

Revisiting unidentified charged-hadron fragmentation functions with modern COMPASS SIDIS multiplicities

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We present HAPS-hFF1.0, a new global QCD analysis of unidentified charged-hadron fragmentation functions (FFs) using single-inclusive electron-positron annihilation (SIA) data together with the modern COMPASS semi-inclusive deep-inelastic scattering (SIDIS) multiplicities. The COMPASS input consists of the 2025 proton-target measurement and the revised ⁶LiD-target multiplicities provided in the 2026 COMPASS addendum. The extraction is performed at both next-to-leading order (NLO) and next-to-next-to-leading order (NNLO), allowing us to study the perturbative stability of the QCD fit and the impact of the updated SIDIS information on the flavor structure of the FFs. The FFs are parametrized using neural networks, while experimental uncertainties are propagated through a Monte Carlo replica methodology. We find that the modern COMPASS multiplicities can be consistently described together with the SIA data and provide important charge-separated constraints on the light-quark and antiquark FFs. The comparison between the NLO and NNLO extractions indicates a stable quark-sector determination, while the gluon FF remains less directly constrained in the present SIA + SIDIS analysis. Our results highlight the importance of the modern COMPASS SIDIS multiplicities for precision studies of unidentified charged-hadron fragmentation and for future global FF determinations. The resulting HAPS-hFF1.0 replicas are publicly available in standard LHAPDF format.

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I. INTRODUCTION

Fragmentation functions (FFs) encode the nonperturbative transition of partons to observed hadrons and are essential ingredients in the factorized description of high-energy hadron-production processes [1–7]. Their universality allows

us to combine information from different reactions in global QCD analyses, most notably single-inclusive electron-positron annihilation (SIA), semi-inclusive deep-inelastic scattering (SIDIS), and inclusive hadron production in hadronic collisions [8–10]. In this framework, perturbatively calculable short-distance hard coefficients are convoluted with universal long-distance FFs, making the latter indispensable for precision QCD phenomenology. While SIA provides clean constraints on charge-summed FF combinations, SIDIS multiplicities are crucial for improving flavor and charge separation through their convolution with target parton distribution functions (PDFs). Hadron production in proton-proton collisions, on the other hand, provides important sensitivity to the gluon FF, especially through high-energy charged-particle spectra.

Unidentified charged-hadron FFs are phenomenologically important because inclusive charged-particle spectra

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are measured with high precision in fixed-target, collider, proton-nucleus, and heavy-ion environments. They enter theoretical predictions for a wide range of observables, including charged-hadron production in SIA, SIDIS, proton-proton collisions, and nuclear collision systems. They are also relevant for future studies at the Electron Ion Collider [11,12], where SIDIS measurements will play a central role in constraining the flavor dependence of hadronization. In contrast to identified-hadron FFs, which describe the production of specific hadron species such as pions, kaons, or protons, unidentified charged-hadron FFs effectively describe the inclusive sum of all charged hadrons produced in the fragmentation of a given parton. This makes them especially useful for collider and heavy-ion applications but also increases the need for accurate global determinations and reliable uncertainty estimates.

Several determinations of unidentified charged-hadron FFs have appeared in the literature. The DSS analysis provided an early global next-to-leading order (NLO) extraction based on SIA, SIDIS, and proton-proton data [13]. Recent next-to-next-to-leading order (NNLO) and finite-mass studies of light charged-hadron fragmentation have also shown the importance of higher-order corrections and hadron-mass effects in precision FF determinations [14–17]. The NNFF1.1h analysis determined unidentified charged-hadron FFs at NLO using SIA data supplemented by Tevatron and LHC charged-hadron spectra through Bayesian reweighting, demonstrating in particular the strong constraining power of hadron-collider data on the gluon FF [18]. The JAM20-SIDIS analysis performed a simultaneous Monte Carlo extraction of PDFs and FFs using SIA and SIDIS data for pions, kaons, and unidentified charged hadrons, emphasizing the role of SIDIS data in testing universality and constraining flavor dependence [7]. More recently, high-energy collider data have been used to update charged-hadron FFs for modern LHC phenomenology [19]. In addition, our previous SHK22.h analysis included COMPASS SIDIS multiplicities in a neural-network determination of unidentified charged-hadron FFs [20]. These developments show that unidentified charged-hadron FFs are active phenomenological inputs whose extraction depends sensitively on the available experimental information.

The central motivation for the present work is the substantial revision of the COMPASS SIDIS input relevant for unidentified charged-hadron FFs. The COMPASS Collaboration has recently published proton-target multiplicities for charged pions, kaons, and unidentified charged hadrons, and has subsequently provided revised isoscalar-target multiplicities in a dedicated addendum [21,22]. The latter supersede the original COMPASS 2017 multiplicities that entered earlier unidentified charged-hadron FF determinations [23,24]. This motivates a new SIA + SIDIS extraction in which the older COMPASS isoscalar input is replaced by the modern COMPASS dataset composed of

the proton-target measurement and the revised multiplicities. The proton-target data provide additional charge-separated flavor sensitivity, while the revised ${}^6\text{LiD}$ -target data provide a more balanced light-flavor constraint.

The aim of the present work is therefore to revisit unidentified charged-hadron FFs using the modern COMPASS SIDIS input. We perform a new global analysis of SIA data together with the COMPASS 2025 proton-target measurement [21] and the ${}^6\text{LiD}$ -target multiplicities provided in the 2026 COMPASS addendum for h^+ and h^- [22]. The analysis is carried out at both NLO and NNLO using the publicly available *MontBlanc* framework [4,25,26].

At NNLO, the SIA coefficient functions and timelike Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [27–30] are included at full NNLO accuracy, while the SIDIS coefficient-function contributions are treated at NNLO within the theoretical framework used in this analysis. Very recently, exact NNLO QCD coefficient functions for SIDIS have become available [31–34], making it possible to incorporate semi-inclusive DIS multiplicities in global FF determinations beyond the approximate threshold-based treatment used in earlier studies [35].

We emphasize that the novelty of the present NNLO analysis should be understood in the context of the updated COMPASS SIDIS input. Previous NNLO studies of unidentified charged-hadron FFs have been performed in the SIA-only context [14]. Thus, the new element of the present work is not the use of NNLO corrections alone, but the incorporation of the COMPASS 2025 proton-target measurement and the revised multiplicities from the COMPASS 2026 in a global SIA + SIDIS determination at NLO and NNLO. The comparison of NLO and NNLO FFs is used to assess the perturbative stability of the extracted FFs within the present theoretical framework.

This paper is organized as follows: In Sec. II we discuss the theoretical framework, including the SIA and SIDIS factorized expressions, timelike evolution, and the neural-network parametrization used for the FFs. In Sec. III we describe the experimental datasets, the updated COMPASS input, the uncertainty treatment, and the kinematic selections. In Sec. IV, we study the dependence of the fit quality on the lower SIDIS scale cut and use this scan to motivate the default choice adopted in the final fit. The main findings and the numerical results are discussed in Sec. V, including the fit quality, the description of the COMPASS multiplicities, the comparison between the NLO and NNLO extractions, and the NLO comparison with NNFF1.1h. Finally, we summarize our conclusions and discuss future directions in Sec. VI.

II. THEORETICAL FRAMEWORK

In this section, we summarize the theoretical framework used for the extraction of unidentified charged-hadron FFs from SIA and SIDIS observables. The analysis is

performed within perturbative QCD using collinear factorization, in which short-distance partonic cross sections are calculable in perturbation theory, while the long-distance hadronization process is encoded in universal FFs [8–10]. We first introduce the factorized expressions for SIA and SIDIS and then define the corresponding kinematic variables and the multiplicities used for the COMPASS data. We also discuss the timelike DGLAP evolution equations, the perturbative accuracy, the flavor basis, charge-conjugation relations, and the neural-network parametrization used at the input scale.

A. Collinear factorization

For the processes considered in this work, the factorized cross sections may be written schematically as

$$\sigma_{\text{SIA}} = \hat{\sigma} \otimes D^h, \quad (1)$$

$$\sigma_{\text{SIDIS}} = \hat{\sigma} \otimes f^N \otimes D^h. \quad (2)$$

Here, $\hat{\sigma}$ denotes the perturbatively calculable hard-scattering coefficient, f^N is the parton distribution function (PDF) of the target nucleon or nucleus N , and D^h is the FF into the observed hadron h . More explicitly, D_i^h denotes the FF for a parton of flavor i into the observed hadron h . The symbol $\otimes$ denotes the appropriate convolution over longitudinal momentum fractions. The universality of FFs allows the same nonperturbative functions to be constrained simultaneously using SIA and SIDIS measurements.

Throughout the analysis, μ_R denotes the renormalization scale, whereas μ_F^{ini} and μ_F^{fin} denote the initial-state and final-state factorization scales, respectively. For compactness, these scales are identified with a common scale μ in the expressions below,

$$\mu_R = \mu_F^{\text{ini}} = \mu_F^{\text{fin}} \equiv \mu, \quad (3)$$

unless otherwise stated. In SIA, only the final-state factorization scale is relevant because no PDFs enter the observable.

B. Single-inclusive annihilation

The SIA process considered in this analysis is

$$e^+e^- \rightarrow h^\pm + X, \quad (4)$$

where $h^\pm$ denotes the observed positively or negatively charged hadron and X represents all unobserved particles in the final state. The annihilation proceeds through an intermediate virtual photon or Z boson carrying total four-momentum q . The characteristic hard scale is timelike and is defined by

$$q^2 = s \equiv Q^2 > 0, \quad (5)$$

where $\sqrt{s}$ is the electron-positron center-of-mass energy. In the massless-hadron approximation, the SIA scaling variable is defined as

$$z = \frac{2p_h \cdot q}{Q^2}, \quad (6)$$

where p_h is the four-momentum of the observed hadron. In the electron-positron center-of-mass frame, this definition reduces to $z = 2E_h/Q$, where E_h is the hadron energy.

The normalized SIA cross section can be expressed as a convolution of perturbative coefficient functions and FFs,

$$\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^h}{dz} = \sum_i C_i(z, \alpha_s, Q^2, \mu^2) \otimes D_i^h(z, \mu^2), \quad (7)$$

where σ_{tot} is the total inclusive hadronic SIA cross section, α_s is the QCD strong coupling, and the index $i \in \{q, \bar{q}, g\}$ runs over the active quark, antiquark, and gluon flavors. The quantity C_i is the perturbatively calculable coefficient function associated with the production and subsequent fragmentation of parton i . Its dependence on the renormalization scale is implicit through $\alpha_s = \alpha_s(\mu_R^2)$. In the notation above, the renormalization and final-state factorization scales are set equal to the common scale μ .

SIA data provide particularly clean constraints on FFs because no initial-state PDFs enter the observable. However, SIA measurements alone have limited power to distinguish quark from antiquark fragmentation. They constrain the gluon FF mainly through the scale dependence of the cross sections and through gluon-initiated contributions to the higher-order coefficient functions [18,20,36].

C. Semi-inclusive DIS multiplicities

The SIDIS process relevant for the COMPASS measurements is

$$\ell(k) + N(p) \rightarrow \ell(k') + h^\pm(p_h) + X, \quad (8)$$

where ℓ denotes the incoming and outgoing charged lepton, N is the target nucleon or nucleus, and k, k', p , and p_h are the four-momenta of the incoming lepton, outgoing lepton, target, and observed hadron, respectively. The quantity X denotes the unobserved final-state particles. The four-momentum transferred from the lepton to the target is

$$q = k - k'. \quad (9)$$

In contrast to SIA, the hard scale in SIDIS is spacelike and is given by the positive photon virtuality

$$Q^2 \equiv -q^2 > 0. \quad (10)$$

We use the standard dimensionless SIDIS variables

$$x = \frac{Q^2}{2p \cdot q}, \quad z_h = \frac{p_h \cdot p}{q \cdot p}, \quad y = \frac{Q^2}{xs}, \quad (11)$$

where x is the Bjorken scaling variable, z_h is the fraction of the virtual-photon energy carried by the observed hadron in the target rest frame, and y is the lepton inelasticity. The variable

$$s = (k + p)^2 \quad (12)$$

is the squared lepton-target center-of-mass energy.

The differential SIDIS cross section for charged-hadron production may be written as

$$\frac{d\sigma^h}{dx dy dz_h} = \frac{2\pi\alpha^2}{Q^2} \left[\frac{1 + (1-y)^2}{y} 2F_1^h(x, z_h, Q^2) + \frac{2(1-y)}{y} F_L^h(x, z_h, Q^2) \right], \quad (13)$$

where α is the electromagnetic fine-structure constant, while F_1^h and F_L^h are the transverse and longitudinal SIDIS structure functions, respectively.

At NLO, these structure functions can be written in terms of PDFs, FFs, and perturbative coefficient functions [37,38]:

$$F_1^h = \frac{1}{2} \sum_{q,\bar{q}} e_q^2 \left\{ f_q^N D_q^h + \frac{\alpha_s}{2\pi} [f_q^N \otimes C_{qq}^1 \otimes D_q^h + f_q^N \otimes C_{gq}^1 \otimes D_g^h + f_g^N \otimes C_{qq}^1 \otimes D_q^h + f_g^N \otimes C_{gq}^1 \otimes D_g^h] \right\}, \quad (14)$$

$$F_L^h = \frac{\alpha_s}{2\pi} \sum_{q,\bar{q}} e_q^2 \left[f_q^N \otimes C_{qq}^L \otimes D_q^h + f_q^N \otimes C_{gq}^L \otimes D_g^h + f_g^N \otimes C_{qq}^L \otimes D_q^h + f_g^N \otimes C_{gq}^L \otimes D_g^h \right]. \quad (15)$$

Here, e_q is the electric charge of quark or antiquark q in units of the positron charge, f_q^N and f_g^N are the quark or antiquark and gluon PDFs of the target, and D_q^h and D_g^h are the corresponding quark or antiquark and gluon FFs. The sum $\sum_{q,\bar{q}}$ runs over all active quark and antiquark flavors.

The coefficient functions C_{ab}^1 and C_{ab}^L correspond to the structure functions F_1^h and F_L^h , respectively. In the index convention used above, the first index labels the fragmenting final-state parton and the second index labels the incoming parton. Thus, for example, C_{gq} describes a channel with an incoming quark and a fragmenting final-state gluon, whereas C_{qq} corresponds to an incoming gluon and a fragmenting quark. The dependence of the

PDFs, FFs, coefficient functions, and strong coupling on the factorization and renormalization scales is suppressed in these equations for readability.

The double convolution appearing in the structure functions is defined as

$$[f \otimes C \otimes D](x, z_h) \equiv \int_x^1 \frac{d\xi}{\xi} \int_{z_h}^1 \frac{d\zeta}{\zeta} \times f\left(\frac{x}{\xi}\right) C(\xi, \zeta) D\left(\frac{z_h}{\zeta}\right), \quad (16)$$

where ξ and ζ are the longitudinal momentum fractions entering the initial-state and final-state convolutions, respectively.

The COMPASS multiplicity is defined as the ratio of the semi-inclusive hadron-production cross section to the corresponding inclusive deep-inelastic-scattering (DIS) cross section,

$$\frac{dM^h(x, z_h, Q^2)}{dz_h} = \frac{d^3\sigma^h(x, z_h, Q^2)/dx dQ^2 dz_h}{d^2\sigma^{\text{DIS}}(x, Q^2)/dx dQ^2}. \quad (17)$$

At leading order (LO), this expression reduces to

$$\frac{dM^h}{dz_h} = \frac{\sum_{q,\bar{q}} e_q^2 f_q^N(x, Q^2) D_q^h(z_h, Q^2)}{\sum_{q,\bar{q}} e_q^2 f_q^N(x, Q^2)}. \quad (18)$$

The different electric-charge and PDF weights associated with the quark and antiquark flavors make the charge-separated SIDIS multiplicities for h^+ and h^- particularly important for determining the flavor dependence of the FFs.

D. Timelike DGLAP evolution and perturbative order

The dependence of the FFs on the factorization scale is governed by the timelike DGLAP evolution equations,

$$\frac{dD_i^h(z, \mu^2)}{d \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \sum_j \int_z^1 \frac{d\xi}{\xi} P_{ji}^T(\xi, \alpha_s) D_j^h\left(\frac{z}{\xi}, \mu^2\right). \quad (19)$$

Here, i and j label quarks, antiquarks, and the gluon, and P_{ji}^T is the timelike splitting function that couples the FF D_j^h to the scale evolution of D_i^h . The superscript T distinguishes the timelike evolution kernels relevant for fragmentation from the spacelike kernels entering PDF evolution.

The timelike splitting functions are expanded perturbatively as

$$P_{ji}^T(z, \alpha_s) = P_{ji}^{T,(0)}(z) + \frac{\alpha_s}{2\pi} P_{ji}^{T,(1)}(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 P_{ji}^{T,(2)}(z) + \mathcal{O}(\alpha_s^3). \quad (20)$$

The leading-order evolution involves only $P^{T,(0)}$, while the NLO and NNLO evolutions additionally include $P^{T,(1)}$ and $P^{T,(2)}$, respectively.

The NNLO timelike evolution used in modern FF extractions is based on the known NNLO timelike splitting functions and their implementations in evolution libraries [39–42]. For SIA, the perturbative coefficient functions are available through NNLO [43–45].

Full fixed-order NNLO QCD coefficient functions for unpolarized SIDIS have also become available [31–34]. In the present analysis, NNLO SIDIS coefficient functions are incorporated through the implementation used in *MontBlanc* [4,25,35]. Consequently, the NNLO analysis consistently combines NNLO timelike evolution with coefficient functions through $\mathcal{O}(\alpha_s^2)$ for both SIA and SIDIS observables. The explicit expressions above display the NLO partonic decomposition for clarity; at NNLO, the additional two-loop coefficient-function contributions and partonic channels are included numerically in the theoretical predictions.

E. Flavor basis and charge conjugation

For positively charged unidentified hadrons, we parametrize the independent FF combinations at the input scale $Q_0 = 5$ GeV as

$$D_u^{h^+}, D_{\bar{u}}^{h^+}, D_{d+s}^{h^+}, D_{\bar{d}+\bar{s}}^{h^+}, D_{c^+}^{h^+}, D_{b^+}^{h^+}, D_g^{h^+}. \quad (21)$$

The strange-quark contribution is included in the SIDIS and SIA flavor sums, but it is not parametrized as an additional independent neural-network output in the present fit. Instead, the strange and antistrange FFs are tied to the light-antiquark sector through the same flavor-basis assumption used in the fit implementation and in the previous SHK22.h analysis [20]. This reduces the number of independent nonperturbative degrees of freedom in a sector that is only weakly constrained by the present unidentified charged-hadron data.

The FFs for negatively charged hadrons are obtained using charge conjugation,

$$D_q^{h^-}(z, Q) = D_{\bar{q}}^{h^+}(z, Q), \quad D_{\bar{q}}^{h^-}(z, Q) = D_q^{h^+}(z, Q), \quad (22)$$

and

$$D_g^{h^-}(z, Q) = D_g^{h^+}(z, Q). \quad (23)$$

For the initial-state parton distributions entering the SIDIS predictions, we use the NNPDF4.0 sets [46], namely *NNPDF40_nlo_pch_as_01180* and *NNPDF40_nnlo_pch_as_01180* for the NLO and NNLO analyses, respectively. The strong coupling is fixed to $\alpha_s(M_Z) = 0.118$, with $M_Z = 91.1876$ GeV, consistently with the corresponding PDF ensembles. The heavy-quark thresholds are set to $Q_c = 1.51$ GeV and $Q_b = 4.92$ GeV for charm and bottom, respectively.

F. Parametrization and uncertainty propagation

The FFs are parametrized at $Q_0 = 5$ GeV using a neural-network representation, following previous neural-network FF extractions and the *MontBlanc* framework [4,20,25,26,36]. For each independent flavor combination, we write

$$zD_i^{h^+}(z, Q_0) = [N_i(z, \theta) - N_i(1, \theta)]^2, \quad (24)$$

where $N_i(z, \theta)$ is the neural-network output and θ denotes the set of internal parameters. The subtraction enforces the end point condition at $z = 1$, while the squared form guarantees positivity at the input scale.

The baseline architecture contains one hidden layer with 20 neurons. Experimental uncertainties are propagated using Monte Carlo replicas. In the present analysis we use $N_{\text{rep}} = 200$ replicas. In the *MontBlanc* implementation, minimization uses the *Ceres Solver* package and analytic neural-network derivatives from NNAD [4,47,48].

III. EXPERIMENTAL DATASETS AND KINEMATIC CUTS

The present analysis uses SIA data and COMPASS SIDIS multiplicities for unidentified charged hadrons. To isolate the impact of the new and revised COMPASS measurements, we use the same SIA baseline as in the previous SHK22.h analysis [20] and update the COMPASS SIDIS input [21,22].

The corresponding kinematic coverage in the (z, Q^2) plane is shown in Fig. 1. The dashed horizontal line indicates the baseline cut $Q^2 > 1.96$ GeV², corresponding to $Q > 1.4$ GeV.

A. SIA datasets

The SIA dataset consists of inclusive and flavor-tagged measurements of unidentified charged-hadron production in

$$e^+e^- \rightarrow h^\pm + X \quad (25)$$

from the TASSO, TPC, ALEPH, DELPHI, OPAL, and SLD Collaborations [49–56]. These measurements provide the cleanest constraints on charge-summed fragmentation combinations, since no PDFs enter the SIA observable. The flavor-tagged data taken at the Z pole are particularly important for separating light-, charm-, and bottom-quark fragmentation components.

For measurements taken at the Z pole we retain $0.02 \leq z \leq 0.9$, while for lower-energy SIA data we impose $0.075 \leq z \leq 0.9$ [4,20]. The more restrictive lower cut applied to the lower-energy data reduces the impact of the small- z region, where fixed-order calculations are more sensitive to small- z logarithms, hadron-mass effects, and other effects beyond the leading-power massless approximation. The upper cut removes the end point region, where

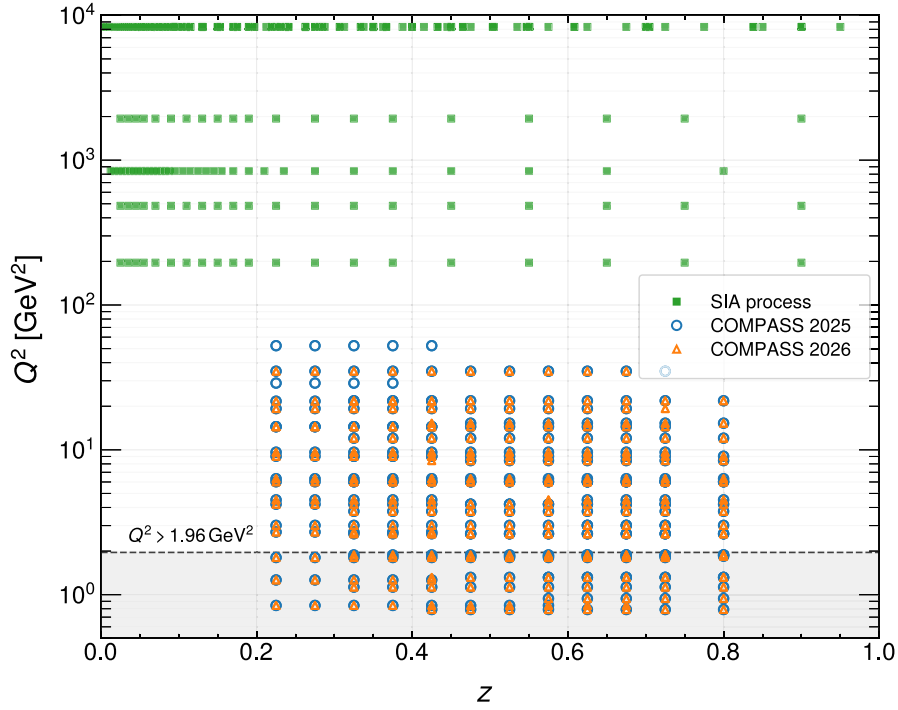


FIG. 1. Kinematic coverage in the (z, Q^2) plane for the datasets included in the present analysis. The COMPASS 2025 proton-target multiplicities and the revised isoscalar-target multiplicities from the 2026 COMPASS addendum for unidentified charged hadrons are shown together with the SIA datasets. The dashed horizontal line indicates the baseline perturbative cut, $Q^2 > 1.96 \text{ GeV}^2$, corresponding to $Q > 1.4 \text{ GeV}$.

threshold logarithms and experimental limitations become increasingly important.

B. COMPASS SIDIS data

The central new ingredient is the use of the COMPASS 2025 proton-target measurement [21] together with the revised ${}^6\text{LiD}$ -target multiplicities provided in the 2026 COMPASS [22]. The new proton-target measurement provides charge-separated multiplicities for $\pi^\pm$, $K^\pm$, and $h^\pm$ from a liquid hydrogen target, covering

$$\begin{aligned} Q^2 &> 1 \text{ GeV}^2, & 0.004 < x < 0.4, \\ 0.1 < y < 0.7, & 0.2 < z < 0.85. \end{aligned} \quad (26)$$

The data referred to here as the COMPASS isoscalar-target data were measured using a solid-state ${}^6\text{LiD}$ target. Owing to small admixtures of H, ${}^3\text{He}$, and ${}^7\text{Li}$, the target has an effective neutron excess of approximately 0.2% and is therefore only approximately isoscalar [22]. Following the standard COMPASS treatment, we approximate the target as effectively isoscalar in the theoretical calculation. The 2026 COMPASS does not correspond to a new target measurement; rather, it provides revised multiplicities for the same ${}^6\text{LiD}$ data using DJANGO-based quantum electrodynamics (QED) radiative corrections. In the following, we refer to this dataset as the revised ${}^6\text{LiD}$ -target data.

The use of the revised multiplicities is an important ingredient of the present analysis. In the COMPASS 2026, the earlier TERAD-based treatment of the radiative corrections was replaced by correction factors derived with the DJANGO Monte Carlo generator, following the strategy used in the recent proton-target measurement. This improved treatment leads to non-negligible changes in some kinematic regions; in particular, the COMPASS addendum reports corrections up to about 12% larger in the low- x , high- z region compared with the previously applied ones. Using the revised isoscalar multiplicities therefore ensures a consistent radiative-correction treatment of the proton- and isoscalar-target COMPASS datasets and avoids combining the new proton data with superseded isoscalar multiplicities.

For unidentified charged hadrons, the pion mass is assumed in the reconstruction of the hadron energy fraction [21]. The fit uses the published unidentified charged-hadron multiplicities in the stated SIDIS phase space. The additional particle-identification and acceptance requirements associated with the COMPASS RICH detector are part of the experimental treatment of the identified-hadron samples and of the parent measurement [21,57]; they are not introduced here as separate cuts beyond the published unidentified charged-hadron multiplicities used in the fit.

The COMPASS 2026 updates the older ${}^6\text{LiD}$ -target multiplicities for charged pions, charged kaons, and unidentified charged hadrons [22]. The revised multiplicities are

obtained by removing the earlier TERAD-based corrections and applying DJANGO-derived correction factors [21,22,58–61]. The updated isoscalar results supersede the previous COMPASS 2017 measurements [22–24]. In the present analysis, this replacement is essential for combining the COMPASS proton-target and ${}^6\text{LiD}$ -target measurements on a consistent radiative-correction footing.

For the FF extraction, we use multiplicities corrected for QED radiation and diffractive vector-meson contributions. Hadrons from diffractive vector-meson decays do not correspond to the independent parton fragmentation mechanism described by standard collinear FFs. For unidentified charged hadrons and pions, the dominant contamination is associated with ρ^0 production, while for kaons it is mainly from ϕ decays [21,62].

C. Kinematic cuts and uncertainty treatment

Small- z and low- Q regions are theoretically delicate because of small- z logarithms, hadron-mass effects, target-mass effects, higher-twist contributions, and possible limitations of the current-fragmentation approximation [63–66]. For COMPASS SIDIS multiplicities we retain the published range $0.2 < z < 0.85$ and impose a lower cut on Q , selected by the scan described in Sec. IV.

The COMPASS systematic uncertainties contain a large bin-to-bin correlated component. Following the COMPASS recommendation and the treatment used in the MAPFF/MontBlanc framework, we take 80% of the systematic uncertainty as correlated and add the remaining uncorrelated component in quadrature with the statistical uncertainty [4,21,22]. Thus, the uncorrelated uncertainty entering the diagonal part of the covariance matrix is taken to be

$$\sigma_{\text{unc}} = \sqrt{\sigma_{\text{stat}}^2 + (0.6\sigma_{\text{syst}})^2},$$

where the factor $0.6 = \sqrt{1 - 0.8^2}$ corresponds to the remaining uncorrelated fraction of the systematic uncertainty. The

correlated systematic component is then

$$\sigma_{\text{corr}} = 0.8\sigma_{\text{syst}}.$$

IV. SELECTION OF THE LOWER SIDIS SCALE CUT

The COMPASS multiplicities extend to relatively low photon virtualities, where a fixed-order leading-power description may become less reliable. In this region, higher-twist effects, target-mass and hadron-mass corrections, and limitations of the current-fragmentation approximation may become increasingly important. Since the present analysis includes both the COMPASS 2025 proton-target measurement and the revised ${}^6\text{LiD}$ -target multiplicities provided in the 2026 COMPASS, it is important to determine a lower cut on the hard scale that provides a stable perturbative description without unnecessarily removing SIDIS information from the fit.

We therefore perform a scan in the lower SIDIS scale cut $Q_{\text{min}} \equiv Q_{\text{cut}}$ using the values $Q_{\text{cut}} = 1.0, 1.2, 1.4, 1.7, 1.8, 2.0$ GeV. For each value of Q_{cut} , the global fit is repeated at both NLO and NNLO accuracy. The scan is performed separately for the charge-separated COMPASS h^+ and h^- samples from the new proton-target data and from the revised isoscalar-target data, and also for the total SIDIS contribution.

The results are shown in Fig. 2. At the lowest cut, $Q_{\text{cut}} = 1.0$ GeV, the fit includes the largest number of COMPASS SIDIS points, but the corresponding values of χ^2/N_{dat} are visibly larger for several subsets. This is particularly evident for the revised COMPASS h^+ 2026 data, and it is also reflected in the total contribution. Increasing the cut from 1.0 to 1.2 GeV improves the description, but some remaining tension is still visible, especially in the low- Q region. A further increase to $Q_{\text{cut}} = 1.4$ GeV leads to a substantial improvement of the total χ^2/N_{dat} at both perturbative orders. At this value, the

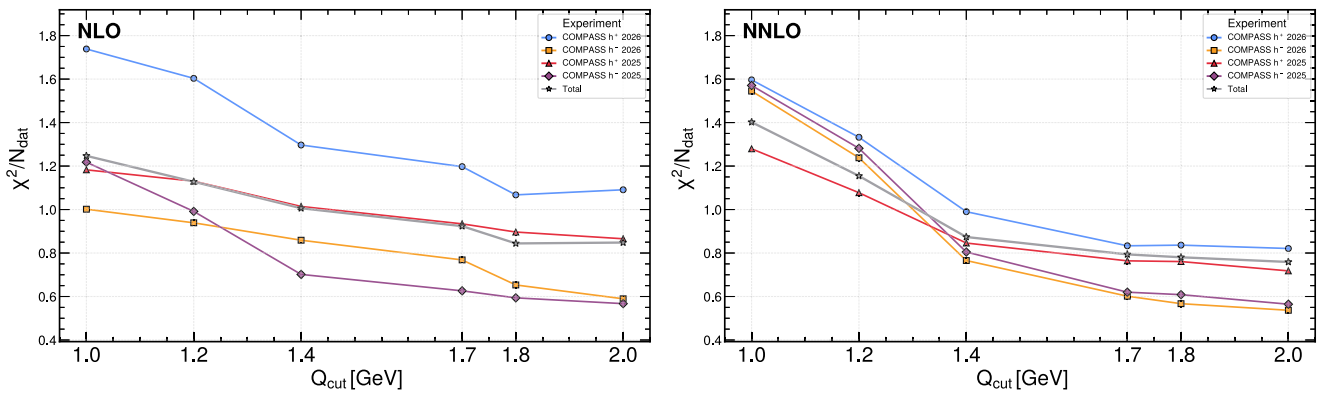


FIG. 2. Values of χ^2/N_{dat} as a function of the lower SIDIS scale cut Q_{cut} for the COMPASS unidentified charged-hadron multiplicities. Results are shown at both NLO (left) and NNLO (right) for the COMPASS 2025 proton-target h^+ and h^- multiplicities, revised ${}^6\text{LiD}$ -target h^+ and h^- multiplicities from the COMPASS 2026, and the corresponding total SIDIS contribution.

description of the new COMPASS 2025 data and the revised COMPASS 2026 one becomes stable and acceptable. The improvement is seen not only in the total contribution, but also in the individual charge-separated subsets. In particular, the larger tension observed at lower cuts is significantly reduced, while a large fraction of the SIDIS data is still retained in the fit.

For larger values of the cut, such as $Q_{\text{cut}} = 1.7, 1.8$, and 2.0 GeV, the total χ^2/N_{dat} decreases further or remains comparably stable. However, these more conservative choices remove a larger fraction of the COMPASS SIDIS data. Since the charge-separated SIDIS multiplicities are the main source of flavor sensitivity in the present analysis, applying too high a cut would weaken the constraining power of the fit, especially for the light-quark and antiquark FFs. We therefore choose $Q_{\text{min}} = 1.4$ GeV as the default scale cut for both the NLO and NNLO analyses. This choice represents the best compromise in the present study: it removes the least stable low- Q region, yields a significant improvement in the fit quality, and preserves a substantial amount of the new and revised COMPASS SIDIS information. The same value of Q_{min} is used for both the NLO and NNLO fits.

V. RESULTS

In this section we present the main results of the global QCD analysis. We discuss the quality of the fit, the description of the modern COMPASS SIDIS multiplicities, and the resulting unidentified charged-hadron FFs. Particular attention is given to the impact of the updated COMPASS input on the light-quark and antiquark fragmentation sectors. We also use the NLO-NNLO comparison to assess the perturbative stability of the extraction and compare the present NLO result with NNFF1.1h.

A. Fit quality

The quality of the final fits is summarized in Fig. 3, where we show the dataset-level values of χ^2/N_{dat} for the SIA datasets, the COMPASS SIDIS multiplicities, and the global total. The final dataset contains

$$N_{\text{dat}}^{\text{SIA}} = 370, \quad N_{\text{dat}}^{\text{SIDIS}} = 886, \quad N_{\text{dat}}^{\text{tot}} = 1256.$$

The corresponding global fit qualities are

$$(\chi^2/N_{\text{dat}})_{\text{NLO}} = 0.943, \quad (\chi^2/N_{\text{dat}})_{\text{NNLO}} = 0.873.$$

These values show that the combined SIA and modern COMPASS SIDIS datasets are described well at both perturbative orders. The smaller global value obtained at NNLO indicates a modest improvement in the overall fit quality. This improvement should be viewed as an indication of perturbative stability within the theoretical setup adopted in our QCD analysis.

Figure 3 provides a compact overview of the dataset-by-dataset fit quality. For each individual SIDIS and SIA dataset, the values of χ^2/N_{dat} are shown at NLO and NNLO using blue and orange open-square markers, respectively. The vertical blue dashed and orange dotted lines indicate the corresponding global-fit values, while the gray dashed line marks the reference value $\chi^2/N_{\text{dat}} = 1$. The number of data points, N_{dat} , is also indicated for each dataset. The COMPASS subsets comprise the 2025 proton-target and revised 2026 ^6LiD -target multiplicities for both h^+ and h^- . The figure shows that the SIDIS datasets are generally well described and do not dominate the total χ^2 . In particular, the revised COMPASS 2026 h^+ contribution decreases noticeably when going from NLO to NNLO, while the other COMPASS subsets remain at an acceptable level. Nevertheless, the combined SIA contribution remains below unity at both perturbative orders,

$$(\chi^2/N_{\text{dat}})_{\text{SIA}}^{\text{NLO}} = 0.954, \quad (\chi^2/N_{\text{dat}})_{\text{SIA}}^{\text{NNLO}} = 0.927.$$

Similarly, the total SIDIS contribution decreases from $(\chi^2/N_{\text{dat}})_{\text{SIDIS}}^{\text{NLO}} = 0.934$ to $(\chi^2/N_{\text{dat}})_{\text{SIDIS}}^{\text{NNLO}} = 0.851$.

The good description of both sectors shows that the modern COMPASS SIDIS input can be incorporated consistently with the SIA data in a single global extraction. The NNLO improvement should be regarded as a perturbative-stability indication within the present theoretical framework.

B. Description of COMPASS multiplicities

Figures 4 and 5 show the comparison between the final fitted theory predictions and the COMPASS multiplicities for unidentified charged-hadron production. The COMPASS 2025 measurement is shown in Fig. 4, while the COMPASS 2026 are shown in Fig. 5. Both figures display the multiplicities as functions of the hadron energy fraction z in bins of x and y . Filled circles denote the h^+ data, open squares denote the h^- data, solid curves show the fitted predictions for h^+ , and dashed curves show the corresponding predictions for h^- . The different y intervals are separated by the multiplicative factors $\alpha = 1, 2, 4, 8, 16$, as indicated in the first panel. The vertical bars represent the experimental uncorrelated uncertainties used in the fit. The plotted predictions correspond to the final global fit, for which the SIDIS data are selected with $Q_{\text{min}} = 1.4$ GeV.

The shaded regions show the prediction uncertainty propagated from the Monte Carlo replica ensemble to the SIDIS multiplicities. For each kinematic point, the central curve corresponds to the fitted theory prediction, while the band represents the one-standard-deviation spread of the corresponding replica predictions. Since we follow the same *MontBlanc* strategy, in which a PDF replica is assigned to each fitted FF replica in the SIDIS calculation, this uncertainty includes both the uncertainty of the fitted FF ensemble and the propagated PDF uncertainty. It does not include additional uncertainties from

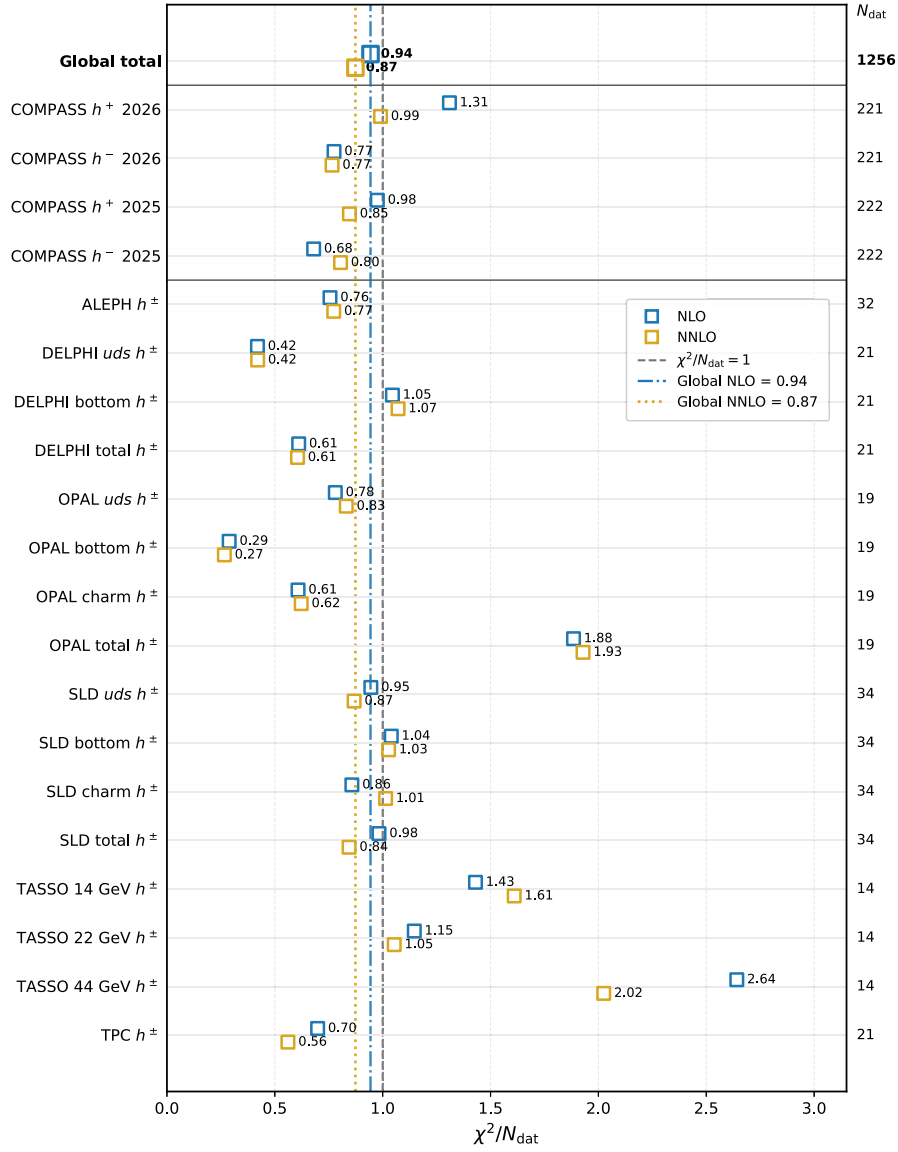


FIG. 3. Dataset-level fit quality for the final global analysis. The figure shows χ^2/N_{dat} for the individual SIA datasets, the COMPASS 2025 proton-target multiplicities, the revised COMPASS 2026 ^6LiD -target multiplicities, and the global total. The NLO and NNLO results are displayed using blue and orange open-square markers, respectively. The corresponding global-fit values are indicated by vertical blue dashed and orange dotted lines, while the gray dashed line marks the reference value $\chi^2/N_{\text{dat}} = 1$. The number of data points, N_{dat} , is shown for each dataset.

variations of α_s , renormalization or factorization scales, or missing higher-order corrections. To improve the visibility of the very narrow uncertainty bands, they are displayed with darker shading and outlined by thin boundary curves. This choice affects only the graphical representation; the numerical uncertainties are not modified or enlarged. The COMPASS 2025 proton-target multiplicities in Fig. 4 shows that the fitted predictions describe the main features of the measured h^+ and h^- distributions. The theory follows the overall decrease of the multiplicities with increasing z across the displayed x and y bins and reproduces the observed charge separation between h^+ and h^- . In many bins the h^+ multiplicities are larger than

the corresponding h^- multiplicities, reflecting the flavor sensitivity of the proton target and its enhanced sensitivity to u -dominated PDF-weighted combinations. This feature is particularly important for the present analysis, since the proton-target data provide direct charge-separated information on the light-quark and antiquark components of the unidentified charged-hadron FFs.

The agreement in Fig. 4 is generally good over most of the measured kinematic range. The fitted curves describe both the normalization and the shape of the data in most panels. Visible deviations, where present, occur mainly near the edges of the measured phase space, especially at larger values of z , in the highest- x bins, or in bins with

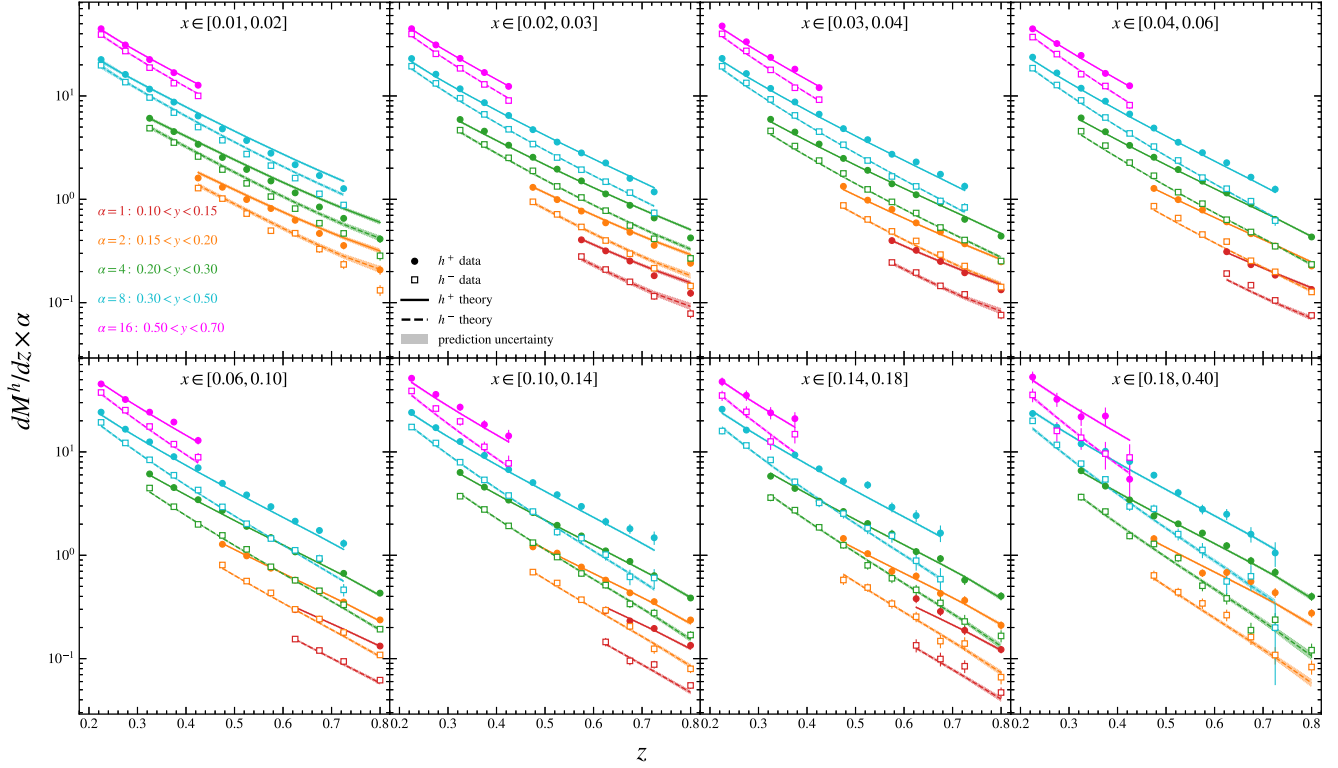


FIG. 4. COMPASS 2025 proton-target multiplicities for unidentified charged hadrons [21] compared with the final fitted theory predictions. The multiplicities are shown as functions of z in bins of x and y . Filled circles denote h^+ data and open squares denote h^- data. Solid curves show the predictions for h^+ , while dashed curves show the corresponding predictions for h^- . The vertical bars represent the experimental uncorrelated uncertainties used in the fit, and the shaded bands indicate the one-standard-deviation prediction uncertainty propagated from the fitted FF replicas. The different y intervals are separated by multiplicative factors α , as indicated in the first panel.

fewer data points. These regions are more sensitive to end point effects, reduced statistics, possible residual power corrections, and limitations of the fixed-order leading-power description. The prediction bands are narrow in most of the well-constrained intermediate- z region and are often comparable to, or smaller than, the thickness of the central theory curves. They become visibly broader mainly in the less constrained parts of the displayed kinematic range, in particular at small x , small y , and toward larger z .

Figure 5 shows the corresponding comparison for the multiplicities from the COMPASS 2026. These multiplicities supersede the original COMPASS 2017 isoscalar results and provide the updated isoscalar SIDIS input used in the present analysis [22–24]. The fitted predictions reproduce the main z dependence of both h^+ and h^- multiplicities and give a good description of the charge separation over a broad range of x and y . Compared with the proton-target data, the isoscalar target provides a more balanced light-flavor weighting and therefore gives complementary information on the quark and antiquark FFs. The successful description of the revised isoscalar multiplicities provides an important consistency check of the present analysis, since these data replace the older COMPASS isoscalar input used in previous charged-hadron FF determinations.

The uncertainty representation is the same in Figs. 4 and 5. In both cases, the experimental uncertainties correspond to the uncorrelated uncertainties entering the diagonal part of the covariance matrix, while the shaded prediction bands represent only the FF-replica uncertainty of the fitted theory curves. The small size of the prediction bands in most bins reflects the strong constraints provided by the combined SIA and modern COMPASS SIDIS data in the displayed kinematic region, rather than an estimate of the full theoretical uncertainty. The overall agreement between the data points and the theory curves indicates that the final fit captures the dominant normalization and shape features of the measured multiplicities.

C. The HAPS-hFF1.0 fragmentation-function set

We now present the resulting HAPS-hFF1.0 determination of unidentified charged-hadron fragmentation functions. The comparison between the NLO and NNLO extractions is shown in Fig. 6 for the independent unidentified charged-hadron FFs at $Q = 5$ GeV

$$D_u^{h^+}, \quad D_{\bar{u}}^{h^+}, \quad D_{d+s}^{h^+}, \quad D_{d+\bar{s}}^{h^+}, \quad D_g^{h^+}, \quad D_{c^+}^{h^+}, \quad D_{b^+}^{h^+}.$$

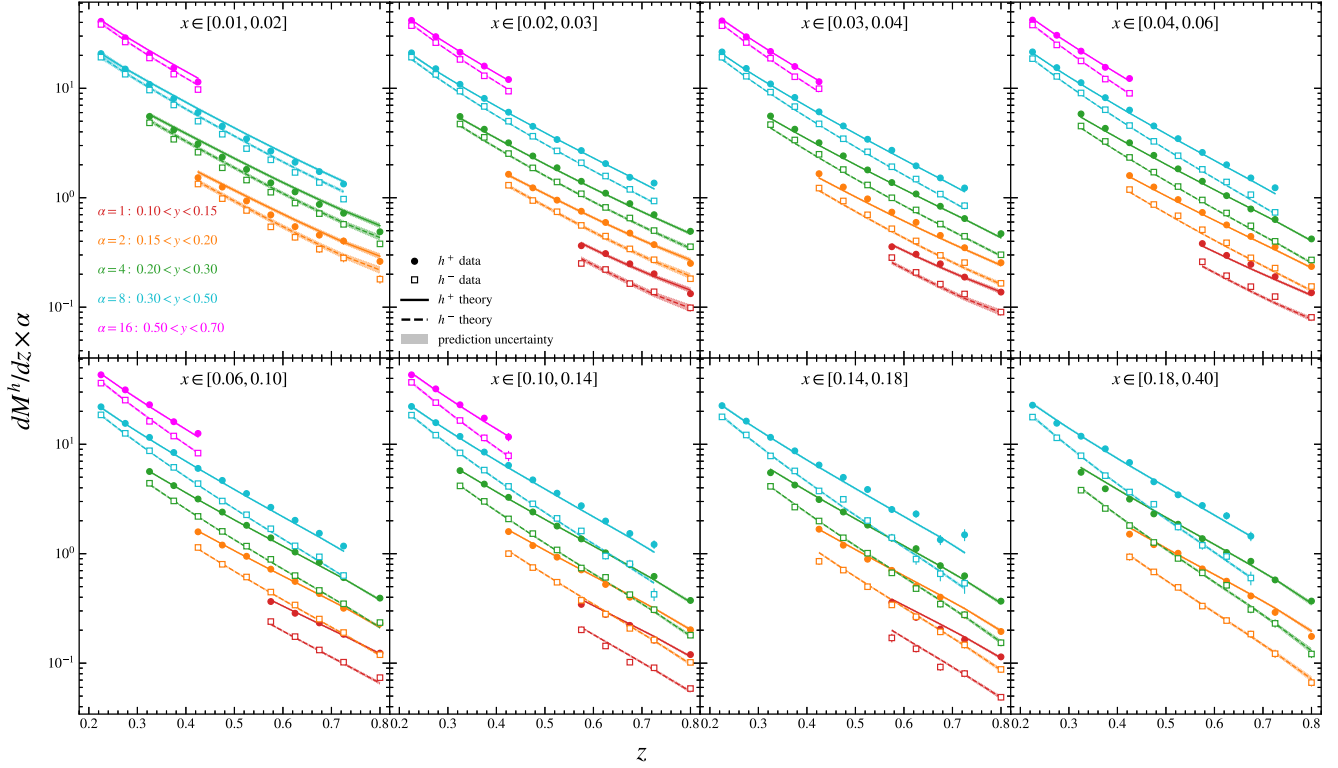


FIG. 5. Revised multiplicities for unidentified charged hadrons provided in the COMPASS 2026 [22], compared with the final fitted theory predictions. These multiplicities supersede the original COMPASS 2017 isoscalar results. The same symbol, line, and uncertainty conventions as in Fig. 4 are used.

The upper panel of each plot displays $zD_t^{h+}(z, Q)$, while the lower panel shows the corresponding self-normalized ratios, obtained by dividing each NLO and NNLO replica band by its own central prediction. The green bands correspond to the NLO extraction and the blue bands to the NNLO extraction.

Overall, the NLO and NNLO FFs are broadly compatible over most of the fitted z range. This agreement is particularly clear for the quark and heavy-quark combinations, where the central values are close and the uncertainty bands largely overlap. The u -quark FF shows very good stability between the two perturbative orders, with only small shifts in the central value. The $\bar{u}$ FF is also compatible between NLO and NNLO, with somewhat larger differences appearing mainly near the edges of the fitted z range. The d and $\bar{d}$ FFs display a similar pattern, although their uncertainty bands are generally broader and their order-by-order variation is more visible than in the u sector. This is expected because the d -type combinations are less directly constrained by the proton-dominated SIDIS flavor weights.

The heavy-quark combinations, $D_{c^+}^{h+}$ and $D_{b^+}^{h+}$, show a high degree of perturbative stability. Their NLO and NNLO central values are close over the fitted range, and their uncertainty bands are well controlled. This behavior reflects the dominant role of flavor-tagged SIA data in

constraining the heavy-quark FFs. By contrast, the gluon FF exhibits the largest visible difference between the NLO and NNLO extractions and also carries the largest uncertainty band. This is consistent with the fact that, in an SIA + SIDIS analysis, the gluon is constrained mainly indirectly through scaling violations, higher-order coefficient functions, and correlations with the quark sector, rather than through a direct leading-order SIDIS sensitivity.

The ratio panels provide a more detailed view of the relative uncertainty of each extraction. Since each band is normalized to its own central prediction, the ratio panels should not be interpreted as direct NLO/NNLO ratios. Instead, they illustrate the size of the replica uncertainties around the corresponding NLO and NNLO central values. For most light-quark and heavy-quark FFs, the relative uncertainties remain moderate in the region where the data provide the strongest constraints. Larger relative uncertainties are observed toward small and large values of z , where extrapolation effects, small- z logarithmic contributions, end point sensitivity, and reduced experimental constraints become more important. The gluon band shows the largest relative uncertainty, confirming that the gluon FF remains the least directly constrained component of the present SIA + SIDIS extraction.

This behavior is consistent with the global fit qualities discussed above. The NNLO fit gives a modestly smaller

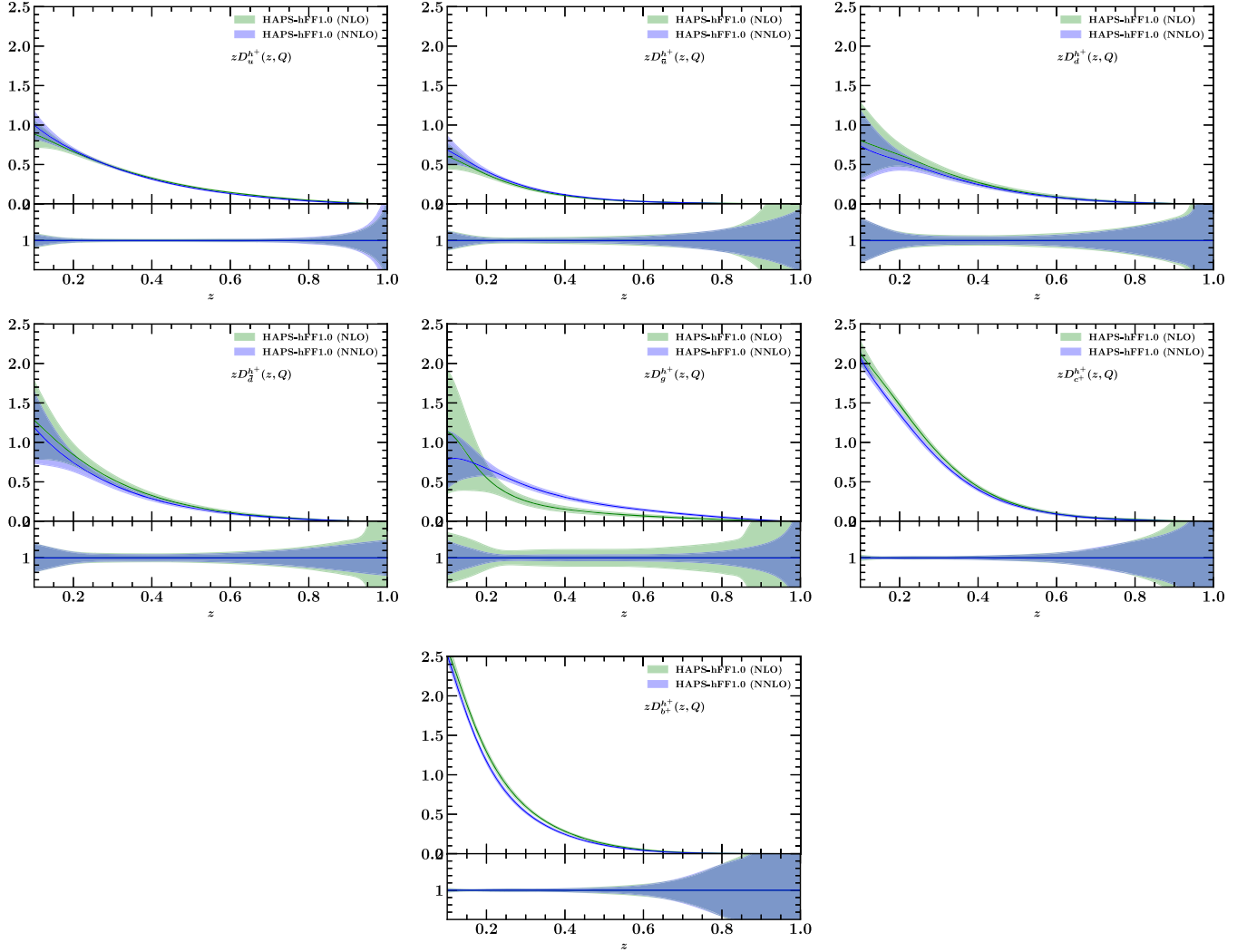


FIG. 6. Comparison of the HAPS-hFF1.0 unidentified charged-hadron FFs at NLO and NNLO at $Q = 5$ GeV. The panels show $zD_i^{h+}(z, Q)$ for the independent flavor combinations $u, \bar{u}, d, \bar{d}, g, c^+$, and b^+ . Green bands denote the NLO result and blue bands denote the NNLO result. The lower panel in each plot shows the self-normalized ratio for each perturbative order, obtained by dividing the corresponding NLO or NNLO replica band by its own central prediction. The bands represent the FF uncertainty estimated from the fitted replica ensemble.

total value $\chi^2/N_{\text{dat}} = 0.873$ compared with $\chi^2/N_{\text{dat}} = 0.943$ at NLO. The improvement in the total fit quality is reflected in the slightly shifted NNLO central values, while the broad overlap of the NLO and NNLO uncertainty bands indicates that the main features of the extraction are stable. We do not interpret the smaller NNLO χ^2/N_{dat} as evidence that NNLO improves every individual dataset or every flavor component. Rather, the comparison should be viewed as a perturbative-stability test of the global extraction.

It is also important to recall the theoretical status of the NNLO calculation used here. The SIA coefficient functions and timelike DGLAP evolution are included at NNLO accuracy, while the SIDIS contribution is treated within the NNLO perturbative setup implemented in the present framework [4,25,26]. The NNLO FFs should

therefore be interpreted in light of this theoretical setup. Within this framework, Fig. 6 shows that the quark-sector FFs are robust under the change of perturbative order, the heavy-quark FFs are stable, and the gluon remains the least directly constrained component. The updated COMPASS SIDIS data thus provide stable constraints on the light-quark flavor separation in the present global analysis.

D. Comparison of HAPS-hFF1.0 with NNFF1.1h

In Fig. 7, we compare the present HAPS-hFF1.0 NLO FFs with the NNFF1.1h determination [18] at $Q = 5$ GeV. The comparison is shown for the independent unidentified charged-hadron FF combinations

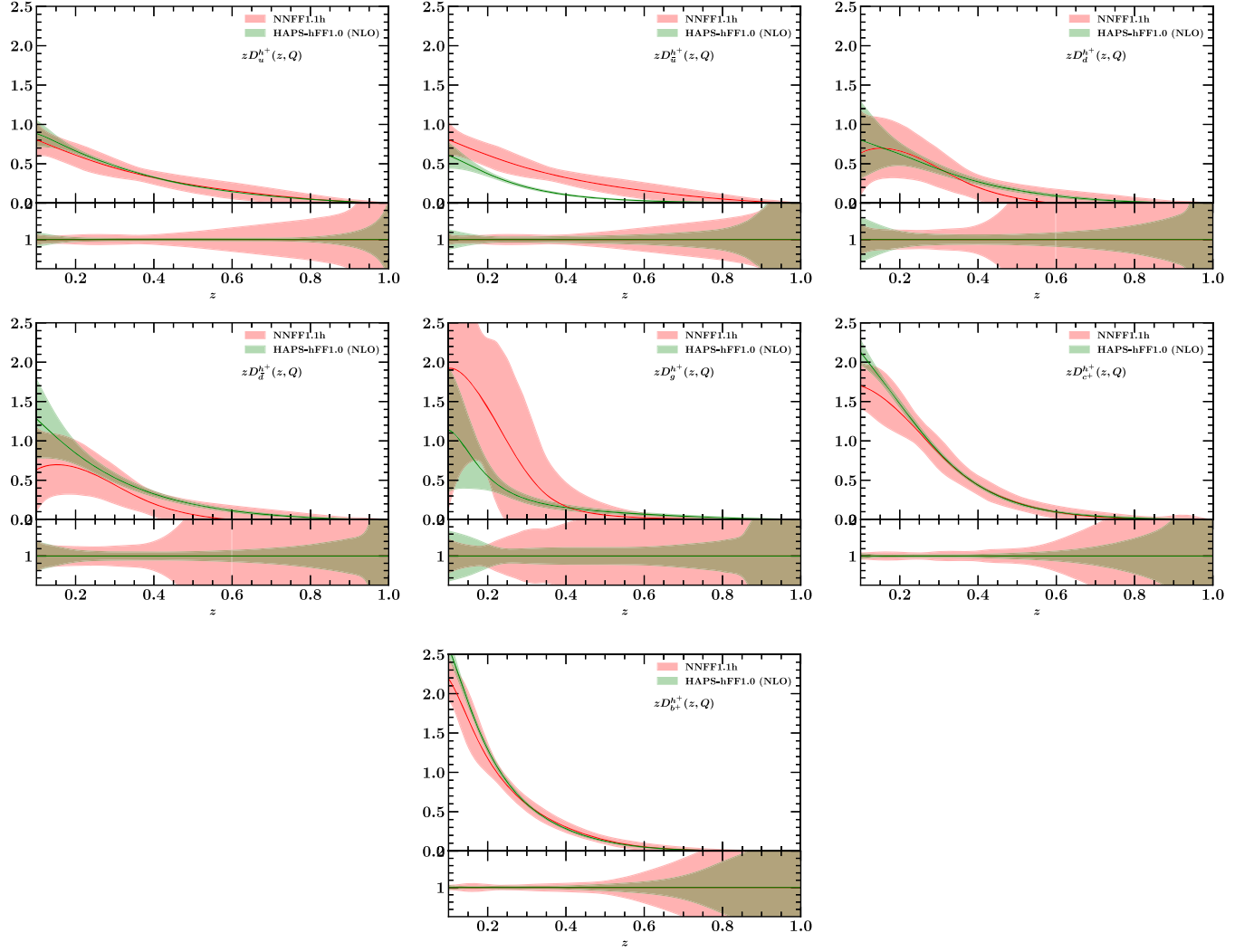


FIG. 7. Comparison of the present HAPS-hFF1.0 NLO FFs with NNFF1.1h [18] at $Q = 5$ GeV. Red bands denote NNFF1.1h and green bands denote the present HAPS-hFF1.0 NLO result. The panels show $zD_i^{h+}(z, Q)$ for the independent flavor combinations, together with the corresponding relative uncertainty bands in the lower panel of each plot, obtained by normalizing each FF ensemble to its own central value. The comparison is performed at NLO because NNFF1.1h is an NLO determination. The largest difference appears in the gluon analysis, reflecting the fact that NNFF1.1h includes hadron-collider data that directly constrain gluon fragmentation, whereas the present analysis uses SIA and modern COMPASS SIDIS multiplicities.

$$D_u^{h+}, \quad D_{\bar{u}}^{h+}, \quad D_{d+s}^{h+}, \quad D_{d+\bar{s}}^{h+}, \quad D_g^{h+}, \quad D_{c^+}^{h+}, \quad D_{b^+}^{h+}.$$

The upper panel of each plot displays $zD_i^{h+}(z, Q)$, while the lower panel shows the corresponding relative uncertainty bands, obtained by normalizing each FF ensemble to its own central value. The red bands denote NNFF1.1h, and the green bands denote the present HAPS-hFF1.0 NLO result.

This comparison is useful for assessing the consistency of the present extraction with an earlier determination of unidentified charged-hadron FFs, but it should not be interpreted as a direct one-to-one comparison of two identical analyses. The two fits are based on different experimental inputs and different methodologies. The

present HAPS-hFF1.0 analysis is a direct global refit using SIA data together with the new COMPASS 2025 SIDIS multiplicities and the revised COMPASS 2026 SIDIS multiplicities. These charge-separated SIDIS data provide direct sensitivity to the light-quark and antiquark flavor structure. In contrast, NNFF1.1h is an NLO determination based on an SIA prior supplemented by hadron-collider data through Bayesian reweighting [18]. The collider data included in NNFF1.1h provide strong sensitivity to the gluon and singlet FF combinations, while the present analysis is designed to isolate the impact of the updated COMPASS SIDIS input.

For the u -quark FF, the HAPS-hFF1.0 and NNFF1.1h central values are broadly compatible over much of the fitted z range, with overlapping uncertainty bands in the

region where the data provide the strongest constraints. The situation is somewhat different for the $\bar{u}$ FF. In this channel, the present HAPS-hFF1.0 result is shifted downward with respect to NNFF1.1h and lies outside the NNFF1.1h one-standard-deviation band in part of the fitted z range. This difference should not be interpreted as a direct inconsistency between the two determinations, since the two fits use different datasets and different constraining mechanisms. In the present analysis, the charge-separated COMPASS SIDIS multiplicities provide direct information on quark-antiquark separation, whereas NNFF1.1h is based on an SIA prior supplemented by hadron-collider data through Bayesian reweighting. The observed shift in the $\bar{u}$ channel therefore reflects the additional flavor information entering the present SIA + SIDIS fit.

The d -type combinations also show visible differences. This is not unexpected, because these channels are less directly constrained than the u -dominated combinations in proton-target SIDIS, and their extraction is more sensitive to the interplay between proton and isoscalar targets. The differences in the low- and intermediate- z regions therefore reflect the different flavor information entering the two analyses. The comparison should also be viewed in light of the fact that the present fit uses the revised COMPASS data together with the new COMPASS data, while NNFF1.1h does not include these charge-separated SIDIS multiplicities in the same way.

The largest difference between the two determinations appears in the gluon FF. This is the most important distinction in Fig. 7. The gluon in NNFF1.1h is strongly affected by the inclusion of hadron-collider charged-particle spectra, which provide direct sensitivity to gluon fragmentation. The present HAPS-hFF1.0 analysis does not include hadron-collider data; in an SIA + SIDIS fit, the gluon is constrained more indirectly through scaling violations, higher-order corrections, and correlations with the quark sector. The difference in the gluon FF should therefore not be interpreted as an inconsistency between the two determinations. Rather, it reflects the complementary constraining power of SIDIS and hadron-collider observables.

The uncertainty band of the gluon FF should also be interpreted with care. Since no proton-proton charged-hadron production data are included in the present fit, the gluon is not directly constrained by hadron-collider observables. The green band shown in Fig. 7 represents the Monte Carlo replica uncertainty within the adopted dataset, parametrization, kinematic cuts, and theoretical framework. It should not be regarded as a complete estimate of all possible methodological and missing-theory uncertainties in the gluon sector. In particular, residual dependence on the functional flexibility, the data selection, the treatment of correlations, and the absence of direct pp constraints may still be relevant. The neural-network parametrization reduces functional-form bias compared with more rigid

analytic forms, but it does not by itself eliminate all possible sources of methodological uncertainty.

The heavy-quark combinations, $D_{c^+}^{h^+}$ and $D_{b^+}^{h^+}$, show a more stable behavior. Their central values are broadly compatible with NNFF1.1h, and the shapes are similar over most of the displayed z range. This agreement is expected because the heavy-quark FFs are mainly constrained by flavor-tagged SIA measurements, which are common in spirit to both analyses and are less directly affected by the inclusion of COMPASS SIDIS multiplicities.

The uncertainty bands in Fig. 7 therefore illustrate the different sources of information in the two fits. In the light-quark and antiquark sectors, the differences in central values show the impact of the updated charge-separated COMPASS SIDIS data. In the gluon sector, the difference is mainly driven by the absence of direct hadron-collider constraints in the present fit. In the poorly constrained small- and large- z regions, the uncertainty bands widen and the ratio panels show larger deviations from unity; these regions should therefore not be overinterpreted.

The comparison in Fig. 7 is restricted to the NLO determination, since NNFF1.1h is an NLO analysis [18]. A direct comparison of the HAPS-hFF1.0 NNLO result with NNFF1.1h is therefore not possible. More generally, previous NNLO studies of unidentified charged-hadron FFs exist in the SIA-only context [14]. HAPS-hFF1.0 is the first determination of unidentified charged-hadron FFs incorporating the new COMPASS 2025 data and the revised COMPASS 2026 data up to NNLO accuracy. For this reason, external comparisons with previous unidentified charged-hadron FF sets are made at NLO, while the HAPS-hFF1.0 NNLO result is used primarily to assess the perturbative stability of the present SIA plus updated-COMPASS SIDIS extraction.

In summary, Fig. 7 shows that the present HAPS-hFF1.0 NLO set is broadly consistent with NNFF1.1h in several quark and heavy-quark channels, while it also reveals notable differences in the light-antiquark and gluon sectors. The shift observed in the $\bar{u}$ FF reflects the impact of the updated charge-separated COMPASS SIDIS information, while the gluon comparison highlights the importance of future analyses combining SIA, updated COMPASS SIDIS, and hadron-collider charged-particle data in a single framework in order to obtain simultaneous light-flavor separation and a more direct gluon constraint.

VI. SUMMARY AND CONCLUSIONS

We have presented HAPS-hFF1.0, a new global QCD analysis of unidentified charged-hadron fragmentation functions based on SIA data and the modern COMPASS SIDIS multiplicities. The analysis updates the SIDIS input used in earlier charged-hadron FF determinations by incorporating the COMPASS 2025 proton-target measurement together with the revised ^6Li -target multiplicities provided in the 2026 COMPASS addendum.

The revised multiplicities supersede the original COMPASS 2017 isoscalar results and therefore provide the appropriate updated isoscalar input for a modern SIA + SIDIS extraction. Together with the proton-target measurement, they form a consistent COMPASS SIDIS data set for reassessing unidentified charged-hadron FFs. The proton-target multiplicities provide enhanced charge-separated sensitivity to u -dominated flavor combinations, while the revised multiplicities provide a more balanced light-flavor constraint.

The modern COMPASS multiplicities are described consistently together with the SIA data by a common set of FFs. Their inclusion provides important constraints on the light-quark and antiquark fragmentation functions and improves the flavor decomposition relative to analyses based on the older COMPASS isoscalar input. This supports the use of the modern COMPASS SIDIS multiplicities as the appropriate replacement for the previous COMPASS input in future charged-hadron FF analyses.

The extraction has been performed at both NLO and NNLO. Within the theoretical framework used here, the comparison between the two perturbative orders indicates good stability in the light-quark and heavy-quark sectors. The gluon FF remains less directly constrained in the present SIA+SIDIS-only analysis, as expected. This interpretation is also supported by the comparison with NNFF1.1h, where larger differences in the gluon sector reflect the impact of hadron-collider data included in NNFF1.1h but not in the present fit.

This work therefore provides the first SIA + SIDIS determination of unidentified charged-hadron FFs incorporating the modern COMPASS proton-target measurement and the revised isoscalar-target multiplicities from the COMPASS 2026. The NNLO result should be viewed as a perturbative-stability extension of this updated SIA + SIDIS extraction, while previous NNLO determinations of unidentified charged-hadron FFs were performed in an SIA-only setting. The resulting HAPS-hFF1.0 replicas

are provided in LHAPDF format [67] for phenomenological applications, with public grids, documentation, and plotting/usage examples available through the accompanying GitHub repository [68].

Future work should extend the present analysis by including proton-proton and LHC charged-hadron production data in order to improve the gluon constraint. It will also be important to study the impact of projected EIC SIDIS measurements on flavor separation and to quantify possible hadron-mass, target-mass, higher-twist, and nuclear effects in the low- Q SIDIS region. In particular, recent LHCb measurements of charged-hadron distributions in charm- and beauty-tagged jets [69] provide a promising additional constraint on heavy-flavor fragmentation and offer a useful testing ground for future charged-hadron FF sets.

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DATA AVAILABILITY

The resulting HAPS-hFF1.0 replicas are provided in LHAPDF format for phenomenological applications, with public grids, documentation, and plotting/usage examples available through the accompanying GitHub repository [68].

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