Differential Distributions for NLO Neutrino-Production of Charm

S. Kretzer\textsuperscript{1}, D. Mason\textsuperscript{2}, F. Olness\textsuperscript{3}

\textsuperscript{1}Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824
\textsuperscript{2}Department of Physics, University of Oregon, Eugene, OR 97403
\textsuperscript{3}Department of Physics, Southern Methodist University, Dallas, TX 75275-0175

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Charged current DIS charm production measures the strange-quark PDF. A complete analysis requires both a fully differential theoretical calculation, and a Monte Carlo detector simulation. We present analytic and numeric results at NLO suitable for experimental analysis.

I. INTRODUCTION

Recent sets of global parton distribution functions (PDFs) have reached a sufficiently high level of accuracy that quantization and propagation of statistical errors have become important issues. It is, therefore, even more unsettling that the strange quark PDF, $s(x, Q^2)$, remains a mystery without a fully consistent picture emerging from the comparative analysis between neutrino and muon structure functions, opposite sign dimuon production in $\nu$Fe-DIS, or the recently measured parity violating structure function $\Delta x F_3$. Given the high precision of the non-strange PDF components, this situation for $s(x, Q^2)$ is unacceptable both in terms of our understanding of the nucleon structure, and for our ability to use precise flavor information to make predictions for present and future experiments.

For extracting the strange quark PDF, the dimuon production data in $\nu$-Fe DIS provide the most direct determination. The basic channel is the weak charged current process $\nu s \rightarrow \mu^- cX$ with a subsequent charm decay $c \rightarrow \mu^+ X'$. 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.

In contrast, HERA provides a large dynamic range in $Q^2$ for the CP conjugated process $e^- s \rightarrow \bar{\nu} c$ which is valuable for testing the underlying QCD evolution. Within the HERMES experimental program the flavor structure of the polarized and unpolarized sea are studied from semi-inclusive DIS where DIS-Kaon production has obvious potential to probe strangeness. In summary, HERA and HERMES can complement fixed-target neutrino dimuon data with information at different energies and from different processes; therefore, neutrino DIS serves, for now, as an important benchmark process to perform rigorous and refined comparisons between the experimental data and the theoretical calculations. In the long run, a high luminosity neutrino factory could, of course, considerably raise the accuracy of present day information from $\nu$-DIS.

The theoretical calculations of inclusive charged current charm production have been carefully studied in the literature. Additionally, the charm fragmentation spectrum has also been calculated in detail. While inclusive calculations are sufficient for many tasks, a comprehensive analysis of the experimental data at NLO requires additional information from the theoretical side. In charged current $\nu$-Fe charm production, the detector acceptance depends on the full range of kinematic variables: $\{x, Q^2, z, \eta\}$. Here, $x$ is the Bjorken-$x$, $Q$ is the virtuality of the $W$-boson, $z$ is the scaled energy of the charm after fragmentation, and $\eta$ is the charm rapidity. The theoretical task is, mutatis mutandis, not too different from the extraction of the neutral current charm structure function $F_2^c$ as performed by the HERA experiments; the HERA analysis uses the theoretical calculation of the differential cross section to extrapolate into regions of poor acceptance.

In this short report,\textsuperscript{1} we briefly discuss the key factors that influence the acceptance of the experimental detector, review the theoretical calculation of the fully differential cross section at NLO in QCD, and present numerical results for typical fixed target kinematics.

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II. EXPERIMENTAL ENVIRONMENT: $\nu-F_{\text{e}}$ DIS

Dimuon events from neutrino charged current charm production can provide a clear set of events from which to study the strange sea. Their signature in a detector is a pair of oppositely charged muons and hadronic shower originating from the same vertex. The second muon is produced in the semileptonic decay of the charmed particle. In order to properly reconstruct these events from data, a minimum energy requirement must be applied to this muon. To be visible at all, it must first be energetic enough that it travels further in the detector than the particles which make up the hadronic shower. The background from muons from nonprompt decays of pions and kaons within the shower is large at low energy, and must also be reduced. Typically a cut on the charm decay muon’s energy of a few GeV is applied to guarantee it is reconstructible, and reduce the nonprompt backgrounds.

This energy requirement leads to a dependence on variables in addition to the typical $E_\nu$, $x$, and $Q^2$ or $y$ dependence of the charged current cross section. The energy of the decay muon depends on the energy of the charmed meson from which it decays, and therefore depends on the fragmentation parameter $z$. In NLO, it also depends on the transverse momentum of the charmed quark. An event with a low $z$, and/or high transverse momentum will be less likely to pass a cut on the decay muon’s energy than one with a high $z$ and no transverse momentum. It is therefore important that the charm production cross section’s dependence on these variables be understood for a Monte Carlo to be able to model dimuon event acceptance properly.

III. DIFFERENTIAL DISTRIBUTIONS AT NLO

Recorded charged-current charm production rates must be corrected for the detector acceptance which, as discussed above, depends on the full range of kinematic variables $\{x, Q^2, z, \eta\}$. Therefore, we must obtain the NLO theoretical cross section which is completely differential in all these variables. As the NLO theoretical cross section contains $\delta$-function distributions and “plus”-distributions, there are many inherent difficulties combining this program with a complex detector simulation MC program. The singular distributions are nothing but an unphysical artifact of regularized perturbation theory; for any physically observable quantity, these singularities will be smeared by soft gluon emission to yield physical C-number distributions.

As the theoretical machinery of soft gluon resummation is not fully developed for semi-inclusive DIS (massive) heavy quark production, we will use a two step phenomenological approach: 1) We regularize the NLO calculation to provide numerical distributions free of $\delta$-function and “plus”-distributions by integrating over bins which reflect the finite resolution of the experimental detector. 2) This result is input to a Monte Carlo (MC) where additional effects, including iterated soft gluon emissions are added to the $p_\perp$ smearing from NLO kinematics to match a Gaussian distribution that has been fit to data.

In addition to the above complications, we also encounter large and negative Sudakov logarithms close to the phase space boundary where, at fixed-order, soft single-gluon emission is enhanced. These Sudakov logarithms diverge in the limit of zero bin-width; as we increase our resolution via narrow binning, we begin to resolve the unphysical $\delta$-functions and “plus-distributions.” Conversely, by using broad bins, we are effectively integrating over enough phase-space so that the KLN theorem ensures that we obtain positive physical results.

IV. NUMERICAL RESULTS

Having addressed the complication of mapping mathematical distributions onto C-number functions by the introduction of bins, we now present some preliminary results of step 1) of this calculation. We compute the normalized differential charm production cross section for the differential structure function with the binning procedure defined above.

For our variables, we choose the set $\{x, Q, z, \eta\}$ where $\eta$ is the charm rapidity evaluated in the collinear ($p_{\perp,W} = 0$) target rest frame. In Fig. (a) we present results for kinematics typical of a wide-band neutrino beam on a fixed target: $E_\nu = 80$ GeV, $x = 0.1$, $Q^2 = 10$ GeV$^2$. We plot $d\sigma$ in 2-dimensions vs. $z$ and $\eta$ in Fig. (a)-a. Fig. (b)-b and Fig. (c)-c show $d\sigma_{x,y,z,\eta}$ for the case where either $\eta$ or $z$ is integrated out. In both cases, we display this for fine-binnings of $0.1 \times 0.1$, and broad-binnings of $1 \times 5$ or $10 \times 1$. As an important cross-check on these results, we verify that the binning $\eta \times \eta = 1 \times n$ (rapidity integrated out) reproduces the integrated results in the literature.

We observe negative Sudakov logarithms which occur at large $z$ where we have $\eta \lesssim \eta_{\text{max}}$ in the integrand. This effect is an artifact of our fixed-order result, and is clearly evident in Fig. (b)-b where we see that in the case of fine binning and large $z$, the distribution turns negative. The fine binning effectively resolves the unphysical $\delta$-functions and “plus-distributions,” and results in an unphysical negative distribution. Conversely, by using broad bins, we are effectively integrating over enough phase-space so that the KLN theorem ensures that we obtain positive physical results. In an actual experimental analysis, this requirement of broad bins arises naturally given the finite detector resolution.
resolution. Hence, we observe that negative weights can be easily avoided by using sufficiently broad bins in a reasonable broadening of the binning.

Our use of bins to regularize the differential distributions will have negligible impact on the experimental analysis because our bin size is small compared to the experimental detector resolution, and also because the detector acceptance is a smooth function in terms of the set of kinematic variables. In particular, given the geometry of typical neutrino detectors, the effective experimental bin size in \( z \) and \( \eta \) is comfortably large enough for the purpose of regularizing the differential distributions with the binning technique.

V. CONCLUSIONS

In conclusion, we have presented a fully differential NLO calculation of the neutrino-induced DIS charm production process. This calculation is an essential ingredient for a complete analysis of the dimuon data, and will allow a precise determination of the strange quark PDF. We have demonstrated that by binning the data appropriately, we can interface the theoretical calculation (containing \( \delta \)-functions and “plus-distributions”) directly to the experimental Monte Carlo analysis program. We observe the enhancement of the Sudakov logarithms at the phase-space boundaries, and verify that these can be controlled with this binning method.

The fully differential distributions obtained here allow charged current neutrino DIS experiments to use the complete NLO QCD result in the Monte Carlo data analysis. This analysis using the NuTeV data is in progress. These tools will allow us to extract the strange quark PDF from the dimuon data at NLO with unprecedented accuracy; this information should prove crucial to understanding the behavior of the strange quark in the proton.

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[1] As space in this short report is limited, we refer the reader to our long paper for a complete set of references: S. Kretzer, D. Mason, F. Olness, Differential Distributions for NLO Analyses of Charged Current Neutrino-Production of Charm, e-Print Archive: [hep-ph/0112191](https://arxiv.org/abs/hep-ph/0112191).