重庆大学
CHONGQING UNIVERSITY

Parton fragmentation from vacuum to nuclear medium

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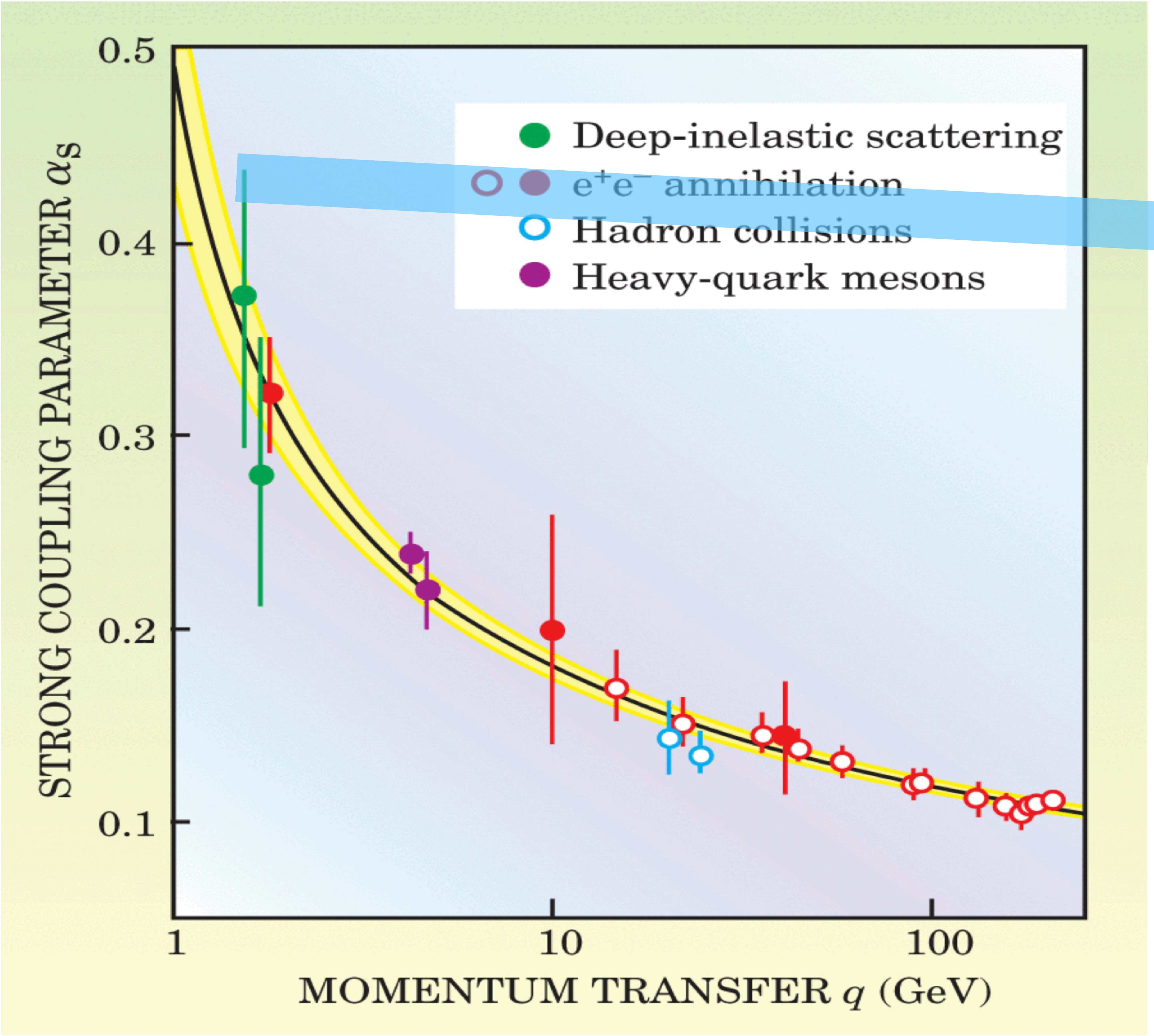
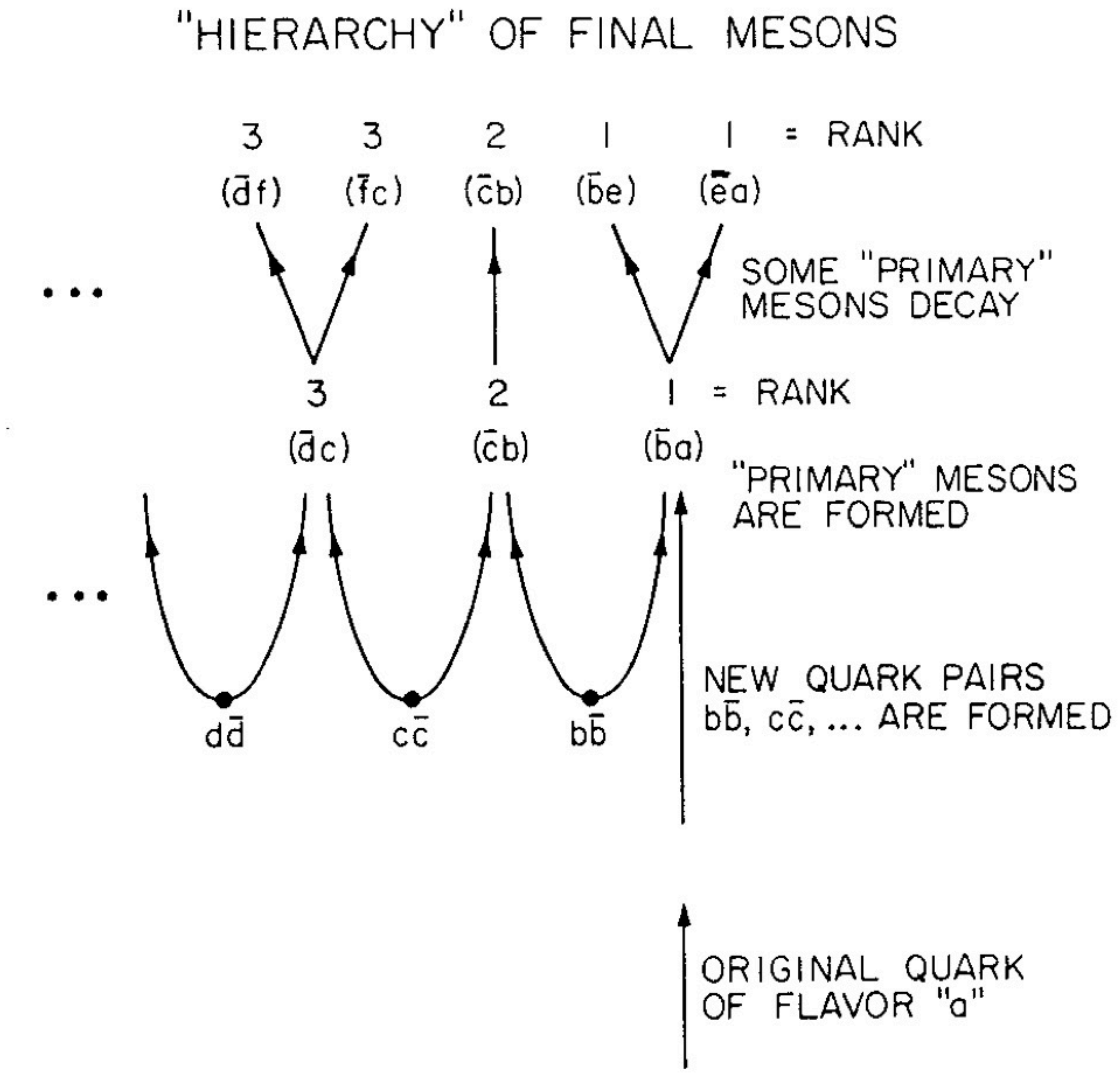
STAR

2024.10.10-15

QCD confinement - hadronization

✦ **QCD as the fundamental theory of strong interaction**





Field, Feynman, NPB 1978

QCD confinement - hadronization

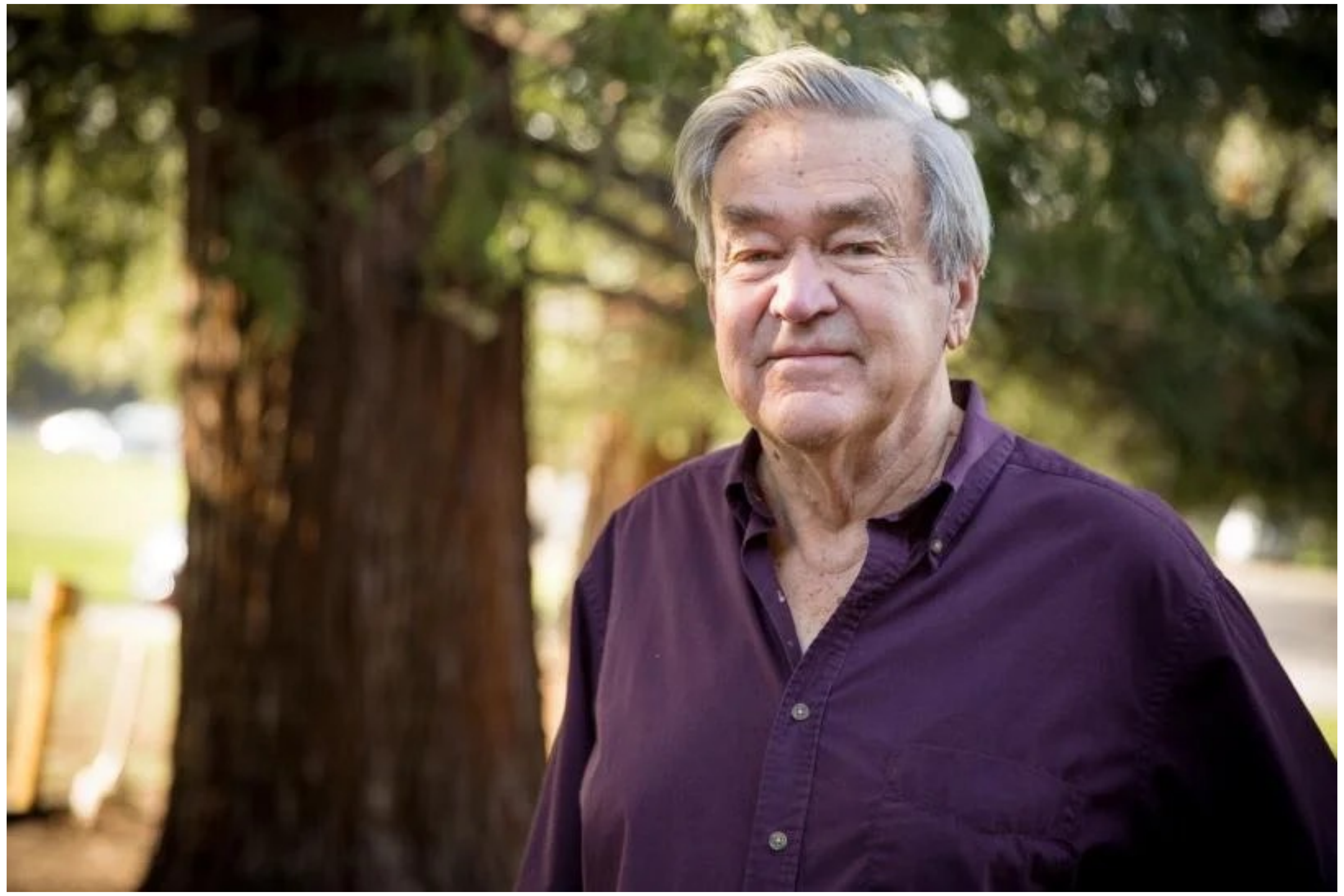
✦ The first concept of parton fragmentation functions

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



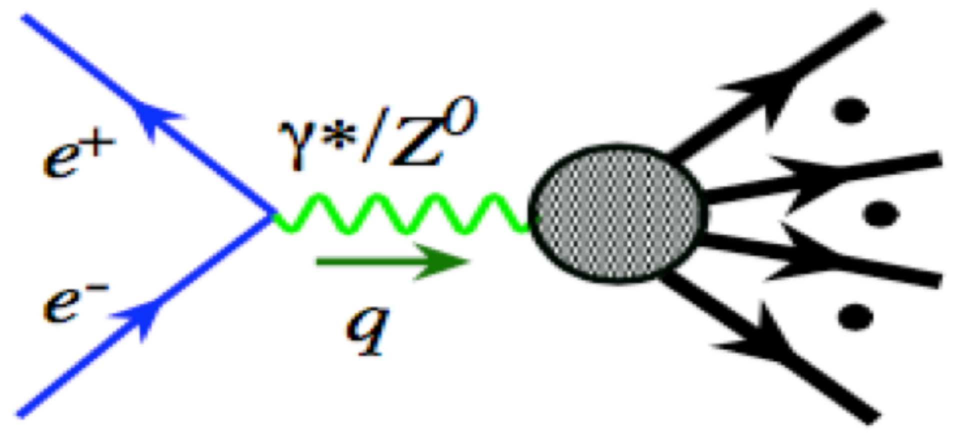
James Bjorken, 1934-2024

Berman, Bjorken, Kogut, PRD 1971

Multiple channels to explore parton hadronization

✦ Indispensable joint efforts from experiments and QCD theory

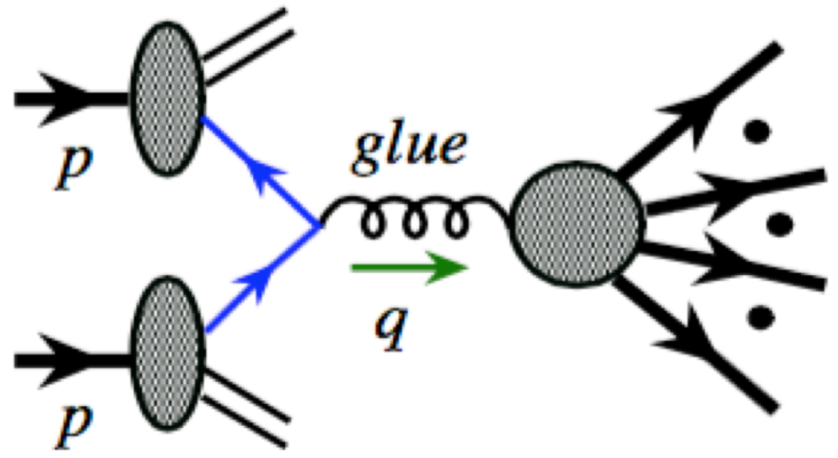
Lepton-lepton colliders



BEPC, SuperKEKB

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

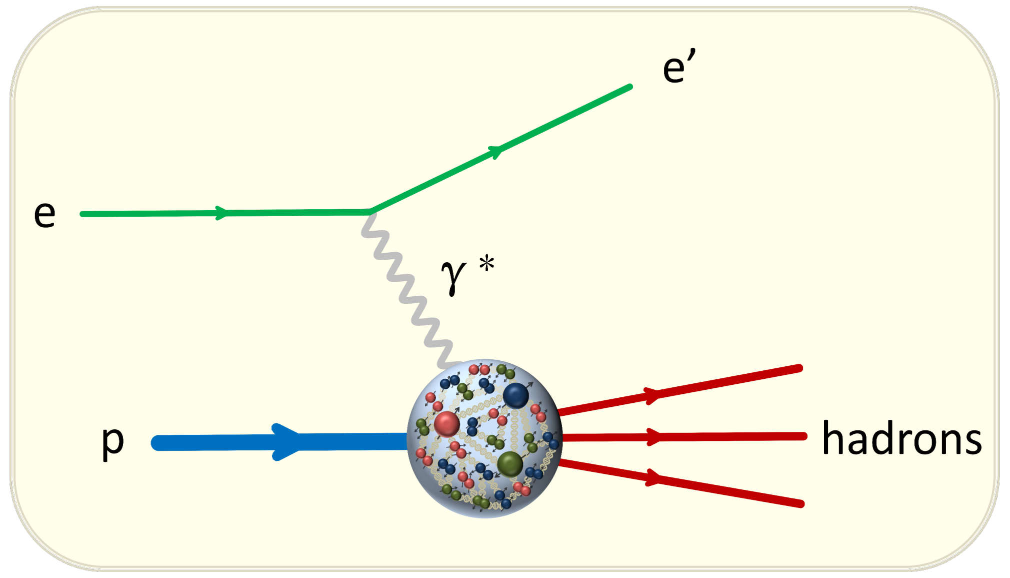
Hadron-hadron colliders



RHIC, LHC

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

lepton-hadron colliders

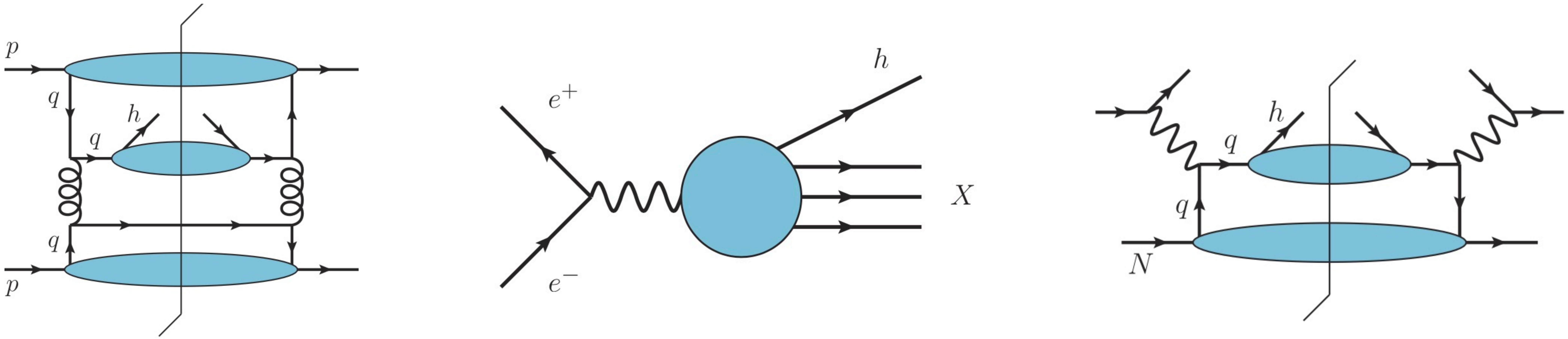


HERA, JLab, EIC/EicC

- 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 proton-proton collisions**

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

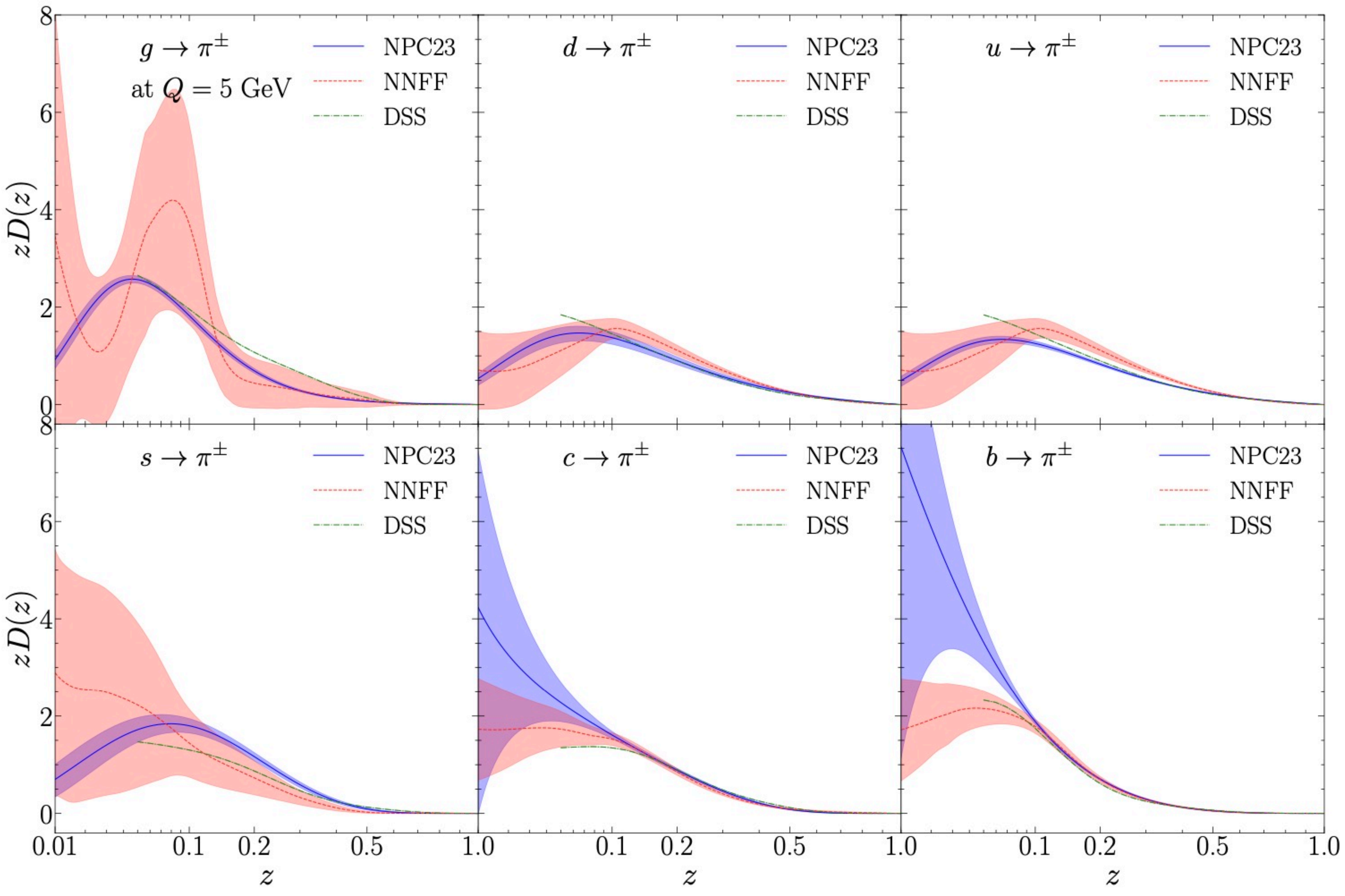
- Large momentum transfer $Q \gg \Lambda_{QCD}$
- High precision control of $\hat{\sigma}$
- D: fragmentation function, also called parton decay function, encodes the information on how patrons produced in hard scattering hadronize into the detected color singlet hadronic bound state.

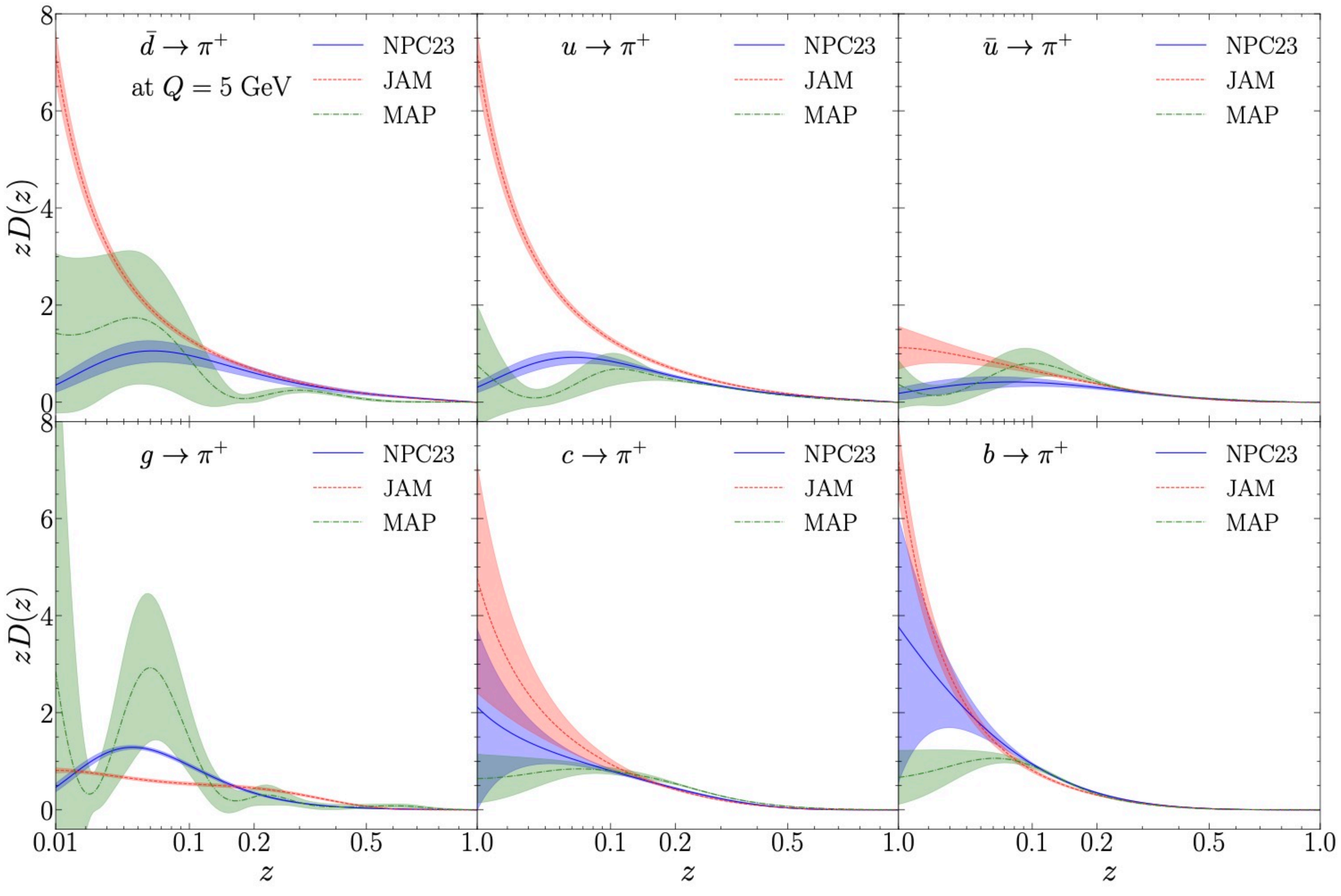
Methodology for global extraction of FFs

FF global fitting panorama

✦ Joint efforts from experiments and theory in extracting FFs

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

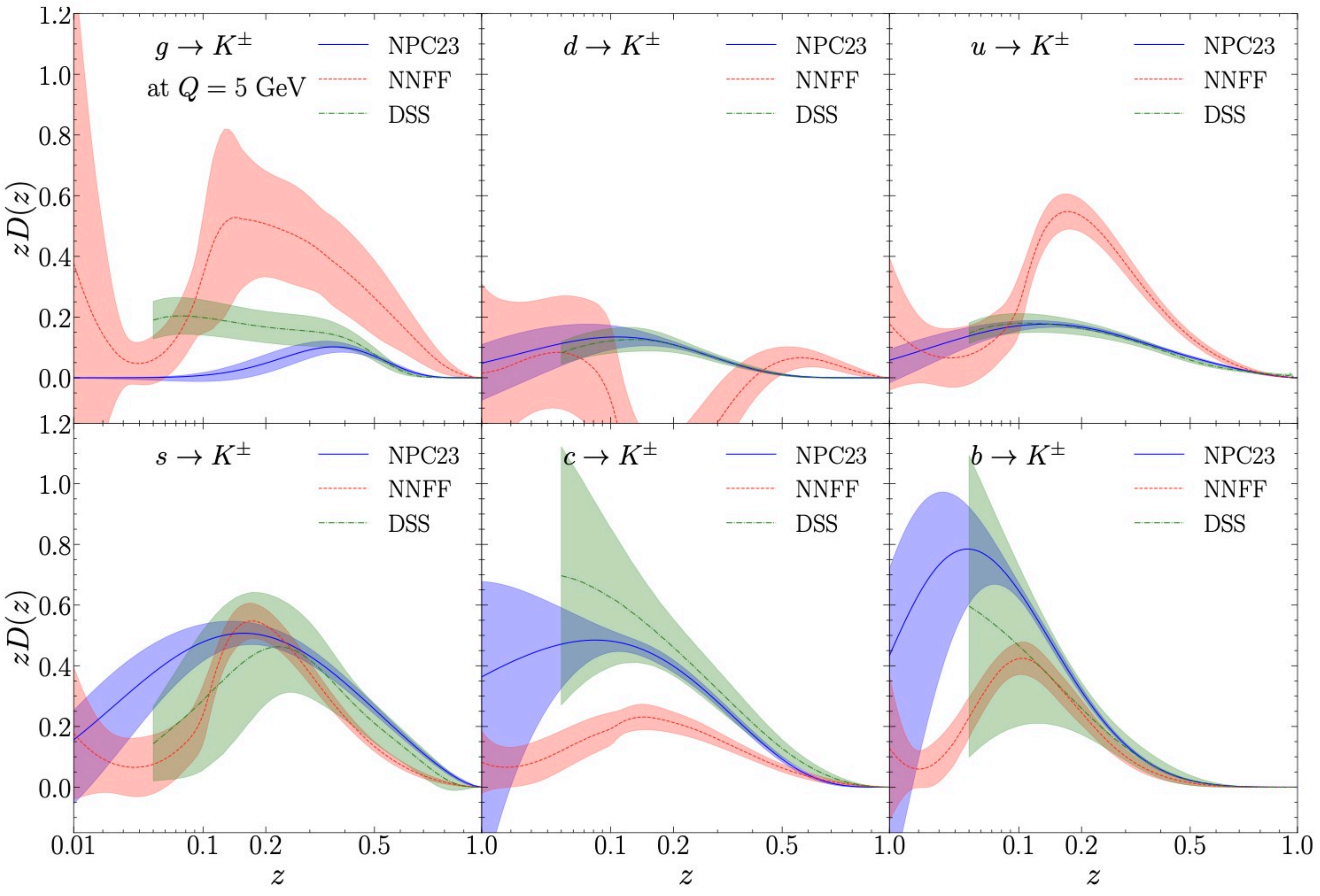




parton to pion fragmentation

FFs panorama

✦ Charged 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

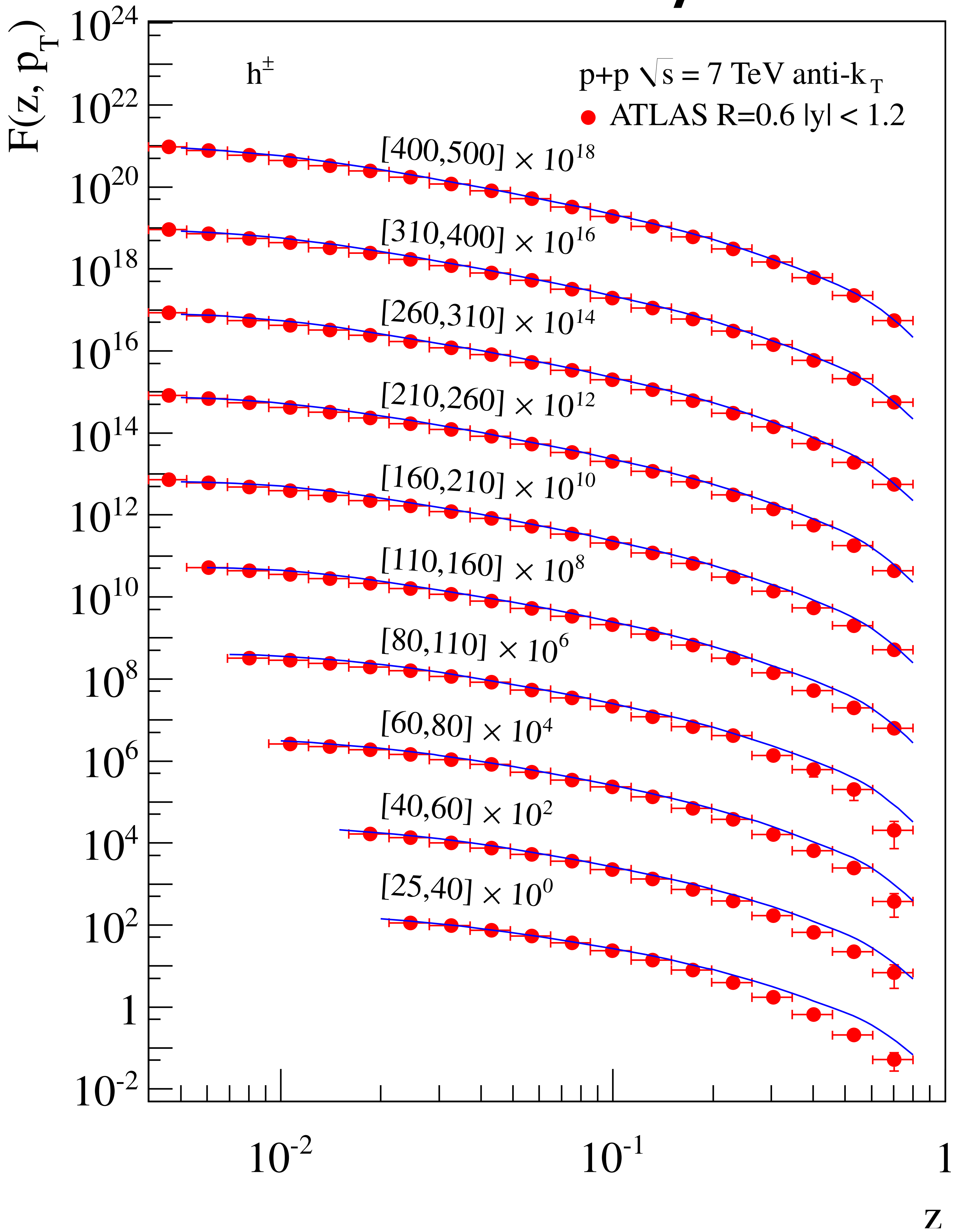
More measurements are needed to further constrain the FFs!

New opportunities in probing FFs at LHC

✦ Jet fragmentation function

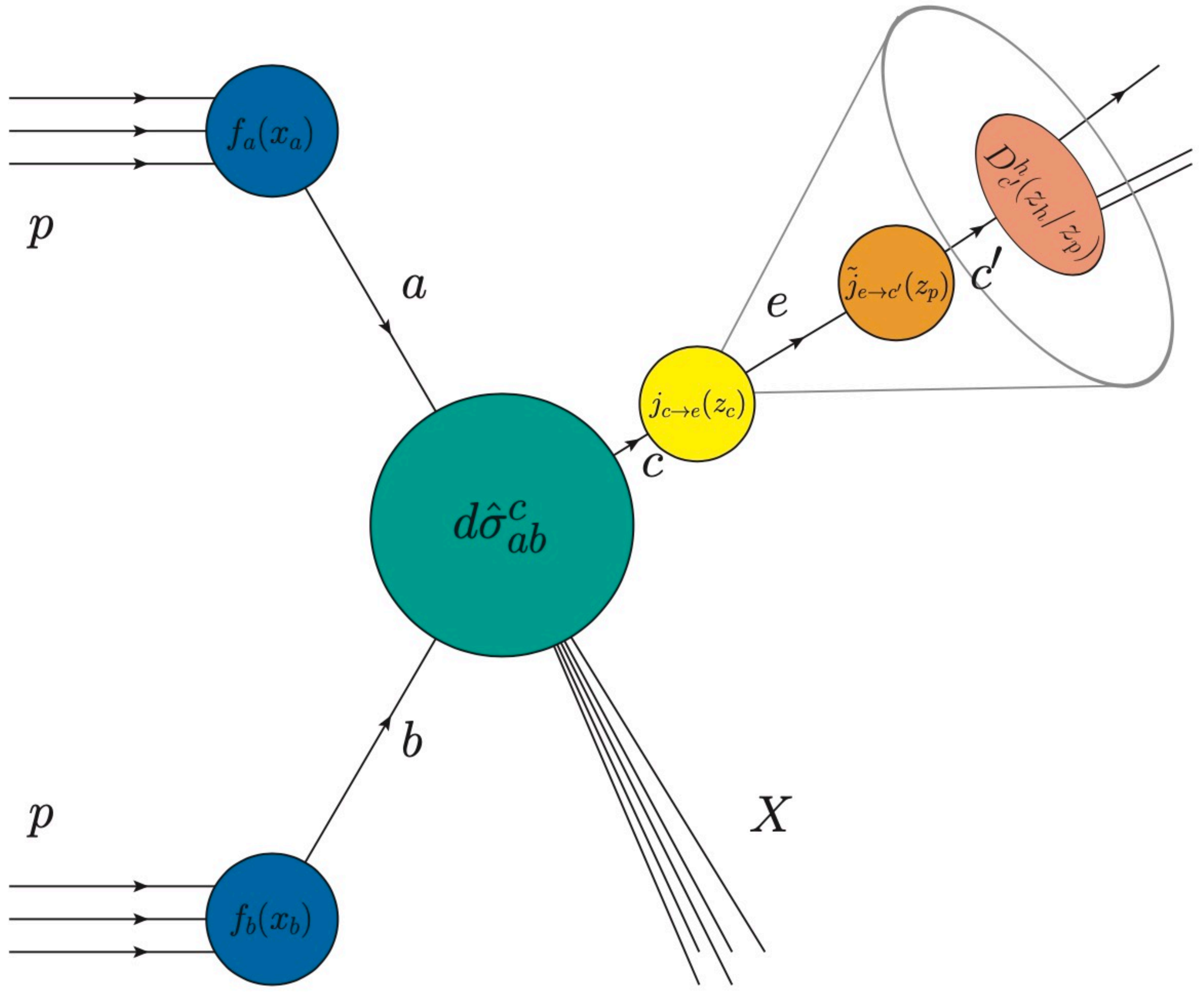
Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

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



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

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



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

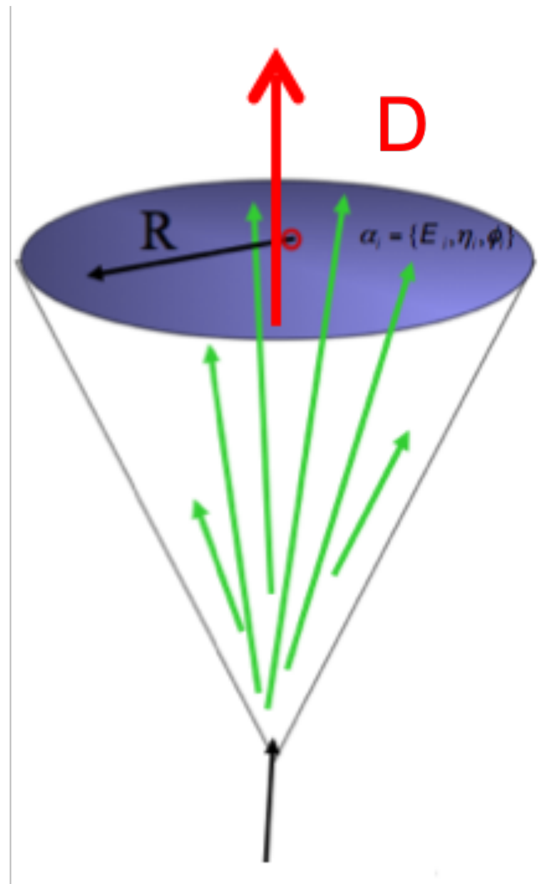
Light hadrons work very well

Heavy flavor in jet

✦ Jet fragmentation function for D meson

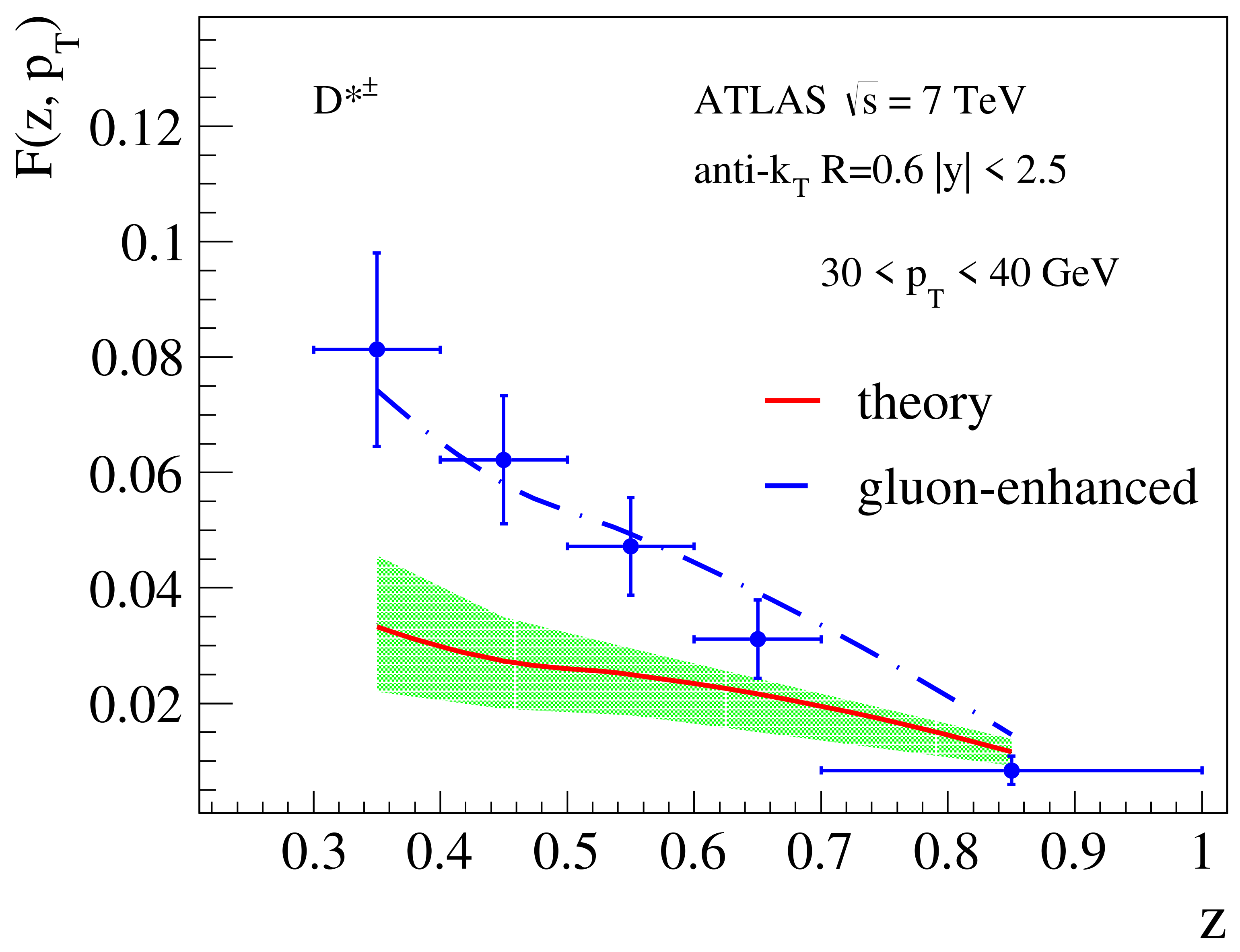
$$F(z_h, p_T) = \frac{d\sigma^{J(h)}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma}{dp_T d\eta}$$

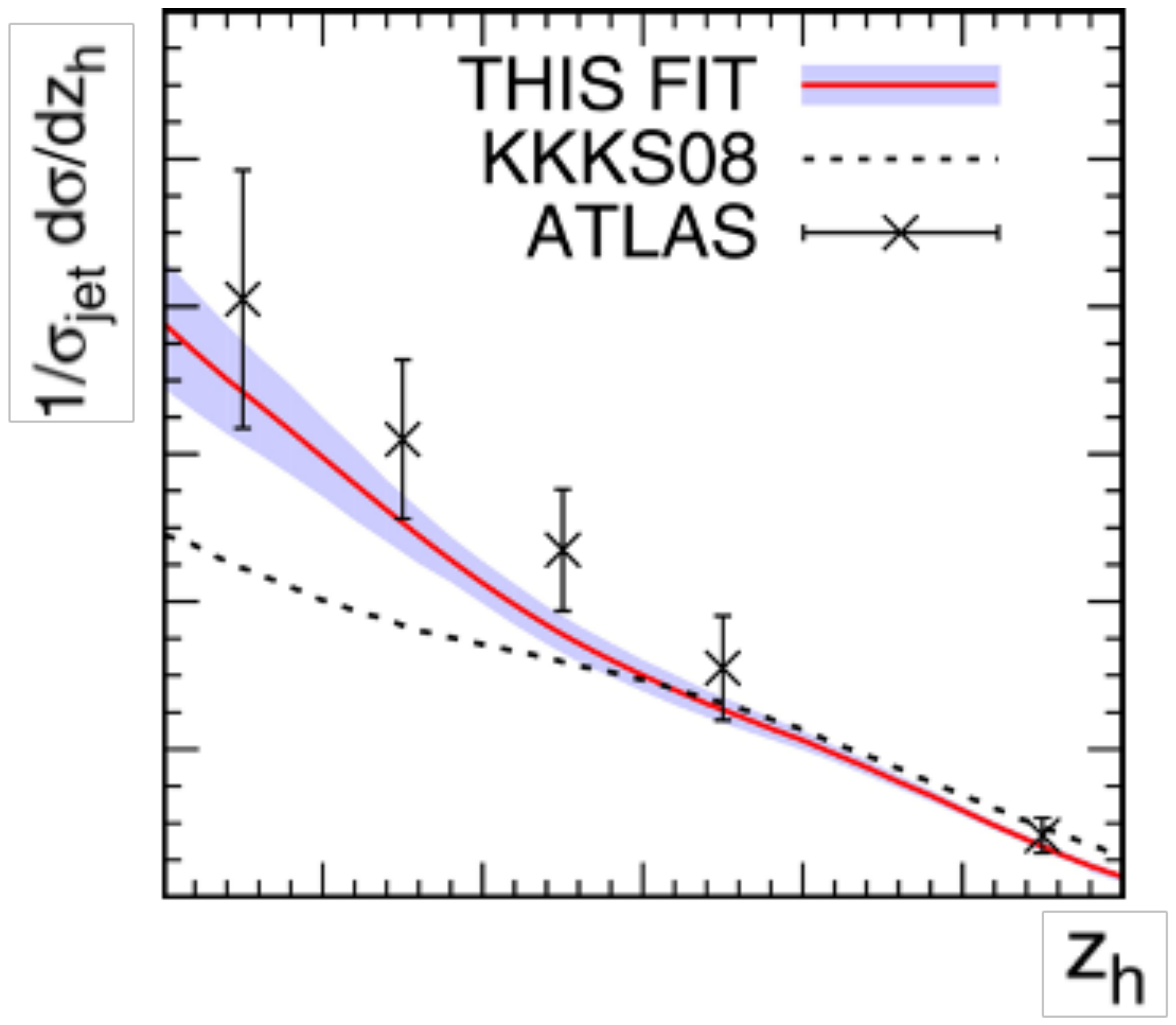
Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

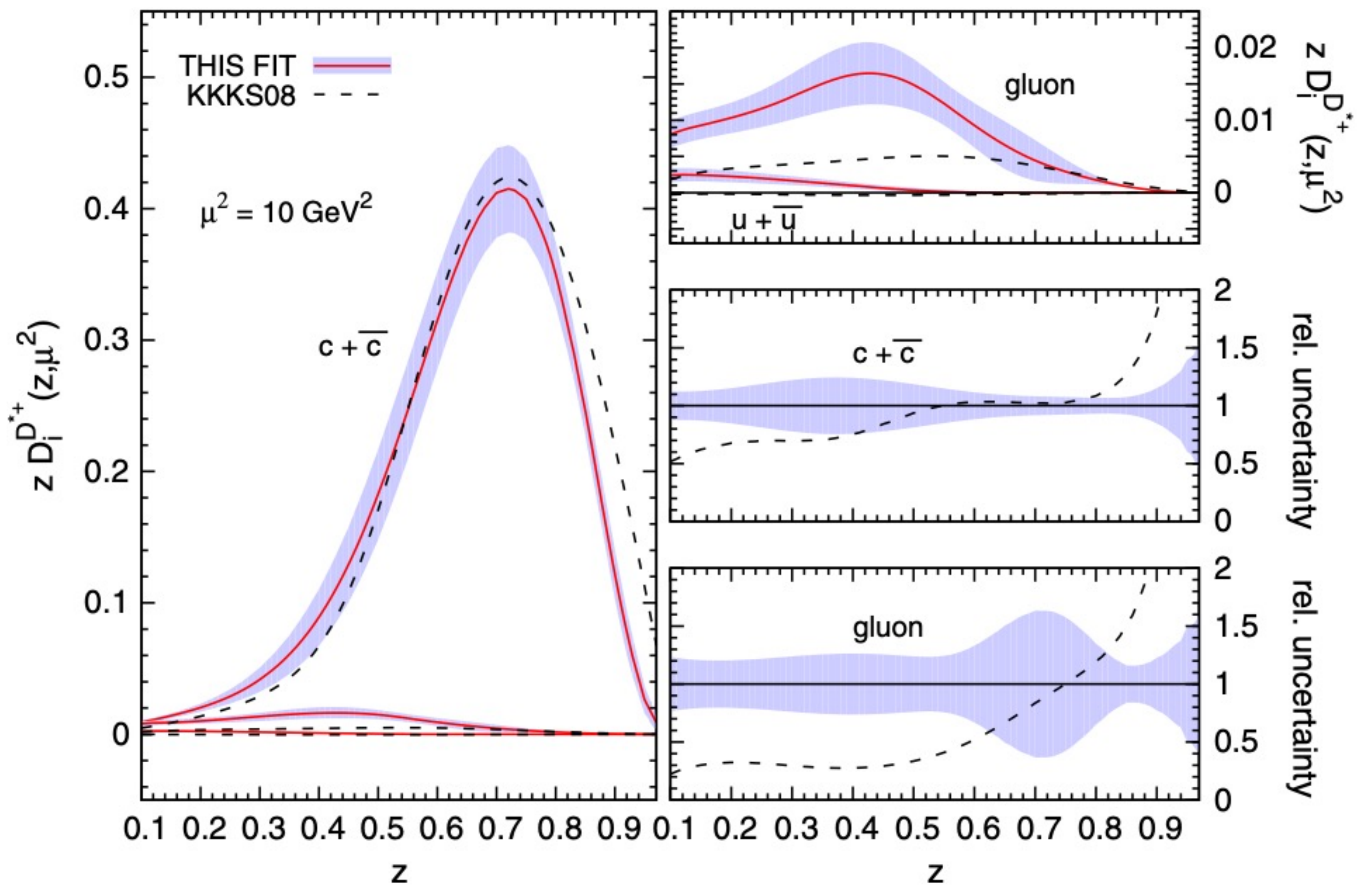


$$z_h = \frac{p_T^h}{p_T}$$

AKSRV, PRD (2017)







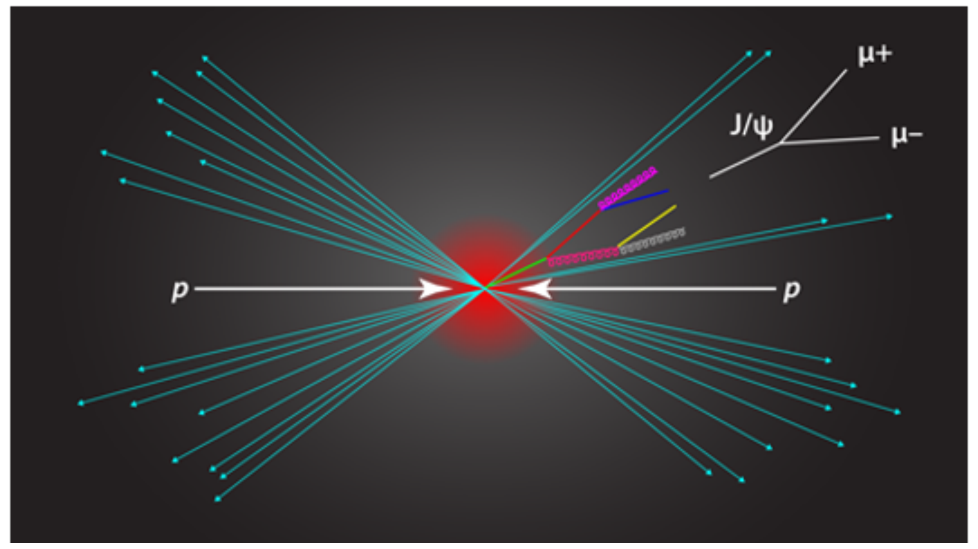
- Failed to describe D meson production in jet using KKK08 FFs
- Leads to new constrain of heavy flavor FFs using measurement of D in jet

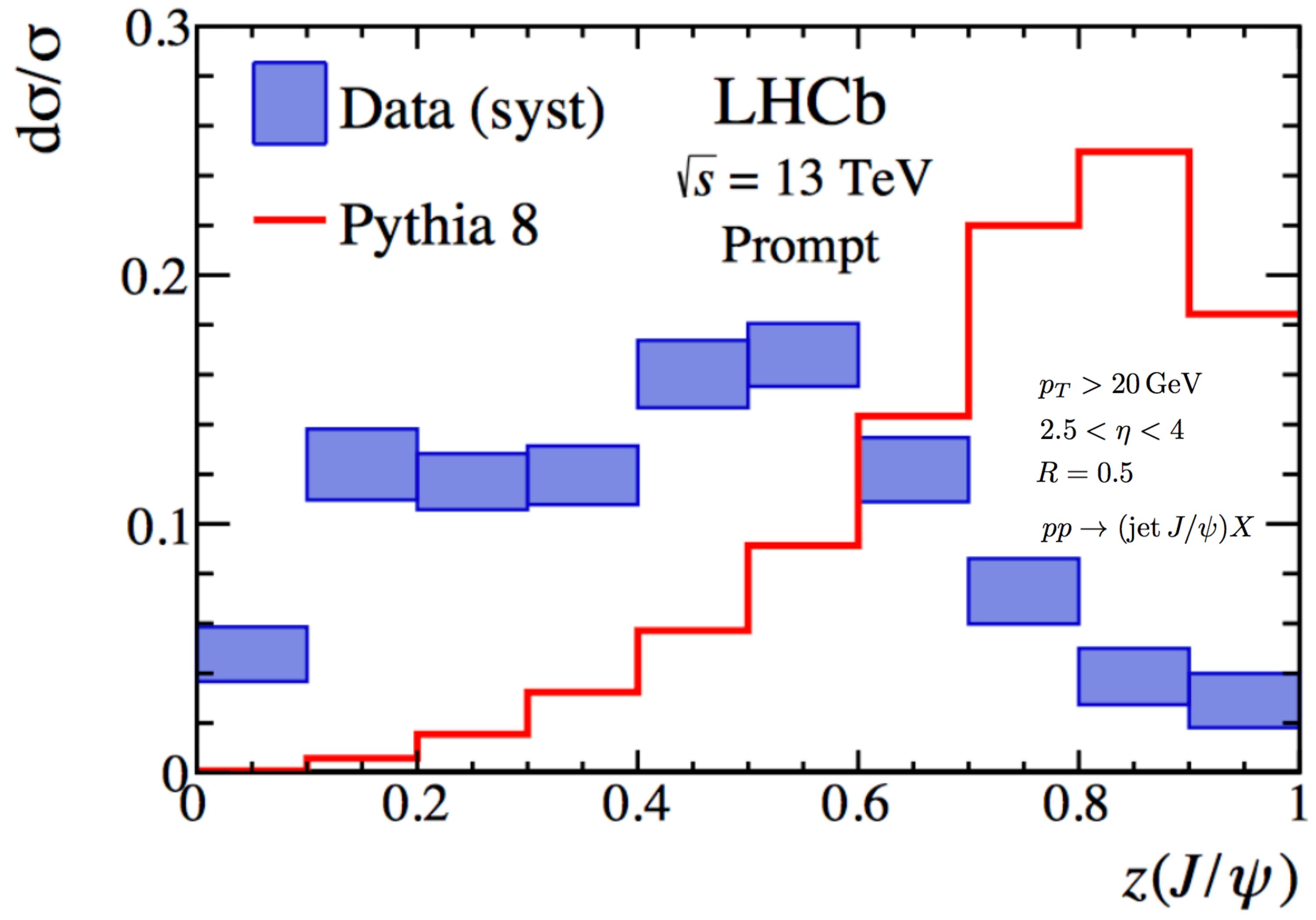
Heavy flavor in jet

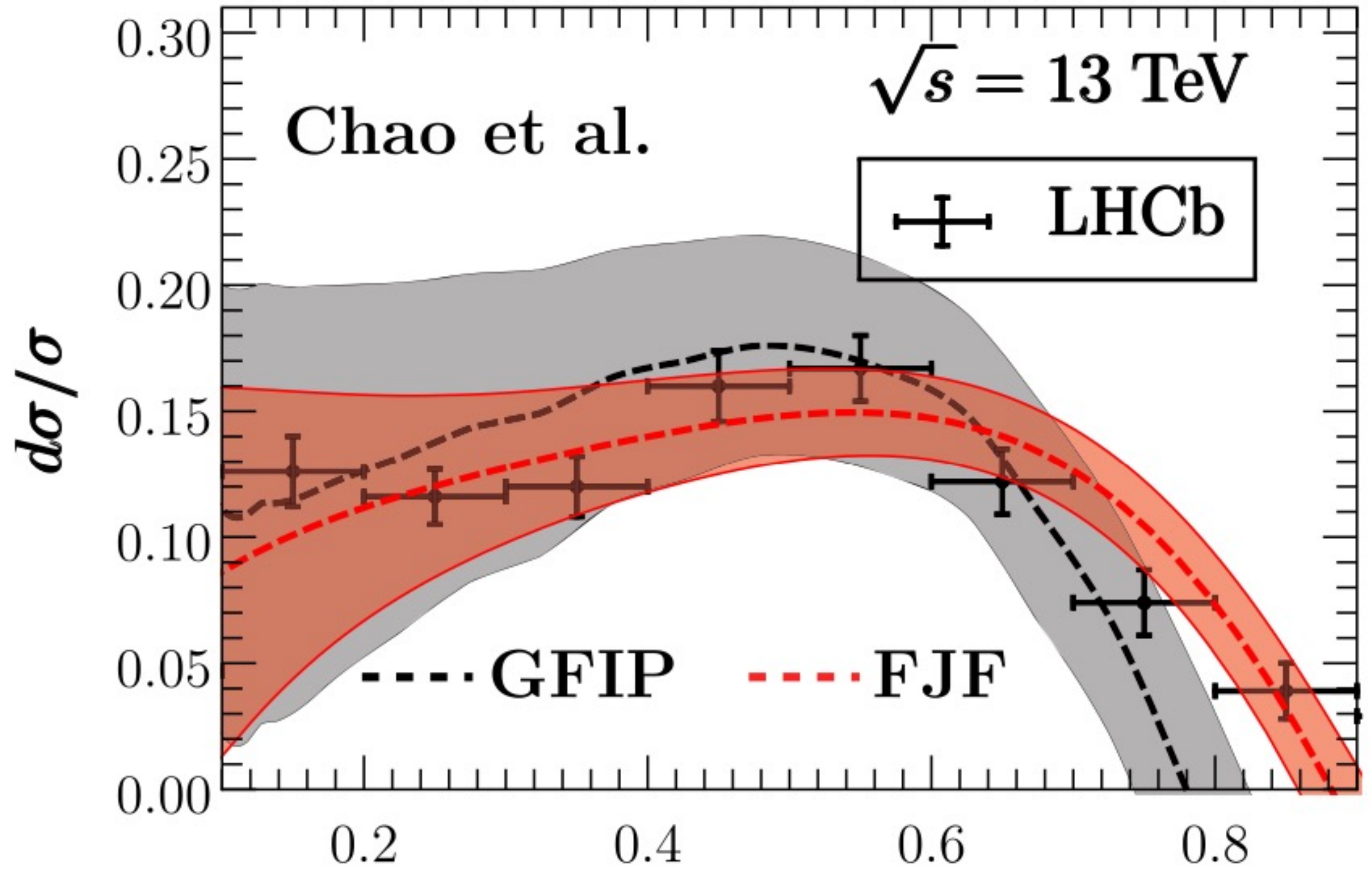
✦ Jet fragmentation function for J/ψ

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

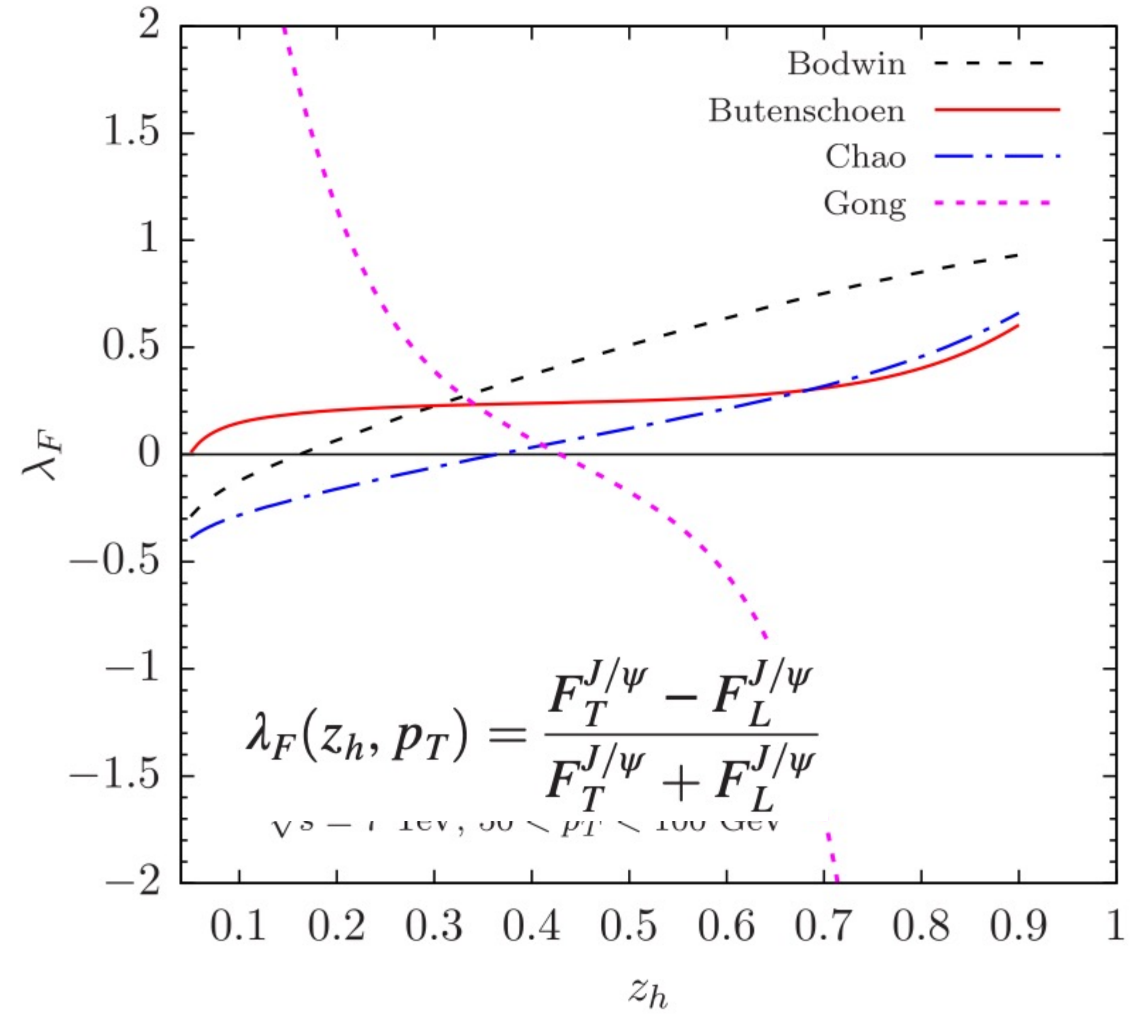
$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\text{jet}}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\text{jet}}^+ R, \mu) \times D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\text{jet}}^+ R)^2)$$







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

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

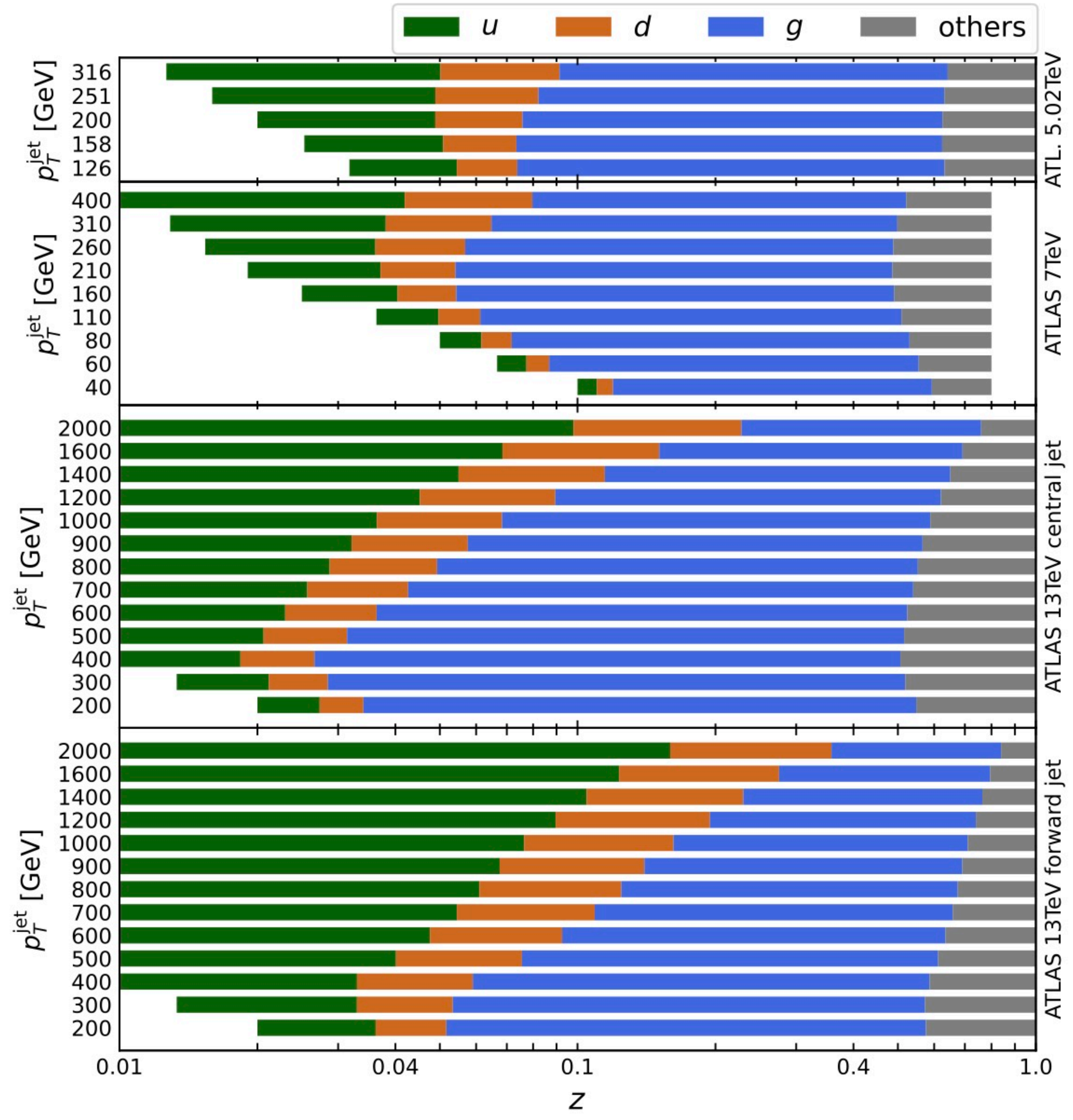
$$zD_i^h(z, Q_0) = z^{\alpha_i^h}(1-z)^{\beta_i^h} \exp\left(\sum_{n=0}^{m} a_{i,n}^h (\sqrt{z})^n\right)$$

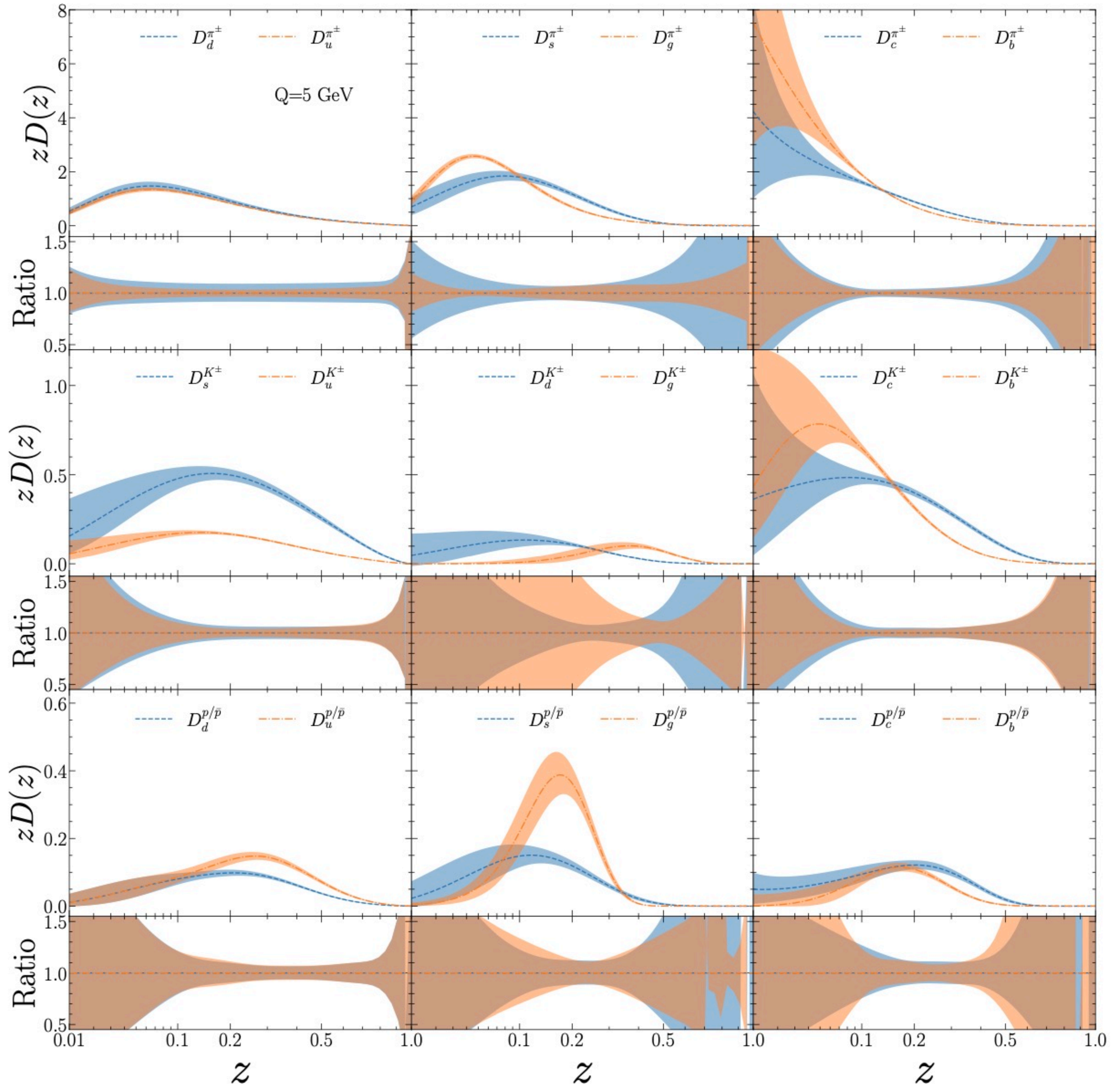
Experiments	N_{pt}	χ^2	χ^2/N_{pt}
ATLAS jets †	446	350.8	0.79
ATLAS $Z/\gamma+$jet †	15	31.8	2.12
CMS $Z/\gamma+$jet †	15	17.3	1.15
LHCb $Z+$jet	20	30.6	1.53
ALICE inc. hadron	147	150.6	1.02
STAR inc. hadron	60	42.2	0.70
pp sum	703	623.3	0.89
TASSO	8	7.0	0.88
TPC	12	11.6	0.97
OPAL	20	16.3	0.81
OPAL (202 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 (06l)	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

LHAPDF 6.5.4

Main page | PDF sets | Class hierarchy | Examples | More... | Search

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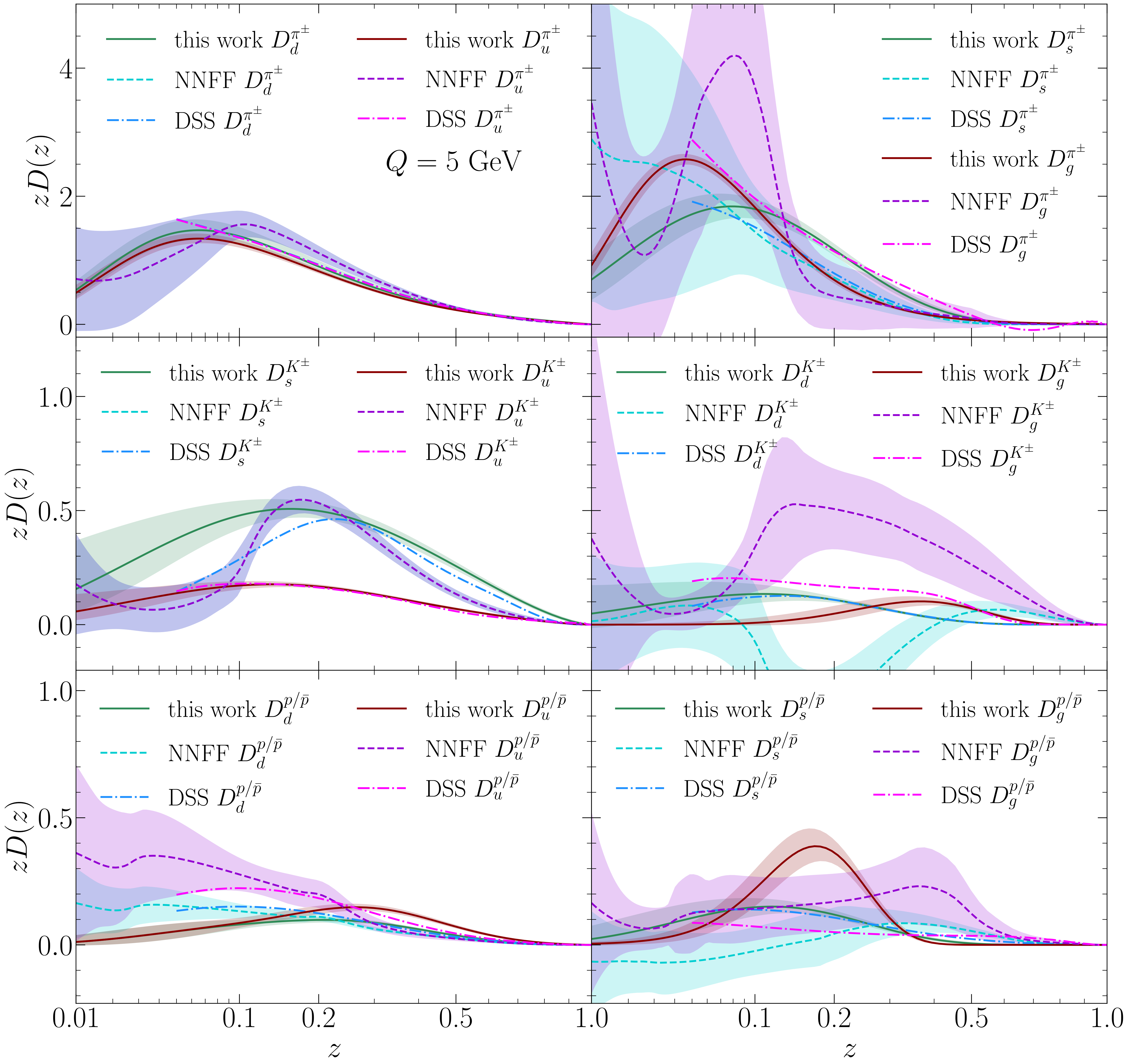
FFs for charged π, k, p are all available in LHAPDF.

✦ NPC23 vs. others

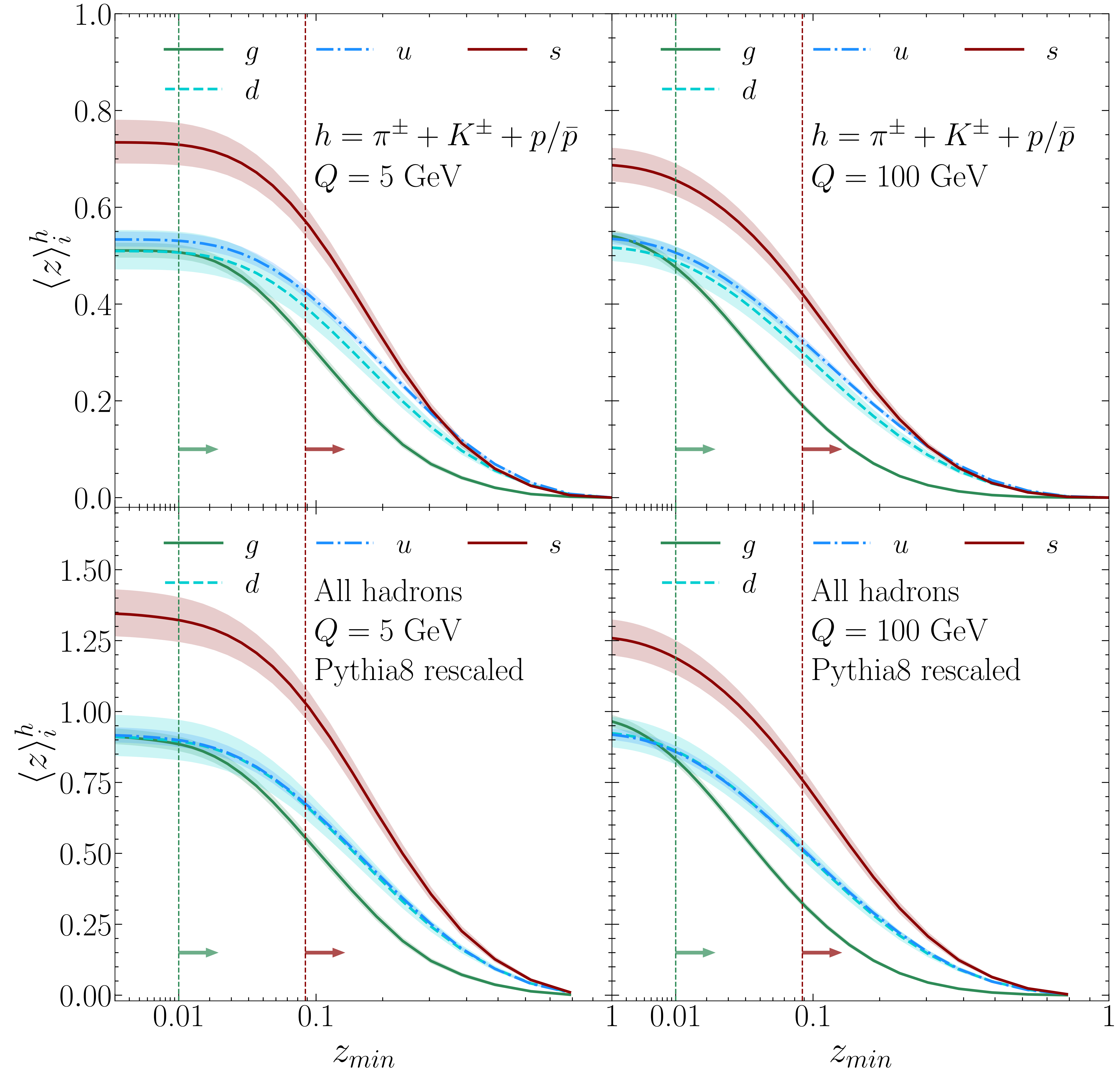


- General agreement for u/d quark to pion
- Discrepancies for FFs to kaon/proton and gluon FFs
- Future benchmark works involving different groups are needed to clarify the discrepancies

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	$0.507^{+0.014}_{-0.013}$	$0.531^{+0.015}_{-0.013}$	$0.506^{+0.042}_{-0.037}$	$0.572^{+0.029}_{-0.028}$

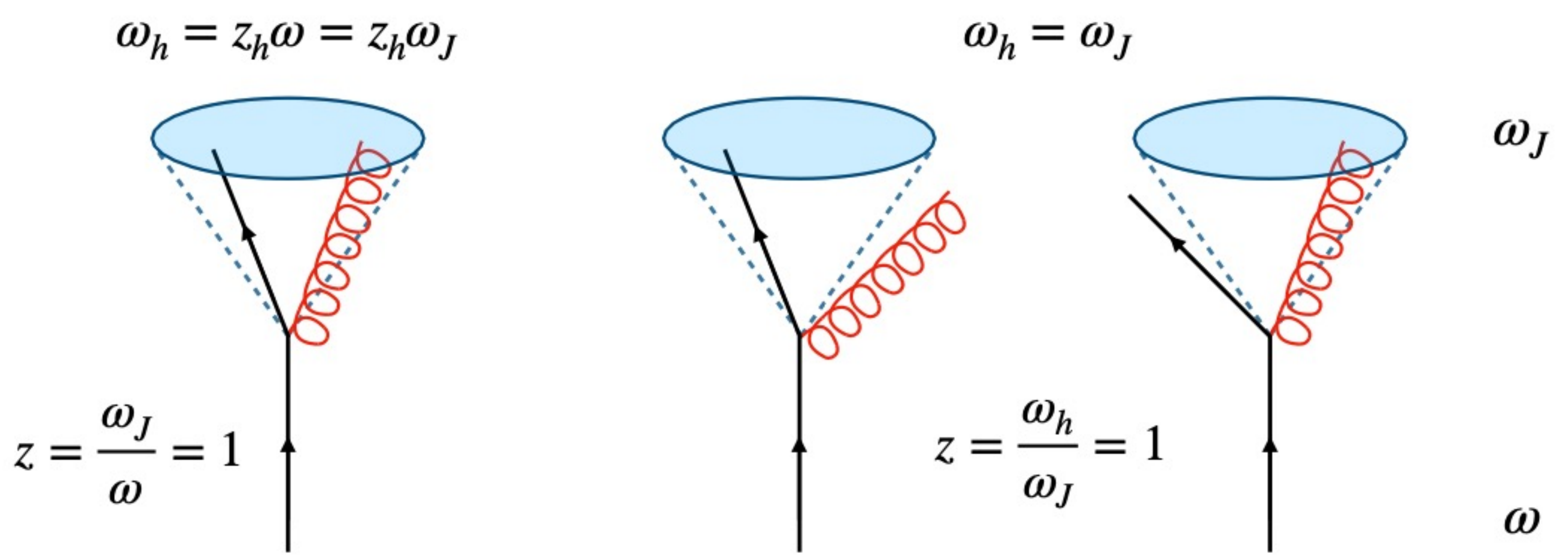
$$\sum_h \sum_{S_h} \int_0^1 dz\, z\, D_1^{h/q}(z) = 1$$

- Hint for violation of momentum sum rule?

Parton to hadron fragmentation in jet

✦ A comprehensive analysis for jet fragmentation functions

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



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

- Collinear fragmenting jet function in semi-inclusive jet production

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

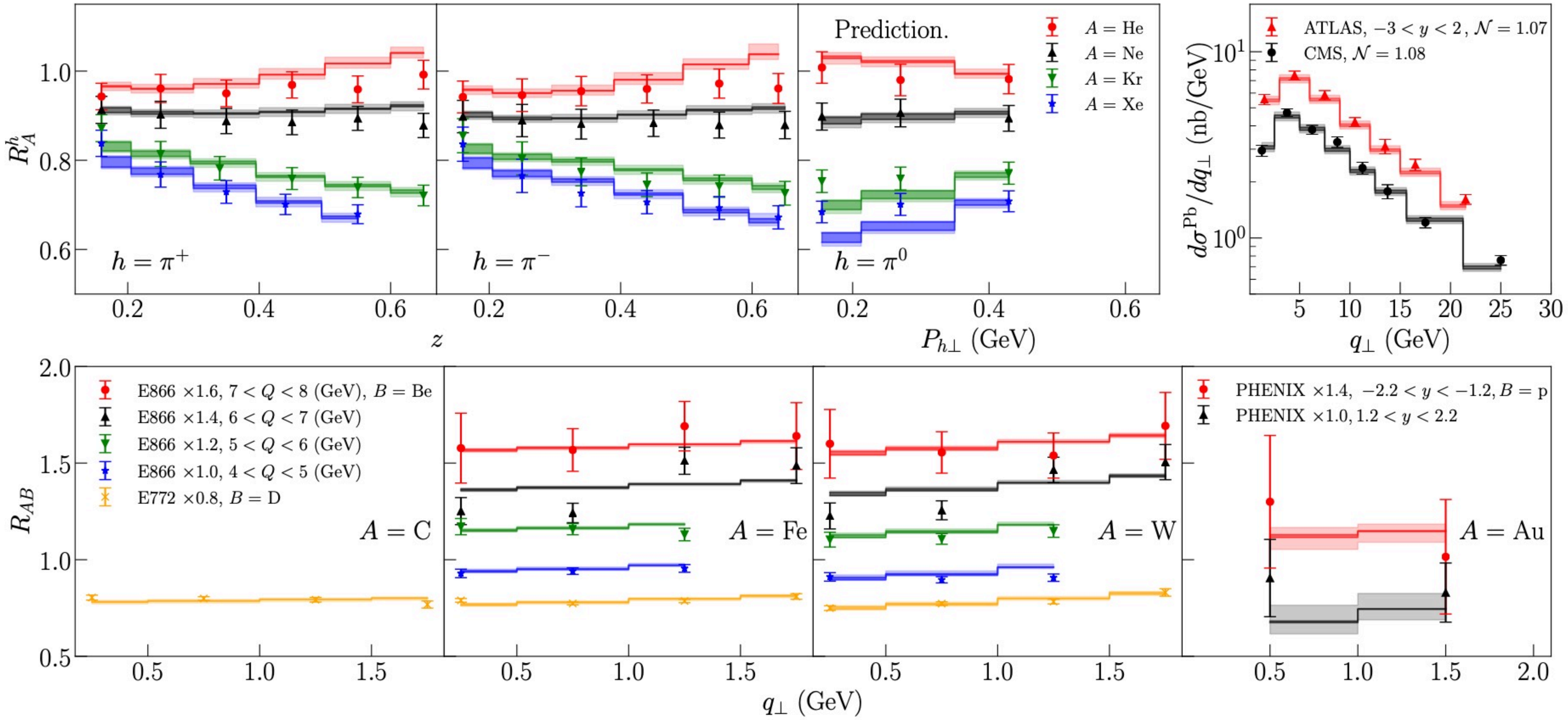
- An alternative way to explore different types of FFs
- Similar FJFs can be defined in exclusive jet production

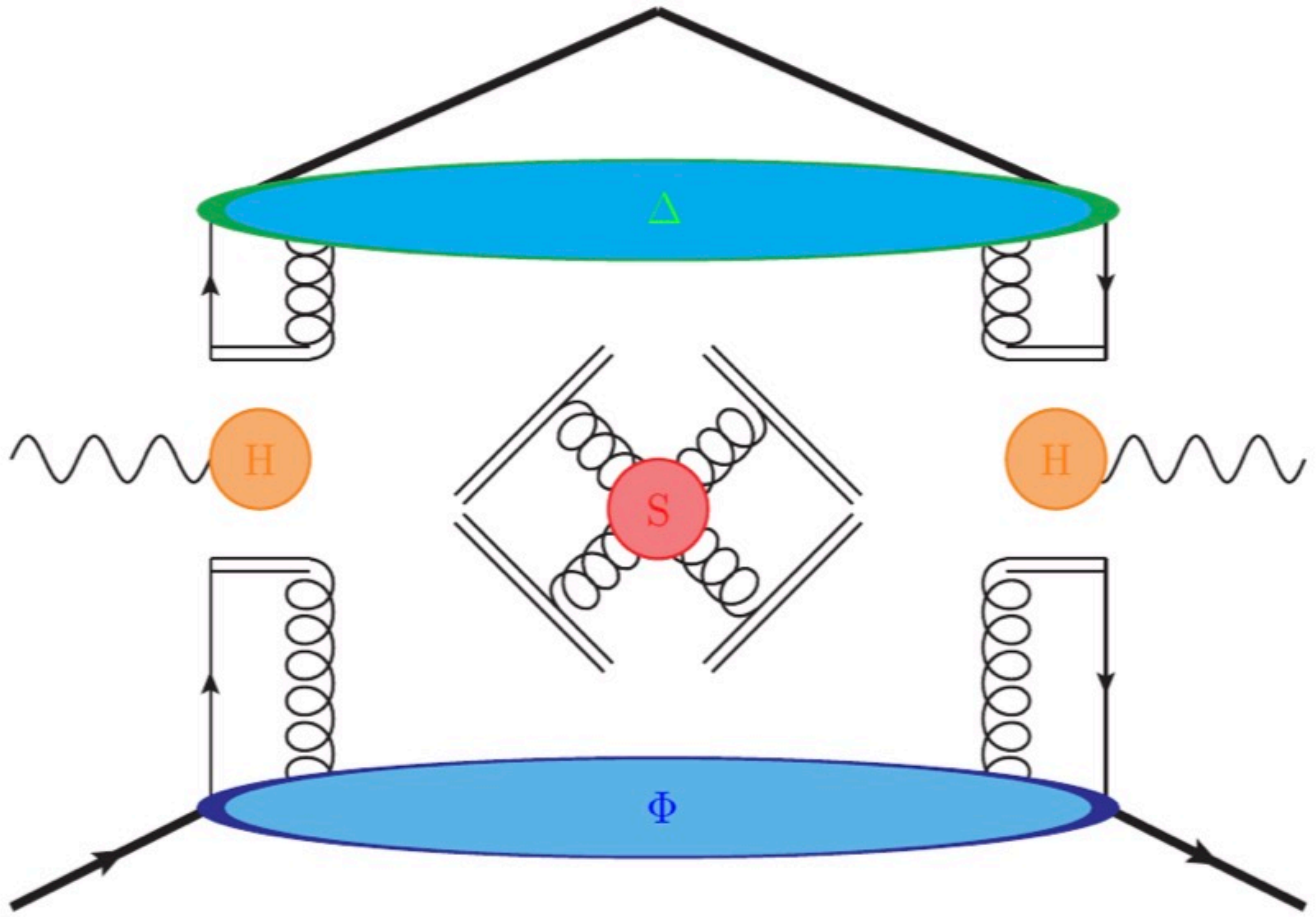
Nuclear modified transverse momentum dependent FFs

✦TMD factorization for SIDIS

Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022

$$\frac{d\sigma^A}{dx\,dQ^2\,dz\,d^2P_{h\perp}} = \sigma_0\,H(Q)\sum_q e_q^2\int_0^\infty \frac{b\,db}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f^A_{q/n}(x,b;Q)\,D^A_{h/q}(z,b;Q)$$

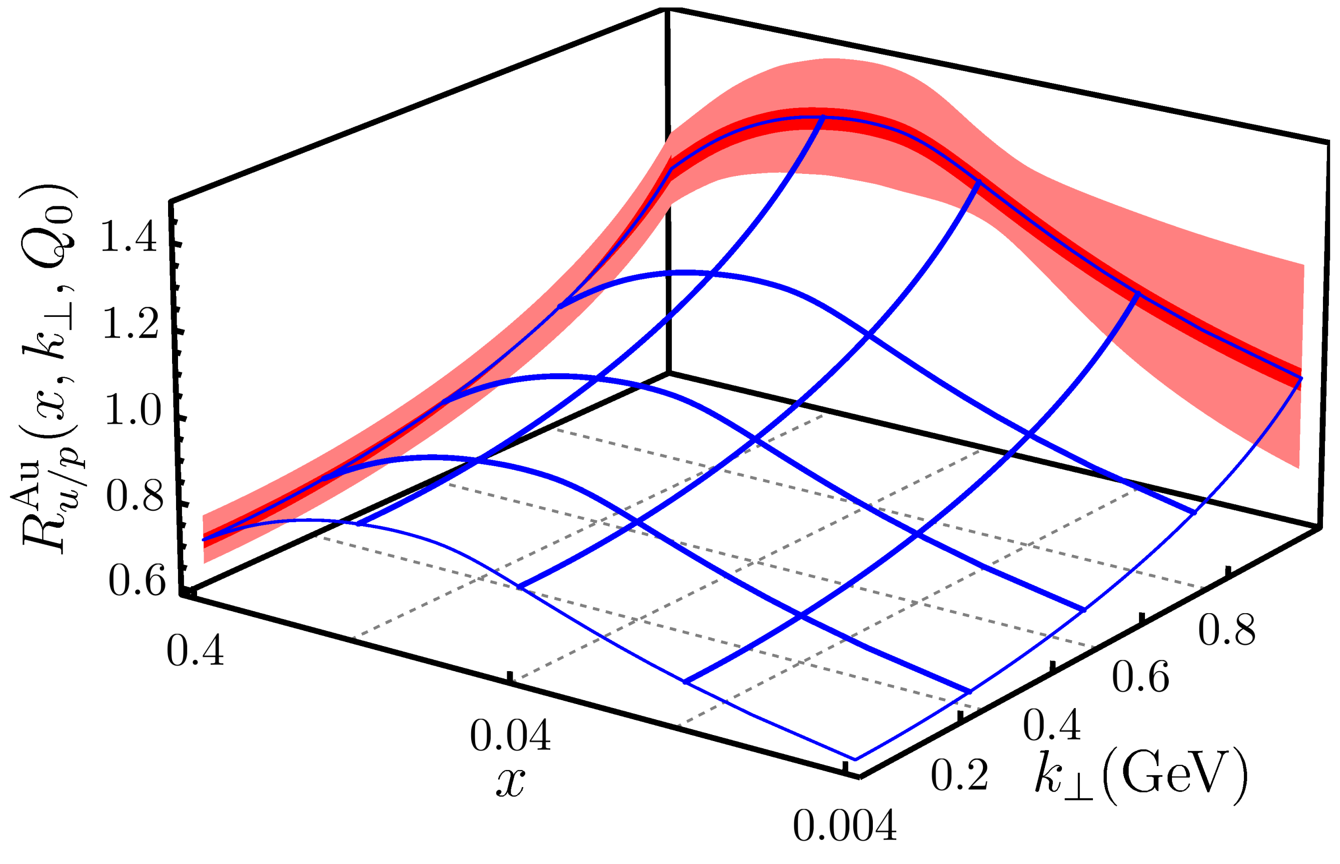




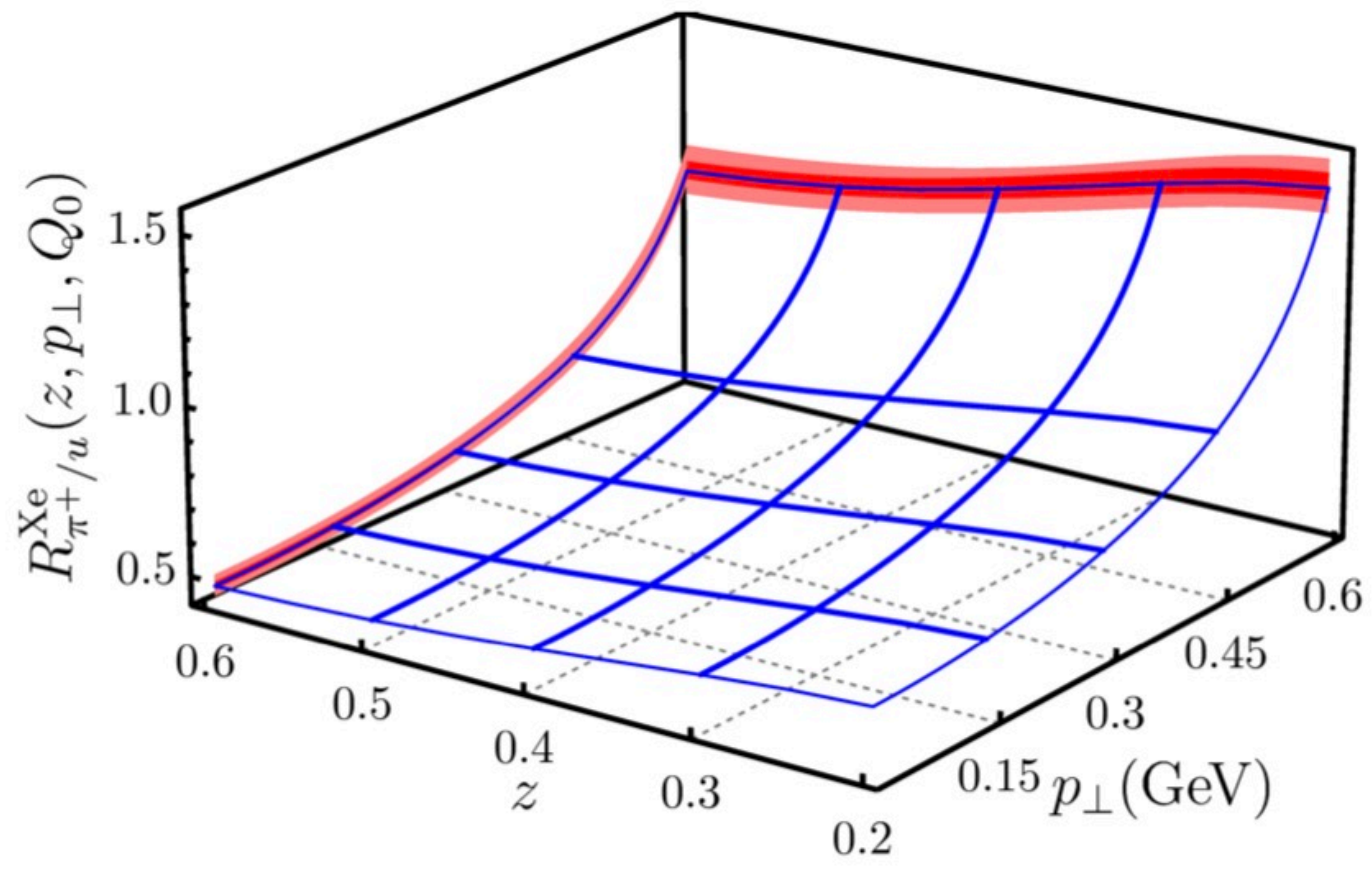
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

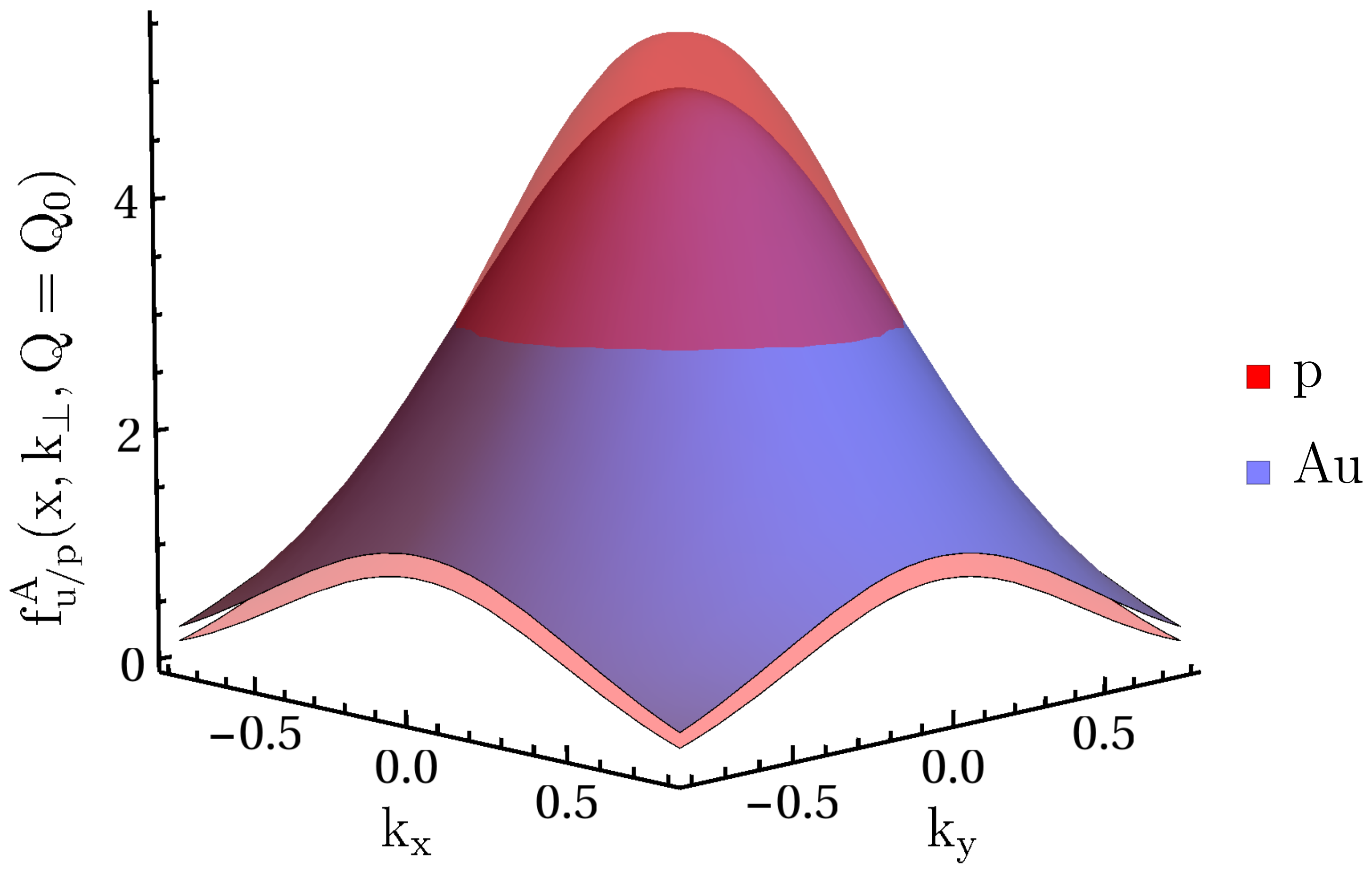
Nuclear imaging in 3D

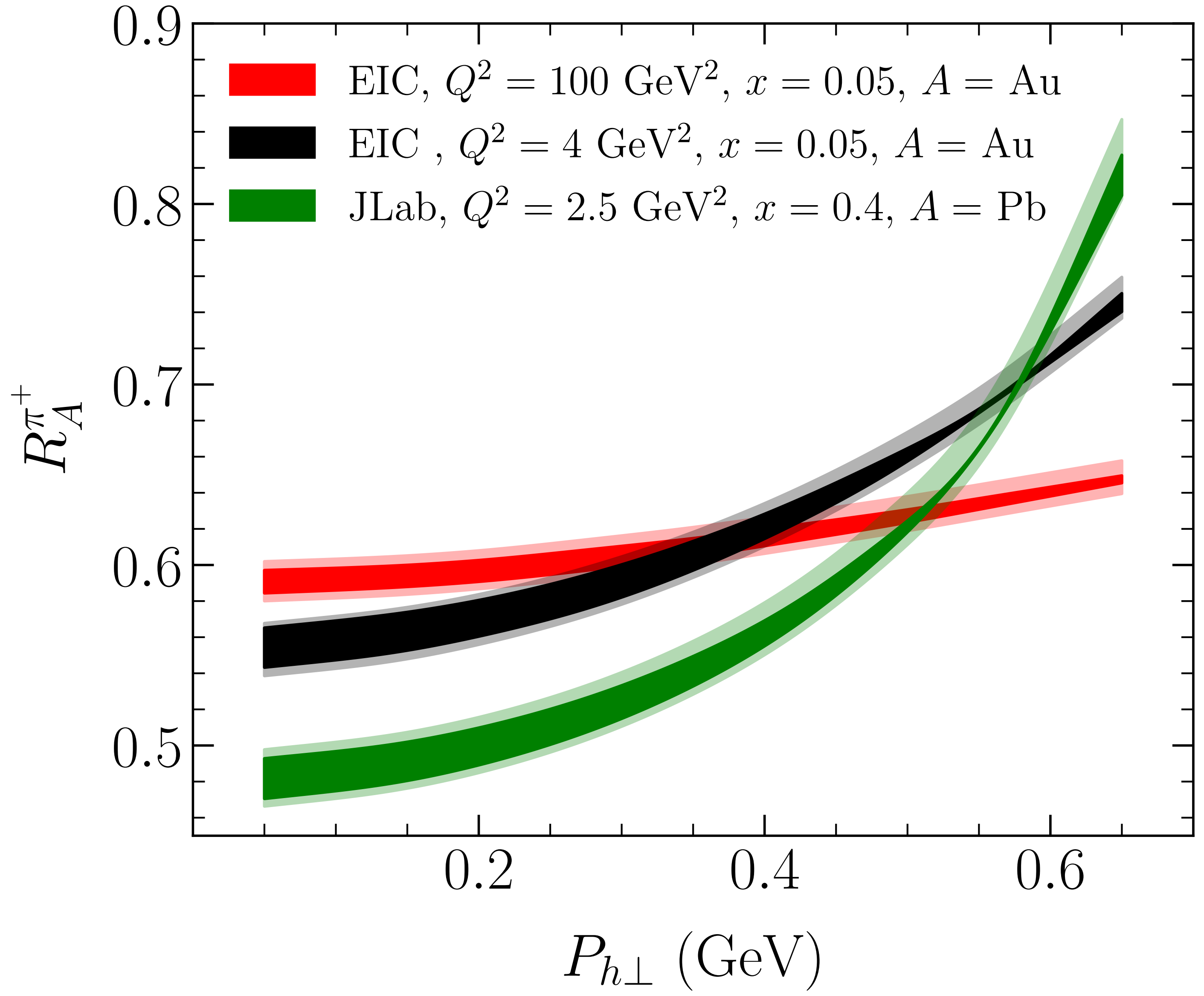
$$R_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0) = \frac{f_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)}$$



$$\mathcal{R}_{\pi^+/u}^{\mathrm{Xe}}(z, p_\perp, Q_0) = \frac{D_{\pi^+/u}^{\mathrm{Xe}}(z, p_\perp, Q_0)}{D_{\pi^+/u}(z, p_\perp, Q_0)}$$





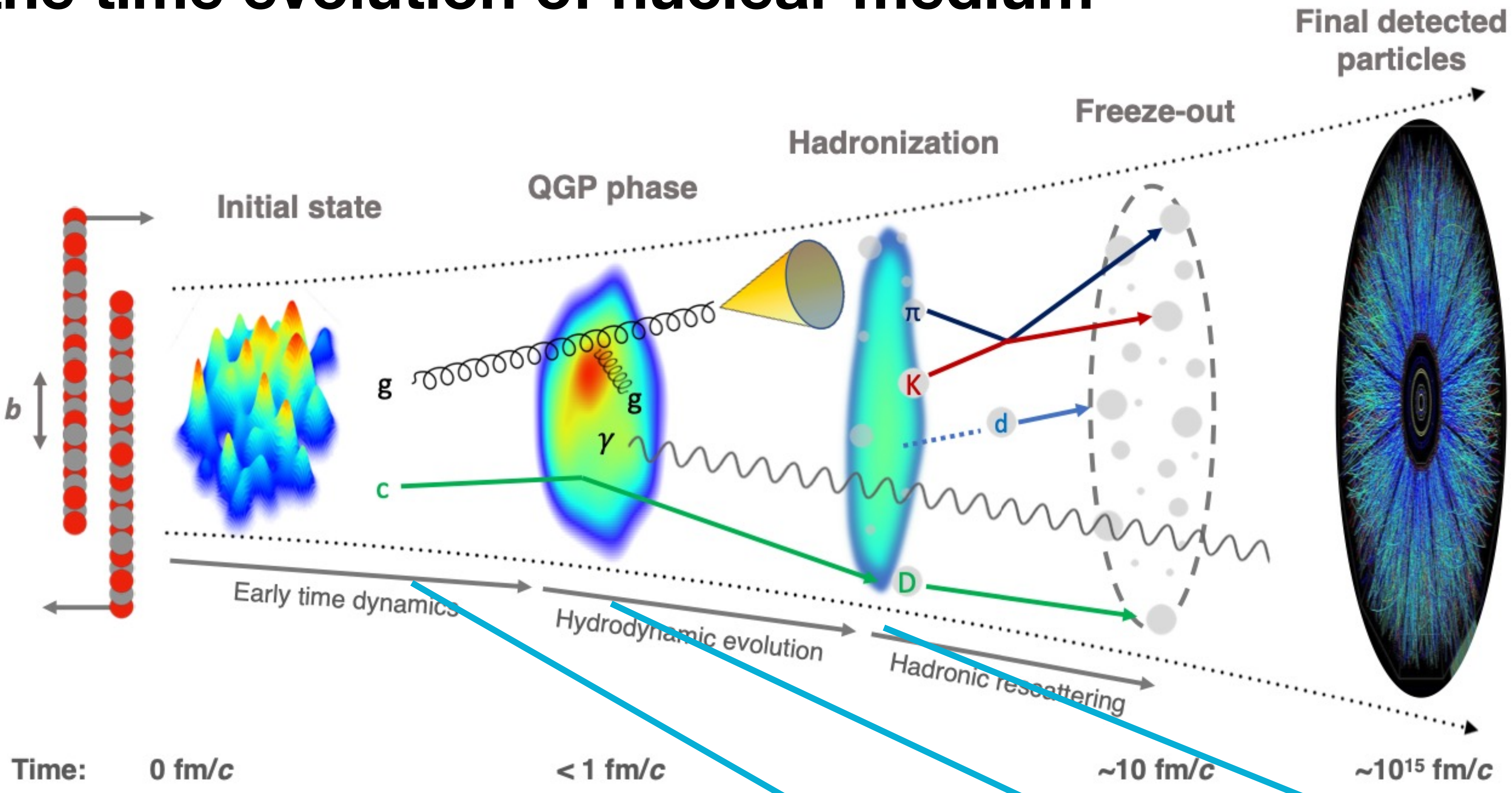


- First time quantitative determination of nuclear TMDs
- Identification of transverse momentum broadening in nuclei

- Update nuclear modified PDFs and FFs by including JLab data (arXiv:2312.09226)

Parton fragmentation in hot dense medium

✦ Track the time evolution of nuclear medium



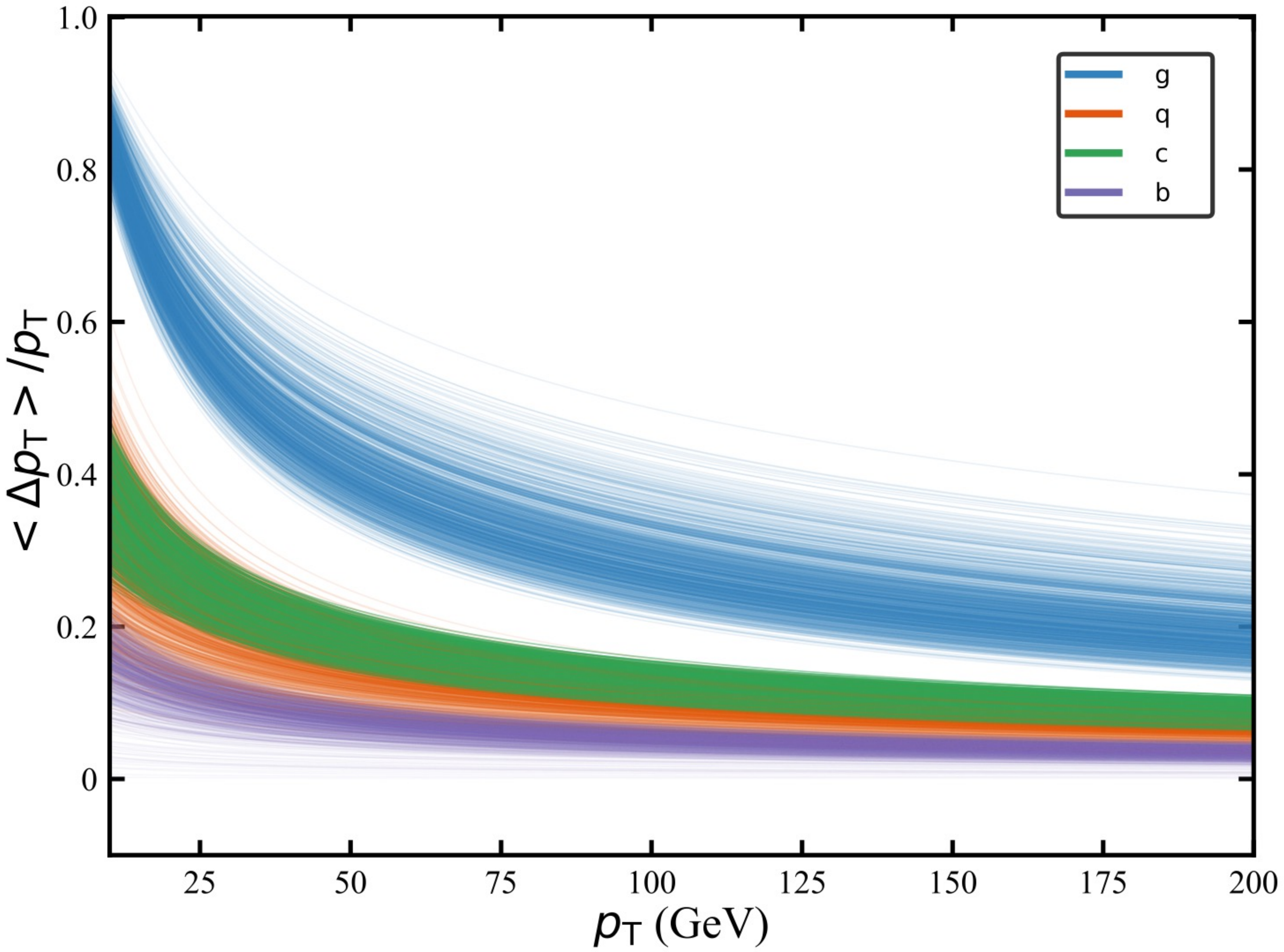
$$\sigma^{AA\to hX} = f_{i/A} \otimes f_{j/A} \otimes \tilde{\sigma}_{ij\to k} \otimes D_{k\to h}$$

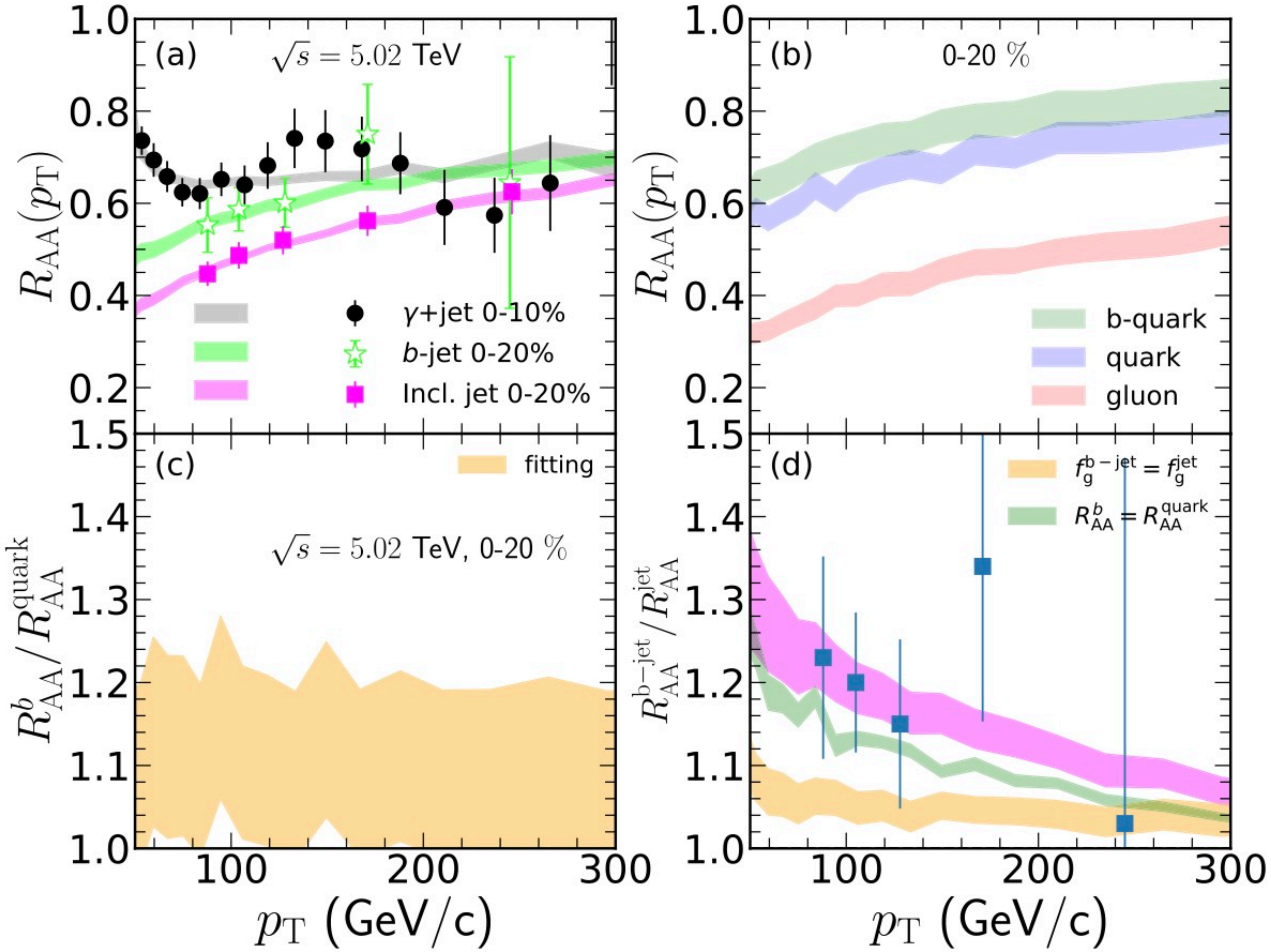
- Observables involving FFs: single inclusive hadron, di-hadron, photon/Z tagged hadron, jet fragmentation function

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

Heavy flavor in jet

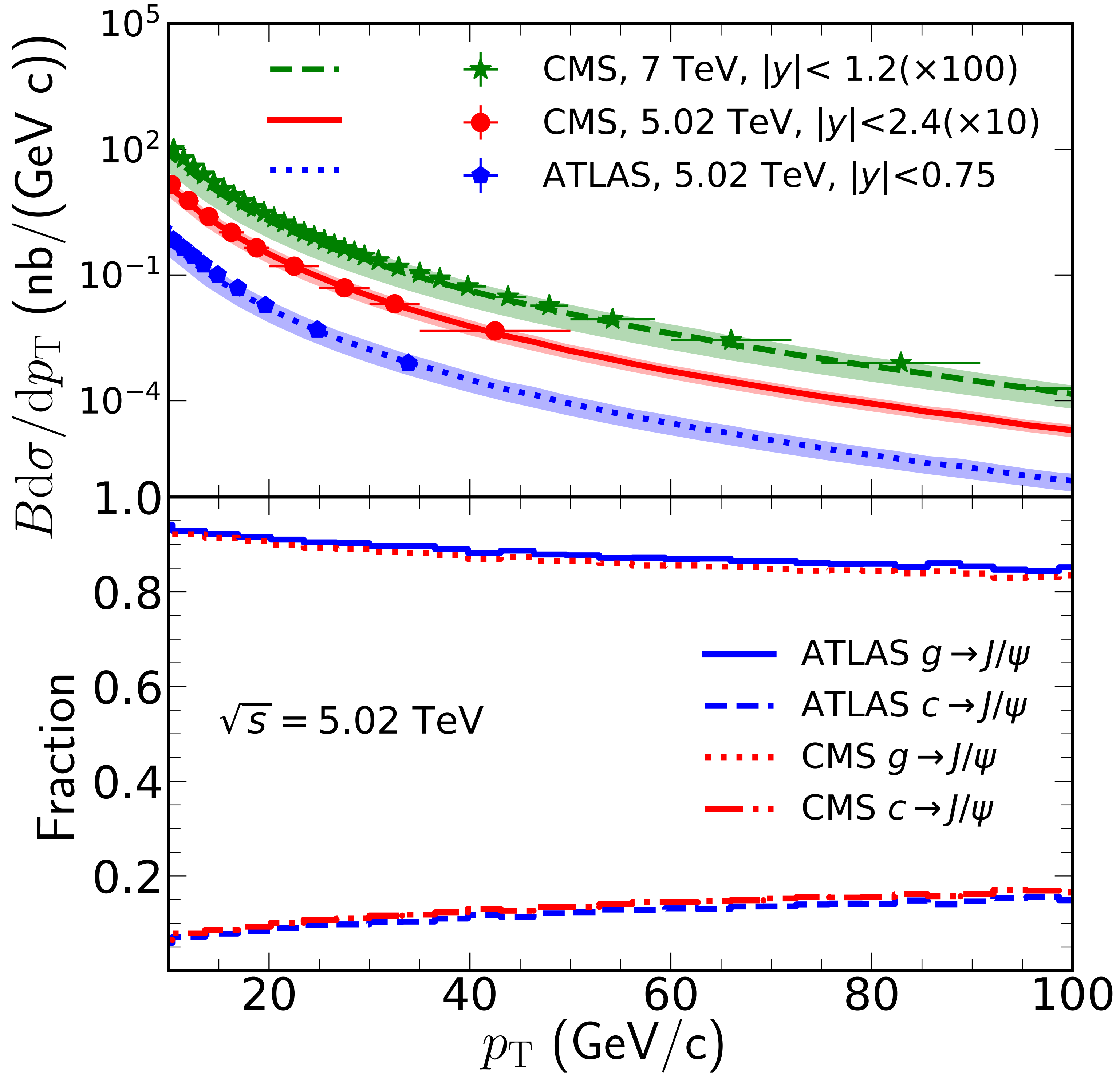
✦ J/ψ **production at** $p_T \gg m$

Zhang, Liao, Qin, Wang, **HX**, Sci.Bull, 2023

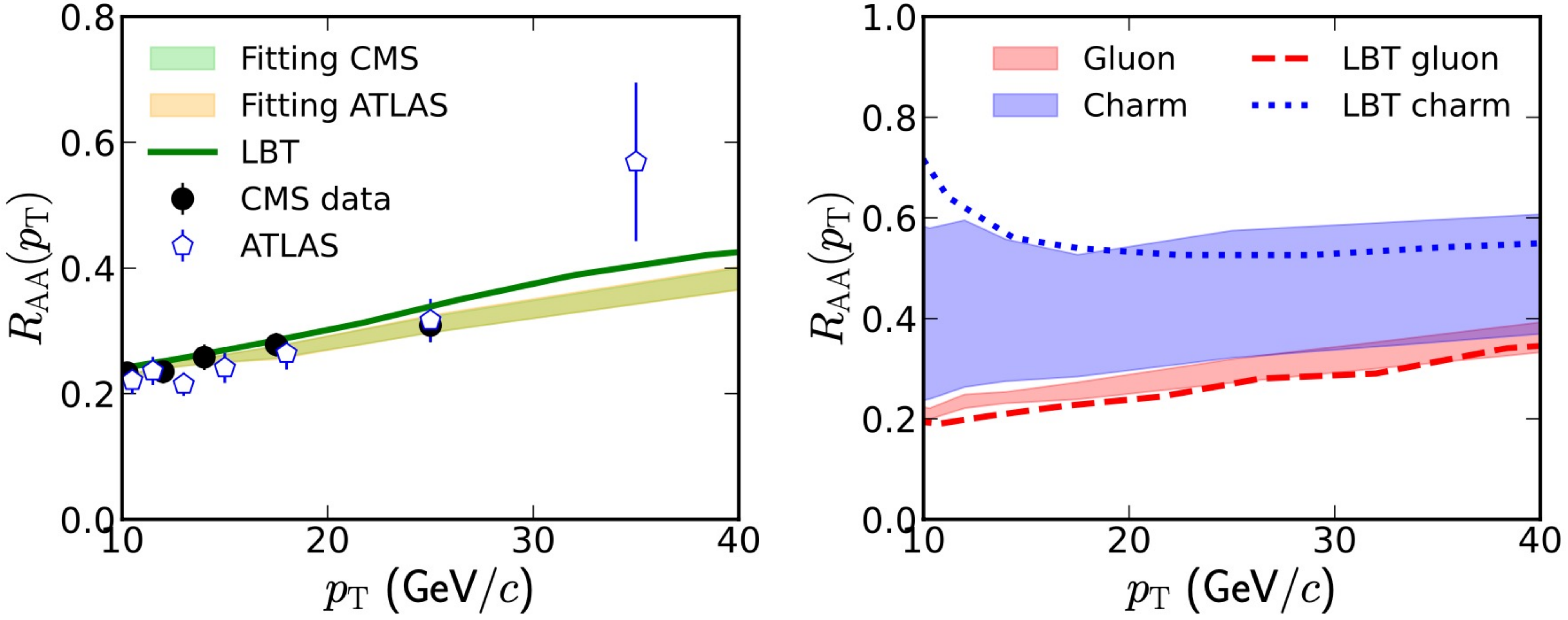
- Gluon fragmentation dominates high-pt J/ψ production

$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$$D_{i\to J/\psi}(z,\mu_0) = \sum_n \hat{d}_{i\to[c\bar{c}(n)]}(z,\mu_0)\langle \mathcal{O}^{J/\psi}_{[c\bar{c}(n)]}\rangle$$



Gluon fragmentation to J/ψ in vacuum

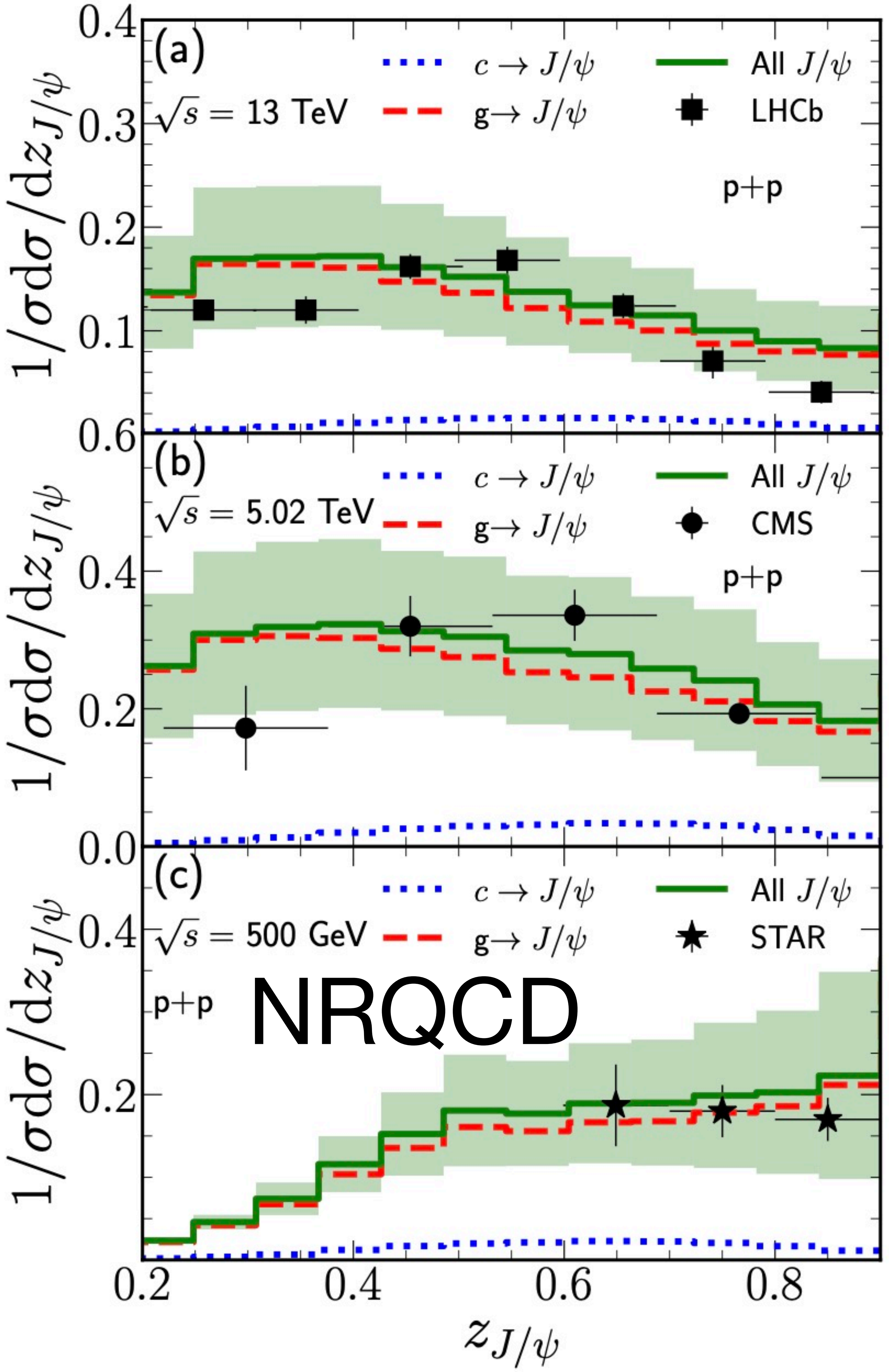


Gluon fragmentation to J/ψ in QGP

Heavy flavor in jet

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

Zhang, **HX**, 2403.12704

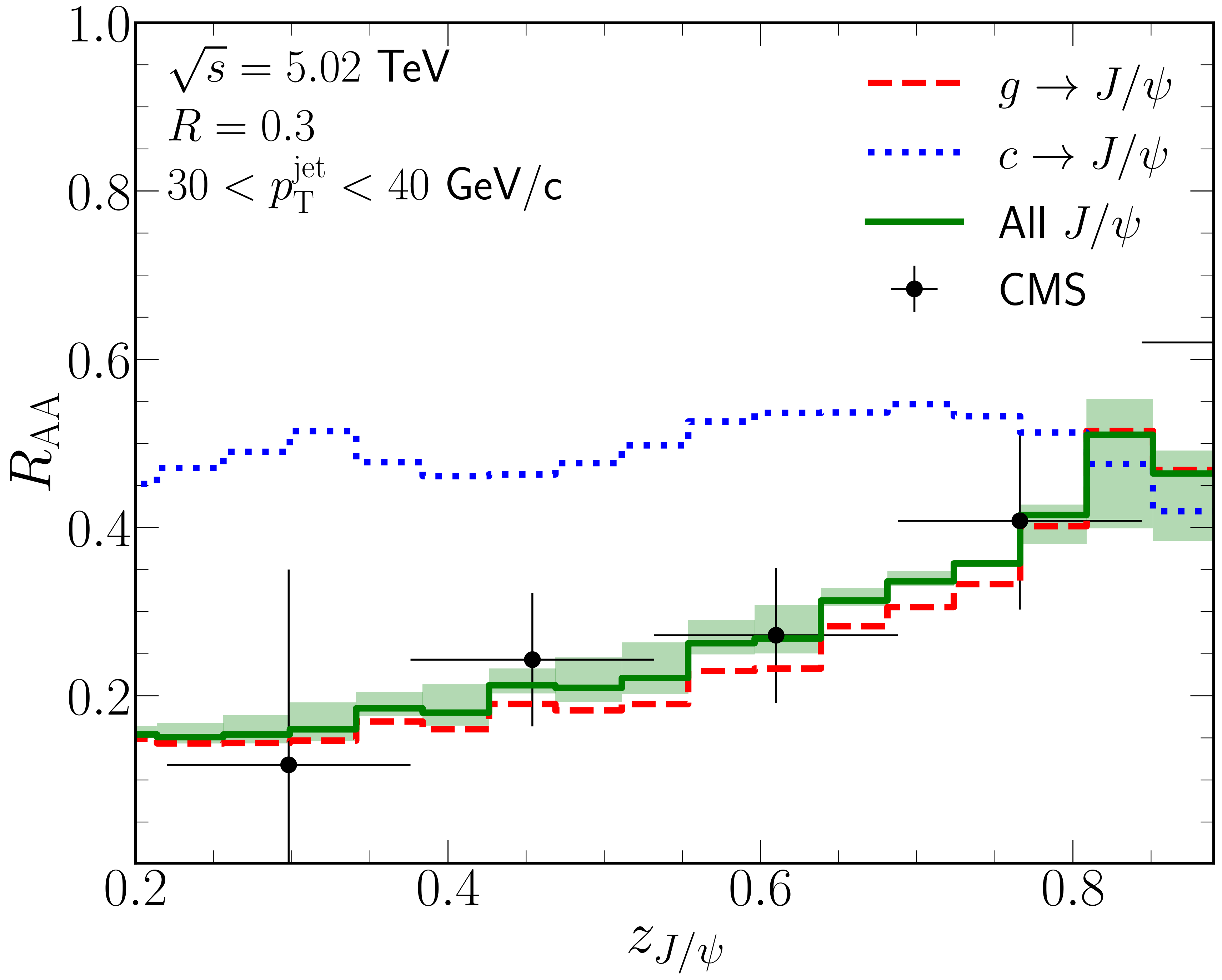


- Gluon fragmentation dominates high-pt J/ψ production

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

$$D_{i\to J/\psi}(z,\mu_0) = \sum_n \hat{d}_{i\to[c\bar{c}(n)]}(z,\mu_0)\langle \mathcal{O}^{J/\psi}_{[c\bar{c}(n)]}\rangle$$

- A unique probe to gluon jet quenching



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

✦ Parton fragmentation in medium as a tool to identify jet quenching mechanism

- Works in progress: a comprehensive study on flavor hierarchy of jet quenching by including various hadrons (π, k, D, B, J/ψ)

The 9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions (HF-HNC 2024)

Guangzhou, China, December 6-11, 2024

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