

The upcoming CTEQ-TEA parton distributions in a nutshell

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We review recent studies by the CTEQ-TEA group toward the development of a new generation of precision parton distribution functions in the nucleon for advanced studies at the high-luminosity LHC and in other experiments. Among several ongoing efforts, we examine sensitivity to the PDFs and mutual compatibility of new measurements in production of Drell-Yan pairs, top-quark pairs, and single-inclusive jets by the ATLAS, CMS, and LHCb collaborations in the LHC Runs 1 and 2.

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Accurate parametrizations for parton distribution functions (PDFs) in the nucleon are essential for a wide range of measurements pursued at the Large Hadron Collider (LHC) and in other experiments. The CTEQ-Tung Et Al. (CTEQ-TEA) group is involved in the global analysis of QCD measurements across a large energy span aimed at determination of PDFs at the precision frontier. As the LHC enters its high-luminosity decade, the knowledge of PDFs becomes even more central for accuracy control in many tests of the Standard Model (SM) and searches for beyond-SM physics. At the DIS'2024 workshop, the CTEQ-TEA group reported on a program of theoretical and methodological developments leading to a new generation of PDFs for advanced studies at the LHC Run-3. The new PDFs will replace the widely used CT18 PDFs [1] in general-purpose and specialized applications. Given the elevated requirements for accuracy of central PDFs and quantification of PDF uncertainties, the development of the new PDF series takes several years and involves implementation of new advances in theoretical calculations, adoption of new data sets constraining the PDFs, and refinement of the fitting methodology.

During the last year, our group published several articles focusing on specific aspects of our PDF fits. In addition, we recently published a summary [2] that highlights the key outcomes from the totality of our recent publications and emphasizes the synergy of all ongoing CTEQ-TEA efforts toward obtaining accurate, comprehensive, and reliable future PDFs. Traditionally, theoretical developments involve implementation of radiative contributions to improve the perturbation theory. With the growing availability of perturbative hard cross sections at N³LO in QCD, there is also increasing interest in producing N³LO PDFs. The CTEQ fitting package already includes components of the N³LO PDF analysis, notably the complete quark flavor infrastructure [3, 4] for implementation of 3-loop radiative contributions in DIS with massive charm and bottom quarks in the SACOT-MPS general mass scheme and for evolution of PDFs at N³LO accuracy. However, many more components at N³LO are needed to guarantee the N³LO accuracy of the PDF fits and will not be available for a while. PDF-fitting groups [5], including CTEQ-TEA, implement the mandatory components as they become available. An additional consideration is that, when perturbative uncertainties are suppressed by including appropriate radiative contributions, other types of uncertainties become prevalent in the full PDF uncertainty. Efforts to control these other uncertainties must complement implementation of N³LO contributions.

The upcoming CTEQ-TEA analysis will therefore release NNLO PDFs as well as some investigations done at partial N³LO – the highest order of QCD available for PDF fits at the moment. The summary article [2] reviews the multi-prong efforts toward this goal: investigations of the impact of candidate data sets from lepton pair [6], top-quark pair [7], and inclusive (di)jet production [8] from the LHC at 5, 7, 8, and 13 TeV; advances in methodology to quantify the mutual agreement of experimental constraints [9–11] and streamline estimations of uncertainties due to PDF parametrizations [12–14]; studies of small- x dynamics that affects the gluon and other PDFs at all x via sum rules, as well as forward charm production [15] and high-energy neutrino scattering [16]; exploration of first lattice QCD constraints on strangeness quark-antiquark asymmetry [17]; NNLO PDF fits with contributions from nonperturbative (power-suppressed) charm quarks [18] and photons in the proton [19] and neutron [20]; investigations of implications and future prospects ranging from low-energy parity-violating DIS [21] to combined PDF-SMEFT fits [22].

In this contribution, we highlight one aspect of the ongoing analysis: investigation of the likely impact of new precision data sets from the LHC Runs 1 and 2 on the upcoming PDFs. In Refs. [6–8],

Table 1: The numbers of points (N_{pt}) and χ^2/N_{pt} values for the LHC Drell-Yan, $t\bar{t}$ and inclusive jet data sets fitted simultaneously in the CT18+nDYTTIncJet NNLO fit. The uncertainties are obtained with the final Hessian error sets at 90% CL. The χ^2/N_{pt} values in parentheses are obtained with the original CT18 NNLO error sets.

ID	Experiment	N_{pt}	CT18+nDYTTIncJet (CT18)
Drell-Yan pair production			
211	ATLAS 8 TeV W	22	$2.42^{+2.49}_{-1.51}$ ($4.25^{+6.39}_{-3.34}$)
212	CMS 13 TeV Z	12	$2.48^{+4.76}_{-0.88}$ ($12.03^{+38.04}_{-21.84}$)
214	ATLAS 8 TeV Z3D	188	$1.12^{+0.46}_{-0.02}$ ($1.99^{+5.10}_{-1.85}$)
215	ATLAS 5.02 TeV W,Z	27	$0.82^{+0.55}_{-0.16}$ ($1.15^{+1.22}_{-0.43}$)
217	LHCb 8 TeV W	14	$1.35^{+0.59}_{-0.61}$ ($1.35^{+0.72}_{-0.64}$)
218	LHCb 13 TeV Z	16	$1.18^{+1.42}_{-0.60}$ ($1.49^{+1.74}_{-0.89}$)
$t\bar{t}$ production at 13 TeV			
521	ATLAS all-hadronic $y_{t\bar{t}}$	12	$1.06^{+0.14}_{-0.09}$ ($1.05^{+0.21}_{-0.10}$)
528	CMS dilepton $y_{t\bar{t}}$	10	$1.10^{+1.08}_{-0.68}$ ($1.03^{+1.60}_{-0.74}$)
581	CMS lepton+jet $m_{t\bar{t}}$	15	$1.44^{+1.18}_{-0.73}$ ($1.37^{+1.86}_{-0.82}$)
587	ATLAS lepton+jet $m_{t\bar{t}} + y_{t\bar{t}} + y_{t\bar{t}}^B + H_T^{t\bar{t}}$	34	$0.92^{+0.32}_{-0.14}$ ($0.94^{+0.59}_{-0.16}$)
Inclusive jet production			
553	ATLAS 8 TeV IncJet	171	$1.76^{+0.20}_{-0.12}$ ($1.80^{+0.33}_{-0.16}$)
554	ATLAS 13 TeV IncJet	177	$1.38^{+0.13}_{-0.10}$ ($1.39^{+0.20}_{-0.11}$)
555	CMS 13 TeV IncJet	78	$1.10^{+0.24}_{-0.17}$ ($1.11^{+0.30}_{-0.16}$)
Total		4457	5402

we examined constraints on NNLO PDFs using measurements from 20 publications on Drell-Yan pair, top-antitop, inclusive jet, and jet pair production published by the ATLAS, CMS, and LHCb Collaborations. Most of these publications provide several differential distributions that may be suitable for the PDF fits. The above publications find that the considered distributions may have non-identical preferences for PDFs because of the impact of collateral systematic factors that are not the same across various measurements. One important case is the gluon PDF at momentum fractions of $x \approx 0.05$ and QCD scales close to 125 GeV that controls Higgs boson production rates via gluon-gluon fusion. Sensitivity analyses like the one in [9] indicate that the main relevant constraints on the gluon PDF arise from several types of processes: scaling violations in DIS at HERA, BCDMS, and NMC; hadron jet production; and, as experimental precision grows, even from Drell-Yan and $t\bar{t}$ pair production data sets. Ref. [2] pointed out that the relevant high-precision LHC data sets generally exert opposing pulls: in the considered scenarios, Drell-Yan pair and $t\bar{t}$ pair production on the whole preferred a smaller gluon PDF at $x \gtrsim 0.05$, while inclusive jet production preferred a larger gluon at $x \gtrsim 0.1$. We also compared the PDF constraints from Run-1 and 2 jet production measurements presented either as distributions of single-inclusive jets or distributions of jet pairs. We found that the PDF constraints from single-inclusive jet distributions were less affected by the QCD scale dependence than the counterpart dijet ones.

For the combined analysis, the central question therefore concerns the selection of the data sets that are both constraining on the PDFs and consistent with one another. Based on the in-depth

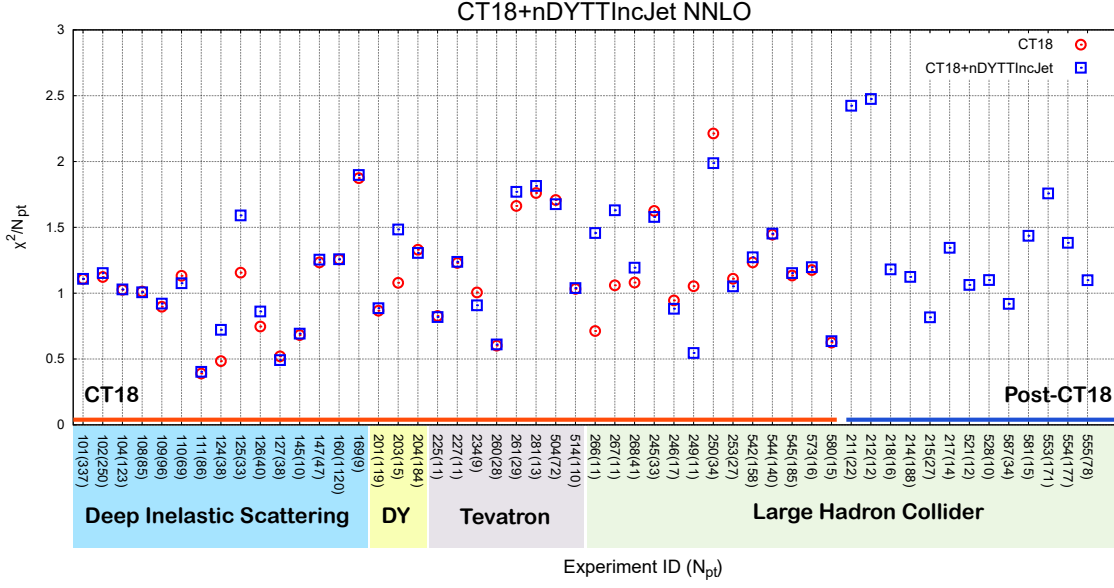


Figure 1: The χ^2/N_{pt} values for each data set included in CT18+nDYTTIncJet NNLO fit, for both the resulting CT18+nDYTTIncJet PDFs and CT18 NNLO PDFs from [1]. The horizontal axis indicates the IDs and N_{pt} of the experiments, with the IDs in the CT18 baseline listed in [1] as well as Table 1.

investigations in Refs. [6–8], we identified such an optimal selection, in which 13 distributions from the three categories of processes (for production of lepton pairs, top-quark pairs, and single-inclusive jets), with a total of 776 new data points, were added to the CT18 NNLO baseline fit, which contains a total of 3681 data points. This extension of the CT18 global data is named “CT18+nDYTTIncJet”. The corresponding fit used the same underlying parametrization and analysis settings as the CT18 NNLO fit. Table 1 lists the newly added LHC data sets, together with the χ^2/N_{pt} values obtained in the “CT18+nDYTTIncJet” NNLO fit and using the original CT18 NNLO PDFs (in parentheses). Figure 1 illustrates the χ^2/N_{pt} values for all experiments in the CT18+nDYTTIncJet study by plotting them against the numerical ID and number of points of each experiment.

The CT18+nDYTTIncJet fit is in good overall agreement with the old and new data sets, with the total $\chi^2/N_{pt} = 5402/4457 \approx 1.21$ comparable to that in the CT18 NNLO baseline fit. We also observe some tensions among the data sets, which reduce their net constraining power. For example, in Fig. 1, χ^2/N_{pt} increases for the NuTeV (124 and 125), CCFR (126 and 127) and E866 DY (203) experiments, and the CMS 7 TeV muon charge asymmetry and electron charge asymmetry data sets (266 and 267). χ^2/N_{pt} decreases for the CMS 8 TeV muon charge asymmetry (249) and LHCb 8 TeV W/Z (250) experiments.

The overall level of tensions remains about the

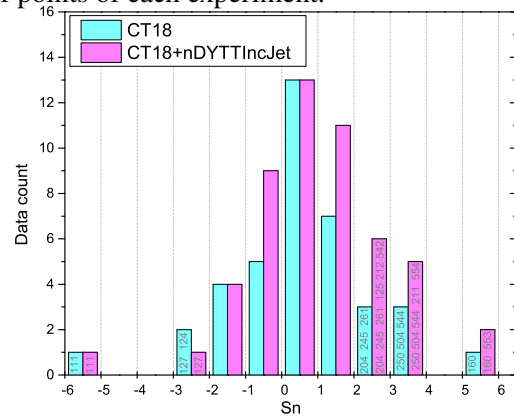


Figure 2: A histogram of the effective Gaussian variable, $S_n \equiv \sqrt{2\chi_n^2} - \sqrt{2N_{pt} - 1}$, distributed over all CT18 and CT18+nDYTTIncJet data sets.

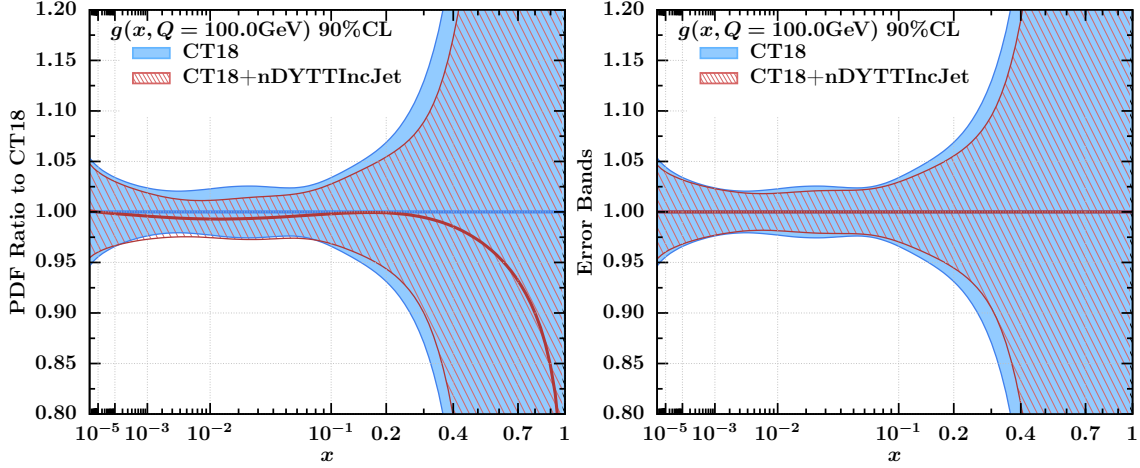


Figure 3: Comparisons of the gluon PDFs in the CT18 (blue) and CT18+nDYTTIncJet (red) NNLO PDF fits. Left: plotted as a ratio to the central CT18 NNLO PDF. Right: plotted as normalized error bands at 90% CL.

same as in the CT18 NNLO baseline fit, as revealed by the histogram of the effective Gaussian variable [23], defined as $S_n \equiv \sqrt{2\chi_n^2} - \sqrt{2N_{\text{pt}} - 1}$, for individual data sets in the CT18 and CT18+nDYTTIncJet fits shown in Fig. 2. The S_n values do not follow the standard normal distribution as would be expected in an ideal fit [24, Sec. 4H]. The S_n values of the DIS HERA (160) and ATLAS 8TeV IncJet (553) data sets are exceptionally large, while the neutrino-iron DIS CCFR F2 (111) data have a very good S_n value.

Figure 3 illustrates the combined impact of these new LHC Drell-Yan, $t\bar{t}$ and inclusive jet data sets on the gluon PDF at $Q = 100 \text{ GeV}$. In the left panel, the CT18+nDYTTIncJet fit prefers a softer gluon PDF at $x > 0.3$. Specifically, the downward pull on the large- x gluon by the included Drell-Yan and $t\bar{t}$ data sets (with the latter given by the “nTT2” combination of $t\bar{t}$ observables introduced in [7]) overcomes the net upward pull from single-inclusive jet data sets. We also observe reduction of order 1% in the gluon at moderate x relevant for Higgs boson production at the LHC. In the right panel, we see that the nominal CT18 uncertainty on the gluon is reduced across most of the x range upon addition of the nDYTTIncJet combination. In this case, the uncertainties on the blue and red error bands are estimated according to the same prescription (tolerance) as in [1]. We note that the tolerance depends on methodology and may result in different uncertainty estimates even when fitting the same data sets [25]. Advancing toward the near-future CTEQ-TEA analysis, we expect the PDF tolerance to evolve, on the one hand, to account for the residual tensions that remain significant in the CT18+nDYTTIncJet fit, cf. Fig. 2, and, on the other hand, to quantify the dependence on PDF parametrization forms along the possibilities explored e.g. in [12–14]. Further details on the new CTEQ-TEA precision fit and its phenomenological implications will be presented in our future publication.

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