Simultaneous extraction of fragmentation functions of light charged hadrons with mass corrections

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School of Mathematics

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Outline

- **Different processes used in determination of FFs**

  ➢ **Single inclusive electron-positron annihilation (SIA)**
  ➢ **Semi inclusive deep inelastic scattering (SIDIS)**
  ➢ **Single inclusive hadron collisions**

- **QCD Framework**

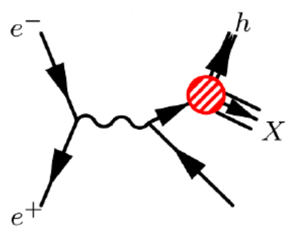
  ➢ **Factorization Theorem**
  ➢ **Universal Functions**

- **Our Analysis**

  ➢ **QCD Fit**
  ➢ **Results**

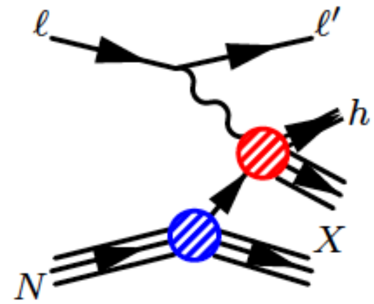
QCD Factorization Theorem

In general, the following processes have played a crucial role in studies of FFs:



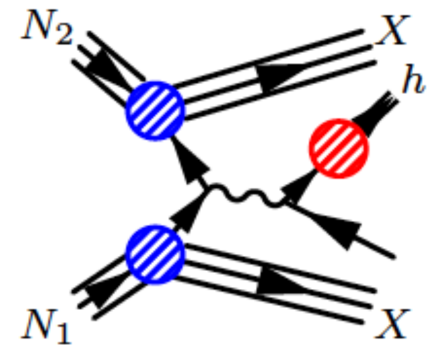
$e^+ + e^- \to h + X$

single-inclusive annihilation (SIA)



$\ell + N \to \ell' + h + X$

semi-inclusive deep-inelastic scattering (SIDIS)



$N_1 + N_2 \to h + X$

high-p_T hadron production in proton-proton collisions (PP)

$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF\,,$$

$$\sigma^{\ell N\to \ell hX} = \hat{\sigma} \otimes PDF \otimes FF\,,$$

$$\sigma^{pp\to hX} = \hat{\sigma} \otimes PDF \otimes PDF \otimes FF$$

$$f \otimes g = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y)$$

PDF: probability densities for finding partons, with a given momentum, inside color-neutral particles.
FF: probability densities for finding color-neutral particles inside partons.

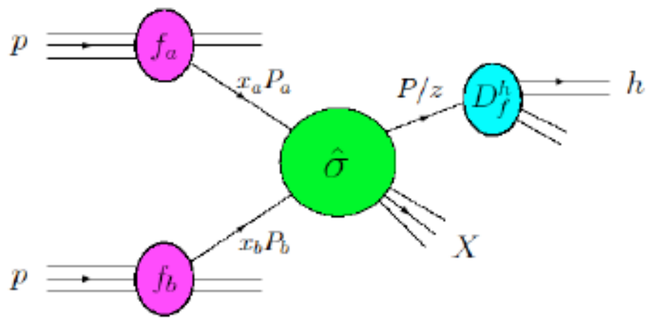
FF: Fragmentation functions, non-perturbative ingredient of QCD factorization formula
PDF:parton distribution function, non-perturbative ingredient of QCD factorization formula

Recent literatures

DESS [*arXiv:1410.6027 and arXiv:1702.06353*]
Parton-to-Pion Fragmentation Reloaded

Parton-to-Kaon Fragmentation Revisited

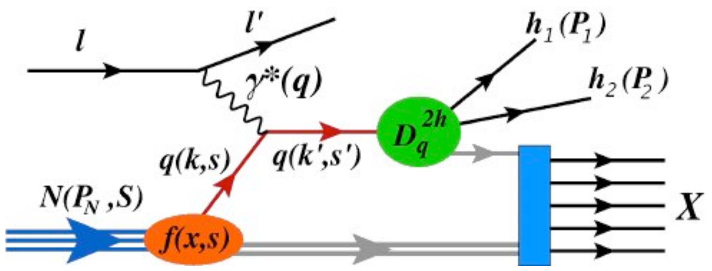
Data: SIA, SIDIS and PP



NNFF1.0 [*arXiv:1706.07049*]
A determination of the fragmentation functions of pions, kaons, and protons with faithful uncertainties
Data: SIA

JAM [*arXiv:2101.04664*]
Simultaneous analysis of parton densities and fragmentation functions
Data: DIS, SIDIS, Drell-Yan, SIA

MAPFF1.0 [*arXiv:2105.08725*]
A determination of unpolarised pion fragmentation functions
Data: SIDIS, SIA



IPM-XFITTER [*arXiv:2105.11306*]
QCD analysis of pion fragmentation functions in the xFitter framework
Data: SIA, Updated Belle data

Impact of unidentified light charged hadron

Since the most contribution of FFs into the unidentified light charged hadron mainly comes from the identified pion FFs, it motivates us to investigate the effect of unidentified light charged hadron data sets on the reduction of pion FFs uncertainties.

PHYSICAL REVIEW D **99,** 034024 (2019)

Impact of unidentified light charged hadron data on the determination of pion fragmentation functions

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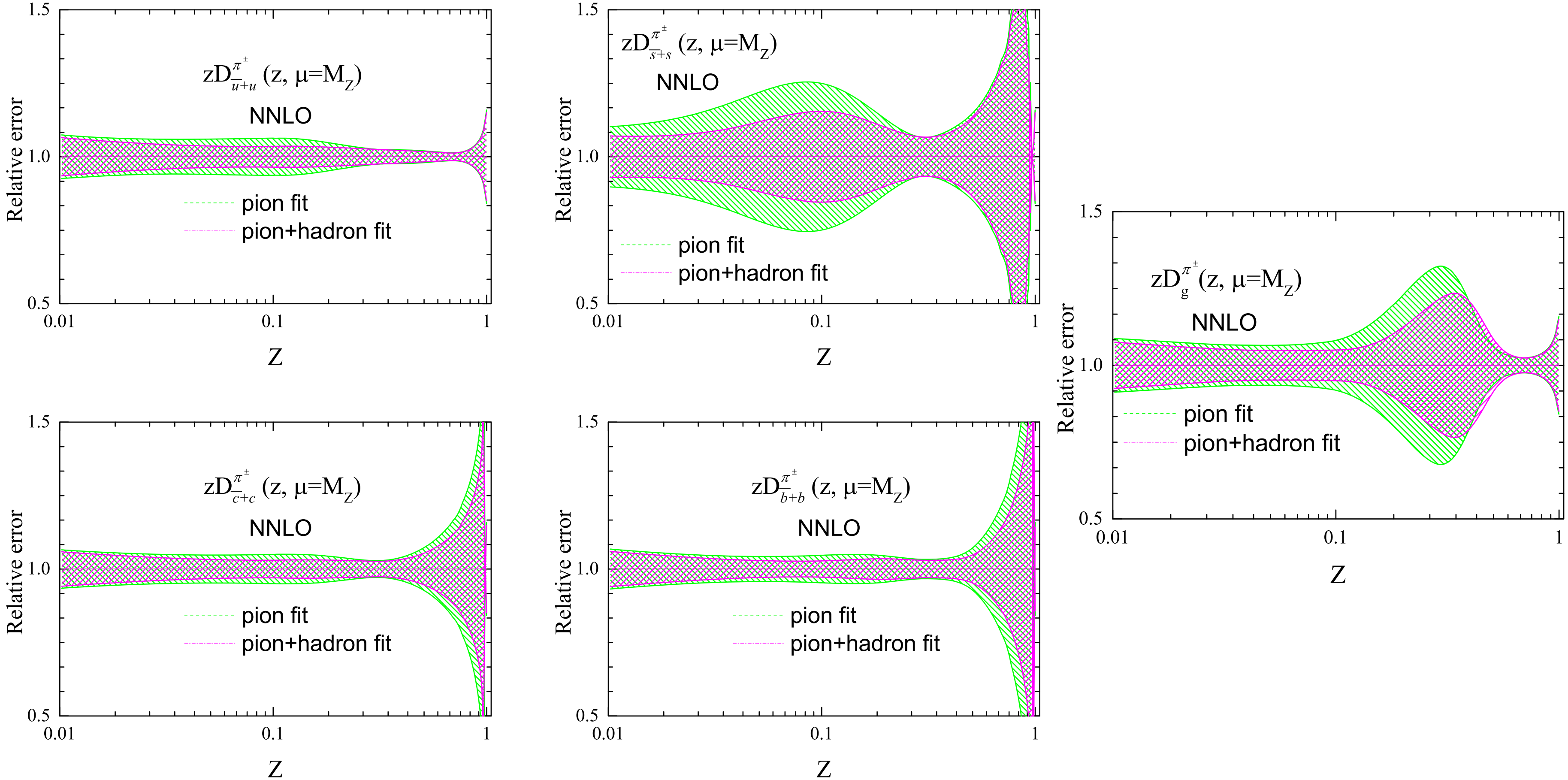
(Received 7 December 2018; published 26 February 2019)

In this paper a new comprehensive analysis of parton-to-pion fragmentation functions (FFs) is performed for the first time by including all experimental datasets on single inclusive pion as well as unidentified light charged hadron production in electron-positron (e^+e^-) annihilation. We determine the pion FFs along with their uncertainties using the standard "Hessian" technique at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) in perturbative QCD. It is shown that the determination of pion FFs using simultaneously the datasets from pion and unidentified light charged hadron production leads to the reduction of all pion FF uncertainties, especially for the case of strange quark and gluon FFs by significant factors. In this study, we have quantified the constraints that these datasets could impose on the extracted pion FFs. Our results also illustrate the significant improvement in the precision of FFs fits achievable by the inclusion of higher-order corrections. The improvements on FF uncertainties as well as fit quality have been clearly discussed.

Impact of unidentified light charged hadron



[PHYSICAL REVIEW D 99, 034024 (2019)]

Impact of unidentified light charged hadron

$$D^{h^\pm} = D^{\pi^\pm} + D^{K^\pm} + D^{p/\bar{p}} + D^{res^\pm}$$

PHYSICAL REVIEW D **103,** 054045 (2021)

Simultaneous extraction of fragmentation functions of light charged hadrons with mass corrections

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Achieving the highest possible precision for theoretical predictions at the present and future high-energy lepton and hadron colliders requires a precise determination of fragmentation functions (FFs) of light and heavy charged hadrons from a global QCD analysis with great accuracy. We describe a simultaneous determination of unpolarized FFs of charged pions, charged kaons and protons/antiprotons from single-inclusive hadron production in electron-positron annihilation (SIA) data at next-to-leading order and next-to-next-to-leading order accuracy in perturbative QCD. A new set of FFs, called SGKS20, is presented. We include data for identified light charged hadrons ($\pi^\pm$, $K^\pm$ and $p/\bar{p}$) as well as for unidentified light charged hadrons, $h^\pm$ and show that these data have a significant impact on both size and uncertainties of the fragmentation functions. We examine the inclusion of higher-order perturbative QCD corrections and finite-mass effects. We compare the new SGKS20 FFs with other recent FFs available in the literature and find in general reasonable agreement, but also important differences for some parton species. We show that theoretical predictions obtained from our new FFs are in very good agreement with the analyzed SIA data, especially at small values of z. The SGKS20 FF sets presented in this work are available via the LHAPDF interface.

Experimental data

The list of input datasets for π, K, p=p̄, and h production included in the present analysis.

Experiment	$\sqrt{s}$	$\frac{\chi^2}{N_{pts}}(\pi^\pm)$	$\frac{\chi^2}{N_{pts}}(K^\pm)$	$\frac{\chi^2}{N_{pts}}(p/\bar{p})$	$\frac{\chi^2}{N_{pts}}(h^\pm)$
BELLE [20]	10.52	0.295	0.993	…	…
BABAR [21]	10.54	1.504	2.503	0.234	…
TASSO12 [22]	12	1.135	0.933	0.669	…
TASSO14 [23,32]	14	1.194	1.392	2.166	0.627
TASSO22 [23,32]	22	2.348	2.580	1.920	0.697
TPC [24]	29	1.099	0.519	4.814	0.438
TASSO30 [22]	30	…	…	1.339	…
TASSO34 [25]	34	1.136	0.175	1.496	…
TASSO35 [23]	34	…	…	…	1.362
TASSO44 [23,25]	44	2.129	…	…	0.799
ALEPH [26,27]	91.2	1.362	0.747	0.991	0.738
DELPHI (incl.) [28]	91.2	1.471	0.684	0.541	0.508
DELPHI (*uds* tag) [28]	91.2	0.991	1.050	0.578	0.413
DELPHI (*b* tag) [28]	91.2	0.850	0.651	1.537	0.295
OPAL (incl.) [29,30]	91.2	1.380	1.126	…	0.780
OPAL (*uds* tag) [29,30]	91.2	…	…	…	0.552
OPAL (*c* tag) [29,30]	91.2	…	…	…	0.624
OPAL (*b* tag) [29,30]	91.2	…	…	…	0.175
SLD (incl.) [31]	91.2	1.181	0.549	0.831	0.289
SLD (*uds* tag) [31]	91.2	1.186	2.065	1.197	0.604
SLD (*c* tag) [31]	91.2	0.818	0.992	3.661	0.617
SLD (*b* tag) [31]	91.2	0.667	1.282	2.664	0.140
Total χ^2/d.o.f			$1558.169/1438 = 1.083$		

[*Phys.Rev.D 103 (2021) 5, 054045*]

Parametrization

$$D_i^H(z,Q_0) = \frac{\mathcal{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i,\beta_i+1]+\gamma_i B[2+\alpha_i,\beta_i+\delta_i+1]},$$

$$H = \pi^\pm, K^\pm \text{ or } p/\bar{p},$$

$$D_{u^+}^{\pi^\pm} = D_{d^+}^{\pi^\pm}$$

$$D_{u^+}^{K^\pm} \neq D_{d^+}^{K^\pm} \neq D_{s^+}^{K^\pm}$$

$$D_{u^+}^{p/\bar{p}} = \mathcal{N} D_{d^+}^{p/\bar{p}}$$

$$D_i^{\text{res}^\pm}(z,Q_0) = \mathcal{N}_i \frac{z^{\alpha_i}(1-z)^{\beta_i}}{B[2+\alpha_i,\beta_i+1]}$$

$$D_{u^+}^{\text{res}^\pm} = D_{d^+}^{\text{res}^\pm} = D_{s^+}^{\text{res}^\pm}$$

$$D^{h^\pm} = D^{\pi^\pm} + D^{K^\pm} + D^{p/\bar{p}} + D^{res^\pm}$$

Best-fit parameters for the fragmentation of partons into π, K, p=p¯, and residual light charged hadrons obtained through a simultaneous analysis at NNLO accuracy.

Parameter	$\pi^\pm$	$K^\pm$	$p/\bar{p}$	res$^\pm$
$\mathcal{N}_{u^+}$	0.9243	0.2409	0.7188	0.0019
α_{u^+}	−0.8411	−0.7248	0.6275	144.9869*
β_{u^+}	1.7556	2.0895	4.8433	16.5308*
γ_{u^+}	3.2186	0*	0*	0*
δ_{u^+}	4.3105	0*	0*	0*
$\mathcal{N}_{d^+}$	0.9243	0.2486	0.0860	0.0019
α_{d^+}	−0.8411	−0.6878	0.6275	144.9869*
β_{d^+}	1.7556	5.6757	4.8433	16.5308*
γ_{d^+}	3.2186	0*	0*	0*
δ_{d^+}	4.3105	0*	0*	0*
$\mathcal{N}_{s^+}$	0.8006	0.2614	0.0162	0.0019
α_{s^+}	−0.1781*	−0.6810*	0.6308	144.9869*
β_{s^+}	8.1331	1.6131	1.8532	16.5308*
$\mathcal{N}_{c^+}$	0.8070	0.2836	0.0369	0.0291
α_{c^+}	−0.8247	−0.4406	3.6331	9.8796*
β_{c^+}	5.6455	4.7087	25.0310*	19.1145*
$\mathcal{N}_{b^+}$	0.7686	0.2279	0.0058	0.1246
α_{b^+}	−0.3955	0.1040	3.3027	0.5507*
β_{b^+}	4.9983	11.4295	166.0012*	5.6387
γ_{b^+}	9.2937	0*	0*	0*
δ_{b^+}	8.7525	0*	0*	0*
$\mathcal{N}_g$	0.4669	0.0884	0.1986	0.0115
α_g	0.7742	12.1509	−0.1871	24.6488*
β_g	24.7398	8.6869	3.7138	11.2409*

Data sets and Fit Results

$$\chi_n^2(\{p_i\}) = \left(\frac{1-\mathcal{N}_n}{\Delta\mathcal{N}_n}\right)^2 + \sum_{k=1}^{N_n^{\text{data}}}\left(\frac{\mathcal{N}_n\mathcal{O}_k^{\text{data}} - \mathcal{T}_k^{\text{theory}}(\{p_i\})}{\mathcal{N}_n\delta D_k^{\text{data}}}\right)^2$$

Experiment	$\sqrt{s}$	$\frac{\chi^2}{N_{\text{pts}}}(\pi^\pm)$	$\frac{\chi^2}{N_{\text{pts}}}(K^\pm)$	$\frac{\chi^2}{N_{\text{pts}}}(p/\bar{p})$	$\frac{\chi^2}{N_{\text{pts}}}(h^\pm)$
BELLE [20]	10.52	0.467	0.966	…	…
BABAR [21]	10.54	1.793	2.838	1.017	…
TASSO12 [22]	12	1.154	0.930	0.648	…
TASSO14 [23,32]	14	1.202	1.447	2.237	0.607
TASSO22 [23,32]	22	2.461	2.472	1.969	0.628
TPC [24]	29	0.601	0.664	4.419	0.636
TASSO30 [22]	30	…	…	1.239	…
TASSO34 [25]	34	1.265	0.136	1.704	…
TASSO35 [23]	34	…	…	…	1.165
TASSO44 [23,25]	44	2.052	…	…	0.770
ALEPH [26,27]	91.2	1.876	0.797	2.248	0.814
DELPHI (incl.) [28]	91.2	1.274	0.731	0.559	0.537
DELPHI (*uds* tag) [28]	91.2	0.813	1.062	0.671	0.378
DELPHI (*b* tag) [28]	91.2	0.928	0.632	0.817	0.374
OPAL (incl.) [29,30]	91.2	1.455	0.879	…	0.682
OPAL (*uds* tag) [29,30]	91.2	…	…	…	0.554
OPAL (*c* tag) [29,30]	91.2	…	…	…	0.619
OPAL (*b* tag) [29,30]	91.2	…	…	…	0.232
SLD (incl.) [31]	91.2	1.865	0.578	0.824	0.307
SLD (*uds* tag) [31]	91.2	1.602	2.045	1.690	0.669
SLD (*c* tag) [31]	91.2	0.880	1.087	2.905	0.592
SLD (*b* tag) [31]	91.2	0.702	1.214	2.888	0.170
Total χ^2/d.o.f.			1685.057/1438 = 1.171		

NLO

Experiment	$\sqrt{s}$	$\frac{\chi^2}{N_{\text{pts}}}(\pi^\pm)$	$\frac{\chi^2}{N_{\text{pts}}}(K^\pm)$	$\frac{\chi^2}{N_{\text{pts}}}(p/\bar{p})$	$\frac{\chi^2}{N_{\text{pts}}}(h^\pm)$
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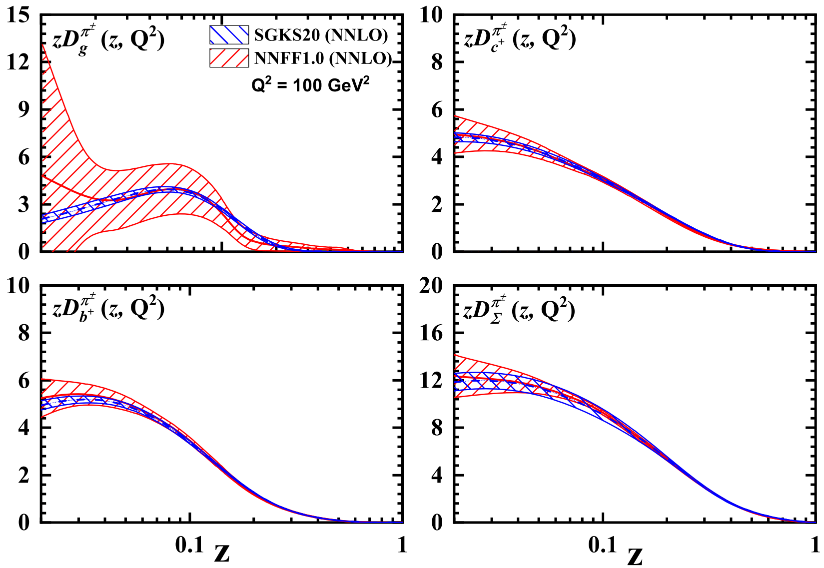
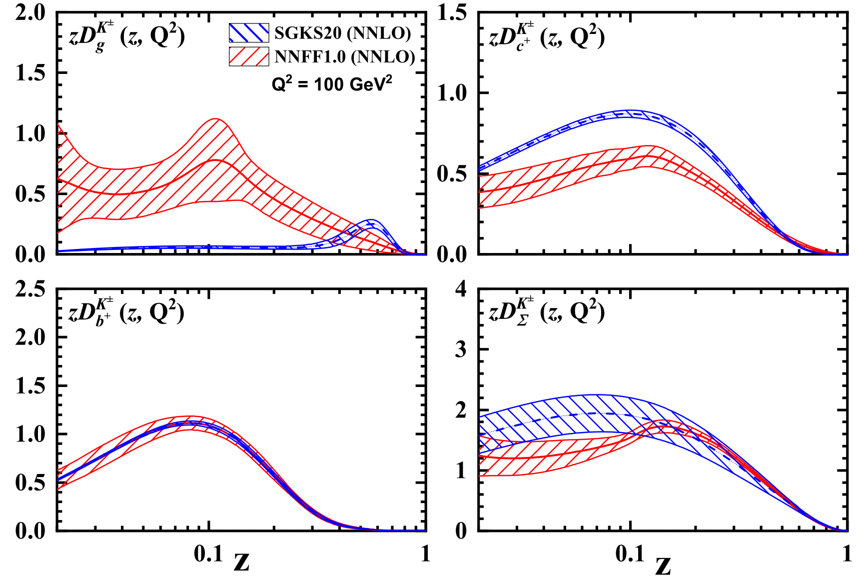
SLD (*b* tag) [31]	91.2	0.667	1.282	2.664	0.140
Total χ^2/d.o.f			1558.169/1438 = 1.083		

NNLO

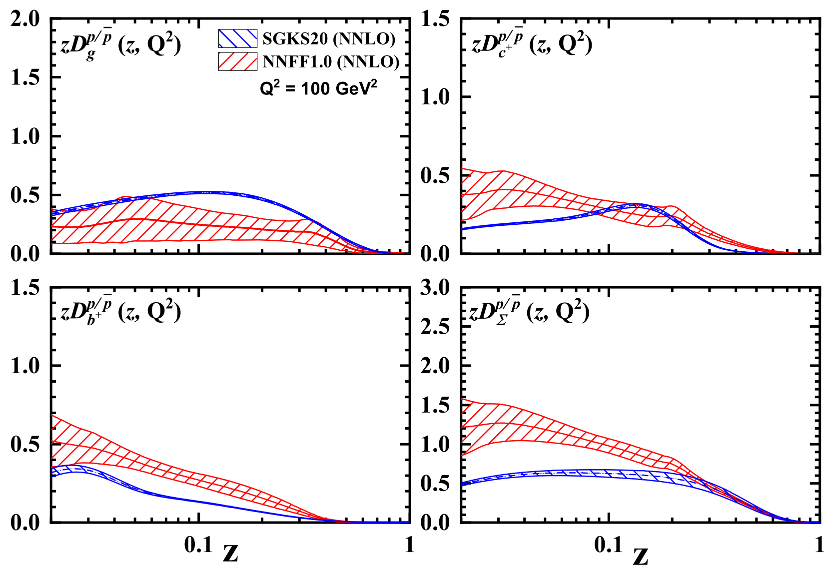
Results



$zD_g^{\pi^\pm}(z, Q^2)$
SGKS20 (NNLO)
NNFF1.0 (NNLO)
Q^2 = 100 GeV^2
$zD_{c^+}^{\pi^\pm}(z, Q^2)$
$zD_{b^+}^{\pi^\pm}(z, Q^2)$
$zD_{\Sigma}^{\pi^\pm}(z, Q^2)$
z

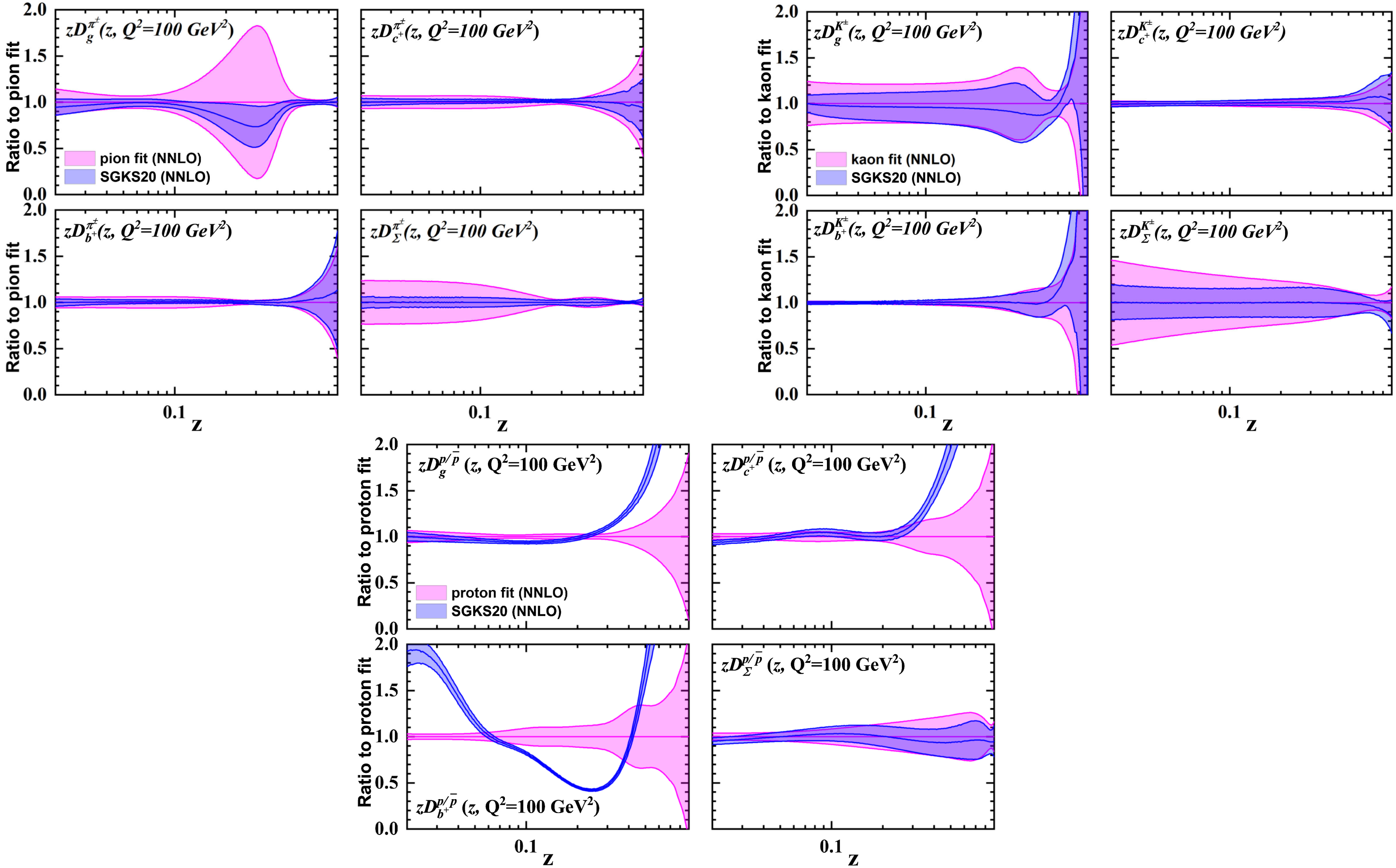


$zD_g^{K^\pm}(z, Q^2)$
SGKS20 (NNLO)
NNFF1.0 (NNLO)
Q^2 = 100 GeV^2
$zD_{c^+}^{K^\pm}(z, Q^2)$
$zD_{b^+}^{K^\pm}(z, Q^2)$
$zD_{\Sigma}^{K^\pm}(z, Q^2)$
z



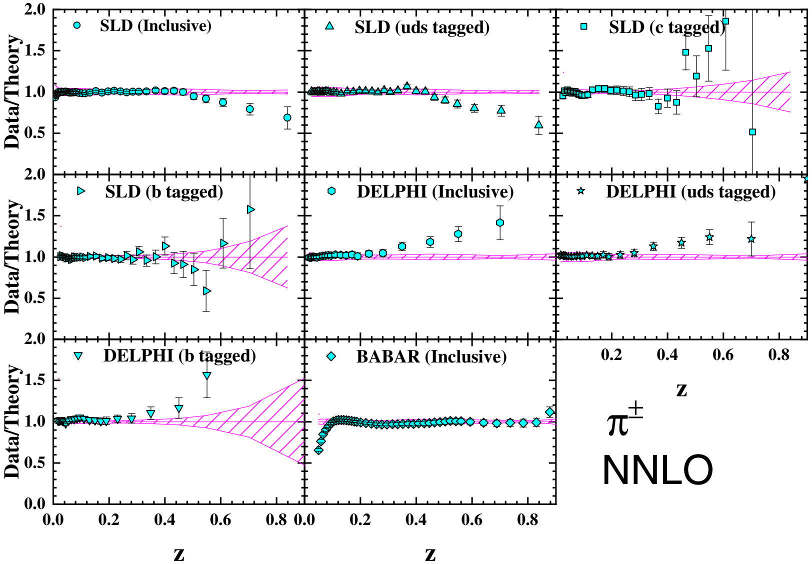
$zD_g^{p/\bar{p}}(z, Q^2)$
SGKS20 (NNLO)
NNFF1.0 (NNLO)
Q^2 = 100 GeV^2
$zD_{c^+}^{p/\bar{p}}(z, Q^2)$
$zD_{b^+}^{p/\bar{p}}(z, Q^2)$
$zD_{\Sigma}^{p/\bar{p}}(z, Q^2)$
z

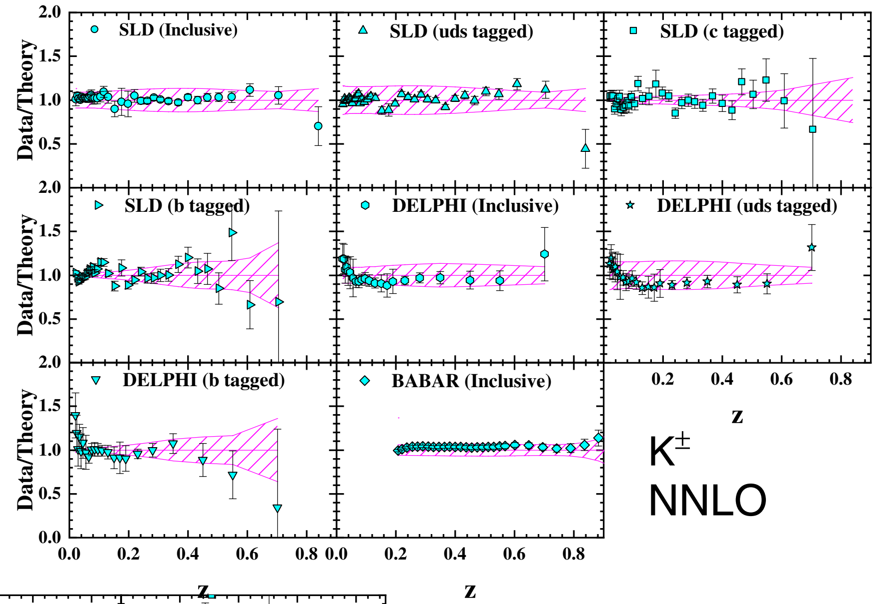
Results

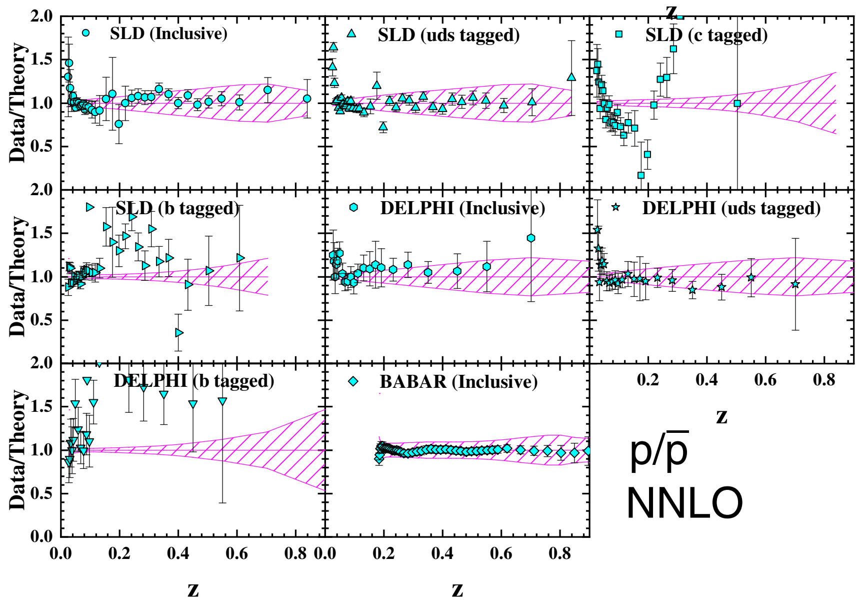


[*Phys.Rev.D 103 (2021) 5, 054045*]

Results


SLD (Inclusive)
SLD (uds tagged)
SLD (c tagged)
SLD (b tagged)
DELPHI (Inclusive)
DELPHI (uds tagged)
DELPHI (b tagged)
BABAR (Inclusive)
Data/Theory
z
π±
NNLO


SLD (Inclusive)
SLD (uds tagged)
SLD (c tagged)
SLD (b tagged)
DELPHI (Inclusive)
DELPHI (uds tagged)
DELPHI (b tagged)
BABAR (Inclusive)
Data/Theory
z
K±
NNLO


SLD (Inclusive)
SLD (uds tagged)
SLD (c tagged)
SLD (b tagged)
DELPHI (Inclusive)
DELPHI (uds tagged)
DELPHI (b tagged)
BABAR (Inclusive)
Data/Theory
z
p/p̄
NNLO

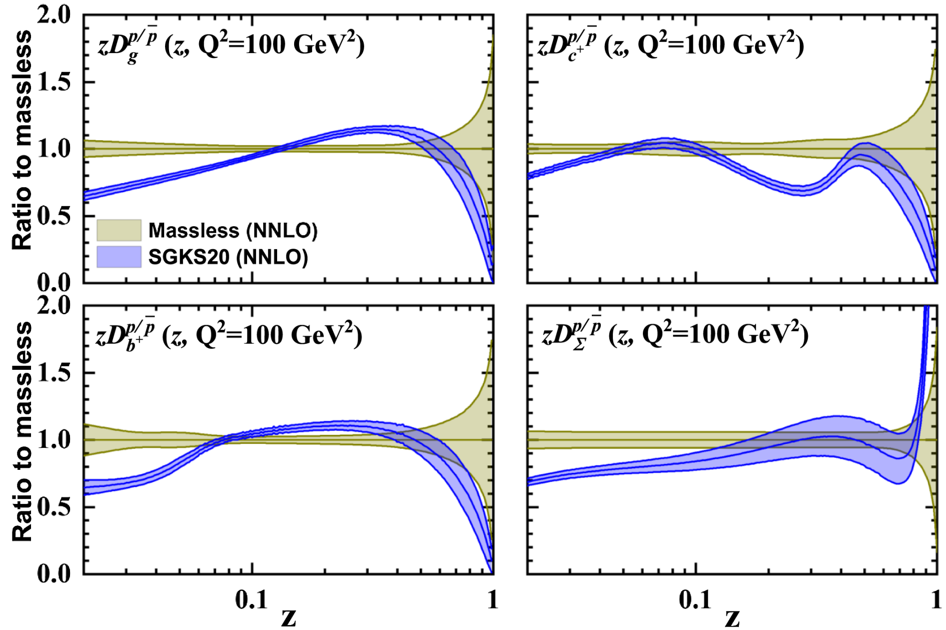
Hadron mass corrections

We define the light-cone scaling variable η as

$$\eta = \frac{z}{2}\left(1 + \sqrt{1 - \frac{4m_H^2}{sz^2}}\right),$$

cross section in the presence of hadron mass effects reads

$$\frac{d\sigma}{dz} = \frac{1}{1 - \frac{m_H^2}{s\eta^2}} \sum_a \int_\eta^1 \frac{dx_a}{x_a} \frac{d\hat{\sigma}_a}{dx_a} D_a^H\left(\frac{\eta}{x_a}, \mu\right).$$



Comparison of SGKS20 NNLO proton and antiproton FFs presented in this study with results extracted from a QCD analysis without including hadron mass corrections.

we find $\chi^2/\text{d.o.f.} = 1.280$ and at NNLO $\chi^2/\text{d.o.f.} = 1.241$ if mass effects are omitted, while with mass effects included the corresponding values decrease to 1.171 and 1.083 for NLO and NNLO, respectively.

Conclusion

- ☑ Essential ingredients of theoretical predictions for the present or future hadron colliders.
- ☑ A simultaneous fit by including both identified and unidentified light charged hadrons data taken from electron-positron annihilation.
- ☑ Improvement the total χ^2 at both NLO and NNLO accuracy and also reduction the uncertainties for the FFs of light hadrons.
- ☑ Inclusion of higher- order QCD corrections helped to obtain a much better agreement of data with theory.
- ☑ The FF parametrizations at NLO and NNLO for hadrons presented in this study are available in the standard LHAPDF format.


A Very Special
Thank you