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Progress in CTEQ-TEA PDF Analysis

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We present new parton distribution functions (PDFs) up to next-to-next-to-leading order (NNLO) from the CTEQ-TEA global analysis of quantum chromodynamics. These differ from previous CT PDFs in several respects, including the use of data from LHC experiments and the new DØ charged lepton rapidity asymmetry data, as well as the use of more flexible parametrization of PDFs that, in particular, allows a better fit to different combinations of quark flavors. Predictions for important LHC processes, especially Higgs boson production at 13 TeV, are presented. These CT14 PDFs include a central set and error sets in the Hessian representation.

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The CT10 parton distribution functions were published at next-to-leading order (NLO) in 2010 [1], followed by the CT10 next-to-next-to leading order (NNLO) parton distribution functions in 2013 [2]. These PDF ensembles were determined using diverse experimental data from fixed-target experiments, HERA and the Tevatron collider, but without data from the LHC. The CT14 PDFs [3] include data from the LHC for the first time, as well as updated data from the Tevatron and from HERA experiments. Various CT14 PDF sets have been produced at the leading order (LO), NLO and NNLO and are available from LHAPDF [4].

The new LHC measurements of W/Z cross sections directly probe flavor separation of u and d (anti-)quarks in an x-range around 0.01 that was not directly assessed by the previously available experiments. We also include an updated measurement of electron charge asymmetry from the DØ collaboration [5], which probes the d quark PDF at $x > 0.1$. To better estimate variations in relevant PDF combinations, such as $d(x,Q)/u(x,Q)$ and $\bar{u}(x,Q)/\bar{d}(x,Q)$, we increased the number of free PDF parameters to 28, compared to 25 in CT10 NNLO. As another important modification, CT14 employs a novel flexible parametrization for the PDFs, based on the use of Bernstein polynomials. In the asymptotic limits of $x \to 0$ or $x \to 1$, the new parametrization forms allow for the possibility of arbitrary constant ratios of d/u or $\bar{d}/\bar{u}$, in contrast to the more constrained behavior assumed in CT10.

A central value of $\alpha_s(M_Z)$ of 0.118 has been assumed in the global fits at NLO and NNLO. For the CT14 LO PDFs, we follow the precedent begun in CTEQ6 [6] by supplying two versions, one with a 1-loop $\alpha_s(M_Z)$ value of 0.130, and the other with a 2-loop $\alpha_s(M_Z)$ value of 0.118.

The relative changes between the CT10 NNLO and CT14 NNLO ensembles are best visualized by comparing the their PDF uncertainties. Fig. 1 compares the PDF error bands at 90% confidence level for the key flavors, with each band normalized to the respective best-fit CT14 NNLO PDF. The blue solid and red dashed error bands are obtained for CT14 and CT10 NNLO PDFs at $Q = 100$ GeV, respectively.

The CT14 d-quark PDF in lower left panel of Fig. 1 has increased by 5% at $x \approx 0.05$, after ATLAS and CMS W/Z production data sets at 7 TeV were included. At $x \gtrsim 0.1$, the update of the DØ charge asymmetry data set in the electron channel, has reduced the magnitude of the d quark PDFs by a large amount, and has moderately increased the $u(x,Q)$ distribution.

The gluon PDF in upper left panel of Fig. 1 has increased in CT14 by 1-2% at $x \approx 0.05$ and has been somewhat modified at $x > 0.1$ by the inclusion of the LHC jet production, multiplicative

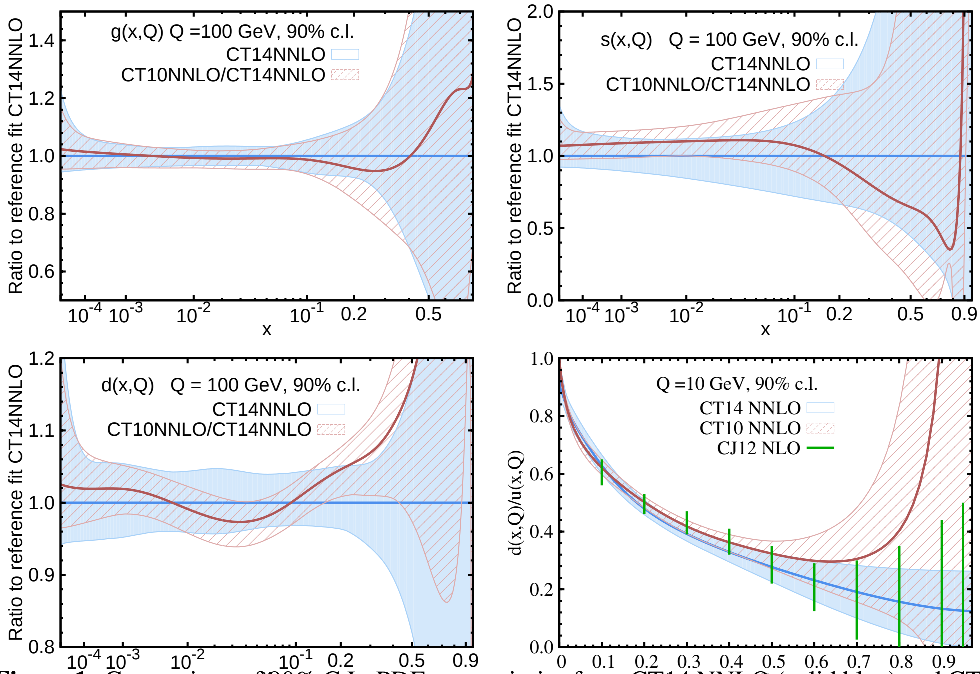

Figure 1: Comparison of 90% C.L. PDF uncertainties from CT14 NNLO (solid blue) and CT10 NNLO (red dashed) error sets. Both error bands are normalized to the respective central CT14 NNLO PDFs.

treatment of correlated errors. For x between 0.1 to 0.5, the gluon PDF has increased in CT14 as compared to CT10.

The central strangeness PDF $s(x,Q)$ in upper right panel of Fig. 1 has decreased for $0.01 < x < 0.15$, within the limits of the CT10 uncertainty, as a consequence of the more flexible parametrization, corrected calculation for massive quarks in charged-current DIS, and the inclusion of the LHC data. The extrapolation of $s(x,Q)$ below $x = 0.01$, where no data directly constrain it, also lies somewhat lower than before; its uncertainty remains large and compatible with that in CT10. At large x, above about 0.2, the strange quark PDF is essentially unconstrained in CT14, just as in CT10.

The changes in d/u in Fig. 1 in CT14 NNLO, as compared to CT10 NNLO, can be summarized as reduction of the central ratio at $x > 0.1$, caused by the 9.7 fb^{-1} DØ charge asymmetry data; and increased uncertainty at $x < 0.05$ allowed by the new parametrization form. At $x > 0.2$, the central CT14 NNLO ratio is lower than that of CT10 NNLO, while their relative PDF uncertainties remain about the same. Collider charge asymmetry data constrains d/u at x up to about 0.4. At even higher x, outside of the experimental reach, the behavior of the CT14 PDFs reflects the parametrization form, which now allows d/u to approach any constant value at $x \to 1$.

At such high x, the CTEQ-JLab analysis (CJ12) [7] has independently determined the ratio d/u at NLO, by including the fixed-target DIS data at lower W and higher x that is excluded by a selection cut $W > 3.5$ GeV in CT14; and by considering higher-twist and nuclear effects that can be neglected in the kinematic range of CT14 data. The CT14 uncertainty band on d/u at NNLO lies for the most part between the CJmin and CJmax predictions at NLO that demarcate the CJ12 uncertainty. We see that CT14 predictions on d/u at $x > 0.1$, which were derived from high-energy measurements that are not affected by nuclear effects, fall within the CJ12 uncertainty range obtained from low-energy DIS with an estimate of various effects beyond leading-twist perturbative QCD. The ratio should be stable to inclusion of NNLO effects; thus, the two ensembles predict a similar trend for collider observables sensitive to d/u.

The overall reduction in the strangeness PDF at $x > 0.01$ leads to a smaller ratio of the strange-to-nonstrange sea quark PDFs, $(s(x,Q)+\bar{s}(x,Q))\,/\,\left(\bar{u}(x,Q)+\bar{d}(x,Q)\right)$. At $x < 0.01$, this ratio is determined entirely by parametrization form and was found in CT10 to be consistent with the exact $SU(3)$ symmetry of PDF flavors, $(s(x,Q)+\bar{s}(x,Q))\,/\,\left(\bar{u}(x,Q)+\bar{d}(x,Q)\right) \to 1$ at $x \to 0$, albeit with a large uncertainty. The $SU(3)$-symmetric asymptotic solution at $x \to 0$ is still allowed in CT14 as a possibility, even though the asymptotic limit of the central CT14 NNLO has been reduced and is now at about 0.6 at $x = 10^{-5}$. The uncertainty of strangeness has increased at such small x and now allows $(s(x,Q)+\bar{s}(x,Q))\,/\,\left(\bar{u}(x,Q)+\bar{d}(x,Q)\right)$ between 0.35 and 2.5 at $x = 10^{-5}$.

Historically, measurements of $W^{\pm}$ charge asymmetry at the Tevatron have been important in the CTEQ-TEA global analysis. For example, the CTEQ6 PDFs and CT10 PDFs included the $W^{\pm}$ asymmetry data from the CDF and DØ experiments to supplement the constraints on u and d quark PDFs at $x > 0.1$ from fixed-target DIS experiments. The charge asymmetry at the Tevatron probes the differences of the *slope in x* of the PDFs for u and d flavors.

A new $W^{\pm}$ charge asymmetry measurement from the DØ experiment at the Tevatron has recently been published, using the full integrated luminosity (9.7 fb^{-1}) from Run-2 [5]. Figure 2 compares the DØ Run 2 data and various theoretical predictions at NNLO for both the latest (left) and the previous DØ data set (right). We show the unshifted data with the total experimental errors as error bars, and the 68% C.L. PDF uncertainties as the shaded regions. From the figures, we conclude that it is difficult to fit both data sets well, given the smallness of the systematic shifts associated with A_{ch}. While the 9.7 fb^{-1} electron data set is in better agreement with the global data, including the DØ muon [8] and CDF [9] A_{ch} measurements, the best-fit χ^2/N_{pt} for the 9.7 fb^{-1} sample remains relatively high (about 2) and is sensitive to detailed implementation of NNLO corrections. In-depth studies on the DØ asymmetry data will be presented in a forthcoming paper. When the high-luminosity DØ A_{ch} measurement was substituted for the low-luminosity one, we observed reduction in the d/u ratio at $x > 0.1$ compared to CT10W NLO and CT10 NNLO sets.

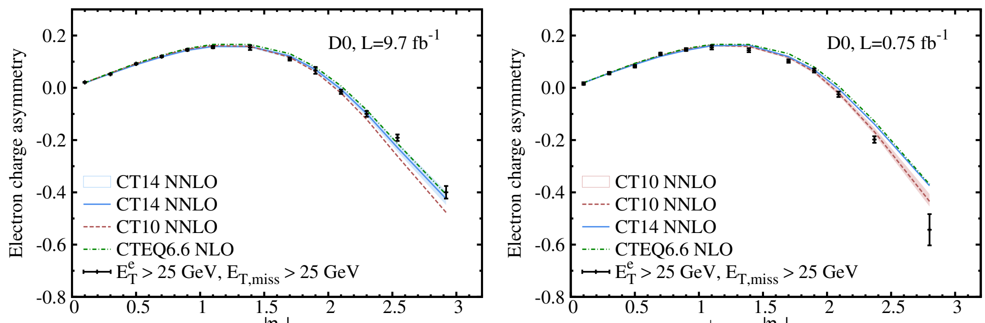

Figure 2: Charge asymmetry of decay electrons from $W^{\pm}$ production measured by the DØ experiment in Run-2 at the Tevatron with high (left) and low (right) luminosities, compared to several generations of CTEQ-TEA PDFs.

Measurements of total cross sections for production of massive electroweak particles at hadron colliders provide cornerstone benchmark tests of the Standard Model. In our paper [3] we provide NNLO theory predictions based on CT14 and CT10 NNLO PDFs for inclusive W and Z boson production, top-quark pair production, Higgs-boson production (through gluon-gluon fusion) at the LHC with center-of-mass energies of 8 and 13 TeV. We also examine correlations between PDF uncertainties of the total cross sections in the context of the Hessian formalism, following the approach summarized in Ref. [13]. PDF-driven correlations reveal relations between PDF uncertainties of QCD observables through their shared PDF parameters.

The ATLAS [10, 11] and CMS [12] experimental collaborations have recently published studies on the strangeness content of the proton and have come to somewhat discrepant conclusions. Both CT14 [3] and CT10 [2]predict a smaller strangeness than the ATLAS result and are compatible with CMS. The NOMAD Collaboration has also completed a study of the strange quark PDF, relying on the $\nu + Fe \to \mu^+ + \mu^- + X$ measurements [14] at lower energies than NuTeV and CCFR. The CT14 calculation is consistent with the NOMAD central value. However, the CT14 PDF uncertainty is considerably larger than the uncertainty quoted in the NOMAD paper, partly because of a different convention for the PDF uncertainty.

Acknowledgments

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