponi,^{67a}
S. Belforte,^{68a} V. Candelise,^{68a,68b} M. Casarsa,^{68a} F. Cossutti,^{68a} G. Della Ricca,^{68a,68b} B. Gobbo,^{68a} C. La Licata,^{68a,68b}
M. Marone,^{68a,68b} D. Montanino,^{68a,68b} D. Scaini,^{68a,68b} A. Schizzi,^{68a,68b,c} T. Umer,^{68a,68b} A. Zanello,^{68a} A. Kropivnitskaya,⁶⁹
S. K. Nam,⁶⁹ D. H. Kim,⁷⁰ G. N. Kim,⁷⁰ M. S. Kim,⁷⁰ D. J. Kong,⁷⁰ S. Lee,⁷⁰ Y. D. Oh,⁷⁰ H. Park,⁷⁰ A. Sakharov,⁷⁰
D. C. Son,⁷⁰ T. J. Kim,⁷¹ J. Y. Kim,⁷² S. Song,⁷² S. Choi,⁷³ D. Gyun,⁷³ B. Hong,⁷³ M. Jo,⁷³ H. Kim,⁷³ Y. Kim,⁷³ B. Lee,⁷³
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Y. K. Choi,⁷⁵ J. Goh,⁷⁵ D. Kim,⁷⁵ E. Kwon,⁷⁵ J. Lee,⁷⁵ H. Seo,⁷⁵ I. Yu,⁷⁵ A. Juodagalvis,⁷⁶ J. R. Komaragiri,⁷⁷
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V. Matveev,^{88,ee} V. V. Mitsyn,⁸⁸ P. Moiseenz,⁸⁸ V. Palichik,⁸⁸ V. Perelygin,⁸⁸ S. Shmatov,⁸⁸ S. Shulha,⁸⁸ N. Skatchkov,⁸⁸
V. Smirnov,⁸⁸ E. Tikhonenko,⁸⁸ A. Zarubin,⁸⁸ V. Golovtsov,⁸⁹ Y. Ivanov,⁸⁹ V. Kim,^{89,ff} P. Levchenko,⁸⁹ V. Murzin,⁸⁹
V. Oreshkin,⁸⁹ I. Smirnov,⁸⁹ V. Sulimov,⁸⁹ L. Uvarov,⁸⁹ S. Vavilov,⁸⁹ A. Vorobyev,⁸⁹ An. Vorobyev,⁸⁹ Yu. Andreev,⁹⁰
A. Dermenev,⁹⁰ S. Gninenko,⁹⁰ N. Golubev,⁹⁰ M. Kirsanov,⁹⁰ N. Krasnikov,⁹⁰ A. Pashenkov,⁹⁰ D. Tlisov,⁹⁰ A. Toropin,⁹⁰
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G. Gomez,⁹⁹ A. Graziano,⁹⁹ A. Lopez Virto,⁹⁹ J. Marco,⁹⁹ R. Marco,⁹⁹ C. Martinez Rivero,⁹⁹ F. Matorras,⁹⁹
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 N. Suwonjandee,¹⁰⁶ A. Adiguzel,¹⁰⁷ M. N. Bakirci,^{107,oo} S. Cerci,^{107,pp} C. Dozen,¹⁰⁷ I. Dumanoglu,¹⁰⁷ E. Eskut,¹⁰⁷
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 K. Ozdemir,¹⁰⁷ S. Ozturk,^{107,oo} A. Polatoz,¹⁰⁷ K. Sogut,^{107,rr} D. Sunar Cerci,^{107,pp} B. Tali,^{107,pp} H. Topakli,^{107,oo} M. Vergili,¹⁰⁷
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 A.-M. Magnan,¹¹⁴ S. Malik,¹¹⁴ B. Mathias,¹¹⁴ J. Nash,¹¹⁴ A. Nikitenko,^{114,mmm} J. Pela,¹¹⁴ M. Pesaresi,¹¹⁴ K. Petridis,¹¹⁴
 D. M. Raymond,¹¹⁴ S. Rogerson,¹¹⁴ A. Rose,¹¹⁴ C. Seez,¹¹⁴ P. Sharp,^{114,a} A. Tapper,¹¹⁴ M. Vazquez Acosta,¹¹⁴ T. Virdee,¹¹⁴
 J. E. Cole,¹¹⁵ P. R. Hobson,¹¹⁵ A. Khan,¹¹⁵ P. Kyberd,¹¹⁵ D. Leggat,¹¹⁵ D. Leslie,¹¹⁵ W. Martin,¹¹⁵ I. D. Reid,¹¹⁵
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O. R. Long,¹²² A. Luthra,¹²² M. Malberti,¹²² H. Nguyen,¹²² M. Olmedo Negrete,¹²² A. Shrinivas,¹²² S. Sumowidagdo,¹²² S. Wimpenny,¹²² W. Andrews,¹²³ J. G. Branson,¹²³ G. B. Cerati,¹²³ S. Cittolin,¹²³ R. T. D'Agnolo,¹²³ D. Evans,¹²³ A. Holzner,¹²³ R. Kelley,¹²³ D. Klein,¹²³ M. Lebourgeois,¹²³ J. Letts,¹²³ I. Macneill,¹²³ D. Olivito,¹²³ S. Padhi,¹²³ C. Palmer,¹²³ M. Pieri,¹²³ M. Sani,¹²³ V. Sharma,¹²³ S. Simon,¹²³ E. Sudano,¹²³ M. Tadel,¹²³ Y. Tu,¹²³ A. Vartak,¹²³ C. Welke,¹²³ F. Würthwein,¹²³ A. Yagil,¹²³ J. Yoo,¹²³ D. Barge,¹²⁴ J. Bradmiller-Feld,¹²⁴ C. Campagnari,¹²⁴ T. Danielson,¹²⁴ A. Dishaw,¹²⁴ K. Flowers,¹²⁴ M. Franco Sevilla,¹²⁴ P. Geffert,¹²⁴ C. George,¹²⁴ F. Golf,¹²⁴ L. Gouskos,¹²⁴ J. Incandela,¹²⁴ C. Justus,¹²⁴ N. Mccoll,¹²⁴ J. Richman,¹²⁴ D. Stuart,¹²⁴ W. To,¹²⁴ C. West,¹²⁴ A. Apresyan,¹²⁵ A. Bornheim,¹²⁵ J. Bunn,¹²⁵ Y. Chen,¹²⁵ E. Di Marco,¹²⁵ J. Duarte,¹²⁵ A. Mott,¹²⁵ H. B. Newman,¹²⁵ C. Pena,¹²⁵ C. Rogan,¹²⁵ M. Spiropulu,¹²⁵ V. Timciuc,¹²⁵ R. Wilkinson,¹²⁵ S. Xie,¹²⁵ R. Y. Zhu,¹²⁵ V. Azzolini,¹²⁶ A. Calamba,¹²⁶ B. Carlson,¹²⁶ T. Ferguson,¹²⁶ Y. Iiyama,¹²⁶ M. Paulini,¹²⁶ J. Russ,¹²⁶ H. Vogel,¹²⁶ I. Vorobiev,¹²⁶ J. P. Cumalat,¹²⁷ W. T. Ford,¹²⁷ A. Gaz,¹²⁷ E. Luiggi Lopez,¹²⁷ U. Nauenberg,¹²⁷ J. G. Smith,¹²⁷ K. Stenson,¹²⁷ K. A. Ulmer,¹²⁷ S. R. Wagner,¹²⁷ J. Alexander,¹²⁸ A. Chatterjee,¹²⁸ J. Chu,¹²⁸ S. Dittmer,¹²⁸ N. Eggert,¹²⁸ N. Mirman,¹²⁸ G. Nicolas Kaufman,¹²⁸ J. R. Patterson,¹²⁸ A. Ryd,¹²⁸ E. Salvati,¹²⁸ L. Skinnari,¹²⁸ W. Sun,¹²⁸ W. D. Teo,¹²⁸ J. Thom,¹²⁸ J. Thompson,¹²⁸ J. Tucker,¹²⁸ Y. Weng,¹²⁸ L. Winstrom,¹²⁸ P. Wittich,¹²⁸ D. Winn,¹²⁹ S. Abdullin,¹³⁰ M. Albrow,¹³⁰ J. Anderson,¹³⁰ G. Apollinari,¹³⁰ L. A. T. Bauerick,¹³⁰ A. Beretvas,¹³⁰ J. Berryhill,¹³⁰ P. C. Bhat,¹³⁰ K. Burkett,¹³⁰ J. N. Butler,¹³⁰ H. W. K. Cheung,¹³⁰ F. Chlebana,¹³⁰ S. Cihangir,¹³⁰ V. D. Elvira,¹³⁰ I. Fisk,¹³⁰ J. Freeman,¹³⁰ Y. Gao,¹³⁰ E. Gottschalk,¹³⁰ L. Gray,¹³⁰ D. Green,¹³⁰ S. Grünendahl,¹³⁰ O. Gutsche,¹³⁰ J. Hanlon,¹³⁰ D. Hare,¹³⁰ R. M. Harris,¹³⁰ J. Hirschauer,¹³⁰ B. Hooberman,¹³⁰ S. Jindariani,¹³⁰ M. Johnson,¹³⁰ U. Joshi,¹³⁰ K. Kaadze,¹³⁰ B. Klima,¹³⁰ B. Kreis,¹³⁰ S. Kwan,¹³⁰ J. Linacre,¹³⁰ D. Lincoln,¹³⁰ R. Lipton,¹³⁰ T. Liu,¹³⁰ J. Lykken,¹³⁰ K. Maeshima,¹³⁰ J. M. Marraffino,¹³⁰ V. I. Martinez Outschoorn,¹³⁰ S. Maruyama,¹³⁰ D. Mason,¹³⁰ P. McBride,¹³⁰ K. Mishra,¹³⁰ S. Mrenna,¹³⁰ Y. Musienko,^{130,ee} S. Nahn,¹³⁰ C. Newman-Holmes,¹³⁰ V. O'Dell,¹³⁰ O. Prokofyev,¹³⁰ E. Sexton-Kennedy,¹³⁰ S. Sharma,¹³⁰ A. Soha,¹³⁰ W. J. Spalding,¹³⁰ L. Spiegel,¹³⁰ L. Taylor,¹³⁰ S. Tkaczyk,¹³⁰ N. V. Tran,¹³⁰ L. Uplegger,¹³⁰ E. W. Vaandering,¹³⁰ R. Vidal,¹³⁰ A. Whitbeck,¹³⁰ J. Whitmore,¹³⁰ F. Yang,¹³⁰ D. Acosta,¹³¹ P. Avery,¹³¹ D. Bourilkov,¹³¹ M. Carver,¹³¹ T. Cheng,¹³¹ D. Curry,¹³¹ S. Das,¹³¹ M. De Gruttola,¹³¹ G. P. Di Giovanni,¹³¹ R. D. Field,¹³¹ M. Fisher,¹³¹ I. K. Furic,¹³¹ J. Hugon,¹³¹ J. Konigsberg,¹³¹ A. Korytov,¹³¹ T. Kypreos,¹³¹ J. F. Low,¹³¹ K. Matchev,¹³¹ P. Milenovic,^{131,zz} G. Mitselmakher,¹³¹ L. Muniz,¹³¹ A. Rinkevicius,¹³¹ L. Shchutka,¹³¹ M. Snowball,¹³¹ J. Yelton,¹³¹ M. Zakaria,¹³¹ S. Hewamanage,¹³² S. Linn,¹³² P. Markowitz,¹³² G. Martinez,¹³² J. L. Rodriguez,¹³² T. Adams,¹³³ A. Askew,¹³³ J. Bochenek,¹³³ B. Diamond,¹³³ J. Haas,¹³³ S. Hagopian,¹³³ V. Hagopian,¹³³ K. F. Johnson,¹³³ H. Prosper,¹³³ V. Veeraraghavan,¹³³ M. Weinberg,¹³³ M. M. Baarmand,¹³⁴ M. Hohmann,¹³⁴ H. Kalakhety,¹³⁴ F. Yumiceva,¹³⁴ M. R. Adams,¹³⁵ L. Apanasevich,¹³⁵ V. E. Bazterra,¹³⁵ D. Berry,¹³⁵ R. R. Betts,¹³⁵ I. Bucinskaite,¹³⁵ R. Cavanaugh,¹³⁵ O. Evdokimov,¹³⁵ L. Gauthier,¹³⁵ C. E. Gerber,¹³⁵ D. J. Hofman,¹³⁵ S. Khalatyan,¹³⁵ P. Kurt,¹³⁵ D. H. Moon,¹³⁵ C. O'Brien,¹³⁵ C. Silkworth,¹³⁵ P. Turner,¹³⁵ N. Varelas,¹³⁵ E. A. Albayrak,^{136,ww} B. Bilki,^{136,aaa} W. Clarida,¹³⁶ K. Dilsiz,¹³⁶ F. Duru,¹³⁶ M. Haytmyradov,¹³⁶ J.-P. Merlo,¹³⁶ H. Mermerkaya,^{136,bbb} A. Mestvirishvili,¹³⁶ A. Moeller,¹³⁶ J. Nachtman,¹³⁶ H. Ogul,¹³⁶ Y. Onel,¹³⁶ F. Ozok,^{136,ww} A. Penzo,¹³⁶ R. Rahmat,¹³⁶ S. Sen,¹³⁶ P. Tan,¹³⁶ E. Tiras,¹³⁶ J. Wetzel,¹³⁶ T. Yetkin,^{136,ccc} K. Yi,¹³⁶ B. A. Barnett,¹³⁷ B. Blumenfeld,¹³⁷ S. Bolognesi,¹³⁷ D. Fehling,¹³⁷ A. V. Gritsan,¹³⁷ P. Maksimovic,¹³⁷ C. Martin,¹³⁷ M. Swartz,¹³⁷ P. Baringer,¹³⁸ A. Bean,¹³⁸ G. Benelli,¹³⁸ C. Bruner,¹³⁸ J. Gray,¹³⁸ R. P. Kenny III,¹³⁸ M. Malek,¹³⁸ M. Murray,¹³⁸ D. Noonan,¹³⁸ S. Sanders,¹³⁸ J. Sekaric,¹³⁸ R. Stringer,¹³⁸ Q. Wang,¹³⁸ J. S. Wood,¹³⁸ A. F. Barfuss,¹³⁹ I. Chakaberia,¹³⁹ A. Ivanov,¹³⁹ S. Khalil,¹³⁹ M. Makouski,¹³⁹ Y. Maravin,¹³⁹ L. K. Saini,¹³⁹ S. Shrestha,¹³⁹ N. Skhirtladze,¹³⁹ I. Svintradze,¹³⁹ J. Gronberg,¹⁴⁰ D. Lange,¹⁴⁰ F. Rebassoo,¹⁴⁰ D. Wright,¹⁴⁰ A. Baden,¹⁴¹ A. Belloni,¹⁴¹ B. Calvert,¹⁴¹ S. C. Eno,¹⁴¹ J. A. Gomez,¹⁴¹ N. J. Hadley,¹⁴¹ R. G. Kellogg,¹⁴¹ T. Kolberg,¹⁴¹ Y. Lu,¹⁴¹ M. Marionneau,¹⁴¹ A. C. Mignerey,¹⁴¹ K. Pedro,¹⁴¹ A. Skuja,¹⁴¹ M. B. Tonjes,¹⁴¹ S. C. Tonwar,¹⁴¹ A. Apyan,¹⁴² R. Barbieri,¹⁴² G. Bauer,¹⁴² W. Busza,¹⁴² I. A. Cali,¹⁴² M. Chan,¹⁴² L. Di Matteo,¹⁴² V. Dutta,¹⁴² G. Gomez Ceballos,¹⁴² M. Goncharov,¹⁴² D. Gulhan,¹⁴² M. Klute,¹⁴² Y. S. Lai,¹⁴² Y.-J. Lee,¹⁴² A. Levin,¹⁴² P. D. Luckey,¹⁴² T. Ma,¹⁴² C. Paus,¹⁴² D. Ralph,¹⁴² C. Roland,¹⁴² G. Roland,¹⁴² G. S. F. Stephans,¹⁴² F. Stöckli,¹⁴² K. Sumorok,¹⁴² D. Velicanu,¹⁴² J. Veverka,¹⁴² B. Wyslouch,¹⁴² M. Yang,¹⁴² M. Zanetti,¹⁴² V. Zhukova,¹⁴² B. Dahmes,¹⁴³ A. Gude,¹⁴³ S. C. Kao,¹⁴³ K. Klapoetke,¹⁴³ Y. Kubota,¹⁴³ J. Mans,¹⁴³ N. Pastika,¹⁴³ R. Rusack,¹⁴³ A. Singovsky,¹⁴³ N. Tambe,¹⁴³ J. Turkewitz,¹⁴³ J. G. Acosta,¹⁴⁴ S. Oliveros,¹⁴⁴ E. Avdeeva,¹⁴⁵ K. Bloom,¹⁴⁵ S. Bose,¹⁴⁵ D. R. Claes,¹⁴⁵ A. Dominguez,¹⁴⁵ R. Gonzalez Suarez,¹⁴⁵ J. Keller,¹⁴⁵ D. Knowlton,¹⁴⁵ I. Kravchenko,¹⁴⁵ J. Lazo-Flores,¹⁴⁵ S. Malik,¹⁴⁵ F. Meier,¹⁴⁵ G. R. Snow,¹⁴⁵ J. Dolen,¹⁴⁶ A. Godshalk,¹⁴⁶ I. Iashvili,¹⁴⁶ A. Kharchilava,¹⁴⁶ A. Kumar,¹⁴⁶ S. Rappoccio,¹⁴⁶ G. Alverson,¹⁴⁷ E. Barberis,¹⁴⁷ D. Baumgartel,¹⁴⁷ M. Chasco,¹⁴⁷ J. Haley,¹⁴⁷ A. Massironi,¹⁴⁷ D. M. Morse,¹⁴⁷ D. Nash,¹⁴⁷ T. Orimoto,¹⁴⁷ D. Trocino,¹⁴⁷

R. J. Wang,¹⁴⁷ D. Wood,¹⁴⁷ J. Zhang,¹⁴⁷ K. A. Hahn,¹⁴⁸ A. Kubik,¹⁴⁸ N. Mucia,¹⁴⁸ N. Odell,¹⁴⁸ B. Pollack,¹⁴⁸ A. Pozdnyakov,¹⁴⁸ M. Schmitt,¹⁴⁸ S. Stoynev,¹⁴⁸ K. Sung,¹⁴⁸ M. Velasco,¹⁴⁸ S. Won,¹⁴⁸ A. Brinkerhoff,¹⁴⁹ K. M. Chan,¹⁴⁹ A. Drozdetskiy,¹⁴⁹ M. Hildreth,¹⁴⁹ C. Jessop,¹⁴⁹ D. J. Karmgard,¹⁴⁹ N. Kellams,¹⁴⁹ K. Lannon,¹⁴⁹ W. Luo,¹⁴⁹ S. Lynch,¹⁴⁹ N. Marinelli,¹⁴⁹ T. Pearson,¹⁴⁹ M. Planer,¹⁴⁹ R. Ruchti,¹⁴⁹ N. Valls,¹⁴⁹ M. Wayne,¹⁴⁹ M. Wolf,¹⁴⁹ A. Woodard,¹⁴⁹ L. Antonelli,¹⁵⁰ J. Brinson,¹⁵⁰ B. Bylsma,¹⁵⁰ L. S. Durkin,¹⁵⁰ S. Flowers,¹⁵⁰ C. Hill,¹⁵⁰ R. Hughes,¹⁵⁰ K. Kotov,¹⁵⁰ T. Y. Ling,¹⁵⁰ D. Puigh,¹⁵⁰ M. Rodenburg,¹⁵⁰ G. Smith,¹⁵⁰ B. L. Winer,¹⁵⁰ H. Wolfe,¹⁵⁰ H. W. Wulsin,¹⁵⁰ O. Driga,¹⁵¹ P. Elmer,¹⁵¹ P. Hebda,¹⁵¹ A. Hunt,¹⁵¹ S. A. Koay,¹⁵¹ P. Lujan,¹⁵¹ D. Marlow,¹⁵¹ T. Medvedeva,¹⁵¹ M. Mooney,¹⁵¹ J. Olsen,¹⁵¹ P. Piroué,¹⁵¹ X. Quan,¹⁵¹ H. Saka,¹⁵¹ D. Stickland,^{151,c} C. Tully,¹⁵¹ J. S. Werner,¹⁵¹ S. C. Zenz,¹⁵¹ A. Zuranski,¹⁵¹ E. Brownson,¹⁵² H. Mendez,¹⁵² J. E. Ramirez Vargas,¹⁵² E. Alagoz,¹⁵³ V. E. Barnes,¹⁵³ D. Benedetti,¹⁵³ G. Bolla,¹⁵³ D. Bortoletto,¹⁵³ M. De Mattia,¹⁵³ Z. Hu,¹⁵³ M. K. Jha,¹⁵³ M. Jones,¹⁵³ K. Jung,¹⁵³ M. Kress,¹⁵³ N. Leonardo,¹⁵³ D. Lopes Pegna,¹⁵³ V. Maroussov,¹⁵³ P. Merkel,¹⁵³ D. H. Miller,¹⁵³ N. Neumeister,¹⁵³ B. C. Radburn-Smith,¹⁵³ X. Shi,¹⁵³ I. Shipsey,¹⁵³ D. Silvers,¹⁵³ A. Svyatkovskiy,¹⁵³ F. Wang,¹⁵³ W. Xie,¹⁵³ L. Xu,¹⁵³ H. D. Yoo,¹⁵³ J. Zablocki,¹⁵³ Y. Zheng,¹⁵³ N. Parashar,¹⁵⁴ J. Stupak,¹⁵⁴ A. Adair,¹⁵⁵ B. Akgun,¹⁵⁵ K. M. Ecklund,¹⁵⁵ F. J. M. Geurts,¹⁵⁵ W. Li,¹⁵⁵ B. Michlin,¹⁵⁵ B. P. Padley,¹⁵⁵ R. Redjimi,¹⁵⁵ J. Roberts,¹⁵⁵ J. Zabel,¹⁵⁵ B. Betchart,¹⁵⁶ A. Bodek,¹⁵⁶ R. Covarelli,¹⁵⁶ P. de Barbaro,¹⁵⁶ R. Demina,¹⁵⁶ Y. Eshaq,¹⁵⁶ T. Ferbel,¹⁵⁶ A. Garcia-Bellido,¹⁵⁶ P. Goldenzweig,¹⁵⁶ J. Han,¹⁵⁶ A. Harel,¹⁵⁶ A. Khukhunaishvili,¹⁵⁶ G. Petrillo,¹⁵⁶ D. Vishnevskiy,¹⁵⁶ R. Ciesielski,¹⁵⁷ L. Demortier,¹⁵⁷ K. Goulios,¹⁵⁷ G. Lungu,¹⁵⁷ C. Mesropian,¹⁵⁷ S. Arora,¹⁵⁸ A. Barker,¹⁵⁸ J. P. Chou,¹⁵⁸ C. Contreras-Campana,¹⁵⁸ E. Contreras-Campana,¹⁵⁸ D. Duggan,¹⁵⁸ D. Ferencek,¹⁵⁸ Y. Gershtein,¹⁵⁸ R. Gray,¹⁵⁸ E. Halkiadakis,¹⁵⁸ D. Hidas,¹⁵⁸ A. Lath,¹⁵⁸ S. Panwalkar,¹⁵⁸ M. Park,¹⁵⁸ R. Patel,¹⁵⁸ S. Salur,¹⁵⁸ S. Schnetzer,¹⁵⁸ S. Somalwar,¹⁵⁸ R. Stone,¹⁵⁸ S. Thomas,¹⁵⁸ P. Thomassen,¹⁵⁸ M. Walker,¹⁵⁸ K. Rose,¹⁵⁹ S. Spanier,¹⁵⁹ A. York,¹⁵⁹ O. Bouhali,^{160,ddd} R. Eusebi,¹⁶⁰ W. Flanagan,¹⁶⁰ J. Gilmore,¹⁶⁰ T. Kamon,^{160,eee} V. Khotilovich,¹⁶⁰ V. Krutelyov,¹⁶⁰ R. Montalvo,¹⁶⁰ I. Osipenkov,¹⁶⁰ Y. Pakhotin,¹⁶⁰ A. Perloff,¹⁶⁰ J. Roe,¹⁶⁰ A. Rose,¹⁶⁰ A. Safonov,¹⁶⁰ T. Sakuma,¹⁶⁰ I. Suarez,¹⁶⁰ A. Tatarinov,¹⁶⁰ N. Akchurin,¹⁶¹ C. Cowden,¹⁶¹ J. Damgov,¹⁶¹ C. Dragoiu,¹⁶¹ P. R. Duderø,¹⁶¹ J. Faulkner,¹⁶¹ K. Kovitanggoon,¹⁶¹ S. Kunori,¹⁶¹ S. W. Lee,¹⁶¹ T. Libeiro,¹⁶¹ I. Volobouev,¹⁶¹ E. Appelt,¹⁶² A. G. Delannoy,¹⁶² S. Greene,¹⁶² A. Gurrola,¹⁶² W. Johns,¹⁶² C. Maguire,¹⁶² Y. Mao,¹⁶² A. Melo,¹⁶² M. Sharma,¹⁶² P. Sheldon,¹⁶² B. Snook,¹⁶² S. Tuo,¹⁶² J. Velkovska,¹⁶² M. W. Arenton,¹⁶³ S. Boutle,¹⁶³ B. Cox,¹⁶³ B. Francis,¹⁶³ J. Goodell,¹⁶³ R. Hirosky,¹⁶³ A. Ledovskoy,¹⁶³ H. Li,¹⁶³ C. Lin,¹⁶³ C. Neu,¹⁶³ J. Wood,¹⁶³ C. Clarke,¹⁶⁴ R. Harr,¹⁶⁴ P. E. Karchin,¹⁶⁴ C. Kottachchi Kankanamge Don,¹⁶⁴ P. Lamichhane,¹⁶⁴ J. Sturdy,¹⁶⁴ D. A. Belknap,¹⁶⁵ D. Carlsmith,¹⁶⁵ M. Cepeda,¹⁶⁵ S. Dasu,¹⁶⁵ L. Dodd,¹⁶⁵ S. Duric,¹⁶⁵ E. Friis,¹⁶⁵ R. Hall-Wilton,¹⁶⁵ M. Herndon,¹⁶⁵ A. Hervé,¹⁶⁵ P. Klabbers,¹⁶⁵ A. Lanaro,¹⁶⁵ C. Lazaridis,¹⁶⁵ A. Levine,¹⁶⁵ R. Loveless,¹⁶⁵ A. Mohapatra,¹⁶⁵ I. Ojalvo,¹⁶⁵ T. Perry,¹⁶⁵ G. A. Pierro,¹⁶⁵ G. Polese,¹⁶⁵ I. Ross,¹⁶⁵ T. Sarangi,¹⁶⁵ A. Savin,¹⁶⁵ W. H. Smith,¹⁶⁵ C. Vuosalo,¹⁶⁵ and N. Woods¹⁶⁵

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*

²*Institut für Hochenergiephysik der OeAW, Wien, Austria*

³*National Centre for Particle and High Energy Physics, Minsk, Belarus*

⁴*Universiteit Antwerpen, Antwerpen, Belgium*

⁵*Vrije Universiteit Brussel, Brussel, Belgium*

⁶*Université Libre de Bruxelles, Bruxelles, Belgium*

⁷*Ghent University, Ghent, Belgium*

⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

⁹*Université de Mons, Mons, Belgium*

¹⁰*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

¹¹*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

^{12a}*Universidade Estadual Paulista, São Paulo, Brazil*

^{12b}*Universidade Federal do ABC, São Paulo, Brazil*

¹³*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

¹⁴*University of Sofia, Sofia, Bulgaria*

¹⁵*Institute of High Energy Physics, Beijing, China*

¹⁶*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

¹⁷*Universidad de Los Andes, Bogota, Colombia*

- ¹⁸*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
- ¹⁹*University of Split, Faculty of Science, Split, Croatia*
- ²⁰*Institute Rudjer Boskovic, Zagreb, Croatia*
- ²¹*University of Cyprus, Nicosia, Cyprus*
- ²²*Charles University, Prague, Czech Republic*
- ²³*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
- ²⁴*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ²⁵*Department of Physics, University of Helsinki, Helsinki, Finland*
- ²⁶*Helsinki Institute of Physics, Helsinki, Finland*
- ²⁷*Lappeenranta University of Technology, Lappeenranta, Finland*
- ²⁸*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
- ²⁹*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
- ³⁰*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
- ³¹*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
- ³²*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
- ³³*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
- ³⁴*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ³⁵*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ³⁶*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ³⁷*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ³⁸*University of Hamburg, Hamburg, Germany*
- ³⁹*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
- ⁴⁰*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁴¹*University of Athens, Athens, Greece*
- ⁴²*University of Ioánnina, Ioánnina, Greece*
- ⁴³*Wigner Research Centre for Physics, Budapest, Hungary*
- ⁴⁴*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁴⁵*University of Debrecen, Debrecen, Hungary*
- ⁴⁶*National Institute of Science Education and Research, Bhubaneswar, India*
- ⁴⁷*Panjab University, Chandigarh, India*
- ⁴⁸*University of Delhi, Delhi, India*
- ⁴⁹*Saha Institute of Nuclear Physics, Kolkata, India*
- ⁵⁰*Bhabha Atomic Research Centre, Mumbai, India*
- ⁵¹*Tata Institute of Fundamental Research, Mumbai, India*
- ⁵²*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁵³*University College Dublin, Dublin, Ireland*
- ^{54a}*INFN Sezione di Bari, Bari, Italy*
- ^{54b}*Università di Bari, Bari, Italy*
- ^{54c}*Politecnico di Bari, Bari, Italy*
- ^{55a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{55b}*Università di Bologna, Bologna, Italy*
- ^{56a}*INFN Sezione di Catania, Catania, Italy*
- ^{56b}*Università di Catania, Catania, Italy*
- ^{56c}*CSFNSM, Catania, Italy*
- ^{57a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{57b}*Università di Firenze, Firenze, Italy*
- ⁵⁸*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{59a}*INFN Sezione di Genova, Genova, Italy*
- ^{59b}*Università di Genova, Genova, Italy*
- ^{60a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{60b}*Università di Milano-Bicocca, Milano, Italy*
- ^{61a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{61b}*Università di Napoli 'Federico II', Napoli, Italy*
- ^{61c}*Università della Basilicata (Potenza), Napoli, Italy*
- ^{61d}*Università G. Marconi (Roma), Napoli, Italy*

- ^{62a}INFN Sezione di Padova, Padova, Italy
^{62b}Università di Padova, Padova, Italy
^{62c}Università di Trento (Trento), Padova, Italy
^{63a}INFN Sezione di Pavia, Pavia, Italy
^{63b}Università di Pavia, Pavia, Italy
^{64a}INFN Sezione di Perugia, Perugia, Italy
^{64b}Università di Perugia, Perugia, Italy
^{65a}INFN Sezione di Pisa, Pisa, Italy
^{65b}Università di Pisa, Pisa, Italy
^{65c}Scuola Normale Superiore di Pisa, Pisa, Italy
^{66a}INFN Sezione di Roma, Roma, Italy
^{66b}Università di Roma, Roma, Italy
^{67a}INFN Sezione di Torino, Torino, Italy
^{67b}Università di Torino, Torino, Italy
^{67c}Università del Piemonte Orientale (Novara), Torino, Italy
^{68a}INFN Sezione di Trieste, Trieste, Italy
^{68b}Università di Trieste, Trieste, Italy
⁶⁹Kangwon National University, Chunchon, Korea
⁷⁰Kyungpook National University, Daegu, Korea
⁷¹Chonbuk National University, Jeonju, Korea
⁷²Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
⁷³Korea University, Seoul, Korea
⁷⁴University of Seoul, Seoul, Korea
⁷⁵Sungkyunkwan University, Suwon, Korea
⁷⁶Vilnius University, Vilnius, Lithuania
⁷⁷National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
⁷⁸Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
⁷⁹Universidad Iberoamericana, Mexico City, Mexico
⁸⁰Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
⁸¹Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
⁸²University of Auckland, Auckland, New Zealand
⁸³University of Canterbury, Christchurch, New Zealand
⁸⁴National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
⁸⁵National Centre for Nuclear Research, Swierk, Poland
⁸⁶Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
⁸⁷Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
⁸⁸Joint Institute for Nuclear Research, Dubna, Russia
⁸⁹Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
⁹⁰Institute for Nuclear Research, Moscow, Russia
⁹¹Institute for Theoretical and Experimental Physics, Moscow, Russia
⁹²P.N. Lebedev Physical Institute, Moscow, Russia
⁹³Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
⁹⁴State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
⁹⁵University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
⁹⁶Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
⁹⁷Universidad Autónoma de Madrid, Madrid, Spain
⁹⁸Universidad de Oviedo, Oviedo, Spain
⁹⁹Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
¹⁰⁰CERN, European Organization for Nuclear Research, Geneva, Switzerland
¹⁰¹Paul Scherrer Institut, Villigen, Switzerland
¹⁰²Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
¹⁰³Universität Zürich, Zurich, Switzerland
¹⁰⁴National Central University, Chung-Li, Taiwan
¹⁰⁵National Taiwan University (NTU), Taipei, Taiwan
¹⁰⁶Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
¹⁰⁷Cukurova University, Adana, Turkey
¹⁰⁸Middle East Technical University, Physics Department, Ankara, Turkey
¹⁰⁹Bogazici University, Istanbul, Turkey
¹¹⁰Istanbul Technical University, Istanbul, Turkey
¹¹¹National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

- ¹¹²*University of Bristol, Bristol, United Kingdom*
¹¹³*Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹¹⁴*Imperial College, London, United Kingdom*
¹¹⁵*Brunel University, Uxbridge, United Kingdom*
¹¹⁶*Baylor University, Waco, USA*
¹¹⁷*The University of Alabama, Tuscaloosa, USA*
¹¹⁸*Boston University, Boston, USA*
¹¹⁹*Brown University, Providence, USA*
¹²⁰*University of California, Davis, Davis, USA*
¹²¹*University of California, Los Angeles, USA*
¹²²*University of California, Riverside, Riverside, USA*
¹²³*University of California, San Diego, La Jolla, USA*
¹²⁴*University of California, Santa Barbara, Santa Barbara, USA*
¹²⁵*California Institute of Technology, Pasadena, USA*
¹²⁶*Carnegie Mellon University, Pittsburgh, USA*
¹²⁷*University of Colorado at Boulder, Boulder, USA*
¹²⁸*Cornell University, Ithaca, USA*
¹²⁹*Fairfield University, Fairfield, USA*
¹³⁰*Fermi National Accelerator Laboratory, Batavia, USA*
¹³¹*University of Florida, Gainesville, USA*
¹³²*Florida International University, Miami, USA*
¹³³*Florida State University, Tallahassee, USA*
¹³⁴*Florida Institute of Technology, Melbourne, USA*
¹³⁵*University of Illinois at Chicago (UIC), Chicago, USA*
¹³⁶*The University of Iowa, Iowa City, USA*
¹³⁷*Johns Hopkins University, Baltimore, USA*
¹³⁸*The University of Kansas, Lawrence, USA*
¹³⁹*Kansas State University, Manhattan, USA*
¹⁴⁰*Lawrence Livermore National Laboratory, Livermore, USA*
¹⁴¹*University of Maryland, College Park, USA*
¹⁴²*Massachusetts Institute of Technology, Cambridge, USA*
¹⁴³*University of Minnesota, Minneapolis, USA*
¹⁴⁴*University of Mississippi, Oxford, USA*
¹⁴⁵*University of Nebraska-Lincoln, Lincoln, USA*
¹⁴⁶*State University of New York at Buffalo, Buffalo, USA*
¹⁴⁷*Northeastern University, Boston, USA*
¹⁴⁸*Northwestern University, Evanston, USA*
¹⁴⁹*University of Notre Dame, Notre Dame, USA*
¹⁵⁰*The Ohio State University, Columbus, USA*
¹⁵¹*Princeton University, Princeton, USA*
¹⁵²*University of Puerto Rico, Mayaguez, USA*
¹⁵³*Purdue University, West Lafayette, USA*
¹⁵⁴*Purdue University Calumet, Hammond, USA*
¹⁵⁵*Rice University, Houston, USA*
¹⁵⁶*University of Rochester, Rochester, USA*
¹⁵⁷*The Rockefeller University, New York, USA*
¹⁵⁸*Rutgers, The State University of New Jersey, Piscataway, USA*
¹⁵⁹*University of Tennessee, Knoxville, USA*
¹⁶⁰*Texas A&M University, College Station, USA*
¹⁶¹*Texas Tech University, Lubbock, USA*
¹⁶²*Vanderbilt University, Nashville, USA*
¹⁶³*University of Virginia, Charlottesville, USA*
¹⁶⁴*Wayne State University, Detroit, USA*
¹⁶⁵*University of Wisconsin, Madison, USA*

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

^cAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

^dAlso at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

- ^e Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
- ^f Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- ^g Also at Universidade Estadual de Campinas, Campinas, Brazil.
- ^h Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
- ⁱ Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ^j Also at Suez University, Suez, Egypt.
- ^k Also at Cairo University, Cairo, Egypt.
- ^l Also at Fayoum University, El-Fayoum, Egypt.
- ^m Also at British University in Egypt, Cairo, Egypt.
- ⁿ Also at Ain Shams University, Cairo, Egypt.
- ^o Also at Université de Haute Alsace, Mulhouse, France.
- ^p Also at Brandenburg University of Technology, Cottbus, Germany.
- ^q Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^r Also at Eötvös Loránd University, Budapest, Hungary.
- ^s Also at University of Debrecen, Debrecen, Hungary.
- ^t Also at University of Visva-Bharati, Santiniketan, India.
- ^u Also at King Abdulaziz University, Jeddah, Saudi Arabia.
- ^v Also at University of Ruhuna, Matara, Sri Lanka.
- ^w Also at Isfahan University of Technology, Isfahan, Iran.
- ^x Also at Sharif University of Technology, Tehran, Iran.
- ^y Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ^z Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- ^{aa} Also at Università degli Studi di Siena, Siena, Italy.
- ^{bb} Also at Centre National de la Recherche Scientifique (CNRS)- IN2P3, Paris, France.
- ^{cc} Also at Purdue University, West Lafayette, USA.
- ^{dd} Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
- ^{ee} Also at Institute for Nuclear Research, Moscow, Russia.
- ^{ff} Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{gg} Also at California Institute of Technology, Pasadena, USA.
- ^{hh} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁱⁱ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ^{jj} Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ^{kk} Also at University of Athens, Athens, Greece.
- ^{ll} Also at Paul Scherrer Institut, Villigen, Switzerland.
- ^{mm} Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁿⁿ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ^{oo} Also at Gaziosmanpasa University, Tokat, Turkey.
- ^{pp} Also at Adiyaman University, Adiyaman, Turkey.
- ^{qq} Also at Cag University, Mersin, Turkey.
- ^{rr} Also at Mersin University, Mersin, Turkey.
- ^{ss} Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{tt} Also at Ozyegin University, Istanbul, Turkey.
- ^{uu} Also at Marmara University, Istanbul, Turkey.
- ^{vv} Also at Kafkas University, Kars, Turkey.
- ^{ww} Also at Mimar Sinan University, Istanbul, Turkey.
- ^{xx} Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^{yy} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{zz} Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{aaa} Also at Argonne National Laboratory, Argonne, USA.
- ^{bbb} Also at Erzincan University, Erzincan, Turkey.
- ^{ccc} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{ddd} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{eee} Also at Kyungpook National University, Daegu, Korea.