PROCEEDINGS OF SCIENCE

Jet measurements in proton-proton collisions from CMS

Daniel Savoiu[a,*] **on behalf of the CMS Collaboration**

[a] *Institut für Experimentalphysik, Universität Hamburg*
Luruper Chaussee 149, Hamburg, Germany

E-mail: daniel.savoiu@uni-hamburg.de

A selection of recent experimental results on jet measurements in proton-proton collisions at $\sqrt{s} = 13$ TeV from the CMS Collaboration is presented. Differential measurements of the inclusive jet and dijet production cross sections are performed as a function of transverse momentum (p_T) and absolute rapidity, and the impact of these data on determinations of the strong coupling constant and the parton distribution functions is presented. In addition, a measurement of jet multiplicity and p_T in multijet events is outlined and compared to predictions obtained for different parton shower models and with various Monte Carlo (MC) event generators. Finally, a measurement of the Lund jet plane density, which represents the phase space of emissions inside jets, is described, and the results are compared to predictions obtained from MC generators with different tunes, parton showers and hadronization models.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

*Speaker

PoS(LHCP2023)028

1. Introduction

The production of particle jets in hadron-induced collisions represents a valuable experimental probe for testing and refining our knowledge of quantum chromodynamics (QCD) and the Standard Model (SM) of particle physics at the highest accessible energy scales.

Measurements of observables such as production cross sections for jets in proton-proton collisions provide important information for improving the precision of the strong coupling α_s, and for constraining the parton distribution functions (PDFs) of the proton. Comparing experimental results to theoretical predictions for jet production, which are currently known up to next-to-next-to-leading order (NNLO) in perturbative QCD (pQCD), is instrumental for improving the theoretical knowledge of these processes in both the perturbative and nonperturbative regimes. Further insights can be gained by examining the substructure of jets in terms of their constituents.

In this note, a selection of recent jet-related experimental results from the CMS Collaboration is presented. A detailed description of the CMS detector can be found in Ref. [1].

2. Measurements

2.1 Inclusive jet production

The differential cross section for inclusive jet production is measured at $\sqrt{s}$ = 13 TeV as a function of the jet p_T and the absolute jet rapidity $|y|$ [2]. Anti-k_T jets clustered with distance parameters of $R = 0.4$ and 0.7 are considered. Fig. 6 in Ref. [2] shows the measured cross sections for $R = 0.7$, which cover a wide range of 97 GeV $< p_\mathrm{T} <$ 3.1 TeV and up to $|y| < 2.0$.

The measured cross sections are unfolded simultaneously in both measurement variables to account for detector effects. The experimental uncertainty is typically <5% in the main measurement region, with the largest contribution stemming from the jet energy scale (JES).

Figure 8 in Ref. [2] shows a comparison of the measured cross sections to theoretical predictions obtained at next-to-leading (NLO) order with next-to-leading-logarithmic resummation (NLL), and at next-to-next-to-leading order (NNLO). The theoretical predictions are derived for various global PDF sets and corrected for nonperturbative (NP) and electroweak (EW) effects. An improved description of the data is observed at NNLO, and the scale uncertainty representing the missing higher orders in perturbation theory is reduced, as expected. However, some disagreement is observed between predictions obtained from global PDF sets, especially in the high-p_T region. The predictions for $R = 0.7$ provide a better description of the measurement than $R = 0.4$.

The impact of the CMS $R = 0.7$ jet data on the PDFs is investigated in a comparison to fits to the baseline dataset, which consists of deep inelastic $\mathrm{e}^{\pm}\mathrm{p}$ scattering (DIS) data from the H1 and ZEUS experiments at HERA. Figs. 14–15 in Ref. [2] shows the resulting PDFs. With the inclusion of the CMS data, a significant reduction of the gluon PDF uncertainty at large parton momentum fractions $x > 0.1$ is observed.

The strong coupling constant at the Z boson mass is determined simultaneously with the PDFs, yielding a value of $\alpha_\mathrm{s}(m_\mathrm{Z}) = 0.1166\,(14)_\mathrm{fit}\,(7)_\mathrm{model}\,(4)_\mathrm{scale}\,(1)_\mathrm{param.}$ at NNLO, with the uncertainty contributions from fit, model, scale and parametrization, calculated as described in Ref. [2].

The inclusive jet measurement is also used together with $\mathrm{t\bar{t}}$ data and theoretical predictions at NLO to perform a simultaneous extraction of $\alpha_\mathrm{s}(m_\mathrm{Z})$ and the top quark pole mass, and for interpretation in the context of four-quark contact interactions in Standard Model effective field theory (SMEFT). Limits at 95% confidence level are derived for Wilson coefficients assuming multiple coupling structures and energy scales (see Fig. 19 in Ref. [2]), and a limit for the energy scale of a possible new interaction is set at $\Lambda > 24$ TeV.

2.2 Dijet production

Differential cross sections are measured for the production of dijets at $\sqrt{s} = 13$ TeV as a function of the kinematic properties of the two p_T-leading jets [3]. Both double- (2D) and triple-differential (3D) measurements are performed as a function of the invariant mass $m_{1,2}$ of the dijet system and either the absolute rapidity $|y|_{\max}$ of the outermost jet (2D), or the rapidity separation y^* of the jets and the total boost y_b of the dijet system (3D). An alternative 3D measurement using the average transverse momentum $\langle p_T \rangle_{1,2}$ instead of $m_{1,2}$ is also performed.

Measurements are performed using anti-k_T jets clustered with distance parameters of $R = 0.4$ and 0.8, covering a maximum range in $m_{1,2}$ from 249 GeV to $\approx$10 TeV. An overview of the measured cross sections for $R = 0.8$ as a function of $m_{1,2}$ is shown in Figs. 8 and 19 in Ref. [3].

Figs. 26 and 10 in Ref. [3] shows a comparison of the measurements for $R = 0.8$ to fixed-order theoretical predictions at NNLO, complemented by NP and EW corrections. The predictions for the larger jet radius, $R = 0.8$, show a better level of agreement with the measurements than for $R = 0.4$. Predictions for different global PDF sets generally agree within the PDF uncertainty, but show larger deviations towards increasing values of $m_{1,2}$.

Simultaneous determinations of the PDFs and the strong coupling constant $\alpha_s(m_Z)$ are carried out using the 2D and 3D dijet measurements for $R = 0.8$ as a function of $m_{1,2}$ together with HERA DIS data. The PDFs resulting from the fit to the 3D data are shown in Figs. 12 and 14 in Ref. [3], demonstrating a reduction in the gluon PDF uncertainty at large parton momentum fractions $x > 0.1$. Similar values for the strong coupling constant are obtained in the fits to the 2D and 3D dijet cross sections, with the latter yielding $\alpha_s(m_Z) = 0.1201\ (10)_{\text{fit}}\ (8)_{\text{model}}\ (5)_{\text{scale}}\ (5)_{\text{param.}}$ at NNLO.

2.3 Multijet production

Measurements of jet multiplicity and transverse momentum spectra in multijet events are performed by the CMS Collaboration at $\sqrt{s} = 13$ TeV [4][1]. While at leading order (LO) QCD partonic final states in hadron collisions typically give rise to two azimuthally well-separated jets, higher-order corrections result in a higher jet multiplicity and a decorrelation in the azimuthal angle. Additional high-energy jets are described as part of the fixed-order matrix element (ME) calculation, while softer radiation is accounted for using parton shower models. Experimental measurements thus provide a means of evaluating the performance of these models in the context of MC event generation.

The multiplicity of jets with $p_T > 50$ GeV and $|y| < 2.5$ is measured in multijet events in multiple regions defined by the leading jet p_T and the azimuthal separation $\Delta\phi$ between the two most energetic jets. In addition, transverse momentum spectra are measured for the first four p_T-leading jets. The measurements are compared to predictions from various MC generators

[1] since published as Ref. [5]

(PYTHIA 8 [6], Herwig++ [7], MadGraph5_aMC@NLO [8]) using LO and NLO matrix element calculations, complemented by different parton shower models. At LO, none of the models yield a good description of the jet multiplicity or transverse momentum distributions, while at NLO the predictions describe the data better in the lower multiplicity regions. The use of NLO matrix elements also results in a better description of the p_{T} distribution of the third and fourth jets. NLO calculations performed using transverse momentum dependent (TMD) PDFs obtained with the parton branching method (PB-TMDs) [9–11] show a similar performance in the low-multiplicity region as the more conventional approach using collinear PDFs. At high multiplicities, neither approach describes the data satisfactorily.

2.4 Primary Lund jet plane density

The density of the primary Lund jet plane [12] is measured by the CMS Collaboration at $\sqrt{s} = 13\,\mathrm{TeV}$ [13]. The primary Lund jet plane is a representation of the phase space of emissions inside jets as a function of the transverse momentum k_{T} of the emitting particle and the emission angle ΔR, and is obtained by iteratively declustering anti-k_{T} jets using the Cambridge–Aachen algorithm.

A binned two-dimensional measurement is performed in the transformed variables $\ln(k_{\mathrm{T}}/\mathrm{GeV})$ and $\ln(R/\Delta R)$, where R is the distance parameter. The density is measured for jets with $R =$ 0.4 and 0.8 satisfying $p_{\mathrm{T}} > 700\,\mathrm{GeV}$ and $|y| < 1.7$. Only charged particle constituents are considered, resulting in an improved experimental resolution. Detector effects are accounted for using an unfolding procedure, and the resulting particle-level density is compared to predictions from different MC generators. An example of the resulting two-dimensional density can be seen in Fig. 7 in Ref. [13]. Contributions from different physical effects are localized in different parts of the Lund plane, as illustrated in Fig. 2 in Ref. [13].

Figures 9–12 in Ref. [13] show a comparison of the measured primary Lund jet plane density to predictions obtained with different MC generators, tunes, parton shower models, and choices of the recoil scheme in HERWIG 7.2 [14]. While the predictions are generally in agreement with the measurements, deviations are observed in certain areas of the primary Lund jet plane for a number of MC configurations. The distributions measured in this analysis can serve as an input for future improvements of MC generators.

3. Summary

Jet measurements from LHC experiments provide valuable experimental data at the highest available energy and precision, with applications ranging from improving the knowledge of fundamental parameters of quantum chromodynamics (QCD) and the structure of protons to improving different aspects of Monte Carlo (MC) event generation. Many such measurements have become available in recent years from the CMS Collaboration at $\sqrt{s} = 13\,\mathrm{TeV}$, targeting a variety of different jet observables. In this note, a selection of these results is presented, including multi-differential measurements of inclusive jet and dijet cross sections, measurements of jet multiplicity and transverse momentum spectra in multijet events, as well as a measurement of the primary Lund jet plane density as a useful observable for probing various regimes of QCD and evaluating MC generator performance.

References

[1] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[2] CMS Collaboration, "Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **02** (2022) 142, doi:10.1007/JHEP02(2022)142, arXiv:2111.10431. [Addendum: JHEP 12, 035 (2022)].

[3] CMS Collaboration, "Multi-differential measurement of the dijet cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-SMP-21-008, 2022. https://cds.cern.ch/record/2843201.

[4] CMS Collaboration, "Cross section measurements of jet multiplicity and jet transverse momenta in multijet events at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-SMP-21-006, 2021. https://cds.cern.ch/record/2776772.

[5] CMS Collaboration, "Measurements of jet multiplicity and jet transverse momentum in multijet events in proton–proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **83** (2023) 742, doi:10.1140/epjc/s10052-023-11753-y, arXiv:2210.13557.

[6] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159–177, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[7] M. Bahr et al., "Herwig++ physics and manual", *Eur. Phys. J. C* **58** (2008) 639–707, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.

[8] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[9] A. Bermudez Martinez et al., "Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method", *Phys. Rev. D* **99** (2019) 074008, doi:10.1103/PhysRevD.99.074008, arXiv:1804.11152.

[10] F. Hautmann et al., "Soft-gluon resolution scale in QCD evolution equations", *Phys. Lett. B* **772** (2017) 446–451, doi:10.1016/j.physletb.2017.07.005, arXiv:1704.01757.

[11] F. Hautmann et al., "Collinear and TMD quark and gluon densities from parton branching solution of QCD evolution equations", *JHEP* **01** (2018) 070, doi:10.1007/JHEP01(2018)070, arXiv:1708.03279.

[12] F. A. Dreyer, G. P. Salam, and G. Soyez, "The Lund jet plane", *JHEP* **12** (2018) 064, doi:10.1007/JHEP12(2018)064, arXiv:1807.04758.

[13] CMS Collaboration, "Measurement of the primary Lund jet plane density in proton-proton collisions at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-SMP-22-007, 2023. https://cds.cern.ch/record/2853467.

[14] J. Bellm et al., "Herwig 7.2 release note", *Eur. Phys. J. C* **80** (2020) 452, doi:10.1140/epjc/s10052-020-8011-x, arXiv:1912.06509.