

Identified Hadron Production in Deeply Inelastic Neutrino-Nucleon Scattering

Leonardo Bonino[✉], Thomas Gehrmann[✉], Markus Löchner[✉], and Kay Schönwald[✉]
 Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

Giovanni Stagnitto[✉]
 Università degli Studi di Milano-Bicocca and INFN, Piazza della Scienza 3, 20126 Milano, Italy

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The production of identified hadrons in semi-inclusive deep-inelastic scattering (SIDIS) is sensitive to parton distribution functions and hadron fragmentation functions. Neutrino-induced SIDIS processes probe combinations of these functions differently from their charged-lepton-induced counterparts. We compute charged pion production in (anti)neutrino-induced SIDIS up to second order in perturbative QCD and compare our predictions to precise legacy fixed-target data. We demonstrate the high sensitivity of these data on the parametrization of the fragmentation functions and discuss future SIDIS probes at the LHC Forward Physics Facility.

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Introduction—Neutrino beams are ideal probes for detailed studies of the partonic content of nucleons in deep-inelastic scattering (DIS) experiments. Of particular interest are (anti)neutrino-nucleon scattering processes with an identified, highly energetic secondary muon. In these processes the momentum transfer between (anti)neutrino and nucleon is mediated by virtual W bosons, resulting in a flavor-changing charged current (CC) interaction on the quark line. This interaction singles out specific flavor combinations of the parton distribution functions (PDFs), providing complementary information with respect to neutral current DIS.

The flavor-discriminating power of CC processes is further increased by additionally identifying a final state hadron, constraining the allowed flavor combinations of initial and final state quarks. The identification of final state hadrons also provides crucial information on the mechanism of hadronization, responsible for the formation of color neutral hadronic states out of quarks and gluons. CC DIS data extracted in neutrino experiments [1–4] are routinely included in global PDF fits [5–7], which are being performed up to next-to-next-to-leading order (NNLO) in QCD. As of today no global fits to light hadron fragmentation functions (FFs) include CC neutrino-nucleon semi-inclusive DIS (SIDIS) information, despite this process providing a clean probe of the quark flavor structure of FFs, which is otherwise poorly constrained from other fragmentation observables.

In this Letter we present precise predictions for semi-inclusive pion production in (anti)neutrino-nucleon scattering at NNLO in massless QCD. We compare our predictions with data from the ABCMO Collaboration [8], which has never been included in any modern extraction of PDFs or FFs. We demonstrate the potential impact of this dataset on future determinations of FFs and discuss the potential of future neutrino-nucleon SIDIS at the Forward Physics Facility at CERN.

SIDIS cross section—We consider the observation of a hadron h following the scattering of an (anti)neutrino on a nucleon:

$$\begin{aligned}\nu(k)p(P) &\rightarrow l^-(k')h(P_h)X, \\ \bar{\nu}(k)p(P) &\rightarrow l^+(k')h(P_h)X,\end{aligned}\quad (1)$$

with X denoting the remaining hadronic final state. The leptonic momenta determine the four-momentum $q = k - k'$ of the exchanged virtual W boson and the rest-frame energy transfer $y = (P \cdot q)/(P \cdot k)$. For $Q^2 = -q^2$ the variables

$$x = \frac{Q^2}{2P \cdot q}, \quad z = \frac{P \cdot P_h}{P \cdot q} \quad (2)$$

correspond to the Born-level momentum fractions of the nucleon carried by the incoming parton (x) and of the outgoing parton carried by the identified hadron (z). The squared center-of-mass energy of the lepton-nucleon system is $s = Q^2/(xy)$ and the invariant mass of the hadronic final state $W^2 = Q^2(1-x)/x$.

Following the notation of [9], the triple-differential cross section reads

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$$\frac{d^3\sigma^h}{dx dy dz} = \frac{16\pi\alpha^2}{Q^2} \eta_W \left[\frac{1 + (1-y)^2}{2y} \mathcal{F}_T^{h,W^\pm} + \frac{1-y}{y} \mathcal{F}_L^{h,W^\pm} - e_\ell \frac{1 - (1-y)^2}{2y} \mathcal{F}_3^{h,W^\pm} \right], \quad (3)$$

where α is the fine structure constant, e_ℓ refers to the outgoing lepton charge, and

$$\eta_W = \frac{1}{2} \left(\frac{G_F M_W^2}{4\pi\alpha} \frac{Q^2}{Q^2 + M_W^2} \right)^2. \quad (4)$$

The CC SIDIS structure functions $\mathcal{F}_T^{h,W^\pm}$, $\mathcal{F}_L^{h,W^\pm}$, and $\mathcal{F}_3^{h,W^\pm}$ are obtained by summing over all partonic channels of the convolution between the PDF for a parton p (f_p), the FF of a parton p' into the hadron h ($D_{p'}^h$), and the coefficient function for the transition $p \rightarrow p'$ ($C_{p'p}^{i,k}$),

$$\begin{aligned} \mathcal{F}_i^{h,W^\pm}(x, z, Q^2) &= \sum_{p,p'} \int_x^1 \frac{d\hat{x}}{\hat{x}} \int_z^1 \frac{d\hat{z}}{\hat{z}} f_p\left(\frac{x}{\hat{x}}, \mu_F^2\right) D_{p'}^h \\ &\times \left(\frac{z}{\hat{z}}, \mu_A^2\right) C_{p'p}^{i,W^\pm}(\hat{x}, \hat{z}, Q^2, \mu_R^2, \mu_F^2, \mu_A^2), \end{aligned} \quad (5)$$

for $i = T, L, 3$. The above factorization introduces two separate factorization scales: μ_F for the initial state and μ_A for the final state. μ_R denotes the renormalization scale. The coefficient functions encode the hard-scattering part of the process and can be computed in perturbative QCD. Their perturbative expansion in the strong coupling constant α_s reads

$$\begin{aligned} C_{p'p}^{i,W^\pm} &= C_{p'p}^{i,W^\pm,(0)} + \frac{\alpha_s(\mu_R^2)}{2\pi} C_{p'p}^{i,W^\pm,(1)} \\ &+ \left(\frac{\alpha_s(\mu_R^2)}{2\pi} \right)^2 C_{p'p}^{i,W^\pm,(2)} + \mathcal{O}(\alpha_s^3). \end{aligned} \quad (6)$$

Analytical expressions for the SIDIS coefficient functions have been computed up to next-to-leading order (NLO) in QCD [10–12].

For this Letter we have performed the first computation of the full set of NNLO corrections to neutrino-induced SIDIS in analytical form [13], closely following our earlier calculation of photon-mediated SIDIS [14,15] at this order. The technical details of our calculation are described in [16,17], and an independent validation of [14,15] was obtained in [18–21]. In order to treat the antisymmetric structures γ_5 and $\epsilon^{\mu\nu\rho\sigma}$ arising from axial couplings and the projector of $\mathcal{F}_3^{h,W^\pm}$ consistently in dimensional regularization, we employed the Larin scheme [22], and subsequently converted the results into the $\overline{\text{MS}}$ scheme by a finite transformation.

Numerical results—The production of charged pions in deeply inelastic (anti)neutrino-proton scattering was measured by the ABCMO Collaboration [8] in 1982, alongside results from several other contemporaneous experiments [23–30]. The experiment exploited the wide-band (anti)neutrino beam generated by 350 and 400 GeV protons from the CERN Super Proton Synchrotron and directed onto the liquid hydrogen-filled Big European Bubble Chamber. It measured the SIDIS processes

$$\nu p \rightarrow \mu^- \pi^\pm X, \quad \bar{\nu} p \rightarrow \mu^+ \pi^\pm X, \quad (7)$$

providing separate results for both pion charges.

The experimental data was analyzed in the variable x_F , which differs from z at higher perturbative orders due to the transverse momentum of extra real radiation. We have performed a detailed analysis of the resulting shift in predictions differential in x_F and z up to NLO and find that for the kinematics under consideration we can safely approximate $x_F \simeq z$.

The normalized distributions of Table 3 in [8] correspond to charged pion multiplicities described by the ratio

$$\frac{dM^{\pi^\pm}}{dz} = \frac{d^3\sigma^{\pi^\pm}/dx dy dz}{d^2\sigma/dx dy}. \quad (8)$$

The numerator is given by the SIDIS cross section of Eq. (3), while the denominator is given by the inclusive DIS cross section. The NNLO DIS structure functions [31,32] are computed using APFEL [33]. The measured multiplicities allow to extract FFs.

As the ABCMO [8] results do not report the average (anti)neutrino beam energy, we infer an average beam energy of $E_{\nu/\bar{\nu}} \simeq 39$ GeV ($\sqrt{s_{\text{avg}}} \simeq 8.8$ GeV) from another group [25] using the same experimental setup. While a weighted average over the beam energy $E_{\nu/\bar{\nu}}$ is in principle required, the exact distributions are not reported in [8,25]. We instead verified that changing the beam energy between 19.5 and 78.0 GeV leads to small variations that are evenly spread around the central value, justifying the assumption of a monoenergetic beam. The numerator and denominator of Eq. (8) are integrated over x , y , and z according to the kinematic cuts reported in [8], $x > 0.1$ and $W > 3$ GeV, resulting in a dynamical range $1 \text{ GeV} < Q < 8.8 \text{ GeV}$.

Our results are shown in Fig. 1. At each perturbative order we use the NNLO PDF set NNPDF31_NNLO [34] and NNLO FF set BDSSV22_NNLO [35]. α_s is taken from the PDF set, and the Cabibbo–Kobayashi–Maskawa (CKM) matrix values are from [36]. We fix the number of flavors to $N_f = 4$ in all ingredients of the calculation and keep all quarks massless. In inclusive charged current processes, charm quark mass effects may be substantial [37–40] due to the $s \rightarrow c$ transition at tree level, which is however suppressed by the fragmentation functions for semi-inclusive pion production.

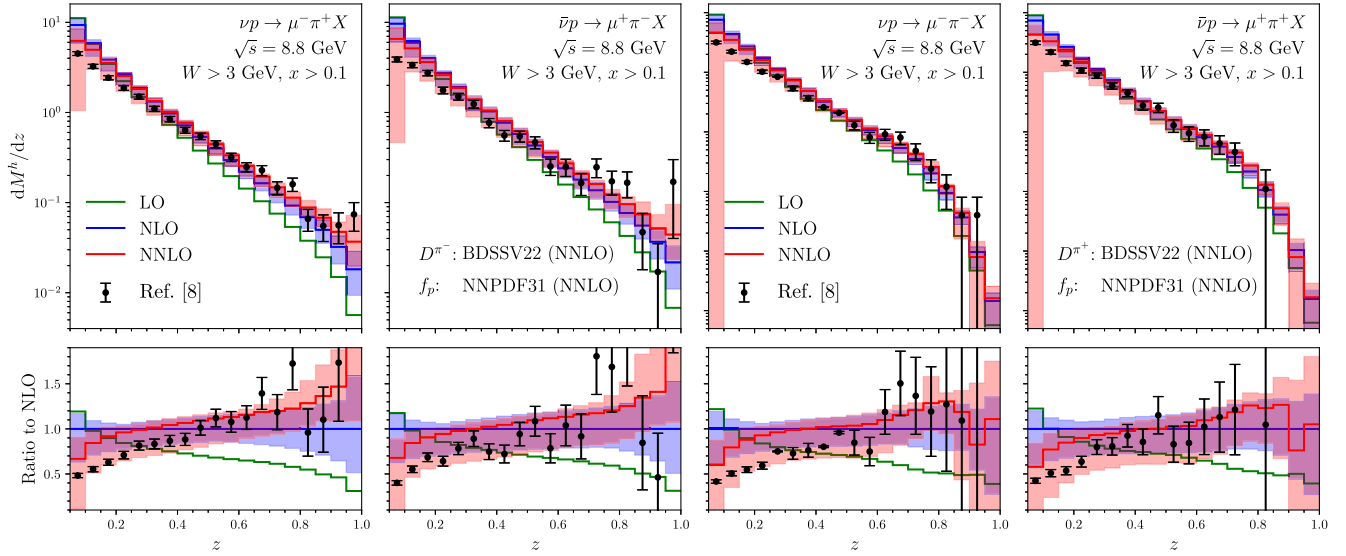


FIG. 1. Theory predictions for pion multiplicities for (anti)neutrino-induced DIS processes up to NNLO compared to the ABCMO measurement [8].

The theory uncertainties are obtained by seven-point scale variation in the numerator for μ_R and $\mu_A = \mu_F$ around the central scale Q , with scale variations cut off at the minimum value $Q_{\min}$ allowed by the PDF and FF sets. We verified that an additional scale variation in the denominator or an uncorrelated variation of μ_A and μ_F have a negligible effect on the theory uncertainty band.

The legacy data shows strikingly good compatibility with the theoretical predictions. While the LO predicts the overall trend, the inclusion of the NLO corrections shifts the prediction closer to the data. The NNLO corrections are sizable and further improve agreement with the data, now reproducing the trend of the data in the entire z range, with the majority of the data points lying within theory uncertainties. For small and moderate z the experimental errors on the data points are significantly smaller than theory uncertainties. The theoretical uncertainties from scale

variation at NLO and NNLO are comparable in size, hinting at an underestimation of NLO uncertainties.

In Fig. 2 we illustrate the channel decomposition for $\nu p \rightarrow \mu^- \pi^+ X$ and $\bar{\nu} p \rightarrow \mu^+ \pi^+ X$ at NLO and NNLO for ABCMO kinematics. Only channels contributing to at least 5% of the total cross section in a single bin are shown, displaying the sensitivity of these data on off-diagonal flavor combinations in the underlying hard interaction, which in turn probe specific FFs.

For $\nu p \rightarrow \mu^- \pi^+ X$ the full cross section is essentially accounted for by the flavor combination “favored” by the valence content of the proton and π^+ : $d \rightarrow u$. This transition is a nonsinglet CKM-allowed channel already present at Born level. For $\bar{\nu} p \rightarrow \mu^+ \pi^+ X$ the favored valence-to-valence flavor combination channels, containing a u quark in the final state, arise only at NNLO and are thus perturbatively suppressed. Instead, the “unfavored” sea-flavor

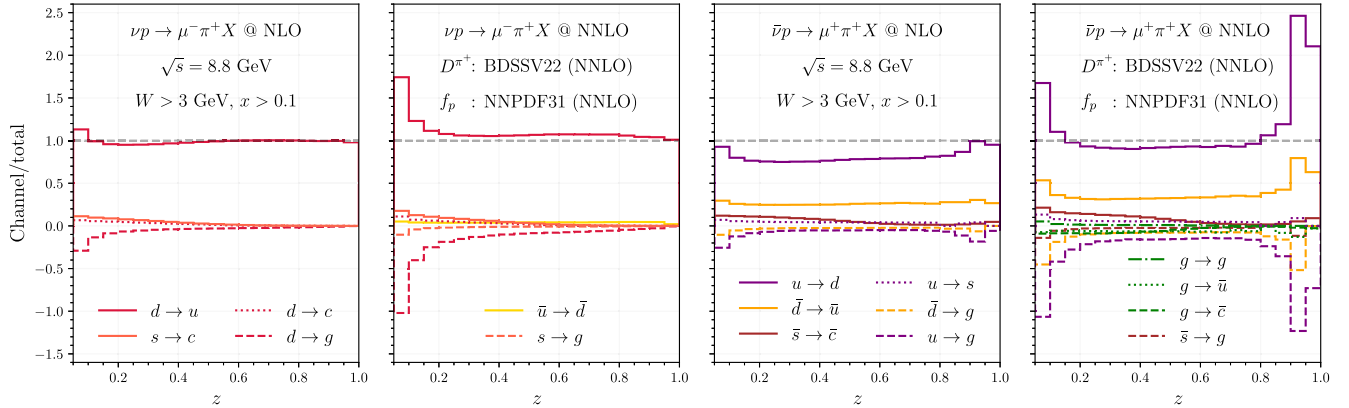


FIG. 2. Dominant partonic channels contributing to flavor-favored (left frames) and flavor-unfavored (right frames) SIDIS reactions at NLO and NNLO. Contributions are normalized to unity in each bin.

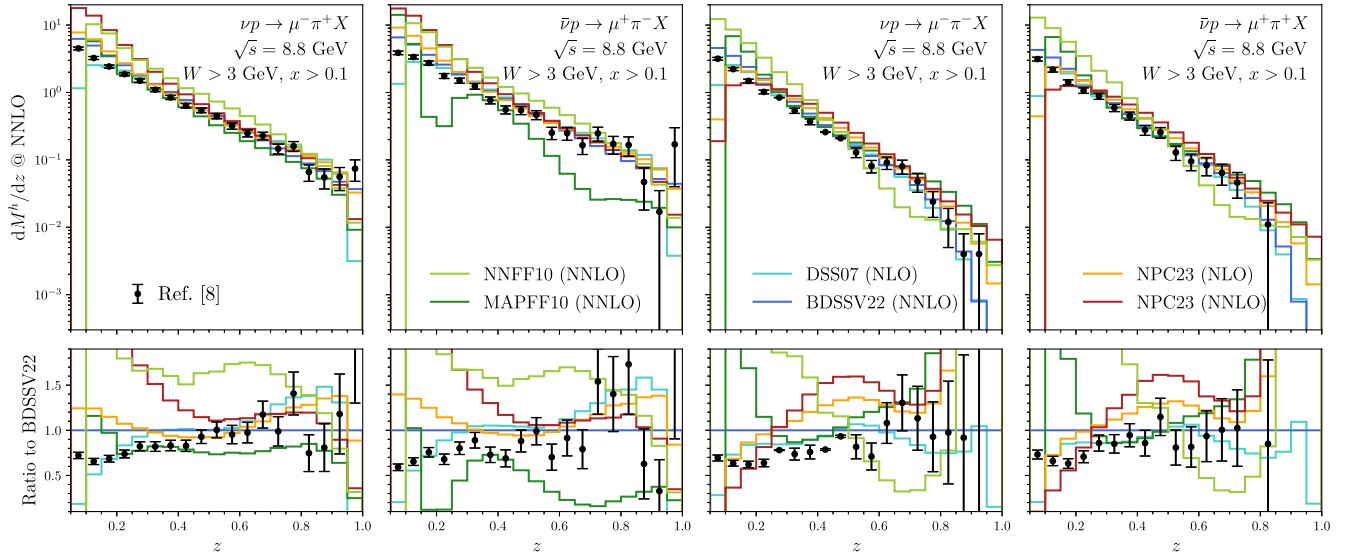


FIG. 3. Comparison of NNLO multiplicities computed with different FF sets to data. Ratios are taken with respect to the multiplicity computed with the BDSSV22_NNLO set.

combinations are dominant, accounting for a significant fraction of the total SIDIS cross section.

The NNLO corrections even enhance the impact of unfavored contributions compared to NLO, and they enlarge the negative $u \rightarrow g$ and $d \rightarrow g$ channels at small z , bringing the overall cross section closer to the data. The induced large cancellations increase the theoretical uncertainty, as already observed for charged-lepton-induced SIDIS [14,15]. Especially in the high z regions, instabilities in the flavor-unfavored channels at NNLO in Fig. 1 are due to large cancellations among partonic channels. The related cross sections $\bar{\nu}p \rightarrow \mu^+\pi^-X$ (favored) and $\nu p \rightarrow \mu^-\pi^-X$ (unfavored) display a similar pattern.

Sensitivity on fragmentation functions—In Fig. 3 we examine the compatibility of the ABCMO data with different modern FF sets. We consider the following parametrizations: BDSSV22_NNLO [35], DSS07_NLO [41], MAPFF10_NNLO [42], NNFF10_NNLO [43], NPC23_NLO [44], and NPC23_NNLO [45] and compute the hadron multiplicity distribution (8) at NNLO. We verified that the multiplicity is insensitive to the choice of PDF.

Both NLO sets [41] and [44] provide a good description of the data, with a tendency of overshooting the data at small z for NPC23_NLO. When comparing NNLO sets instead, we observe significant differences. Among all NNLO sets, the BDSSV22_NNLO set provides the best description of the data. This is most likely due to the inclusion of lower-virtuality ($Q^2 < 4 \text{ GeV}^2$) SIDIS data in the fit [35]. The NPC23_NNLO set provides an overall good description of the data, in particular at moderate and large z for the favored channels. The excess of NPC23_NNLO in the low z region for the flavor-favored processes can be attributed to the inclusion of e^+e^- data

from BESIII [46] into the fit. The NNFF10_NNLO set also provides an overall satisfactory description of the data, but it does not capture the shape of the distributions as accurately as the former and systematically overshoots the data by 50% in the favored channels. This is most likely due to the absence of SIDIS data in this fit, which help constrain the magnitude of individual FFs. The MAPFF10_NNLO provides a reasonable description of the data in the $\nu p \rightarrow \mu^-\pi^+X$ channel as well as in the unfavored channels for $z \gtrsim 0.2$. Unlike the other FF sets, the MAPFF10_NNLO FFs (central value and all replicas) fail to predict the shape and size for $\bar{\nu}p \rightarrow \mu^+\pi^-X$. This is due to a significant amount of isospin breaking in this parametrization: $D_u^{\pi^+} \neq D_d^{\pi^-}$.

We verified that the spread among the different parametrizations in Fig. 3 is considerably larger than the uncertainty on each parametrization, as quantified by their associated replicas. This spread clearly demonstrates the stringent constraints that (anti)neutrino SIDIS data provide on the flavor structure of the FFs, highlighting their potential relevance for future global FF fits.

Future experiments—The FASER experiment, which is situated in the very-forward region of the ATLAS interaction point at the CERN LHC, has established the flux of forward high-energy neutrinos from proton-proton collisions [47]. Experiments in the context of the planned Forward Physics Facility (FPF, [48]) at the HL-LHC could be equipped to study SIDIS processes for various final-state hadron species. In Fig. 4 we investigate the behavior of the π^+ multiplicity distribution (8) in such a measurement. We consider a representative muon neutrino energy of $E_\nu \sim 300 \text{ GeV}$ [49] and employ the same kinematic cuts as before: $x > 0.1$ and $W > 3 \text{ GeV}$. In the kinematic range of

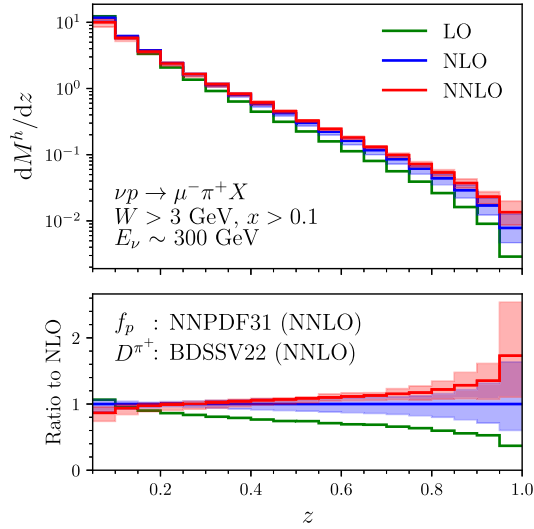


FIG. 4. Expected pion multiplicity distribution for FPF-type experiments at the LHC.

the FPF the multiplicity displays a non-negligible dependence on E_ν such that more dedicated studies will require a weighted average over the neutrino beam energy. We observe sizable QCD corrections also at higher energies with improved perturbative stability with respect to Fig. 1 due to the higher average value of Q : the increase in energy results in a drastic reduction of scale uncertainties at NNLO. The corrections become sizable only for large z , which can be attributed to soft gluon radiation, requiring resummation in this region.

Conclusions—We have performed the first NNLO QCD precision study of identified hadron production in (anti)neutrino-induced DIS processes. By comparing our newly derived theoretical predictions to legacy fixed-target data from the ABCMO Collaboration [8], we observe a considerably improved description of their kinematical shape upon inclusion of the NNLO corrections. We also demonstrate the high sensitivity of these data on the hadron FFs, thus calling for the inclusion of formerly ignored (anti)neutrino SIDIS data in future global determinations of FFs, and for future measurements at the CERN FPF.

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Data availability—The data that support the findings of this article are openly available [50]; embargo periods may apply.

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