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CMS jet measurements and constraints on PDFs and α_s

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A selection of recent jet measurements in proton-proton collisions from the CMS Collaboration at the CERN LHC is presented. Several experimental results targeting jet production are summarized, including differential measurements of the inclusive jet cross section at center-of-mass energies of $\sqrt{s}$ = 13 TeV and 5.02 TeV, and of the dijet cross section at $\sqrt{s}$ = 13 TeV. The measurements are compared to state-of-the-art theoretical predictions at next-to-next-to-leading-order accuracy in perturbative QCD, and the strong coupling constant $\alpha_s(m_Z)$ is extracted simultaneously with the parton distribution functions (PDFs) of the proton at 13 TeV. A further experimental handle on $\alpha_s(m_Z)$ is provided by a measurement of jet azimuthal correlations. Finally, a novel measurement of the energy-energy correlators inside jets is outlined. These provide an additional way of determining $\alpha_s(m_Z)$ while also constituting useful observables for probing phase spaces dominated by nonperturbative processes like hadronization and have applications in the context of Monte Carlo event generator tuning.

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1. Introduction

Hadronic jets are produced abundantly at hadron colliders, primarily through processes mediated by the strong interaction. Measurements of jet properties in proton collisions thus constitute a high-precision probe of the quantum chromodynamics (QCD) sector of the Standard Model (SM), providing essential experimental input for the determination of fundamental QCD parameters like the strong coupling constant $\alpha_s(m_Z)$, and of the parton distribution functions of the proton (PDFs). Moreover, the examination of jet topologies in multijet events and of the substructure of jets can provide further constraints on QCD parameters and provide insights for modeling hadron-induced scattering processes in both the perturbative and nonperturbative regimes.

This article presents a summary of recent jet measurements using data recorded by the CMS experiment [1] at the CERN LHC during Run 2 of its operation, with a focus on differential jet cross section measurements and measurements of event shape and jet substructure observables, providing constraints on $\alpha_s(m_Z)$ and/or PDFs.

2. Differential jet cross sections

Differential jet production cross sections are fundamental observables at hadron colliders. The cross section for inclusive jet production ("inclusive jet cross section") was measured [2] double-differentially as a function of the transverse momentum (p_T) and rapidity (y) of the jets using data collected by the CMS experiment in the year 2016 at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$, amounting to an integrated luminosity of up to $36.5\,\text{fb}^{-1}$.

Both double- (2D) and triple-differential (3D) measurement [3] of the dijet production cross section were performed with a similar data set as a function of the invariant mass of the two p_T-leading jets ($m_{1,2}$) and several rapidity-related observables. In the 2D case, the cross section is measured as a function of the rapidity of the outermost jet ($|y|_{\text{max}}$), while for 3D the variables y^* and y_b are used, calculated, respectively, as half the absolute value of the difference and sum of the rapidities of the two p_T-leading jets.

The data are compared to state-of-the-art theoretical predictions obtained in the framework of perturbative QCD (pQCD) at next-to-next-to-leading-order (NNLO) accuracy using the *NNLOJET* program [4] interfaced to *fastNLO* [5, 6] via the *APPLfast* interface [7, 8], and complemented by nonperturbative and electroweak corrections. The predictions describe the data well within the experimental uncertainties. A ratio of the measured inclusive jet cross sections to the theoretical predictions is shown in Fig. 1.

A determination of the PDFs and $\alpha_s(m_Z)$ was performed for each of the above measurements individually, in a fit together with measurements of deep inelastic scattering from the H1 and ZEUS collaborations at HERA [9, 10]. As an example, Fig. 2 shows the gluon PDF resulting from the fit including the CMS 2D and 3D dijet data (left) and a comparison of the fits to the HERA data alone (right). The addition of CMS jet data improve the precision of the gluon PDF at a parton momentum fraction $x > 0.3$. The values of $\alpha_s(m_Z)$ obtained simultaneously with the PDFs are shown in Eqns. (1)–(3), with the one obtained from the inclusive jet measurement being the most precise value obtained so far from a single measurement of jet cross sections at a hadron collider.

$$\alpha_s(m_Z)_{\text{incl. jet}} = 0.1166\ (14)_{\text{fit}}\ (7)_{\text{model}}\ (4)_{\text{scale}}\ (1)_{\text{param.}} \tag{1}$$

$$\alpha_s(m_Z)_{\text{dijet 2D}} = 0.1179\ (15)_{\text{fit}}\ (8)_{\text{model}}\ (8)_{\text{scale}}\ (1)_{\text{param.}} \tag{2}$$

$$\alpha_s(m_Z)_{\text{dijet 3D}} = 0.1181\ (13)_{\text{fit}}\ (9)_{\text{model}}\ (6)_{\text{scale}}\ (2)_{\text{param.}} \tag{3}$$

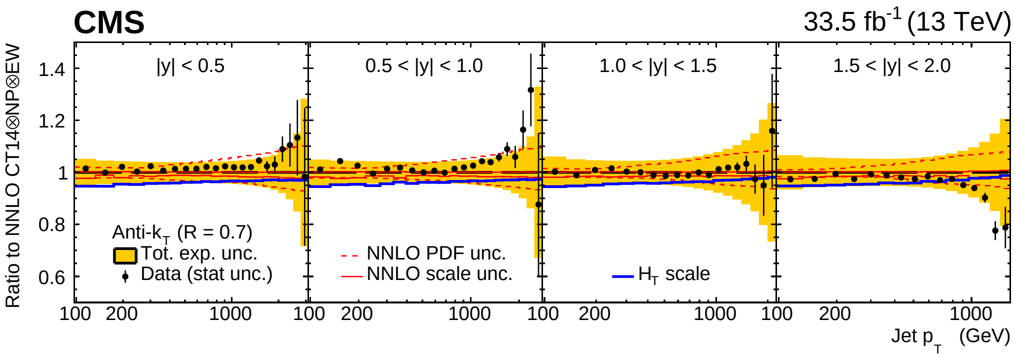

Figure 1: Ratio of double-differential inclusive jet cross section for anti-k_T jets with $R = 0.8$ and corresponding pQCD predictions at NNLO accuracy, corrected for nonperturbative and electroweak effects. The data agree with the theory within the total experimental uncertainty. Taken from Ref. [2].

A measurement of the inclusive jet cross section is also performed at a center-of-mass energy of $\sqrt{s} = 5.02$ TeV [11] using 27.4 pb^{-1} of data, providing a complementary data set that can be used as an input to future QCD fits.

3. Azimuthal jet correlations

Further sensitivity to $\alpha_s(m_Z)$ can be gained by constructing observables designed to separate between back-to-back dijet topologies and a three-jet arrangement, which arises from the radiation of additional color-charged particles, and for which the cross section is thus proportional to α_s. One such observable is the azimuthal correlation $R_{\Delta\phi}$, which was recently measured by the CMS Collaboration [12] using the full Run 2 data set amounting to an integrated luminosity of 134 fb^{-1}. The observable $R_{\Delta\phi}$ is calculated as a ratio of jet counts in events with a three-jet topology, with the numerator taking all neighboring ("nbr") jets into account that lie within an azimuthal angle distance of $\Delta\phi$ from the reference jet, and the denominator including all jets:

$$R_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T,\min}^{\text{nbr}})}{N_{\text{jet}}(p_T)}\,. \tag{4}$$

Experimentally, this observable benefits from cancellations of systematic uncertainties in the numerator and denominator, increasing the precision with which SM parameters can be extracted. The observable $R_{\Delta\phi}$ is measured as a function of the jet p_T and compared to predictions from various Monte Carlo (MC) event generators at leading order (LO) and next-to-LO (NLO). Among these the data appears best described by the NLO predictions obtained with POWHEG [13–16] and Pythia 8 [17, 18] configured with the CUETP8M2T4 tune [19]. An extraction of $\alpha_s(m_Z)$ is

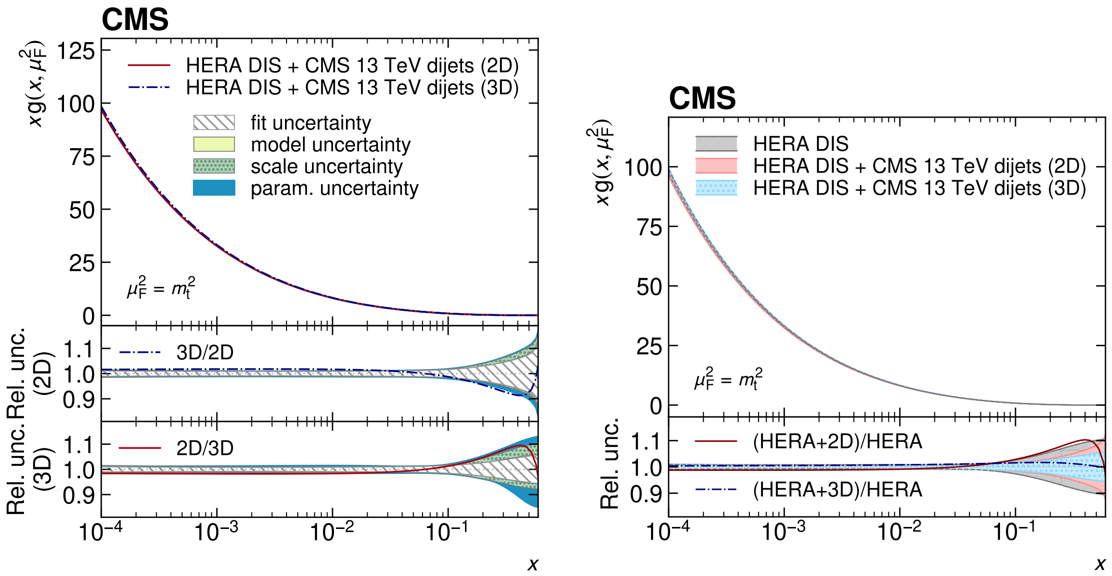

Figure 2: *(left)* Gluon PDF obtained from fits including 2D and 3D CMS dijet data at $\sqrt{s} = 13$ TeV, shown together with the relative systematic uncertainties from the fit, variations of non-PDF model parameters, missing higher orders in perturbation theory ("scale") and PDF parametrization. *(right)* Comparison of the gluon PDF obtained with and without CMS data, showing a reduction in the fit uncertainty in the region at $x > 0.3$. Taken from Ref. [3].

performed using these data together with pQCD predictions at NLO and several global PDF sets, with the extraction using the NNPDF3.1 [20] set yielding a value of

$$\alpha_s(m_Z)_{R_{\Delta\phi},\mathrm{NLO}} = 0.1177\ (13)_{\mathrm{exp}}\ \left(^{+116}_{-\ 73}\right)_{\mathrm{theo.}}\ . \tag{5}$$

4. Energy-energy correlators inside jets

Energy-energy correlators (EECs) are jet substructure observables that describe the correlations of kinematic properties of particles clustered as part of jets, using the particle energy as a weight. In a recent measurement by the CMS Collaboration [21], EECs calculated based on either pairs ("E2C") or triplets ("E3C") of constituent particles were measured differentially as a function of the variable x_L, defined as the (largest) angular distance between the particles forming an E2C pair or an E3C triplet: $x_L = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$

The observable x_L maps the transition between the free-hadron regime at low values, and the perturbative regime at high values, thereby providing a probe for the timescale of hadron formation. Fig. 3 shows a comparison of the data to several MC generators. While the data appears to be described best by Pythia 8, deviations are observed in parts of the phase space, suggesting that these data may be useful for the development of higher-order corrections in parton shower algorithms.

Aside from potential applications for improving the modeling in MC simulations, the ratio E2C/E3C is sensitive to $\alpha_s(m_Z)$. As shown in Fig. 4, this ratio is approximately linear as a function of $\alpha_s \ln x_L$. Furthermore, the dependence of this observable on the PDFs is largely suppressed, reducing the impact of associated systematic uncertainties. An extraction of $\alpha_s(m_Z)$ from these

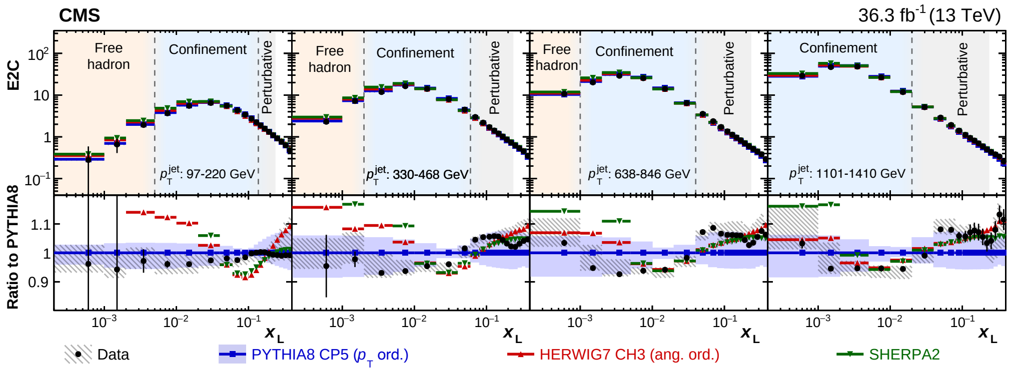

Figure 3: Measurement of the EEC calculated based on pairs of particles inside jets and corresponding theoretical predictions from three MC event generators. Taken from Ref. [21].

data is performed using theoretical predictions at NLO accuracy and approximate next-to-next-to-leading-logarithm resummation, yielding the most precise value of this parameter obtained so far from jet substructure as:

$$\alpha_s(m_Z)_{\text{EEC}} = 0.1229\ (^{+14}_{-12})_{\text{stat.}}\ (^{+23}_{-36})_{\text{exp.}}\ (^{+30}_{-33})_{\text{theo.}}\ . \tag{6}$$

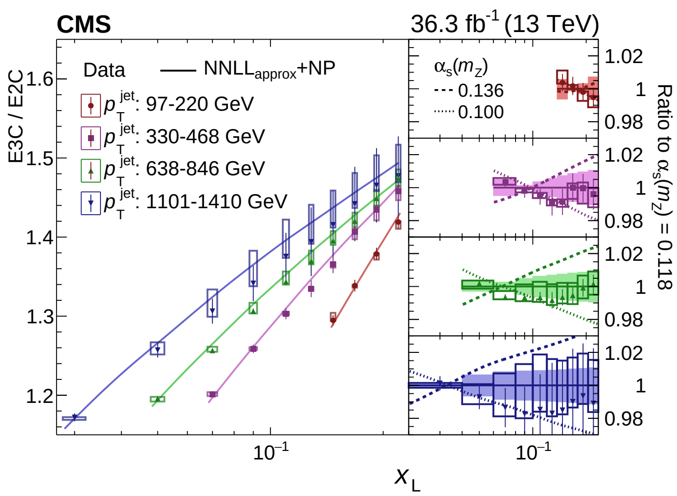

Figure 4: Ratio of E2C and E3C observables as a function of x_L in different p_T ranges. The panels on the right-hand side show a comparison to theoretical predictions for different values of $\alpha_s(m_Z)$, demonstrating the sensitivity to this parameter. Taken from Ref. [21].

5. Summary

A series of recent jet measurements from the CMS Collaboration at the CERN LHC was presented. Differential cross sections for inclusive jet and dijet production were measured at a center-of-mass energy of $\sqrt{s}$ = 13 TeV and used for deriving constraints on the strong coupling constant $\alpha_s(m_Z)$ and the proton PDFs, resulting in improved constraints of the gluon PDF at

$x > 0.3$ and the most precise single-measurement value of $\alpha_s(m_Z)$ obtained thus far at a hadron collider. An additional measurement of the inclusive jet cross section at $\sqrt{s} = 5.02$ TeV provides a complementary data set available for use in QCD fits. Measurements of the azimuthal correlations among jets and of energy-energy correlators inside jets are also summarized, providing alternative observables with sensitivity to $\alpha_s(m_Z)$.

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