

Progress in CTEQ-TEA PDF analysis

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Recent developments in the CTEQ-TEA global QCD analysis are presented. The parton distribution functions CT10-NNLO are described, constructed by comparing data from many experiments to NNLO approximations of QCD.

The global analysis of QCD makes use of experimental data from many short-distance scattering processes to construct, within some approximations, universal parton distribution functions (PDFs) for the proton. Then these functions can be used to calculate hadronic cross sections in the Standard Model and other theories. Global analysis and the resulting PDFs are necessary for the interpretation of experimental results at hadron colliders.

Recently published PDFs are based on next-to-next-to-leading order (NNLO) approximations for perturbative QCD [1]. Complete calculations for this order of approximation are available for the running coupling $\alpha_s(Q)$, PDF evolution in Q , matrix elements in deep-inelastic scattering [2] and vector boson production [3]. The CTEQ analysis treats quark-mass effects in the S-ACOT- χ factorization scheme, which has been recently extended to two-loop, or NNLO, accuracy [4]. Though the NNLO matrix elements are still unknown for some important processes, such as the inclusive jet production in $pp/p\bar{p}$ collisions, it is important to use NNLO approximations, where available.

CTEQ has developed PDFs for general-purpose computations and estimates of PDF-driven uncertainties over many years [5]. The most recent PDFs in this class, named CT10 and CT10W, were published in 2010 [6]. We now present a new family of CTEQ parton distributions, named CT10 NNLO. There are several reasons for publishing them. First, the CT10 NNLO global analysis is based on the NNLO approximation of perturbative QCD, whereas the CT10 and earlier analyses were based on NLO. Second, benchmarking of NLO jet cross sections [7] and DIS cross sections was performed to quantify theoretical uncertainties, and an in-depth study of the treatment of correlated experimental errors has been completed. Third, selection of experimental data sets has been revisited. The new NNLO PDFs are closely related to both CT10 and CT10W NLO PDFs and can be matched to either of two NLO PDF sets when comparing the NLO and NNLO cross sections. In all three cases, only data from pre-LHC experiments were used in the global fit. The same values of the QCD coupling and heavy-quark masses as in CT10 NLO were assumed. Some results concerning CT10 NNLO PDFs were presented at DIS2012 [8] and will be described here. A longer paper on CT10 NNLO is

in preparation. The CT10 NNLO PDFs are now available in the LHAPDF library.

In the near future, a new release of NLO and NNLO PDFs, named CT12, will include available data from LHC experiments. Some preliminary results of the CT12 analysis were also presented at DIS2012 [8].

Selection of data. At NLO, the main distinction between CT10 and CT10W sets concerns the inclusion of the D0 Run-2 W electron and muon asymmetry [11], $A_\ell(y_\ell)$, that constrains the behavior of the ratio $d(x, Q)/u(x, Q)$ at $x > 0.1$. The CT10 NLO set does not include the D0 Run-2 A_ℓ data, while the CT10W NLO set includes 4 $p_{T\ell}$ bins of A_ℓ . The CT10 NNLO analysis includes all data sets that were used in the NLO fits, with the exception of the Tevatron Run-1 inclusive jet cross sections [9] that have been superseded by more precise Tevatron Run-2 jet cross sections [10]; and the D0 Run-2 A_ℓ data sets, of which only most inclusive (best understood) bins of $p_{T\ell}$ are included in both the electron and muon channel. Since CT10 NNLO includes only a part of the D0 A_ℓ data that distinguishes between CT10 NLO and CT10W NLO, it can be treated as a counterpart of either the CT10 NLO or CT10W NLO PDF set.

Overview of the PDFs. Figure 1 gives an overview of the CT10 NNLO PDFs. Four PDFs are shown: $u_{\text{valence}}(x, Q) = (u - \bar{u})(x, Q)$; $d_{\text{valence}}(x, Q) = (d - \bar{d})(x, Q)$; $g(x, Q)$; and $q_{\text{sea}}(x, Q) = 2(\bar{d} + \bar{u} + \bar{s})(x, Q)$. The vertical axis is $x f(x, Q)$. The CT10 NNLO PDFs are illustrated by plotting all the error PDFs; hence the figure shows not only the central fit but also the uncertainty ranges. The dashed curves are the central-fit CT10 NLO PDFs.

Both NLO and NNLO fits have about the same $\chi^2/N_{pt} \approx 1.1$ for $N_{pt} = 2700$ data points. Slide 5 in Ref. [8] shows a more complete comparison of CT10 NNLO to CT10W NLO, for $Q = 2 \text{ GeV}$ and for three parton flavors, g , u , and \bar{u} . The various PDFs are plotted as a ratio to the central CT10W NLO. The curves are the ratios of the central CT10 NNLO to CT10W NLO. The shaded regions are the *error bands* for the PDFs (both NLO and NNLO). The central NNLO PDFs differ from the central NLO PDFs, but the difference is comparable in size to the error bands. The error band for NNLO is slightly smaller than for NLO.

Compared to CT10W NLO, the NNLO PDF set at a small scale Q has a suppressed gluon and increased sea quarks at $x < 10^{-2}$, reduced $g(x, Q)$ and $d(x, Q)$ at $x > 0.1$, and very different charm and bottom PDFs (slide 6 in [8]). The reduction in $g(x, Q)$ Compared to MSTW'08 NNLO, the central CT10 NNLO gluon PDF is somewhat harder at $x < 10^{-3}$ and $x = 0.1 - 0.5$, and softer at $x > 0.5$ (slide 9 in [8]). The strangeness PDF is larger at $x \sim 10^{-2}$ in CT10 NNLO than in MSTW'08 NLO, producing a good agreement with the ATLAS measurement of

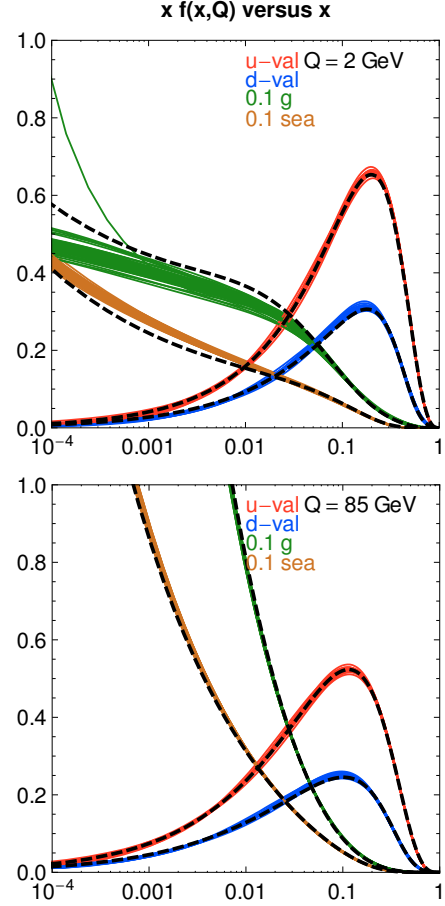


Figure 1: CT10 NNLO (solid color) and NLO (dashed) parton distribution functions.

the $\bar{s}(x)/\bar{u}(x)$ at this x value.

Boson/collider	CT10 NLO	CT10 NNLO	MSTW'08 NNLO
W^+ LHC14 (nb)	12.2 ± 0.5	12.7 ± 0.5	12.4 ± 0.2
W^+ LHC7 (nb)	6.0 ± 0.2	6.3 ± 0.2	6.2 ± 0.1
W^+ Tevatron (nb)	1.35 ± 0.05	1.38 ± 0.05	1.38 ± 0.02
W^- LHC'14 (nb)	8.9 ± 0.4	9.4 ± 0.4	9.3 ± 0.2
W^- LHC'7 (nb)	4.10 ± 0.15	4.29 ± 0.16	4.31 ± 0.07
Z LHC14 (nb)	2.07 ± 0.08	2.17 ± 0.08	2.13 ± 0.03
Z LHC7 (nb)	0.96 ± 0.03	1.00 ± 0.03	0.99 ± 0.02
Z Tevatron (pb)	260 ± 9	263 ± 8	261 ± 5
H_{SM}^0 LHC14 (pb)	101 ± 9	99 ± 8	102 ± 7
H_{SM}^0 LHC7 (pb)	31.2 ± 1.9	29.7 ± 1.7	29.8 ± 1.3
H_{SM}^0 Tevatron (pb)	1.77 ± 0.12	1.77 ± 0.12	1.80 ± 0.11

Table 1: Total cross sections for production of electroweak bosons.

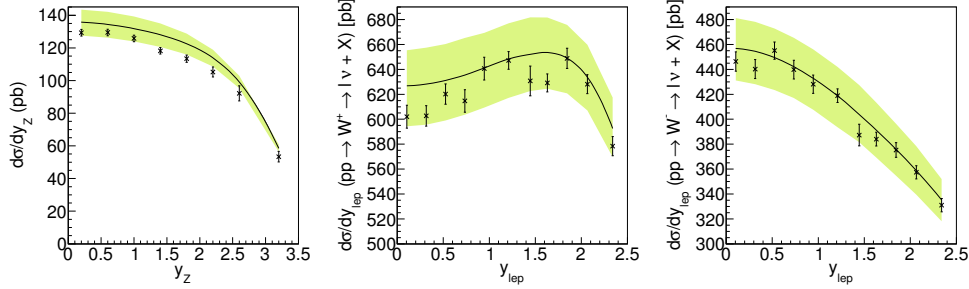


Figure 2: Comparisons of ATLAS data with ResBos predictions for Z^0 and W^\pm lepton rapidity distributions.

Predictions for the LHC. In a future paper we will provide detailed comparisons of theory and data, where the theory is calculated from the CT10 NNLO PDFs. Here we collect some representative cross sections for the hadron colliders. Table 1 compares predictions for total cross sections for W , Z and Higgs boson production via gluon fusion (with Higgs mass of 125 GeV) at the Tevatron and the LHC (with $\sqrt{s}=7$ and 14 TeV). The comparison is between CT10 NLO, CT10 NNLO, and MSTW'08 NNLO. The CT10 NNLO central PDF increases the total cross sections by a few percent compared with CT10 NLO accuracy and is close to MSTW'08. Theoretical uncertainties from alternative PDF sets for CT10 NNLO are similar to those for CT10, and in W/Z production they are about twice as those for MSTW'08.

Fig. 2 shows the comparison of ATLAS data [14] with ResBos [15] predictions for Z and W -lepton rapidity distributions at the LHC ($\sqrt{s}=7$ TeV) using CT10 NNLO PDFs. Theoretical uncertainty bands were calculated using the error PDF sets. The ResBos prediction of Z and W^+ -lepton rapidity distribution, using the central PDF set, is higher than ATLAS data by a few percent. However, for W^- -lepton rapidity distribution, the ResBos prediction is more consistent with ATLAS data. It is expected that these data could further refine the PDFs at the NNLO accuracy.

Fig. 3 compares the ATLAS data for inclusive jet transverse momentum distribution with

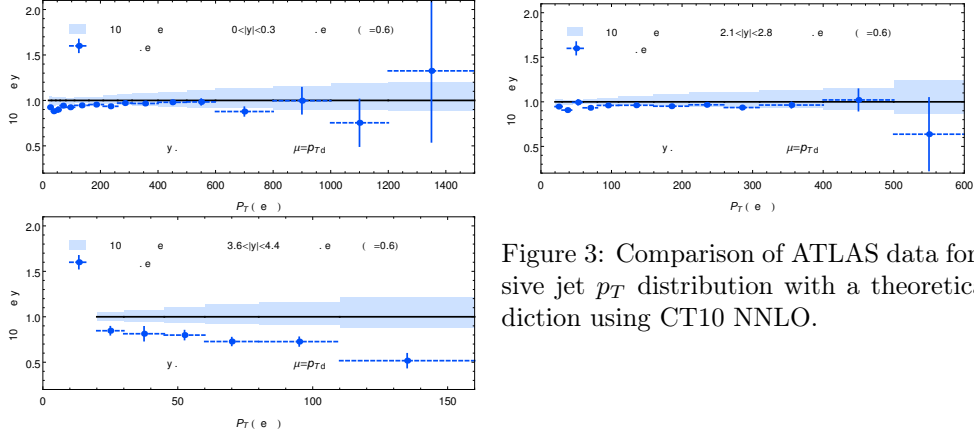


Figure 3: Comparison of ATLAS data for inclusive jet p_T distribution with a theoretical prediction using CT10 NNLO.

theoretical predictions based on the NLO matrix elements and CT10 NNLO PDFs. They agree well even without including the systematic shifts, except for the large rapidity region. After accounting for the systematic shifts, the reduced χ^2 is 0.78 for the measurement with $R=0.4$ and 0.76 for the one with $R=0.6$. The effect of the LHC data on the PDFs will be explored in the CT12 analysis.

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