HERA Events, Tevatron Jets and Uncertainties on Quarks at Large $x^*$

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Abstract

The recently reported excess of events at HERA compared to QCD calculations impels us to examine all possible Standard Model explanations before invoking “new physics”. We explore the possibility of adding an unusual, but small, component of additional quarks at large $x$ (beyond $x > 0.75$) as a way to increase the predicted SM cross-section in the HERA kinematic region by the QCD evolution feed-down effect. We describe various scenarios under which this can be achieved while maintaining good global fits to all established data sets. This implies a much larger SM uncertainty than commonly assumed. In addition, the modified parton distributions provide another possible mechanism to account for the CDF high-$p_t$ jet excess which occurs at similar $x$ and $Q^2$ values.

* This work was supported in part by the DOE and NSF.
Recently the H1 and ZEUS experiments at HERA have reported an excess of large- \( x, Q^2 \) deep inelastic scattering (DIS) events compared to next-to-leading order QCD expectations (NLO QCD). In order to determine whether this enhancement constitutes a signal for new physics, it is crucial to investigate all possible explanations within the Standard Model. Both experiments attribute a \( 7 - 8\% \) uncertainty to the QCD expectations, using standard procedures based on conventional parton distributions, which is small compared to the observed effect. In this note we investigate more closely an important part of this uncertainty – that relating to the quark distributions at large \( x, Q^2 \) beyond the range which is well measured by existing fixed target experiments. The goal is to explore possible unconventional features in this uncharted kinematic region and to quantify their effects on existing experimental data used in global QCD analyses and on the new observations.

It is useful to carefully define the question we are addressing. The H1 data shows a fairly discrete jump in its last \( x \) bin which, if correct, certainly rules out a parton distribution interpretation, since QCD effects at such large \( Q^2 \) should be smooth. If the excess persists it is still an open question whether, with increased statistics, the excess will be more spread out like the present ZEUS data. This is the scenario that our study addresses. We shall ask the question: under what conditions, if any, is it possible to have a substantially increased quark contribution to the DIS cross-section in the new HERA kinematic range and still maintain consistency with all established lower energy data? We shall not be concerned with describing any detailed features of the new HERA data, nor include them in the analysis directly.

The first task is to try to improve the existing estimates of the uncertainties on \( q(x, Q^2) \) due to a conventional parton distribution analysis. We performed a series of special purpose global fits designed to quantify how far \( q(x, Q^2) \) can be forced to deviate from its nominal values at the kinematic region of the HERA events and still maintain a good fit to the existing global data sets. Using conventional functional forms for the input non-perturbative parton distributions such as those used by the CTEQ and MRS groups, we confirm the H1 and ZEUS results: one can induce at most a \( \approx 7\% \) change in parton distributions in the relevant kinematic range.

Therefore to find a way to produce a larger change in the quark distributions, one must go beyond the usual assumptions. Because of the well-known feed-down effect of QCD evolution (as the result of parton splitting with increasing resolution power), the observed effect in the range \( 0.5 < x < 0.7 \) and \( 100 \text{ GeV} < Q < 200 \text{ GeV} \) can be obtained only by introducing some unexpected large \( x \) feature at the low \( Q \) value where QCD evolution starts. In order not to upset the existing agreement between theory and established fixed-target measurements which extend to \( x \sim 0.65 - 0.75, \ Q \sim 20 \text{ GeV} \), the new feature has to be fairly close to \( x = 1 \) if it sets in at \( Q = Q_0 = 1 - 2 \text{ GeV} \). This is graphically illustrated in figure. This graph also suggests perhaps the feed-down mechanism is the only possible one with the desired effect involving parton distributions.

Since very little experimental information is available about the flavor dependence of parton distributions above \( x = 0.75 \), one can in principle explore a variety of possibilities: variations in the valence quarks \( u_v, d_v \) as well as unusual non-perturbative heavy flavor components. We begin by examining the \( u_v \) distribution which gives the largest contribution to the cross-section. To demonstrate how restrictive the commonly used parameterizations

\[ ^1 \text{If } Q_0 \text{ is higher, say 5 GeV for a } b \text{ quark, then the new feature can be more spread out in } x. \]
for valence quark distributions are in regard to changes in the $x > 0.75$ region, the following exercise is performed: we randomly varied all 5 parameters in the $u_v$ distribution (and all combinations), and removed trials that changed the total momentum of the $u_v$ distribution by more than 3%. We also removed trials that disagreed with the conventional distribution by more than 5% between $x = 0.01$ and $x = 0.65$. Of the remaining trials we found the one that gave the largest increase in the distribution for $x > 0.75$, this is shown in Fig. 2 (as diamonds) for both the CTEQ and MRS parameterizations. Compared to the original CTEQ4M and MRSR1 distributions (dark triangles), the maximum deviation is very small. On the other hand, if a small non-conventional component of the form $0.02 \ast (1 - x)^{0.1}$ is added to the original parameterizations with the same constraints mentioned above at lower $x$, one obtains a dramatically increased valence distribution for $x > 0.75$ (shown by the circles in Fig. 2). This modification is somewhat too large to agree with the fixed target data, but the exercise demonstrates that to explore the possibility of increasing the quarks in the HERA kinematic region, it is necessary to go beyond the conventional parameterizations.

We will now systematically investigate what are the effects of introducing a small addition of $u_v$ quarks near $x = 1$ in the global analysis. Since we are only concerned about the possibility of establishing a generic scenario, rather than trying to advance a realistic model, we shall implement this additional component in the form of a simple function concentrated near $x = 1$ at $Q_0 = 1.6$ GeV. The optimal amount of this component, measured in terms of the momentum fraction carried, will turn out to be in the range $0.5 - 1\%$. The exact shape is not important as long as the initial shape is sharply peaked, as we are assuming in our simple model. We find it is not hard to obtain a satisfactory global fit to established data with such an additional component. The resulting $u_v$ distribution at a typical scale for existing experiments, $Q = 5$ GeV, is shown in figure 3, along with the $u_v$ distribution from CTEQ4M.

The additional large-$x$ component of the $u_v$ distribution has a significant impact on the quark distributions in the new HERA $Q^2$ range. In figure 4 we show the ratio of the sum of the quark distributions with the new component divided by the same sum with CTEQ4M. Two curves are shown, one for $Q^2 = 40,000$ GeV$^2$ and one for $Q^2 = 25$ GeV$^2$. At $x = 0.7$ the change in the quarks is 30%, much larger than the 6% uncertainty coming from the conventional analyses. In the lower $Q^2$ fixed target region, the change is minimal. This is because it takes a significant amount of QCD evolution for the additional component to propagate down to the $x$ values of the fixed target experiments, and by then the region of $Q^2$ is beyond that probed at fixed target experiments. The comparison of this fit to large-$x$ DIS data is shown in figure 5. Plotted are the relative differences between the large $x$ DIS data of the BCDMS and CCFR experiments and the theoretical values from this global fit. Although the effect of the additional $u_v$ component can already be seen in the highest $x$ bin of the BCDMS data, the general agreement is still quite good, and the agreement with the CCFR data is excellent. The quality of this new global fit to other DIS, DY, W-asymmetry and direct photon data sets are indistinguishable from that of standard parton distributions such as CTEQ4M. Thus, it serves as an example of a new class of viable parton distributions consistent with existing data below $x < 0.75$, with the feature that it gives rise to a significantly larger quark distribution than conventional sets at large $x, Q^2$.

Previously CDF had reported an excess of high-$p_t$ jets compared to conventional NLO QCD expectations. The relevant $x$ and $p_t$ range of their high $p_t$ events ($0.3 < x < 2$).
0.5; 200 < \pT < 450 \, \text{GeV}) are remarkably similar to that of the HERA events. Since jet production in this region is mostly due to quark-quark scattering, any modification of the quark distributions will affect jet cross sections. It has been known that it is impossible to modify quark distributions of the conventional type to fit the CDF jets simultaneously with fixed target DIS data \cite{7, 8}. But the additional \(u_v\) component introduced above does fit fixed target data and it will give additional contribution to the jet cross section at the high \(p_T\) range in the right direction as observed by CDF. To see this effect in quantitative terms, we compare in Fig. 6 the inclusive jet cross sections calculated using three different sets of parton distributions: (i) the new distributions, including 0.5\% additional \(u_v\); (ii) the conventional set CTEQ4M (which undershoots the CDF data at high \(p_T\); and (iii) the CTEQ4HJ set \cite{2, 7} (which contains a modified gluon distribution to accommodate the jet data). We see that the effect of the new quark component is similar to that found for additional gluons at large \(x\). Thus, modification of the quark distributions can be considered as an alternative to the large-\(x\) gluon as the source of the jet excess if it persists. We note that both CDF and D0 experiments have found that the angular distribution of these jet events is consistent with QCD predictions \cite{9}. Hence, in this case, at least, it is important to have viable Standard Model explanations of the observed cross sections.

If with more data the excess at HERA turns out to be larger than that shown in Fig. 4, can one go further and increase the quark distributions even more? Two possible scenarios come to mind. The first is to make the additional component even more peaked towards \(x = 1\) than in our toy model. We have obtained acceptable fits under this scenario with a 1\% additional component of \(u_v\), and this effectively doubles the size of the effect shown in Fig. 4. Beyond 1\%, it becomes very difficult to reconcile with the fixed target DIS measurements, especially BCDMS since it is sensitive to the electric charge squared and we are adding charge 2/3 quarks. The second possibility to increase the effect at HERA beyond our toy model is to make an additional modification of one of the charge 1/3 quark distributions, most likely the \(d\) valence distribution. The BCDMS measurement on hydrogen mentioned above is four times less sensitive to charge 1/3 quarks, while for the HERA data \(Z\) exchange is larger than photon exchange and therefore almost equally sensitive to either electric charge. We note that the best measurement of this distribution is the BCDMS measurement with a deuterium target, and the last \(x\) bin of this measurement is 20\% above NLO QCD using conventional parton distributions. This is shown in Fig. 4 where the relative difference between data and theory is shown, using both CTEQ4M and MRSR1 parton distributions. Here, an increase in \(d_v\) at large \(x\) will actually improve agreement with existing data.

For completeness we now review the other quark flavors. The sea quarks are significantly smaller than the valence quarks at large \(x\), but also less well measured. There are several measurements that indirectly constrain the \(\bar{u}\) and \(\bar{d}\) partons, these extend out to \(x = 0.65\). The strange quark distribution is constrained both by global fits and by dimuon neutrino scattering experiments, but also with a limited \(x\) range. Overall, it seems very unlikely that

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2One can also wonder whether uncertainties on the data in the last \(x\) bin of the BCDMS measurement might be larger than estimated. If one allows for a relatively small mismeasurement in this bin then it becomes much easier to increase the effect at HERA. We know of no reason to question this measurement, but if it means the difference between a new physics signal or a Standard Model explanation it should be closely scrutinized.
any modification of $\bar{u}, \bar{d}, s$ could ever be large enough to compare to the valence distributions. Another intriguing possibility is that of intrinsic heavy flavor. The charm and bottom distributions are normally generated completely from perturbative gluon splitting. Intrinsic heavy flavor would be an additional non-perturbative component that is now assumed to be zero. In addition, these distributions are predicted in non-perturbative models $^{[10, 11]}$ to peak at relatively large $x$ due to their larger mass. The 0.5% additional component of $u$ in our toy model could be replaced with intrinsic charm with identical results. If intrinsic charm exists, then intrinsic bottom probably also exists with a smaller total momentum fraction. But since the evolution of the bottom quarks would not start until $Q_0^2 = 25$ GeV$^2$, much of the bottom quark distribution simply by-passes the fixed target region in its QCD evolution, cf. Fig. 1. The combination of this effect with the charge 1/3 advantage mentioned earlier would make it much easier to fit fixed target and HERA at the same time, thereby perhaps compensating for the expected smaller momentum fraction. Even though the sea quarks are typically much smaller than valence at these $x$ values, if the HERA excess persists there are scenarios with intrinsic heavy flavor that should be investigated as possible modifications of the structure of the proton.

In summary, we have investigated effects of the current uncertainty of the quark distribution functions at large $x$ in the kinematic region of the HERA excess. Using conventional parametrizations, we confirm the $6 - 7\%$ uncertainty quoted by H1 and ZEUS. However, it is possible to enhance the quark contribution to DIS cross-sections at high-$x$, high-$Q^2$ while maintaining good agreement with established fixed target data by introducing a small additional high $x$ component to some quark flavors, through the feed-down mechanism of QCD evolution. The enhanced quarks can provide an alternative explanation of the CDF jet excess. Even if the scenarios described in this note eventually turn out to be improbable, for either theoretical or experimental reasons, they do demonstrate that conventional estimates of a small Standard Model uncertainty for the HERA measurements rest on implicit assumptions of the non-perturbative quark distributions which are not founded on known experimental results. Effects such as those explored here could also be only a part of the explanation of the observed events, if they persist and if they prove to be smooth in their $x$-dependence.

To pursue these effects further, it is important to investigate in more detail all processes which are sensitive to quarks at large $x$. Fig. 8 illustrates the kinematic regions of three different classes of measurements that could in the future provide additional constraints on large-$x$ quark distributions. They include fixed target data beyond $x > 0.75$ that are not currently being used due to concerns about nuclear or higher twist effects. There are also jet measurements at the Tevatron and other data from HERA that should provide useful constraints. In addition, whether the large $x$ component is due to heavy flavors needs to be investigated by measuring the flavor content of the HERA events and the CDF high $p_t$ jets.

We thank members of the CTEQ collaboration for useful discussions. This work was supported in part by the Department of Energy and the National Science Foundation.

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Figure 1: How large-$x$ quarks can evolve into the HERA kinematic region.
Figure 2: The u valence distributions of CTEQ4M and MRSR1 are compared to variations described in the text.
Figure 3: The u valence distribution from the CTEQ4M fit (dashed line) and the additional 0.5% component.
Figure 4: Comparison of the sum of the quark distributions from a conventional analysis, and with the fit including a 0.5% additional component of $u_\nu$. 
Figure 5: The BCDMS and CCFR data sets are shown compared to NLO QCD calculations using the fit including the 0.5% additional component of u valence quarks. The agreement is good in both cases. (see text)
Figure 6: Comparisons of NLO QCD jet cross sections from a conventional analysis (CTEQ4M), an analysis with additional high-$x$ gluons (CTEQ4HJ), and an analysis with an additional 0.5% component of $u_v$ at large-$x$. 
Figure 7: The BCDMS data with a deuterium target is shown compared to NLO QCD with the CTEQ4M partons and with the MRSR1 partons.
Figure 8: The kinematic regions are shown of three additional classes of measurements that may provide additional constraints on the large-$x$ quarks in the future. The Tevatron dijet and “Other HERA” blocks are separated only for the purpose of clear labelling; they overlap throughout the region bridging the established data and the “ZEUS Events” regions.