Cold Nuclear Matter Effect for Heavy Flavor at EIC

Haitao Li
Shandong University

Based on the works with Zelong Liu and Ivan Vitev

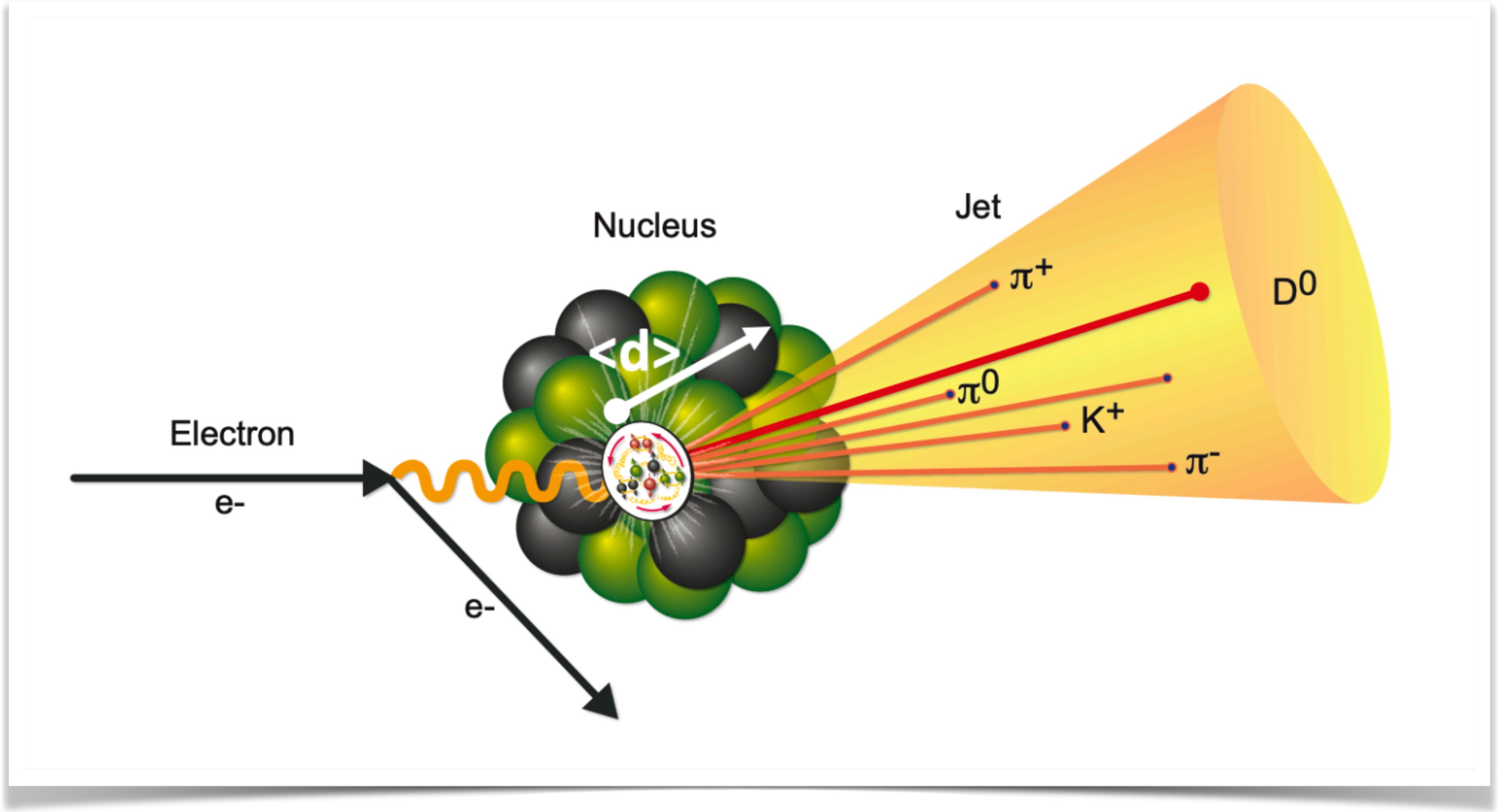
HTL, Liu, Vitev, Phys.Lett.B 816 (2021) 136261
HTL, Vitev, Phys.Rev.Lett. 126 (2021) 25, 252001
HTL, Liu, Vitev, Phys.Lett.B 827 (2022) 137007
HTL, Liu, Vitev, Phys.Lett.B 848 (2024) 138354

HF-HNC 2024
Guangzhou, China

Introduction

Use jet and hadron production at EIC to get better understanding of QCD and nucleon structure

- nucleon and nuclear spin structure
- nuclear PDFs
- gluon saturation
- .....



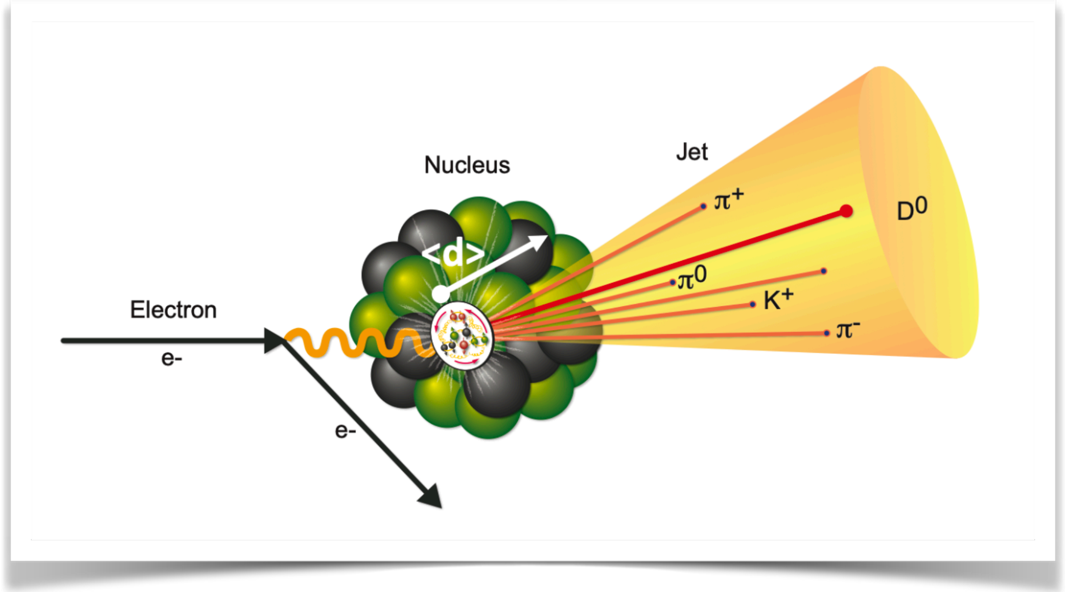
Jet or hadron p_T spectrum at an EIC

- to go as low as possible in p_T to ensure enough statistics
- to go as high as possible in p_T for substructures to avoid large NP

Main Motivation

- **to identify kinematic region where nuclear matter effect is relative large**
- **to disentangle the effects from nuclear PDFs and final state interaction**
- **to identify the mass effects using heavy flavor jet and hadron production**

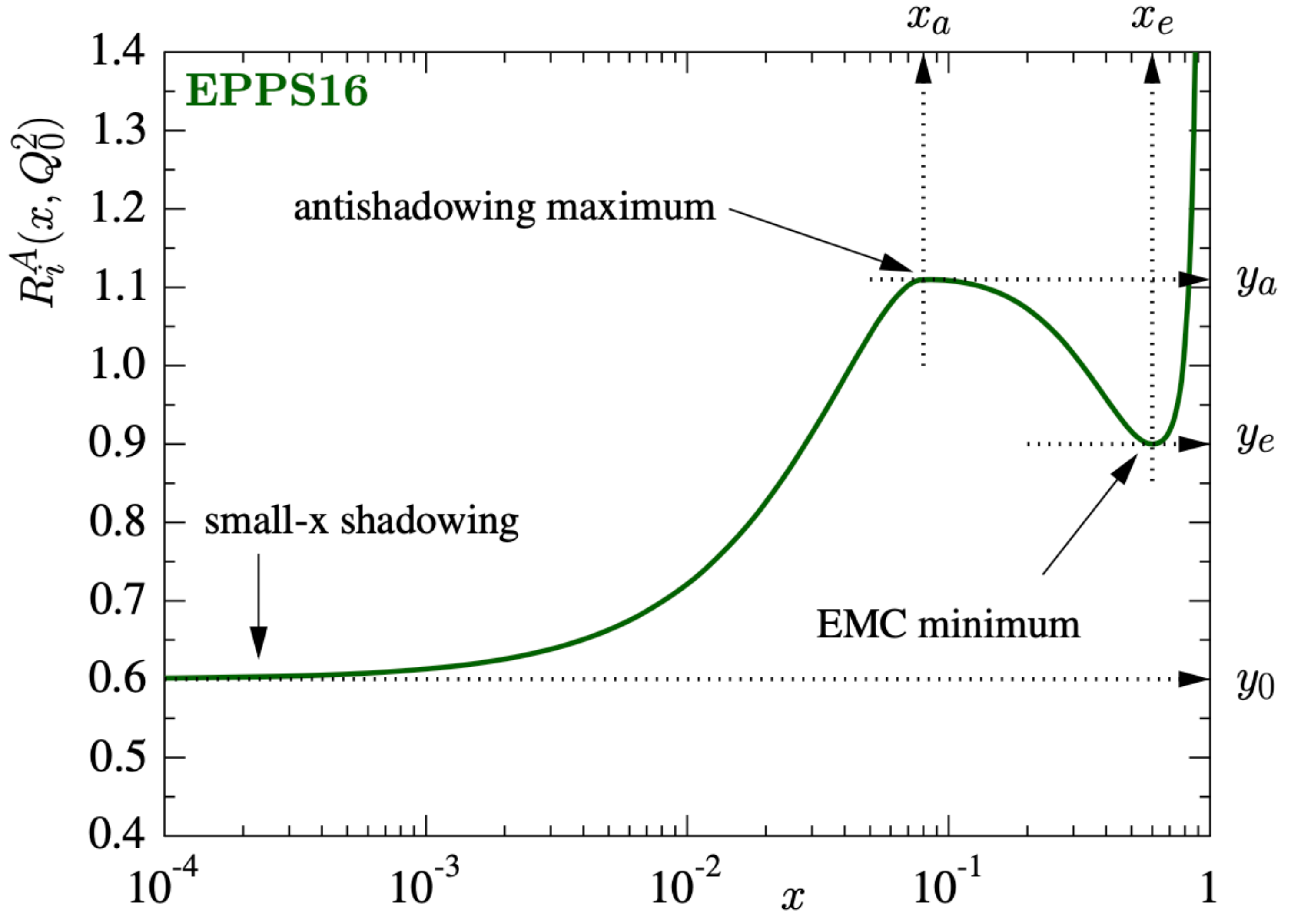
Introduction

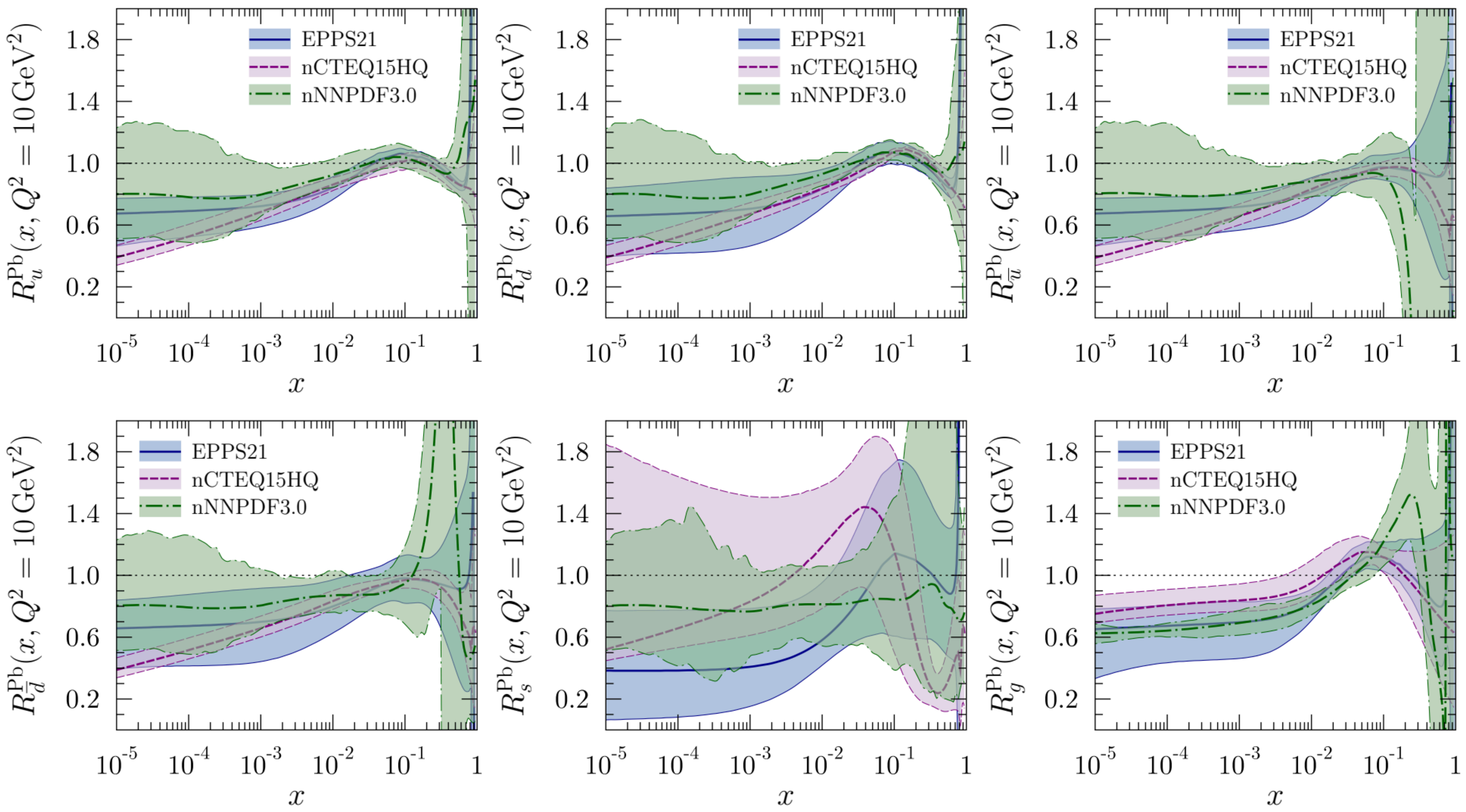


Difference between e+p and e+A collisions

1. Initial-state effects: parton densities are different, included in global-fit nuclear PDFs, or from Lattice QCD

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

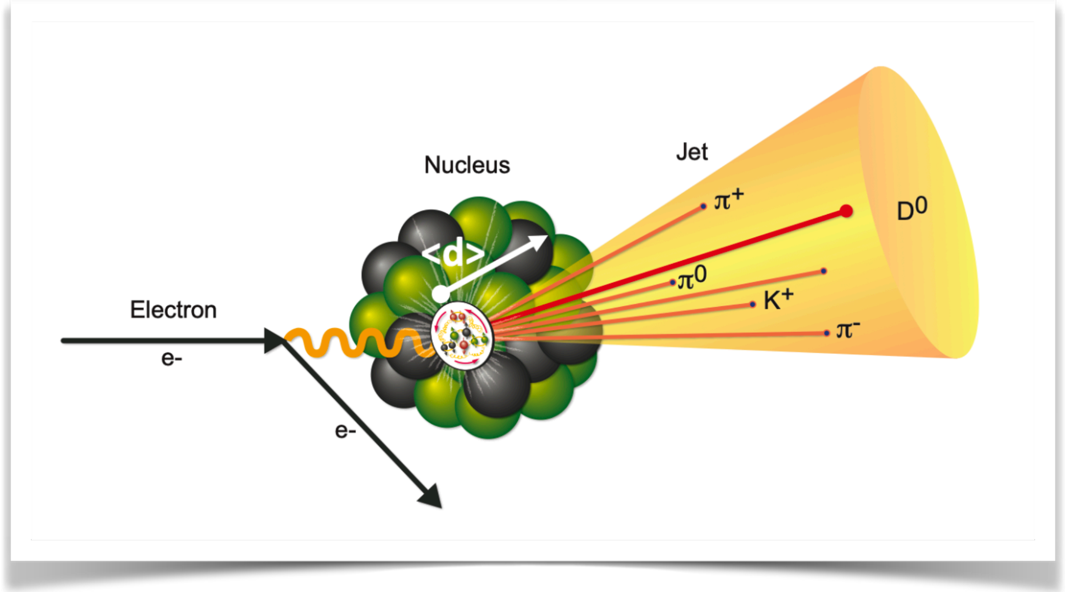




nCTEQ15, EPPS21, nNNPDF3.0, TUJU21, KSASG20 et al

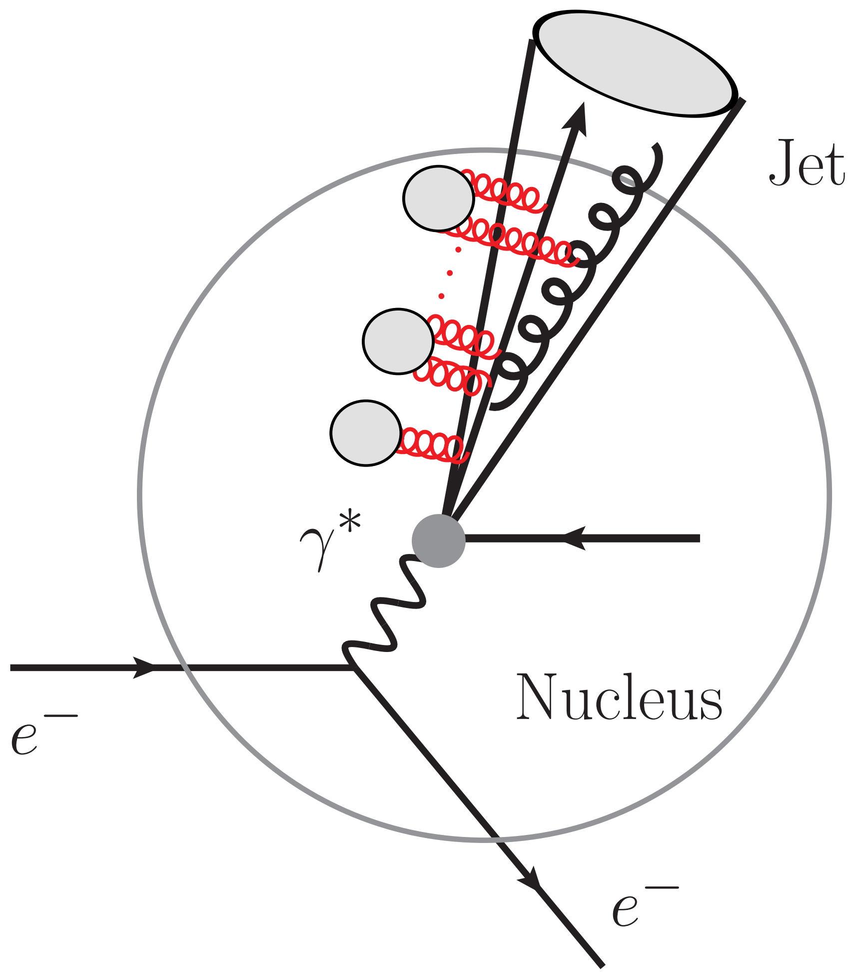
Klasen, Paukkunen, arXiv: 2311.00450

Introduction



Difference between e+p and e+A collisions

2. Final State effects from interactions between jet and nuclear matter

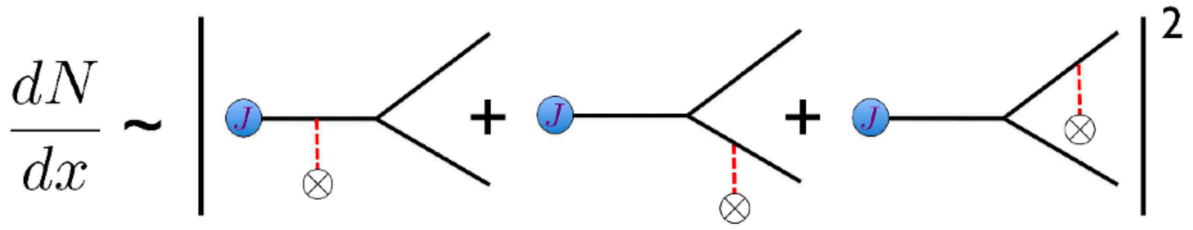


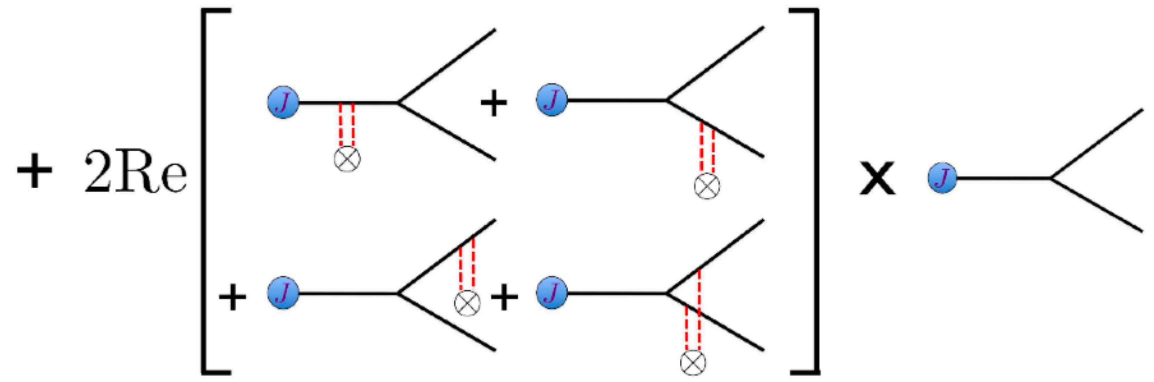
In-medium parton showers for parton propagating through medium

Many methods to calculate the medium modified splitting process for a energetic parton in QCD medium

In our works, we used the functions with SCET$_G$

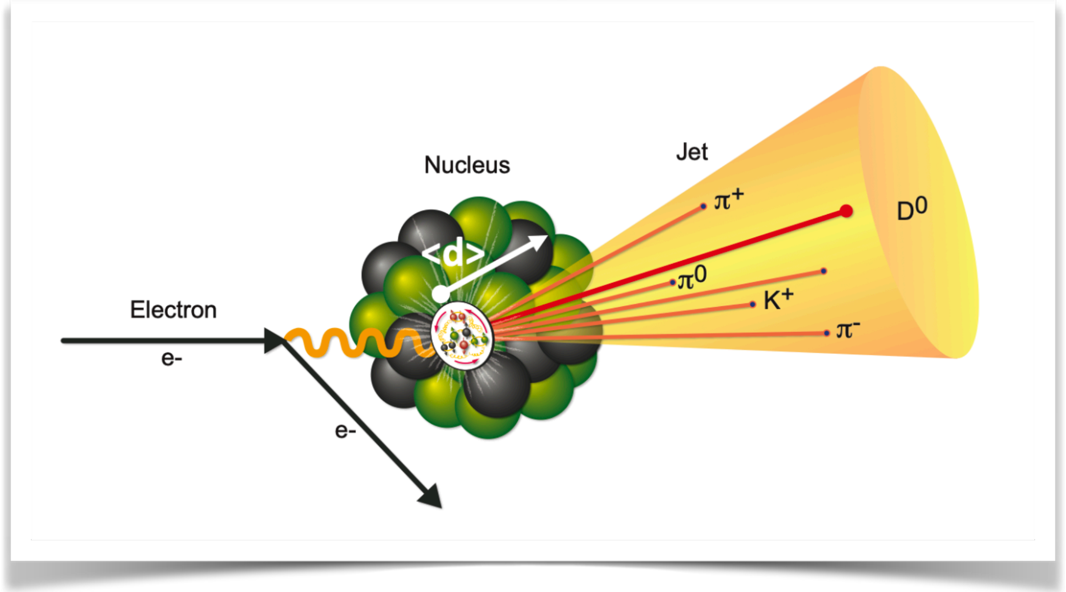
For example $q \to qg$ splitting function





Ovanesyan, Vites, arXiv: 1103.1074, 1109.5619

Introduction



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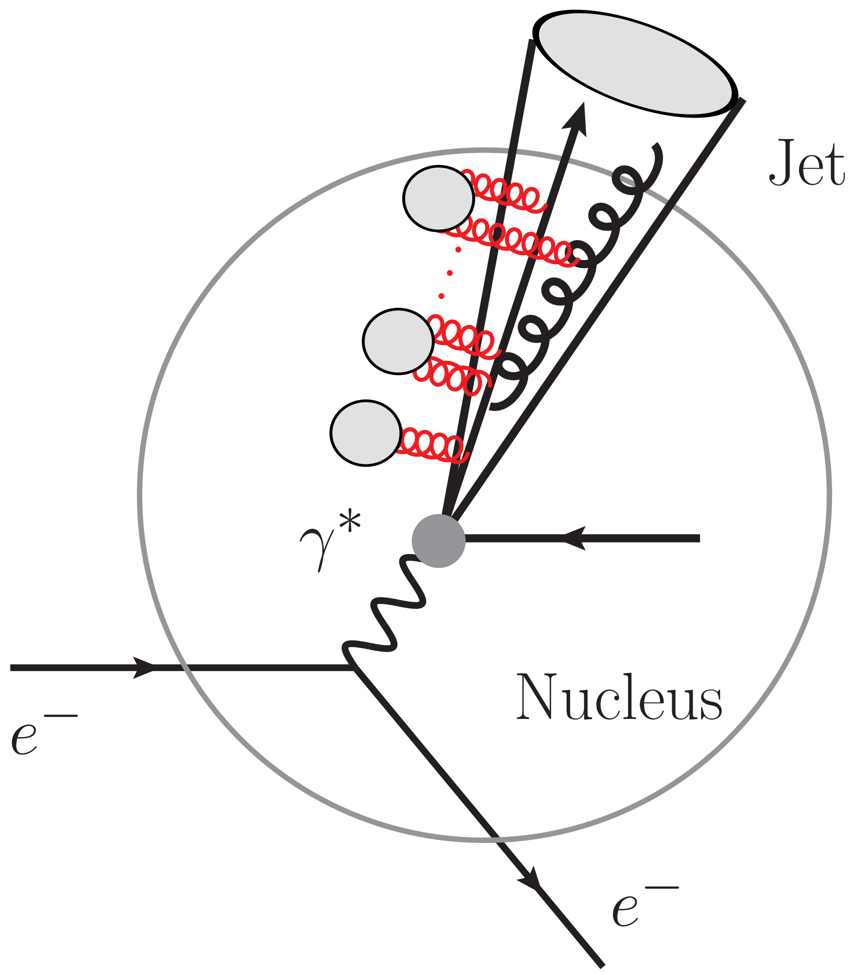

In-medium parton showers for parton propagating through medium

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For example $q \to qg$ splitting function

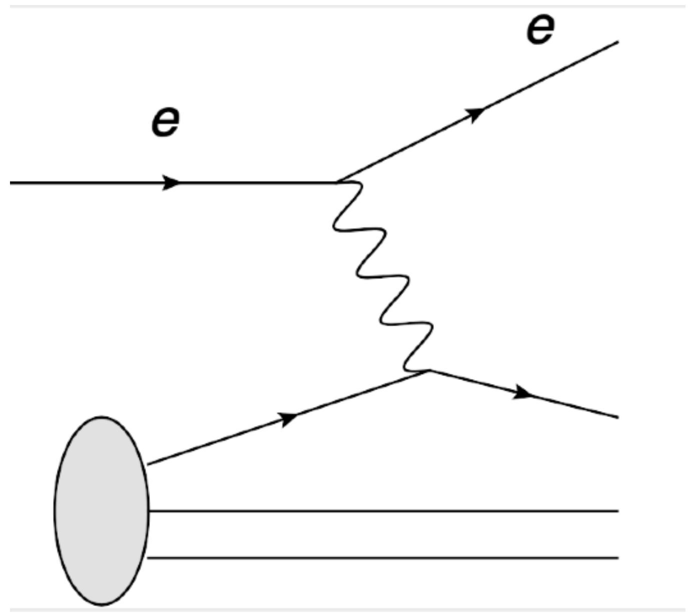
$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right)\right.$$
$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$
$$+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right)+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)$$
$$\left.-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\left(1-\cos[\Omega_5\Delta z]\right)+\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right],$$

Ovanesyan, Vites, arXiv: 1103.1074, 1109.5619

Jet@EIC

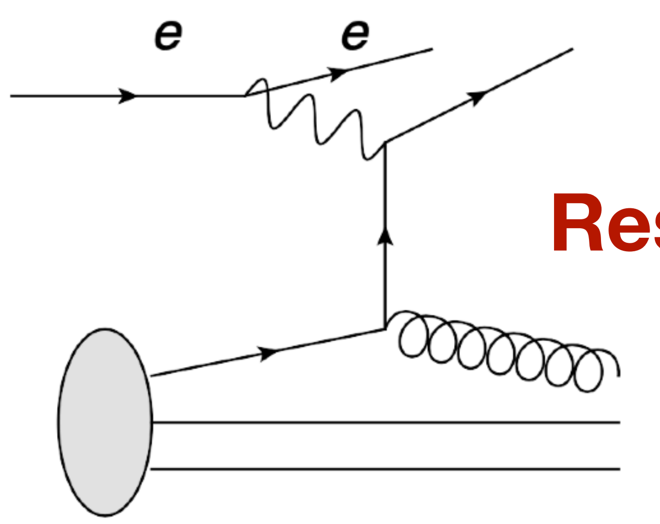
Jet Inclusive cross section

Comparison between NLO and factorized cross section

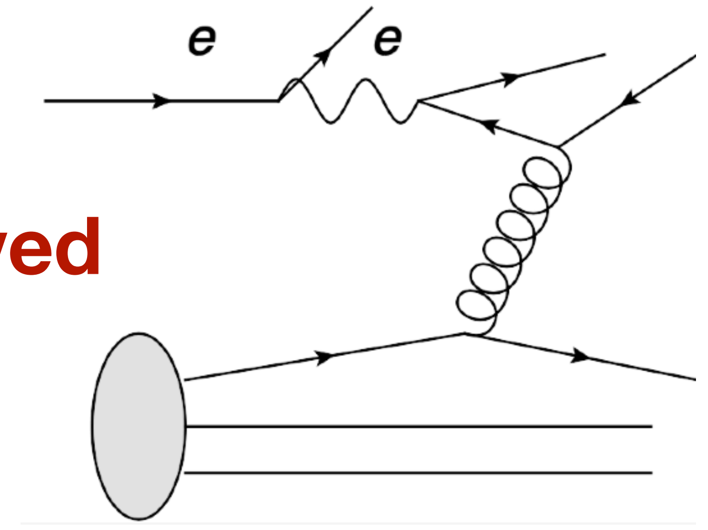


Large Q

Weizsacker-Williams quasi real photon

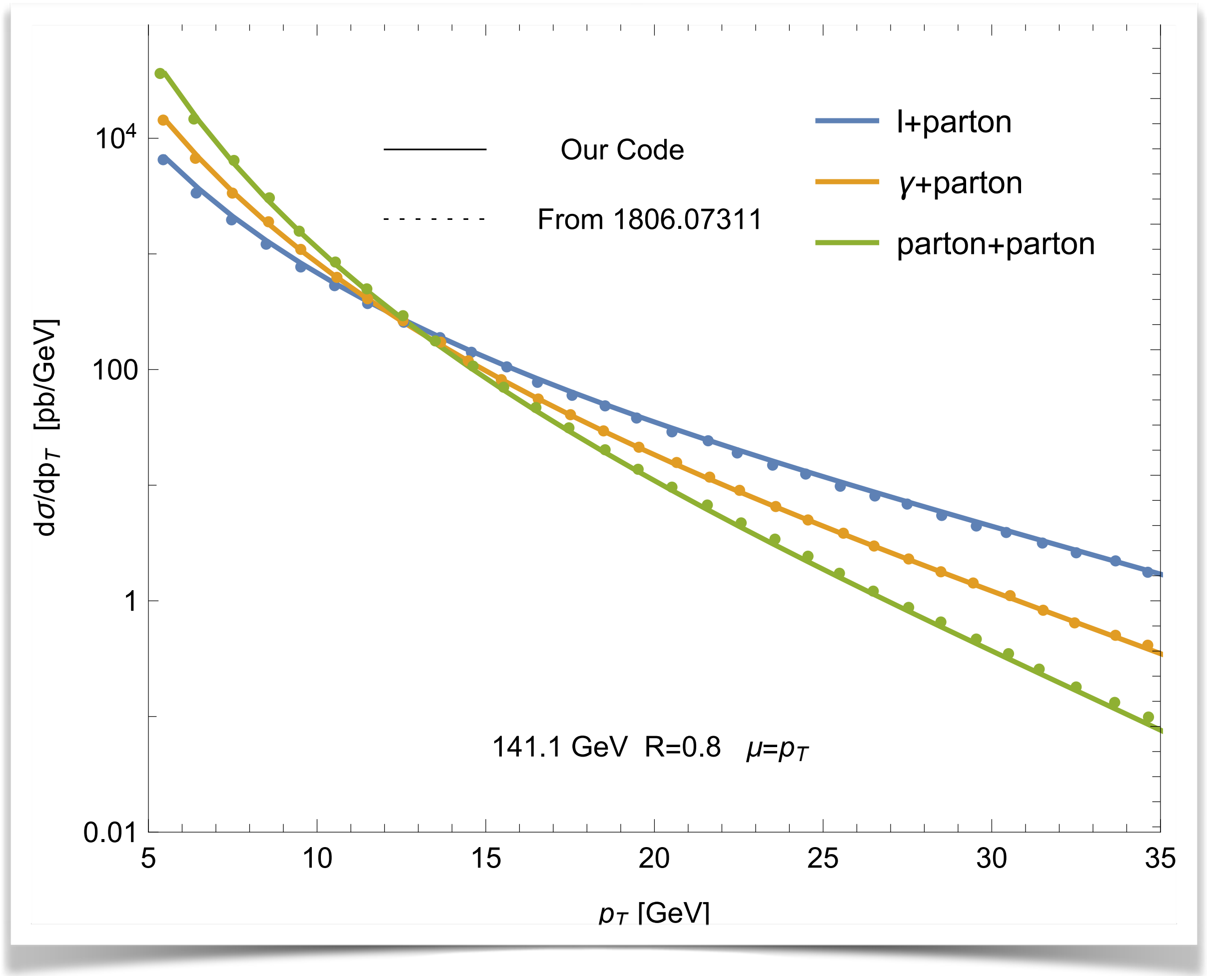


Resolved



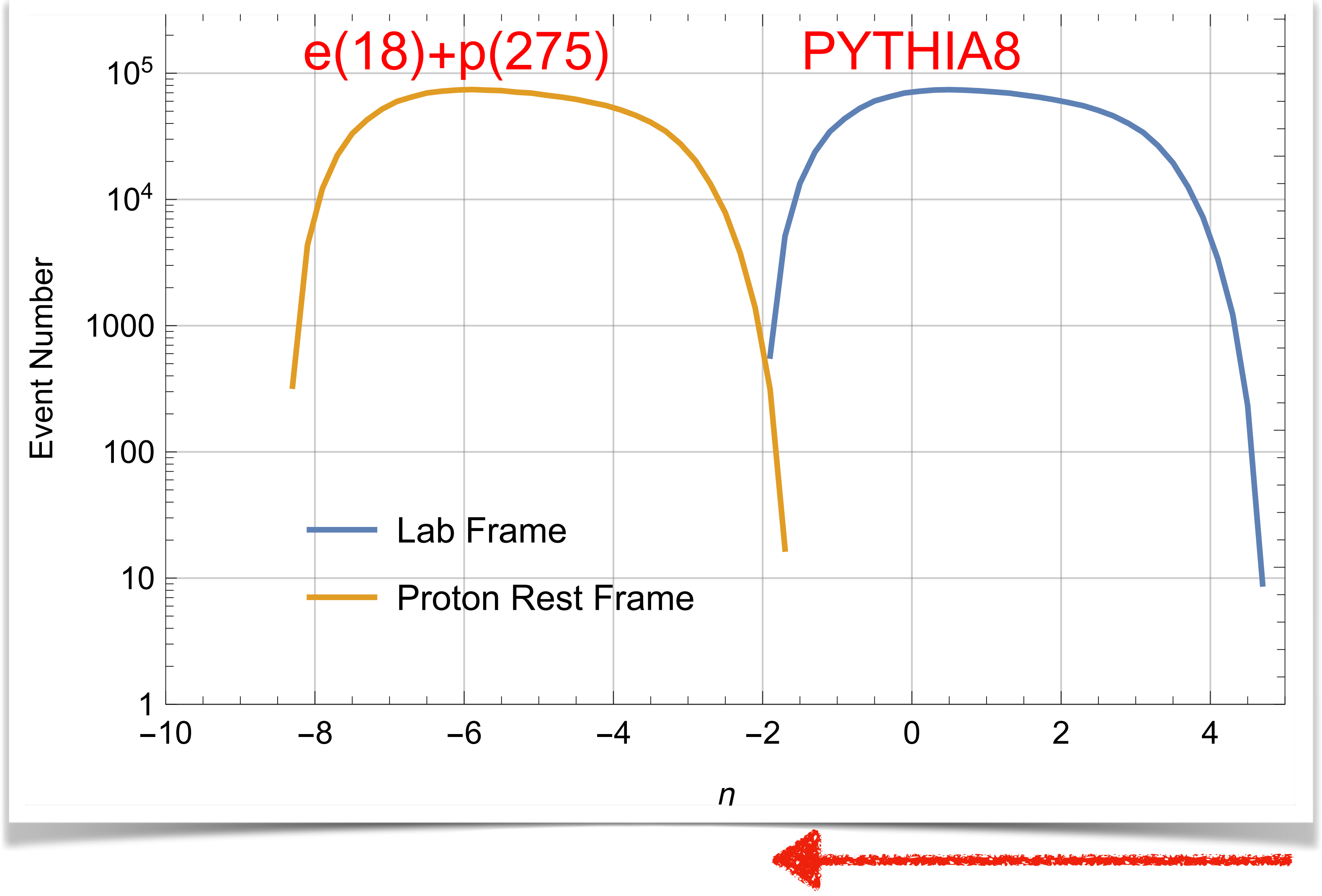
Small Q
Effective Photon PDF from lepton

Small Q
Quark PDF from lepton



NLO results from Boughezal, Petriello, Xing, arXiv:1806.07311

Large Corrections from photon production and resolved contribution in small p_T



From Lab to the proton rest frame

In-medium shower corrections vary with the parton energy in the nuclear rest frame, where the lower energy partons receive larger medium corrections.

Jet@EIC

Jet Inclusive cross section

The inclusive jet cross section can be expressed in a factorized form with the help of semi-inclusive jet functions

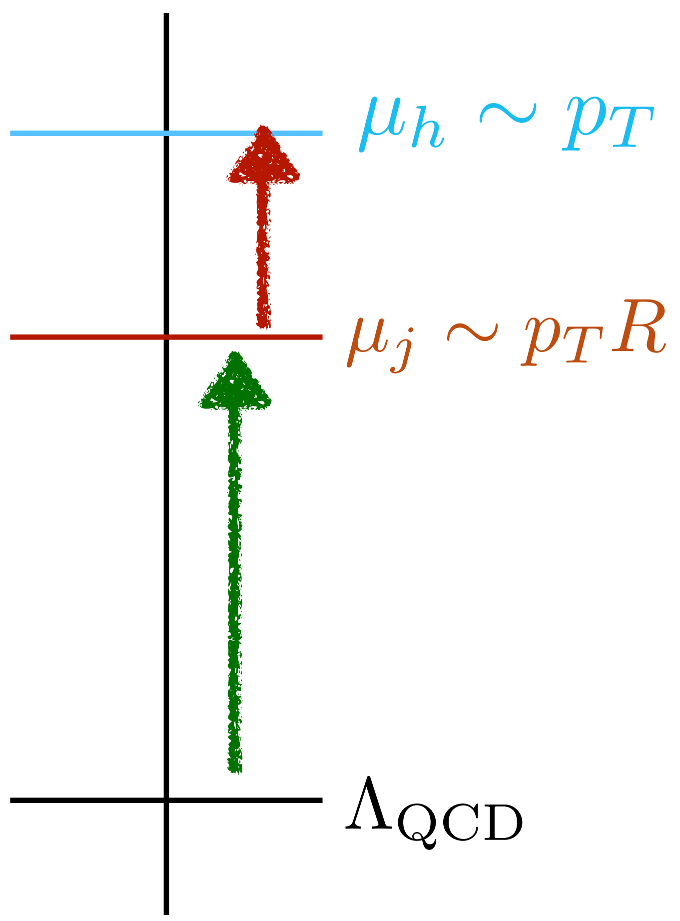
$$\frac{d\sigma^{\ell N\to JX}}{dy_J d^2\mathbf{p}_{T,J}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu)\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right] J_f\left(z, p_T R, \mu\right)$$

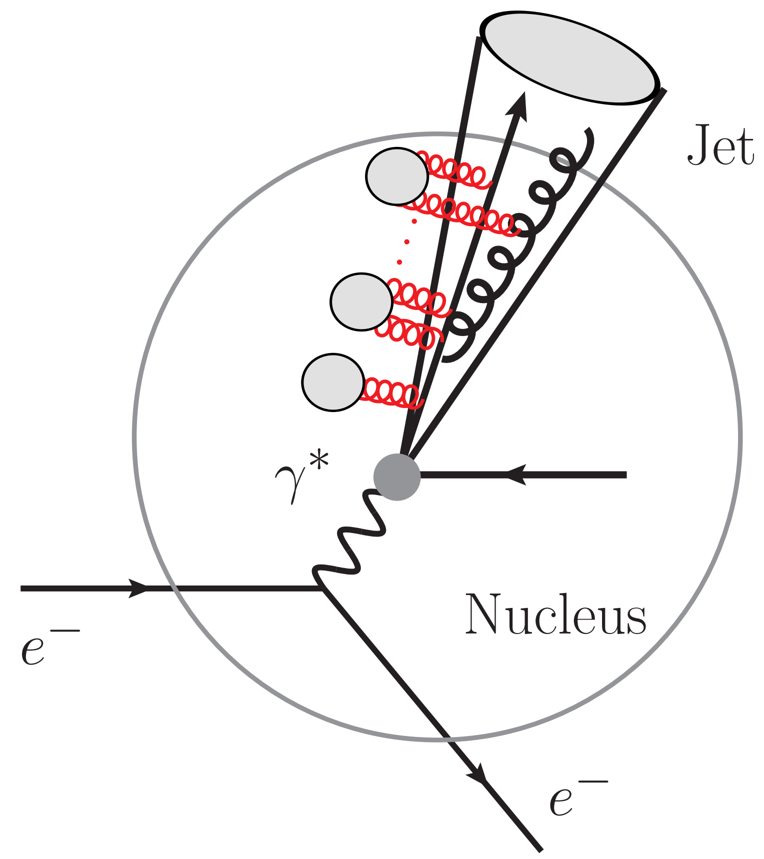
Hard part: arXiv:1505.06415

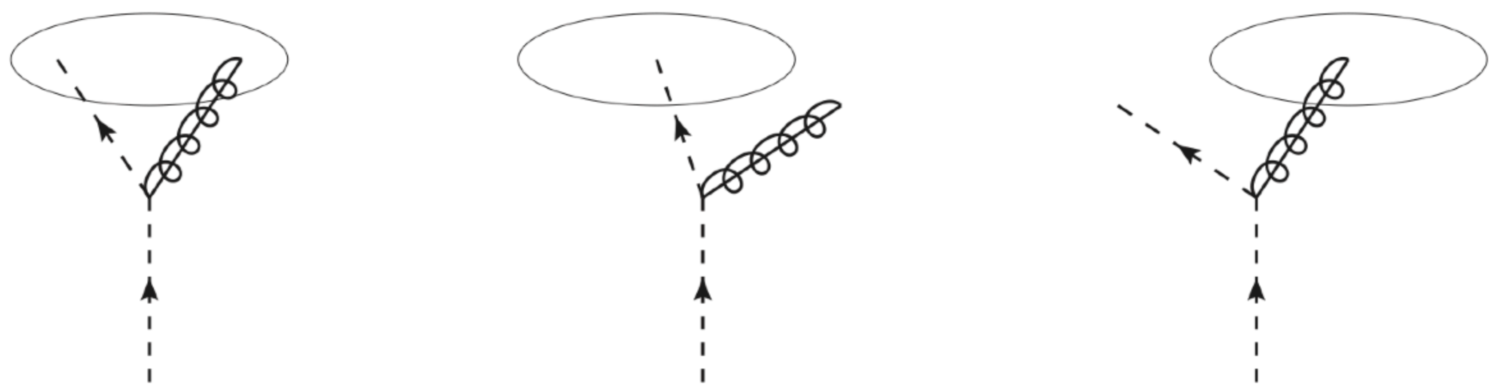
Light Jet Function: arXiv:1606.06732

Heavy Flavor Jet Function: arXiv:1805.06014

scales



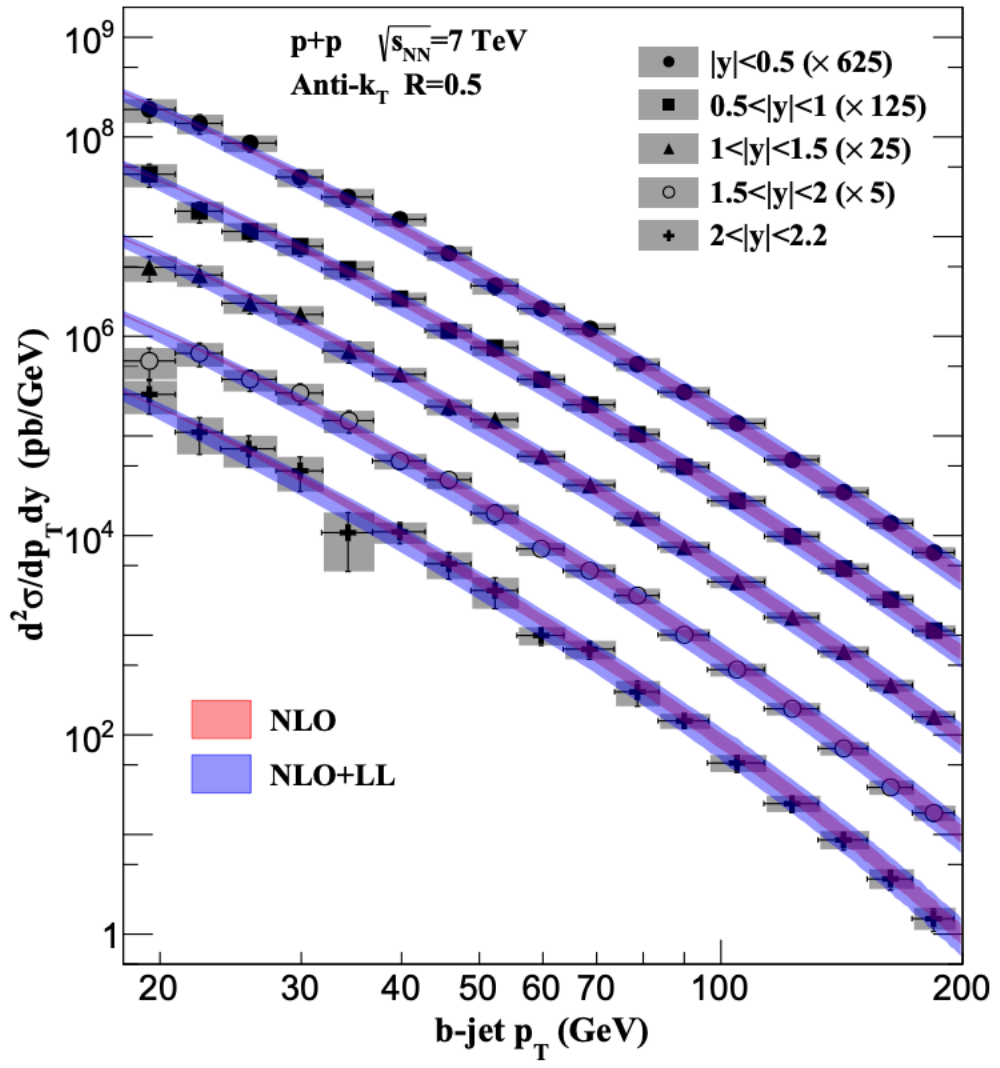


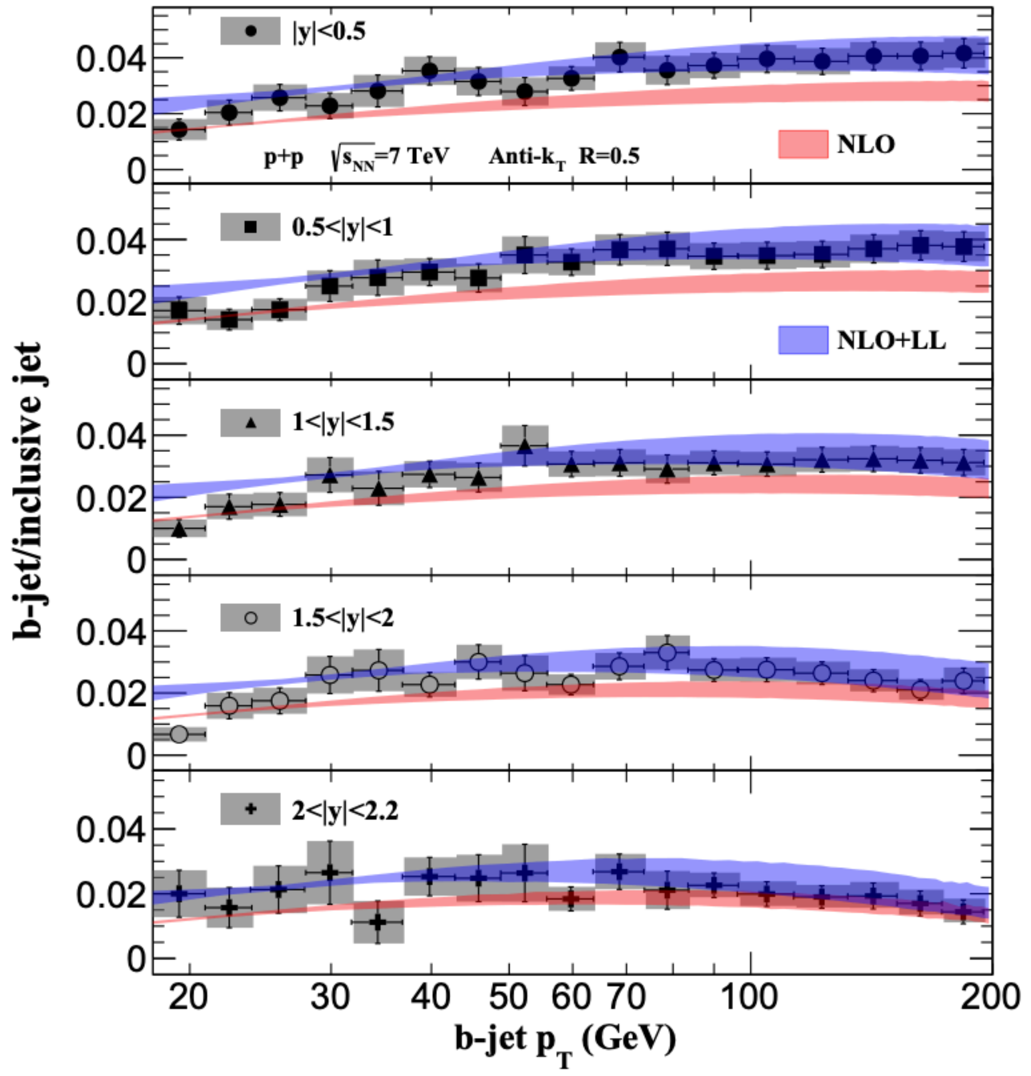


Contribution to the semi-inclusive quark jet function with the medium modified splitting function from SCET$_G$

Kang, Ringer, Vitev, arXiv:1701.05839

HTL, Vitev, arXiv:1811.07905





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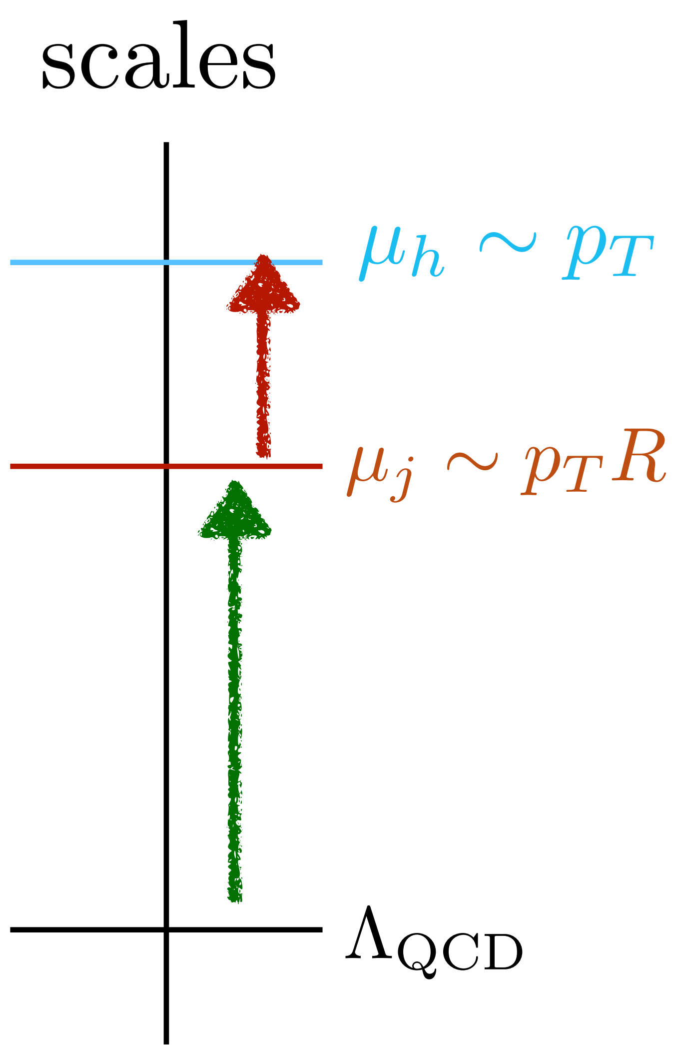

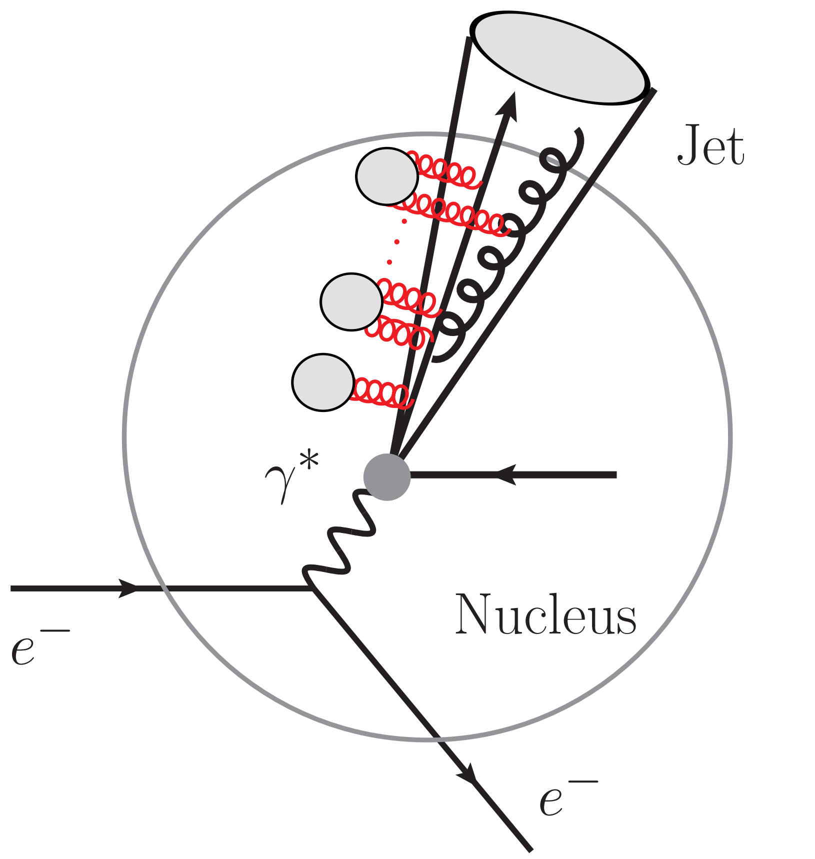

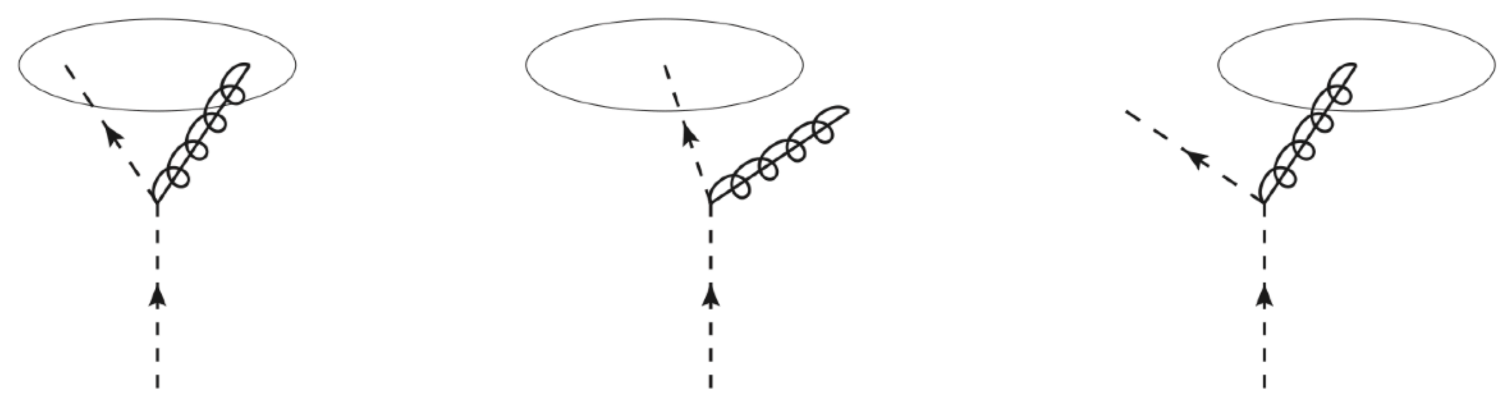

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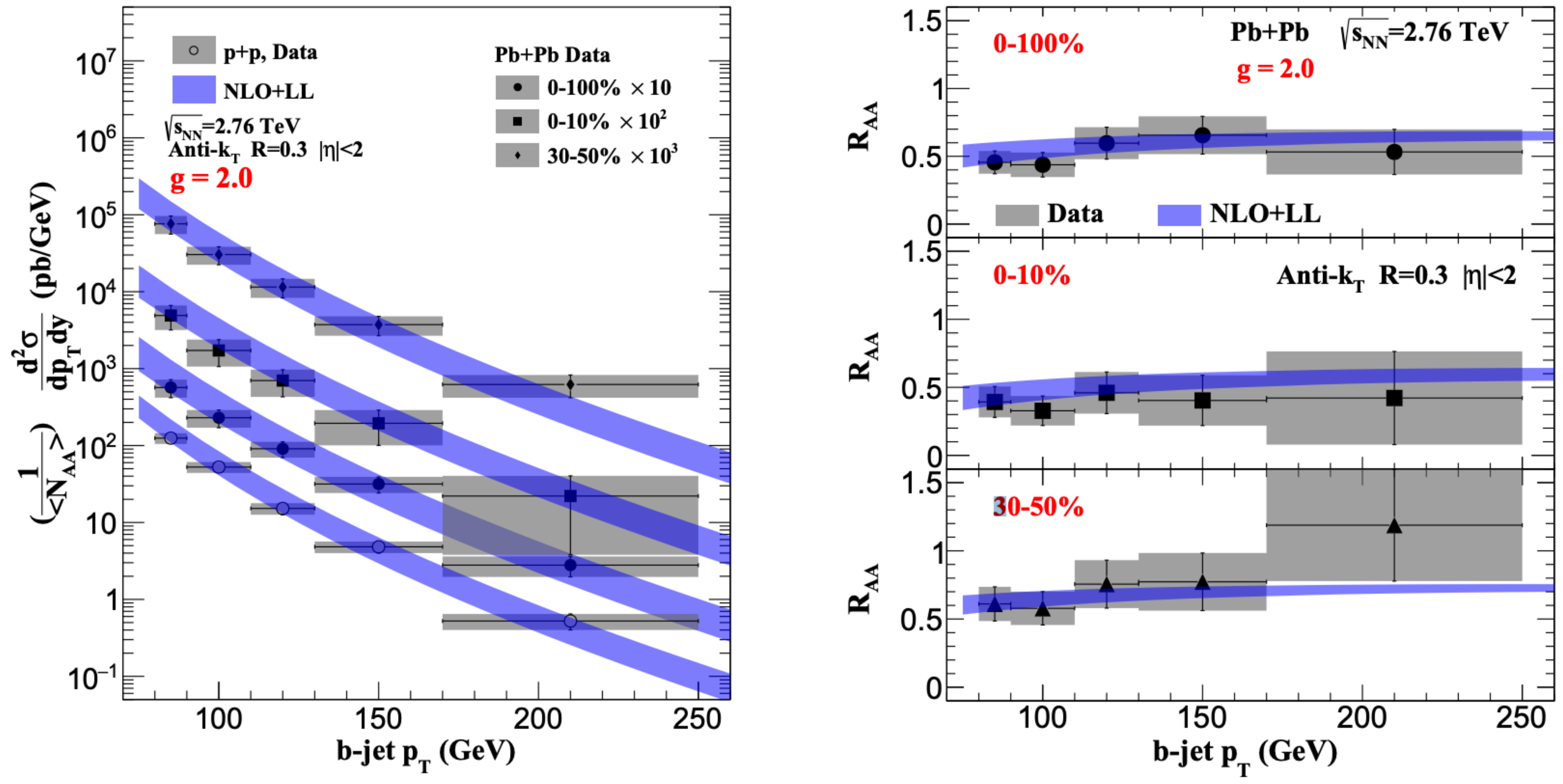

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Jet@EIC

Jet Inclusive cross section

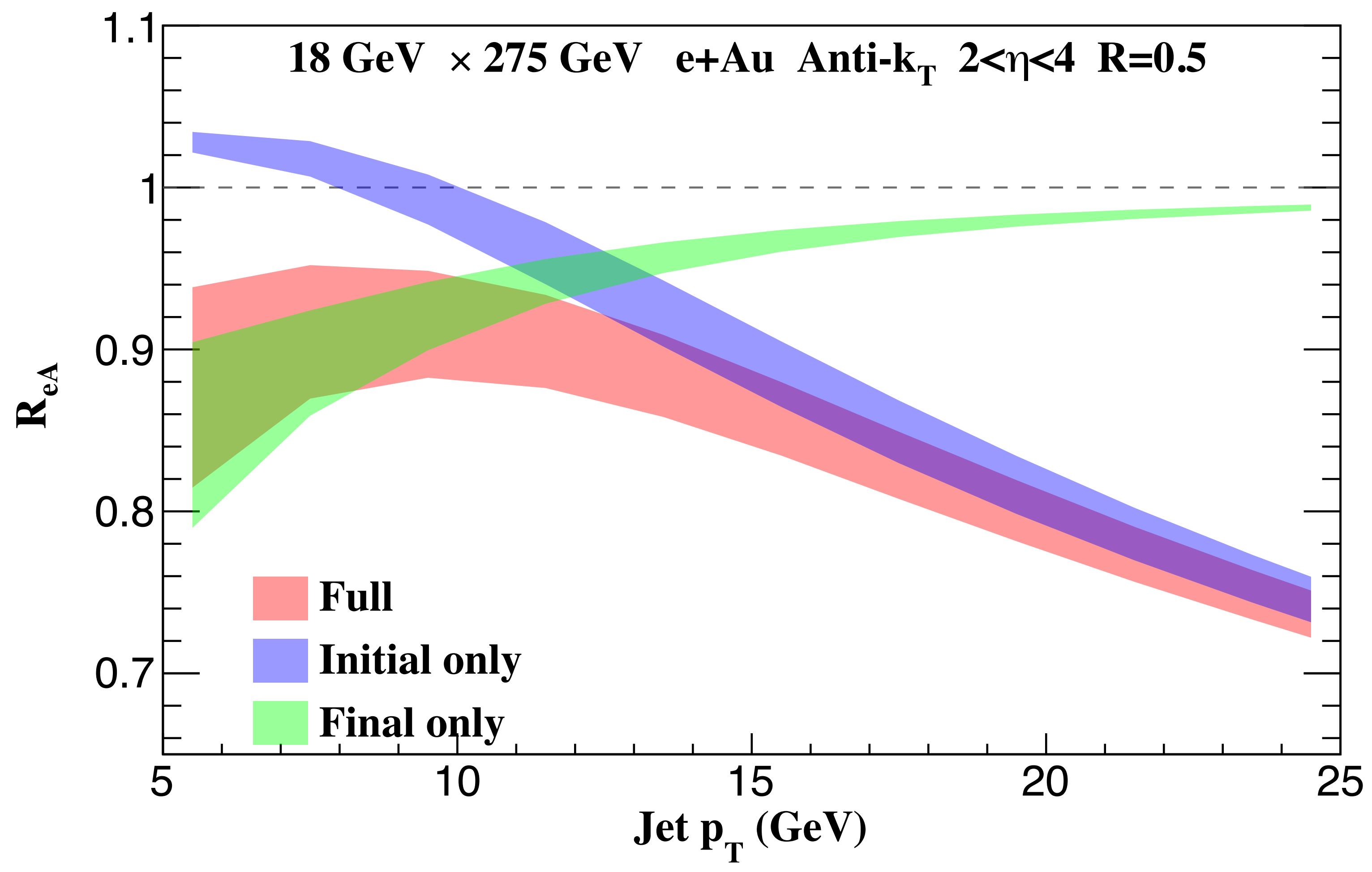
The forward proton/nucleus going rapidity region 2< η <4 produce the largest nuclear effects.

Modifications defined as

$$R_{\mathrm{eA}}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+p}}$$

- ❑ **Bjorken x in the anti-shadowing and EMC region**
- ❑ **Final State effects decreasing with p_T increasing**
- ❑ **Bands are scale uncertainties**

Light jet, HTL, Vitev, arXiv:2010.05912



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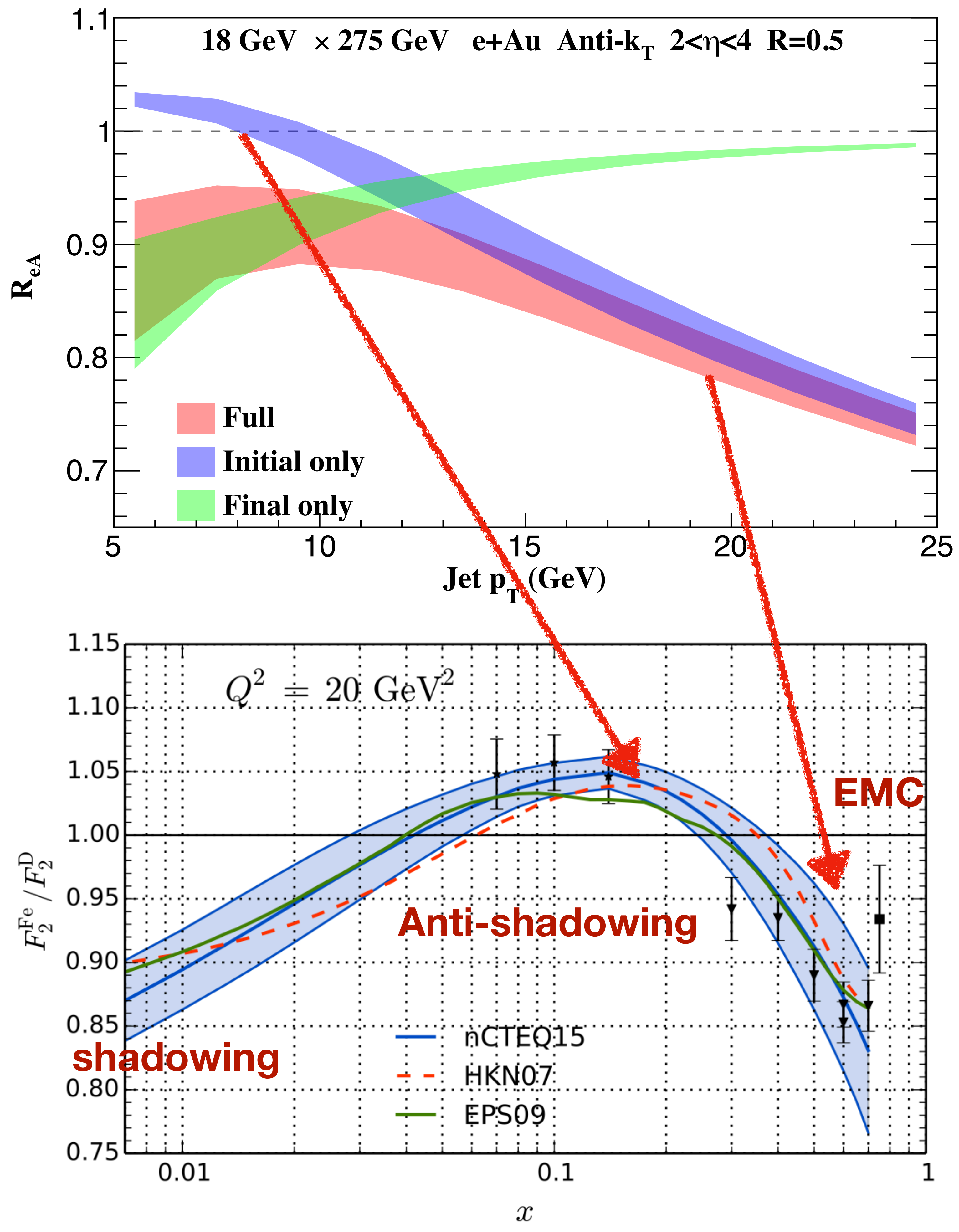

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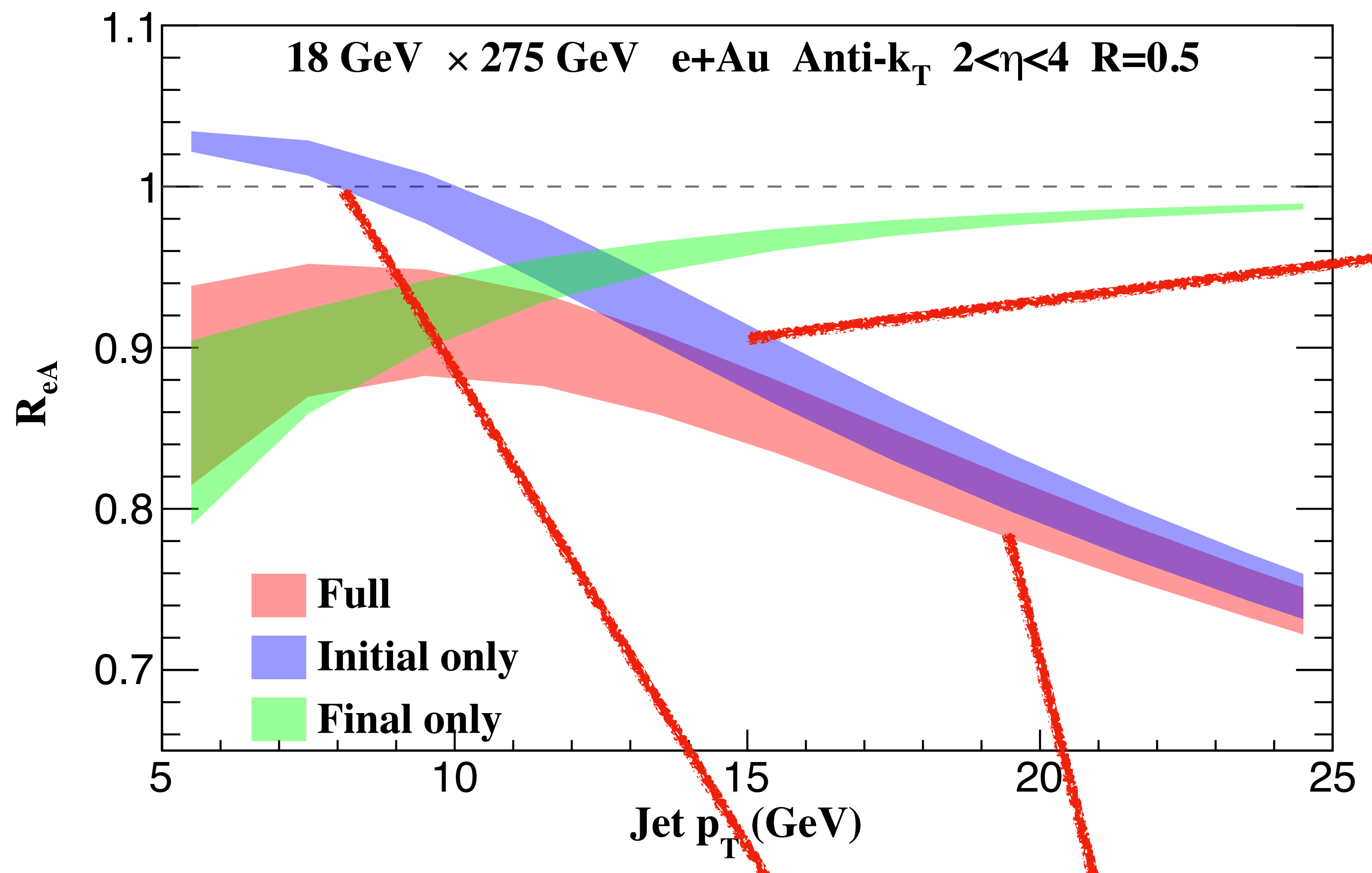
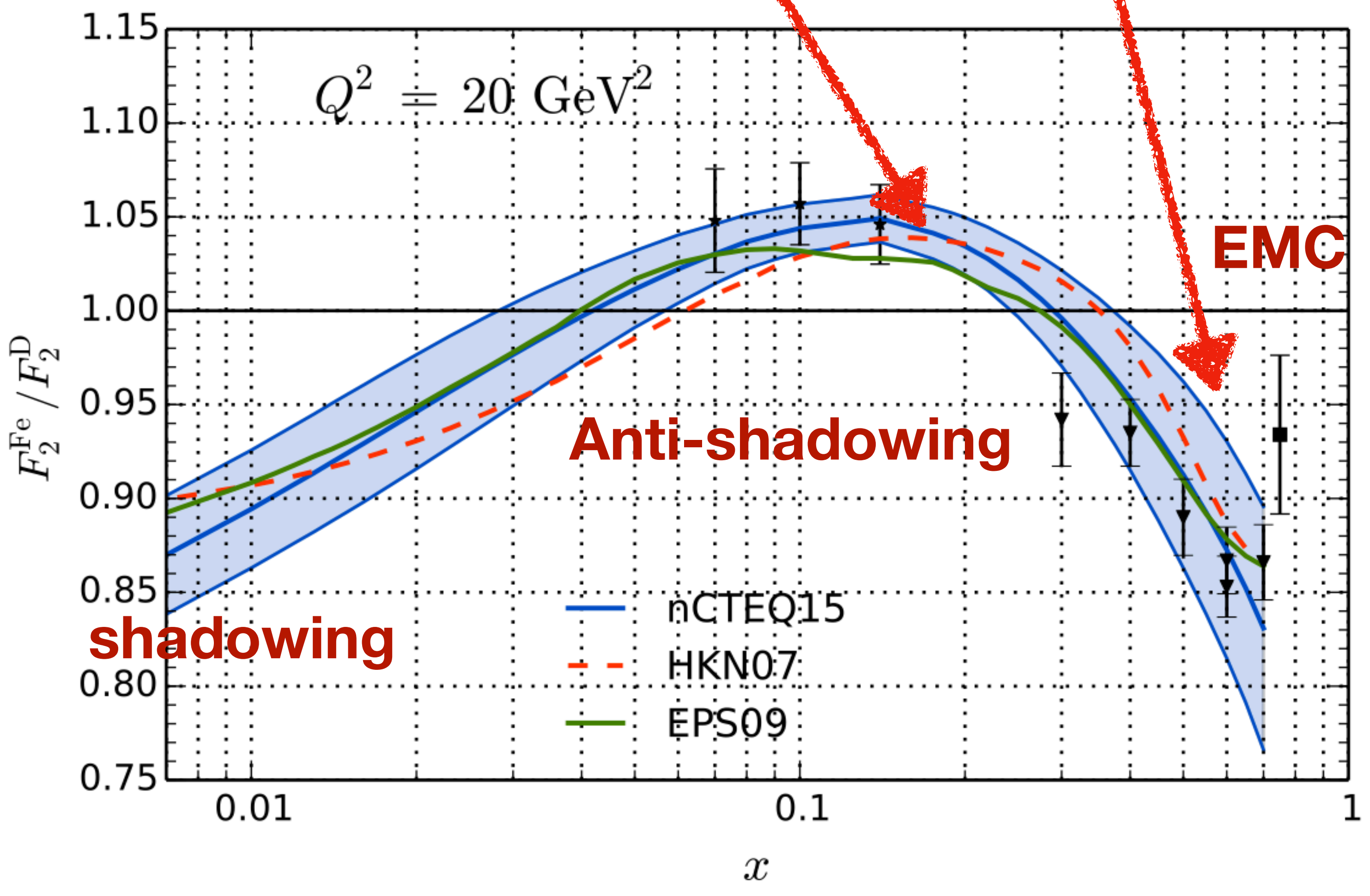


expect to be R dependent



Jet@EIC

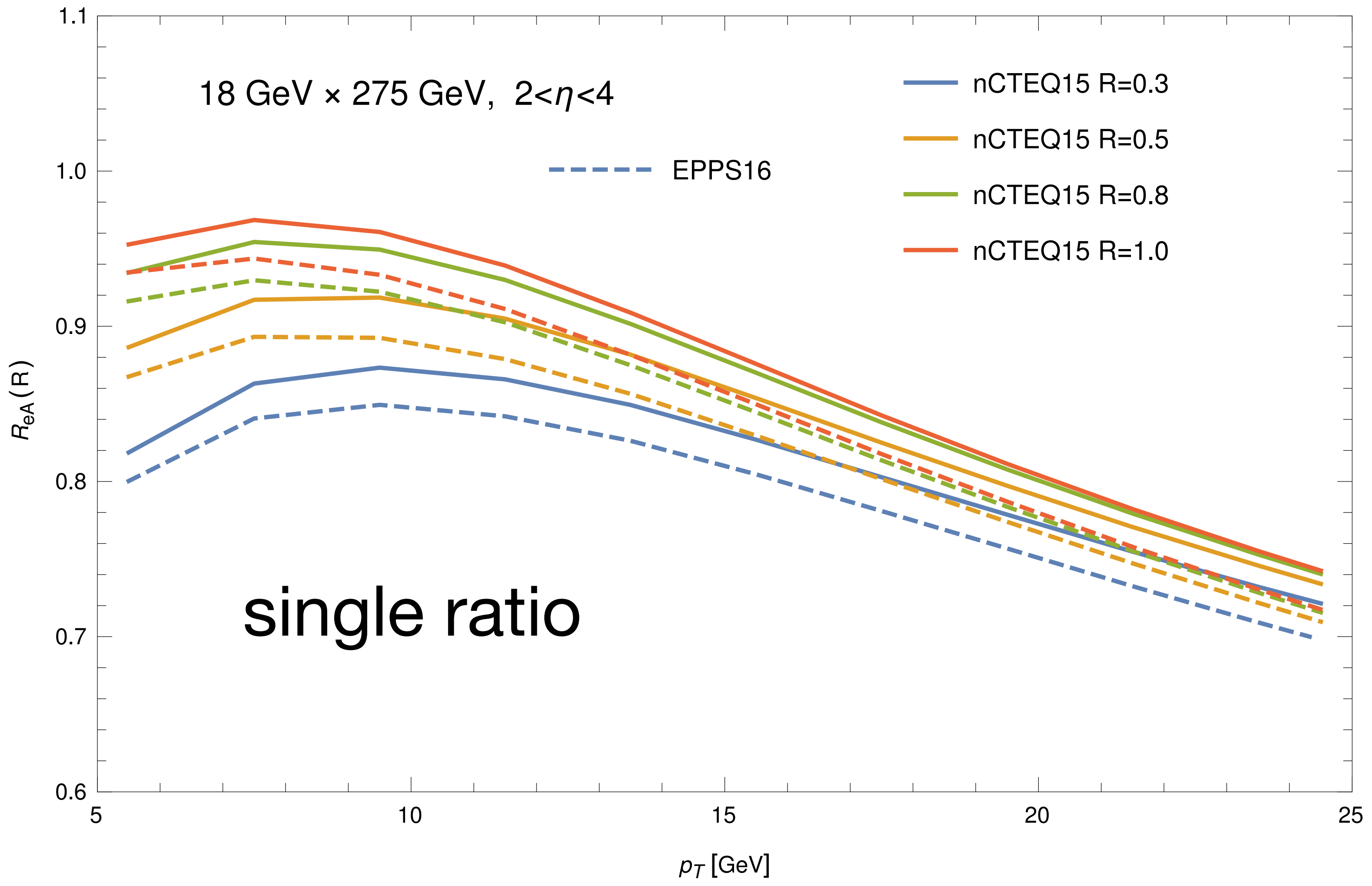
Jet Inclusive cross section

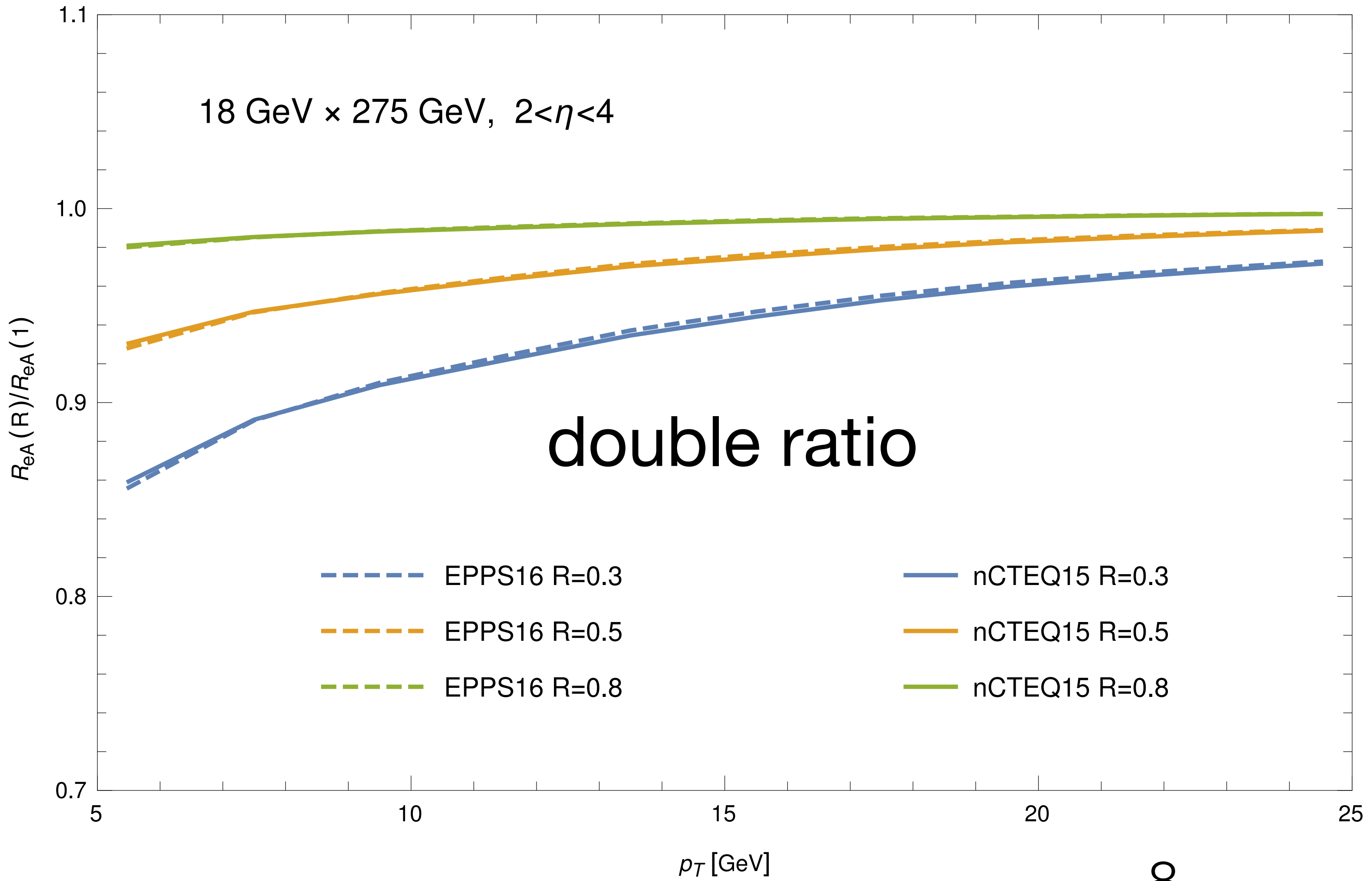
We proposed the double ratio

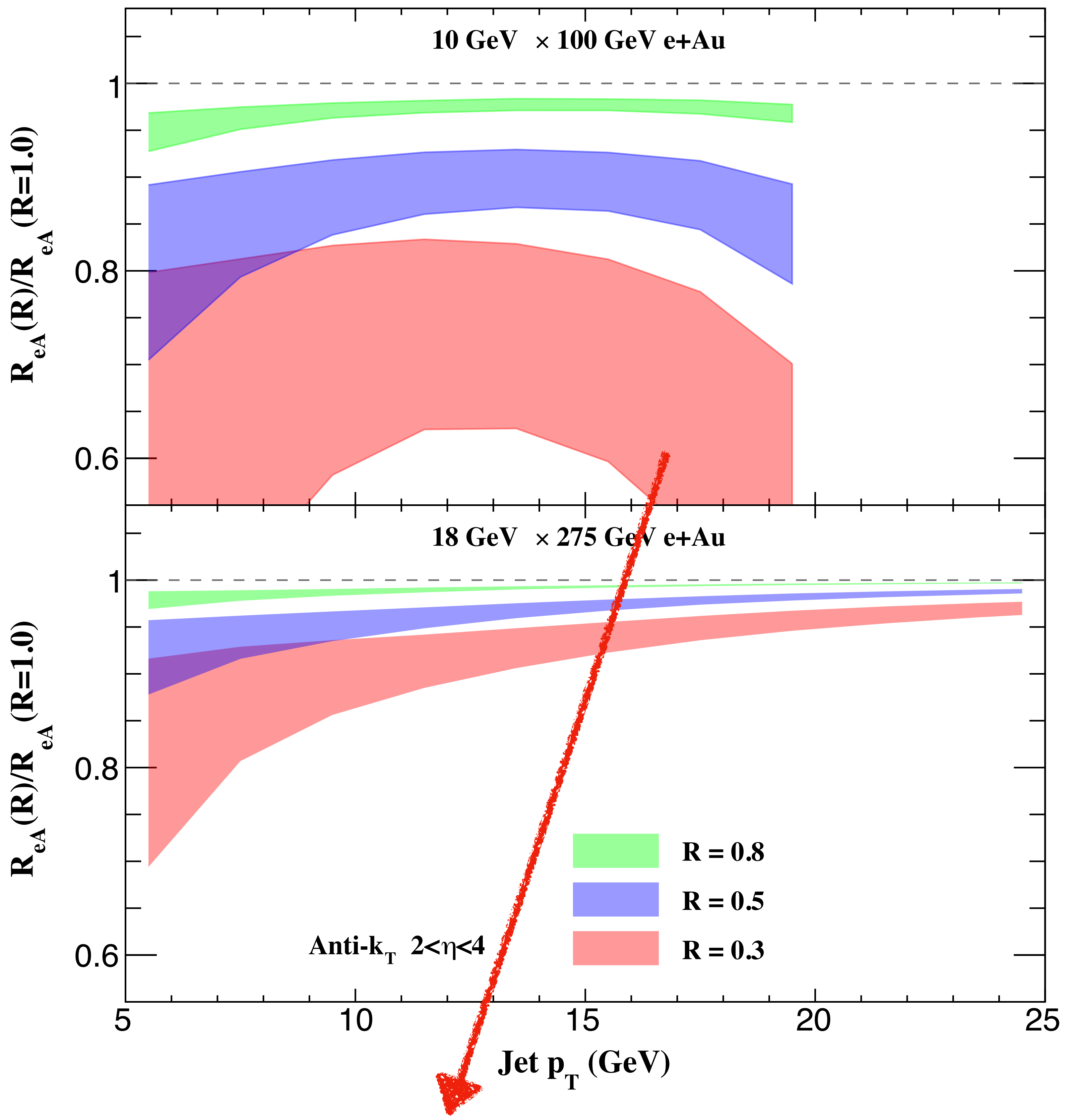
$$\frac{R_{\mathrm{eA}}(R)}{R_{\mathrm{eA}}(R=1)}$$

- Essential reduce the role of nPDFs
- Enhance the effects due to final-state interactions

HTL, Vitev, arXiv:2010.05912





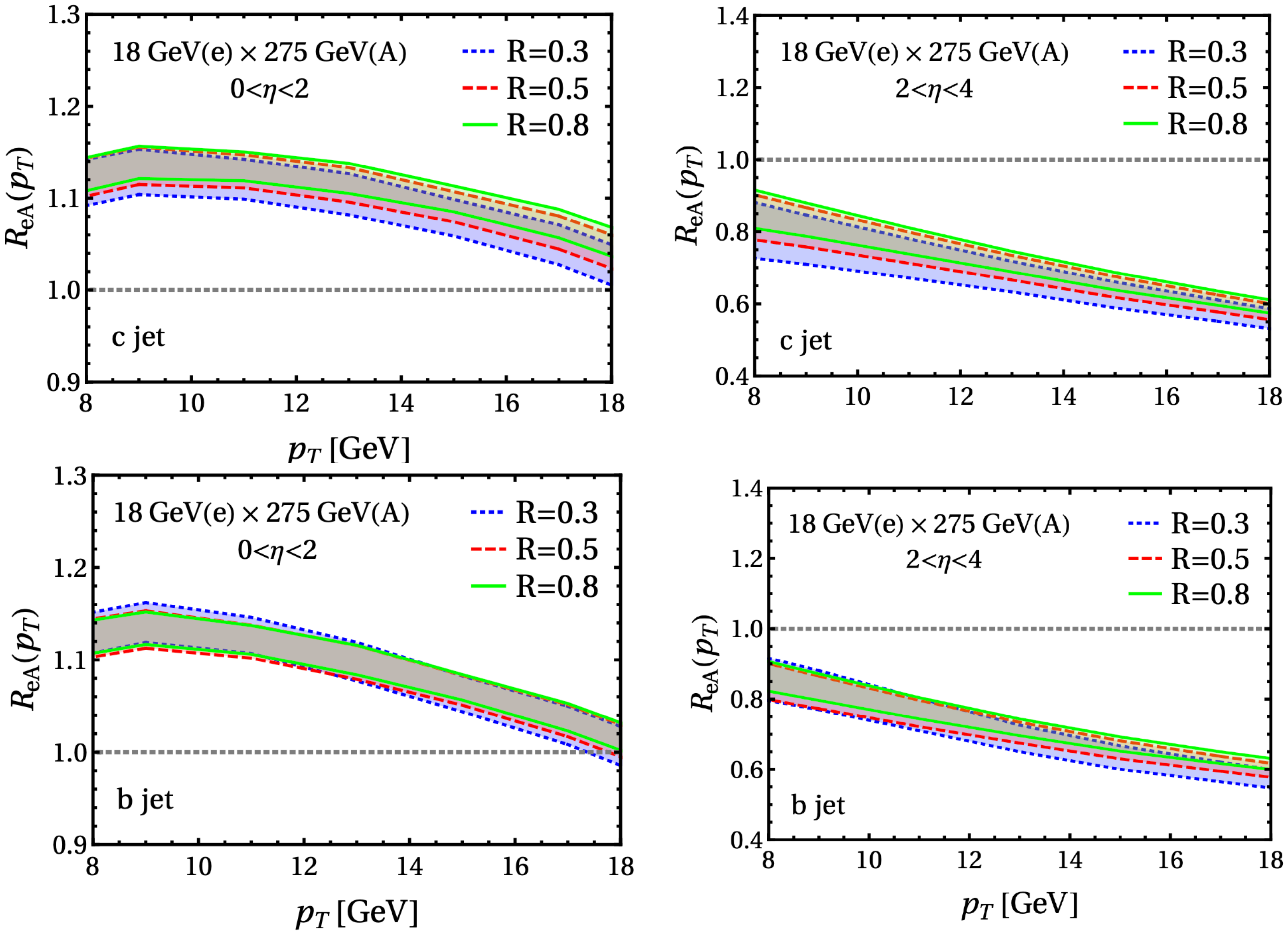


enhanced by the steeper pT spectra near the phase space boundary

Jet@EIC

Jet Inclusive cross section

$\langle q_\perp \rangle / \lambda_q \approx \langle q_\perp \rangle / \lambda_g C_F / C_A = 0.05$ GeV^2/fm   **Uncertainties by varying transport parameter**



- ❑ separation of jet suppression for different radius *R*
- ❑ Initial-state effects play an important role
- ❑ primarily sensitive to the so called EMC region

HTL, Liu, Vitev, arXiv:2108.07809

Jet@EIC

Jet Inclusive cross section

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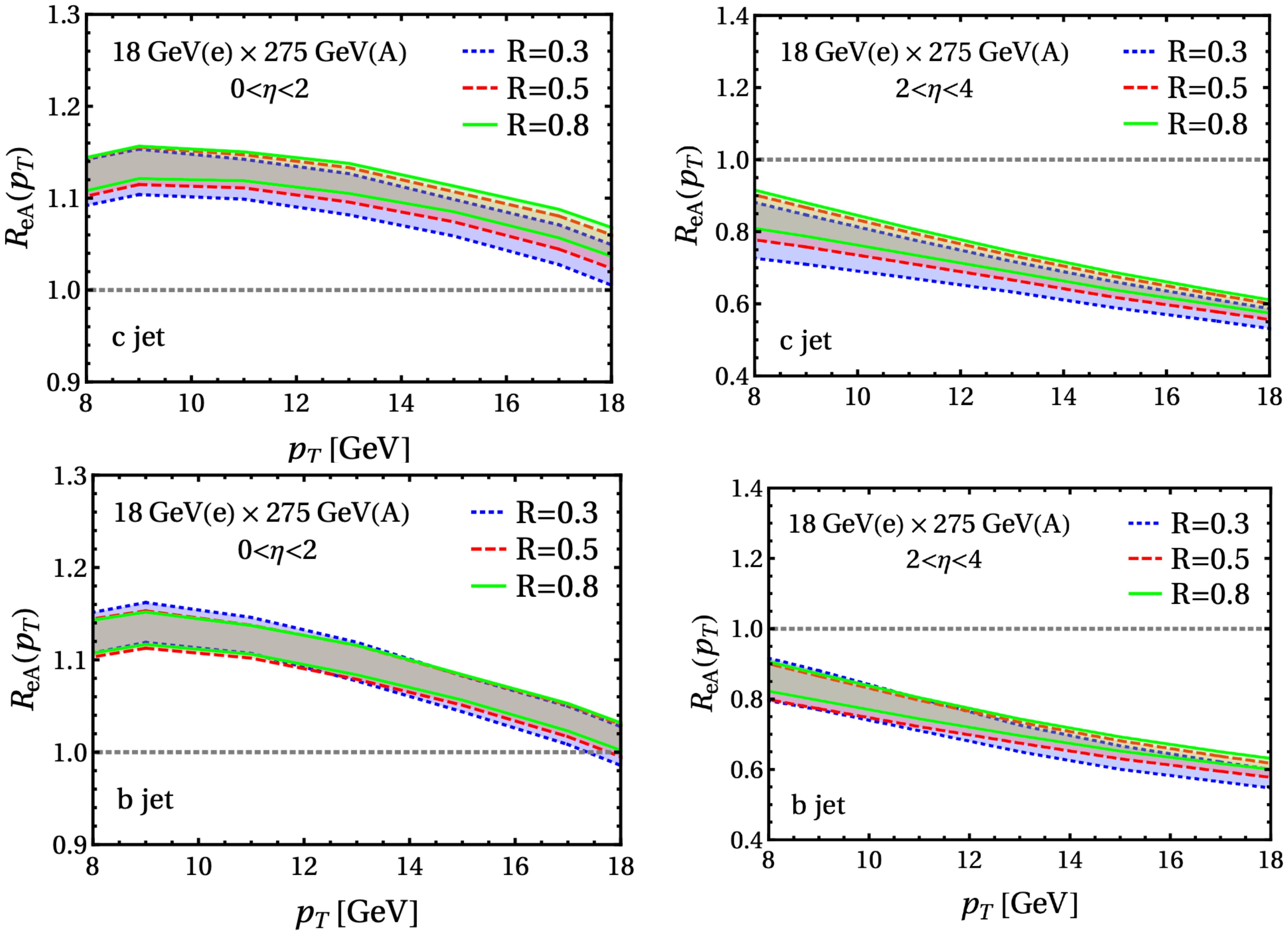
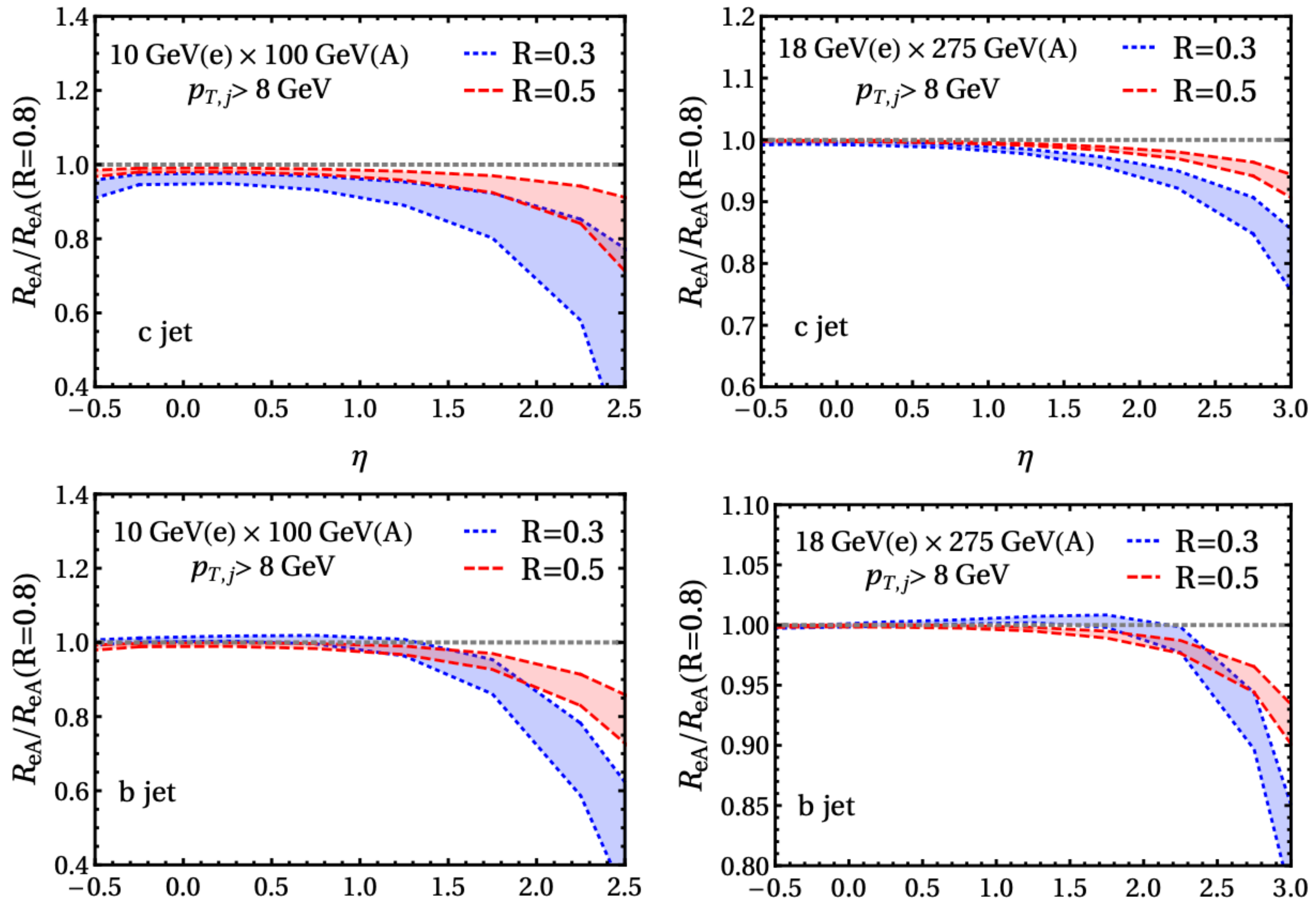


proton rapidity $\eta_p = 5.3$ **proton rapidity $\eta_p = 6.3$**



large energy in nuclear rest frame

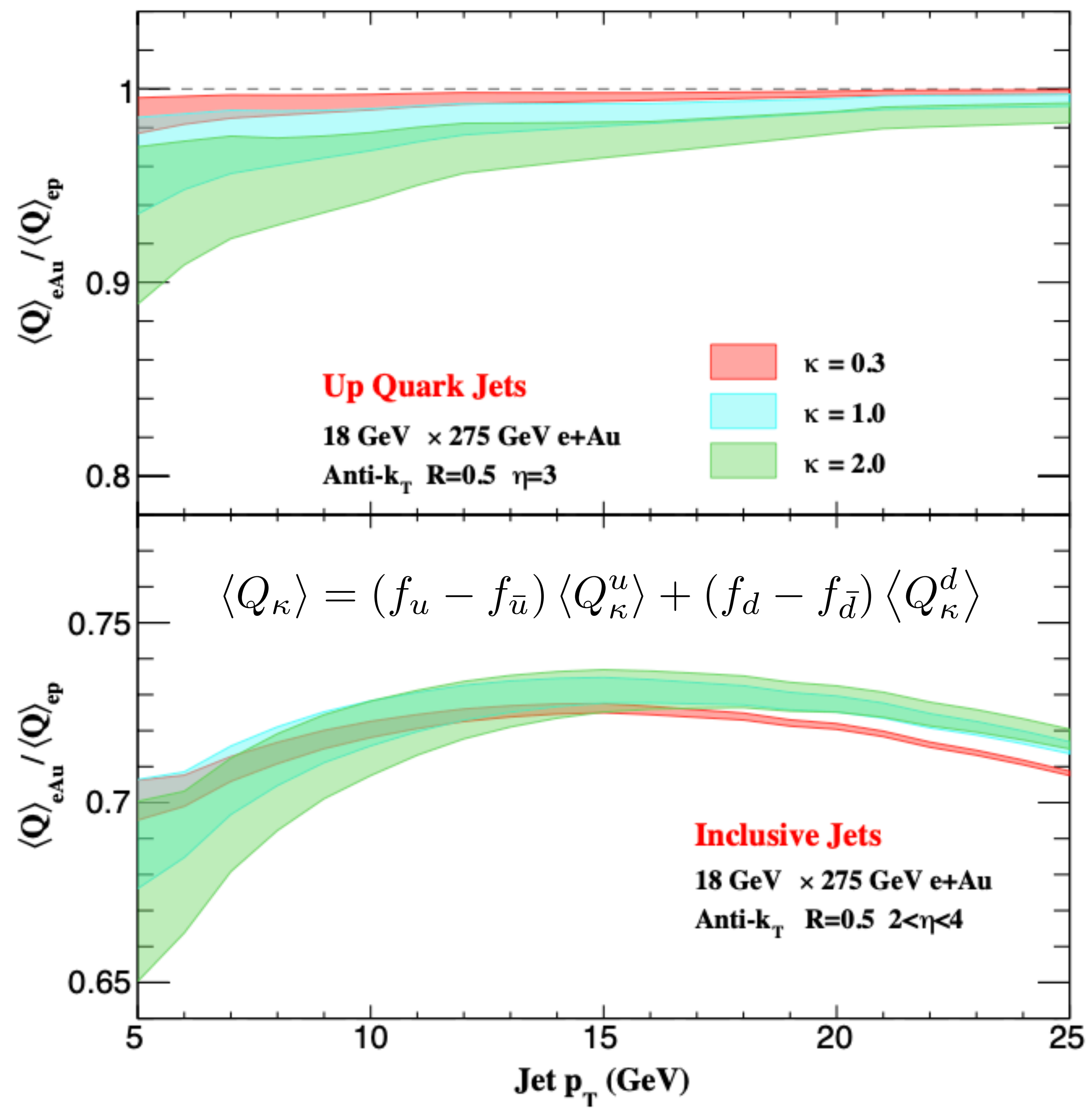
large Bjorken x

Medium-induced suppression is much enhanced in the forward rapidity region

HTL, Liu, Vitev, arXiv:2108.07809

Jet@EIC

Jet structures



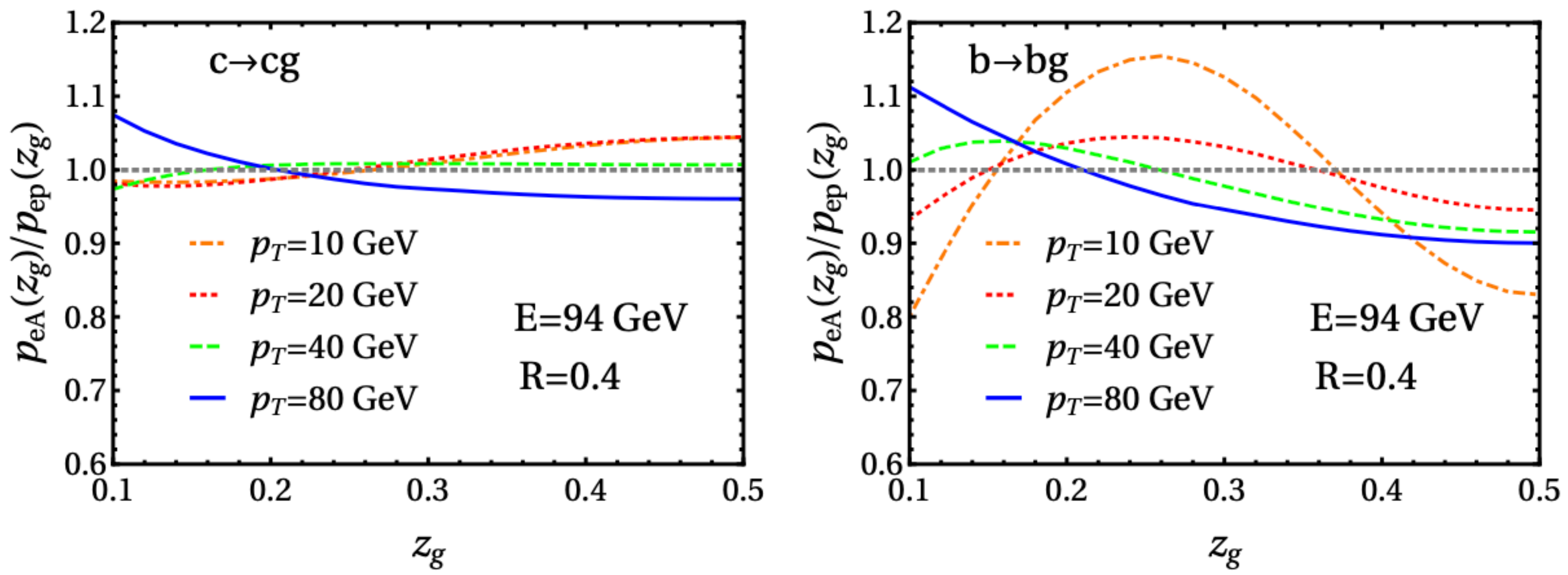
Cancellation between u and d jet

Excellent way to constrain isospin effects and the up/down quark PDFs in the nucleus.

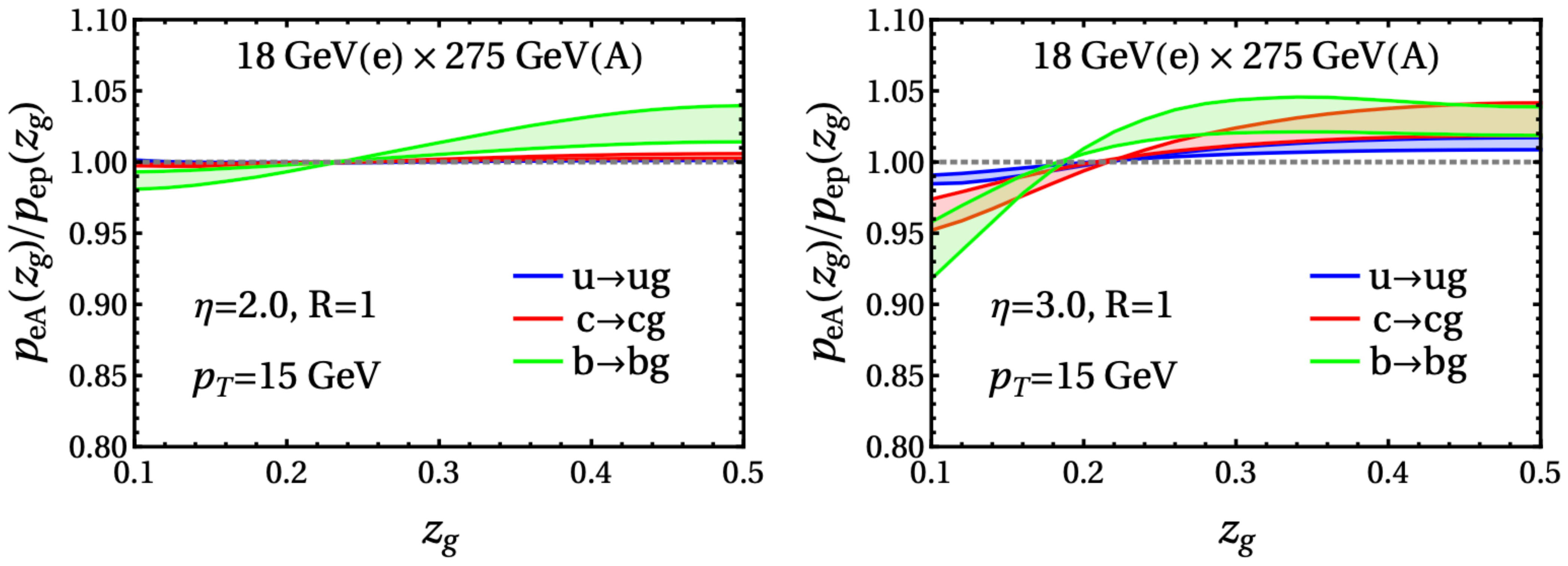
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \quad \textbf{with} \quad z_g > z_{cut}$$

Groomed jet splitting functions for *c* → *cg* and *b* → *bg*.

For 94 GeV jet in rest frame of the nucleus

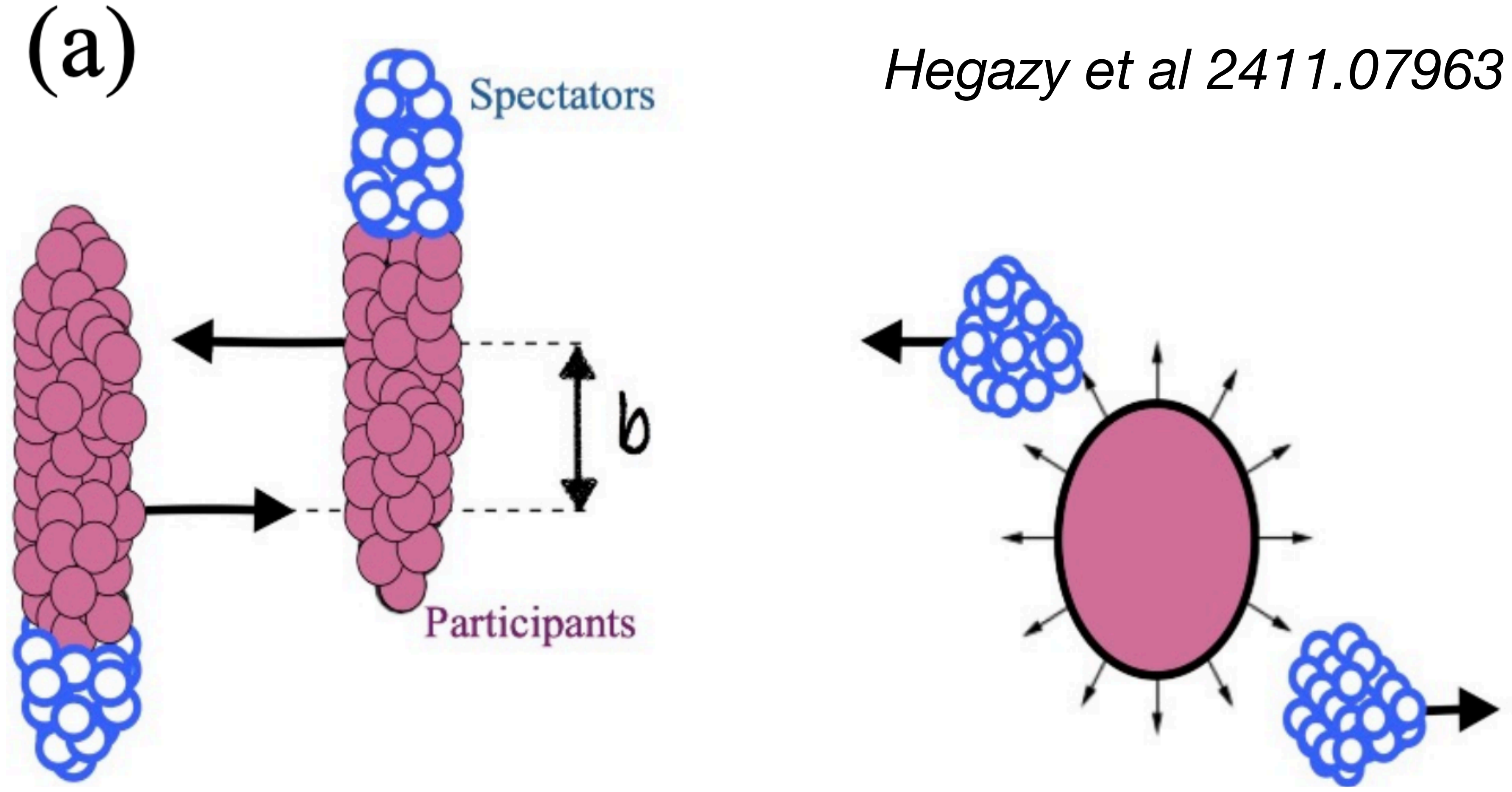


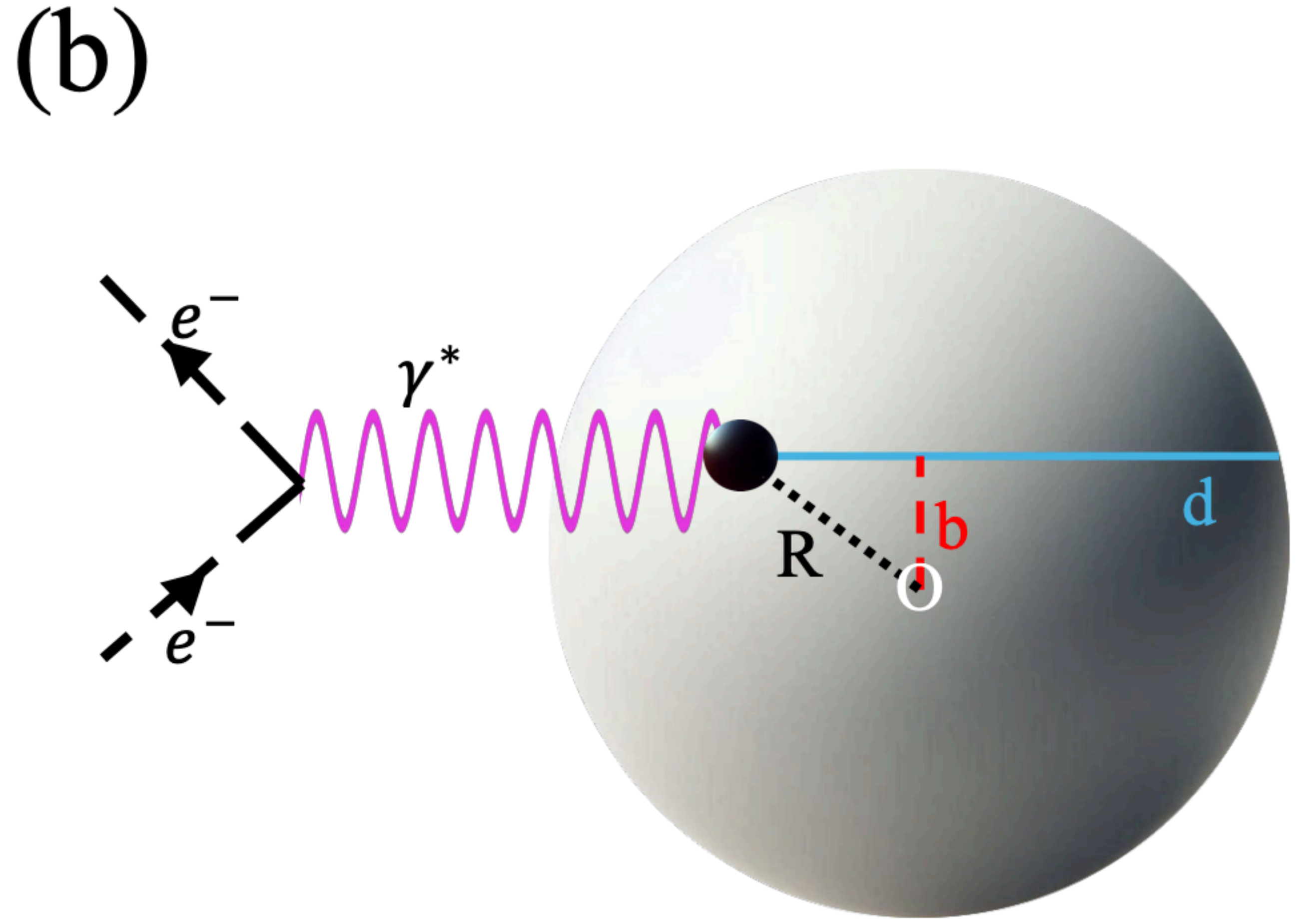
For inclusive jet at EIC



Jet@EIC

Hegazy et al 2411.07963





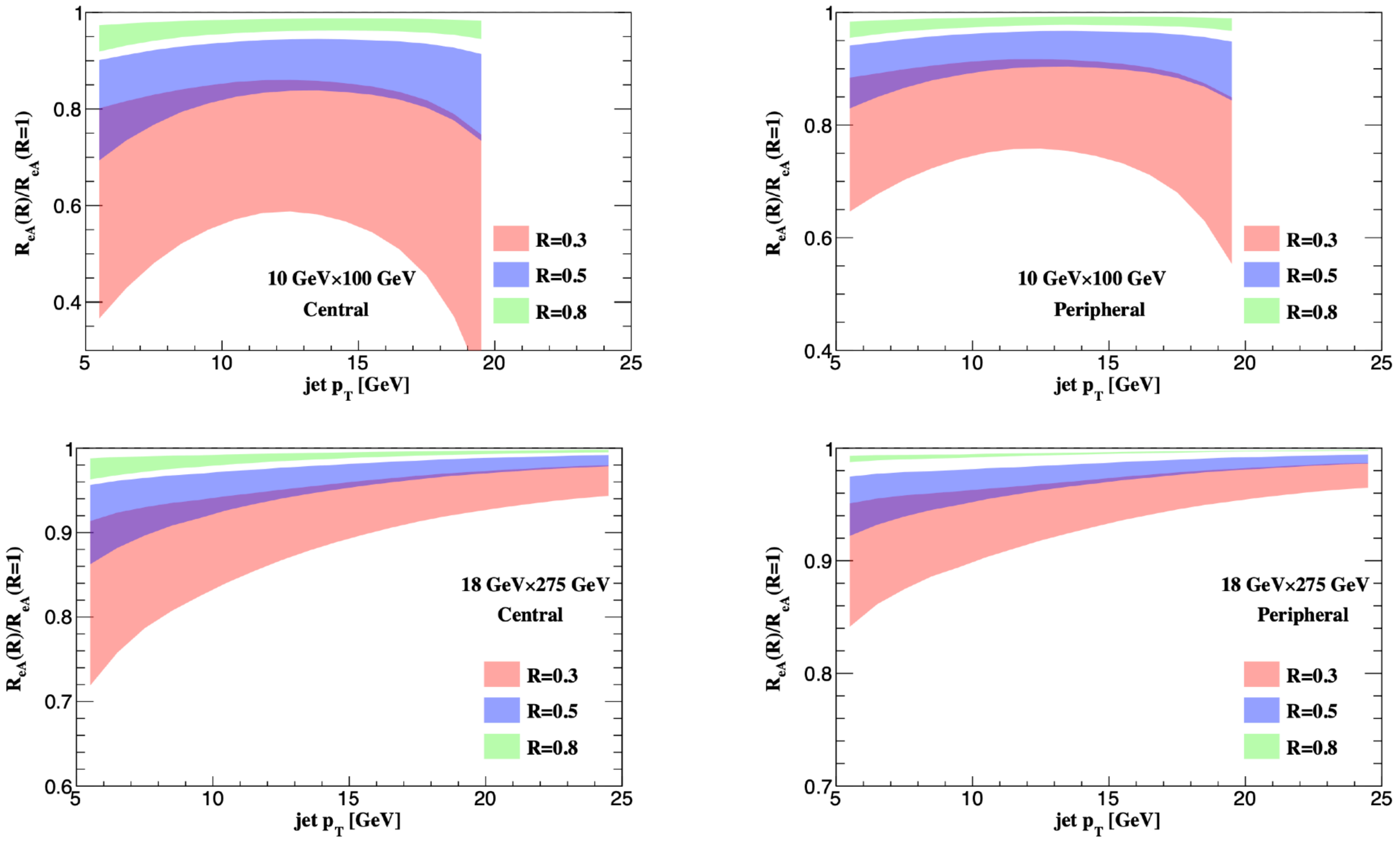
Jet@EIC

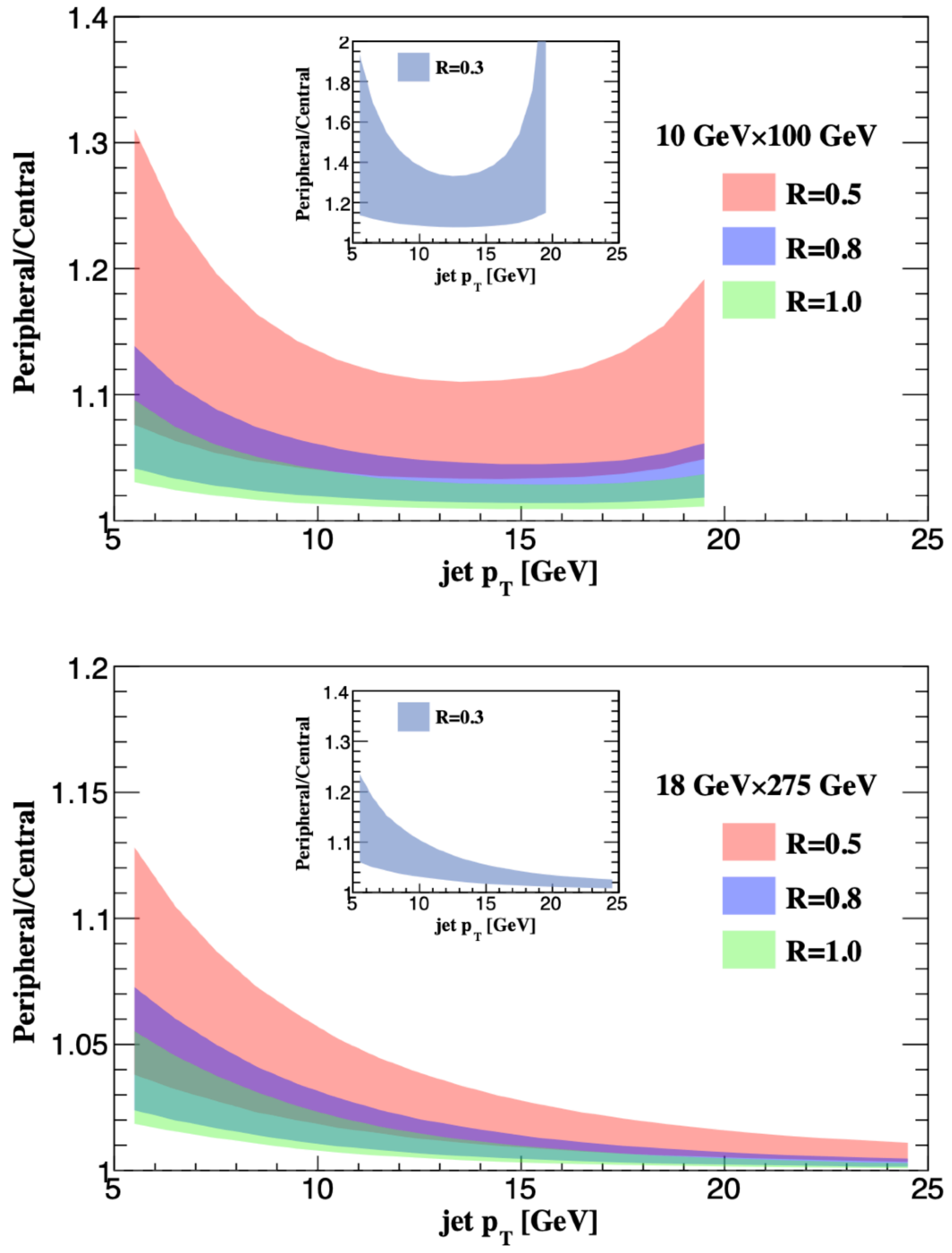
Centrality-dependent modification

Centrality	0 – 1%	0 – 3 %	0 – 10 %	60 – 100 %	80 – 100 %	90 – 100 %	0 – 100 %
$\langle d \rangle [fm]$	9.09	8.48	7.61	2.88	2.71	2.71	4.40
$\langle d \rangle / \langle d \rangle_{\mathrm{min.bias}}$	2.07	1.93	1.73	0.65	0.62	0.62	1.00

average interaction length of a parton in a Pb nucleus as a function of centrality obtained in BeAGLE

$$\frac{\text{Peripheral}}{\text{Central}}(J) = \frac{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}|_{\mathrm{eA,Peri.}}}{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}|_{\mathrm{eA,Cent.}}}$$





Hadron@EIC

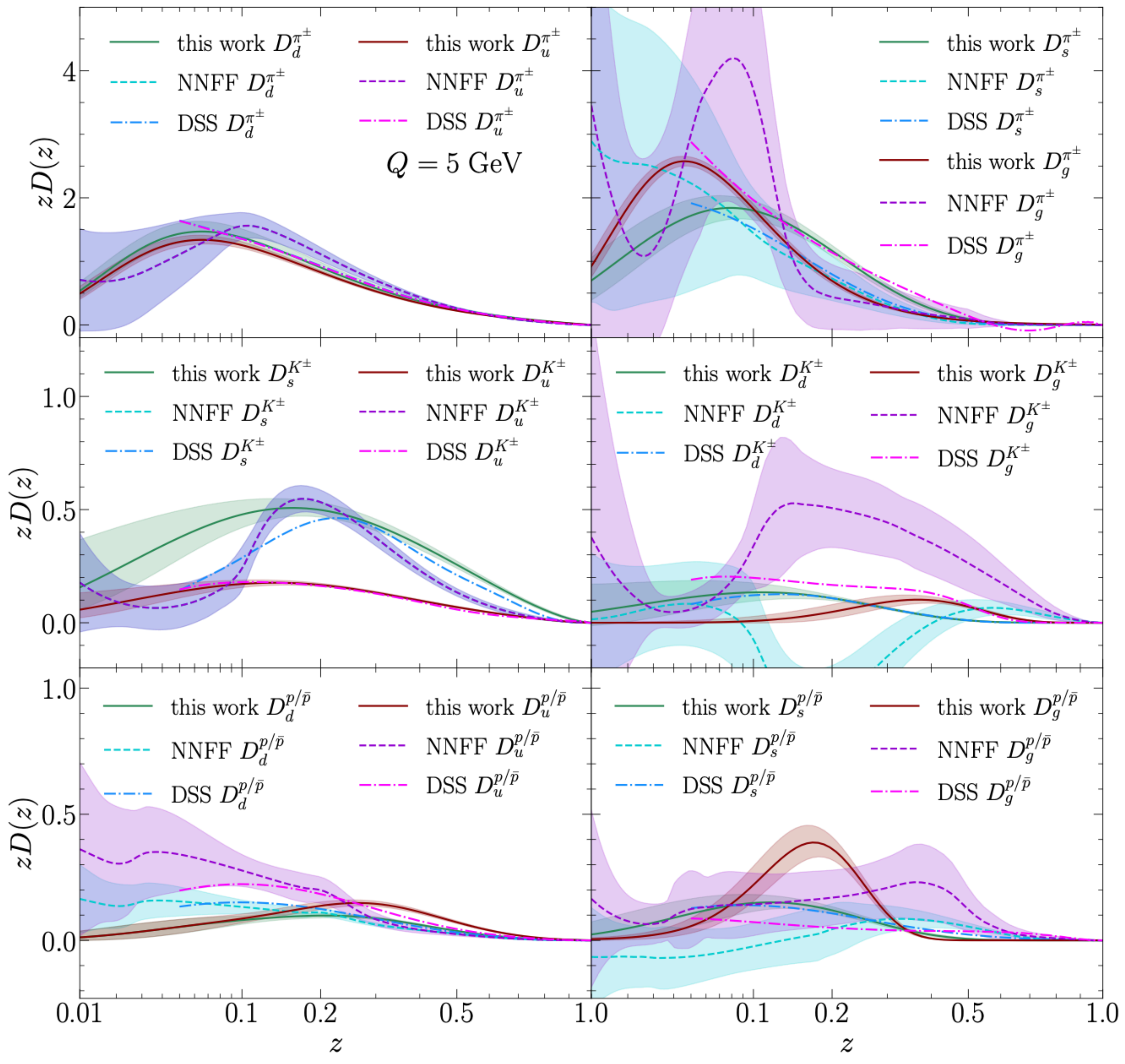
In collinear factorization, the inclusive cross section for hadron production is

$$\frac{d\sigma^{\ell N\to hX}}{dy_h d^2\mathbf{p}_{T,h}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu)\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right] D^{h/f}(z,\mu)$$

Hard part: arXiv:1505.06415

DSS, HKNS, AKK, SGK, NNFF, MAPFF, JAM. NPC23

Gao, Liu, Shen, Xing, Zhao, arXiv:2401.02781, 2407.04422



We used HKNS FF for pion and results from HQET for heavy flavors

medium effects included by

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}\left(z,\alpha_s(\mu)\right) + P_{ji}^{\rm med}(z,\mu)\right)$$

Hadron@EIC

In collinear factorization, the inclusive cross section for hadron production is

$$\frac{d\sigma^{\ell N\to hX}}{dy_h d^2\mathbf{p}_{T,h}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu)\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right] D^{h/f}(z,\mu)$$

Hard part: arXiv:1505.06415

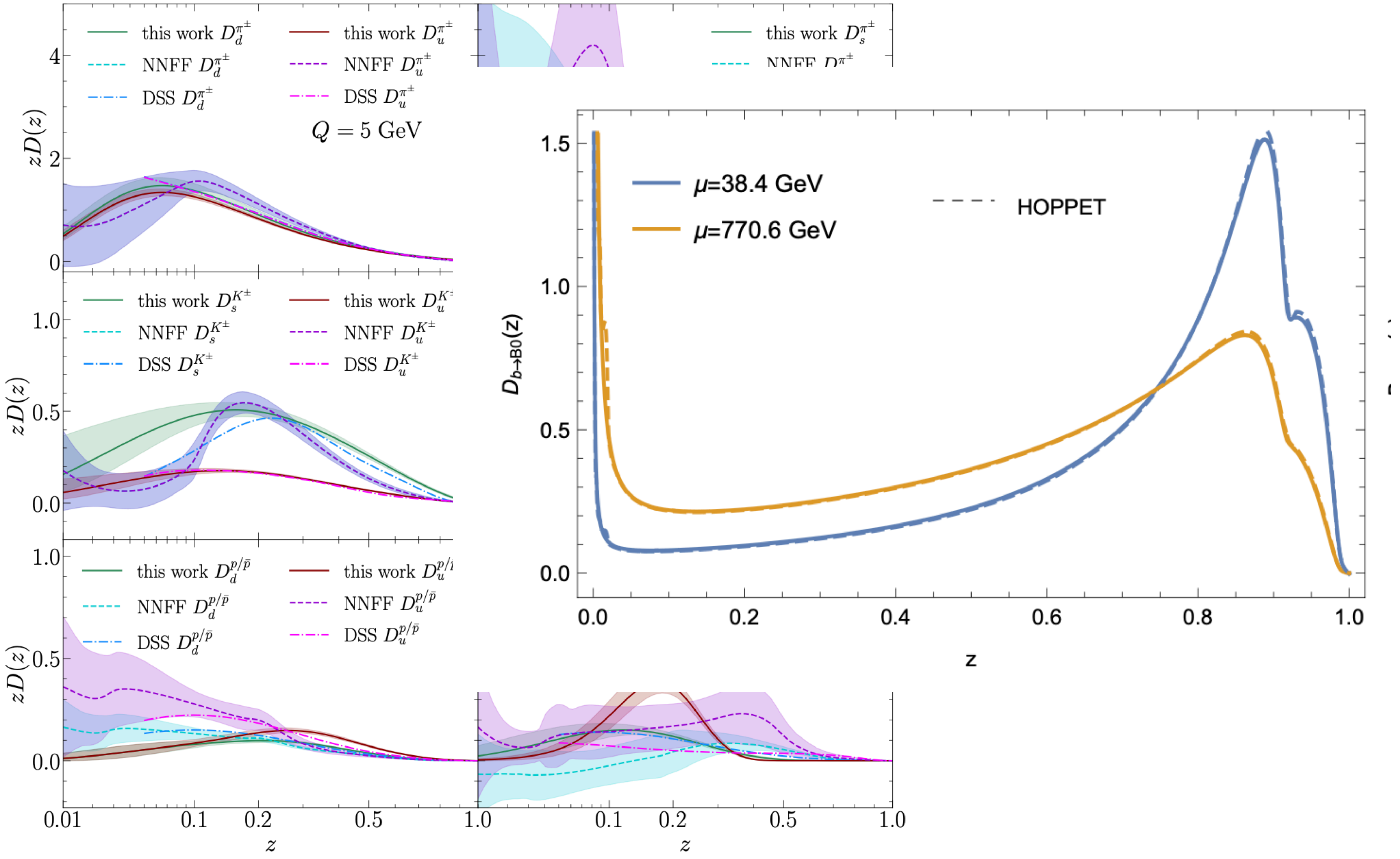
DSS, HKNS, AKK, SGK, NNFF, MAPFF, JAM. NPC23

Gao, Liu, Shen, Xing, Zhao, arXiv:2401.02781, 2407.04422

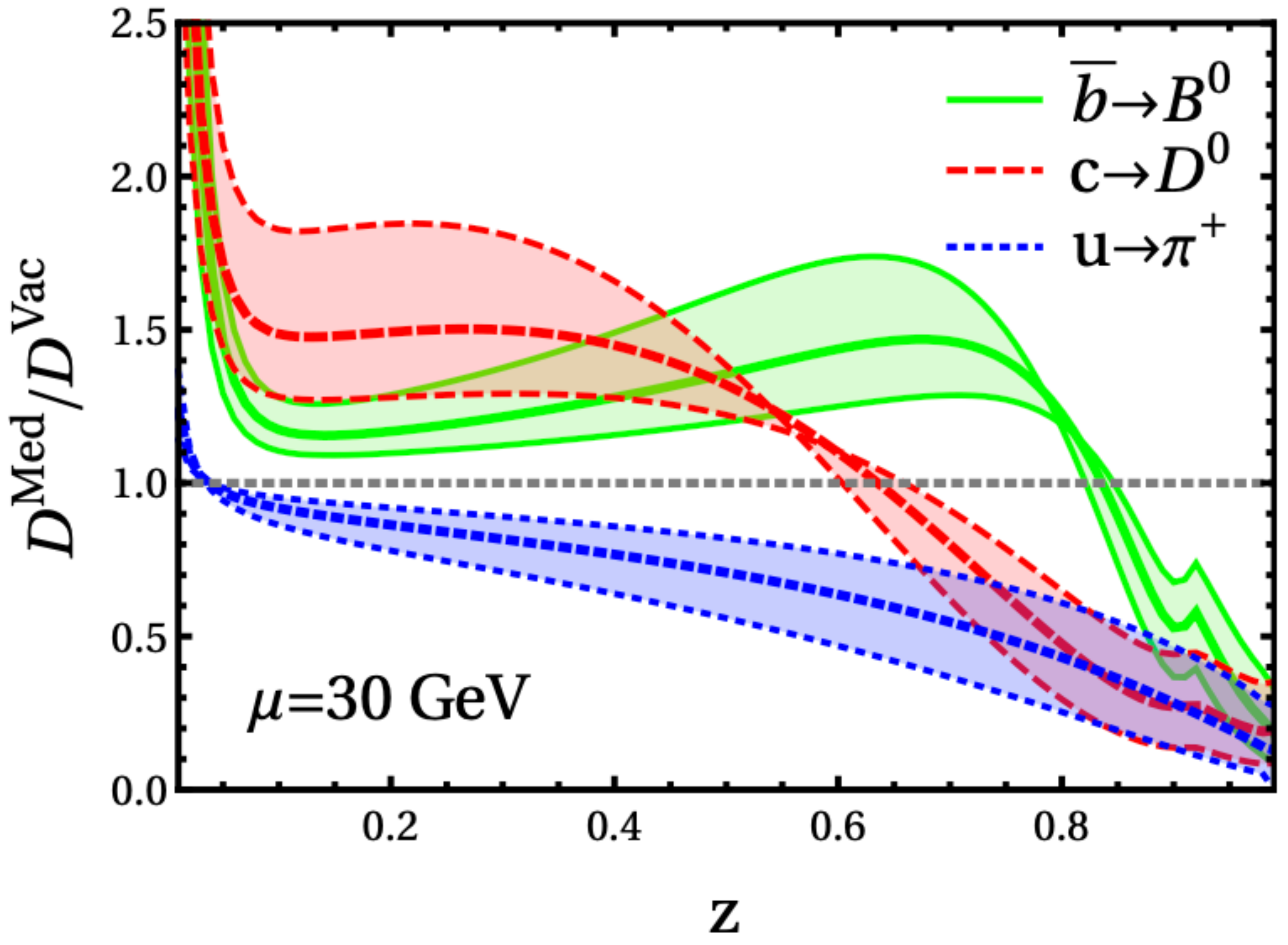
We used HKNS FF for pion and results from HQET for heavy flavors

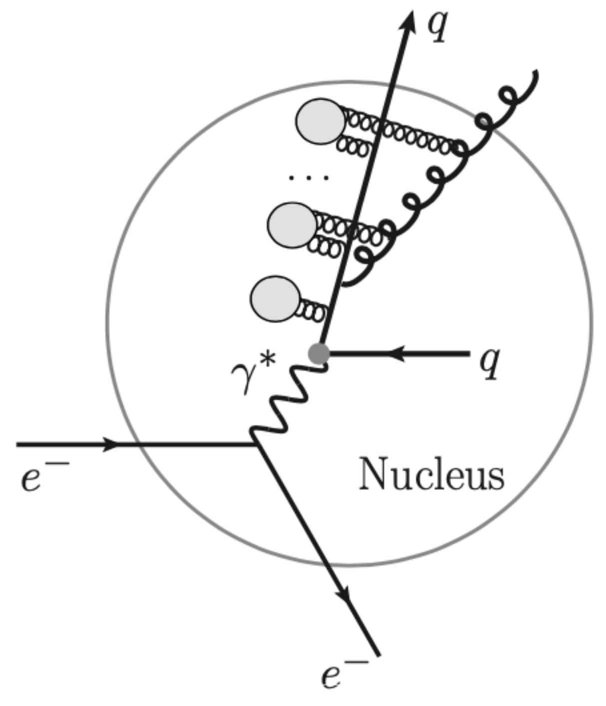
medium effects included by

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\rm med}(z,\mu)\right)$$



Hadron@EIC



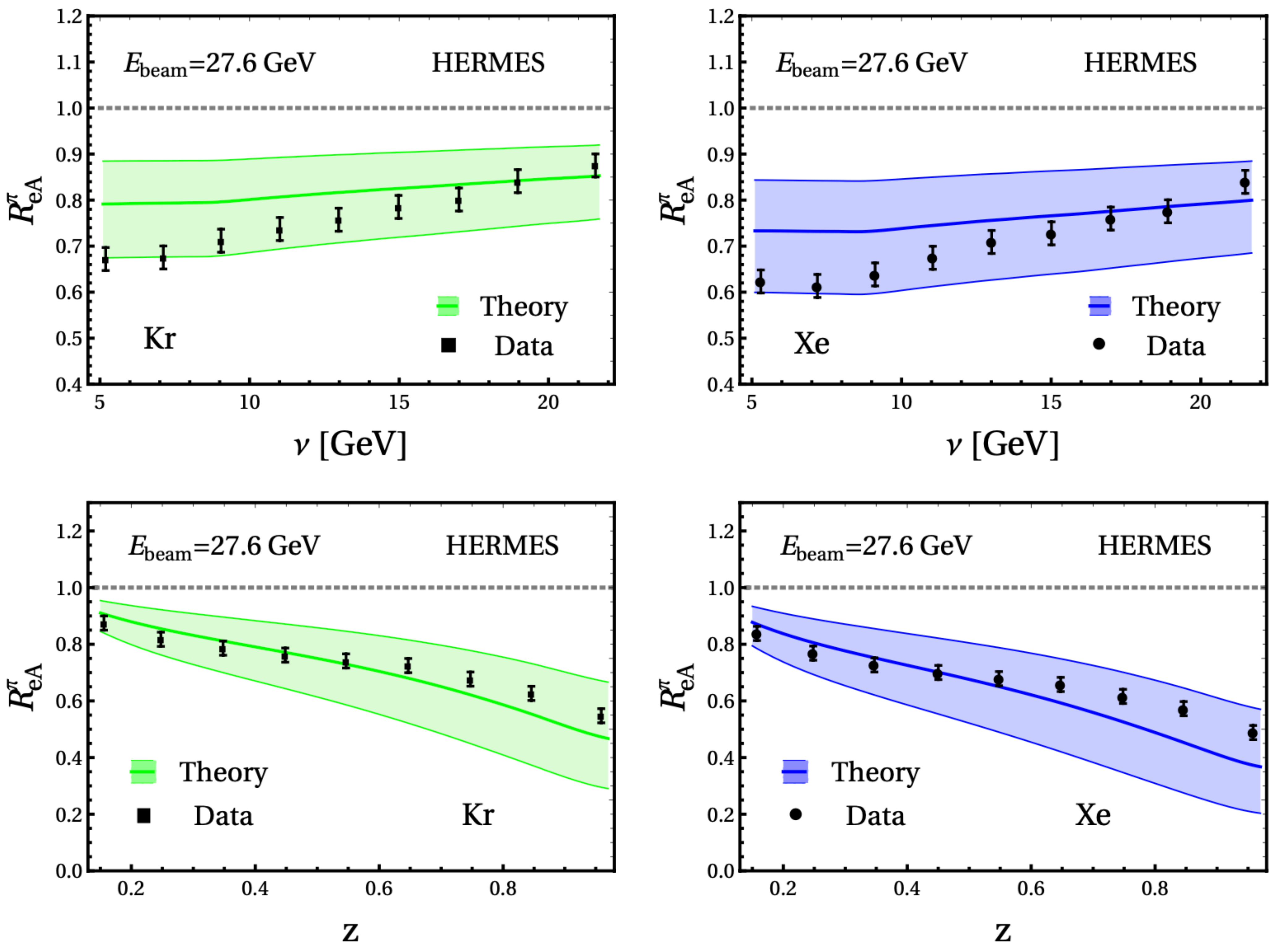


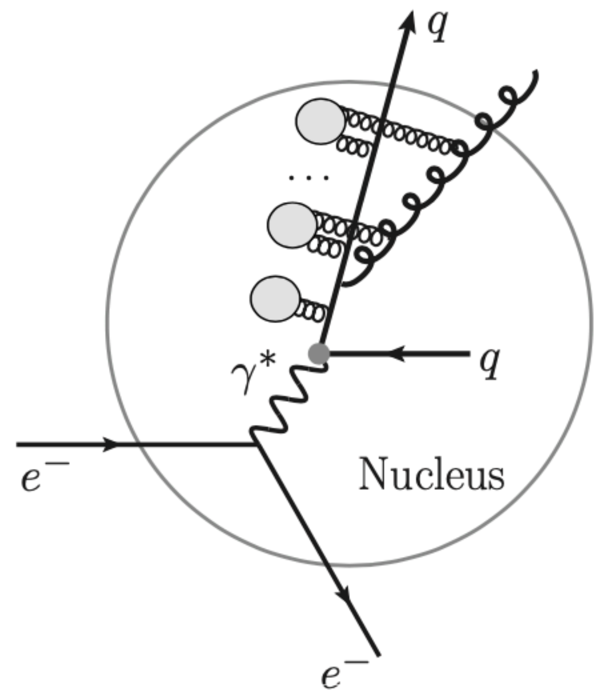
$\langle q_\perp \rangle/\lambda_q \approx \langle q_\perp \rangle/\lambda_g C_F/C_A = 0.05$ **GeV^2/fm**

Uncertainties by varying transport parameter

HTL, Liu, Vitev, arXiv:2007.10994

Hadron@EIC





Compare our calculations with HERMES measurements

HTL, Liu, Vitev, arXiv:2007.10994

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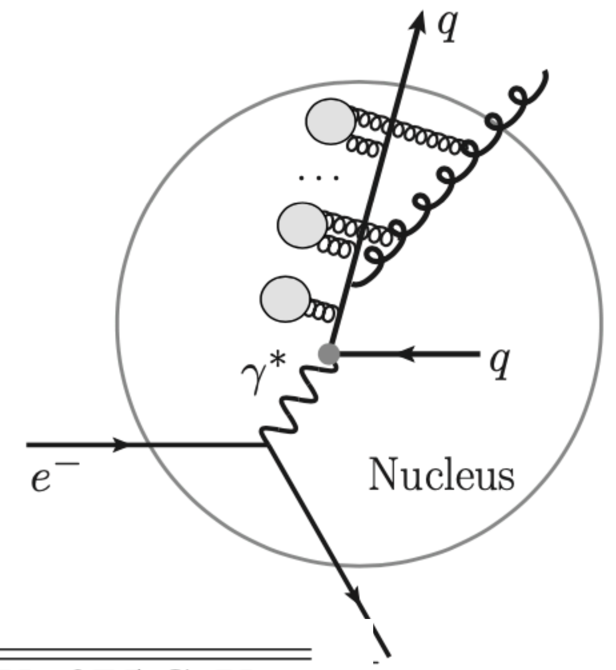
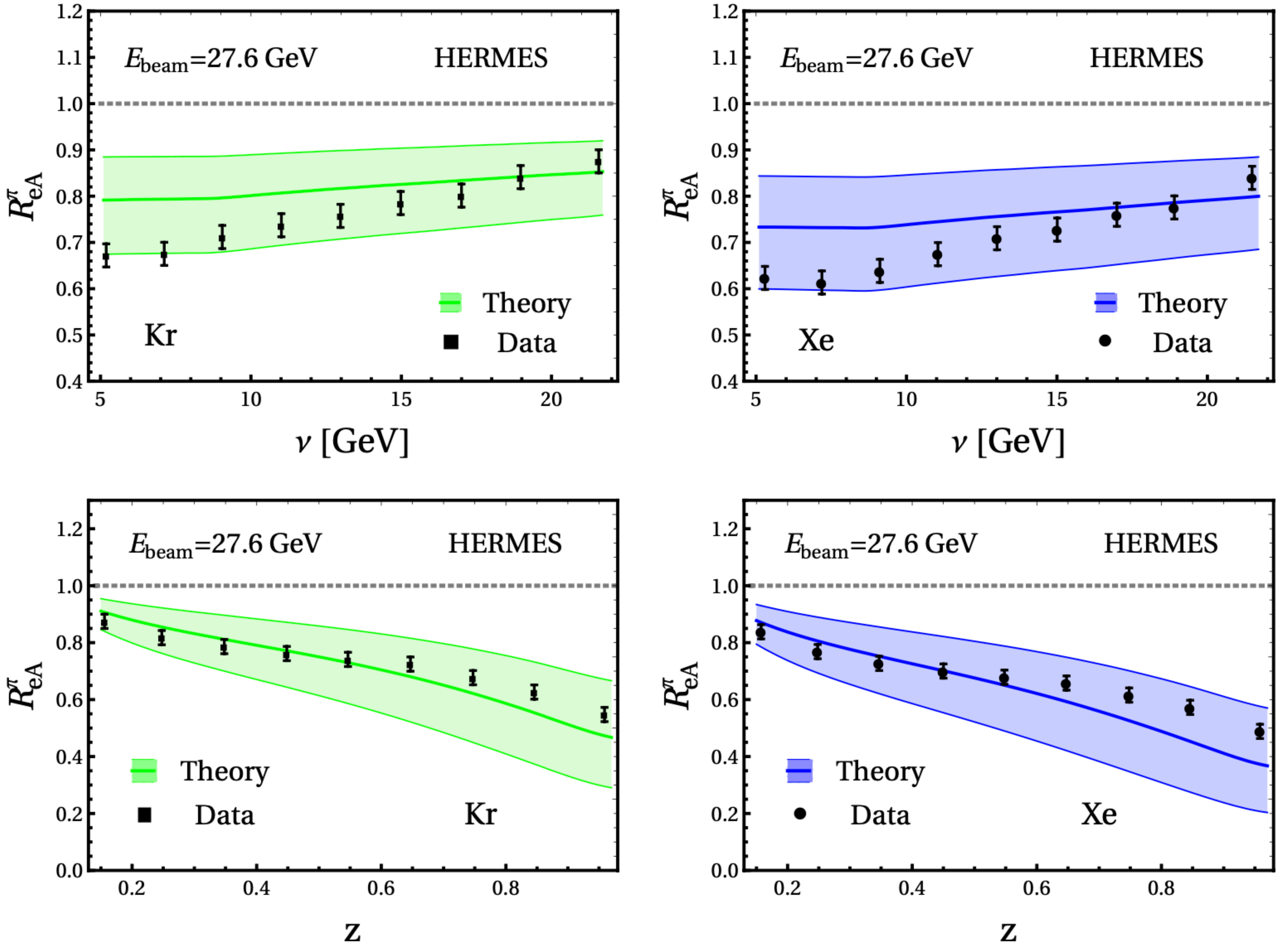


Energy		5 GeV×40 GeV		10 GeV×100 GeV		18 GeV×275 GeV	
p_T^h [GeV]		[2,3]	[5,6]	[2,3]	[5,6]	[2,3]	[5,6]
π^+	LO	5.3×10^6	2.4×10^4	1.4×10^7	3.0×10^5	2.9×10^7	9.6×10^5
	NLO	1.1×10^7	6.9×10^4	2.8×10^7	6.1×10^5	5.6×10^7	1.9×10^6
D^0	LO	1.4×10^6	3.2×10^3	8.6×10^6	9.0×10^4	3.1×10^7	6.6×10^5
	NLO	3.7×10^6	8.5×10^3	2.1×10^7	2.1×10^5	7.2×10^7	1.5×10^6
B^0	LO	3.7×10^5	1.2×10^3	2.4×10^6	2.8×10^4	9.0×10^6	2.0×10^5
	NLO	1.1×10^6	3.3×10^3	6.2×10^6	7.2×10^4	2.1×10^7	4.7×10^5

numbers of light, charm, and bottom hadron produced at the EIC with a typical one year integrated luminosity of 10 fb^{-1}



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HTL, Liu, Vitev, arXiv:2007.10994

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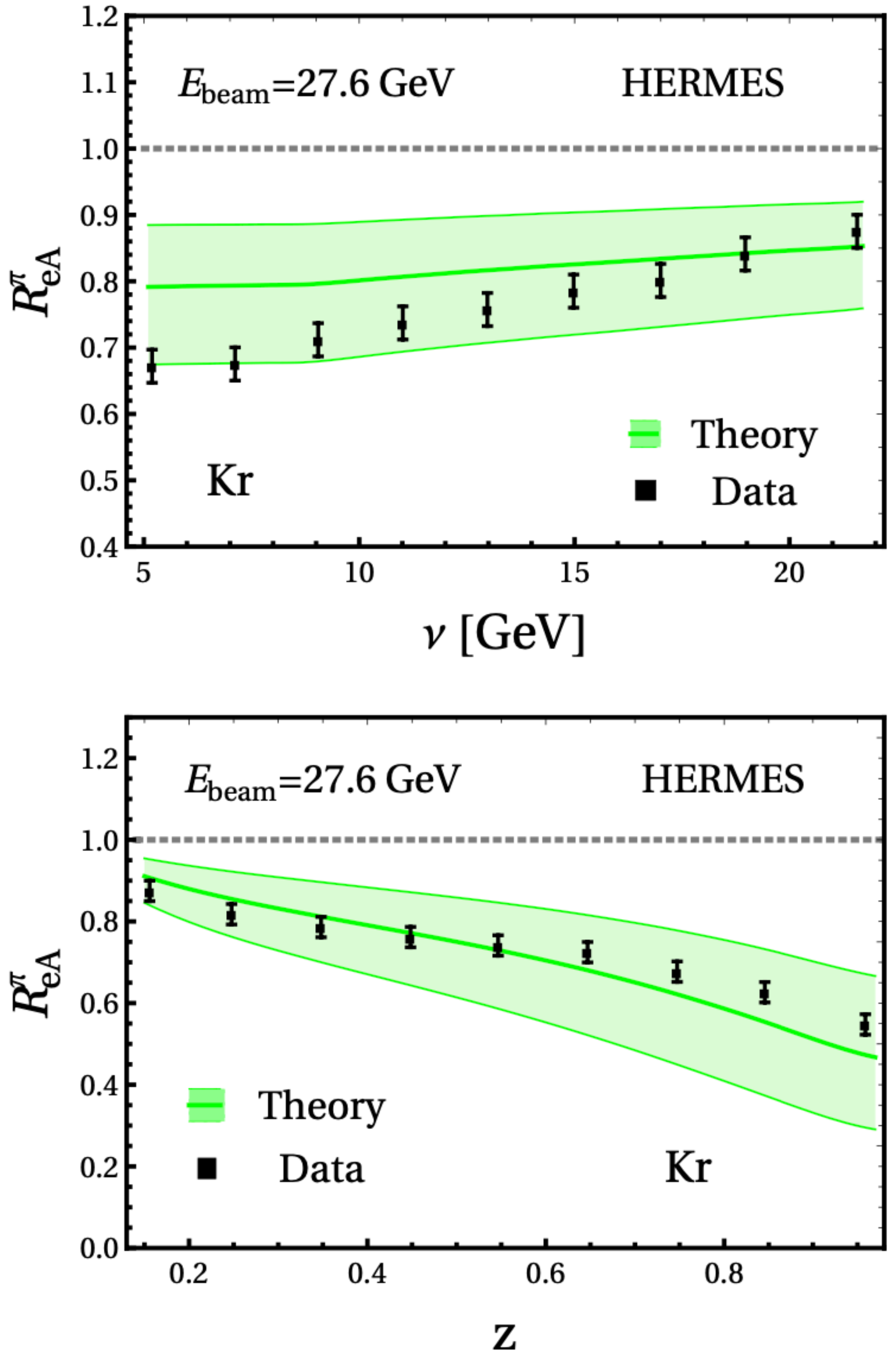

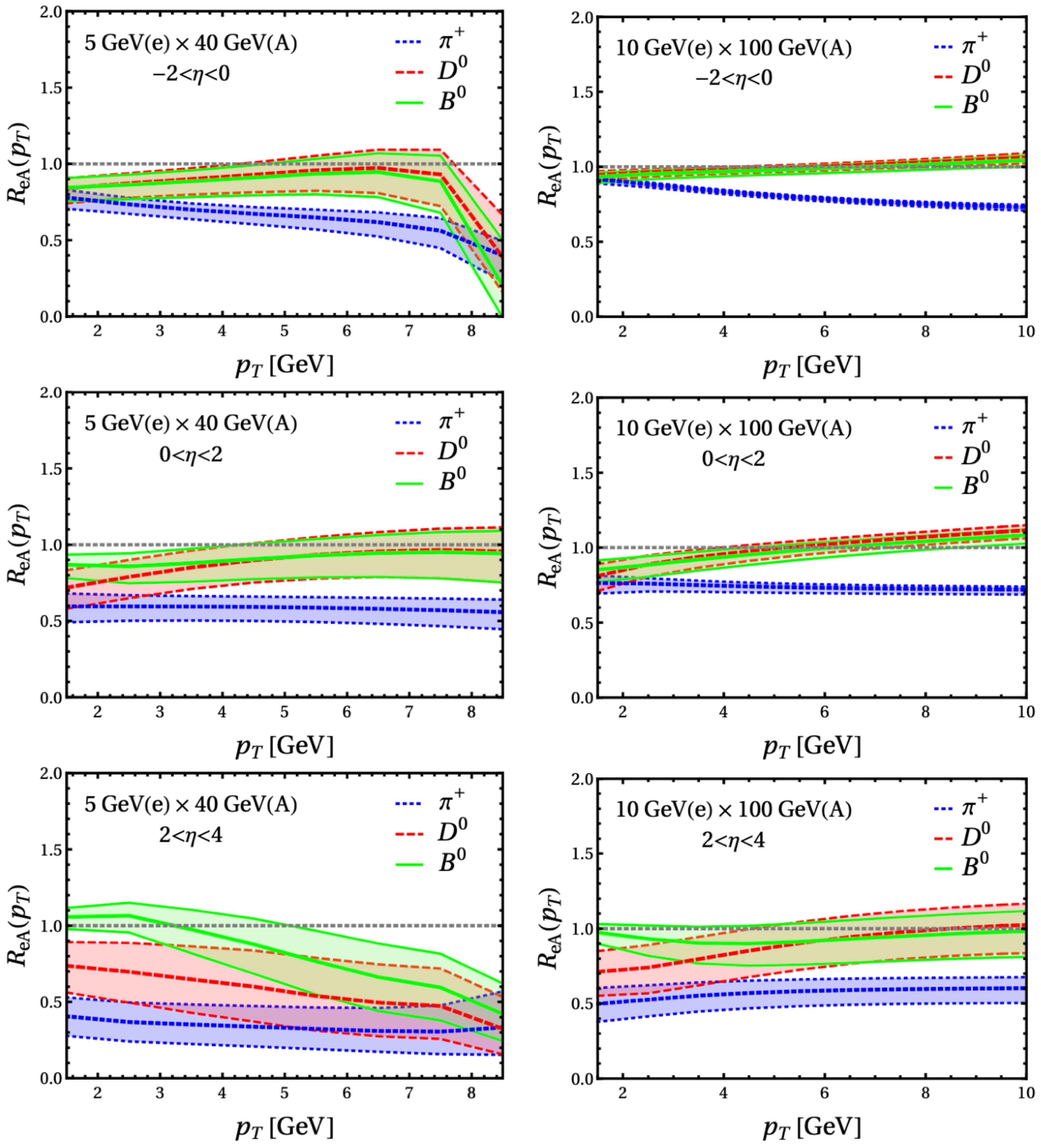

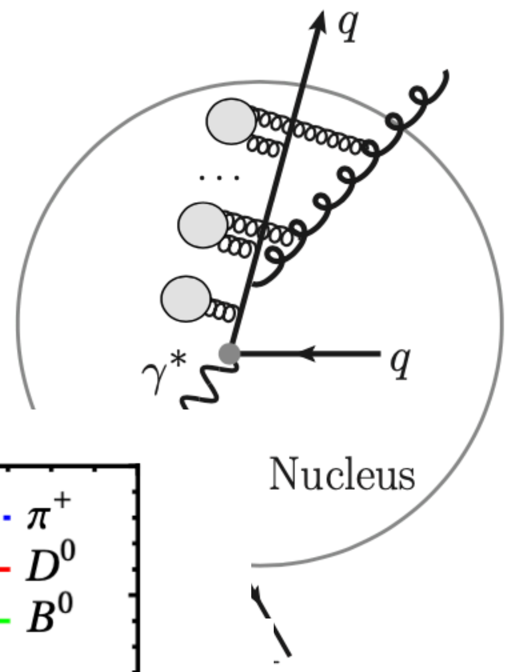

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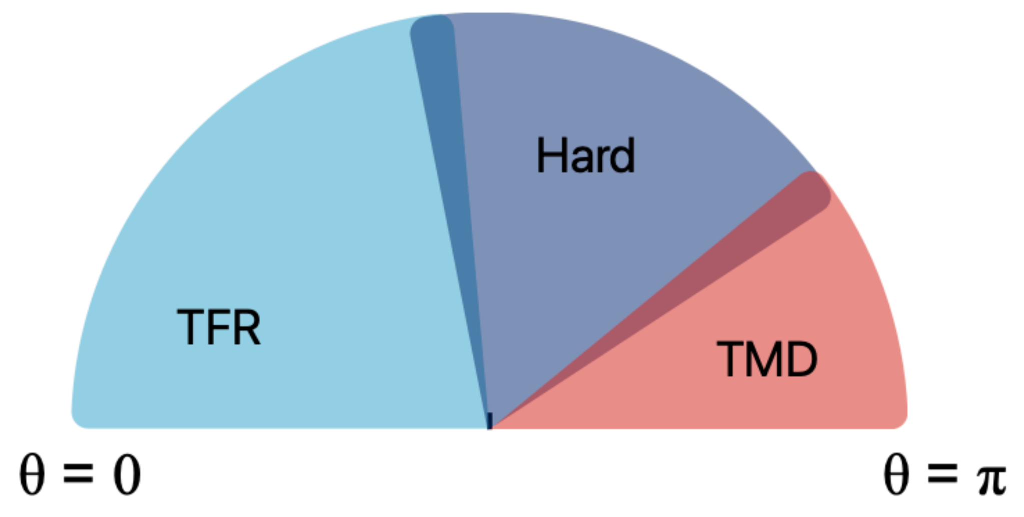
EEC@EIC

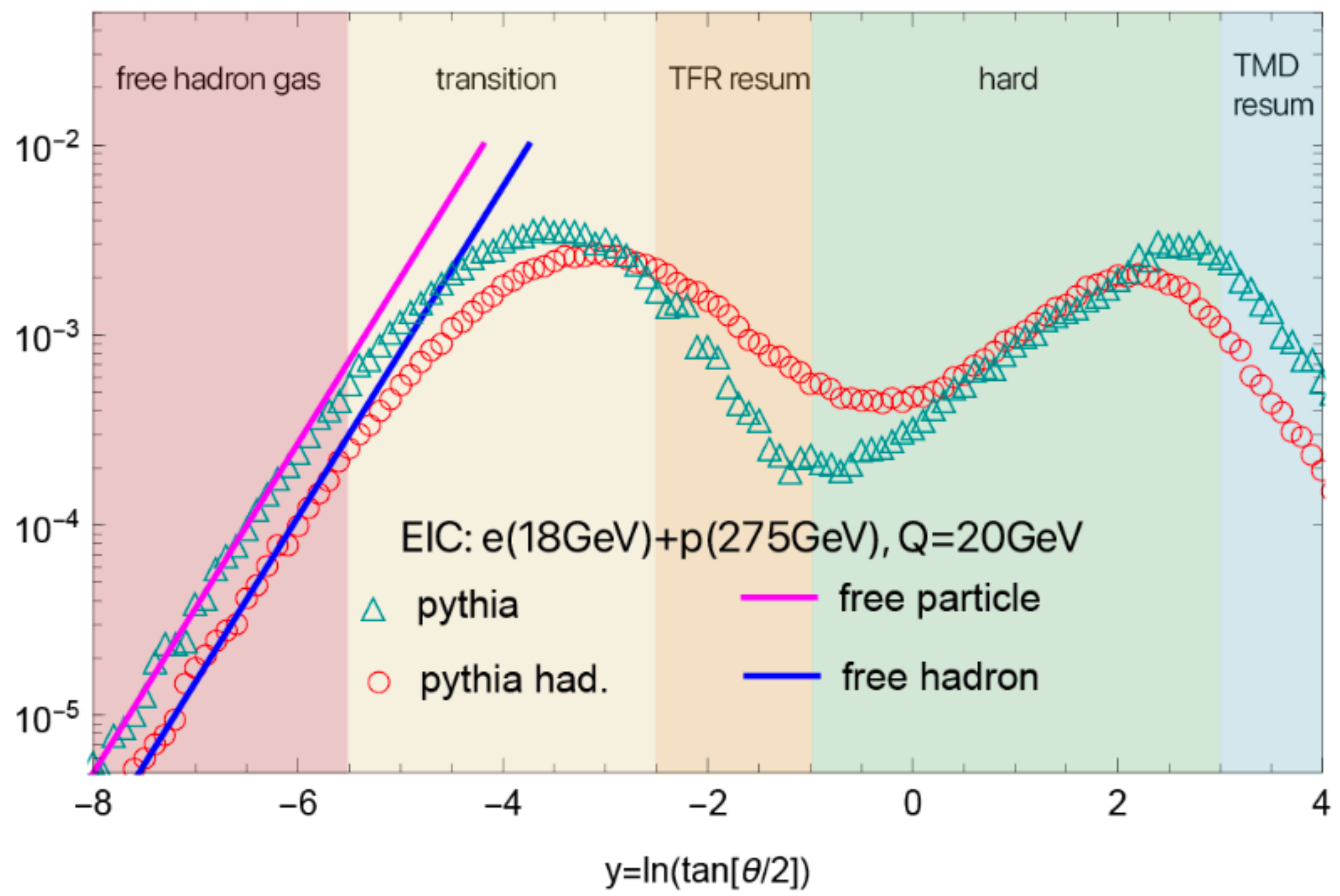
Nucleon Energy Correlators

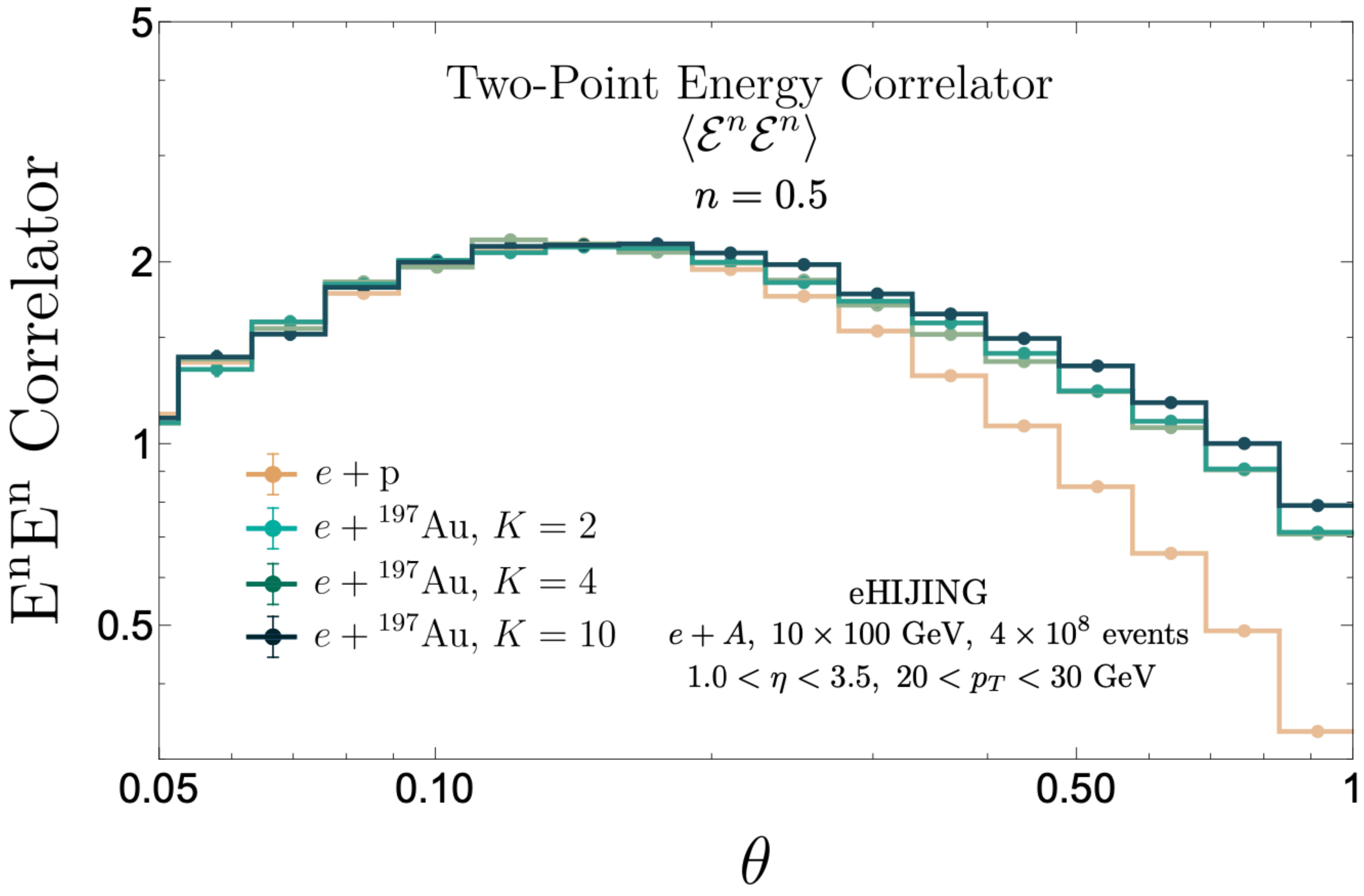
$$\Sigma_N(Q^2,\theta^2) = \sum_i \int d\sigma(x_B,Q^2,p_i)\, x_B^{N-1}\frac{\bar{n}\cdot p_i}{P}\,\delta(\theta^2-\theta_i^2)$$

Liu, Zhu, arXiv:2209.02080

Cao, Liu, Zhu, arXiv:2303.01530







TFR: the correlation of the energy flows from the initial nucleon.

Hard: measures the perturbative behavior of QCD

TMD: measures perturbative and nonperturbative TMD physics

Devereaux, Fan, Ke, Lee, Moult, arXiv: 2303.08143

Fu, Muller, Sirimanna, arXiv: 2411.04866

Andres, Dominguez,Holguin,Marquet, Moult, arXiv:2411.15298

HTL, Vitev, Zhu, arXiv:2006.02437

HTL, Makris, Vitev, arXiv: 2102.05669

Cao, HTL, Mi, arXiv:2312.07655

EEC@EIC

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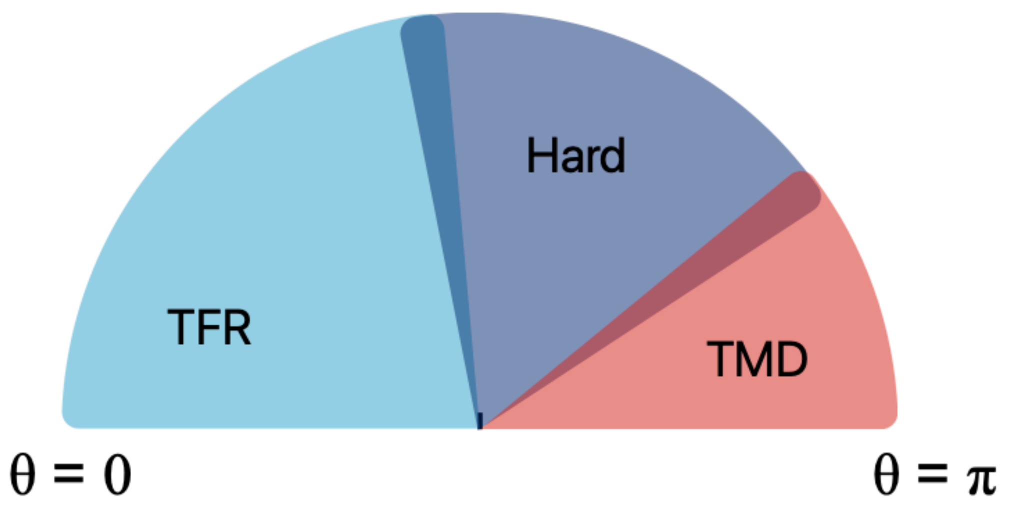

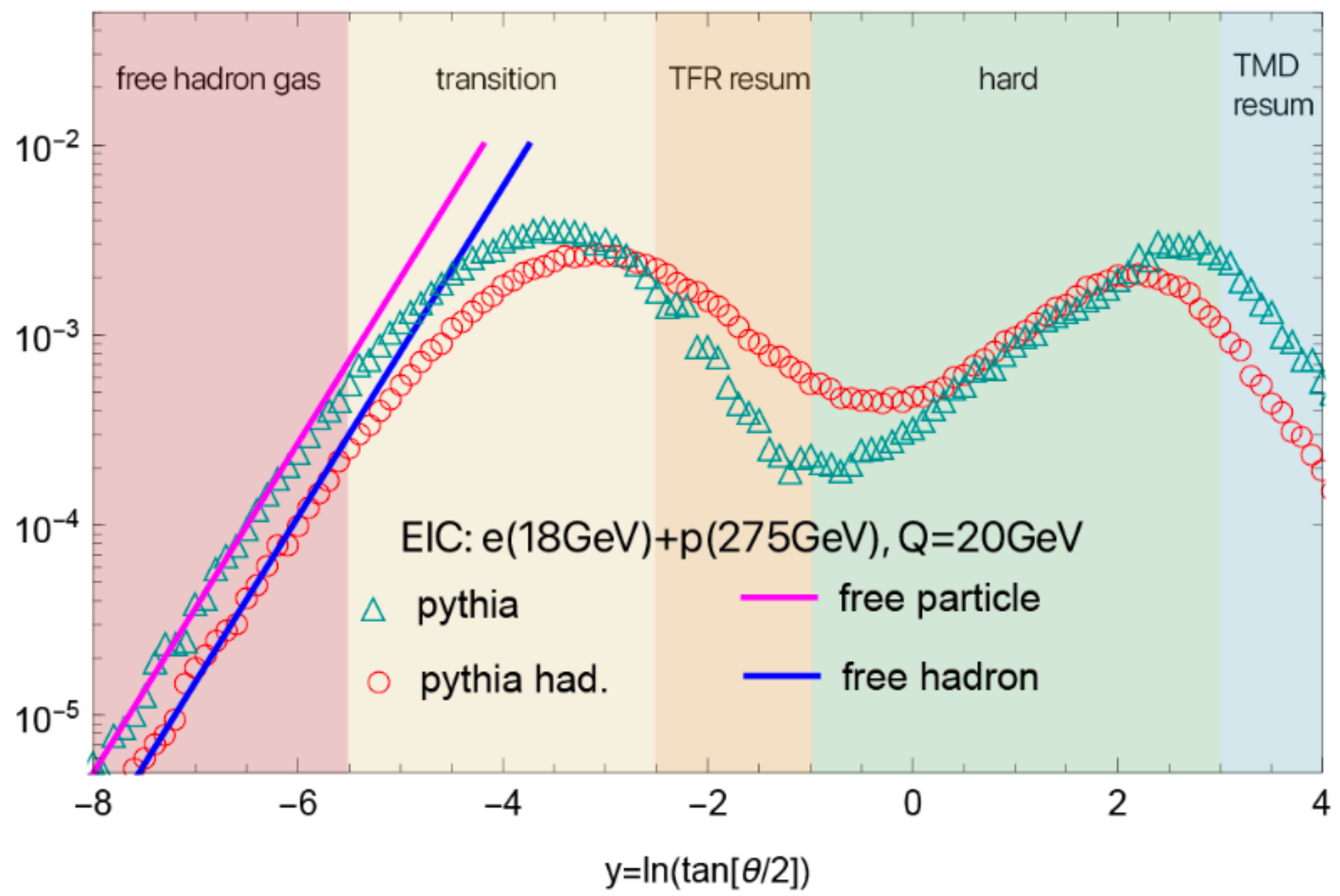

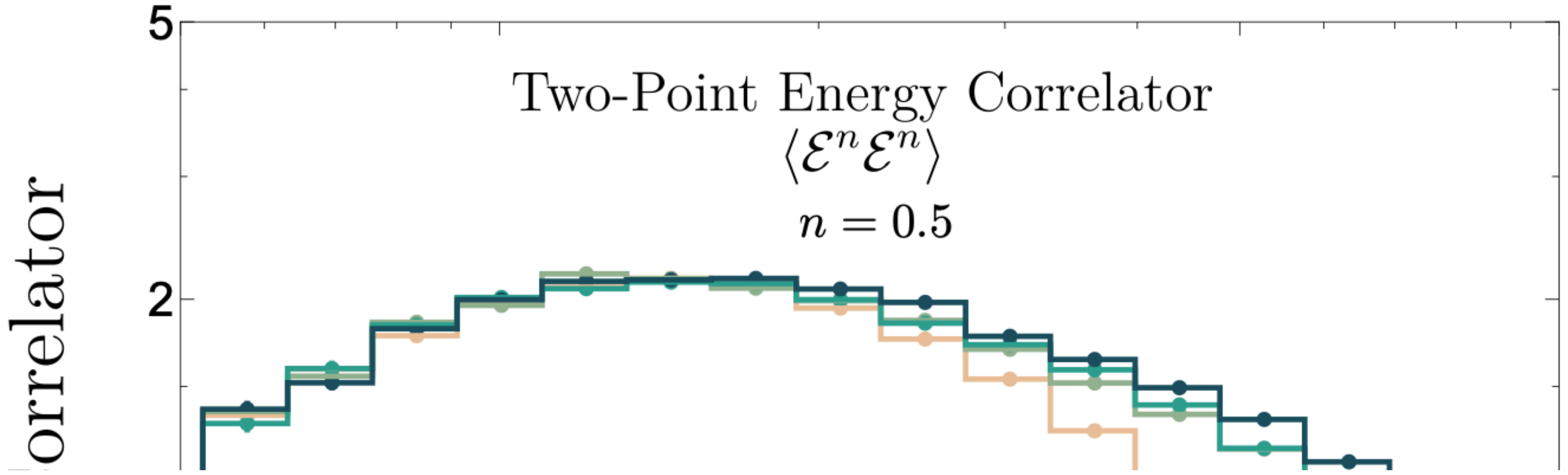

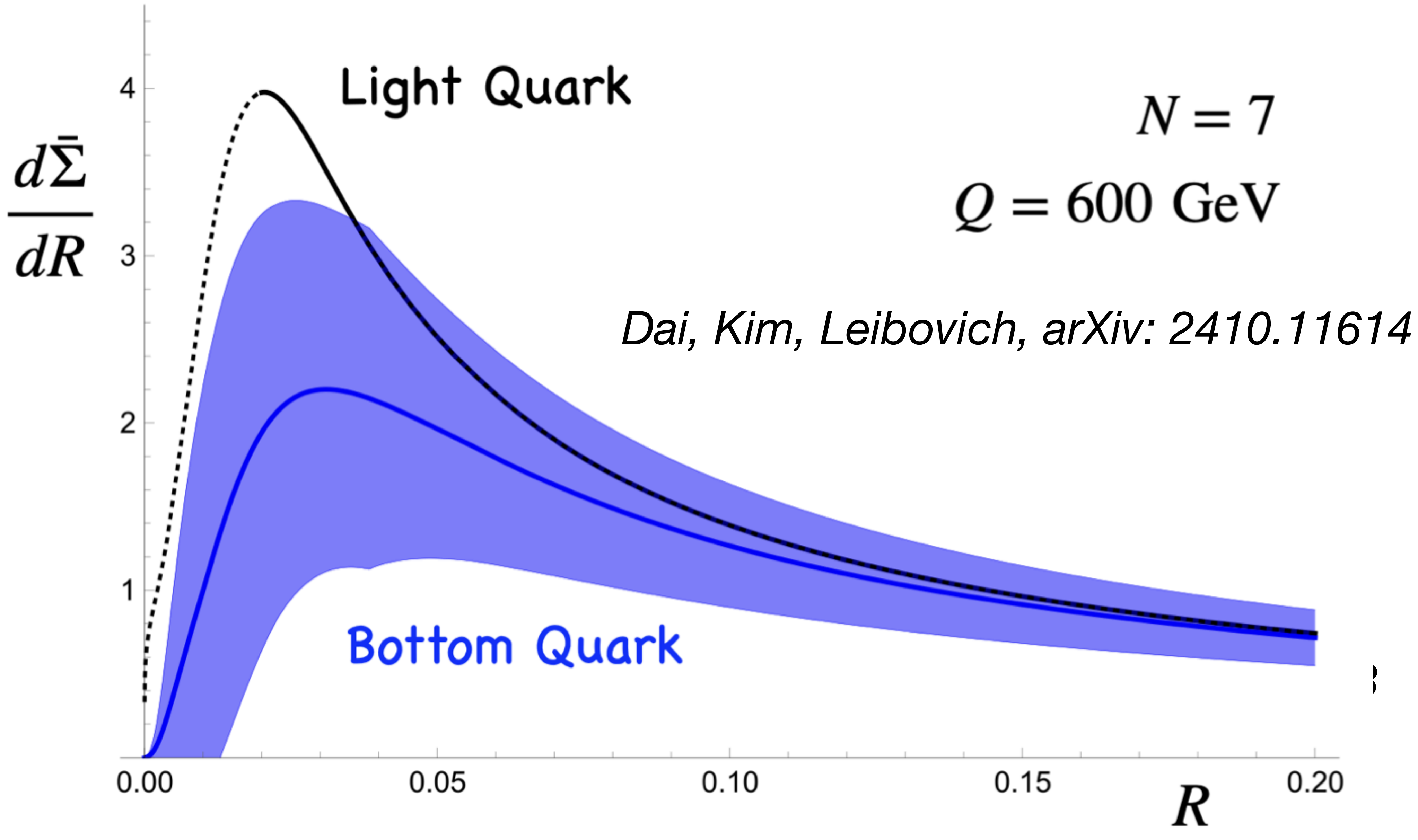

Dai, Kim, Leibovich, arXiv: 2410.11614

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HTL, Vitev, Zhu, arXiv:2006.02437

HTL, Makris, Vitev, arXiv: 2102.05669

Cao, HTL, Mi, arXiv:2312.07655

Conclusion

- ❑ Investigated nuclear matter corrections to light and heavy flavor jet production at EIC
- ❑ Presented the method to separate the initial and final state effects
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Thank you!