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

The CMS Collaboration[*]

Abstract

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 $4.9\,\text{fb}^{-1}$. 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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[*] See Appendix A for the list of collaboration members

1 Introduction

Measurements of the production of a Z boson with one or more jets in hadron collisions, hereafter Z+jets, can be compared with predictions of perturbative quantum chromodynamics (pQCD). Also, this process contributes a large background to many electroweak production processes and searches for phenomena beyond the standard model. Measurements of Z+jets production were published by the CDF and D0 Collaborations based on a sample of proton-antiproton collisions at $\sqrt{s} = 1.96\,\text{TeV}$ [1, 2], and by the ATLAS [3] and CMS [4] Collaborations from a sample of proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ collected at the CERN LHC, corresponding to an integrated luminosity of $0.036\,\text{fb}^{-1}$. ATLAS has reported an updated measurement at the same center-of-mass energy with a dataset corresponding to an integrated luminosity of $4.6\,\text{fb}^{-1}$ [5].

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 $4.9 \pm 0.1\,\text{fb}^{-1}$ [6] collected in 2011. We present fiducial cross sections for Z+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 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 paper is organized as follows. Section 2 presents a description of the CMS apparatus and its main characteristics. Section 3 provides details about the simulation used in this analysis. Section 4 discusses the event reconstruction and selection. Section 5 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 Section 6. Section 7 describes the estimation of the systematic uncertainties, and in Section 8 the results are presented and compared to theoretical predictions.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter that provides a magnetic field of 3.8 T. 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 endcaps. The magnet flux-return yoke is instrumented with gas-ionization tracking devices for muon detection. In addition to the barrel and endcap 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 $4\,\mu$s. 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. [7].

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 $15\,\mu$m 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% [8].

3 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^*, $\mathrm{t\bar{t}}$, and W+jets events are generated using the MADGRAPH 5.1.1 [9] 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 $\mathrm{t\bar{t}}$ events. The leading-order CTEQ6L1 parton distribution functions (PDF) [10] are used with MADGRAPH. The residual QCD radiation, described by a parton shower algorithm, and the hadronization, which turns partons into physical particles, are implemented with PYTHIA 6.424 [11] using the Z2 underlying event and fragmentation tune [12]. The matrix-element and parton shower calculations are matched using the k_{T}-MLM algorithm [13]. Decays of the τ lepton are described by the TAUOLA 1.27 [14] package. Diboson events (WW, WZ, ZZ) are modeled entirely with PYTHIA. Single-top events in the Wt channel are simulated using POWHEG-BOX [15–18], and followed by PYTHIA to describe QCD radiation beyond next-to-leading-order (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 [19–22] tree level matrix-element calculation, which has up to four additional partons in the final state, and uses the NLO CTEQ6.6M [23] 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 [24] and the MSTW2008 [25] PDF set. The $\mathrm{t\bar{t}}$ cross section is normalized to the NNLO prediction from Ref. [26]. Diboson cross sections are rescaled to the NLO predictions obtained with MCFM [27].

The interaction of the generated particles in the CMS detector is simulated using the GEANT4 toolkit [28, 29]. 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.

4 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 GeV 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 [30, 31], which combines the information from all CMS subdetectors to reconstruct and classify muons, electrons, photons, charged hadrons, and neutral hadrons.

Electrons are selected with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ in the fiducial region of pseudorapidity $|\eta| < 2.4$, but excluding the region $1.44 < |\eta| < 1.57$ between the barrel and the endcaps of ECAL to ensure uniform quality of reconstruction. The electron identification criteria [32, 33] comprise requirements on the distance in η–ϕ 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 η–ϕ plane. An isolation variable is defined as $I_{\text{rel}} = (I_{\text{charged}} + I_{\text{photon}} + I_{\text{neutral}})/p_{\mathrm{T}}^{\mathrm{e}}$, 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 $p_{\mathrm{T}}^{\mathrm{e}}$ 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 [34].

The selected muons must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ 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 [35] with a radius parameter $\Delta R = 0.5$ as implemented in the FASTJET package [36, 37]. In order to reject misreconstructed jets and instrumental noise, identification quality criteria are imposed on the jets based on the multiplicity and energy fraction of the charged, electromagnetic, and neutral hadronic components.

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 [8] relies on a combination of PYTHIA multijet simulations and measurements of exclusive dijet and photon+jet events from data. The corrections are parameterized 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 [34], 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.

A minimum threshold of $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ is required for the jets to reduce contamination from the underlying event and to ensure a good jet energy resolution. 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 η–ϕ plane.

5 Signal efficiency and background

A "tag-and-probe" technique [38] is used to estimate efficiencies for trigger selection, event reconstruction, and the offline selection of the Z+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 endcap electromagnetic calorimeters. In order to facilitate the combination of results from the $\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}$ and $\mathrm{Z} \to \mu^{+}\mu^{-}$ final states, this difference is evaluated using the simulation, giving a correction to the $\mathrm{e}^{+}\mathrm{e}^{-}$ 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 $\mathrm{t\bar{t}}$, while dibosons contribute near the Z-boson invariant-mass peak. Other minor contributions arise from $\mathrm{Z} \to \tau^{+}\tau^{-}$ as well as single-top and W+jets events. The contamination from multijet events produced through the strong interaction is negligible [39]. The total contribution of the backgrounds is approximately 1% of the total yield of the selected events, although the background contribution is larger at higher jet multiplicities, where it can reach 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 jet multiplicity in data and that in signal plus background simulation, shown in the bottom part of the figure, is compatible with unity within the uncertainties.

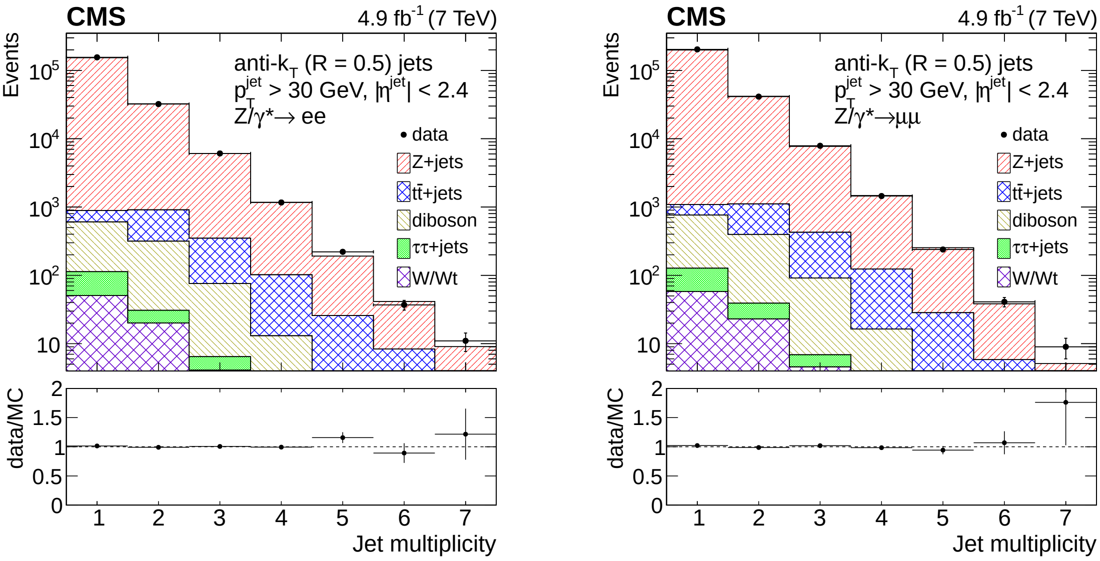

Figure 1: Distributions of the exclusive jet multiplicity for the electron channel (left) and muon channel (right). Data are compared to the simulation, which is the sum of signal and background events. Scale factors have been used to correct simulation distributions for residual efficiency differences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

6 Unfolding

The distributions of the observables are corrected for event selection efficiencies and for detector resolution effects in order to compare with predictions from event generators. The correction procedure is based on unfolding techniques, as implemented in the ROOUNFOLD toolkit [40], which provides both "singular value decomposition" (SVD) [41] and D'Agostini [42] methods. Both algorithms use a "response matrix" that correlates the values of the observable with and without detector effects. Each algorithm depends on regularization parameters, which are tuned to obtain results that are robust against numerical instabilities and statistical fluctuations. Migration effects across kinematic thresholds due to experimental resolution, inducing a yield variation in the measured cross section, are taken into account.

The response matrix is evaluated using Z+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. Particles are considered stable if their proper average lifetime τ satisfies $c\tau > 10\,\mathrm{cm}$. 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 $\Delta R = 0.1$. 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 $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$, the jet contains at least one charged particle, 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. 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.

7 Systematic uncertainties

The sources of systematic uncertainties that affect the Z+jets cross section measurement are divided into the following categories: jet energy scale (JES) and jet energy resolution (JER) [8], 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 of the JES systematic uncertainty. The JER in data is known to be worse than in the simulation, so the simulated resolution is degraded to compensate for this effect. The effect of the systematic uncertainties from this JER degradation is estimated by varying it 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 $\mathrm{t\bar{t}}$ 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 Section 3) and the corresponding CMS measurement [43–46]. The largest of these two values is taken as the magnitude of the uncertainty. As observed in previous studies [39], the single-top and W+jets contributions are very small, 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 $\mathrm{t\bar{t}}$ background as a function of the jet multiplicity is compared with the data using a control sample enriched in $\mathrm{t\bar{t}}$ events. This sample is selected by requiring the presence of two leptons of different flavors, i.e., $\mathrm{e}\mu$ combinations, and an agreement is found between data and simulation at the 6% level [39]. The CMS measurement of the $\mathrm{t\bar{t}}$ differential cross section [47], 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 subsample. Variations in the MADGRAPH prediction 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 ±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 1, 2, and 3.

Table 1: 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 (%)	$\sigma(\mathrm{Z}/\gamma^* + \text{jets})$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}(1^{\text{st}}\text{ jet})$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}(2^{\text{nd}}\text{ jet})$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}(3^{\text{rd}}\text{ jet})$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}}(4^{\text{th}}\text{ jet})$
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 syst. 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

Table 2: 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 (%)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}$ (1^{st} jet)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}$ (2^{nd} jet)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}$ (3^{rd} jet)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}$ (4^{th} 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 syst. 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 3: 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 (%)	$\frac{\mathrm{d}\sigma}{\mathrm{d}H_{\mathrm{T}}}, N_{\text{jet}} \geq 1$	$\frac{\mathrm{d}\sigma}{\mathrm{d}H_{\mathrm{T}}}, N_{\text{jet}} \geq 2$	$\frac{\mathrm{d}\sigma}{\mathrm{d}H_{\mathrm{T}}}, N_{\text{jet}} \geq 3$	$\frac{\mathrm{d}\sigma}{\mathrm{d}H_{\mathrm{T}}}, N_{\text{jet}} \geq 4$
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 syst. 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

8 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 obtained with the same analysis on generated events as in the unfolding procedure.

Theoretical predictions at leading order in QCD 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 dynamically chosen on an event-by-event basis as the transverse mass of the event, clustered with the k_T algorithm down to a 2$\to$2 topology, and k_T at each vertex splitting, respectively. The MADGRAPH predictions are rescaled to the available NNLO inclusive cross section [24], 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 [19–22, 48], using the CT10 NLO PDF set [49], 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 [50]. In this calculation, the factorization and renormalization scales are dynamically defined for each event by clustering the 2$\to n$ parton level kinematics onto a core 2$\to$2 configuration using a k_T-type algorithm, and using the smallest invariant mass or virtuality in the core configuration as the scale [48]. 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 [15–17, 51], 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 dynamically 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 comparison 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 from the NLO alternatives MSTW2008 and NNPDF2.1 [52].

8.1 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 event sample is too small to perform the unfolding procedure. The trend of the jet multiplicity represents the expectation of the pQCD prediction for a staircase-like scaling, with an approximately constant ratio between cross sections for successive multiplicities [53]. This result confirms the previous observation, which was based on a more statistically limited sample [4]. Within the uncertainties, there is agreement between theory and measurement for both the inclusive and the exclusive distributions.

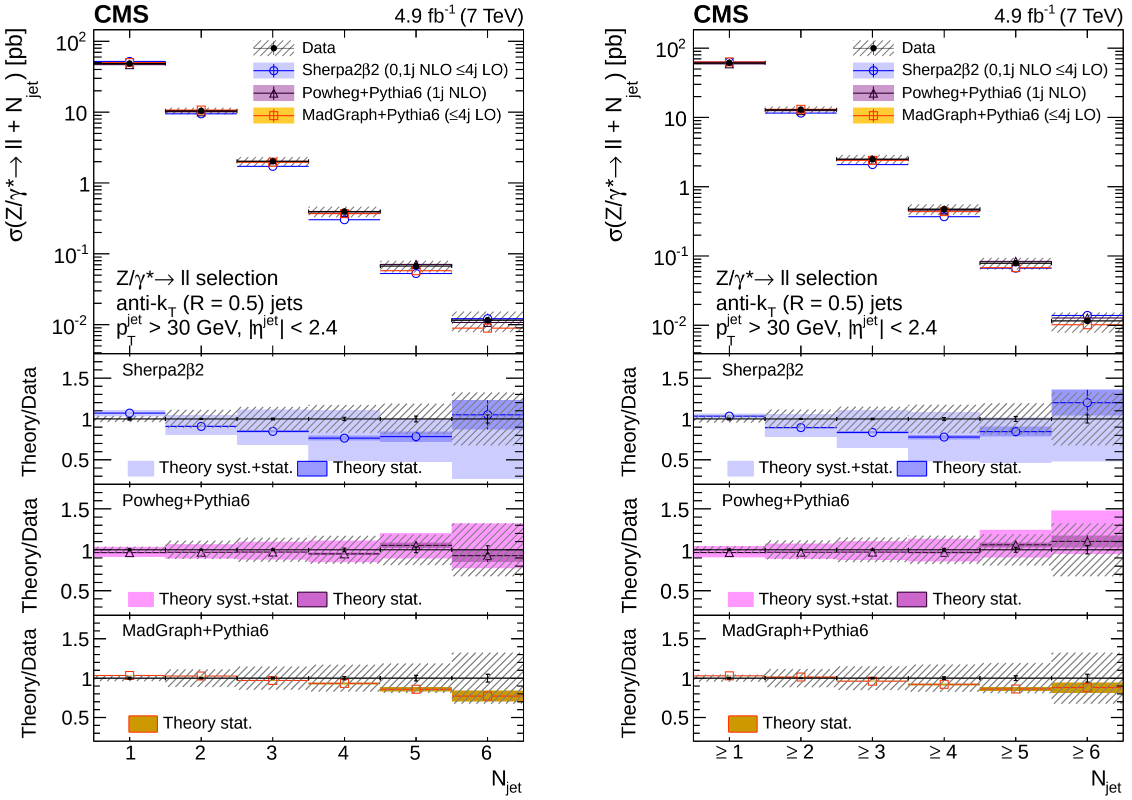

Figure 2: Exclusive (left) and inclusive (right) jet multiplicity distributions, after the unfolding procedure, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, while cross-hatched bands represent statistical plus 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.

8.2 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 MADGRAPH prediction 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 $p_T > 100\,\text{GeV}$. 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.

9 Summary

The fiducial production cross section of a Z boson with at least one hadronic jet has been measured in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ in a sample corresponding to an integrated luminosity of $4.9\,\text{fb}^{-1}$. 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 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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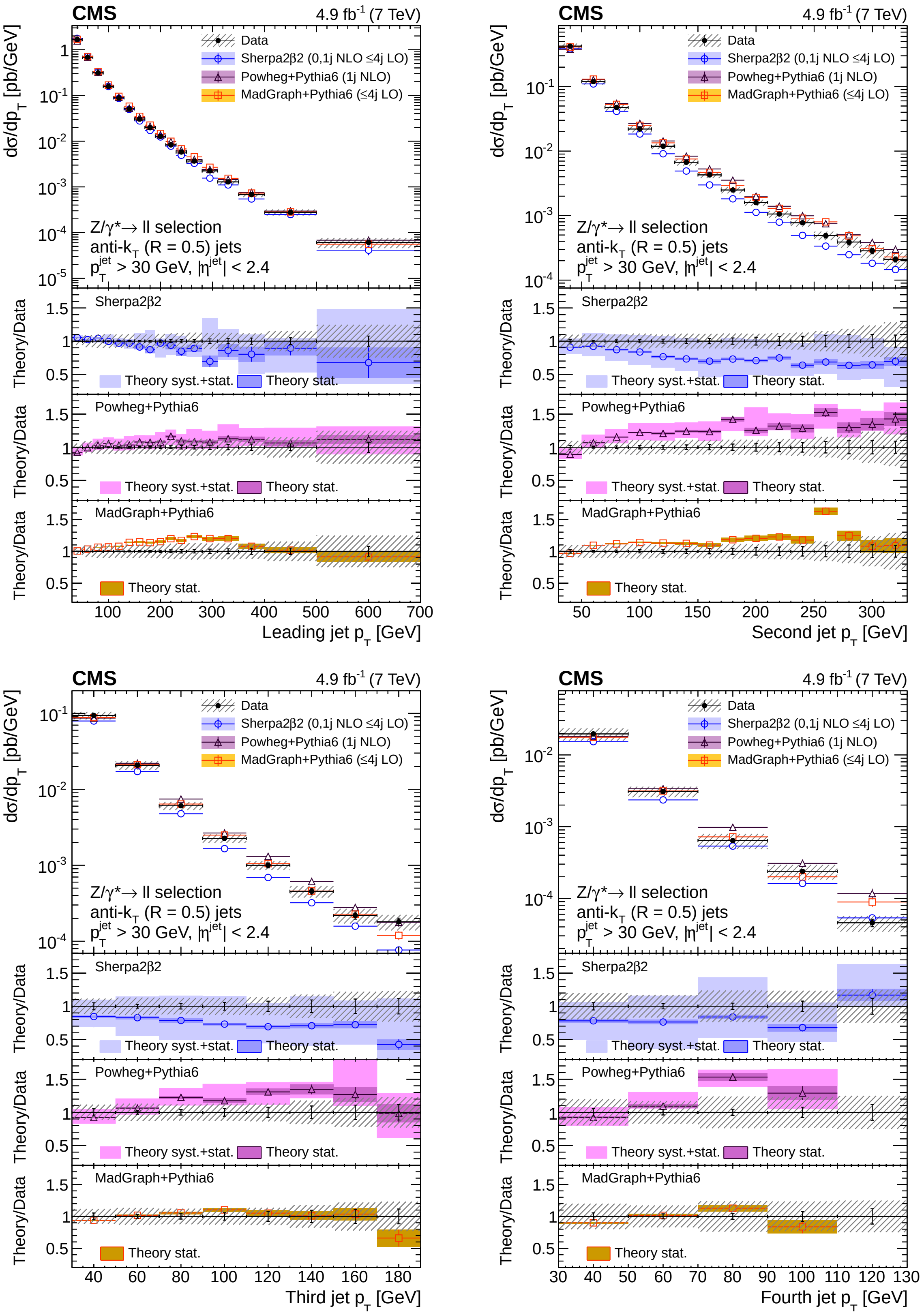

Figure 3: Unfolded differential cross section as a function of p_{T} for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_{T} jets, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical 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.

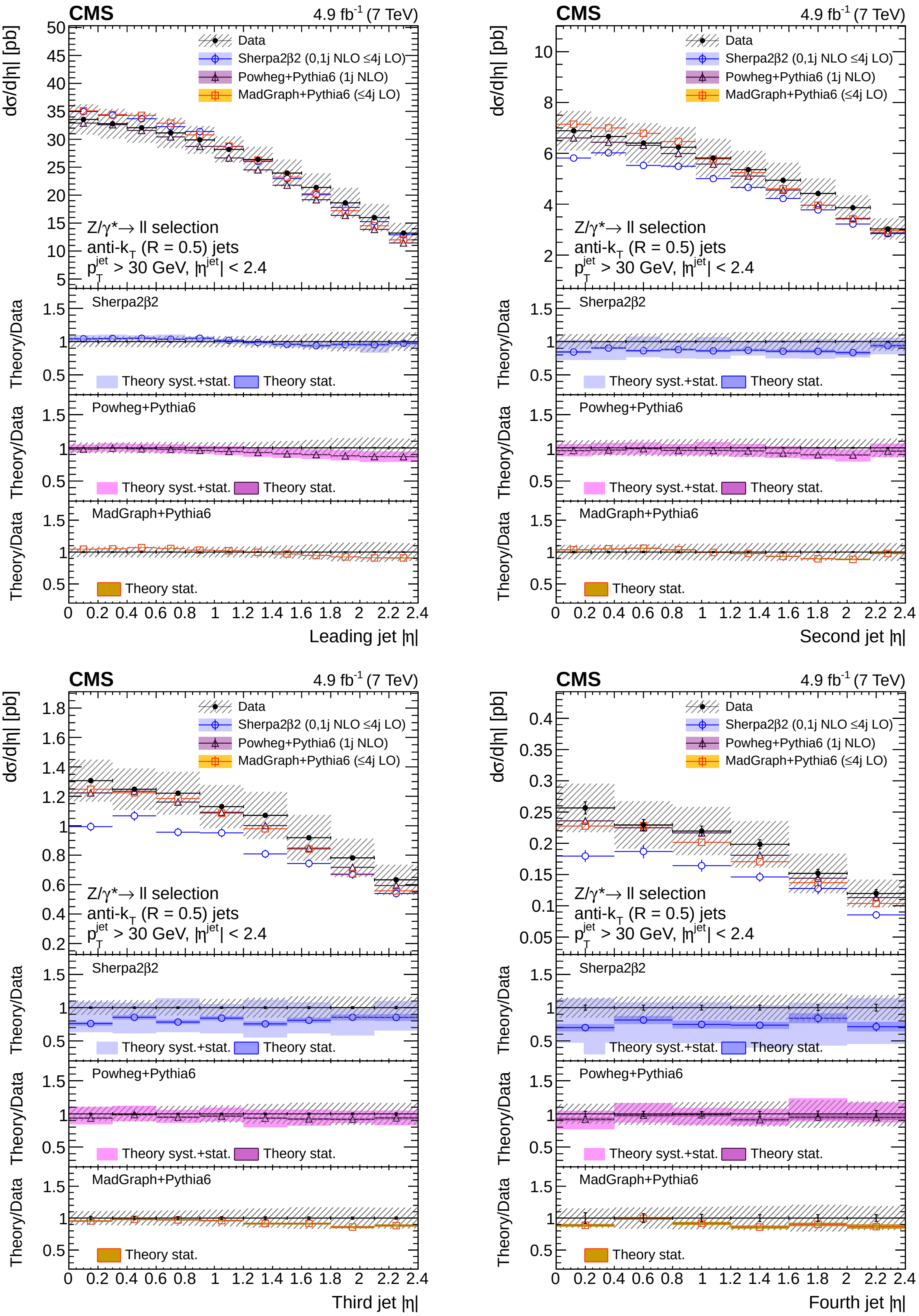

Figure 4: Unfolded differential cross section as a function of the jet absolute pseudorapidity $|\eta|$ for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_{T} jets, compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental 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.

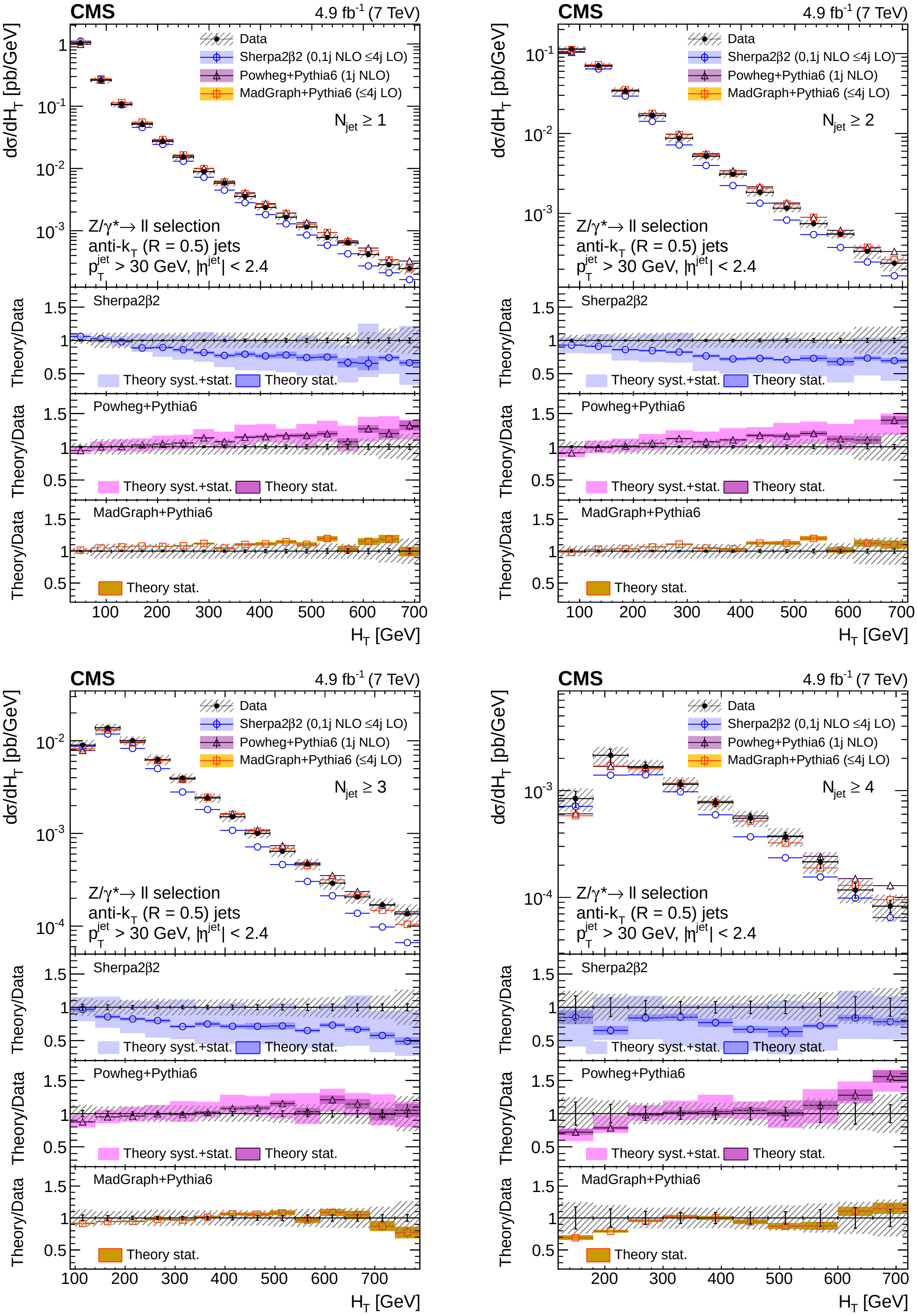

Figure 5: Unfolded differential cross section as a function of H_T for events with at least one (top left), two (top right), three (bottom left), and four (bottom right) jets compared with SHERPA, POWHEG, and MADGRAPH predictions. Error bars around the experimental points represent the statistical uncertainty, 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.

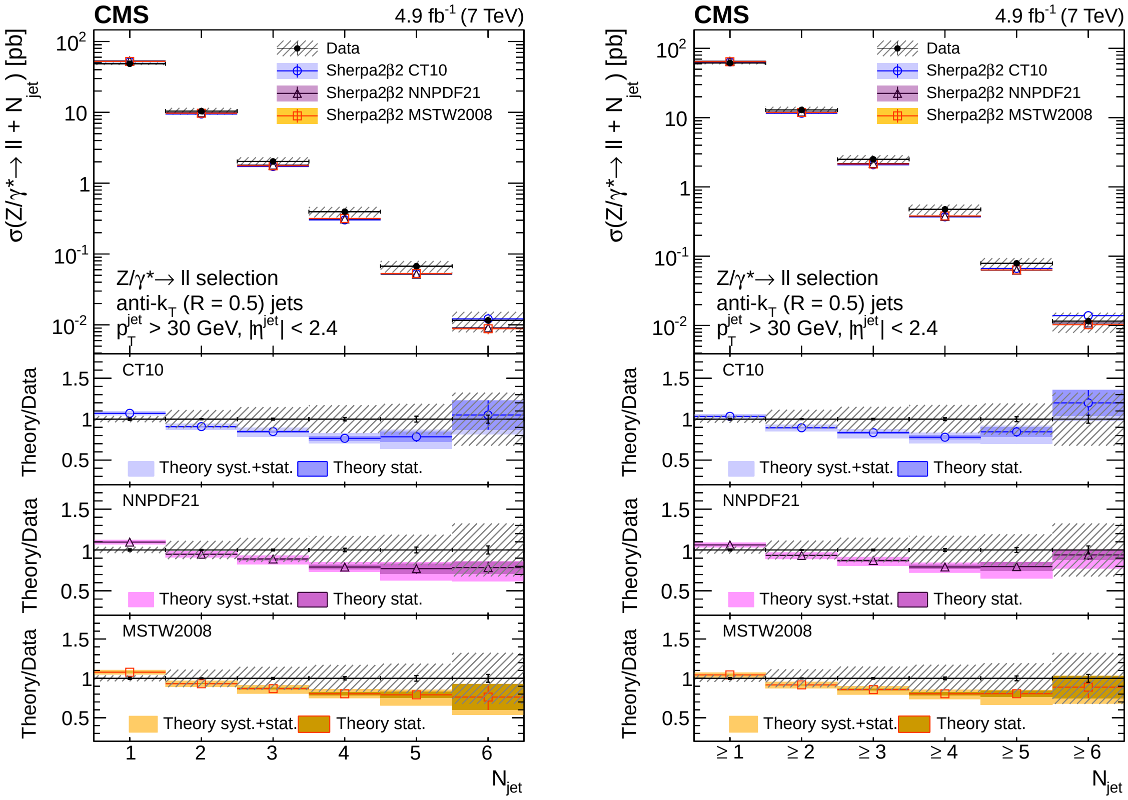

Figure 6: Exclusive jet multiplicity distribution (left) and inclusive jet multiplicity distribution (right), after the unfolding procedure, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points represent the statistical uncertainty, 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.

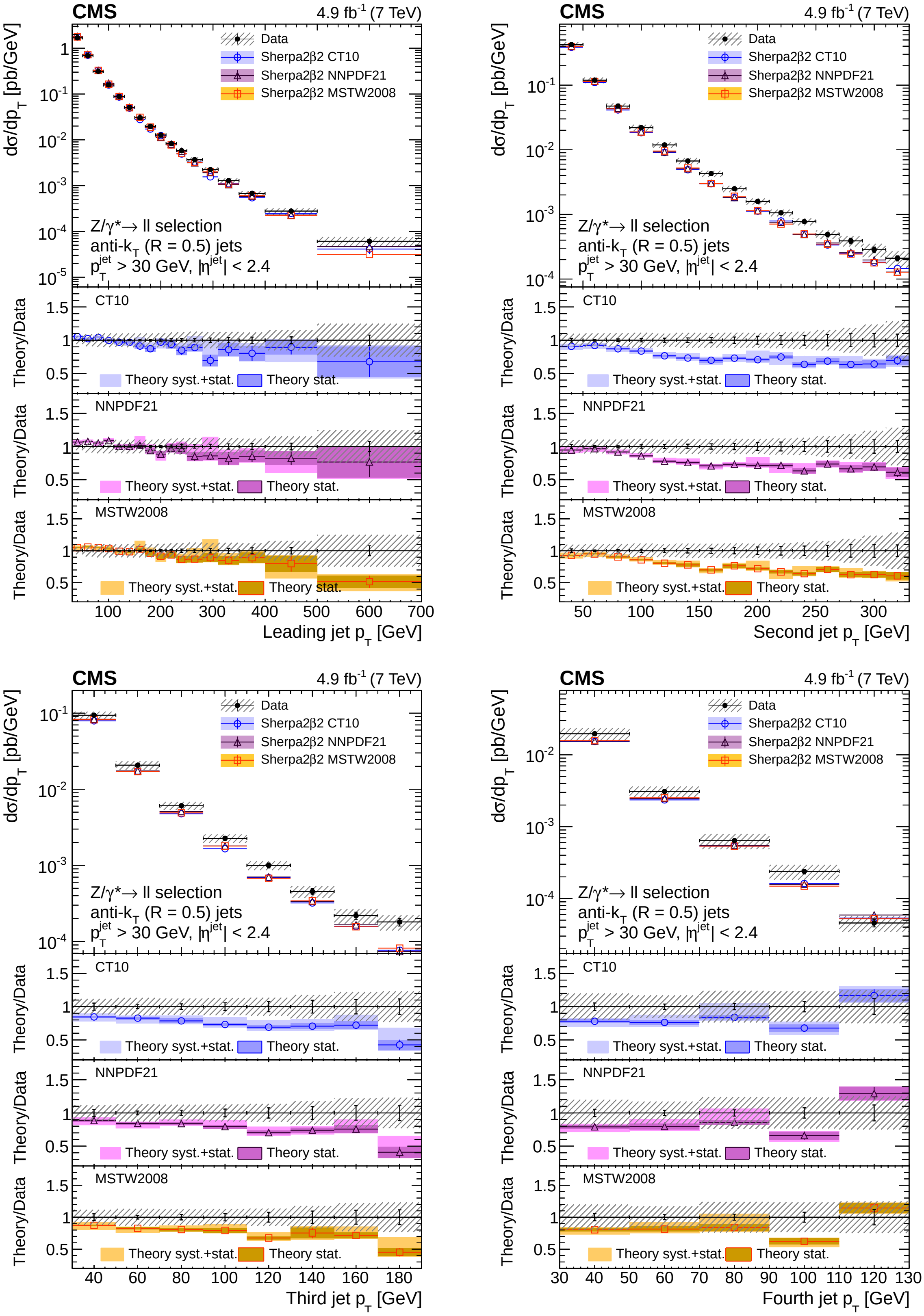

Figure 7: Unfolded differential cross section as a function of p_T for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points 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.

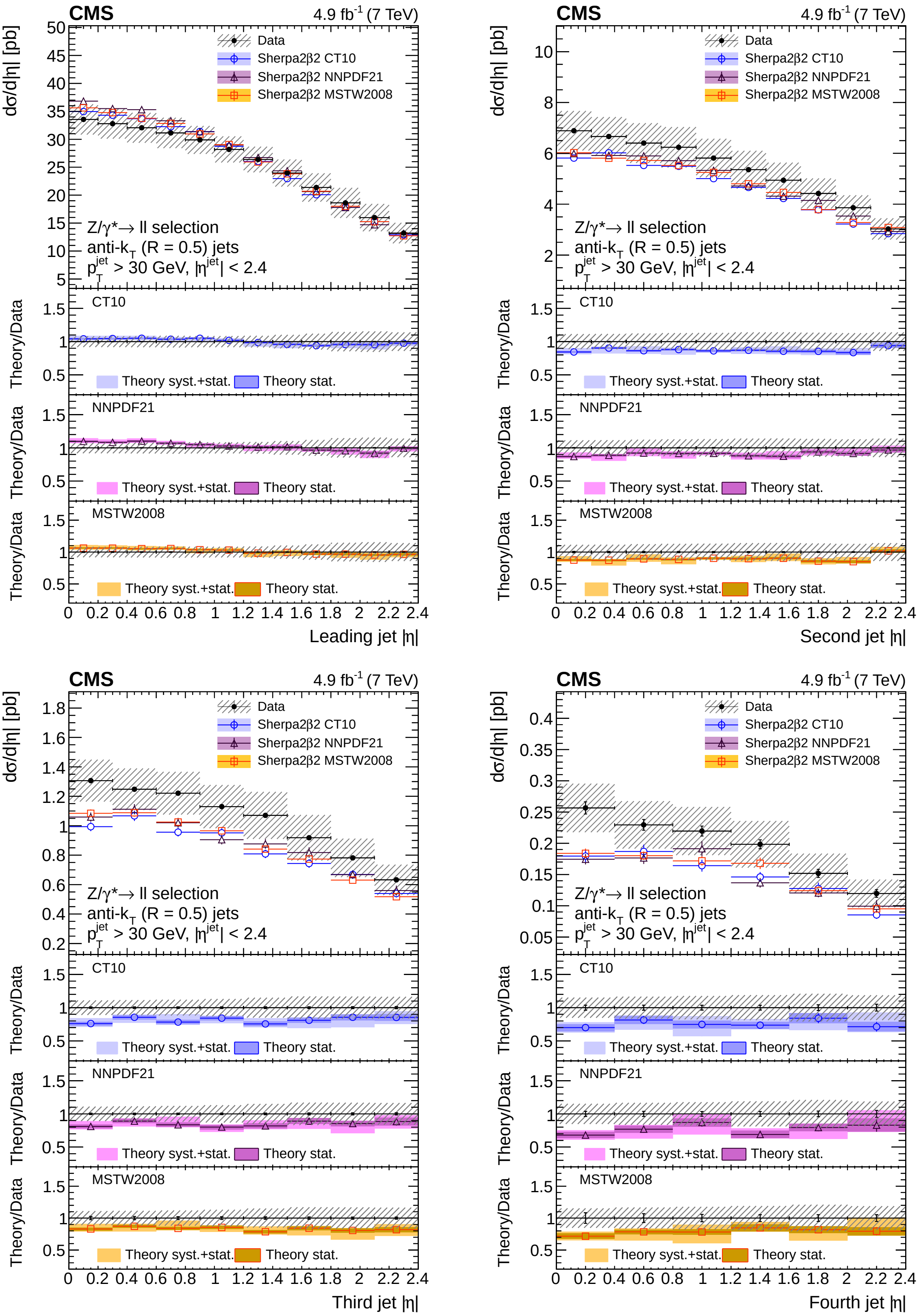

Figure 8: Unfolded differential cross section as a function of the jet absolute pseudorapidity $|\eta|$ for the first (top left), second (top right), third (bottom left), and fourth (bottom right) highest p_T jets, compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error 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.

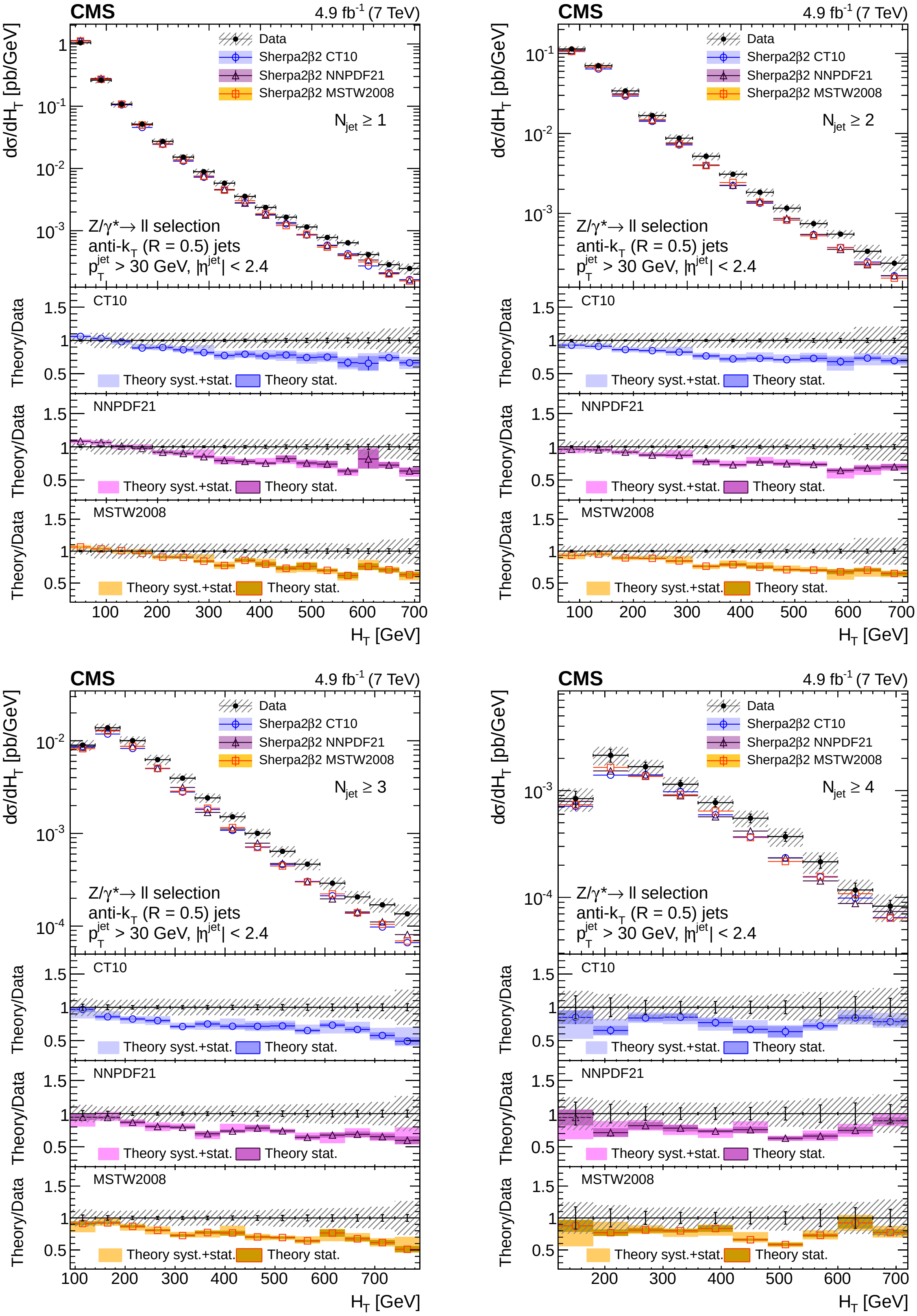

Figure 9: Unfolded differential cross section as a function of H_T for events with at least one (top left), two (top right), three (bottom left), and four (bottom right) jets compared with SHERPA predictions based on the PDF sets CT10, MSTW2008, and NNPDF2.1. Error bars around the experimental points 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.

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51: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
52: Also at Argonne National Laboratory, Argonne, USA
53: Also at Erzincan University, Erzincan, Turkey
54: Also at Yildiz Technical University, Istanbul, Turkey
55: Also at Texas A&M University at Qatar, Doha, Qatar
56: Also at Kyungpook National University, Daegu, Korea