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Rapidity distributions in exclusive Z + jet and γ + jet events in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration[*]

Abstract

Rapidity distributions are presented for events containing either a Z boson or a photon with a single jet in proton-proton collisions produced at the CERN LHC. The data, collected with the CMS detector at $\sqrt{s} = 7\,\text{TeV}$, correspond to an integrated luminosity of $5.0\,\text{fb}^{-1}$. The individual rapidity distributions of the boson and the jet are consistent within 5% with expectations from perturbative QCD. However, QCD predictions for the sum and the difference in rapidities of the two final-state objects show discrepancies with CMS data. In particular, next-to-leading-order QCD calculations, and two common Monte Carlo event generators using different methods to match matrix-element partons with parton showers, appear inconsistent with the data as well as with each other.

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[*] See Appendix A for the list of collaboration members

From the time of Rutherford's first scattering experiments, measuring angular distributions has provided a tool for understanding the structure and interactions of matter. Measurements of the rapidity distributions in V + jet events, where V refers either to a Z boson or a photon, can provide an important check of quantum chromodynamics (QCD) and event generators used to simulate elementary processes. For Z boson decays into $\mathrm{e}^+\mathrm{e}^-$ or $\mu^+\mu^-$, triggering is very efficient and nearly background-free, and from a theoretical point of view, the presence of the electroweak vertex makes the perturbative calculation of dynamical quantities even more robust. Since next-to-leading-order (NLO) perturbative QCD calculations are available for Z bosons produced in association with four or fewer jets [1], as well as for γ + jet production [2–4], detailed comparison with data is possible. In addition, a precise understanding of these processes is also required in searches for new physics and in studies of the Higgs boson, for which Z + jets events constitute an important background.

The rapidity of a particle is defined as $y = (1/2)\ln[(E + p_z)/(E - p_z)]$, where E is the energy and p_z is the momentum component along the direction of the counterclockwise circulating proton beam. The invariant rapidity difference can be written in terms of the measured quantities y_V and y_{jet} as $y_{\text{dif}} = |y_V - y_{\text{jet}}|/2$. The quantity $y_{\text{sum}} = |y_V + y_{\text{jet}}|/2$ is the boost from the laboratory frame to the center-of-mass frame of the V and jet. In the laboratory frame, y_V and y_{jet} are highly correlated because V + jet production usually involves a relatively high-momentum valence quark interacting with a low-momentum gluon or antiquark, which results in events where the V and jet are usually on the same end of the detector. The rapidities y_{sum} and y_{dif} are effectively rotations in phase space of the y_V and y_{jet} system that yield two approximately uncorrelated quantities. The distribution in y_{sum} depends mainly on the parton distribution functions (PDF), while the distribution in y_{dif} reflects the leading order (LO) partonic differential cross section. Distributions in the y_{sum} and y_{dif} quantities were measured previously at $\sqrt{s} = 1.96\,\text{TeV}$ by the D0 Collaboration [5]. Related angular quantities in V + jet events have been measured at the LHC by CMS [6] and ATLAS [7–10]. In this Letter, we compare theoretical predictions for normalized distributions in $|y_V|$, $|y_{\text{jet}}|$, y_{sum}, and y_{dif} with data collected by the Compact Muon Solenoid (CMS) experiment.

The kinematic properties of Z + jets events at the Tevatron [5] were found to be well-described by the NLO MCFM program [11, 12]. For Z + jets production at the LHC, MCFM provides predictions together with estimates of their uncertainties. For γ + jet events, the program developed by Owens [3] is used for NLO predictions and their uncertainties. This calculation employs fragmentation functions [4] to parametrize small-angle photon emission. Previous studies of the transverse momentum (p_{T}) distributions of photons showed agreement between LHC data and a variety of QCD predictions [13–16]. In all MCFM calculations, both the renormalization (μ_{R}) and factorization (μ_{F}) scales are set to the invariant mass of the lepton pair. For NLO prompt photon calculations, the scales are set to the p_{T} of the photon.

Programs that use matrix-element descriptions of jet systems are accurate only when the partons have large transverse momentum or are well separated, while event generators using parton showers perform well in describing soft and small-angle radiation [17]. Hybrid methods are used to combine matrix-element prescriptions and parton showers to optimize performance for all regions of phase space. These programs generally proceed in three stages: (i) calculating the lowest-order "tree-level" contribution, (ii) simulating parton showering and clustering of final-state partons into jets, and (iii) employing one of two schemes to minimize double-counting of matrix-element jets and those produced by parton showering. The MLM [18] procedure rejects events when showering changes the event topology, while the CKKW method [19] uses a weighting scheme based on shower history. A previous comparison of hybrid methods [20] found large differences in distributions of y_{dif} between the MLM and

CKKW methods for W + jet production. Hybrid models have been compared with V + jet data at the Tevatron [5], where the CKKW method implemented in SHERPA provided the best overall description of the observed distributions in y_{sum} and y_{dif}, but with a significantly different cross section. We also compare predictions from the two hybrid event generators with our V + jet data using MADGRAPH 5.1.1.0 [21], which implements the MLM scheme, and SHERPA 1.3.1 [22], which uses the CKKW method. For MADGRAPH, matching scales are chosen to be 20 GeV for Z bosons and 9–12 GeV for photons. The μ_{R} and μ_{F} scales are set to $\sqrt{m_{\mathrm{Z}}^2 + \Sigma_{\mathrm{jets}} p_{\mathrm{T}}^2}$ and $\sqrt{\left(p_{\mathrm{T}}^{\gamma}\right)^2 + \Sigma_{\mathrm{jets}} p_{\mathrm{T}}^2}$ for Z bosons and photons, respectively, where m_{Z} is the mass of the Z boson and p_{T}^{γ} is the photon transverse momentum. The PYTHIA 6.4.24 event generator is used for parton showers and hadronization [23]. For the SHERPA events, the matching scales are 20 and 10 GeV for Z bosons and photons, respectively. The μ_{F} and μ_{R} scales are set to m_{Z} and p_{T}^{γ} for Z bosons and photons, respectively. The parton-shower module APACIC++ 2.0 [24] is used before the PYTHIA hadronization procedure. In our comparison, the SHERPA simulations use the NLO CTEQ6.6M [25] PDF. The use of different order PDF in hybrid calculations is disputed [26]: both LO and NLO PDF have been used in theory [20] and experiments [5, 9]. To investigate this effect, the MADGRAPH simulation is studied using both the LO and NLO CTEQ6 [27] PDF.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter reside within the magnetic field volume. Muons are detected in gas-ionization detectors embedded in the steel of the flux-return yoke of the magnet. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. A more detailed description of CMS is given in Ref. [28]. A right-handed coordinate system is defined in CMS, with the origin at the center of the detector, the x axis pointing to the center of the LHC ring, and the y axis perpendicular to the plane of the LHC. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane in radians. Pseudorapidity, which is given by $\eta = -\ln[\tan(\theta/2)]$, is used for specifying acceptance requirements.

The data were collected during 2011 at a pp center-of-mass energy of 7 TeV, corresponding to an integrated luminosity of $5.0 \pm 0.1\,\mathrm{fb}^{-1}$ [29]. Because of limitations in data handling, the triggers used for photon candidates had to be partially suppressed, and the effective luminosity for prompt-photon production was $4.9 \pm 0.1\,\mathrm{pb}^{-1}$. The multilevel trigger requires two electron or two muon candidates, with respective minimum-p_{T} thresholds of 17 and 8 GeV, or 18 and 8 GeV, for the lepton of highest and next-highest p_{T}. A photon candidate is required to have $p_{\mathrm{T}}^{\gamma} > 30\,\mathrm{GeV}$.

Event reconstruction requires at least one vertex with $|z| < 15\,\mathrm{cm}$ located within the beam pipe (radius <2 cm). Jets and leptons are reconstructed using the particle flow algorithm [30], which classifies all stable particles in an event using the full ensemble and redundancy of the CMS detector. Jets are clustered using the anti-k_{T} algorithm [31], with a distance parameter of 0.5, and are required to have $|\eta| < 2.4$ to assure good tracker coverage. Jets, which have typical energy-scale uncertainties of <3% and resolution better than 10% [32], are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. The difference between actual and simulated resolution is <1%, and simulations showed the difference has a negligible effect on the rapidity distributions. The energy of particles arising from additional overlapping pp interactions in the same bunch crossing, but not associated with the hard scattering, is referred to as “pileup”. Pileup from charged particles is subtracted based on tracking information from the other reconstructed vertices. Neutral particle pileup contributes ≈0.5 GeV to any jet for each additional pp interaction, and is subtracted from the jet energy. The probabilities of observing pileup from additional hard interactions or from double parton scattering are both <1% for V + jet events [33, 34]. Jets below threshold are ignored, and if any other jet exceeds threshold, the event is rejected.

Reconstructed Z boson events are required to have at least two oppositely charged leptons of the same flavor (electrons or muons), each with $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.1$. The pair is required to have an invariant mass in the range of 76–106 GeV (close to m_Z), and $p_T > 40\,\mathrm{GeV}$. To include final-state radiation, the lepton energy is corrected by adding all photon energy deposited within an (η, ϕ) cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.1$, centered on the track direction. The relative isolation of a lepton is defined by the sum of the scalar p_T of all reconstructed particles (excluding the lepton) within a (η, ϕ) cone of $\Delta R = 0.4$ of the lepton direction, divided by the lepton p_T. Electron and muon candidates are required to have an isolation of less than 20% and 15%, respectively. Leptons and jets are required to be separated by $\Delta R > 0.5$. Detailed discussions of electron and muon reconstruction at CMS can be found in Refs. [35–37]. Following these selections, the Z + jet sample is 99% pure. The remaining contributions from $t\bar{t}$ pairs, diboson (ZZ, WW, or WZ), and multijet processes are negligible [38].

Reconstructed photon candidates are required to have $p_T^\gamma > 40\,\mathrm{GeV}$ to assure a fully efficient trigger, and $|\eta| < 1.44$ to avoid systematic effects associated with crossing calorimeter boundaries. Photons are reconstructed and selected as described in Ref. [13], using an isolation cone of $\Delta R = 0.4$ in (η, ϕ) space. The isolation variables for photons are defined with the sum of the charged-particle scalar p_T required to be less than 2 GeV, and the sums of the electromagnetic and hadron calorimeter contributions to be less than 4.2 and 2.2 GeV, respectively. The background resulting from fragmentation of jets into collimated neutral mesons that mimic a photon is estimated using the “matrix” method of Ref. [38]. The transverse spatial distribution of the energy in a cluster is used as a discriminant. Templates for the spatial transverse distributions of photon showers are taken from PYTHIA events, and reconstructed through the full CMS detector simulation via GEANT4 [39]. The templates for background are obtained from data using events passing all selection requirements, but with less stringent charged-particle isolation criteria (set between 2 and 5 GeV). Following the selection requirements, the fraction of photons in the sample is determined individually for each bin in y_{dif}. The photon fraction decreases from $(61 \pm 2)\%$ at $y_{\mathrm{dif}} = 0$ to $(36 \pm 5)\%$ at $y_{\mathrm{dif}} = 1.4$, where the uncertainties are statistical. To correct for background in the y_{sum}, $|y_{\mathrm{jet}}|$, and $|y_\gamma|$ distributions, events are weighted by the photon fractions as a function of y_{dif}, while using the independence on y_{sum} to reduce point-to-point fluctuations. The resulting effective fractions (photon purities) change by less than 12% within the examined ranges of y_{sum}, $|y_{\mathrm{jet}}|$, and $|y_\gamma|$.

The reconstructed distributions are corrected for efficiency and resolution before determining the differential distributions in rapidity. For Z + jet events, efficiencies are evaluated from data and simulation using a “tag-and-probe” procedure introduced in Ref. [38]. The simulated spectra are scaled to match collision data as a function of the lepton p_T and η, and are then used to compute the efficiency as a function of the rapidity variables. Photon efficiencies are obtained from simulation, and rescaled using the measured electron efficiency, which is assumed to have the same η dependence as photons. All rapidity distributions are corrected for the effects of detector resolution using simulated events in an iterative unfolding method [40], as implemented in the ROOUNFOLD package [41]. For all rapidity variables, the size of the correction is smaller than 1%. Only the distribution of $|y_{\mathrm{jet}}|$ has significant bin migration due to effects of resolution. The other variables have a correction factor consistent with unity.

The sources and relative experimental uncertainties in the rapidity distributions for the largest y values of binned rapidity for the three analyses are shown in Table 1. The contributions include the uncertainty in jet energy scale, unfolding of rapidity distributions, and the scaling

Table 1: Summary of the relative experimental uncertainties in the yields for the bins of largest $|y|$. At smaller $|y|$ values, these uncertainties are in general smaller. The first three rows reflect uncertainties common to all three analyses. The following nine rows quantify the uncertainties by particle type according to (i) uncorrelated statistical uncertainty, (ii) trigger and selection efficiency, and (iii) correlated estimation of the background, separately for e^+e^-, $\mu^+\mu^-$, and γ events.

Source	$\lvert y_V \rvert$ (%)	$\lvert y_{jet} \rvert$ (%)	y_{sum} (%)	y_{dif} (%)
Jet energy	0.4	0.6	0.3	0.4
Pileup reweight	0.5	0.1	0.3	0.1
Unfolding	—	5.0	—	—
e Statistical	7.1	2.2	8.0	5.7
e Efficiency	3.1	0.9	3.2	2.8
e Background	0.2	0.2	0.2	0.2
μ Statistical	6.3	1.9	6.1	4.6
μ Efficiency	1.5	0.4	1.2	1.2
μ Background	0.2	0.2	0.2	0.2
γ Statistical	6.6	19	8.6	15
γ Efficiency	0.4	0.6	0.4	1.0
γ Background	7.0	2.0	1.0	11

of simulated pileup interactions (corresponding to a 5% uncertainty in the total inelastic cross section). For Z + jet production, the contributions to the relative experimental uncertainties also include the uncertainty in lepton identification efficiency, dominated by the limited statistical precision of simulated event samples, and the uncertainty in the background subtraction.

For photon production, bounds on the systematic uncertainty in the modeling of background are determined from the difference between data and the PYTHIA simulation in two-jet events. The maximum extent of the y_{dif} measurement for photon production is limited by the number of simulated events used to estimate the uncertainty from background. The systematic uncertainty in the photon background as a function of y_{dif} varies between 2% and 11%, and is highly correlated across the range of y_{dif}. There is also an uncorrelated uncertainty from the statistical precision in the estimated background that is included in the "Statistical" row of Table 1.

The best linear unbiased estimator (BLUE) [42, 43] method is used to combine the corrected distributions for the electron and muon decay channels. A covariance matrix of $2N \times 2N$ dimensions, where 2 refers to the measurements for the electron and the muon channels and N is the number of bins, is ascribed to each distribution. The diagonal variances represent the quadratic sum of both correlated and uncorrelated uncertainties. The off-diagonal elements are defined by 100% correlated uncertainties associated with the jet energy scale in the electron and muon channels. The size of the uncorrelated uncertainty in each bin is a factor of 3–5 times greater than the size of the correlated uncertainty.

The sources of theoretical uncertainty in all three analyses include the choice of PDF, the value of the strong coupling (α_s), and μ_R and μ_F. These are studied using the MCFM and Owens calculations. The uncertainty in the PDF is obtained using the PDF4LHC [44] prescription. The baseline set of PDF is CTEQ6.6M, while the CT10 [45], MSTW2008 [46], and NNPDF21 [47] PDF are used as alternatives. For both Z + jet and γ + jet events, these alternatives correspond to <2% shift in all y distributions; however, using the LO rather than NLO parameterizations of PDF produces ≈10% difference in the y_{sum} and $|y_V|$ distributions, whereas the y_{dif} and $|y_{jet}|$ distributions are affected only slightly. Changes of α_s within the CT10 bounds cause <1%

change in all variables. The theoretical uncertainty from the choice of μ_F and μ_R is estimated by changing these scales up and down by a factor of two. For Z + jet and γ + jet events, the differences in the normalized distributions as a function of y_sum, $|y_\mathrm{jet}|$, and $|y_V|$ are <2%, while the change in y_dif is ≈8%. Moreover, the changes are similar for both LO and NLO calculations, although the normalization factor can be quite different. The NLO calculations do not include effects from final-state photon radiation, parton showering, and hadronization, since these are estimated as negligible using the PYTHIA program.

The normalized rapidity distributions for $|y_\mathrm{Z}|$, $|y_\mathrm{jet}|$, y_dif, and y_sum, along with predictions from theory, are shown in Fig. 1 for Z + jet events. The data for the $|y_\mathrm{Z}|$ and $|y_\mathrm{jet}|$ distributions agree to better than 5% accuracy with SHERPA, MADGRAPH, and MCFM over the full range of the measurement. The SHERPA simulation reproduces the features of the y_sum distribution better than the MADGRAPH or MCFM programs. As shown in Fig. 1, when MADGRAPH events are simulated using the LO PDF, the distributions of y_sum and $|y_\mathrm{Z}|$ are less consistent with the data. The y_dif distribution is consistent with MCFM for $y_\mathrm{dif} < 1.0$. As was noted in Ref. [20], the two hybrid programs differ considerably in the prediction for y_dif. Since both MADGRAPH and SHERPA use the same LO matrix elements and approaches to parton showering, the difference in the distribution of y_dif can be attributed to the matching algorithm, with the SHERPA CKKW scheme appearing more consistent with the data. Indeed, the MADGRAPH distribution of y_dif resembles the LO distribution. The difference in y_dif between the LO and NLO calculations is due to the contribution from NLO diagrams with a gluon propagator that yield more forward rapidities. The rapidity distributions for γ + jet events shown in Fig. 2 are consistent with perturbative QCD. The qualitative difference in y_dif for the hybrid generators MADGRAPH and SHERPA is comparable to that observed in Z + jet events, although the statistical precision of the γ + jet measurement is insufficient to discriminate between the theoretical alternatives.

In summary, the CMS detector was used to measure the rapidities of particles in events containing a vector (V) boson (either a Z boson or photon) in association with a single jet in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ for an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$. The rapidity distributions of $|y_V|$ and $|y_\mathrm{jet}|$ are found to agree with predictions from the SHERPA, MADGRAPH, and MCFM QCD models. The distribution for the sum of the V and jet rapidities is described by all predictions to better than 5% precision for $y_\mathrm{sum} < 1.0$, and is best described by hybrid calculations that employ NLO PDF. The distribution in the difference in rapidities (y_dif) is described to better than 10% by the MCFM prediction. The two hybrid event generators differ by as much as ≈50% in their predictions for distributions in y_dif, but SHERPA is significantly closer to data than MADGRAPH. Nevertheless, SHERPA overestimates the cross section at higher y_dif. We attribute the difference between the hybrid event generator distributions to the respective methods by which partons from matrix elements are matched to parton showers.

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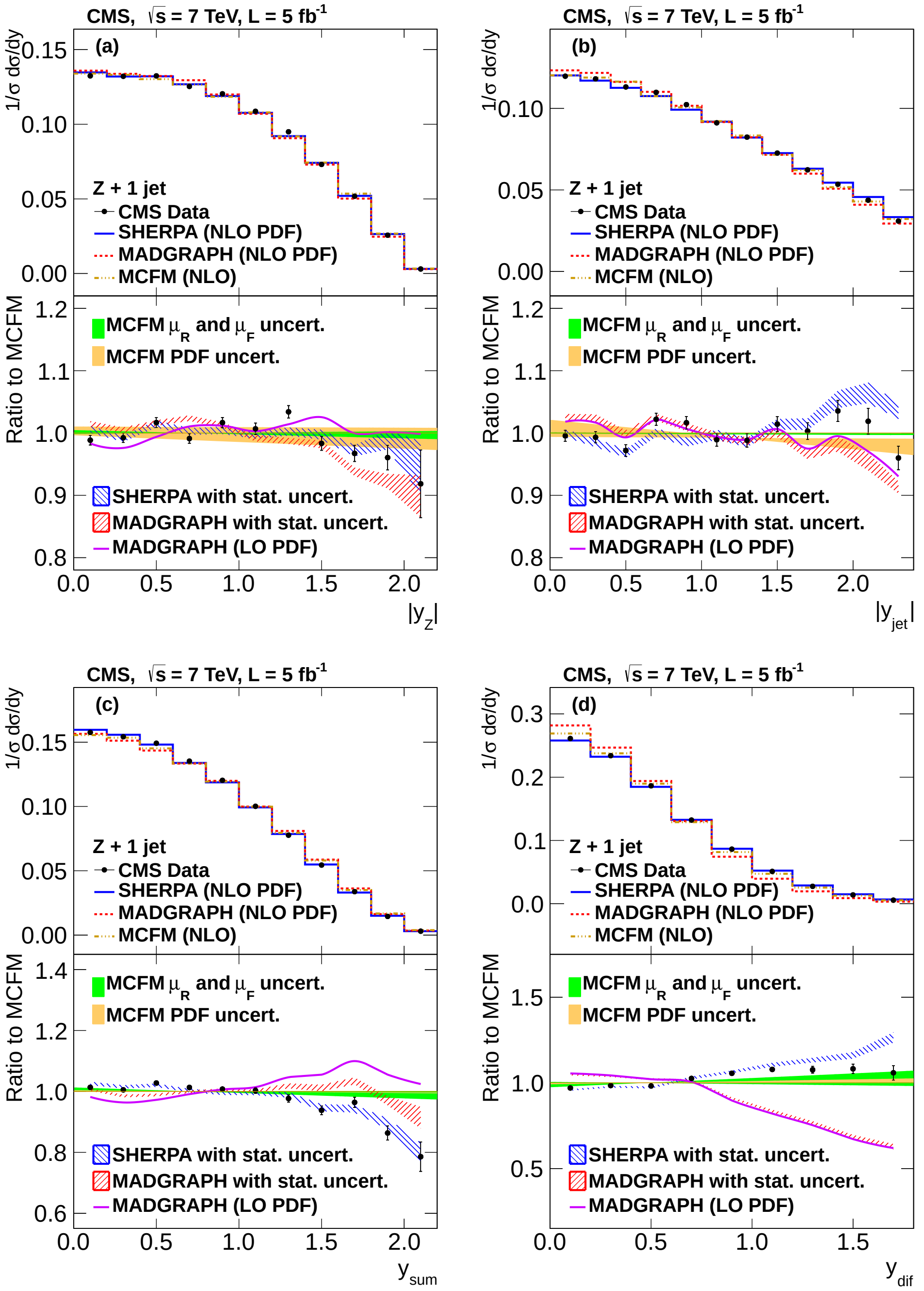

Figure 1: Distributions in absolute values of rapidities for (a) the Z boson, (b) the jet, (c) their sums, and (d) their differences, normalized to unity. The data are shown after correcting for efficiency and resolution, and displayed with statistical and systematic uncertainties combined in quadrature. The lower panel of each figure gives ratios of the data and simulations to the NLO calculation of MCFM. The ratio error bars include MCFM statistical uncertainties folded with data statistical and systematic uncertainties. Theoretical uncertainties in the MCFM calculations are shown as shaded areas representing variations of μ_R, μ_F, and PDF. Statistical uncertainties for the MADGRAPH and SHERPA predictions are displayed as bands around the central values. The central value for MADGRAPH simulations using LO PDF is depicted by a line. All other calculations use NLO versions of PDF.

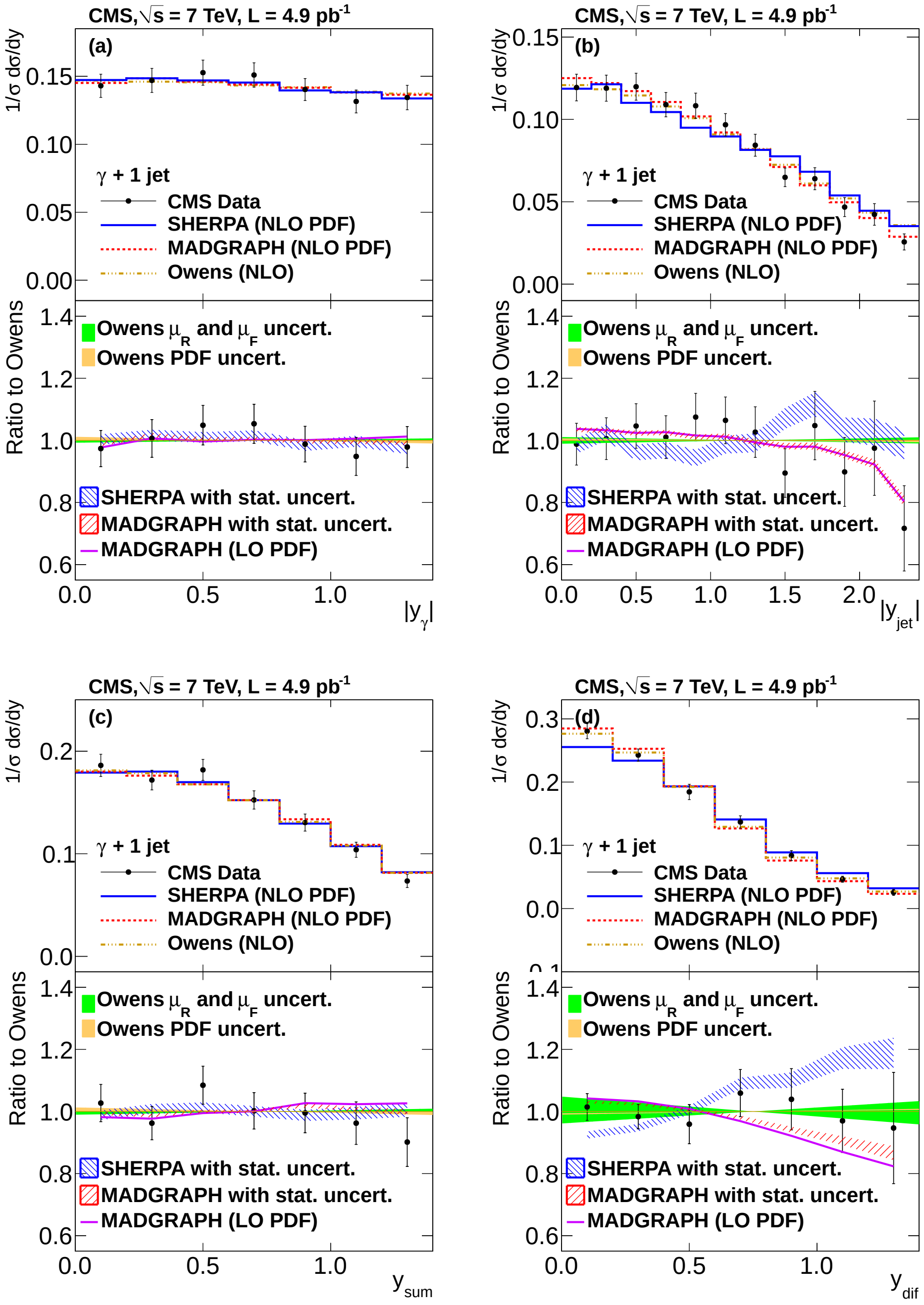

Figure 2: Distributions in absolute values of rapidities for (a) the photon, (b) the jet, (c) their sums, and (d) their differences, normalized to unity. The data are shown after correcting for efficiency and resolution, and displayed with statistical and systematic uncertainties combined in quadrature. The lower panel of each figure gives ratios of the data and simulations to the NLO calculation of Owens. The ratio error bars include Owens statistical uncertainties folded with data statistical and systematic uncertainties. Theoretical uncertainties in the Owens calculations are shown as shaded areas representing variations of μ_{R}, μ_{F}, and PDF. Statistical uncertainties for the MADGRAPH and SHERPA predictions are displayed as bands around the central values. The central value for MADGRAPH simulations using LO PDF is depicted by a line. All other calculations use NLO versions of PDF.

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