Neutrino Charm Production and Implications for PDF’s *†

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Abstract

We have performed the first comprehensive global QCD analysis including the CCFR and NuTeV di-muon data; this data provides strong constraints on the strange quark PDF.

Introduction

The recent measurements of both neutrino and anti-neutrino production of charm (as di-muon final states) by the CCFR and NuTeV collaborations provide important new information on the strange quark distribution, $s(x)$, of the nucleon.[1, 2] We report here the first comprehensive global QCD analysis that includes the CCFR and NuTeV di-muon data.

In previous global analyses, the predominant information on $s$ came from the difference of (large) inclusive cross sections for neutral and charged current DIS; hence, the comparably small $s$ and $\bar{s}$ distributions extracted had large uncertainties. Lacking better information, these studies often assumed the distribution was of the form $s(x) = \bar{s}(x) \sim \kappa(\bar{u} + \bar{d})/2$ with $\kappa \sim 0.5$. The recent

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high-statistics measurements of $\sigma^{\mu^+\mu^-}_{\nu N}$ and $\sigma^{\mu^+\mu^-}_{\bar{\nu} N}$ by the CCFR and NuTeV experiments allow us to separately determine $s(x)$ and $\bar{s}(x)$ with unprecedented accuracy. Neutrino induced di-muon production, $\nu/\bar{\nu} N \rightarrow \mu^+\mu^- X$, proceeds primarily through the subprocess $s \rightarrow c$ or $\bar{s} \rightarrow \bar{c}$, and hence provides information on $s$ and $\bar{s}$ directly. (Cf., Fig 1a.)

We present a global analysis including this new di-muon data, corrected for experimental cuts and efficiencies using information provided by the experimental group. The new results are rich in physical content, in part, due to the interplay of these high statistics measurements and the strong constraints of the PQCD framework.

## Global Analysis

The inclusion of the CCFR-NuTeV neutrino and anti-neutrino di-muon production data give direct handles on $s$ and $\bar{s}$ in the important $x$ range $\sim [0.01, 0.2]$. CCFR has recorded 5030 $\nu$ and 1060 $\bar{\nu}$ di-muon events, while NuTeV has recorded 5012 $\nu$ and 1458 $\bar{\nu}$ di-muon events. Additionally, NuTeV had a sign-selected beam to separate the $\nu$ and $\bar{\nu}$ events. The global QCD analysis contains the full data set from the CTEQ6 analysis, in addition to the di-muon data; as such, this can be considered as an extension of the on-going CTEQ series of global analysis.[3]

Incorporating this into the global QCD analysis is a non-trivial task. The
experimental measurement is the cross section for producing two final state
muons \(d\sigma_{\mu^+\mu^-}\) with experimental cuts, whereas the theoretical quantities that
are most directly related to the parton distribution analysis are the underlying
“charm quark production cross sections” \(d\sigma_{c\mu^\pm}\) for the process \(\nu_\mu/\bar{\nu}_\mu N \rightarrow \mu^+ cX\). We can relate these quantities via the equation:

\[
\frac{d\sigma_{\mu^+\mu^-}}{dx\,dy} = \int d\Gamma\,d\Omega\,d\sigma_{c\mu^\pm} \otimes D_c(\Gamma) \otimes \Delta_c(\Omega) \quad \bigg|_{E_{\mu^\pm} > 5 \text{GeV}}
\]  

(1)

Here, \(\Gamma\) and \(\Omega\) denote the fragmentation and decay kinematic variables of the
charmed quark and charmed hadron, respectively; \(D_c(\Gamma)\) is the fragmentation
function, and \(\Delta_c(\Omega)\) is the decay distribution function.

The gap between these two cross sections are usually bridged by Monte
Carlo programs which incorporate experimental cuts and efficiencies as well as
fragmentation models. In our analysis, we rely on a Pythia program provided
by the CCFR-NuTeV collaboration.\(^1\) This Monte Carlo calculation in done in
the spirit and the framework of leading-order (LO) QCD. Accordingly, the theo-
etrical formulas used are also in LO. Since charm production has such a small
cross section in the experimental kinematic range covered, this approximation
is perfectly adequate (as we will verify later) for a first study of the di-muon
data within the global QCD analysis framework. Needless to say, all fully in-
clusive (large) cross sections used in this study are treated in NLO QCD, as in
all modern global analyses.

Results

We parameterize the strange quark in the form:

\[
s(x, Q_0) \equiv \bar{s}(x, Q_0) = a_0 x^{a_1} (1 - x)^{a_2} e^{a_3 x} (1 + e^{a_4 x})^{a_5}
\]  

(2)

In the present analysis, we take \(s(x) \equiv \bar{s}(x)\); in later studies we shall consider
a non-symmetric strange distribution,\(^{[4–7]}\)

We will consider four separate sets of PDF’s: the CTEQ6M set (which is not fit to the di-muon data), a Constrained fit where only the normalization

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\(^1\) We thank Tim Bolton and Max Goncharov, in particular, for providing this program, as well as assistance to use it. Both are vital for carrying out this project.
Figure 2: Plot of \((Data - Theory)/Theory\) for the NuTeV \(\nu\) and \(\bar{\nu}\) data vs. data point number. Note the larger error bars on the \(\bar{\nu}\) data due to the lower statistics.

\(\{a_0\}\) is allowed to vary; a Mixed fit where both \(\{a_0, a_2\}\) are allowed to vary; a Free fit where all \(\{a_i\}\) are allowed to vary;

The CTEQ6M PDF’s yield a respectable \(\chi^2\) of 2173 for 1991 data points (CTEQ6M was not fit with the di-muons), and the Constrained, Mixed, and Free fits yield 2144, 2142, and 2133, respectively. While it is reassuring to see the \(\chi^2\) decrease as we increase the number of free parameters, it will require additional study to determine whether the data can actually constrain all these parameters.

It is also interesting to note that as we move from the CTEQ6M fit to the fits including the di-muons, the \(\chi^2/DOF\) for all the experiments (excluding the di-muons) are generally unchanged to within a percent. From this observation, it is evident that the effect of adding in the di-muon data serves to adjust the strange PDF, but has virtually no effect on the other data sets. Or, equivalently, this demonstrates that the di-muon data plays a dominant role in determining the strange distribution.

The observation that it is primarily the di-muon data which influence the strange distribution prompts us to fit the neutrino and anti-neutrino data separately to investigate the extent to which this data can determine the \(s(x)\) and \(\bar{s}(x)\) distributions independently.\(^2\) At leading-order, the neutrino induced process \(\nu s \rightarrow \mu^- c\) is tied to the strange distribution, while the anti-neutrino induced process \(\bar{\nu} \bar{s} \rightarrow \mu^+ \bar{c}\) is tied to the anti-strange distribution. Of course,

\(^2\)A complete analysis which fits the neutrino and anti-neutrino data simultaneously and allows \(s(x \neq \bar{s}(x))\) is in progress.\([6, 7]\)
these relations will be complicated at NLO; however it is useful to see if, and how, these separate data sets pull the fit.

In Fig.1b we display the obtained strange distribution for the combined $\nu$ and $\bar{\nu}$ fit, as well as the individual fits. We observe that the $\nu$ data yields a smaller PDF, while the $\bar{\nu}$ yields a slightly larger fit than the combined set. Note that this effect is consistent with the results of the NuTeV fit by Goncharov,[1] which obtained $\kappa = 0.35$ for the $\nu$ data and $\bar{\kappa} = 0.41$ for the $\bar{\nu}$ data.

This result suggests that the di-muon data is capable of providing information about the $s$ and $\bar{s}$ distributions separately. However, to properly extract this information requires a simultaneous fit to the $\nu$ and $\bar{\nu}$ while imposing the strangeness sum rule on the PDFs: $\int dx s(x) - \bar{s}(x) = 0$.

**Conclusion**

We present the first global analysis which includes the CCFR and NuTeV neutrino and anti-neutrino di-muon production data. We find several classes of solutions in the strangeness sector that are consistent with all relevant world data used in these global analyses.

While the CTEQ6M PDF provided a good description of the data, we obtained an improved fit if we free the parameters of the strange quark PDF to allow them to conform to the di-muon data. A more comprehensive study of this data is in progress,[6, 7] and future work includes relaxing the constraint of $s = \bar{s}$, and including the NLO modeling of the charm production cross section.

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