The 7th International Workshop
on Future Tau Charm Facilities
FTCF2025, Huangshan
November 23rd - 27th, 2025

Recent Progress on Parton Fragmentation Functions

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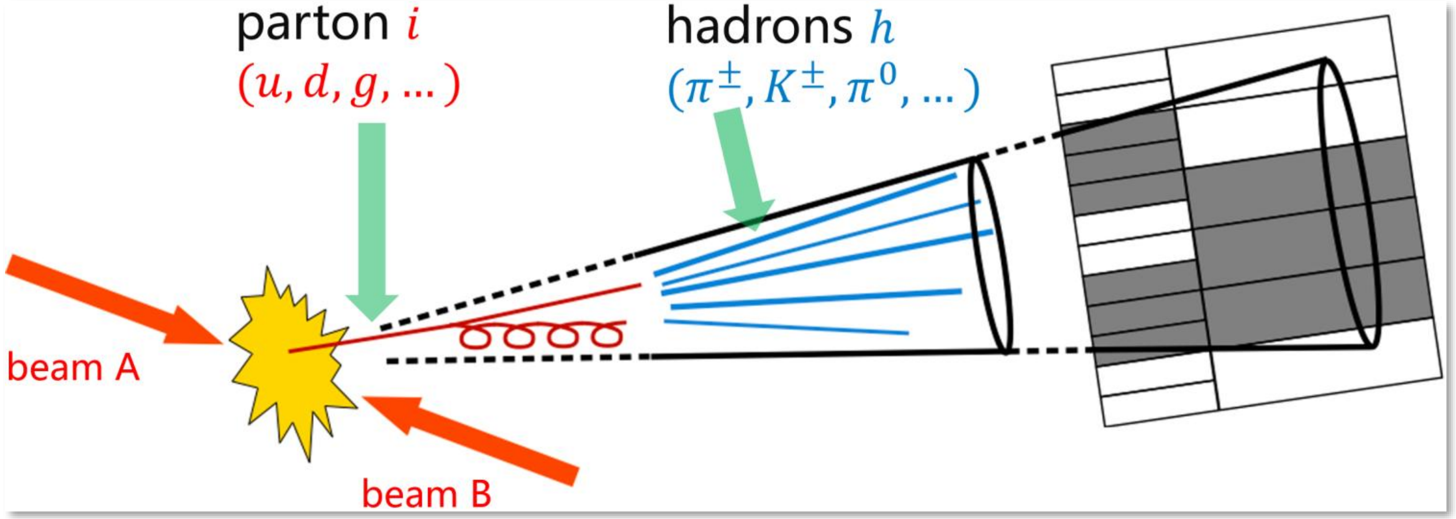
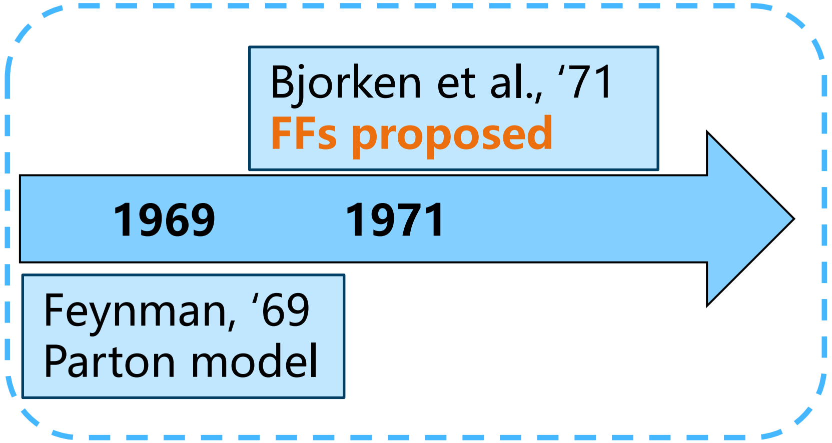
On behalf of the NPC Collaboration

Fragmentation Functions (FFs) in the parton model



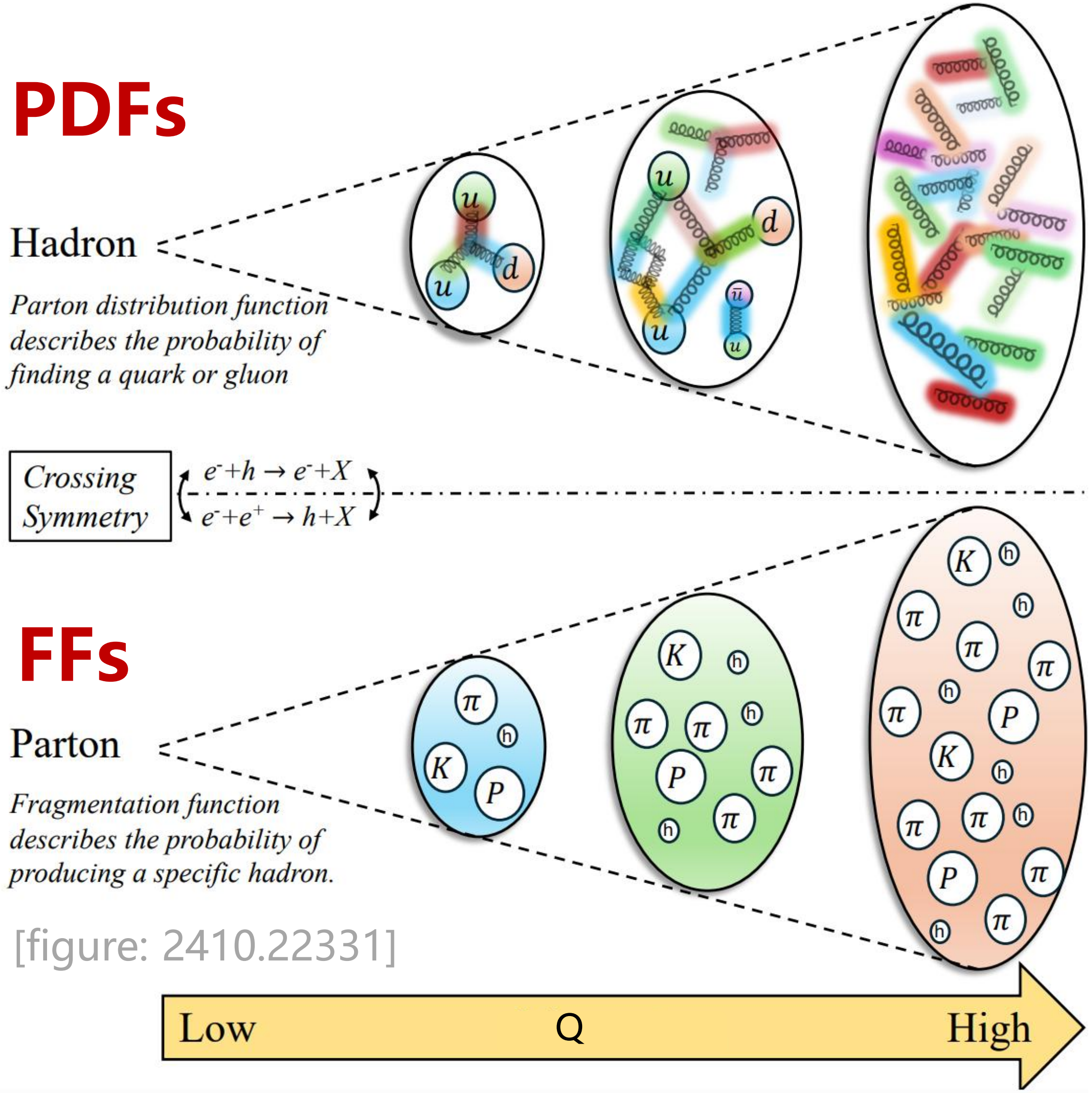


- **Collinear FFs** introduced as extension of the **parton model in final state**
  - **number density** of finding
    - a specific hadron h
    - with momentum fraction z "in" parton i

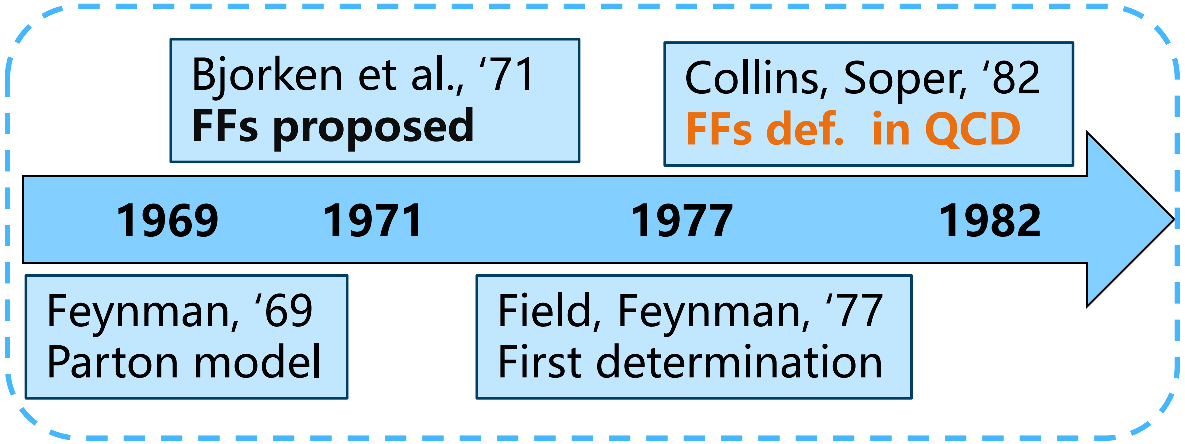
$$D_{h/i}\left(z = \frac{p_h^+}{p_i^+}\right) \longleftrightarrow f_{i/h}\left(x = \frac{p_i^+}{p_h^+}\right)$$

FF PDF

Fragmentation Functions (FFs) in QCD



[figure: 2410.22331]



$$D(z, Q_0)$$

$$\frac{\mathrm{d}D_{h/i}(z,Q)}{\mathrm{d}\ln^2 Q} = P_{ji}(y) \otimes D_{h/j}\left(\frac{z}{y}, Q\right)$$

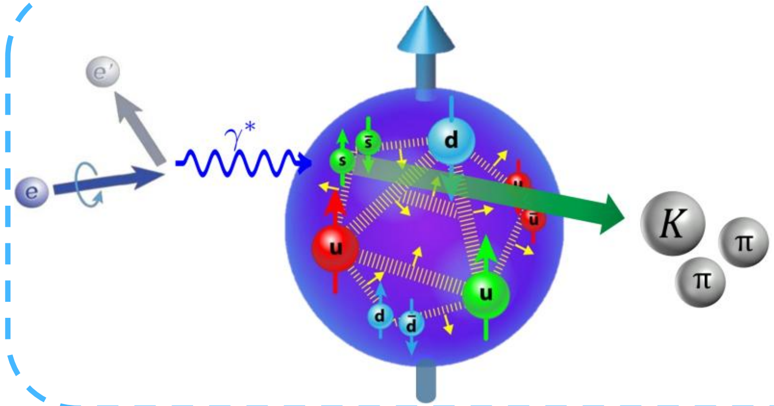
$$D(z, Q)$$

scaling violation predicted by **timelike** DGLAP evolution

FFs are key ingredients of QCD factorization framework

1969	1971	1977	1982	1989
Feynman, '69 Parton model	Bjorken et al., '71 FFs proposed	Field, Feynman, '77 First determination	Collins, Soper, '82 FF def. in QCD	Collins et al., '89 **Factorization thm.**

- Semi-Inclusive DIS (SIDIS) : e + N -> e + **h** + X

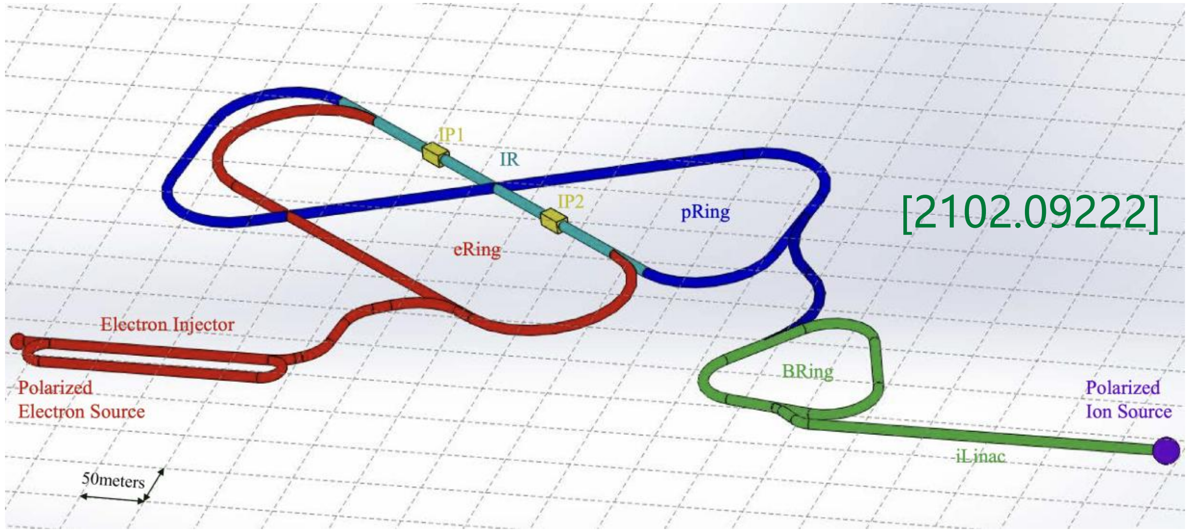


$$\frac{d^3\sigma_h}{dx_B dy dz_h} = f_{i/p}(x) \otimes \hat{\sigma}_{j\leftarrow i}(x, y, z) \otimes D_{h/j}(z)$$

PDF pQCD **FF**

- $e^+e^- \to h + X$ (SIA) => σ = pQCD ⊗ **FF**
- $pp \to h + X$ => σ = PDF ⊗ PDF ⊗ pQCD ⊗ **FF**

FFs play a key role in the era of high-precision physics



❖ Electron-Ion Collider (EIC)

- start operation in the early 2030s
- unprecedented access to nucleon structure
- FFs will be key inputs/outputs

❖ Efforts from China

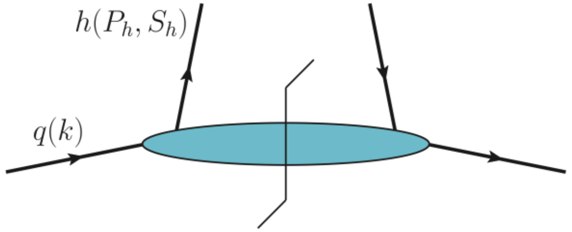
- **BESIII** [2211.11253, 2401.17873, 2502.16084]
- **STCF** See Haiping Peng's talk on Nov.24
- **EicC**: helicity structure of sea quarks

FFs are major physical targets and key inputs of future colliders.

Determination of FFs

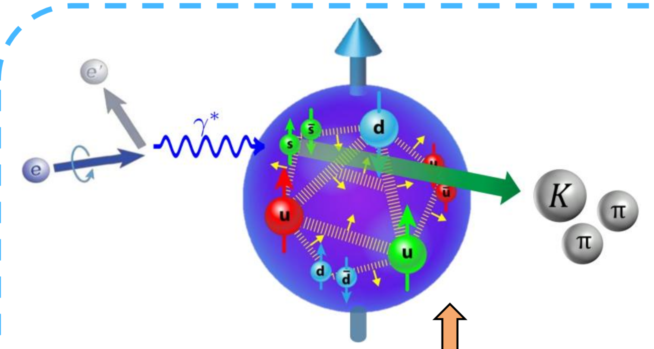
❖ Field theory definiton of the collinear (integrated) quark FFs [Collins, Soper '82]

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



❖ Using quantum computers [2406.05683, 2510.18869]

❖ **Global data fits** based on factorization formula



$$= f_{i/p}(x) \otimes \hat{\sigma}_{j\leftarrow i}(x,y,z) \otimes D_{h/j}(z)$$

measurement — input — pQCD — to be determined. — Universal !

+ ee(SIA) + pp collisions

Outline

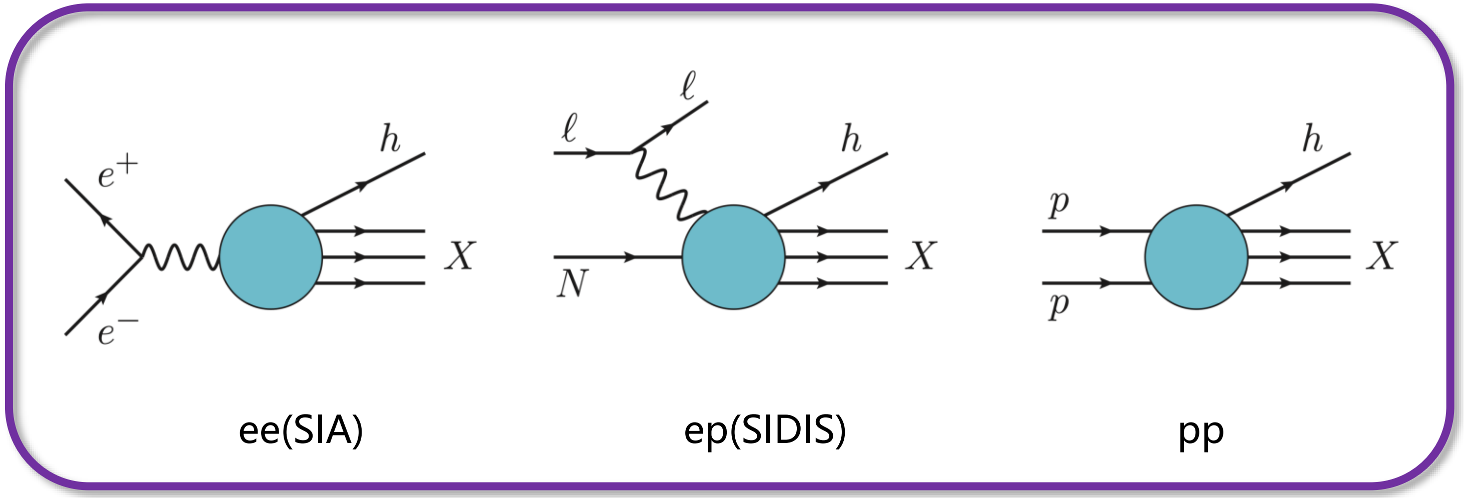
- ➢ Introduction
- ➢ Global fits of FFs at NLO
- ➢ Global fits of FFs at NNLO
- ➢ Summary

NPC= Non-Perturbative Physics Collaboration

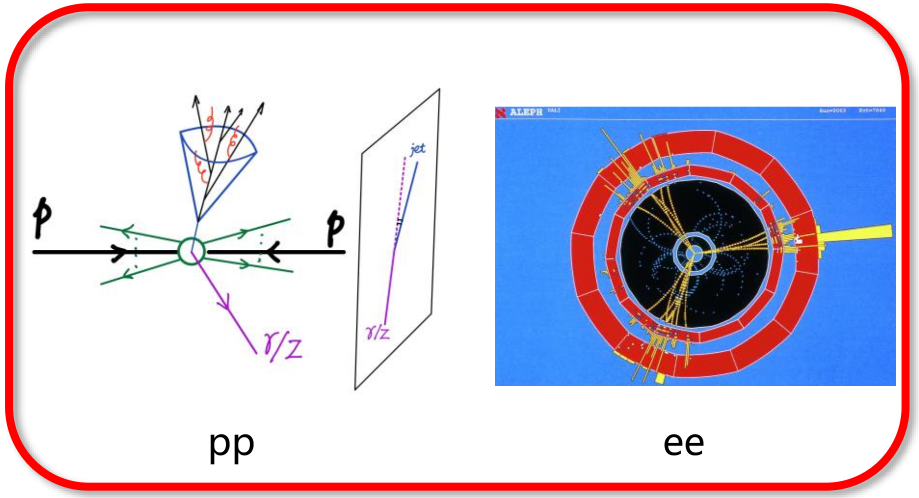
collaboration	NNFF	JAM	DSS+	BDSSV	MAP	NPC
SIA (ee)	✓	✓	✓	✓	✓	✓
SIDIS (ep)	✗	✓	✓	✓	✓	✓
pp incl. hadron	✗	✗	✓	✗	✗	✓
hadron in jet	✗	✗	✗	✗	✗	✓
FFs (charged h)	$\pi^{\pm}$,$K^{\pm}$,p	$\pi^{\pm}$,$K^{\pm}$	$\pi^{\pm}$,$K^{\pm}$,p	$\pi^{\pm}$	$\pi^{\pm}$,$K^{\pm}$	$\pi^{\pm}$,$K^{\pm}$,p
FFs (neutral h)			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

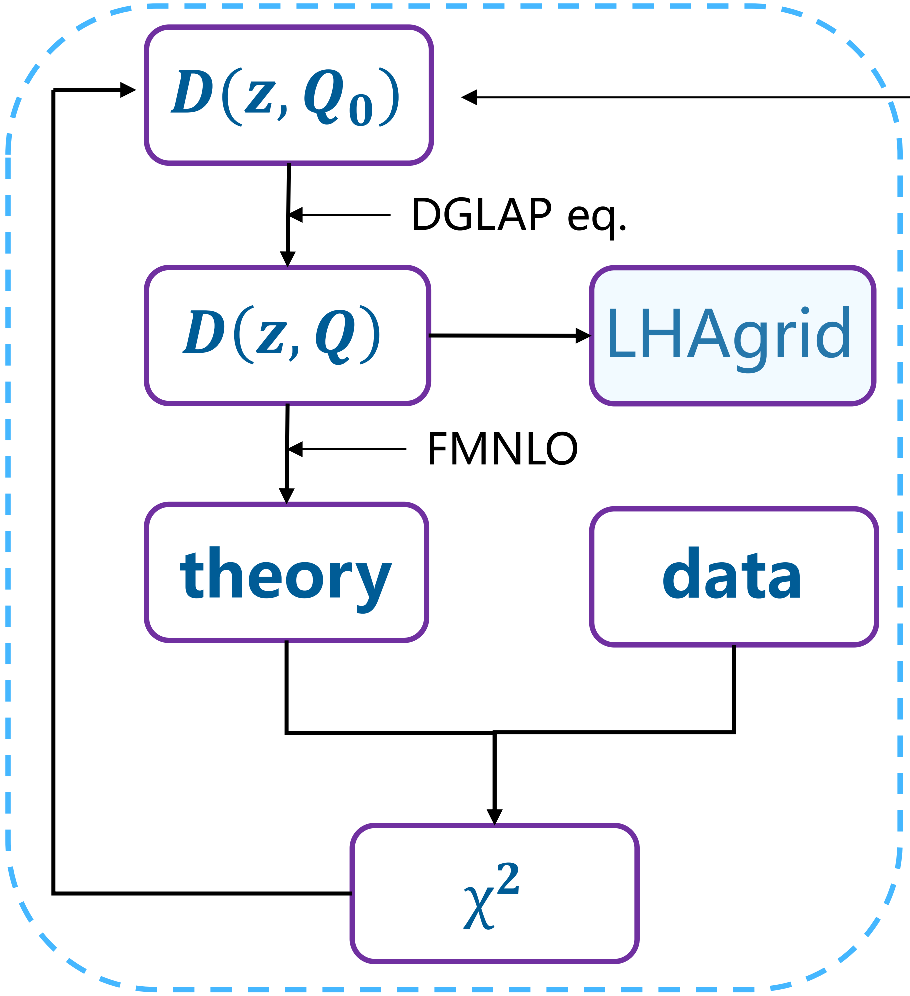
$$\frac{p_{T,h}}{p_{T,j}} \xrightarrow{\text{LO}} z$$

- All theoretical predictions calculated with **FMNLO.**

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

figure credit: A. Metz, A. Vossen,1607.02521; ALEPH Collaboration

Fit framework



Parameterization at starting scale Q_0=4.0 GeV

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

parton-to-π^+	favored	α	β	a_0	a_1	a_2	d.o.f.
u	Y						5
$\bar{d} \simeq u$	Y	-	-		-	-	1
$\bar{u} = d$	N					x	4
$s = \bar{s} \simeq \bar{u}$	N	-				x	3
$c = \bar{c}$	N					x	4
$b = \bar{b}$	N					x	4
g	N		F				4

parton-to-K^+	favored	α	β	a_0	a_1	a_2	d.o.f.
u	Y					x	4
$\bar{s} \simeq u$	Y	-	-		-	x	1
$\bar{u}=d=\bar{d}=s$	N					x	4
$c = \bar{c}$	N					x	4
$b = \bar{b}$	N					x	4
g	N		F			x	3

parton-to-p	favored	α	β	a_0	a_1	a_2	d.o.f.
$u = 2d$	Y					x	4
$\bar{u} = \bar{d} = s = \bar{s}$	N				x	x	3
$c = \bar{c}$	N					x	4
$b = \bar{b}$	N					x	4
g	N		F			x	3

simultaneous fit of $\pi^{\pm}, K^{\pm}, p/\bar{p}$ FFs

Good agreement between theory and data

	Experiments	N_{pt}	χ^2	χ^2/N_{pt}
h in jet	ATLAS jets †	446	350.8	0.79
	ATLAS $Z/\gamma+$jet †	15	31.8	2.12
	CMS $Z/\gamma+$jet †	15	17.3	1.15
	LHCb $Z+$jet	20	30.6	1.53
pp	ALICE inc. hadron	147	150.6	1.02
	STAR inc. hadron	60	42.2	0.70
	pp sum	**703**	**623.3**	**0.89**
ee	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**
ep	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	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$
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 $Q^2 \in 160, 640$ GeV^2	2012	318	4.41	5	0.88
ZEUS $Q^2 \in 640, 2560$ GeV^2	2012	318	3.26	5	0.65
ZEUS $Q^2 \in 2560, 10240$ GeV^2	2012	318	2.74	2	1.37
SIDIS sum			**10.41**	**12**	**0.87**
ALICE $N_{K_S^0}^{13\,\rm TeV}/N_{K_S^0}^{7\,\rm TeV}$	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**

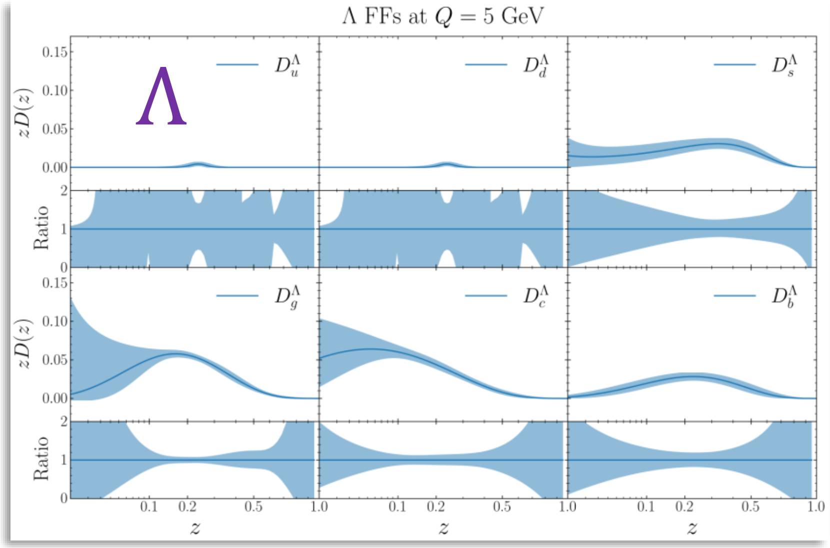
NPC23 K^0 FFs fit

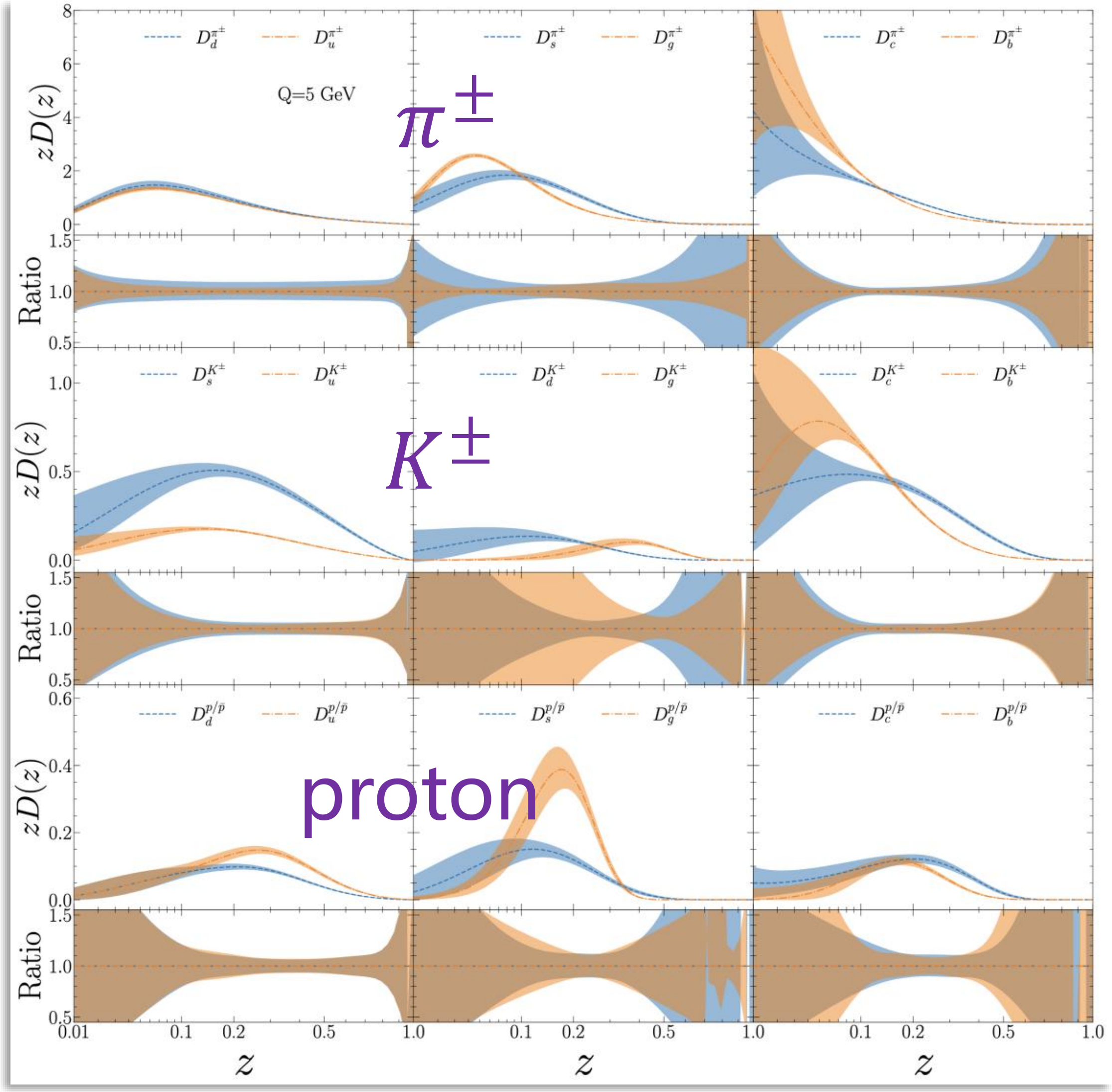
The NPC FF sets at NLO

… are publicly available

LHAPDF 6.5.5

Main page	PDF sets	Class hierarchy	Examples	More...
2070000	NPC23_PIp_nlo	(tarball)	(info file)	127
2070200	NPC23_KAp_nlo	(tarball)	(info file)	127
2070400	NPC23_PRp_nlo	(tarball)	(info file)	127
2070600	NPC23_PIm_nlo	(tarball)	(info file)	127
2070800	NPC23_KAm_nlo	(tarball)	(info file)	127
2071000	NPC23_PRm_nlo	(tarball)	(info file)	127
2071200	NPC23_PIsum_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





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 Non-perturbative 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:

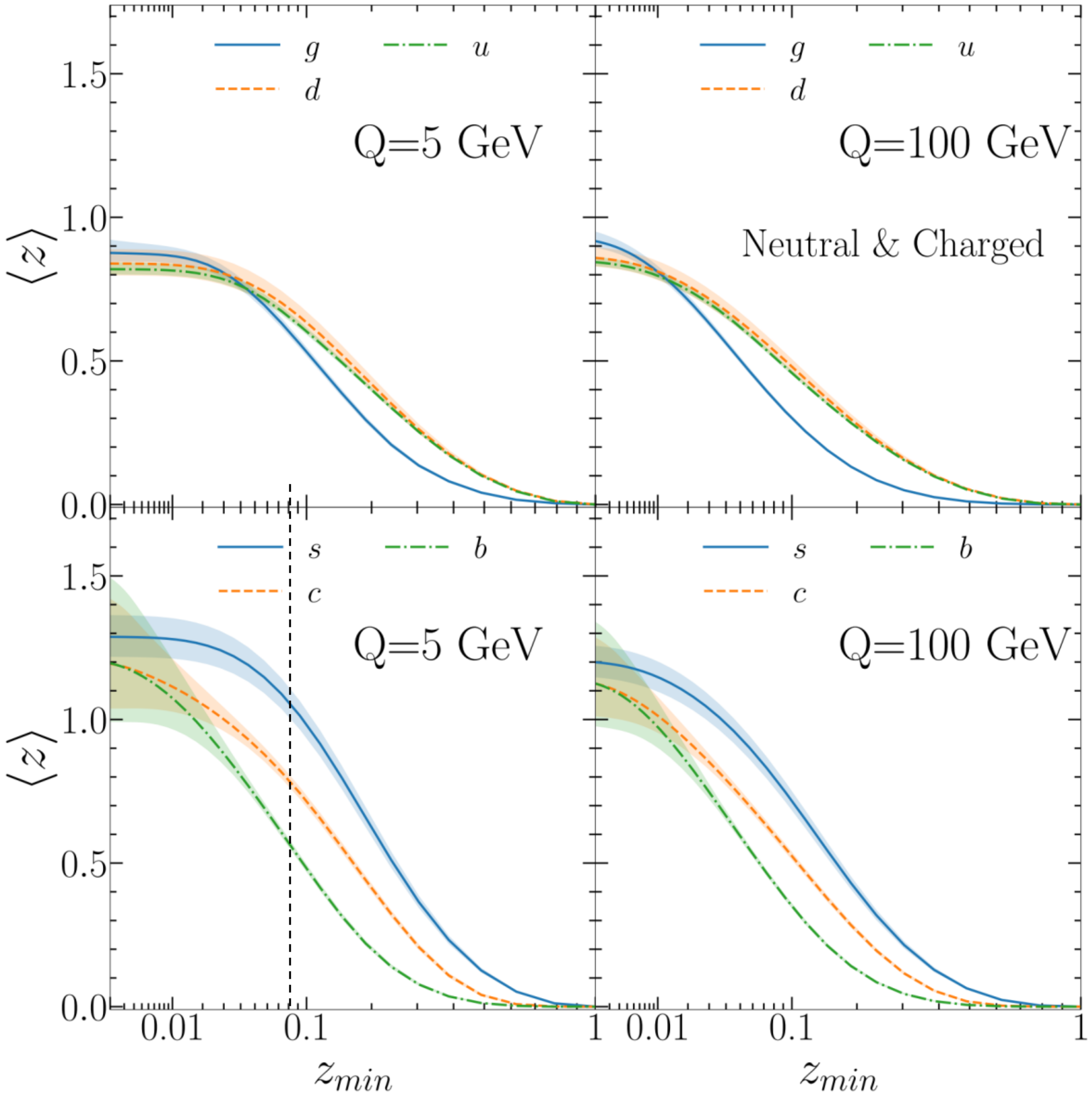
    Gao, Liu, Li, **XS**, Xing, Zhao, Zhou, *PRD 112, 054045, '25*

Test sum rule using neutral + charged hadron FFs

parton i ➡ hadrons $h = \pi^{\pm}, \pi^0, K^{\pm}, K^0, \cdots$

The **momentum sum rule**:

$$\lim_{z_{\min}\to 0} \sum_h \int_{z_{min}}^{1} \left[z D_{h/i}(z) \right] \mathrm{d}z = 1$$



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
- Summary

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]

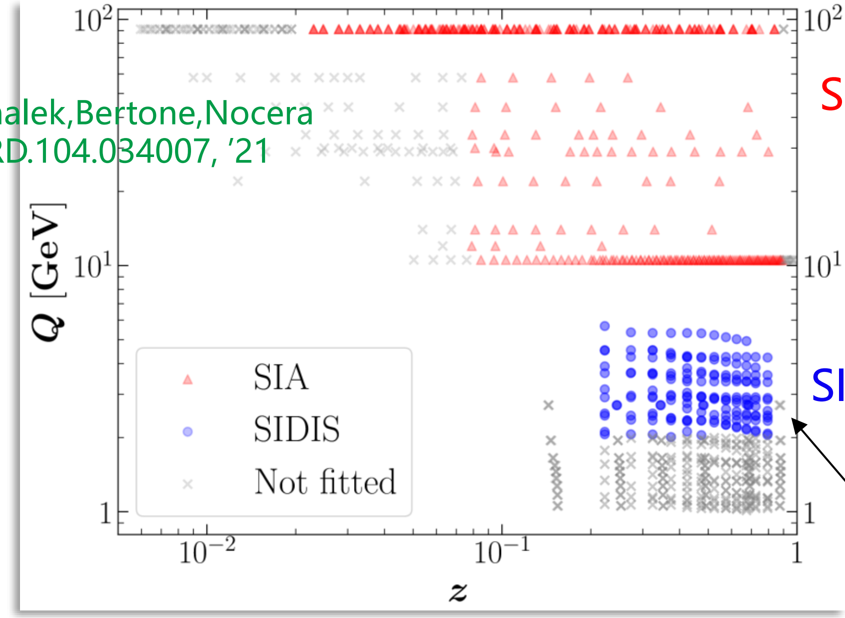
Global analysis of FFs at full NNLO: the datasets

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

exp.	$\sqrt{s}$/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	$Z \to q\bar{q}$	$\pi^\pm, K^\pm$
ALEPH	m_Z	520 000	1995	$Z \to q\bar{q}$	$\pi^\pm, K^\pm$
DELPHI	m_Z	1 400 000	1998	$Z \to q\bar{q}$	$\pi^\pm, K^\pm$
				$Z \to b\bar{b}$	$\pi^\pm, K^\pm$
SLD	m_Z	400 000	2004	$Z \to q\bar{q}$	$\pi^\pm, K^\pm$
				$Z \to b\bar{b}$	$\pi^\pm, K^\pm$
				$Z \to c\bar{c}$	$\pi^\pm, K^\pm$
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/2γ	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]

- **separated** kinematic region of e^+e^- and ep data (before BESIII measurement)



Khalek,Bertone,Nocera PRD.104.034007, '21

SIA(e^+e^-)

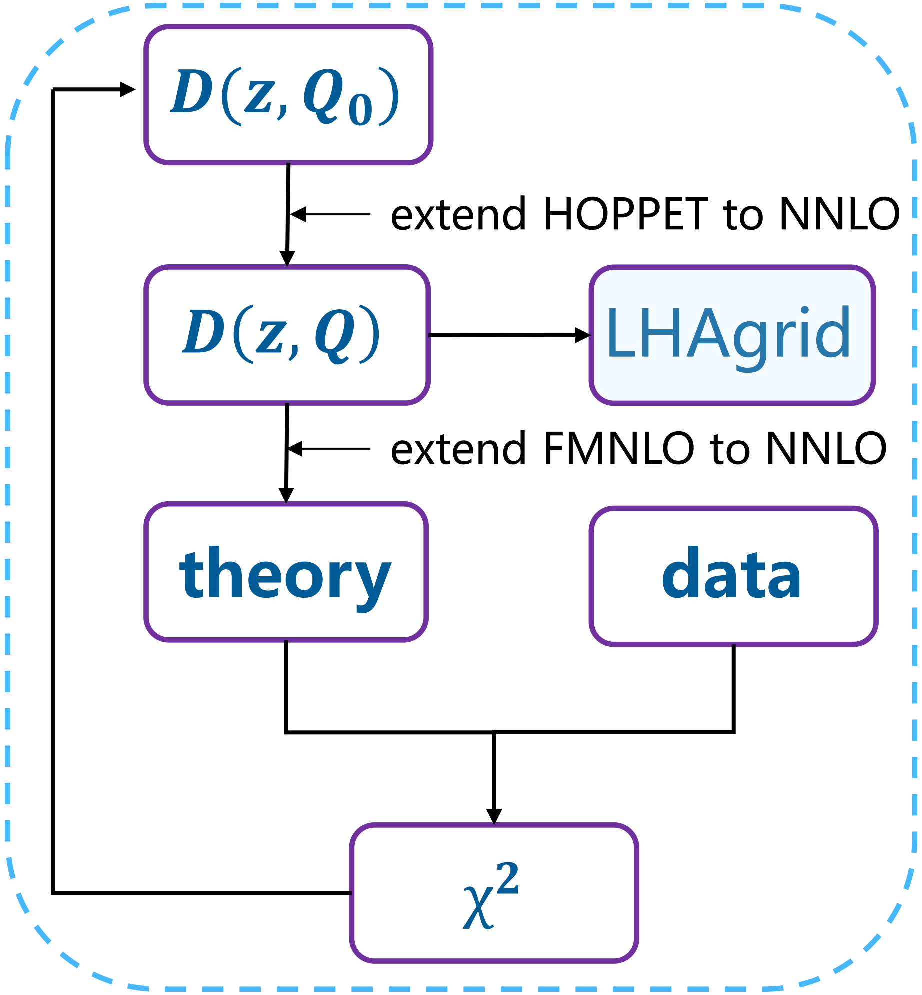
SIDIS(ep)

BESIII

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

the **first** test on **universality of FFs** at Q~3 GeV using both **ee** and **SIDIS** data

Global analysis of FFs at full NNLO: theoretical prediction



- FFs at starting scale $Q_0 = 1.4$ GeV

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

+charge/isospin symmetries

- FFs at arbitrary energy scale Q

3-loop timelike DGLAP evolution

[Mitov, Moch, Vogt, Almasy]

[Chen, Yang, Zhu, Zhu, '20]

- SIA/SIDIS coefficient functions at NNLO

[Bonino+, '24], [Goyal+, '24]

the **first** global FF fit (ee+SIDIS) at full NNLO accuracy

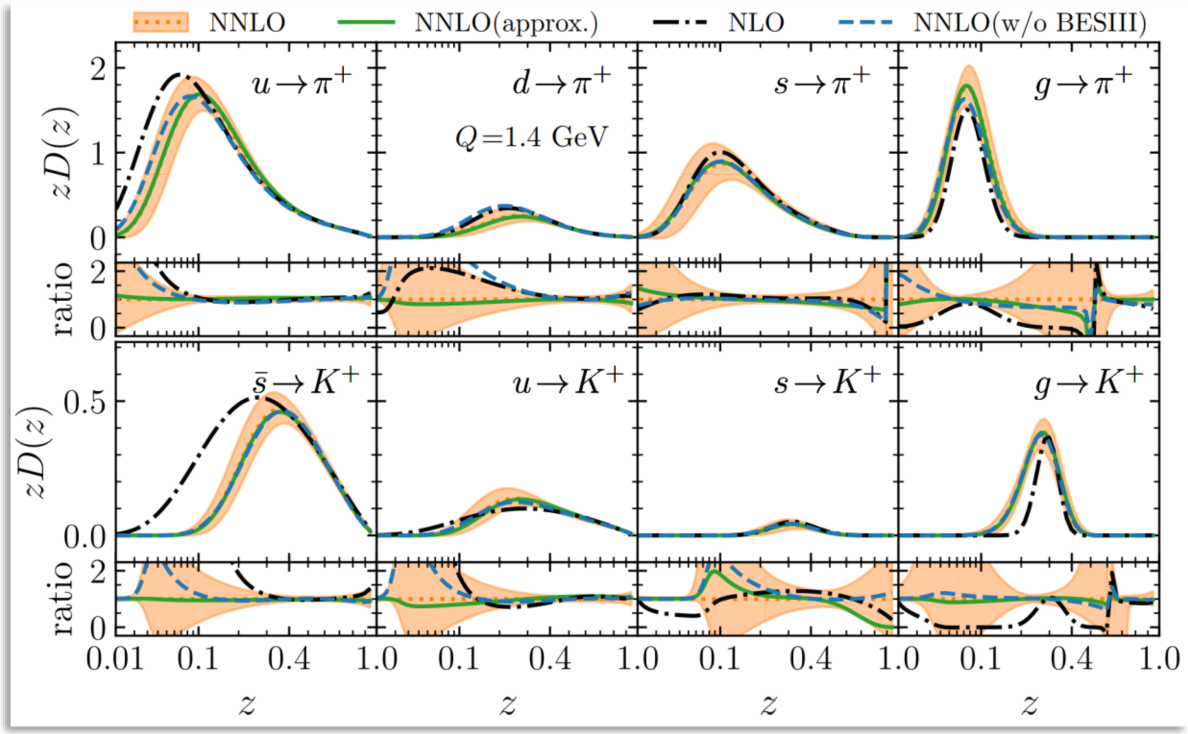
Global analysis of FFs at full NNLO: results

➢ Fit quality of the NNLO analyses

	BESIII		COMPASS		B-factories		HE-SIA		global		
$E_{h,\min}$[GeV]	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$	$N_{\rm pt}$	χ^2	$\chi^2/N_{\rm pt}$
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.

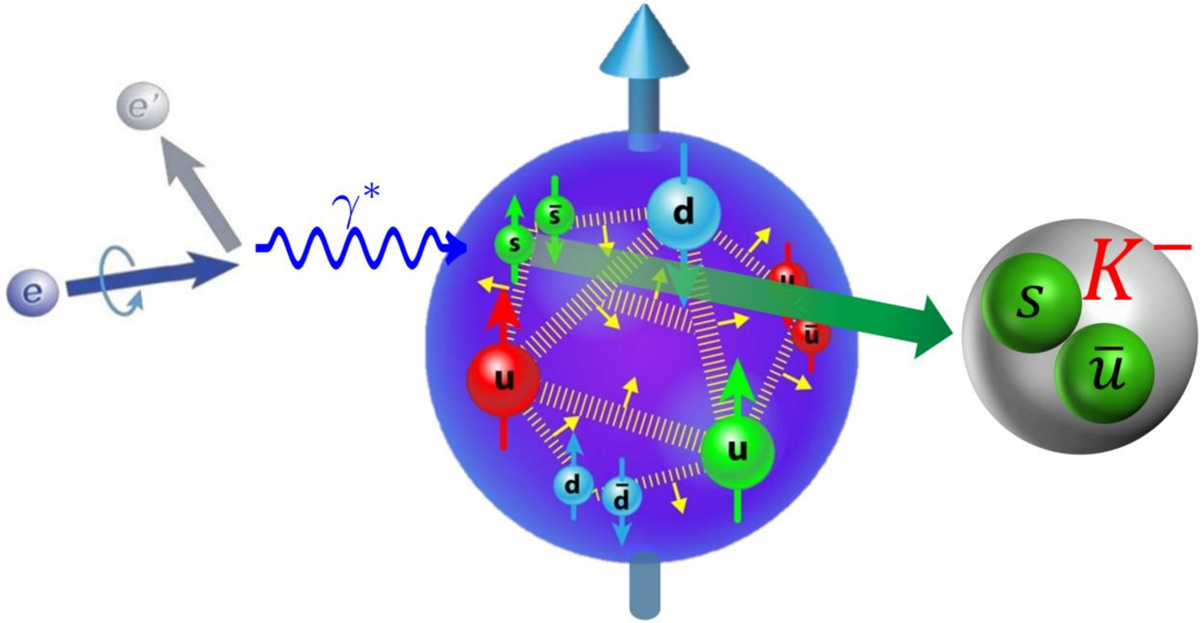
https://www.lhapdf.org/pdfsets.html

Application: constraining proton PDFs at NNLO

SIDIS may also constrain PDFs:

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

unpolarized PDF FF



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

$$\frac{d\sigma^{K^+}}{dxdydz} - \frac{d\sigma^{K^-}}{dxdydz}$$

$$\sim 2\Big(u_v(x) + d_v(x)\Big)\Big(D_u^{K^+}(z) - D_{\bar{u}}^{K^+}(z)\Big)$$

$$+\Big(s(x) - \bar{s}(x)\Big)\Big(D_s^{K^+}(z) - D_{\bar{s}}^{K^+}(z)\Big) + \cdots$$

PDF FF

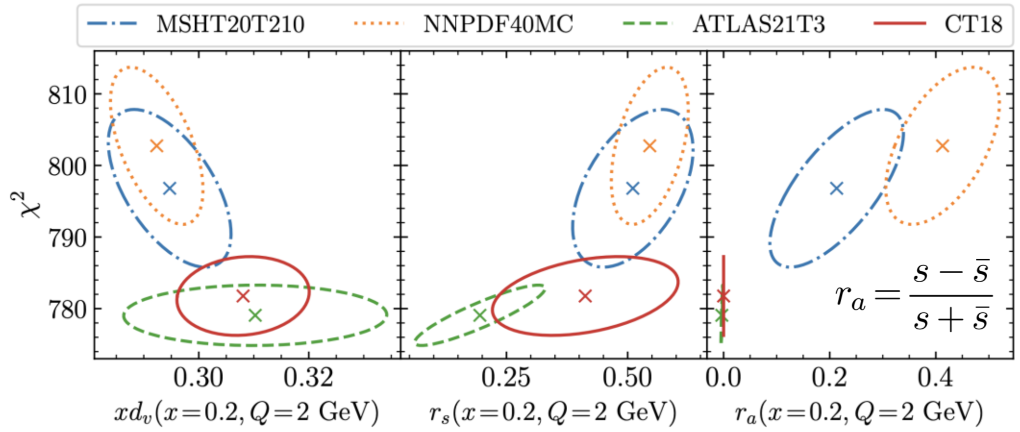
is sensitive to **strangeness asymmetry**

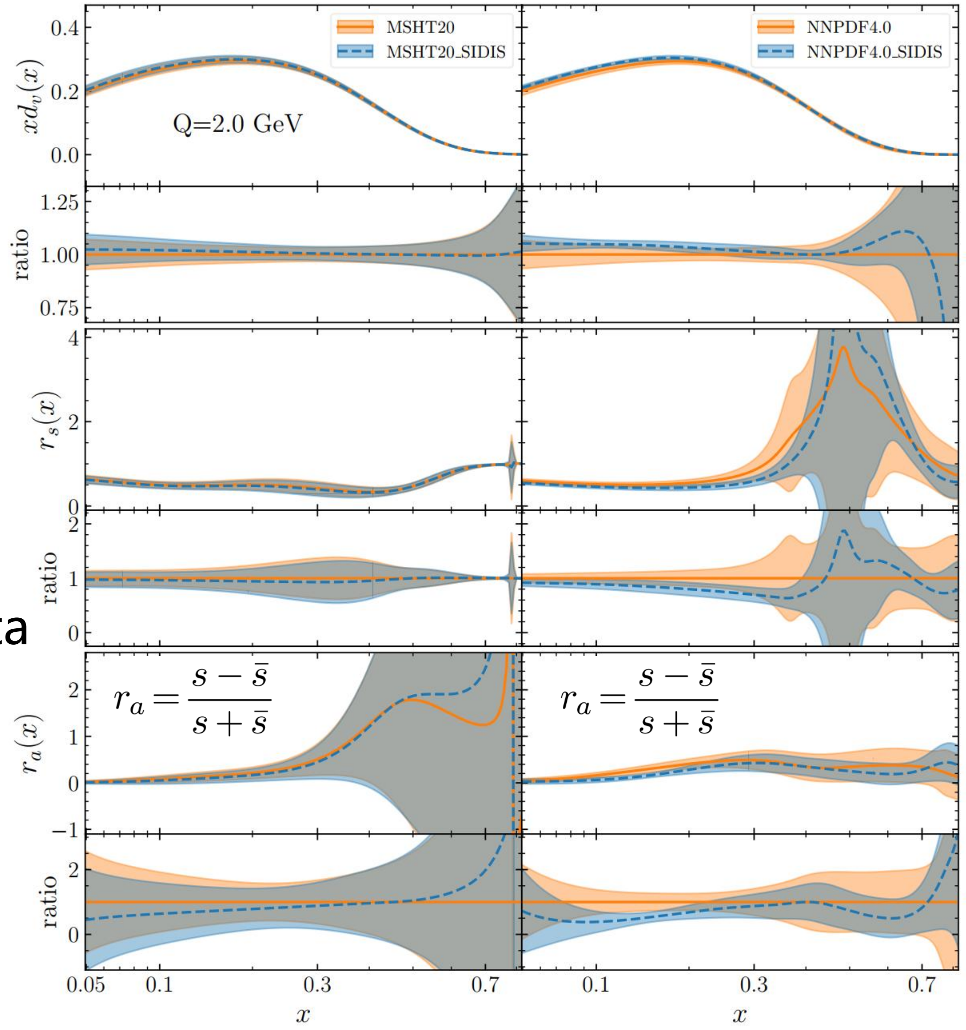
$$r_a = \frac{s - \bar{s}}{s + \bar{s}}$$

Application: constraining proton PDFs at NNLO

- Correlation between χ^2 and PDFs

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





- **Modified PDFs** which reflect the impact of SIDIS data
  - Reweighting of the NNPDF4.0 PDF set
  - Profiling of the MSHT20 PDF set

PDF sets before and after reweighting/profiling

Summary

- FFs are key inputs for calculations of hadron production rate from first principles.
- NPC collaboration has delivered precise and comprehensive FF sets at NLO.
- We present the **first** global (SIA+SIDIS) FFs determination at full NNLO.

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 available from 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

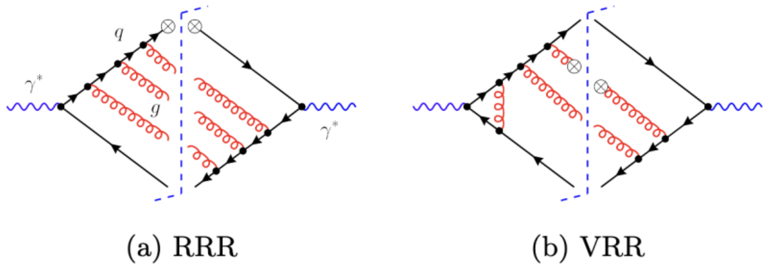
NNLO:

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

Thank you for your attention!

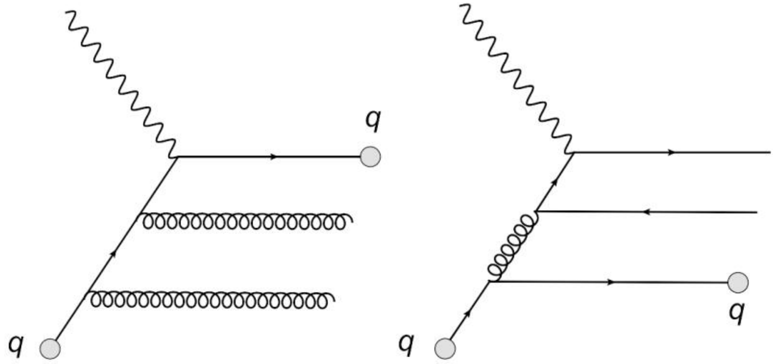
Recent progress from pQCD

❖SIA(e^+e^-) at N3LO



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

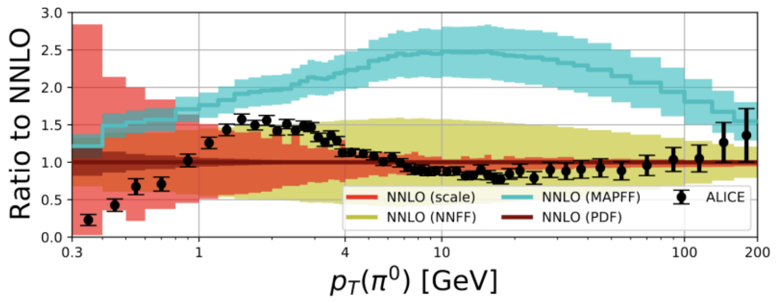
❖SIDIS(ep) at NNLO



[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, 2506.24078, 2510.00100, 2510.18872

❖pp at NNLO



[Czakon, Generet, Mitov, Poncelet, PRL.135.171902(2025)]

NPC collaboration gathering on July 19th 2025

in neighborhood of Huizhou city (host of EICc)

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NPC=Non-perturbative Physics Collaboration

Slide from Jun Gao