PDF's: What Do We Need To Know?

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Reliable knowledge of parton distribution functions (PDFs) is crucial for many searches for new physics signals in the next generation of experiments. Presently, there remain a number of open questions regarding the PDF's and their uncertainties. We briefly discuss these issues, and consider aspects where a future high-precision fixed-target experiment might contribute [1].

1. Introduction

In the past few years there has been considerable progress towards understanding some of the uncertainties in the individual measurements that contribute to our knowledge of parton distributions (PDFs) [2, 3]. While high energy collider experiments can cover a large kinematic region in $\{x, Q^2\}$-space, there are still a number of questions that can be best answered by a high-precision low-energy fixed-target experiment.

2. Nuclear Effects

To decipher the flavor content of the proton, it is essential to use both charged and neutral current processes. For the charged current process, neutrino DIS plays an important role as the basic process $\nu N \to \ell^\pm X$ contains an easily detected charged lepton ($\ell^\pm$) in the final state. Unfortunately, as the neutrino cross section is relatively small, we are forced to use massive targets with high-Z nucleons in order to obtain reasonable statistics. For example, in the case of NuTeV, an iron (Fe) target was used. Scaling the ν-Fe cross section to a ν-isoscalar cross section poses a significant challenge as this involves complex nuclear effects for which we do not have a comprehensive theory.

When we attempt to extract PDF's from ν-DIS on heavy nucleons our task is compounded by the difficulty that we must simultaneously deal with these nuclear effects and the separation of the PDF flavors [4]. Clearly, this is an area where a future high luminosity neutrino factory could considerably improve our understanding of the ν-DIS process [5, 6, 7]. Such a facility would allow us to perform high statistics measurements on light targets (hydrogen, deuterium, ...) thereby enabling us to separate the nuclear effects from the nucleon structure [8].

Specifically, one can envision a comprehensive two-step program.

1. Use light targets to accurately determine the flavor structure of the proton by combining this data with neutral current data also taken on light targets.

2. Compare the light target data (both charged and neutral current processes) with data from heavy targets to extract the nuclear effects.

Such a program would represent a tremendous advance in the understanding of both the proton structure and the corrections due to high-Z nuclei.

3. PDFs at Large-x

While nuclear binding effects are clearly seen in heavier nuclei, the size of these effects for Deuterium is under debate. Specifically, the ratio of the density of down quarks to that of up

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quarks in the proton in the region $x \to 1$ can provide valuable information on both higher twist corrections and nuclear binding effects. This issue is complicated as: 1) it depends critically on a nuclear physics model with many parameters fit to the data, and 2) the deuteron is a very special nucleus with binding energies much smaller than the rest, so that a large extrapolation from the heavier nuclei is needed.

While future high luminosity HERA measurements of positron-induced charged current interactions will address this issue, preliminary calculations indicate a very large luminosity is required to impose strong constraints on possible nuclear corrections. Conversely, one possible way to constrain the d quark is from measurements of π^+/π^- production in DIS interactions [9]. A careful design of the beam and detector would allow for precision measurements in the large-x region that are competitive with collider facilities.

4. Extraction of $s(x, Q^2)$ from neutrino DIS

For extracting the strange quark PDF, the dimuon production data in ν-Fe DIS provide the most direct determination. The basic channel is the weak charged current process $\nu s \to \mu^- c X$ with a subsequent charm decay $c \to \mu^+ X'$. These events provide a direct probe of the sW-vertex, and hence the strange quark PDF. In contrast, single muon production only provides indirect information about $s(x, Q^2)$ which must then be extracted from a linear combination of structure functions in the context of the QCD parton model. For this reason, fixed-target neutrino dimuon production will provide a unique perspective on the strange quark distribution of the nucleon in the foreseeable future.

The analysis of the recent NuTeV data is in progress. This uses both the differential NLO calculation of the neutrino-induced DIS charm production process and the Monte Carlo experimental detector simulation program. This project will extract the strange quark PDF from the dimuon data at NLO with unprecedented accuracy.

In the long run, a high luminosity neutrino factory could, of course, considerably raise the accuracy of present day information from ν-DIS, and allow us to investigate additional distributions. For example, with high statistics ν-DIS data one can investigate the character of Sudakov logarithms arising from multiple gluon emission. The resummation of such soft gluons in the case of heavy quark production is a program that is currently under development. High statistics ν-DIS data would allow us to not only study the integrated distributions, but also study more differential distributions which are sensitive to the details of the resummation procedure.

5. $\Delta x F_3$

There are a number of outstanding puzzles where theoretical expectations don't match experimental measurements, and $\Delta x F_3$ is a recent example. $\Delta x F_3$ is obtained by taking the difference of F_3 neutrino and anti-neutrino structure function; in the simple LO parton model, this quantity is proportional to the difference between the strange and charm quark PDF. Specifically, $\Delta x F_3 \simeq x F_3^{\nu N} - x F_3^{\bar{\nu} N} \simeq 4x\{s - c\}$, where N represent an isoscalar nucleon.

Theoretical predictions for $\Delta x F_3$ systematically undershoot fixed target data at the $\sim 1\,\sigma$-level at low x and Q. The neutrino structure function $\Delta x F_3$ is obviously sensitive to the strange sea of the nucleon and the details of deep inelastic charm production. A closer inspection reveals, however, considerable dependence upon factors such as the charm mass, factorization scale, higher twists, contributions from longitudinal $W^\pm$ polarization states, nuclear shadowing, charge symmetry violation, and the PDF's. This makes $\Delta x F_3(x, Q^2)$ an excellent tool to probe both perturbative and non-perturbative QCD.

As the situation stands now, this $\Delta x F_3(x, Q^2)$ puzzle poses an important challenge to our understanding of QCD and the related nuclear processes in an important kinematic region. The resolution of this puzzle is important for future data analysis, and the solution is sure to be enlightening, and allow us to expand the applicable regime of the QCD theory [10].

6. Heavy Quark Production

The production of heavy quarks, both hadroproduction and leptoproduction, has become an important theoretical and phenomenological issue [11]. In part, heavy quark production has attracted much attention because in many instances the theoretical expectations differ significantly from experimental measurements. While the hadroproduction mode has a higher mass reach (e.g., the top-quark), the simpler leptoproduction process can provide important insights into the fundamental production mechanisms.

An important theoretical consideration which enters the calculations of heavy quark production is the existence of multiple mass scales. For example, in a DIS experiment the important scales are the virtuality of the exchanged boson Q, and the mass of the heavy quark M_Q. This represents a significant theoretical challenge because extending theorems of factorization and resummation to the case involving multiple scales is nontrivial.

Ideally we would like to explore the full kinematic range from $Q \ll M_Q$ as in heavy quark photoproduction, to the transition region $Q \sim M_Q$, and finally to $Q \gg M_Q$ where the mass effects become negligible. Setting the very massive top-quark aside, in the case of charm and bottom with masses in the few GeV range, fixed-target experiments are best suited to cover the kinematic range where $Q \ll M_Q$ and $Q \sim M_Q$; additionally they can also cover a portion of the $Q \gg M_Q$ region. Therefore, a complete program to investigate heavy quarks must consider information from a variety of sources including charm and bottom production at both fixed-target and collider lepton and hadron facilities [12].

One degree of freedom that has not been fully studied or exploited in this area is the issue of an "intrinsic" heavy quark component. While the question of intrinsic heavy quarks has been discussed in the literature for many years, it still remains unresolved. This is a controversial theoretical issue; hence a definitive experiment is called for. A particularly incisive test of this theory would be to make precise measurements of heavy quark production in the threshold region. In this kinematic regime, the usual "perturbative" heavy quark component arising from gluon splitting ($g \to Q\bar{Q}$) is comparatively small; therefore a measurement in this region has more discriminating power to distinguish the "intrinsic" heavy quark component. Such an experiment could put the theoretical debate on "intrinsic" heavy quarks to rest once-and-for-all. Furthermore, such an experiment will answer important questions regarding heavy quark production and our ability to make accurate calculation in the presence of disparate mass scales.

7. Higher Twist

Higher twist (or power suppressed) corrections represent a long-standing hurdle to making accurate theoretical predictions for structure function data over the full kinematic range. Higher twist corrections should not simply be avoided; accurate characterization of higher twist corrections provides new information on parton–parton correlations within the nuclei [9].

The kinematic limits where considerations of higher twist contributions become important are 1) at high-x, and 2) at low Q^2 where terms of order Λ^2/Q^2 become significant. In the high-x region, the limiting factor is primarily statistics. In the low Q^2 region the statistics are generally adequate, but if the data is taken on heavy targets the higher twist effects are entangled with nuclear effects.

Consequently, the ideal testing ground would be to have high statistics measurements on a light nuclear target. This would allow systematic separation of the higher twist effects from the nuclear effects, and better allow us to learn about both in the process.

8. Conclusions

In recent years, new information has become available concerning parton distributions and their uncertainties. The issues have become more important with the realization that these uncertainties could be hampering searches for physics beyond the Standard Model. The different topics reviewed in this report have clarified some of the issues, but have also raised new questions to be addressed. We have outlined a program of measurements, as well as important theoretical work, that is needed to improve the uncertainties in parton distributions. Therefore, a complete program to investigate the nucleon structure must consider information from a variety of sources including both fixed-target and collider lepton and hadron facilities.

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