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PARTON DISTRIBUTIONS, d/u, AND HIGHER TWISTS AT HIGH X

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Abstract

We extract the ratio of the down (d) and up (u) parton distribution functions (PDF's) from the ratio of deuteron and proton structure function F_2^d/F_2^p measured by NMC. We use corrections for nuclear binding effects in the deuteron, which are extracted from the nuclear dependence of SLAC F_2 data. Significant corrections to the d quark distribution in standard PDF's are required, especially at high x. The corrected d/u ratio is in agreement with the QCD prediction of 0.2 at $x = 1$. The predictions for the W asymmetry in hadron colliders using PDF's with the corrected d/u ratio are in much better agreement with recent CDF data at large rapidity. Using the updated d/u ratio and the most recent world average for α_s, we perform a NLO global fit to all DIS data for F_2 and R, and estimate the size of the higher twist contributions using both a renormalon model and an empirical model. We find that with the updated value of α_s, the magnitude of the higher twist terms is half the value of previous analysis. With the inclusion of target mass and higher twist corrections, the standard NLO PDF's with the updated d/u ratio describe the SLAC F_2 data up to $x = 1.0$. When the analysis is repeated in NNLO, we find that the additional NNLO contributions to R account for most of the higher twist effects extracted in the NLO fit. The analysis in NNLO indicates that the higher twist effects in R, F_2 and xF_3 (e.g. GLS sum rule) are very small.

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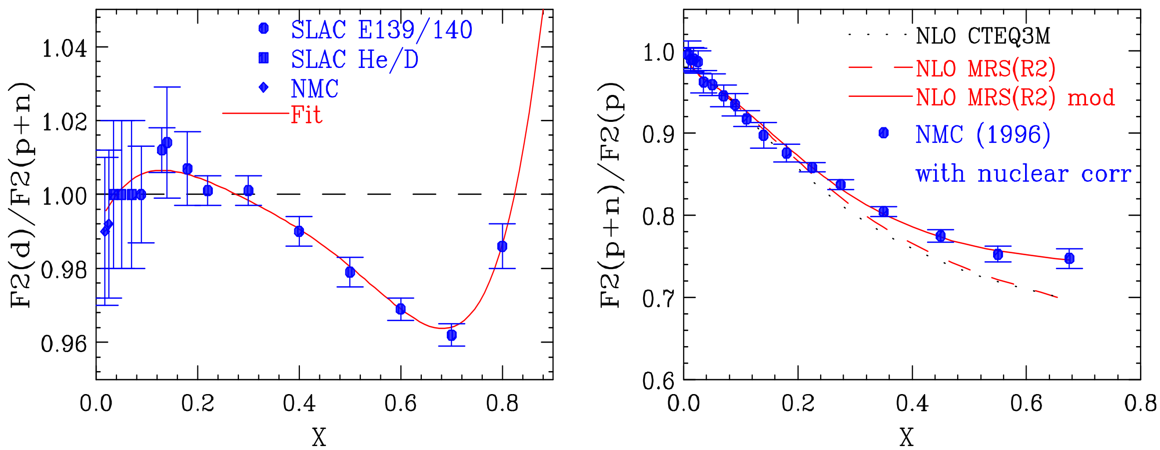

Figure 1: (Left) The total correction for nuclear effects (binding and Fermi motion) in the deuteron, F_2^d/F_2^{n+p}, as a function of x, extracted from fits to the nuclear dependence of SLAC F_2 electron scattering data. (Right) Comparison of NMC F_2^{n+p}/F_2^p (corrected for nuclear effects) and the prediction in NLO using the MRS(R2) PDF with and without our proposed modification to the d/u ratio.

1 Introduction

Recent work on parton distributions functions (PDF's) in the nucleon has focussed on probing the sea and gluon distribution at small x. The valence quarks distribution has been thought to be relatively well understood. However, the precise knowledge of the u and d quark distribution at high x is very important at collider energies in searches for signals for new physics at high Q^2. In addition, the value of d/u as $x \to 1$ is of theoretical interest. Recently, a proposed CTEQ toy model [1] included the possibility of an additional contribution to the u quark distribution (beyond $x > 0.75$) as an explanation for both the initial HERA high Q^2 anomaly [2], and for the jet excess at high-P_t at CDF [3]. In this communication we conclude that a re-analysis of data from NMC and SLAC leads to a great improvement in the determination of PDF's at large x.

2 Extraction of d/u at high x

Information about valence quarks originates from the proton and neutron structure function data. The u valence quark distribution at high x is relatively well constrained by the proton structure function F_2^p. However, the neutron structure function F_2^n, which is sensitive to the d valence quark at high x, is actually extracted from deuteron data. Therefore, there is an uncertainty in the d valence quark distribution from the corrections for nuclear binding effects in the deuteron. In past extractions of F_2^n from deuteron data, only Fermi motion corrections were considered, and other binding effects were assumed to be negligible. Recently, the corrections for nuclear binding effects in the deuteron, F_2^d/F_2^{n+p}, have been extracted empirically from fits to the nuclear dependence of electron scattering data from SLAC experiments E139/140 [4]. The empirical extraction uses a model proposed by Frankfurt and Strikman [5], in which all binding effects in the deuteron and heavy nuclear targets are assumed to scale with the nuclear density. The correction extracted in this empirical way is also in agreement (for $x < 0.75$) with recent purely theoretical calculations [6] of nuclear binding effects in the deuteron. The total correction for nuclear binding in the deuteron is about 4% at $x = 0.7$ (shown in Fig. 1, left), and in a direction which is opposite to what is expected from the previous models which only included the Fermi motion effects.

The ratio F_2^d/F_2^p is directly related to d/u. In leading order QCD, $2F_2^d/F_2^p - 1 \simeq (1 + 4d/u)/(4 + d/u)$ at high x. We perform a NLO analysis on the precise NMC F_2^d/F_2^p data [7]

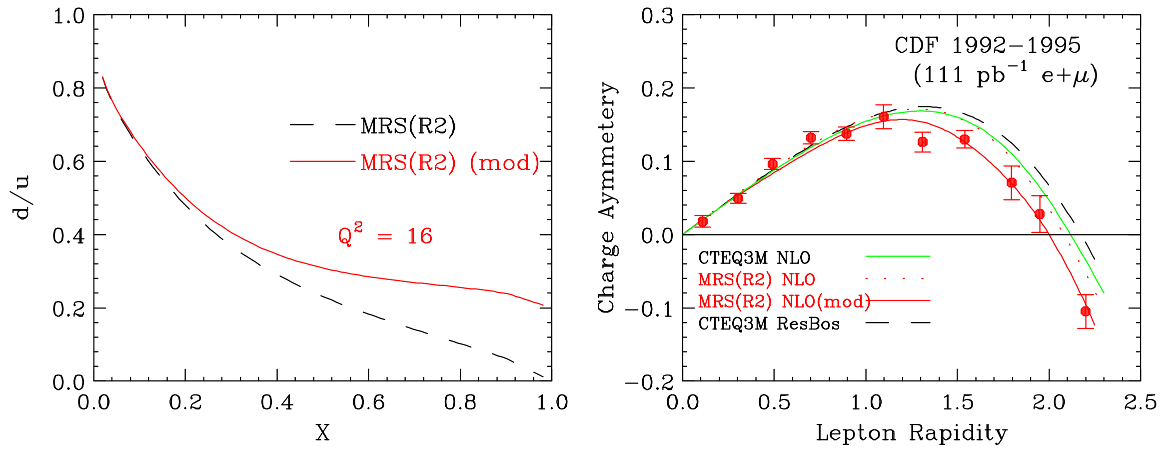

Figure 2: (Left) The d/u distribution at Q^2=16 as a function of x. The standard MRS(R2) is compared to our modified MRS(R2). (Left) Comparison of the CDF W asymmetry data with NLO standard CTEQ3M, MRS(R2), and modified MRS(R2) as a function of the lepton rapidity. The standard CTEQ3M with a resummation calculation is also shown for comparison.

to extract d/u as a function of x. We extract the ratio F_2^{p+n}/F_2^p by applying the nuclear binding correction F_2^d/F_2^{n+p} to the F_2^d/F_2^p data.

As shown in Fig. 1(right), the standard PDF's do not describe the extracted F_2^{p+n}/F_2^p. Because the u distribution is relatively well constrained, we find a correction term to d/u in the standard PDF's, as a function of x by only varying the d distribution to fit the data. The correction term is parametrized as a simple quadratic form, $\delta(d/u) = (0.1 \pm 0.01)(x+1)x$ for the MRS(R2) PDF, where the corrected d/u ratio $(d/u)'$, is $(d/u)' = (d/u) + \delta(d/u)$. Based on this correction, we obtain a MRS(R2)-modified PDF as shown in Fig 2. The corrections to other PDF's such as CTEQ3M is similar. The NMC data, when corrected for nuclear binding effects in the deuteron, clearly indicate that d/u in the standard PDF's [8,9] is significantly underestimated at high x as shown in Fig. 2. Fig.2 (left) also shows that the modified d/u ratio approaches 0.2 ± 0.02 as $x \to 1$, in agreement with a QCD prediction [10]. In contract, if the deuteron data is only corrected for Fermi motion effects (as was mistakenly done in the past) both the d/u from data and the d/u in the standard PDF's fits approach 0 as $x \to 1$.

Information (which is not affected by the corrections for nuclear effects in the deuteron) on d/u can be extracted from W production data in hadron colliders. Fig.2 (right) shows that the predicted W asymmetry calculated with the DYRAD NLO QCD program using our modified PDF is in much better agreement with recent CDF data [11] at large rapidity than standard PDF's.

When the modified PDF at Q^2=16 is evolved to Q^2=10,000 using the DGLAP NLO equations, we find that the modified d distribution at $x = 0.5$ is increased by about 40 % in comparison to the standard d distribution. The modified PDF could have a significant impact on the prediction of the cross sections in the HERA high Q^2 region because the charged current scattering with positrons is on d quarks only. It also impacts neutral current scattering because of the large coupling of the Z to d quarks at high Q^2.

3 Higher twists effects at high x

Since all the standard PDF's, including our modified version are fit to data with x less than 0.75, we now investigate the validity of the modified MRS(R2) at very high x by comparing to F_2^p data at SLAC. Although the SLAC data at very high x are at reasonable values of Q^2 ($7 < Q^2 < 31$ GeV^2), there are in a region in which non-perturbative effects such as target mass and higher twist are very large. We use the Georgi-Politzer calculation [12] for the target mass corrections (TM). These involve using the scaling variable $\xi = 2x/(1 + \sqrt{1 + 4M^2x^2/Q^2})$ instead of x. Since a complete calculation of higher twist effects is not available, the very low Q^2 data is used to obtain information on the size of these terms.

We use two approaches in our investigation of the higher twist contributions, an empirical method, and the renormalon model. In the empirical approach, the higher twist contribution is evaluated by adding a term $h(x)/Q^2$ to the perturbative QCD (pQCD) prediction of the structure function (including target mass effects). The x dependence of the higher twist coefficients $h(x)$ is fitted to the global DIS F_2 (SLAC, BCDMS, and NMC) data [13,14,15] in the kinematic region ($0.1 < x < 0.75$, $1.25 < Q^2 < 260\ GeV^2$) with the following form, $F_2 = F_2^{pQCD+TM}(1 + h(x)/Q^2)f(x)$. Here $f(x)$ is a floating factor to investigate possible x dependent corrections to our modified PDF. A functional form, $a(\frac{x^b}{1-x} - c)$ for $h(x)$ is used in the higher twist fit to estimate the size of the higher twist terms above $x = 0.75$. The SLAC and BCDMS data are normalized to the NMC data. In the case of the BCDMS data, a systematic shift error λ is allowed to account for the point-to-point correlated systematic errors. The empirical higher twist fits with the modified NLO MRS(R2) pQCD prediction with TM have been performed simultaneously on the proton and deuteron F_2 data with 11 free parameters (2 relative normalizations and 3 parameters for $C(x)$ per target and the BCDMS λ). We find that empirical higher twist fit describes the data well ($\chi^2/DOF = 843/805$). The size of the higher twist contributions in the proton and deuteron are similar. The magnitude is almost half of those extracted in previous analysis of SLAC/BCDMS data [16]. This is because that analysis was based on $\alpha_s(M_Z^2) = 0.113$, while the MRS(R2) PDF uses $\alpha_s(M_Z^2) = 0.120$, which is close to the current world average.

In the renormalon model approach [18], the model predicts the complete x dependence of the higher twist contributions to F_2, $2xF_1$, and xF_3 ,with only two unknown parameters A_2 and A_4. We extract the A_2 and A_4 parameters, which determine the overall level of the $1/Q^2$ and $1/Q^4$ terms by fitting to the global data set for F_2 and $R(= F_2(1 + 4Mx^2/Q^2)/2xF_1 - 1)$. The values of A_2 and A_4 for the proton and deuteron are same in this model. The x dependence of $2xF_1$ differs from that of F_2 but is same as that of xF_3 within a power correction of $1/Q^2$. Our fits can also be used to estimate the size of the higher twist effects in xF_3 (e.g. the GLS sum rule). The higher twist fit in this approach has employed the same procedure as the empirical method. Fig. 3 shows that the model yields description of x dependence of higher twist terms in both F_2 and R with just the two free parameters ($\chi^2/DOF = 1577/1045$). The CCFR neutrino data [17] is shown for comparison though it is not used in the fit. The extracted values of A_2 are -0.093 ± 0.005 and -0.101 ± 0.005, for proton and deuteron, respectively. The contribution of A_4 is found to be negligible. We find that the floating factor $f(x)$ for the deuteron deviates from 1 and is also bigger than that for the proton, unless the modified MRS(R2) PDF is used. This reflects our earlier conclusion that the standard d distribution is underestimated at high x region. As expected, the extracted A_2 value is half of the previous estimated value [18] of A_2 based on SLAC/BCDMS analysis. Since both of these approaches yield a reasonable description for the higher twist effects, we proceed to compare the predictions of the modified PDF's (including target mass and renormalon higher twist corrections) to the SLAC proton F_2 data at very high x ($0.7 < x < 1$).

4 Parton distributions functions at very high x

There is a wealth of SLAC data [19] in the region up to $x = 0.98$ and intermediate Q^2 ($7 < Q^2 < 31\ GeV^2$). Previous PDF fits have not used these data. We use the estimate of the higher twist effects from the models, based on the data (below $x < 0.75$) described above. Note that

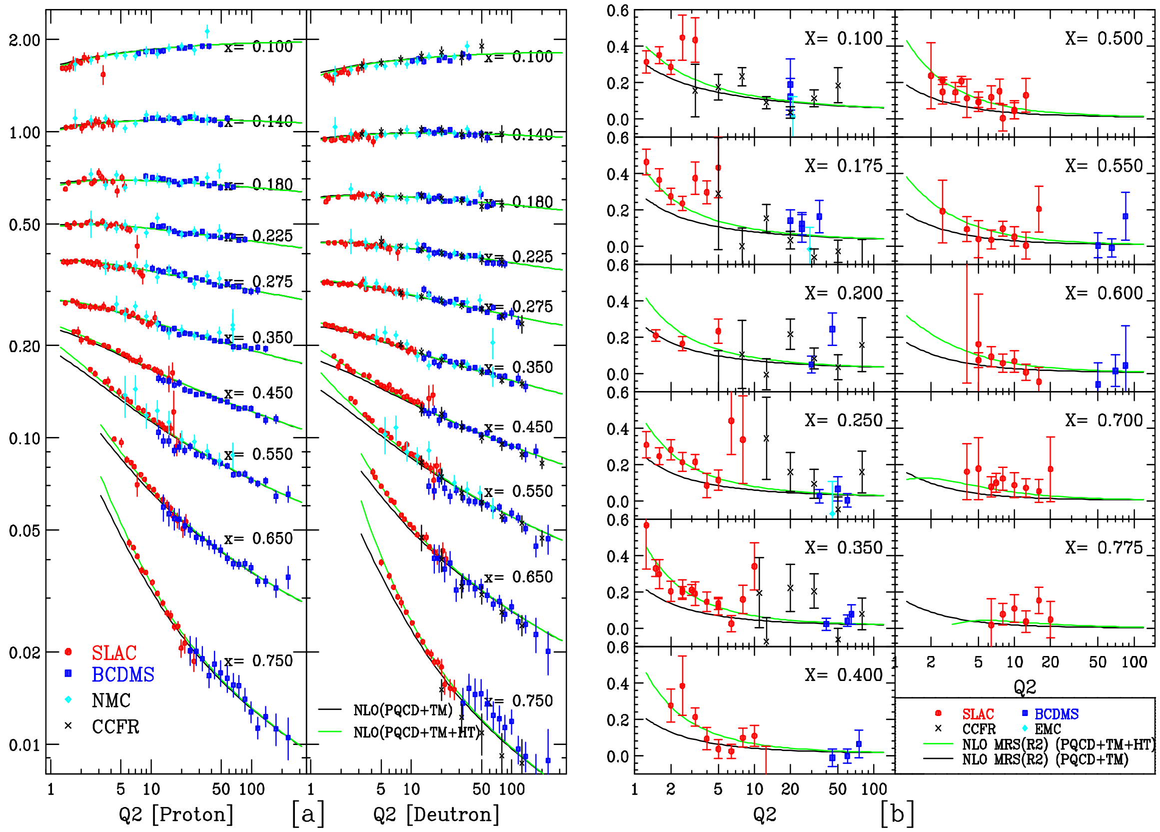

Figure 3: The description of higher twist fit using the renormalon model with the modified NLO MRS(R2) PDF. The CCFR neutrino data is also shown for comparison. (Left) Comparison of F_2 and NLO prediction with and without higher twist contributions. (Right) Comparison of R and NLO prediction with and without the renormalon higher twist contributions.

the data for $x > 0.75$ is in the DIS region, and the data for $x > 0.9$ is the resonance region. It is worthwhile to investigate the resonance region also because from duality arguments [20] it is expected that the average behaviour of the resonances and elastic peak should follows the DIS scaling limit curve.

Fig.4 shows the ratio of the SLAC data at high x to the predictions of the modified MRS(R2). With the inclusion of target mass and the renormalon higher twist effects, the very high x data from SLAC is remarkably well described by the modified MRS(R2) up to $x = 0.98$. The data is somewhat lower than the fit at $x > 0.9$ and $7 < Q^2 < 11\ GeV^2$. This could be due to the missing elastic contribution (as expected from duality arguments). The good decription of the data by the modified MRS(R2) is also achieved using the empirical estimate $(h(x)/Q^2)$ of higher twist effects. From these comparisons, we find that the SLAC F_2 data do not favor the CTEQ Toy model which proposed an additional u quark contribution at high x (beyond $x > 0.75$) as an explanation of the initial HERA high Q^2 anomaly and the CDF high-P_t jet excess. This model (with an additional 0.5% component of u quarks) overstimates the SLAC data by a factor of two at $x = 0.9$ (DIS region).

5 Conclusion

We find that nuclear binding effects in the deuteron play a significant role in understanding of the d/u at high x region. The modified PDF's with our d/u correction are in good agreement with the prediction of QCD at $x = 1$, and with the CDF W asymmetry data. With the inclusion of target mass and higher twist corrections, the modified PDF's describe all DIS data not only

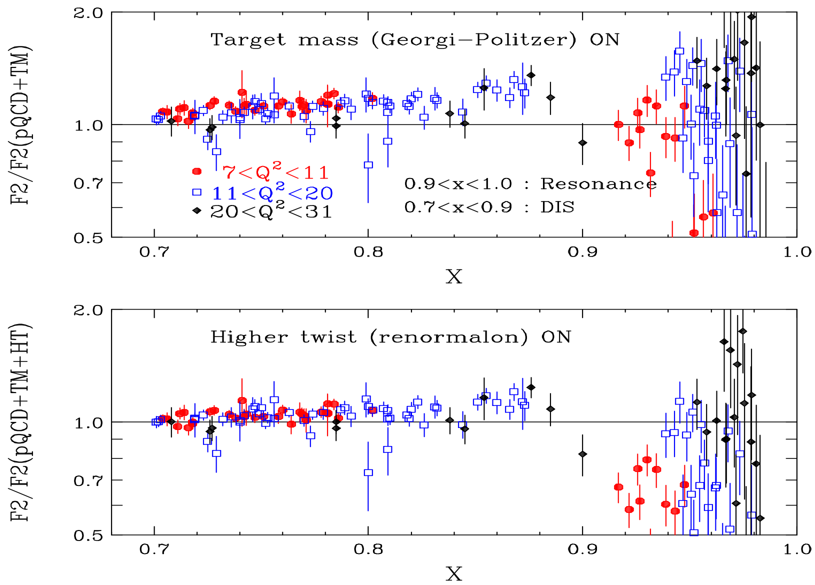

Figure 4: The ratio of SLAC F_2^p data at high x to the predictions of the modified MRS(R2). (Top) The data are compared to the NLO pQCD prediction with the inclusion of target mass effects. (Bottom) The data are compared to the NLO pQCD prediction with the inclusion of target mass and renormalon higher twist effects.

up to the very highest x, but also all the way down to $Q^2 = 1\ GeV^2$.

Note that when the analysis is repeated in NNLO [21], We find that the additional NNLO contributions to R account for most of the higher twist effects extracted in the NLO fit. The analysis in NNLO indicates that the highest twist corrections to the GLS sum rule are very small (the fractional contribution to the pQCD GLS sum rule is $-0.0058/Q^2 - 0.013/Q^4$).

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