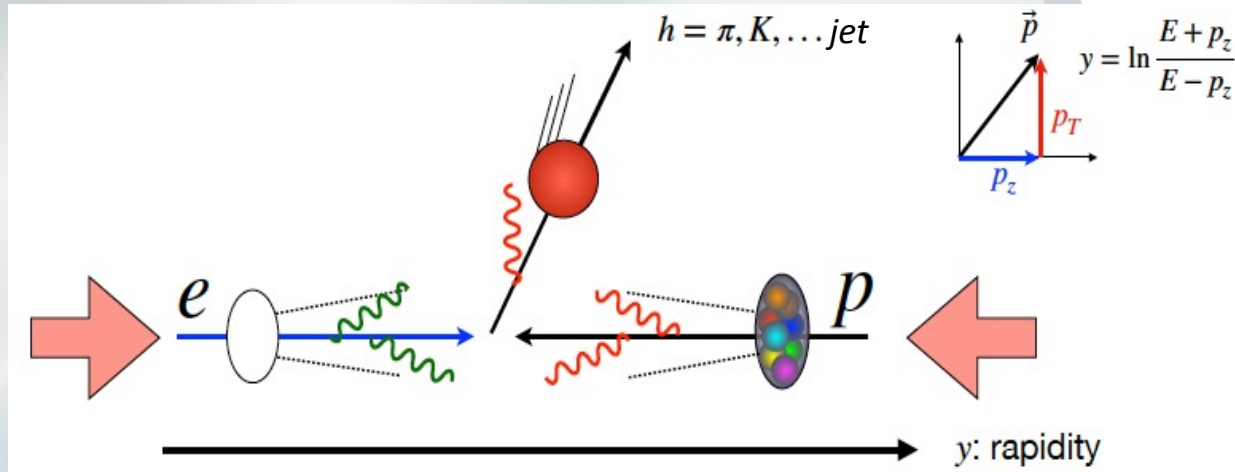


Inclusive high- p_T single hadron and jet production at the EIC



Kang, Meta, Qiu, Zhou, PRD 2011
Hinderer, Schlegel, Vogelsang, PRD 2015, 2016
Abelof, Boughezal, Liu, Petriello, PLB, 2016
Qiu, Wang, Xing, CPL, 2021
Qiu, Watanabe, Prog. Theor. Exp. Phys. 2026

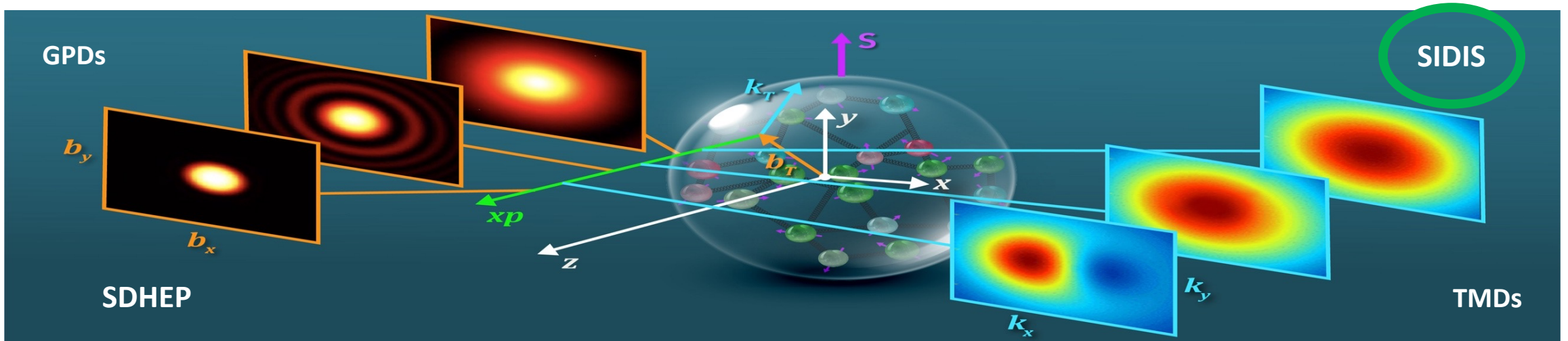


In collaboration with
Kazu Watanabe, ...

Jianwei Qiu
Jefferson Lab, Theory Center

Two-Scale Observables in Lepton-Hadron Collisions

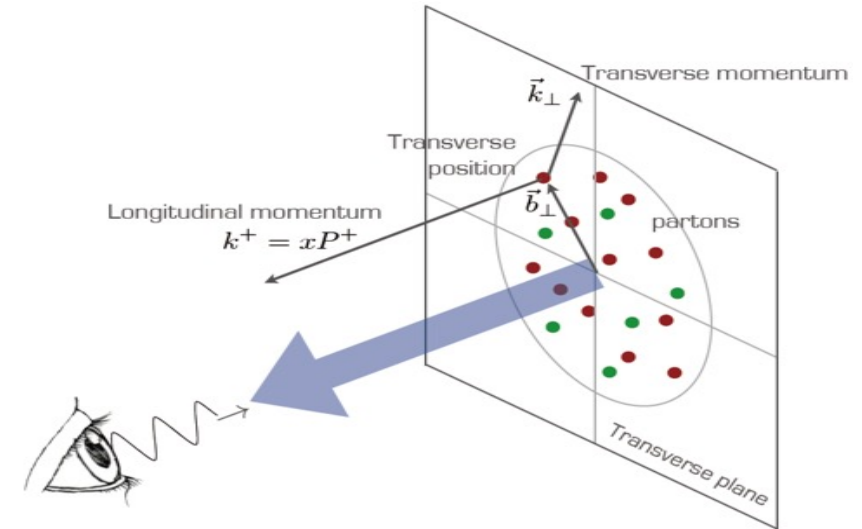
3-D hadron structure:



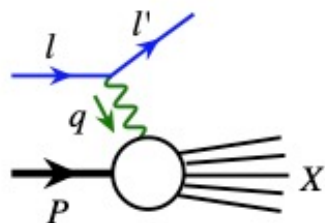
Need new observables with 2 distinctive scales:

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\text{QCD}}$$

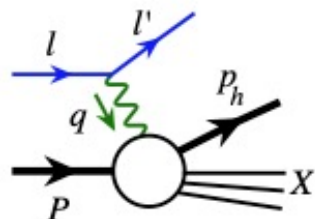
- **Hard scale:** Q_1 to localize the probe to see the particle nature of quarks/gluons
- **"Soft" scale:** Q_2 to be more sensitive to the emergent regime of hadron structure $\sim 1/\text{fm}$



Lepton-Hadron Semi-Inclusive DIS (SIDIS): $Q^2 \gg P_{hT}^2$ in Breit frame

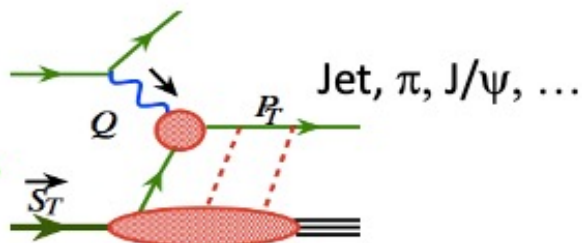


Scale: Q^2 - PDFs



$Q^2 \gg P_{hT}^2$

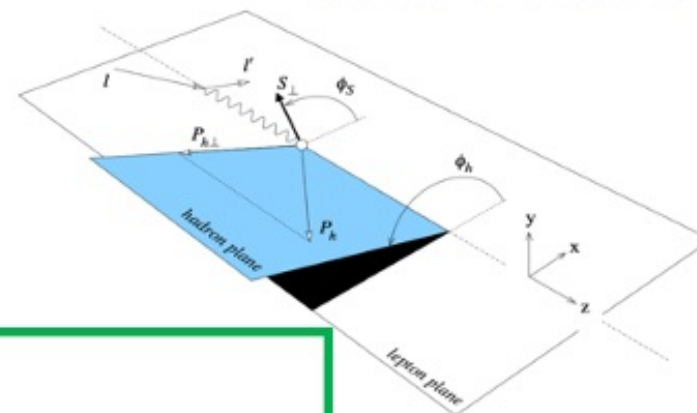
In photon-hadron frame!



$f(x, k_T, Q)$ - TMDs

$$\begin{aligned} \frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = & \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\ & + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \\ & + S_{\parallel} \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\ & + S_{\parallel} \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \\ & + |S_{\perp}| \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\ & + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\ & + \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\ & + |S_{\perp}| \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right. \\ & \left. \left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\} \end{aligned}$$

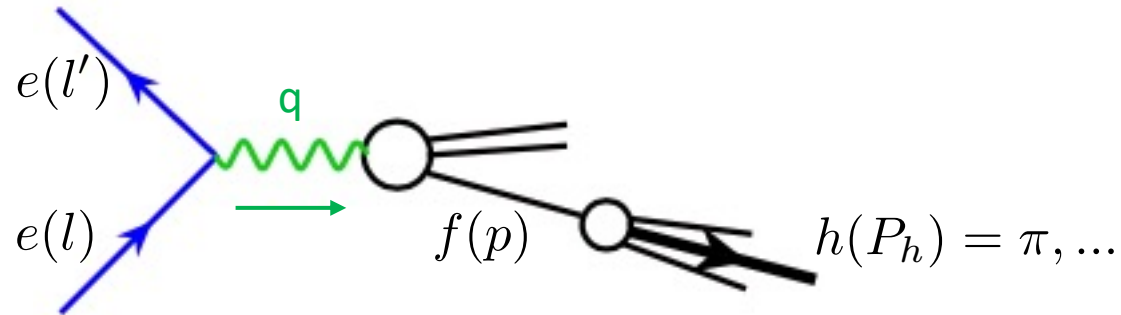
18 SIDIS
Structure Functions



How was the Hadron Produced in the SIDIS?

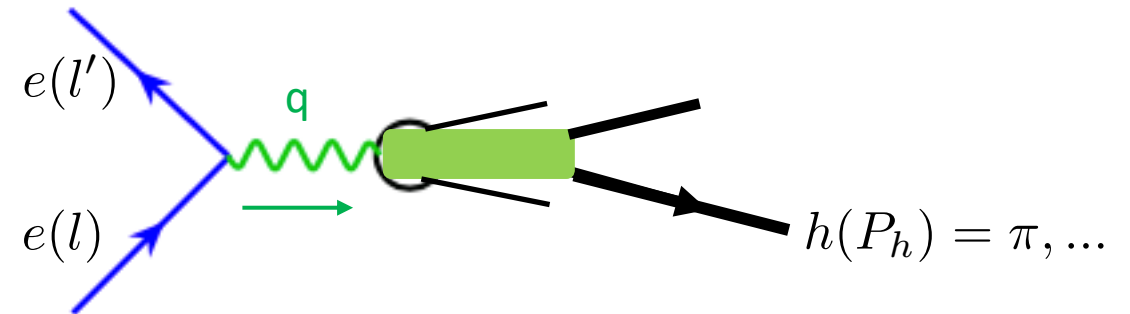
□ **Physical Process:** $e(l) + N(P, \uparrow) \rightarrow e(l') + h(P_h) + X$

■ **Production of a parton + parton fragmentation:**

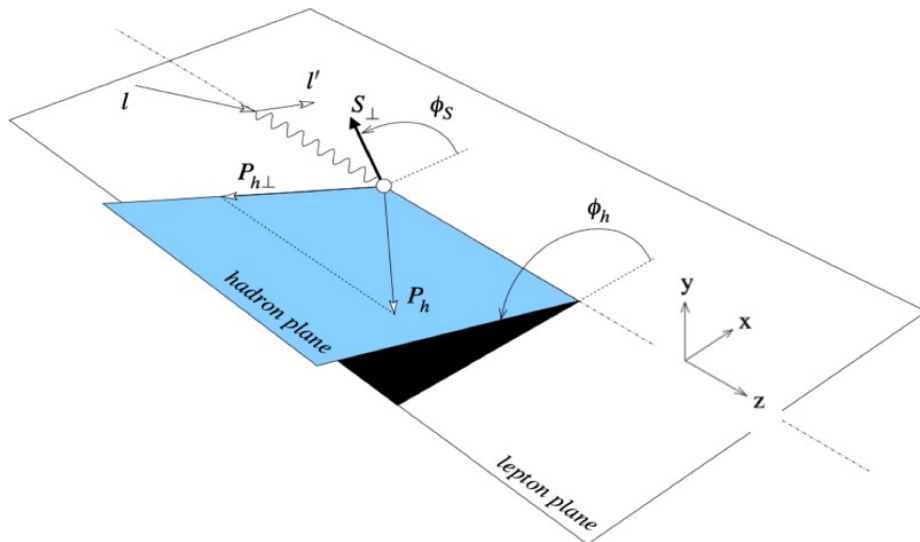


$$E_{l'} E_h \frac{\sigma^{\text{DIS}}}{d^3 l' d^3 P_h} \propto \sum_{a,b} f_{a/N}(x, k_T) \otimes D_{h/b}(z, p_T)$$

■ **Vector-Meson production + decay:**



$$E_{l'} E_h \frac{\sigma^{\text{DIS}}}{d^3 l' d^3 P_h} \not\propto \sum_{a,b} f_{a/N}(x, k_T) \otimes D_{h/b}(z, p_T)$$



Experiment measures cross section & both amplitudes contribute to SIDIS cross section!

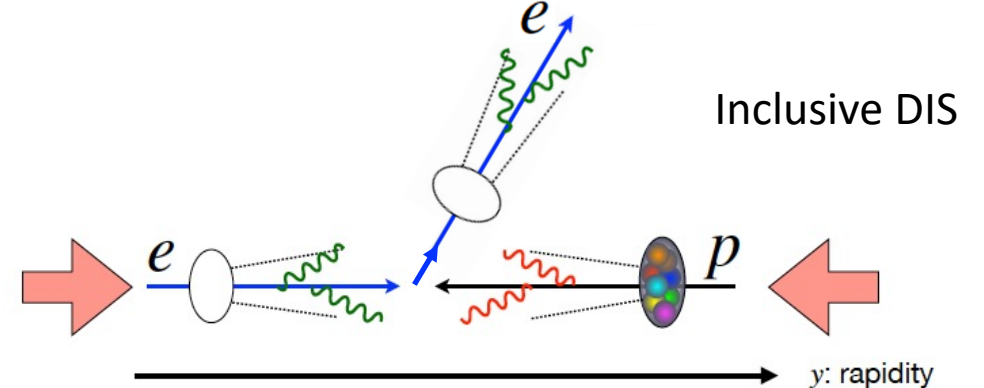
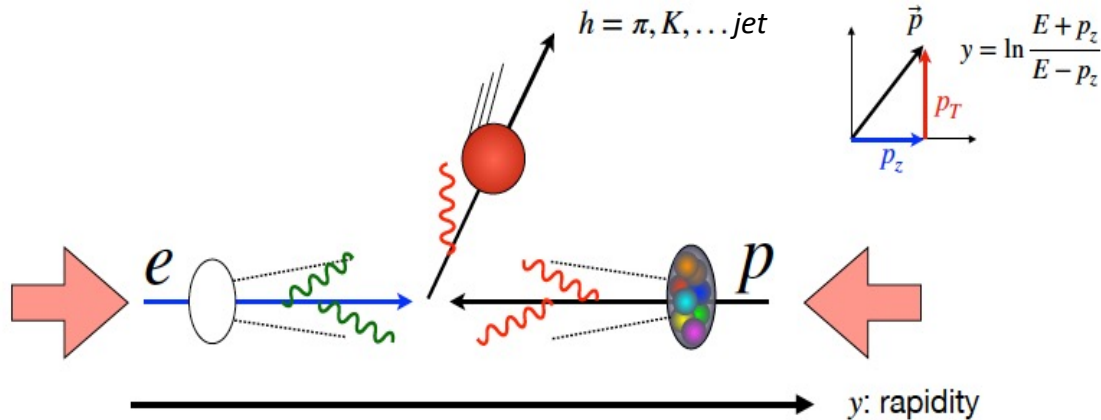
$$\sigma^{\text{DIS}} \propto |\mathcal{M}_{\text{FF}} + \mathcal{M}_{\text{VM}} + \dots|^2 \propto |\mathcal{M}_{\text{FF}}|^2 + \mathcal{O}\left(\left[\frac{M_V}{Q}\right]^n\right)$$

Q: At what kinematics, production via parton fragmentation dominates?

A Prerequisite for understanding SIDIS data

Qiu, Watanabe, Prog. Theor. Exp. Phys. 2026
arXiv:2607.07664

□ Single hadron (Jet) production in lepton-hadron scattering:



HERA experience:

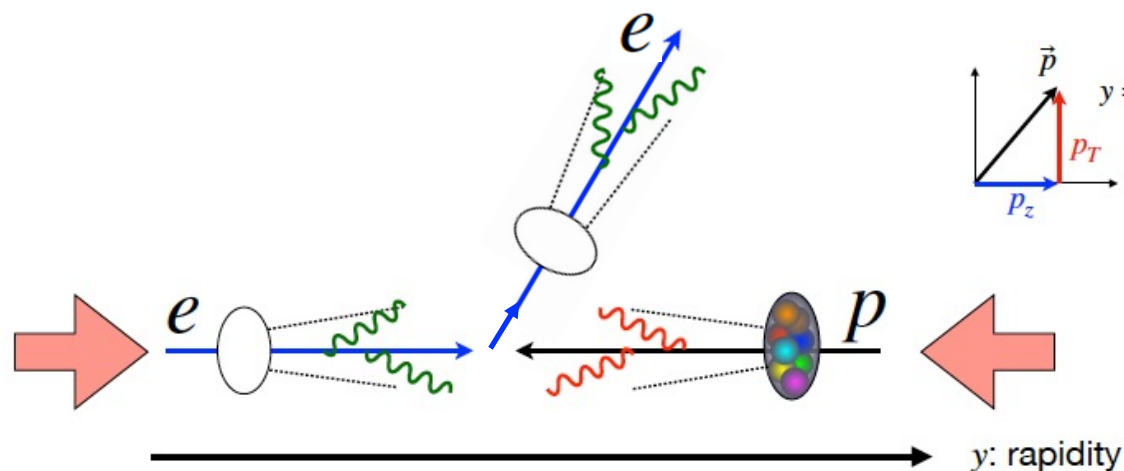
Without measuring the scattered electron, photoproduction of the observed hadron becomes a very important channel, and could be a dominated channel in some cases (e.g., quarkonium production)

Collision-induced QCD and QED radiation:

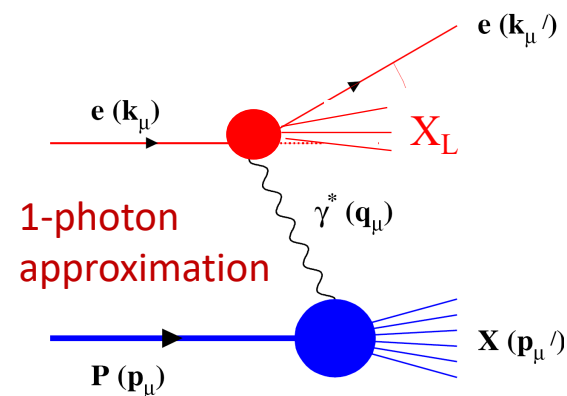
QCD: Factorization move collinear (CO) sensitive radiation to PDFs, FFs, ...;
include CO safe contribution to perturbatively calculable hard coefficients

QED: Change the direction and magnitude of the “exchange photon”, need unknown parameter for Radiative Corrections (RC), which is energy and process dependent, ...

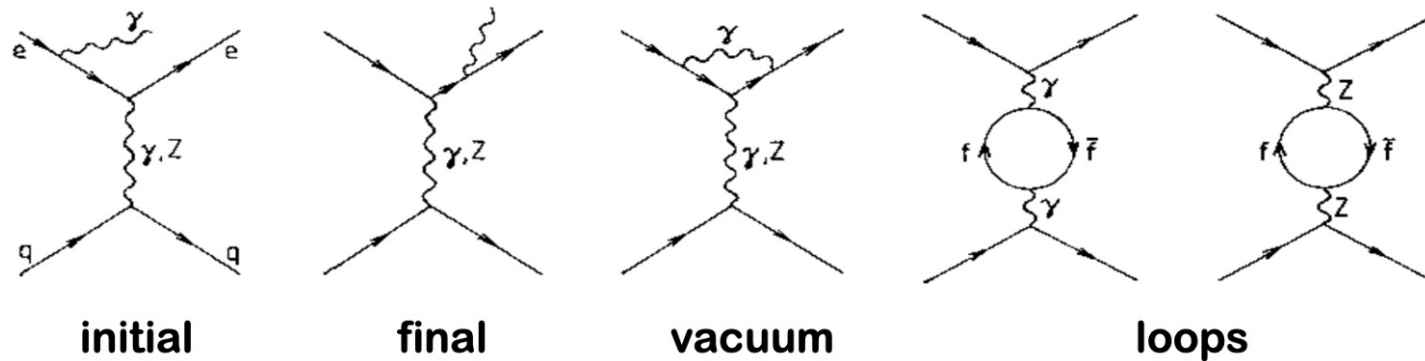
Hard Collision Induces both QCD and QED Radiations



Historically, 1-photon approximation
+ radiative corrections (radiation from leptons)



“We know how to calculate QED radiation perturbatively!”



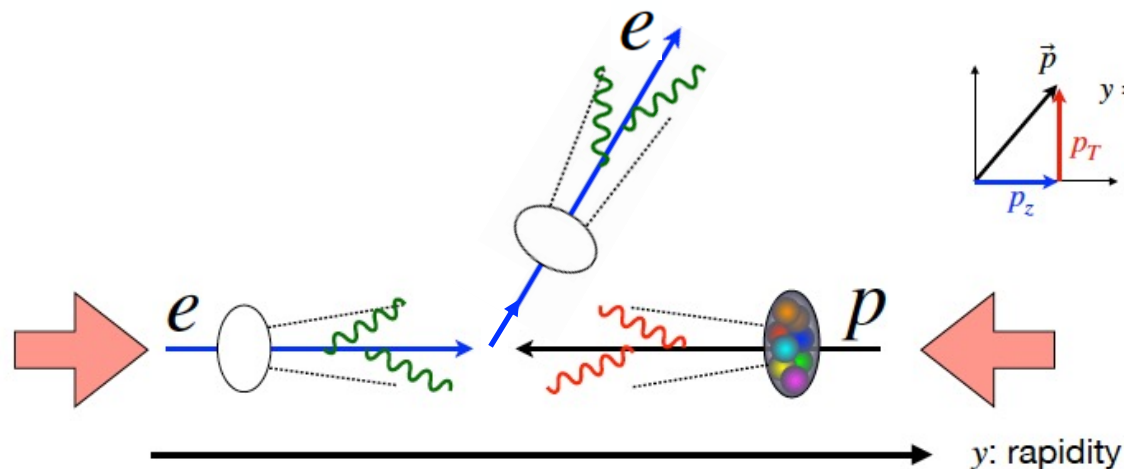
+ two-photon channel + ...



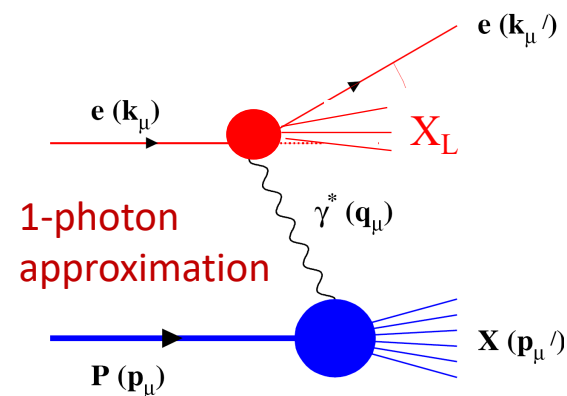
MC program(s) for the RC
with “cutoff(s)”

Always keep the γ^* virtual!

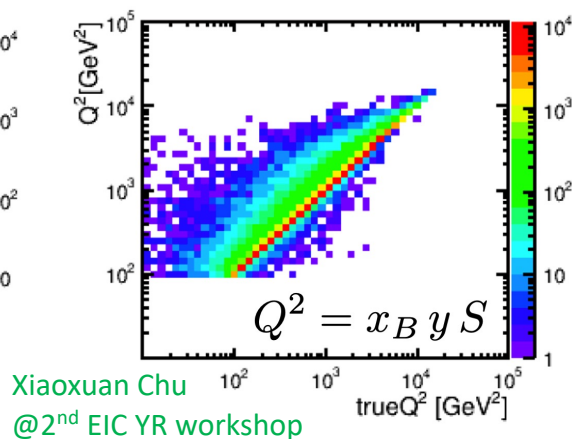
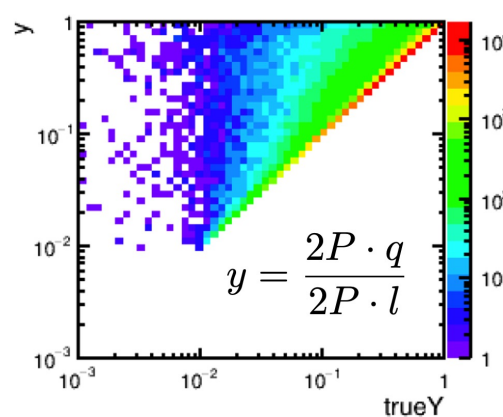
Hard Collision Induces both QCD and QED Radiations



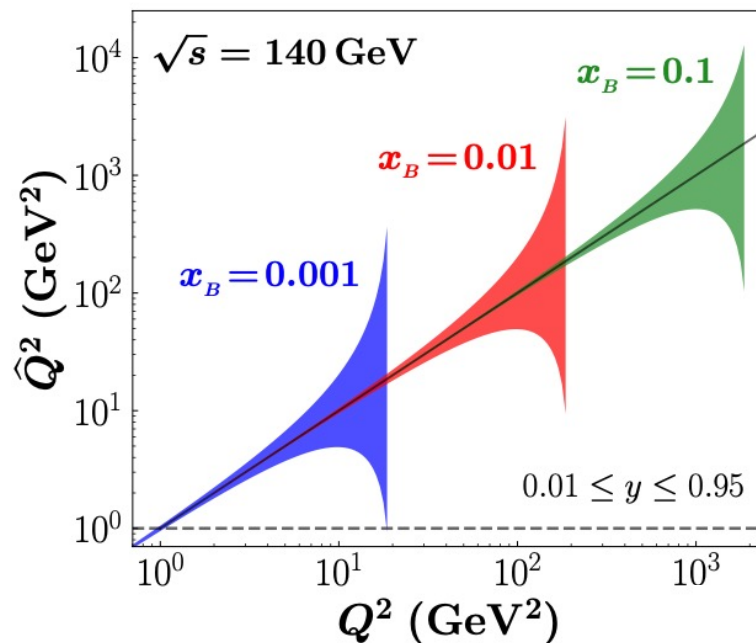
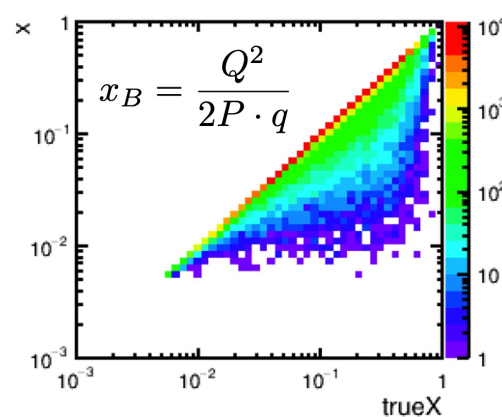
Historically, 1-photon approximation
+ radiative corrections (radiation from leptons)



“We know how to calculate QED radiation perturbatively!”



Xiaoxuan Chu
@2nd EIC YR workshop



$$x_B \rightarrow \hat{x}_B \in [x_B, 1]$$

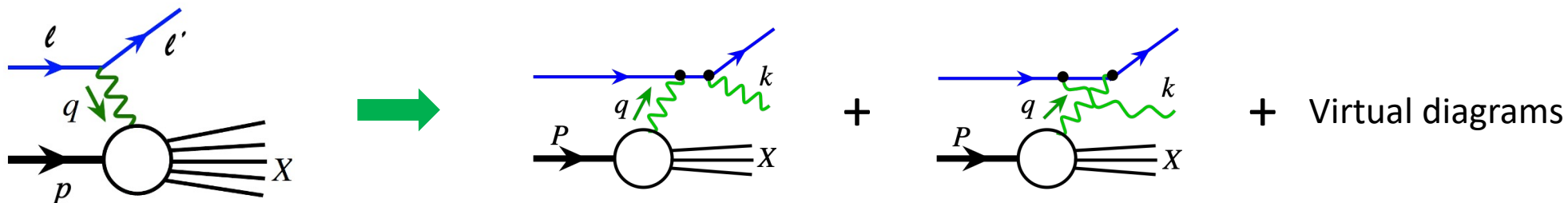
$$\hat{Q}_{\min}^2 = Q^2 \frac{(1-y)}{(1-x_B y)}$$

$$\hat{Q}_{\max}^2 = Q^2 \frac{1}{(1-y + x_B y)}$$

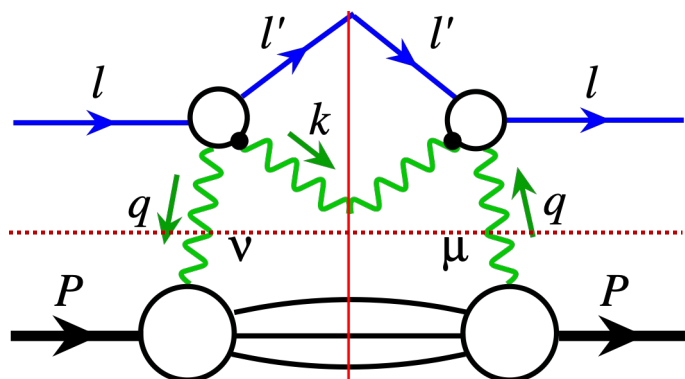
Why We Need Parameter(s) for the Traditional RC Approach?

❑ Leading Order Radiative Correction (from leptons):

Cammarota, Qiu, Watanabe, Zhang
arXiv: 2408.08377, 2505.23487



Contribution to the cross section – cut diagram notation:



The virtuality of the exchange photon q^2 depends on the phase-space of unobserved photon of momentum k

$$E' \frac{d\sigma_{eh \rightarrow eX}^{\text{RC}}}{d^3\ell'} \propto \int d^4q \left[W^{\mu\nu}(P, q) \frac{1}{q^2 + i\epsilon} L_{\mu\nu}^{(1)}(\ell, \ell', q) \frac{1}{q^2 - i\epsilon} \right] \rightarrow \infty$$

The q^2 is perturbatively pinched to $q^2 = 0$ if the phase space allows!

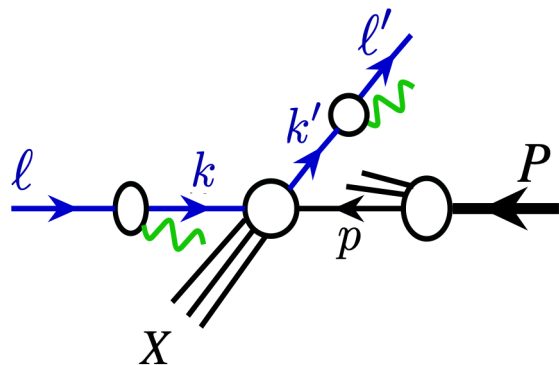
➡ Impose “cutoff/limit” on the radiated and un-observed photon(s) to keep q “virtual” – parameter(s)

The parameter(s) must be collision energy dependent – tuning parameter(s) in MC for RC
– Predictive power?

Joint QCD and QED Factorization for Deep Inelastic Scattering (DIS)

Without the “one-photon” approximation:

~ Inclusive single lepton production at high transverse momentum



$$E_{k'} \frac{d\sigma_{kP \rightarrow k'X}}{d^3k'} = \frac{1}{2s} \sum_{i,j,a} \int_{\zeta_{\min}}^1 \frac{d\zeta}{\zeta^2} \int_{\xi_{\min}}^1 \frac{d\xi}{\xi} D_{e/j}(\zeta, \mu^2) f_{i/e}(\xi, \mu^2) \times \int_{x_{\min}}^1 \frac{dx}{x} f_{a/N}(x, \mu^2) \hat{H}_{ia \rightarrow jX}(\xi k, xP, k'/\zeta, \mu^2) + \dots$$

LFFs

LDFs

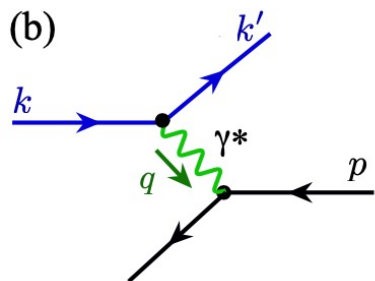
PDFs

No structure functions, but have PDFs, LDFs, LFFs, ...

Hard parts in power of $\alpha^m \alpha_s^n - \hat{H}_{ia \rightarrow jX}^{(m,n)}$:

Hard parts are not sensitive to long-distance physics or the colliding states

■ LO – Let $h(P)$ to be $q(P)$:



$$\begin{aligned} \hat{H}_{eq \rightarrow eq}^{(2,0)} &= (2\hat{s}) \left[E_{k'} \frac{d\sigma_{eq \rightarrow eq}^{(LO)}}{d^3k'} \right] = e_q^2 (4\alpha_{em}^2) \left[\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \right] \delta(\hat{s} + \hat{t} + \hat{u}) \\ &= e_q^2 (4\alpha_{em}^2) \frac{x^2 \zeta [(\zeta \xi s)^2 + u^2]}{(\xi t)^2 (\zeta \xi s + u)} \delta(x - x_{\min}) \end{aligned}$$

$$x_{\min} = \frac{\xi x_B y}{\xi \zeta + y - 1},$$

$$\xi_{\min} = \frac{1 - y}{\zeta - x_B y},$$

$$\zeta_{\min} = 1 - (1 - x_B)y,$$

$$s = (\ell + P)^2,$$

$$u = (\ell' - P)^2 = (y - 1)s,$$

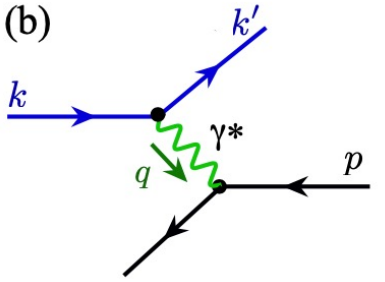
$$t = (\ell - \ell')^2 = -Q^2$$

Joint QCD and QED Factorization for Deep Inelastic Scattering (DIS)

Liu, Melnitchouk, Qiu, Sato,
Phys.Rev.D 104 (2021) 094033
JHEP 11 (2021) 157
Cammarota, Qiu, Watanabe,
Zhang [2408.08377]

□ Keep the “one-photon” approximation – resum collinear radiation:

(b)



$$\frac{d^2\sigma_{\ell P \rightarrow \ell' X}}{dx_B dy} \approx \int_{\zeta_{\min}}^1 \frac{d\zeta}{\zeta^2} \int_{\xi_{\min}}^1 d\xi D_{e/e}(\zeta, \mu^2) f_{e/e}(\xi, \mu^2) \left[\frac{Q^2}{x_B} \frac{\hat{x}_B}{\hat{Q}^2} \right]$$

$$\times \underbrace{\frac{4\pi\alpha^2}{\hat{x}_B \hat{y} \hat{Q}^2} \left[\hat{x}_B \hat{y}^2 F_1(\hat{x}_B, \hat{Q}^2) + \left(1 - \hat{y} - \frac{1}{4} \hat{y}^2 \hat{\gamma}^2 \right) F_2(\hat{x}_B, \hat{Q}^2) \right]}_{\frac{d^2\sigma_{kP \rightarrow k' X}}{d\hat{x}_B d\hat{y}}}$$

When: $D_{e/e}(\zeta) = \delta(1 - \zeta) \delta^{ee}$

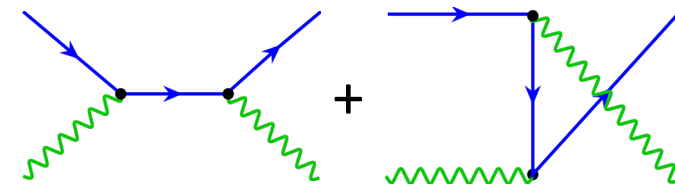
$f_{e/e}(\xi) = \delta(1 - \xi) \delta^{ee}$

➡ Recover the Born expression

□ Next-to-Leading Order (NLO) to the leading subprocess: $e(k) + q(p) \rightarrow e(k') + X$

▪ NLO – Let $h(P)$ to be $q(P)$:

$$\begin{aligned} \hat{H}_{eq \rightarrow eX}^{(3,0)} &= \sigma_{eq \rightarrow eX}^{(3,0)} - D_{e/e}^{(1)} \otimes_{\zeta} \hat{H}_{eq \rightarrow eX}^{(2,0)} - f_{e/e}^{(1)} \otimes_{\xi} \hat{H}_{eq \rightarrow eX}^{(2,0)} \\ &\quad - f_{q/q}^{(1)} \otimes_x \hat{H}_{eq \rightarrow eX}^{(2,0)} - \boxed{f_{\gamma/q}^{(1)} \otimes_x \hat{H}_{e\gamma \rightarrow eX}^{(2,0)}} \end{aligned}$$



Similar to the Bethe-Heitler subprocess
for Exclusive Processes

Completely UV, IR, CO safe!

No need for any free parameter other than the standard factorization scale

NLO QED contributions – beyond 1-vector boson exchange

□ NLO QED contribution – IR & CO safe:

$$\hat{H}_{eq \rightarrow eX}^{(3,0)} \propto \alpha^3 e_q^2 \left\{ e_l^2 \frac{2(1 + \hat{v}^2)}{9\hat{v}} \left[3 \ln \frac{(1 - \hat{v})s}{\mu^2} - 5 \right] \delta(1 - \hat{w}) \right.$$

$$e_l^2 = \sum_f N_c^f e_f^2$$

Sum over the flavors
appeared in the photon
vacuum polarization

$$\hat{v} = 1 - \frac{x_B}{x} \frac{y}{\zeta}$$

$$+ e_q \left[a_1 \delta(1 - \hat{w}) + \frac{a_7}{(1 - \hat{w})_+} + a_6 \right]$$

$$\hat{w} = \frac{1 - y}{\xi (\zeta - (x_B/x) y)}$$

$$+ e_q^2 \left[b_1 \delta(1 - \hat{w}) + b_2 \left(\frac{1}{1 - \hat{w}} \right)_+ + b_3 \left(\frac{\ln(1 - \hat{w})}{1 - \hat{w}} \right)_+ + b_4 \right]$$

Two-photon exchange, IR &
CO safe, no μ dependence

Radiation from quark lines
Same as QCD NLO correction

a_1, a_6, a_7

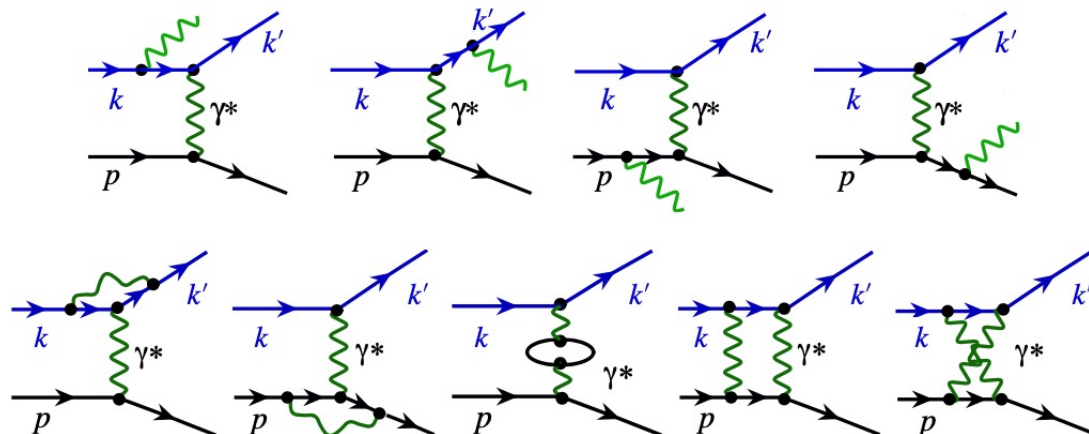
b_1, b_2, b_3, b_4

c_1, c_2, c_3, c_4

$$+ c_1 \delta(1 - \hat{w}) + c_2 \left(\frac{1}{1 - \hat{w}} \right)_+ + c_3 \left(\frac{\ln(1 - \hat{w})}{1 - \hat{w}} \right)_+ + c_4 \left\{ \right.$$

RC - Radiation from electron
Need photon distribution of
the proton

are analytic functions
of $\hat{v}$ and $\hat{w}$.



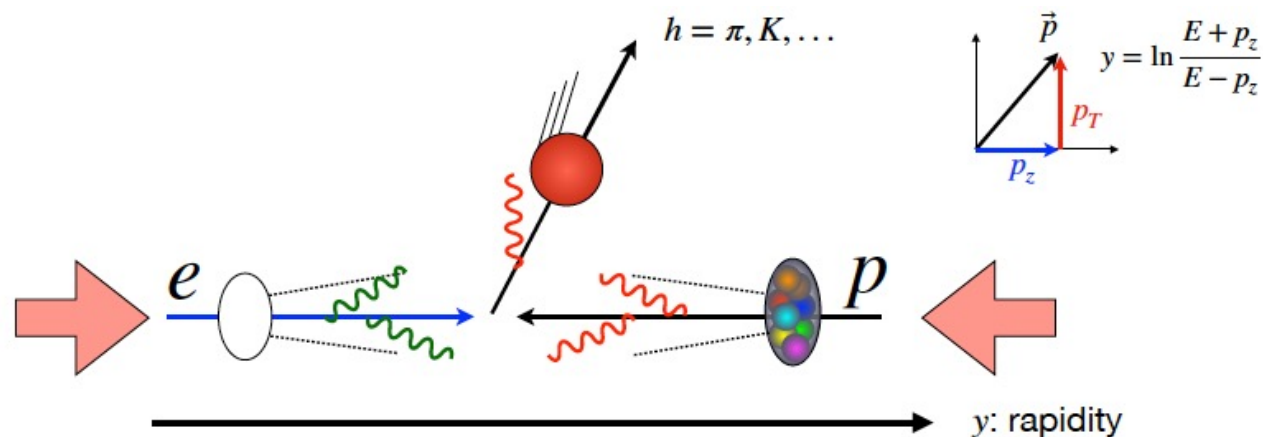
In joint QCD & QED factorization:

Lepton-distributions are not pure QED !

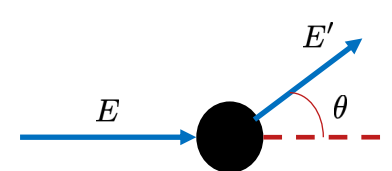
Hadron's parton distributions are not pure QCD !

Prompt Single Hadron/Jet Production:

□ Single hadron (Jet) production in lepton-hadron scattering:



JLab kinematics – fixed target:



$$p_T = E' \sin(\theta) \gtrsim 1 \text{ GeV?}$$

Factorization:

$$E \frac{d\sigma_{\ell P \rightarrow pX}}{d^3p} \approx \frac{1}{2s} \sum_{i,a,b} \int_{z_{\min}}^1 \frac{dz}{z^2} \int_{\xi_{\min}}^1 \frac{d\xi}{\xi} D_{h/b}(z, \mu^2) f_{i/e}(\xi, \mu^2) \times \int_{x_{\min}}^1 \frac{dx}{x} f_{a/N}(x, \mu^2) \hat{H}_{ia \rightarrow bX}(\xi \ell, xP, p/z, \mu^2) + (1/p_T)^\alpha$$

Single hard scale
Collinear factorization

Nayak, Qiu, Sterman, PRD72, 114012 (2005)

Hard parts are valid at NLO
Partially available at NNLO
in QCD

The new unknown is $f_{i/e}(\xi, \mu^2)$

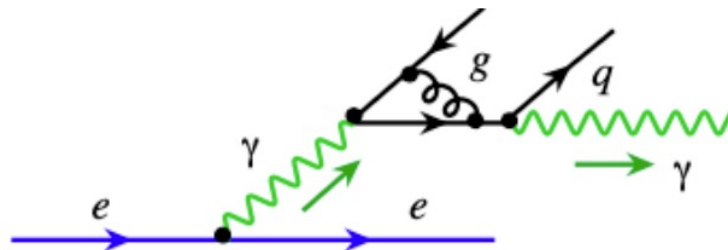
lepton distribution functions (LDFs)

Hadron fragmentation functions (FFs):

Known, but, limited knowledge, in particular, at large z !

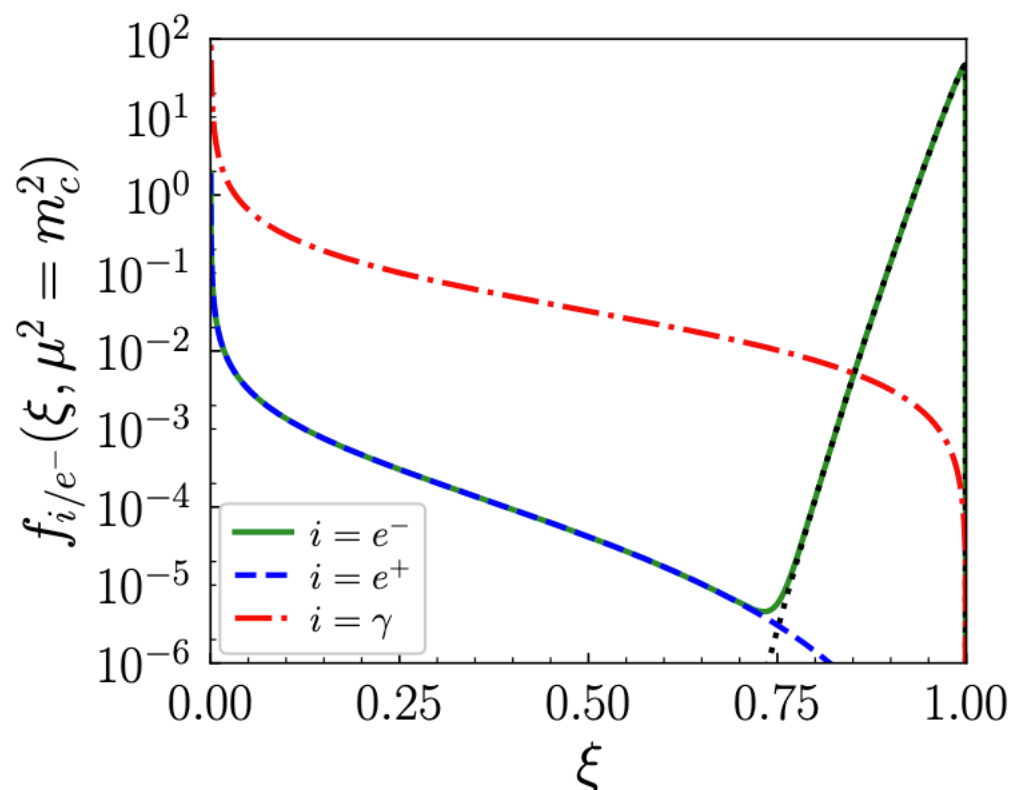
Lepton Distribution Functions (LDFs):

□ LDFs are non-perturbative:



QCD corrections make the LDFs non-perturbative when evolved to below the perturbative hard scale

□ Default Input LDFs at $\mu_0 = m_c$ (Approximation) – need to be fixed by future data:



$$f_{i/e}(\xi, m_c^2) = N_i \xi^{\alpha_i} (1 - \xi)^{\beta_i}$$

	N_i	α_i	β_i
$f_{e/e}^V$	96.808	60	0.1
$f_{\gamma/e}$	0.035	-0.995	1.082
$f_{\bar{e}/e}$	1.894×10^{-4}	-1.001	3.182

Evolved from m_e to m_c via QED:

$$f_{e/e}(\xi, m_e^2) = \frac{\xi^{\alpha_0} (1 - \xi)^{\beta_0}}{B[\alpha_0 + 1, \beta_0 + 1]}$$

$$f_{\gamma/e}(\xi, m_e^2) = 0, \quad \text{To match: } f_{e/e}^V(\xi, \mu_0^2) \approx f_{e/e}^{\text{NLO}}(\xi, \mu_0^2)$$

$$f_{\bar{e}/e}(\xi, m_e^2) = 0.$$

Evolution of Lepton Distribution Functions (LDFs):

□ Modified DGLAP equation for LDFs:

Qiu, Watanabe, Prog. Theor. Exp. Phys. 2026

$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} f_{e/e}(\xi, \mu^2) \\ f_{\bar{e}/e}(\xi, \mu^2) \\ f_{\gamma/e}(\xi, \mu^2) \\ f_{q/e}(\xi, \mu^2) \\ f_{\bar{q}/e}(\xi, \mu^2) \\ f_{g/e}(\xi, \mu^2) \end{pmatrix} = \begin{pmatrix} P_{ee}^{(1,0)} & P_{e\bar{e}}^{(2,0)} & P_{e\gamma}^{(1,0)} & P_{eq}^{(2,0)} & P_{e\bar{q}}^{(2,0)} & P_{eg}^{(2,1)} \\ P_{\bar{e}e}^{(2,0)} & P_{\bar{e}\bar{e}}^{(1,0)} & P_{\bar{e}\gamma}^{(1,0)} & P_{\bar{e}q}^{(2,0)} & P_{\bar{e}\bar{q}}^{(2,0)} & P_{\bar{e}g}^{(2,1)} \\ P_{\gamma e}^{(1,0)} & P_{\gamma\bar{e}}^{(1,0)} & P_{\gamma\gamma}^{(1,0)} & P_{\gamma q}^{(1,0)} & P_{\gamma\bar{q}}^{(1,0)} & P_{\gamma g}^{(1,1)} \\ P_{qe}^{(2,0)} & P_{q\bar{e}}^{(2,0)} & P_{q\gamma}^{(1,0)} & P_{qq}^{(0,1)} & P_{q\bar{q}}^{(0,2)} & P_{qg}^{(0,1)} \\ P_{\bar{q}e}^{(2,0)} & P_{\bar{q}\bar{e}}^{(2,0)} & P_{\bar{q}\gamma}^{(1,0)} & P_{\bar{q}q}^{(0,2)} & P_{\bar{q}\bar{q}}^{(0,1)} & P_{\bar{q}g}^{(0,1)} \\ P_{ge}^{(2,1)} & P_{g\bar{e}}^{(2,1)} & P_{g\gamma}^{(1,1)} & P_{gq}^{(0,1)} & P_{g\bar{q}}^{(0,1)} & P_{gg}^{(0,1)} \end{pmatrix} \otimes \begin{pmatrix} f_{e/e}(\xi, \mu^2) \\ f_{\bar{e}/e}(\xi, \mu^2) \\ f_{\gamma/e}(\xi, \mu^2) \\ f_{q/e}(\xi, \mu^2) \\ f_{\bar{q}/e}(\xi, \mu^2) \\ f_{g/e}(\xi, \mu^2) \end{pmatrix}$$

■ Input Factorization scale:

$$\mu^2 \sim m_c^2$$

The QCD/QED mixing is critically important for canceling all collinear divergence beyond LO!

Evolution kernels in both QCD and QED:

$$P_{ij}(\xi, \mu^2) = \sum_{n,m=0}^{\infty} \left(\frac{\alpha_{em}(\mu^2)}{2\pi} \right)^n \left(\frac{\alpha_s(\mu^2)}{2\pi} \right)^m \hat{P}_{ij}^{(n,m)}(\xi) = \sum_{n,m=0}^{\infty} P_{ij}^{(n,m)}(\xi, \mu^2)$$

$$\text{with } P_{ij}^{(0,0)} = 0, \quad N_F, \quad N_l$$

Solution for Evolution Equations of LDFs:

□ Re-organization of LDFs:

$$F_{i\pm} = f_{i/e} \pm f_{\bar{i}/e}$$

$$F_{\pm 3} = F_{u\pm} - F_{d\pm},$$

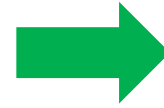
$$F_{\pm 8} = F_{u\pm} + F_{d\pm} - 2F_{s\pm},$$

$$F_{\pm 15} = F_{u\pm} + F_{d\pm} + F_{s\pm} - 3F_{c\pm},$$

$$F_{\pm 24} = F_{u\pm} + F_{d\pm} + F_{s\pm} + F_{c\pm} - 4F_{b\pm},$$

$$F_{\pm} = F_{\pm 35} = F_{u\pm} + F_{d\pm} + F_{s\pm} + F_{c\pm} + F_{b\pm}$$

where $i = 3, 8, 15, 24, 35$, the $\mathbf{F} = (F_{e^+}, f_{\gamma}, F_+, F_{+24}, F_{+15}, F_{+8}, F_{+3}, f_g)^{\top}$



Qiu, Watanabe, Prog. Theor. Exp. Phys. 2026

$$\frac{\partial \mathbf{F}}{\partial \ln \mu^2} = \mathbf{P} \otimes \mathbf{F},$$

$$\frac{\partial F_{e^-}}{\partial \ln \mu^2} = P_{ee}^{(1,0)} F_{e^-},$$

$$\frac{\partial F_-}{\partial \ln \mu^2} = P_{qq}^{(0,1)} F_-,$$

$$\frac{\partial F_{-i}}{\partial \ln \mu^2} = P_{qq}^{(0,1)} F_{-i},$$

Evolution kernels:

$$\mathbf{P} = \begin{pmatrix} \mathbf{P}_{EE} & \mathbf{P}_{EC} \\ \mathbf{P}_{CE} & \mathbf{P}_{CC} \end{pmatrix}$$

$$\mathbf{P}_{EE} = \begin{pmatrix} P_{ee}^{(1,0)} & 2P_{e\gamma}^{(1,0)} \\ P_{\gamma e}^{(1,0)} & P_{\gamma\gamma}^{(1,0)} \end{pmatrix}$$

$$\mathbf{P}_{EC} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{e_+^2}{5} P_{\gamma e}^{(1,0)} & \frac{e_{+24}^2}{20} P_{\gamma e}^{(1,0)} & \frac{e_{+15}^2}{12} P_{\gamma e}^{(1,0)} & \frac{e_{+8}^2}{6} P_{\gamma e}^{(1,0)} & \frac{e_{+3}^2}{2} P_{\gamma e}^{(1,0)} & 0 \end{pmatrix}$$

Similarly for the others

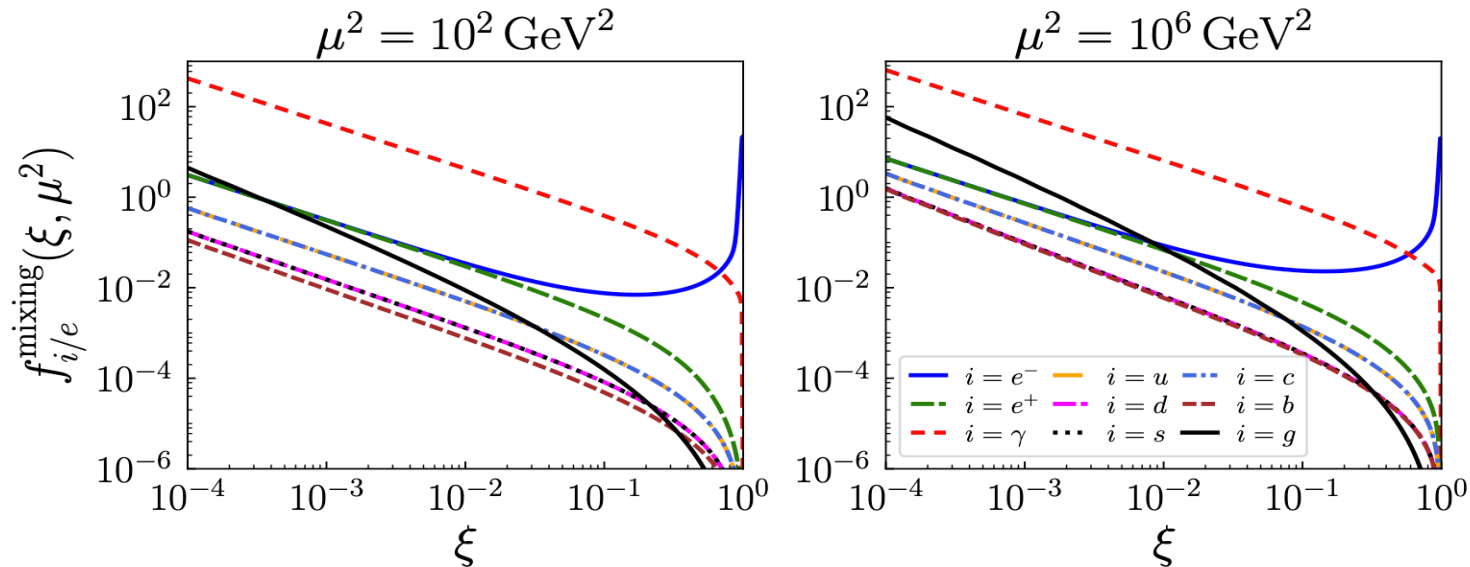
with

$$e_+^2 = e_u^2 + e_d^2 + e_s^2 + e_c^2 + e_b^2, \quad e_{+24}^2 = e_u^2 + e_d^2 + e_s^2 + e_c^2 - 4e_b^2,$$

$$e_{+15}^2 = e_u^2 + e_d^2 + e_s^2 - 3e_c^2, \quad e_{+8}^2 = e_u^2 + e_d^2 - 2e_s^2, \quad e_{+3}^2 = e_u^2 - e_d^2.$$

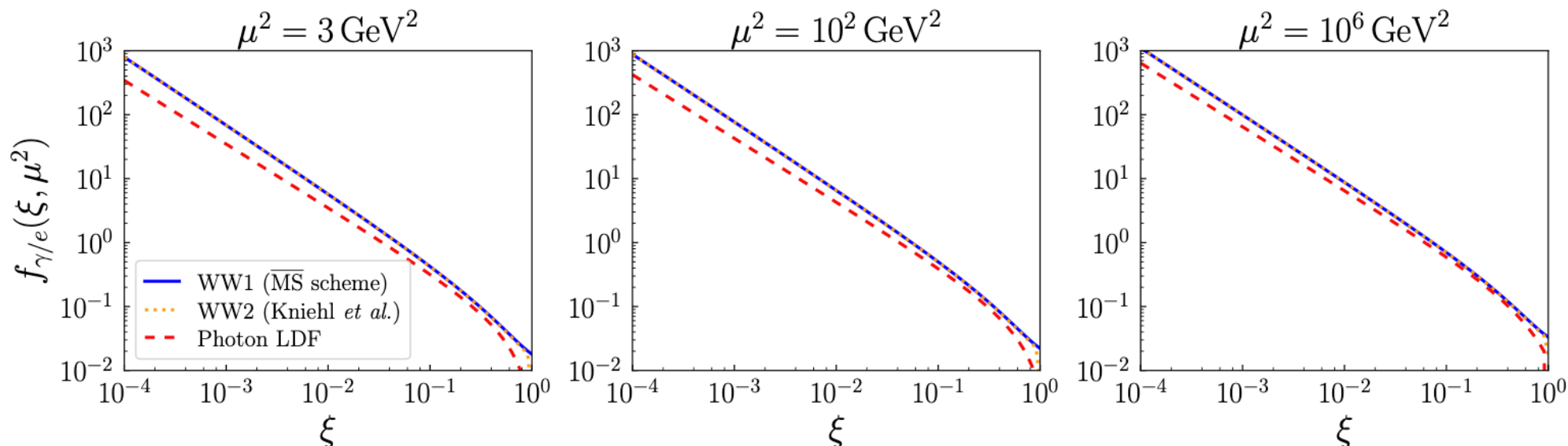
Evolved LDFs:

□ Default LDFs:



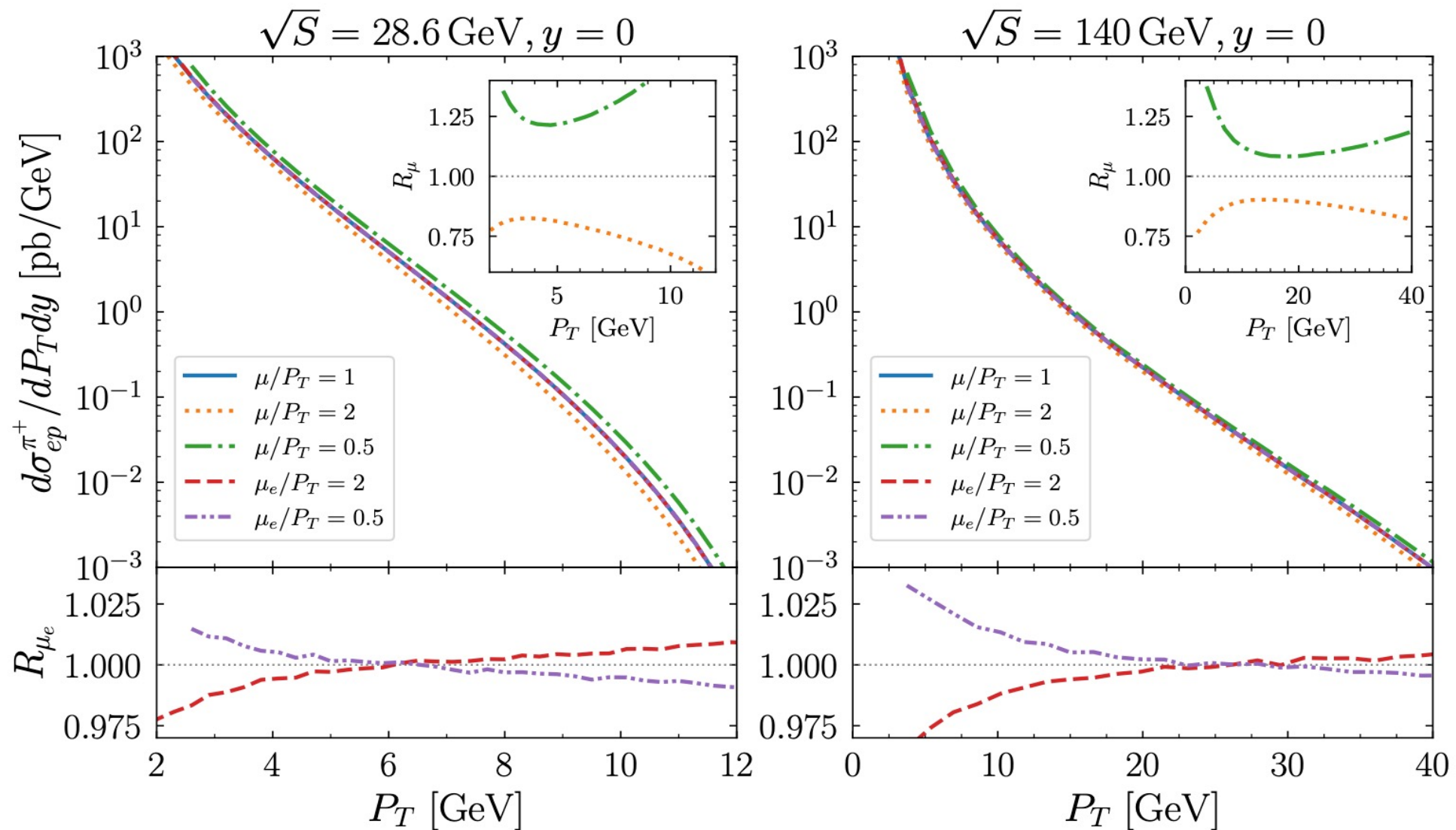
Qiu, Watanabe, Prog. Theor. Exp. Phys. 2026

□ Impact of QCD evolution on LDFs:



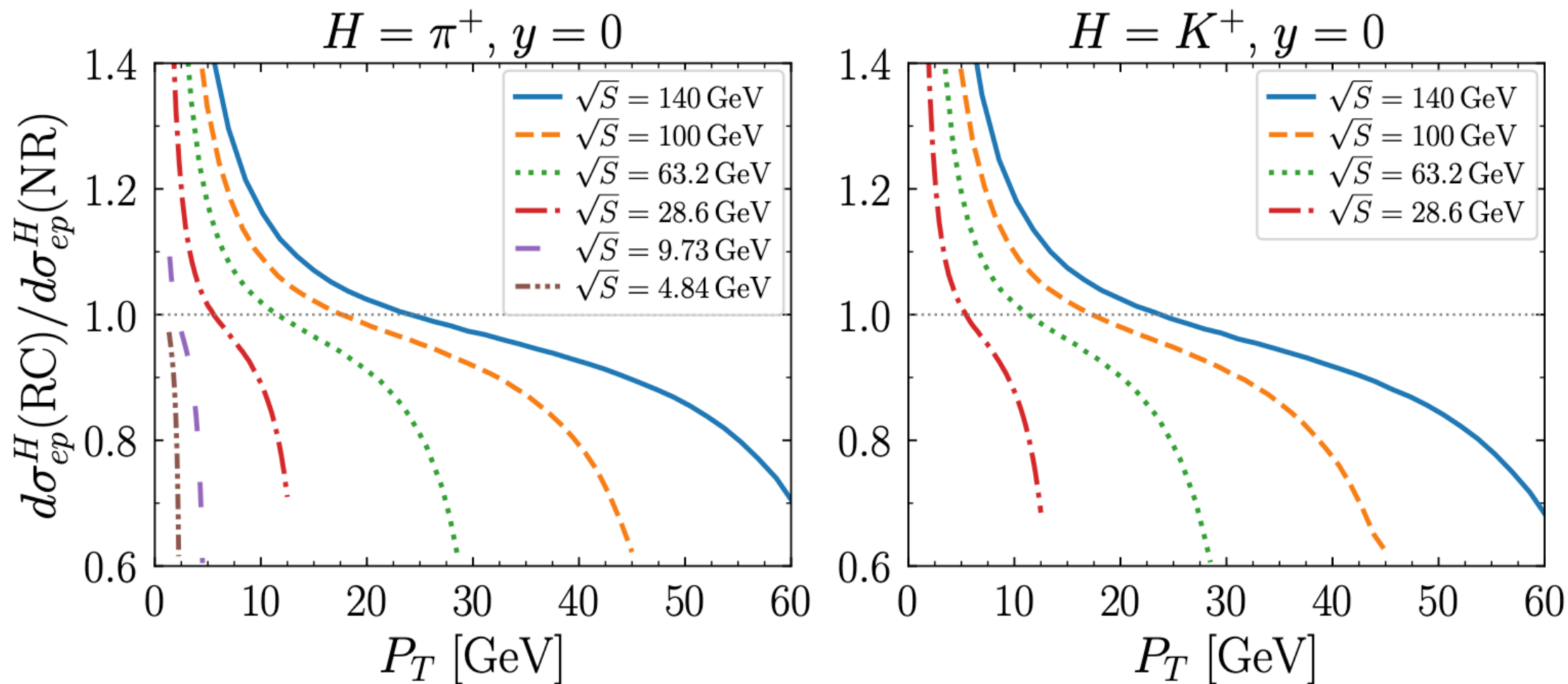
PT Spectrum of Single Hadron Production at the EIC energies

□ FFs – Central set of JAM20 – scale dependence:



Leading Power QED Radiative Corrections

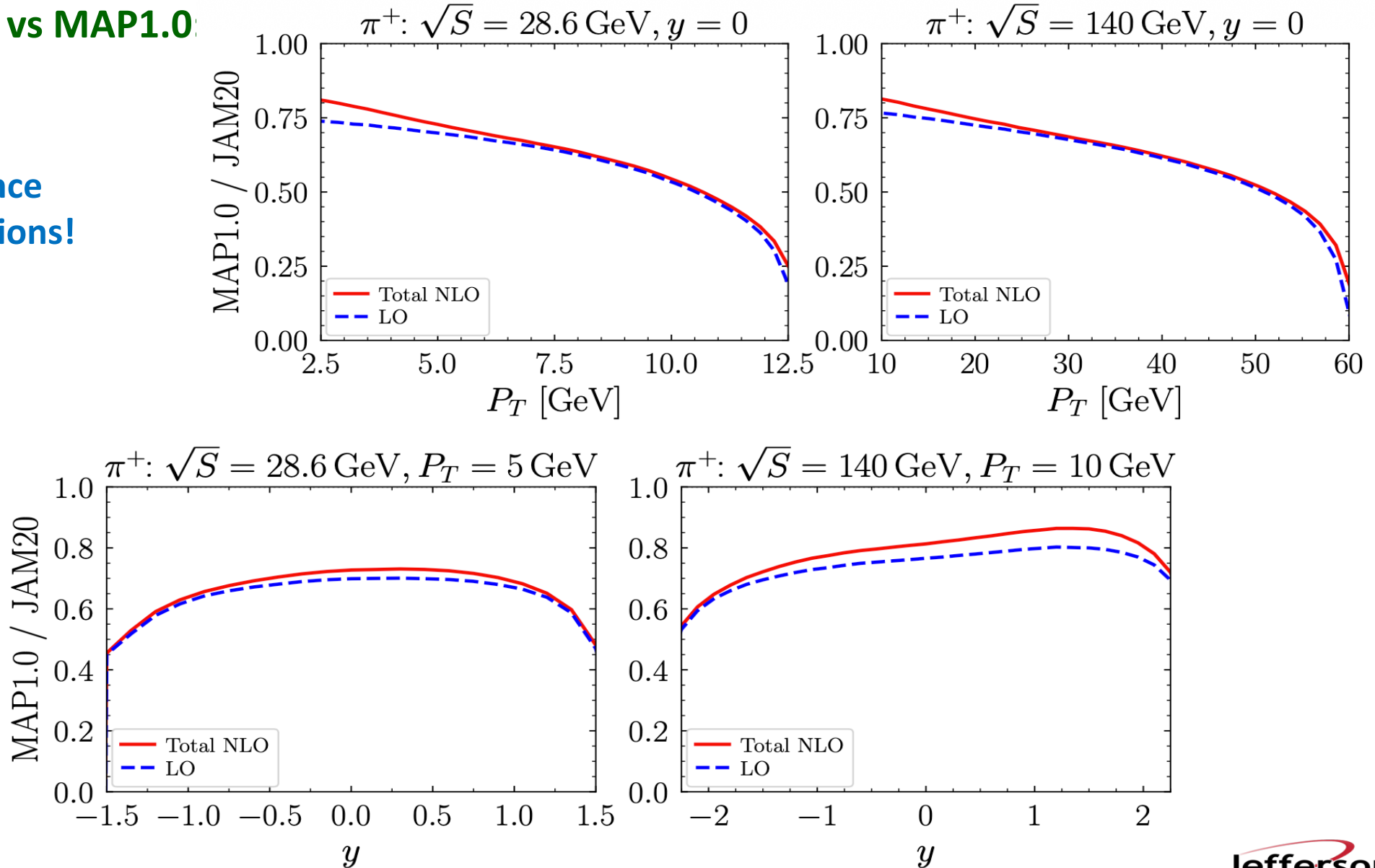
□ FFs – Central set of JAM20 – QED RCs:



Uncertainty of Hadron Fragmentation Functions:

FFs – JAM20 vs MAP1.0

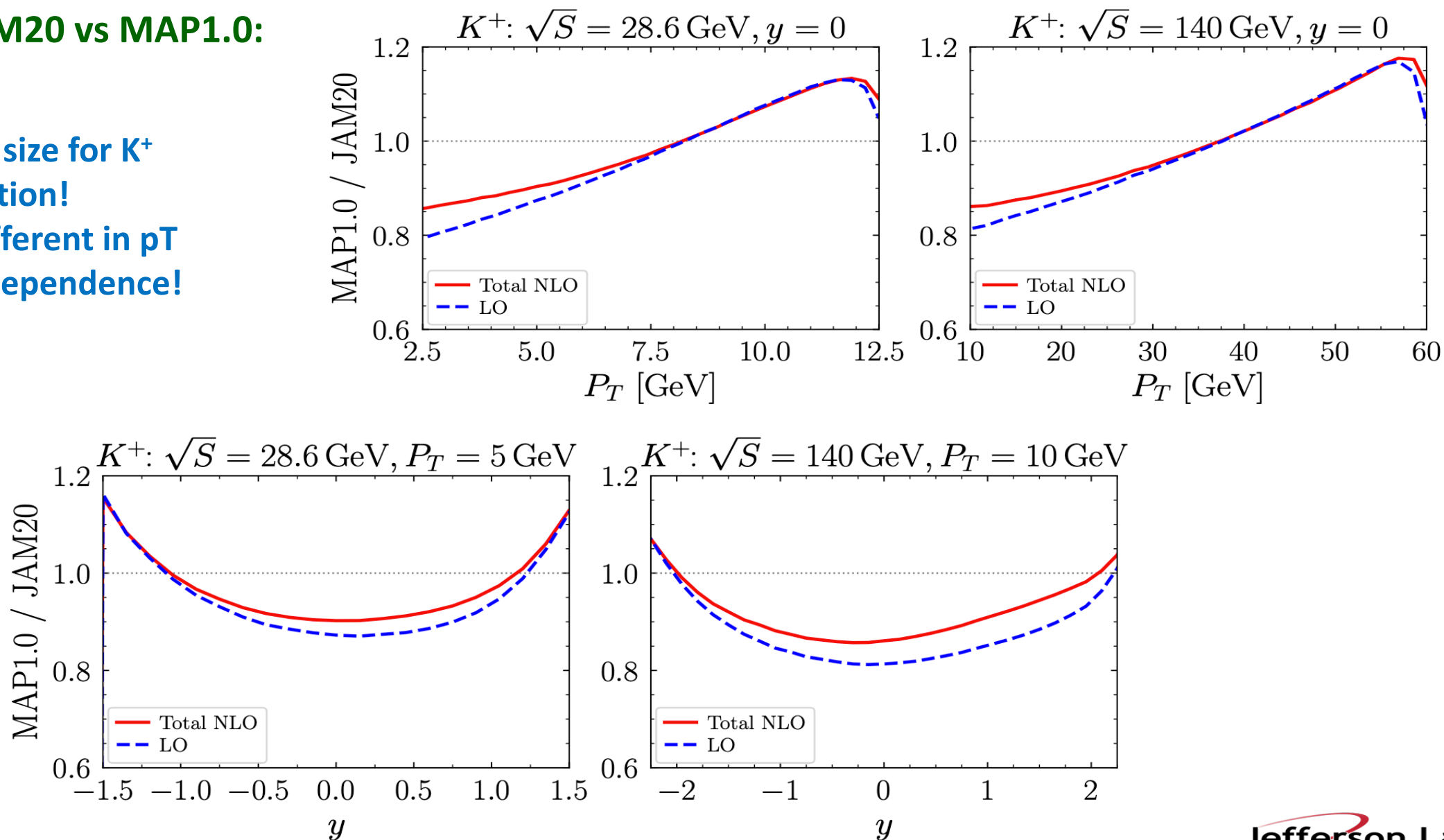
25% difference
in cross sections!



Uncertainty of Hadron Fragmentation Functions:

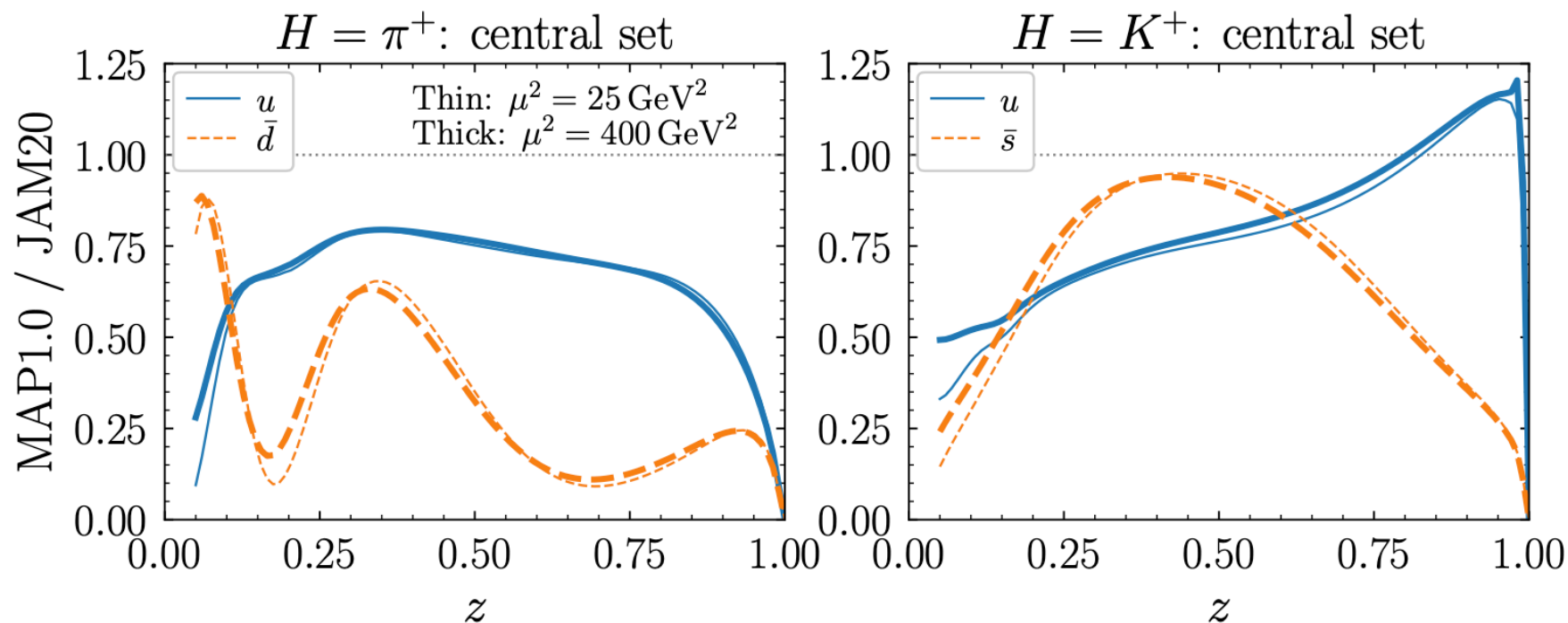
FFs – JAM20 vs MAP1.0:

Similar size for K^+
production!
But, different in p_T
and y dependence!



Uncertainty of Hadron Fragmentation Functions:

FFs – JAM20 vs MAP1.0:



JAM20: Phys. Rev. D, **104**(1), 016015 (2021).

MAP1.0: Phys. Rev. D, **104**(3), 034007 (2021).

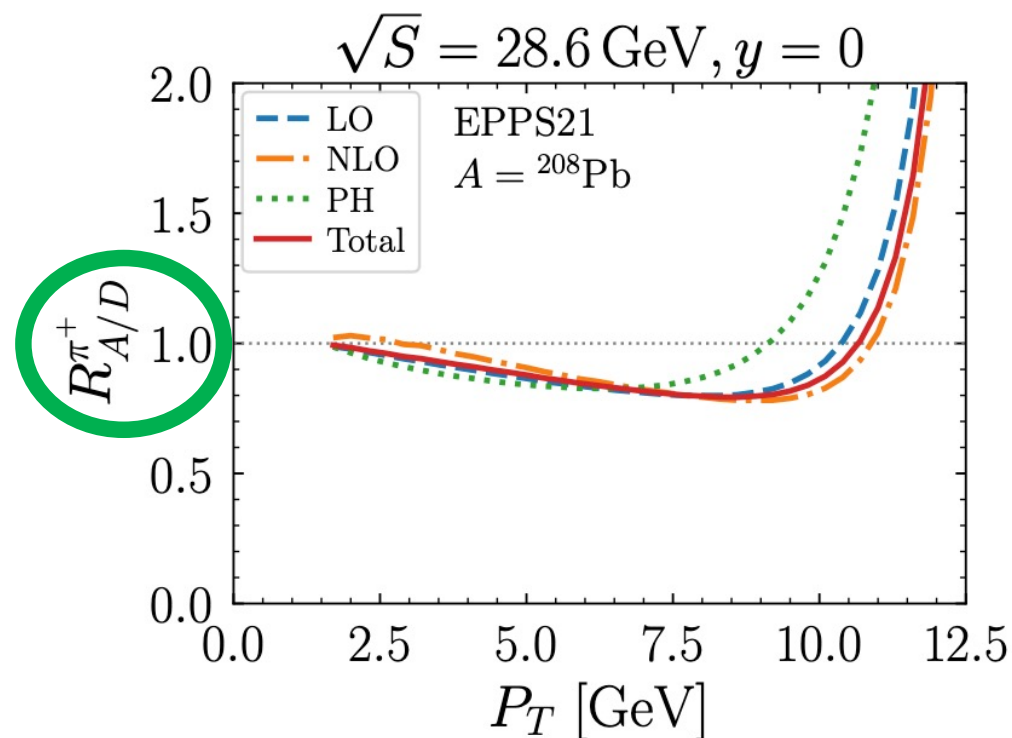
Large uncertainty in hadron fragmentation functions!

Nuclear Dependence from nPDFs only:

Various nPDFs :

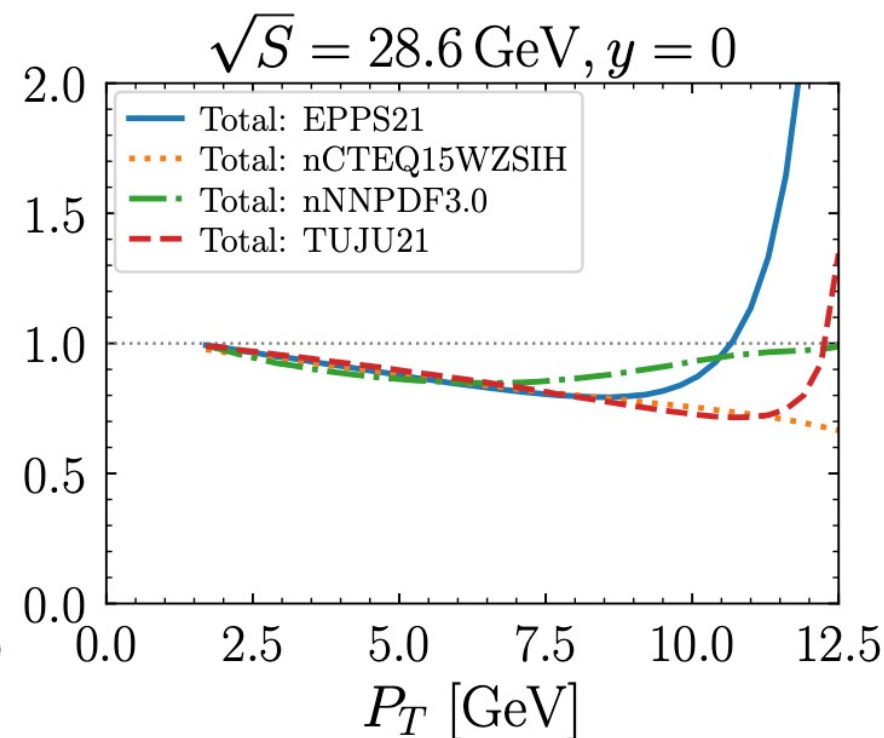
$$R_{A/D}^H = \frac{2}{A} \frac{d\sigma_{eA \rightarrow H+X}/dP_T dy}{d\sigma_{eD \rightarrow H+X}/dP_T dy}$$

Similar in EMC region, but,
large difference at high x



EPPS21: Eur. Phys. J. C, **82**(5), 413 (2022)

nCTEQ15WZSIH: Eur. Phys. J. C, **80**(10), 968 (2020)

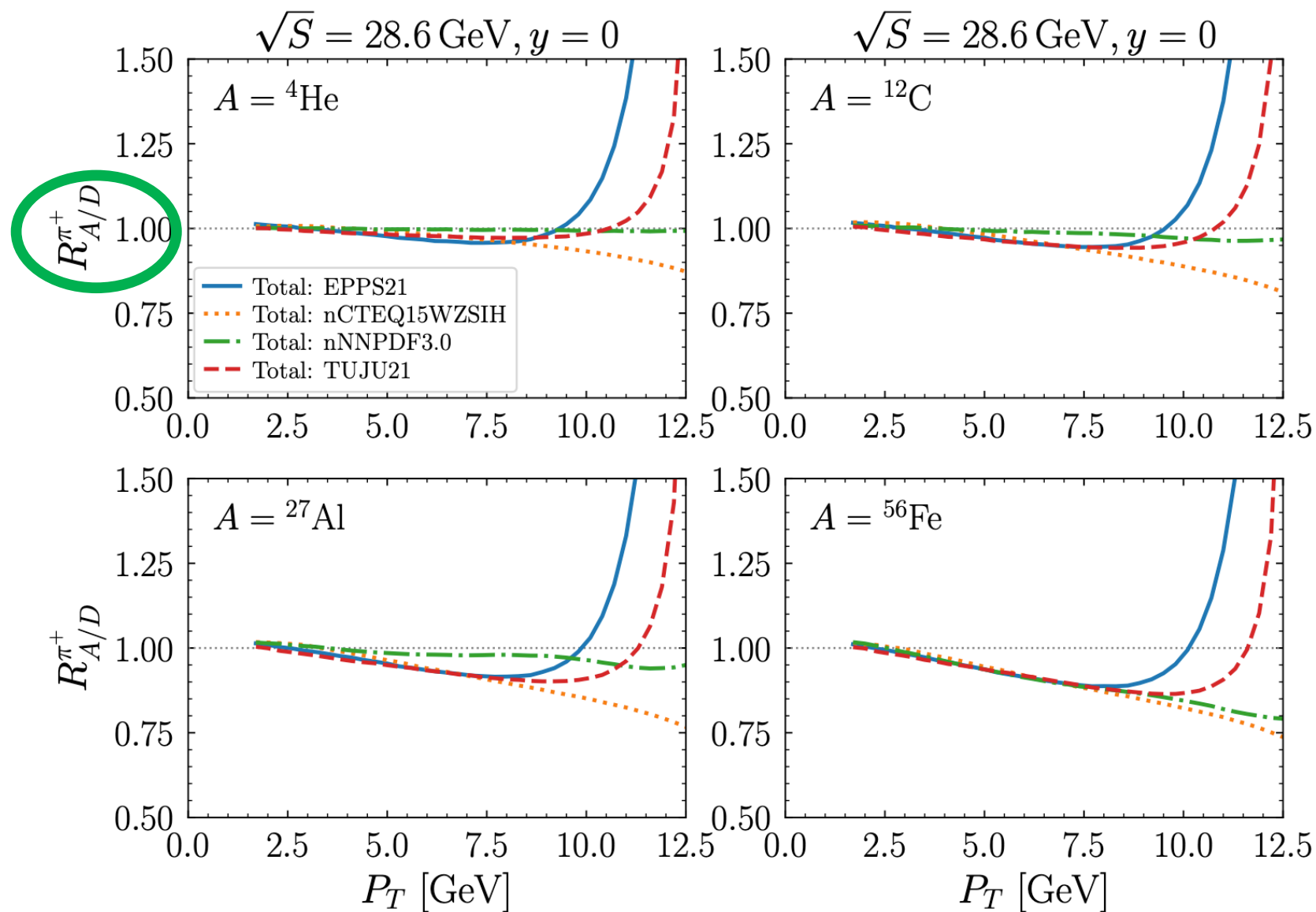


nNNPDF3.0: Eur. Phys. J. C, **82**(6), 507 (2022)

TUJU21: Phys. Rev. D, **105**(9), 094031 (2022)

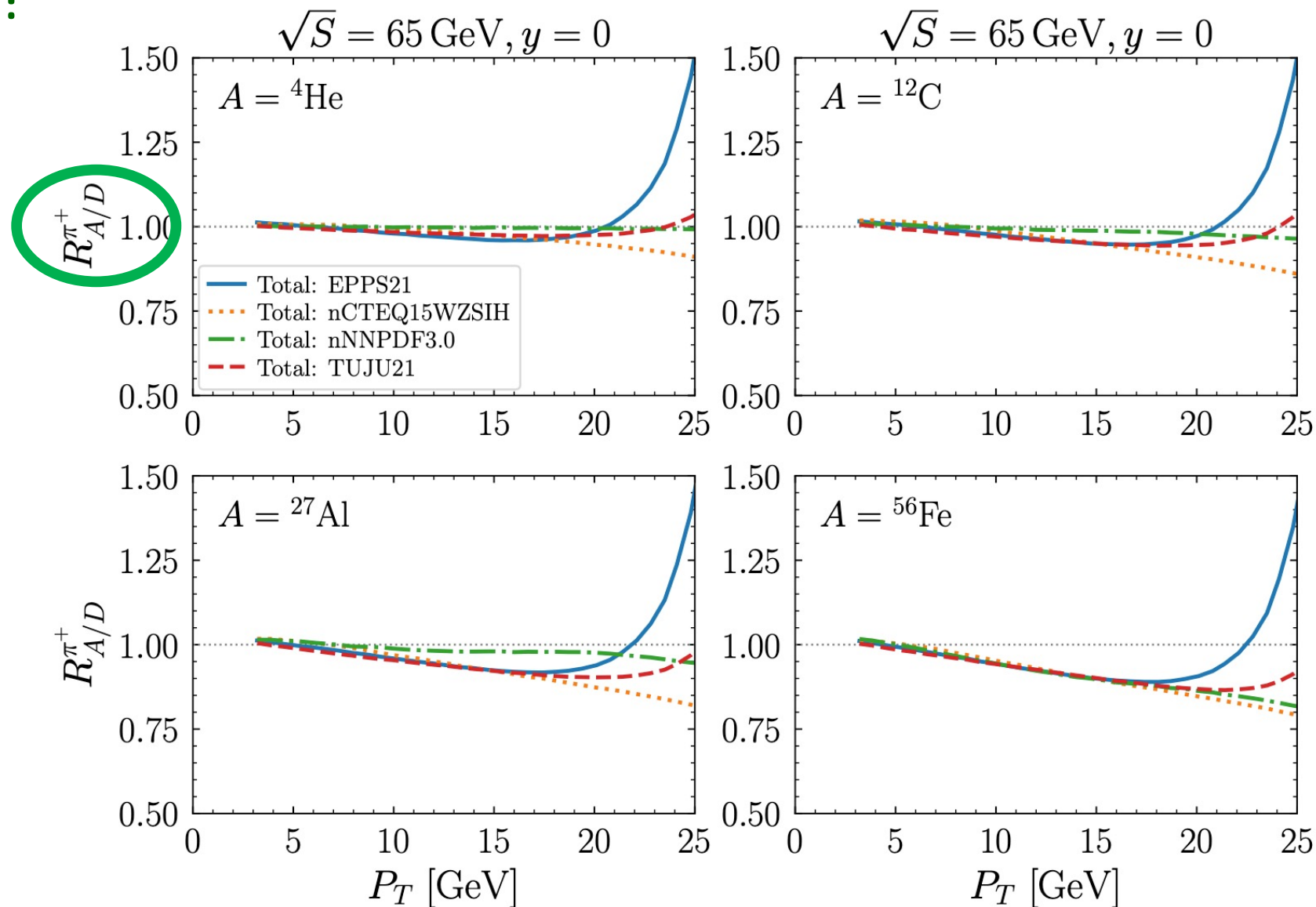
Nuclear Dependence from nPDFs only:

Various nPDFs :



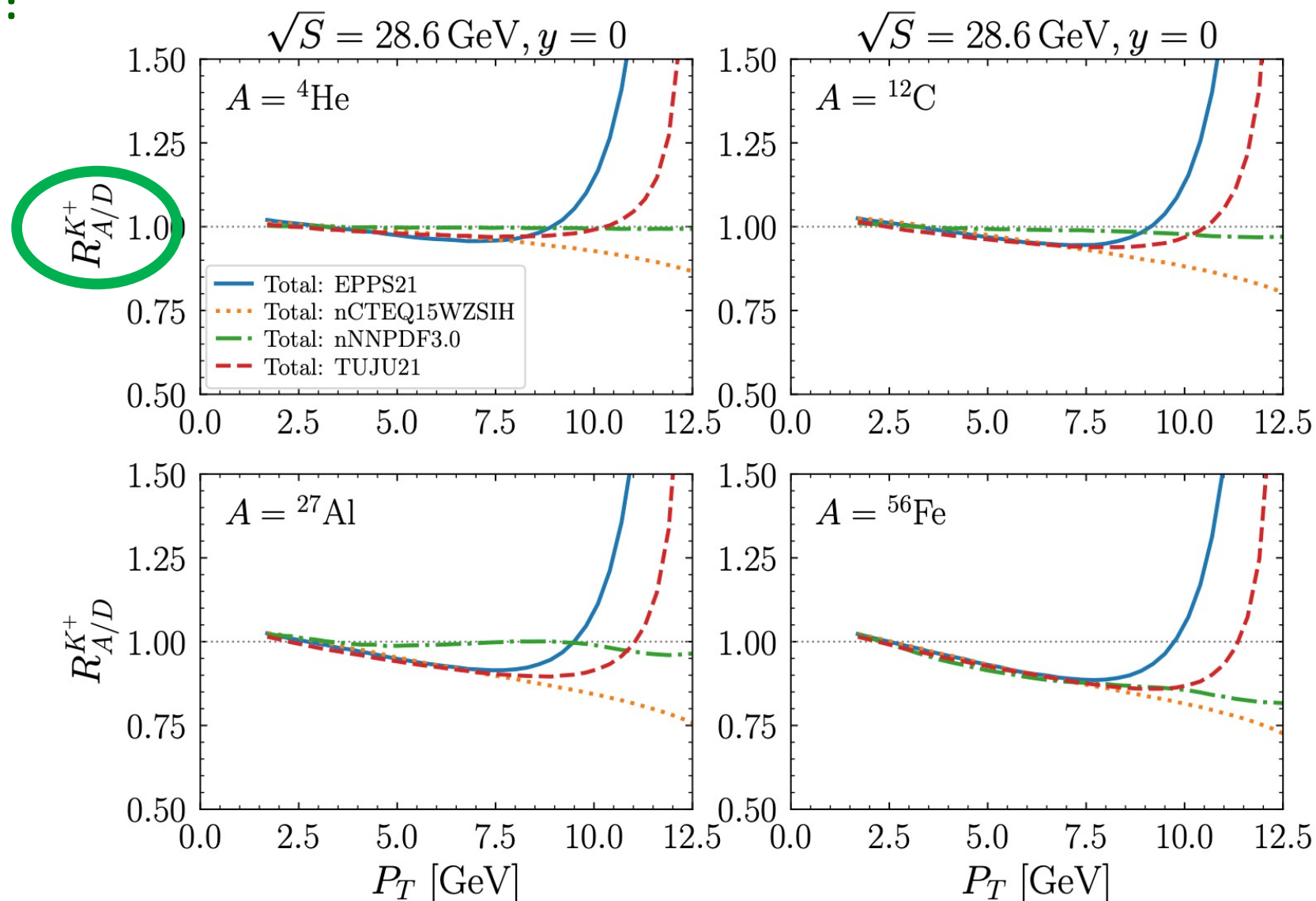
Nuclear Dependence from nPDFs only:

Various nPDFs :



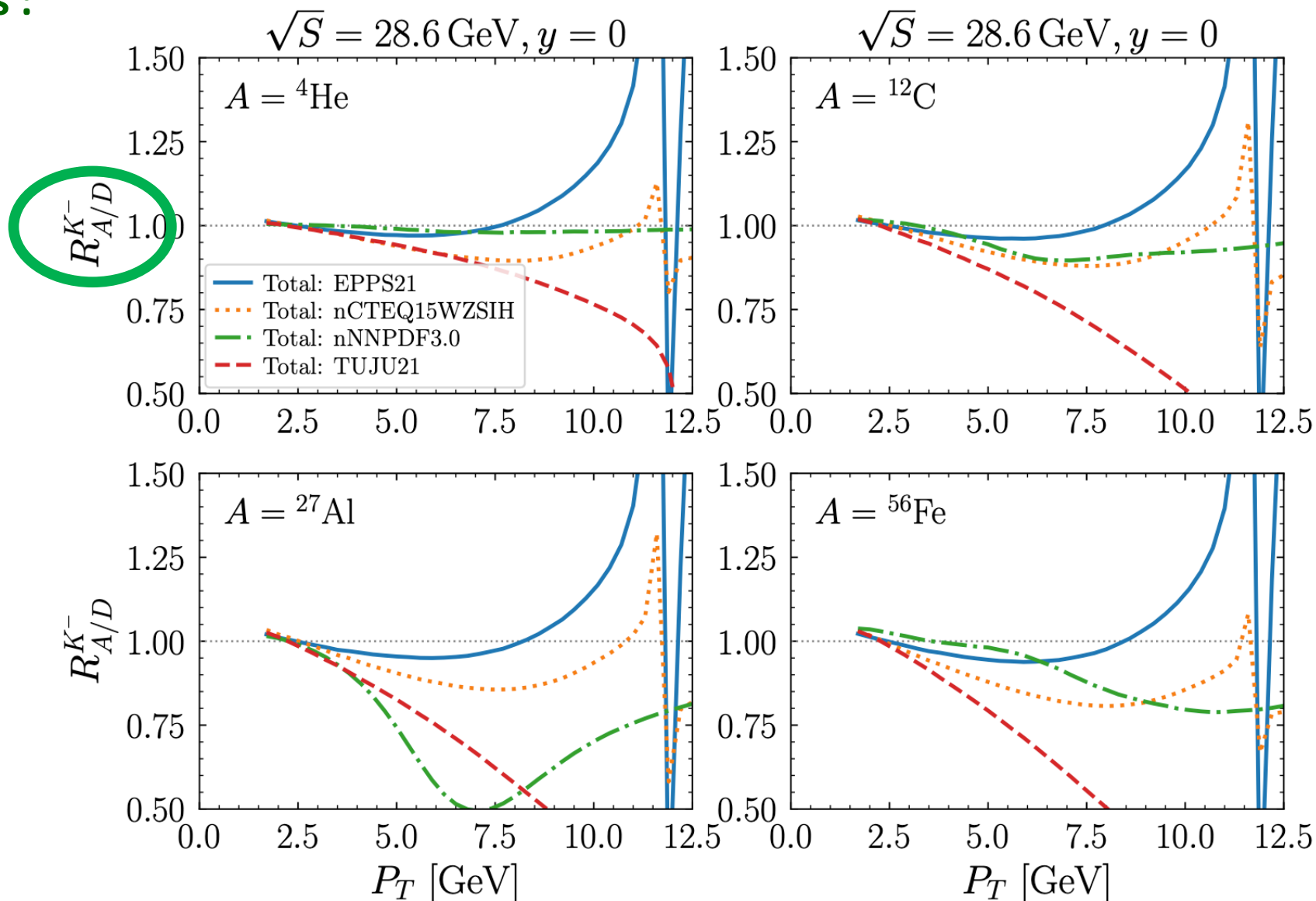
Nuclear Dependence from nPDFs only:

Various nPDFs :



Nuclear Dependence from nPDFs only:

Various nPDFs :



Single inclusive jet production:

□ Jet Functions (JFs):

B. Jager, M. Stratmann, and W. Vogelsang,
Phys. Rev. D, 70, 034010 (2004),

$$\mathcal{J}_i(z, \mu^2) = \sum_{n=0} \left(\frac{\alpha_s(\mu^2)}{2\pi} \right)^n \hat{\mathcal{J}}_i^{(n)}(z, \mu^2) = \mathcal{J}_i^{(0)}(z, \mu^2) + \mathcal{J}_i^{(1)}(z, \mu^2) + \dots$$

□ JFs at LO:

$$\mathcal{J}_i^{(0)}(z, \omega_J, \mu^2) = \delta(1 - z) \quad \text{for } i = q, g$$

□ JFs at NLO:

Zhong-Bo Kang, Felix Ringer, and Ivan Vitev,
JHEP, 10, 125 (2016)

$$\begin{aligned} \mathcal{J}_q^{(1)}(z, \omega_J, \mu^2) = & L P_{qq}^{(0,1)}(z, \mu^2) + [L - 2 \ln(1 - z)] P_{gq}^{(0,1)}(z, \mu^2) \\ & - \frac{\alpha_s(\mu^2)}{2\pi} \left\{ C_F \left[2(1 + z^2) \left(\frac{\ln(1 - z)}{1 - z} \right)_+ + 1 \right] - \delta(1 - z) d_J^{q, \text{alg}} \right\}, \end{aligned}$$

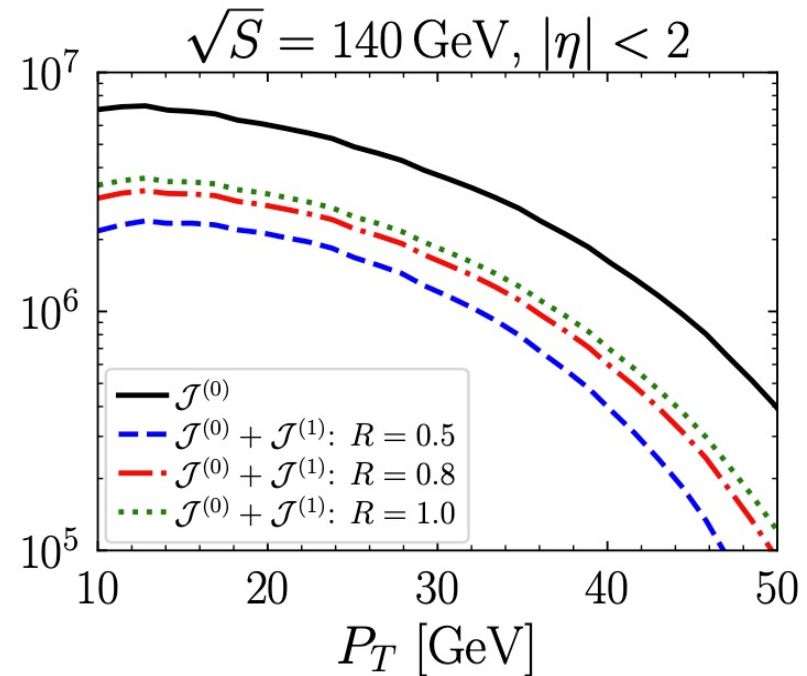
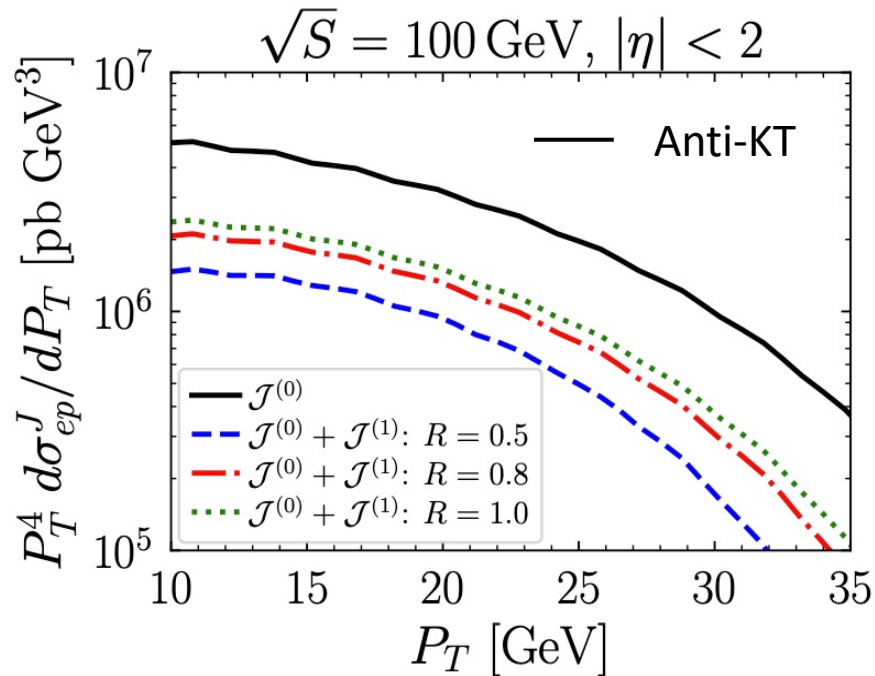
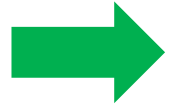
$$\begin{aligned} \mathcal{J}_g^{(1)}(z, \omega_J, \mu^2) = & L P_{gg}^{(0,1)}(z, \mu^2) + 2n_f [L - 2 \ln(1 - z)] P_{qg}^{(0,1)}(z, \mu^2) \\ & - \frac{\alpha_s(\mu^2)}{2\pi} \left\{ \frac{4C_A(1 - z + z^2)^2}{z} \left(\frac{\ln(1 - z)}{1 - z} \right)_+ - \delta(1 - z) d_J^{g, \text{alg}} + 4n_f T_R z(1 - z) \right\}, \end{aligned}$$

$$L = \ln \frac{\mu^2}{\omega_J^2 \tan^2(\mathcal{R}/2)}, \quad \mathcal{R} \equiv \frac{R}{\cosh \eta} \quad P_{ij}^{(0,1)} \quad \text{One-loop QCD splitting functions with } i, j = q, g$$

Single inclusive jet production:

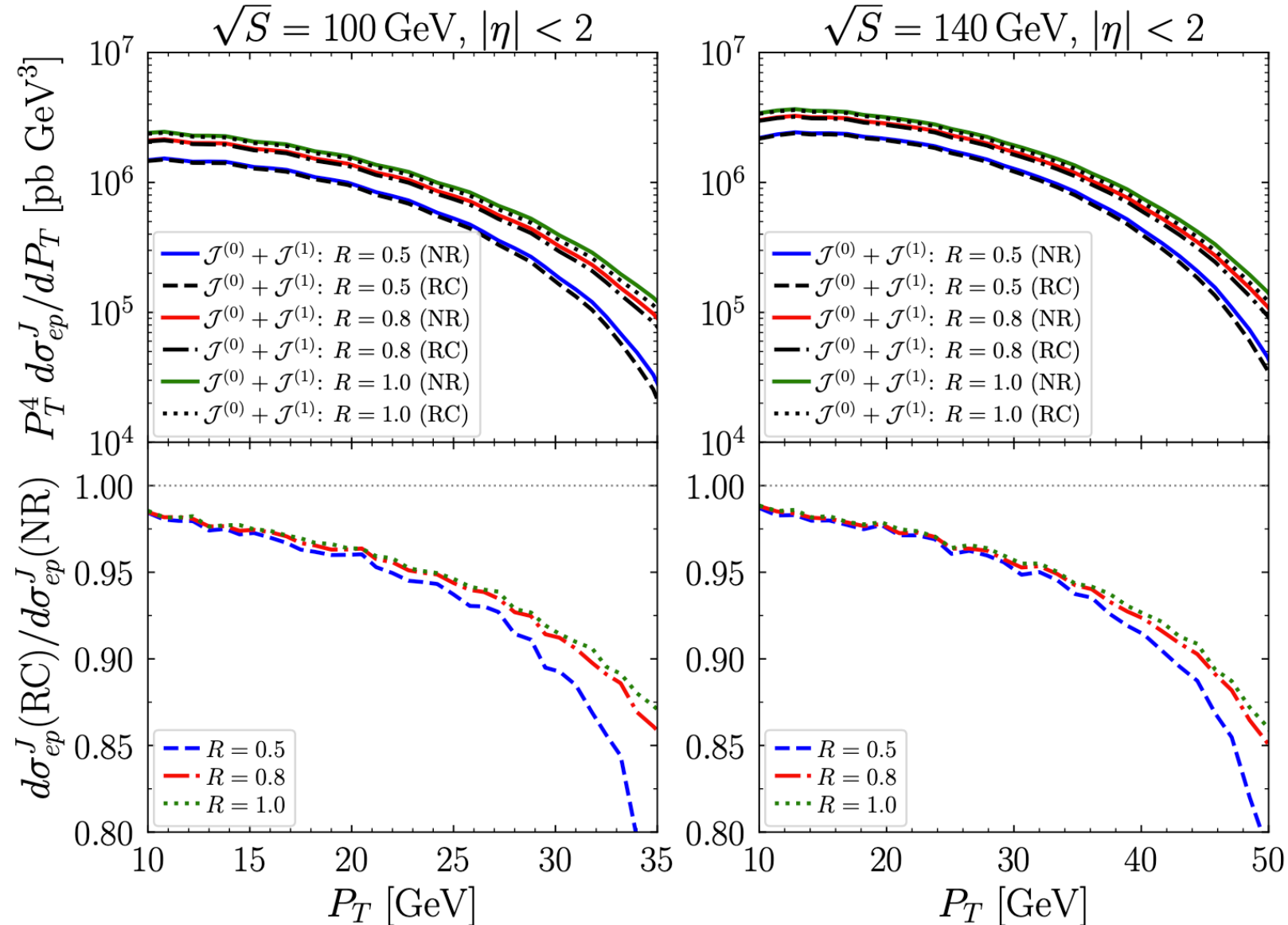
□ Order of α_s :

$$\begin{aligned}
 d\sigma_J = & \sum_{i=e,\bar{e}} \sum_{j=q,\bar{q}} \sum_{k=q,\bar{q}} f_{i/e}(\mu_e) \otimes_{\xi} f_{j/p}(\mu_h) \otimes_x \mathcal{J}_k^{(0)}(\mu_J) \otimes_z H_{ij \rightarrow k}^{(0)}(\mu_r) \\
 & + \sum_{i=e,\bar{e},\gamma} \sum_{j=q,\bar{q},g} \sum_{k=q,\bar{q},g} f_{i/e}(\mu_e) \otimes_{\xi} f_{j/p}(\mu_h) \otimes_x \mathcal{J}_k^{(0)}(\mu_J) \otimes_z H_{ij \rightarrow k}^{(1)}(\mu_r) \\
 & + \sum_{i=e,\bar{e}} \sum_{j=q,\bar{q}} \sum_{k=q,\bar{q}} f_{i/e}(\mu_e) \otimes_{\xi} f_{j/p}(\mu_h) \otimes_x \mathcal{J}_k^{(1)}(\mu_J) \otimes_z H_{ij \rightarrow k}^{(0)}(\mu_r)
 \end{aligned}$$



Single inclusive jet production:

Impact of RC:



Summary and Outlook – Thank you!

- ❑ Proposed to use the prompt single hadron inclusive production to test the fragmentation picture in particular at JLab energy – Prerequisite to fitting SIDIS data with current factorization formalism
 - Current fragmentation functions with the NLO perturbative coefficients can fit the RHIC data
 - But, have a difficulty to fit the JLab data, which could have included “non-prompt” pions (those from rho decay, ...)
- ❑ Collision induced QED radiation is an integrated part of the lepton-hadron collision
 - Radiative correction approach is difficult for a consistent treatment beyond the inclusive DIS
 - No well-defined photon-hadron frame, if we cannot recover all QED radiation
 - Radiative corrections are more important for events with high momentum transfers and large phase space to shower – such as those at the EIC

Factorization approach to include both QCD and QED radiative contributions provides a consistent and controllable approximation to high-energy lepton-hadron scattering processes
- ❑ Hadron FFs are poorly determined!
- ❑ Need data of lepton-hadron scattering without implementing RCs for determining universal LDFs !

Backup Slides