Parton fragmentation functions

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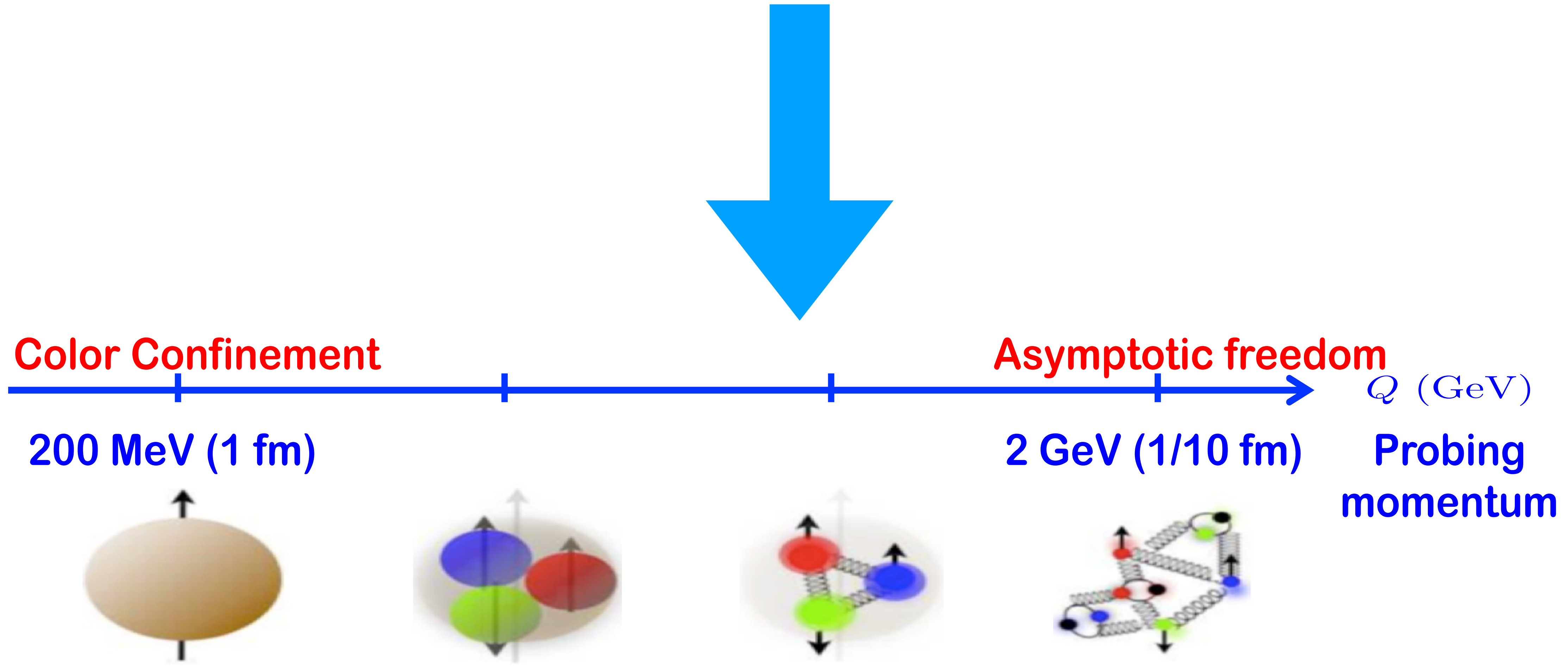
2024.6.16

A fundamental property of QCD - color confinement

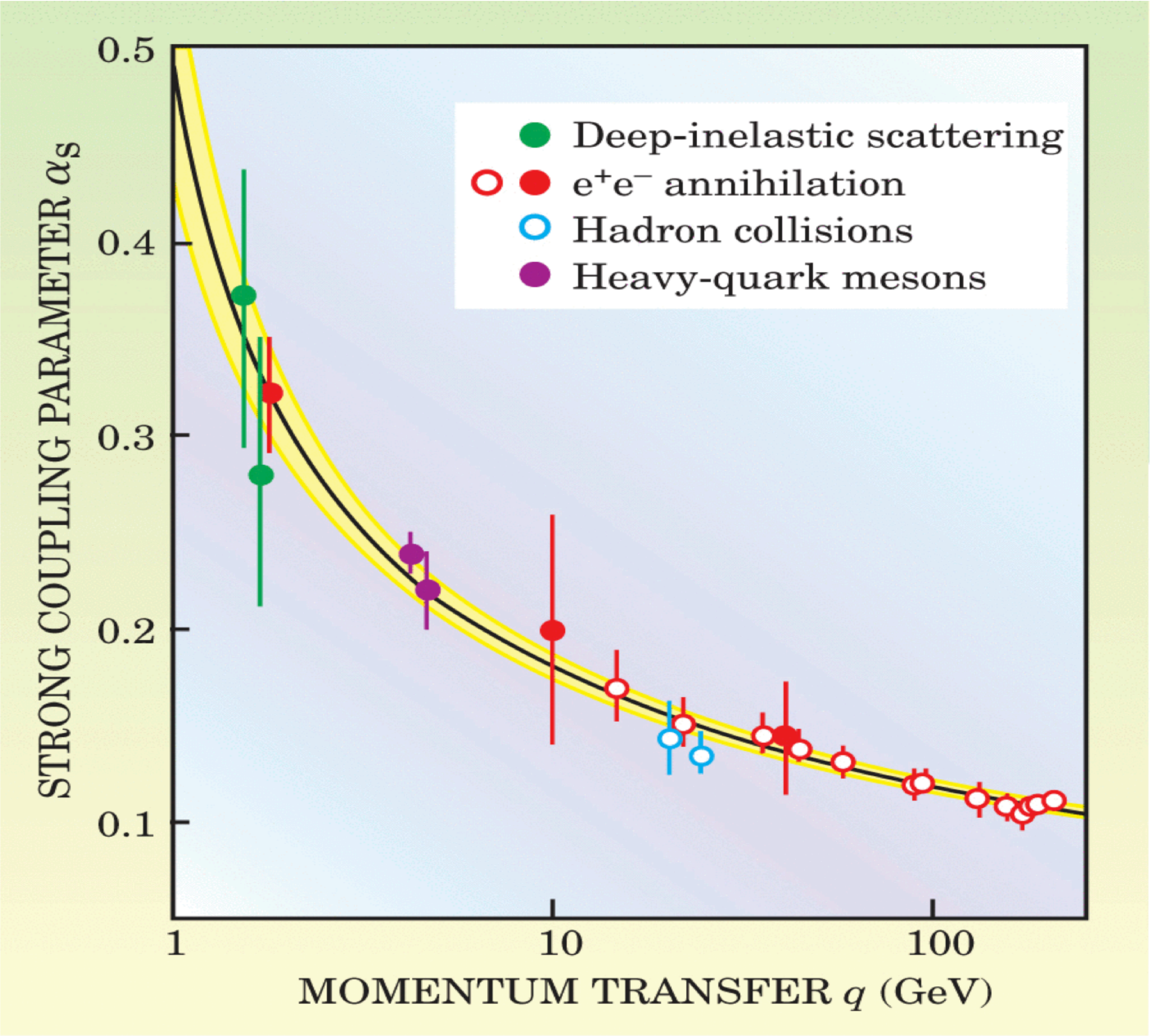
✦ QCD as the fundamental theory of strong interaction

$$\mathcal{L} = \overline{\Psi}_c(i\gamma^\mu\partial_\mu - m)\Psi_c + g\,\overline{\Psi}_c\gamma^\mu T_a\Psi_c G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} \equiv \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f_{abc} G^b_\mu G^c_\nu$$

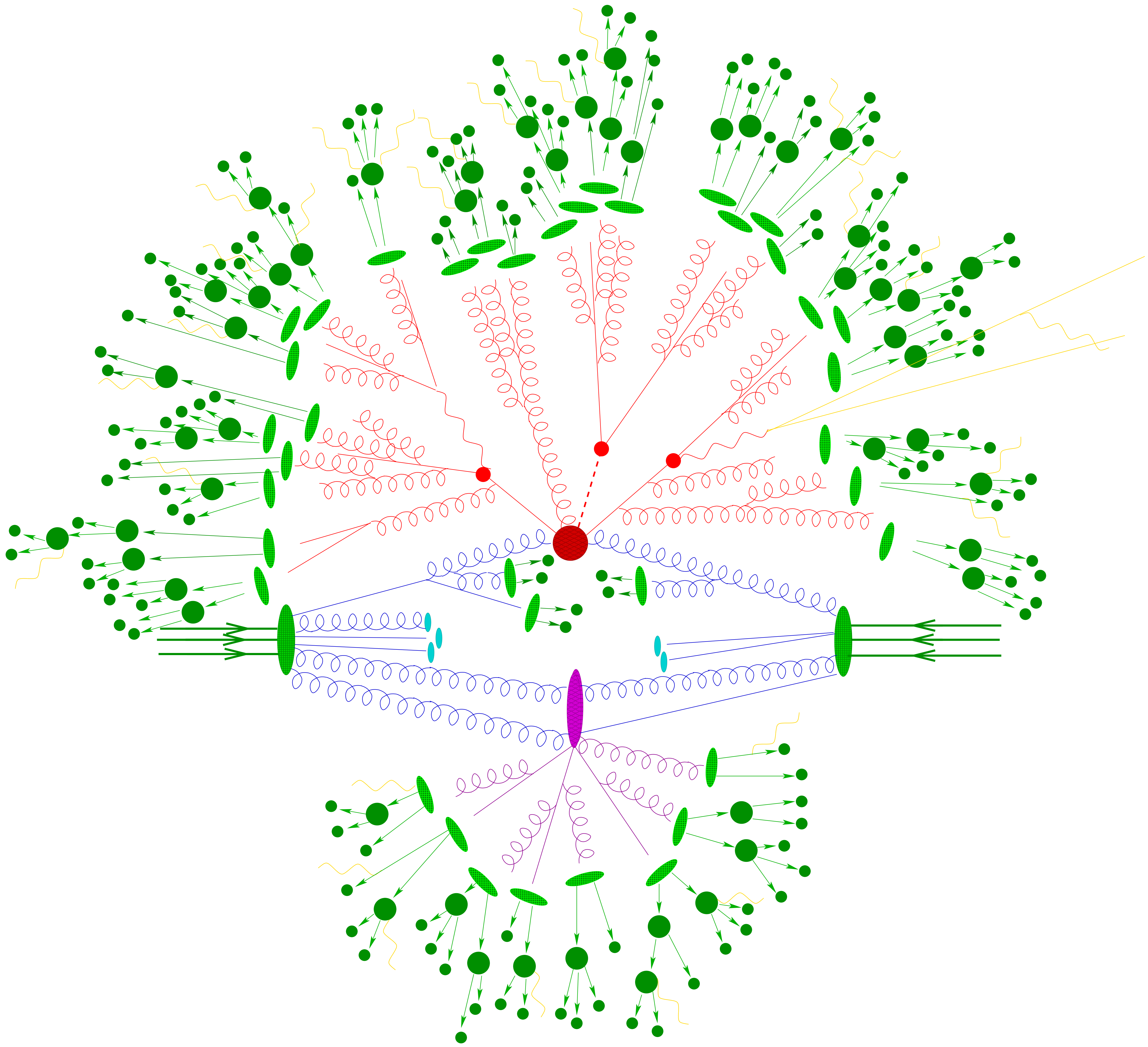


Color confinement in low energy/long distance scale



High energy scattering event

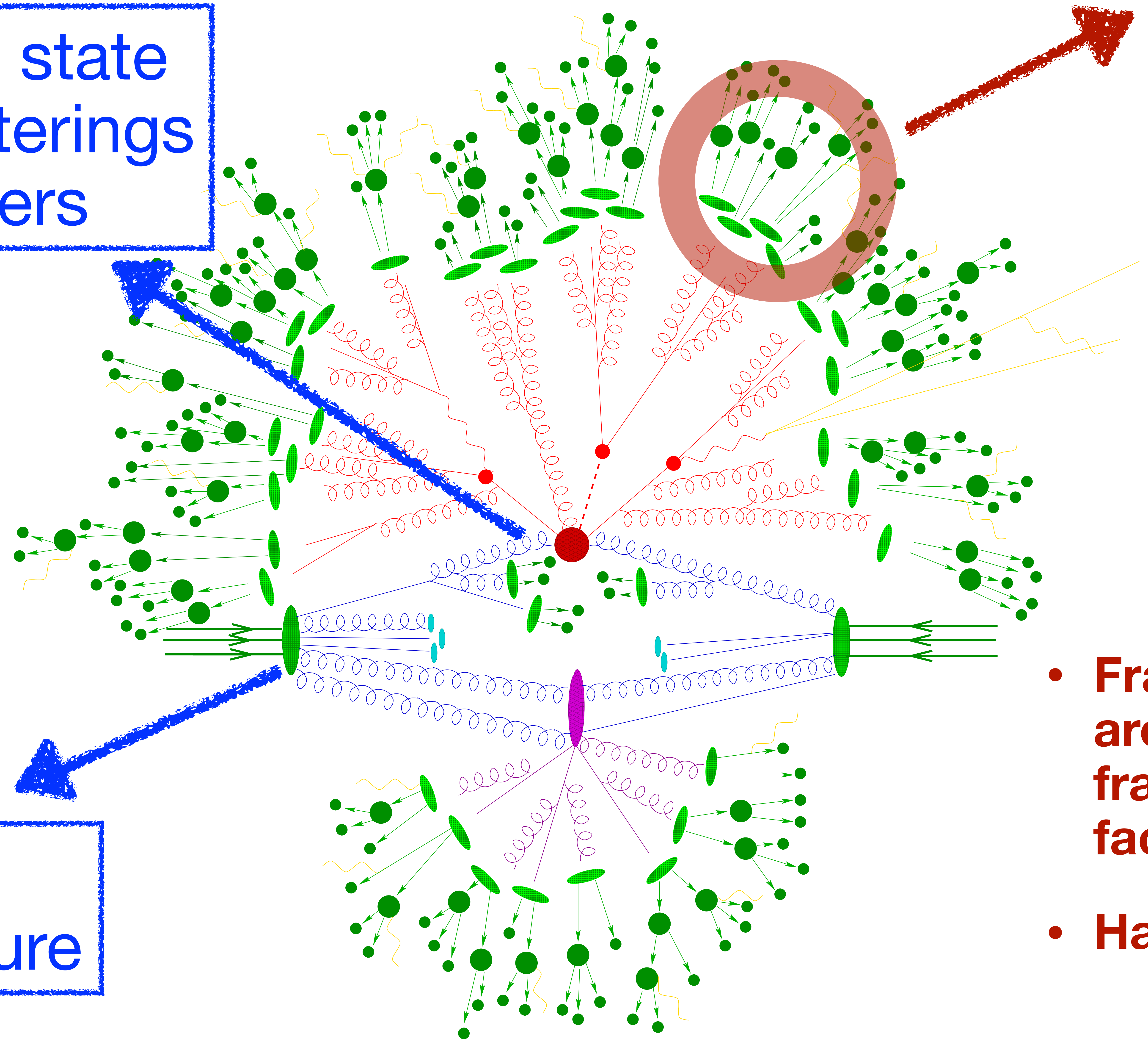
- ✦ **Proton-proton collision**



Hadronization is everywhere

✦ **Proton-proton collision**

Intermediate state partonic scatterings and showers



Initial state hadron structure

Final state hadronization

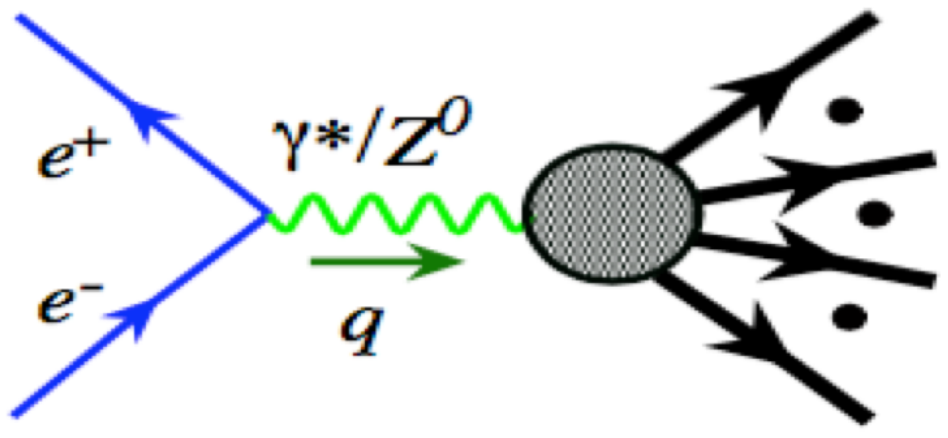
- String fragmentation in PYTHIA
- Cluster hadronization in HERWIG and SHERPA
- Coalescence in AMPT

- **Fragmentation Functions (FFs) are defined within the framework of QCD factorization!**
- **Hadronization $\neq$ FFs**

Multiple channels to explore parton hadronization

✦ Indispensable joint efforts from experiments and QCD theory

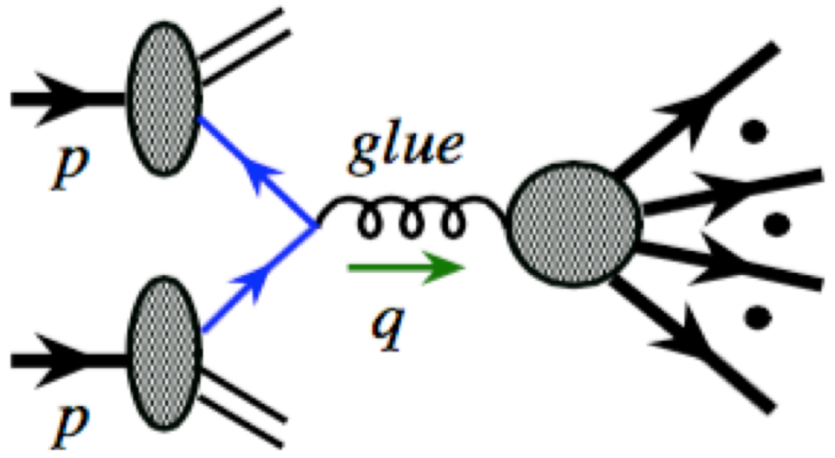
Lepton-lepton colliders



BEPC, SuperKEKB

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

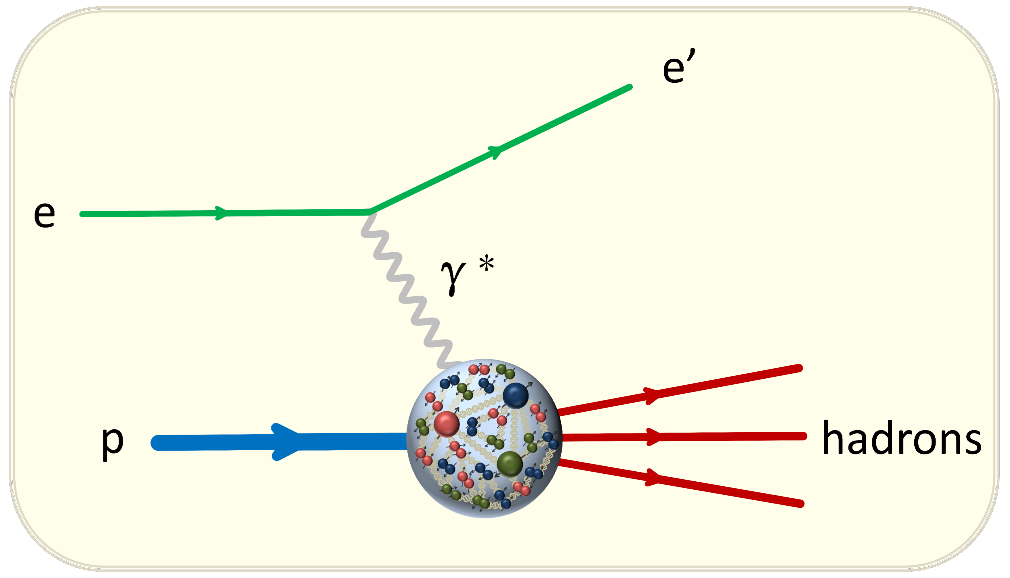
Hadron-hadron colliders



RHIC, LHC

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

lepton-hadron colliders

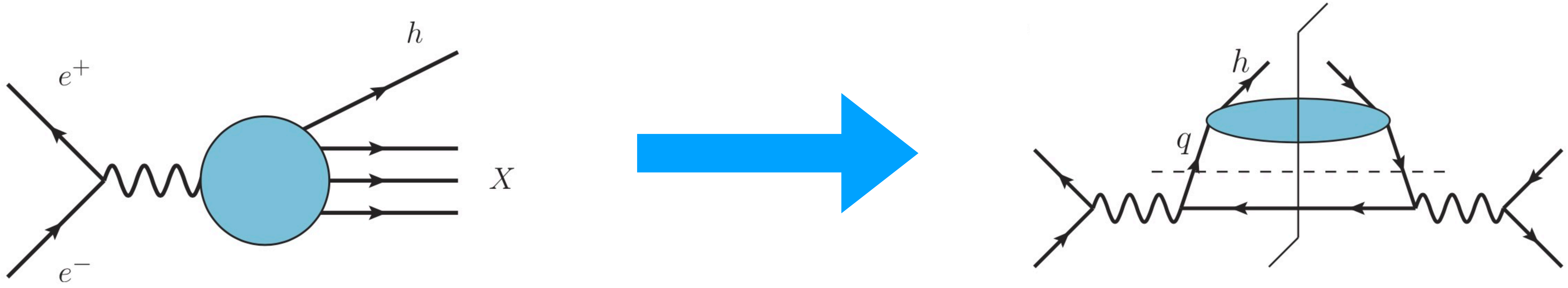


HERA, JLab

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

A clean access to fragmentation functions

✦ QCD factorization in electron-positron annihilation



- Leading power/twist collinear factorization

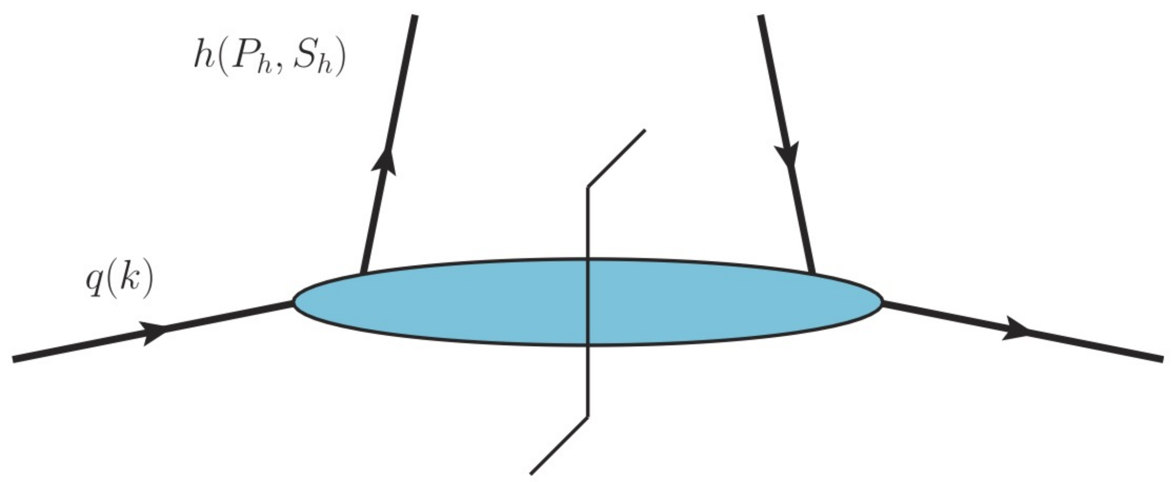
$$\sigma^{e^+e^-\to hX} = \hat{\sigma}_{e^+e^-\to i} \otimes D_{i\to h}$$

- 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.

✦ Leading twist unpolarized fragmentation functions

- **Operator definition**

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



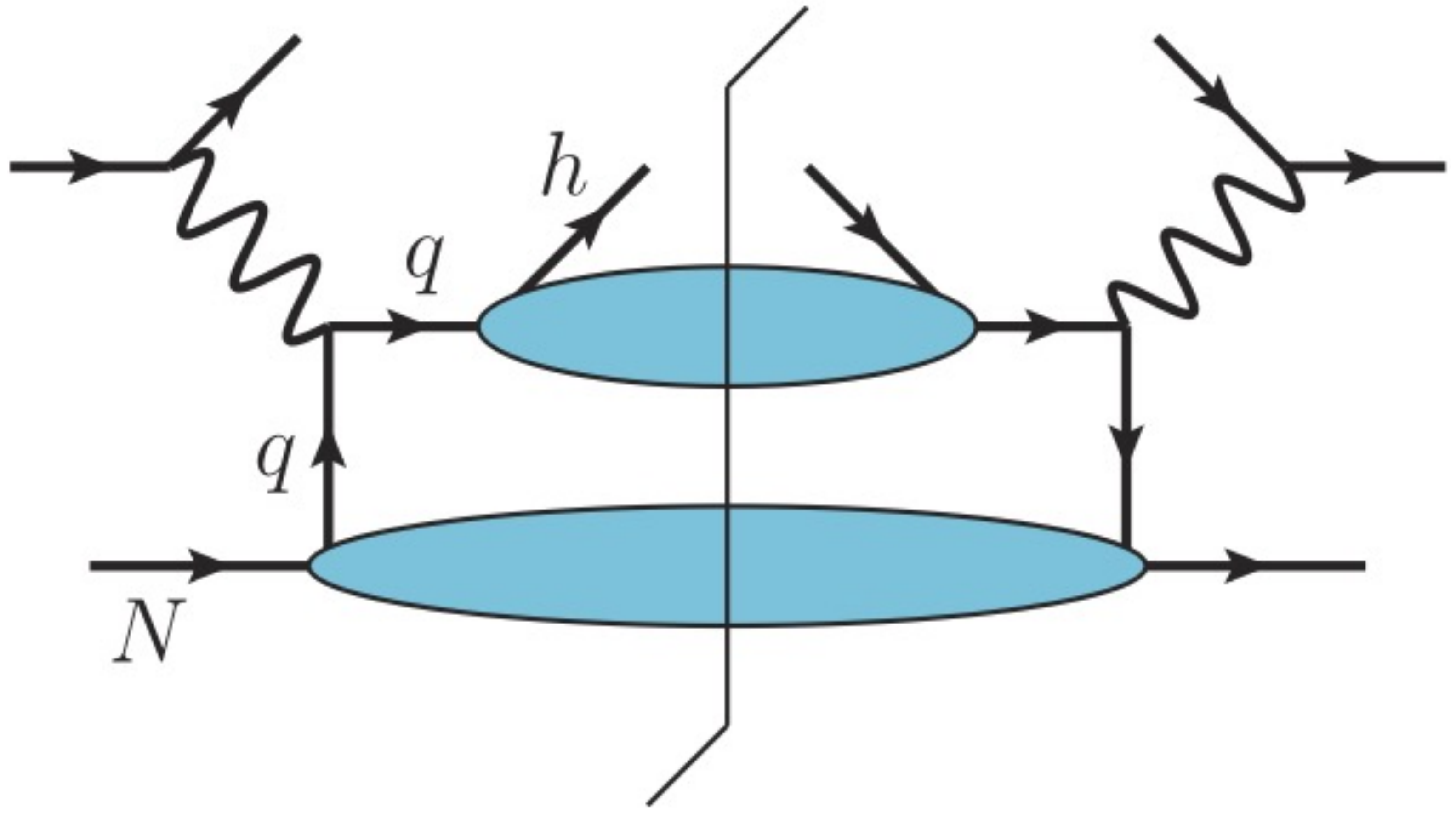
- **Probability densities for finding color-neutral particles inside partons**
- **Momentum sum rule** $$\sum_h \sum_{S_h} \int_0^1 dz\, z\, D_1^{h/q}(z) = 1$$
- **Time-like DGLAP QCD evolution**

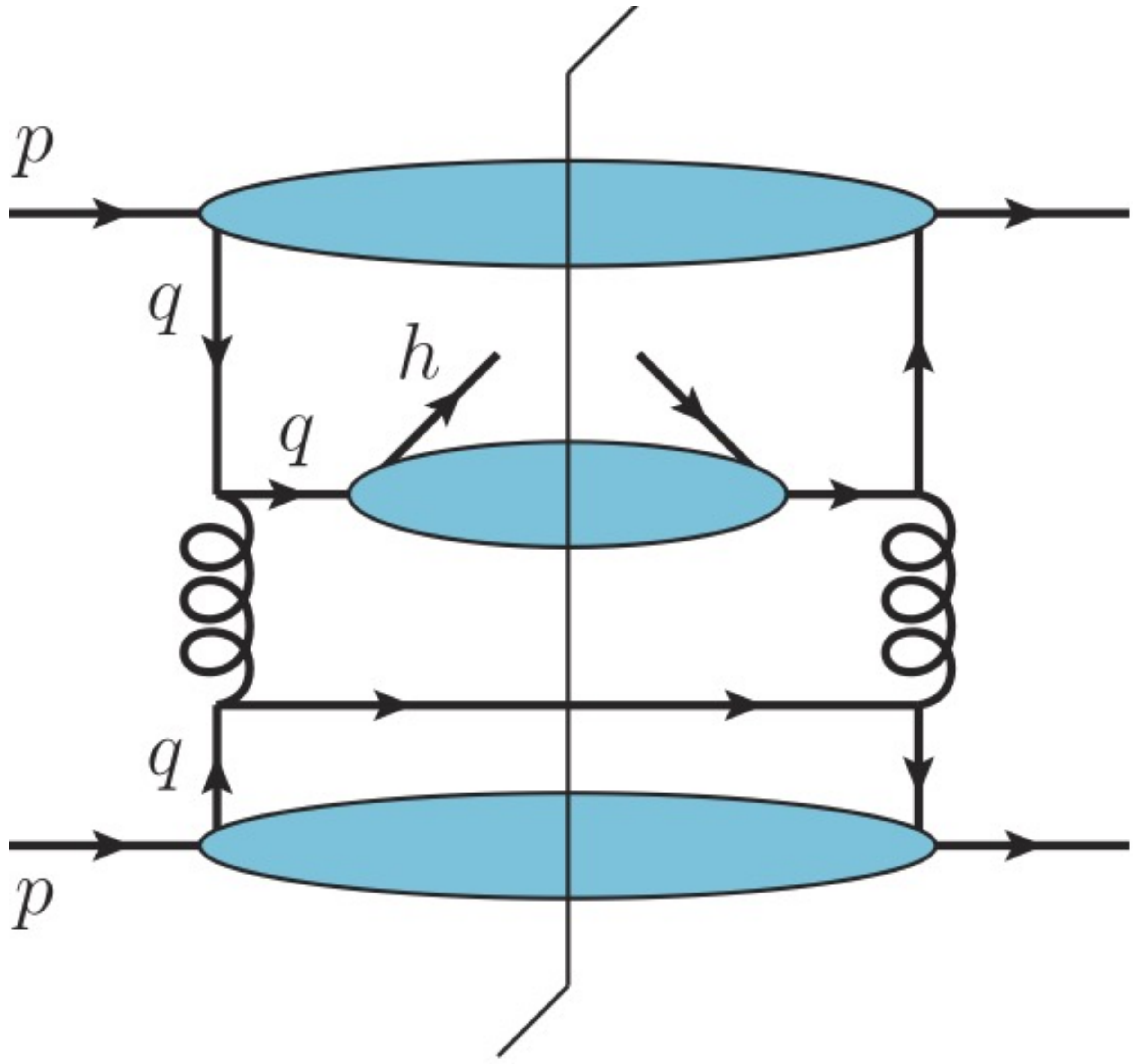
$$\frac{d}{d\ln\mu^2} D_1^{h/i}(z, \mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \sum_j \int_z^1 \frac{du}{u} P_{ji}(u, \alpha_s(\mu^2))\, D_1^{h/j}\left(\frac{z}{u}, \mu^2\right)$$

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

Fragmentation Functions

✦ 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

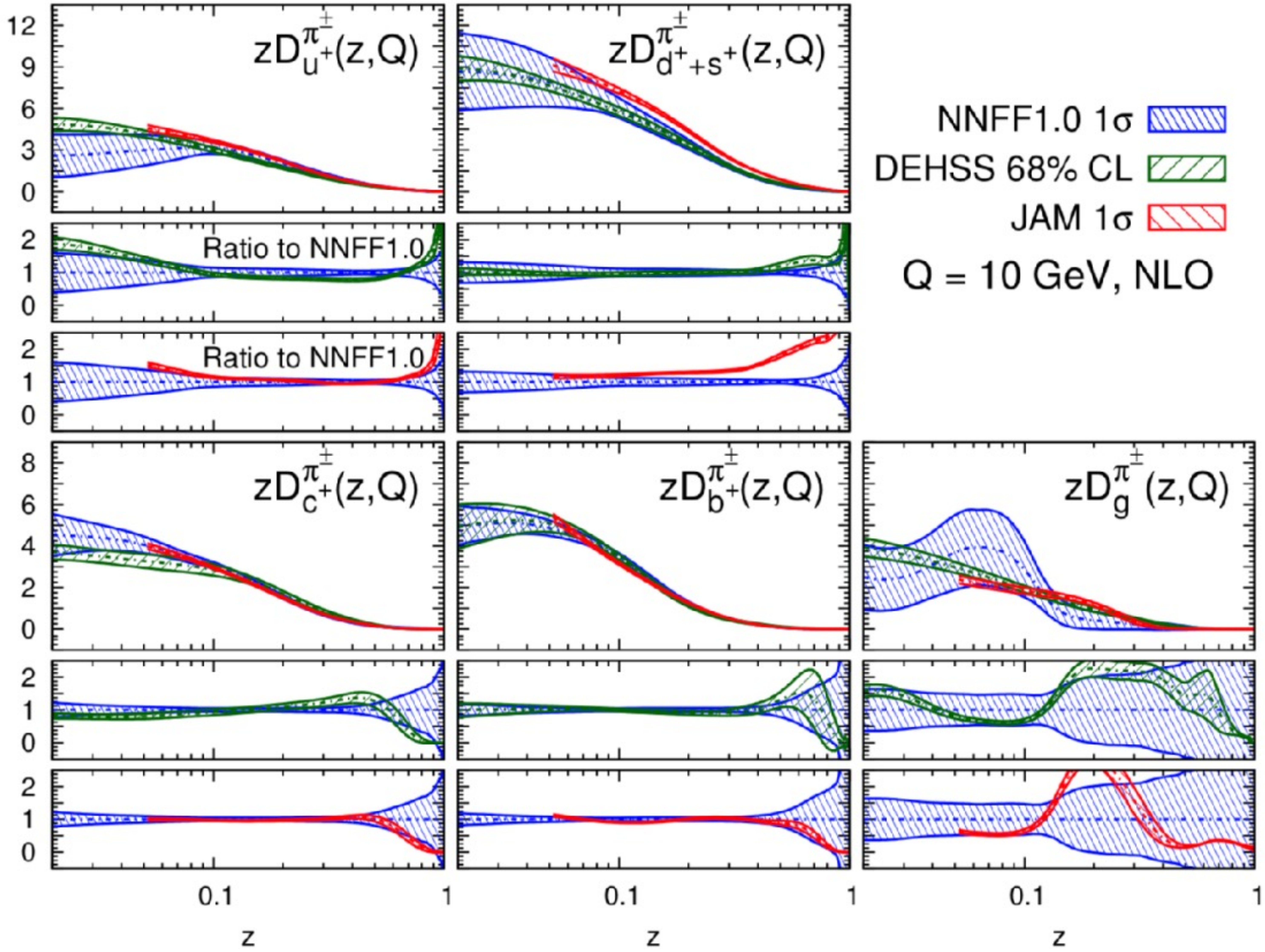
FF global fitting panorama

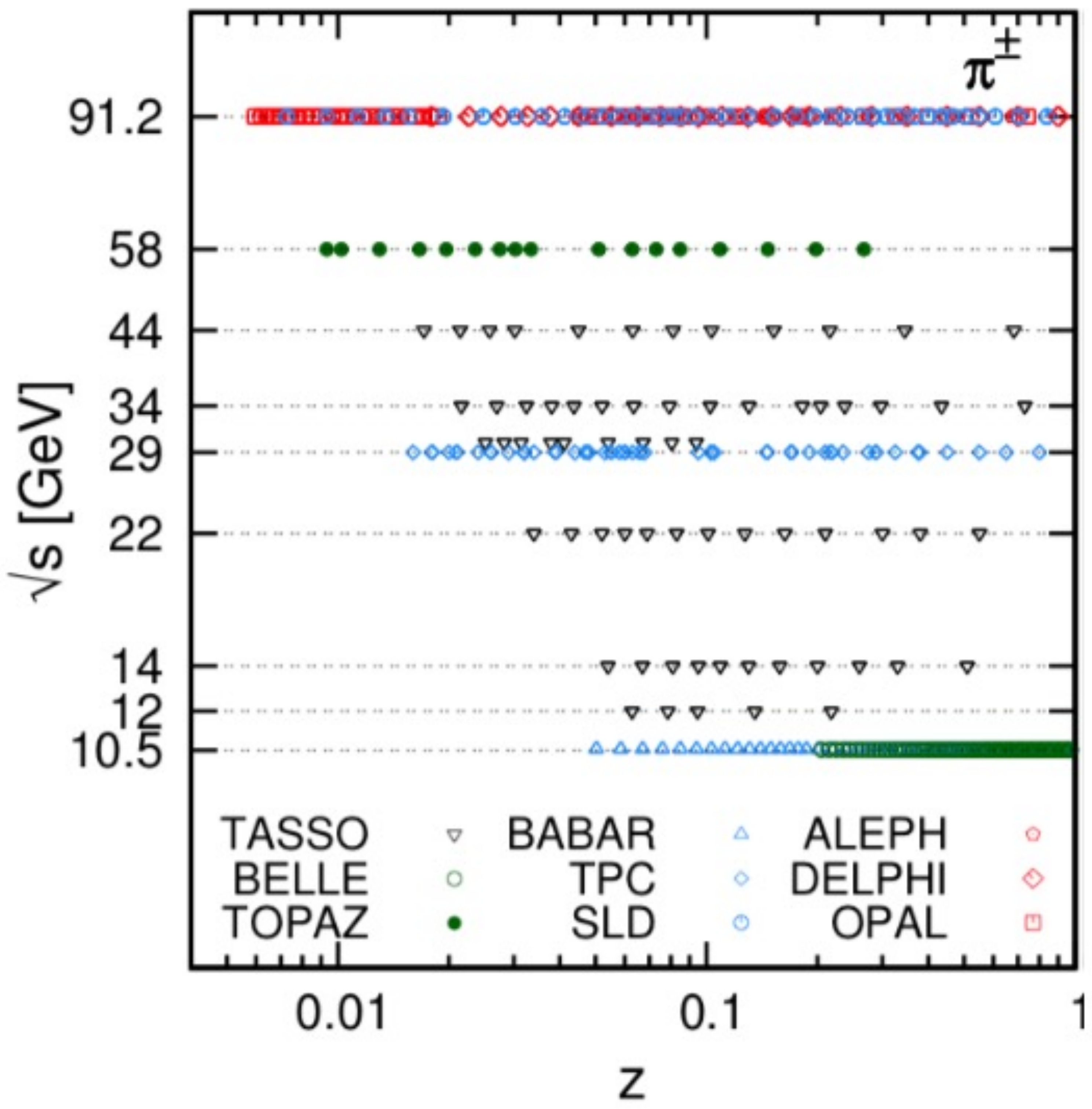
✦ Joint efforts from experiments and theory in extracting FFs

	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

✦ The best known FFs - π

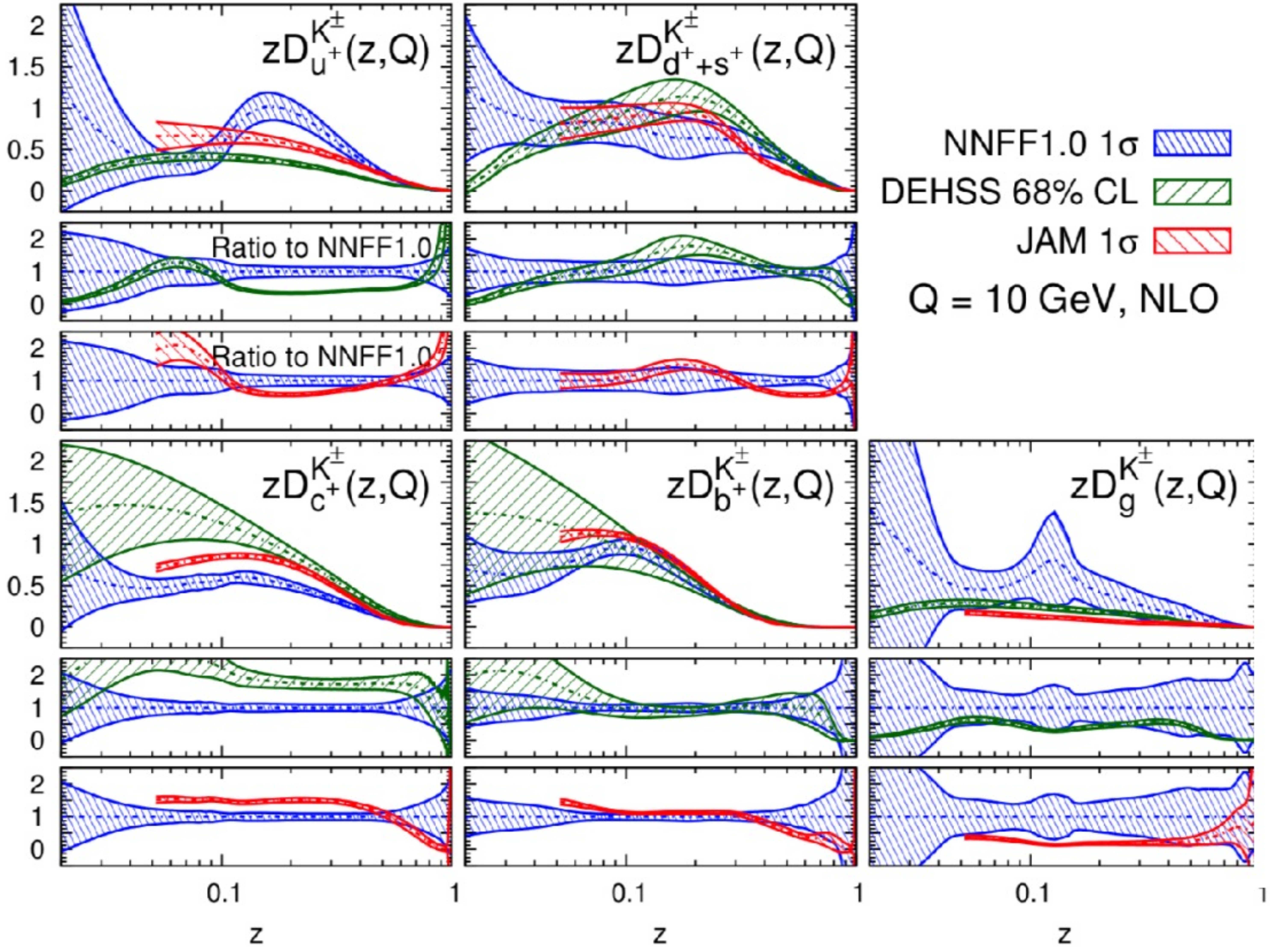
V.Bertone et al. [NNPDF collaboration] Eur.Phys.J.C 77 (2017) 8, 516
D. de Florian et al. , Phys. Rev. D 91 (2015), 4035, D 95 (2017), 094019
N. Sato et al. [JAM Collaboration] Physical Review D, 94 (2016) 11, 114004

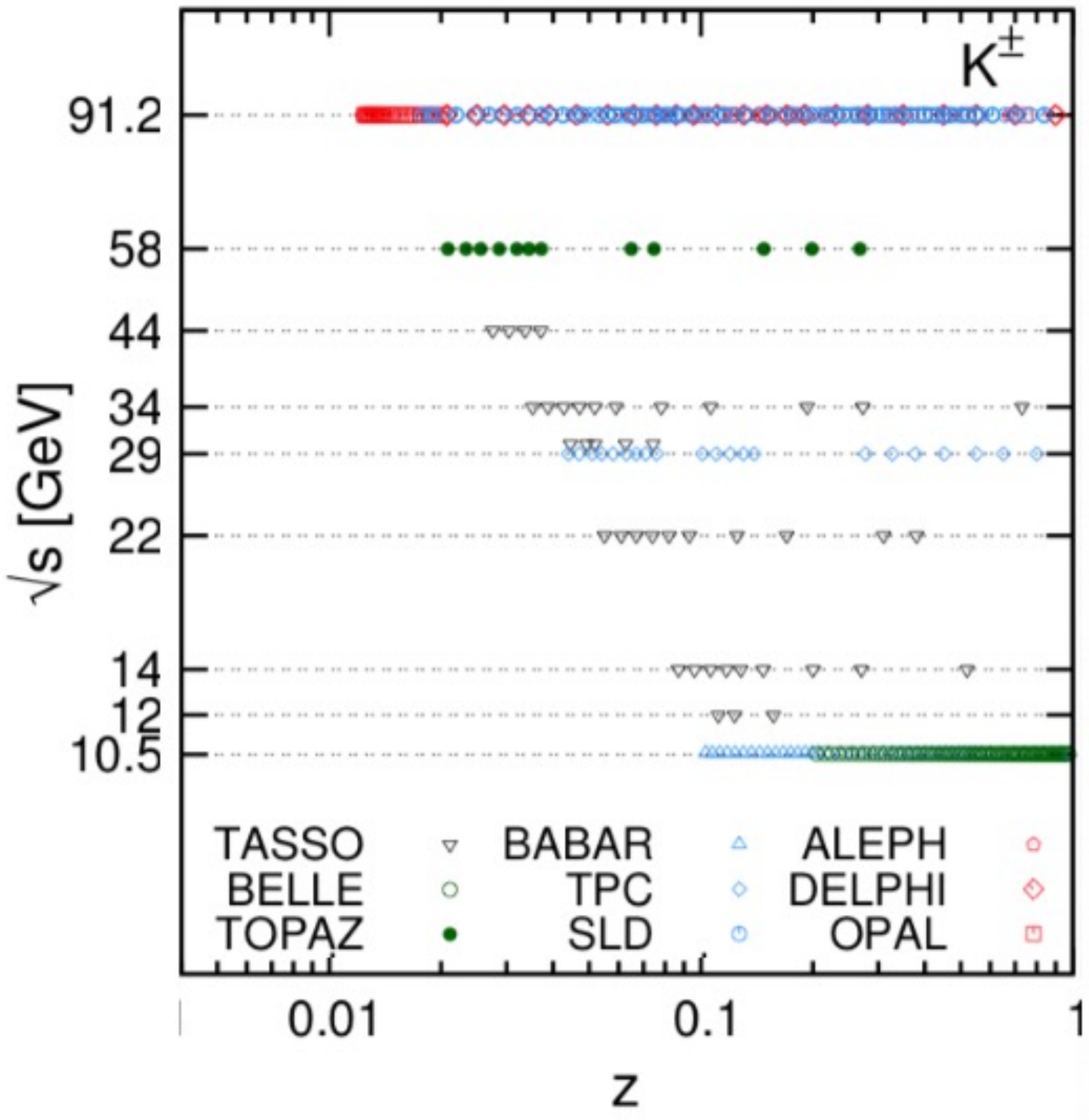




FFs panorama

✦ kaon FFs

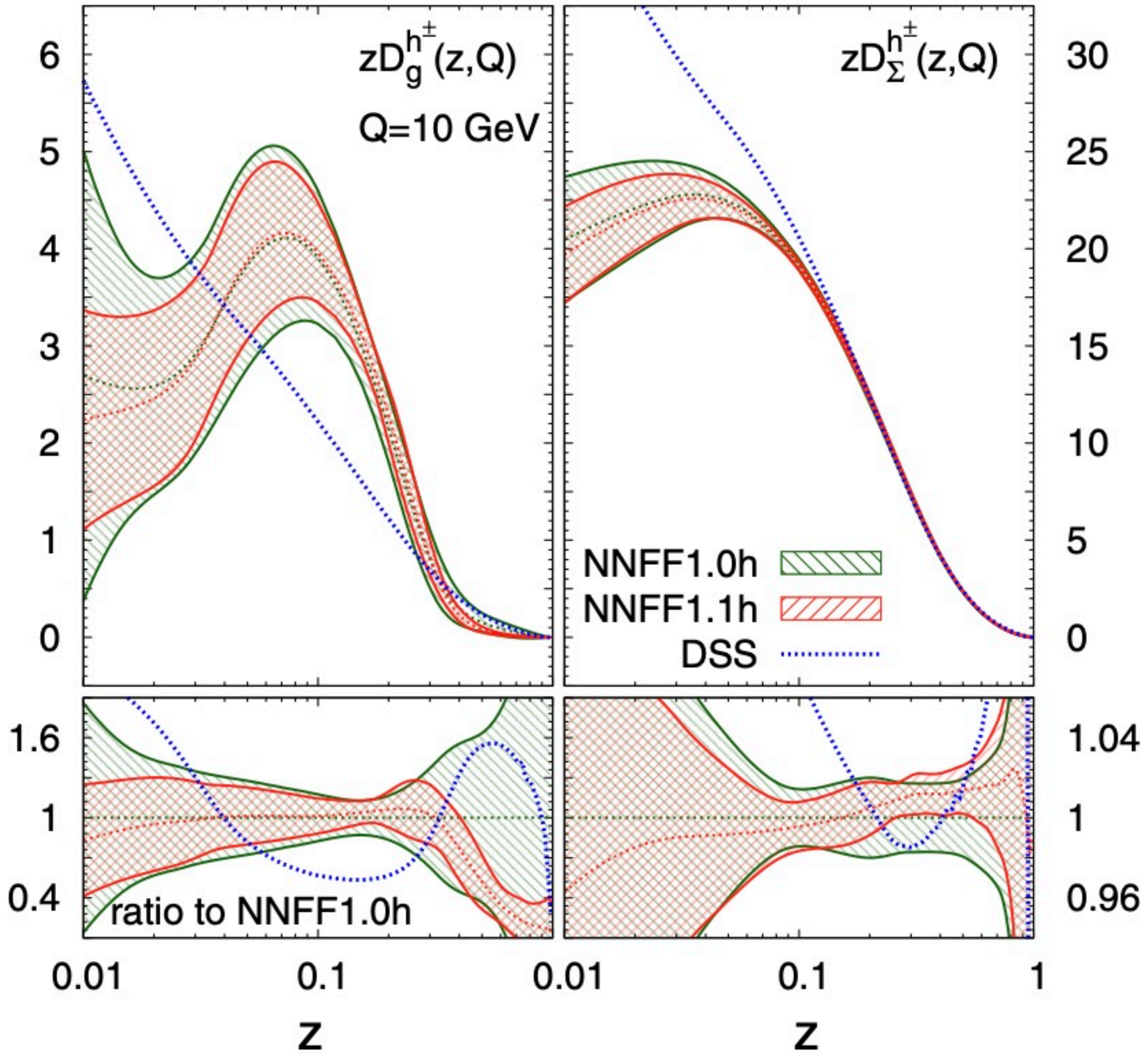




Fragmentation Functions

✦ 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

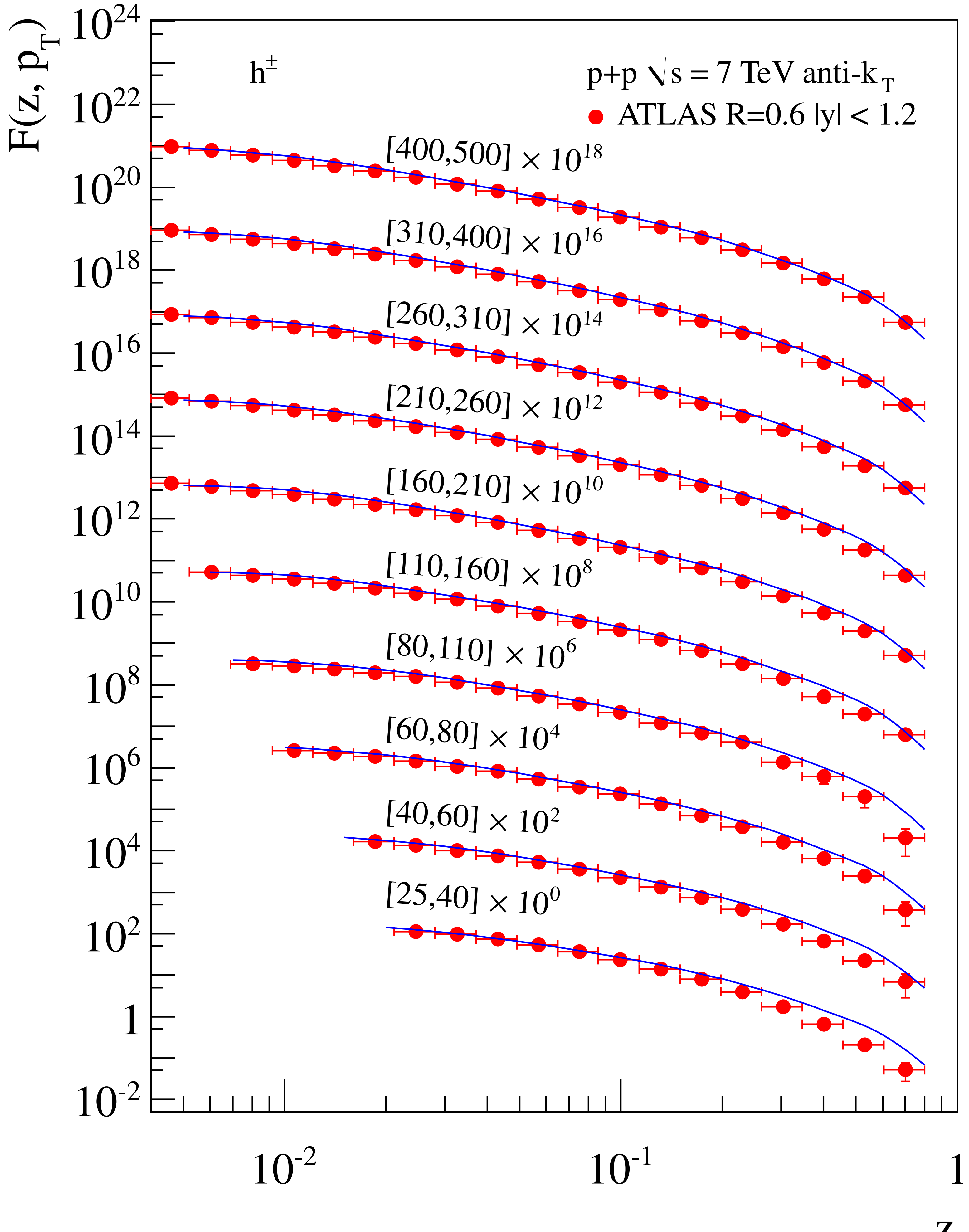
More measurements are needed to further constrain the FFs, SIA will play very important role!

New opportunities in probing FFs

✦ Jet fragmentation function

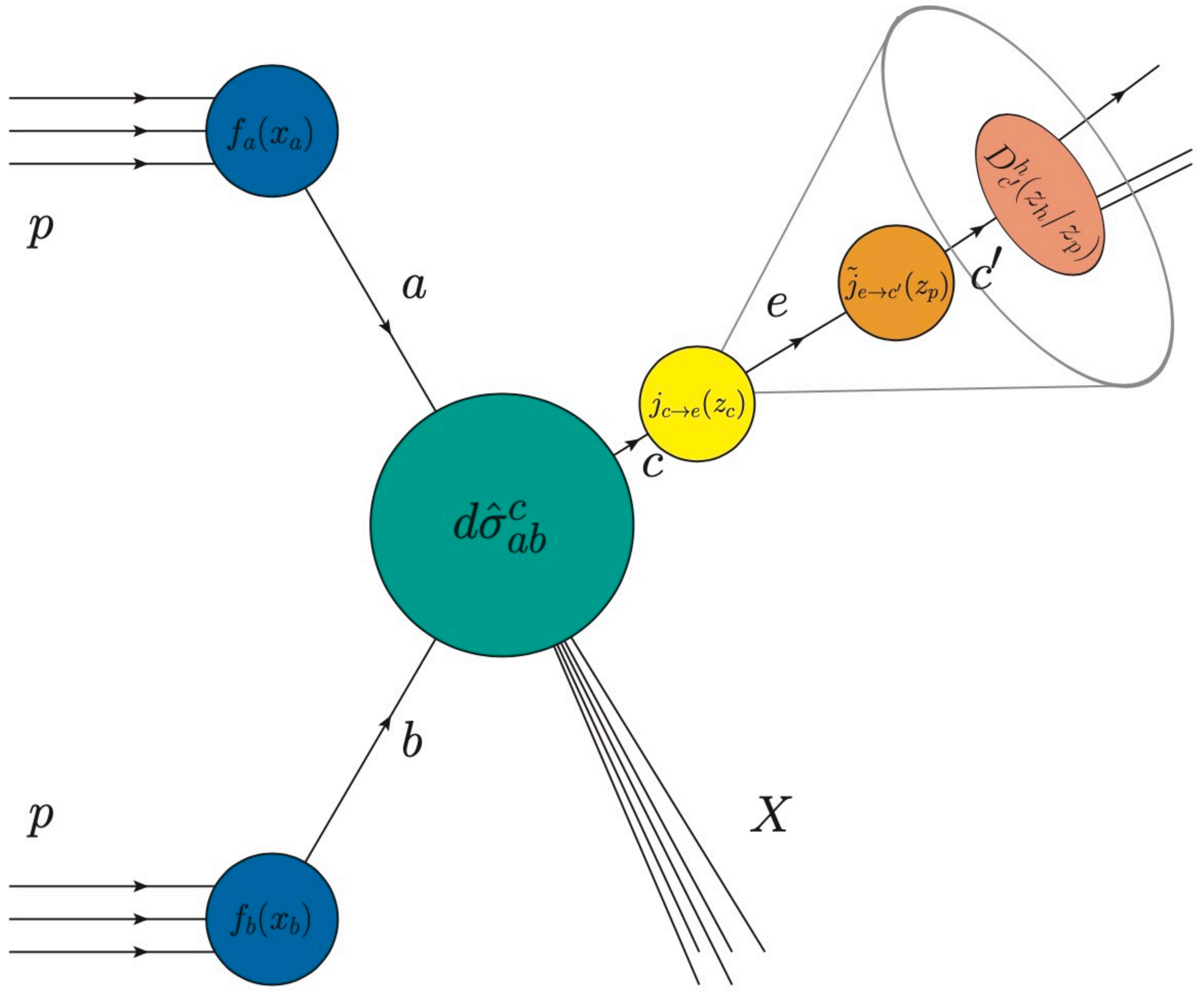
Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

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



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

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



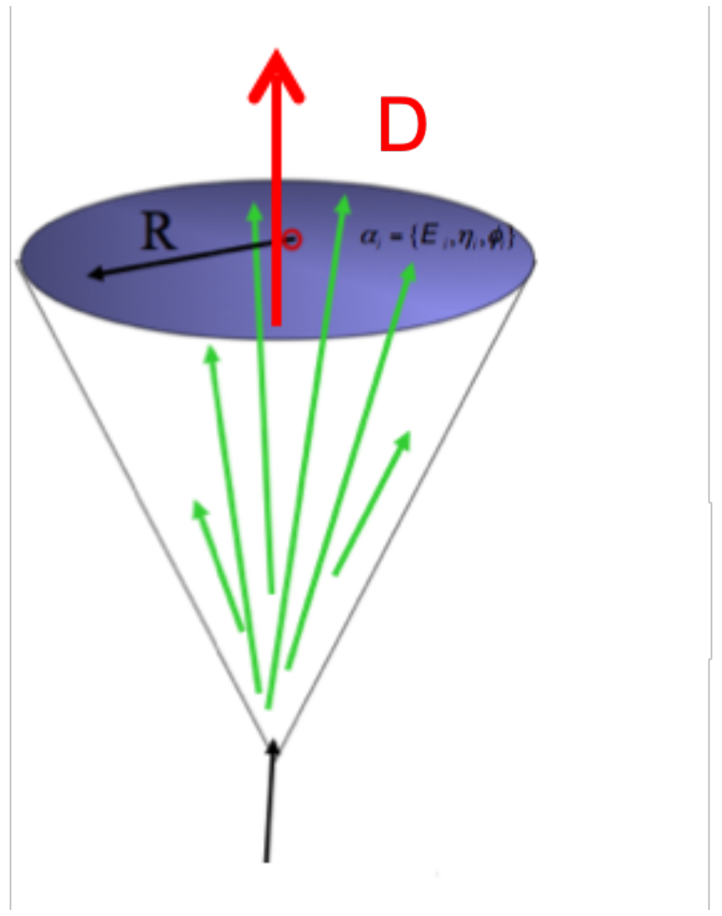
$$z_h = \frac{p_T^h}{p_T}$$

Light hadrons work very well

Heavy flavor in jet

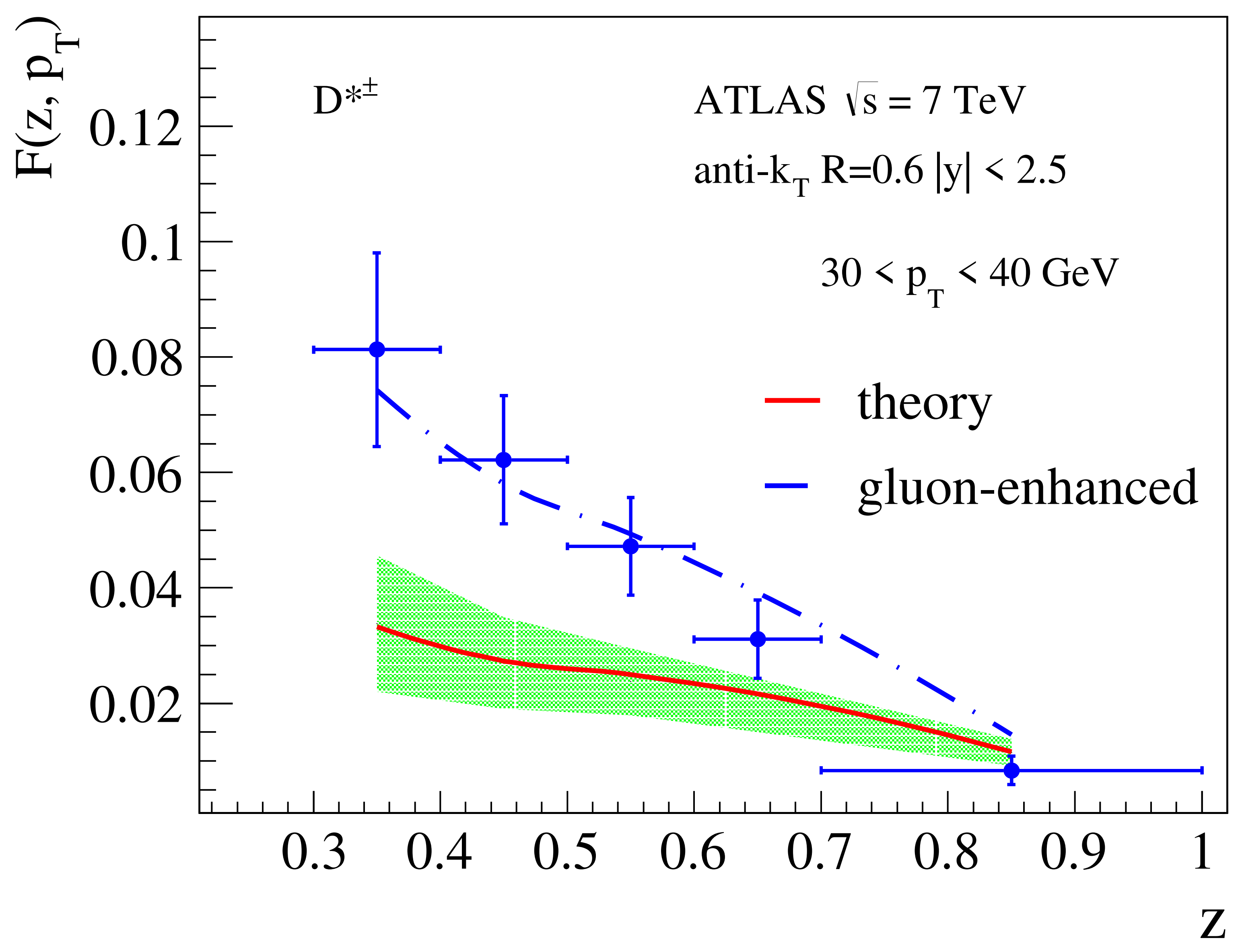
✦ Jet fragmentation function for D meson

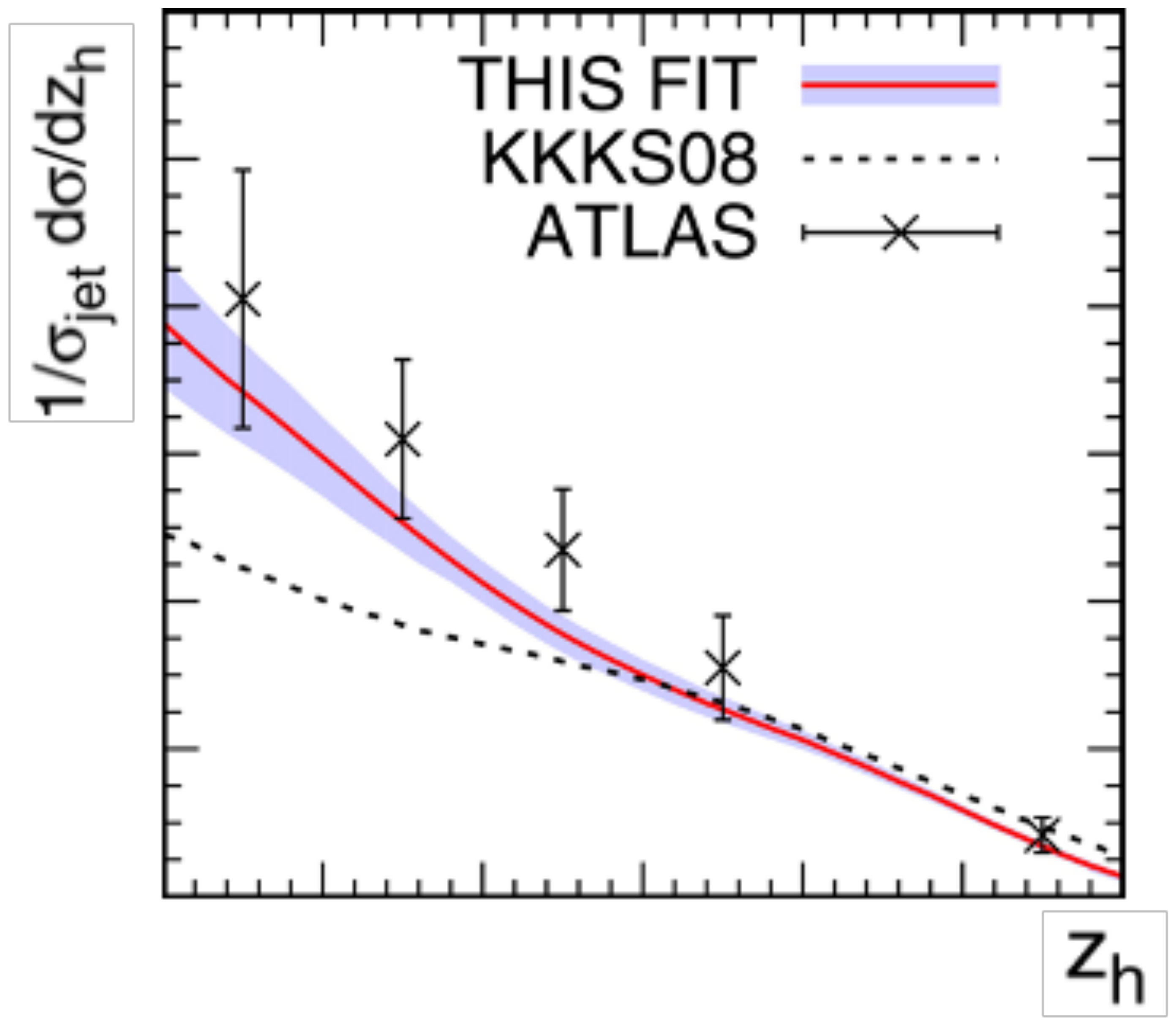
$$F(z_h, p_T) = \frac{d\sigma^{J(h)}}{dp_T d\eta dz_h} \Big/ \frac{d\sigma}{dp_T d\eta}$$

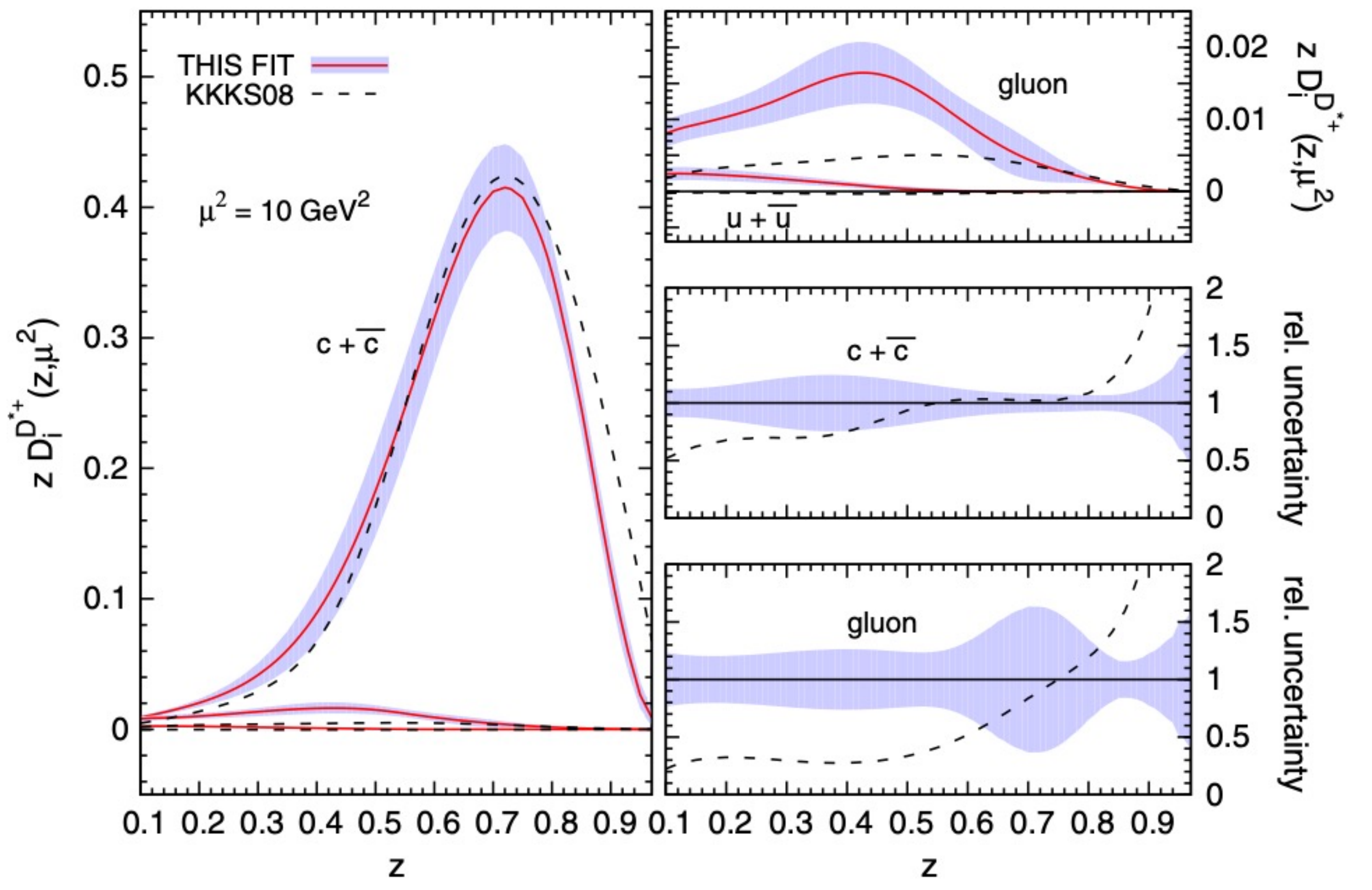


Chien, Kang, Ringer, Vitev, **HX**, JHEP (2016)

AKSRV, PRD (2017)





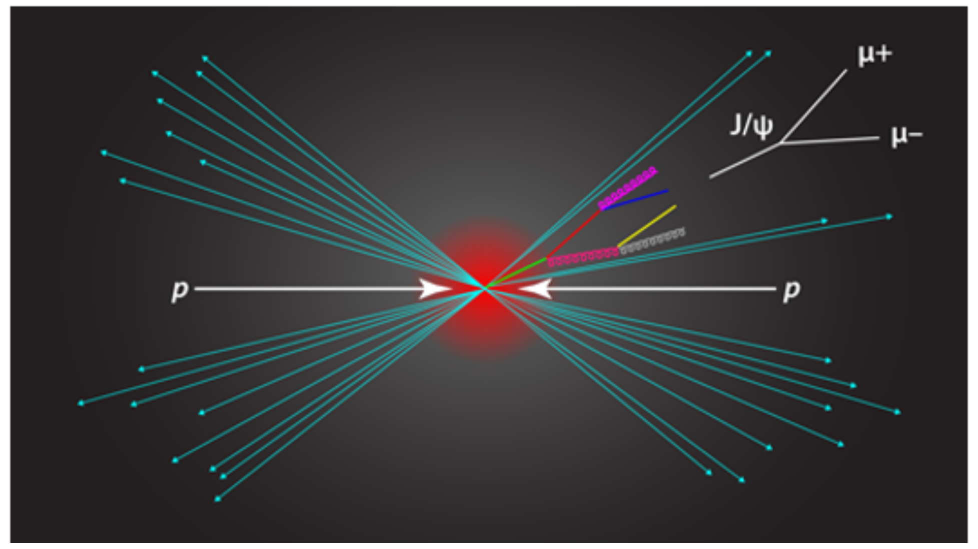


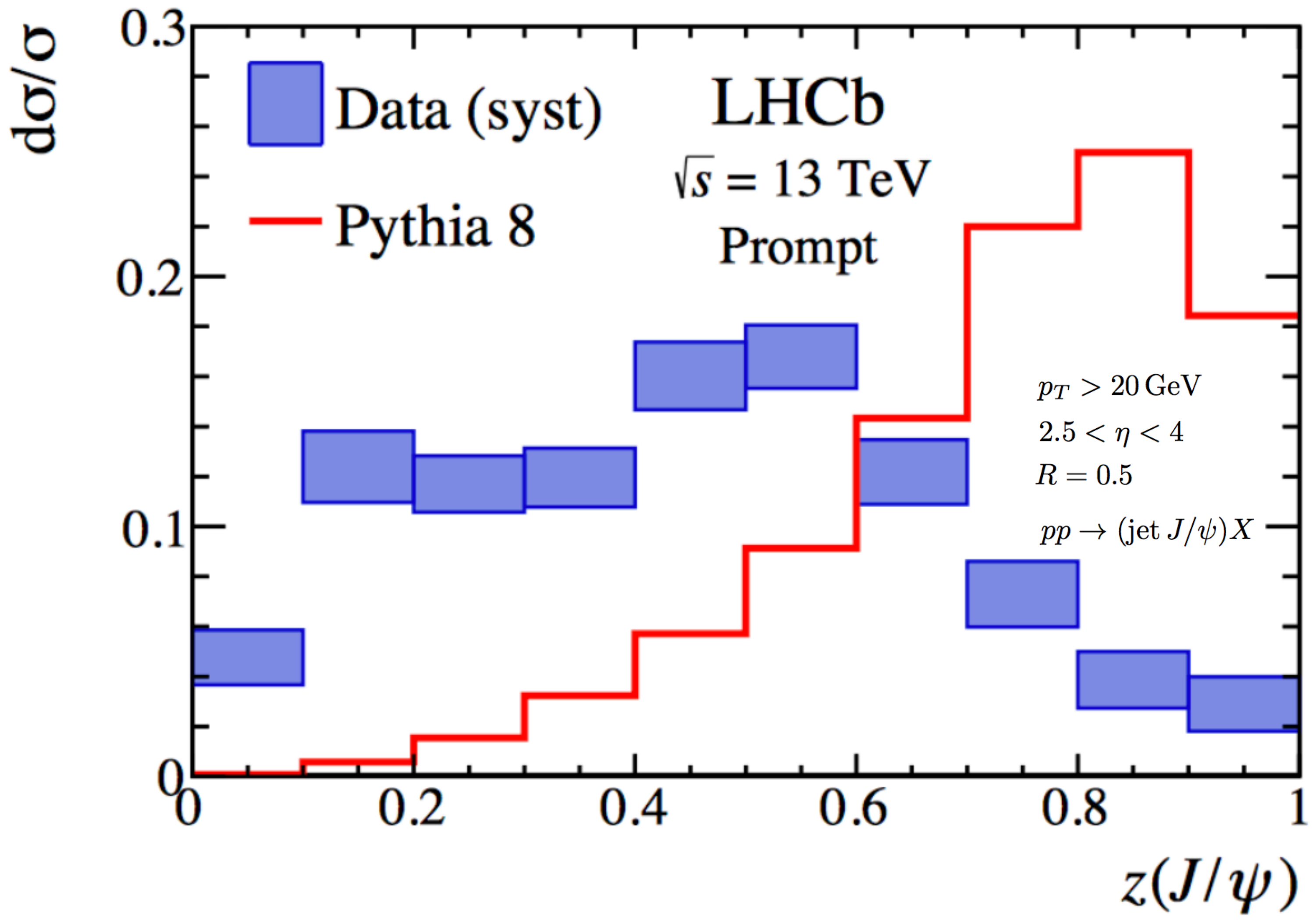
- Failed to describe D meson production in jet using KKK08 FFs
- Leads to new constrain of heavy flavor FFs using measurement of D in jet

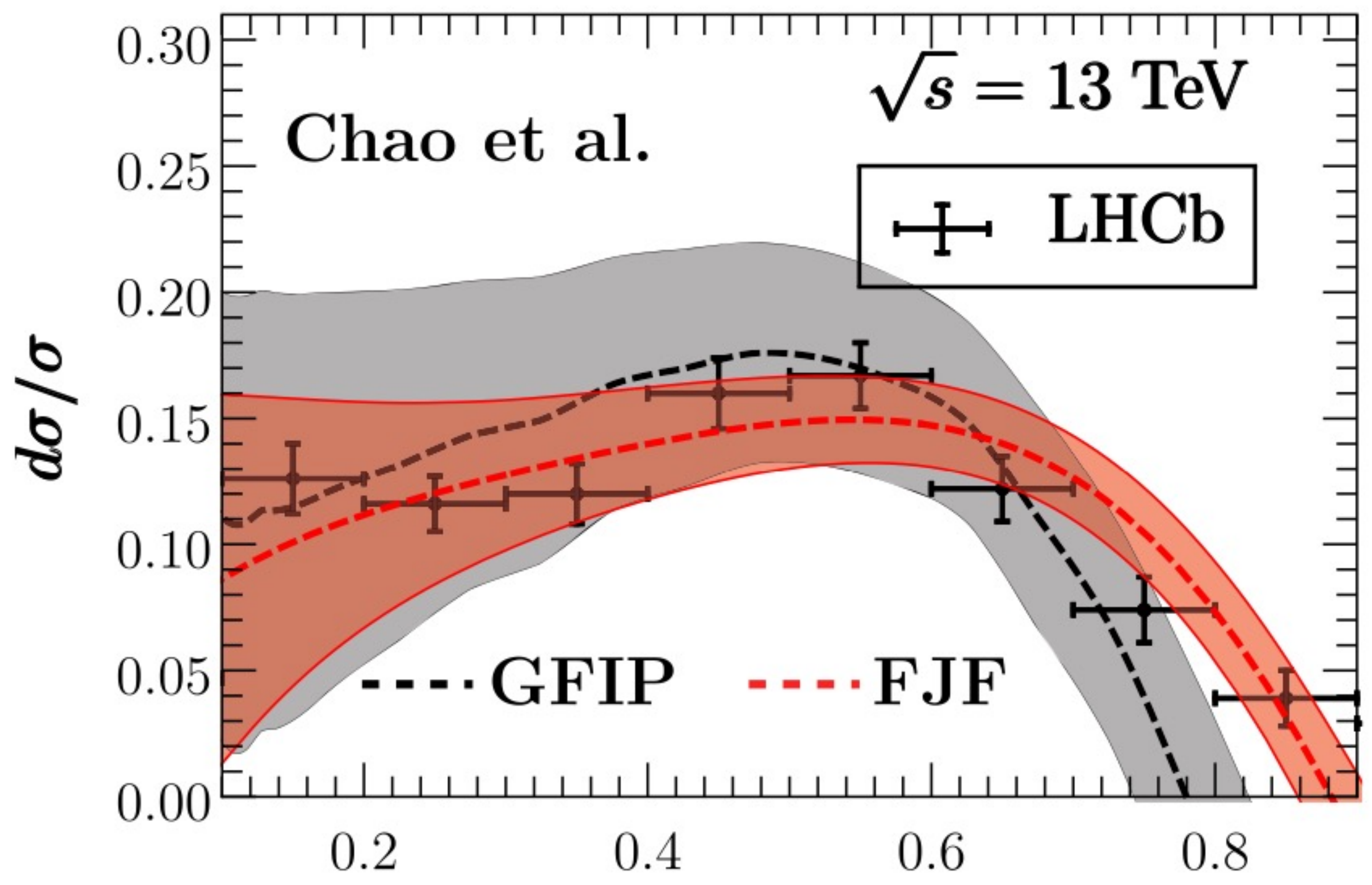
✦ Jet fragmentation function for J/ψ

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

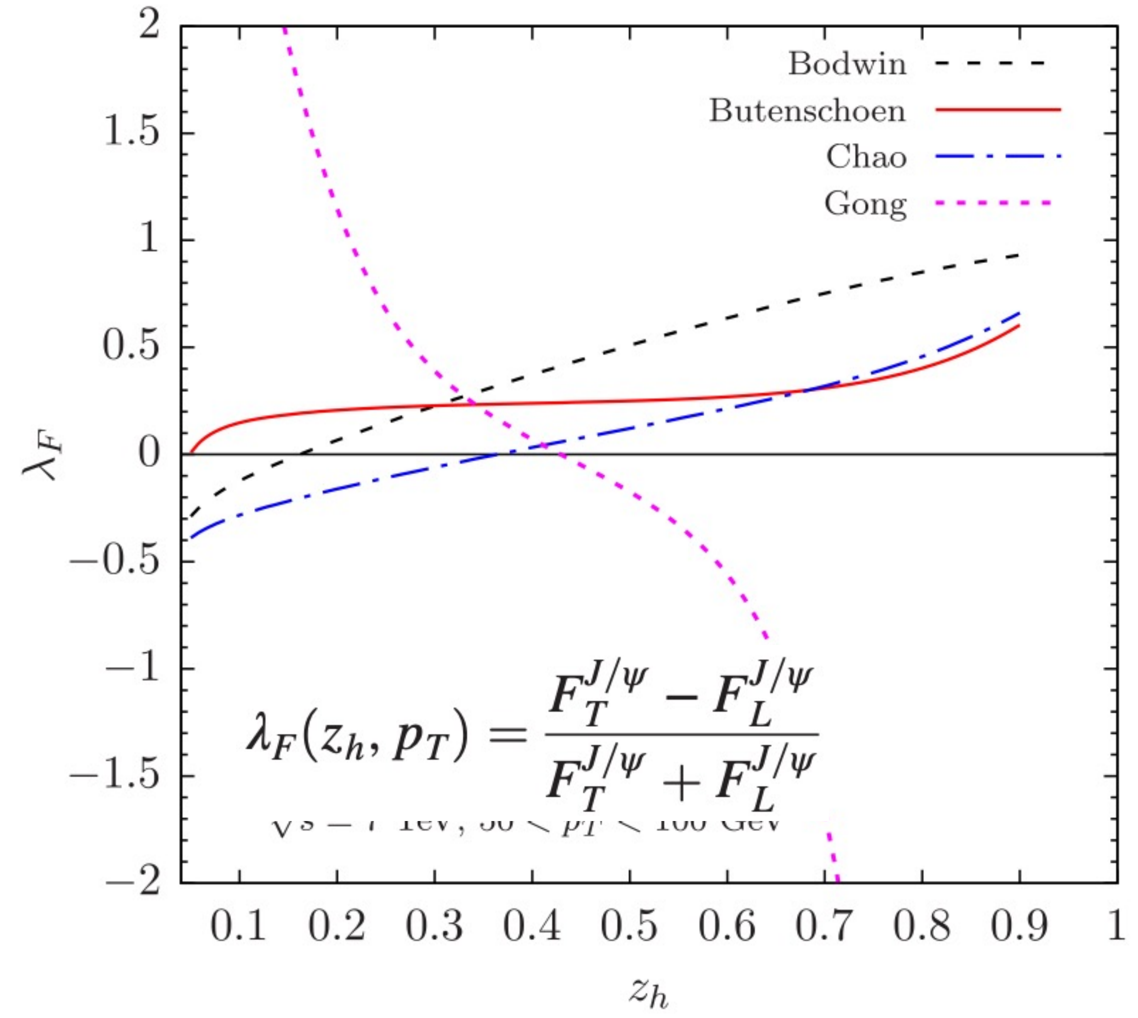
$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^+ R, \mu) \times D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^+ R)^2)$$







Bain et al, PRL (2017)

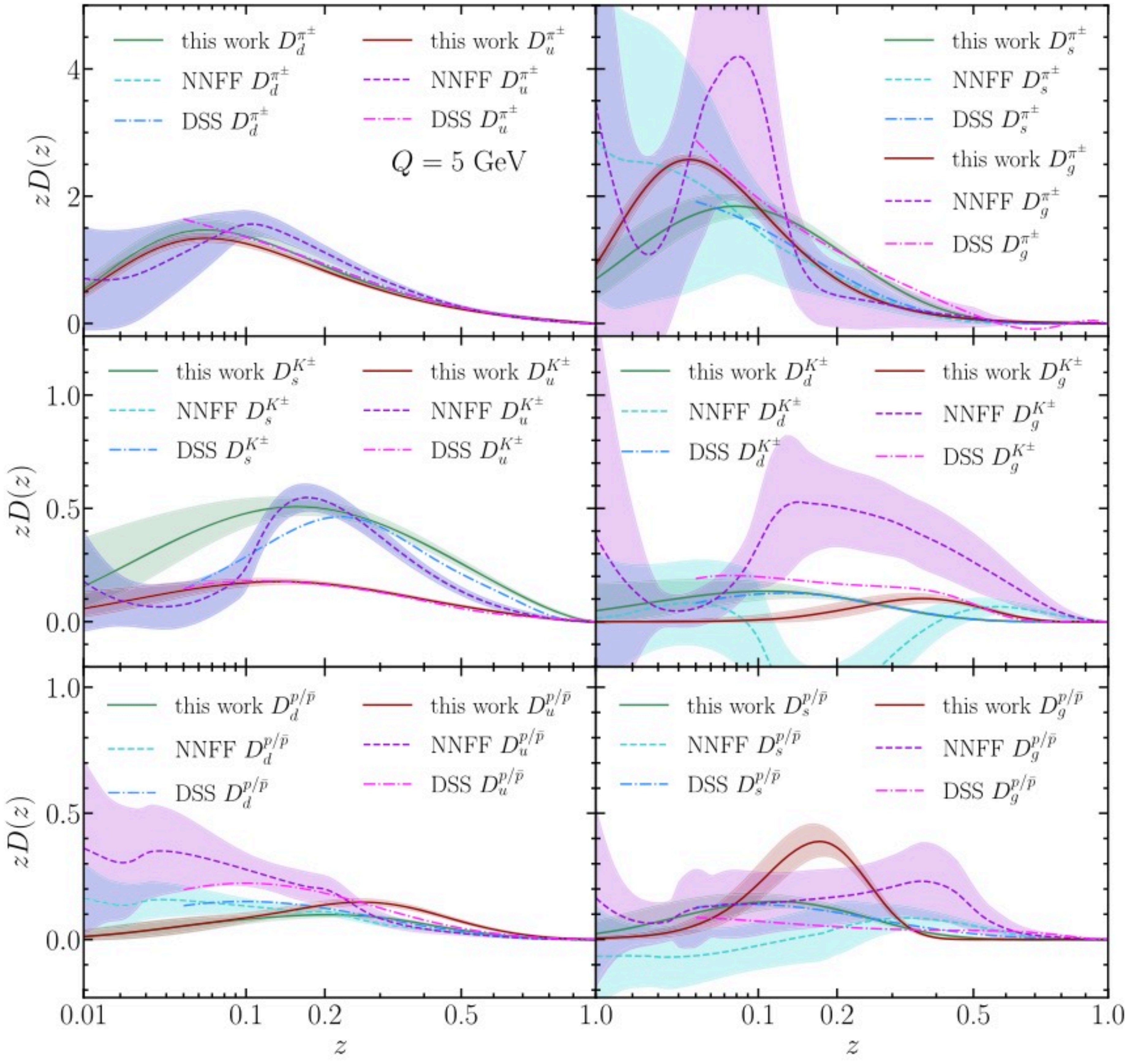


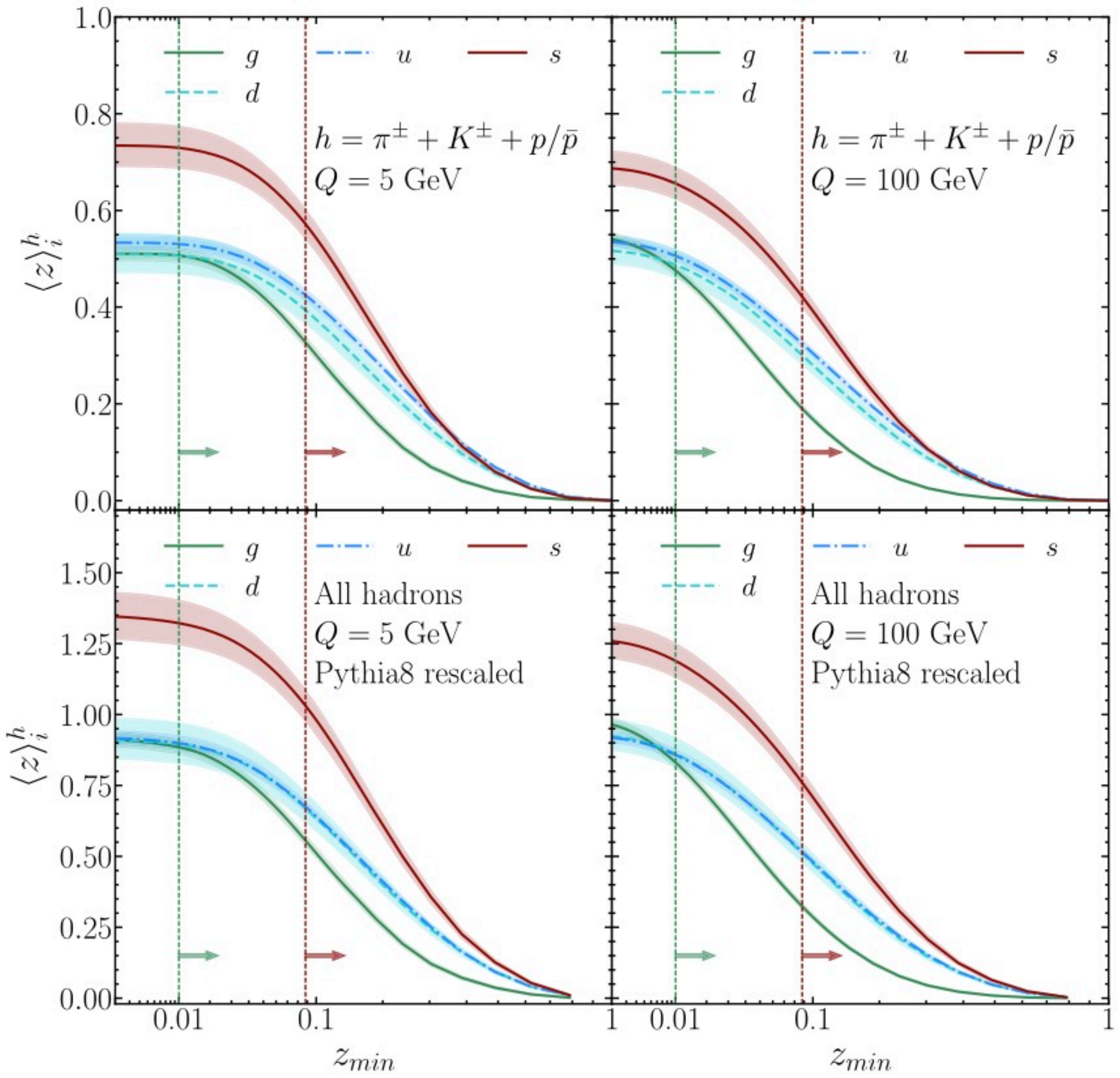
Kang, Qiu, Ringer, **HX**, Zhang PRL (2017)

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

New efforts from NPC

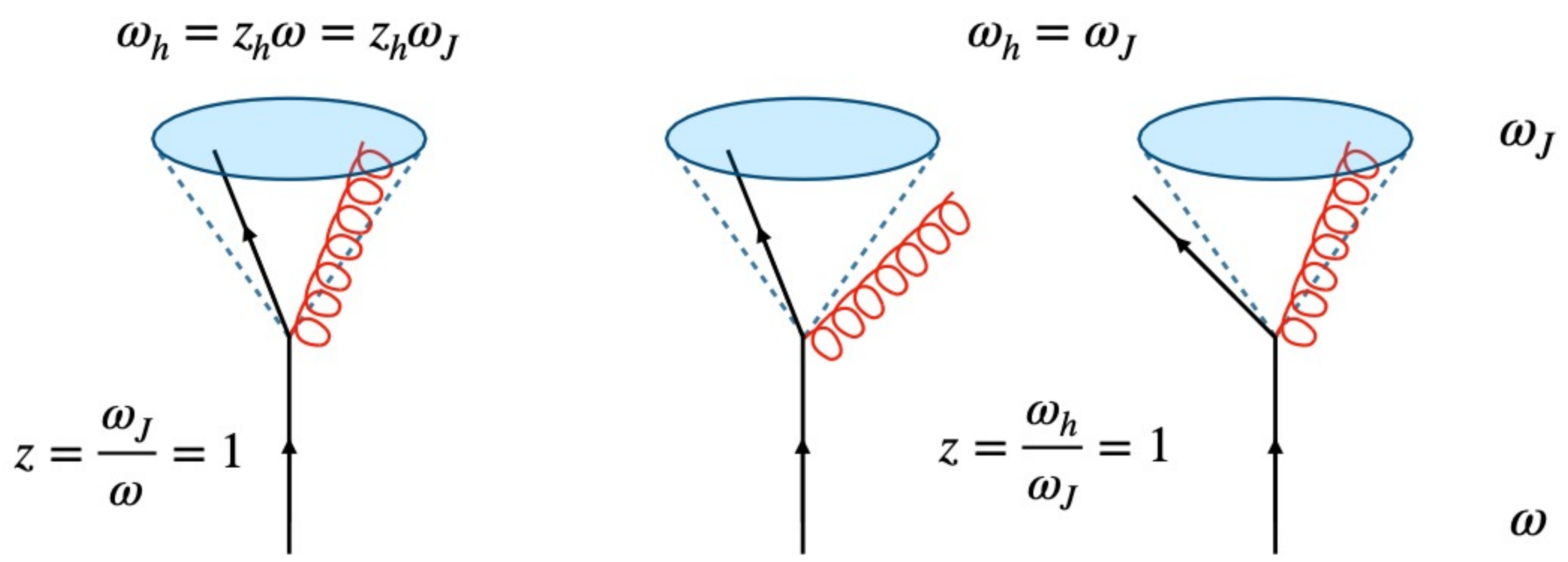
✦ **Joint analysis from NPC (SJTU+SCNU+IMP)** Gao, Liu, Shen, **HX**, Zhao, PRL, 2024





- Higher precision determination of FFs for charged hadron
- 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

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

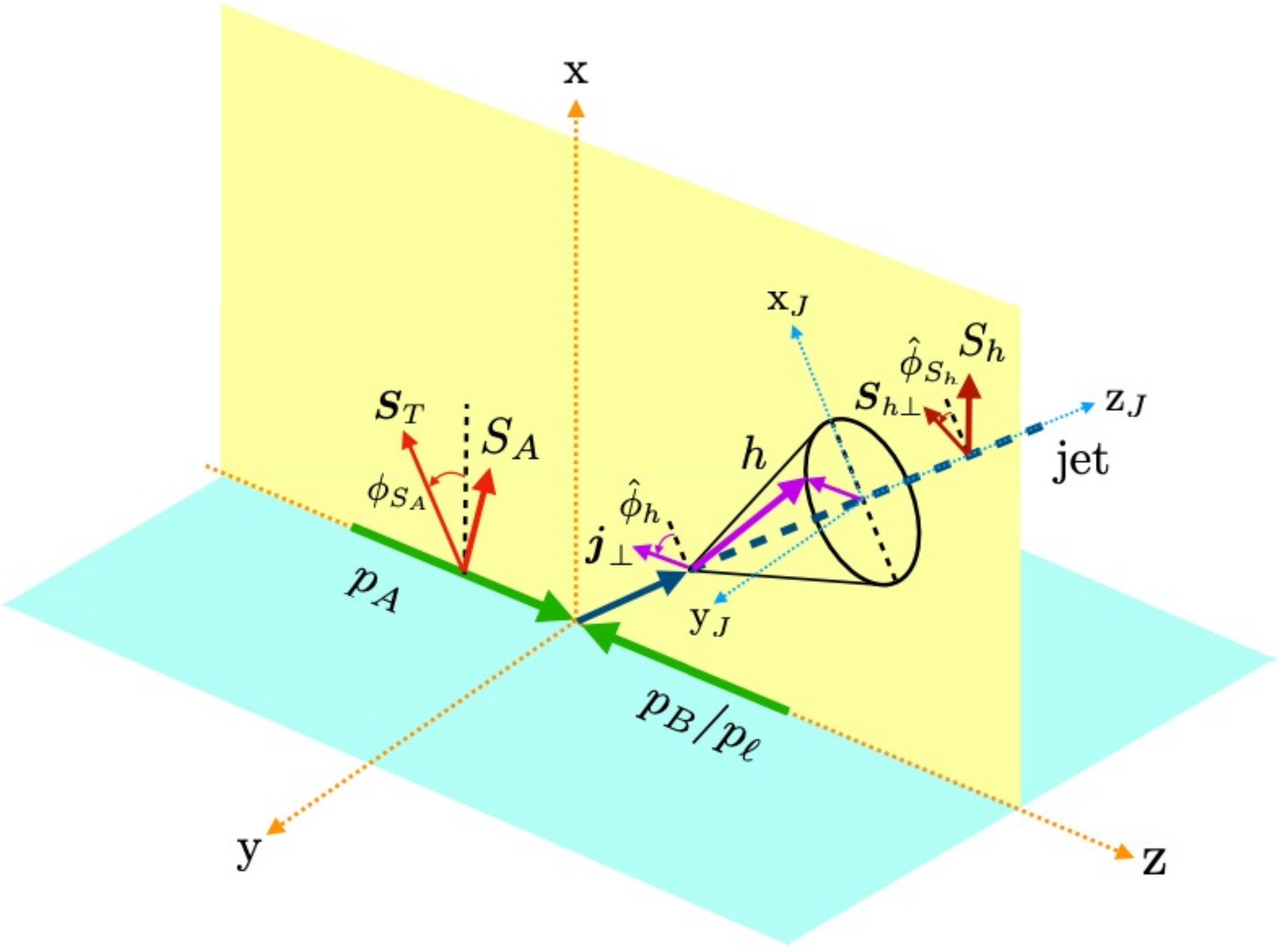
- An alternative way to explore different types of FFs
- Similar FJFs can be defined in exclusive jet production

Parton to hadron fragmentation in jet

✦ single inclusive jet production in hadronic collisions

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

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



- Unpolarized case as an example

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

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

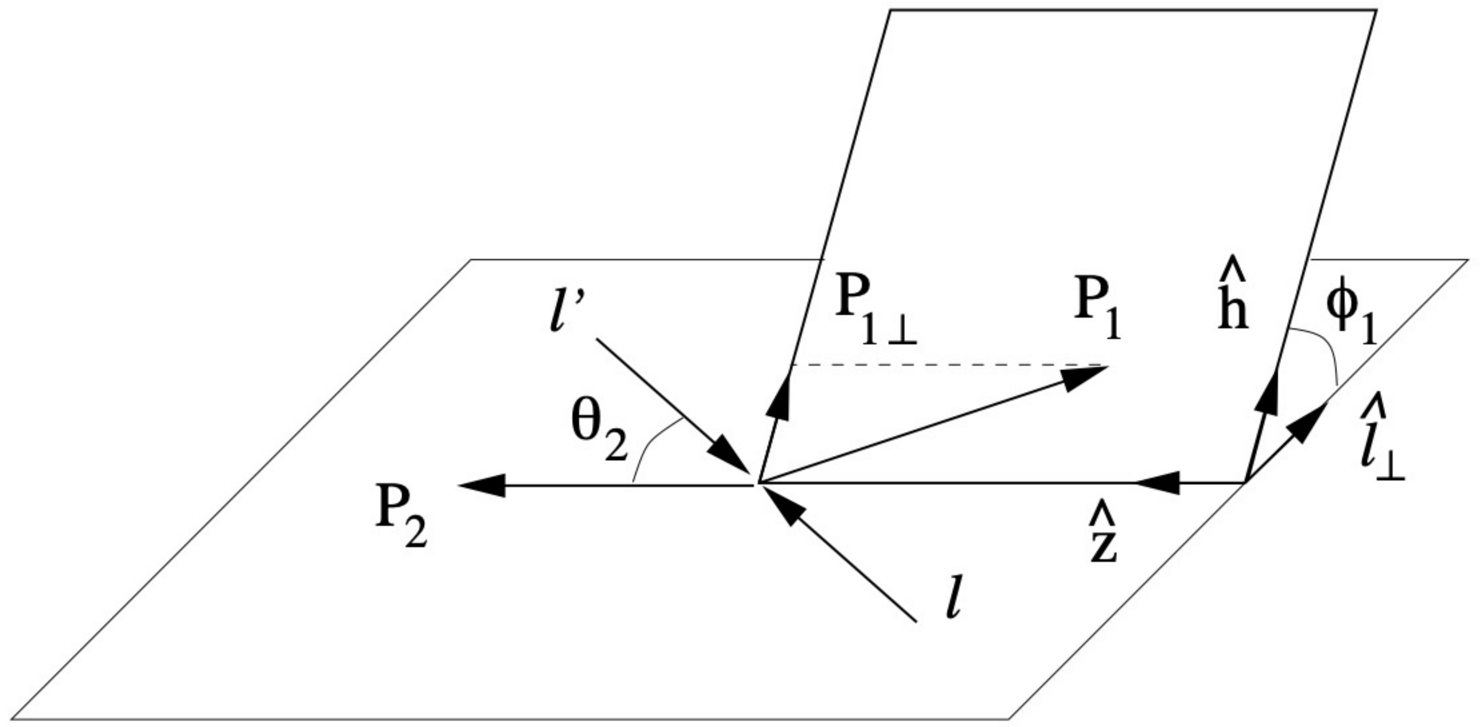
$$F_{TU,U}^{\sin(\phi_S-\phi_h)}(z_h,j_\perp) = \mathcal{C}\Big[\frac{j_\perp}{z_h M_h}h_1 f_1 \mathcal{H}_1^\perp \Delta_T\hat{H}\Big],$$
$$F_{LU,L}(z_h,j_\perp) = \mathcal{C}\big[g_{1L}f_1\mathcal{G}_{1L}\Delta_L\hat{H}\big],$$
$$F_{TU,L}^{\cos(\phi_S-\phi_h)}(z_h,j_\perp) = -\mathcal{C}\Big[\frac{j_\perp}{z_h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

Opportunities to probe various FFs at BES/STCF

- **Probe collinear FFs**

$$\frac{d\sigma^O(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2}\sum_{a,\bar{a}} {e_a}^2 \Big\{A(y)\Big(D_1\overline{D}_1 - \lambda_1\lambda_2 G_1\overline{G}_1\Big) + B(y)\,|\boldsymbol{S}_{1T}|\,|\boldsymbol{S}_{2T}|\,\cos(\phi_{S_1}+\phi_{S_2})\Big(H_1\overline{H}_1\Big)$$

$$\frac{d\sigma^L(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2}\lambda_e\sum_{a,\bar{a}} {e_a}^2 \Big\{\frac{C(y)}{2}\Big(\lambda_2 D_1\overline{G}_1 - \lambda_1 G_1\overline{D}_1\Big)$$



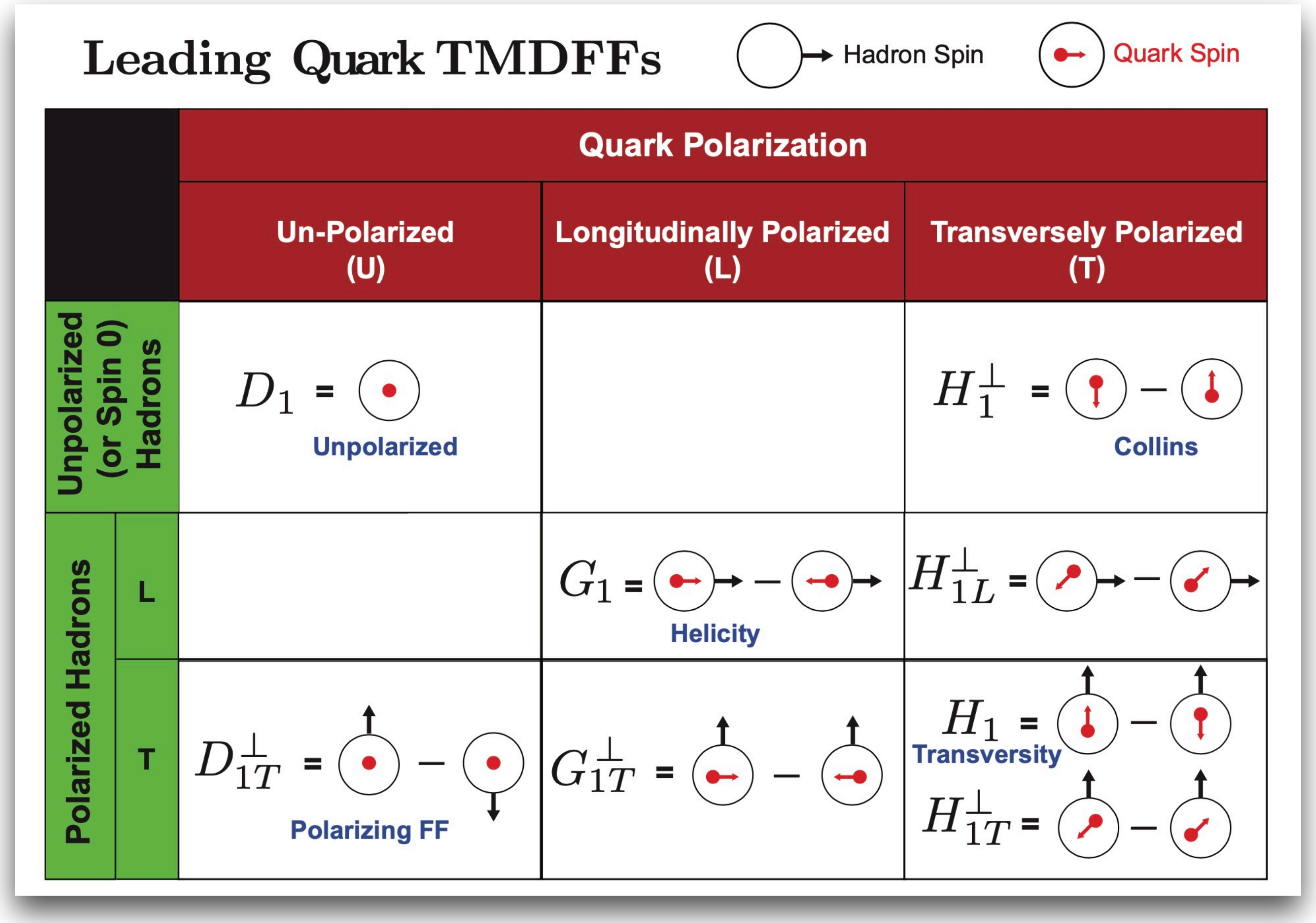
- **Back to back unpolarized hadron production in unpolarized SIA - TMDFFs**

$$\frac{d\sigma^O(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2}\,z_1^2z_2^2\left\{A(y)\,\mathcal{F}\left[D_1\overline{D}_1\right] + B(y)\,\cos(2\phi_1)\,\mathcal{F}\left[\left(2\,\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\;\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_1^\perp\overline{H}_1^\perp}{M_1M_2}\right]\right\}$$

- **One hadron polarized and another one unpolarized**

$$\frac{d\sigma^O(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2}\,z_1^2z_2^2\left\{\ldots + B(y)\,\lambda_1\,\sin(2\phi_1)\,\mathcal{F}\left[\left(2\,\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\;\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_{1L}^\perp\overline{H}_1^\perp}{M_1M_2}\right]\right.$$
$$-A(y)\,|\boldsymbol{S}_{1T}|\,\sin(\phi_1-\phi_{S_1})\,\mathcal{F}\left[\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\,\frac{D_{1T}^\perp\overline{D}_1}{M_1}\right] + B(y)\,|\boldsymbol{S}_{1T}|\,\sin(\phi_1+\phi_{S_1})\,\mathcal{F}\left[\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\,\frac{H_1\overline{H}_1^\perp}{M_2}\right]$$
$$\left.+B(y)\,|\boldsymbol{S}_{1T}|\,\sin(3\phi_1-\phi_{S_1})\,\mathcal{F}\left[\left(4\,\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)^2 - 2\,\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\;\boldsymbol{k}_T\cdot\boldsymbol{p}_T - \hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\;\boldsymbol{k}_T^2\right)\frac{H_{1T}^\perp\overline{H}_1^\perp}{2{M_1}^2M_2}\right]\right\},$$

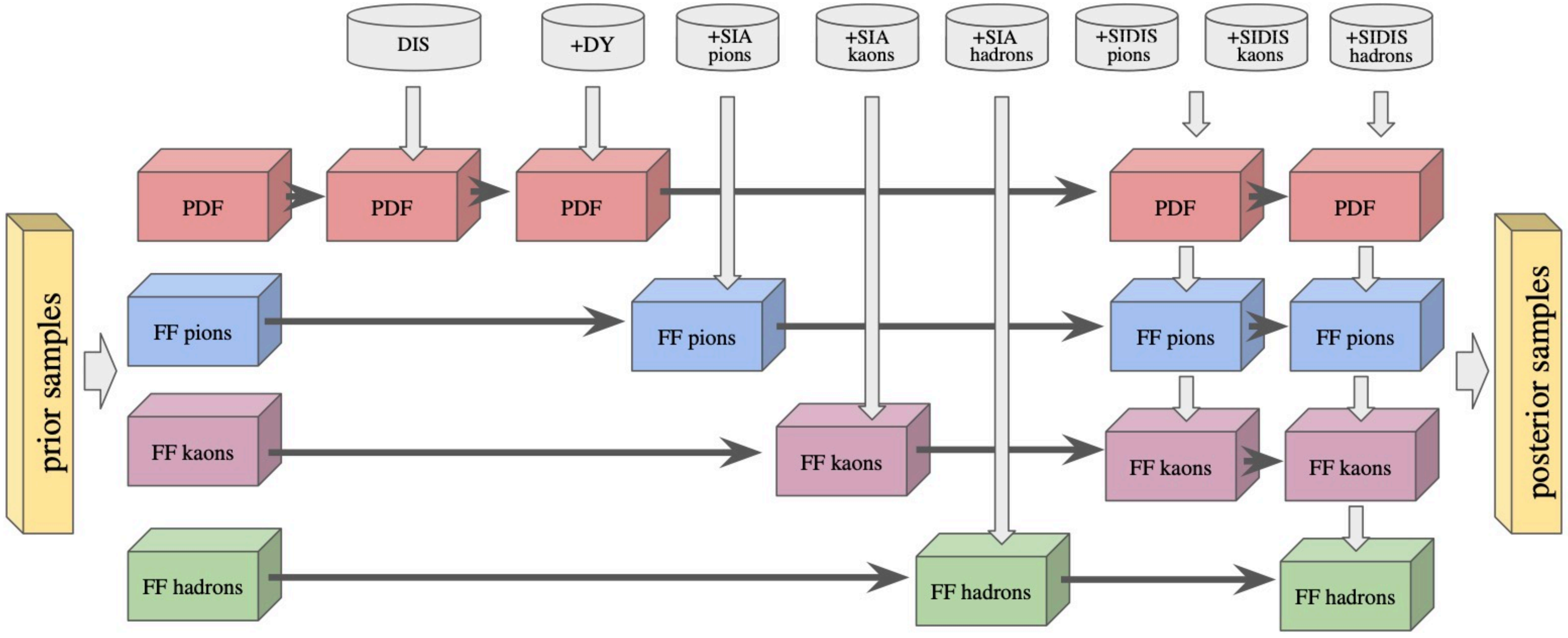
A complete analysis can be found in hep/ph9702281

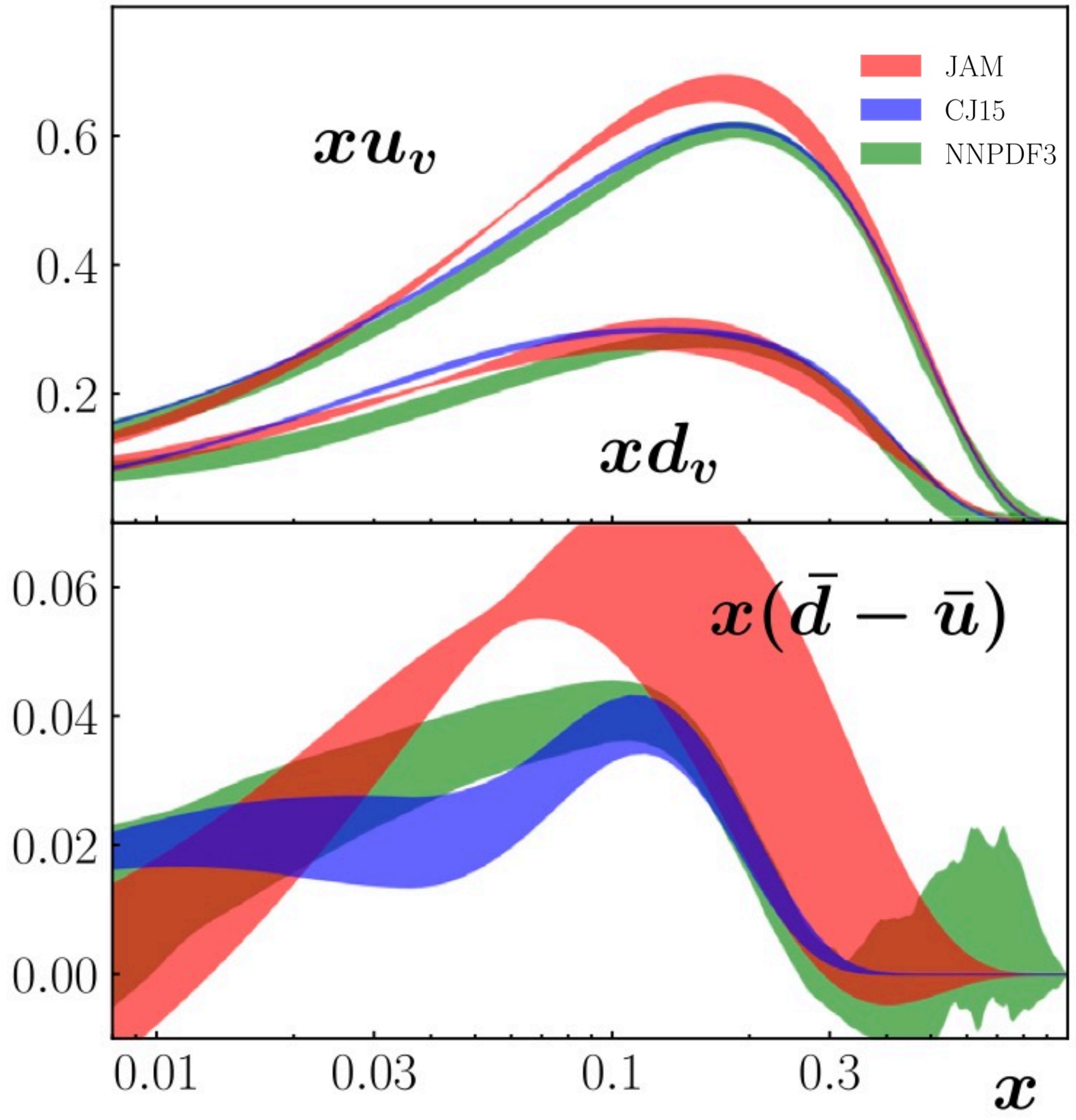


FFs as a tool to probe nucleon structure

✦ **Probe the nucleon structure**

JAM, PRD 2021





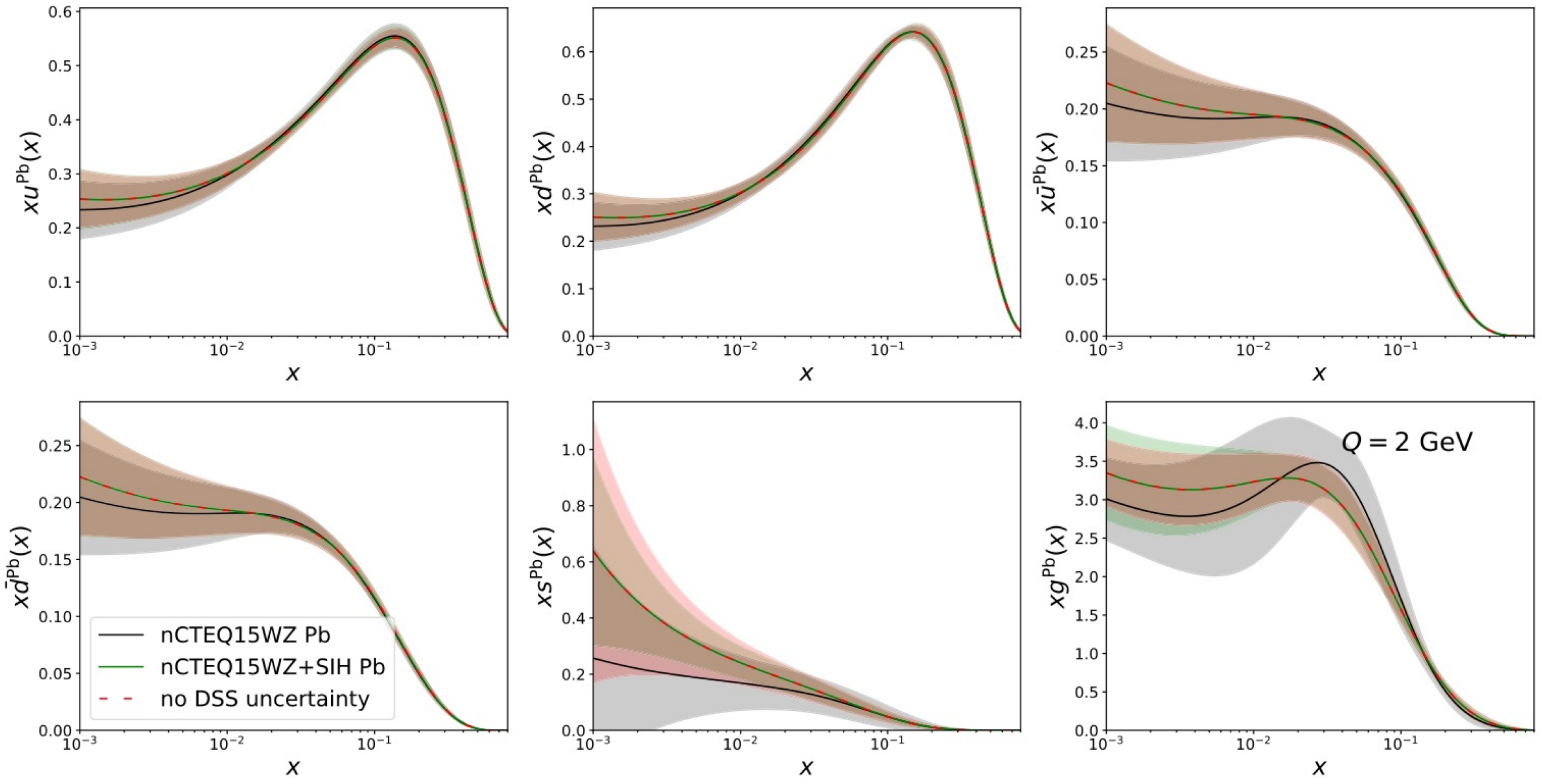
$$\sigma^{lp\to l'hX} = f_{i/p} \otimes \hat{\sigma}_{li\to j} \otimes D_{j\to h}$$

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

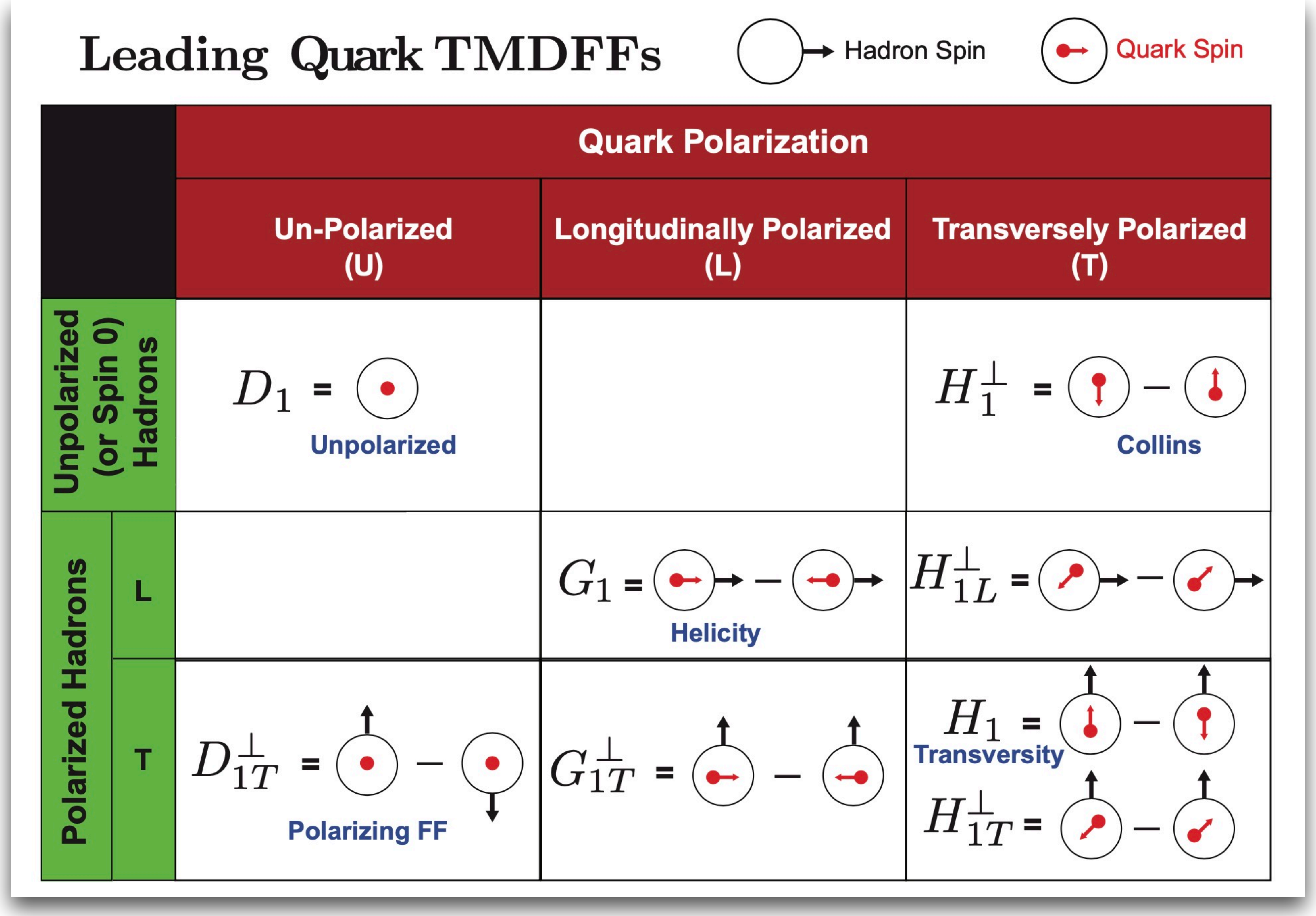


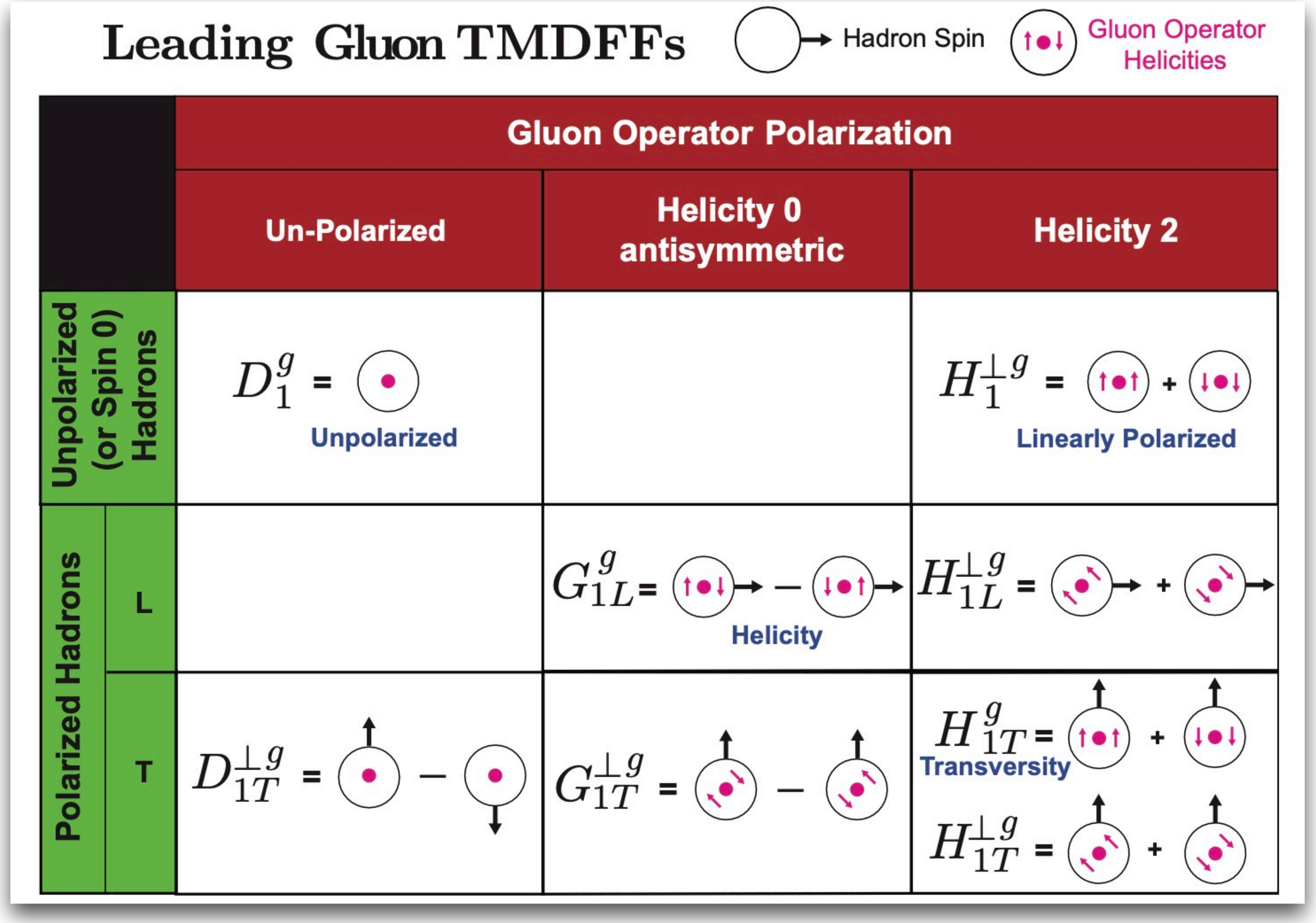
$$\sigma^{pPb\to hX} = f_{i/p} \otimes f_{j/Pb} \otimes \hat{\sigma}_{ij\to k} \otimes D_{k\to h}$$

Precise information of FF is helpful for nuclear PDF determination

Transverse momentum dependent FFs

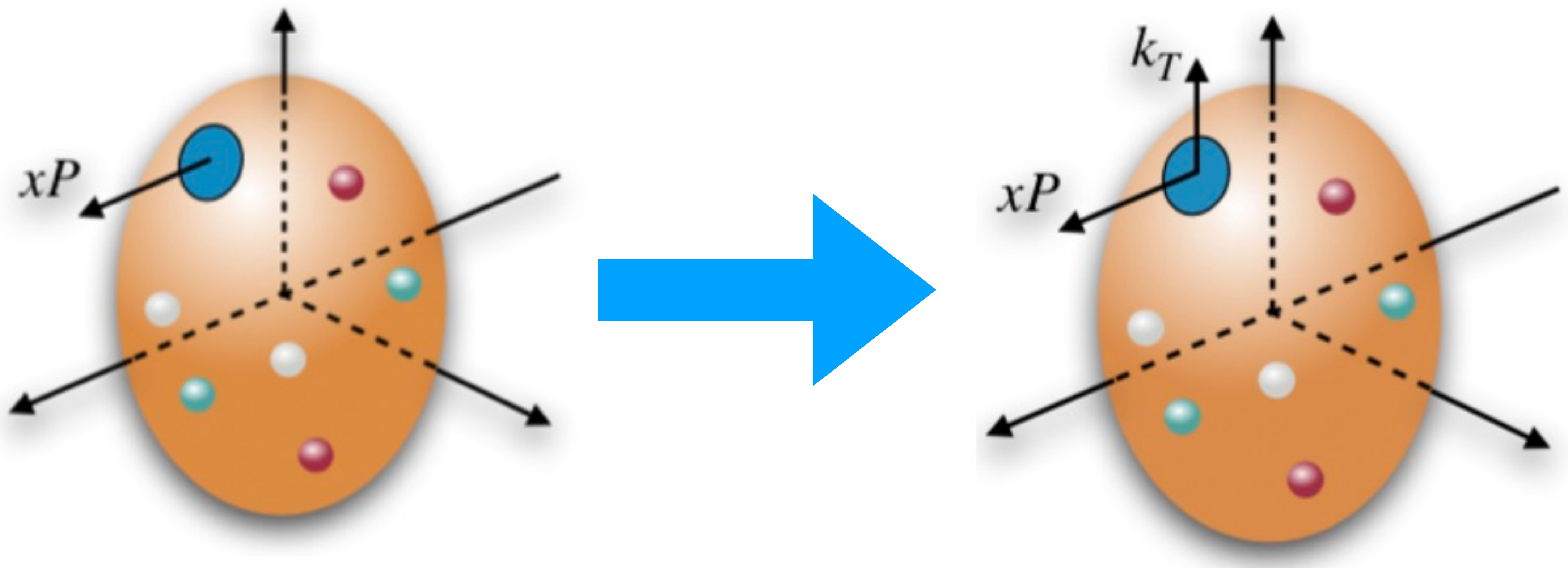
- ✦ **FFs: 8 transverse momentum dependent FFs at leading twist**

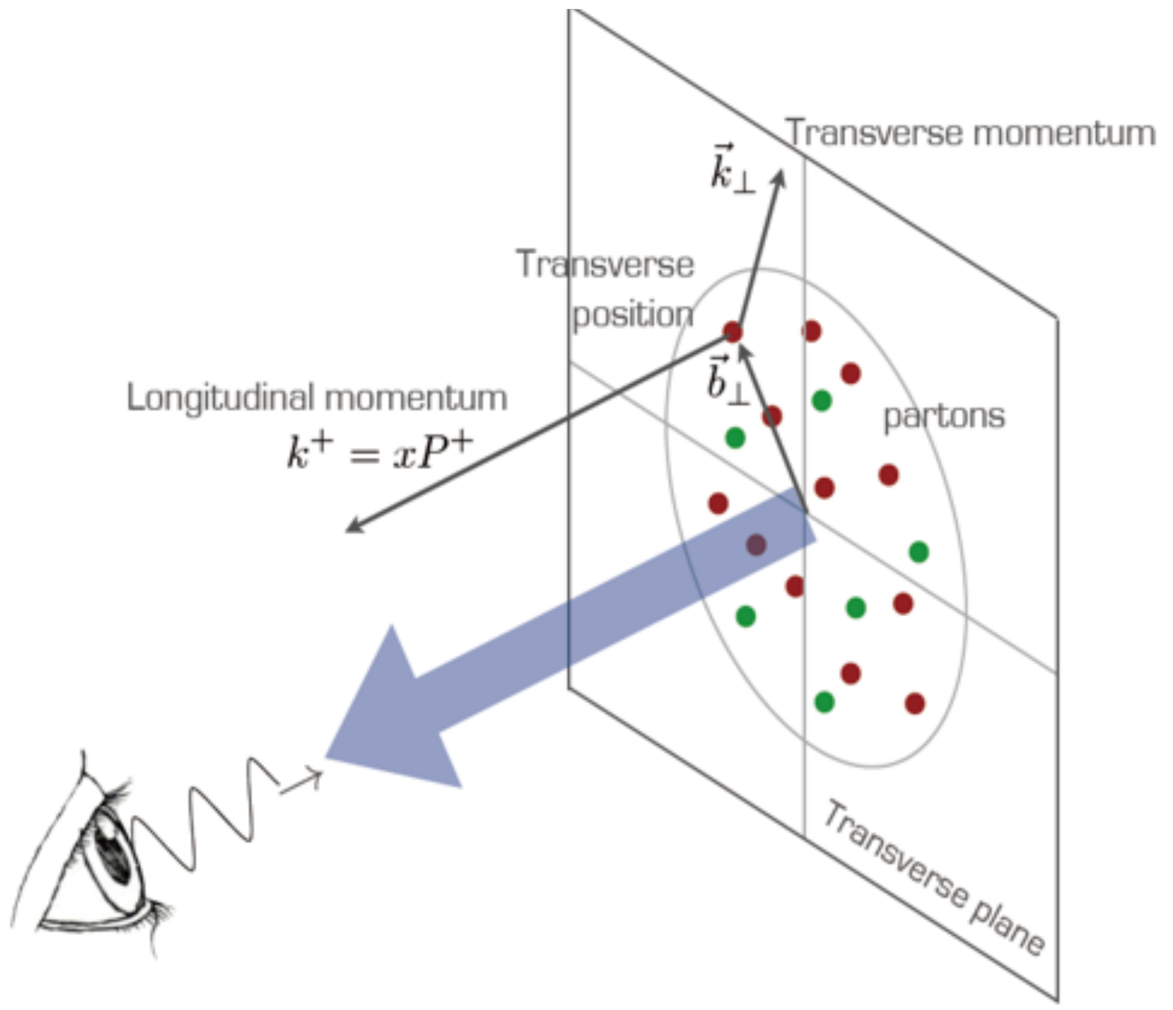




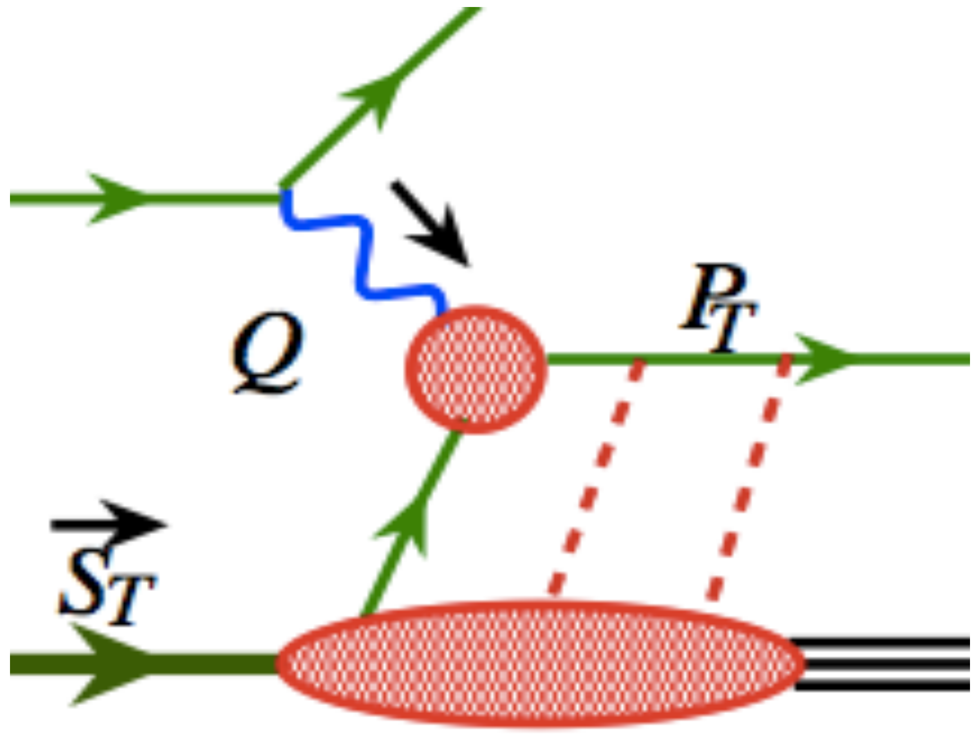
How to probe transverse momentum dependent FFs

✦ Transverse momentum dependent PDFs (TMDs)





- Probing nucleon 3D structure requires two momentum scales
- Hard scale $Q_1 \gg 1/fm$ localizes the probes (particle nature of quarks/gluons)
- Soft scale $Q_2 \sim 1/fm$ accesses the transverse motion of quarks/gluons



SIDIS: $Q \gg P_T$

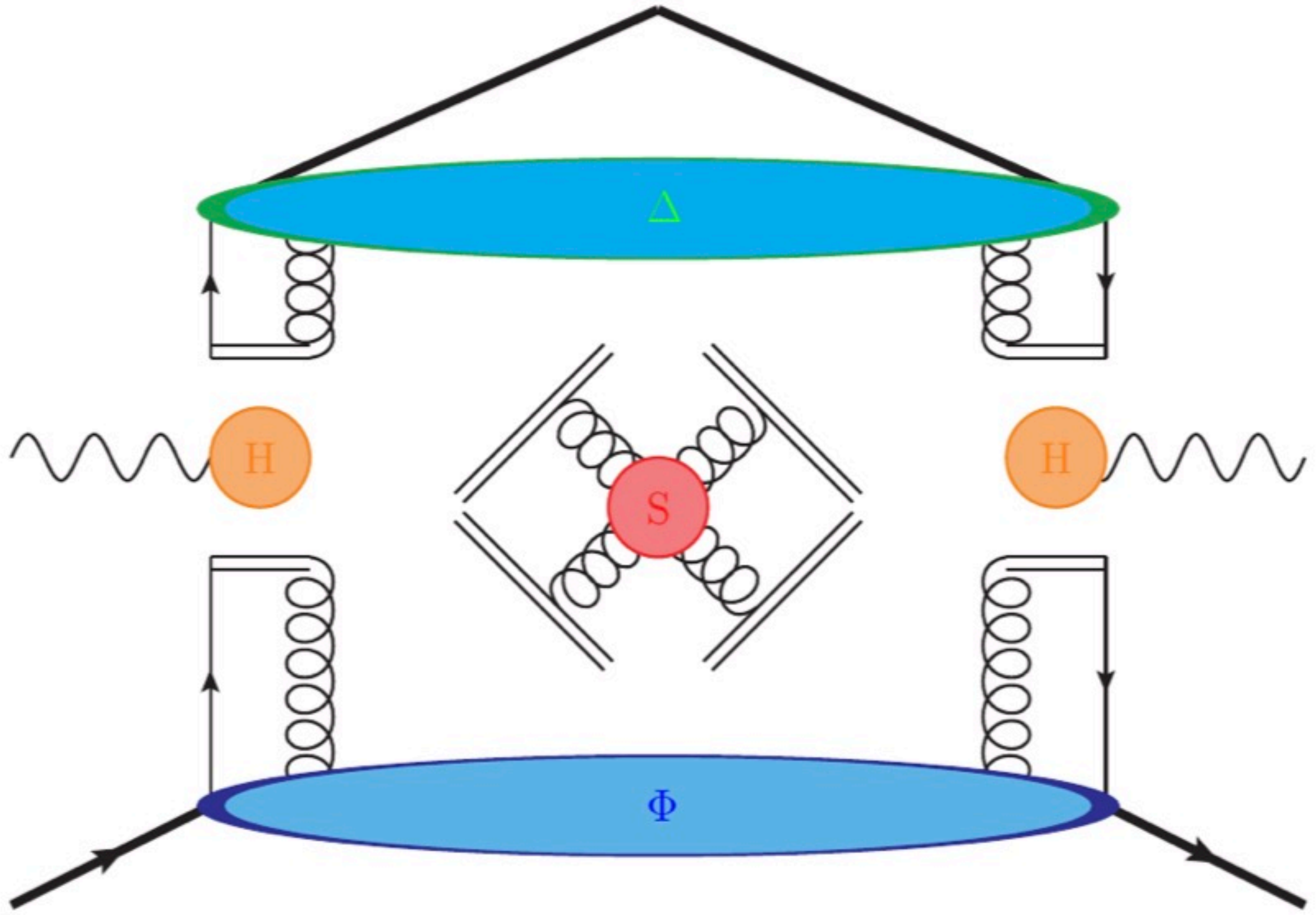
✦ Same requirement on two scales also apply to TMDFFs

Nuclear modified transverse momentum dependent FFs

✦TMD factorization for SIDIS

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

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



✦TMDs

$$f_{q/n}^A(x,b;Q) = \left[C_{q\leftarrow i}\otimes f_{i/n}^A\right](x,\mu_{b_*})\exp\left\{-S_{\rm pert}(\mu_{b_*},Q) - S_{\rm NP}^f(b,Q,A)\right\}$$

$$D_{h/q}^A(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D_{h/i}^A\right](z,\mu_{b_*})\exp\left\{-S_{\rm pert}(\mu_{b_*},Q) - S_{\rm NP}^D(b,z,Q,A)\right\}$$

Our assumptions

- Perturbative information is left unchanged by the nuclear medium. $C_{q\leftarrow i}$, $\hat{C}_{i\leftarrow q}$, and $S_{\rm pert}$ are unchanged.
- Non-perturbative information is modified. $f_{i/n}^A$, $D_{h/i}^A$, $S_{\rm NP}^D$, and $S_{\rm NP}^f$ are altered.

$$S_{\rm NP}^D(z,b,Q,A) = S_{\rm NP}^D(z,b,Q) + b_N\left(A^{1/3}-1\right)\frac{b^2}{z^2}$$

$$S_{\rm NP}^D(z,b,Q,A) = S_{\rm NP}^D(z,b,Q) + b_N\left(A^{1/3}-1\right)\frac{b^2}{z^2}$$

✦ Data selections

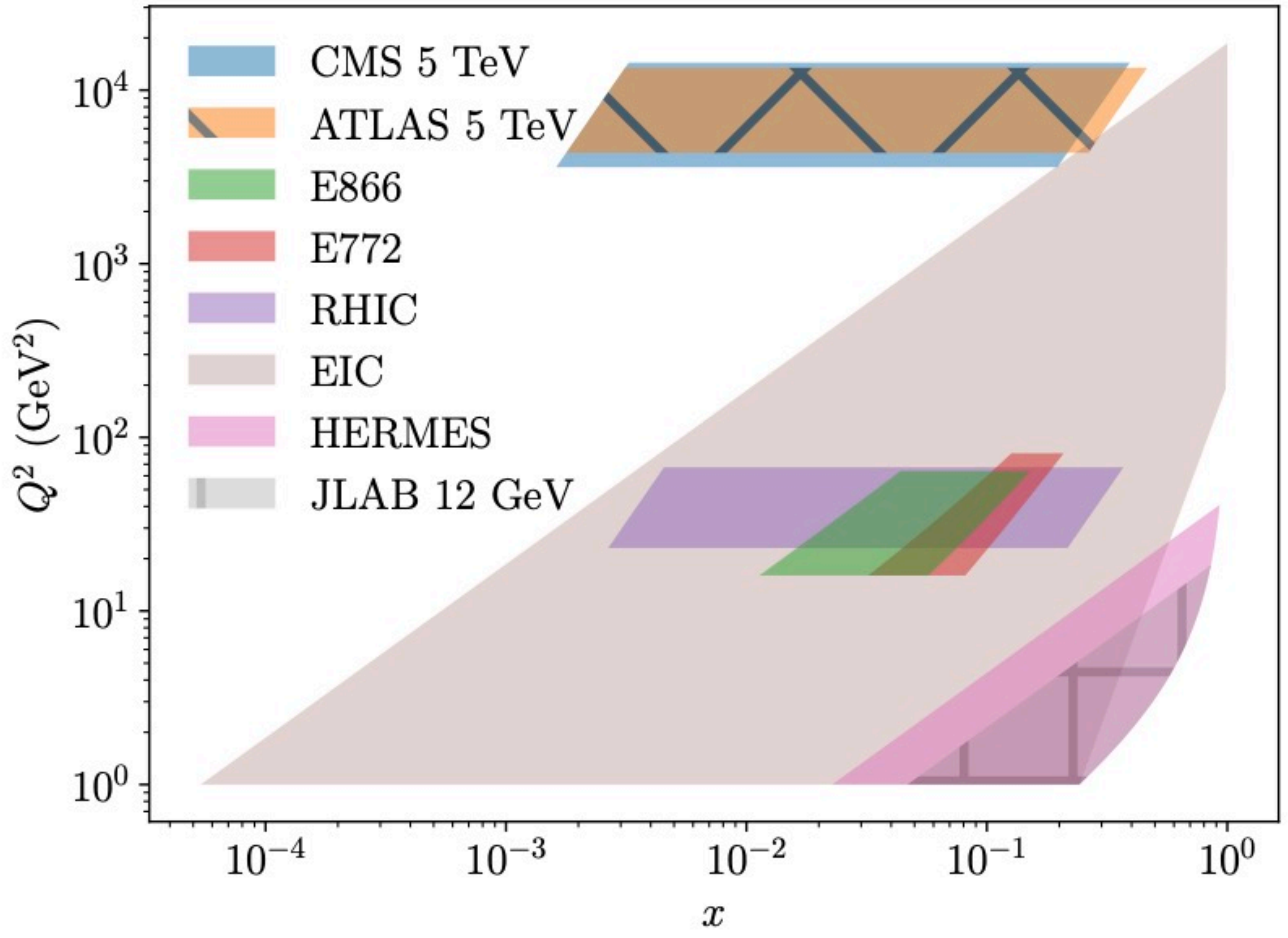
Drell-Yan Measurements

- $R_{AB} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
  -E866
  -E772
  -Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
  ATLAS
  CMS

SIDIS Measurements

- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -Prelim. JLab
  -Planned JLab
  -Possible EIC.

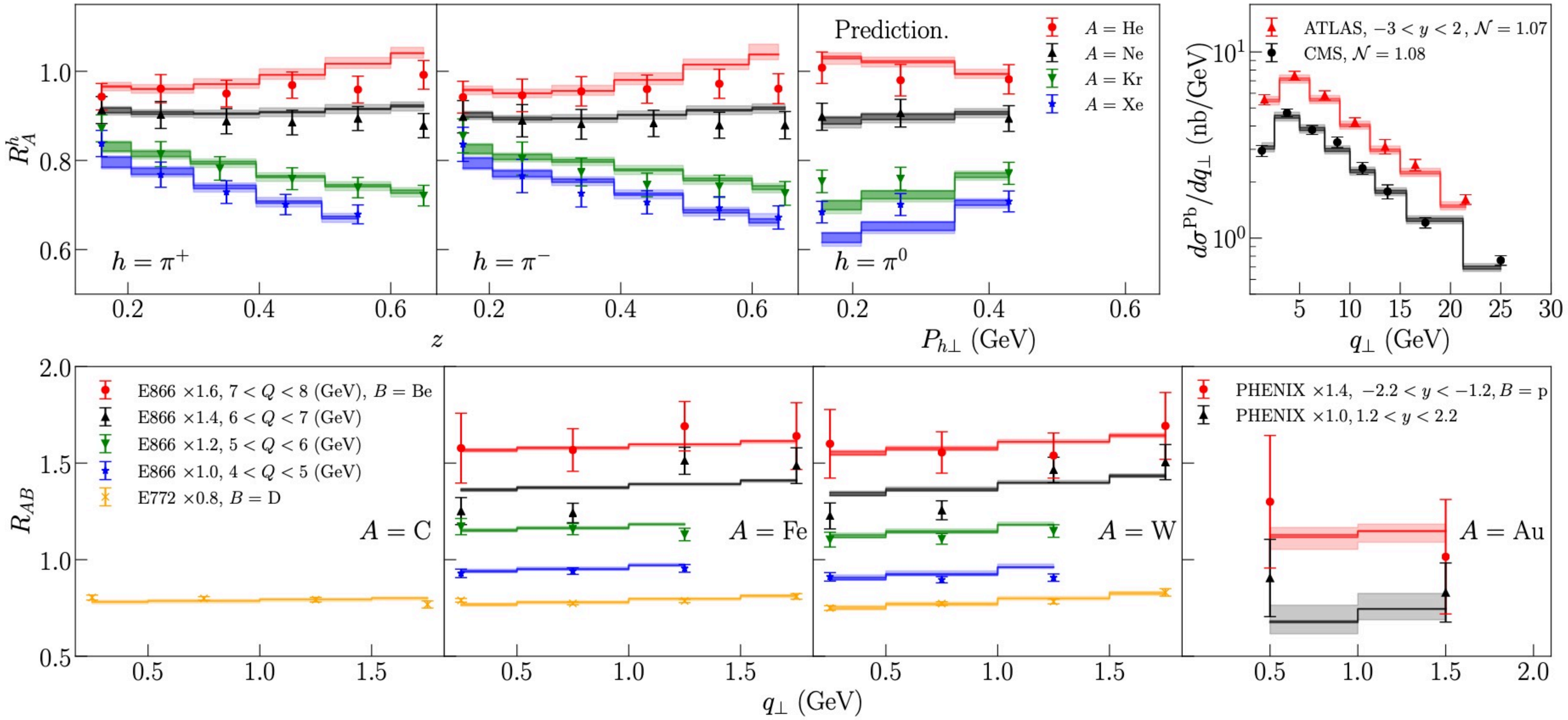
Collaboration	Process	Baseline	Nuclei	N_{dat}	χ^2
HERMES [36]	SIDIS (π)	D	Ne, Kr, Xe	27	16.3
RHIC [44]	DY	p	Au	4	2.0
E772 [42]	DY	D	C, Fe, W	16	20.1
E866 [43]	DY	Be	Fe, W	28	43.3
CMS [45]	γ^*/Z	NA	Pb	8	9.7
ATLAS [46]	γ^*/Z	NA	Pb	7	13.1
Total				90	105.2



Nuclear imaging in 3D

✦ Global fitting of nuclear TMDs

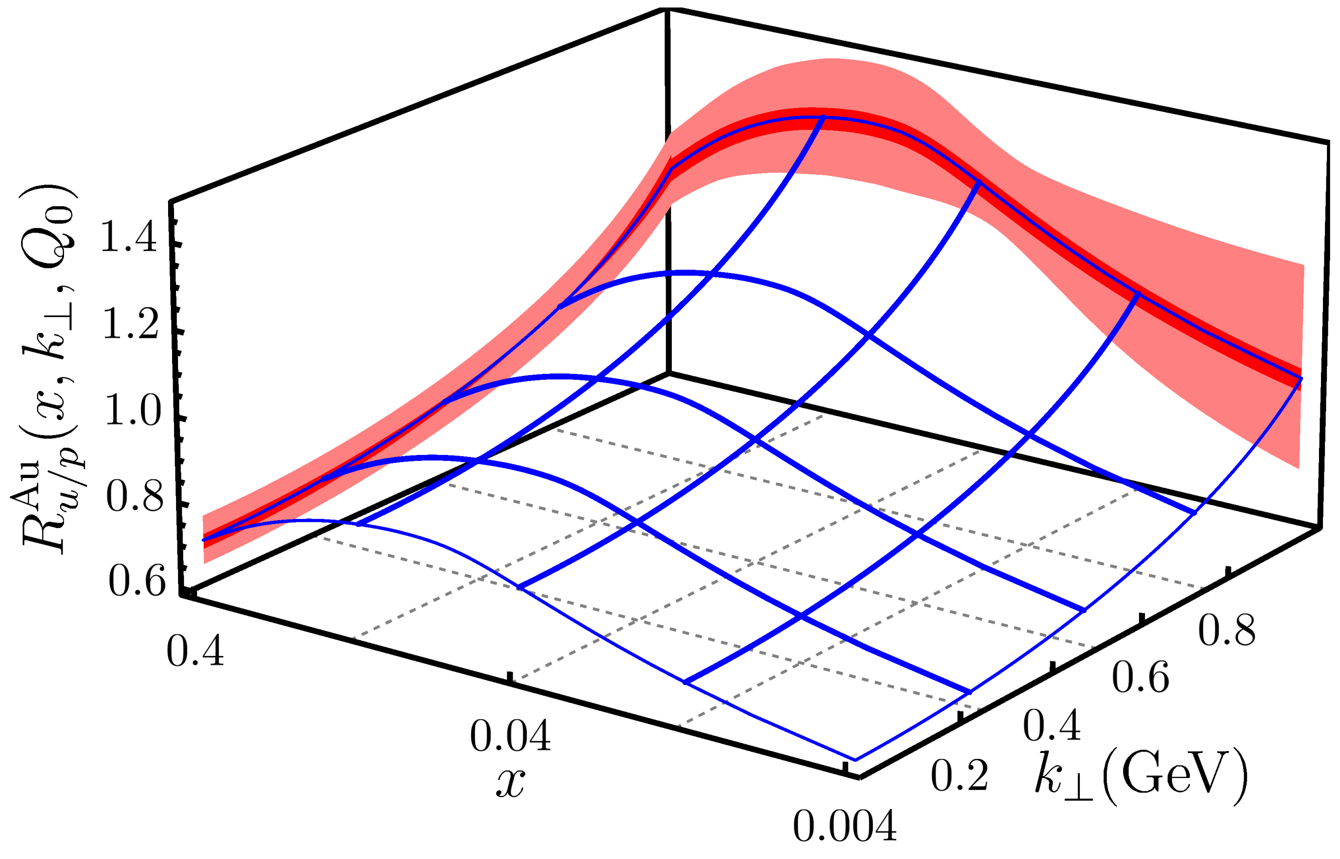
Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022



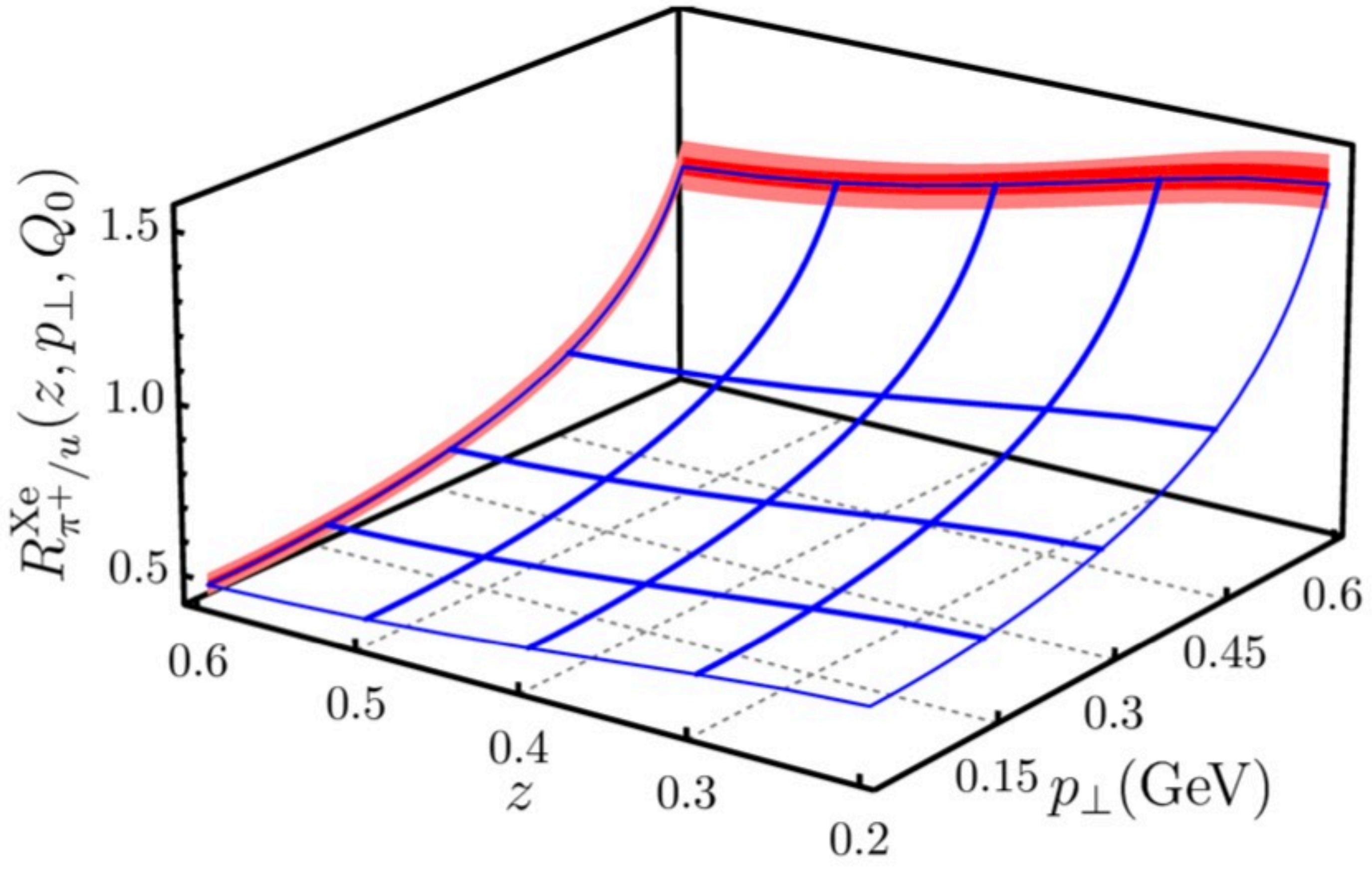
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

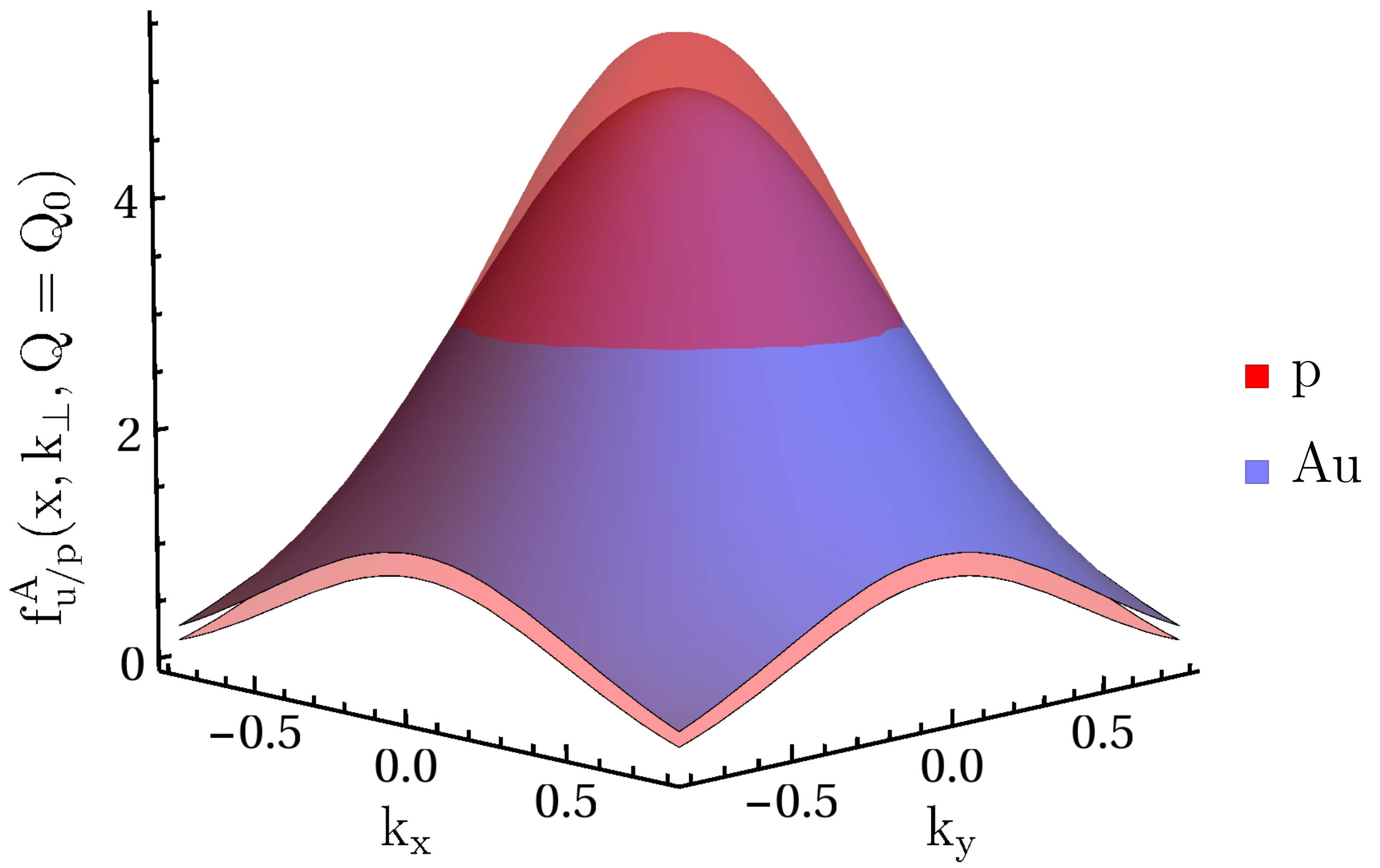
Nuclear imaging in 3D

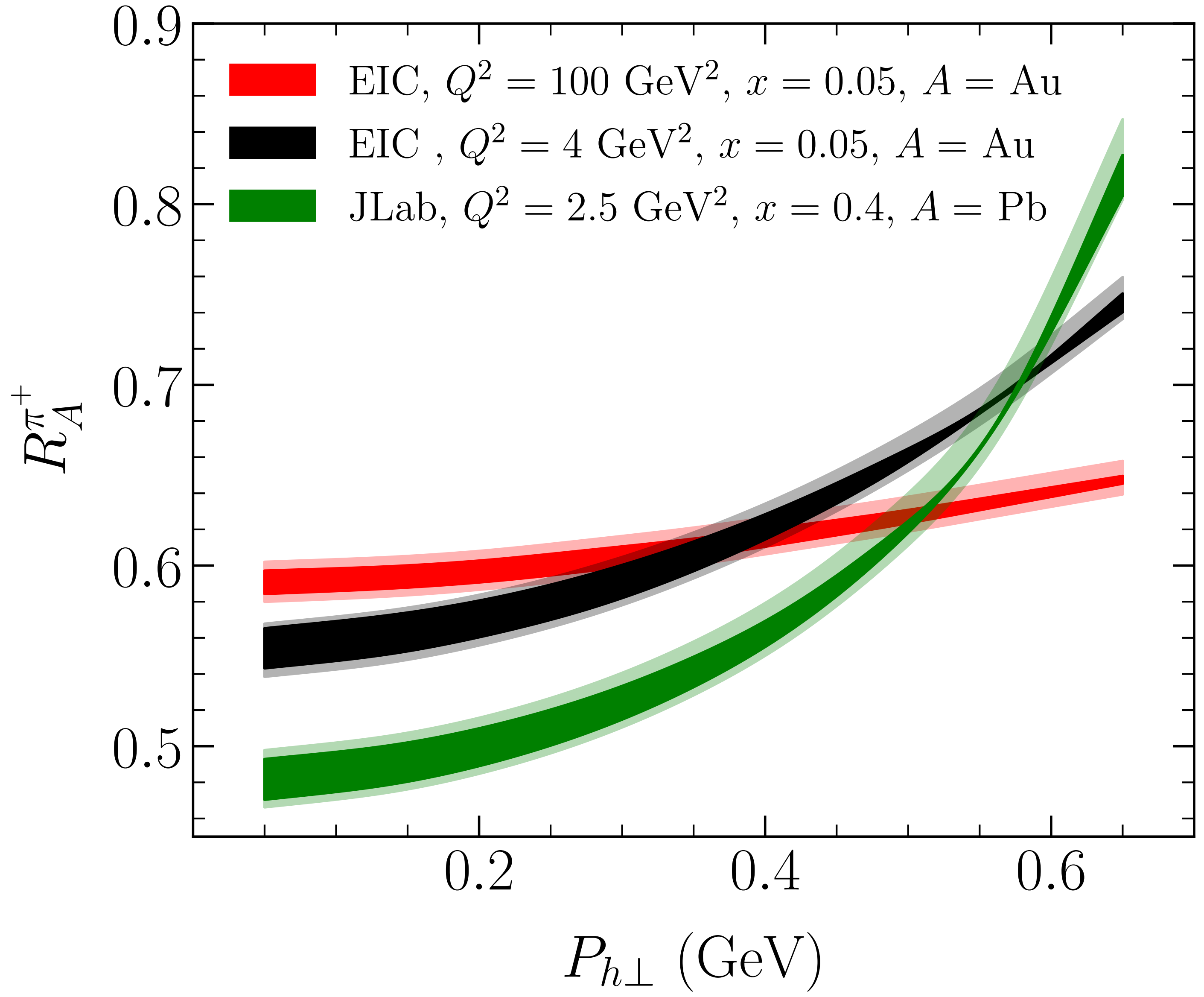
$$R_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0) = \frac{f_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)}$$



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







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

Testing leading power QCD factorization at BES/STCF

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

✦ **Generalized factorization theorem**

perturbative expansion →

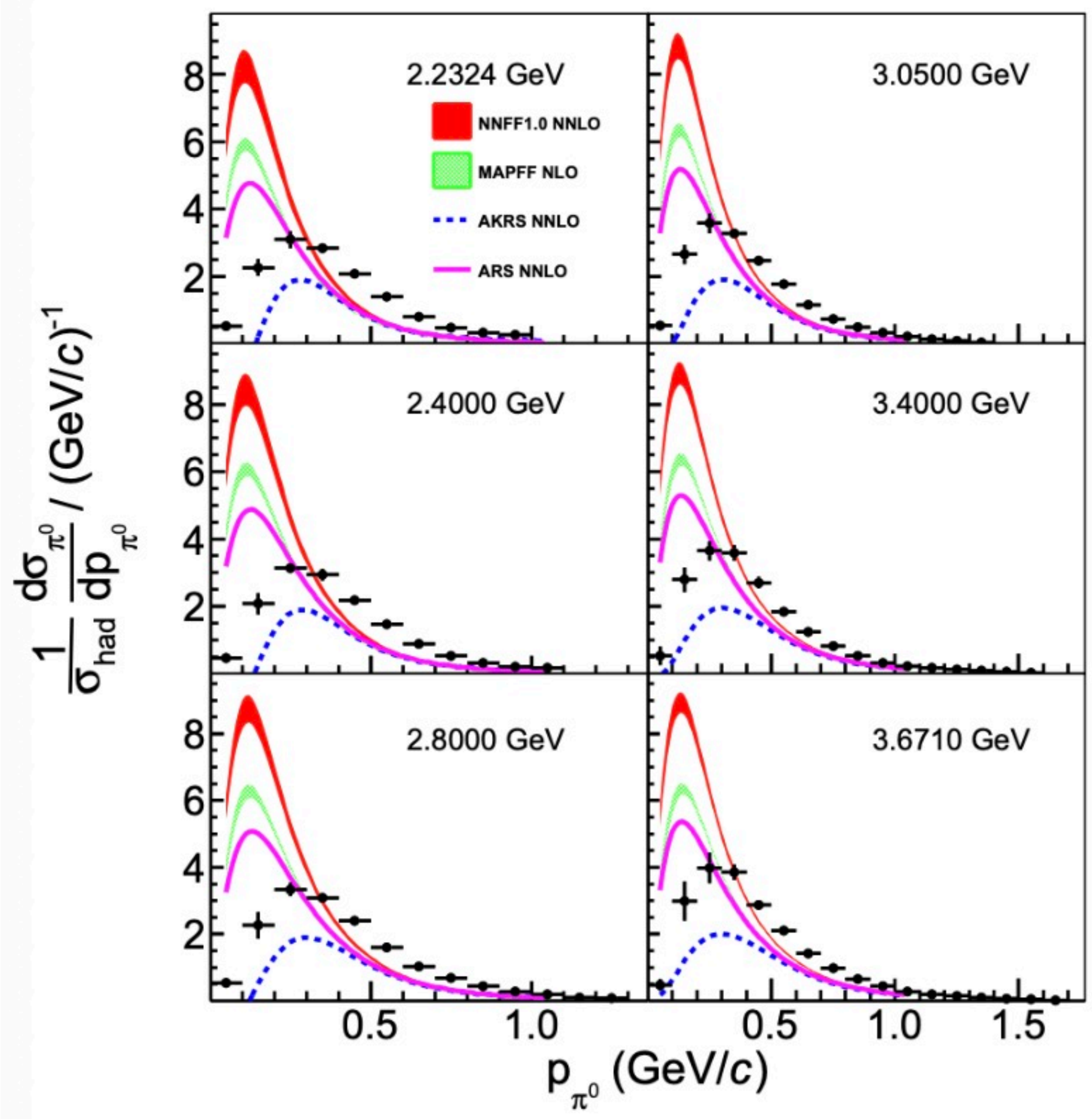
Multiple scattering expansion ↓

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

Test leading power QCD factorization at BES/STCF

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

BESIII Collaboration • M. Ablikim et al. e-Print: 2211.11253



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

NNLO (SIA data only)

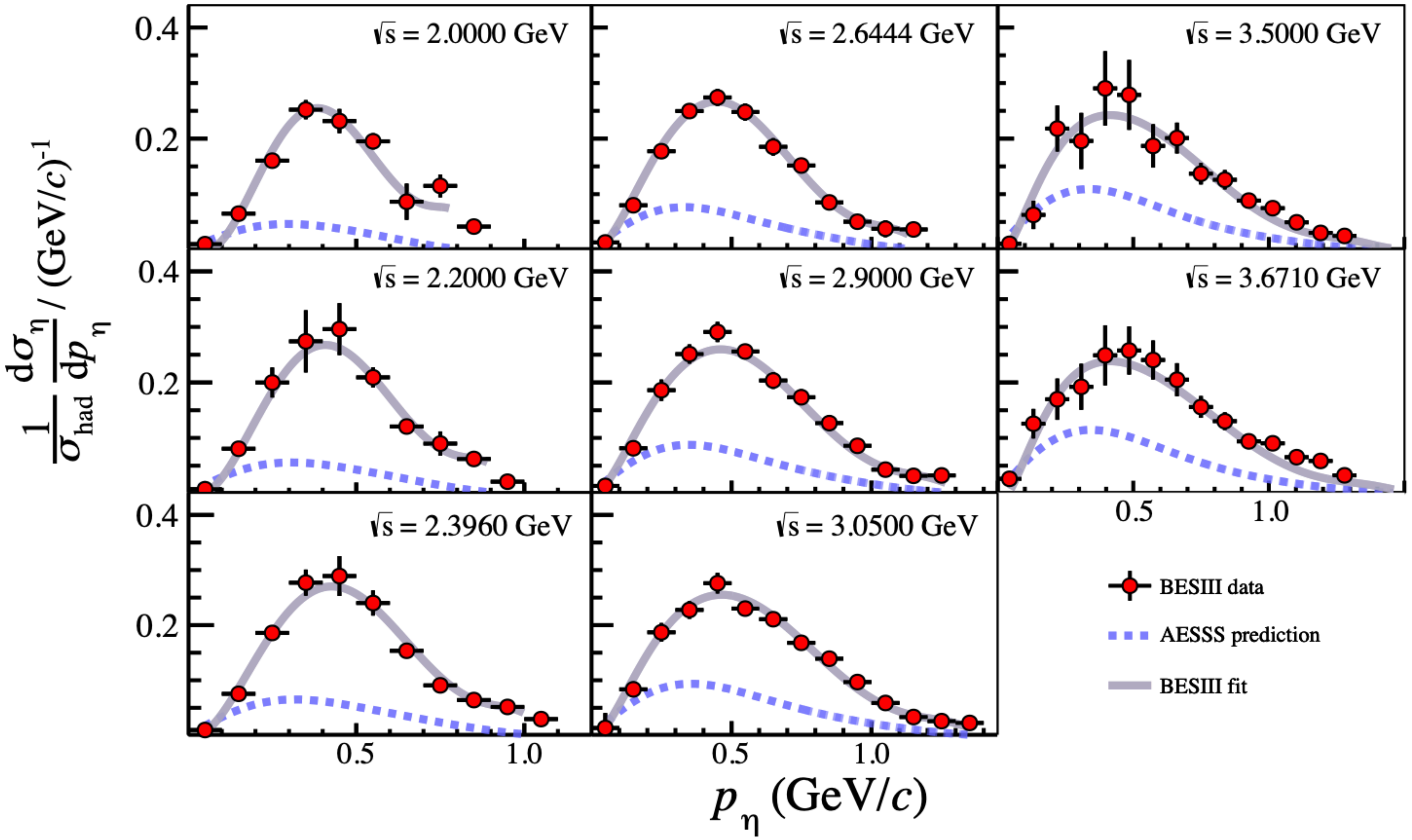
- ARS → Fixed order calculation
- AKRS → Includes small-z resum.
- NNFF1.0 → Includes hadron mass effects

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



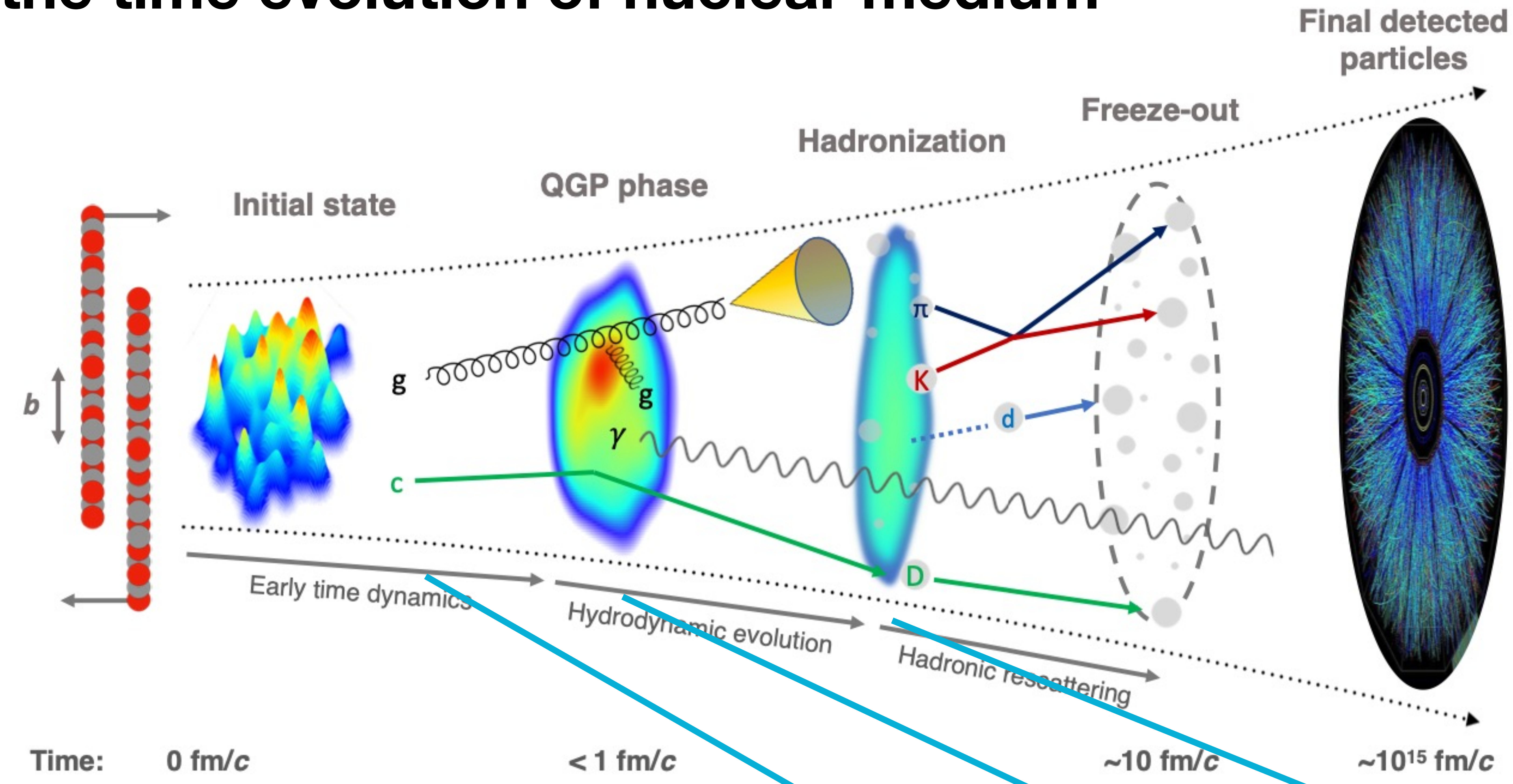
$$\sigma \approx \sigma^{LT} \left[1 + \sum_i N_i \frac{x^{a_i}(1-x)^{b_i}}{Q^{2i}} \right]$$

- Hint of leading twist factorization breaking?
- BES/STCF kinematic coverage is unique to answer this question!

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

Li, Anderle, **HX**, Zhao, 2024

✦ Track the time evolution of nuclear medium



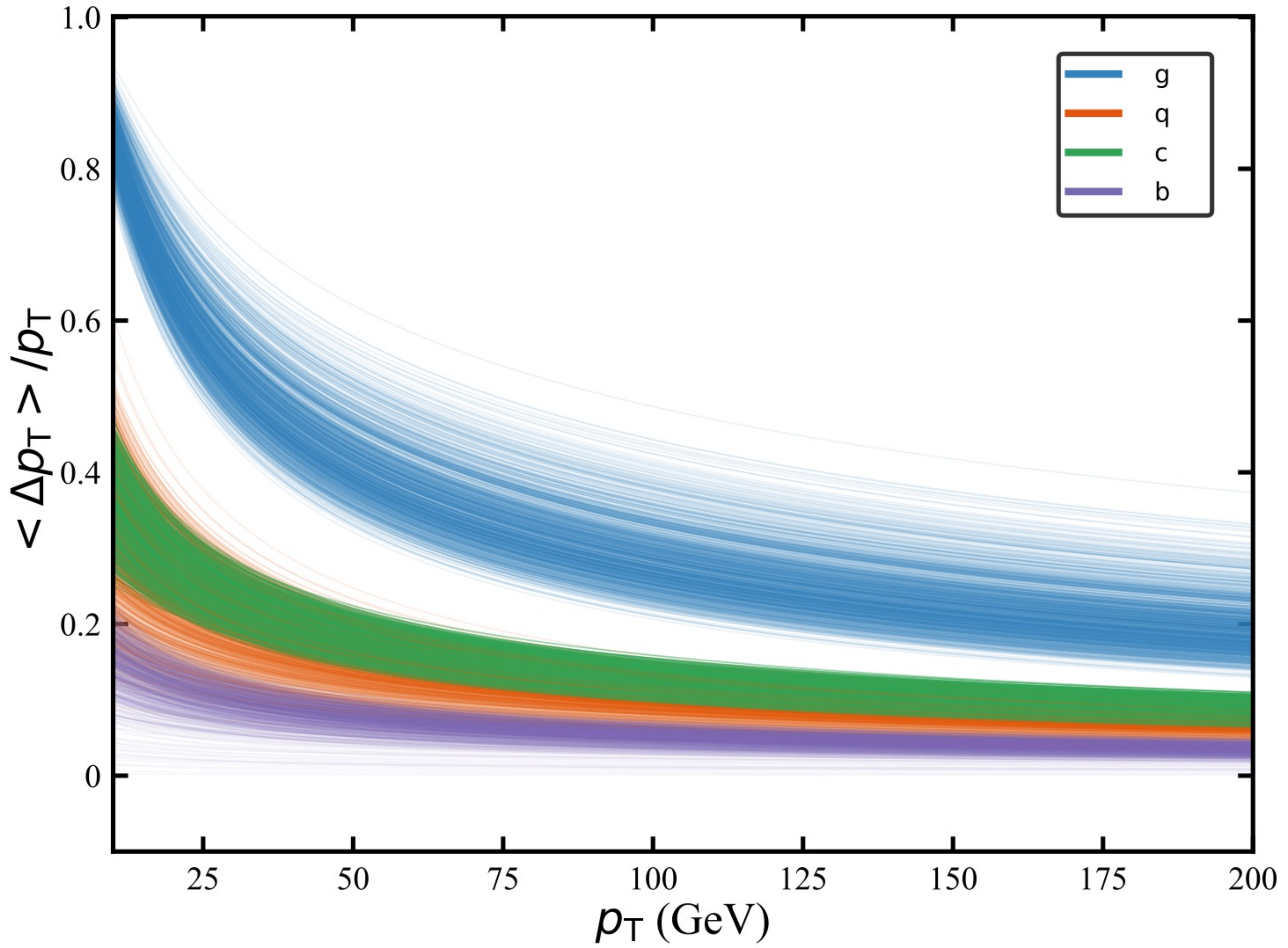
$$\sigma^{AA\to hX} = f_{i/A} \otimes f_{j/A} \otimes \tilde{\sigma}_{ij\to k} \otimes D_{k\to h}$$

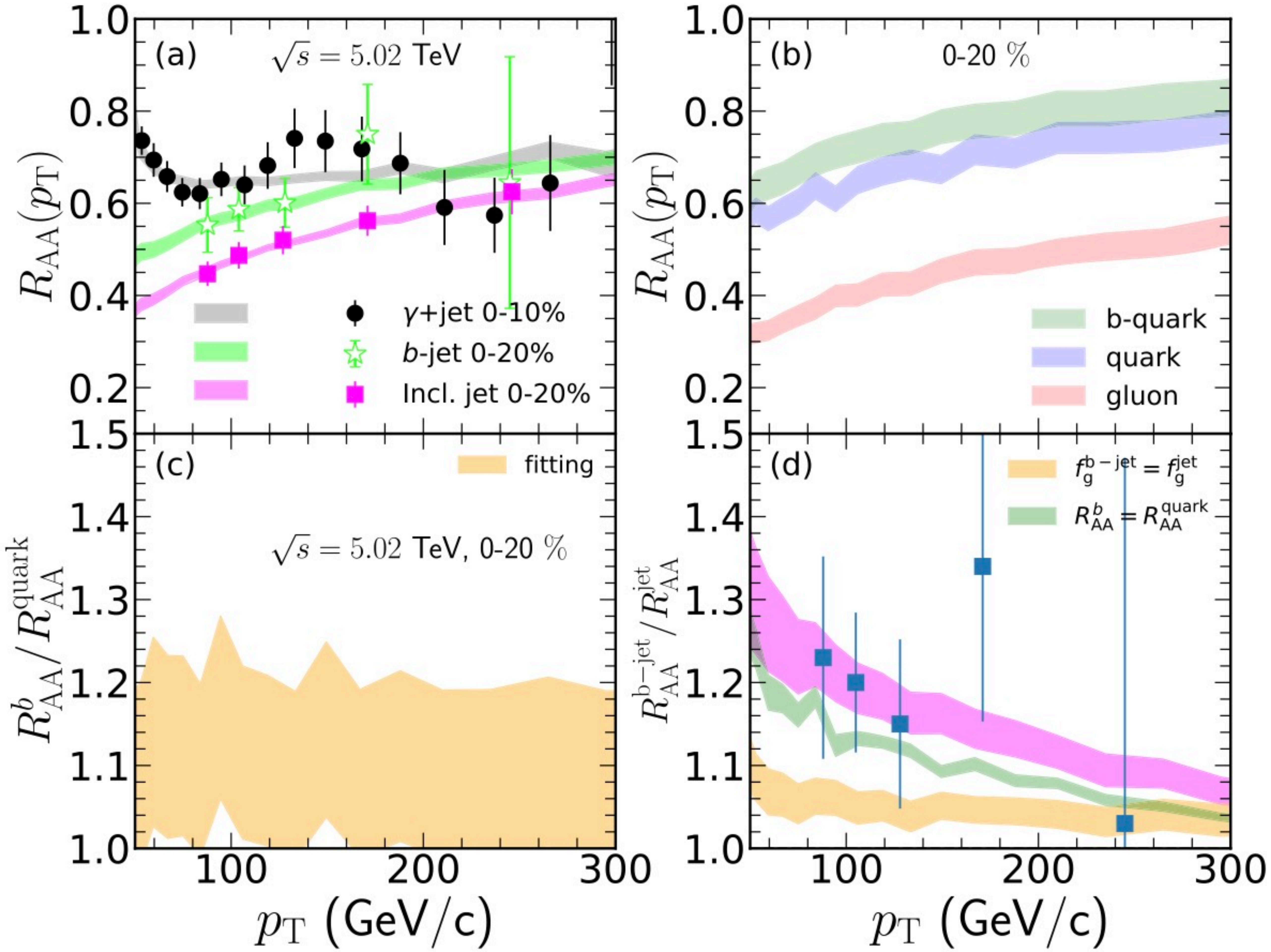
- Observables involving FFs: single inclusive hadron, di-hadron, photon/Z tagged hadron, jet fragmentation function

FFs as a tool to probe hot dense medium

✦ Extract the medium property

Xing, Cao, Qin, 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

Summary

- ✦ Introduction of collinear and transverse momentum dependent fragmentation functions
- ✦ Benefits of using FFs to probe nucleon/nuclear/hot dense medium property
- ✦ Unique opportunities to test QCD factorization for hadron production at BES/STCF

Thanks for your attention!