Parton fragmentation functions from NPC23

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The 2024 international workshop on CEPC

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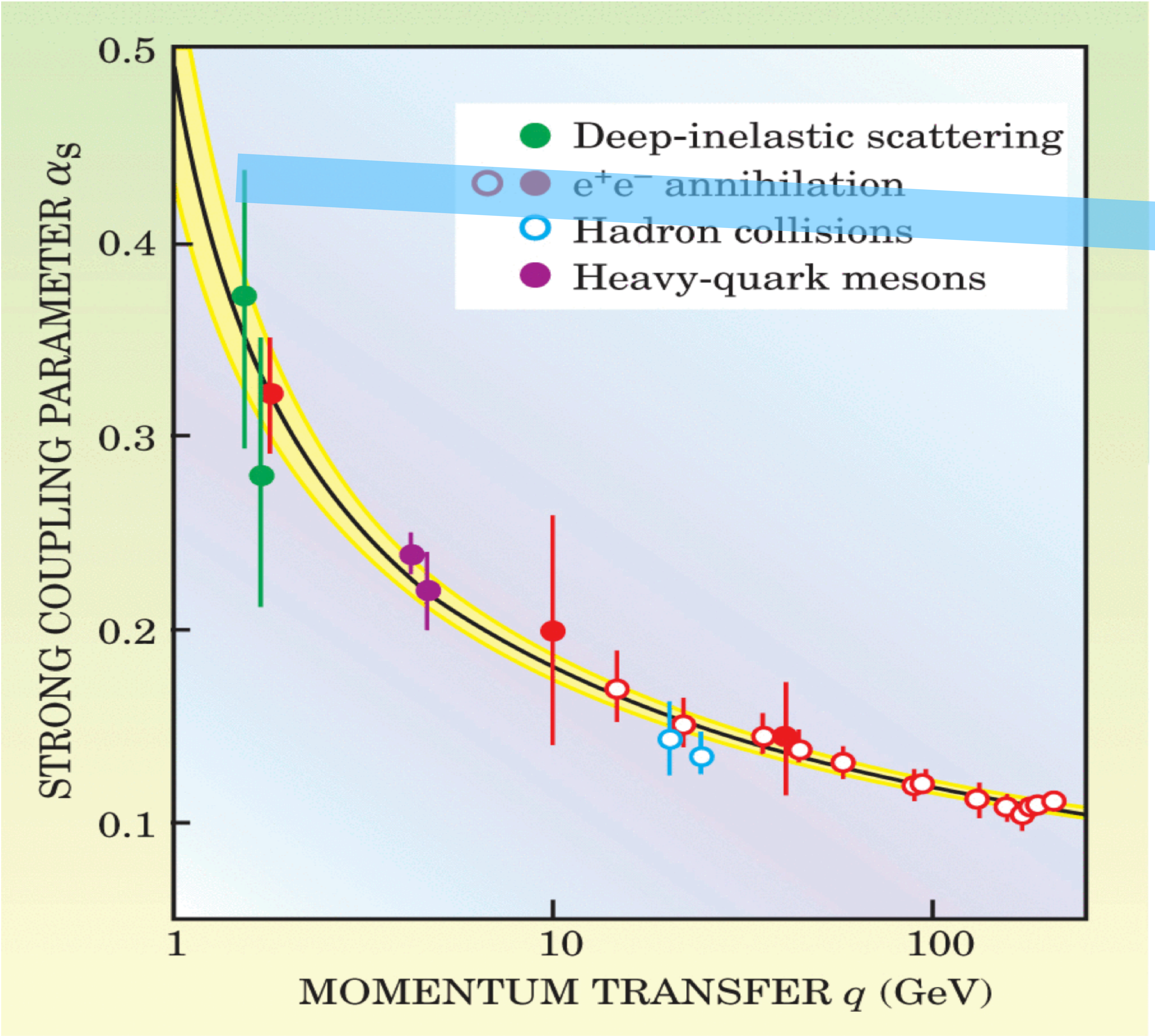
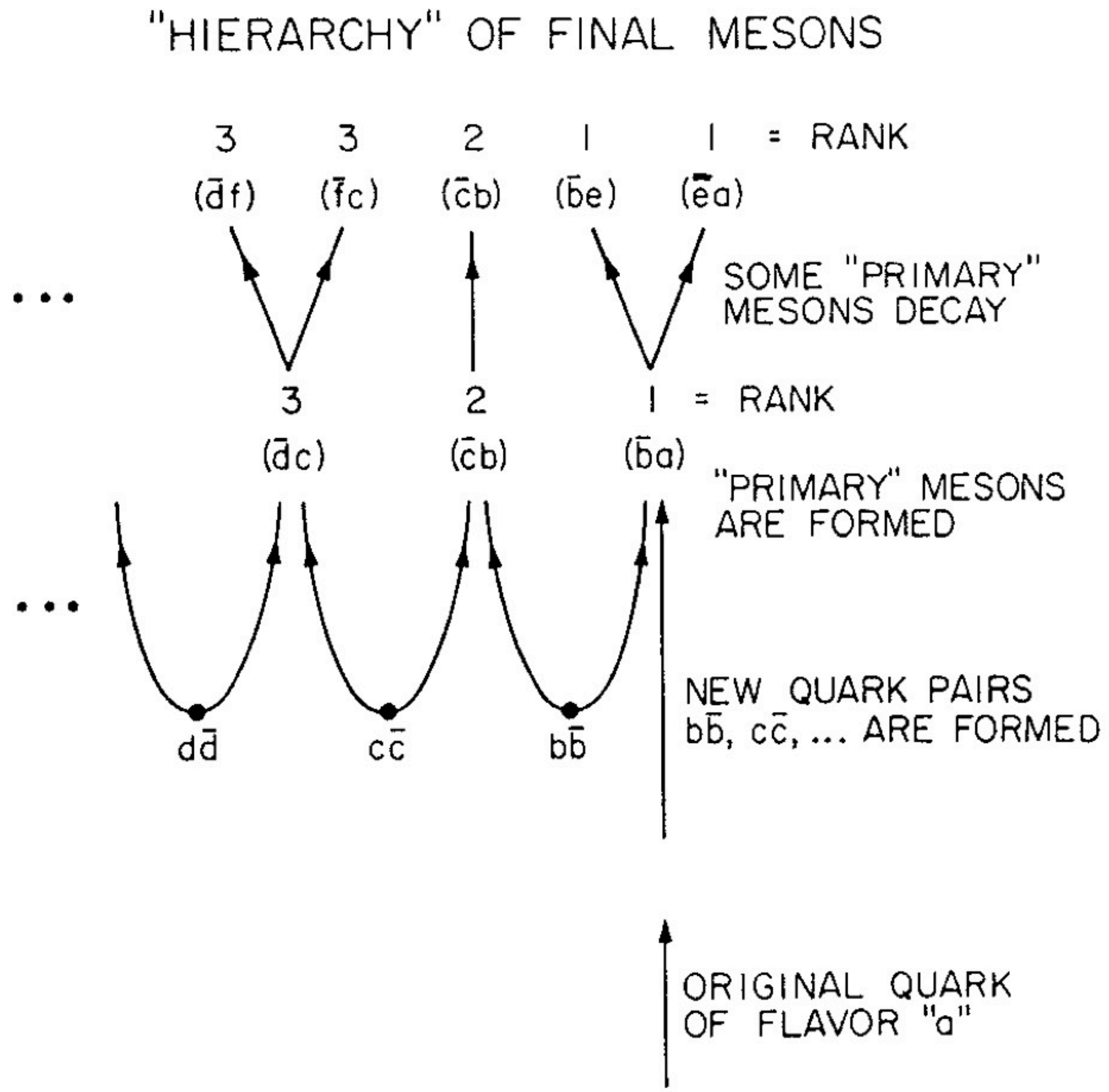
QCD confinement - hadronization

✦ QCD as the fundamental theory of strong interaction





Field, Feynman, NPB 1978

QCD confinement - hadronization

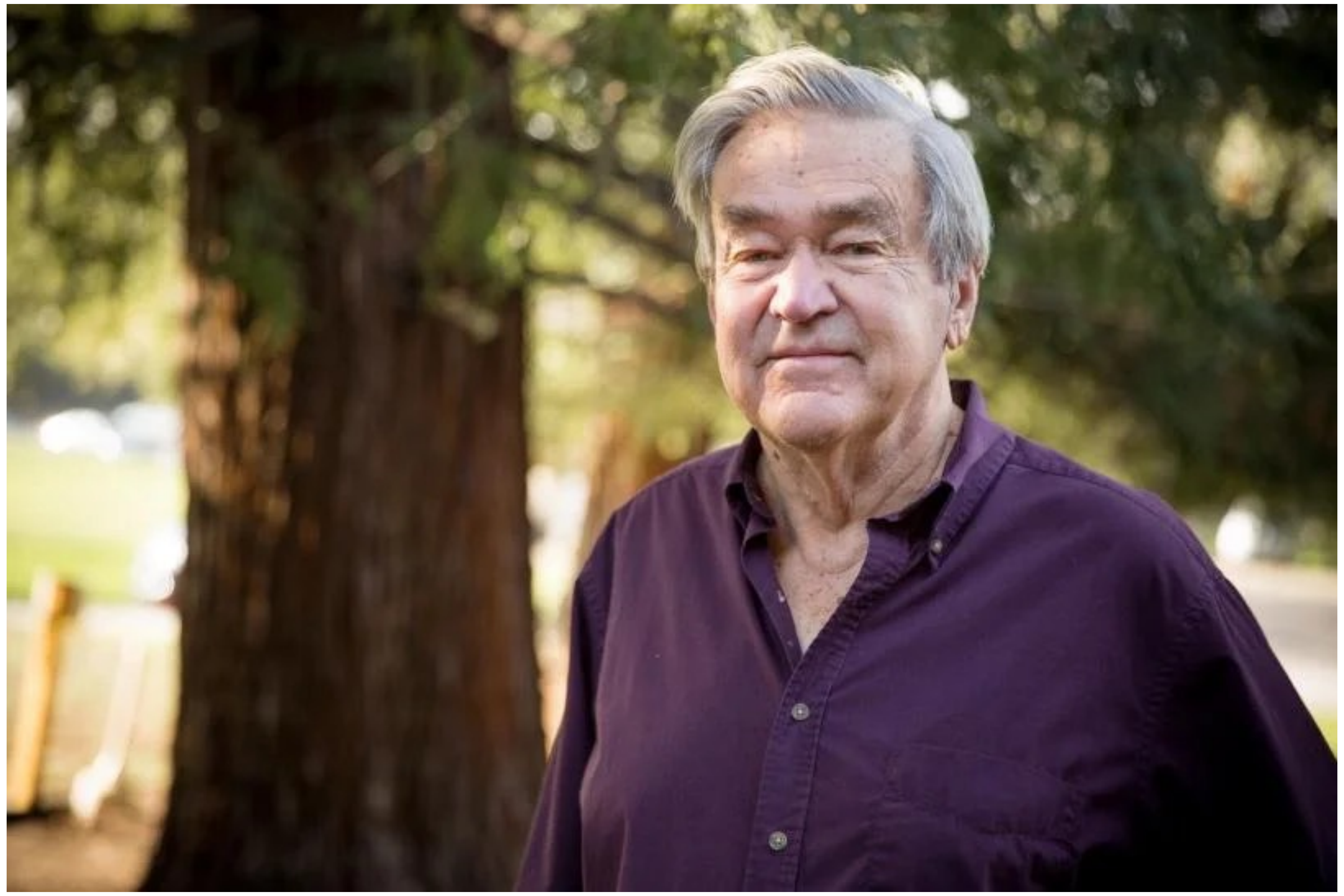
✦ The first concept of parton fragmentation functions

INCLUSIVE PROCESSES AT HIGH TRANSVERSE MOMENTUM†

S. M. Berman, J. D. Bjorken and J. B. Kogut
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT

We calculate the distribution of secondary particles C in processes $A + B \to C +$ anything at very high energies when (1) particle C has transverse momentum p_T far in excess of 1 GeV/c, (2) the basic reaction mechanism is presumed to be a deep-inelastic electromagnetic process, and (3) particles A, B and C are either lepton (ℓ), photon (γ), or hadron (h). We find that such distribution functions possess a scaling behavior, as governed by dimensional analysis. Furthermore, the typical behavior even for A, B and C all hadrons, is a power law decrease in yield with increasing p_T, implying measurable yields at NAL of hadrons, leptons, and photons produced in 400 GeV pp collisions even when the observed secondary-particle p_T exceeds 8 GeV/c. There are similar implications for particle yields from $e^{\pm} - e^{-}$ colliding-beam experiments and for hadron yields in deep-inelastic electroproduction (or neutrino processes). Among the processes discussed in some detail are $\ell\ell \to h$, $\gamma\gamma \to h$, $\ell h \to h$, $\gamma h \to h$, $\gamma h \to \ell$, as well as $hh \to \ell$, $hh \to \gamma$, $hh \to W$, and $W \to h$, where W is the conjectured weak-interaction intermediate boson. The basis of the calculation is an extension of the parton model. The new ingredient necessary to calculate the processes of interest is the inclusive probability for finding a hadron emerging from a parton struck in a deep-inelastic collision. This probability is taken to have a form similar to that generally presumed for finding a parton in an energetic hadron. We study the dependence of our conclusions on the validity of the



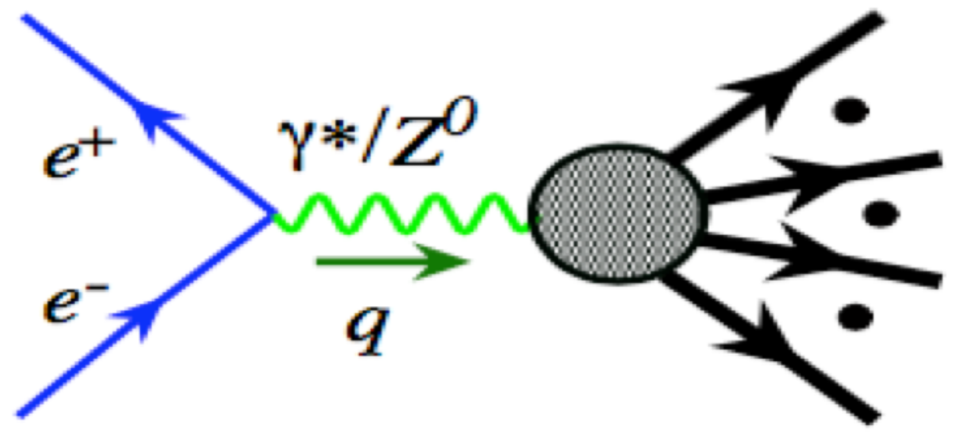
James Bjorken, 1934-2024

Berman, Bjorken, Kogut, PRD 1971

Multiple channels to explore parton hadronization

✦ Indispensable joint efforts from experiments and QCD theory

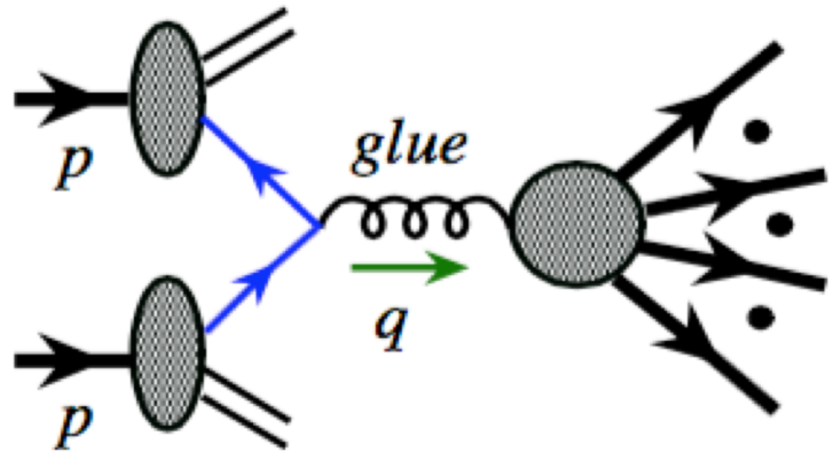
Lepton-lepton colliders



BEPC, SuperKEKB

- No hadron in the initial-state
- Hadrons are emerged from energy
- Not ideal for studying hadron structure, but ideal for FFs

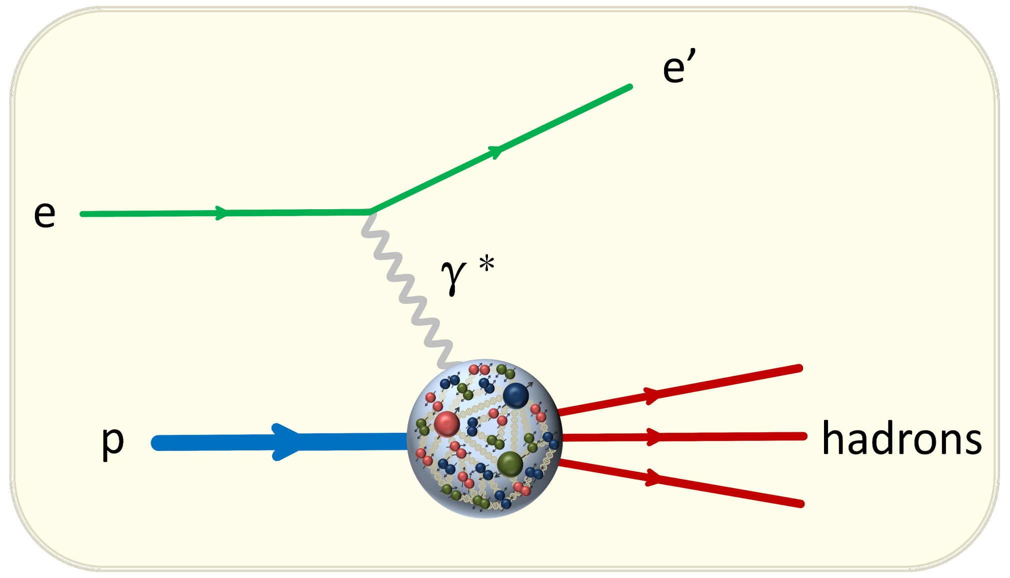
Hadron-hadron colliders



RHIC, LHC

- Hadrons in the initial-state
- Hadrons are emerged from energy
- Currently used for studying hadron structure and FFs

lepton-hadron colliders

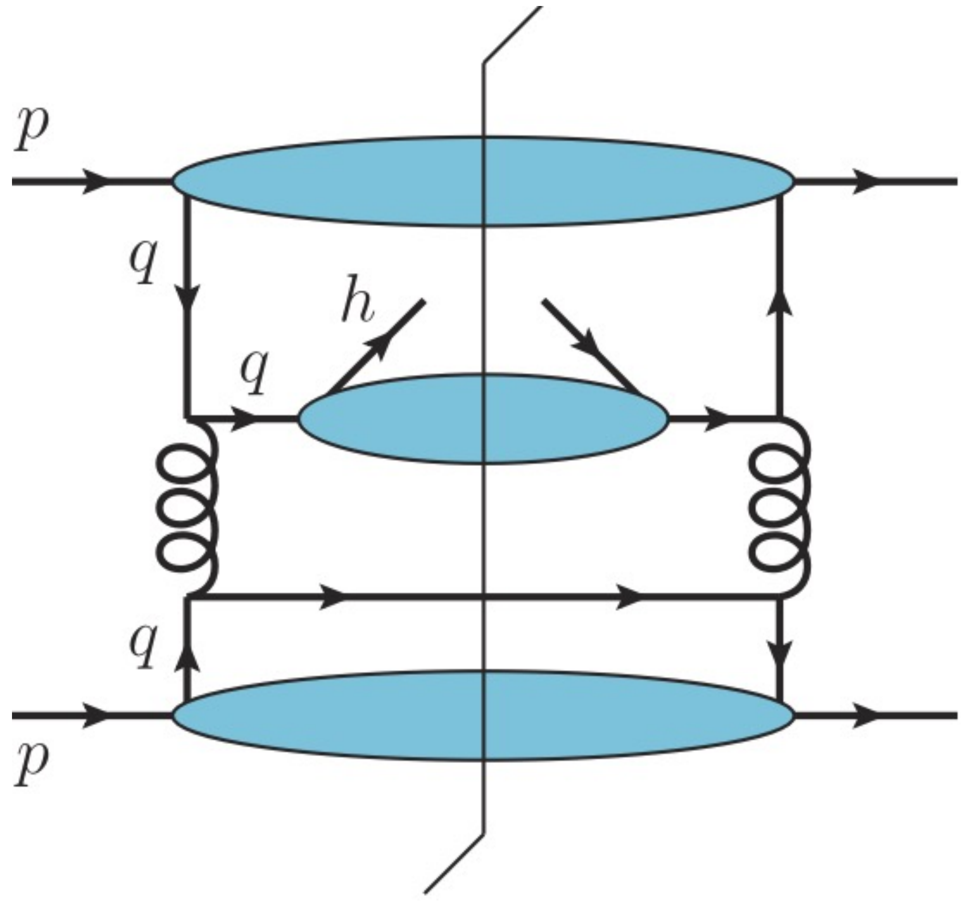


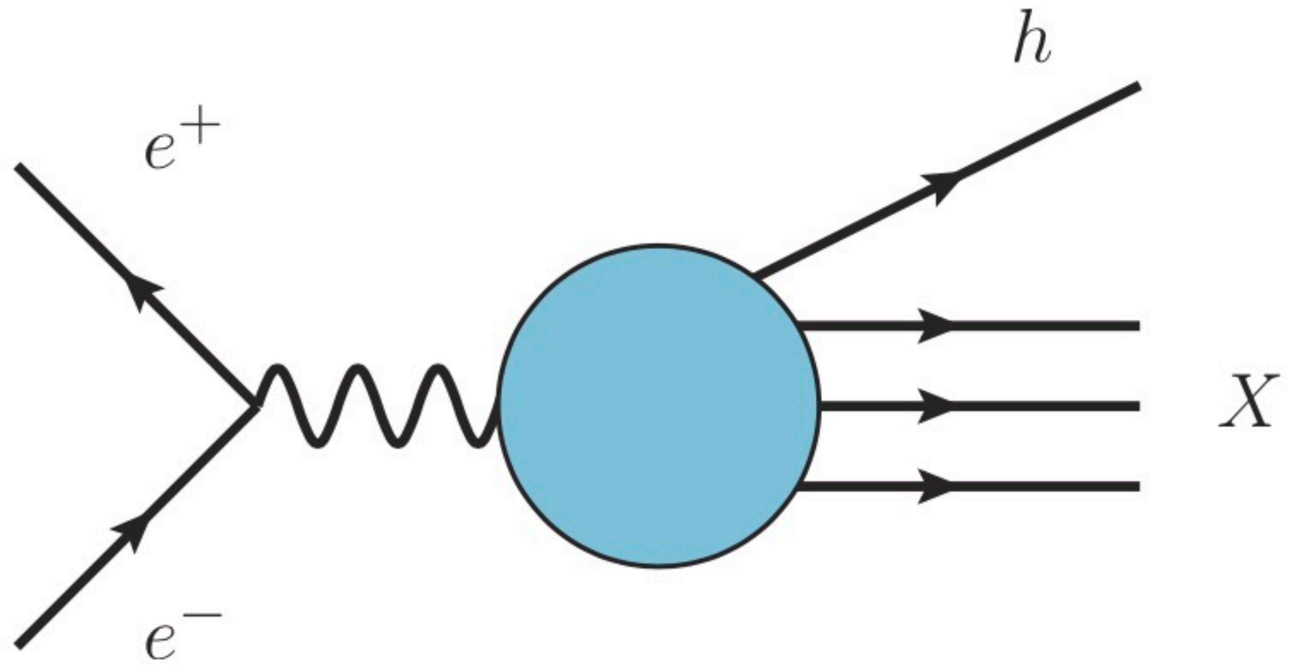
HERA, JLab, EIC/EicC

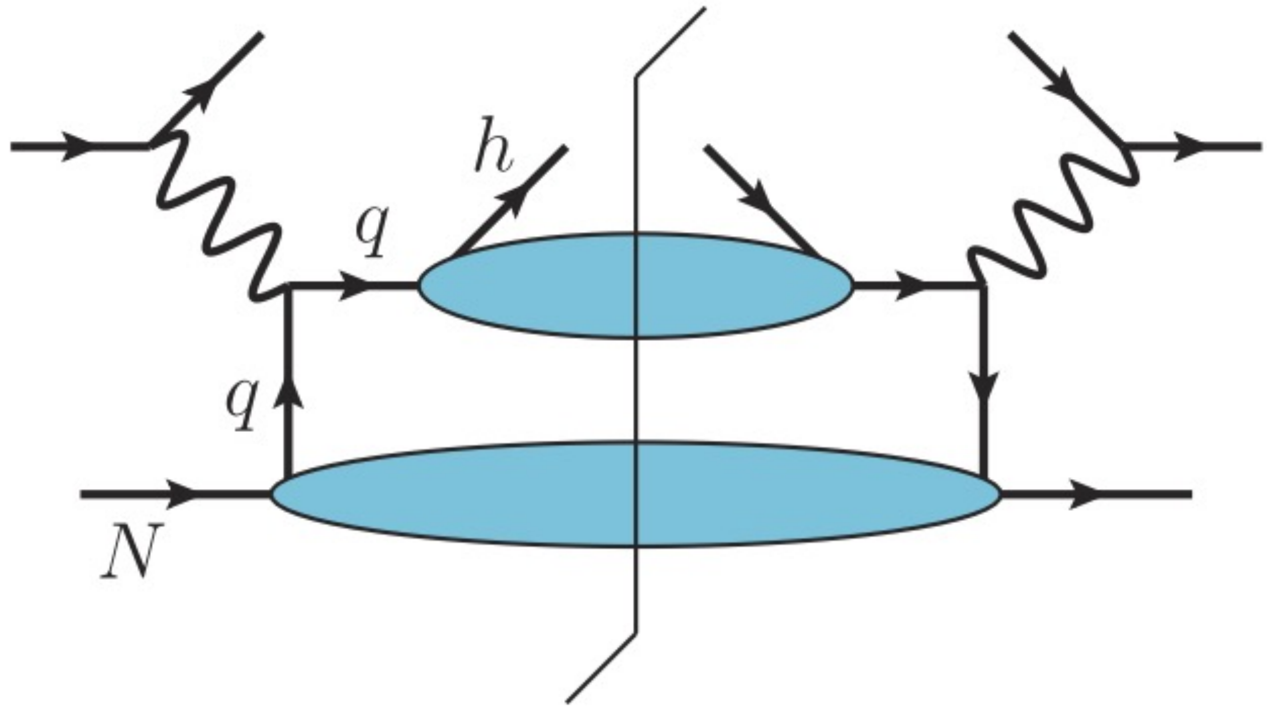
- Hadrons in the initial-state
- Hadrons are emerged from energy
- Ideal for studying hadron structure, can also involve FFs

Fragmentation Functions

✦ **Access to FFs in pp, e^+e^- and ep collisions: universality of FFs**







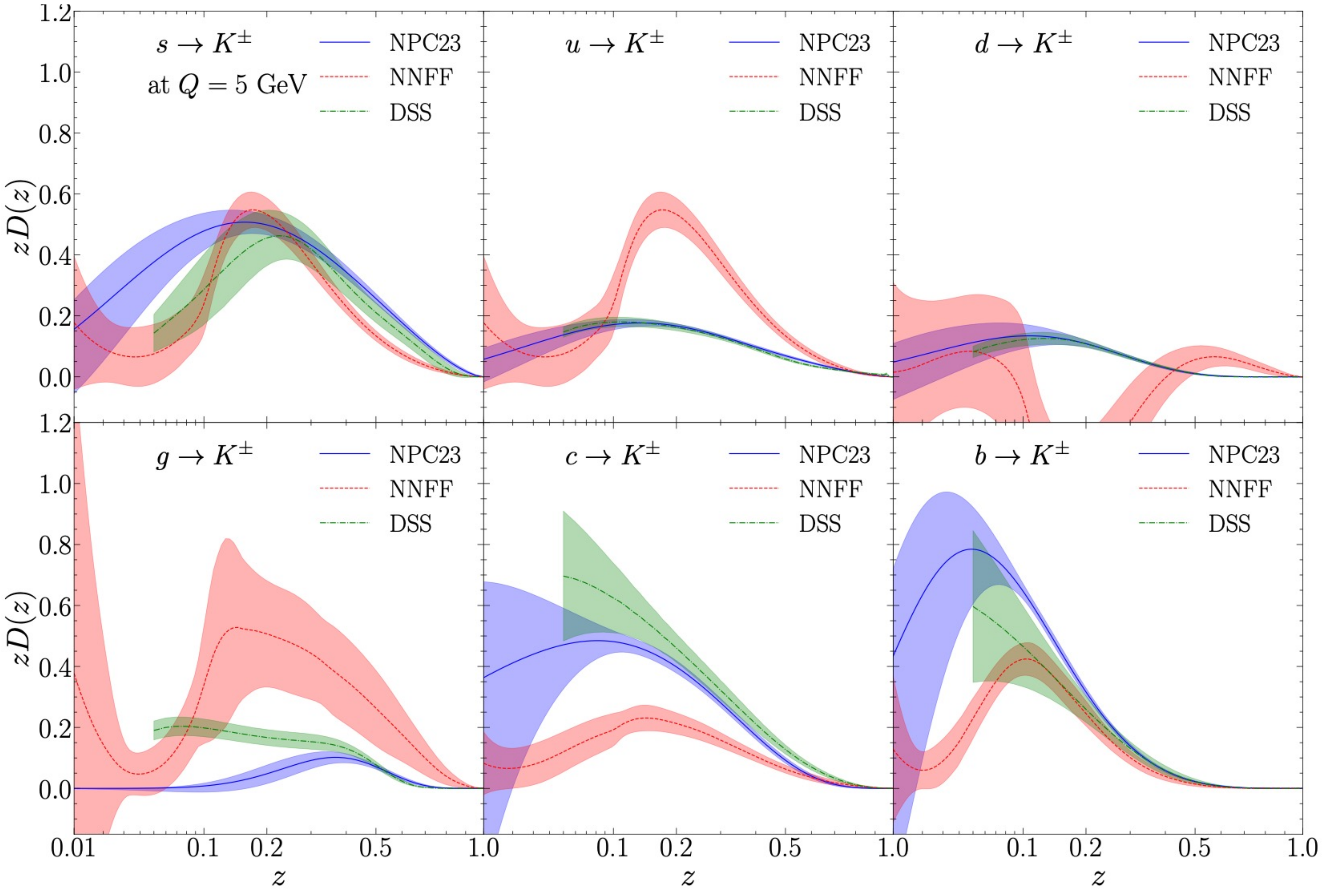
- **Factorization in single inclusive hadron production in electron-positron collisions**

$$\sigma^{e^+e^-\to hX} = \sum_i \hat{\sigma}_{e^+e^-\to i} \otimes D_{i\to h}$$

- Large momentum transfer $Q \gg \Lambda_{QCD}$
- High precision control of $\hat{\sigma}$
- D: fragmentation function, also called parton decay function, encodes the information on how patrons produced in hard scattering hadronize into the detected color singlet hadronic bound state.

Methodology for global extraction of FFs

✦ Comparison of kaon FFs



It is proved that FFs are universal, why they look different?

- Different selections of experimental data (kinematic cut)
- Different parametrization for FFs at initial scale, NNFF unbiased? DSS biased?
- Everything else is the same

More measurements are needed to further constrain the FFs!

Gao, Liu, Shen, **HX**, Zhao, arXiv: 2407.04422

New opportunities in probing FFs at LHC

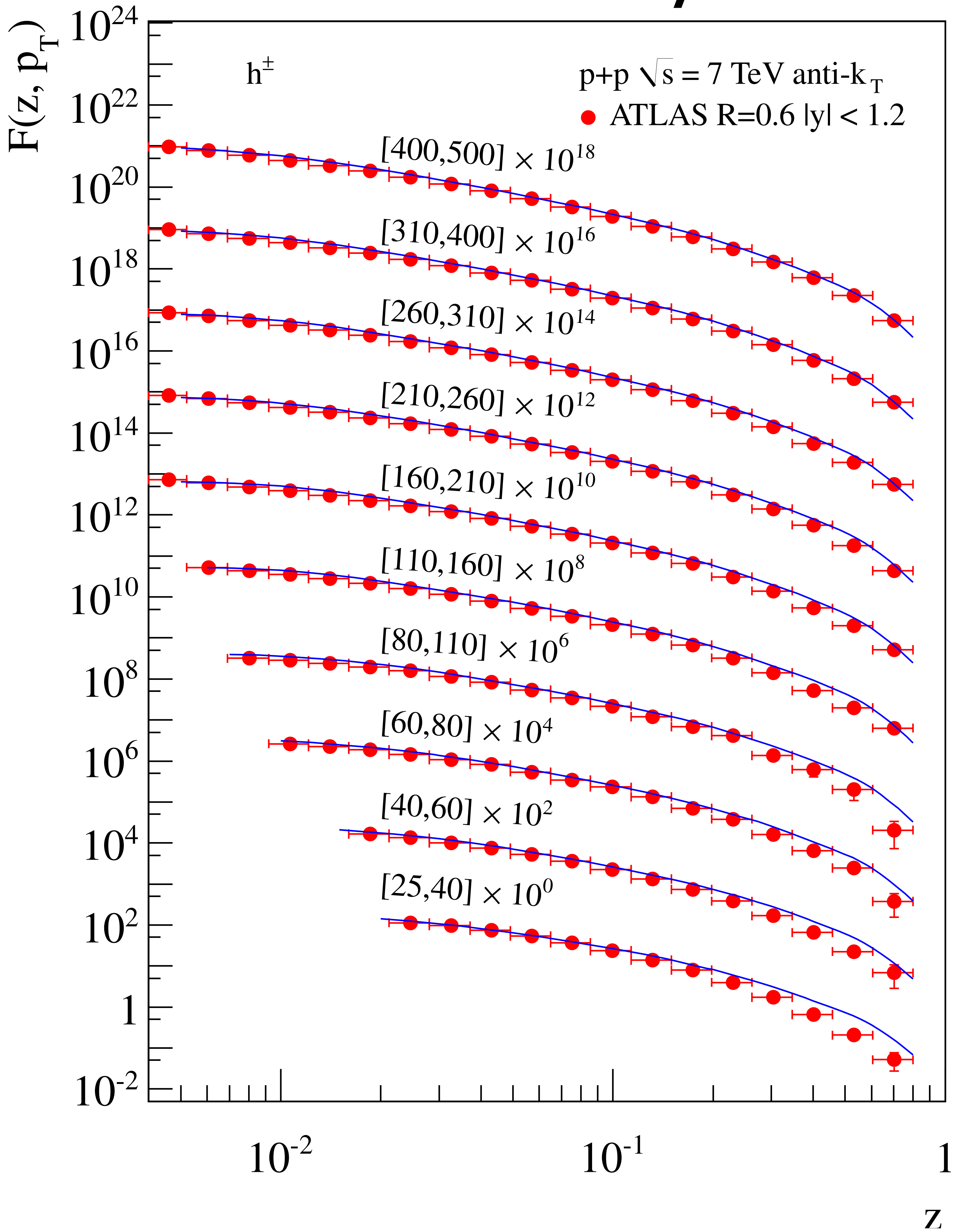
✦ **Jet fragmentation function**

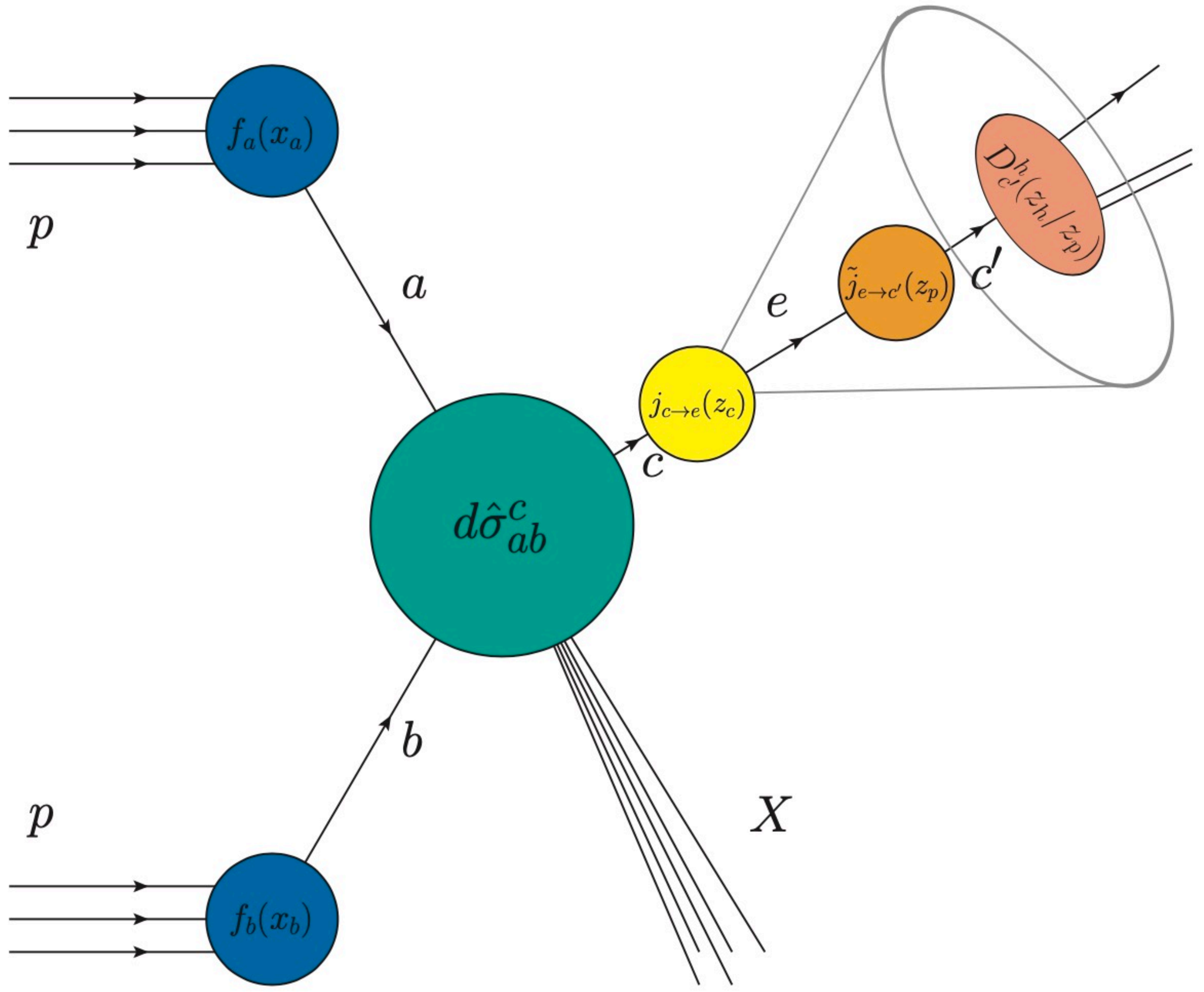
Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

$$F(z_h, p_T) = \frac{d\sigma^{J(h)}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma}{dp_T d\eta}$$

$$\sigma^{pp\to J(h)X} = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to k} \otimes \mathcal{G}_{k\to J(h)}$$

$$\mathcal{G}_{i\to J(h)} = \mathcal{J}_{ij} \otimes D_{j\to h}$$





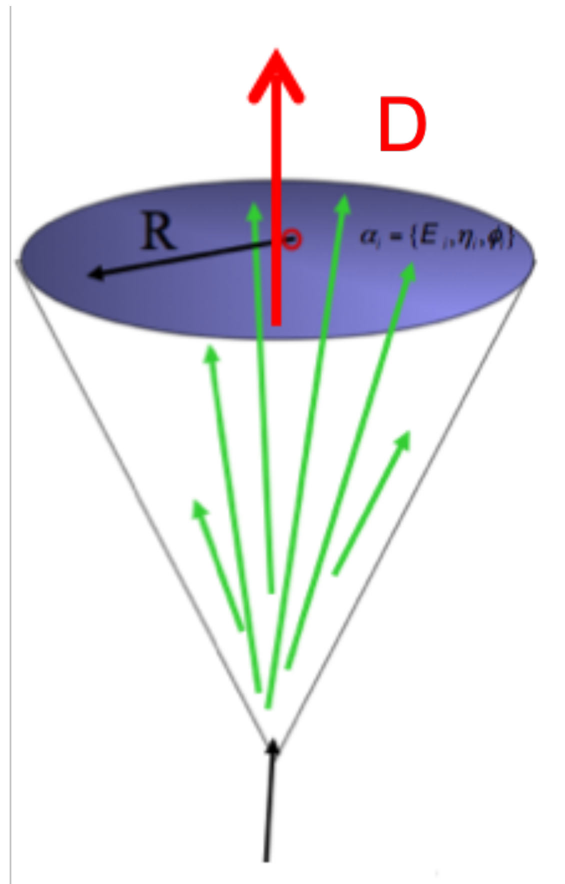
$$z_h = \frac{p_T^h}{p_T}$$

Light hadrons work very well

Heavy flavor in jet

✦ Jet fragmentation function for D meson

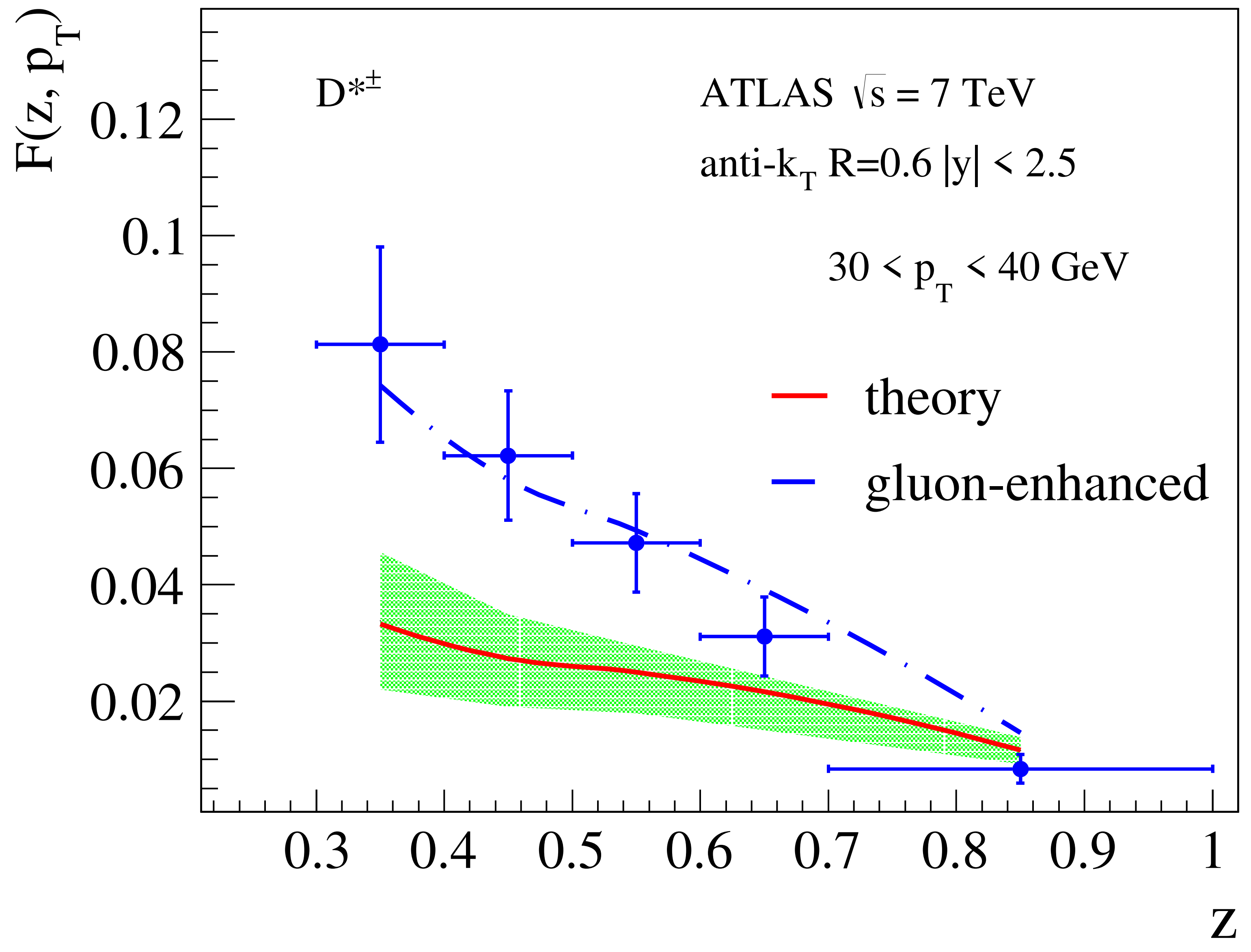
$$F(z_h, p_T) = \frac{d\sigma^{J(h)}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma}{dp_T d\eta}$$

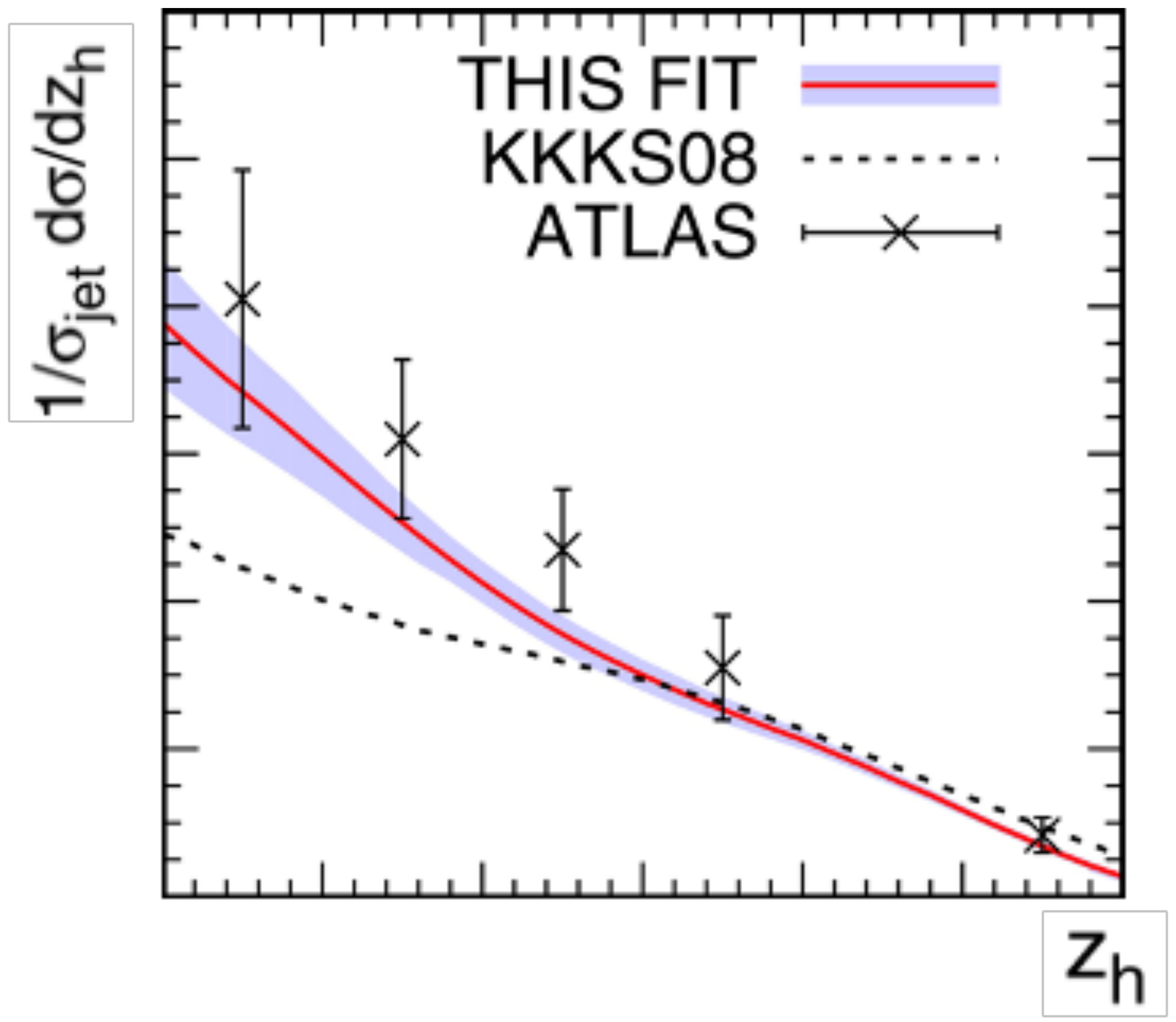


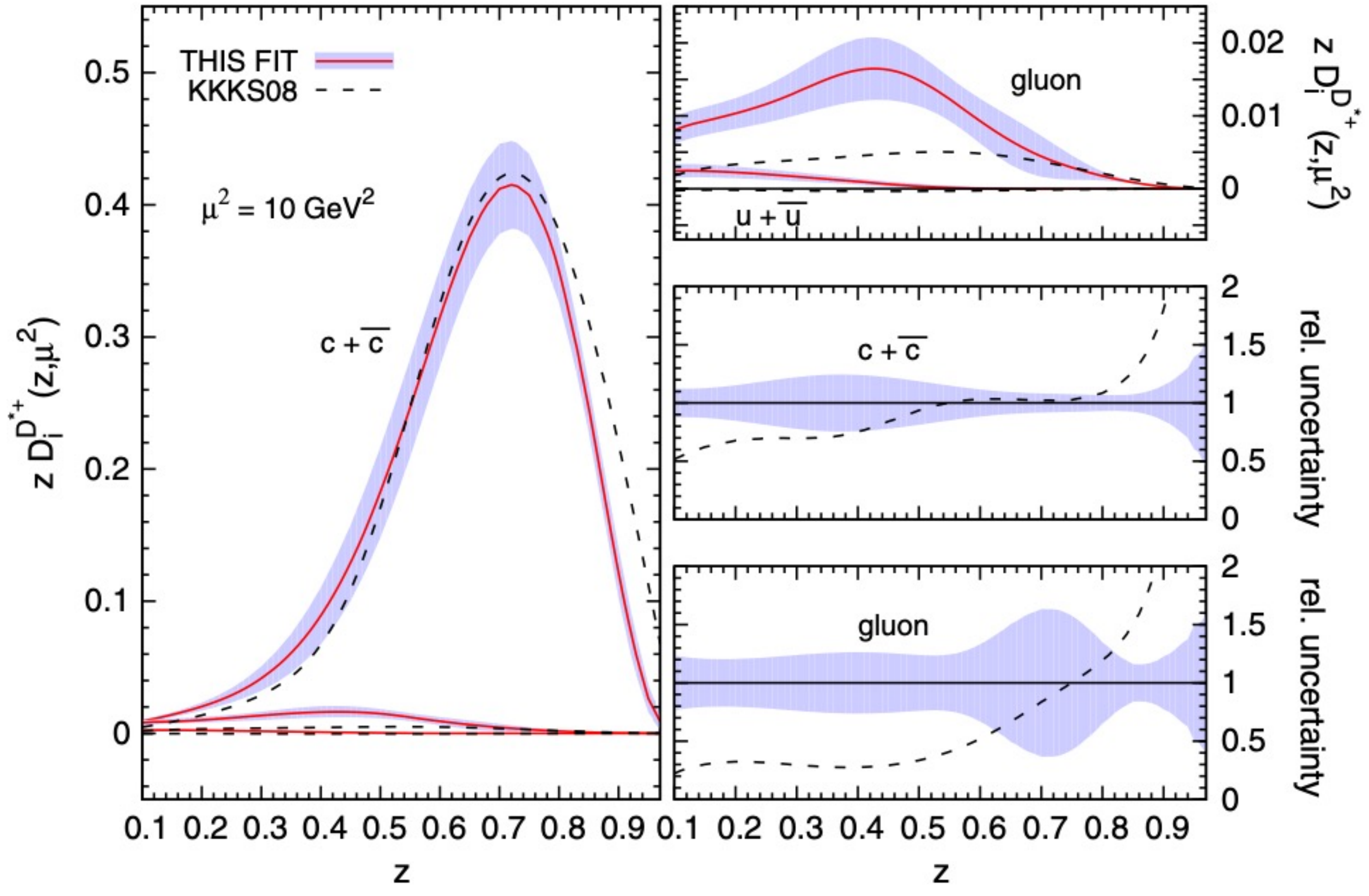
$$z_h = \frac{p_T^h}{p_T}$$

Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

AKSRV, PRD (2017)







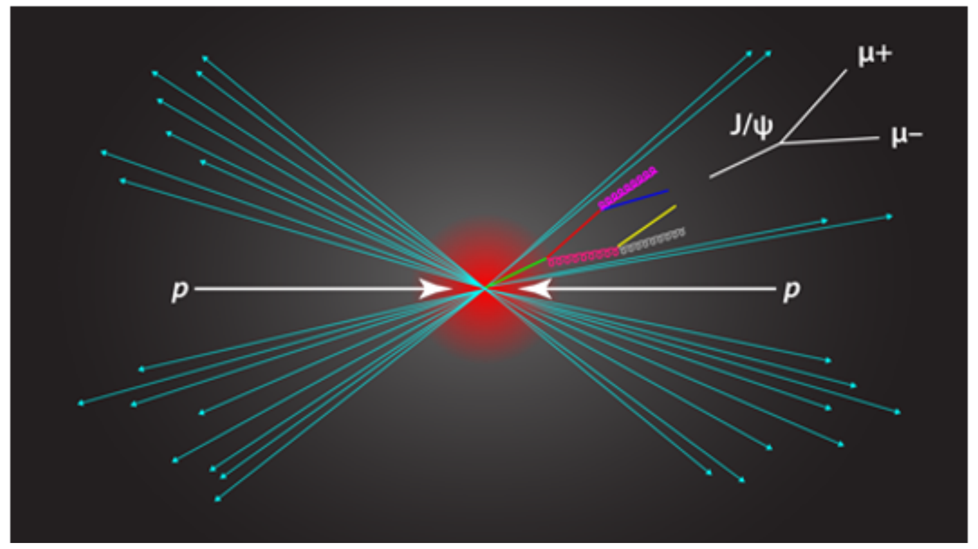
- Failed to describe D meson production in jet using KKK08 FFs
- Leads to new constraint of heavy flavor FFs using measurement of D in jet

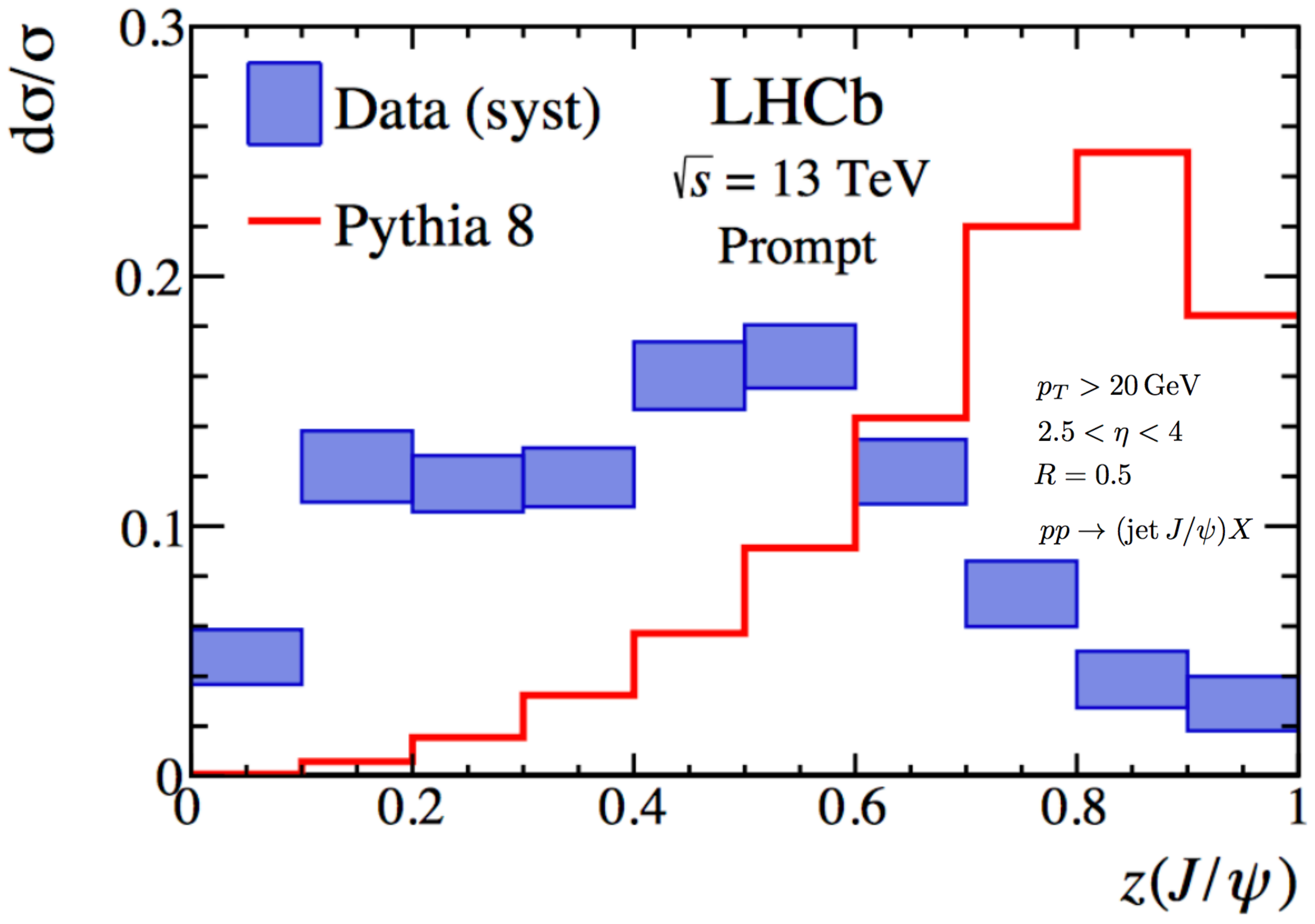
Heavy flavor in jet

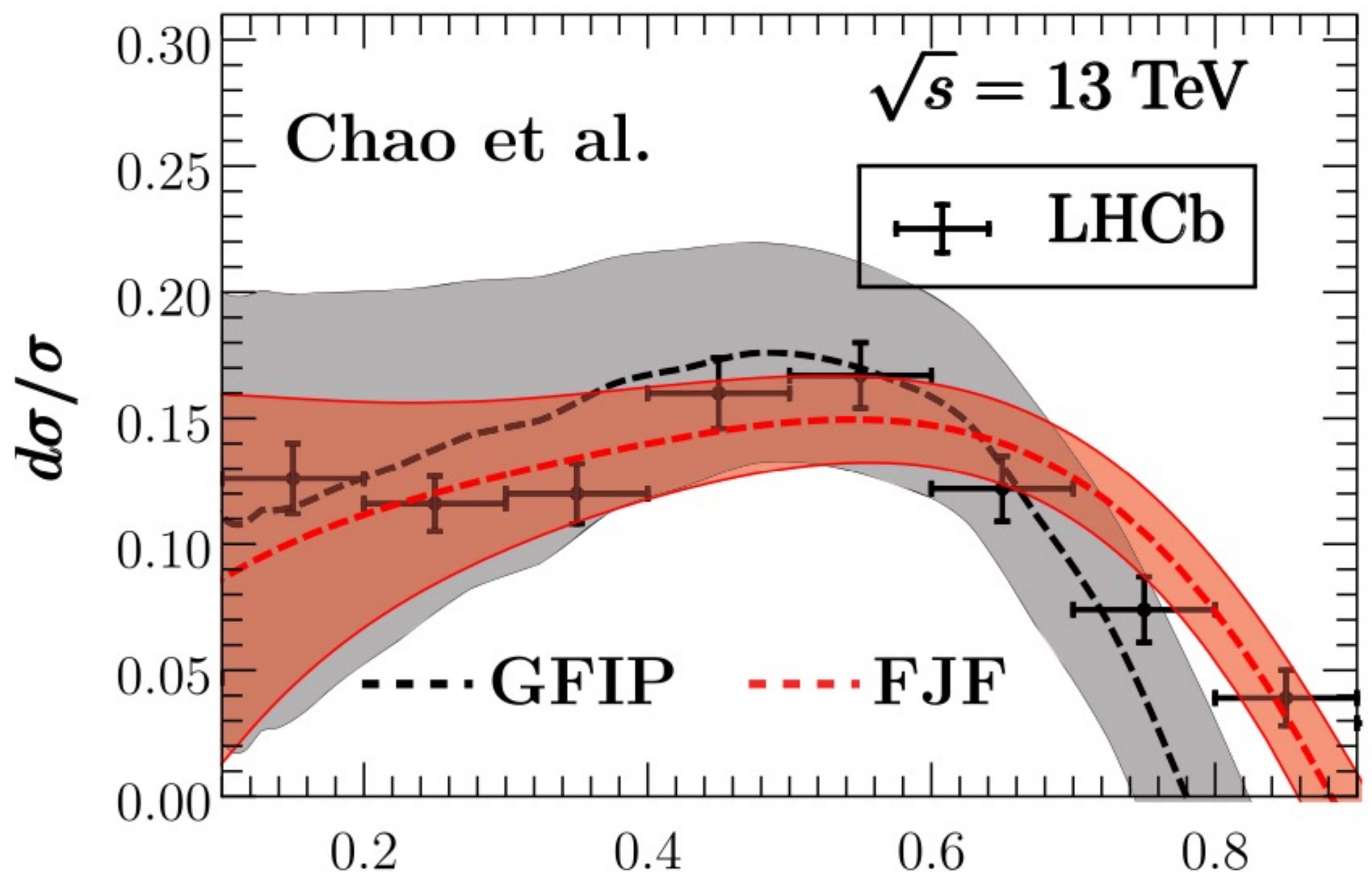
✦ Jet fragmentation function for J/ψ

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^{J/\psi}$$

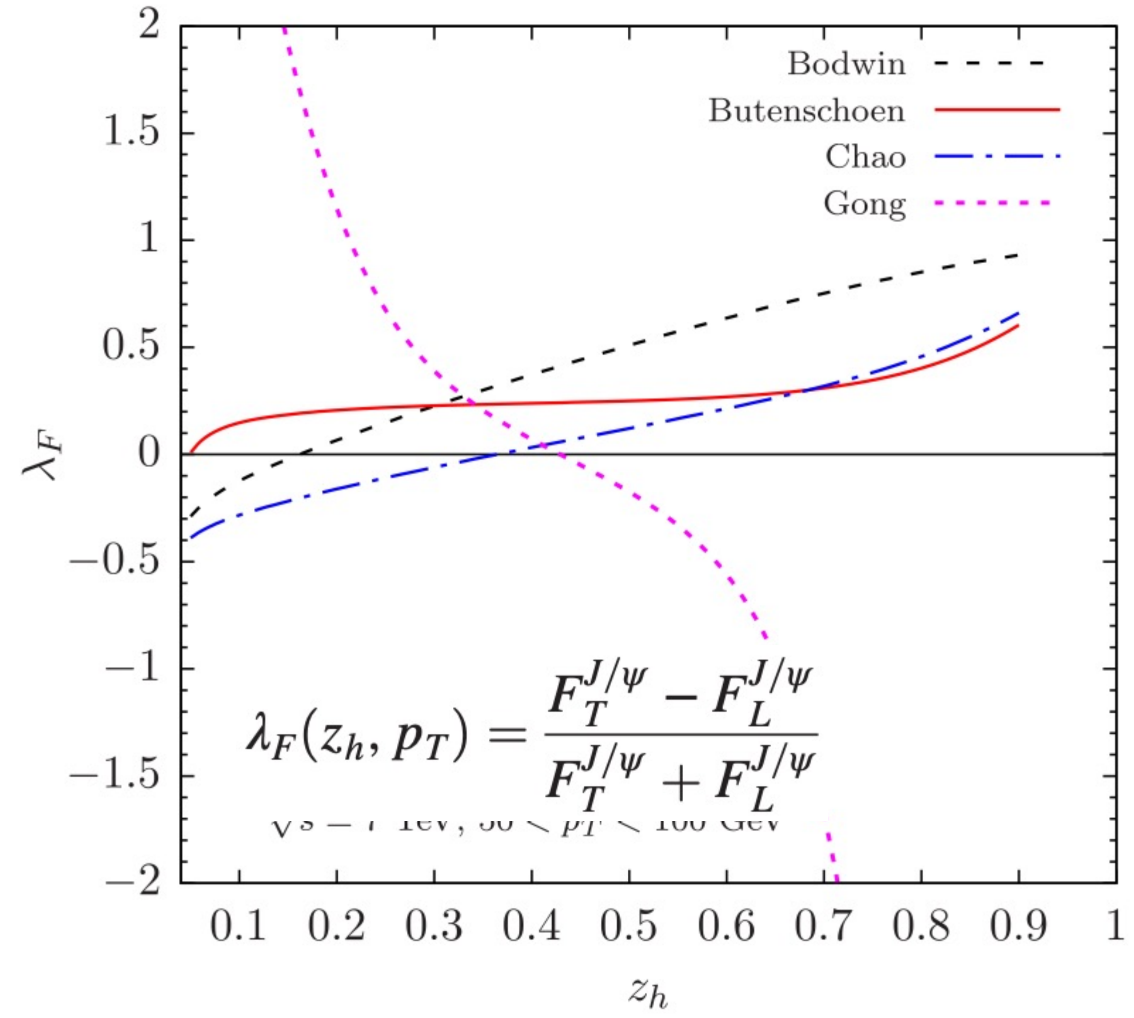
$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^+ R, \mu) \times D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^+ R)^2)$$







Bain et al, PRL (2017)



Kang, Qiu, Ringer, **HX**, Zhang PRL (2017)

- Disagreement between default Pythia and data
- New insight into the shower mechanism for J/ψ production, and new constrain of LDMEs

New opportunities in probing FFs at LHC

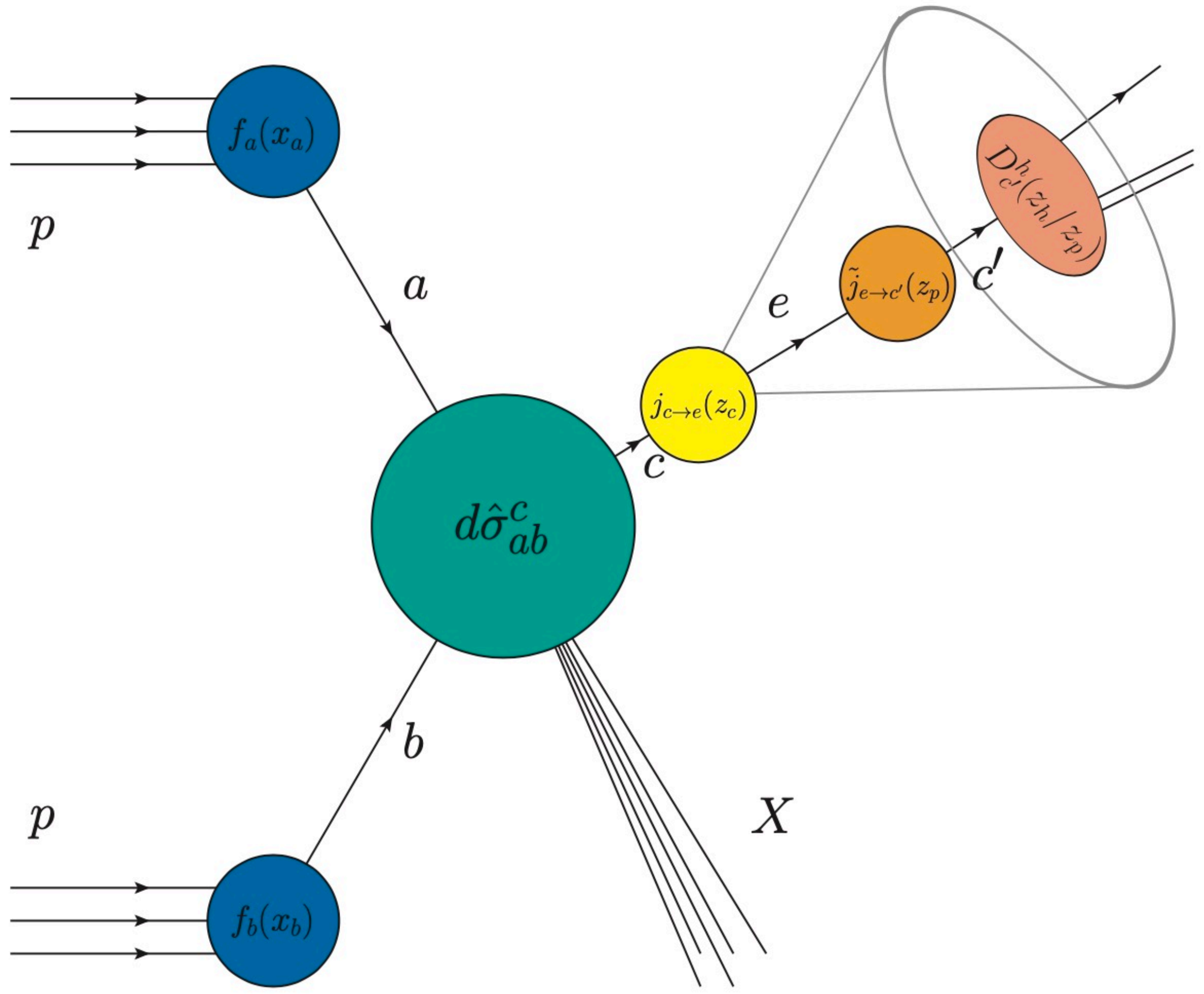
✦ Inclusive hadron production

$$\sigma^{pp\to hX} = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to k} \otimes D_{k\to h} \quad \propto \quad \int dz D(z)$$

Only sensitive to the area of FFs

✦ Inclusive hadron production

$$\sigma^{pp\to J(h)X} = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to k} \otimes \mathcal{G}_{k\to J(h)} \quad \propto \quad \int_{z_h}^{1} dz D(z) \qquad z_h = \frac{p_T^h}{p_T}$$



Scan the area of FFs with different low z limit using jet

New efforts from NPC

✦ Nonperturbative Physics Collaboration - NPC (SJTU+SCNU+IMP)

Gao, Liu, Shen, **HX**, Zhao, PRL, 2024

Gao, Liu, Shen, **HX**, Zhao, arXiv: 2407.04422

- First time including jet fragmentation data
- Joint determination of FFs to charge pion/kaon/proton at NLO
- Strong selection criteria to ensure validity of leading twist factorization
- "Unbiased" parametrization of FFs

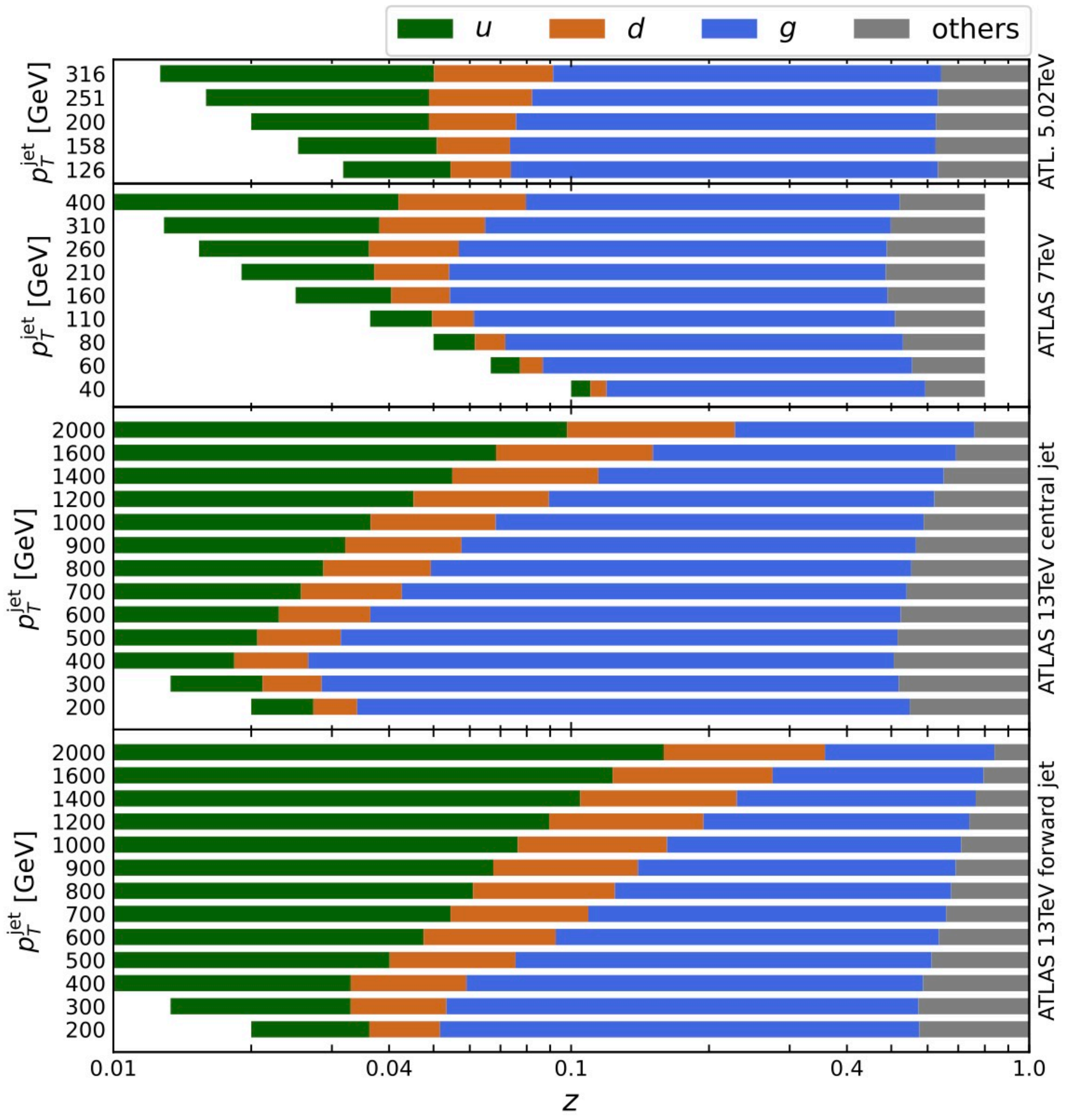
$$zD_i^h(z,Q_0) = z^{\alpha_i^h}(1-z)^{\beta_i^h}\exp\left(\sum_{n=0}^{m} a_{i,n}^h(\sqrt{z})^n\right)$$

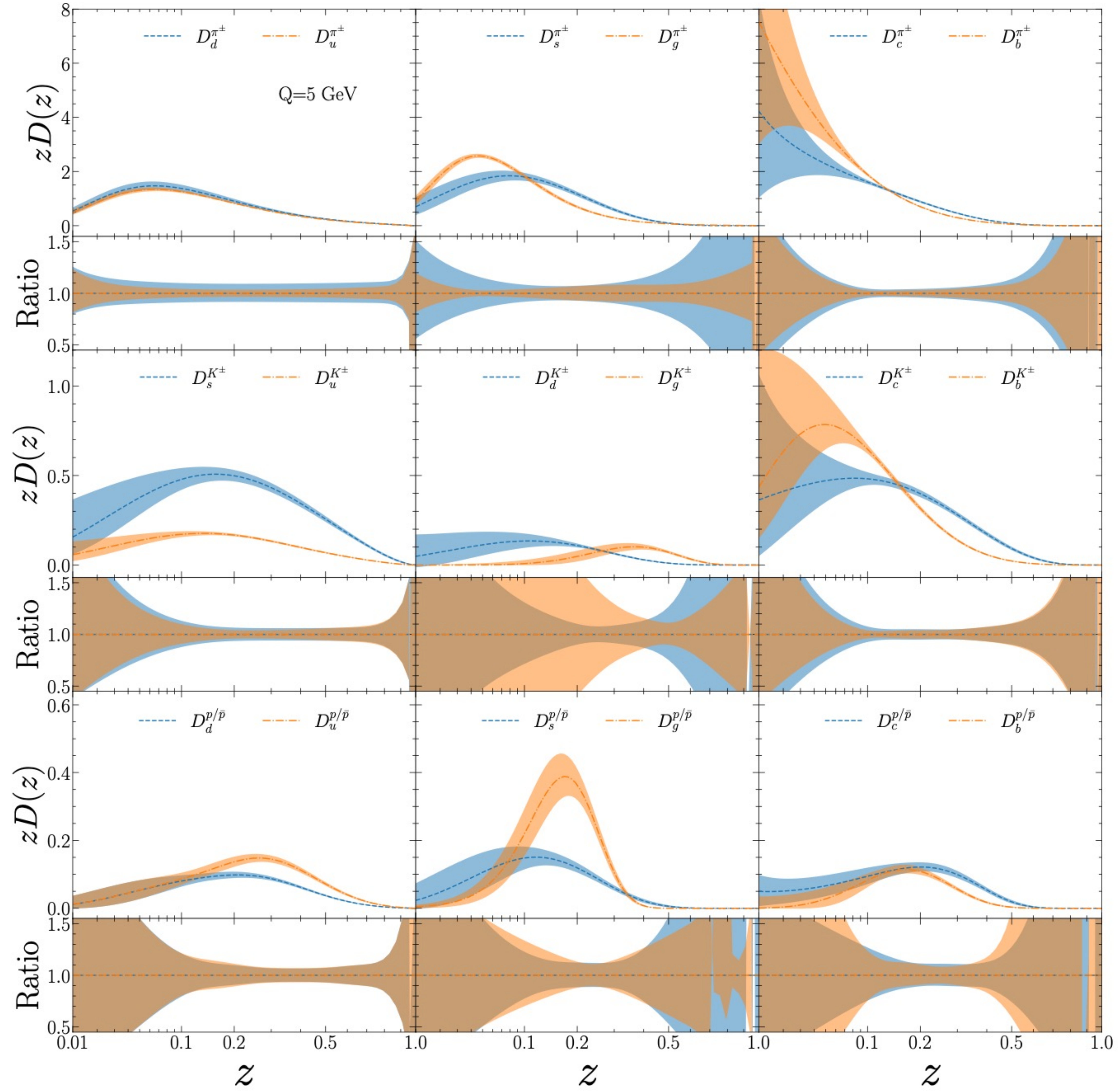
Experiments	N_{pt}	χ^2	χ^2/N_{pt}
ATLAS 5.02 TeV $\gamma+j$	6	9.6	1.61
CMS 5.02 TeV $\gamma+j$	4	11.1	2.78
ATLAS 5.02 TeV $Z+h$	9	22.2	2.47
CMS 5.02 TeV $Z+h$	11	6.2	0.56
LHCb 13 TeV $Z+j$	20	30.6	1.53
ATLAS 5.02 TeV inc. jet	63	67.9	1.08
ATLAS 7 TeV inc. jet	103	91.3	0.89
ATLAS 13 TeV dijet	280	191.6	0.68
pp hadron in jet sum	496	430.5	0.87
ALICE 13 TeV	49	45.0	0.92
ALICE 7 TeV	37	36.3	0.98
ALICE 5.02 TeV	34	37.5	1.10
ALICE 2.76 TeV	27	31.8	1.18
STAR 200 GeV	60	42.2	0.70
pp inclusive sum	207	192.8	0.93
H1 †	16	12.5	0.78
H1 (asy.) †	14	12.2	0.87
ZEUS †	32	65.5	2.05
COMPASS 06 (D)	124	107.3	0.87
COMPASS 16 (p)	97	56.8	0.59
SIDIS sum	283	254.4	0.90
OPAL $Z\to q\bar{q}$	20	16.3	0.81
ALEPH $Z\to q\bar{q}$	42	31.4	0.75
DELPHI $Z\to q\bar{q}$	39	12.5	0.32
DELPHI $Z\to b\bar{b}$	39	23.9	0.61
SLD $Z\to q\bar{q}$	66	53.0	0.8
SLD $Z\to b\bar{b}$	66	82.0	1.24
SLD $Z\to c\bar{c}$	66	76.5	1.16
TASSO 34 GeV inc. had.	3	2.7	0.9
TASSO 44 GeV inc. had.	5	4.3	0.86
TPC 29 GeV inc. had.	12	11.6	0.97
OPAL (202 GeV) inc. had. †	17	24.2	1.42
DELPHI (189 GeV) inc. had.	9	15.3	1.70
SIA sum	384	353.8	0.92
Global total	1370	1231.5	0.90

New efforts from NPC

✦ NPC23 FFs

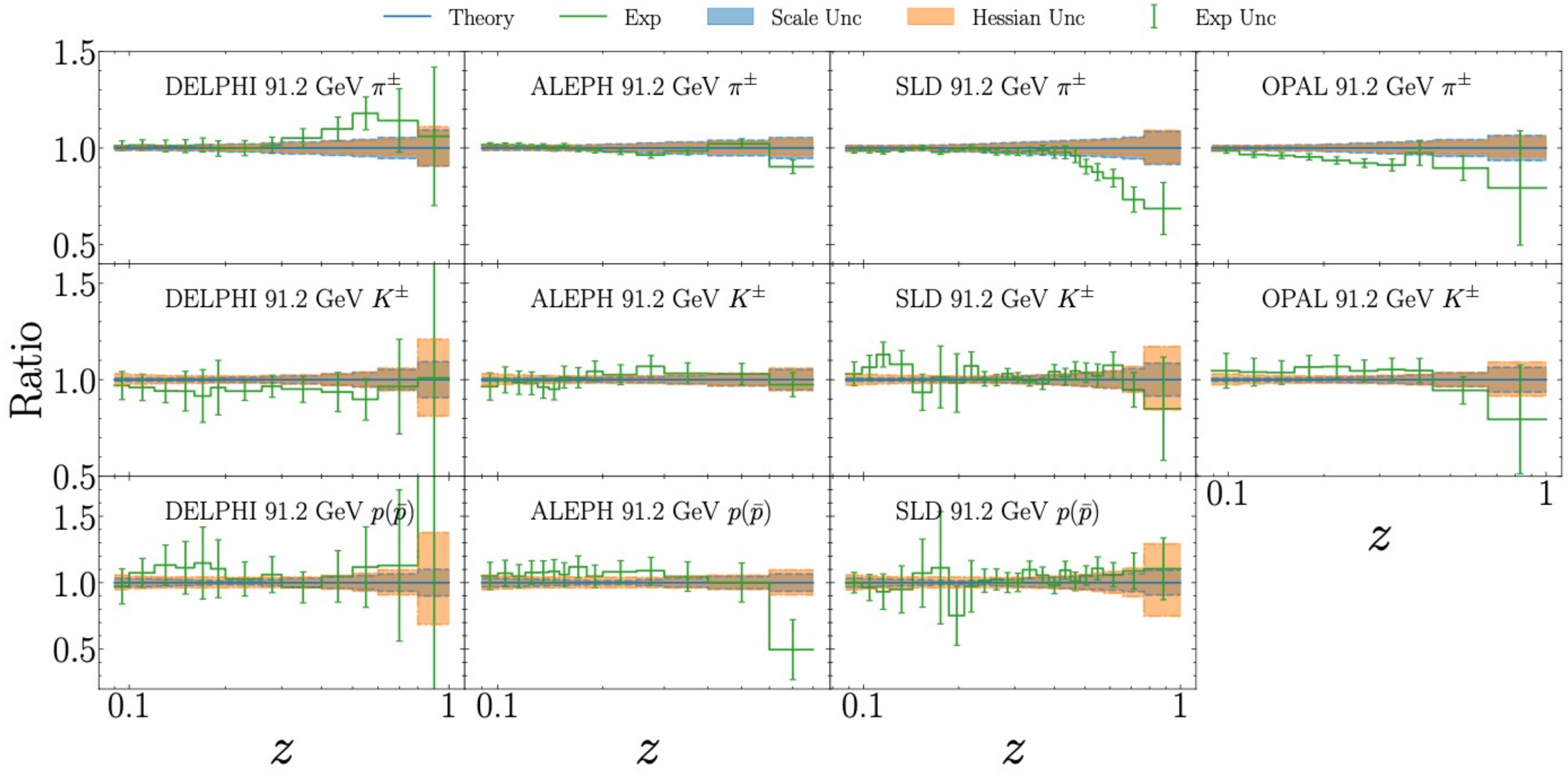
Gao, Liu, Shen, **HX**, Zhao, PRL, 2024





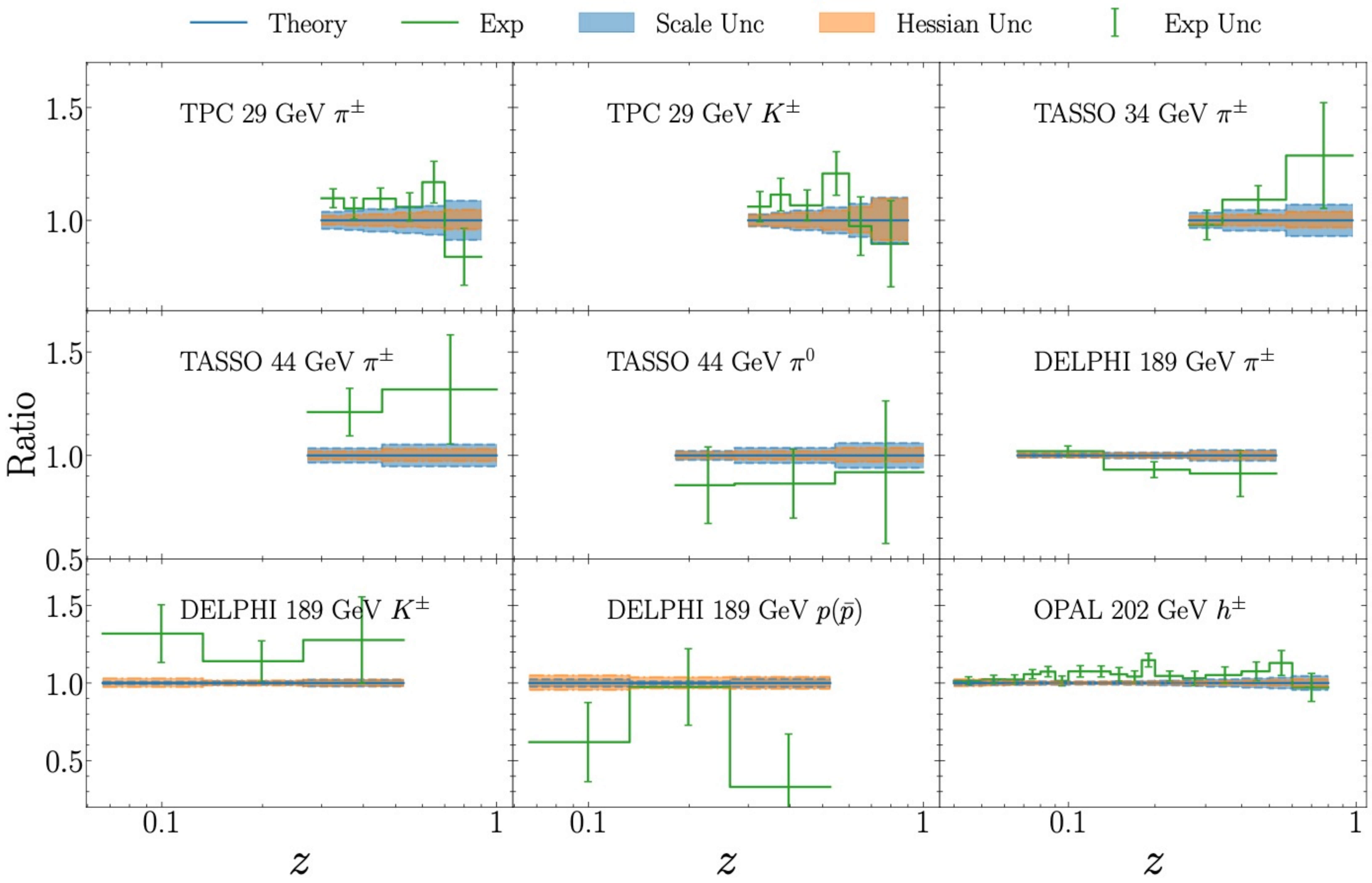
- Higher precision determination of FFs for charged hadron

✦ Comparison with SIA data

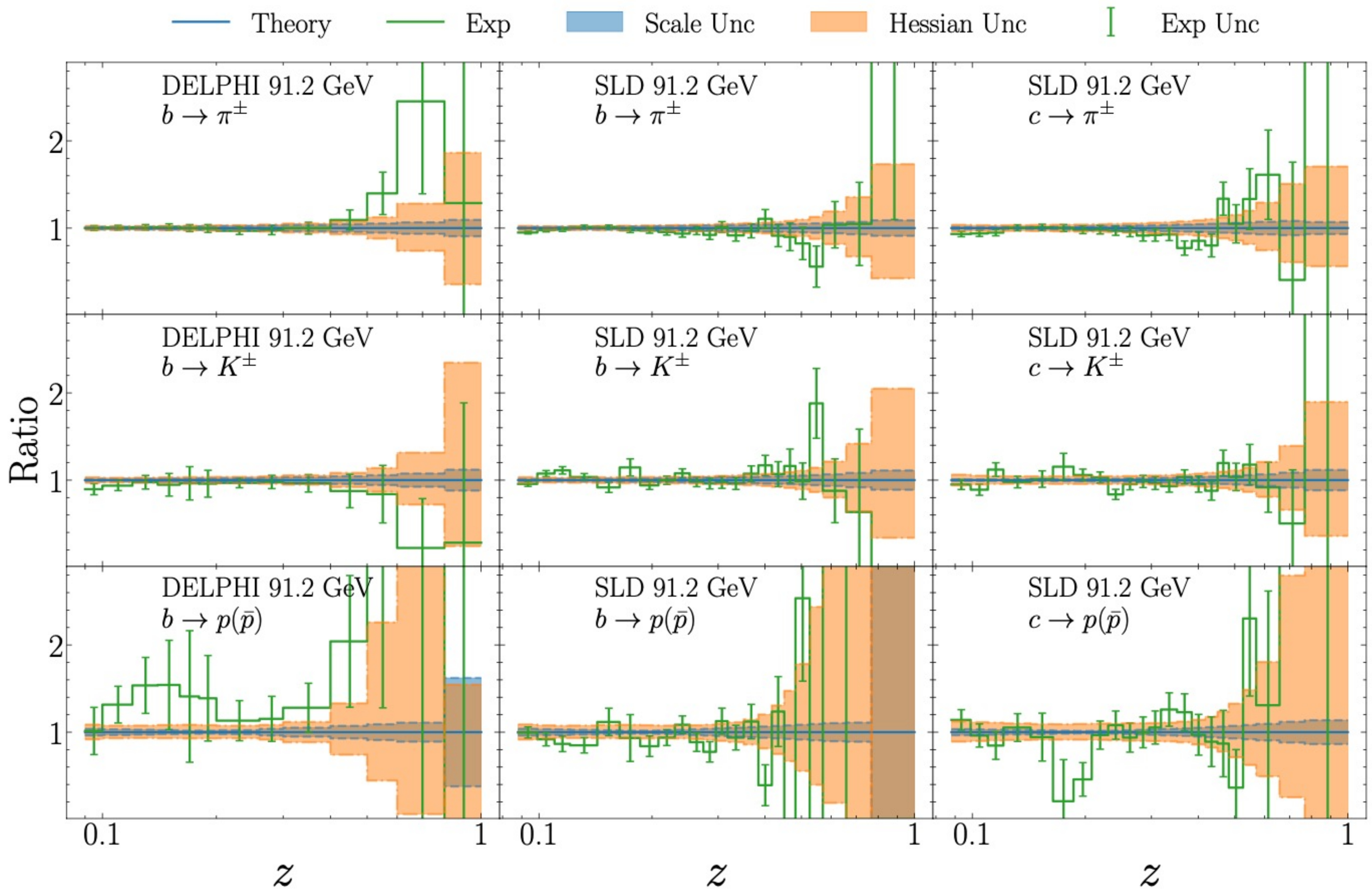


Impact from SIA

✦ Comparison with SIA data

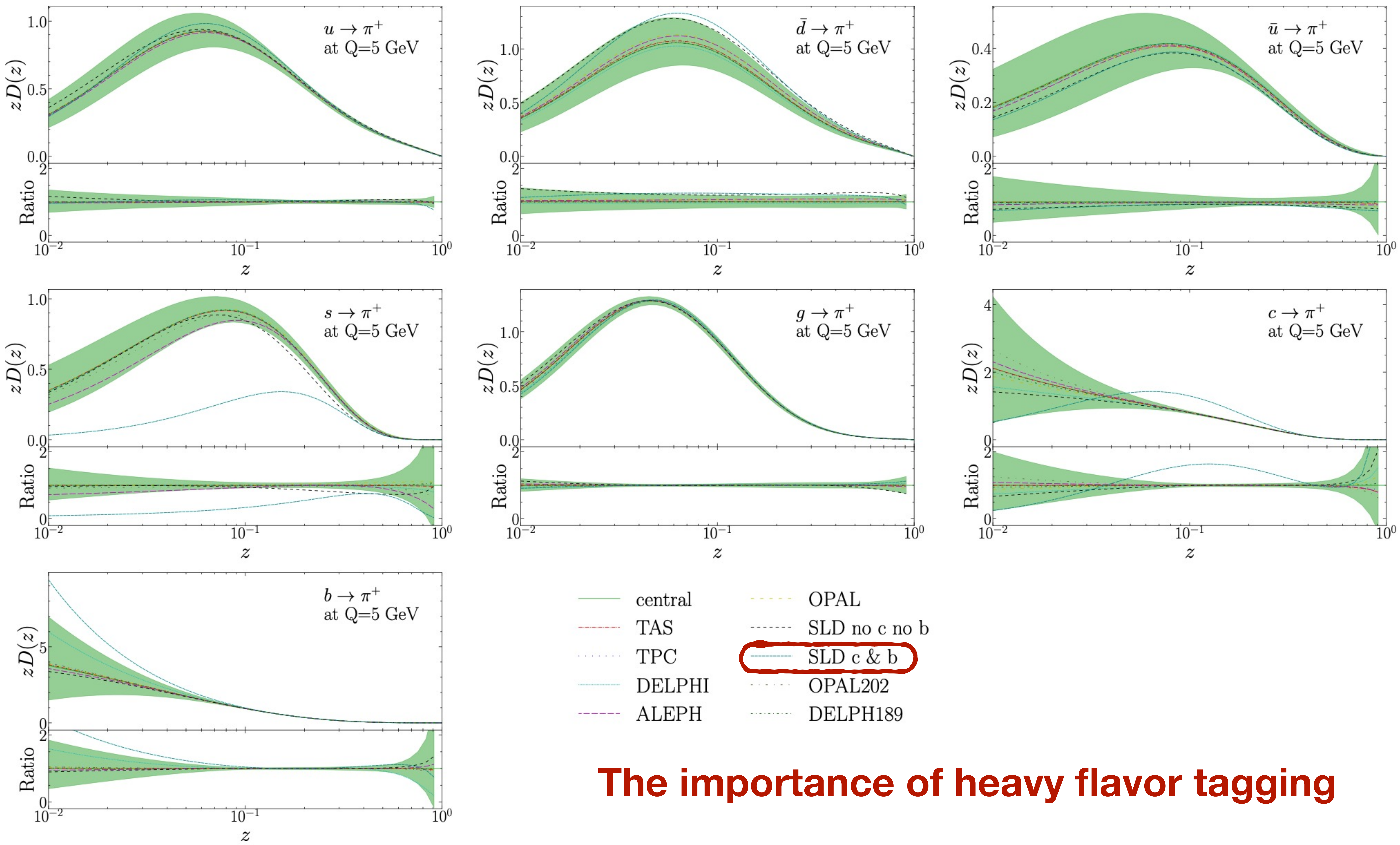


✦ Comparison with SIA data



Impact from SIA

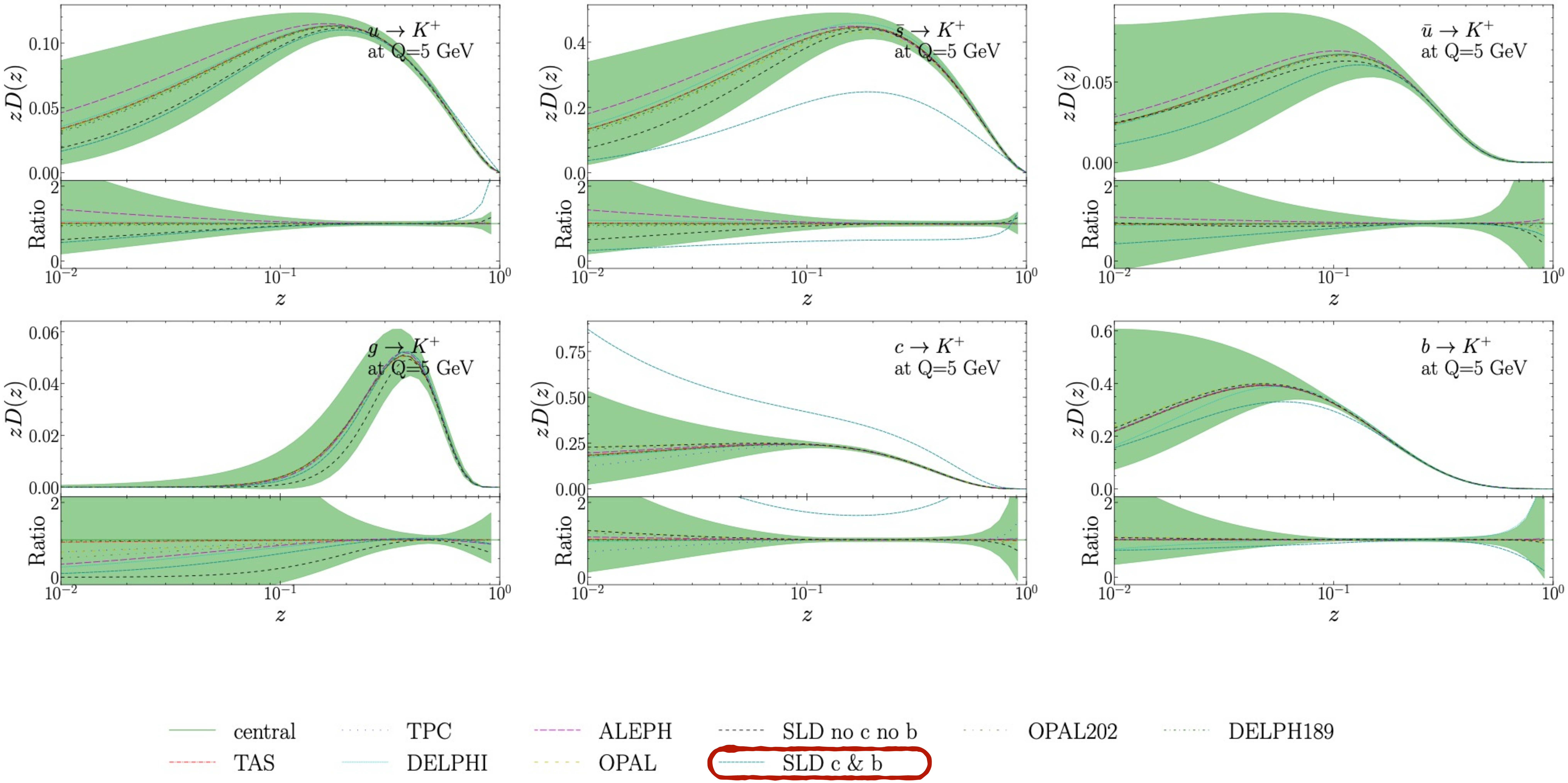
✦ Impact of each data set



The importance of heavy flavor tagging

Impact from SIA

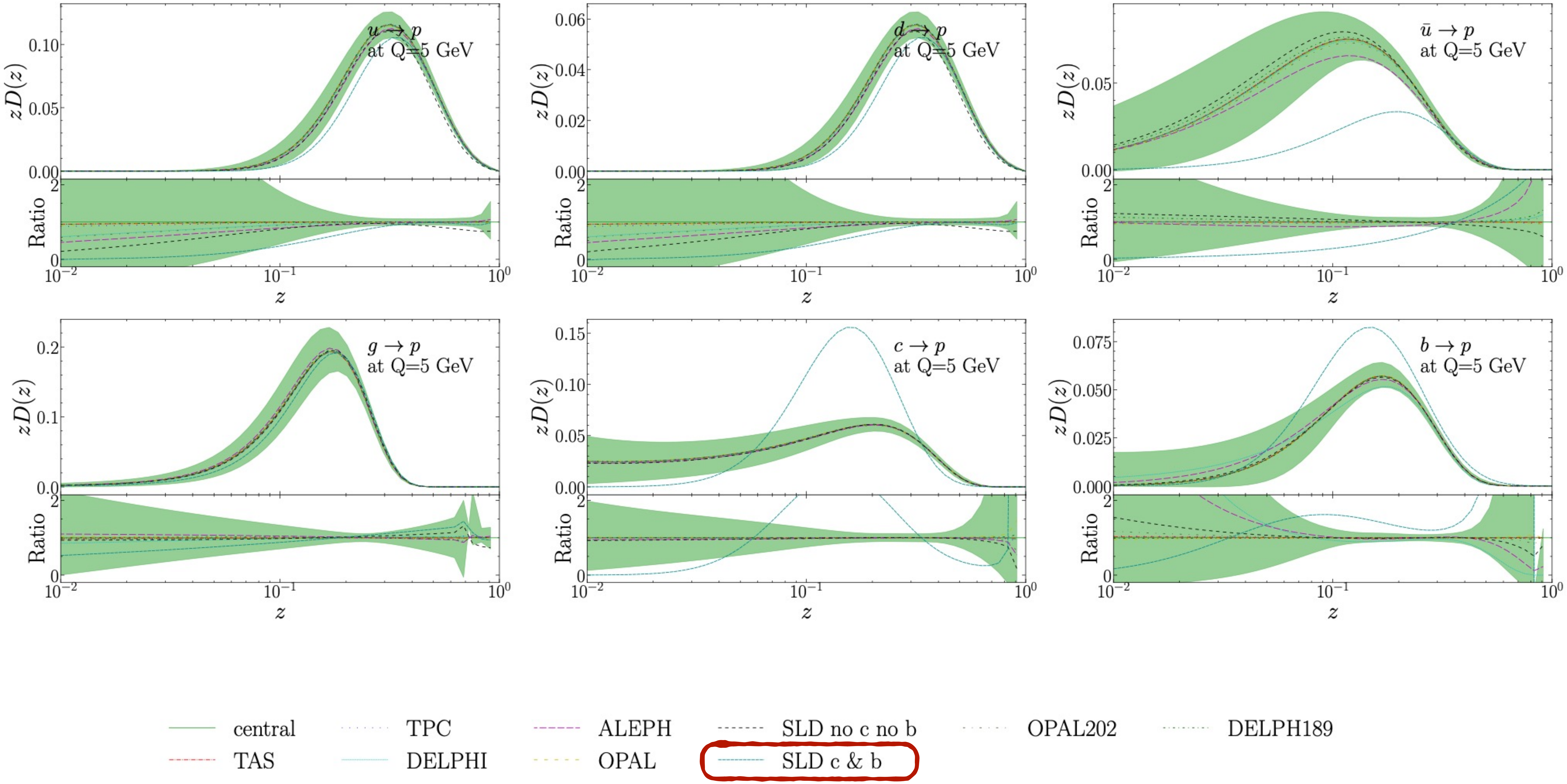
✦ Impact of each data set



The importance of heavy flavor tagging

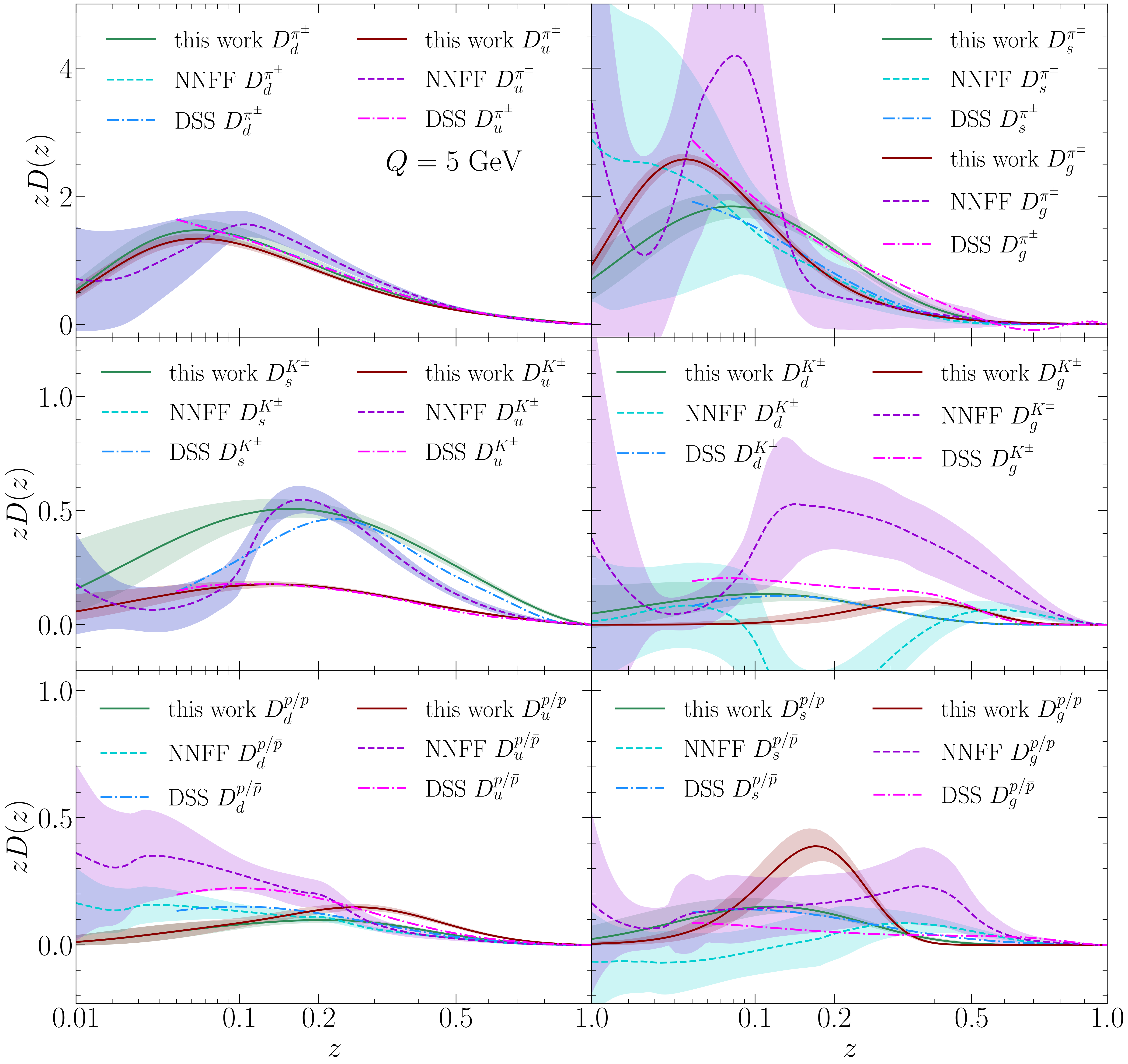
Impact from SIA

✦ Impact of each data set



The importance of heavy flavor tagging

✦ NPC23 vs. others



- General agreement for u/d quark to pion
- Discrepancies for FFs to kaon/ proton and gluon FFs
- Future benchmark works involving different groups are needed to clarify the discrepancies

New efforts from NPC

LHAPDF 6.5.4

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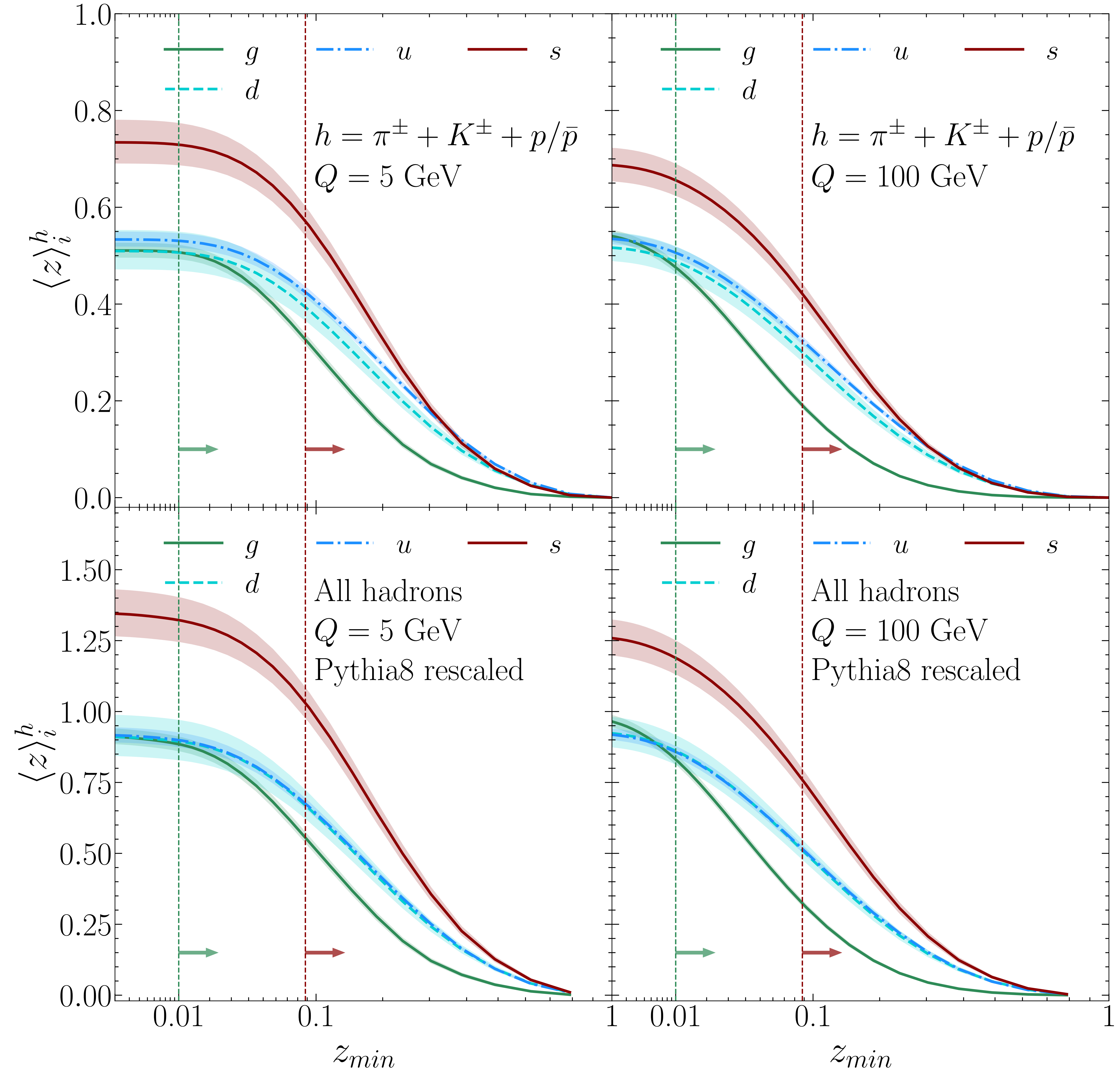
FFs for charged π, k, p are all available in LHAPDF.

New efforts from NPC

✦ momentum sum rule

Gao, Liu, Shen, **HX**, Zhao, PRL, 2024



$\langle z \rangle_i^h$	$g(z > 0.01)$	$u(z > 0.01)$	$d(z > 0.01)$	$s(z > 0.088)$
π^+	$0.200^{+0.008}_{-0.008}$	$0.262^{+0.017}_{-0.016}$	$0.128^{+0.020}_{-0.019}$	$0.161^{+0.013}_{-0.013}$
K^+	$0.018^{+0.004}_{-0.003}$	$0.058^{+0.005}_{-0.004}$	$0.019^{+0.004}_{-0.004}$	$0.015^{+0.002}_{-0.002}$
p	$0.035^{+0.006}_{-0.005}$	$0.044^{+0.004}_{-0.004}$	$0.022^{+0.002}_{-0.002}$	$0.015^{+0.002}_{-0.002}$
π^-	$0.200^{+0.008}_{-0.008}$	$0.128^{+0.020}_{-0.019}$	$0.299^{+0.054}_{-0.049}$	$0.161^{+0.013}_{-0.013}$
K^-	$0.018^{+0.004}_{-0.003}$	$0.019^{+0.004}_{-0.004}$	$0.019^{+0.004}_{-0.004}$	$0.205^{+0.014}_{-0.013}$
$\bar{p}$	$0.035^{+0.006}_{-0.005}$	$0.019^{+0.003}_{-0.003}$	$0.019^{+0.003}_{-0.003}$	$0.015^{+0.002}_{-0.002}$
Sum	$0.507^{+0.014}_{-0.013}$	$0.531^{+0.015}_{-0.013}$	$0.506^{+0.042}_{-0.037}$	$0.572^{+0.029}_{-0.028}$

$$\sum_h \sum_{S_h} \int_0^1 dz\, z\, D_1^{h/q}(z) = 1$$

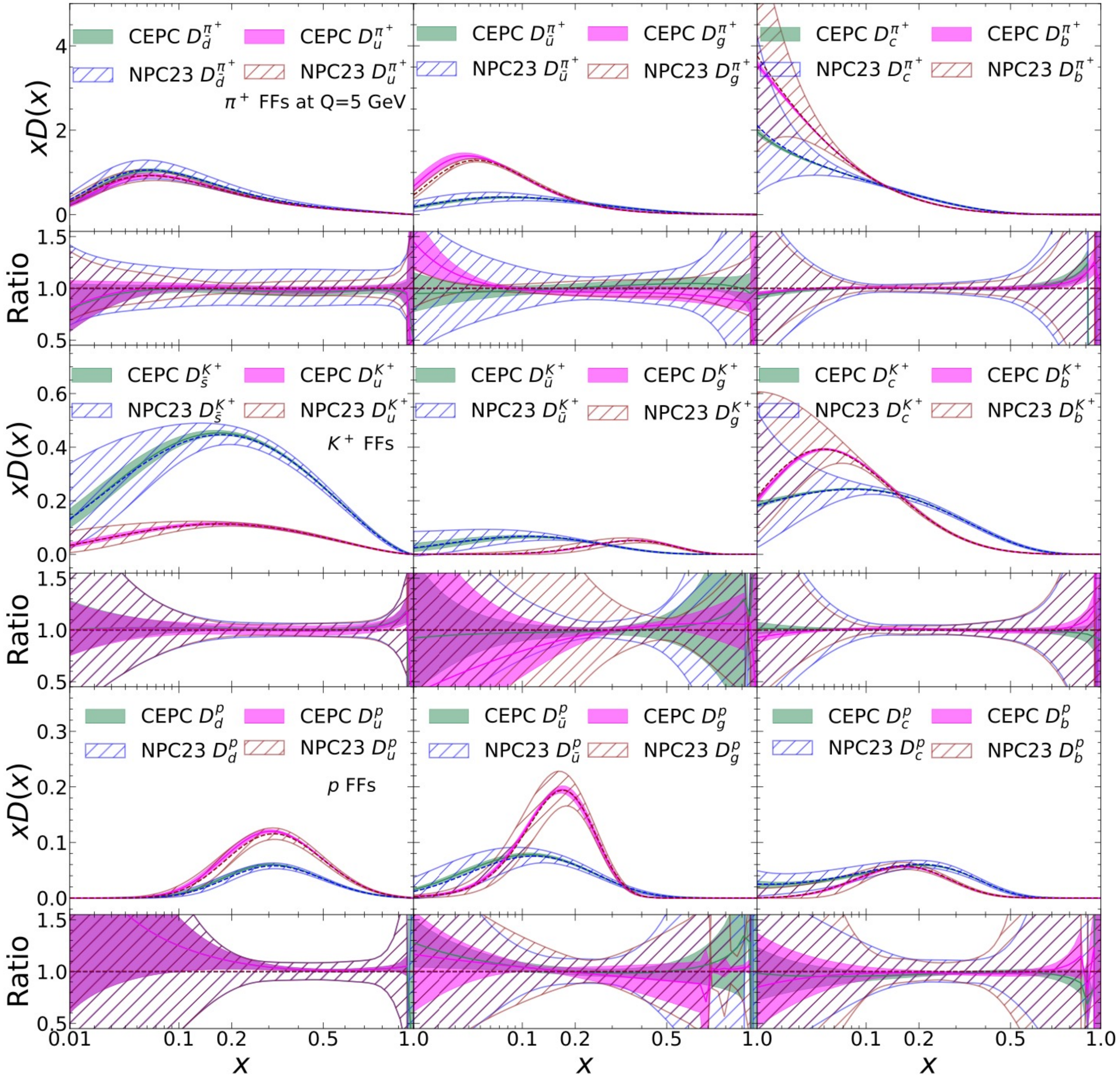
- Hint for violation of momentum sum rule?

The impact from future experiments

✦ The impact of CEPC based on NPC23

Zhou, Gao, 2407.10059

e^+e^- annihilation							
$\sqrt{s}$ (GeV)	luminosity (ab^{-1})			final state	kinematic cuts	hadrons	$N_{\rm pt}$
	CEPC	FCC-ee	ILC				
91.2	60	150	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	132
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	65
160	4.2	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	83
161	-	10	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	83
240	13	5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	92
250	-	-	2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	92
350	-	0.2	0.2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
360	0.65	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
365	-	1.5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
500	-	-	4	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
W boson decay channels							
$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	$N_{\rm pt}$
	CEPC	FCC-ee	ILC				
80.419	116	68	62	$W^-W^{+*} \to W^-q\bar{q}$	-	$h^{+,-}$	120
	58	34	31	$W^-W^{+*} \to W^-c\bar{s}$			
Higgs boson decay channels							
$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	$N_{\rm pt}$
	CEPC	FCC-ee	ILC				
125	0.23	0.09	0.07	gg	-	$h^\pm$	77
	0.08	0.03	0.02	$c\bar{c}$			
	1.53	0.59	0.47	$b\bar{b}$			

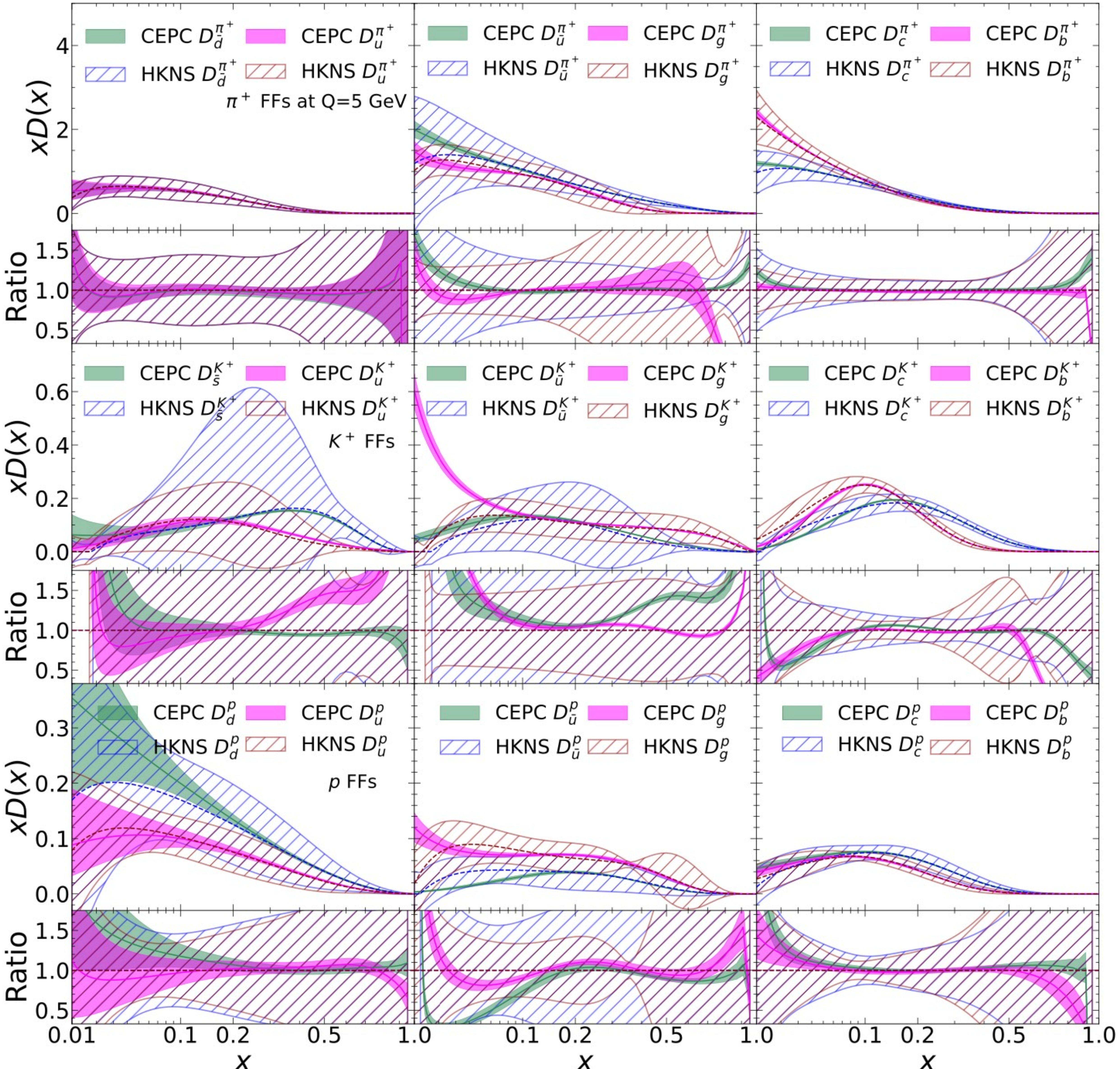


The impact from future experiments

✦ The impact of CEPC based on HKNS

Zhou, Gao, 2407.10059

e^+e^- annihilation							
$\sqrt{s}$ (GeV)	luminosity (ab^{-1})			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-ee	ILC				
91.2	60	150	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	132
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	65
160	4.2	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	83
161	-	10	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	83
240	13	5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	92
250	-	-	2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	92
350	-	0.2	0.2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
360	0.65	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
365	-	1.5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
500	-	-	4	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
W boson decay channels							
$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-ee	ILC				
80.419	116	68	62	$W^-W^{+*} \to W^-q\bar{q}$	-	$h^{+,-}$	120
	58	34	31	$W^-W^{+*} \to W^-c\bar{s}$			
Higgs boson decay channels							
$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-ee	ILC				
125	0.23	0.09	0.07	gg	-	$h^{\pm}$	77
	0.08	0.03	0.02	$c\bar{c}$			
	1.53	0.59	0.47	$b\bar{b}$			

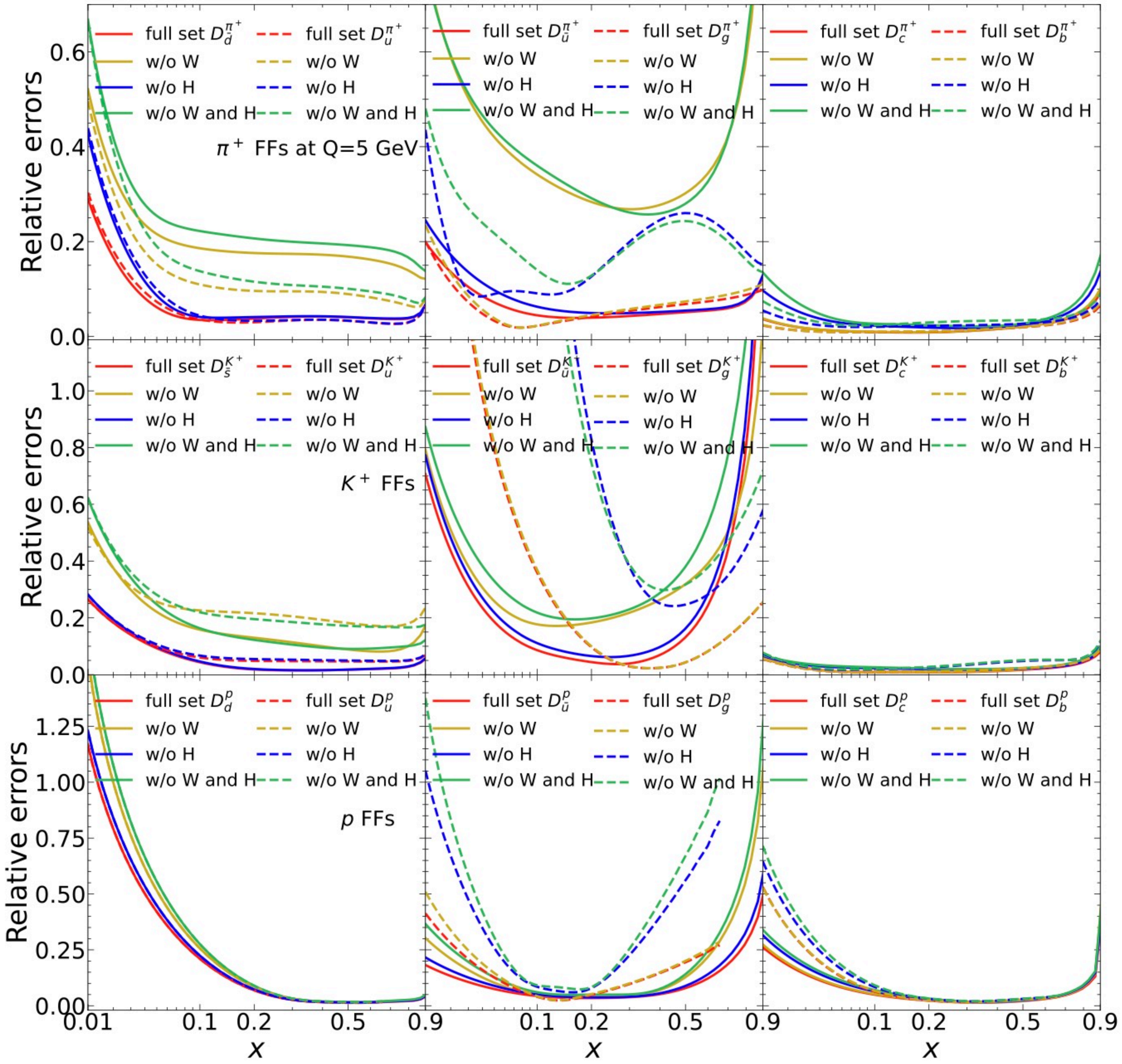


The impact from future experiments

✦ The impact of CEPC from each channel

Zhou, Gao, 2407.10059

$\sqrt{s}$ (GeV)	luminosity (ab^{-1}) CEPC	FCC-ee	ILC	final state	kinematic cuts	hadrons	$N_{\rm pt}$
e^+e^- annihilation							
91.2	60	150	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	132
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	65
160	4.2	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	83
161	-	10	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	83
240	13	5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	92
250	-	-	2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	92
350	-	0.2	0.2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
360	0.65	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
365	-	1.5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
500	-	-	4	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^{\pm}$	98
W boson decay channels							
$\sqrt{s}$ (GeV)	# events (million) CEPC	FCC-ee	ILC	final state	kinematic cuts	hadrons	$N_{\rm pt}$
80.419	116	68	62	$W^-W^{+*} \to W^-q\bar{q}$	-	$h^{+,-}$	120
	58	34	31	$W^-W^{+*} \to W^-c\bar{s}$			
Higgs boson decay channels							
$\sqrt{s}$ (GeV)	# events (million) CEPC	FCC-ee	ILC	final state	kinematic cuts	hadrons	$N_{\rm pt}$
125	0.23	0.09	0.07	gg	-	$h^{\pm}$	77
	0.08	0.03	0.02	$c\bar{c}$			
	1.53	0.59	0.47	$b\bar{b}$			



Summary

✦ NPC23 - high precision determination of parton fragmentation in vacuum from world data

- Works in progress: NPC24 - FFs for neutral hadrons, higher precision at NNLO

✦ High impact of CEPC in constraining Parton FFs

Thanks for your attention!