Global analysis of parton fragmentation functions from LHC to BESIII

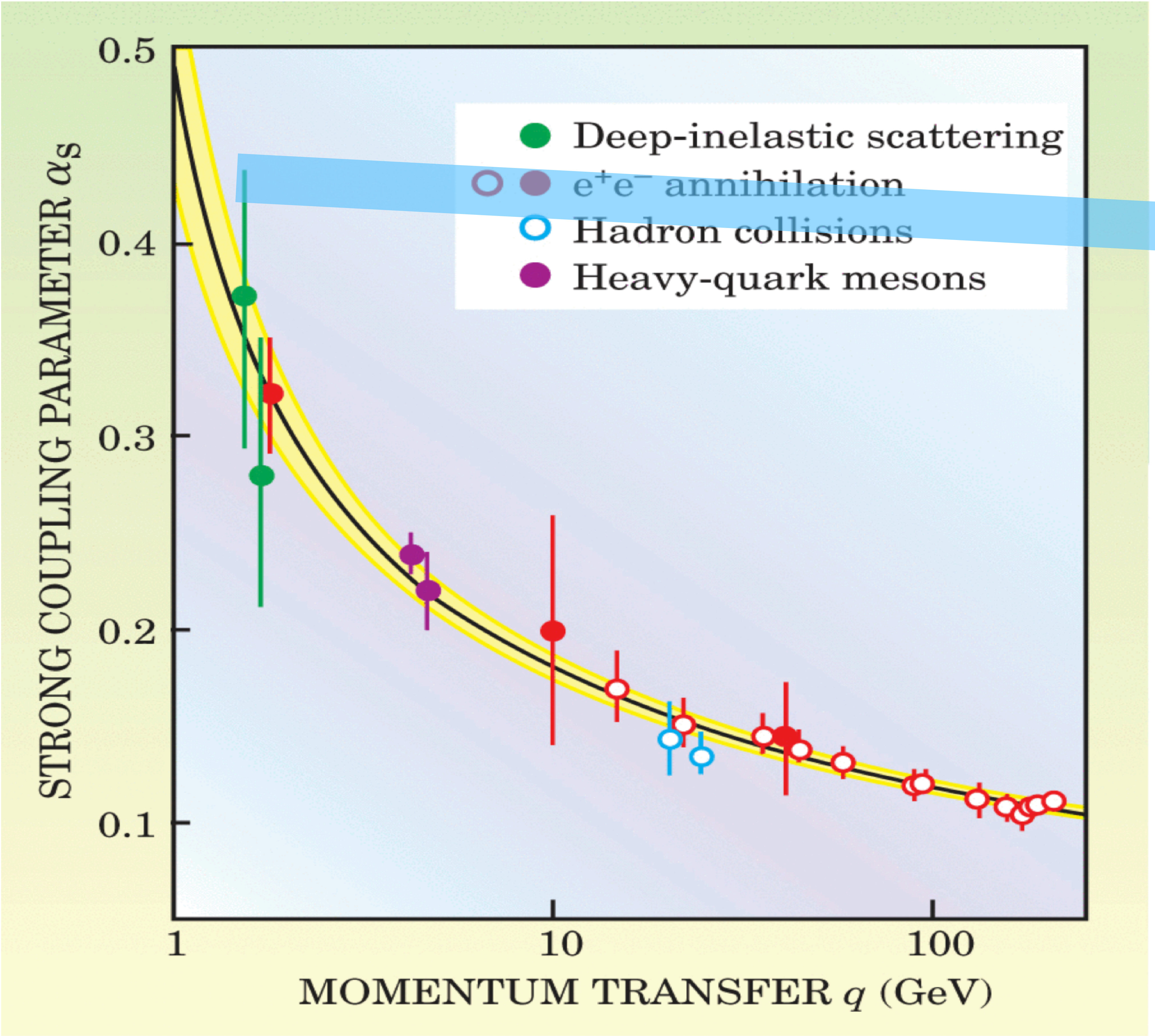
Hongxi Xing

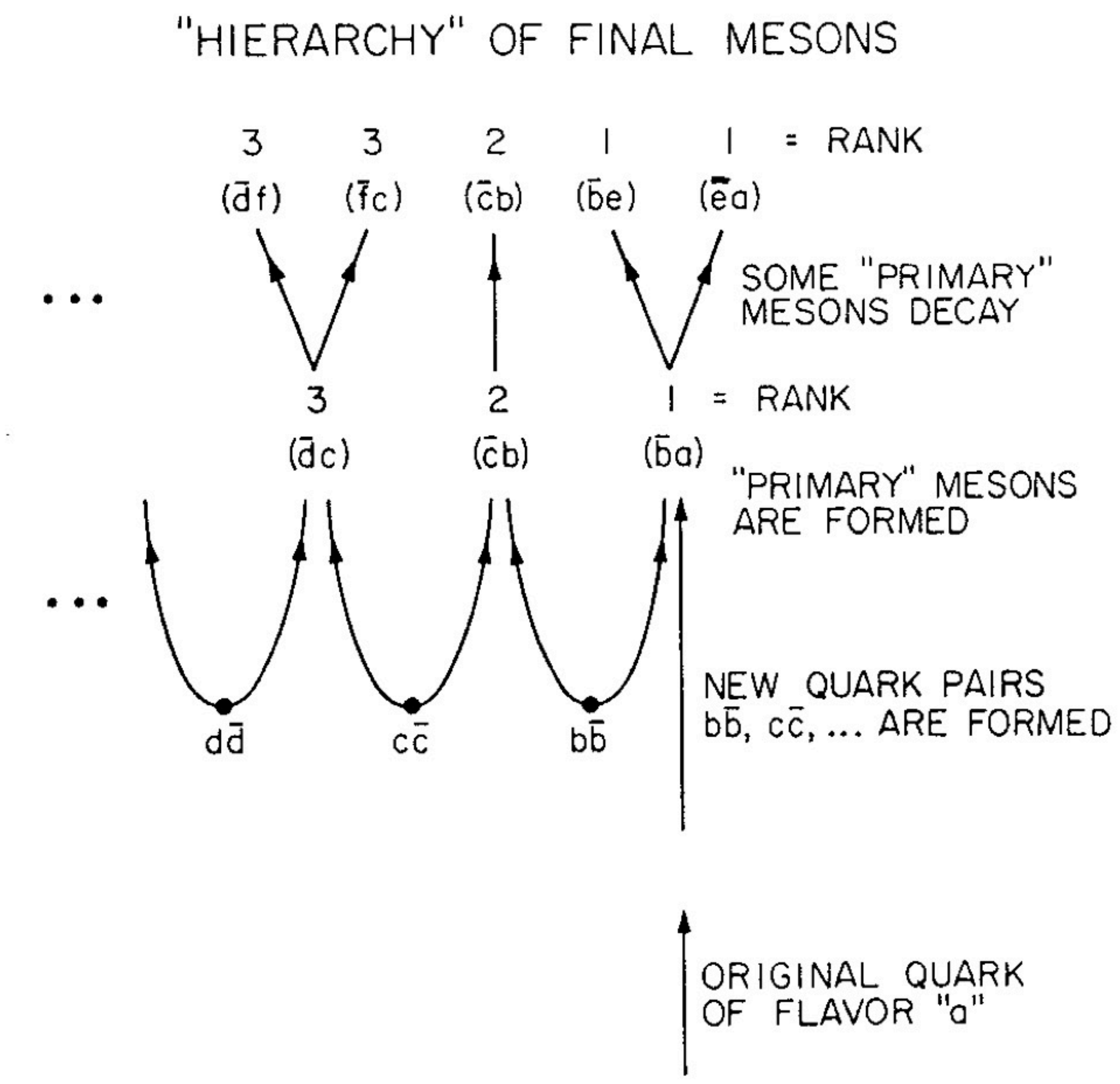
Heavy Ion Physics in the EIC Era

Aug. 12, 2024, INT

QCD confinement - hadronization

✦ QCD as the fundamental theory of strong interaction





Field, Feynman, NPB 1978

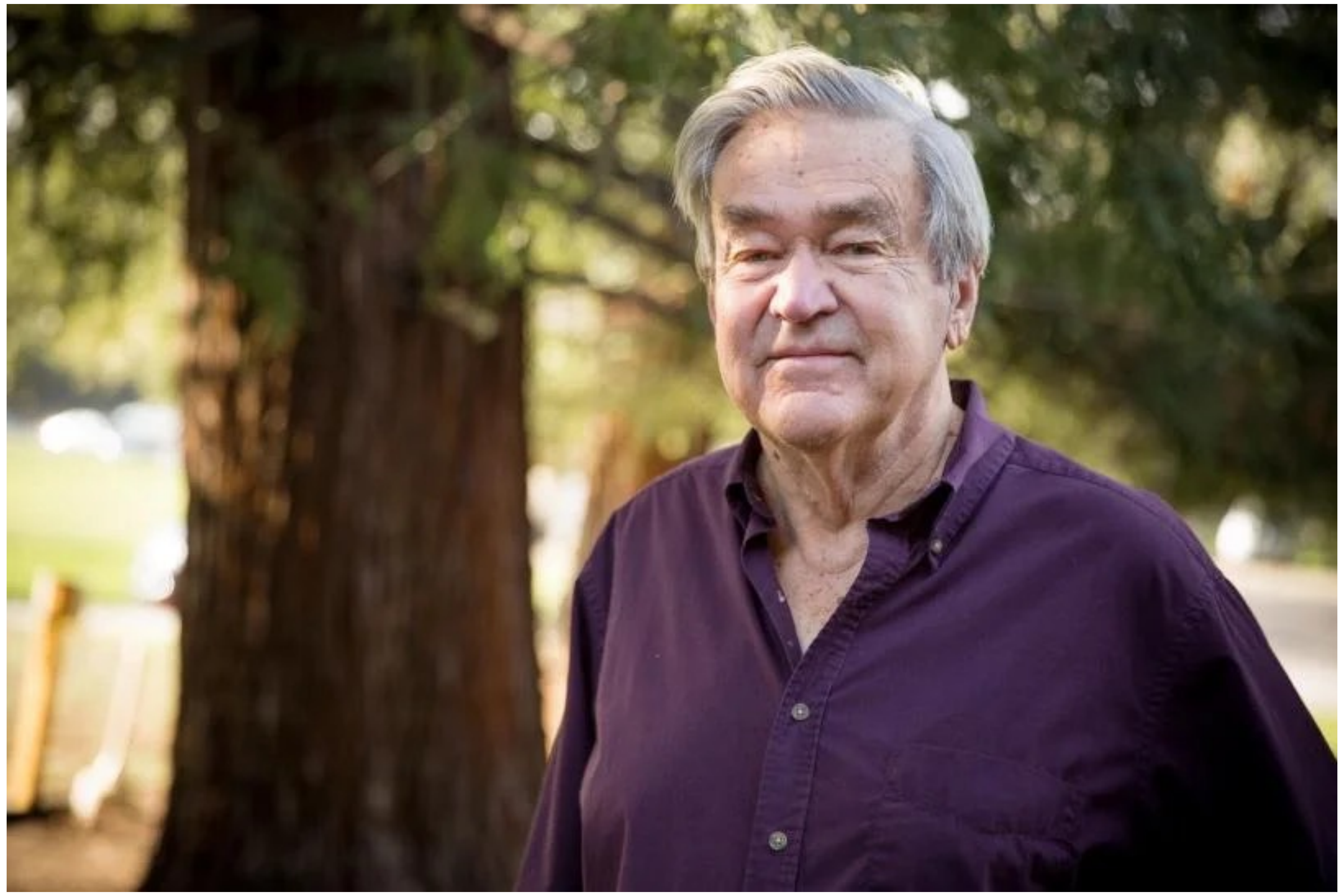
✦ The first concept of parton fragmentation functions

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



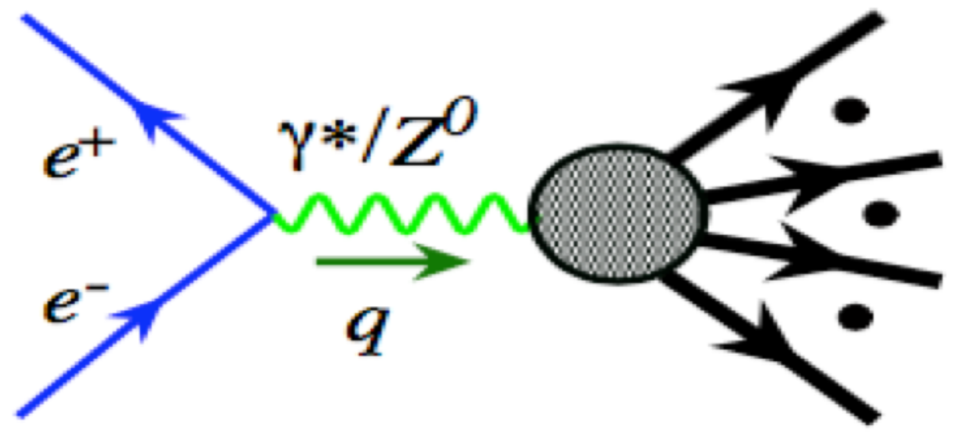
James Bjorken, 1934-2024

Berman, Bjorken, Kogut, PRD 1971

Multiple channels to explore parton hadronization

✦ Indispensable joint efforts from experiments and QCD theory

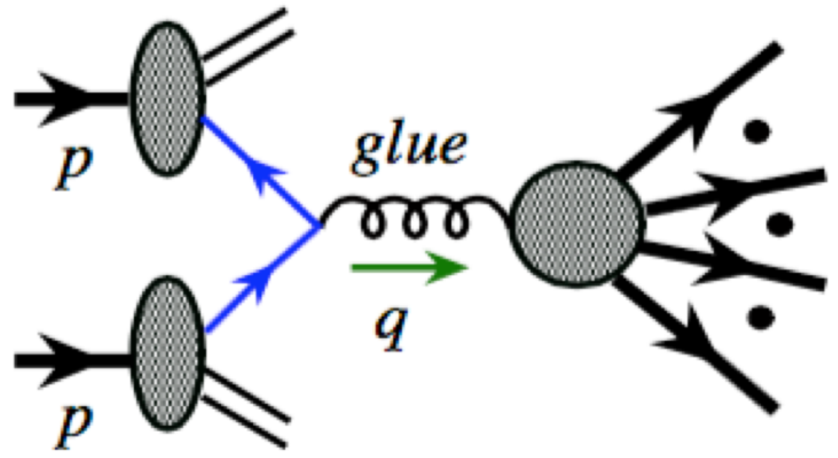
Lepton-lepton colliders



BEPC, SuperKEKB

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

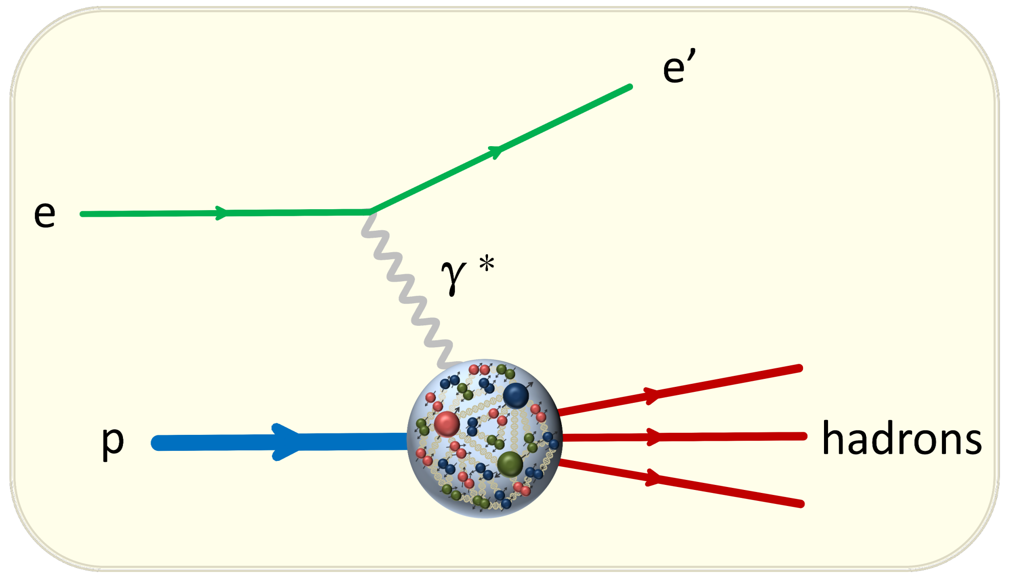
Hadron-hadron colliders



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

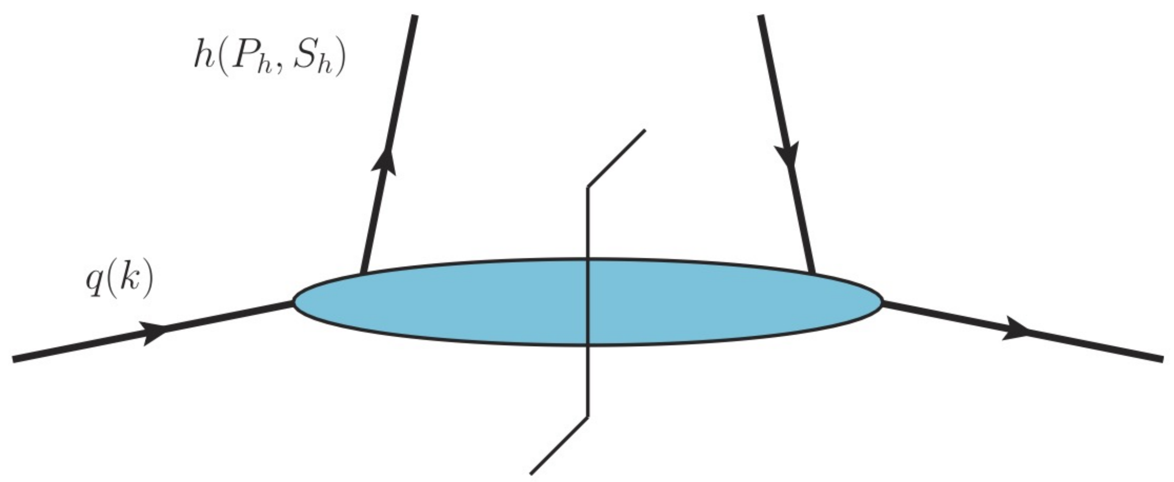
- Hadrons in the initial-state
- Hadrons are emerged from energy
- Ideal for studying hadron structure, can also involve FFs

Fragmentation Functions

✦ Leading twist unpolarized fragmentation functions

- **Operator definition**

$$D_1^{h/q}(z) = \frac{z}{4}\sum\!\!\!\!\!\!\!\int_X \int \frac{d\xi^+}{2\pi} e^{ik^-\xi^+}\,\mathrm{Tr}\Big[\langle 0|\,\mathcal{W}(\infty^+,\xi^+)\,\psi_q(\xi^+,0^-,\vec{0}_T)\,|P_h,S_h;X\rangle \times \langle P_h,S_h;X|\,\bar{\psi}_q(0^+,0^-,\vec{0}_T)\,\mathcal{W}(0^+,\infty^+)|0\rangle\,\gamma^-\Big].$$

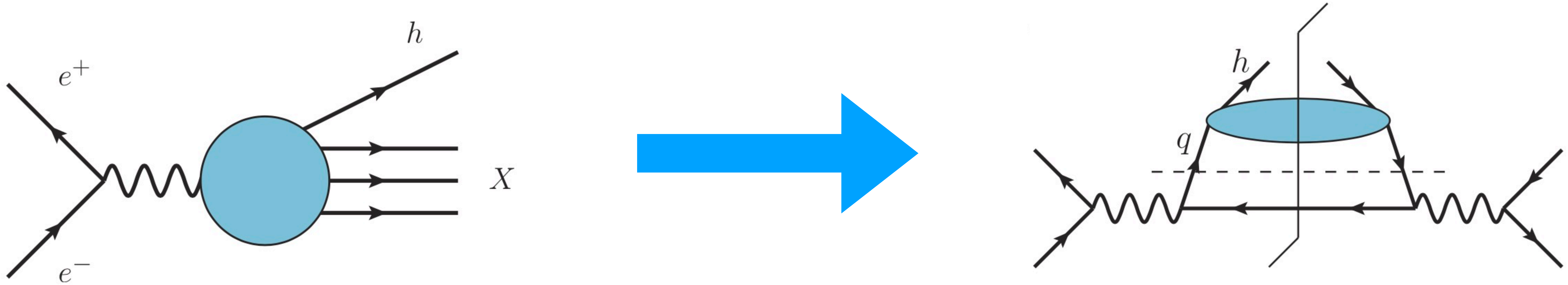


- **Probability densities for finding color-neutral particles inside partons**
- **Momentum sum rule** $\sum_h \sum_{S_h} \int_0^1 dz\, z\, D_1^{h/q}(z) = 1$
- **Time-like DGLAP QCD evolution**

$$\frac{d}{d\ln\mu^2} D_1^{h/i}(z,\mu^2) = \frac{\alpha_s(\mu^2)}{2\pi}\sum_j \int_z^1 \frac{du}{u} P_{ji}(u,\alpha_s(\mu^2))\, D_1^{h/j}\left(\frac{z}{u},\mu^2\right)$$

Perturbative splitting function: $P_{ji}(u,\alpha_s(\mu^2)) = P_{ji}^{(0)}(u) + \frac{\alpha_s(\mu^2)}{2\pi} P_{ji}^{(1)}(u) + \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2 P_{ji}^{(2)}(u) + \cdots$

✦ QCD factorization in electron-positron annihilation

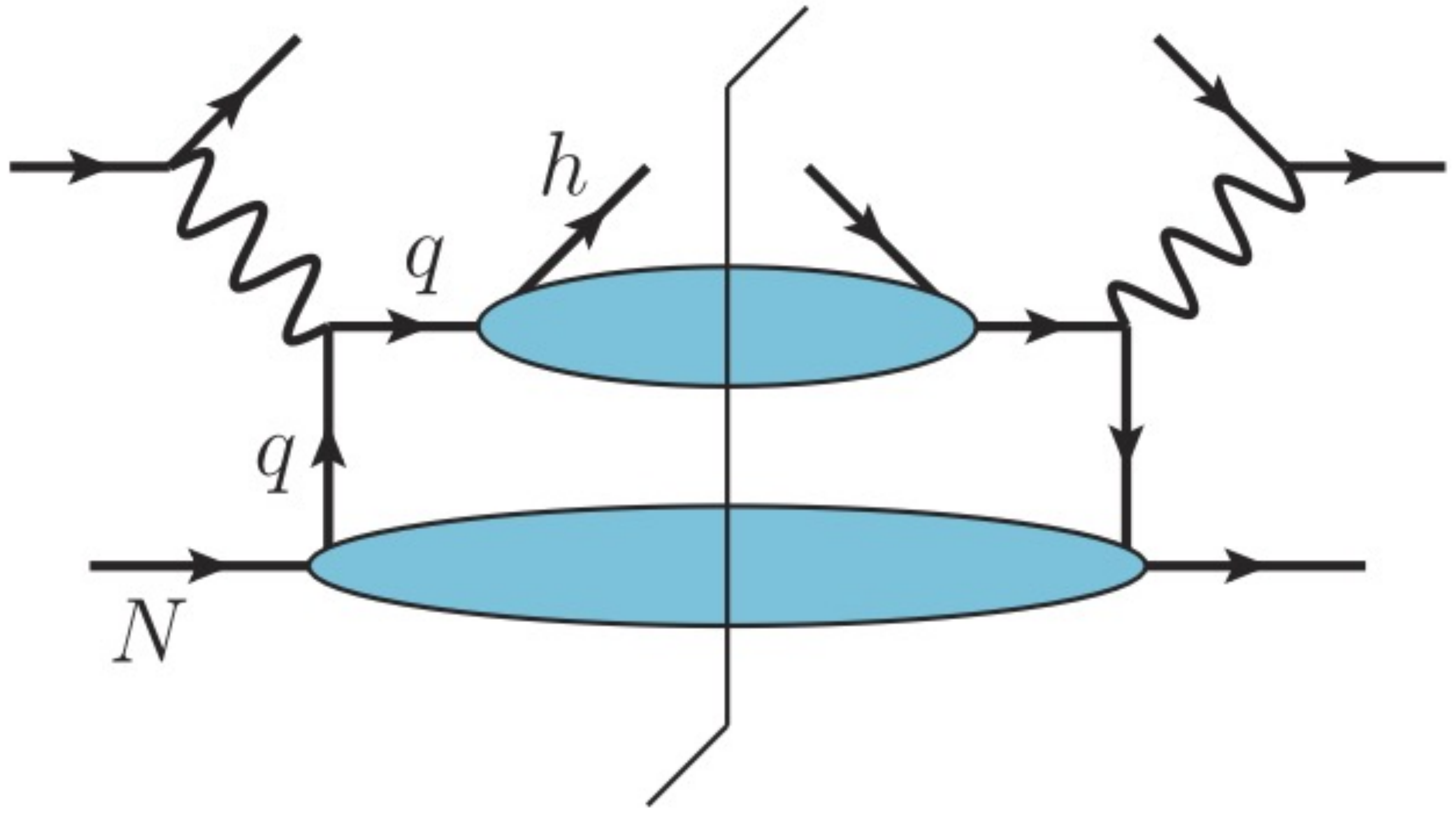


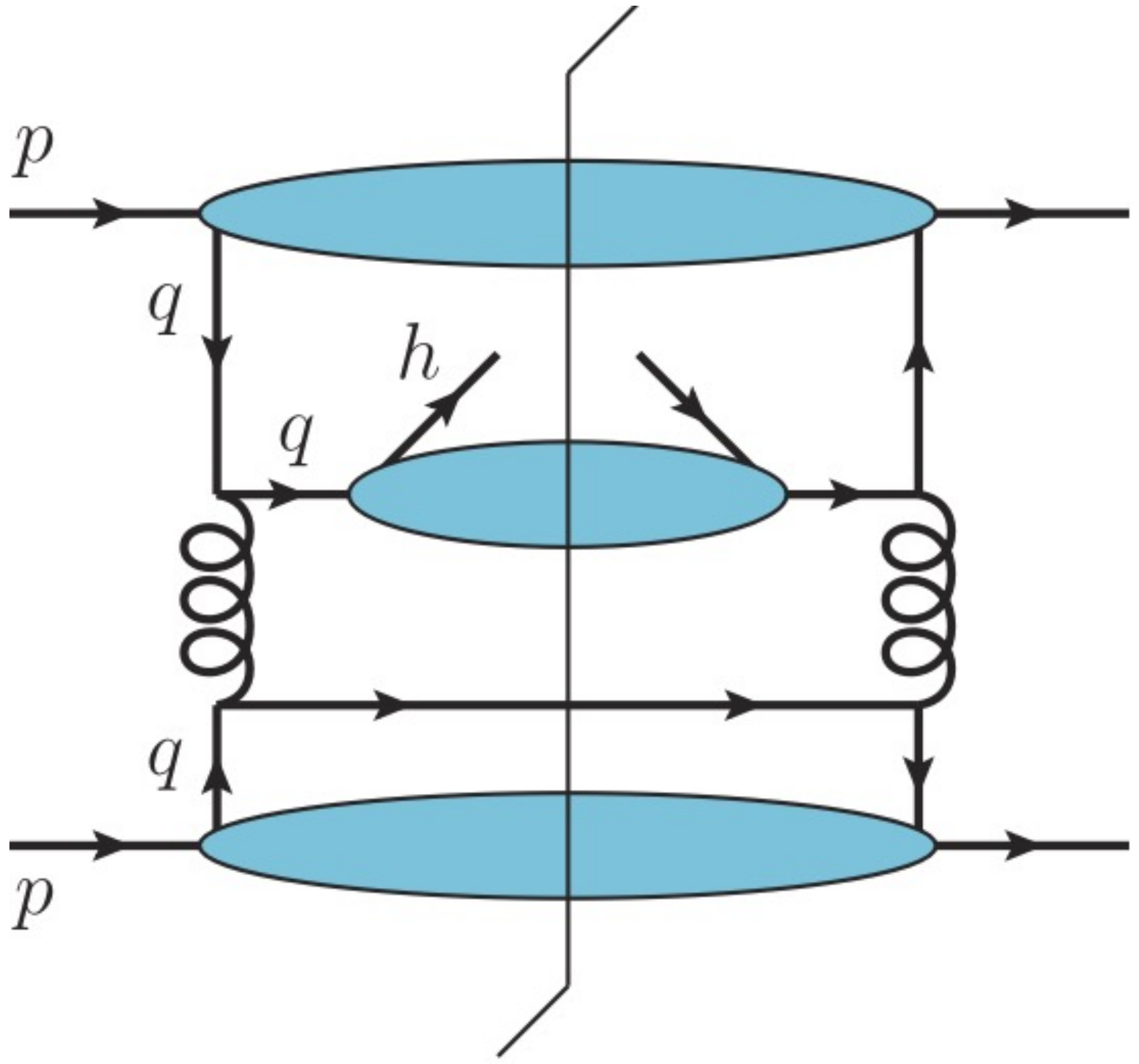
- Leading power/twist collinear factorization *Collins, Soper, Sterman, 1989*

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

- 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.

✦ Access to FFs in ep and pp collisions: universality of FFs





- **Factorization in semi-inclusive deep inelastic scattering**

$$\sigma^{lp\to l'hX} = f_{i/p} \otimes \hat{\sigma}_{li\to j} \otimes D_{j\to h}$$

- **Factorization in single inclusive hadron production in proton-proton collisions**

$$\sigma^{pp\to hX} = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to k} \otimes D_{k\to h}$$

Methodology for global extraction of FFs

FF global fitting panorama

✦ **Joint efforts from experiments and theory in extracting FFs**

Table courtesy of E.R.Nocera

	DHESS	HKNS	JAM	NNFF1.0/1.1h
SIA	☑	☑	☑	☑
SIDIS	☑	☒	☒	☒
PP	☑	☒	☒	☑
statistical treatment	Iterative Hessian 68% - 90%	Hessian $\Delta\chi^2 = 15.94$	Monte Carlo	Monte Carlo
parametrisation	standard	standard	standard	neural network
HF scheme	ZM-VFN	ZM-VFN	ZM-VFN	ZM-VFN
hadron species	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$	$\pi^\pm$, $K^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$
latest update	PRD 91 (2015) 014035 PRD 95 (2017) 094019	PTEP 2016 (2016) 113B04	PRD 94 (2016) 114004	Eur.Phys.J.C 77 (2017) 8, 516 Eur.Phys.J.C 78 (2018) 8, 651
perturbative order	LO/NLO	LO/NLO	LO/NLO	LO/NLO/NNLO

FF global fitting panorama

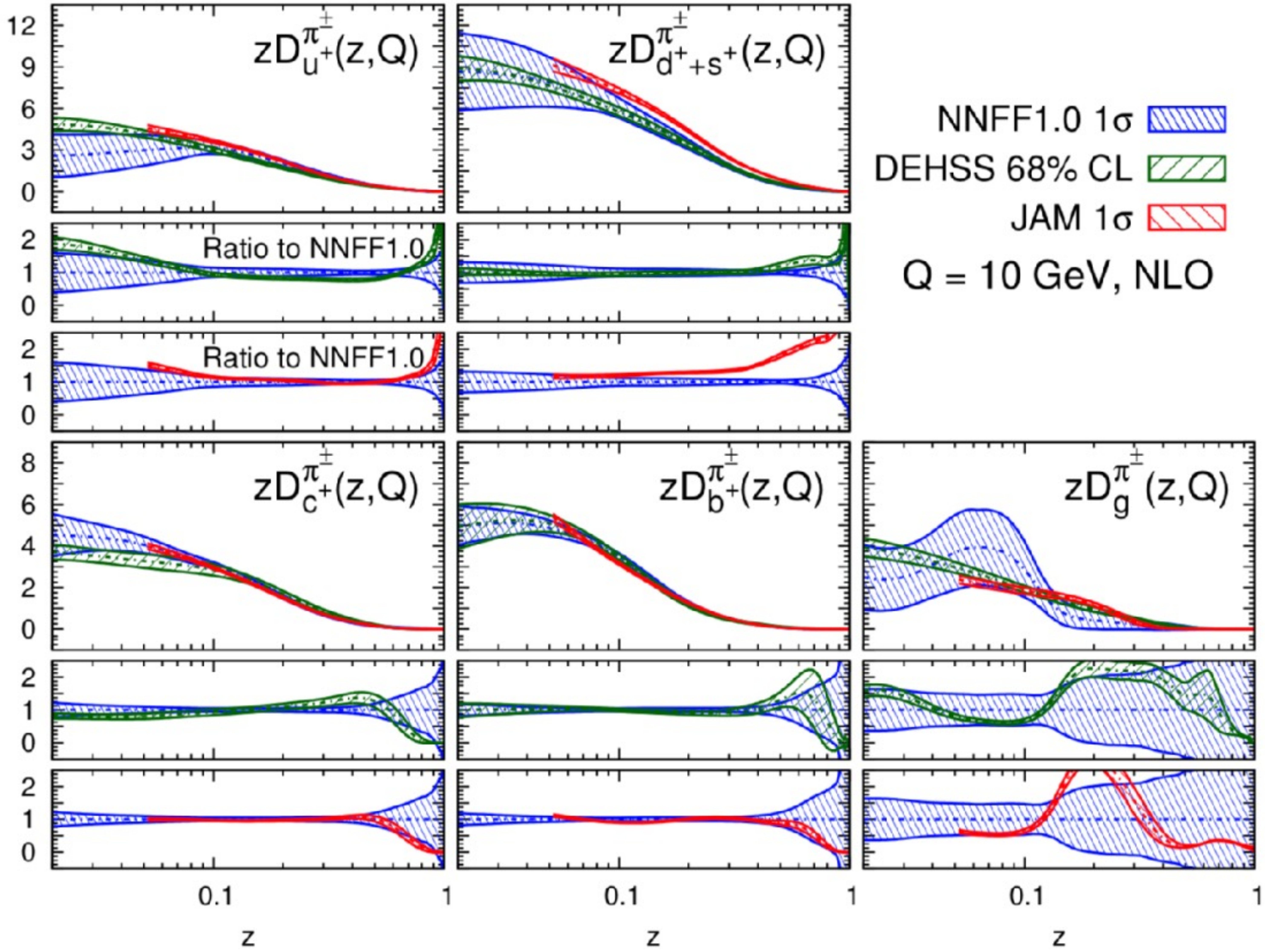
✦ Joint efforts from experiments and theory in extracting FFs

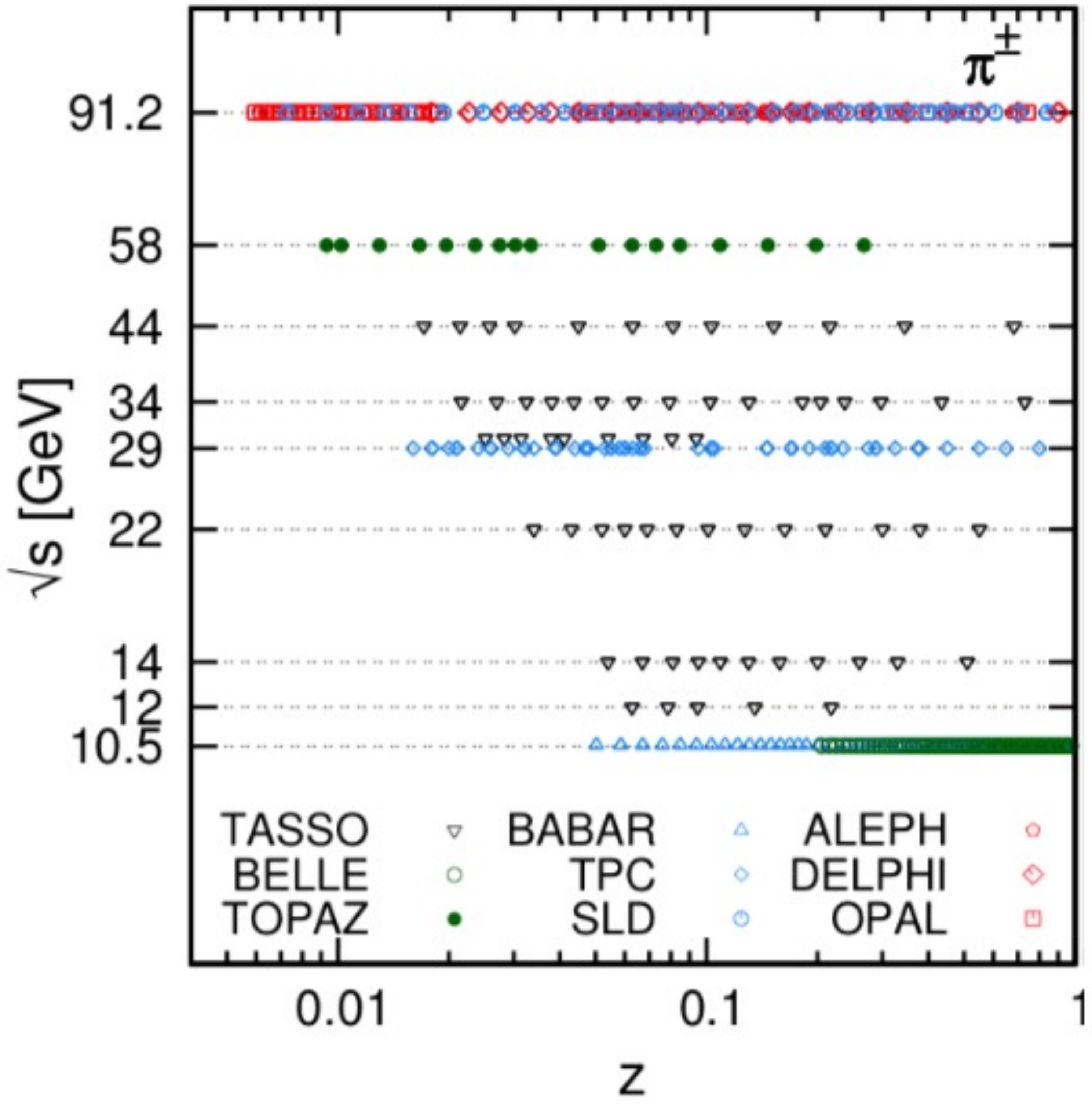
	MAPFF	BSFSV	ARS	AKRS
SIA SIDIS PP	✓ ✓ (Approximate NLL+NLP) ✖	✓ ✓ (Approximate NLL+NLP) ✖	✓ ✖ ✖	✓ ✖ ✖
Statistical treatment	Monte Carlo	NO	NO	NO
Parametrization	Neural network	Standard	Standard	Standard
HF Scheme	ZM-VFNS	ZM-VFNS	ZM-VFNS	ZM-VFNS
Hadron spices	$\pi^{\pm}, K^{\pm}$	$\pi^{\pm}$	$\pi^{\pm}$	$\pi^{\pm}$
Latest update	PRD 104 (2021) 3, 034007 PLB 834 (2022) 137456	PRL 129 (2022) 1, 012002	PRD 92 (2015) 11, 114017	PRD 95 (2017) 5, 054003
perturbative order	LO/NLO/NNLO	NLO/NNLO	LO/NLO/NNLO	LO/NLO/NNLO

Not a complete list!

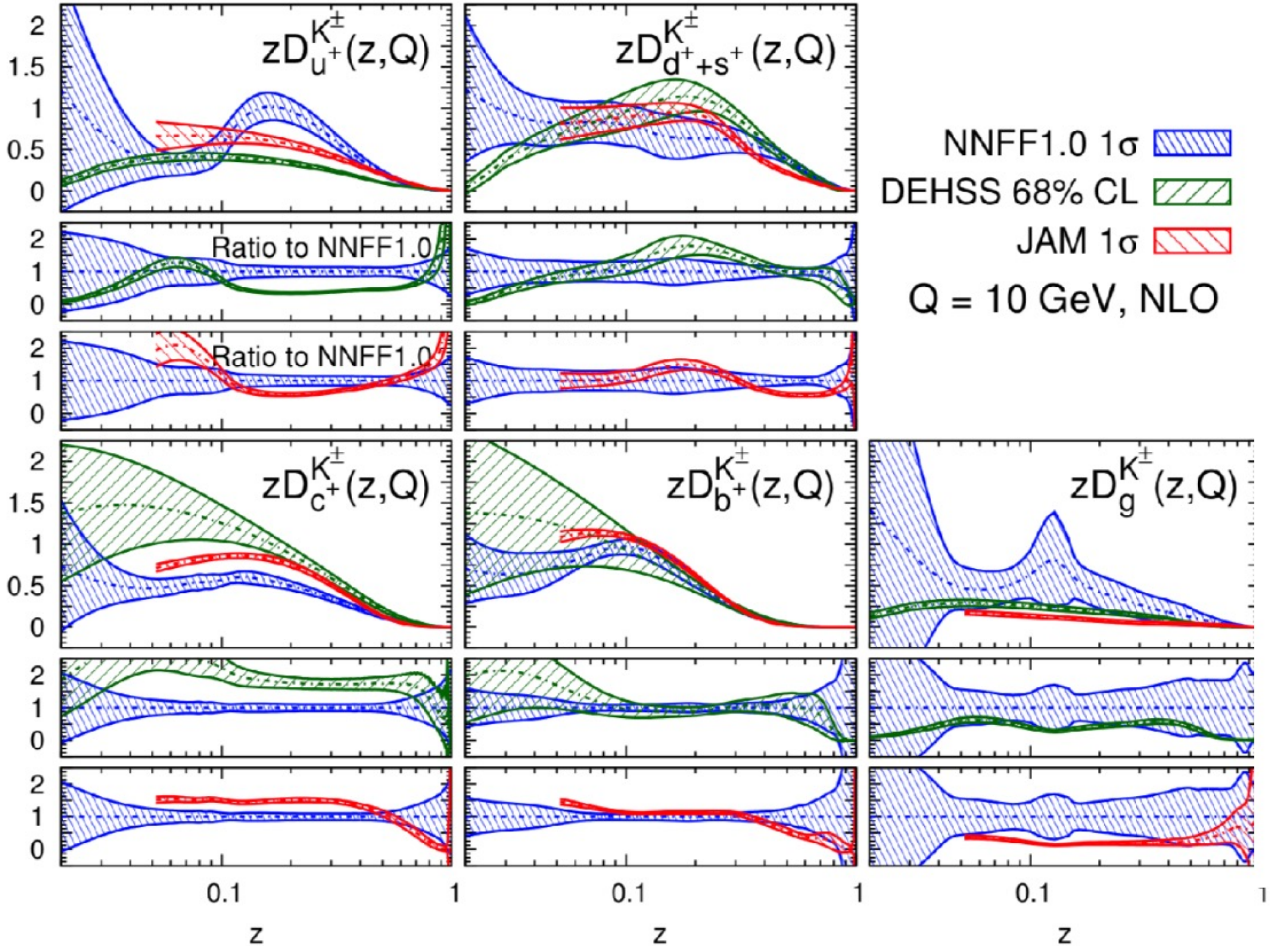
✦ The best known FFs - π

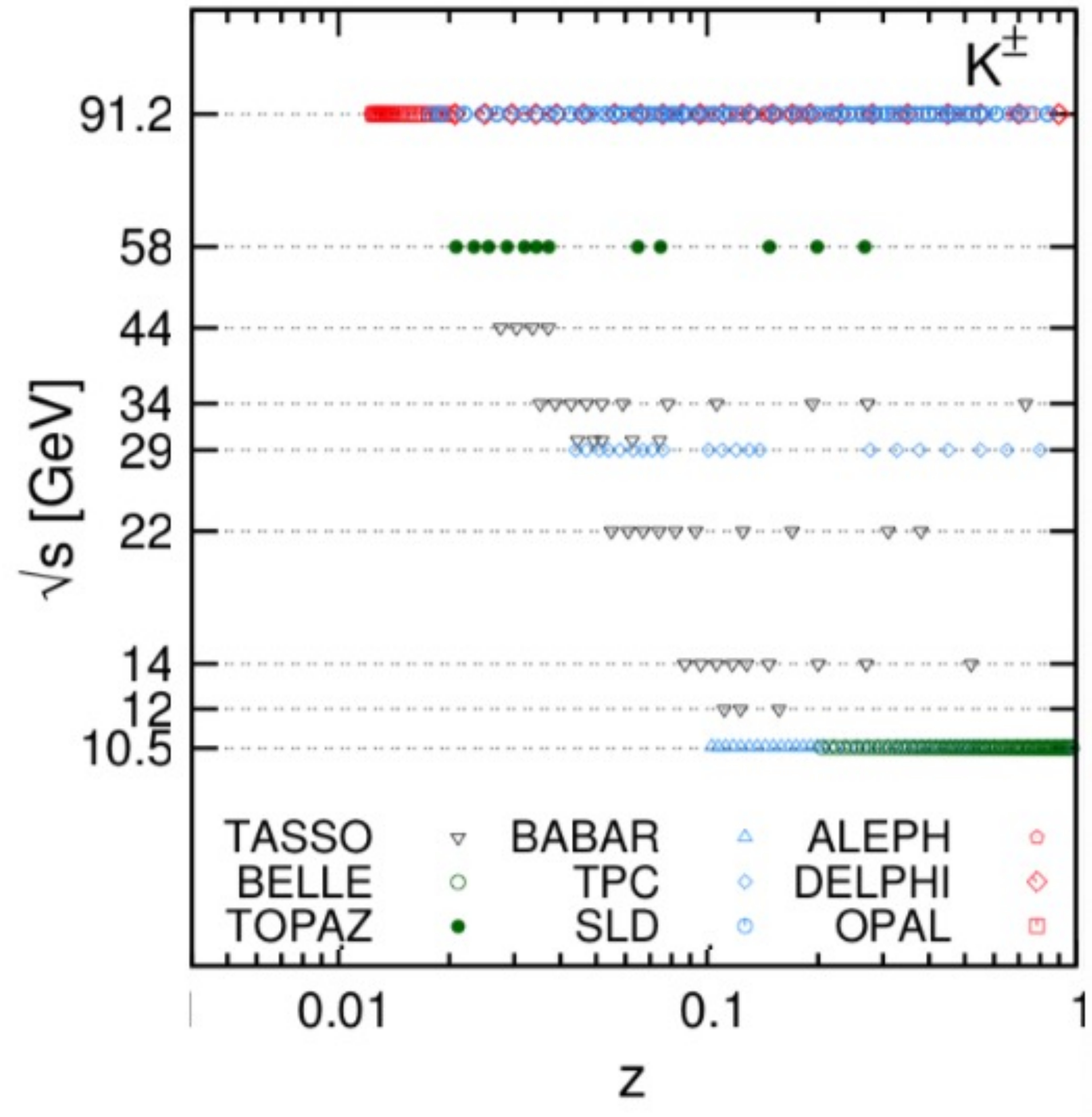
V.Bertone et al. [NNPDF collaboration] Eur.Phys.J.C 77 (2017) 8, 516
D. de Florian et al. , Phys. Rev. D 91 (2015), 4035, D 95 (2017), 094019
N. Sato et al. [JAM Collaboration] Physical Review D, 94 (2016) 11, 114004





✦ kaon FFs

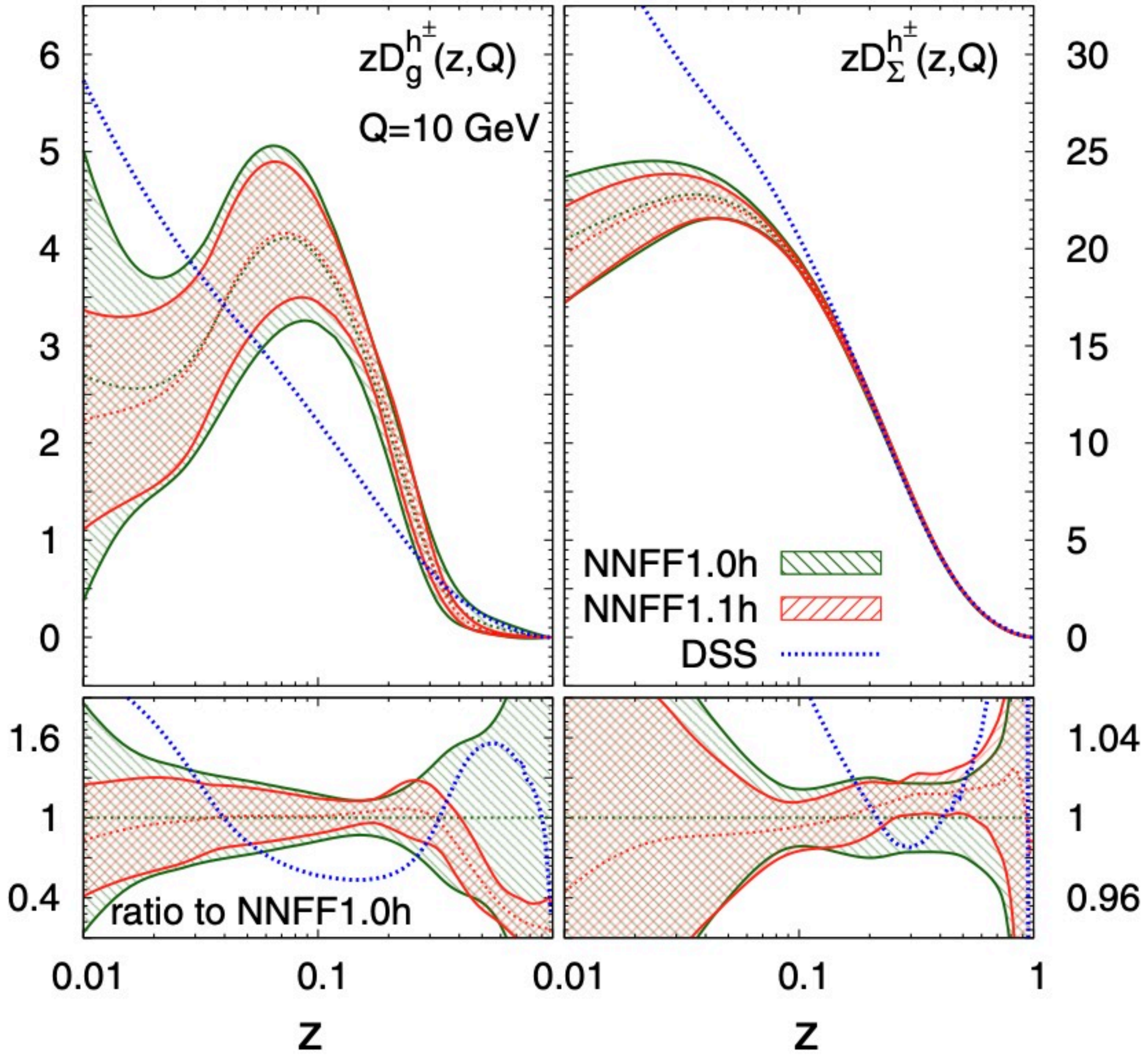

$zD^{K^\pm}_{u^+}(z,Q)$
$zD^{K^\pm}_{d^++s^+}(z,Q)$
Ratio to NNFF1.0
Ratio to NNFF1.0
NNFF1.0 1σ
DEHSS 68% CL
JAM 1σ
Q = 10 GeV, NLO
$zD^{K^\pm}_{c^+}(z,Q)$
$zD^{K^\pm}_{b^+}(z,Q)$
$zD^{K^\pm}_{g}(z,Q)$
z


$K^\pm$
√s [GeV]
91.2
58
44
34
29
22
14
12
10.5
TASSO
BELLE
TOPAZ
BABAR
TPC
SLD
ALEPH
DELPHI
OPAL
0.01
0.1
1
z

FFs panorama

✦ Charged hadron FFs

NNPDF, EPJC 2018　　DSS, PRD 2007



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, SIA will play a very important role!

New opportunities in probing FFs at LHC

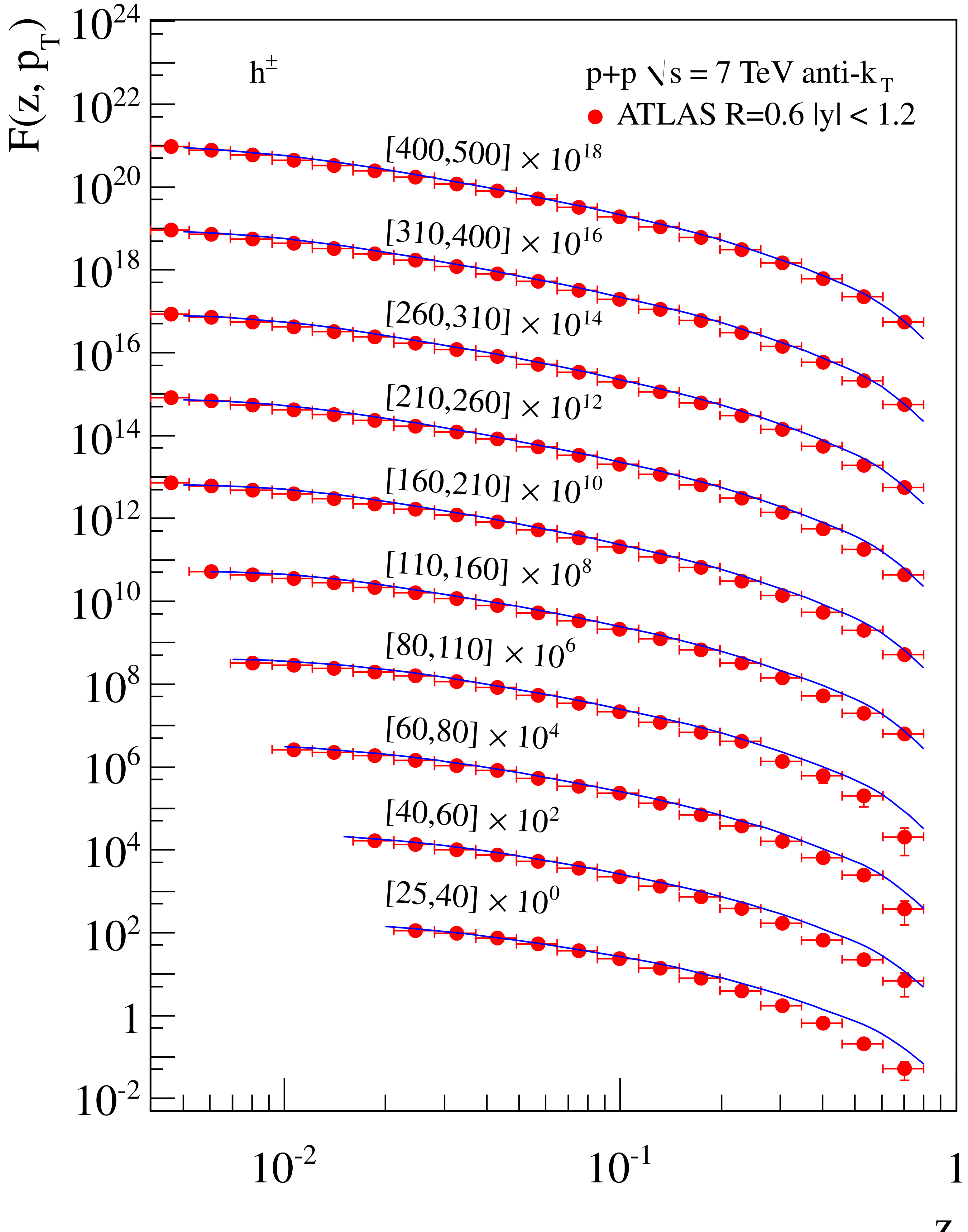
✦ Jet fragmentation function

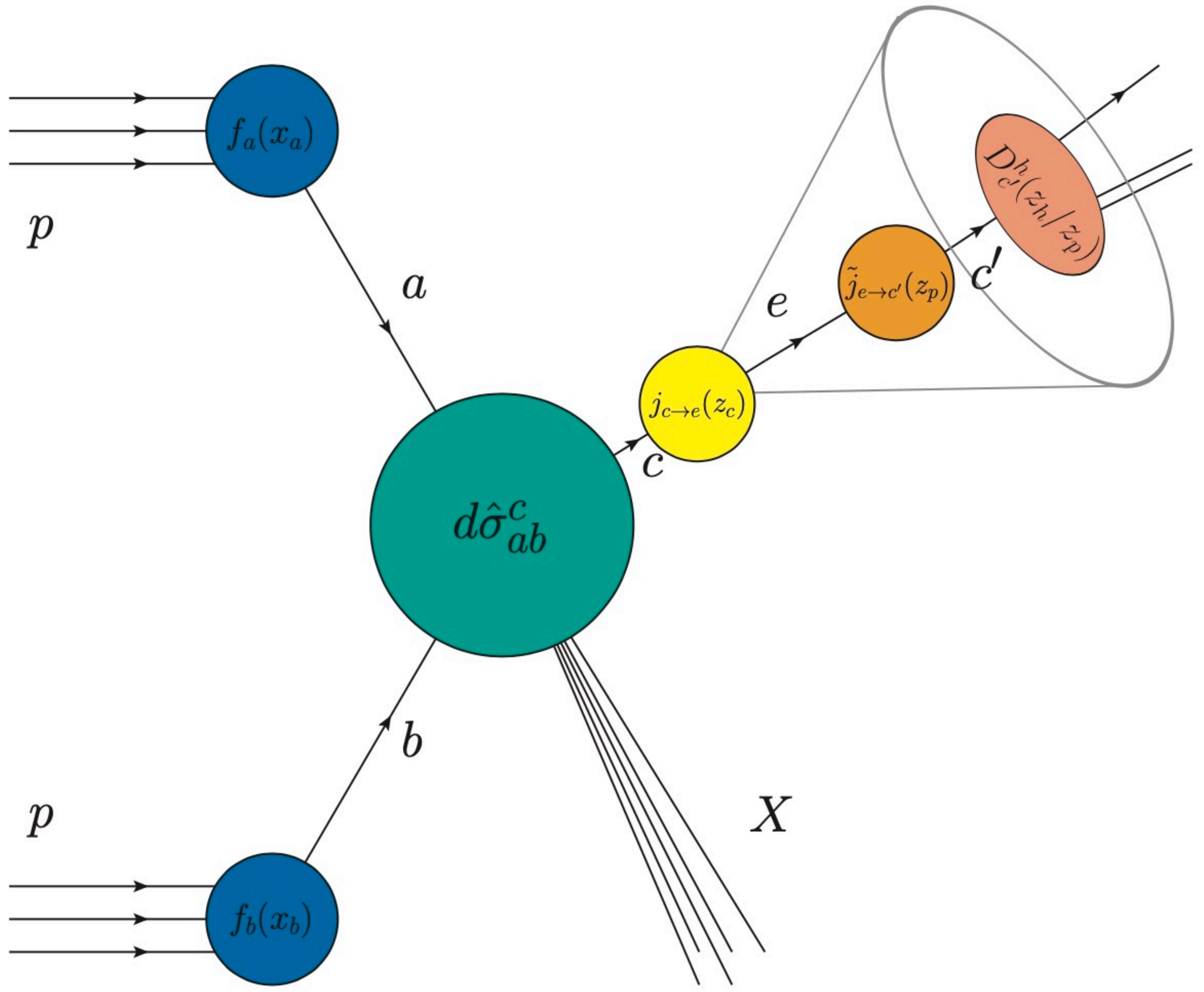
Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

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

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

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





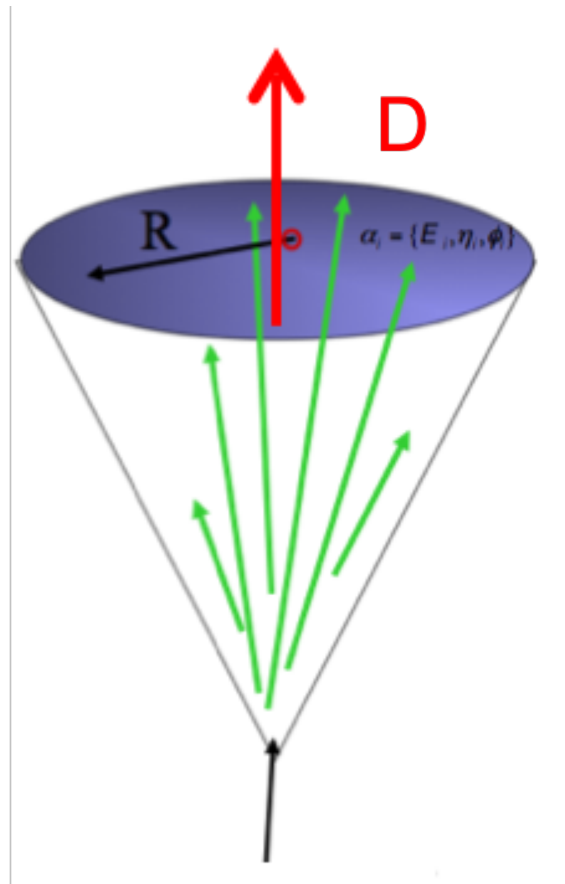
$$z_h = \frac{p_T^h}{p_T}$$

Light hadrons work very well

Heavy flavor in jet

✦ Jet fragmentation function for D meson

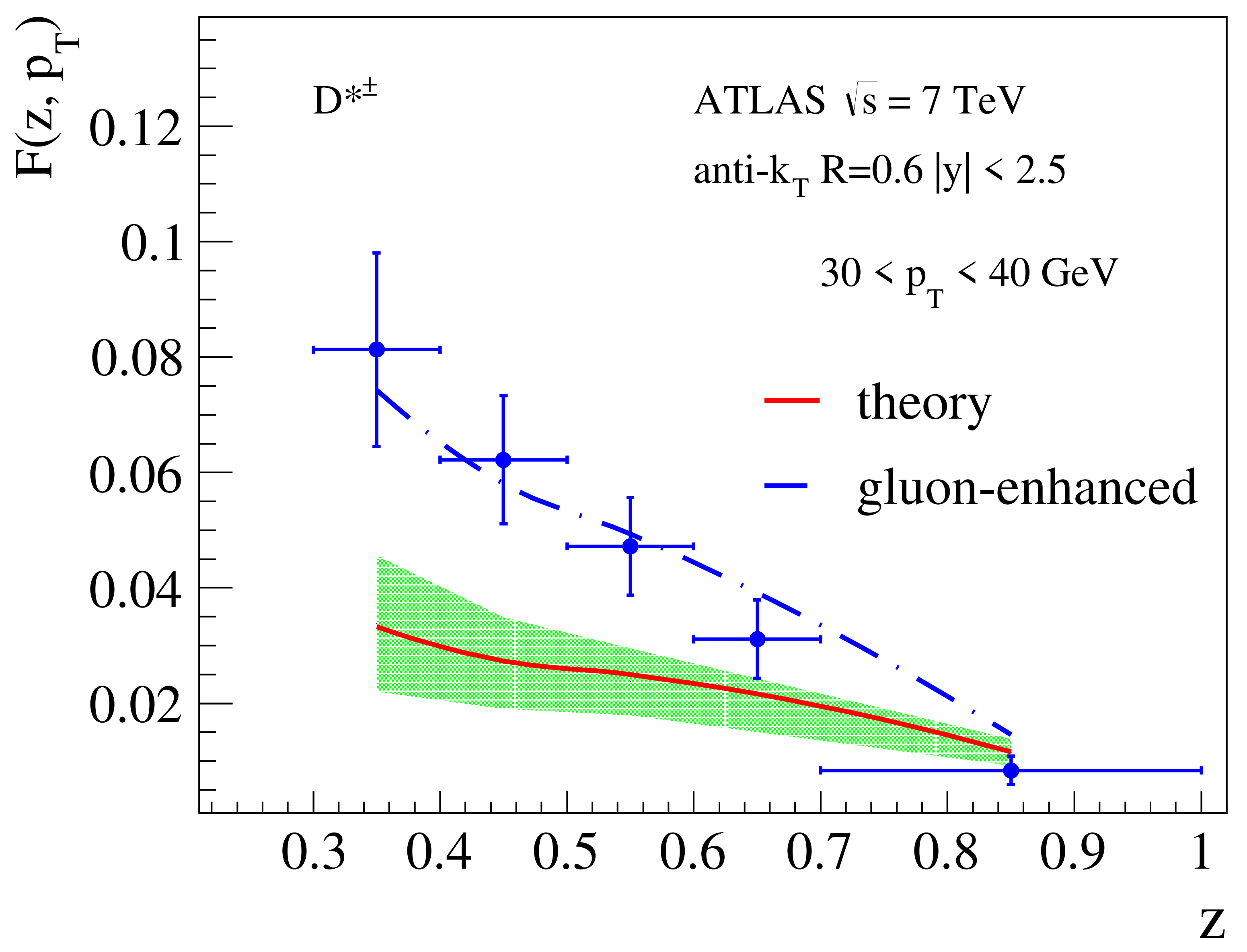
$$F(z_h, p_T) = \frac{d\sigma^{J(h)}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma}{dp_T d\eta}$$

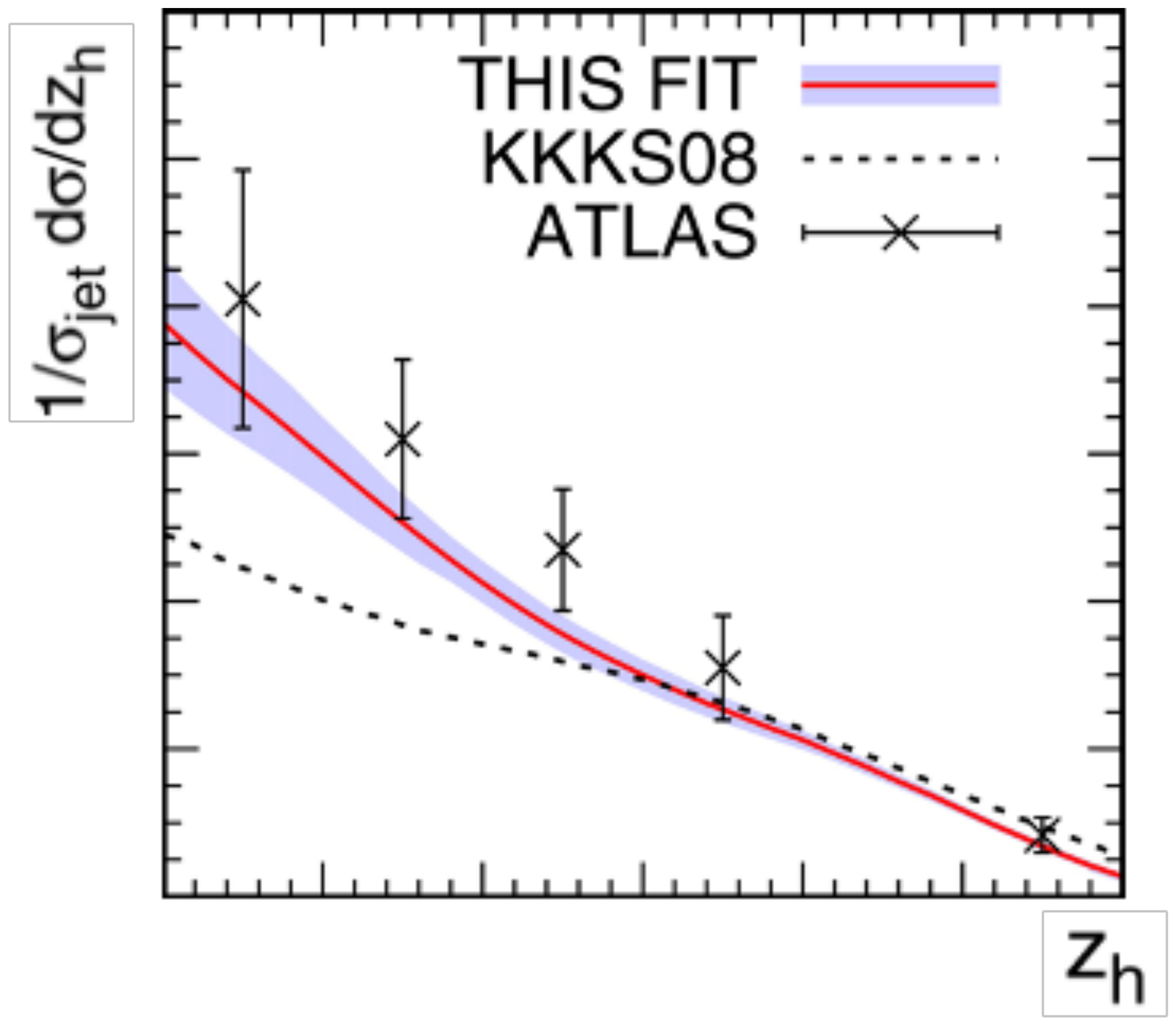


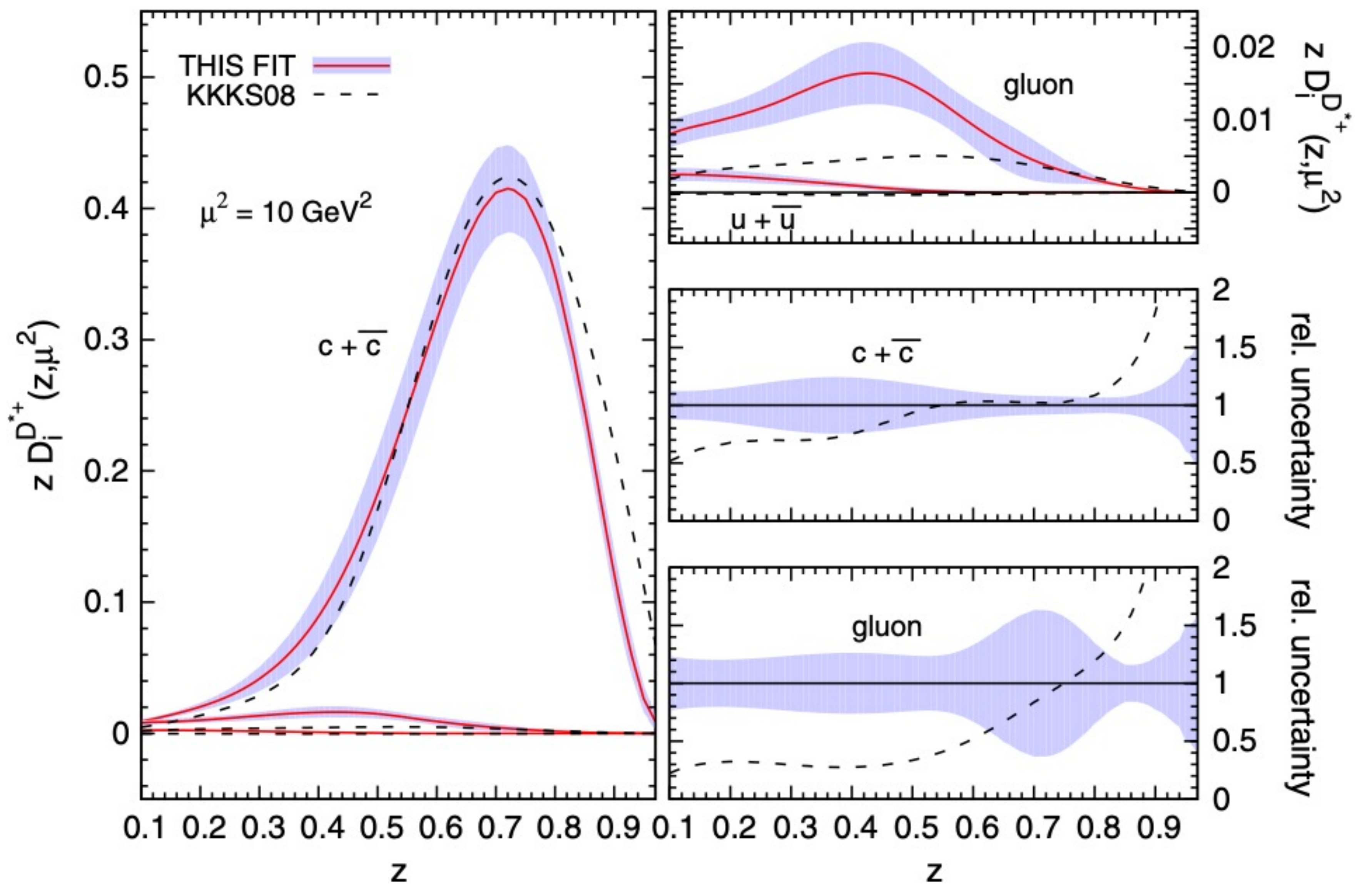
$$z_h = \frac{p_T^h}{p_T}$$

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

AKSRV, PRD (2017)





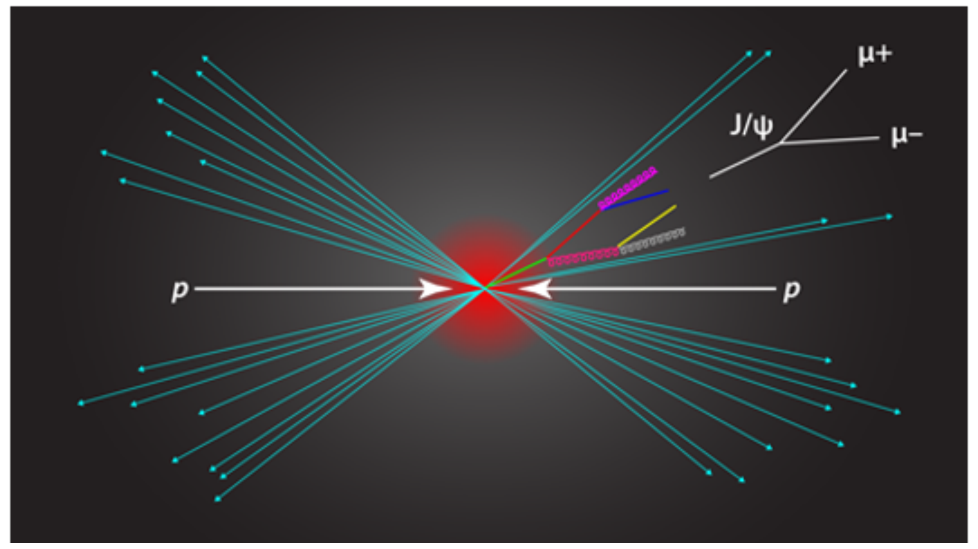


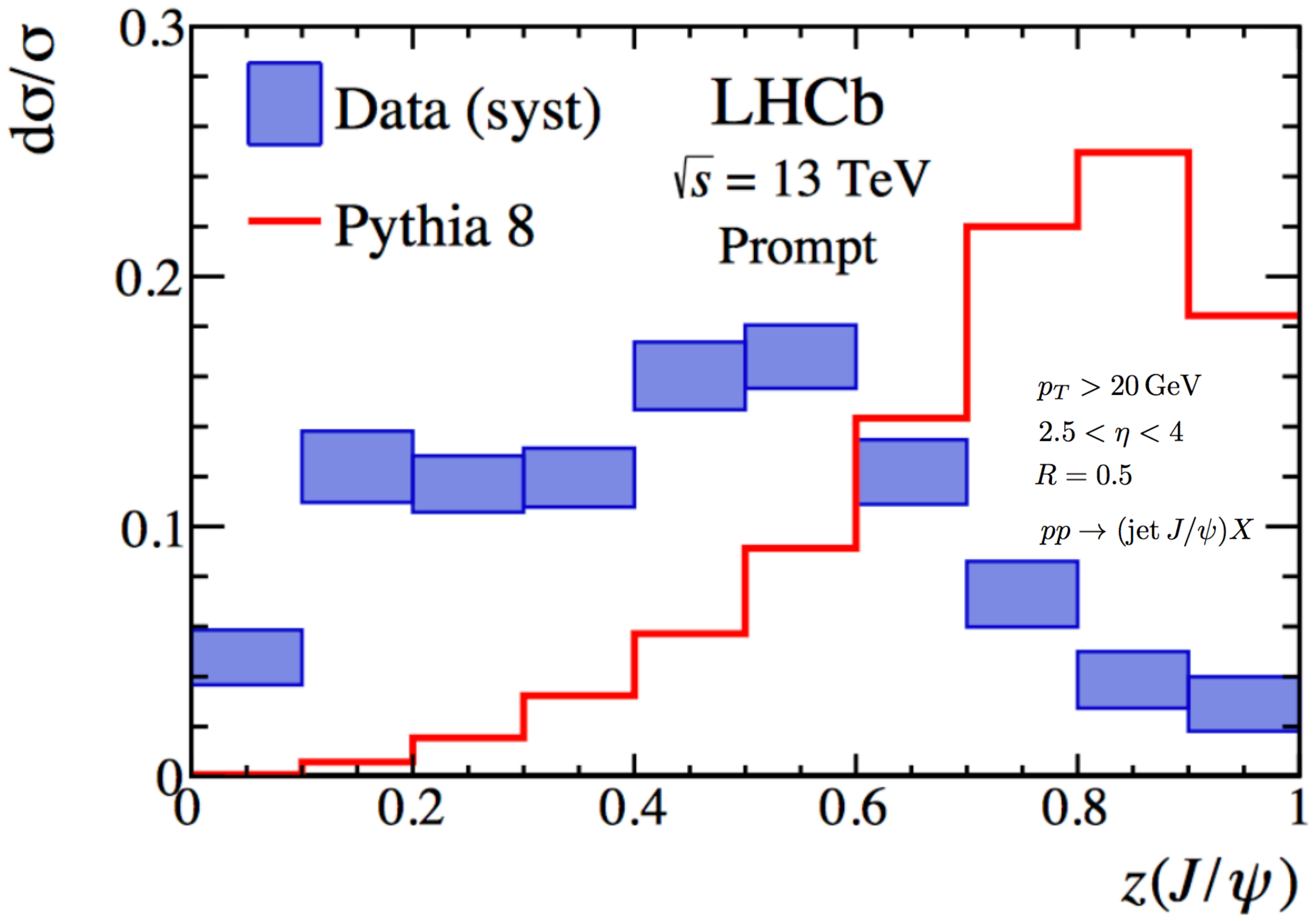
- Failed to describe D meson production in jet using KKK08 FFs
- Leads to new constrain of heavy flavor FFs using measurement of D in jet

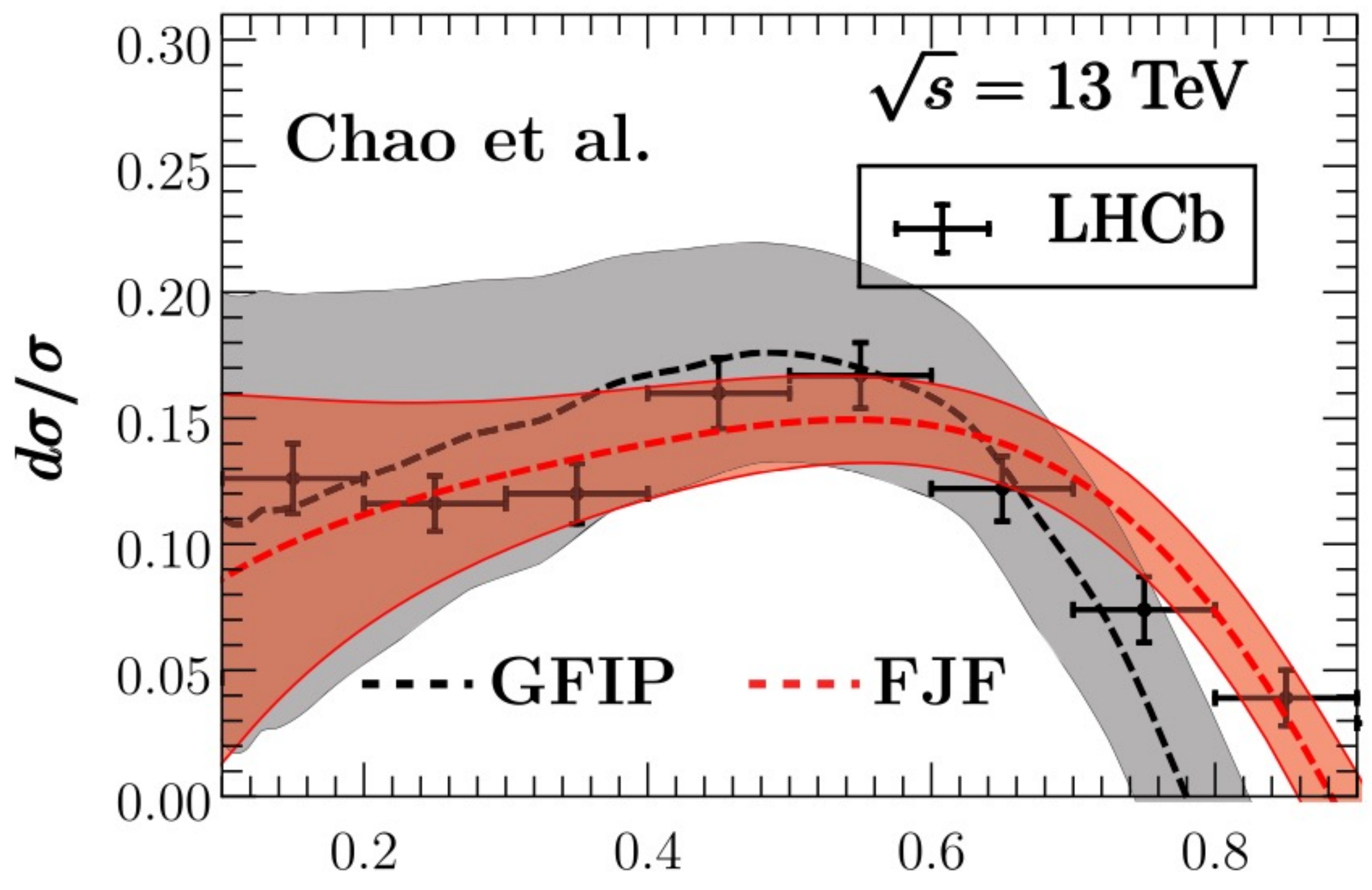
✦ Jet fragmentation function for J/ψ

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

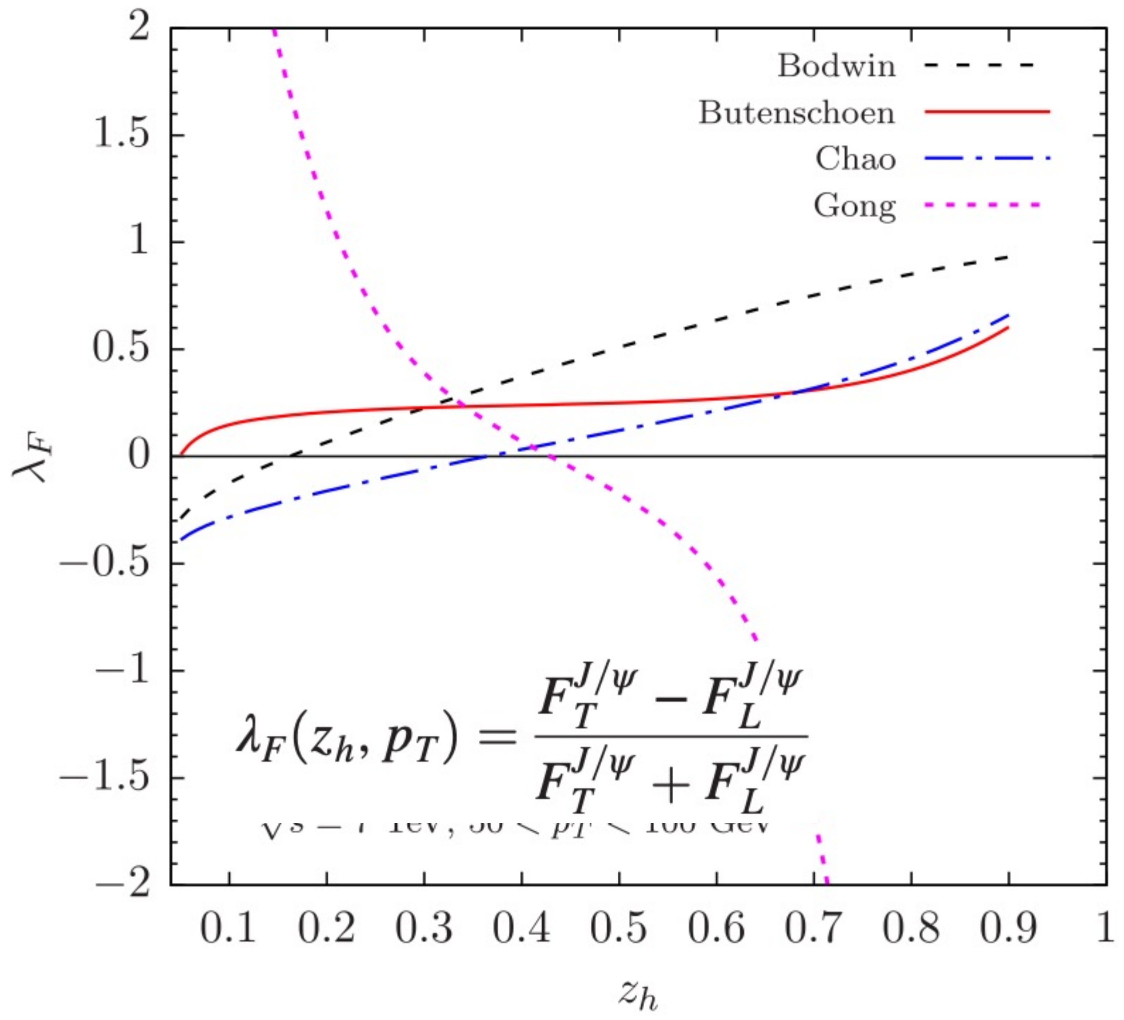
$$\mathcal{G}^{J/\psi}_i(z, z_h, p^+_{\text{jet}}R, \mu) = \sum_j \int_{z_h}^1 \frac{dz'_h}{z'_h} \mathcal{J}_{ij}(z, z_h/z'_h, p^+_{\text{jet}}R, \mu) \times D^{J/\psi}_j(z'_h, \mu) + \mathcal{O}(m^2_{J/\psi}/(p^+_{\text{jet}}R)^2)$$







Bain et al, PRL (2017)



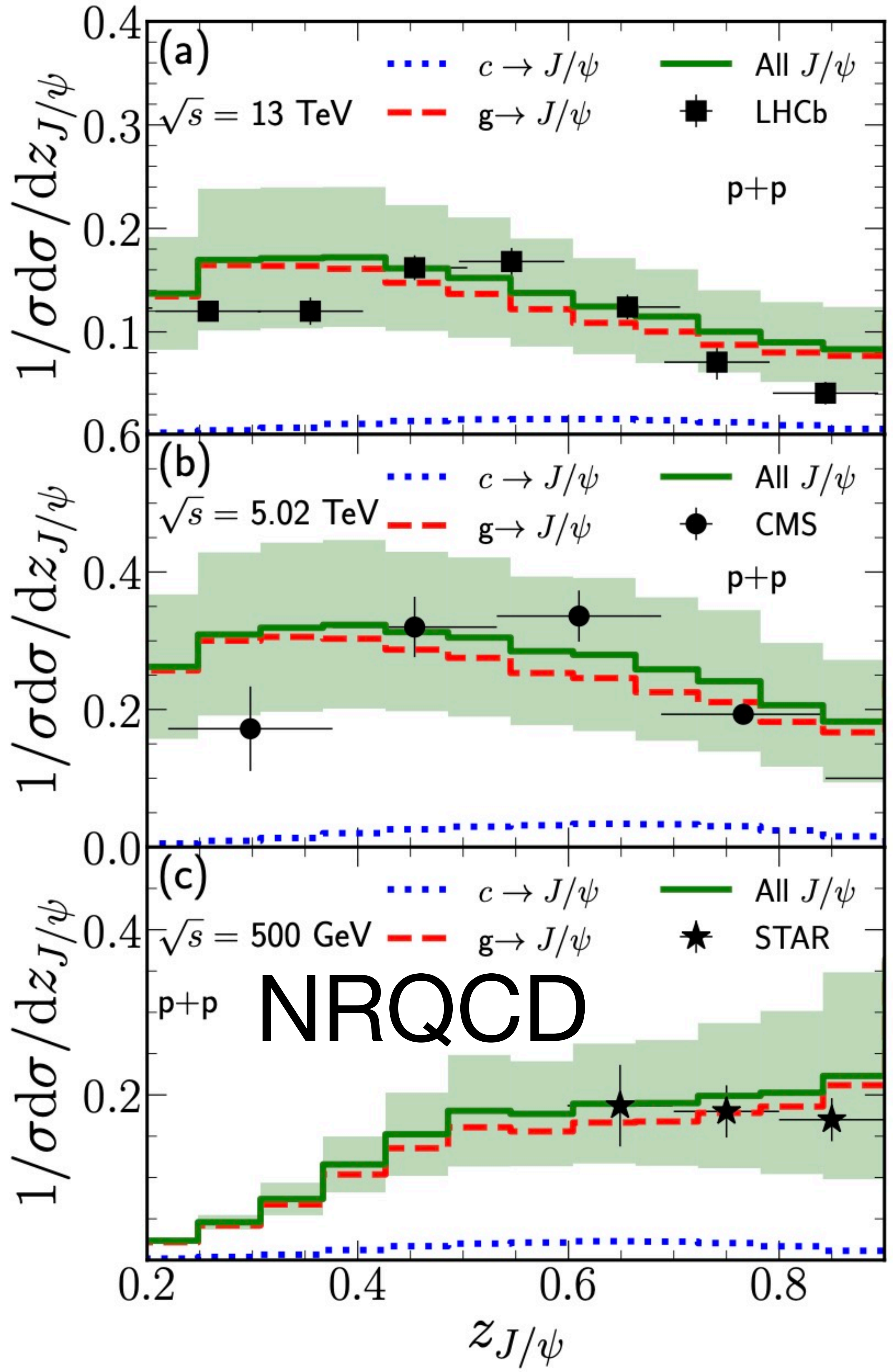
Kang, Qiu, Ringer, **HX**, Zhang PRL (2017)

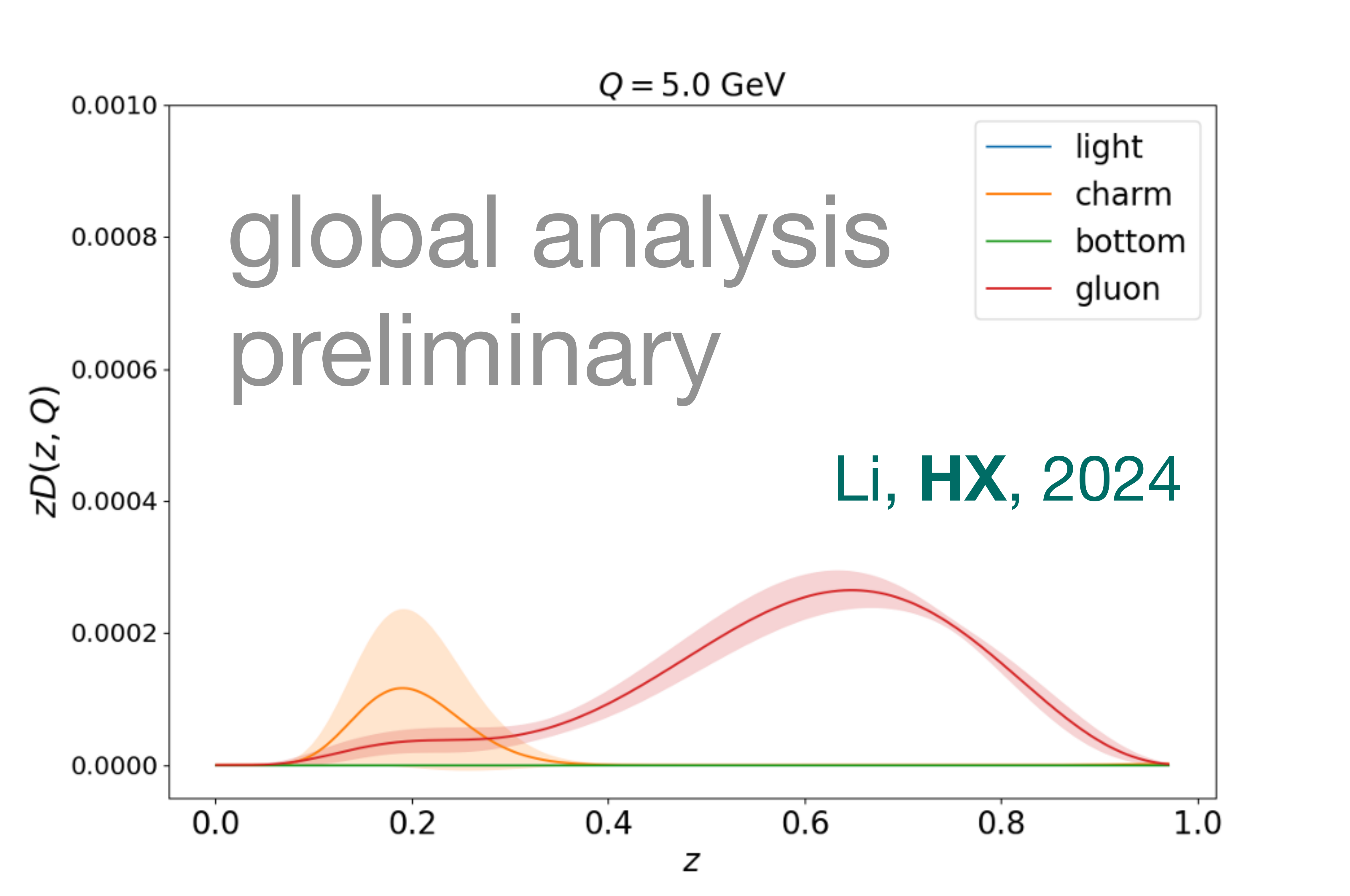
- Disagreement between default Pythia and data
- New insight into the shower mechanism for J/ψ production, and new constrain of LDMEs

Heavy flavor in jet

✦ **Jet fragmentation function for J/ψ at $p_T \gg m$**

Zhang, **HX**, 2403.12704





$$d\sigma[pp \to (\text{jet } J/\psi) + X] = \sum_i d\hat{\sigma}_{pp\to(\text{jet } i)+X} \otimes D_{i\to J/\psi}$$

- Gluon fragmentation dominates high-pt J/ψ production

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

- Joint determination of FFs to charge pion/kaon/proton at NLO
- Strong selection criteria on the kinematics of fragmentation to ensure validity of leading twist factorization
- Parametrization of FFs to charge pion/kaon/proton at initial scale $Q_0 = 5GeV$

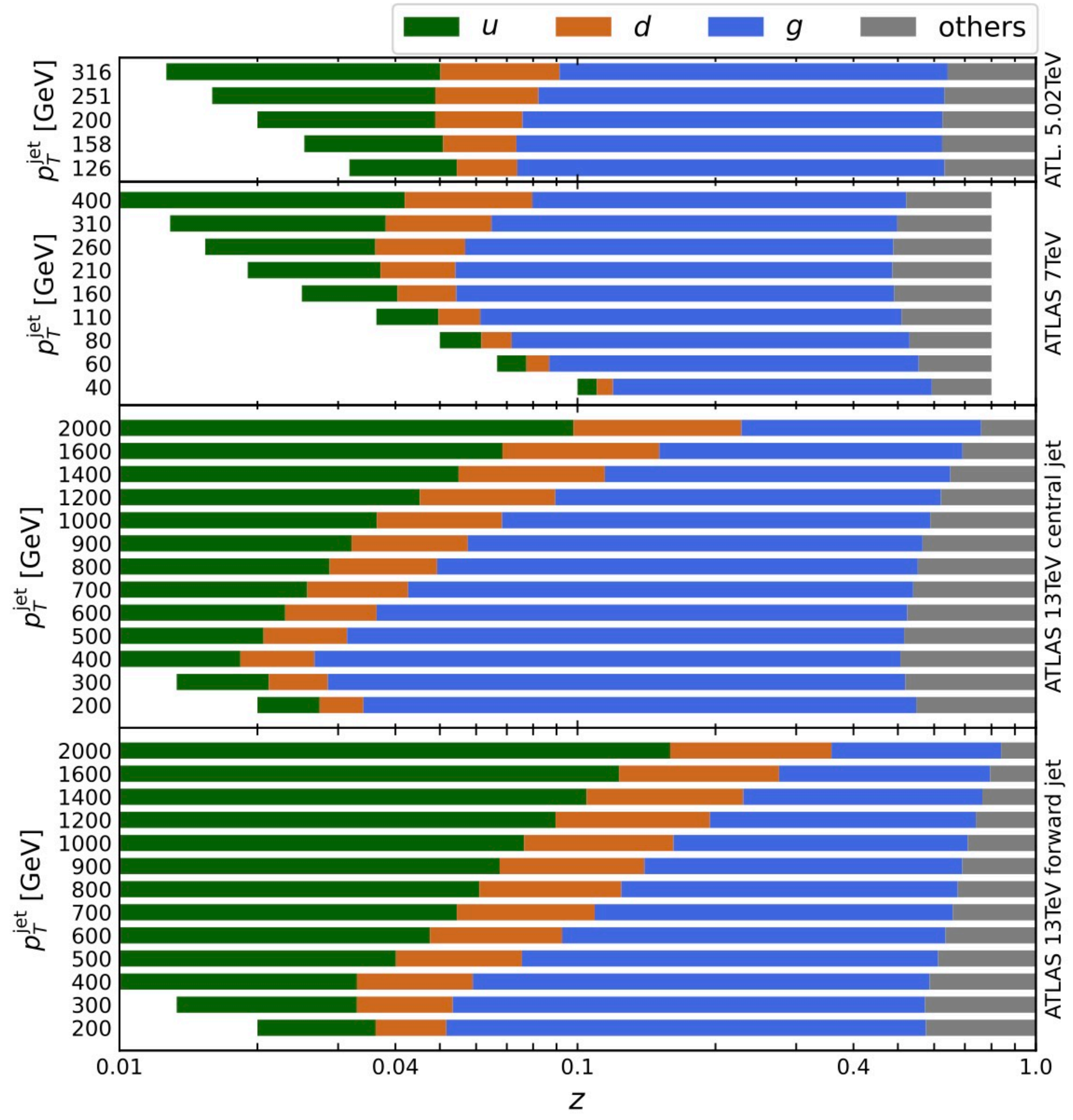
$$zD_i^h(z, Q_0) = z^{\alpha_i^h}(1-z)^{\beta_i^h} \exp\left(\sum_{n=0}^{m} a_{i,n}^h (\sqrt{z})^n\right)$$

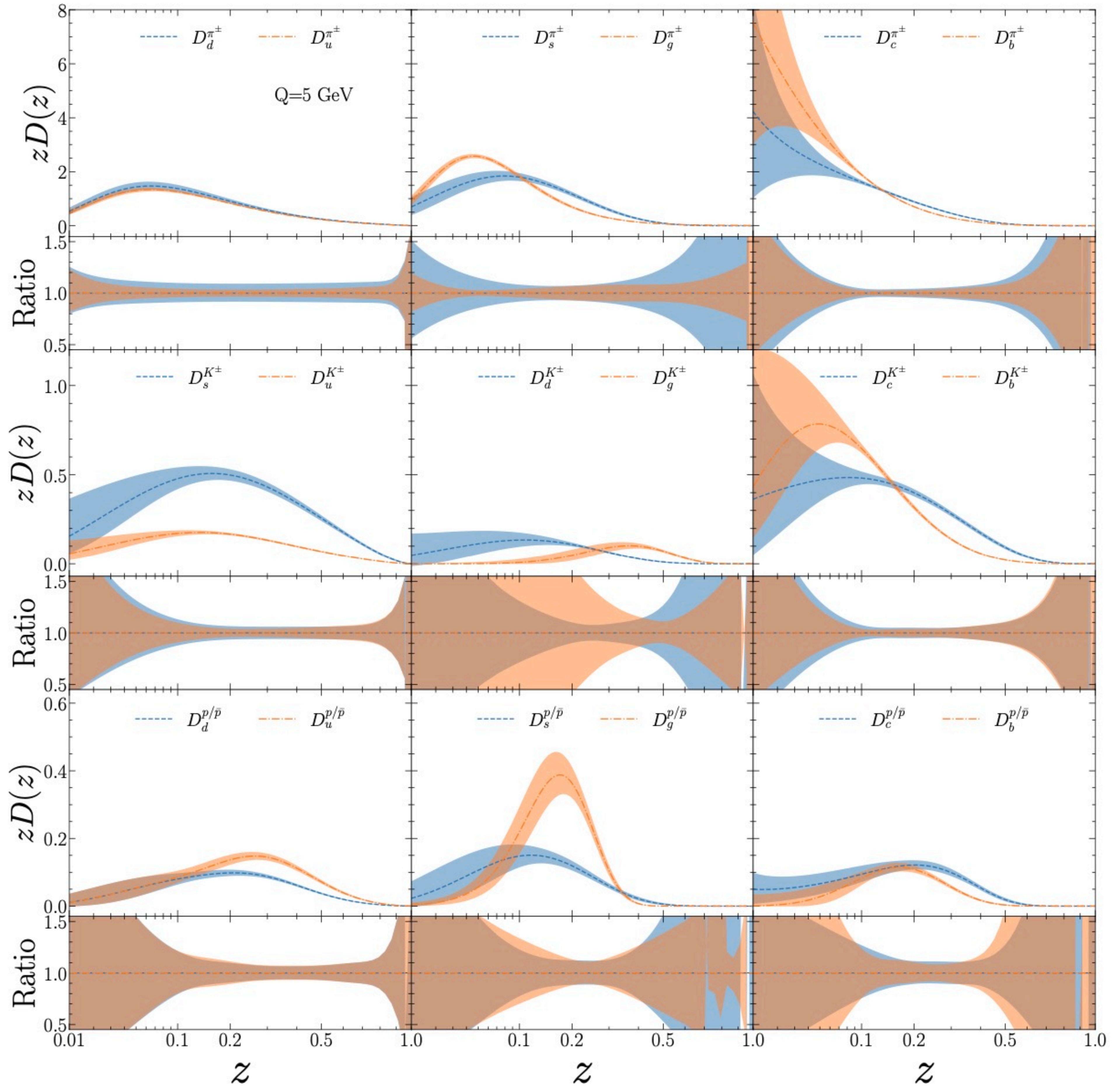
Experiments	N_{pt}	χ^2	χ^2/N_{pt}
ATLAS jets †	446	350.8	0.79
ATLAS $Z/\gamma + \text{jet}$ †	15	31.8	2.12
CMS $Z/\gamma + \text{jet}$ †	15	17.3	1.15
LHCb $Z + \text{jet}$	20	30.6	1.53
ALICE inc. hadron	147	150.6	1.02
STAR inc. hadron	60	42.2	0.70
pp sum	703	623.3	0.89
TASSO	8	7.0	0.88
TPC	12	11.6	0.97
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

New efforts from NPC

✦ NPC23 FFs

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

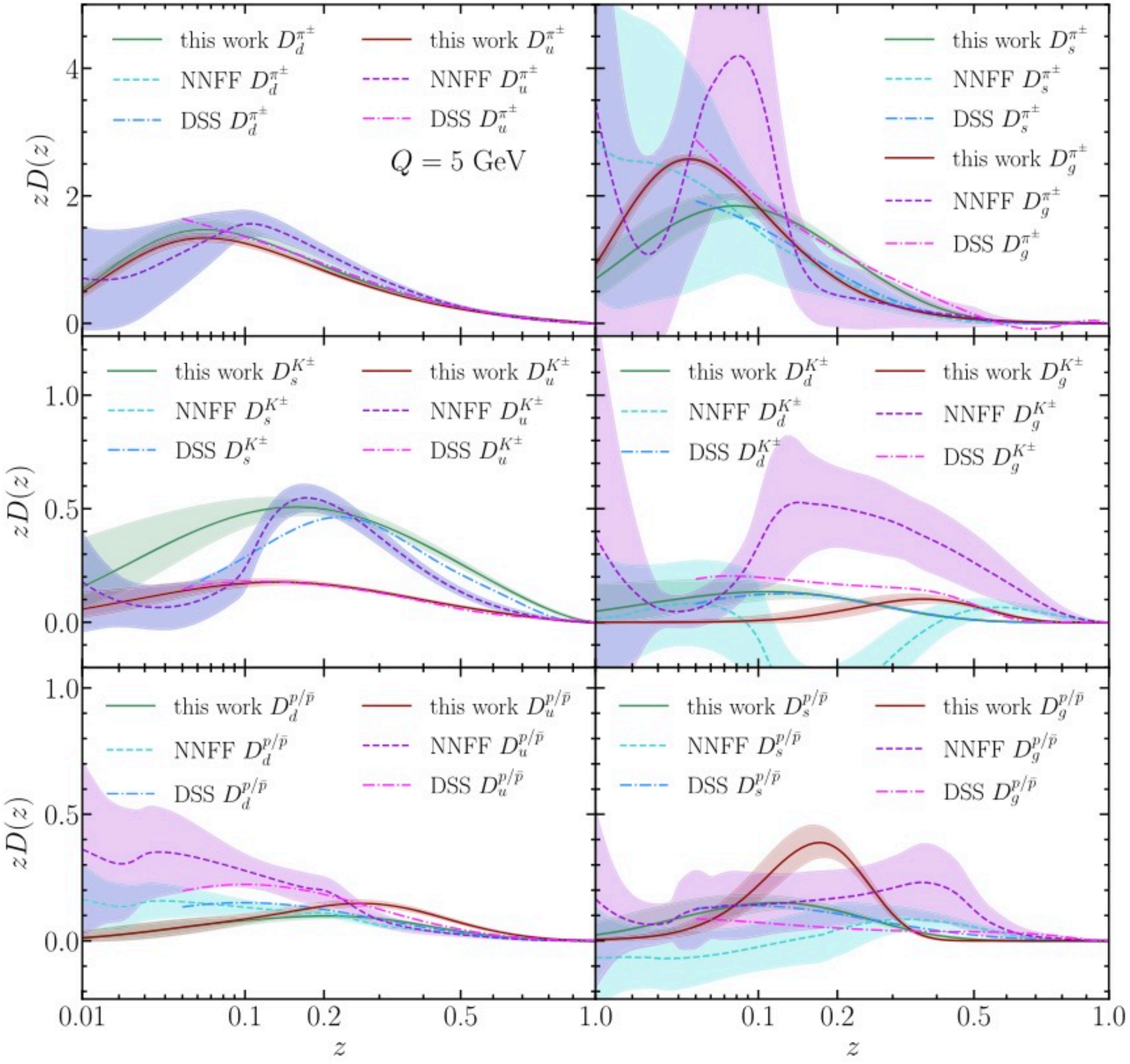




- Higher precision determination of FFs for charged hadron

New efforts from NPC

✦ NPC23 vs. others

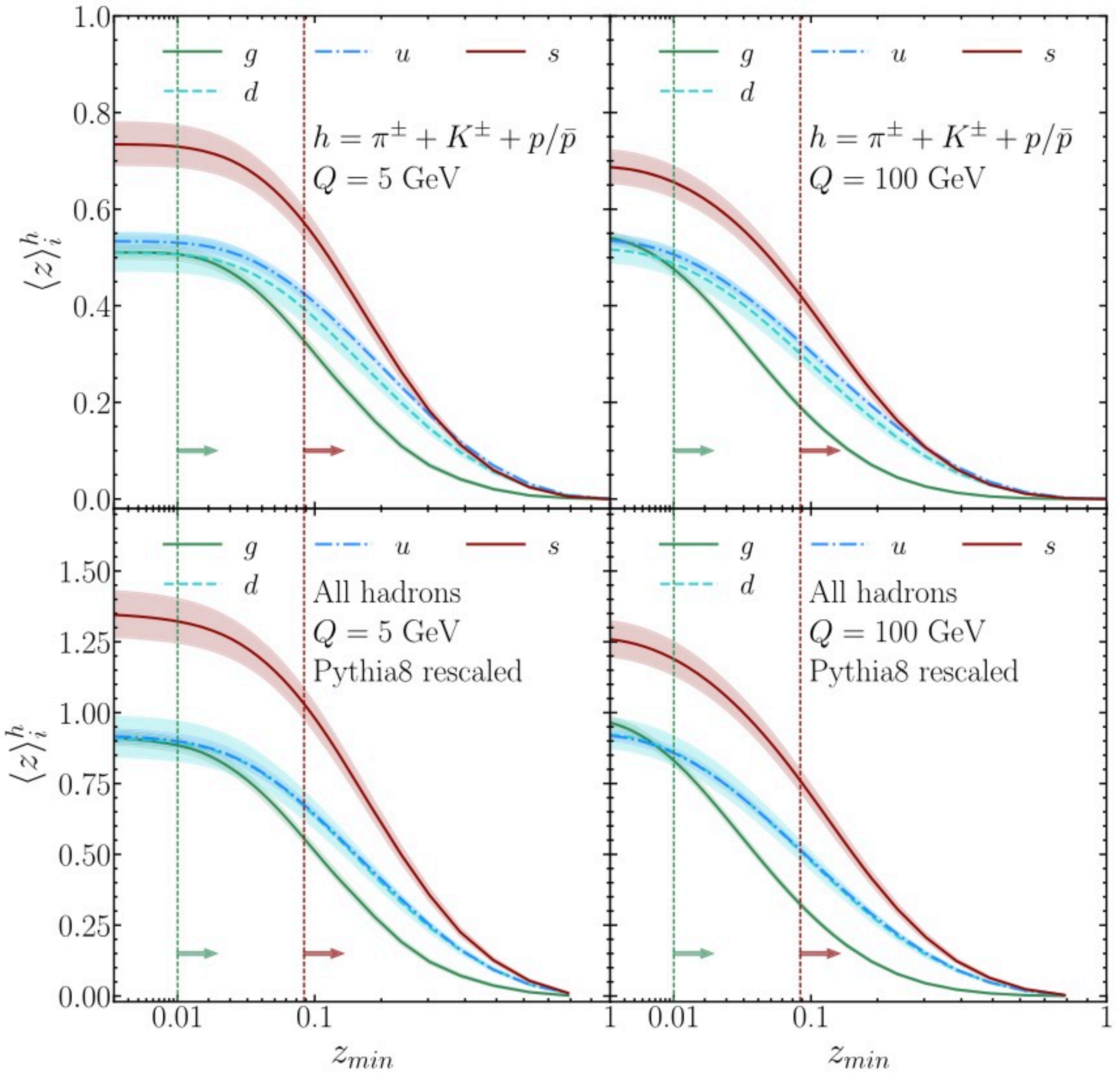


- General agreement for u/d quark to pion
- Discrepancies for FFs to kaon/ proton and gluon FFs
- Future benchmark works involving different groups are needed to clarify the discrepancies

New efforts from NPC

✦ momentum sum rule

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

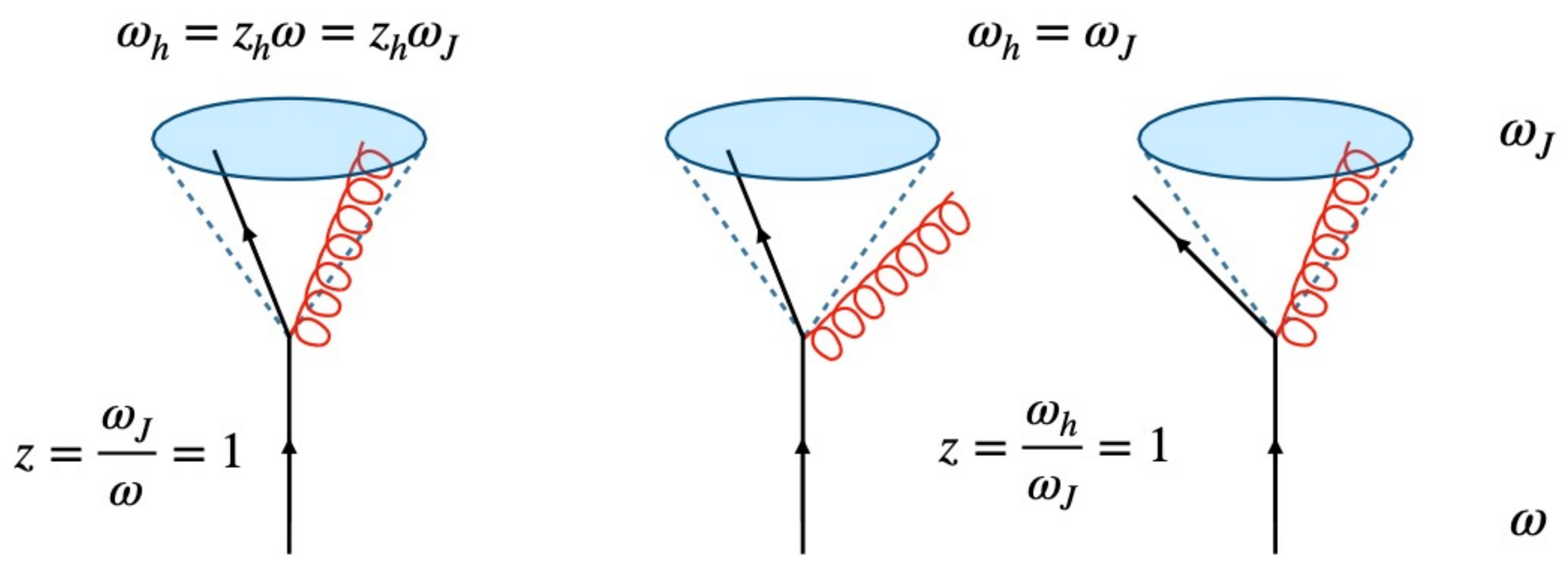


$\langle z \rangle_i^h$	$g(z > 0.01)$	$u(z > 0.01)$	$d(z > 0.01)$	$s(z > 0.088)$
π^+	$0.200^{+0.008}_{-0.008}$	$0.262^{+0.017}_{-0.016}$	$0.128^{+0.020}_{-0.019}$	$0.161^{+0.013}_{-0.013}$
K^+	$0.018^{+0.004}_{-0.003}$	$0.058^{+0.005}_{-0.004}$	$0.019^{+0.004}_{-0.004}$	$0.015^{+0.002}_{-0.002}$
p	$0.035^{+0.006}_{-0.005}$	$0.044^{+0.004}_{-0.004}$	$0.022^{+0.002}_{-0.002}$	$0.015^{+0.002}_{-0.002}$
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?

✦ A comprehensive analysis for jet fragmentation functions



		Quark polarization		
		U	L	T
Hadron polarization	U	$\mathcal{D}_1 =$		$\mathcal{H}_1^\perp =$ −
	L		$\mathcal{G}_{1L} =$ −	$\mathcal{H}_{1L}^\perp =$ −
	T	$\mathcal{D}_{1T}^\perp =$ −	$\mathcal{G}_{1T} =$ −	$\mathcal{H}_1 =$ − $\mathcal{H}_{1T}^\perp =$ −

Kang, **HX**, Zhao, Zhou, JHEP, 2024

- Collinear fragmenting jet function in semi-inclusive jet production

$$\Delta_{(T)}\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \Delta_{(T)}\mathcal{J}_{ij}(z, z_h', \omega_J, \mu) \Delta_{(T)} D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

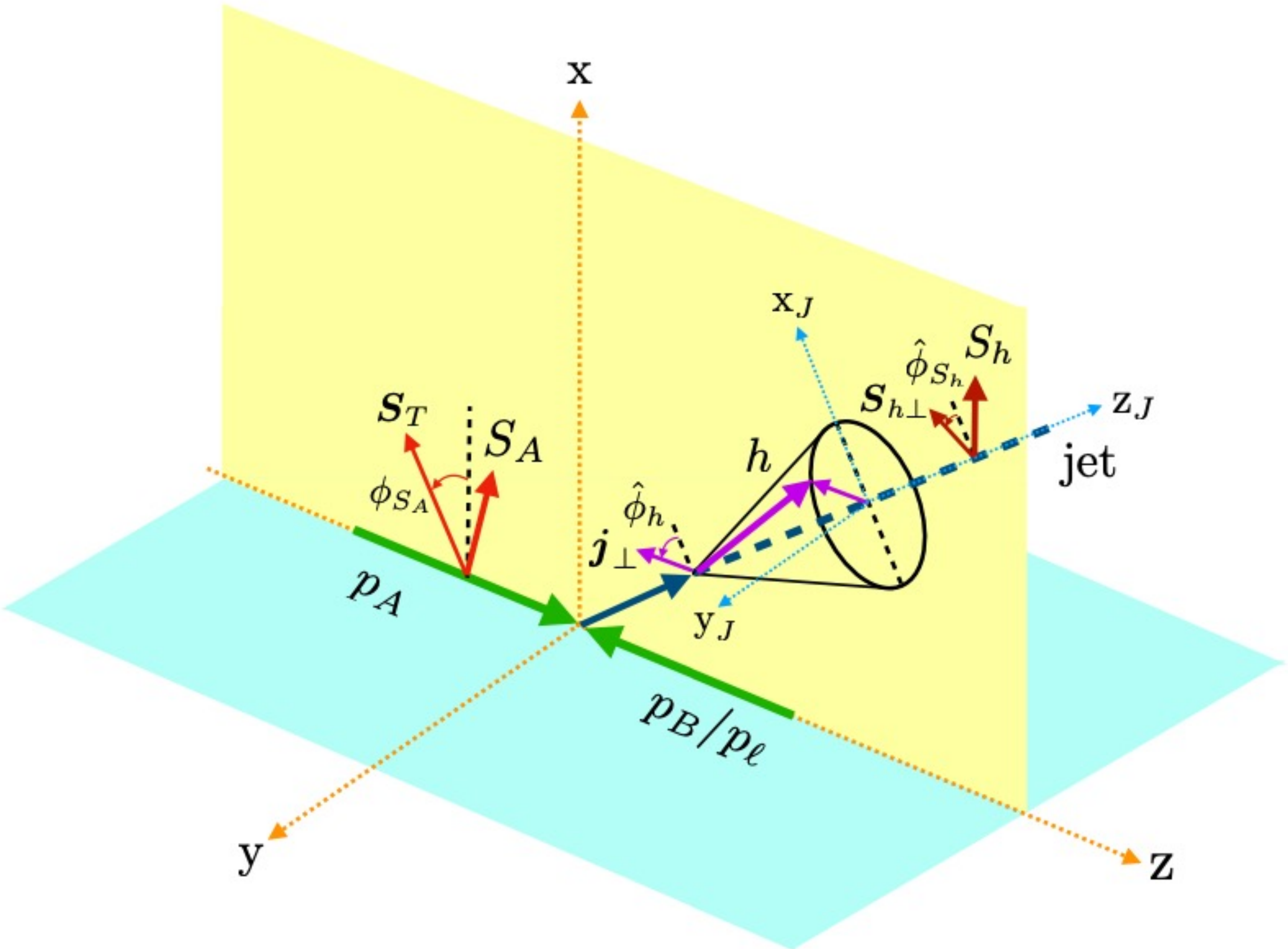
- An alternative way to explore different types of FFs
- Similar FJFs can be defined in exclusive jet production

Parton to hadron fragmentation in jet

✦ single inclusive jet production in hadronic collisions

Kang, **HX**, Zhao, Zhou, 2024

$$
\begin{aligned}
\frac{\mathrm{d}\sigma^{p(S_A)+p\to \mathrm{jet}\,h(S_h)\,X}}{\mathrm{d}\eta\,\mathrm{d}^2\boldsymbol{p}_T\,\mathrm{d}z_h\,\mathrm{d}^2\boldsymbol{j}_\perp} = {} & F_{UU,U} + |\boldsymbol{S}_T|\sin(\phi_{S_T}-\phi_h)F_{TU,U}^{\sin(\phi_{S_T}-\phi_h)} \\
& + \Lambda_h\Big[\lambda F_{LU,L} + |\boldsymbol{S}_T|\cos(\phi_{S_T}-\phi_h)F_{TU,L}^{\cos(\phi_{S_T}-\phi_h)}\Big] \\
& + |\boldsymbol{S}_{h_T}|\Big[\sin(\phi_h-\phi_{S_h})F_{UU,T}^{\sin(\phi_h-\phi_{S_h})} + \lambda\cos(\phi_h-\phi_{S_h})F_{LU,T}^{\cos(\phi_h-\phi_{S_h})} \\
& \quad + |\boldsymbol{S}_T|\Big(\cos(\phi_{S_T}-\phi_{S_h})F_{TU,T}^{\cos(\phi_{S_T}-\phi_{S_h})} \\
& \quad\quad + \cos(2\phi_h-\phi_{S_T}-\phi_{S_h})F_{TU,T}^{\cos(2\phi_h-\phi_{S_T}-\phi_{S_h})}\Big)\Big], \qquad (4.11)
\end{aligned}
$$



- Unpolarized case as an example

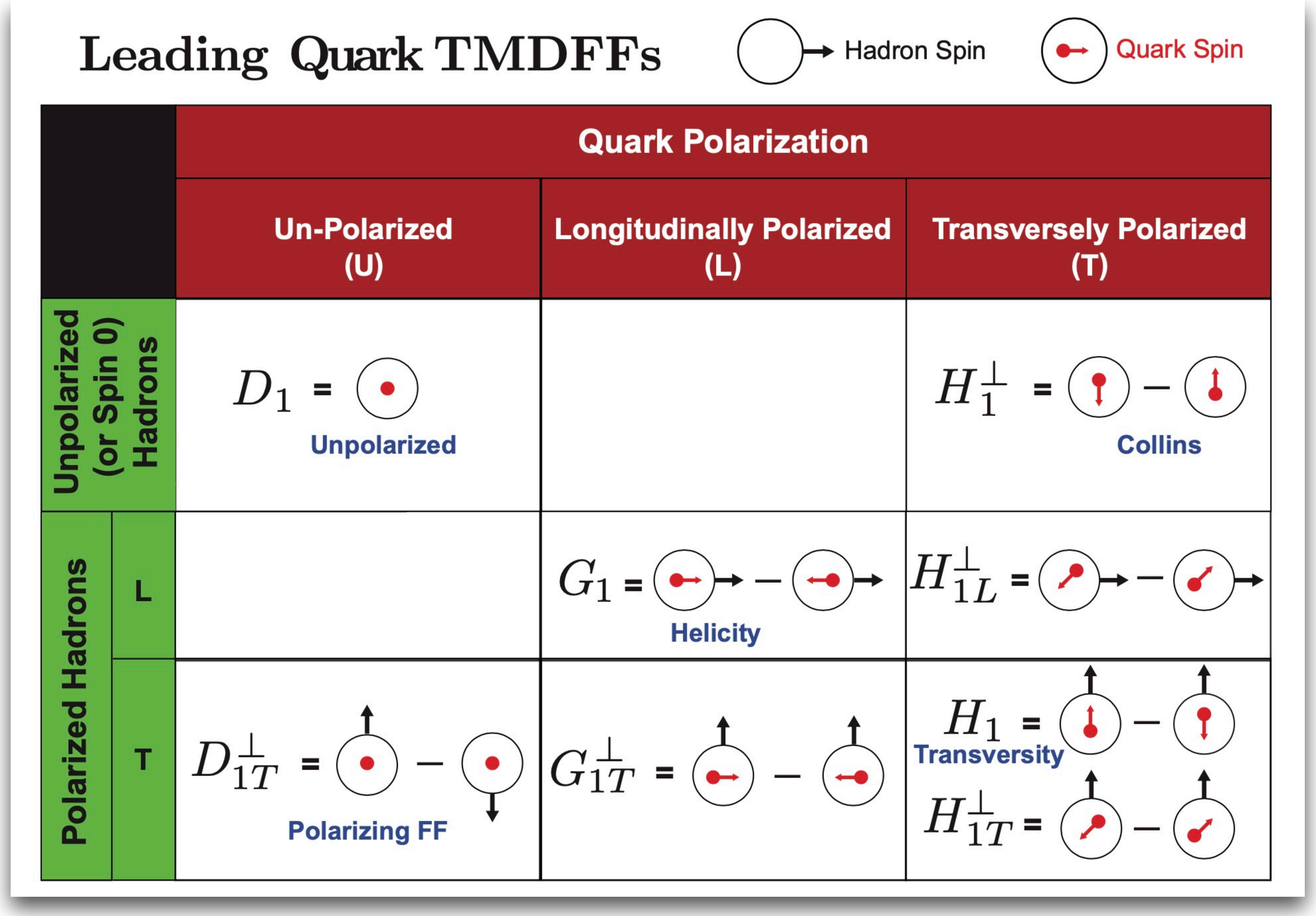
$$
\begin{aligned}
F_{UU,U}(z_h, j_\perp) = {} & \frac{\alpha_s^2}{s}\sum_{a,b,c}\int_{x_1^{\min}}^1 \frac{\mathrm{d}x_1}{x_1} f_1^{a/A}(x_1,\mu)\int_{x_2^{\min}}^1 \frac{\mathrm{d}x_2}{x_2} f_2^{b/B}(x_2,\mu) \\
& \times \int_{z^{\min}}^1 \frac{\mathrm{d}z}{z^2}\hat{H}_{ab}^c(\hat{s},\hat{p}_T,\hat{\eta},\mu)\mathcal{D}_1^{h/c}(z, z_h, j_\perp^2, Q) \\
\equiv {} & \mathcal{C}\big[f\,f\,\mathcal{D}_1\hat{H}\big],
\end{aligned}
$$

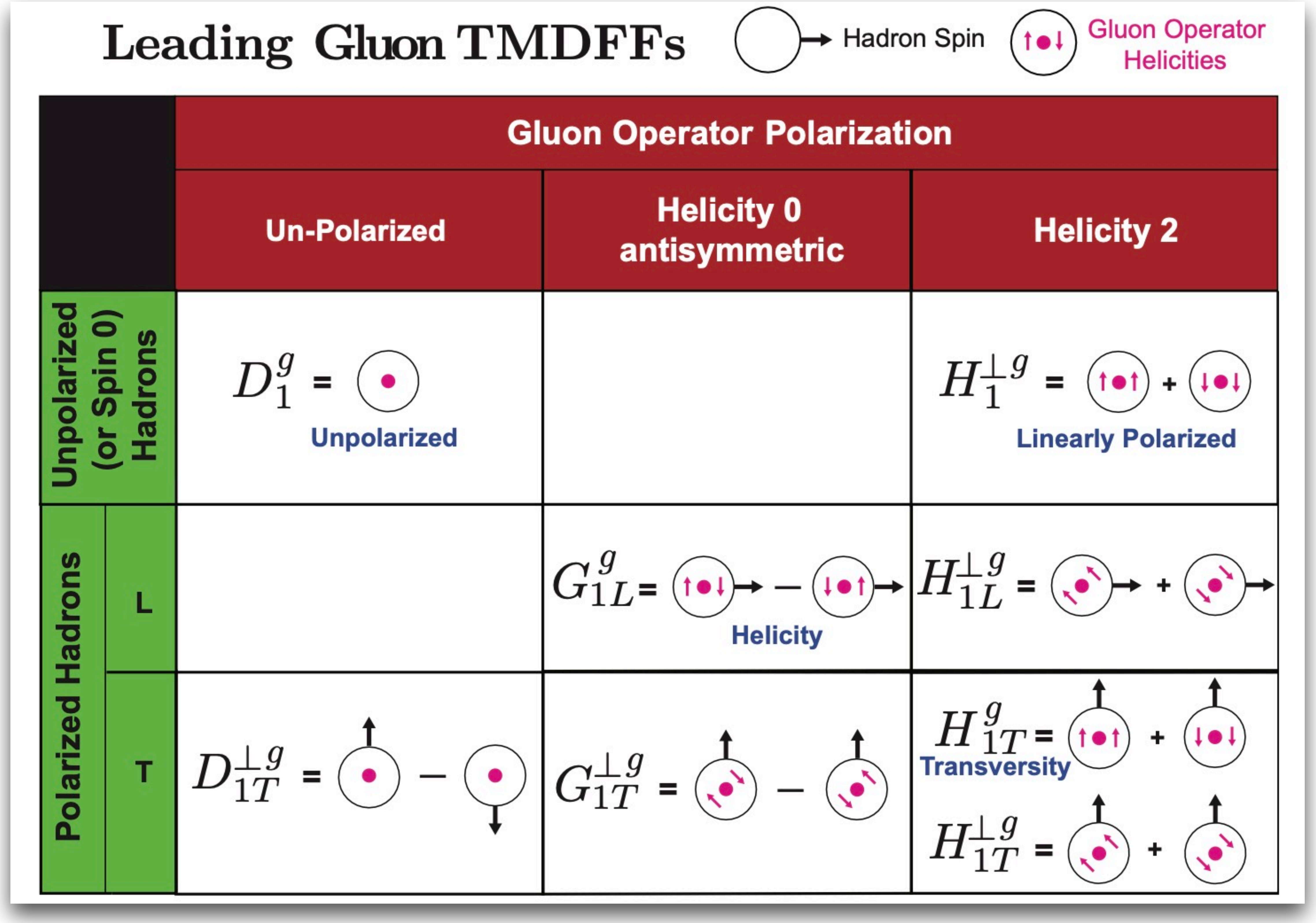
$$
\mathcal{D}_1^{h/c}(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \hat{\mathcal{C}}_{c\to i}^U(z, \omega_J R, \mu)\int\frac{\mathrm{d}^2\boldsymbol{b}}{(2\pi)^2}e^{i\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_h}\widetilde{D}_1^{h/i}(z_h, \boldsymbol{b}, \mu_J, \nu)\widetilde{S}_i(\boldsymbol{b}, \mu_J, \nu R)
$$

$$
\begin{aligned}
F_{TU,U}^{\sin(\phi_S-\phi_h)}(z_h, j_\perp) &= \mathcal{C}\Big[\frac{j_\perp}{z_h M_h}h_1 f_1 \mathcal{H}_1^\perp \Delta_T\hat{H}\Big], \\
F_{LU,L}(z_h, j_\perp) &= \mathcal{C}\big[g_{1L} f_1 \mathcal{G}_{1L}\Delta_L\hat{H}\big], \\
F_{TU,L}^{\cos(\phi_S-\phi_h)}(z_h, j_\perp) &= -\mathcal{C}\Big[\frac{j_\perp}{z_h M_h}h_1 f_1 \mathcal{H}_{1L}^\perp \Delta_T\hat{H}\Big], \\
F_{UU,T}^{\sin(\phi_h-\phi_{S_h})}(z_h, j_\perp) &= -\mathcal{C}\Big[\frac{j_\perp}{z_h M_h}f_1 f_1 \mathcal{D}_{1T}^\perp \hat{H}\Big], \\
F_{LU,T}^{\cos(\phi_h-\phi_{S_h})}(z_h, j_\perp) &= -\mathcal{C}\Big[\frac{j_\perp}{z_h M_h}g_{1L} f_1 \mathcal{G}_{1T}\Delta_L\hat{H}\Big], \\
F_{TU,T}^{\cos(\phi_S-\phi_{S_h})}(z_h, j_\perp) &= \mathcal{C}\big[h_1 f_1 \mathcal{H}_1\Delta_T\hat{H}\big], \\
F_{TU,T}^{\cos(2\phi_h-\phi_S-\phi_{S_h})}(z_h, j_\perp) &= -\mathcal{C}\Big[\frac{j_\perp^2}{2z_h^2 M_h^2}h_1 f_1 \mathcal{H}_{1T}^\perp\Delta_T\hat{H}\Big].
\end{aligned}
$$

Transverse momentum dependent FFs

- ✦ **FFs: 8 transverse momentum dependent FFs at leading twist**





Testing leading power QCD factorization

- ✦ **What's the boundary for Q^2 to ensure the validity of leading twist QCD factorization?**

- ✦ **Generalized factorization theorem**

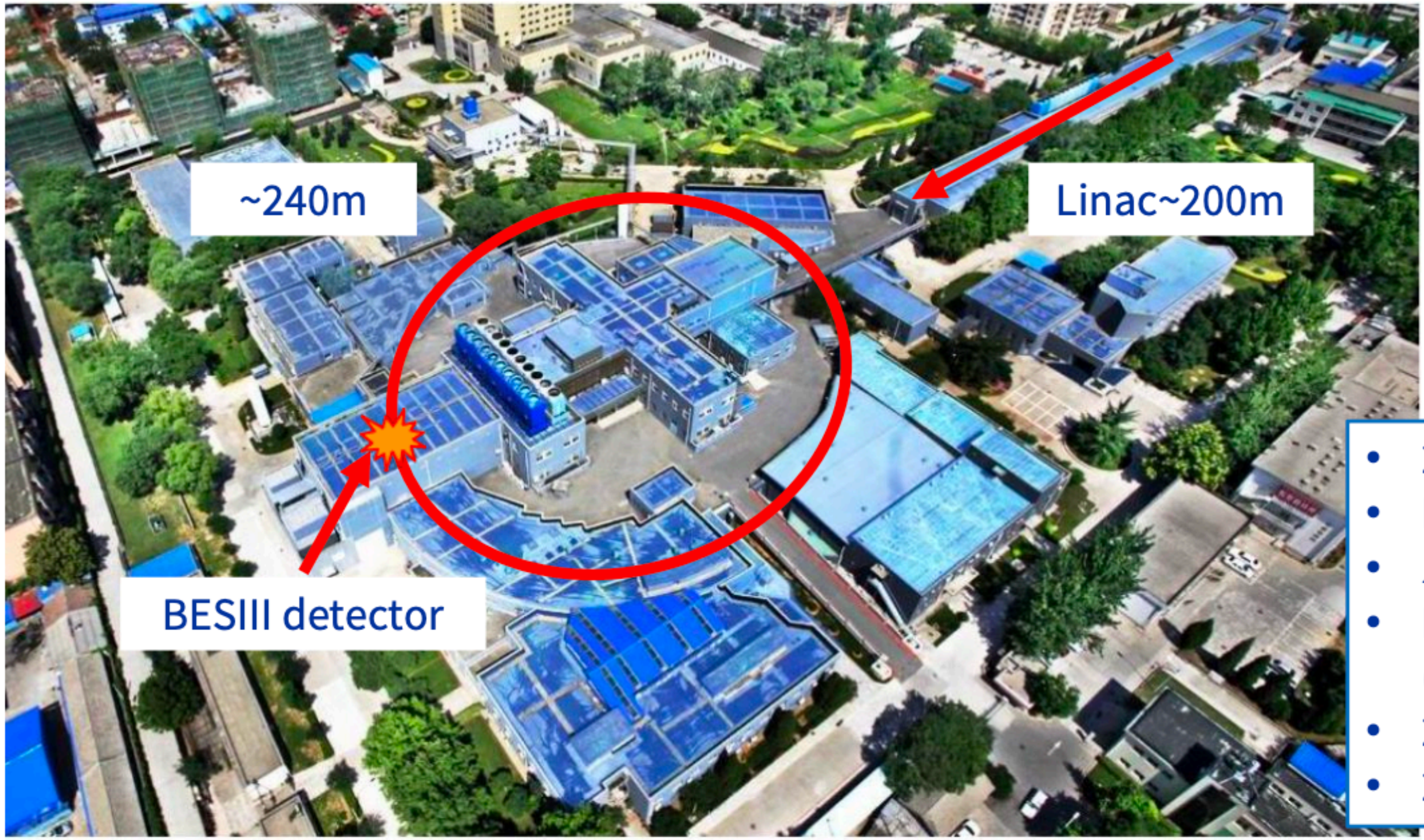
perturbative expansion →

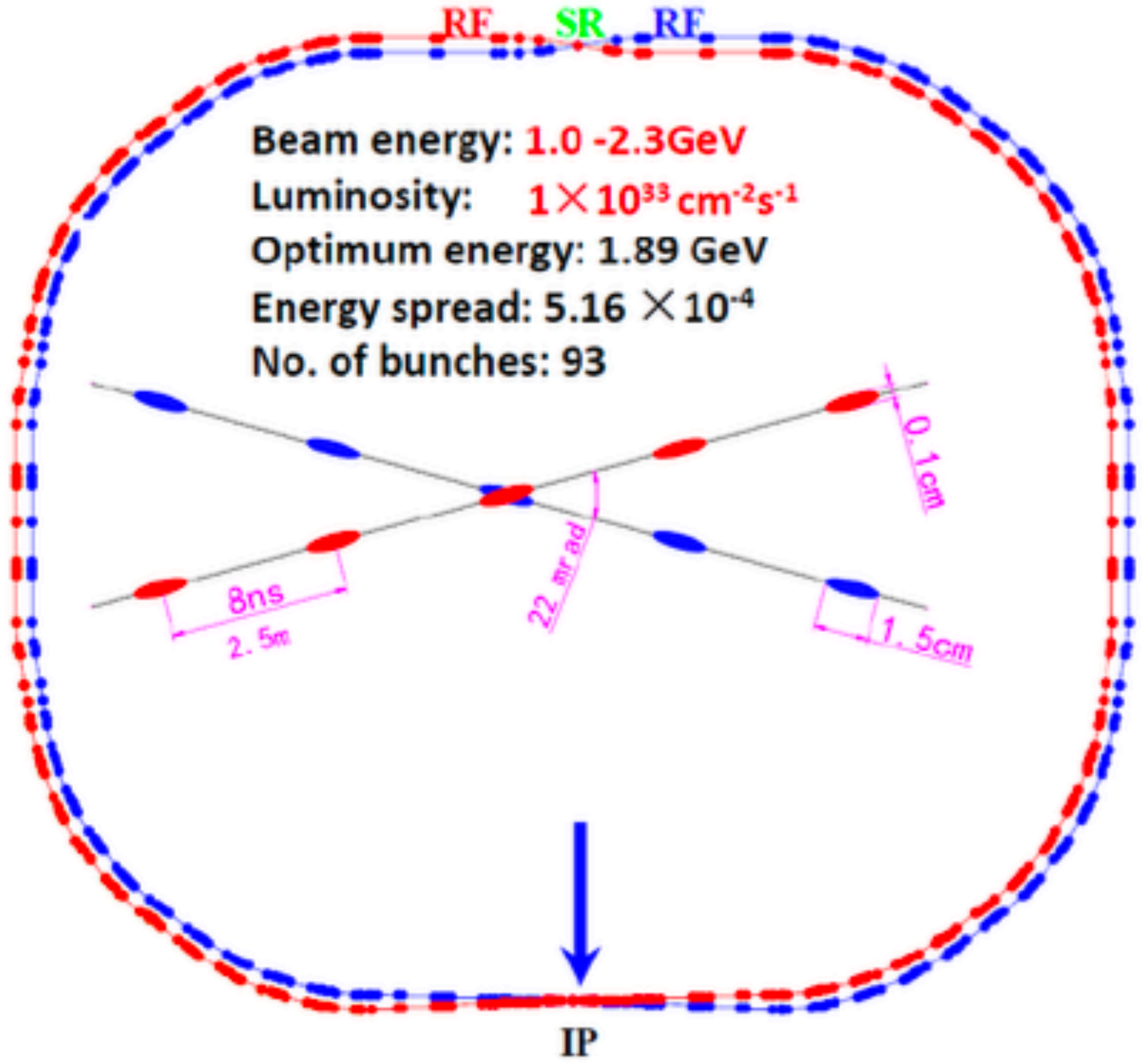
twist expansion ↓

$$
\begin{aligned}
\sigma^h_{phys} = & \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x) \\
& + \frac{1}{Q}\left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x) \\
& + \frac{1}{Q^2}\left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x) \\
& + \ldots
\end{aligned}
$$

Beijing Electron Positron Collider (BEPCII)

World unique e^+e^- accelerator in charm physics energy region



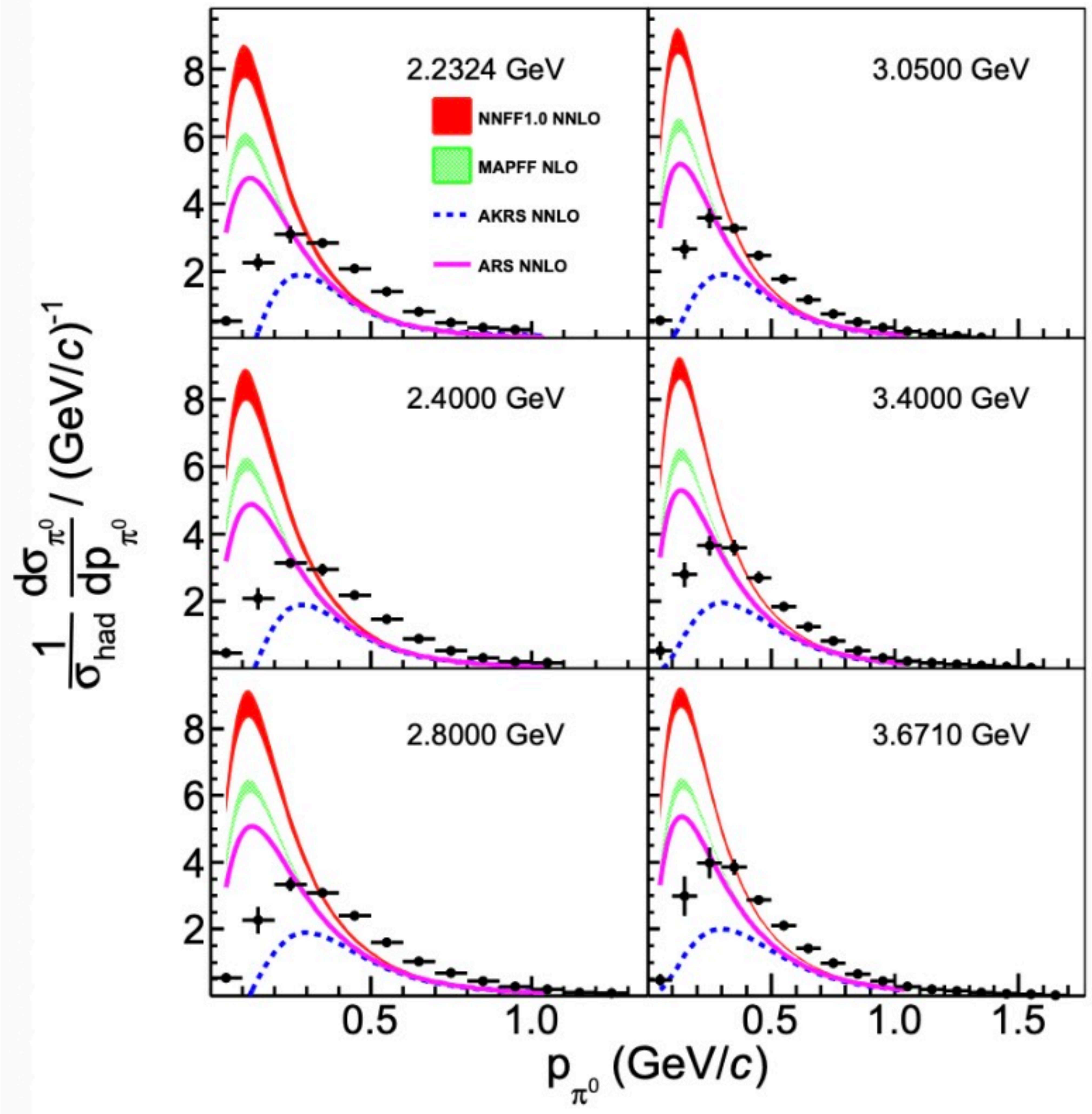


- 2004: started BEPCII/BESIII construction
- Double rings
- $E_{cm} = 2.0{\sim}4.6$ (4.9 since 2019) GeV
- Design luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$ (reached 2016 @$E_{cm} = 3.77$ GeV)
- 2008: test run
- 2009~ today: BESIII physics runs

Test leading power QCD factorization at BES

Predictions on low-z and low-Q^2 do not agree with data and depend on chosen FFs:

BESIII, PRL 2023



Data input, initial evolution scale μ_0 and kinematical cuts are different for the FFs.

NNLO (SIA data only)

ARS → Fixed order calculation

AKRS → Includes small-z resum.

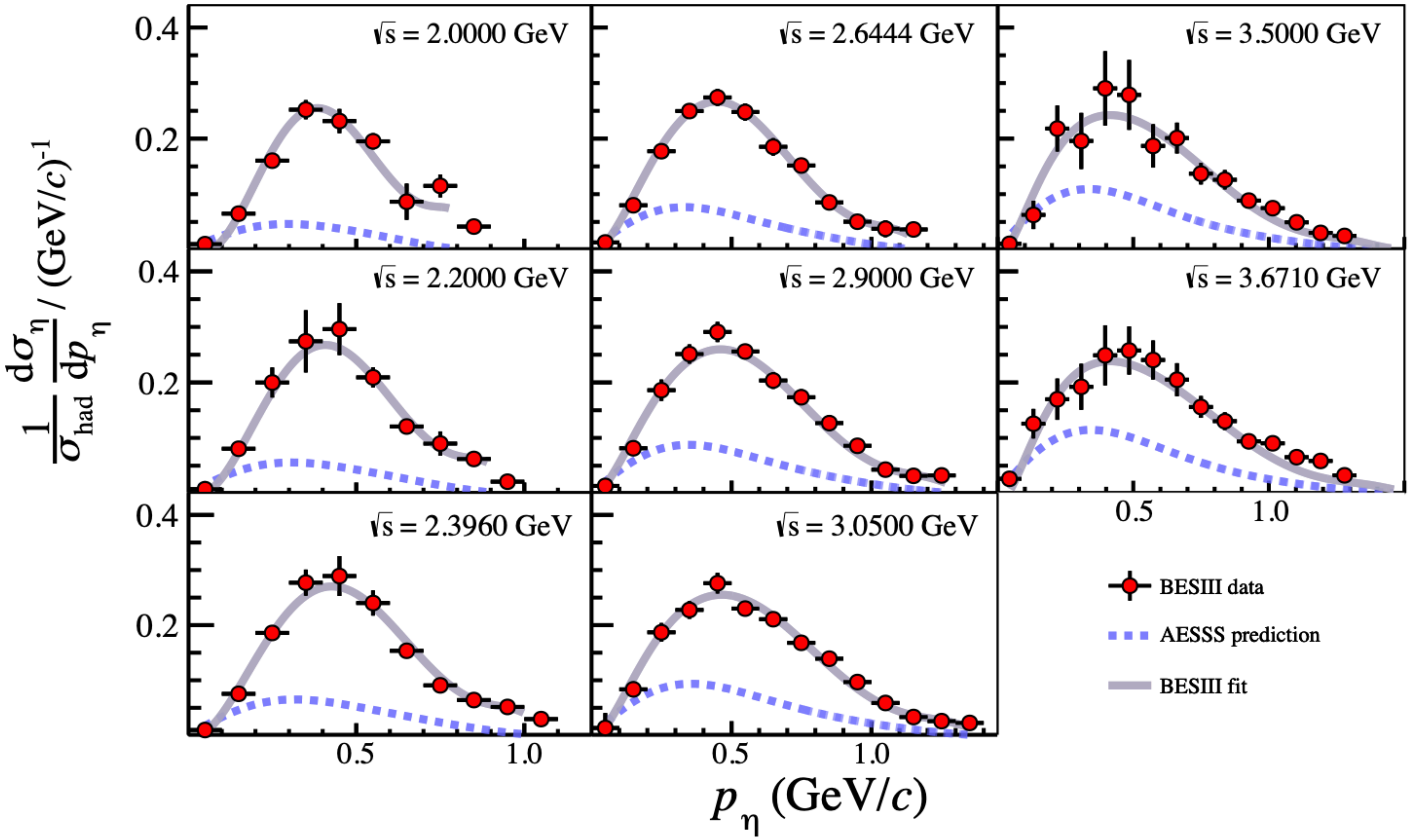
NNFF1.0 → Includes hadron mass effects

NLO

MAPFF → Includes low energy SIDIS data

Testing leading power QCD factorization at BES/STCF

✦ A test from data driving analysis of high twist contribution



$$\sigma \approx \sigma^{LT}\left[1+\sum_i N_i \frac{x^{a_i}(1-x)^{b_i}}{Q^{2i}}\right]$$

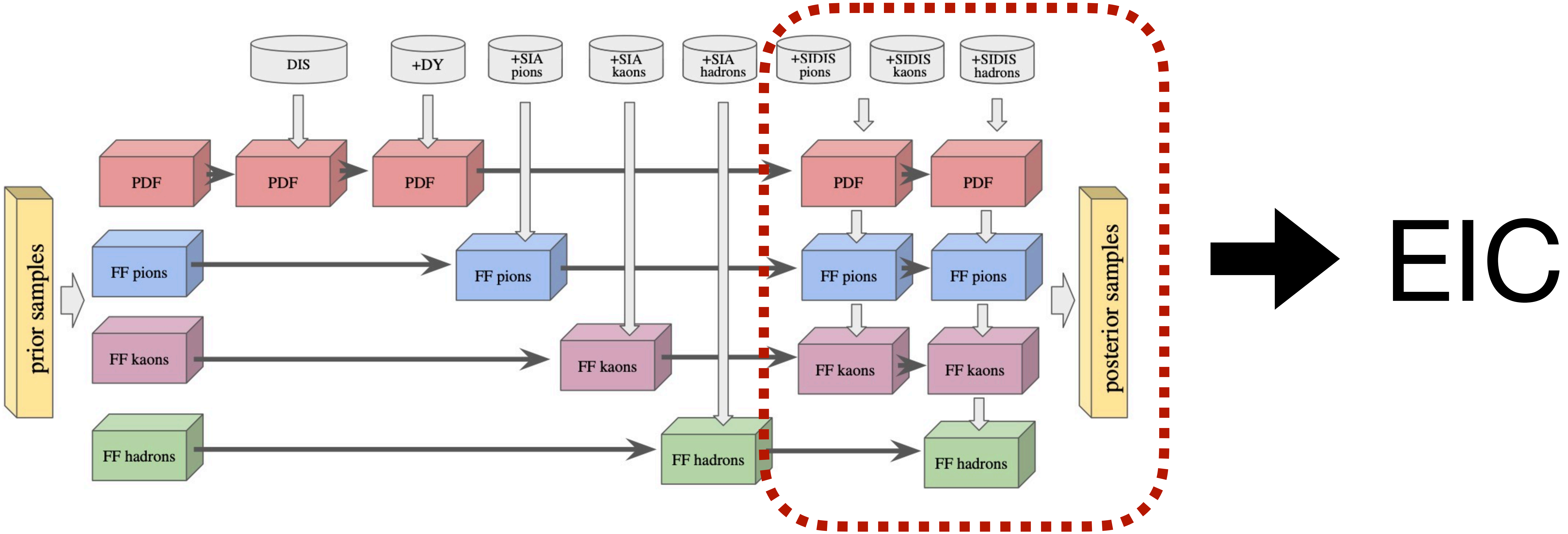
- Hint of leading twist factorization breaking?

BESIII + Li, **HX,** PRL, 2024

Li, Anderle, **HX**, Zhao, 2024.11527

✦ Probe the nucleon structure

JAM, PRD 2021



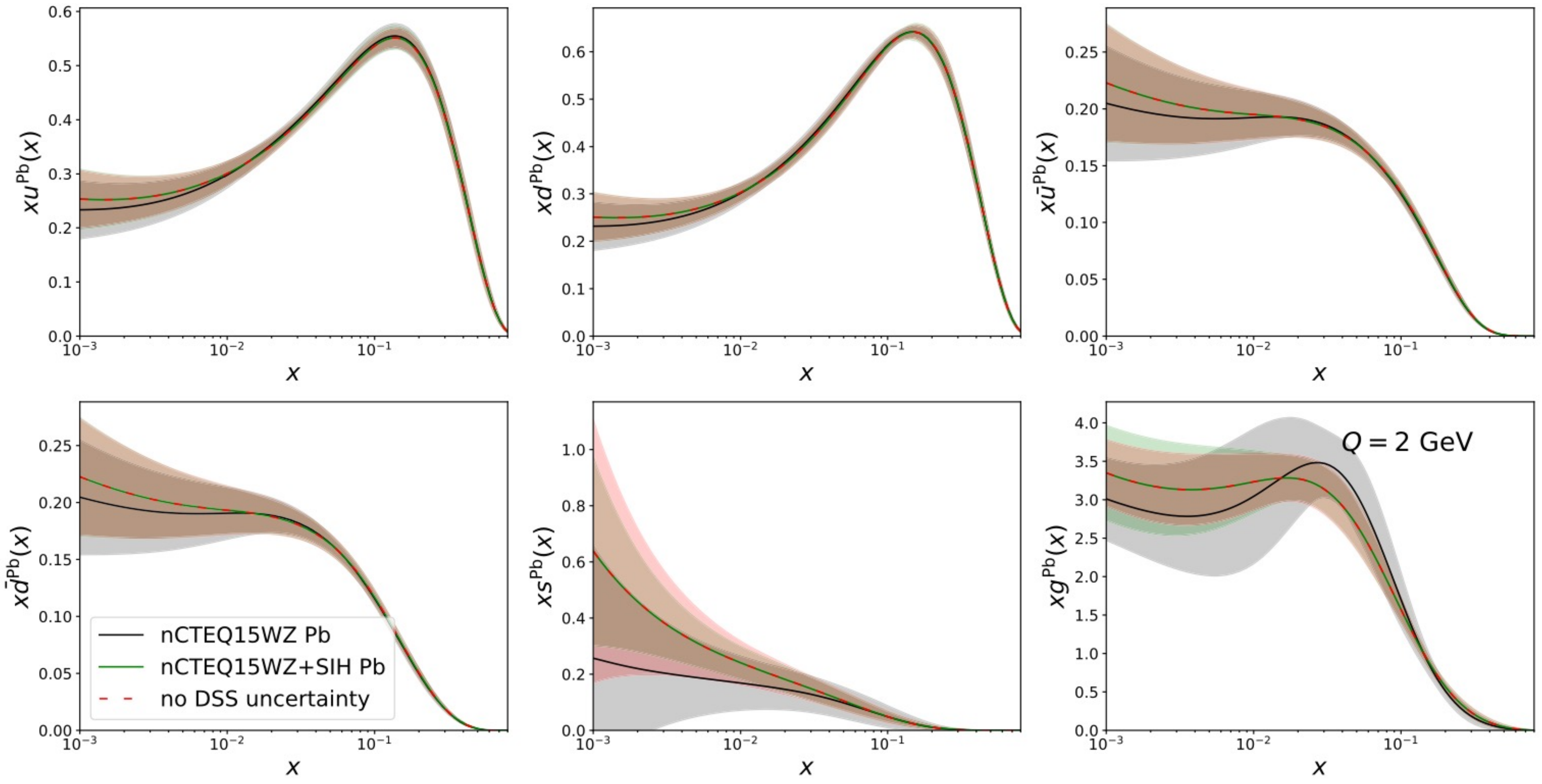
$$\sigma^{lp\to l'hX} = f_{i/p} \otimes \hat{\sigma}_{li\to j} \otimes D_{j\to h}$$

A simultaneous fit of PDF and FF can provide further constrain for flavor separation

FFs as a tool to probe nuclear PDFs

✦ **Inclusive hadron production in p+Pb collisions**

Duwentaster et al, PRD 2021

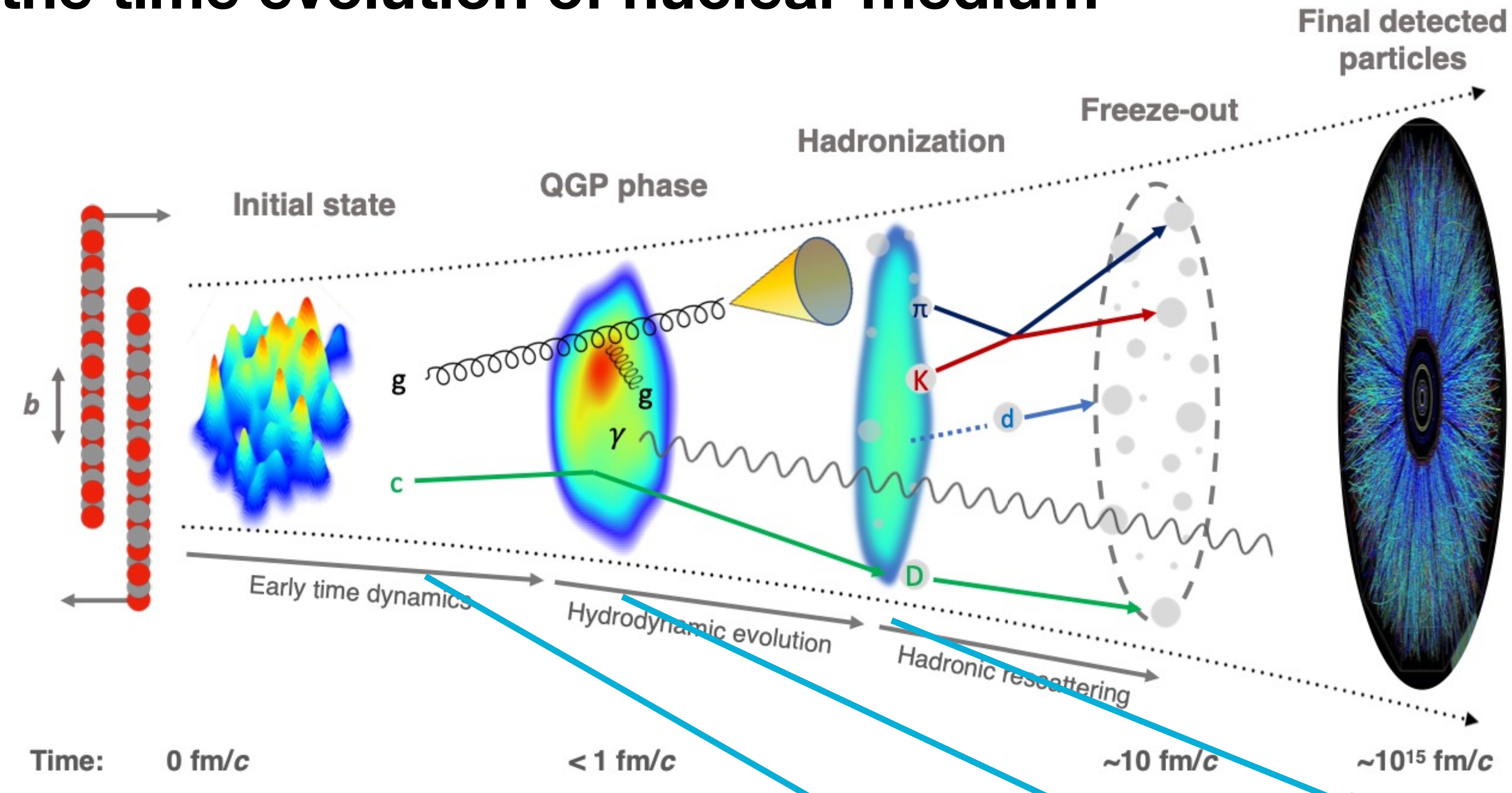


$$\sigma^{pPb\to hX} = f_{i/p} \otimes f_{j/Pb} \otimes \hat{\sigma}_{ij\to k} \otimes D_{k\to h}$$

Precise information of FF is helpful for nuclear PDF determination

FFs as a tool to probe hot dense medium

✦ **Track the time evolution of nuclear medium**



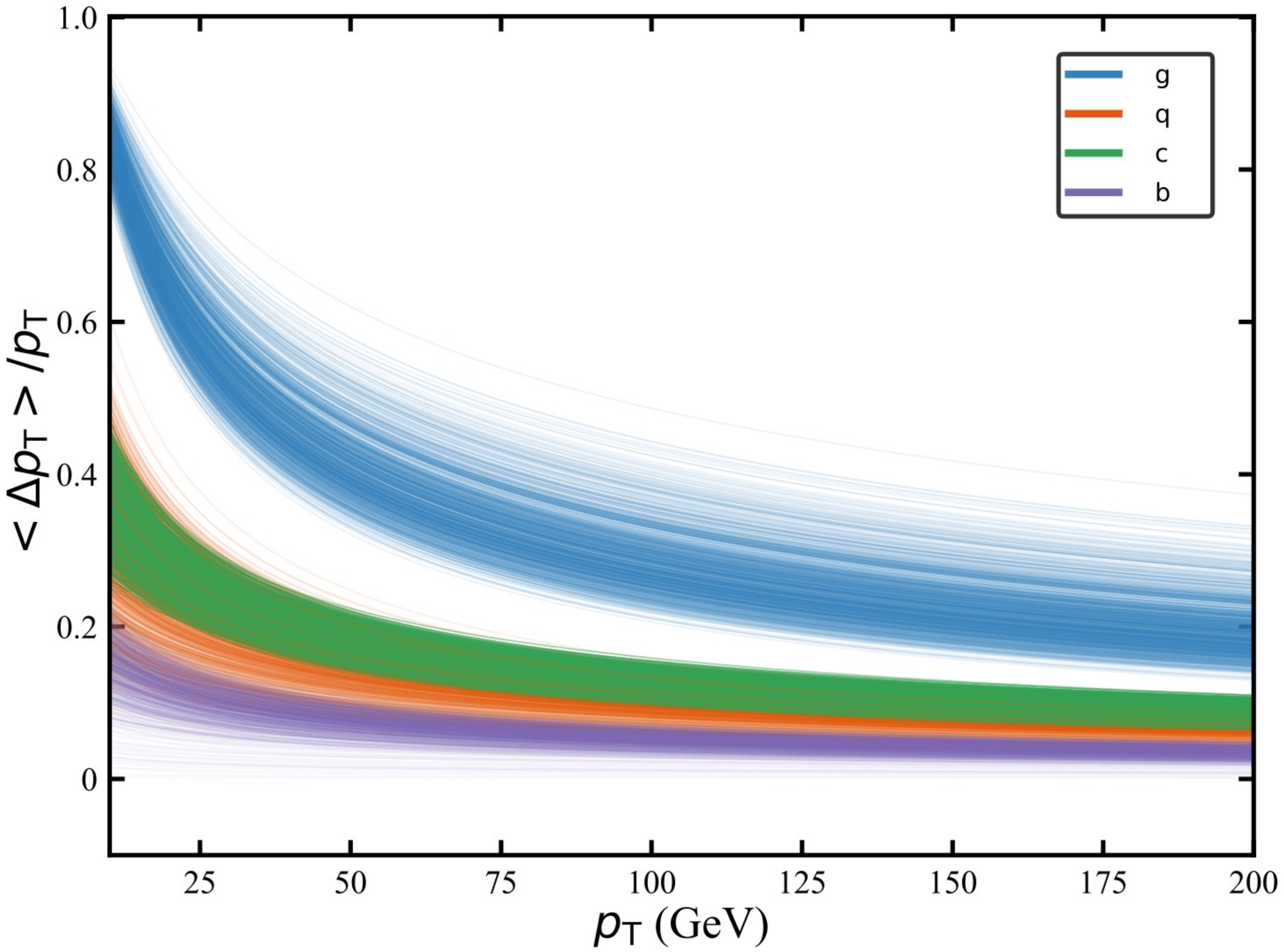
$$\sigma^{AA\to hX} = f_{i/A} \otimes f_{j/A} \otimes \tilde{\sigma}_{ij\to k} \otimes D_{k\to h}$$

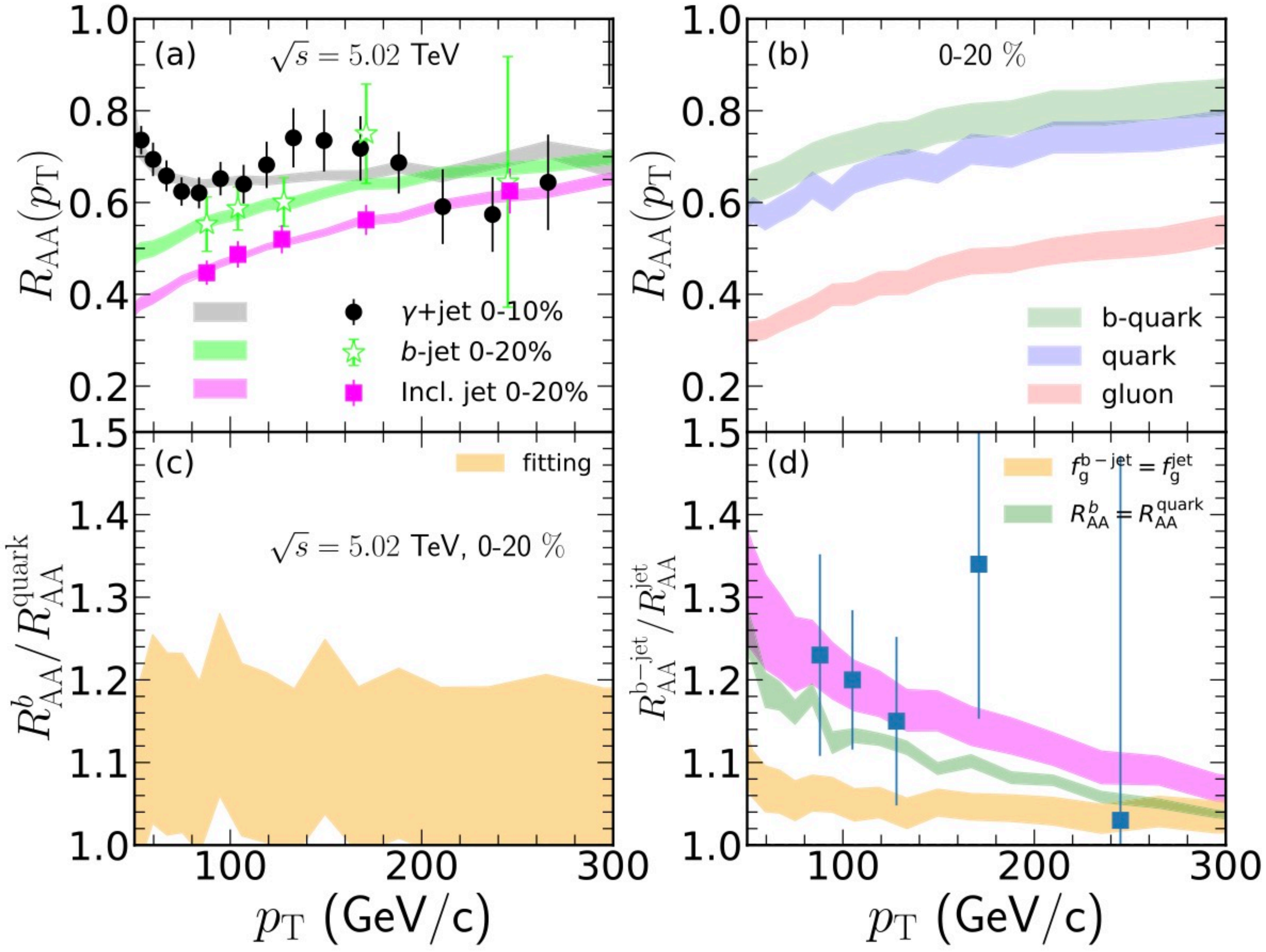
- Observables involving FFs: single inclusive hadron, di-hadron, photon/Z tagged hadron, jet fragmentation function

FFs as a tool to probe hot dense medium

✦ Extract the medium property

Xing, Cao, Qin, PLB, 2023





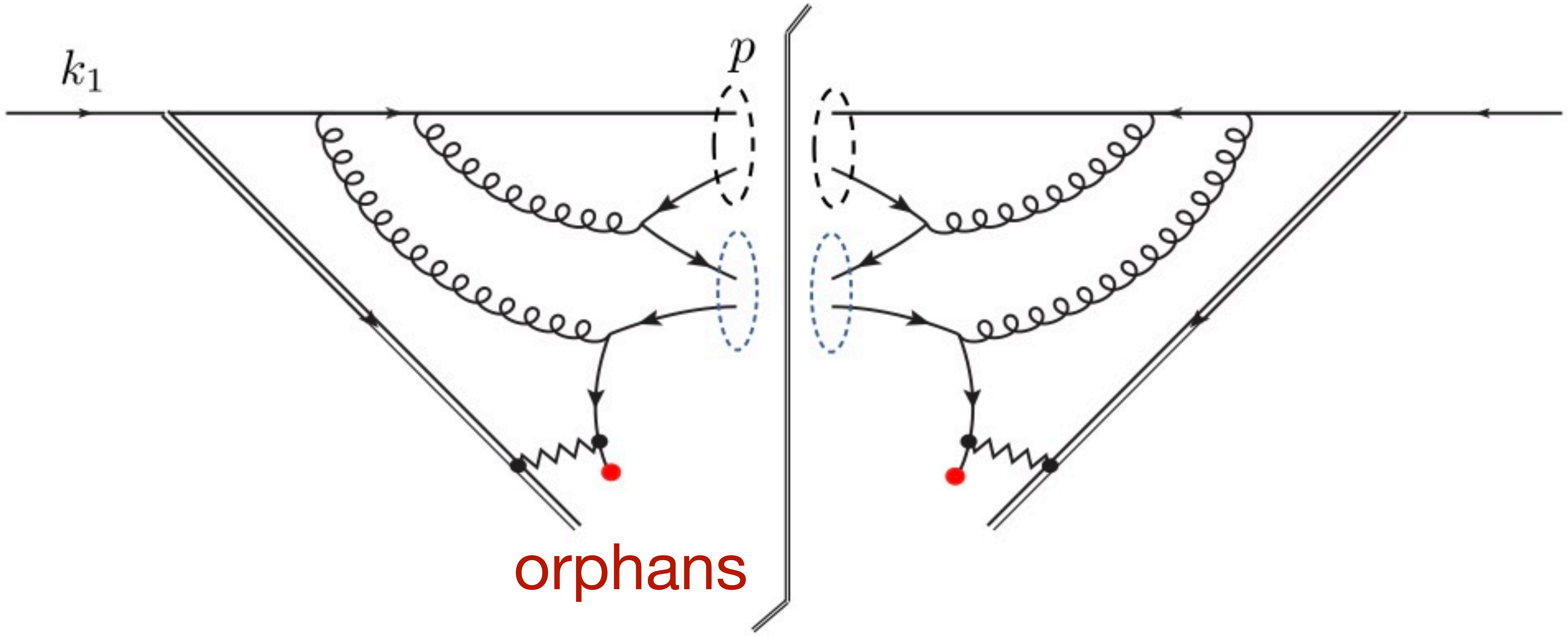
Zhang, Wang, **HX**, Zhang, PLB, 2024

- Verify the flavor hierarchy of parton energy loss in medium
- Extract the jet transport parameter of quark-gluon plasma

IBM Can we simulate parton fragmentation from first principle?

Challenges in lattice QCD for FFs

Collins, Rogers, PRD 2024



$$D_q^h(z) = z^{d-3} \int \frac{dy^-}{4\pi} e^{-iy^- p^+/z} Tr\Big\{ \langle \Omega | \psi(y^-) \sum_X | h, X \rangle \langle h, X | \bar{\psi}(0) | \Omega \rangle \gamma^+ \Big\}$$

1. **Real-time dynamical quantity -> sign problem**
2. **Unidentified X -> exponentially increasing complexity**

Simulate parton fragmentation on quantum computer

✦ A toy model - 1+1D NJL (Gross, Neveu, 1974), no gauge field

$$\mathcal{L} = \bar{\psi}_\alpha (i\gamma^\mu \partial_\mu - m_\alpha)\psi_\alpha + g(\bar{\psi}_\alpha \psi_\alpha)^2$$

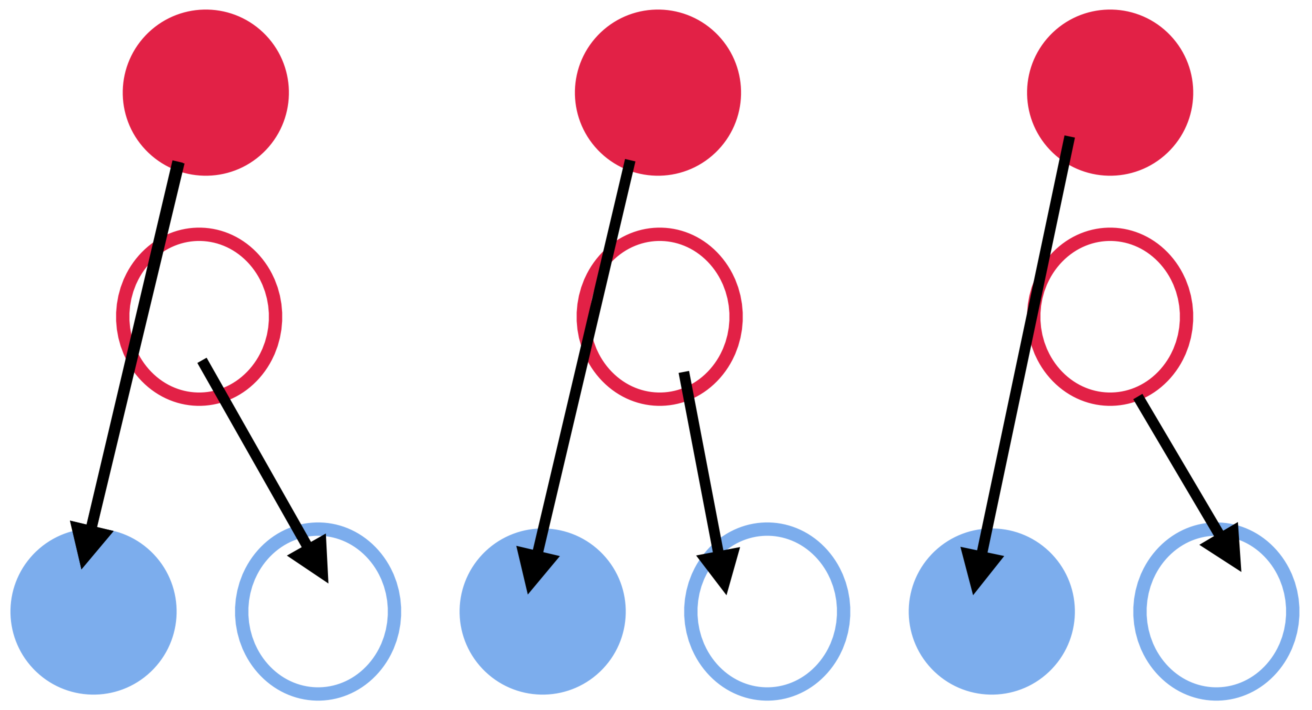
$$D_q^h(z) = z^{d-3} \int \frac{dy^-}{4\pi} e^{-iy^- p^+/z} Tr\left\{ \langle \Omega | \psi(y^-) \sum_X | h, X \rangle \langle h, X | \bar{\psi}(0) | \Omega \rangle \gamma^+ \right\}$$

✦ Challenges in quantum computing

- Map QFT to qubits+gates system
- Prepare the external hadronic state $|h, X\rangle$
- Evaluate the real-time dynamical correlation function
- Measurement of final observable

Qubitization of Hamitonian

✦ Quantum field to qubits+gates $\mathscr{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g(\bar{\psi}\psi)^2$



- Discretization: staggered fermion, put different fermion components, flavors on different sites

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \rightarrow \begin{pmatrix} \phi_{2n} \\ \phi_{2n+1} \end{pmatrix}$$

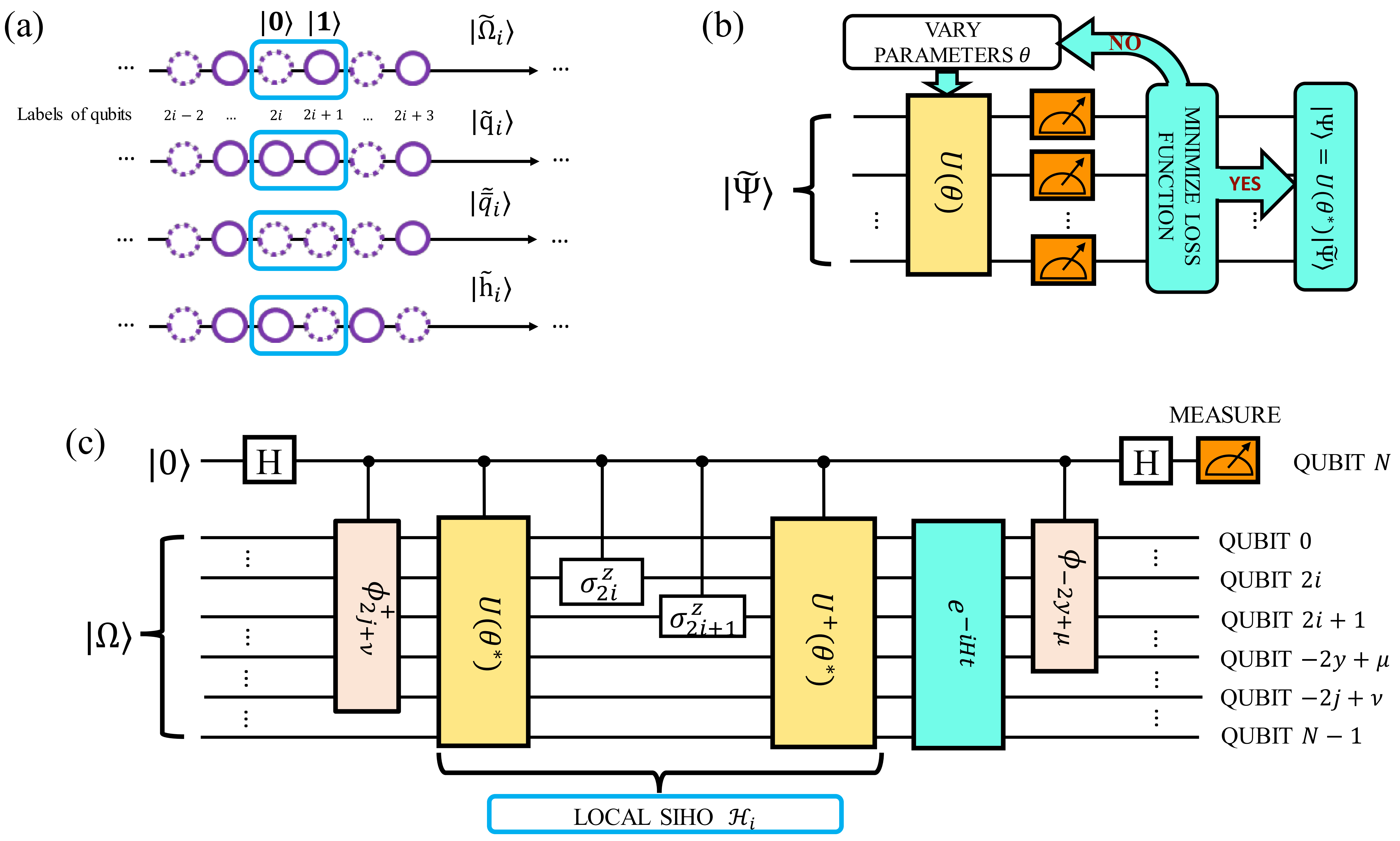
- Jordan-Wigner transformation

$$\phi_n = \prod_{i<n} Z_i (X + iY)_n$$

- Discretized PDF:

$$H = \sum_{\alpha,n} [-\frac{i}{2a}(\phi^\dagger_{\alpha,n}\phi_{\alpha,n+1} - h.c) + (-1)^n m_\alpha \phi^\dagger_{\alpha,n}\phi_{\alpha,n}]$$
$$-g \sum_{\alpha,n=even} [\phi^\dagger_{\alpha,n}\phi_{\alpha,n} + \phi^\dagger_{\alpha,n+1}\phi_{\alpha,n+1} - 2\phi^\dagger_{\alpha,n}\phi_{\alpha,n}\phi^\dagger_{\alpha,n+1}\phi_{\alpha,n+1}]$$

Quantum circuit for FFs



- VQE

$$U|I_i^{\Omega}\rangle = |\Omega_i\rangle$$

$$U|I_i^{q}\rangle = |q_i\rangle$$

$$U|I_i^{h}\rangle = |h_i\rangle$$

…

- Semi-inclusive hadronic operator

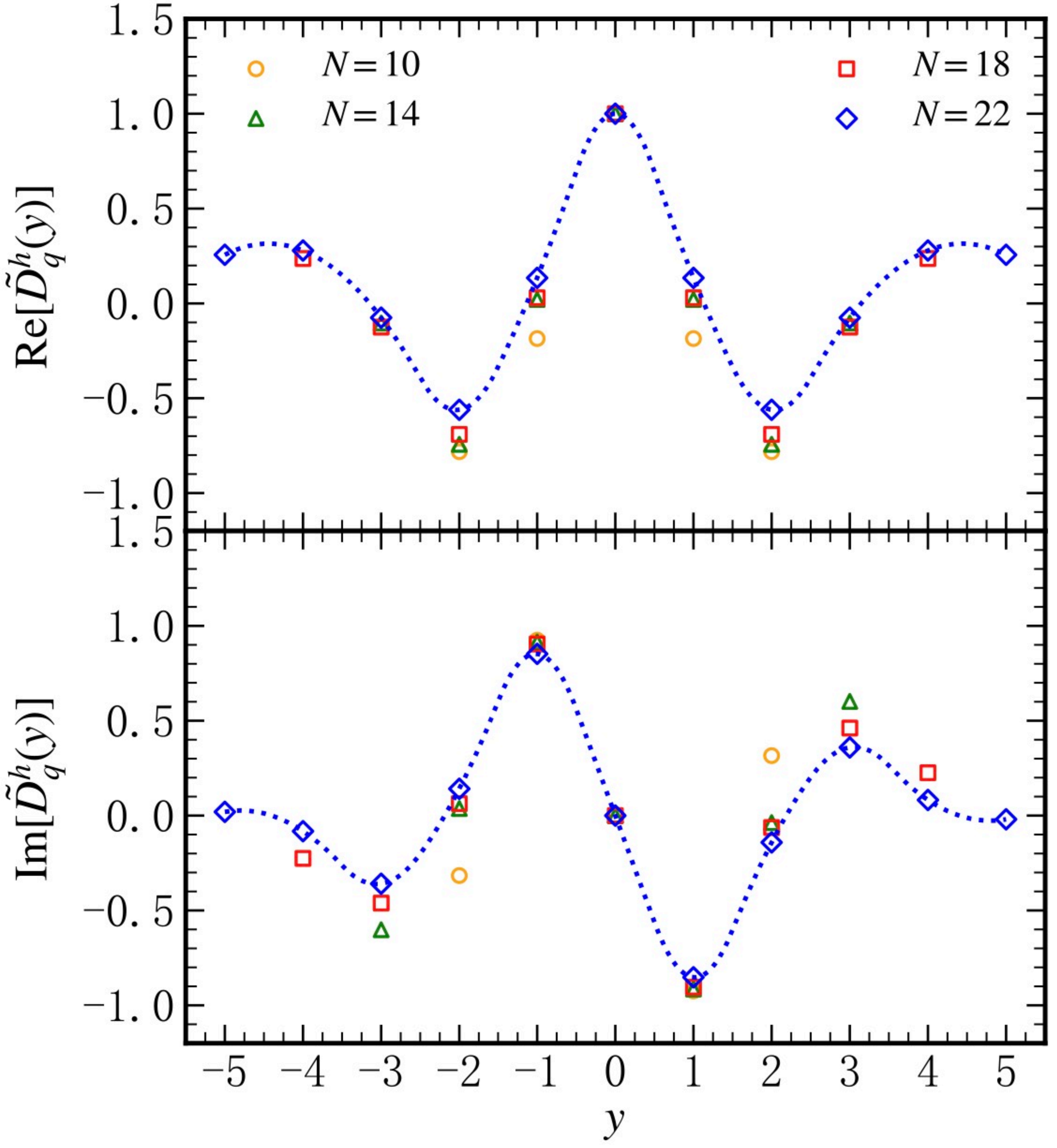
$$|h_i, X_{\{j\neq i\}}\rangle = U\,|\tilde{h}_i, \tilde{X}_{\{j\neq i\}}\rangle$$

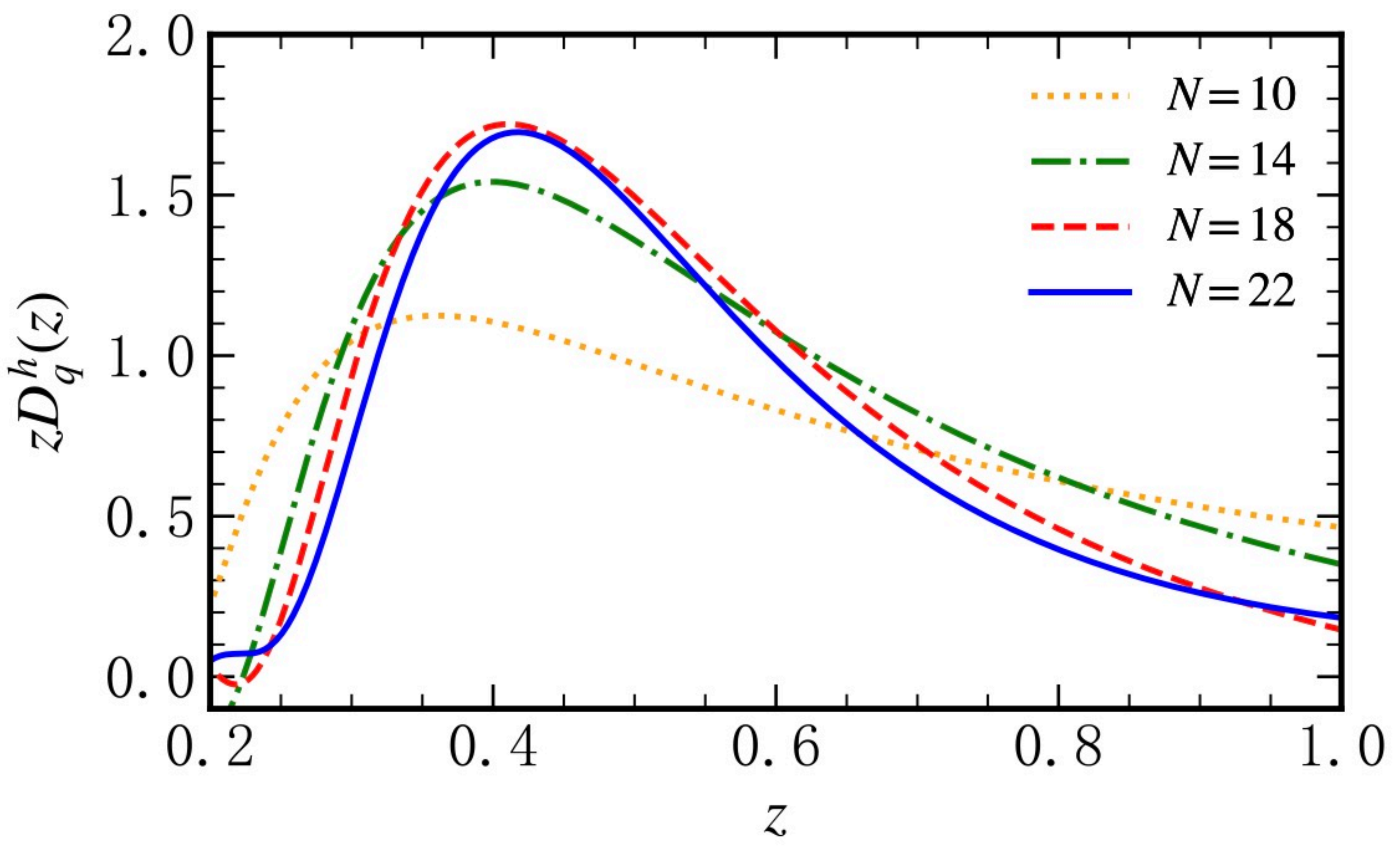
$$\sum_a |I_i^a\rangle\langle I_i^a| = \mathrm{Id}_i$$

$$\mathcal{H}_i = U\,\mathrm{Tr}_{\{j\neq i\}}\,|\tilde{h}_i, \tilde{X}_{\{j\neq i\}}\rangle\,\langle\tilde{h}_i, \tilde{X}_{\{j\neq i\}}|\,U^\dagger$$
$$= U\,|\boldsymbol{I}_i^h\rangle\,\langle\boldsymbol{I}_i^h|\otimes \mathrm{Id}_{\{j\neq i\}}U^\dagger\,,$$

Li, **HX**, Zhang, arXiv:2406.05683

FFs from quantum simulation





- Converges with the increase of qubit number N
- Finite volume effect in large z
- Qualitative agreement with real FFs and other model calculations

Summary

- ✦ NPC23 - precise determination of parton fragmentation from world data
- ✦ Unique opportunities to test QCD factorization for hadron production at BESIII experiment
- ✦ New approach for first principle calculation - quantum computing

Thanks for your attention!