New constraints on PDFs, strong coupling, and SMEFT results using CMS jet data

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Abstract

Measurements of the double-differential inclusive jet cross sections and triple-differential top quark-antiquark pair production cross sections have been performed at the center of mass energy of 13 TeV by the CMS Collaboration. The results of these measurements are used together with the data of inclusive deep inelastic scattering to extract the proton parton distribution functions, the top quark mass and the strong coupling constant. Using standard model predictions, the analysis results in the most precise determination of the strong coupling constant using LHC jet data. In an alternative analysis, the standard model is extended with effective couplings for 4-quark contact interactions, leading to a first-ever simultaneous extraction of the standard model parameters and the contact interactions' Wilson coefficients using LHC data.

1 Introduction

The standard model (SM) of particle physics describes the elementary building blocks of matter, fermions - quarks and leptons, and the fundamental interactions, mediated by bosons. The masses of the elementary particles and the coupling strengths of the interactions are parameters of the SM, however their values have to be extracted experimentally. In spite of the great success of the SM to describe the observed phenomena, its structure hints to necessity for extensions, introducing new physics (NP) - new massive particles or new interactions. For example, the SM operates with 3 fermion families. However, stable matter is made only of fermions from the first family. This fact has no SM explanation. One hypothesis is that fermions are made of more fundamental objects, subject to a new interaction at a scale much larger than their mass. Often, NP is modelled using effective field theory (EFT) to describe fermion contact interactions (CI). In the recent work [1] by the CMS Collaboration [2] at the CERN LHC, production of jets and top quark-antiquark pairs in proton-proton collisions is used in a SM analysis improved for EFT (SMEFT), in which the parameters of quantum chromodynamics (QCD) of SM are extracted simultaneously with the constraints on CI.

2 SM and SMEFT interpretation of CMS measurements

The LHC proton-proton collision data at 13 TeV are used by the CMS Experiment to measure the cross section of inclusive jet production as a function of individual jet transverse momentum p_T and rapidity $|y|$. The details of the measurement, theoretical predictions and the interpretation are given in Ref. [1] and the references therein.

The present results involve jets reconstructed using the anti-k_T algorithm [3] with the distance parameter R=0.7, for which the data correspond to an integrated luminosity of 33.5 fb^{-1}. The data are compared with fixed-order QCD predictions available at NLO and NNLO, obtained by using the NLOJet++ [4, 5] and NNLOJET [6, 7, 8] programs. The NLO calculations are implemented in FastNLO [9]. The NLO cross-section is improved by next-to-leading logarithmic (NLL) corrections [10]. The theoretical predictions are corrected for electroweak and nonperturbative effects. The comparison of data with the theoretical predictions at NLO+NLL is shown in Fig. 1.

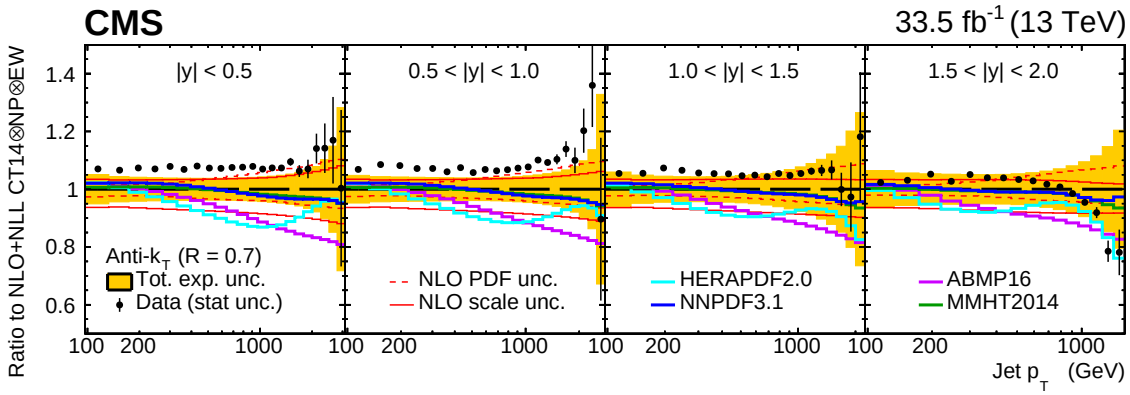

Figure 1: CMS measurements compared with the QCD prediction at NLO+NLL using different PDFs. The distributions are divided by the prediction obtained using the CT14 PDF [1].

The sensitivity of the present measurement to the proton PDFs and $\alpha_S(m_Z)$ is investigated in a comprehensive QCD analysis, where the inclusive jet production cross sections are used together with the charged and neutral current deep inelastic scattering (DIS) cross sections measured at HERA [11]. In addition, the normalised triple-differential $t\bar{t}$ cross section measurement [12] is used. The QCD analysis [1] is performed at NLO and NNLO by using the xFitter QCD analysis framework version 2.2.1 [13, 14, 15]. In the QCD analysis, the NNLO calculation is approximated by k-factors, obtained as a ratio of the NNLO to NLO calculations using CT14nnlo PDF [16] in each bin in p_T and $|y|$. These are applied to the NLOJet++ prediction interfaced to xFitter using fast-grid techniques of fastNLO. In a similar way, the NLO prediction is improved to NLO+NLL. The QCD prediction for the normalised triple-differential cross section of the $t\bar{t}$ production is available only at NLO. To account for possible CI contributions, the SM Lagrangian is extended as $\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{4\pi}{2\Lambda^2}\sum_n c_n O_n$, where Λ is the scale of new physics, c_n are Wilson coefficients and O_n are dimension-6 operators for 4-quark CI corresponding to purely left-handed, vector-like or axial vector-like colour singlet exchanges. For the purpose of the SMEFT analysis, xFitter is interfaced to the CIJET [17, 18] code, providing CI contributions to SM jet production at NLO. In

the scope of the SMEFT analysis, the PDFs, $\alpha_S(m_Z)$, m_t and the Wilson coefficient c_1 of 4-quark contact interactions can be extracted simultaneously, for the first time.

The impact of the new CMS jet measurement on PDFs and $\alpha_S(m_Z)$ is investigated at NNLO, assuming only SM. The precision of the resulting PDFs is significantly improved, as shown in Fig. 2. Simultaneously, the value of $\alpha_S(m_Z) = 0.1170 \pm 0.0019$ is obtained, which is the most precise measurement at a hadron collider, to date.

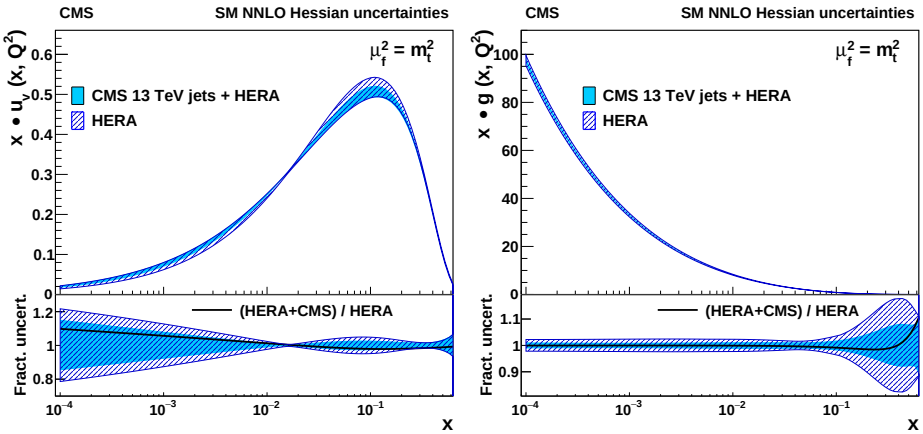

Figure 2: The u-valence (left) and gluon (right) distributions, shown as a function of x at the scale of the top quark mass. The filled (hatched) band represents the results of the NNLO fit using HERA DIS and the CMS inclusive jet cross section at $\sqrt{s} = 13$ TeV (using the HERA DIS data only). The PDFs are shown with their total uncertainty. In the lower panels, the comparison of the relative PDF uncertainties and the PDF ratios of the two fits are shown [1].

The SM fit at NLO includes the $t\bar{t}$ measurements, so that simultaneous extraction of PDFs, $\alpha_S(m_Z)$ and the top quark pole mass m_t is possible. The obtained value is $m_t = 170.4 \pm 0.7$ GeV, which agrees with the previous CMS result [12] and improves its precision.

In the alternative SMEFT analysis, the PDFs, $\alpha_S(m_Z)$, and m_t are extracted simultaneously with the Wilson coefficient c_1 of CI models with purely left-handed, vector-like or axial vector-like colour singlet exchange. Simultaneous extraction of SM and EFT parameters assures that no NP effect is absorbed in the SM prediction and is the novelty and the advantage of the SMEFT analysis. The PDFs and QCD parameters resulting from the SMEFT fit agree with those obtained in the SM variant of the fit, as detailed in Ref. [1]. The ratio of the fitted c_1 to Λ^2 for different CI models is presented in Fig. 3. The result of negative c_1 implies constructive interference with the SM gluon exchange, but is statistically compatible with zero.

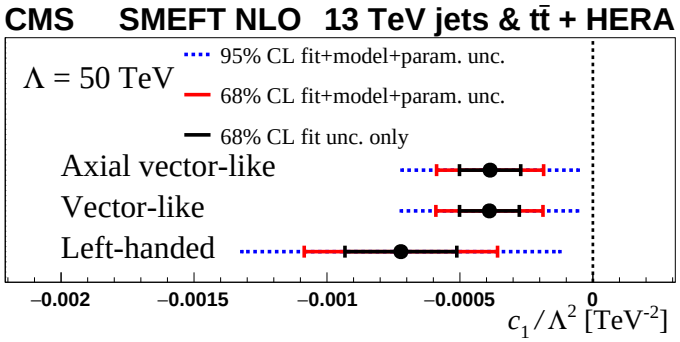

Figure 3: The Wilson coefficients c_1 obtained in the SMEFT analysis at NLO, divided by Λ^2, for Λ=50 TeV. The solid (dashed) lines represent the total uncertainty at 68 (95)% confidence level (CL). The inner (outer) error bars show the fit (total) uncertainty at 68% CL [1].

Conventional searches for CI are performed by scanning for Λ with c_1 fixed to $+1$ for destructive or -1 for constructive interference with the SM gluon exchange. The results of the present fit are translated into non-biased 95% CL exclusion limits on Λ with $c_1 = -1$. These are 24 TeV for left-handed, 32 TeV for vector-like, and 31 TeV for axial-vector-like CI. The most stringent comparable result is 22 TeV for left-handed CI with constructive interference, obtained by the ATLAS Collaboration using 13 TeV dijet cross sections data [19].

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