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PROGRESS OF CTEQ GLOBAL QCD ANALYSES

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A brief overview of recent work of the CTEQ group on global QCD analysis of the parton structure of the nucleon is presented. A detailed study of the stability of predictions of parton distribution functions (PDFs) in NLO global analysis is described, because of its important implications for collider physics. Two topics on flavor dependence of PDFs are touched upon: (i) status of $d(x)/u(x)$ at large x; and (ii) charge asymmetry in the strangeness sector of nucleon structure ($s(x) \neq \bar{s}(x)$).

1 Stability of NLO global analysis

The vast majority of work on global QCD analysis of parton distribution functions (PDFs) and their application to high energy processes has been performed at NLO (1 loop hard cross sections and 2-loop evolution kernel). In recent years, some preliminary NNLO analyses have been carried out, even though not all necessary hard cross sections are yet available, and the evolution kernel was only known approximately (until this conference). Since errors on most of the experimental data used in global analysis are generally larger than the NNLO corrections in the processes for which the latter are available, the necessity to extend the analysis to NNLO, at the expense of vastly more complicated calculations, is not obvious.

A strong motivation to go to NNLO would exist, however, if the conventional NLO analysis does not yield stable PDFs and physical predictions. This possibility was indeed raised by a recent MRST study [1,2]. In particular, they found a 20% variation in the predicted cross section for W production at LHC—a very important "standard candle" process for hadron colliders—in their NLO analysis, depending on kinematic cuts placed on input data.[a] Their results on the total cross section and on the rapidity distribution of the W boson are shown in Fig. 1. For both the Tevatron Run II and LHC physics programs this is clearly a critical issue; it is important to investigate whether this result is confirmed by an independent study.

We have investigated this problem in considerable detail within the CTEQ global analysis framework [3]. Applying the same theoretical and experimental inputs to the global analysis, we systematically varied the kinematic cuts in x and Q, and generated new sets of best-fit PDFs. To explore the dependence of the results on

[*] The work reported in this talk is mostly based on collaborations with Joey Huston, Stefan Kretzer, Stephen Kuhlmann, H.L. Lai, Frederick Olness, Joseph Owens, Jonathan Pumplin, and Daniel Stump.

[a] In the absence of general methods of assessing theoretical uncertainties in the global analysis due to a variety of effects such as power-law corrections (low Q), parton saturation (low x), ... etc., raising kinematic cuts on input experimental data serves, in principle, as a poor-man's method of reducing the theoretical uncertainties. This is done, however, at the expense of leaving out large amounts of data that can otherwise provide valuable constraints on the PDFs.

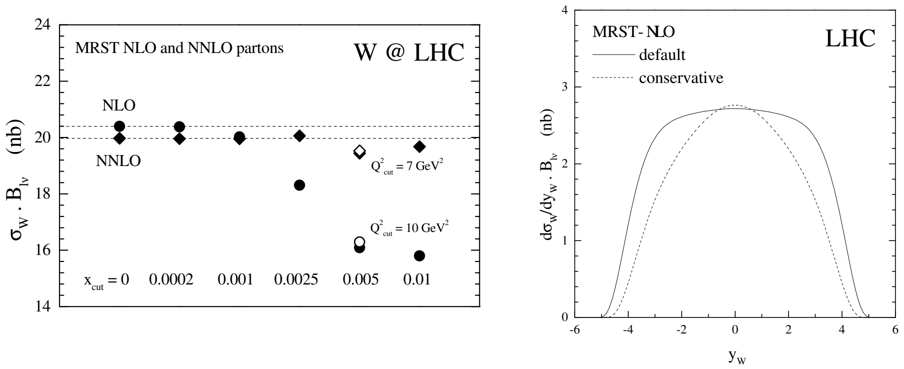

Figure 1. (a) Dependence of MRST predictions for W total cross section at LHC on kinematic cuts of input data; (b) W rapidity distribution according to the MRST default and the "conservative" (relatively high x and Q cuts) PDFs.

assumptions made about the parametrization of PDFs at the starting scale Q_0 (1.3 GeV), we also studied cases where the gluon distribution function is allow to go negative at small x, a possibility favored by the MRST NLO analysis in the past few years. The main results of this study [4] are discussed below.

Fig. 2a shows the variation of the W total cross section (W^++W^-) at LHC with respect to a series of best fit PDFs obtained with increasing x-cuts comparable to those of the MRST study; the results are super-imposed on Fig. 1a. Also included is a point corresponding to a higher Q-cut of $Q^2 > 10$ GeV^2. These results show full stability of the predicted W cross section versus the kinematic cuts used in the global analysis of PDFs, in marked contrast to the results of [1]. (Results at Tevatron energies, not shown due to lack of space, are even more stable, as one would expect.) Fig. 2b shows a comparison of the predicted rapidity (y) distribution for (W^++W^-) at LHC. Instead of showing the predicted y-distribution from the fits with different kinematic cuts (which are all similar to one another), we show the range of variation of the y-distribution when the 2nd moment of the y-distribution are maximized using the Lagrange multiplier method of [5]. These "extreme" cases allowed by our global analysis are compared to the MRST "default" and "conservative" predictions. The MRST conservative prediction, which corresponds to strong kinematic cuts, clearly stands out.

The stability of the prediction versus variations of kinematic cuts we found is reassuring. It indicates that NLO QCD should provide an adequate framework for studying high energy phenomenology at the Tevatron and LHC, except perhaps for processes that are known to have large corrections to the hard cross section beyond NLO. On the other hand, the difference between our results and those of MRST needs to be understood. The two global analysis efforts share many common theoretical and experimental inputs. Most of their predictions have been found to be compatible with each other. However, historically, they also have arrived at different conclusions on a number of specific issues, due to subtle (or not so subtle) differences in methodology and/or input. These were eventually resolved when the causes for the difference was identified. The situation with regard to the stability of

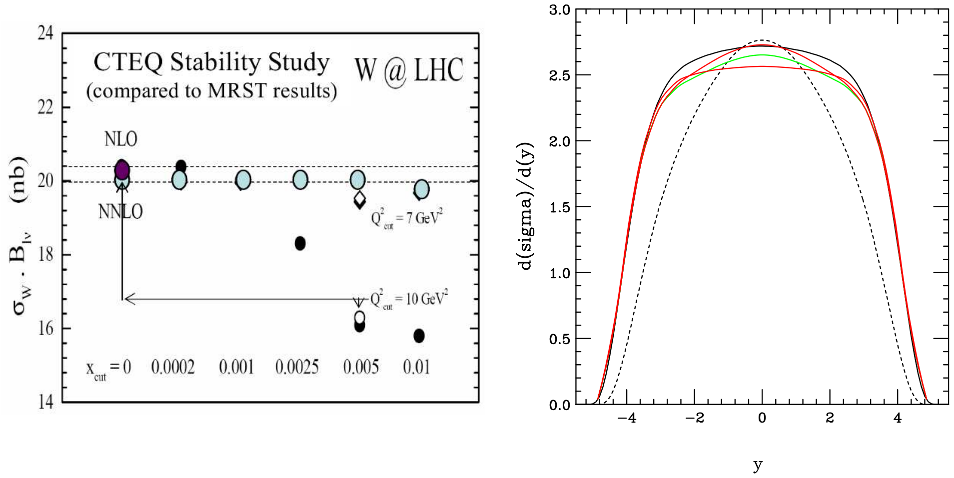

Figure 2. (a) Dependence of CTEQ predictions (light dots) on W total cross section at LHC on kinematic cuts of input data, super-imposed on Fig. 1a; (b) W rapidity distribution at LHC, CTEQ6 prediction plus those extremized w.r.t. the 2nd moment of y in solid color lines, compared to that of the MRST default and conservative PDF predictions (in black solid and dotted lines).

NLO analysis seems to represent such a situation. In particular, the instability of the MRST NLO analyses appears to be associated with two other unique features of their recent analyses: (i) an apparent "tension" between inclusive jet production data at relatively large x and DIS data at small x by HERA; and (ii) a relatively strong preference for negative gluon distribution $g(x,Q)$ at small x and small Q.

In order to look a little closer into these issues, we have investigated the χ^2 values of the jet data sets and the HERA data sets separately as we vary the kinematic cuts. No discernable improvement in the fit to the jet data sets is seen as the x-cut is raised.[b] The χ^2/N for the CDF and D0 experiments are $(1.47, 1.48, 1.47, 1.47, 1.48)$ and $(0.718, 0.715, 0.723, 0.726, 0.697)$ for x-cuts of $(0, .001, .0025, .005, .01)$ respectively. The quality of fit to the HERA data (as measured by χ^2/N) also remains stable with respect to the change in the kinematic cuts.

An important effect of raising the kinematic cuts in x and Q is that constraints provided by the precision HERA data in the small x and low Q region are removed from the global fit. Thus, the uncertainty of the resulting PDFs and their physical predictions will increase. We quantified this effect for the specific case of W production at LHC. Using the Lagrange Multiplier method [5], we examine the best χ^2 values obtained in constrained global fits, as a function of the W cross section for several choices of kinematic cuts: (i) the *normal* CTEQ cuts ($Q^2 > 4$ GeV^2); (ii) *medium* cuts ($Q^2 > 6.25$ GeV^2, $x > 0.001$); (iii) *strong* cuts ($Q^2 > 10$ GeV^2, $x > 0.005$); and (iv) *very strong* cuts ($Q^2 > 100$ GeV^2).[c] Fig. 3a shows the results when the normal CTEQ parametrization, with positive PDFs at the input

[b]If there were tension between the two, an improvement would result, because the pull of small-x HERA data would have been reduced.
[c]A W-cut of 3.5 GeV is maintained in all cases. Note that the strong cuts are similar to that of the MRST conservative fit.

scale of $Q = 1.3$ GeV, is used. We see that, as stronger kinematic cuts are imposed, the range of uncertainty on the prediction for the W production cross section becomes progressively larger. Whereas the change from the normal to medium cuts is small, the range of uncertainty almost doubles from normal to strong cuts at any tolerance level of χ^2. The *very-strong-cuts* case removes most of DIS data from the fit, thus heavily emphasizes collider data input—it represents a step toward a hypothetical "collider-data-only prediction" from Tevatron to LHC. It results in a very large range of uncertainty for the LHC cross section, as one would have expected.

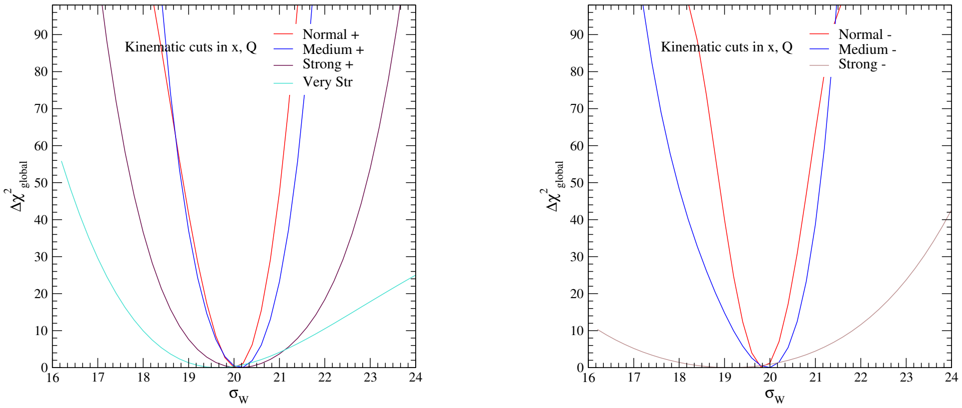

Figure 3. Ranges of uncertainty on W production cross section at LHC: $\Delta\chi^2$ (over best fit) vs. σ_W for several choices of kinematic cuts to the input data. (a) Normal fits with positive PDFs; and (b) Similar fits, but allowing the input gluon distribution at $Q = 1.3$ GeV to go negative at small x. Note the stability of the minima of the curves—reflecting the same results of Fig. 2a.

We have also performed similar fits, removing our usual constraint that parton distributions remain positive. This affects mostly the gluon, as quark distributions are more directly related to (positive) input structure functions. As a rule, our best fits for any given sets of kinematic cuts do not require negative gluons at our input scale of $Q_0 = 1.3$ GeV. However, when σ_W^{LHC} is pulled away from the best-fit values by the constrained fits in the Lagrange Multiplier study, the additional freedom provided by a negative gluon widens the allowed range of variation of σ_W^{LHC}. The results of this analysis (except that of the very strong cuts) are shown in Fig. 3b. Compared to the corresponding cases in Fig. 3a, we see that the medium-cuts curve has opened up noticeably at the lower end, and the strong-cuts case has widened at both ends.

Should the fits with negative gluons be taken seriously as candidate PDF sets, hence providing better determination of the true range of uncertainty? We think not. The reason is: whereas PDFs are not strictly forbidden to become negative, ***all*** *physical quantities calculated from them, in* ***all*** *parts of physical phase space, must remain positive definite.* This is a very strong condition that is extremely difficult to satisfy if some PDFs become negative in some region of the (x, Q) plane. For all the solutions involving negative gluons at small x and low Q (including the MRST ones), we found it is possible to identify ***some*** physical cross sections, at ***some*** high energies, near ***some*** boundary of phase space, that become non-positive definite. These negative gluon solution must therefore be considered as unphysical (at this order of α_s).

Another possible source of discrepancy between the CTEQ and MRST results is the treatment of heavy quark mass effects in DIS:—we primarily use the widely used zero-mass $\overline{MS}$ formalism, whereas MRST uses the Thorne-Roberts prescription for the non-zero-charm-mass variable flavor number scheme. In general, the difference is nominally a small one. However, since charm production accounts for nearly 25% of the DIS cross section at small x, and since the HERA data at small x have very small errors, the difference could have an effect on the issues discussed above.[d] Further study is clearly needed to fully settle the stability issue. We should add that, independent of the stability of NLO global analysis, NNLO calculations are needed for processes that require a high level of accuracy, or that are known to have large corrections.

2 Ratio of d/u at large x

One of the open issues in quark distributions is the behavior of d/u at large x. (Cf. [6]) In most conventional global analyses, this ratio is constrained to approach zero as $x \to 1$ by the parametrization adopted for the non-perturbative input functional forms. Whereas the usual assumption $d/u \to (1-x)^\alpha$ with $\alpha \sim 1$ is suggested by quark counting rules, other quark model and related SU(6) considerations lead to constant ratios in the $x \to 1$ limit. Only detailed global analysis work based on solid experimental input can determine the true behavior.

Preliminary results from E866 (NuSea) on pp and pd lepton-pair production (Drell-Yan) cross sections raised the possibility that the separation of u and d quarks in existing global analyses may not be correct in the large x region. [7] This motivated us to study this issue in detail, including an assessment of the effects due to deuteron target correction, which can affect the outcome of the analysis. In the absence of a generally accepted reliable theoretical calculation, we have tried to use a phenomenological approach, and make a best estimate of, say, $R(x) = F_2^d(x)/2F_2^p(x)$ by fitting available high precision fixed-target DIS data on deuteron and on proton, with only general theoretical constraints. The plan is to incorporate this effect in a comprehensive global analysis, including the final E866 results, to determine both the best fit to $d(x)$ and $u(x)$ and the range of uncertainty of the d/u ratio at large x, without requiring it to approach 0 in the $x \to 1$ limit. This analysis will be completed as soon as the final E866 data become available [7].

3 Strangeness Asymmetry

An important, but so far poorly determined, frontier of parton structure of the nucleon is the strangeness sector. This can be separated into two parts: the total strangeness sea, $s_+(x) = s(x) + \bar{s}(x)$, and the strangeness charge asymmetry $s_-(x) = s(x) - \bar{s}(x)$. Advance on both fronts is expected by detailed study of the recent CCFR-NuTeV dimuon production data in neutrino and anti-neutrino

[d] This is particularly so, since the Thorne-Roberts prescription produces an artificial bump in F_2^c above the charm production threshold before falling back to the expected higher energy limit.

scattering [8] in the global analysis context.[e]

The separate measurement of ν and $\bar{\nu}$ cross sections is crucial in order to separate the s and $\bar{s}$ distributions, and hence allow the measurement of $s_-(x)$ and determine whether the strange sea of the nucleon is charge asymmetric. Although the strangeness number sum rule requires $\int_0^1 s_-(x)\ dx = 0$, a charge asymmetric strange sea, manifested by, say, a non-zero first moment $[S_-] = \int_0^1 x\ s_-(x)\ dx$, has important physical consequences such as the NuTeV anomaly [9].

Our group has studied this issue in the past year [10], and is continuing the effort to achieve a full NLO analysis of the CCFR-NuTeV data in the global analysis context. Due to space limitations here, we can only mention the current status of this study, and leave the details to [10,9]. Our study is currently limited by the fact that the CCFR-NuTeV measurement is not available as inclusive cross sections (that theory can calculate), but is in the form of cross sections with specific kinematic cuts. In order to perform a global fit, incorporating these new data, a LO model bridging the inclusive and the measured cross sections has to be invoked. With this caveat, we found that a positive value for $[S_-]$ on the order of 0.0017 is favored. We also found that the range of uncertainty, both theoretical and experimental, is rather large. We estimate that $-0.001 < [S_-] < 0.004$. This result will be significantly improved in the next round of analysis, in which we are collaborating with members of CCFR-NuTeV to incorporate the best NLO MC model in conjunction with the NLO global analysis.

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[e] PDFs in PQCD, by definition, are *universal*, i.e. they must be applicable to all processes. Specialized PDFs derived from analysis of very limited data sets (or processes) that do not fit a broad range of data may not reflect true behavior of PDFs of nature, hence can be misleading.