

Toward precision helicity PDFs from global DIS and SIDIS fits with projected EIC measurements

Hamzeh Khanpour^{1,2,*} Maryam Soleymaninia^{2,†} Majid Azizi^{2,‡} Michael Klasen^{3,§}
Hadi Hashamipour^{4,||} Maral Salajegheh^{5,¶} and Ulf-G. Meißner^{5,6,7,**}

(HAPS Collaboration)

¹*AGH University, Faculty of Physics and Applied Computer Science,
Al. Mickiewicza 30, 30-055 Krakow, Poland*

²*School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM),
P.O.Box 19395-5531, Tehran, Iran*

³*Institut für Theoretische Physik, Universität Münster, Wilhelm-Klemm-Straße 9, 48149 Münster, Germany*

⁴*Istituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza, I-87036 Arcavacata di Rende, Cosenza, Italy*

⁵*Helmholtz-Institut für Strahlen-und Kernphysik and Bethe Center for Theoretical Physics,
Universität Bonn, D-53115 Bonn, Germany*

⁶*Institute for Advanced Simulation (IAS-4), Forschungszentrum Jülich, D-52425 Jülich, Germany*

⁷*Peng Huanwu Collaborative Center for Research and Education,
International Institute for Interdisciplinary and Frontiers, Beihang University, Beijing 100191, China*



(Received 23 February 2026; accepted 17 April 2026; published 5 June 2026)

We present HAPS-pPDF1.0, a new global determination of the helicity-dependent parton distribution functions (PDFs) of the proton, based on inclusive deep-inelastic scattering (DIS) and semi-inclusive DIS (SIDIS) data within a consistent next-to-leading order (NLO) QCD framework. In addition to existing measurements, we incorporate simulated pseudodata for the future Electron-Ion Collider (EIC), considering two beam-energy configurations, $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and $18 \times 275 \text{ GeV}^2$, corresponding to an extended kinematic reach down to $x \sim 10^{-5}$. We focus on longitudinal double-spin asymmetries A_1^h for charge-separated pion and kaon production in SIDIS off a longitudinally polarized proton target. These projected measurements significantly improve the flavor separation of sea-quark polarized PDFs ($\Delta\bar{u}$, $\Delta\bar{d}$, Δs) and reduce the uncertainties on both quark and gluon helicity distributions, with the largest impact at small x . Polarized PDFs are extracted using a neural-network parametrization and a Monte Carlo replica methodology to propagate experimental uncertainties, while theoretical constraints such as positivity are imposed during the fit. We demonstrate that the inclusion of EIC pseudodata leads to a substantially more precise determination of polarized PDFs, with the largest impact in the small- x region. The resulting polarized PDF sets are provided in the LHAPDF format.

DOI: [10.1103/wc54-mnfh](https://doi.org/10.1103/wc54-mnfh)

I. INTRODUCTION

A precise understanding of the internal spin structure of the proton remains a central goal of high-energy nuclear and particle physics. Within QCD, the proton spin can be decomposed into contributions from quark and gluon helicities and from partonic orbital angular momentum. The experimental discovery that quark spins account for only a limited fraction of the proton spin, first observed in polarized inclusive deep-inelastic scattering (DIS) measurements of the spin-dependent structure function g_1 by the European Muon Collaboration (EMC), initiated the so-called *proton spin puzzle* and motivated an extensive experimental and theoretical program over the past three decades [1–3].

*Contact author: Hamzeh.Khanpour@cern.ch

†Contact author: Maryam_Soleymaninia@ipm.ir

‡Contact author: Ma.Azizi@ipm.ir

§Contact author: Michael.Klasen@uni-muenster.de

||Contact author: Hadi.Hashamipour@Inf.infn.it

¶Contact author: Maral@hiskp.uni-bonn.de

**Contact author: Meissner@hiskp.uni-bonn.de

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

A key ingredient of this program is the determination of helicity-dependent (polarized, henceforth) parton distribution functions (PDFs), which quantify the difference between the densities of partons with spin aligned parallel and antiparallel to the longitudinal polarization of the parent proton. They are denoted as $\Delta q(x, Q^2)$ for quarks and $\Delta g(x, Q^2)$ for gluons, and their lowest moments are related to axial currents and to the spin decomposition of the proton [1,4,5]. In contrast to unpolarized PDFs, the polarized PDFs can only be constrained through measurements of spin-dependent observables, most notably inclusive DIS asymmetries and polarized structure functions, and semi-inclusive DIS (SIDIS) asymmetries in which identified hadrons are detected in the final state. In SIDIS, the sensitivity to individual flavors is enhanced by the use of fragmentation functions (FFs), which connect partonic flavors to charge-separated hadron yields.

Over the years, global QCD analyses of helicity PDFs have incorporated an increasingly diverse set of data, including inclusive DIS measurements from fixed-target experiments and, more recently, longitudinal spin asymmetries from polarized proton-proton collisions at RHIC, which provide essential constraints on the gluon helicity distribution $\Delta g(x, Q^2)$. Modern global determinations differ in their fitted datasets, perturbative accuracy, and methodology [6–31]. While inclusive DIS alone has limited sensitivity to the separation of quark and antiquark helicities and to Δg , the combined use of DIS, SIDIS, and (where included) proton-proton data enables a more differential flavor decomposition and a stronger handle on the gluon contribution. Recent years have also seen major progress in the theoretical description of polarized observables, including higher-order QCD corrections to inclusive DIS structure functions and to SIDIS structure functions [19–23], as well as improvements in PDF-fitting methodologies based on neural-network parametrization and Monte Carlo representations of uncertainties [30,31].

On the experimental side, the forthcoming Electron-Ion Collider (EIC) is expected to provide a qualitative leap in our knowledge of polarized PDFs [27,32,33], proton PDFs [34–36] and fragmentation functions (FFs) [37,38]. The EIC will collide longitudinally polarized lepton and proton beams with high luminosity and broad kinematic coverage in the proton momentum fraction x and the hard scale Q^2 . This will enable percent-level measurements of inclusive and semi-inclusive spin asymmetries over a range that significantly extends that of existing data (see, e.g., the EIC projections discussed in Refs. [5,27,32]). In particular, access to the small- x region is essential because present constraints on Δg and on sea-quark polarized PDFs remain comparatively weak there, and the corresponding contributions to the proton spin are therefore still uncertain.

A distinctive asset of the EIC program is the measurement of longitudinal double-spin asymmetries for charge-separated pion and kaon production in SIDIS process.

These observables provide enhanced sensitivity to the flavor structure of the polarized sea, including $\Delta \bar{u}$, $\Delta \bar{d}$, and Δs , through the combined dependence on helicity PDFs and FFs [27]. Quantifying the impact of these measurements requires realistic projections that account for detector acceptance, binning, and systematic effects. In this work we adopt the EIC pseudodata generation strategy developed in the ECCE studies of Ref. [39] and, specifically, we follow the detector-level pseudodata framework described in Ref. [40], which provides projected SIDIS asymmetries for charge-separated pions and kaons for two beam-energy configurations, $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and $18 \times 275 \text{ GeV}^2$, corresponding to an extended kinematic reach down to $x \sim 10^{-5}$.

The main aim of the present paper is to provide a new global determination of polarized PDFs based on a consistent next-to-leading order (NLO) QCD framework for polarized inclusive DIS, SIDIS, and DGLAP evolution, and to quantify the impact of EIC projected measurements. Our analysis closely follows the methodology developed in the MAP Collaboration determination of polarized PDFs, notably the use of a neural-network parametrization and a Monte Carlo replica representation of uncertainties, together with theoretical constraints such as positivity [30]. Building upon this baseline, we include EIC pseudodata for SIDIS longitudinal asymmetries in pion and kaon production, generated following Ref. [40], and we assess their impact on the precision of sea-quark flavor separation and on the small- x behavior of polarized PDFs.

Our baseline fit is intentionally restricted to polarized inclusive DIS and SIDIS data, so as to isolate in a controlled way the incremental impact of projected EIC SIDIS measurements within the same DIS/SIDIS framework. Hence, the polarized proton-proton measurements from RHIC, such as jet and W -boson asymmetry data, are not included here, although they provide important complementary constraints, especially on Δg and the sea-quark flavor decomposition, and their inclusion is left for a future extended global analysis.

The primary objectives of this study are: (i) to improve the determination of quark and gluon polarized PDFs by incorporating EIC pseudodata, with particular emphasis on the small- x region; and (ii) to strengthen the flavor separation of the polarized sea using charge-separated SIDIS measurements, thereby enabling tighter constraints on $\Delta \bar{u}$, $\Delta \bar{d}$, and the strange sector.

The structure of this paper is as follows. In Sec. II we summarize the theoretical framework used to compute DIS and SIDIS observables at NLO. The experimental input and the EIC pseudodatasets are described in Sec. III. The fitting methodology, including the neural-network parametrization and Monte Carlo replica strategy, is presented in this section as well. Results are discussed in Sec. IV, where we compare fits with and without EIC pseudodata and quantify the resulting improvements in flavor separation and small- x constraints. Finally, conclusions and an outlook for future research directions in this area are given in Sec. V.

II. THEORETICAL INPUT

In this work, the theoretical framework for polarized inclusive DIS and SIDIS observables is computed consistently at NLO in perturbative QCD within leading-twist collinear factorization. Polarized PDFs are parametrized at the input scale $Q_0^2 = 1 \text{ GeV}^2$ and evolved to higher scales using the NLO DGLAP evolution equations for spin-dependent parton distributions. All results are obtained in the $\overline{\text{MS}}$ renormalization and factorization schemes. We work in a zero-mass variable-flavor-number scheme (ZM-VFNS) and therefore neglect heavy-quark mass effects [41–47]; in practice, this choice is adequate for the kinematics of the datasets considered here (see also Ref. [30,48] for a recent discussion).

- (a) *Inclusive DIS*: The experimental information entering the fit is provided in terms of the spin-dependent structure function $g_1(x, Q^2)$ (or ratios involving g_1), which in leading-twist collinear factorization can be written as [9–13]

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 [\Delta q(x, Q^2) \otimes_x \Delta C_q(x, Q^2) + \Delta g(x, Q^2) \otimes_x \Delta C_g(x, Q^2)], \quad (1)$$

$$g_1^h(x, z, Q^2) = \frac{1}{2} \sum_q e_q^2 \left\{ [\Delta q(x, Q^2) \otimes_x \Delta C_{qq}(x, z, Q^2) + \Delta g(x, Q^2) \otimes_x \Delta C_{qg}(x, z, Q^2)] \otimes_z D_q^h(z, Q^2) + \Delta q(x, Q^2) \otimes_x \Delta C_{gq}(x, z, Q^2) \otimes_z D_g^h(z, Q^2) \right\}, \quad (3)$$

where z denotes the light-cone momentum fraction of the observed hadron with respect to the fragmenting parton, and $D_i^h(z, Q^2)$ are the corresponding FFs. The NLO massless SIDIS coefficient functions entering Eq. (3) are taken from Refs. [55,56]. The convolution acting on z is defined by

$$[f \otimes_z g](z) \equiv \int_z^1 \frac{d\zeta}{\zeta} f(\zeta) g\left(\frac{z}{\zeta}\right). \quad (4)$$

In the present QCD analysis, we use the MAPFF1.0 FFs for charged pions and kaons at the NLO accuracy [57,58].

- (c) *Spin asymmetries*: The longitudinal double-spin asymmetry for SIDIS is defined as

$$A_1^h(x, z, Q^2) = \frac{g_1^h(x, z, Q^2)}{F_1^h(x, z, Q^2)}, \quad (5)$$

where F_1^h is the corresponding unpolarized SIDIS structure function, built from the unpolarized PDFs and FFs [11],

where the sum runs over active quark and antiquark flavors, e_q is the electric charge of flavor q ; Δq and Δg denote quark and gluon polarized PDFs, and $\Delta C_{q,g}$ are the corresponding massless coefficient functions computed through the NLO in perturbative QCD [49]. The helicity-dependent splitting functions (polarized anomalous dimensions) entering DGLAP evolution at NLO follow Refs. [50,51]. Polarized splitting functions are also known beyond NLO, including the three-loop (NNLO) results [52–54]; however, in the present analysis we consistently use NLO evolution. The Mellin convolution acting on the Bjorken variable x is defined as

$$[f \otimes_x g](x) \equiv \int_x^1 \frac{dy}{y} f(y) g\left(\frac{x}{y}\right). \quad (2)$$

- (b) *Semi-inclusive DIS*: For SIDIS, we consider the longitudinally polarized structure function $g_1^h(x, z, Q^2)$ associated with the production of an identified hadron h in the current fragmentation region. At leading twist, it factorizes into polarized PDFs, perturbative coefficient functions, and unpolarized FFs as [11]

$$F_1^h(x, z, Q^2) = \frac{1}{2} \sum_q e_q^2 [q(x, Q^2) \otimes C_q(x, z, Q^2) \otimes D_q^h(z, Q^2) + g(x, Q^2) \otimes C_g(x, z, Q^2) \otimes D_g^h(z, Q^2)] \quad (6)$$

It is computed consistently by replacing Δf_i and ΔC in Eq. (3) with their unpolarized counterparts f_i and C . The unpolarized PDFs entering Eq. (6) are taken from the very recent NNPDF4.0 PDF set [59] parton set with perturbative charm. Analogous expressions are used for inclusive DIS observables (such as g_1/F_1) whenever experiments provide data in ratio form.

- (d) *Kinematic cuts and nonperturbative corrections*: To limit the impact of kinematic regions where non-perturbative corrections may become more important, we impose the cuts $Q^2 > 1 \text{ GeV}^2$ and $W^2 = Q^2(1-x)/x > 4 \text{ GeV}^2$ on all fitted data points. These cuts reduce, but do not eliminate, sensitivity to target-mass corrections (TMCs) [26,60,61], higher-twist contributions (HT) [26,28,62], and nuclear effects in deuteron data. Accordingly, we do not include TMC,

HT, or deuteron nuclear corrections in the present analysis, and our results should be interpreted as a leading-twist NLO determination within this approximation. The practical justification for this choice is not that such effects are absent, but rather that, within the scope and precision of the present study, a leading-twist treatment provides an adequate description of the fitted data. A dedicated assessment of these non-perturbative corrections is left for future work.

- (e) *Implementation:* All the expressions for the coefficient and splitting functions are implemented in the publicly available code APFEL++ [63,64], which one can use to compute the theoretical predictions that enter the fit. All theoretical calculations—PDF evolution, polarized inclusive DIS and SIDIS structure functions, and the corresponding spin asymmetries—are performed with the MONTBLANC [58,65] and DENALI [66] frameworks, which enables efficient replica-by-replica evaluations and a flexible interface to FF-dependent SIDIS observables, including the incorporation of EIC pseudodata. The strong coupling in this analysis is fixed to $\alpha_s(M_Z) = 0.118$ [67], and the charm and bottom quark masses are set to $m_c = 1.51$ GeV, and $m_b = 4.92$ GeV [30].

III. DATASETS

In this section we summarize the experimental datasets included in our global QCD analysis. We first describe the world polarized inclusive DIS and SIDIS measurements that define our pDIS+SIDIS base fit, and we then introduce the projected EIC SIDIS pseudodata used to assess the impact of future EIC measurements.

A. Spin-dependent observables in polarized inclusive DIS and SIDIS

This analysis is based on a comprehensive set of measurements of spin-dependent observables in polarized inclusive DIS and SIDIS off longitudinally polarized nucleon targets. For inclusive DIS, we consider data from the EMC [3], SMC [68], and COMPASS [69,70] experiments at CERN; from the SLAC experiments E142 [71], E143 [72], E154 [73], and E155 [74]; from HERMES at DESY [75,76]; and from Jefferson Lab measurements, including Hall A [77–79] and CLAS [80]. These experiments provide measurements of the polarized structure function g_1 , or of ratios such as g_1/F_1 reconstructed from longitudinal double-spin asymmetries (see, e.g., Sec. II. 1 of the NNPDFpol1.0 paper [81], for details). The target in the aforementioned polarized DIS datasets is a proton, deuteron, or neutron. We note that the present baseline dataset does not include the Jefferson Lab EG1b [82,83] and SANE [84] measurements. Their omission reflects the deliberately restricted DIS + SIDIS input adopted in this work and is consistent with our leading-twist NLO setup, in

which TMCs and HT corrections are not included explicitly. A dedicated study including these datasets together with a more complete treatment of low- W^2 effects is left for future work.

For polarized SIDIS, we include charge-separated hadron production data from COMPASS [85] and HERMES [86]. Both experiments deliver measurements of the polarized semi-inclusive structure function g_1^h normalized to its unpolarized counterpart F_1^h , for identified hadrons $h = \pi^+, \pi^-, K^+, K^-$ and for proton and deuteron targets. These SIDIS measurements provide enhanced sensitivity to the flavor decomposition of polarized PDFs, and in particular help constrain the polarized sea-quark distributions $\Delta\bar{u}$, $\Delta\bar{d}$, and Δs through their dependence on FFs.

The kinematic coverage of the fitted data spans approximately $0.005 \lesssim x \lesssim 0.5$ and $1 \lesssim Q^2 \lesssim 100$ GeV² for the fixed-target measurements, with additional coverage at larger x from Jefferson Lab. To ensure the validity of the leading-twist perturbative framework, we impose kinematic cuts on the photon virtuality and on the invariant mass of the hadronic final state,

$$Q^2 \geq Q_{\text{cut}}^2, \quad W^2 \equiv Q^2 \left(\frac{1-x}{x} \right) \geq W_{\text{cut}}^2, \quad (7)$$

with the default choice $Q_{\text{cut}}^2 = 1$ GeV² and $W_{\text{cut}}^2 = 4$ GeV² [16]. The cut on Q^2 suppresses regions where the strong coupling becomes large and perturbative predictions are less reliable, while the cut on W^2 reduces sensitivity to power-suppressed effects beyond leading twist. We note that this W^2 cut is looser than the default choice adopted in some recent analyses (e.g. $W_{\text{cut}}^2 = 6.25$ GeV² in Ref. [30]), and therefore retains additional data points at lower W^2 that would be excluded by a more restrictive cut. Reference [16] summarized the theoretical assumptions implied by this choice, and in Sec. IV we assess the robustness of the fit quality under these kinematic selections.

Statistical and systematic uncertainties are provided separately for most measurements, while detailed information on correlated systematics is available only for a subset of datasets. In line with the common treatment adopted in global QCD analyses, whenever an experimental covariance matrix or correlated normalization uncertainties are provided (notably for selected polarized DIS and polarized SIDIS datasets), we incorporate the corresponding correlation information. For measurements where no correlation information is available, systematic and statistical uncertainties are added in quadrature [30].

B. EIC SIDIS pseudodata

To enhance the flavor separation of sea polarized PDFs and extend the kinematic reach toward small x , we incorporate projected EIC measurements in polarized

SIDIS. We adopt the EIC pseudodata strategy developed within the ECCE studies of Ref. [39] and, in particular, we follow the detector-level framework presented in Ref. [40]. We consider charge-separated hadron production π^+ , π^- , K^+ and K^- in longitudinally polarized electron-proton scattering for two beam-energy configurations, $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and $18 \times 275 \text{ GeV}^2$, which provide complementary sensitivity across (x, Q^2) and extend the SIDIS reach down to very small x .

In the ECCE simulation setup of Ref. [40], events are selected in the DIS regime with $Q^2 > 1 \text{ GeV}^2$, a photon-nucleon invariant mass cut $W^2 > 10 \text{ GeV}^2$ to suppress the resonance region, and an inelasticity selection $0.01 < y < 0.95$ to control radiative effects and ensure robust reconstruction. Identified hadrons are required to satisfy $z > 0.01$ (to limit target-fragmentation contributions), and no explicit rapidity requirement is imposed. Statistical uncertainties are scaled to an integrated luminosity of 10 fb^{-1} , assuming realistic longitudinal polarization of 70% for both beams; in addition, an overall $\sim 2\%$ polarization (scale) uncertainty is quoted as a separate normalization component [40]. The kinematic binning in (x_B, Q^2, z) used for the projections follows Ref. [40].

For the purposes of this global analysis, we construct EIC pseudodata for the longitudinal double-spin asymmetries $A_1^h(x, z, Q^2)$ by starting from NLO theory predictions computed with the MONTBLANC [58,65] and DENALI [66] frameworks in the same SIDIS kinematics, and then applying a smearing procedure consistent with the projected uncertainties. In constructing these central NLO predictions, we use the helicity PDFs from our pDIS +SIDIS base fit, together with the NNPDF4.0 NLO unpolarized PDFs [59] (with perturbative charm) and the MAPFF1.0 NLO FFs for charged pions and kaons [57,58].

Concretely, for each kinematic bin i we take the NLO prediction $A_{1,i}^{h,\text{th}}$ and define a pseudomeasurement as

$$A_{1,i}^{h,\text{(EIC)}} = A_{1,i}^{h,\text{th}} + r_i \sigma_i^{\text{unc}} + \delta_{\text{pol}} A_{1,i}^{h,\text{th}}, \quad (8)$$

where r_i is a standard normal variate modeling an uncorrelated bin-by-bin fluctuation, and σ_i^{unc} is the absolute projected uncertainty for that bin (constructed from the relative uncertainty quoted by the ECCE projections). The parameter δ_{pol} is a correlated systematic shift with width 2%, applied coherently to all bins to emulate the overall beam-polarization (scale) uncertainty discussed in Ref. [40]. In our numerical implementation, we additionally enforce sign stability of the smeared asymmetries in each bin by resampling the uncorrelated fluctuation if a sign flip occurs; this avoids unphysical pseudomeasurements in bins where A_1^h is small compared to its uncertainty.

In Fig. 1, we illustrate the impact of the projected EIC SIDIS ($5 \times 41 \text{ GeV}^2$) measurements for charged pions and kaons. The upper panels show representative $A_{1p}^h(x)$ comparisons with the existing fixed-target data, where the EIC points are restricted to the slice $0.30 < z < 0.60$ and $1.0 < Q^2 < 20.0 \text{ GeV}^2$ in order to provide a readable observable-level comparison. The lower panels instead show the broader EIC coverage for $0.10 < z < 0.90$ and $Q^2 > 1.0 \text{ GeV}^2$, thereby emphasizing the substantial extension of the SIDIS kinematic reach toward lower x and over a wider Q^2 range. The figure illustrates both the continuity of the projected EIC pseudodata with the existing fixed-target measurements in the overlap region and, more importantly, the substantial extension of the accessible SIDIS phase space toward lower x and over a wider Q^2 lever arm.

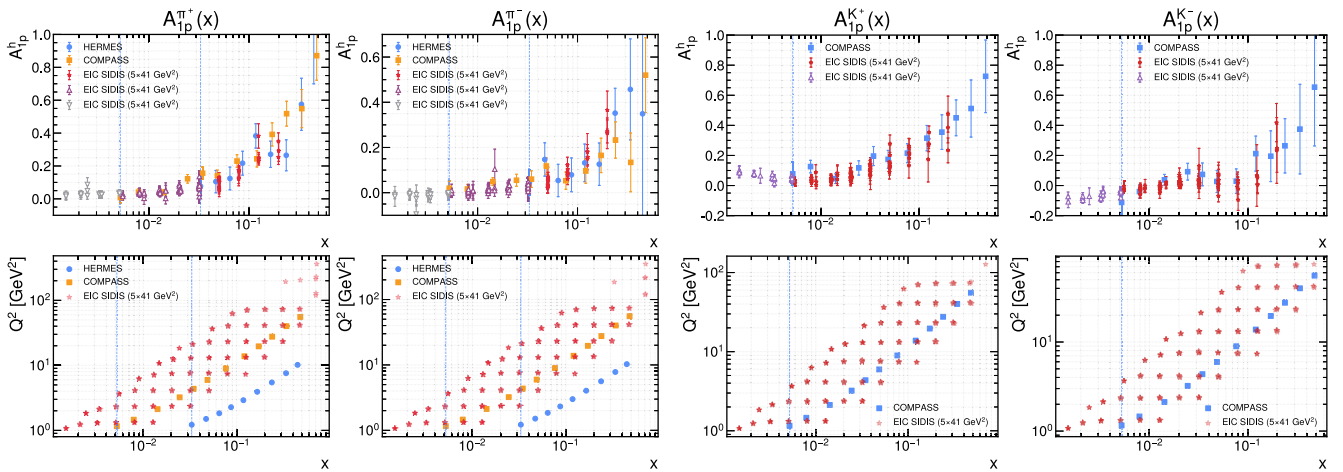


FIG. 1. Comparison of representative proton SIDIS asymmetries and kinematic coverage for charged-pion (left) and charged-kaon (right) production. In each case, the upper panels display representative $A_{1p}^h(x)$ comparisons in a restricted EIC kinematic slice, $0.30 < z < 0.60$ and $1.0 < Q^2 < 20.0 \text{ GeV}^2$, chosen to provide a clear observable-level comparison in a region relevant to the existing fixed-target measurements. The lower panels show the corresponding broader EIC coverage for $0.10 < z < 0.90$ and $Q^2 > 1.0 \text{ GeV}^2$.

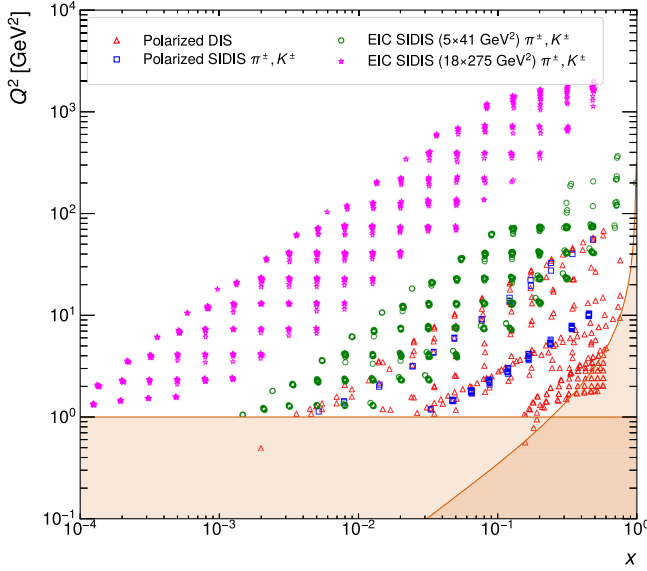


FIG. 2. Kinematic coverage in the (x, Q^2) plane for the datasets included in this analysis: polarized inclusive DIS (triangles) and polarized SIDIS π^+ , π^- , K^+ and K^- from HERMES and COMPASS (squares), together with projected EIC SIDIS asymmetries for π^+ , π^- , K^+ and K^- at $5 \times 41 \text{ GeV}^2$ (circles) and $18 \times 275 \text{ GeV}^2$ (stars). The shaded region corresponds to the excluded domain imposed by the cuts $Q^2 > 1 \text{ GeV}^2$ and $W^2 > 4 \text{ GeV}^2$; the horizontal line indicates the Q^2 threshold, and the curved line indicates the W^2 boundary.

The projected EIC SIDIS asymmetries provide strong new constraints on polarized PDFs down to $x \sim 10^{-5}$. At moderate and large x , they sharpen the flavor separation through hadron tagging and its sensitivity to FFs, while at small x they significantly improve the reach and precision of the extracted sea-quark helicity distributions and, indirectly, the gluon helicity distribution through the global fit interplay.

Figure 2 shows the kinematic coverage in the (x, Q^2) plane for the polarized inclusive DIS data, the polarized SIDIS measurements from HERMES and COMPASS, and the projected EIC SIDIS asymmetries for identified π^+ , π^- , K^+ and K^- production at the $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and $E_e \times E_p = 18 \times 275 \text{ GeV}^2$ beam-energy configurations. As discussed above, a common set of DIS cuts is imposed throughout the analysis, $Q^2 > 1 \text{ GeV}^2$ and $W^2 > 4 \text{ GeV}^2$, with the excluded regions indicated by the shaded area (the Q^2 cut) and the curved boundary (the W^2 cut). As can be seen from Fig. 2, while the existing polarized DIS and SIDIS data primarily constrain the moderate-to-large x region at relatively low-to-intermediate Q^2 , the EIC projections provide a substantially extended lever arm in both x and Q^2 , including dense coverage at fixed x over multiple Q^2 values. This enhanced lever arm is particularly valuable for improving sensitivity to the

gluon and sea-quark polarized distributions through QCD evolution.

We perform three QCD fits in order to quantify the impact of EIC projected measurements. The baseline determination, denoted as the pDIS+SIDIS base fit, includes the available polarized DIS and SIDIS datasets described in Sec. III, namely inclusive polarized DIS measurements from EMC, SMC, the SLAC experiments E142, E143, E154, and E155, HERMES, COMPASS, and Jefferson Lab (Hall A and CLAS), together with charge-separated SIDIS $\pi^\pm$ and $K^\pm$ measurements from HERMES and COMPASS. Starting from this baseline, we then include the EIC projected SIDIS pseudodata at $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and at $18 \times 275 \text{ GeV}^2$, producing the two additional fits pDIS + SIDIS + EIC(5×41) and pDIS + SIDIS + EIC(18×275). We treat the two EIC energy configurations separately, which allows us to disentangle their individual impact, since the two setups probe complementary kinematic regions. The lower-energy configuration provides an important benchmark for the first-stage EIC sensitivity, while the higher-energy configuration primarily enlarges the (x, Q^2) lever arm and extends the reach further into the small- x region.

A detailed summary of the experimental datasets entering the pDIS+SIDIS base fit, together with the corresponding number of data points N_{dat} and their contribution to the goodness-of-fit χ^2/N_{dat} evaluated at the best-fit point, is provided in Table I.

C. Fitting methodology

The helicity-dependent PDFs are extracted using a Monte Carlo (MC) replica methodology combined with a neural-network (NN) parametrization, closely following the strategy adopted in MAPPDFp011.0 determinations [30]. Experimental uncertainties (including those of the EIC pseudodata) are propagated to the fitted polarized PDFs by generating an ensemble of statistically equivalent replicas of the input dataset. Whenever an experimental covariance matrix or correlated normalization uncertainties are available, the corresponding correlations are included; otherwise statistical and systematic uncertainties are added in quadrature, in line with the treatment described in Sec. III.

For each replica k , a fluctuated data vector may be written schematically as

$$y^{(k)} = y + Lr^{(k)}, \quad r^{(k)} \sim \mathcal{N}(0, I), \quad (9)$$

where $C = LL^T$ is the total covariance matrix.

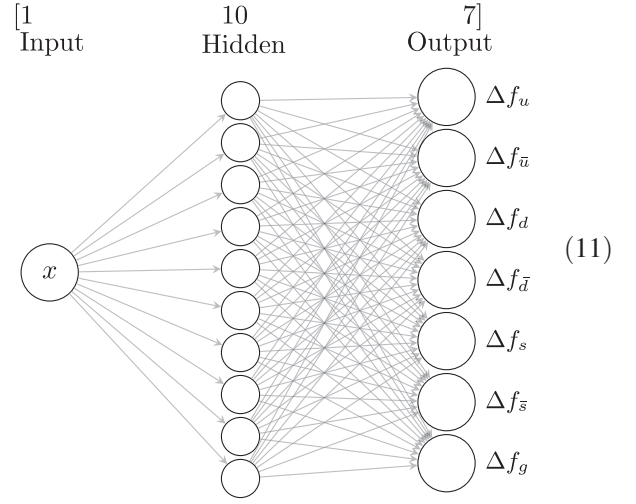
- (a) *Parametrization and flavor basis:* At the input scale $Q_0 = 1 \text{ GeV}$, polarized PDFs are parametrized by a single feed-forward NN implemented in the MONTBLANC framework [58,65]. To construct the independent PDF basis

TABLE I. Summary of the polarized DIS and SIDIS datasets included in the pDIS+SIDIS base fit. For each experiment and observable we report the number of data points, N_{dat} , and the corresponding contribution to the goodness-of-fit, χ^2/N_{dat} , evaluated at the best-fit point.

Experiment	Ref.	Observable	N_{dat}	χ^2/N_{dat}
COMPASS	[85]	$A_1^p(K^-)$	12	0.727
COMPASS	[85]	$A_1^p(K^+)$	12	0.719
COMPASS	[85]	$A_1^p(\pi^-)$	12	1.201
COMPASS	[85]	$A_1^p(\pi^+)$	12	2.500
COMPASS	[85]	$A_1^d(K^-)$	10	0.891
COMPASS	[85]	$A_1^d(K^+)$	10	0.321
COMPASS	[85]	$A_1^d(\pi^-)$	10	0.448
COMPASS	[85]	$A_1^d(\pi^+)$	10	0.320
HERMES	[86]	$A_1^d(K^-)$	9	0.612
HERMES	[86]	$A_1^d(K^+)$	9	1.459
HERMES	[86]	$A_1^d(\pi^-)$	9	1.265
HERMES	[86]	$A_1^d(\pi^+)$	9	0.334
HERMES	[86]	$A_1^p(\pi^-)$	9	1.103
HERMES	[86]	$A_1^p(\pi^+)$	9	1.889
E142	[71]	g_1^n	8	0.714
E143	[72]	g_1^d	27	1.315
E143	[72]	g_1^p	27	0.902
E154	[73]	g_1^n	11	0.324
E155	[74]	g_1^p/F_1^p	24	0.630
E155	[74]	g_1^n/F_1^n	24	0.644
EMC	[3]	g_1^p	10	0.639
JLab E06-014	[77]	g_1^n/F_1^n	4	2.010
JLab E97-103	[78]	g_1^n	2	0.414
JLab E99-117	[79]	g_1^n/F_1^n	1	0.006
JLab EG1-DVCS	[80]	g_1^d/F_1^d	19	0.162
JLab EG1-DVCS	[80]	g_1^p/F_1^p	21	0.132
SMC	[68]	g_1^d	12	1.315
SMC	[68]	g_1^p	12	0.373
COMPASS	[70]	g_1^d	15	0.331
COMPASS	[69]	g_1^p	17	0.455
HERMES	[75]	g_1^n	9	0.226
HERMES	[76]	g_1^d	15	1.197
HERMES	[76]	g_1^p	15	1.005
Total			415	0.727

$$\{\Delta f_u, \Delta f_{\bar{u}}, \Delta f_d, \Delta f_{\bar{d}}, \Delta f_s, \Delta f_{\bar{s}}, \Delta f_g\}, \quad (10)$$

in the way explained in the next subsection, i.e. allowing Δf_s and $\Delta f_{\bar{s}}$ to be fitted independently, the run configuration adopts one input node (x), a single hidden layer with 10 nodes, and 7 output nodes,



(b) *Positivity constraints:* The fit enforces the standard LO-motivated positivity bound [30,87],

$$|\Delta f_i(x, Q^2)| \leq f_i(x, Q^2), \quad (12)$$

using an unpolarized PDF ensemble to provide the x -dependent upper limit. In the default configuration, positivity is implemented by construction at the parametrization scale through

$$\Delta f_i^{(k)}(x, Q_0^2) = [2\text{NN}_i(x) - 1]f_i^{(r_k)}(x, Q_0^2), \quad i = g, u, \bar{u}, d, \bar{d}, s, \bar{s}. \quad (13)$$

where $f_i^{(r_k)}$ denotes a replica of the chosen unpolarized PDF set. With the replica policy used here, the unpolarized-PDF replica index r_k is selected randomly for each fitted polarized replica, thereby propagating the uncertainty of the positivity bound into the polarized PDFs. An alternative (looser) option, available in the framework, is to impose the positivity bound using the unpolarized central set inflated by a multiplicative factor; this option is disabled in the present analysis.

(c) *Theory settings and external inputs:* All theory predictions entering the fit are computed consistently at NLO in QCD. Polarized PDFs are evolved from Q_0 using NLO DGLAP evolution in the $\overline{\text{MS}}$ scheme. The strong coupling is fixed to $\alpha_s(M_Z) = 0.118$ and the heavy-flavor thresholds are set to $m_c = 1.51$ GeV and $m_b = 4.92$ GeV [30]. Unpolarized PDFs required for the positivity bounds and for unpolarized denominators are taken from the NNPDF4.0 NLO set with perturbative charm [59]. For SIDIS observables, fragmentation functions are taken from the MAPFF1.0 NLO sets for charged pions and kaons [57,58]. For each Monte Carlo replica of the fit, replicas of the

external unpolarized PDF and FF sets are selected accordingly, and hence, that the corresponding uncertainties are consistently propagated to the theory predictions and, ultimately, to the fitted polarized PDFs. Since NNPDF4.0 and MAPFF1.0 are themselves neural-network Monte Carlo determinations, this procedure preserves methodological consistency across inputs and ensures a faithful propagation of external-set uncertainties in the QCD fit.

- (d) *Optimization, cross-validation, and replica selection:* For each data replica k , the NN parameters are determined by minimizing the (correlated) χ^2 function

$$\chi_k^2 = (\mathbf{T}[\Delta f^{(k)}] - \mathbf{y}^{(k)})^T \mathbf{C}^{-1} (\mathbf{T}[\Delta f^{(k)}] - \mathbf{y}^{(k)}), \quad (14)$$

where $\mathbf{T}$ denotes the vector of theory predictions for all fitted points. The minimization is performed with the Levenberg-Marquardt algorithm as implemented in CERES-SOLVER [88], with a maximum number of iterations. To mitigate overfitting, cross-validation is applied using an 80%/20% training/validation split for datasets with more than 10 points, while smaller datasets are used fully for training. Finally, replicas that fail to converge or yield an anomalously poor description of the data are discarded according to the configured χ^2 tolerance ($\chi_{\text{Max}}^2 = 3.0$). The resulting ensemble $\{\Delta f^{(k)}(x, Q^2)\}_{k=1}^{N_{\text{rep}}}$ provides a Monte Carlo representation of the probability distribution in functional space, from which central values and uncertainties are computed as replica statistics.

All steps of the analysis—PDF evolution, computation of polarized inclusive DIS and polarized SIDIS observables, replica generation, and minimization—are performed within the MONTBLANC [58,65] and DENALI [66] fitting frameworks.

IV. RESULTS

In this section we present the results of our NLO global determination of helicity-dependent PDFs and quantify the impact of the projected EIC SIDIS measurements. We consider three fit scenarios throughout: (i) the pDIS+SIDIS base fit to existing world data (world polarized DIS and SIDIS data only); (ii) pDIS + SIDIS + EIC(5×41 GeV²) including EIC SIDIS pseudodata at $E_e \times E_p = 5 \times 41$ GeV²; and (iii) pDIS + SIDIS + EIC(18×275 GeV²) including EIC SIDIS pseudodata at $E_e \times E_p = 18 \times 275$ GeV². The present analysis should therefore be interpreted as a DIS+SIDIS baseline to EIC-SIDIS impact study, and the inclusion of polarized RHIC proton-proton data, which provide important complementary constraints on Δg and on sea-quark flavor separation, is deferred to future work.

A. Fit quality

We quantify the fit quality by evaluating the χ^2 per data point for each fitted dataset at the best-fit point of the corresponding Monte Carlo determination. A detailed breakdown of the polarized DIS and SIDIS measurements entering the pDIS+SIDIS base fit is provided in Table I, where we report the number of data points N_{dat} and the corresponding χ^2/N_{dat} contribution for each experiment and observable. The total fit quality for the baseline determination is $\chi^2/N_{\text{dat}} = 0.727$ for $N_{\text{dat}} = 415$. At the level of individual subsets, the description is generally very good: the majority of subsets have $\chi^2/N_{\text{dat}} < 1$ (and many well below unity), while a small number exhibit larger values. The most pronounced tensions are observed for the COMPASS proton π^+ asymmetry and the JLab E06-014 subset (see Table I), with a few additional subsets showing mild tension at the level $\chi^2/N_{\text{dat}} \sim 1.2$ – 1.5 . Experimental correlations are included whenever an experimental covariance matrix or correlated normalization uncertainties are provided; otherwise statistical and systematic uncertainties are added in quadrature. Our baseline kinematic selections are $Q^2 \geq 1$ GeV² and $W^2 \geq 4$ GeV². The cut on Q^2 suppresses regions where the strong coupling becomes large and fixed-order perturbative predictions are less reliable, while the cut on W^2 reduces sensitivity to power-suppressed effects beyond leading twist. This W^2 cut is looser than that adopted in some recent analyses (including the MAP study, which uses a tighter W^2 cut and notes that some Jefferson Lab subsets are excluded by its kinematic selections), and therefore retains additional points at lower W^2 that would be removed by more restrictive choices.

B. z_{min} dependence and χ^2 stability of the global fit

In this section, we quantify the dependence on z_{min} by scanning the goodness-of-fit as a function of the minimum z requirement for the EIC pseudodata. The corresponding χ^2 profiles are shown in Fig. 3 for the two EIC energy configurations. For both 5×41 GeV² and 18×275 GeV², the total χ^2 exhibits a smooth dependence on z_{min} , with a mild preference for tighter z cuts. Importantly, the partial contributions from polarized DIS and SIDIS remain stable across the scan, indicating that the overall description of the existing world data is not driven by the specific z_{min} choice adopted for the EIC pseudodata. Based on these trends, and to provide a conservative baseline against potential low- z hadronization effects, we take $z_{\text{min}} > 0.2$ as default, while also reporting results for $z_{\text{min}} > 0.1$ to illustrate the sensitivity of the conclusions to this selection.

A further consistency check is provided by the dataset-by-dataset comparison in Fig. 4, where we display the χ^2 contributions of each fitted subset when the EIC pseudodata are excluded (blue) or included (red). Results are displayed for the default $z_{\text{min}} > 0.2$ selection. The overall pattern is that adding EIC pseudodata does not deteriorate

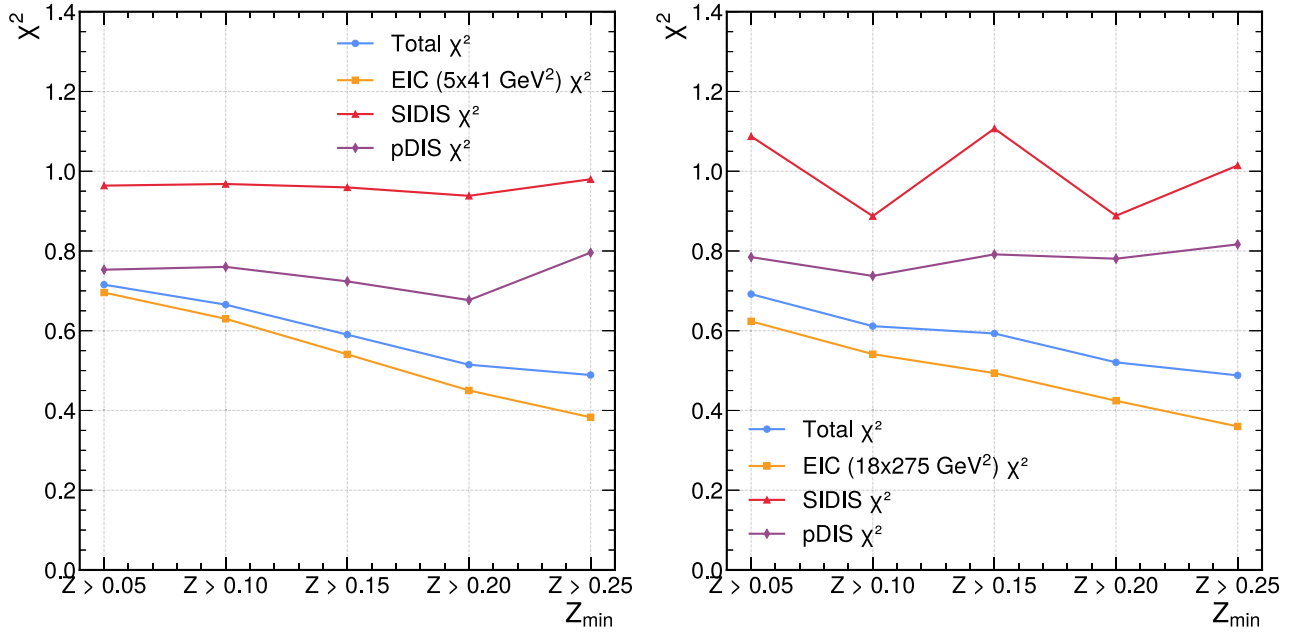


FIG. 3. Impact of different z -cut thresholds on the quality of the global fit. The left (right) panel shows the χ^2 values for the total dataset and its individual components, polarized DIS (pDIS), SIDIS, and EIC pseudodata, as a function of the minimum z cut, separately for the 5×41 GeV² and (18×275) GeV² configurations.

the description of the existing world measurements: changes in the χ^2 contributions are modest and fluctuate around the baseline values, as expected when additional constraints are introduced primarily in kinematic regions not covered by current data.

C. Impact of EIC pseudodata on helicity PDFs

Since the projected EIC pseudodata considered in this work correspond exclusively to semi-inclusive DIS measurements with identified hadrons π^+ , π^- , K^+ , and K^- in the final state, their primary impact is expected on the flavor-separated sea-quark helicity distributions. In particular, charge-separated pion asymmetries provide strong constraints on the light antiquark distributions $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$, while kaon production offers a unique sensitivity to the polarized strange-quark sector, $\Delta s(x)$ and $\Delta\bar{s}(x)$. The valence polarized PDFs are already relatively well constrained by existing inclusive DIS data, and the gluon helicity distribution is affected only indirectly through NLO QCD evolution and PDF correlations. We first emphasize a sea-quark-focused presentation, showing $\Delta\bar{u}(x)$, $\Delta d(x)$, and $\Delta s(x)$ [or alternatively $\Delta\bar{s}(x)$], which provides the cleanest demonstration of the enhanced sensitivity to the polarized sea afforded by pion and kaon SIDIS measurements at the EIC. As a complementary perspective, one also highlight the role of EIC data in enabling full flavor separation by presenting $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ together with the corresponding valence distributions $\Delta u(x)$ and $\Delta d(x)$. Finally, given the unique role of kaon production, a dedicated focus on the strange sector

can be achieved by showing $\Delta s(x)$, $\Delta\bar{s}(x)$, and the truncated quark-singlet helicity $\Delta\Sigma(Q^2)$, directly addressing the long-standing question of the polarized strange-quark contribution to the proton spin.

1. EIC at 5×41 GeV²

We first assess the impact of adding the 5×41 GeV² EIC pseudodata. Figure 5 compares representative polarized PDFs at $Q = 10$ GeV obtained with two alternative selections, $z_{\min} > 0.1$ and $z_{\min} > 0.2$. We adopt, however, a minimal and representative set of distributions that best illustrate the physics impact of the EIC SIDIS pseudodata, namely the sea-quark-focused presentation, by showing $\Delta\bar{u}(x)$, $\Delta d(x)$, and $\Delta s(x)$ [or alternatively $\Delta\bar{s}(x)$]. While the central values are broadly consistent between the two choices, the more conservative cut $z_{\min} > 0.2$ typically leads to a tighter and smoother determination in the kinematic region populated most densely by the EIC pseudodata, and it is therefore adopted as the default. The fact that the $z_{\min} > 0.2$ selection can yield smaller PDF uncertainties than the looser cut $z_{\min} > 0.1$ reflects the fact that, in a global SIDIS fit, more pseudodata points do not automatically imply a stronger effective constraint. The lower- z region is theoretically less clean and more sensitive to residual hadronization effects and to the present level of fragmentation function uncertainties, since SIDIS asymmetries depend explicitly on both helicity PDFs and FFs. Consequently, the additional bins included for $z_{\min} > 0.1$ may carry weaker or less stable constraining power, which can broaden the spread of fitted replicas.

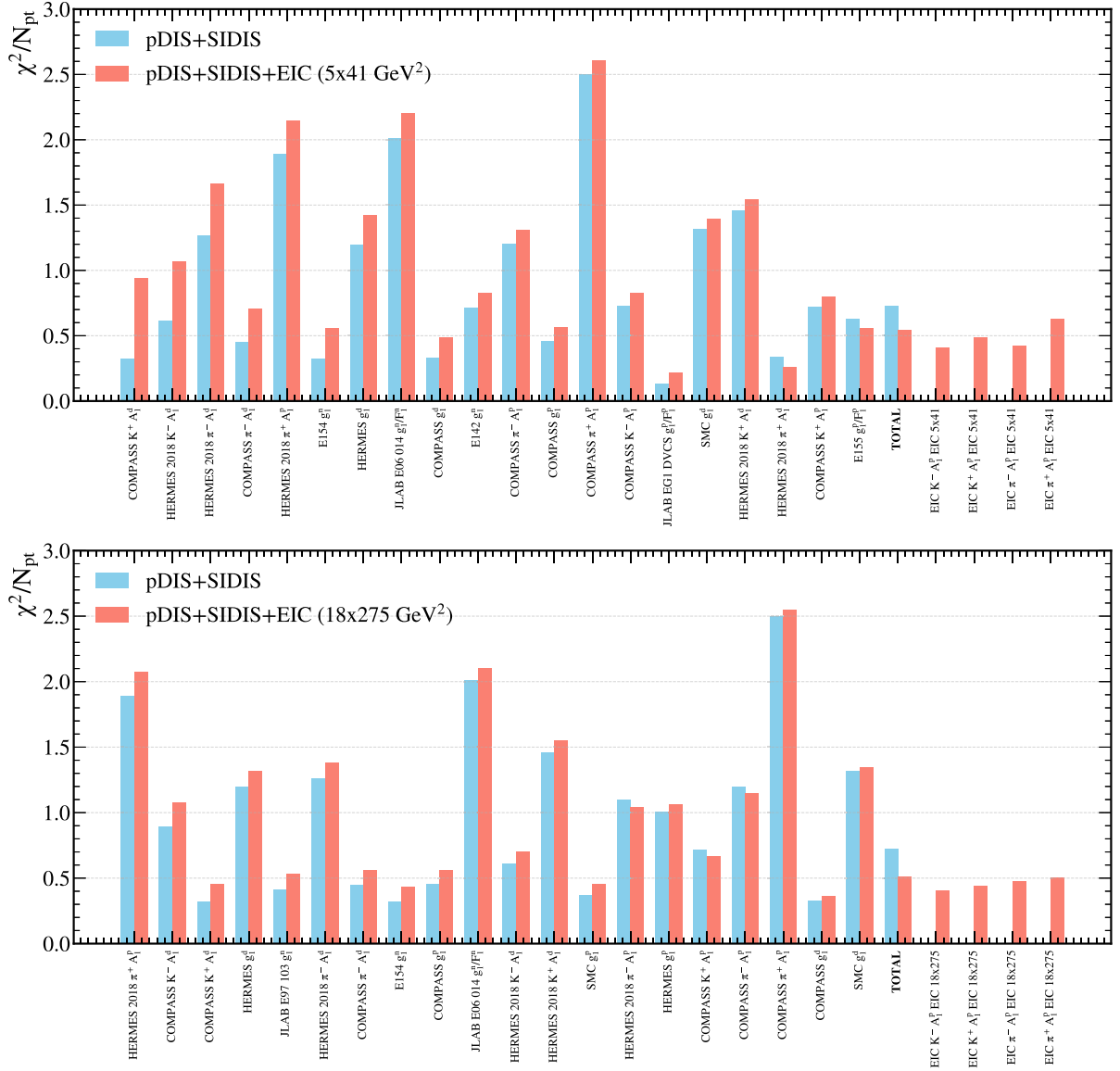


FIG. 4. Comparison of χ^2 contributions for the fitted data subsets in the pDIS+SIDIS base fit (blue) and in the EIC-augmented fits (red), shown separately for the $5 \times 41 \text{ GeV}^2$ (upper) and $18 \times 275 \text{ GeV}^2$ (lower) EIC configurations. Results are displayed for the default $z_{\min} > 0.2$ selection.

As can be seen from Fig. 5, the most visible impact is observed for sea-quark distributions that are primarily constrained by SIDIS, and for the gluon distribution at small x , reflecting the combination of SIDIS flavor tagging and the extended evolution lever arm provided by EIC kinematics.

From a physics standpoint, these trends follow from two EIC features. The extended (x, Q^2) lever arm improves sensitivity to $\Delta g(x, Q^2)$ through scaling violations in NLO evolution, while charge separation in SIDIS improves the disentangling of sea flavor: pion channels are especially effective for $\Delta \bar{u}$ and $\Delta \bar{d}$, whereas kaon channels enhance sensitivity to Δs (and $\Delta \bar{s}$), subject to the FF dependence.

A more systematic propagation of FF uncertainties is therefore a natural direction for future work.

2. EIC at $18 \times 275 \text{ GeV}^2$

We next include the higher-energy $18 \times 275 \text{ GeV}^2$ EIC pseudodata. Relative to $5 \times 41 \text{ GeV}^2$, this configuration provides a substantially extended reach in x and a broader Q^2 span, strengthening constraints in the small- x region where current data provide limited direct sensitivity. The dependence on the $z_{\min}$ selection is illustrated in Fig. 6, again showing that the $z_{\min} > 0.2$ choice yields a stable and typically tighter determination.

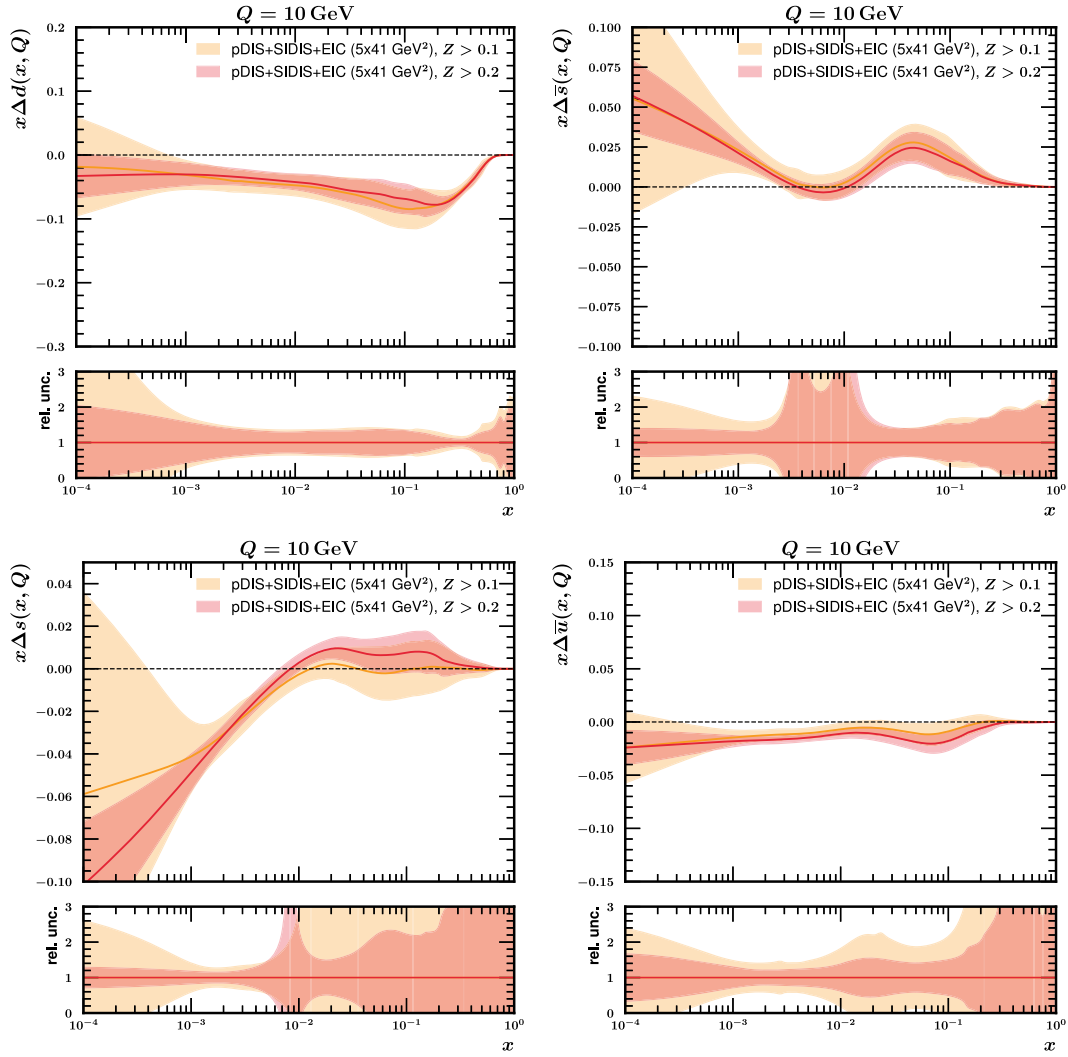


FIG. 5. Comparison of polarized PDFs at $Q = 10$ GeV obtained with EIC pseudodata at 5×41 GeV² using two minimum- z selections, $z_{\min} > 0.1$ and $z_{\min} > 0.2$.

D. Comparison with pDIS+SIDIS base fit

To emphasize the net impact of the default EIC setup, Fig. 7 compares the pDIS+SIDIS base fit with the EIC-augmented fit using $z_{\min} > 0.2$. The overall trend is that EIC pseudodata reduce the PDF uncertainties in the regions where EIC data provide dense coverage in (x, Q^2) , thereby reducing extrapolation uncertainties associated with the previously weakly constrained small- x domain. This effect is particularly evident for SIDIS-driven sea-quark combinations and for the gluon helicity distribution, which benefits from the extended scaling-violation information at small x .

E. Comparison with recent global determinations

Finally, we compare our default EIC-augmented PDFs ($z_{\min} > 0.2$) to recent NLO global determinations. Figure 8 compares our results to the MAPPDFpol10NLO set [30].

Overall agreement in the well-constrained region provides a nontrivial validation of the baseline methodology and dataset treatment. Differences are expected given the different analysis choices and, in particular, the inclusion in our study of projected EIC pseudodata that enhance constraints at small x .

A complementary comparison to the NNPDFpol2.0 NLO set [31] is shown in Fig. 9. While the scope and dataset choices differ between analyses, qualitative consistency in the data-constrained region is expected. In our analysis, the inclusion of charge-identified SIDIS asymmetries for π^+ , π^- , K^+ and K^- from HERMES and COMPASS, supplemented by EIC SIDIS projections, provides direct sensitivity to flavor separation in the light sea and, crucially, to strangeness through the kaon channels. This additional information is reflected in the significantly reduced uncertainty bands at medium-to-small x and in shape differences that are most visible for the strange

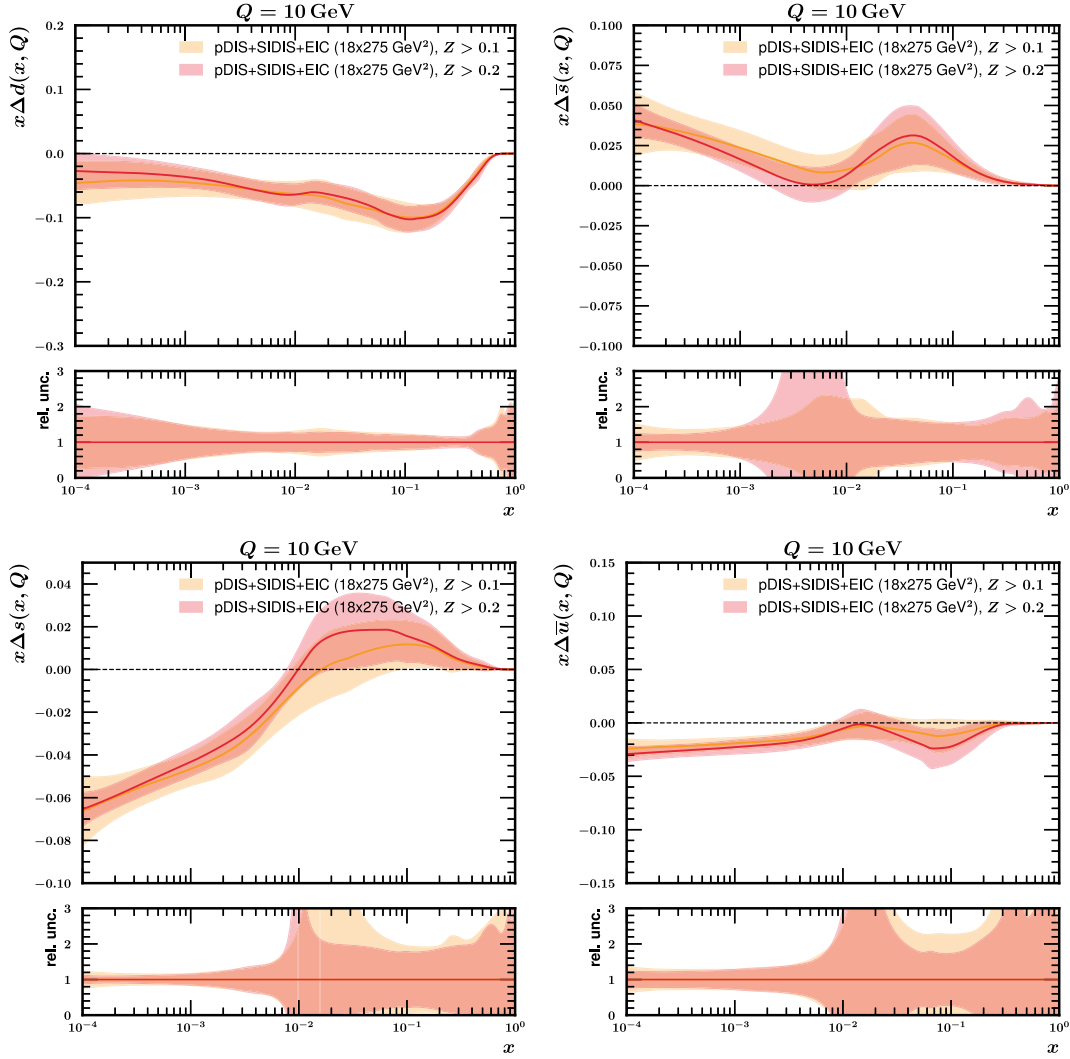


FIG. 6. Comparison of polarized PDFs at $Q = 10$ GeV obtained with EIC pseudodata at 18×275 GeV² using two minimum- z selections, $z_{\min} > 0.1$ and $z_{\min} > 0.2$.

sector. In particular, while NNPDFp012.0 assumes $\Delta s(x, Q_0) = \Delta \bar{s}(x, Q_0)$ at the parametrization scale, we allow Δs and $\Delta \bar{s}$ to be fitted independently; with charge-separated kaon observables, the EIC projections further enhance sensitivity to a possible $\Delta s - \Delta \bar{s}$ helicity asymmetry and lead to a noticeably improved constraint on both $x\Delta s$ and $x\Delta \bar{s}$ in the region where current data provide only limited leverage. In regions where present measurements provide limited constraints, the inclusion of EIC pseudodata in our study therefore plays a central role in reducing uncertainties, highlighting the potential impact of future EIC SIDIS measurements on the determination of polarized PDFs, and in particular on the strange helicity density and its possible quark-antiquark asymmetry.

Overall, these results indicate that the inclusion of EIC SIDIS pseudodata preserves a stable description of the existing polarized DIS and SIDIS measurements, as seen

from the largely unchanged fit quality across datasets. The main phenomenological outcome is the significant increase in constraining power, especially for SIDIS-sensitive sea-quark helicity PDFs and for the gluon helicity distribution at small x . In the present setup, the more conservative selection $z_{\min} > 0.2$ also leads to the most stable and, in several cases, the tightest PDF determination.

To quantify the impact of EIC pseudodata on the quark and gluon spin contributions, we study the truncated first moments of the quark-singlet and gluon helicity distributions,

$$M_{\Sigma}(x_{\min}) = \int_{x_{\min}}^1 dx \Delta \Sigma(x, Q^2), \quad (15)$$

$$M_g(x_{\min}) = \int_{x_{\min}}^1 dx \Delta g(x, Q^2), \quad (16)$$

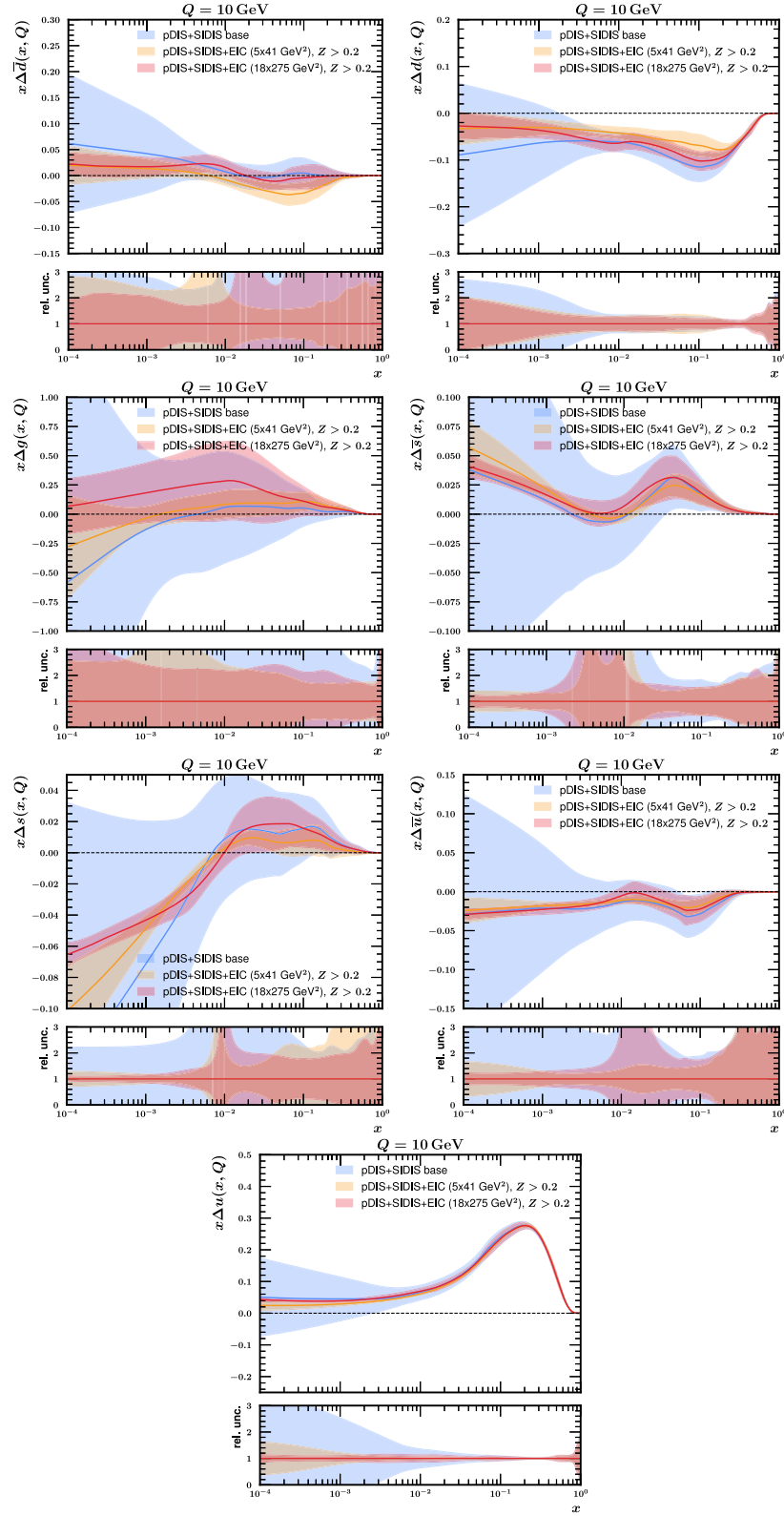


FIG. 7. Comparison of polarized PDFs at $Q = 10$ GeV obtained from the pDIS+SIDIS base fit and from fits including projected EIC SIDIS pseudodata for the two beam-energy configurations $E_e \times E_p = 5 \times 41$ GeV² and 18×275 GeV², using the default hadron-energy cut $z > z_{\min} = 0.2$.

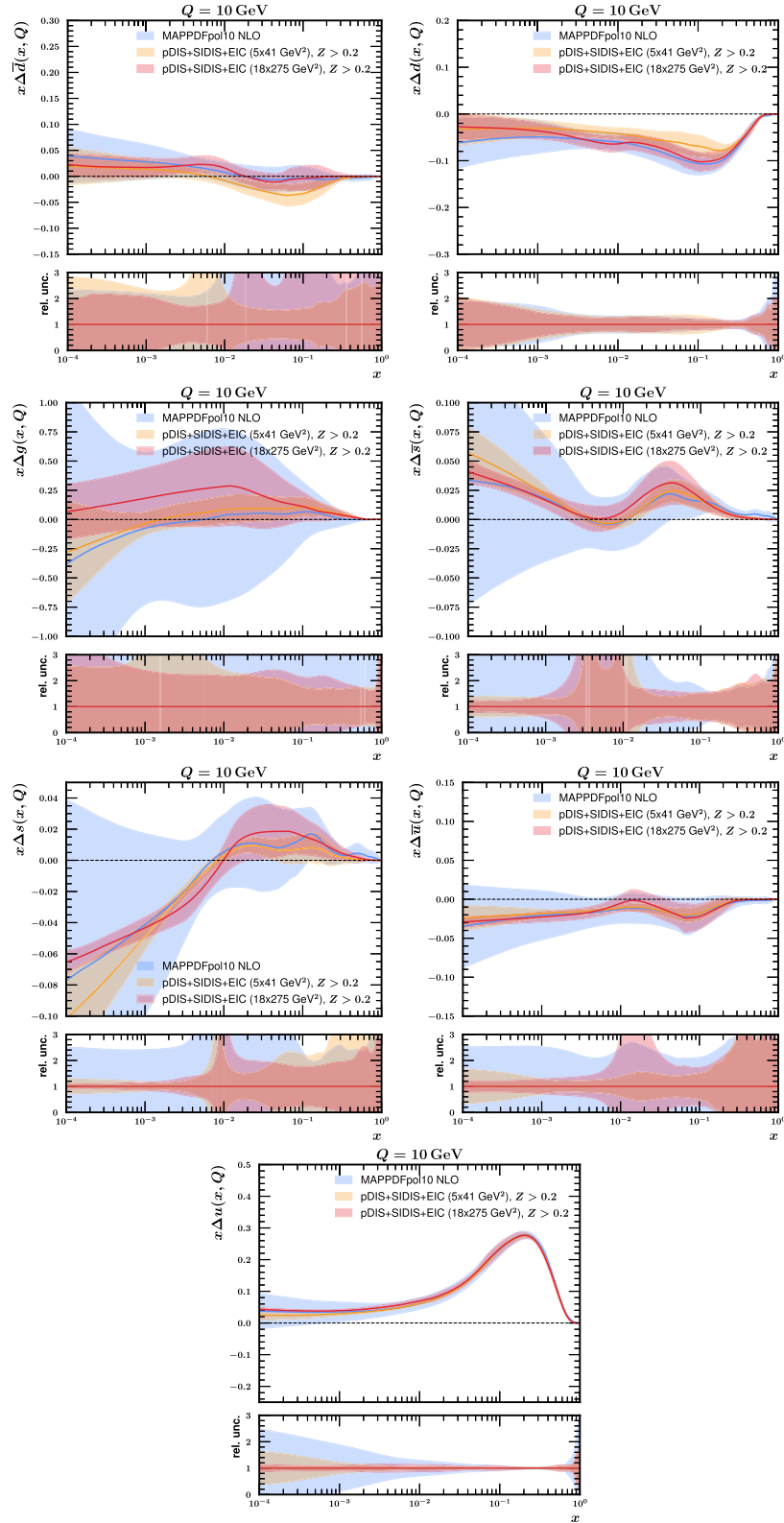


FIG. 8. Comparison of polarized PDFs at $Q = 10$ GeV between our default EIC-augmented fit (with $z_{\min} > 0.2$) and the MAPPDFpol10NLO determination [30] at NLO accuracy.

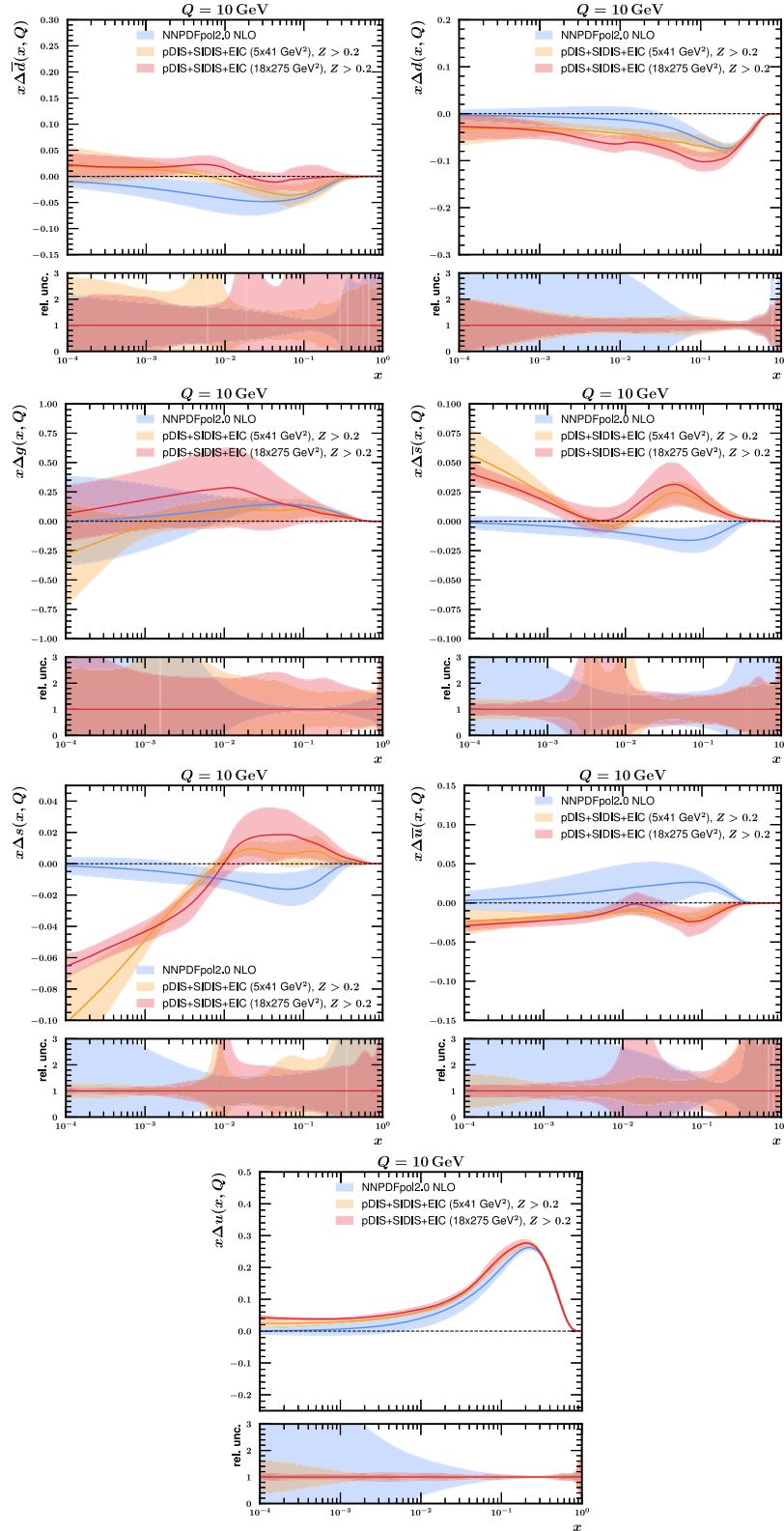


FIG. 9. Comparison of polarized PDFs at $Q = 10$ GeV between our default EIC-augmented fit (with $z_{\min} > 0.2$) and the NNPDFpol2.0 NLO determination [31].

$$M_{\text{spin}}(x_{\min}) = \int_{x_{\min}}^1 dx \left[\frac{1}{2} \Delta\Sigma(x, Q^2) + \Delta g(x, Q^2) \right], \quad (17)$$

evaluated at $Q^2 = 100 \text{ GeV}^2$. Here $\Delta\Sigma = \sum_q (\Delta q + \Delta\bar{q})$ denotes the quark-singlet helicity combination, with the sum taken over the active quark flavor in the ZM-VFNS (at this scale including u , d , s and charm, and, where applicable, bottom).

Figure 10 shows these moments as functions of the lower integration limit $x_{\min}$ for our baseline pDIS+SIDIS QCD fit and for fits augmented by EIC pseudodata at $5 \times 41 \text{ GeV}^2$ and $18 \times 275 \text{ GeV}^2$ (with $z > 0.2$). The baseline fit exhibits rapidly growing uncertainties as $x_{\min}$ is lowered, reflecting the limited present-day constraints on polarized PDFs in the small- x region, most notably for Δg . Upon including EIC information, the uncertainty bands shrink substantially across all panels, with the strongest improvement at small $x_{\min}$ where extrapolation effects are otherwise dominant. In particular, the reduction of the uncertainty on $M_g(x_{\min})$ propagates directly to the combination $M_{\text{spin}}(x_{\min})$, highlighting that EIC measurements provide decisive leverage on the low- x contribution to the gluon helicity and thus sharpen the determination of the quark-plus-gluon helicity contribution entering the proton spin sum rule. At larger $x_{\min}$, the moments become increasingly stable and the three fits converge, consistent with existing fixed-target constraints at moderate and large x .

To illustrate the impact of the EIC pseudodata on polarized SIDIS phenomenology, we compare COMPASS measurements of the longitudinal double-spin asymmetry $A_1^{p,h^\pm}$ for identified hadrons with the corresponding NLO predictions obtained from our global analysis. Figure 11 shows the COMPASS $A_1^{p,\pi^\pm}$ and $A_1^{p,K^\pm}$ data as functions of Bjorken x , together with the NLO predictions from the pDIS+SIDIS Base fit and from the pDIS+SIDIS+EIC fit ($18 \times 275 \text{ GeV}$, $z > 0.2$). The shaded bands represent the propagated fit uncertainty on the theoretical predictions, evaluated point-by-point at the same kinematics as the data.

Overall, both fits provide a comparable description of the COMPASS asymmetries within uncertainties, and the inclusion of EIC information does not induce visible distortions of the central predictions in the fixed-target kinematic region. The main effect is a clear reduction of the theory uncertainty toward the lowest- x bins, where

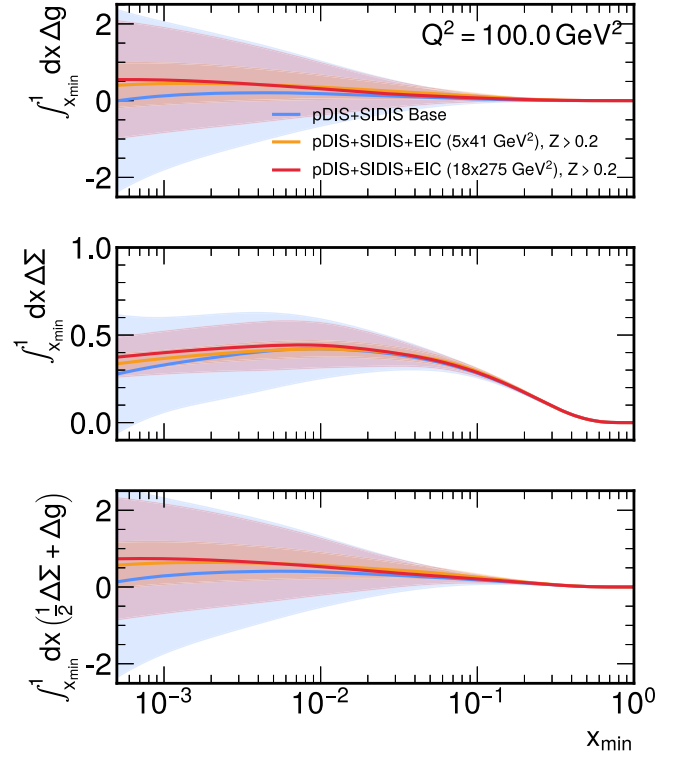


FIG. 10. Truncated first moments of the gluon and quark-singlet polarized PDFs at $Q^2 = 100 \text{ GeV}^2$ as functions of the lower integration limit $x_{\min}$. Shown are the truncated integrals $M_g(x_{\min}) = \int_{x_{\min}}^1 dx \Delta g(x, Q^2)$ (top), $M_\Sigma(x_{\min}) = \int_{x_{\min}}^1 dx \Delta\Sigma(x, Q^2)$ (middle), and $M_{\text{spin}}(x_{\min}) = \int_{x_{\min}}^1 dx [\frac{1}{2} \Delta\Sigma(x, Q^2) + \Delta g(x, Q^2)]$ (bottom), where $\Delta\Sigma = \sum_q (\Delta q + \Delta\bar{q})$ is summed over the active quark flavors in the ZM-VFNS. The solid curves correspond to the central member (replica 0) of each LHAPDF set, while the shaded bands represent the 1σ uncertainties obtained from the Monte Carlo replica ensemble. We compare the baseline fit (pDIS+SIDIS Base) with two fits including EIC pseudodata at $(5 \times 41 \text{ GeV}^2)$ and $(18 \times 275 \text{ GeV}^2)$ (both with $z > 0.2$).

present-day constraints are weakest and the baseline fit is more sensitive to small- x extrapolation. This trend is visible across the pion and kaon channels and is particularly relevant for kaon asymmetries, where the flavor sensitivity to the strange sea is intrinsically intertwined with the fragmentation input. The lower ratio panels further confirm that the changes induced by EIC pseudodata are primarily a tightening of uncertainties rather than a systematic shift in the central theory/data agreement.

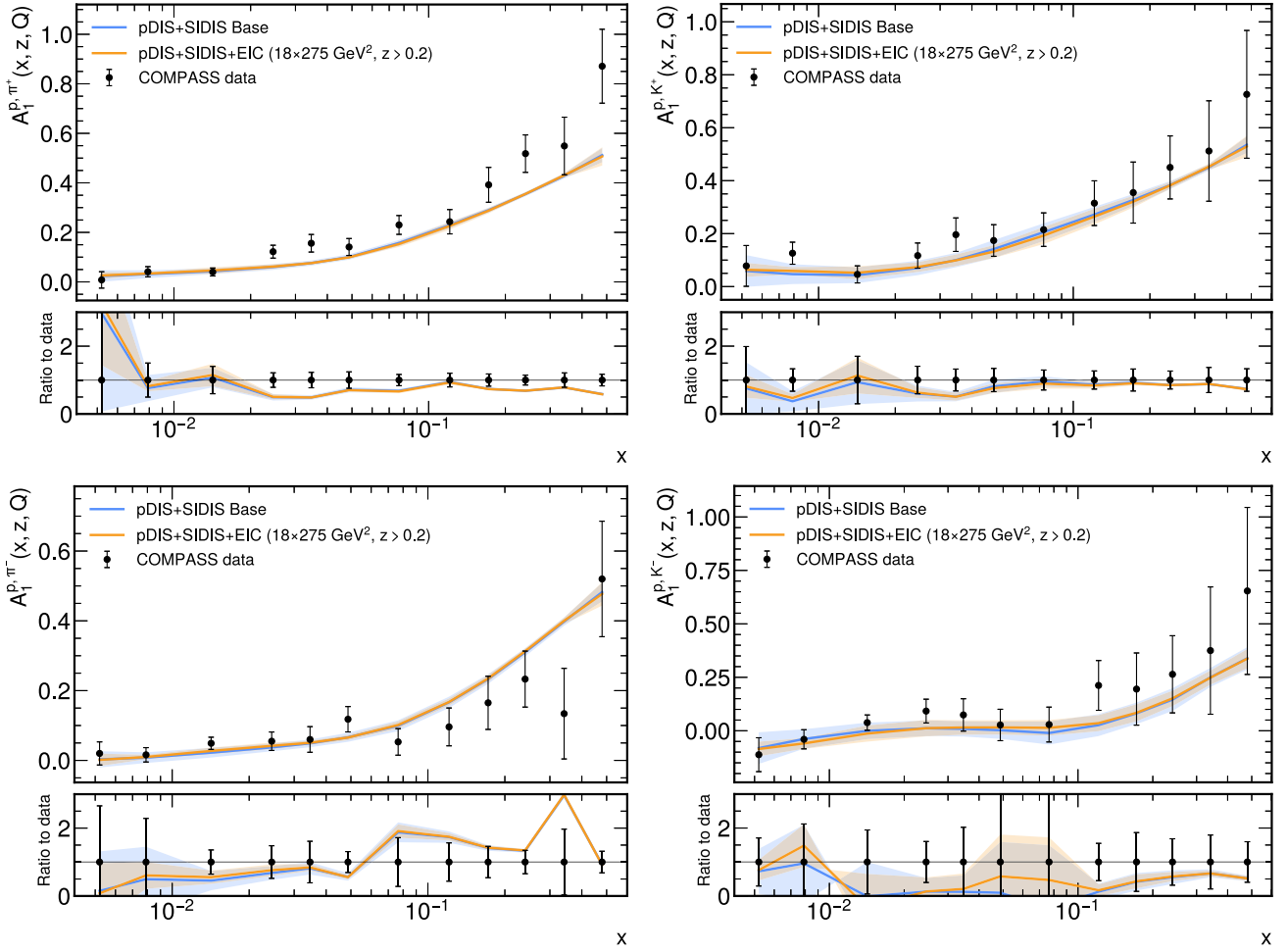


FIG. 11. COMPASS measurements of the longitudinal SIDIS double-spin asymmetry $A_1^{p,h^\pm}(x, z, Q)$ for identified hadrons, compared to NLO predictions from the pDIS+SIDIS Base fit and from the pDIS+SIDIS+EIC fit ($18 \times 275 \text{ GeV}^2$, $z > 0.2$). Shaded bands represent the propagated fit uncertainty. Lower panels show the ratio theory/data, with the data displayed at unity and their relative experimental uncertainties.

V. SUMMARY AND CONCLUSION

In this work, we have presented HAPS-pPDF1.0, a new NLO determination of the helicity-dependent parton distribution functions of the proton from a global QCD analysis of longitudinally polarized inclusive DIS and charge-separated SIDIS measurements. The baseline fit is built upon the world fixed-target dataset, including proton, deuteron and neutron information, and uses a consistent leading-twist collinear factorization framework with NLO DGLAP evolution in the $\overline{\text{MS}}$ scheme. For SIDIS, the predicted double-spin asymmetries are computed at NLO accuracy through the convolution of polarized PDFs with NLO coefficient functions and fragmentation functions, and the analysis is performed within a Monte Carlo replica methodology, providing an ensemble of PDF replicas suitable for uncertainty propagation.

A central physics goal of this study is to quantify the potential impact of future EIC measurements on the flavor decomposition of the polarized PDFs and on the poorly

constrained small- x behavior of the sea-quark and gluon helicity distribution. To this end we have supplemented the baseline data set with detector-level EIC SIDIS pseudodata for identified π^+ , π^- , K^+ and K^- production in two representative beam-energy configurations, $E_e \times E_p = 5 \times 41 \text{ GeV}^2$ and $18 \times 275 \text{ GeV}^2$, corresponding to complementary kinematic reaches in (x, Q^2) . The projected EIC measurements provide a substantially extended lever arm in both x and Q^2 , including dense coverage in Q^2 at fixed x , which enhances the scaling-violation information entering the NLO DGLAP evolution. When combined with charge-separated SIDIS flavor tagging, this translates into improved constraints on sea-quark helicity combinations (through pion channels for $\Delta\bar{u}$ and $\Delta\bar{d}$, and kaon channels for Δs) and into a significant reduction of the uncertainty on Δg in the small- x region where current data are largely extrapolative.

To connect these improvements to the proton spin decomposition, we have examined truncated first moments

of the quark-singlet and gluon helicity distributions as functions of the lower integration limit $x_{\min}$. The baseline fit exhibits rapidly growing uncertainties as $x_{\min}$ is lowered, reflecting the limited present constraints at small x , especially for Δg . With the addition of EIC pseudodata, the uncertainty on the truncated gluon moment is markedly reduced at small $x_{\min}$, and this improvement propagates directly to the uncertainty of the combination $\frac{1}{2}\Delta\Sigma + \Delta g$ relevant for the quark-plus-gluon spin contribution. We find that the EIC-augmented fit yields a visibly improved agreement and reduced theory uncertainty toward the lowest- x region covered by the existing SIDIS datasets.

Several refinements are natural targets for future work. On the theory side, a more complete assessment of non-perturbative effects (target-mass and higher-twist corrections at low Q^2 and W^2 , and nuclear corrections for deuteron data) would sharpen the interpretation of the fixed-target constraints, particularly given our comparatively loose W^2 selection. In addition, the extraction of sea-quark helicity PDFs from SIDIS remains intrinsically linked to the FFs input; a systematic propagation of FFs uncertainties and/or a combined global fit of polarized PDFs and FFs would further strengthen the robustness of the flavor separation. Finally, extending the perturbative accuracy and/or the phenomenological scope—for example through higher-order SIDIS corrections, a broader set of polarized processes (such as polarized proton-proton data), and/or future treatments beyond collinear factorization—will be important for fully exploiting the precision program enabled by the EIC.

Overall, our results provide a quantitative demonstration of the transformative potential of EIC SIDIS measurements for polarized PDF phenomenology. By extending the kinematic reach to much smaller x and providing a multi-scale lever arm in Q^2 , the EIC enables decisive improvements in the determination of the gluon helicity at low x and in the flavor decomposition of the polarized sea. These advances represent a key step toward a more complete and precise understanding of the spin structure of the proton within QCD.

A. Availability of polarized proton PDF sets

The polarized PDFs extracted in this analysis are made publicly available in the standard LHAPDF format [89]. The

released grids contain the full Monte Carlo ensemble of replicas, which encodes the PDF uncertainties and enables their propagation to any observable of interest.

The sets are provided at NLO accuracy and follow the naming convention `pDIS_SIDIS_<SETNAME>`, where the label indicates the perturbative accuracy and the inclusion of the EIC SIDIS pseudodata in the fit.¹ Each replica corresponds to an independent fit to a Monte Carlo replica of the input dataset. Central values are obtained as the average over the replica ensemble, while PDF uncertainties can be computed using either the standard deviation (for approximately Gaussian distributions) or percentiles.

The Public grid of HAPS-pPDF1.0, documentation, and plotting/usage examples are hosted in the accompanying GitHub repository [90]. Future updates—including additional EIC configurations and refinements of the SIDIS theory inputs (such as an extended treatment of fragmentation-function uncertainties)—will be released through the same platform.

ACKNOWLEDGMENTS

The authors gratefully acknowledge helpful discussions with Charlotte Van Hulse. This work was supported by the School of Particles and Accelerators at the Institute for Research in Fundamental Sciences (IPM). Hamzeh Khanpour appreciates the financial support from NAWA under Grant No. BPN/ULM/2023/1/00160, as well as from the IDUB program at AGH University. The work of U.G.M. was also supported in part by the Chinese Academy of Sciences (CAS) President's International Fellowship Initiative (PIFI) (Grant No. 2025PD0022).

DATA AVAILABILITY

The data used in this work are publicly available from the original experimental publications cited in this article and, where available, through the HEPData repository [91].

¹We provide separate sets corresponding to the different fit scenarios discussed in Sec. IV, e.g. the `pDIS+SIDIS` base fit and the EIC-augmented fits for the 5×41 and 18×275 configurations, and for both choice of $z > 0.1$ and $z > 0.2$.

- [1] X. Ji, F. Yuan, and Y. Zhao, What we know and what we don't know about the proton spin after 30 years, *Nat. Rev. Phys.* **3**, 27 (2021).
- [2] J. Ashman *et al.* (European Muon Collaboration), A measurement of the spin asymmetry and determination of the structure function g_1 in deep inelastic muon-proton scattering, *Phys. Lett. B* **206**, 364 (1988).
- [3] J. Ashman *et al.* (European Muon Collaboration), An investigation of the spin structure of the proton in deep inelastic scattering of polarized muons on polarized protons, *Nucl. Phys.* **B328**, 1 (1989).
- [4] M. Anselmino, A. Efremov, and E. Leader, The theory and phenomenology of polarized deep inelastic scattering, *Phys. Rep.* **261**, 1 (1995); **281**, 399(E) (1997).
- [5] J. J. Ethier and E. R. Nocera, Parton distributions in nucleons and nuclei, *Annu. Rev. Nucl. Part. Sci.* **70**, 43 (2020).
- [6] M. Gluck, E. Reya, M. Stratmann, and W. Vogelsang, Models for the polarized parton distributions of the nucleon, *Phys. Rev. D* **63**, 094005 (2001).
- [7] M. Hirai *et al.* (Asymmetry Analysis Collaboration), Determination of polarized parton distribution functions and their uncertainties, *Phys. Rev. D* **69**, 054021 (2004).
- [8] M. Hirai, S. Kumano, and N. Saito, Determination of polarized parton distribution functions with recent data on polarization asymmetries, *Phys. Rev. D* **74**, 014015 (2006).
- [9] J. Blumlein and H. Bottcher, QCD analysis of polarized deep inelastic scattering data, *Nucl. Phys.* **B841**, 205 (2010).
- [10] E. Leader, A. V. Sidorov, and D. B. Stamenov, Determination of polarized PDFs from a QCD analysis of inclusive and semi-inclusive deep inelastic scattering data, *Phys. Rev. D* **82**, 114018 (2010).
- [11] D. Adamiak *et al.* (Jefferson Lab Angular Momentum (JAM) Collaboration), Global analysis of polarized DIS and SIDIS data with improved small- x helicity evolution, *Phys. Rev. D* **108**, 11 (2023).
- [12] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Extraction of spin-dependent parton densities and their uncertainties, *Phys. Rev. D* **80**, 034030 (2009).
- [13] E. R. Nocera, Small- and large- x nucleon spin structure from a global QCD analysis of polarized parton distribution functions, *Phys. Lett. B* **742**, 117 (2015).
- [14] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Global analysis of helicity parton densities and their uncertainties, *Phys. Rev. Lett.* **101**, 072001 (2008).
- [15] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Evidence for polarization of gluons in the proton, *Phys. Rev. Lett.* **113**, 012001 (2014).
- [16] N. Sato *et al.* (Jefferson Lab Angular Momentum Collaboration), Iterative Monte Carlo analysis of spin-dependent parton distributions, *Phys. Rev. D* **93**, 074005 (2016).
- [17] J. J. Ethier, N. Sato, and W. Melnitchouk, First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis, *Phys. Rev. Lett.* **119**, 132001 (2017).
- [18] E. R. Nocera *et al.* (NNPDF Collaboration), A first unbiased global determination of polarized PDFs and their uncertainties, *Nucl. Phys.* **B887**, 276 (2014).
- [19] I. Borsa, M. Stratmann, W. Vogelsang, D. de Florian, and R. Sassot, Next-to-next-to-leading order global analysis of polarized parton distribution functions, *Phys. Rev. Lett.* **133**, 15 (2024).
- [20] L. Bonino, T. Gehrmann, M. Löchner, K. Schönwald, and G. Stagnitto, Polarized neutral and charged current semi-inclusive deep-inelastic scattering at NNLO in QCD, *J. High Energy Phys.* **03** (2026) 109.
- [21] S. Goyal, R. N. Lee, S. O. Moch, V. Pathak, N. Rana, and V. Ravindran, NNLO QCD corrections to unpolarized and polarized SIDIS, *Phys. Rev. D* **111**, 9 (2025).
- [22] L. Bonino, T. Gehrmann, M. Löchner, K. Schönwald, and G. Stagnitto, NNLO corrections to SIDIS coefficient functions, *Proc. Sci.*, LL2024 (2024) 054 [arXiv:2408.08741].
- [23] T. Gehrmann and M. Löchner, The unresolved behaviour of polarized scattering matrix elements at NNLO in QCD, *J. High Energy Phys.* **02** (2026) 097.
- [24] F. Arbabifar, S. Atashbar Tehrani, and H. Khanpour, AAK24: Global QCD analysis on polarized parton distribution in the presence of A_2 asymmetry measurements, *Eur. Phys. J. Plus* **139**, 834 (2024).
- [25] H. Khanpour, S. T. Monfared, and S. Atashbar Tehrani, Study of spin-dependent structure functions of ^3He and ^3H at NNLO approximation and corresponding nuclear corrections, *Phys. Rev. D* **96**, 074037 (2017).
- [26] H. Khanpour, S. T. Monfared, and S. Atashbar Tehrani, Nucleon spin structure functions at NNLO in the presence of target mass corrections and higher twist effects, *Phys. Rev. D* **95**, 074006 (2017).
- [27] I. Borsa, G. Lucero, R. Sassot, E. C. Aschenauer, and A. S. Nunes, Revisiting helicity parton distributions at a future electron-ion collider, *Phys. Rev. D* **102**, 094018 (2020).
- [28] C. Cocuzza *et al.* (JAM Collaboration (Spin PDF Analysis Group)), Global QCD analysis of spin PDFs in the proton with high- x and lattice constraints, *Phys. Rev. D* **112**, 11 (2025).
- [29] D. Adamiak *et al.* (JAM Collaboration (Small- x Analysis Group)), First study of polarized proton-proton scattering with small- x helicity evolution, *Phys. Rev. D* **112**, 094032 (2025).
- [30] V. Bertone *et al.* (MAP (Multi-dimensional Analyses of Partonic distributions) Collaboration), Helicity-dependent parton distribution functions at next-to-next-to-leading order accuracy from inclusive and semi-inclusive deep-inelastic scattering data, *Phys. Lett. B* **865**, 139497 (2025).
- [31] J. Cruz-Martinez, T. Hasenack, F. Hekhorn, G. Magni, E. R. Nocera, T. R. Rabemananjara, J. Rojo, T. Sharma, and G. van Seeventer, NNPDFpol2.0: A global determination of polarised PDFs and their uncertainties at next-to-next-to-leading order, *J. High Energy Phys.* **07** (2025) 168.
- [32] R. Abdul Khalek, A. Accardi, J. Adam, D. Adamiak, W. Akers, M. Albaladejo, A. Al-bataineh, M. G. Alexeev, F. Ameli, P. Antonioli *et al.*, Science requirements and detector concepts for the electron-ion collider: EIC yellow report, *Nucl. Phys.* **A1026**, 122447 (2022).
- [33] R. Abdul Khalek, U. D'Alesio, M. Arratia, A. Bacchetta, M. Battaglieri, M. Begel, M. Boglione, R. Boughezal, R. Boussarie, G. Bozzi *et al.*, Snowmass 2021 white paper: Electron ion collider for high energy physics, arXiv:2203.13199.
- [34] M. Azizi, M. Soleymaninia, H. Hashamipour, M. Salajegheh, H. Khanpour, and U. G. Meißner, Revisiting

- constraints on proton PDFs from HERA DIS, Drell-Yan, W and Z boson production, and projected EIC measurements, *Phys. Rev. D* **111**, 034023 (2025).
- [35] N. Armesto, T. Cridge, F. Giuliani, L. Harland-Lang, P. Newman, B. Schmookler, R. Thorne, and K. Wichmann, Impact of inclusive electron ion collider data on collinear parton distributions, *Phys. Rev. D* **109**, 054019 (2024).
- [36] J. Jiménez-López, S. Maple, P.R. Newman, and K. Wichmann, Inclusive electron-proton measurement prospects in the electron-ion collider early science stage, [arXiv:2602.00860](https://arxiv.org/abs/2602.00860).
- [37] M. Soleymaninia, H. Khanpour, M. Azizi, and H. Hashamipour, Improved constraints on pion fragmentation functions from simulated electron-ion collider data, *Phys. Rev. D* **112**, 054032 (2025).
- [38] E. C. Aschenauer, I. Borsa, R. Sassot, and C. Van Hulse, Semi-inclusive deep-inelastic scattering, parton distributions and fragmentation functions at a future electron-ion collider, *Phys. Rev. D* **99**, 094004 (2019).
- [39] J. K. Adkins, Y. Akiba, A. Albataineh, M. Amarian, I. C. Arsene, C. Ayerbe Gayoso, J. Bae, X. Bai, M. D. Baker, M. Bashkanov *et al.*, Design of the ECCE detector for the electron ion collider, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1073**, 170240 (2025).
- [40] C. Van Hulse, J. K. Adkins, Y. Akiba, A. Albataineh, M. Amarian, I. C. Arsene, C. Ayerbe Gayoso, J. Bae, X. Bai, M. D. Baker *et al.*, Evaluation of longitudinal double-spin asymmetry measurements in semi-inclusive deep-inelastic scattering from the proton for the ECCE detector design, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1056**, 168563 (2023).
- [41] F. Hekhorn and M. Stratmann, Next-to-leading order QCD corrections to inclusive heavy-flavor production in polarized deep-inelastic scattering, *Phys. Rev. D* **98**, 014018 (2018).
- [42] A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel, and C. Schneider, The 3-loop non-singlet heavy flavor contributions to the structure function $g_1(x, Q^2)$ at large momentum transfer, *Nucl. Phys.* **B897**, 612 (2015).
- [43] J. Ablinger, A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel, C. Schneider, and K. Schönwald, The three-loop single mass polarized pure singlet operator matrix element, *Nucl. Phys.* **B953**, 114945 (2020).
- [44] A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel, K. Schönwald, and C. Schneider, The polarized transition matrix element $A_{gq}(N)$ of the variable flavor number scheme at $O(\alpha_s^3)$, *Nucl. Phys.* **B964**, 115331 (2021).
- [45] J. Blümlein, A. De Freitas, M. Saragnese, C. Schneider, and K. Schönwald, Logarithmic contributions to the polarized $O(\alpha_s^3)$ asymptotic massive Wilson coefficients and operator matrix elements in deeply inelastic scattering, *Phys. Rev. D* **104**, 034030 (2021).
- [46] I. Bierenbaum, J. Blümlein, A. De Freitas, A. Goedicke, S. Klein, and K. Schönwald, $O(\alpha_s^2)$ polarized heavy flavor corrections to deep-inelastic scattering at $Q^2 \gg m^2$, *Nucl. Phys.* **B988**, 116114 (2023).
- [47] J. Ablinger, A. Behring, J. Blümlein, A. De Freitas, A. von Manteuffel, C. Schneider, and K. Schönwald, The first-order factorizable contributions to the three-loop massive operator matrix elements $A_{Qg}^{(3)}$ and $\Delta A_{Qg}^{(3)}$, *Nucl. Phys.* **B999**, 116427 (2024).
- [48] F. Hekhorn, G. Magni, E. R. Nocera, T. R. Rabemananjara, J. Rojo, A. Schaus, and R. Stegeman, Heavy quarks in polarised deep-inelastic scattering at the electron-ion collider, *Eur. Phys. J. C* **84**, 189 (2024).
- [49] E. B. Zijlstra and W. L. van Neerven, Order- α_s^2 corrections to the polarized structure function $g_1(x, Q^2)$, *Nucl. Phys.* **B417**, 61 (1994); **B426**, 245(E) (1994); **B773**, 105(E) (2007); **B501**, 599(E) (1997).
- [50] R. Mertig and W. L. van Neerven, The calculation of the two loop spin splitting functions $P_{(ij)}^{(1)}(x)$, *Z. Phys. C* **70**, 637 (1996).
- [51] W. Vogelsang, A rederivation of the spin dependent next-to-leading order splitting functions, *Phys. Rev. D* **54**, 2023 (1996).
- [52] S. Moch, J. A. M. Vermaseren, and A. Vogt, The three-loop splitting functions in QCD: The helicity-dependent case, *Nucl. Phys.* **B889**, 351 (2014).
- [53] J. Blümlein, P. Marquard, C. Schneider, and K. Schönwald, The three-loop polarized singlet anomalous dimensions from off-shell operator matrix elements, *J. High Energy Phys.* **01** (2022) 193; **02** (2026) 49.
- [54] J. Blümlein, P. Marquard, C. Schneider, and K. Schönwald, The three-loop unpolarized and polarized non-singlet anomalous dimensions from off shell operator matrix elements, *Nucl. Phys.* **B971**, 115542 (2021).
- [55] W. Furmanski and R. Petronzio, Lepton—hadron processes beyond leading order in quantum chromodynamics, *Z. Phys. C* **11**, 293 (1982).
- [56] D. de Florian, M. Stratmann, and W. Vogelsang, QCD analysis of unpolarized and polarized Lambda baryon production in leading and next-to-leading order, *Phys. Rev. D* **57**, 5811 (1998).
- [57] R. A. Khalek *et al.* (MAP (Multi-dimensional Analyses of Partonic distributions) Collaboration), Determination of unpolarized pion fragmentation functions using semi-inclusive deep-inelastic-scattering data, *Phys. Rev. D* **104**, 034007 (2021).
- [58] R. Abdul Khalek *et al.* (MAP (Multi-dimensional Analyses of Partonic distributions) Collaboration), Pion and kaon fragmentation functions at next-to-next-to-leading order, *Phys. Lett. B* **834**, 137456 (2022).
- [59] R. D. Ball *et al.* (NNPDF Collaboration), The path to proton structure at 1% accuracy, *Eur. Phys. J. C* **82**, 428 (2022).
- [60] J. Blumlein and A. Tkabladze, Target mass corrections for polarized structure functions and new sum rules, *Nucl. Phys.* **B553**, 427 (1999).
- [61] I. Schienbein, V. A. Radescu, G. P. Zeller, M. E. Christy, C. E. Keppel, K. S. McFarland, W. Melnitchouk, F. I. Olness, M. H. Reno, F. Steffens *et al.*, A review of target mass corrections, *J. Phys. G* **35**, 053101 (2008).
- [62] E. Leader, A. V. Sidorov, and D. B. Stamenov, Some remarks on methods of QCD analysis of polarized DIS data, *Phys. Rev. D* **80**, 054026 (2009).
- [63] V. Bertone, S. Carazza, and J. Rojo, APFEL: A PDF evolution library with QED corrections, *Comput. Phys. Commun.* **185**, 1647 (2014).
- [64] V. Bertone, APFEL++: A new PDF evolution library in C++, *Proc. Sci., DIS2017* (2018) 201 [[arXiv:1708.00911](https://arxiv.org/abs/1708.00911)].
- [65] <https://github.com/MapCollaboration/MontBlanc>.

- [66] V. Bertone, A. Chiefa, and E. R. Nocera, Mapcollaboration/denali: Sheldon chalet (2024).
- [67] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [68] B. Adeva *et al.* (Spin Muon Collaboration), Spin asymmetries A_1 and structure functions g_1 of the proton and the deuteron from polarized high-energy muon scattering, *Phys. Rev. D* **58**, 112001 (1998).
- [69] C. Adolph *et al.* (COMPASS Collaboration), The spin structure function g_1^p of the proton and a test of the Bjorken sum rule, *Phys. Lett. B* **753**, 18 (2016).
- [70] C. Adolph *et al.* (COMPASS Collaboration), Final COMPASS results on the deuteron spin-dependent structure function g_1^d and the Bjorken sum rule, *Phys. Lett. B* **769**, 34 (2017).
- [71] P. L. Anthony *et al.* (E142 Collaboration), Deep inelastic scattering of polarized electrons by polarized He-3 and the study of the neutron spin structure, *Phys. Rev. D* **54**, 6620 (1996).
- [72] K. Abe *et al.* (E143 Collaboration), Measurements of the proton and deuteron spin structure functions g_1 and g_2 , *Phys. Rev. D* **58**, 112003 (1998).
- [73] K. Abe *et al.* (E154 Collaboration), Precision determination of the neutron spin structure function g_1^n , *Phys. Rev. Lett.* **79**, 26 (1997).
- [74] P. L. Anthony *et al.* (E155 Collaboration), Measurements of the Q^2 dependence of the proton and neutron spin structure functions g_1^p and g_1^n , *Phys. Lett. B* **493**, 19 (2000).
- [75] K. Ackerstaff *et al.* (HERMES Collaboration), Measurement of the neutron spin structure function g_1^n with a polarized He-3 internal target, *Phys. Lett. B* **404**, 383 (1997).
- [76] A. Airapetian *et al.* (HERMES Collaboration), Precise determination of the spin structure function g_1 of the proton, deuteron and neutron, *Phys. Rev. D* **75**, 012007 (2007).
- [77] D. Flay *et al.* (Jefferson Lab Hall A Collaboration), Measurements of d_2^n and A_1^n : Probing the neutron spin structure, *Phys. Rev. D* **94**, 052003 (2016).
- [78] K. M. Kramer (Jefferson Lab E97-103 Collaboration), The search for higher twist effects in the spin-structure functions of the neutron, *AIP Conf. Proc.* **675**, 615 (2003).
- [79] X. Zheng *et al.* (Jefferson Lab Hall A Collaboration), Precision measurement of the neutron spin asymmetries and spin-dependent structure functions in the valence quark region, *Phys. Rev. C* **70**, 065207 (2004).
- [80] Y. Prok *et al.* (CLAS Collaboration), Precision measurements of g_1 of the proton and the deuteron with 6 GeV electrons, *Phys. Rev. C* **90**, 025212 (2014).
- [81] R. D. Ball *et al.* (NNPDF Collaboration), Unbiased determination of polarized parton distributions and their uncertainties, *Nucl. Phys. B* **874**, 36 (2013).
- [82] N. Guler *et al.* (CLAS Collaboration), Precise determination of the deuteron spin structure at low to moderate Q^2 with CLAS and extraction of the neutron contribution, *Phys. Rev. C* **92**, 055201 (2015).
- [83] R. Fersch *et al.* (CLAS Collaboration), Determination of the proton spin structure functions for $0.05 < Q^2 < 5 \text{ GeV}^2$ using CLAS, *Phys. Rev. C* **96**, 065208 (2017).
- [84] W. Armstrong *et al.* (SANE Collaboration), Revealing color forces with transverse polarized electron scattering, *Phys. Rev. Lett.* **122**, 022002 (2019).
- [85] M. G. Alekseev *et al.* (COMPASS Collaboration), Quark helicity distributions from longitudinal spin asymmetries in muon-proton and muon-deuteron scattering, *Phys. Lett. B* **693**, 227 (2010).
- [86] A. Airapetian *et al.* (HERMES Collaboration), Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons, *Phys. Rev. D* **99**, 112001 (2019).
- [87] A. L. Kataev, The constraints on the nonsinglet polarized parton densities from the infrared renormalon model, *JETP Lett.* **77**, 458 (2003).
- [88] S. Agarwal, K. Mierle, and T. C. S. Team, Ceres Solver, 2023.
- [89] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, LHAPDF6: Parton density access in the LHC precision era, *Eur. Phys. J. C* **75**, 132 (2015).
- [90] HAPS Collaboration, Public grid of HAPS-pPDF1.0, GitHub repository available at <https://github.com/HAPS-Collaboration/HAPS-pPDF1.0>.
- [91] E. Maguire, L. Heinrich, and G. Watt, HEPData: A repository for high energy physics data, *J. Phys. Conf. Ser.* **898**, 102006 (2017); HEPData repository, available at <https://www.hepdata.net/>.