Global QCD Analysis and Collider Phenomenology—CTEQ

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An overview is given of recent progress on a variety of fronts in the global QCD analysis of the parton structure of the nucleon and its implication for collider phenomenology, carried out by various subgroups of the CTEQ collaboration.

1 Introduction

Parton distribution functions (PDFs) are essential input to all calculations on high energy cross sections with initial state hadrons. PDFs are extracted from comprehensive *global analysis* of available hard scattering data within the framework of *perturbative QCD.* This report covers recent progress on global QCD analysis made by members of the CTEQ collaboration on a variety of fronts. [1]

The basis of most of the recent progress is a new implementation of the general mass (GM) formulation for perturbative QCD that systematically includes heavy quark mass effects, both in kinematics and in the order-by-order factorization formula. [2] The next section describes the main implications of the new global QCD analysis on collider phenomenology at the Tevatron and the LHC. [3]

This is followed by the first in-depth study of the strangeness sector of the parton parameter space, based on the most up-to-date global analysis. [4] We found that current data imply a symmetric component of the strange parton distribution, $s(x) + \bar{s}(x)$, that has a shape independent of that of the isospin singlet non-strange sea; and a strangeness asymmetry function $s(x) - \bar{s}(x)$ that has a slightly positive first moment.

The same formalism has been applied to investigate the possibility of a non-perturbative (intrinsic) charm component in the nucleon. [5] This study is discussed in a separate talk in this workshop [6]. In a significant expansion of global QCD analysis, we have succeeded in combining the traditional fixed-order global fits with p_t resummation calculations. Combined conventional and p_t-resummed global fits can now be made to pin down parton degrees of freedom that are most pertinent for precision W-mass measurement and Higgs particle phenomenology. [7] Another subgroup of CTEQ has performed a detailed investigation of the role of recent neutrino scattering experiments (NuTeV, Chorus) and fixed-target Drell-Yan cross section measurement (E866) on global analysis, particularly pertaining to the large-x behavior of parton distributions. The results are reported in [8].

Due to space limitation, it is impossible to include in this short written report the figures that illustrate the results discussed in the corresponding talk, as summarized above. However, since the slides for the talk have been made available at the official conference URL [1], we shall make use of these, and refer the reader to the actual figures by the slide numbers where they appear in the posted talk [1]. The same space limitation restricts citations to only the papers and talks on which this report is directly based.

2 New Generation of PDFs and Their Implications for Collider Phenomenology

The base parton distribution set from the new generation of global analysis incorporating the GM formalism for heavy quark mass effects is the CTEQ6.5M PDF set [2]. The main improvements over the previous generation of PDFs—CTEQ6.0 and CTEQ6.1—are the mass treatment and the incorporation of the full HERA Run 1 cross section measurements, with their correlated systematic errors.

The most noticeable change in the output parton distributions is a sizable increase in the u- and d-quark distributions in the region $x \sim 10^{-3}$ for a wide range of Q. The three figures on slides 4/5 of [1] show the ratio of the CTEQ6.1 u, d-quark and the gluon distribution to that of CTEQ6.5 at $Q = 2$ GeV. The differences are moderated by QCD evolution, but still persist to a high energy scale such as the W/Z masses. The origin of these differences can be traced to the treatment of the heavy quark mass, as explained in slide 6. This change has immediate phenomenological consequences. The figure on slide 7 shows ratios of predicted cross sections at the LHC for the standard model (SM) processes $W^{\pm}/Z$ production, Higgs production $gg \rightarrow H^0$, and associated production of $W^{\pm}H$; as well as some representative beyond standard model (BSM) processes, e.g. charged Higgs production $\bar{s}c \rightarrow H^+ \rightarrow \bar{b}t$.

Of immediate interest is the 7% increase in the predicted W and Z production cross sections at LHC (which are sensitive to PDFs in the $x \sim 10^{-3}$ range) compared to previous estimates. The plot on slide 10 shows the predicted Z vs. the W cross sections for several commonly available PDF sets. The predictions seem to fall into two groups, with no obvious pattern. The results on slide 11 represent an attempt to see whether the difference between Zeus and H1 predictions can be reproduced in the CTEQ framework. We do not see a substantial difference between the two experimental inputs, but do see a clear dependence on how mass effects are treated. Further mysteries are (i) why are the Zeus predictions independent of their mass treatment; and (ii) why are their predictions with mass effects so different from that of MRST, even though they use the MRST formalism for mass treatment. The resolution of these apparent puzzles concerning the W and Z cross sections at the LHC is clearly of great importance to its physics program.

To see the impact of the new PDFs on collider phenomenology in general, it is convenient to examine the luminosity curves. These are shown in slides 8-9 over the range 10 GeV $< \hat{s} < 5$ TeV for LHC (normalized to that of CTEQ6.1), including bands representing the estimated uncertainties due to experimental input to the global analysis. The quark-quark (q-q) luminosity curves show the largest change between the two generations of PDFs; the g-g luminosity is shifted only slightly, and the g-q luminosity shift lies in between.

The cross sections shown in slide 7 also include some typical BSM processes. Notice in particular the very large predicted cross section for the last process due to a new PDF set CTEQ6.5C that permits a non-perturbative (intrinsic) charm component of the nucleon [5].

In the base PDF set CTEQ6.5M, we adopted the conventional assumptions that the strange distributions $s(x)$ and $\bar{s}(x)$ are of the same shape as the isospin symmetric non-strange sea at the initial scale $\mu = Q_0$ for QCD evolution, and that the charm distribution $c(x)$ is zero at the scale $\mu = m_c$. There are of no independent degrees of freedom for strange and charm. The improved theoretical and experimental inputs to the new generation of global analysis now permit us to relax these ad hoc assumptions, and hence to study where the truth lies. The results on strange PDFs obtained by [4] will be summarized in the following section. The subject of charm PDF is covered in [6].

3   Systematic Study of the Strangeness PDFs

Within the global QCD analysis framework, the only currently measurable process that is directly sensitive to the strange distributions $s(x)$ and $\bar{s}(x)$ is dimuon (charm) production in neutrino (and anti-neutrino) scattering off nucleons, via the partonic process $W^+(W^-)+s(\bar{s}) \to c(\bar{c})$. The final data of the NuTev experiment [9] is thus crucial for this analysis. The constraining power of these data can be realized, however, *only within the framework of a comprehensive global analysis*, since the same final state is produced also by the down quarks, and since the strange sea is intricately coupled to the gluon and the non-strange partons by QCD interactions. Also, because of the presence of the charm particle in the final state of the dimuon signal, a consistent theoretical treatment of heavy quark mass effects for both charged-current and neutral-current DIS processes [2] is essential to obtain reliable results.

For convenience, we define the symmetric strange sea $s_+(x) \equiv s(x) + \bar{s}(x)$ and the strangeness asymmetry $s_-(x) \equiv s(x) - \bar{s}(x)$. All these functions refer to the initial distributions at $\mu = Q_0$; QCD evolution then dictates their μ dependence at higher energy scales. We address the following three issues in turn.

Is the shape of the symmetric strange sea independent of that of the non-strange sea? The answer appears to be yes, according to the up-to-date global analysis [4]. The evidence is shown on slide 14. The table gives the changes in the goodness-of-fit for the full set of 3542 data points used in the global analysis, as well as the subset of 149 points for neutrino dimuon data sets, that we found in performing a series of global analysis, using 2/3/4 independent strangeness shape parameters, compared to the CTEQ6.5M reference fit that tied the shape of $s(x)$ and $\bar{s}(x)$ to that of the non-strange sea. We see that there is a substantial improvement in the quality of the fit to the dimuon data with $s_+(x)$ different from that of the non-strange sea. We also see that current data cannot discriminate between 2-, 3-, or 4-parameter forms for $s_+(x)$. Thus, a 2-parameter form will serve as a practical working hypothesis.

What is the size of the symmetric strange sea, and what are the allowed ranges for its size and shape? Slide 15 presents results of our study on these issues. The upper figure shows the goodness-of-fit in terms of χ^2/point for the dimuon data (deep parabola) and for the global data (shallow parabola) as a function of the momentum fraction carried by the strange sea, $\langle x \rangle_{s+} = \int xs_+(x)dx$. The dimuon data clearly favor a central value of $\langle x \rangle_s \sim 0.027$. The range of allowed size is obtained by adopting a 90% confidence level criterion. In terms of the ratio of the first moments (fractional momentum) of the strange to non-strange sea, this range corresponds to (0.27, 0.67), as indicated on the slide. The range of possible shape of $s_+(x)$ is a little more elusive to quantify. The lower figure presents a range of possible candidates, within the 90% C.L. criterion, when both the size and shape parameters are allowed to vary. These representative PDF sets are labeled CTEQ6.5Sn, $n = 0, 1, ..., 4$, with $n = 0$ being the central fit.

Current status of the strangeness asymmetry: Non-perturbative models of nucleon structure suggest a possible non-vanishing strangeness asymmetry. Within the PQCD framework, QCD evolution beyond the first two leading orders causes a non-vanishing $s_-(x, \mu)$, even if one starts with a symmetric strange sea. Historically, $s_-(x)$ was first studied phenomenologically in 2003 as a possible explanation for the "NuTeV anomaly" associated with the Weinberg angle measurement. Therefore, it is natural to ask: what can we say about $s_-(x)$ currently, now that both the theory and experimental situation have improved? The

results of our study, [4], are summarized in slide 17: (i) current global analysis still does not require a non-zero $s_-(x)$, although it is consistent with one; (ii) the best fit corresponds to a positive asymmetry $\langle x \rangle_{s-} = \int x s_-(x) dx \sim 0.002$; and (iii) the 90% C.L. range for $\langle x \rangle_{s-}$ is $(-0.001, \ 0.005)$. These results are consistent with both the 2003 CTEQ study and the most recent NuTeV analysis [9]. The figures on slide 17 show the shape of $s_-(x)$ and the momentum distribution $x s_-(x)$ for a variety of possible candidate PDFs within the 90% C.L. criterion.

4 New neutrino DIS and Drell-Yan data and large-x PDFs

It has been known for some time that the relatively recent NuTeV total cross section and E866 Drell-Yan cross section data sets pose puzzling dilemmas for quantitative global QCD analysis of PDFs, as indicated in slides 20 and 21. Attempts to incorporate these data in global analysis by Owens *et.al.* [8] led to the following key observations: (i) the NuTeV data set pulls against several of the other data sets, notably the E-866 and the BCDMS and NMC data. Nuclear corrections (heavy target) do not improve the situation. (In fact, assuming no nuclear correction lessens, but does not remove, the problem.); (ii) the conflicts are most pronounced when one examines the d/u ratio. Adding NuTeV and E-866 simultaneously in the global analysis causes the d/u ratio to flatten out substantially, resulting in worsened fits to other precision DIS data; and (iii) the E866 pp data is more comparable with precision DIS data sets than the pd data. Slides 23 - 26 show the figures that support these observations.

Conclusion: Results presented here, in conjunction with those covered in [3, 6, 7], represent significant evolutionary advancement of global QCD analysis, as well as some ground-breaking development (such as the incorporation of p_t resummation [7]). There are, however, also open problems that require further study and resolution [8]. Much remains to be done.

References

[1] Slides for this talk:
http://indico.cern.ch/contributionDisplay.py?contribId=189&sessionId=8&confId=9499.

[2] W. K. Tung, H. L. Lai, A. Belyaev, J. Pumplin, D. Stump and C. P. Yuan, JHEP **0702**, 053 (2007).

[3] See also C.-P. Yuan, talk in the Electroweak work group of this Workshop:
http://indico.cern.ch/contributionDisplay.py?contribId=120&sessionId=9&confId=9499.

[4] H. L. Lai, P. Nadolsky, J. Pumplin, D. Stump, W. K. Tung and C. P. Yuan, JHEP **0704**, 089 (2007).

[5] J. Pumplin, H. L. Lai and W. K. Tung, Phys. Rev. D **75**, 054029 (2007).

[6] Wu-Ki Tung, talk in the Heavy Flavors work group of this Workshop:
http://indico.cern.ch/contributionDisplay.py?contribId=276&sessionId=5&confId=9499.

[7] Cf. C.-P. Yuan, talk in the Structure Function work group of this Workshop:
http://indico.cern.ch/contributionDisplay.py?contribId=251&sessionId=8&confId=9499.

[8]   J. F. Owens *et al.*, Phys. Rev. D **75**, 054030 (2007).

[9] D. A. Mason, Proceedings of 14th International Workshop on Deep Inelastic Scattering (DIS 2006), Tsukuba, Japan; and FERMILAB-THESIS-2006-01.