PROCEEDINGS OF SCIENCE

Inclusive Jet measurements at collision energies $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV from CMS

Paolo Gunnellini[*†]
Deutsches Elektronen-Synchrotron (DESY), Hamburg (Germany)
E-mail: paolo.gunnellini@desy.de

Measurements of double-differential inclusive jet cross sections as a function of jet transverse momentum p_T and absolute jet rapidity $|y|$ are presented for different collision energies. The analysis are based on proton-proton collisions collected by the CMS experiment. Jets are defined through the anti-k_T clustering algorithm for different cone sizes. It is observed that predictions of perturbative quantum chromodynamics at next-to-leading order precision, complemented with nonperturbative corrections, are able to reproduce the measured data for the considered energies with a very good level of agreement. Parton-shower contributions are crucial for the description of jets, reconstructed with smaller cone sizes.

XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects
11-15 April, 2016
DESY Hamburg, Germany

[*]Speaker.
[†]On behalf of the CMS collaboration.

PoS(DIS2016)086

1. Introduction

The inclusive cross section for jets produced with high transverse momenta in proton-proton collisions is described by quantum chromodynamics (QCD) in terms of parton-parton scattering. The partonic cross section σ_{jet} is convolved with the parton distribution functions (PDFs) of the proton and is computed in perturbative QCD (pQCD) as an expansion in powers of the strong coupling constant, α_S. A measurement of the jet cross section as a function of the rapidity y and the transverse momentum p_T of the jet is a sensitive probe for the calculation of the hard partonic cross section as well as for the parton densities. Jet cross sections at the parton level are not well defined unless one uses a jet algorithm that is safe from collinear and infrared divergences, i.e., an algorithm that produces a cluster result that does not change in the presence of soft gluon emissions or collinear splittings of partons. Analyses conducted with LHC data at the CMS experiment [1] generally employ the anti-k_T jet algorithm [2] with different jet size parameters R ranging between 0.4 and 0.7. Jets of different sizes are differently affected by the impact of perturbative radiation and of the nonperturbative (NP) effects of hadronization and the underlying event.

In this note, results of inclusive jet measurements at centre-of-mass energies $\sqrt{s}$ = 2.76 [3], 7 [4], 8 [5], and 13 [6] TeV are presented. The phase space in rapidity is subdivided into six bins from $y = 0$ to $|y| = 3$ with $|\Delta y| = 0.5$. For the measurement at 13 TeV, one bin from $|y| = 3.2$ to 4.7 is also added and is normally referred to as "forward rapidity region". In the analysis performed at 7 TeV, the ratio between the cross sections measured for jets reconstructed with $R = 0.5$ and 0.7, R(0.5,0.7) is also shown.

2. Jet measurements at different energies

The data samples used for the measurements were collected with single-jet HLT triggers, where in each event at least one jet is required to exceed a minimal p_T. Triggers are then combined in independent regions of the phase space according to the exclusive division method [7]. In each region, the firing triggers are chosen to have an efficiency bigger than 99% to detect a jet in the full rapidity coverage of the CMS experiment. Jets are reconstructed by clustering the particle-flow [9] candidates with the collinear- and infrared-safe anti-k_T jet algorithm, as implemented in the FASTJET package [8]. Different jet sizes R are used in the measurements: larger values, e.g. $R = 0.7$, favourably compare to fixed-order predictions. Smaller values of R emphasize different aspects of perturbative and NP QCD and permits complementary tests to be performed.

The double-differential inclusive jet cross section is defined as:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}y} = \frac{1}{\varepsilon L_{int}} \frac{\mathrm{N_j}}{\Delta p_T \cdot \Delta y} , \tag{2.1}$$

where N_{jets} is the number of jets in the bin, L_{int} is the integrated luminosity of the data sample from which the events are taken, ε is the product of the trigger and event selection efficiencies, and Δp_T and Δy are the transverse momentum and rapidity bin widths, respectively. The widths of the p_T bins are proportional to the p_T resolution and thus increase with p_T.

The double-differential inclusive jet cross section is corrected for the detector resolution and unfolded to the stable particle level. In this way, a direct comparison of this measurement to results from other experiments and to QCD predictions is possible. Particles are considered stable if their mean path length $c\tau$ is greater than 10 mm.

The unfolding procedure used for the correction is based on the iterative d'Agostini method [10], as implemented in the RooUnfold software package [11], using a response matrix that maps the predicted distribution onto the measured one. The response matrix is derived from a simulation, which uses the theoretically predicted spectrum as input and introduces smearing effects by taking into account the jet p_T resolution. The predicted spectrum is evaluated from fixed-order calculations at next-to-leading order (NLO).

The dominant contribution to experimental systematic uncertainty on the measured cross sections is due to scale corrections, determined as discussed in [12]. Other systematic effects which contribute to the inclusive jet cross section measurements are the inaccuracy of the determination of the integrated luminosity, the model dependence and the uncertainty on the jet energy resolution.

Comparisons to different sets of predictions are considered:

- Fixed-order NLO calculations obtained with the NLOJet++ [13, 14] program within the framework of the FASTNLOv2.3.1 package [15], using several parton distribution functions (PDF). This NLO parton level calculation is supplemented with corrections due to NP effects, i.e. hadronization and multiparton interactions (MPI) and electroweak contributions. The former corrections range between 1.4 and 1 depending on rapidity region, jet p_T and cone size. The latter ones are negligible for $p_T < 1$ TeV and increase up to 15% for higher p_T.
- NLO dijet matrix element calculations obtained with the POWHEG [16] event generator, interfaced to the parton shower and underlying event simulation provided by the PYTHIA event generator with the most recent tunes [17].
- LO dijet matrix element calculations, obtained with the PYTHIA 6 [18], PYTHIA 8 [19] and HERWIG++ [20].

In Figure 1, the inclusive jet cross sections are shown in different rapidity regions as a function of p_T for $R = 0.5$ and 0.7 compared to predictions of NLOJet++ based on the CT10 [22] PDF set. The ratio R(0.5,0.7) is also shown in Fig. 1 for the six measured rapidity ranges and is compared to the considered predictions. The best overall agreement is provided by POWHEG + PYTHIA 6. Comparing the parton showering predictions of PYTHIA 6 and HERWIG++ to data exhibits agreement across some regions of phase space, and disagreement in other regions. The PYTHIA 6 tune Z2 prediction agrees with data at the low p_T end of the measurement, where NP effects dominate. This is where PYTHIA 6 benefits most from having been tuned to the LHC underlying event data. The HERWIG++ predictions, on the other hand, are in disagreement with the low p_T data, which is expected to be primarily due to the limitations of the underlying event tune 2.3 [21] in HERWIG++.

Figure 2 shows the double-differential inclusive jet cross section measurement at 2.76 and 8 TeV, presented as a function of p_T in the $|y|$ ranges considered. The measurements are compared to the NLO theory prediction, based on the CT10 PDF set. The data are consistent with the theory predictions for a wide range of jet p_T from 74 GeV up to 2.5 TeV. Among the investigated PDFs,

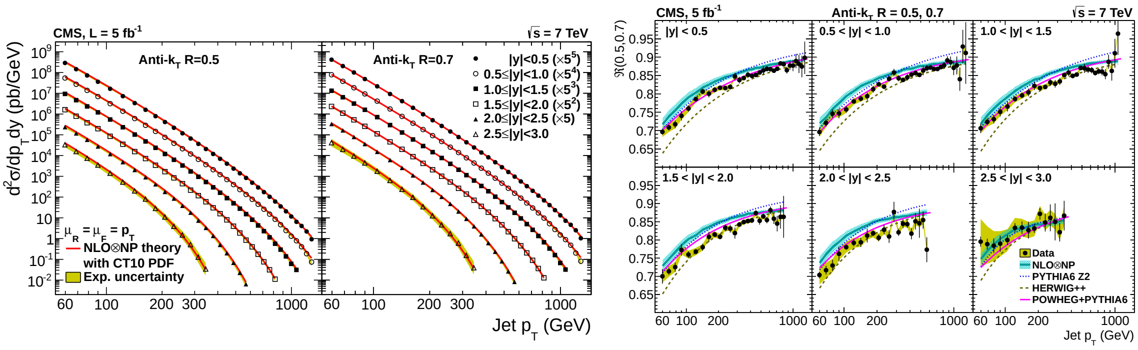

Figure 1: Double-differential cross sections for two choices of R, compared to NLO×NP predictions (left). Jet radius ratio R(0.5, 0.7) in six rapidity bins up to $|y| = 3.0$, compared to various MC predictions (right).

an overall good agreement with observations is found for the CT10 and NNPDF3.0 [23] PDF sets. For these measurements, only jets clustered with $R = 0.7$ have been considered.

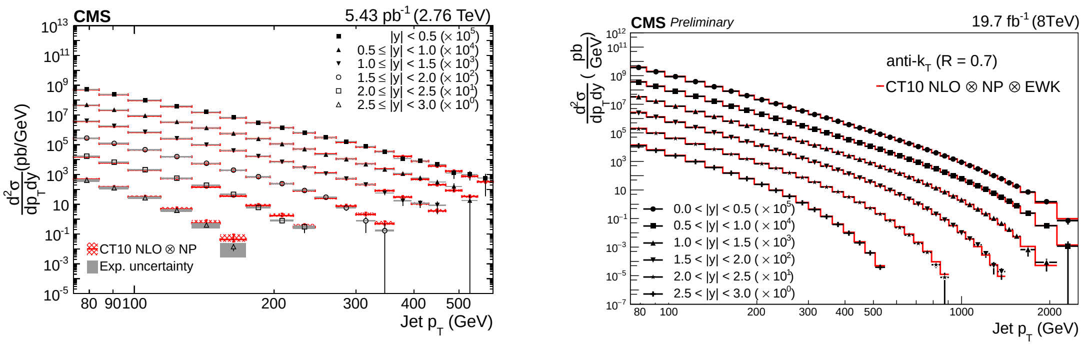

Figure 2: Double-differential inclusive jet cross sections as function of jet p_T measured at $\sqrt{s} = 2.76$ (left) and 8 (right) TeV. Data (points) and NLO predictions based on CT10 PDF set corrected for the NP factor and electroweak correction factor (line).

In Fig. 3, the double-differential inclusive jet cross section measurements at 13 TeV is shown, presented as a function of p_T for seven $|y|$ ranges using the anti-k_T algorithm with $R = 0.7$ and 0.4. The measurements are compared to the NLOJET++ predictions based on the CT14 [24] PDF set, corrected for NP and electroweak effects. The data are consistent with the predictions over a wide range of jet p_T from 114 GeV up to 2 TeV. The ratios of data over the NLOJET++ predictions using the CT14 PDF set are shown in Fig. 4 for the jets with $R = 0.7$. The error bars on the points correspond to the statistical uncertainties, and the shaded bands correspond to the total experimental systematic uncertainties. For comparison, predictions employing three alternative PDF sets are also shown. Figure 4 shows the results for the jets with $R = 0.4$. Overall, a good agreement within the uncertainties is observed between the data and predictions in the entire kinematic range studied, for both jet cone sizes. However, for $R = 0.4$, the data are systematically overestimated by about 5-10%, while a better description is provided for jets reconstructed with $R = 0.7$. The relatively poor agreement for $R = 0.4$ is due to PS and soft gluon resummation contributions, which are missing in fixed-order calculations, and that are more relevant for smaller jet cone sizes because of out-of-cone effects.

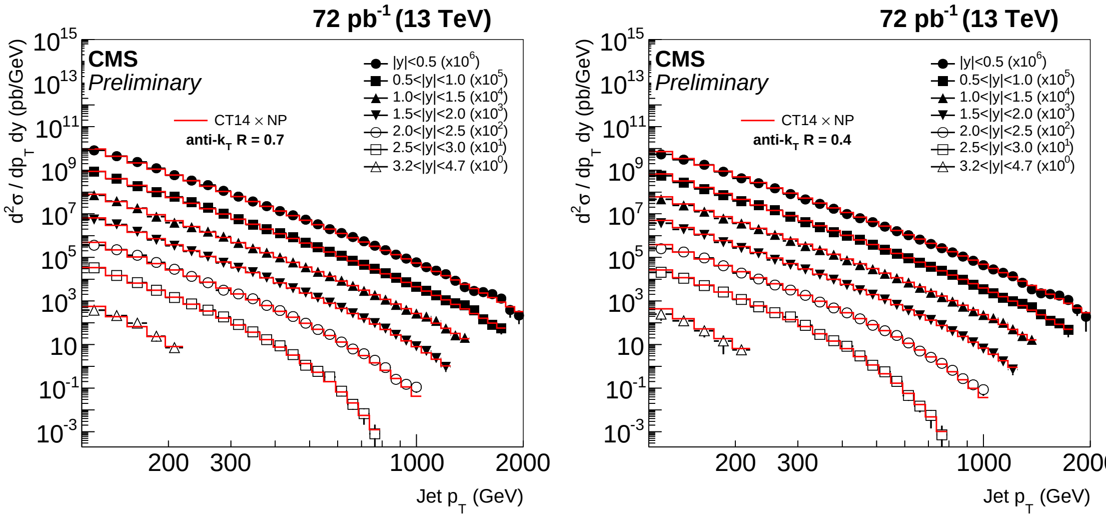

Figure 3: Double-differential inclusive jet cross sections as function of jet p_T measured at $\sqrt{s}$ = 13 TeV. Jets are clustered with $R = 0.7$ (left) and 0.4 (right). Data (points) and NLO predictions based on CT10 PDF set corrected for the NP factor and electroweak correction factor (line).

3. Summary and conclusions

Measurements of the double-differential cross section as a function of jet p_T and absolute rapidity $|y|$ are presented for several centre-of-mass energies in proton-proton collisions collected with the CMS detector. For some of the measured energies, different jet sizes are considered.

Measurements are compared to predictions based on perturbative QCD and a very good level of agreement is achieved for all energies. In particular, it is observed that jet cross sections for larger jet sizes are accurately described by fixed-order predictions complemented with corrections for nonperturbative and electroweak effects, while for smaller jet cone sizes, theory overestimates the cross section by 5-10% almost globally. In contrast, NLO predictions matched to parton showers and underlying event simulation perform equally well for both jet sizes. No dependence on the underlying event tune is observed. Predictions obtained with MC event generators, which rely on dijet leading order matrix element calculations matched to parton showers, fail to reproduce the absolute cross sections in each rapidity range but are able to reproduce the jet radius ratio R(0.5, 0.7) at 7 TeV. However, the best description of this ratio is obtained by matching the cross section prediction at NLO with parton showers.

This collection of jet measurements is a crucial baseline for more exclusive analyses and shows that jet physics is well understood within the wide range of centre-of-mass energies at the TeV scale delivered by the LHC.

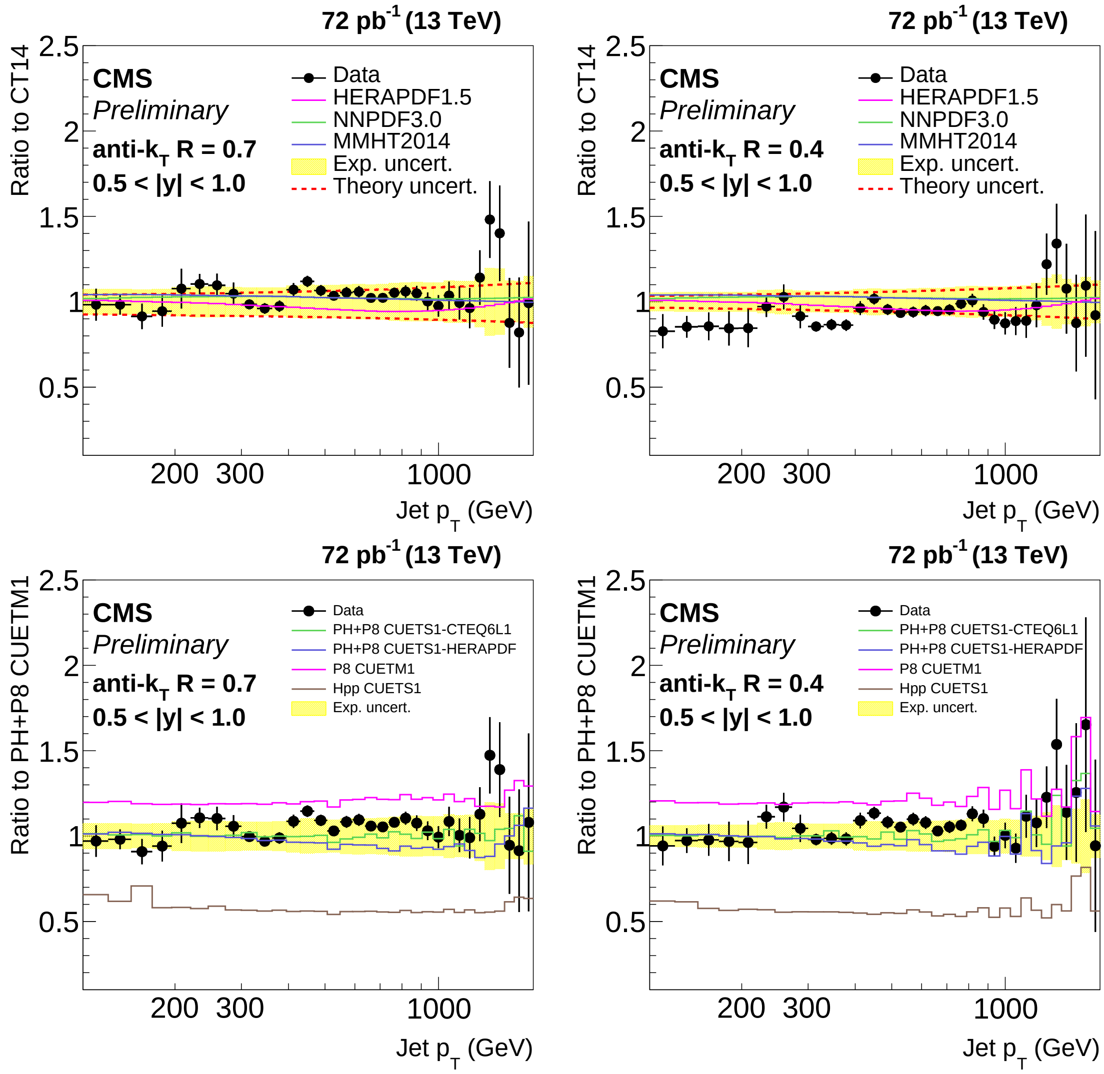

Figure 4: (top) Ratio of measured values to theoretical prediction from NLOJET++ using the CT14 PDF set and corrected for the NP and electroweak effects for $R = 0.7$ (left) and 0.4 (right). (bottom) Ratio of measured values to predictions from POWHEG (PH) + PYTHIA 8 (P8) with tune CUETM1 for $R = 0.7$ (left) and 0.4 (right).

References

[1] S. Chatrchyan *et al.* [CMS Collaboration], JINST **3** (2008) S08004.

[2] M. Cacciari, G. P. Salam and G. Soyez, JHEP **0804** (2008) 063.

[3] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **76** (2016) 5, 265.

[4] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. D **90** (2014) 7, 072006.

[5] CMS Collaboration [CMS Collaboration], CMS-PAS-SMP-14-001.

[6] CMS Collaboration [CMS Collaboration], CMS-PAS-SMP-15-007.

[7] V. Lendermann, J. Haller, M. Herbst, K. Kruger, H. C. Schultz-Coulon and R. Stamen, Nucl. Instrum. Meth. A **604** (2009) 707 doi:10.1016/j.nima.2009.03.173

[8] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **72** (2012) 1896 doi:10.1140/epjc/s10052-012-1896-2

[9] [CMS Collaboration], CMS-PAS-PFT-09-001.

[10] G. D'Agostini, Nucl. Instrum. Meth. A **362** (1995) 487. doi:10.1016/0168-9002(95)00274-X

[11] T. Adye, Proceedings of the PHYSTAT 2011 Workshop, CERN, Geneva, Switzerland, January 2011, CERN-2011-006, pp 313-318

[12] S. Chatrchyan *et al.* [CMS Collaboration], JINST **6** (2011) P11002 doi:10.1088/1748-0221/6/11/P11002

[13] Z. Nagy, Phys. Rev. Lett. **88** (2002) 122003.

[14] Z. Nagy, Phys. Rev. D **68** (2003) 094002.

[15] D. Britzger *et al.* [fastNLO Collaboration], doi:10.3204/DESY-PROC-2012-02/165

[16] S. Alioli, K. Hamilton, P. Nason, C. Oleari and E. Re, JHEP **1104** (2011) 081.

[17] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **76** (2016) 3, 155.

[18] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026 doi:10.1088/1126-6708/2006/05/026

[19] T. Sjöstrand *et al.*, Comput. Phys. Commun. **191** (2015) 159 doi:10.1016/j.cpc.2015.01.024

[20] J. Bellm *et al.*, arXiv:1310.6877.

[21] S. Gieseke *et al.*, arXiv:1102.1672 [hep-ph].

[22] H. L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin and C.-P. Yuan, Phys. Rev. D **82** (2010) 074024 doi:10.1103/PhysRevD.82.074024

[23] R. D. Ball *et al.* [NNPDF Collaboration], JHEP **1504** (2015) 040 doi:10.1007/JHEP04(2015)040

[24] S. Dulat *et al.*, Phys. Rev. D **93** (2016) 3, 033006.