

Global Analyses of Collinear Fragmentation Functions from the NPC Collaboration

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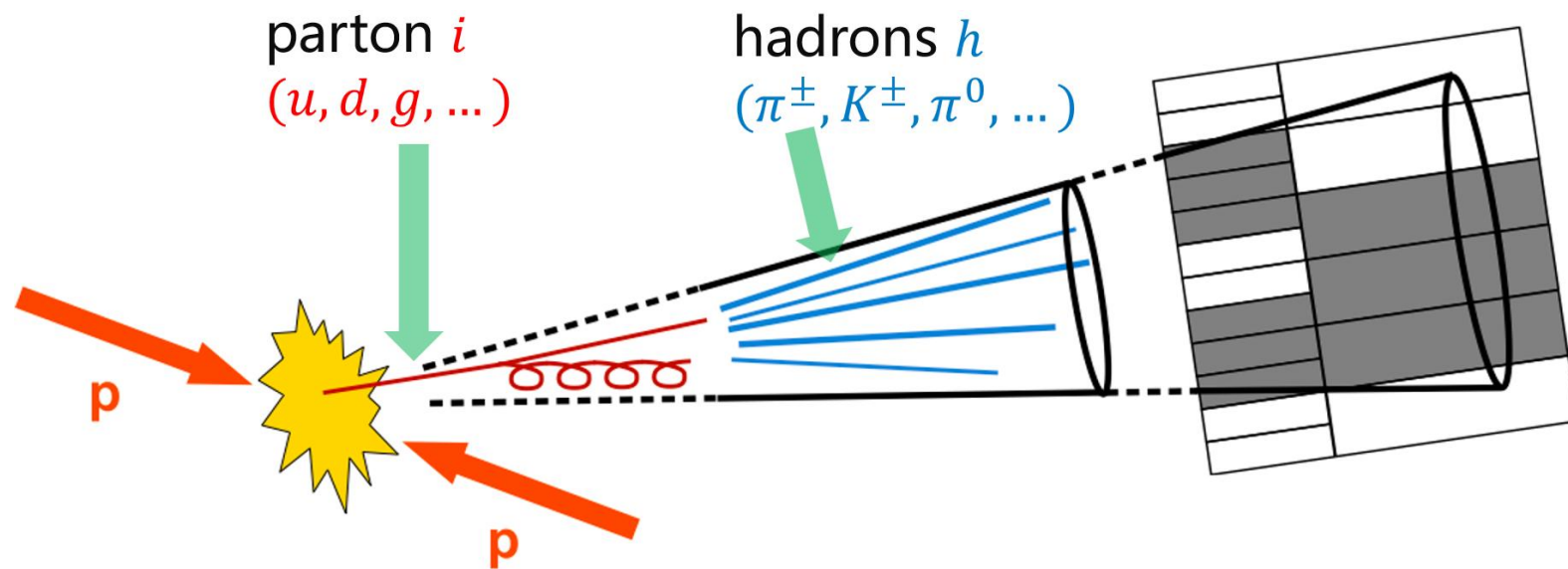
On behalf of
the Non-Perturbative Physics Collaboration (NPC)



Oct. 27, 2025



Fragmentation Functions (FFs)

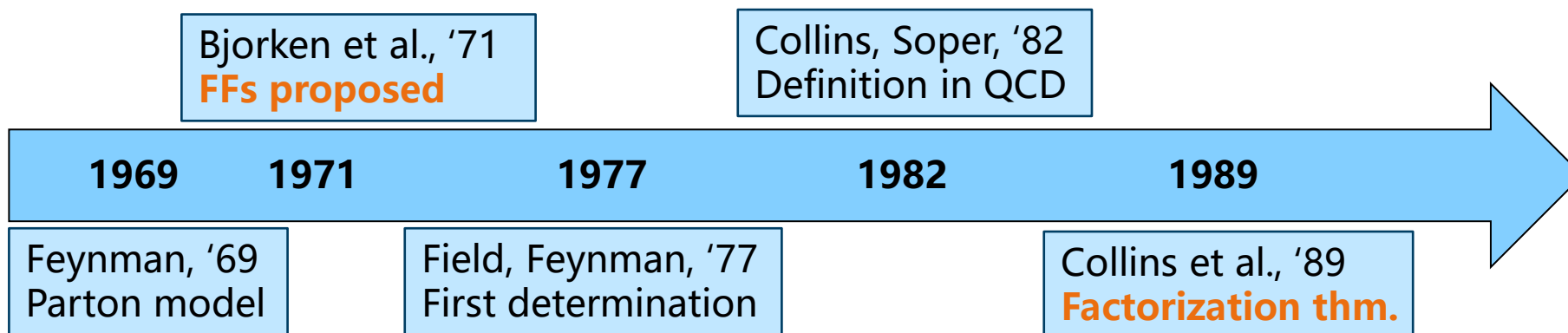


To describe hadronization **parton i** $\longrightarrow$ **hadron h**

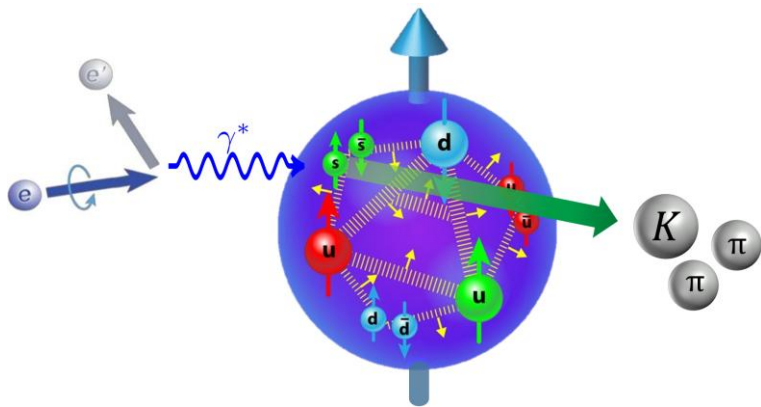
$$D_{h/i}(z \equiv p_h^+ / p_i^+) \longleftarrow$$

- the number density of hadron h
- carrying a fraction of momentum z
- of parton i

Why FFs: key ingredients of QCD factorization framework



- Semi-Inclusive DIS (SIDIS) : $e + N \rightarrow e + \mathbf{h} + X$



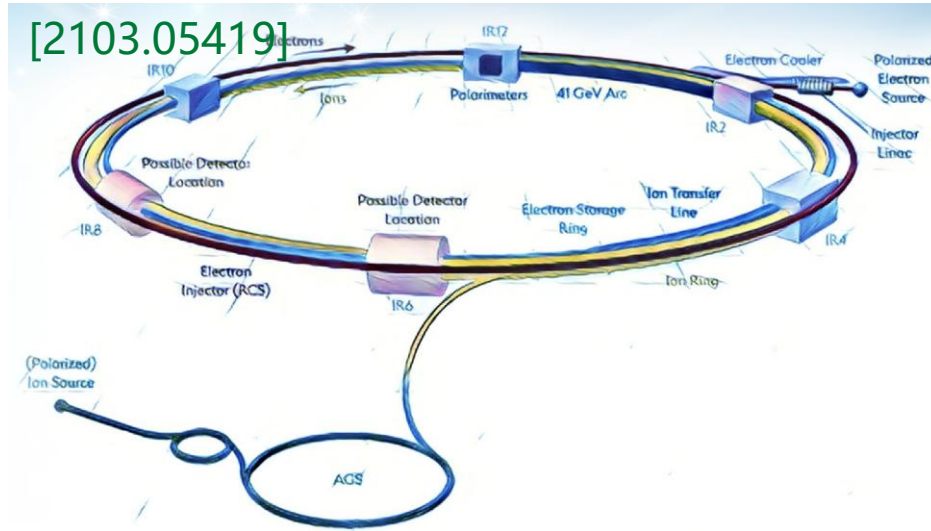
$$\frac{d^3\sigma_h}{dx_B dy dz_h} = \underbrace{f_{i/p}(x)}_{\text{PDF}} \otimes \underbrace{\hat{\sigma}_{j \leftarrow i}(x, y, z)}_{\text{pQCD}} \otimes \underbrace{D_{h/j}(z)}_{\text{FF}}$$

- $e^+e^- \rightarrow h + X$ pQCD $\otimes$ FF

- $pp \rightarrow h + X$ PDF $\otimes$ PDF $\otimes$ pQCD $\otimes$ FF

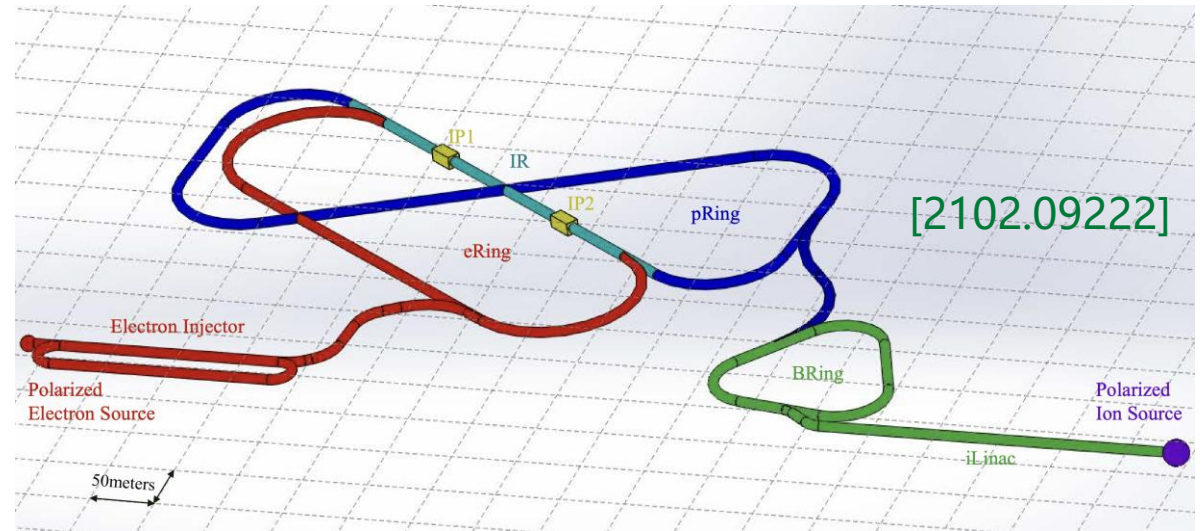


Why FFs: key role in the era of high-precision physics



❖ Electron-Ion Collider (EIC)

- start operation in the early 2030s
- unprecedented access to nucleon structure



❖ Electron-ion collider in China(EicC)

- helicity structure of sea quarks

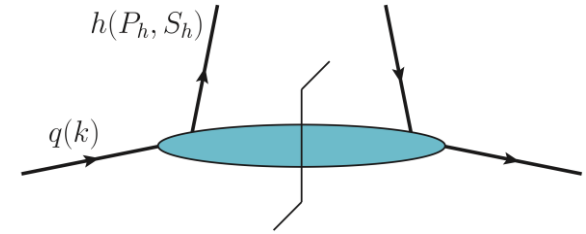
[see Yuxiang's talk on Tuesday]

High-precision FFs will be key input to the EIC/EicC physics.

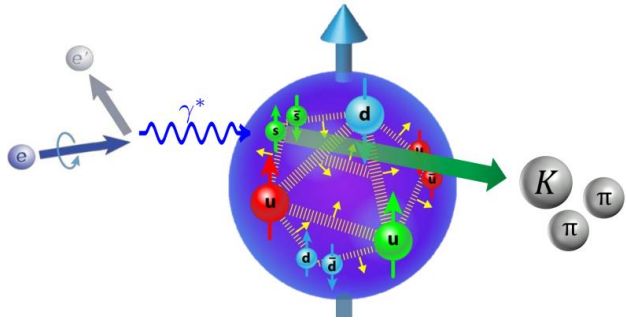
Determination of FFs from global data fit

- ❖ Field theory definition of the collinear (integrated) quark FFs [Collins, Soper '82]

$$D_{h/q}(z) = \frac{z}{4} \sum_X \int \frac{d\xi^+}{2\pi} e^{iP_h^- \xi^+ / z} \text{Tr} \left[\langle 0 | \mathcal{W}(\infty^+, \xi^+) \psi_q(\xi^+, 0^-, \vec{0}_T) | P_h, S_h; X \rangle \right. \\ \left. \times \langle P_h, S_h; X | \bar{\psi}_q(0^+, 0^-, \vec{0}_T) \mathcal{W}(0^+, \infty^+) | 0 \rangle \gamma^- \right]$$



- ❖ **Global data fits** based on factorization formula **ep(SIDIS) + ee(SIA) + pp collisions**



$$\frac{d^3\sigma_h}{dx_B dy dz_h} = f_{i/p}(x) \otimes \hat{\sigma}_{j \leftarrow i}(x, y, z) \otimes D_{h/j}(z)$$

↑ measurement
↕ input/output
↑ pQCD
↓ to be determined. Universal !

Outline

➤ Introduction

NPC=Non-Perturbative Physics Collaboration

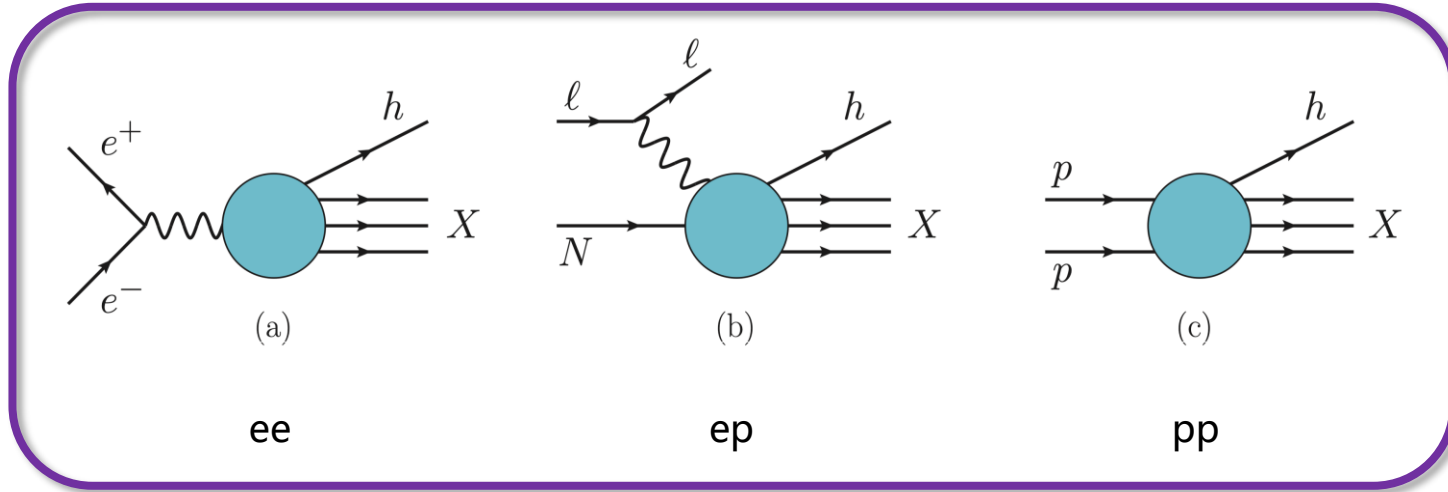
➤ Global fits of FFs at NLO from NPC

➤ NPC analyses of FFs at NNLO

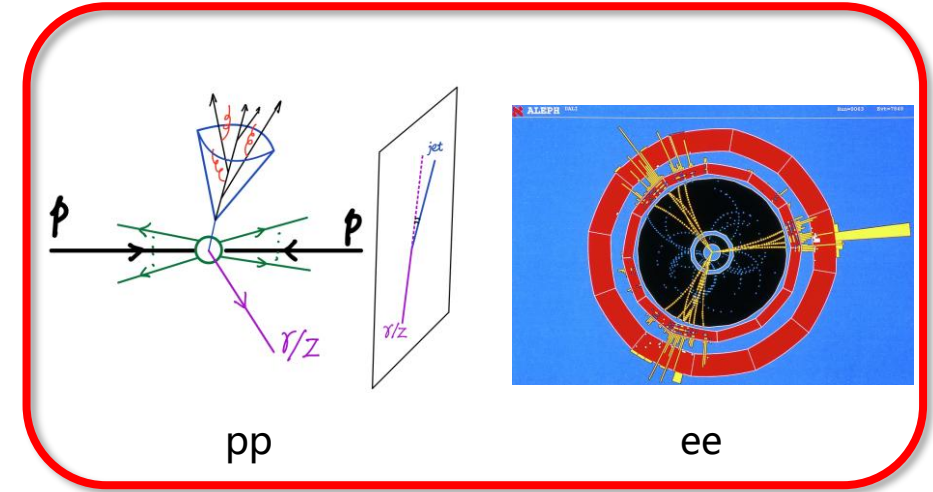
collaboration	NNFF	JAM	DSS+	BDSSV	MAP	NPC
SIA (ee)	✓	✓	✓	✓	✓	✓
SIDIS (ep)	✗	✓	✓	✓	✓	✓
pp incl. hadron	✗	✗	✓	✗	✗	✓
hadron in jet	✗	✗	✗	✗	✗	✓
FFs (charged h)	$\pi^\pm, K^\pm, p$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p$	$\pi^\pm$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p$
FFs (neutral h)			η			K^0, η, Λ
pQCD order	NNLO	NLO	NLO	appr. NNLO	appr. NNLO	NLO

Only some of the recent global analyses are shown here.

NPC FFs analyses incorporate various types of data



single-inclusive hadron production



hadron in jet measurements

- Hadron-in-jet data provides **direct probe of z dependence** $\frac{p_{T,h}}{p_{T,j}} \xrightarrow{\text{LO}} z$
- All theoretical predictions calculated with **FMNLO**.

[Liu, **XS**, Zhou, Gao, 2305.14620 (JHEP)]

Experiments	N_{pt}	χ^2	χ^2/N_{pt}
ATLAS jets [†]	446	350.8	0.79
ATLAS Z/ γ + jet [†]	15	31.8	2.12
CMS Z/ γ + jet [†]	15	17.3	1.15
LHCb Z + jet	20	30.6	1.53
ALICE inc. hadron	147	150.6	1.02
STAR inc. hadron	60	42.2	0.70
pp sum	703	623.3	0.89
TASSO	8	7.0	0.88
TPC	12	11.6	0.97
OPAL	20	16.3	0.81
OPAL (202 GeV) [†]	17	24.2	1.42
ALEPH	42	31.4	0.75
DELPHI	78	36.4	0.47
DELPHI (189 GeV)	9	15.3	1.70
SLD	198	211.6	1.07
SIA sum	384	353.8	0.92
H1 [†]	16	12.5	0.78
H1 (asy.) [†]	14	12.2	0.87
ZEUS [†]	32	65.5	2.05
COMPASS (06I)	124	107.3	0.87
COMPASS (16p)	97	56.8	0.59
SIDIS sum	283	254.4	0.90
Global total	1370	1231.5	0.90

NPC23 $\pi^\pm, K^\pm, p$ FFs fit

collaboration	year	$\sqrt{s}$ [GeV]	χ^2	N_{pt}	χ^2/N_{pt}
TASSO	1985	14	5.65	9	0.63
TASSO	1985	22	5.87	6	0.98
TASSO	1985	34	16.03	13	1.23
TASSO	1990	14.8	12.56	9	1.40
TASSO	1990	21.5	3.78	6	0.63
TASSO	1990	34.5	17.51	13	1.35
TASSO	1990	35	14.76	13	1.14
TASSO	1990	42.6	33.60	13	2.58
TPC	1984	29	2.75	8	0.34
MARK II	1985	29	12.65	17	0.74
HRS	1987	29	33.16	12	2.76
CELLO	1990	35	2.71	9	0.30
TOPAZ	1995	58	0.29	4	0.07
OPAL	1991	91.2	7.75	7	1.11
OPAL	1995	91.2	13.63	16	0.85
OPAL	2000	91.2	8.62	16	0.54
ALEPH	1998	91.2	6.39	16	0.40
ALEPH	2000	91.2	12.72	14	0.91
ALEPH jet 1	2000	91.2	14.91	12	1.24
ALEPH jet 2	2000	91.2	8.21	13	0.63
ALEPH jet 3	2000	91.2	8.55	11	0.78
DELPHI	1995	91.2	7.55	13	0.58
SLD	1999	91.2	7.39	9	0.82
SLD c -tagged	1999	91.2	17.44	9	1.94
SLD b -tagged	1999	91.2	11.12	9	1.24
SIA sum			285.60	277	1.03
ZEUS $Q^2 \in 160, 640 \text{ GeV}^2$	2012	318	4.41	5	0.88
ZEUS $Q^2 \in 640, 2560 \text{ GeV}^2$	2012	318	3.26	5	0.65
ZEUS $Q^2 \in 2560, 10240 \text{ GeV}^2$	2012	318	2.74	2	1.37
SIDIS sum			10.41	12	0.87
ALICE $N_{K_S^0}^{13 \text{ TeV}} / N_{K_S^0}^{7 \text{ TeV}}$	2021	13000 & 7000	2.88	10	0.29
ALICE $N_{K_S^0} / N_{\pi^\pm}$	2021	13000	5.79	15	0.39
pp sum			8.67	25	0.35
total sum			304.68	314	0.97

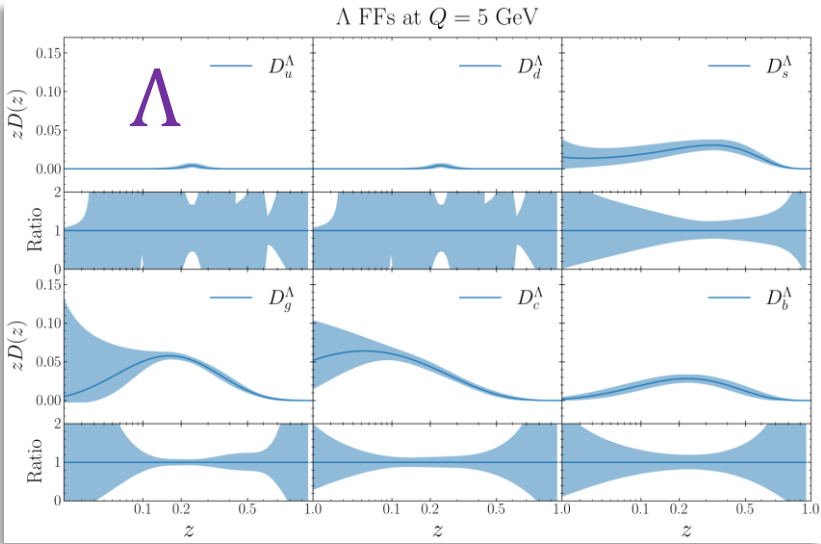
NPC23 K^0 FFs fit

The NPC FF sets at NLO

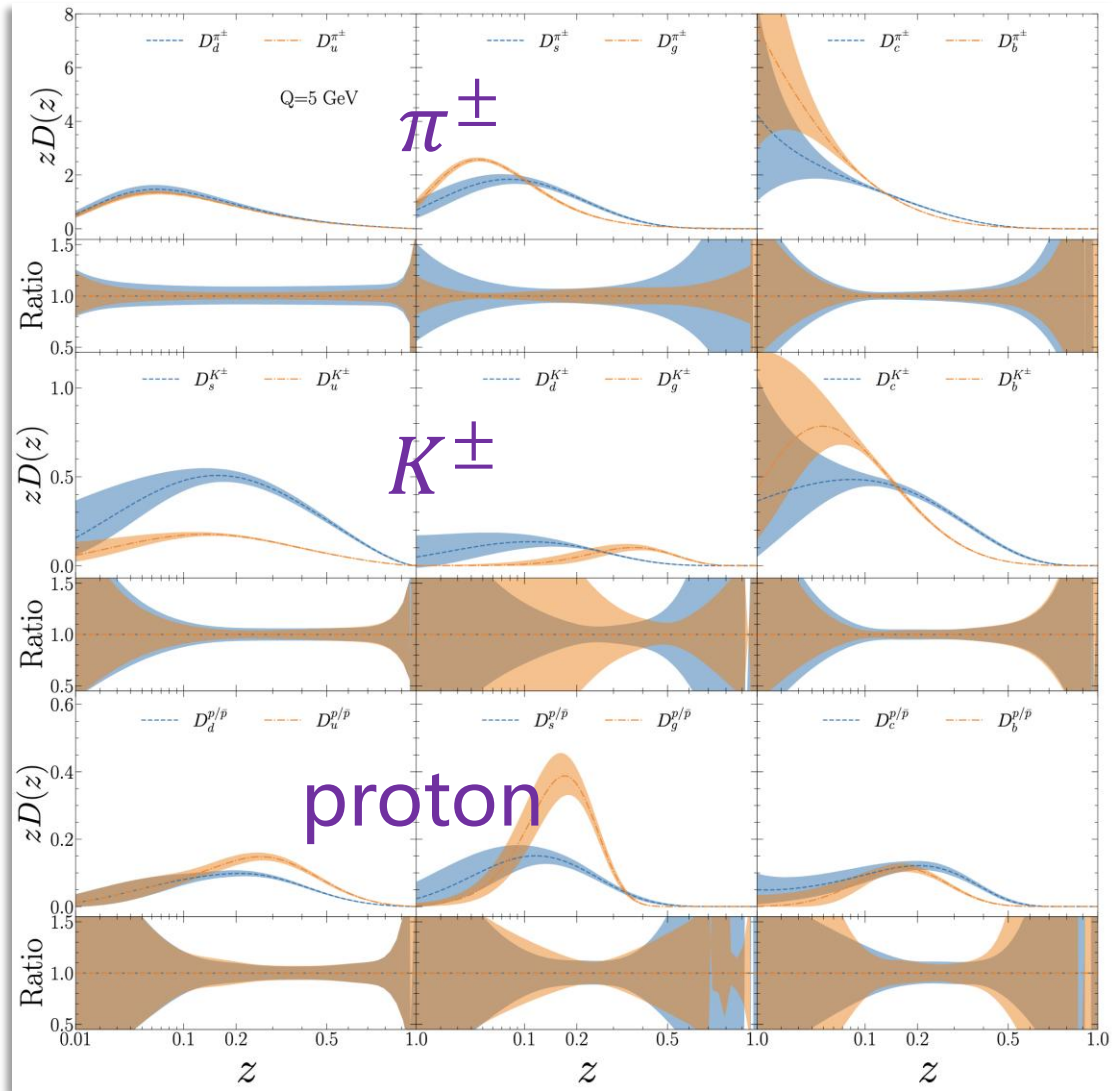
NPC FF sets are publicly available

LHAPDF 6.5.5

Main page	PDF sets	Class hierarchy	Examples	More...	
2070000	NPC23_Plp_nlo		(tarball)	(info file)	127
2070200	NPC23_KAp_nlo		(tarball)	(info file)	127
2070400	NPC23_PRp_nlo		(tarball)	(info file)	127
2070600	NPC23_Plm_nlo		(tarball)	(info file)	127
2070800	NPC23_KAm_nlo		(tarball)	(info file)	127
2071000	NPC23_Prm_nlo		(tarball)	(info file)	127
2071200	NPC23_Plsum_nlo		(tarball)	(info file)	127
2071400	NPC23_KAsum_nlo		(tarball)	(info file)	127
2071600	NPC23_PRsum_nlo		(tarball)	(info file)	127
2071800	NPC23_CHHAp_nlo		(tarball)	(info file)	127
2072000	NPC23_CHHAm_nlo		(tarball)	(info file)	127
2072200	NPC23_CHHAsum_nlo		(tarball)	(info file)	127



Gao, Liu, **XS**, Xing, Zhao, *PRL* 132, 261903, '24
Gao, Liu, **XS**, Xing, Zhao, *PRD* 110, 114019, '24 (Editors' suggestion)
Gao, Liu, Li, **XS**, Xing, Zhao, Zhou, *PRD* 112, 054045, '25



Combination of all types of hadron production data leads to **good constraints** on FFs.



Both charged and neutral hadron FFs determined

collaboration	NNFF	JAM	DSS+	BDSSV	MAP	NPC
SIA (ee)	✓	✓	✓	✓	✓	✓
SIDIS (ep)	✗	✓	✓	✓	✓	✓
pp incl. hadron	✗	✗	✓	✗	✗	✓
hadron in jet	✗	✗	✗	✗	✗	✓
FFs (charged h)	$\pi^\pm, K^\pm, p$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p$	$\pi^\pm$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p$
FFs (neutral h)			η			K^0, η, Λ
pQCD order	NNLO	NLO	NLO	appr. NNLO	appr. NNLO	NLO

➤ FFs determination at NLO from **Nonperturbative Physics Collaboration (NPC)**

- NPC23 FFs to light **charged** hadrons:

Gao, Liu, **XS**, Xing, Zhao, *PRL* 132, 261903, '24

Gao, Liu, **XS**, Xing, Zhao, *PRD* 110, 114019, '24 (Editors' suggestion)

- NPC23 FFs to light **neutral** hadrons:

Gao, Liu, Li, **XS**, Xing, Zhao, Zhou, *PRD* 112, 054045, '25

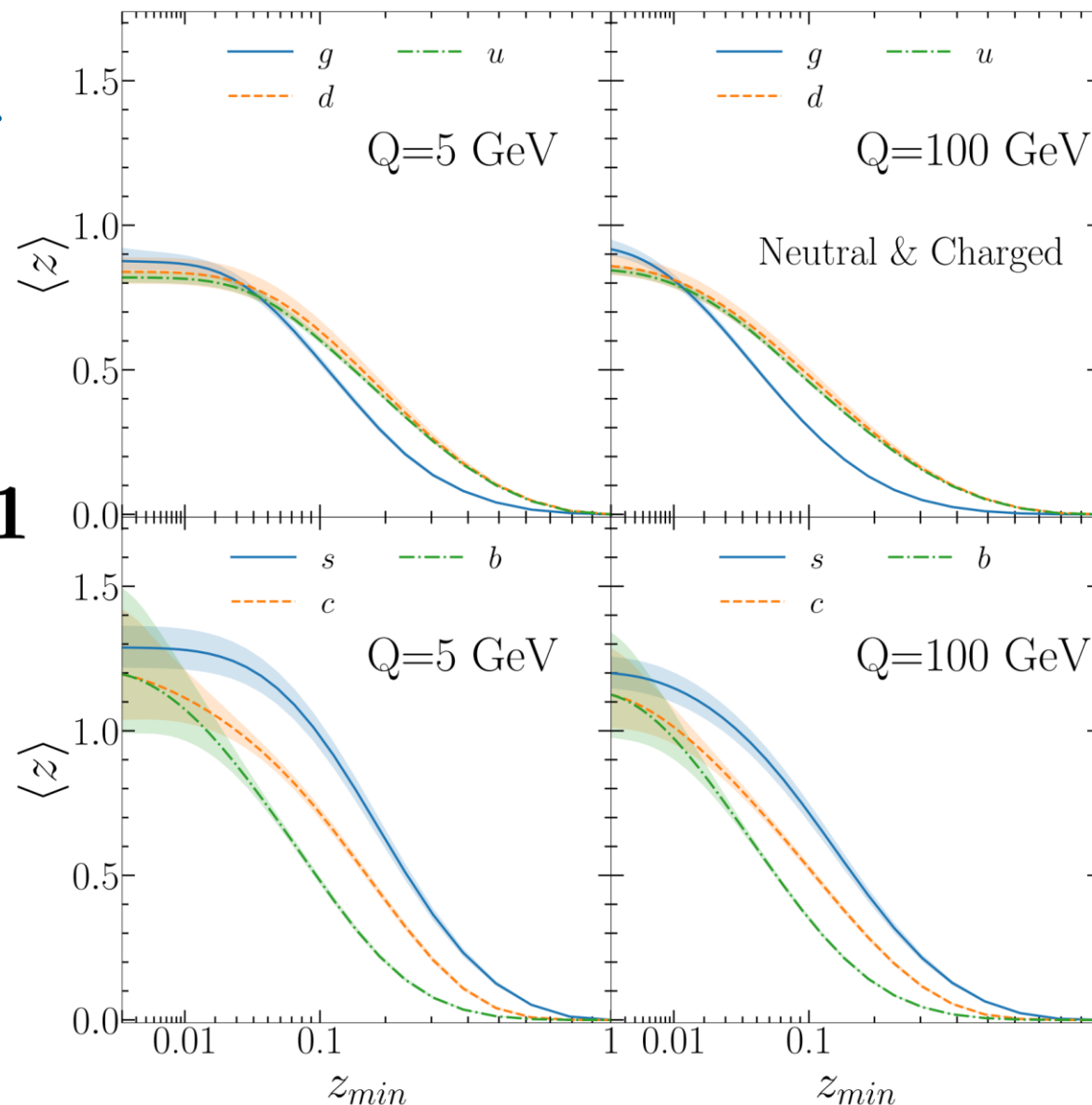
Test sum rule using neutral + charged hadron FFs

parton $i \longrightarrow$ hadrons $h = \pi^\pm, \pi^0, K^\pm, K^0, \dots$

➤ The **momentum sum rule**:

$$\lim_{z_{\min} \rightarrow 0} \sum_h \int_{z_{\min}}^1 [z D_{h/i}(z)] dz = 1$$

Gao, Liu, **XS**, Xing, Zhao, *PRL* 132, 261903, '24
 Gao, Liu, Li, **XS**, Xing, Zhao, Zhou, *PRD* 112, 054045, '25



Outline

➤ Introduction

➤ NPC analyses of FFs at NLO

➤ NPC analyses of FFs at **NNLO** + constraints on PDFs

collaboration	NNFF	JAM	DSS+	BDSSV	MAP	NPC	NPC
SIA (ee)	✓	✓	✓	✓	✓	✓	✓
SIDIS (ep)	✗	✓	✓	✓	✓	✓	✓
pp incl. hadron	✗	✗	✓	✗	✗	✓	✗
hadron in jet	✗	✗	✗	✗	✗	✓	✗
FFs	$\pi^\pm, K^\pm, p$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p, h^\pm$ η	$\pi^\pm$	$\pi^\pm, K^\pm$	$\pi^\pm, K^\pm, p, h^\pm$ K^0, η, Λ	$\pi^\pm, K^\pm$
pQCD order	NNLO	NLO	NLO	appr. NNLO	appr. NNLO	NLO	NNLO

Only some of the recent global analyses are shown here.

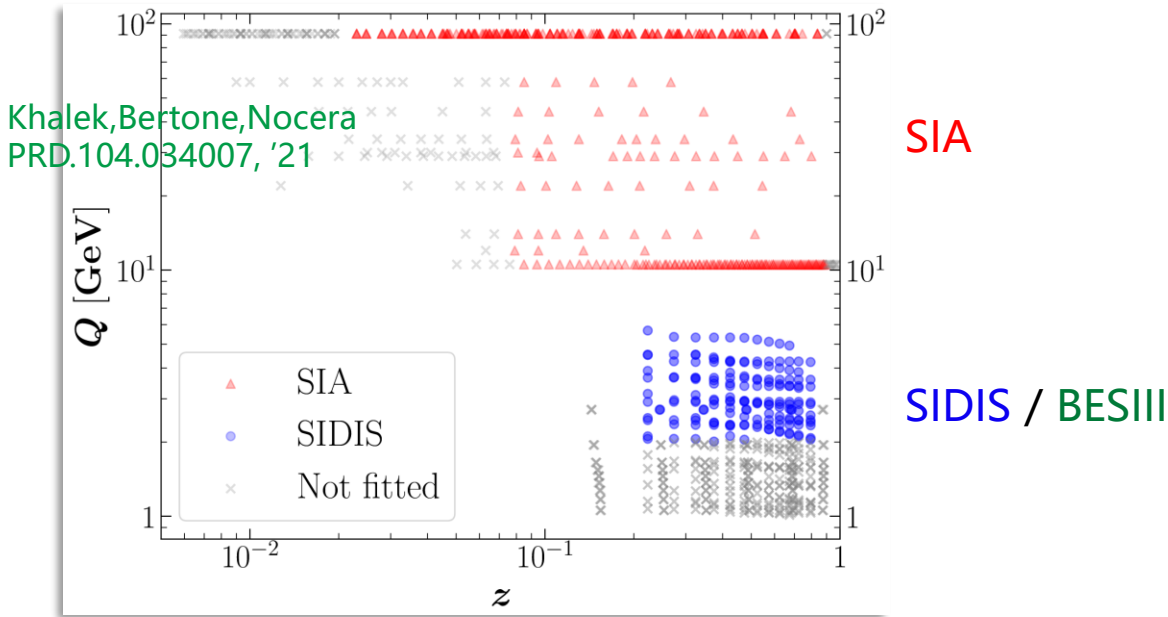
[Gao, **XS**, Xing, Zhao, Zhou, **PRL** 135, 041902, 2025]

Global analysis of FFs at full NNLO: the datasets

SIA(e^+e^-) data used in the fit:

exp.	$\sqrt{s}/\text{GeV}$	lum.(n_Z)	year	final states	hadrons
DELPHI	189	157.7 pb ⁻¹	2002	inc. had.	$\pi^\pm, K^\pm$
OPAL	m_Z	780 000	1994	$Z \rightarrow q\bar{q}$	$\pi^\pm, K^\pm$
ALEPH	m_Z	520 000	1995	$Z \rightarrow q\bar{q}$	$\pi^\pm, K^\pm$
DELPHI	m_Z	1 400 000	1998	$Z \rightarrow q\bar{q}$	$\pi^\pm, K^\pm$
				$Z \rightarrow b\bar{b}$	$\pi^\pm, K^\pm$
				$Z \rightarrow c\bar{c}$	$\pi^\pm, K^\pm$
SLD	m_Z	400 000	2004	$Z \rightarrow q\bar{q}$	$\pi^\pm, K^\pm$
				$Z \rightarrow b\bar{b}$	$\pi^\pm, K^\pm$
				$Z \rightarrow c\bar{c}$	$\pi^\pm, K^\pm$
TASSO	44	34 pb ⁻¹	1989	inc. had.	$\pi^\pm, \pi^0$
TASSO	34	77 pb ⁻¹	1989	inc. had.	$\pi^\pm, K^\pm$
TPC/2 γ	29	70 pb ⁻¹	1988	inc. had.	$\pi^\pm, K^\pm$
Belle	10.52	68 fb ⁻¹	2013	inc. had.	$\pi^\pm, K^\pm$
BaBar	10.54	0.91 fb ⁻¹	2013	inc. had.	$\pi^\pm, K^\pm$
BESIII	2.0-3.671	253 pb ⁻¹	2025	inc. had.	$\pi^\pm, K^\pm$

[BESIII, **PRL**135, 151901, 2025]



- Kinematic cuts in our analyses:
- $Q > 3 \text{ GeV}$ (SIA)
 - $Q > 2 \text{ GeV}$ (SIDIS)
 - $z > 0.01, E_h > E_{h,min}$ (0.8 GeV by default)

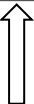
the **first** test on **universality** of FFs at $Q \sim 3 \text{ GeV}$ using both **ee** and **SIDIS** data

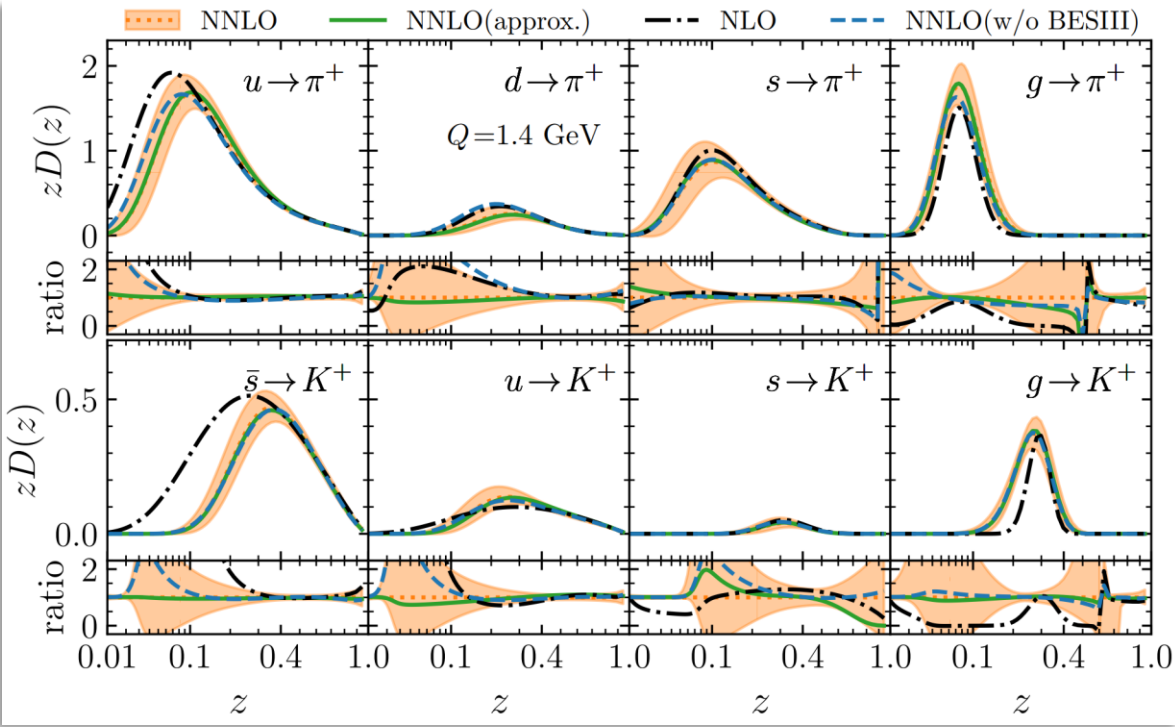


Global analysis of FFs at full NNLO: results

➤ Fit quality of the NNLO analyses

	BESIII		COMPASS		B-factories		HE-SIA		global		
$E_{h,min} [GeV]$	N_{pt}	χ^2/N_{pt}	N_{pt}	χ^2/N_{pt}	N_{pt}	χ^2/N_{pt}	N_{pt}	χ^2/N_{pt}	N_{pt}	χ^2	χ^2/N_{pt}
0.5	242	1.26	358	1.65	233	1.06	426	1.19	1259	1650.2	1.31
0.6	212	1.21	290	1.59	228	0.92	423	0.97	1153	1338.8	1.16
0.7	182	1.11	214	1.47	223	0.61	413	0.84	1032	997.2	0.97
0.8	152	0.98	142	1.30	218	0.53	407	0.82	919	781.8	0.85
0.9	122	1.05	94	1.29	213	0.52	407	0.80	836	687.1	0.82
1.0	98	1.14	54	0.97	209	0.49	403	0.80	764	587.2	0.77


 energy cut of the identified hadron



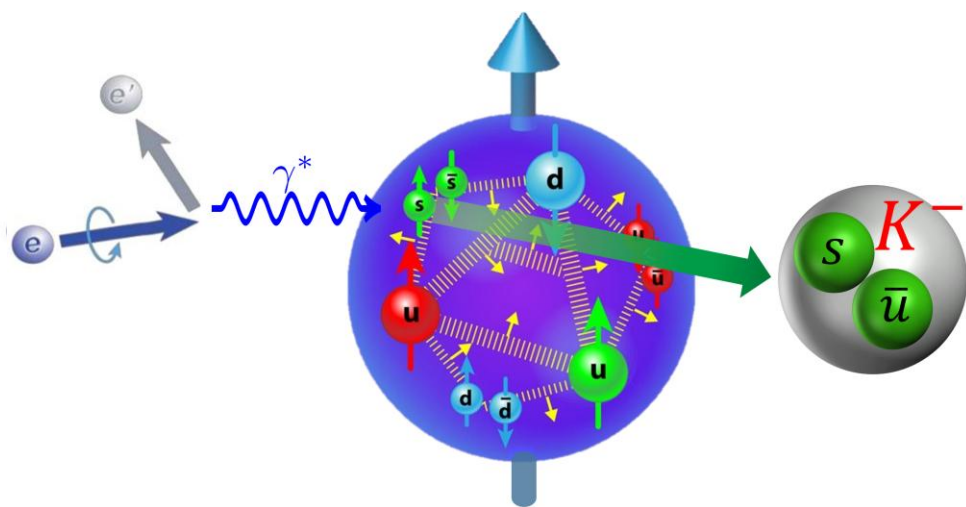
LHAGrids of our FFs have been submitted to the LHAPDF repository.

<https://www.lhapdf.org/pdfsets.html>

Application: constraining proton PDFs at NNLO

SIDIS may also constrain PDFs:

$$\frac{d^3\sigma_h}{dx_B dy dz_h} = \underbrace{f_{i/p}(x)}_{\text{unpolarized PDF}} \otimes \hat{\sigma}_{j \leftarrow i}(x, y, z) \otimes \underbrace{D_{h/j}(z)}_{\text{FF}}$$



➤ LO xsec of SIDIS off an isoscalar target (COMPASS)

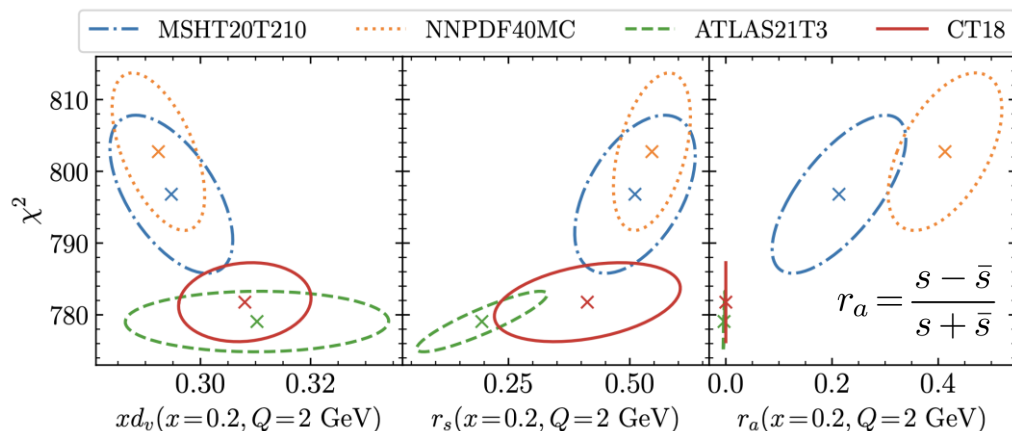
$$\begin{aligned} & \frac{d\sigma^{K^+}}{dx dy dz} - \frac{d\sigma^{K^-}}{dx dy dz} \\ & \sim 2 \left(u_v(x) + d_v(x) \right) \left(D_u^{K^+}(z) - D_{\bar{u}}^{K^+}(z) \right) \\ & + \underbrace{\left(s(x) - \bar{s}(x) \right)}_{\text{PDF}} \underbrace{\left(D_s^{K^+}(z) - D_{\bar{s}}^{K^+}(z) \right)}_{\text{FF}} + \dots \end{aligned}$$

is sensitive to **strangeness asymmetry**

$$r_a = \frac{s - \bar{s}}{s + \bar{s}}$$

Application: constraining proton PDFs at NNLO

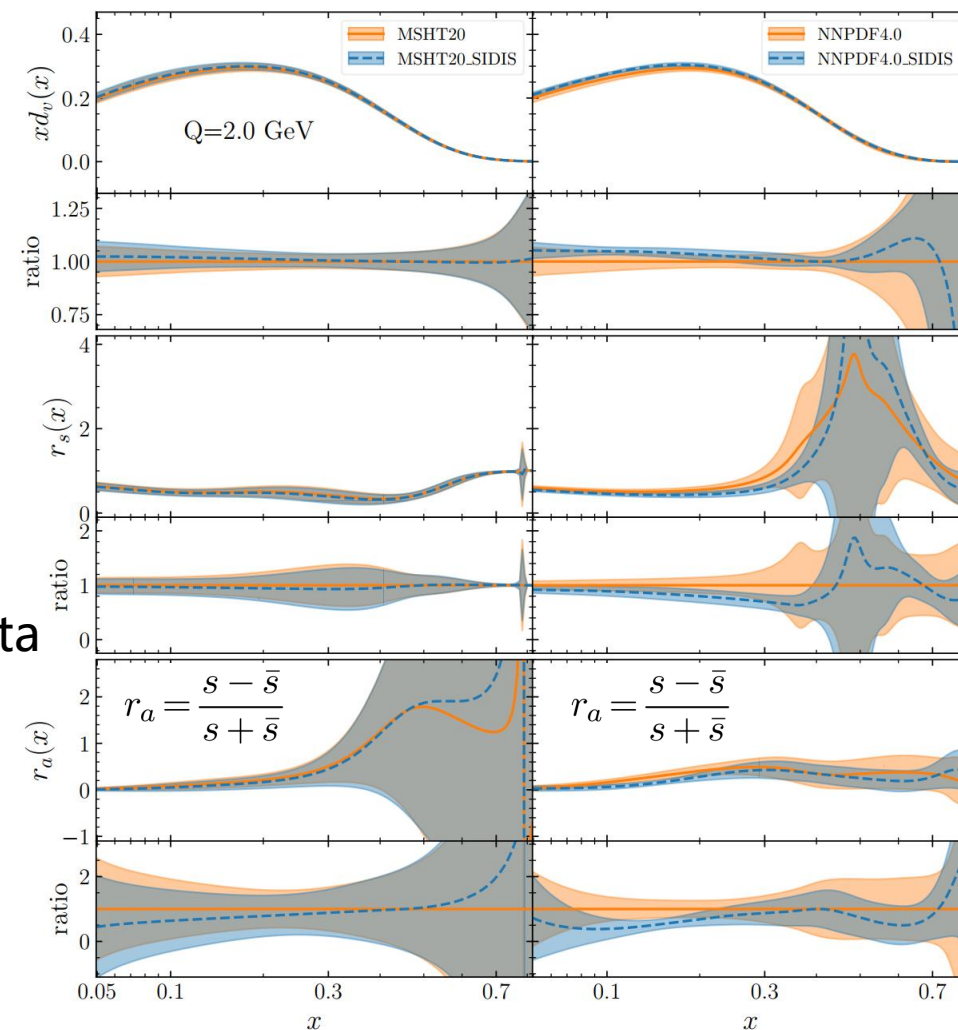
➤ Correlation between χ^2 and PDFs



➤ **Modified PDFs** which reflect the impact of SIDIS data

- Reweighting of the **NNPDF4.0** PDF set
- Profiling of the **MSHT20** PDF set

[Gao, **XS**, Xing, Zhao, Zhou, *PRL* **135**, 041902, 2025]



PDF sets before and after reweighting/profiling

Summary

- NPC collaboration has delivered **precise and comprehensive** FF sets at NLO.
- We present the **first** global (SIA+SIDIS) FFs determination at full **NNLO**.
- **FFs** studies may also contribute to **nucleon structure analyses**.

collaboration	NPC	NPC
SIA (ee)	✓	✓
SIDIS (ep)	✓	✓
pp incl. hadron	✓	✗
hadron in jet	✓	✗
FFs	$\pi^\pm, K^\pm, p$ K^0, η, Λ	$\pi^\pm, K^\pm$
pQCD order	NLO	NNLO

FF sets from NPC: <https://www.lhapdf.org/pdfsets.html>
NLO charged hadron:
Gao, Liu, **XS**, Xing, Zhao, *PRL* 132, 261903, 2024
Gao, Liu, **XS**, Xing, Zhao, *PRD* 110, 114019, 2024
NLO neutral hadron:
Gao, Liu, Li, **XS**, Xing, Zhao, Zhou, *PRD* 112, 054045, 2025
NNLO:
Gao, **XS**, Xing, Zhao, Zhou, *PRL* 135, 041902, 2025

Thank you for your attention!



Backup slides

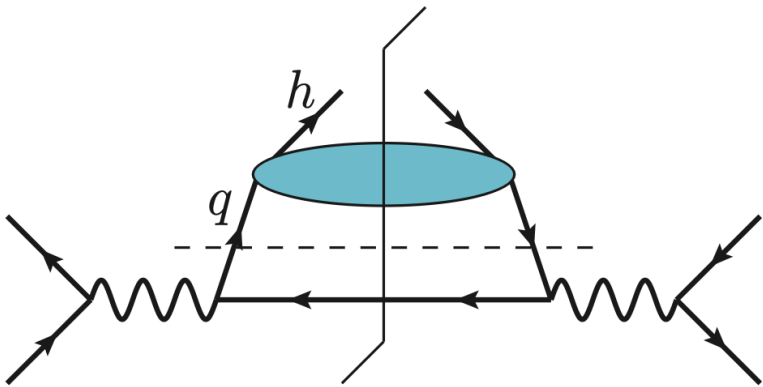
NPC collaboration gathering on July 19th 2025



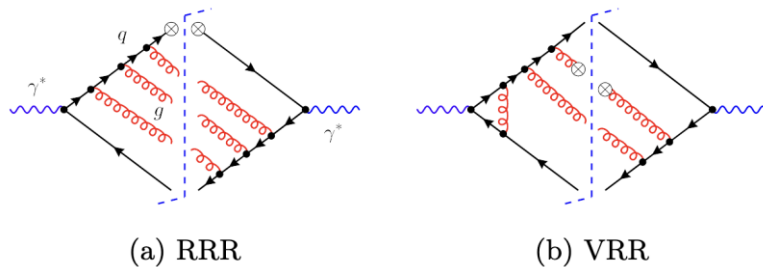
in neighborhood of Huizhou city (host of EICc)

Jun Gao, ChongYang Liu, Meng Yang Li, **XiaoMin Shen**, **HongXi Xing**, **YuXiang Zhao**, Bin Zhou, YiYu Zhou
Shanghai JiaoTong Univ., South China Normal Univ., Institute of Modern Physics, CAS

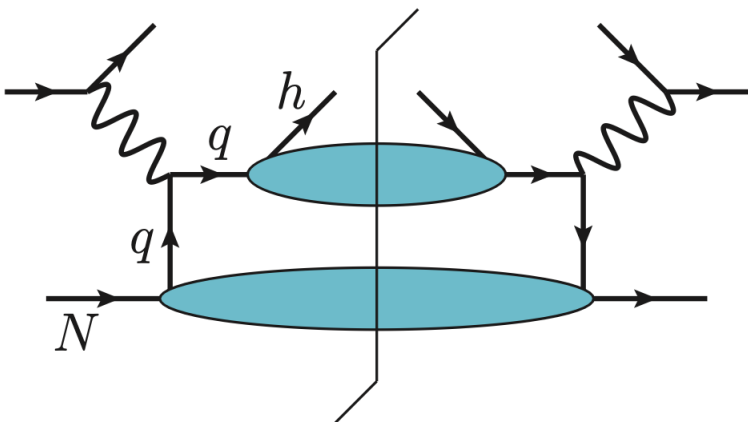
Recent progresses from pQCD



❖ SIA(e^+e^-) at N3LO



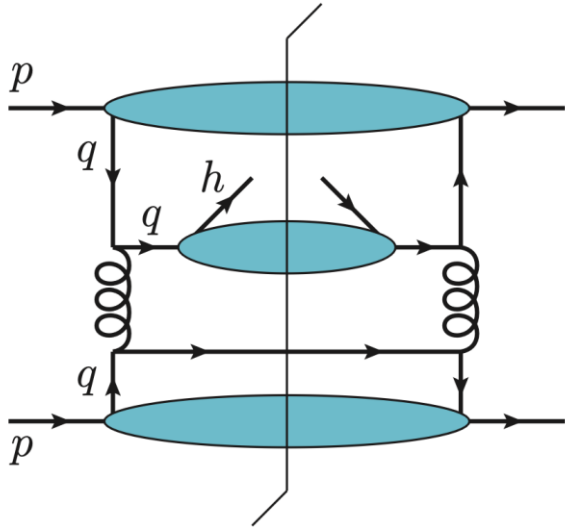
[He, Xing, Yang, Zhu, PRL.135.101901(2025)]



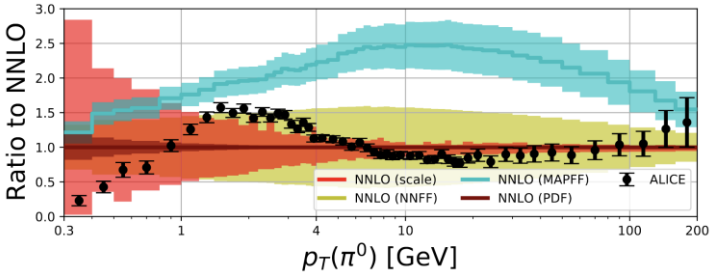
❖ SIDIS(ep) at NNLO

[Bonino, Gehrmann, et al.
& Goyal, Moch, et al.

PRL.132.251901, '24, PRL.132.251902, '24,
PRL.133.211904, '24, PRL.133.211905, '24,
2504.05376]



❖ pp at NNLO



[Czakon, Generet, Mitov, Poncelet,
2503.11489]



Figure credit: A. Metz, A. Vossen,1607.02521

Global analysis of FFs at full NNLO: theoretical prediction

FFs at starting scale $Q_0 = 1.4$ GeV

- parameterized as

$$zD_i^h(z, Q_0) = z^{\alpha_i^h} (1-z)^{\beta_i^h} \exp\left(\sum_{n=0}^m a_{i,n}^h z^{n/2}\right)$$

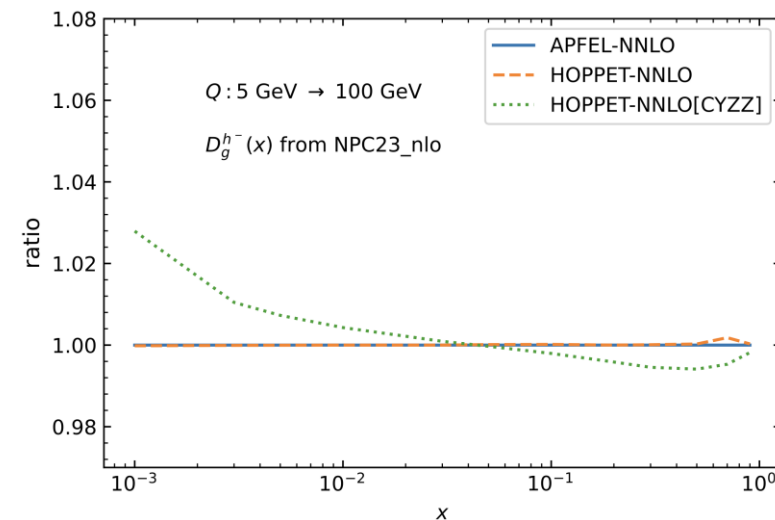
- charge/isospin symmetries suppress number of free parameters (54 in total)

$$D_{u \rightarrow \pi^+}(z, Q) = D_{\bar{u} \rightarrow \pi^-}(z, Q)$$

$$D_{u \rightarrow \pi^+}(z, Q_0) = D_{\bar{d} \rightarrow \pi^+}(z, Q_0)$$

FFs at arbitrary energy scale ($Q_0 \rightarrow Q$)

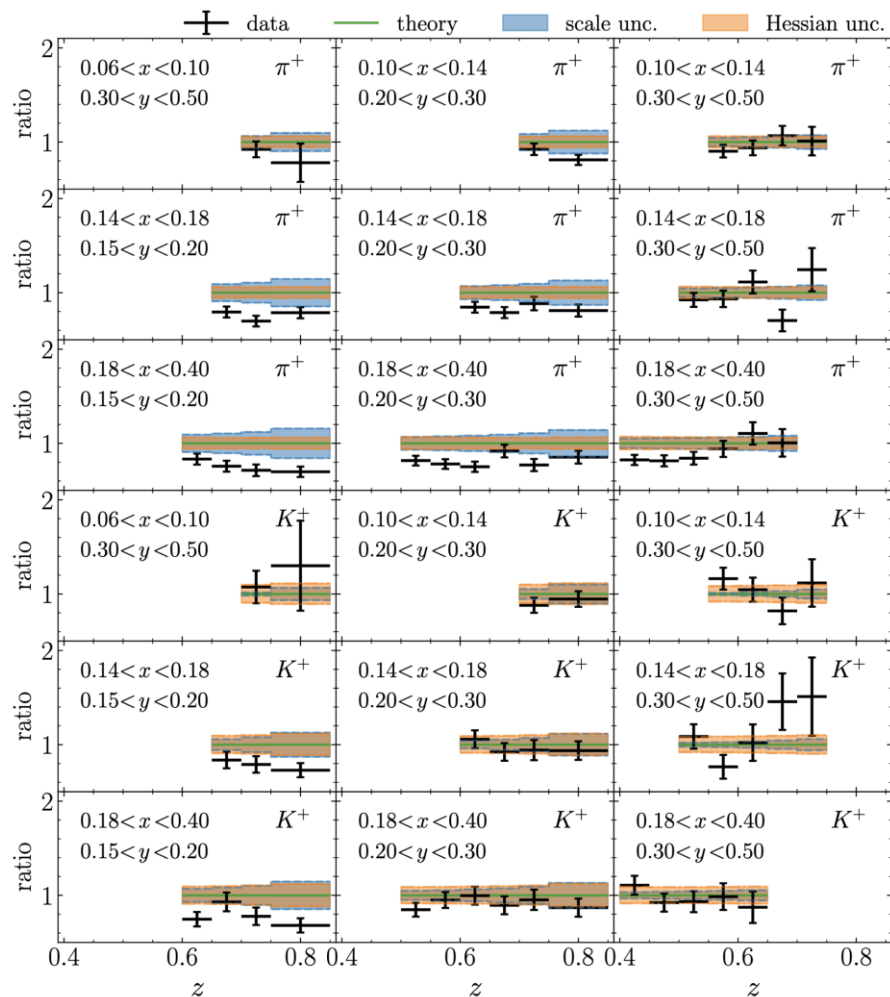
- 3-loop timelike DGLAP evolution
[Mitov, Moch, Vogt, Almasy]
- $+P_{qg}^{T(2)}$ correction [Chen, Yang, Zhu, Zhu, '20]



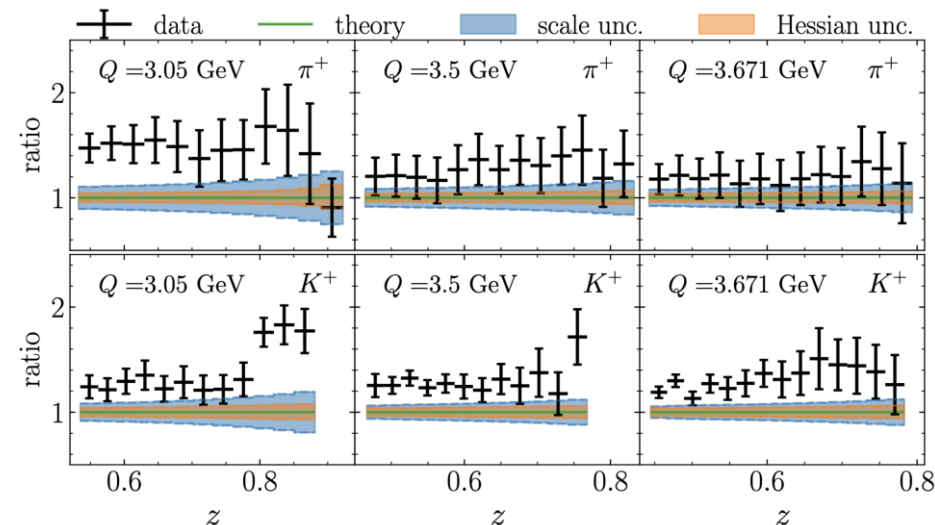
- Heavy quark FFs are frozen below mass threshold.

Test on leading-twist collinear factorization at low Q

Theory v.s. data for COMPASS06 (SIDIS: 2~5GeV)



Theory v.s. data for BESIII (SIA: ~3GeV)



➤ Kinematic cuts in our analyses:

- $Q > 3$ GeV (SIA)
- $Q > 2$ GeV (SIDIS)
- $z > 0.01, E_h > 0.8$ GeV

the **first** test on **universality of FFs** at $Q \sim 3$ GeV using ee and SIDIS data