Cold Nuclear Matter Effect at EIC

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第一届中国电子离子对撞机相关物理年会

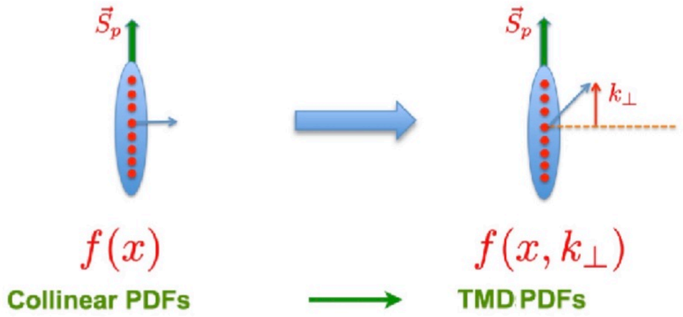
4月19-22日，青岛

Electron-Proton Collisions

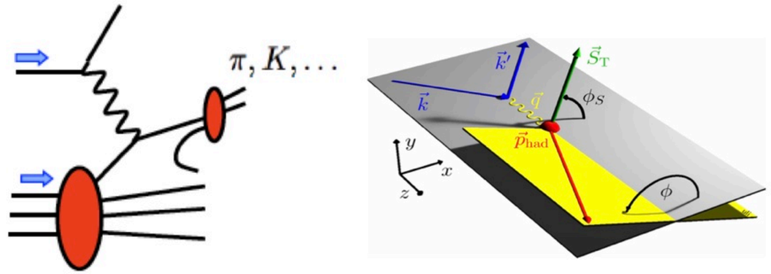
Nucleon tomography and SIDIS

- Semi-inclusive DIS (SIDIS) play an essential role in study of multi-dimensional structure of nucleon and dynamics of hadronization which rely on complementary information from additional hadrons or jets

Transverse momentum dependent PDFs

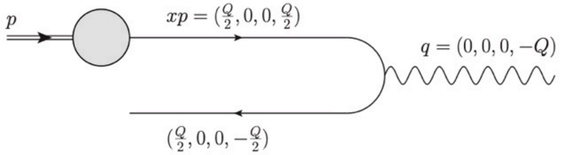


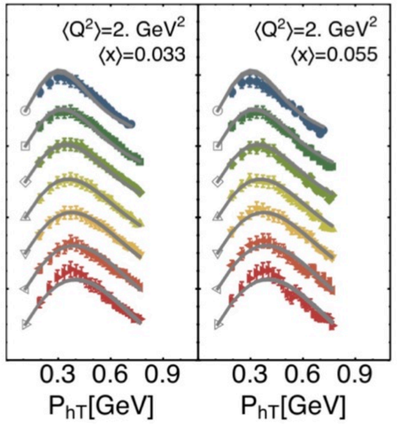
semi-inclusive DIS

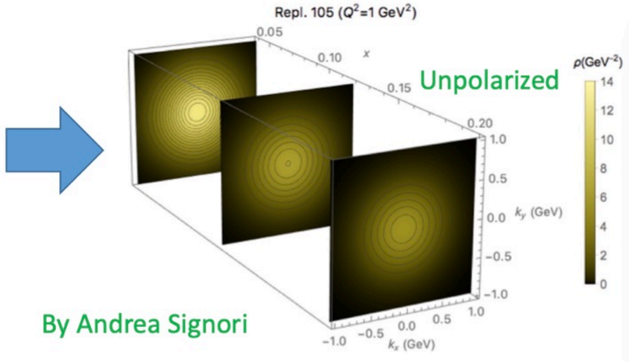


From Jun Gao's talk

- Transverse momentum of final state hadrons provide us the access to the initial parton's TMD PDFs; in addition tagged hadron also help with flavor separation of initial partons

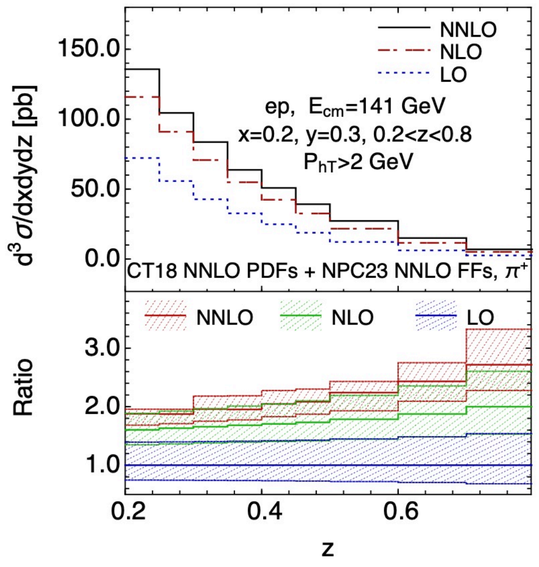


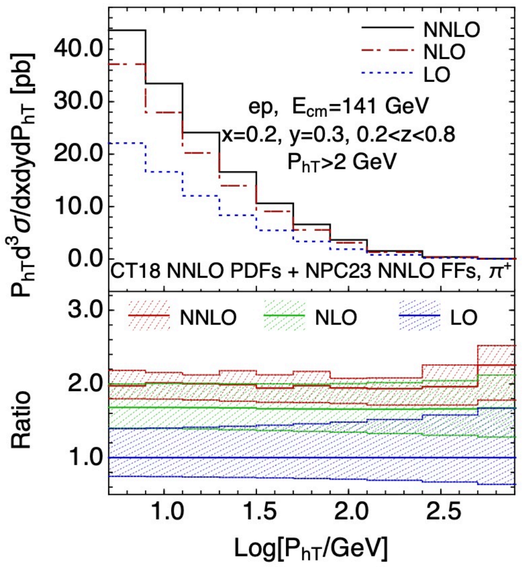




Electron-Proton Collisions

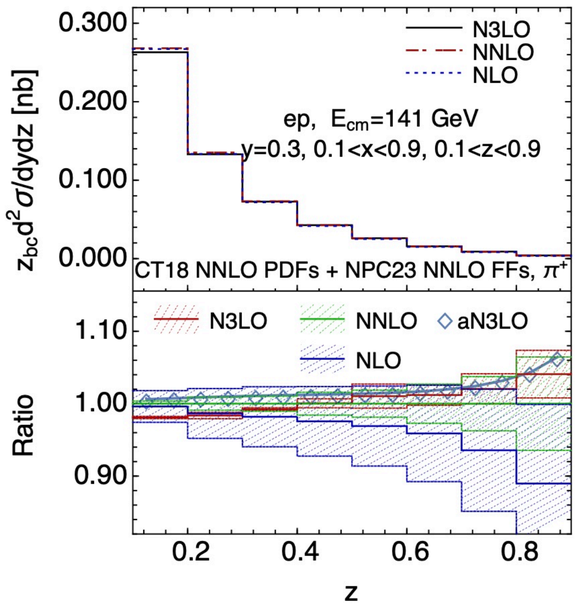
Identified hadron production is essential for the study of nucleon structure and QCD hadronization at high energies.





$$e + p \to e + j + \pi^+ \quad \text{@NNLO}$$

From Dingyu Shao's talk



$$e + p \to e + \pi^+ \quad \text{@NNNLO}$$

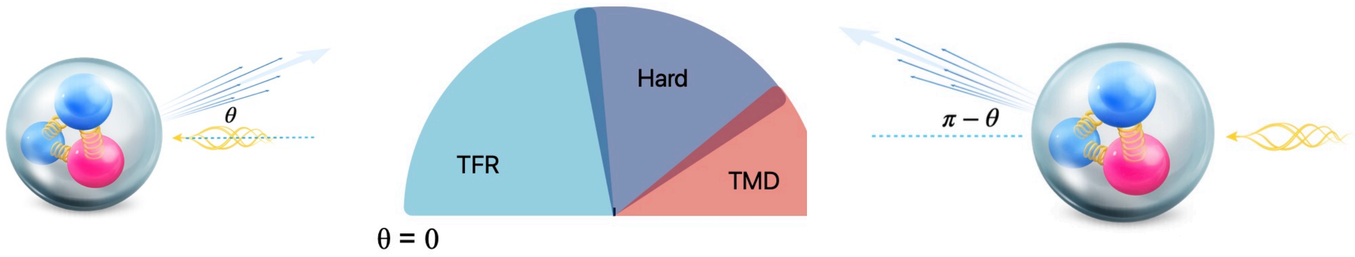
Dong, Fang, Gao, HTL, Shao, Zhu, Zhu, arXiv:2602.22972, 2603.29673

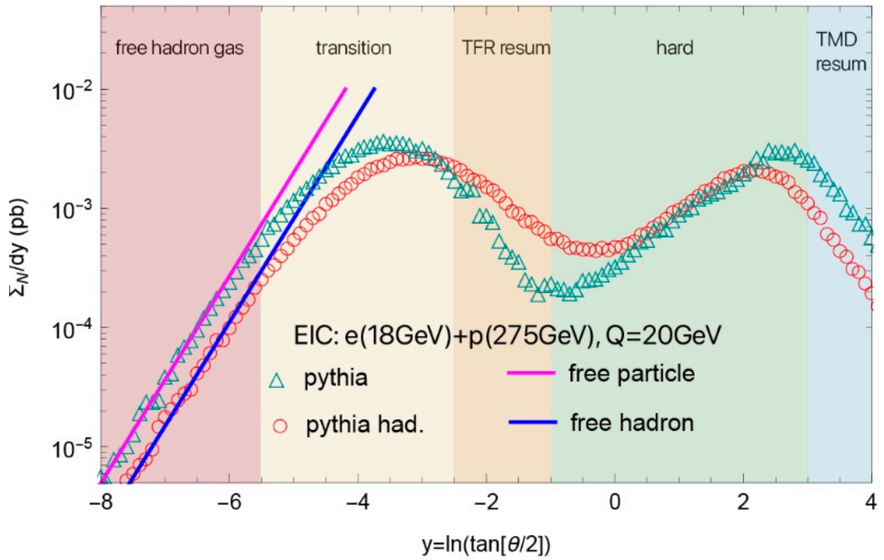
Electron-Proton Collisions

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

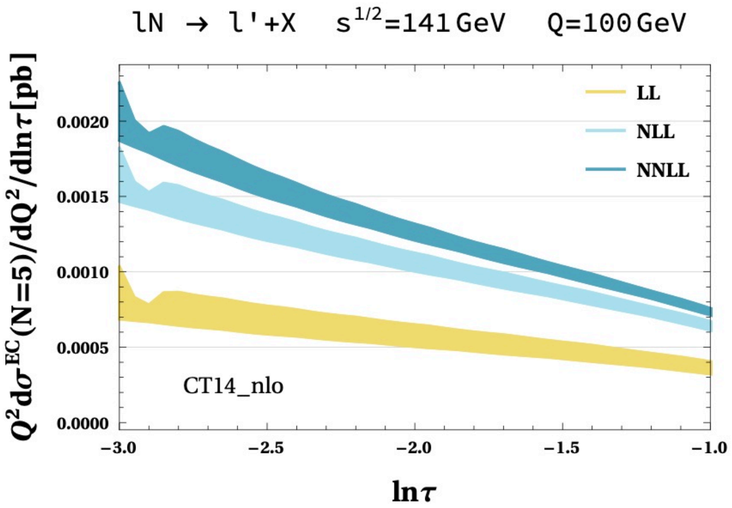
TMD: measures perturbative and nonperturbative TMD physics

HTL, Vitev, Zhu, arXiv:2006.02437

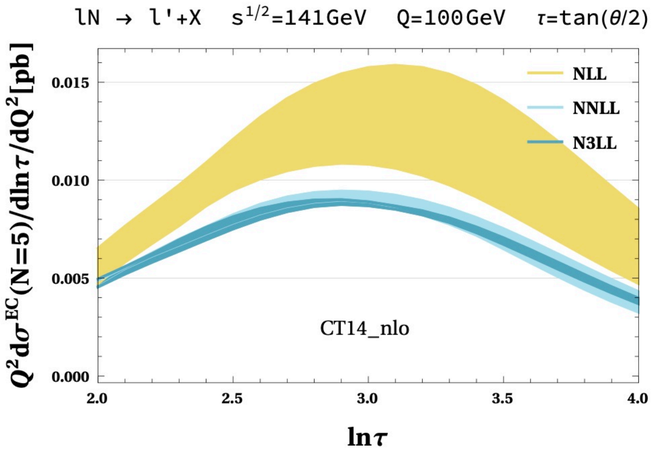
HTL, Makris, Vitev, arXiv: 2102.05669

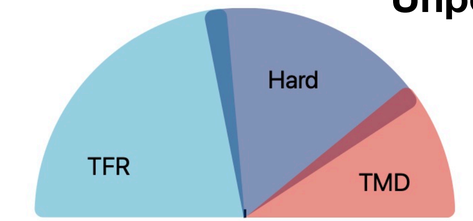
Cao, HTL, Mi, arXiv:2312.07655

Electron-Proton Collisions



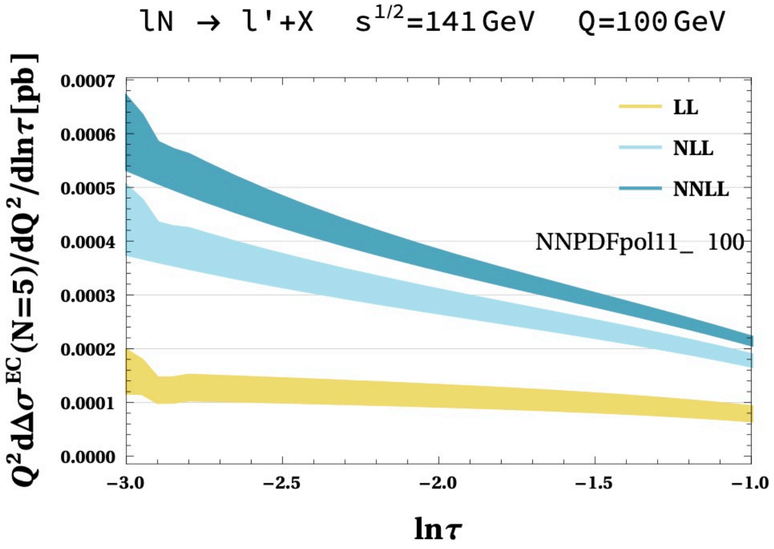
Target Region ⟷ Current Region

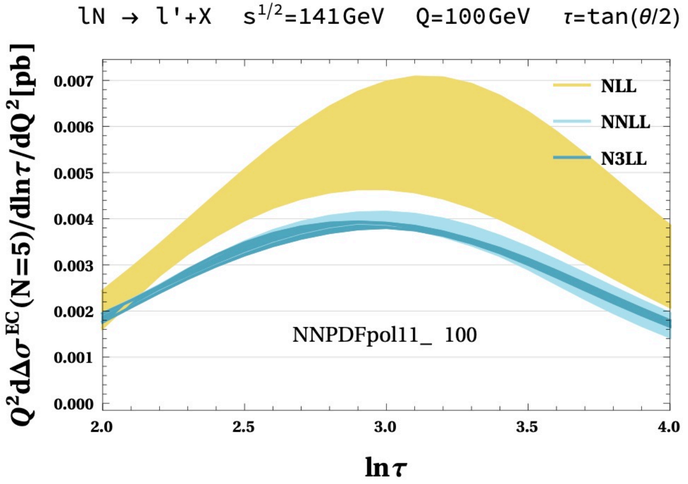




Unpolarized

longitudinal polarized



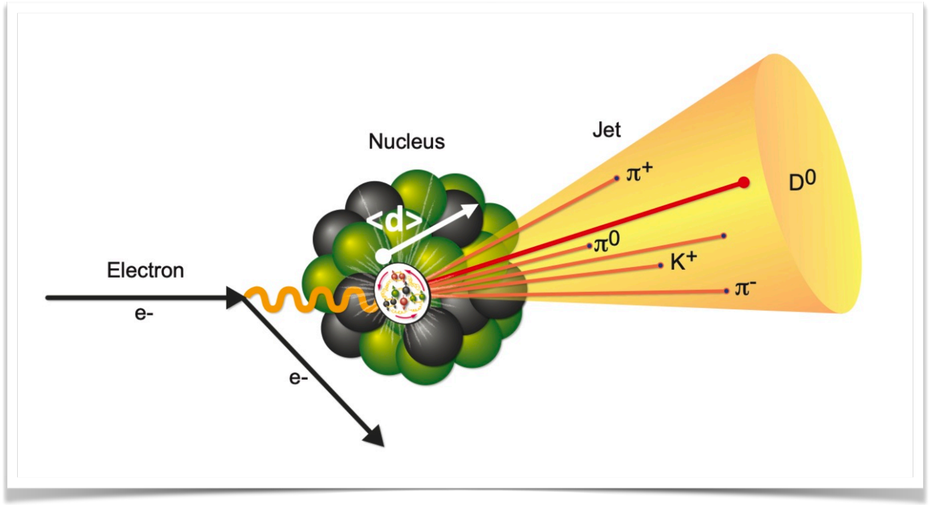


Gao, HTL, Zhu, arXiv:2509.17596

Electron-Ion Collisions

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
- .....



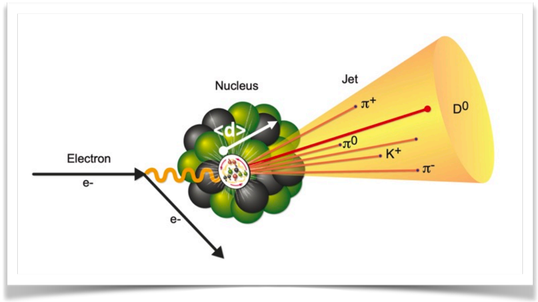
Jet or hadron p_T spectrum at an EIC

- 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**

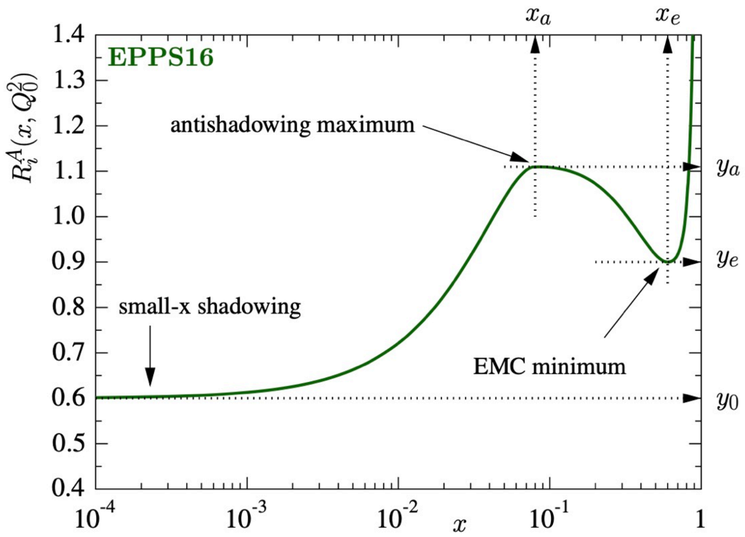
Electron-Ion Collisions



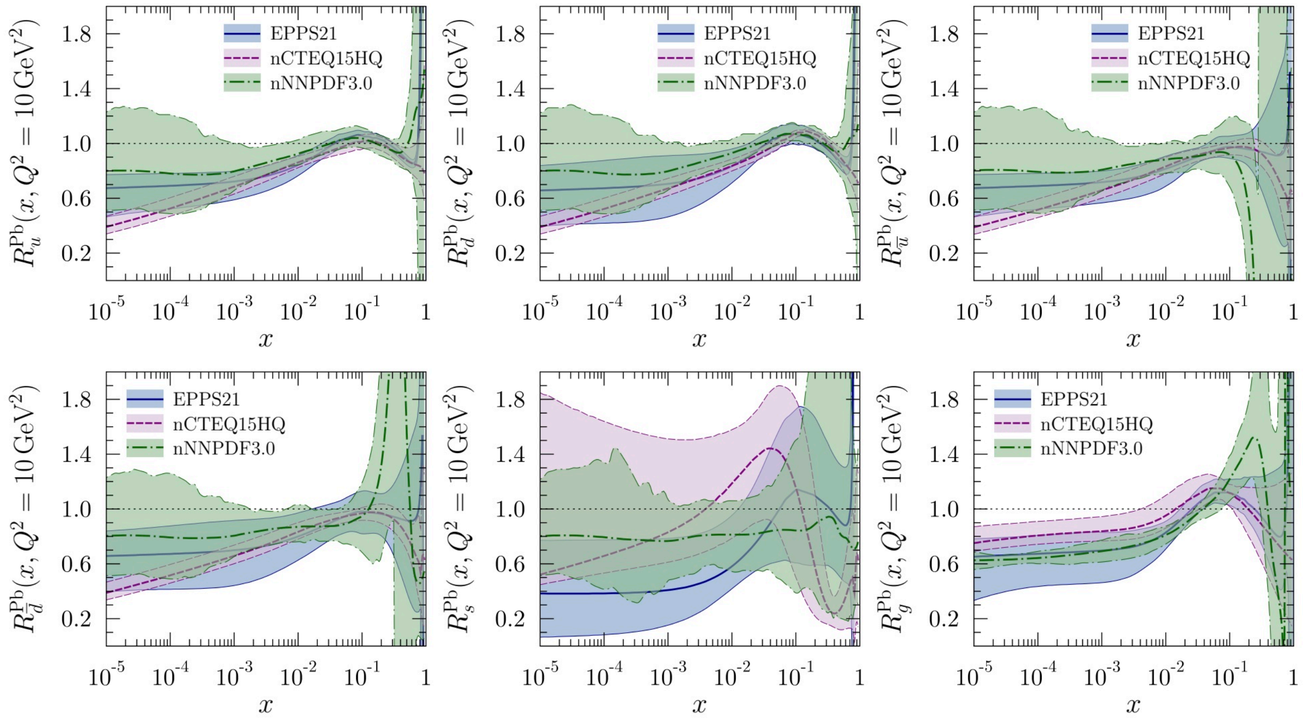
Difference between e+p and e+A collisions

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

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

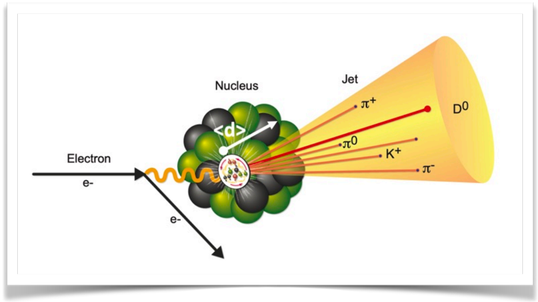


nCTEQ15, EPPS21, nNNPDF3.0, TUJU21, KSASG20 et al



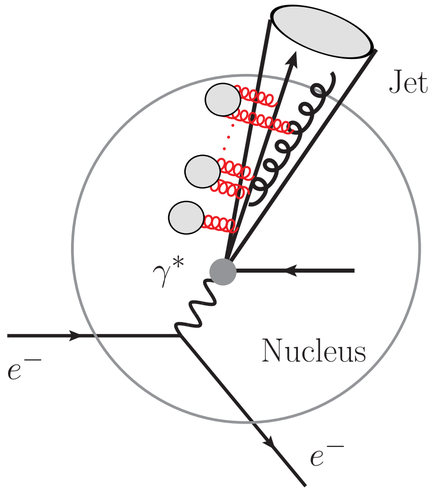
Klasen, Paukkunen, arXiv: 2311.00450

Electron-Ion Collisions



Difference between e+p and e+A collisions

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

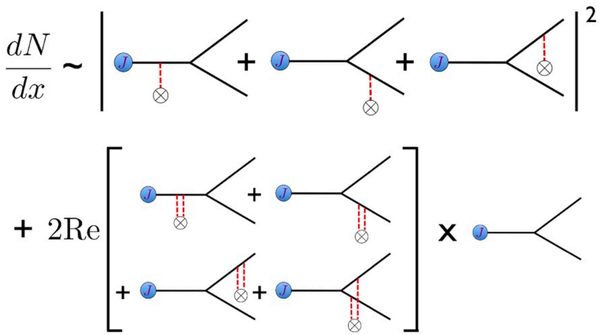


In-medium parton showers for parton propagating through medium

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$_G$

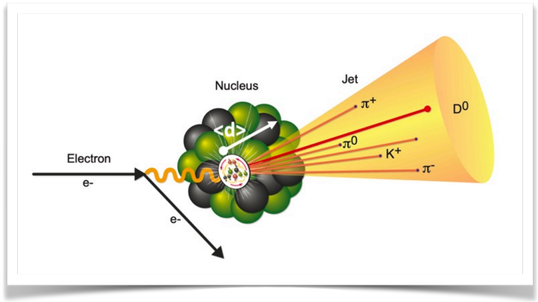
For example $q \to qg$ splitting function



See Weiyao's talk for in-medium evolution

Ovanesyan, Vites, arXiv: 1103.1074, 1109.5619

Electron-Ion Collisions



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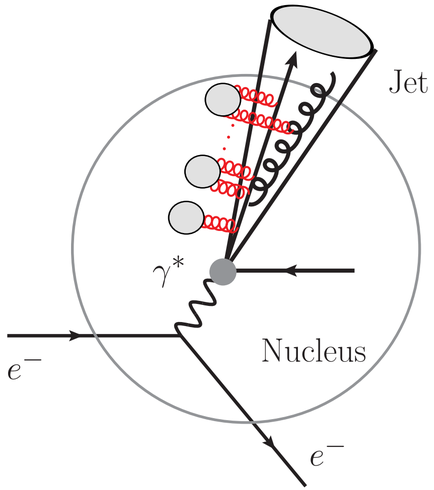

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$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}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

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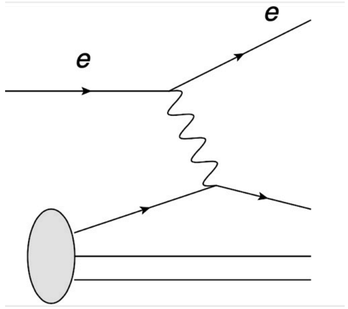
Electron-Ion Collisions

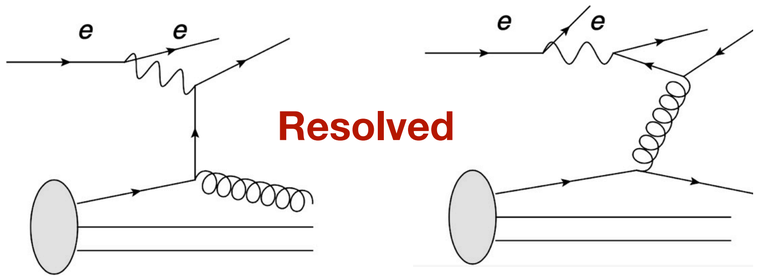
Jet Inclusive cross section

Comparison between NLO and factorized cross section



Large Q

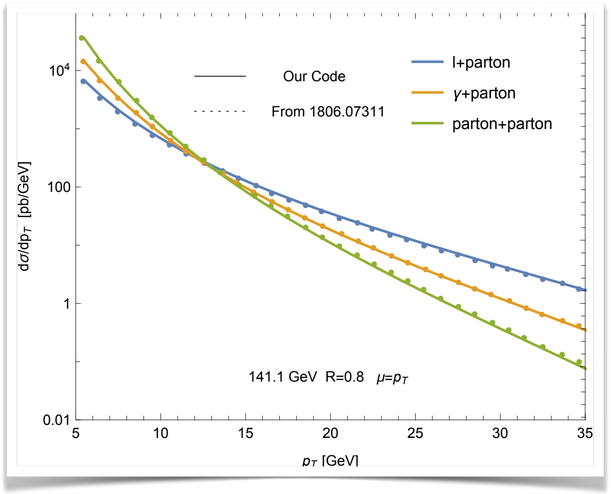
Weizsacker-Williams quasi real photon



Resolved

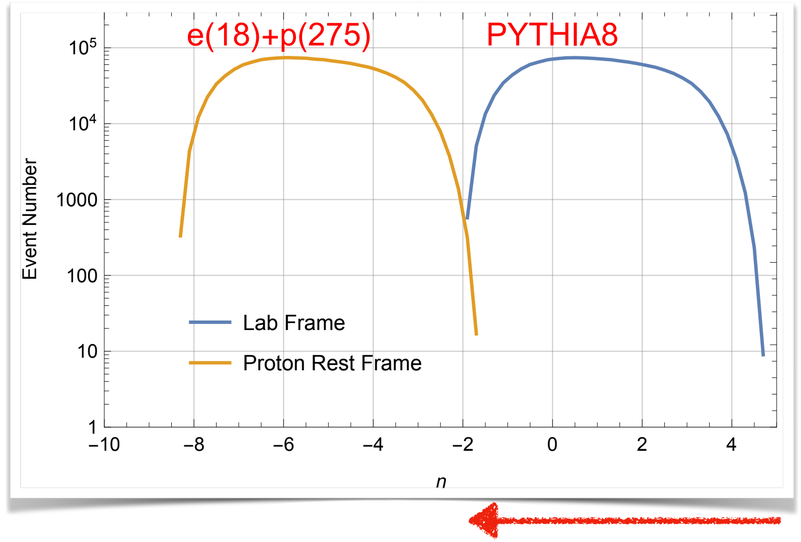
Small Q
Effective Photon PDF from lepton

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

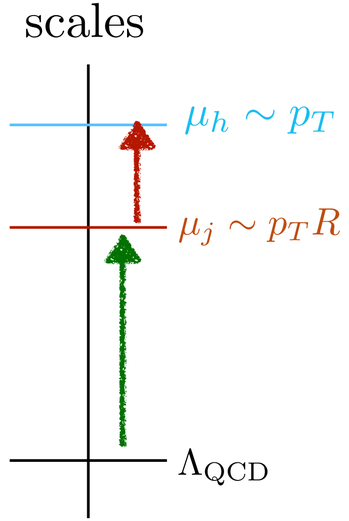
In-medium shower corrections vary with the parton energy in the nuclear rest frame, where the lower energy partons receive larger medium corrections.

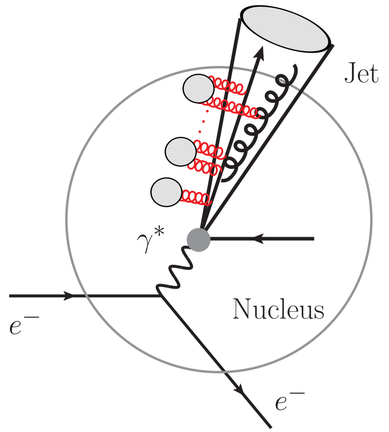
Electron-Ion Collisions

Jet Inclusive cross section

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

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

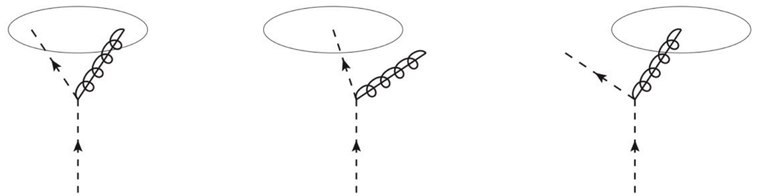




Hard part: arXiv:1505.06415

Light Jet Function: arXiv:1606.06732

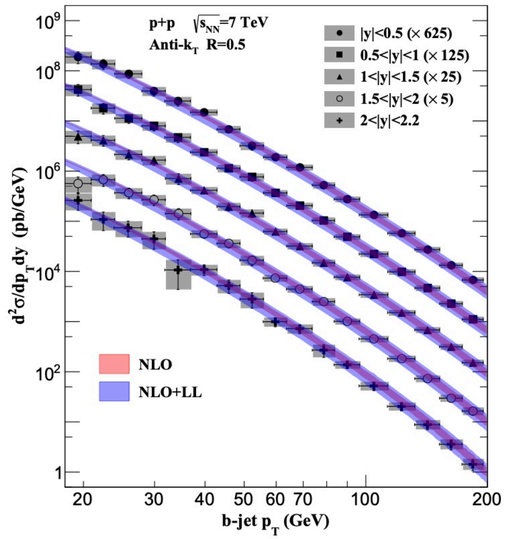
Heavy Flavor Jet Function: arXiv:1805.06014

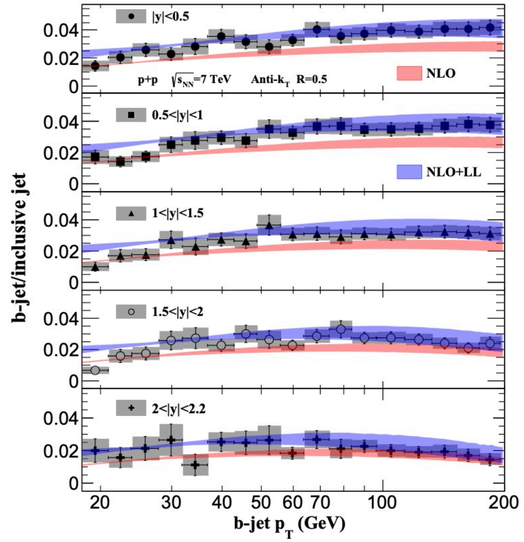


Contribution to the semi-inclusive quark jet function with the medium modified splitting function from SCET$_G$

Kang, Ringer, Vitev, arXiv:1701.05839

HTL, Vitev, arXiv:1811.07905





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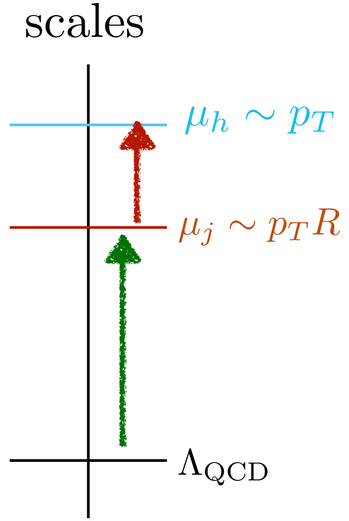

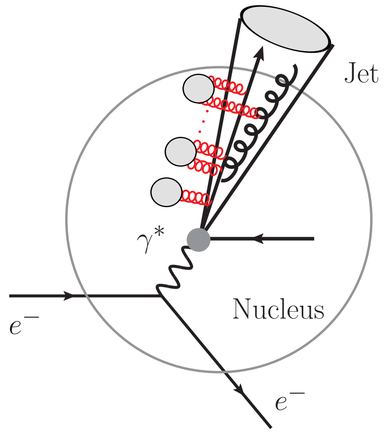

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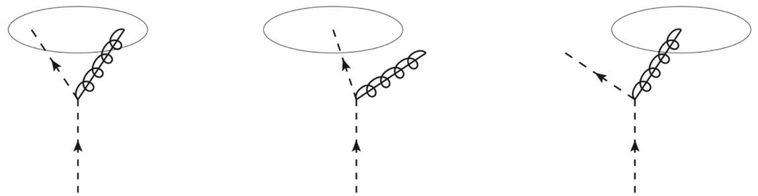

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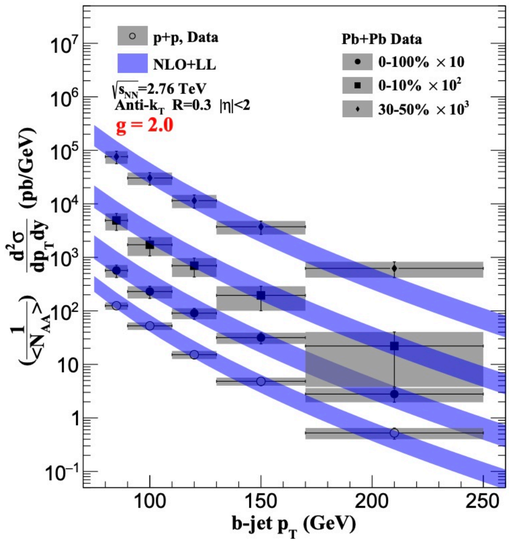
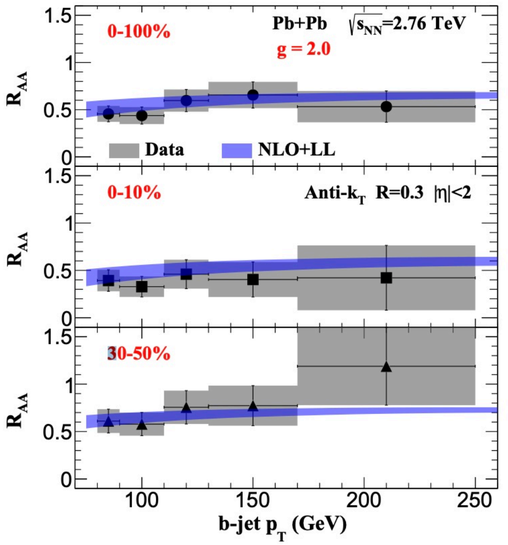




HTL, Vitev, arXiv:1811.07905

Electron-Ion Collisions

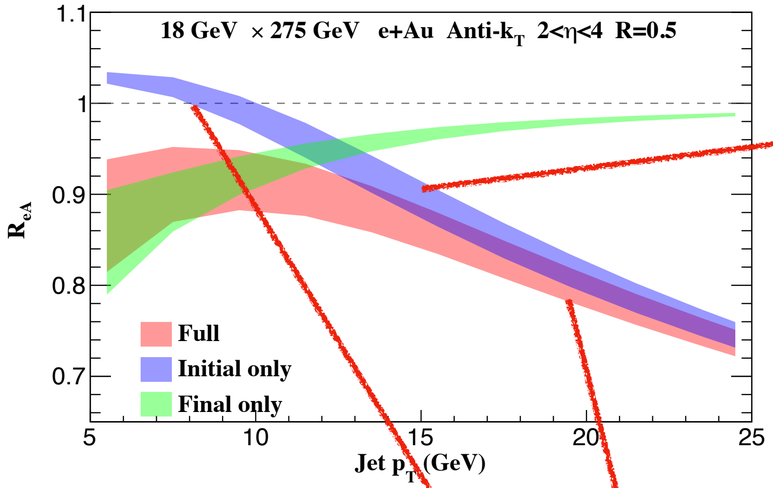
Jet Inclusive cross section

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

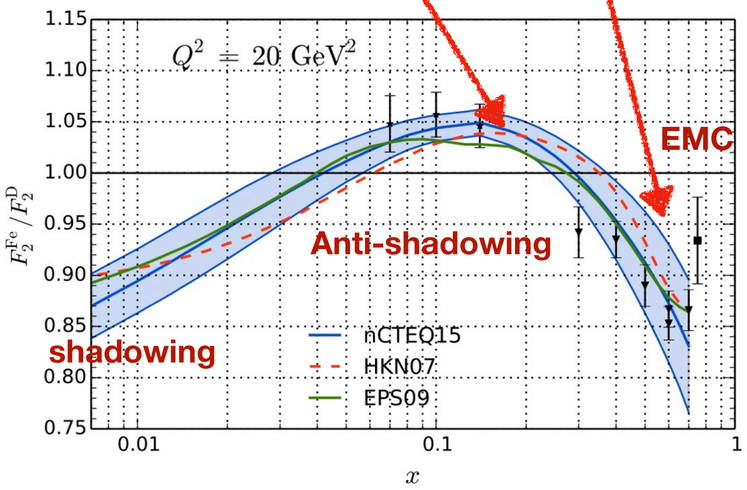
Modifications defined as

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

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



expect to be R dependent



Light jet, HTL, Vitev, arXiv:2010.05912

Electron-Ion Collisions

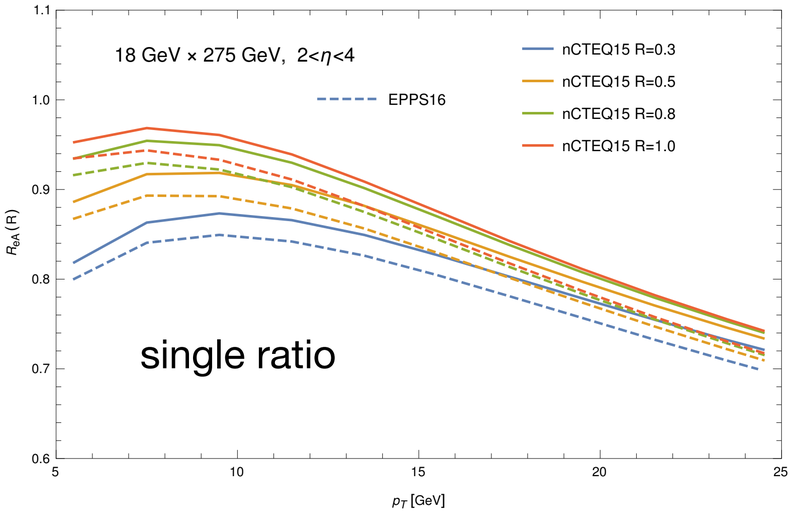
Jet Inclusive cross section

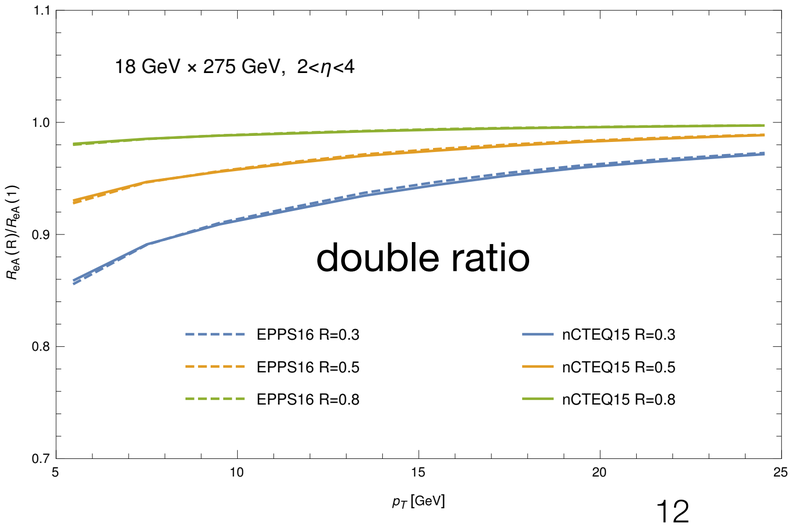
We proposed the double ratio

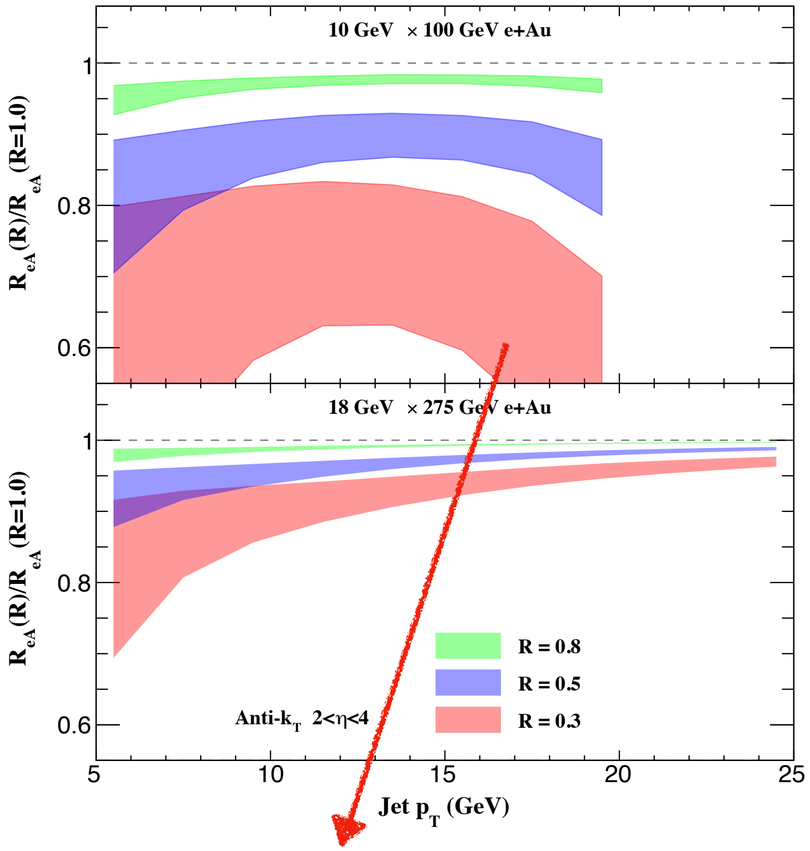
$$\frac{R_{\rm eA}(R)}{R_{\rm eA}(R=1)}$$

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

HTL, Vitev, arXiv:2010.05912





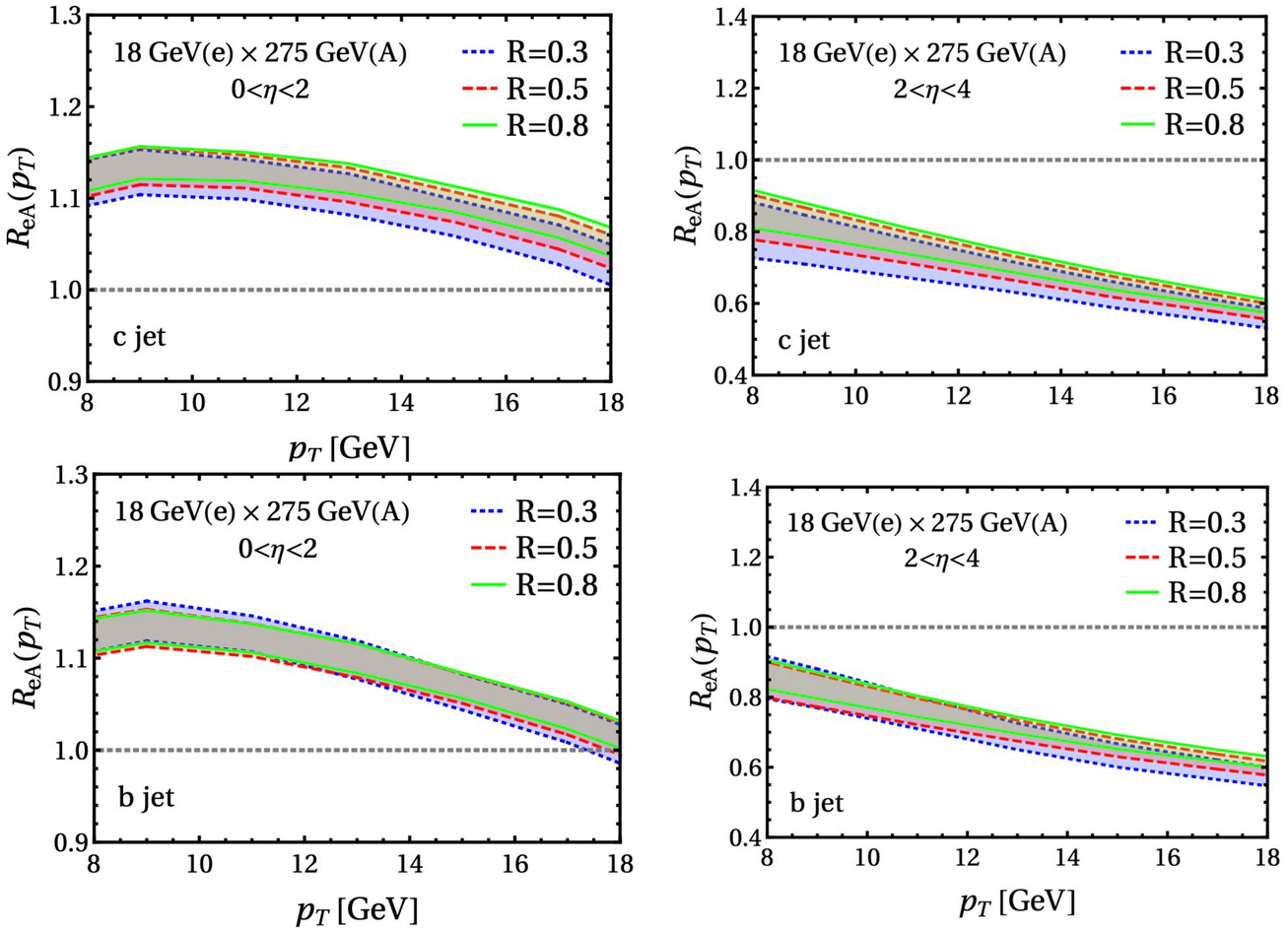


enhanced by the steeper pT spectra near the phase space boundary

Electron-Ion Collisions

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

Electron-Ion Collisions

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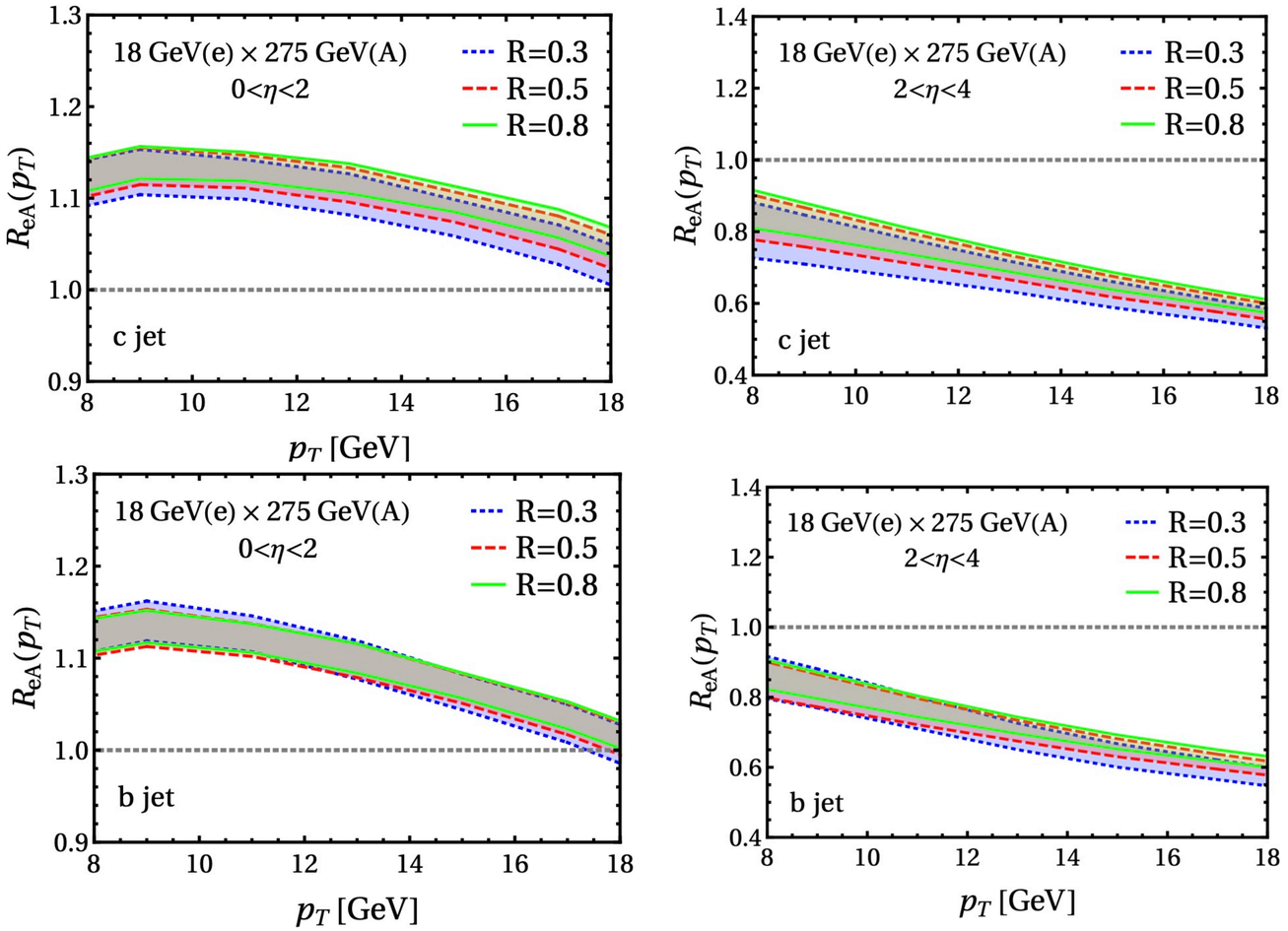
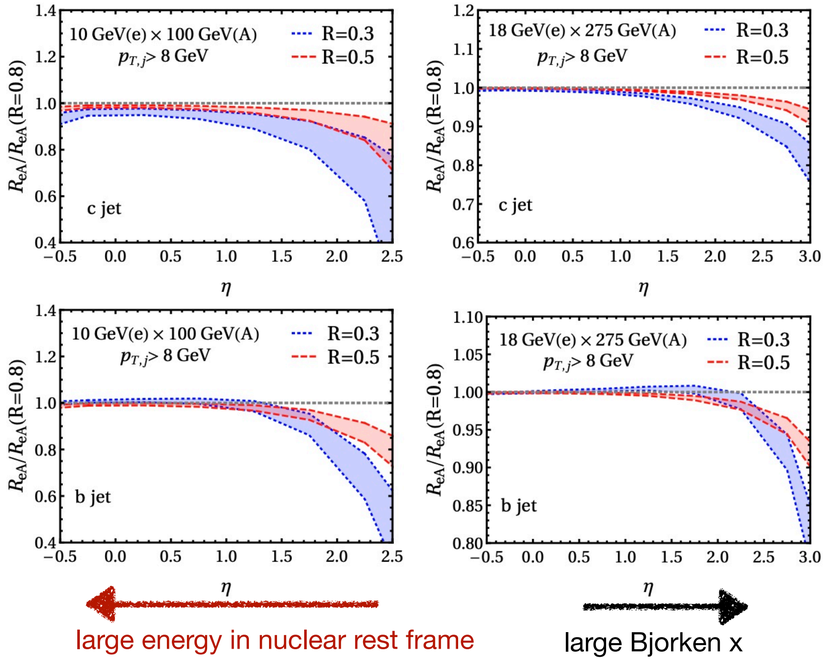


proton rapidity $\eta_p = 5.3$ **proton rapidity $\eta_p = 6.3$**

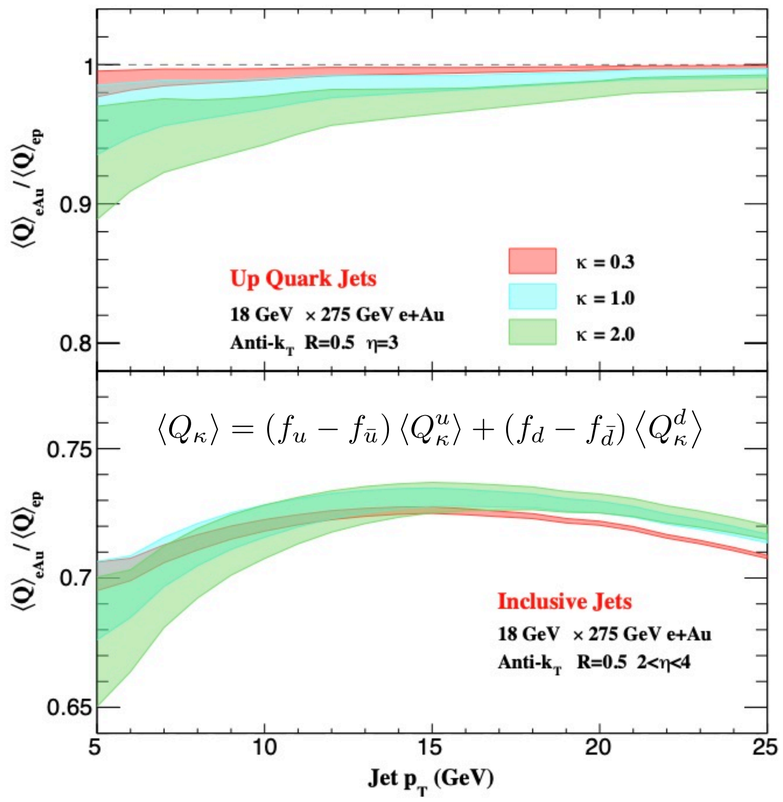


Medium-induced suppression is much enhanced in the forward rapidity region

HTL, Liu, Vitev, arXiv:2108.07809

Electron-Ion Collisions

Jet structures



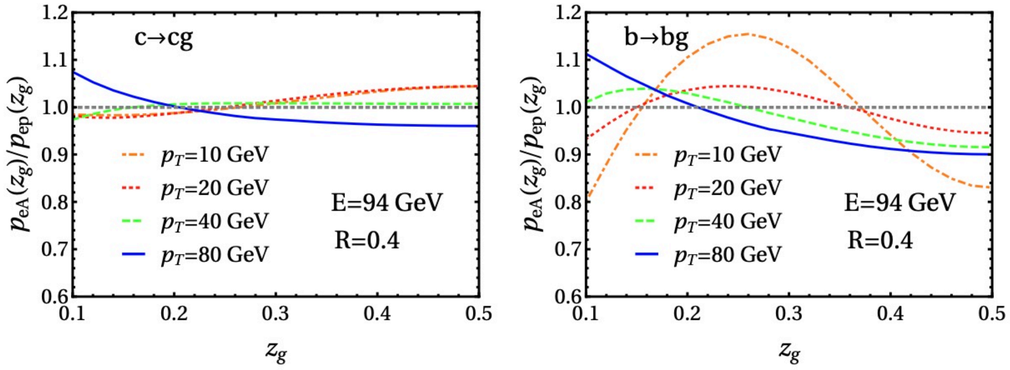
Cancellation between u and d jet

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

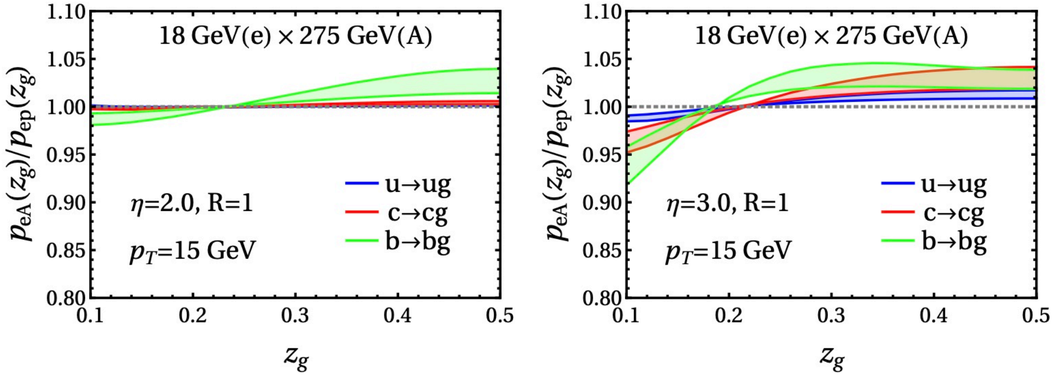
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \quad \textbf{with} \quad z_g > z_{cut}$$

Groomed jet splitting functions for $c \rightarrow cg$ and $b \rightarrow bg$.

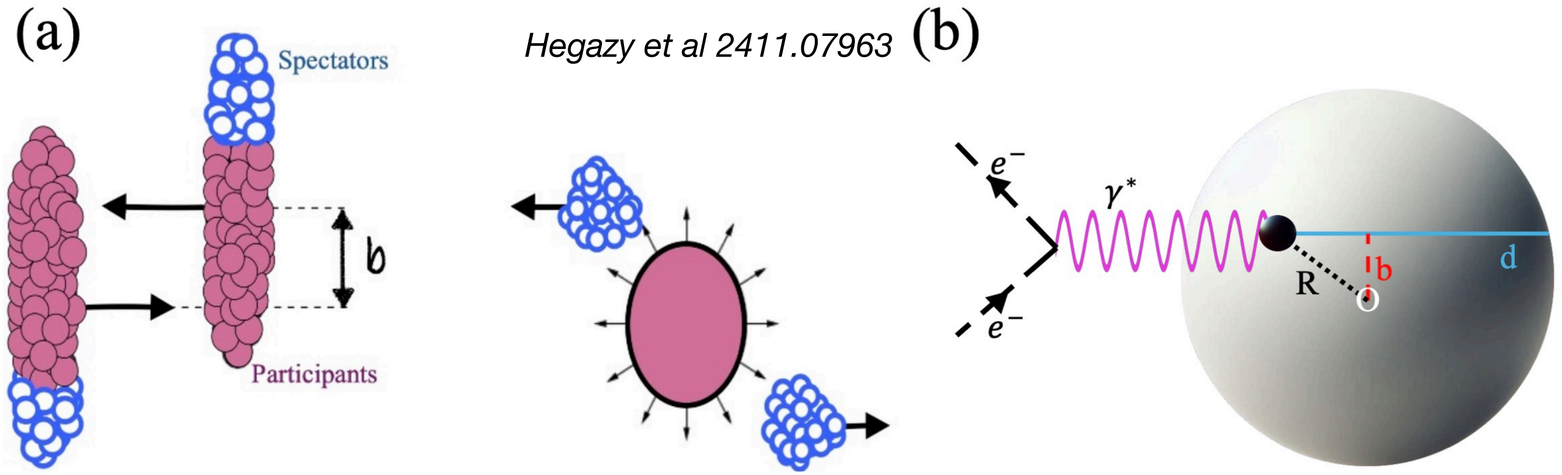
For 94 GeV jet in rest frame of the nucleus



For inclusive jet at EIC



Electron-Ion Collisions

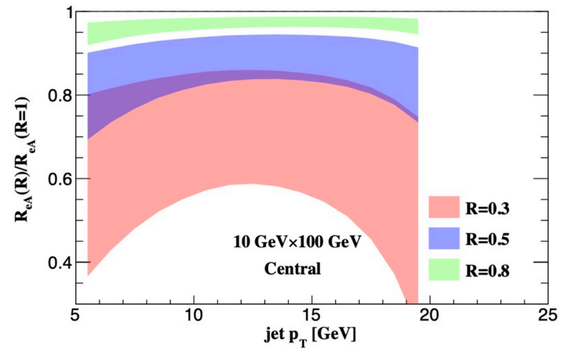


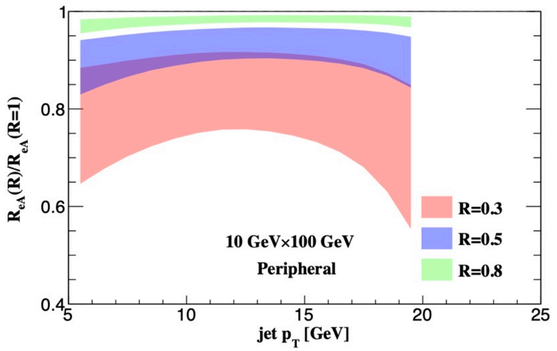
Electron-Ion Collisions

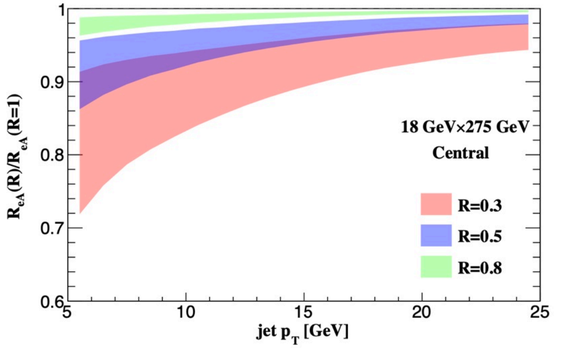
Centrality-dependent modification

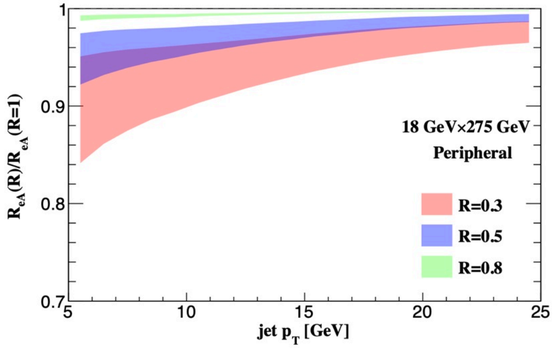
Centrality	$0-1\%$	$0-3\ \%$	$0-10\ \%$	$60-100\ \%$	$80-100\ \%$	$90-100\ \%$	$0-100\ \%$
$\langle d \rangle [fm]$	9.09	8.48	7.61	2.88	2.71	2.71	4.40
$\langle d \rangle / \langle d \rangle_{\text{min.bias}}$	2.07	1.93	1.73	0.65	0.62	0.62	1.00

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

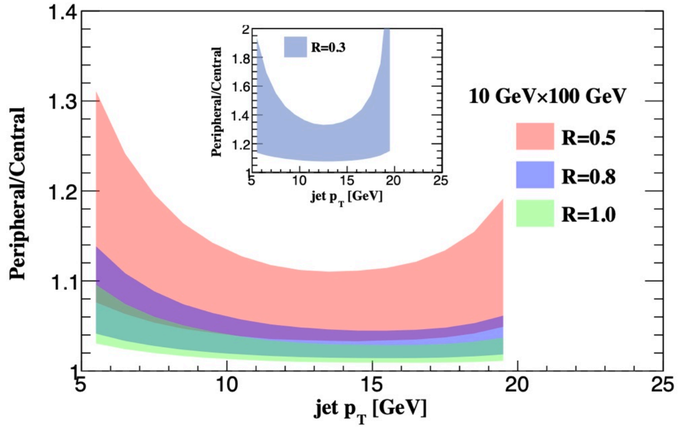


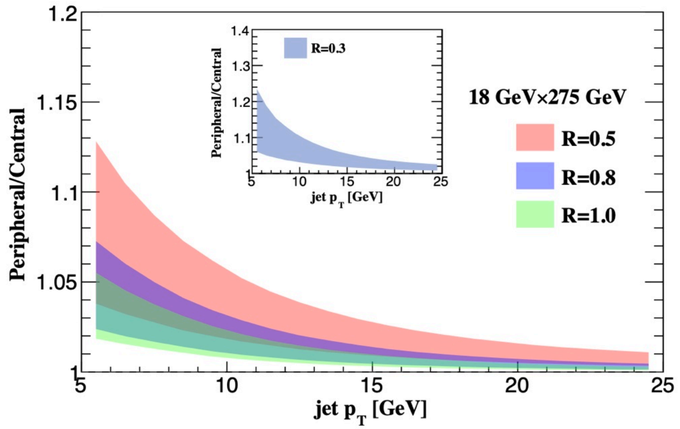






$$\frac{\text{Peripheral}}{\text{Central}}(J) = \frac{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}|_{\text{eA,Peri.}}}{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}|_{\text{eA,Cent.}}}$$





Electron-Ion Collisions

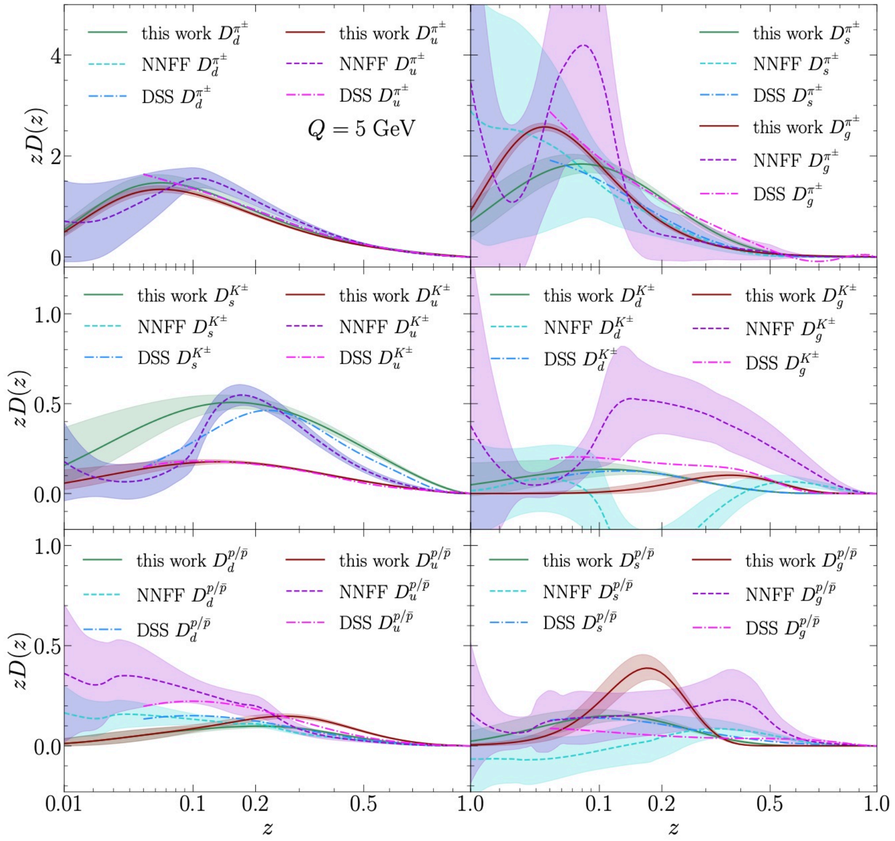
In collinear factorization, the inclusive cross section for hadron production is

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

Hard part: arXiv:1505.06415

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

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

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

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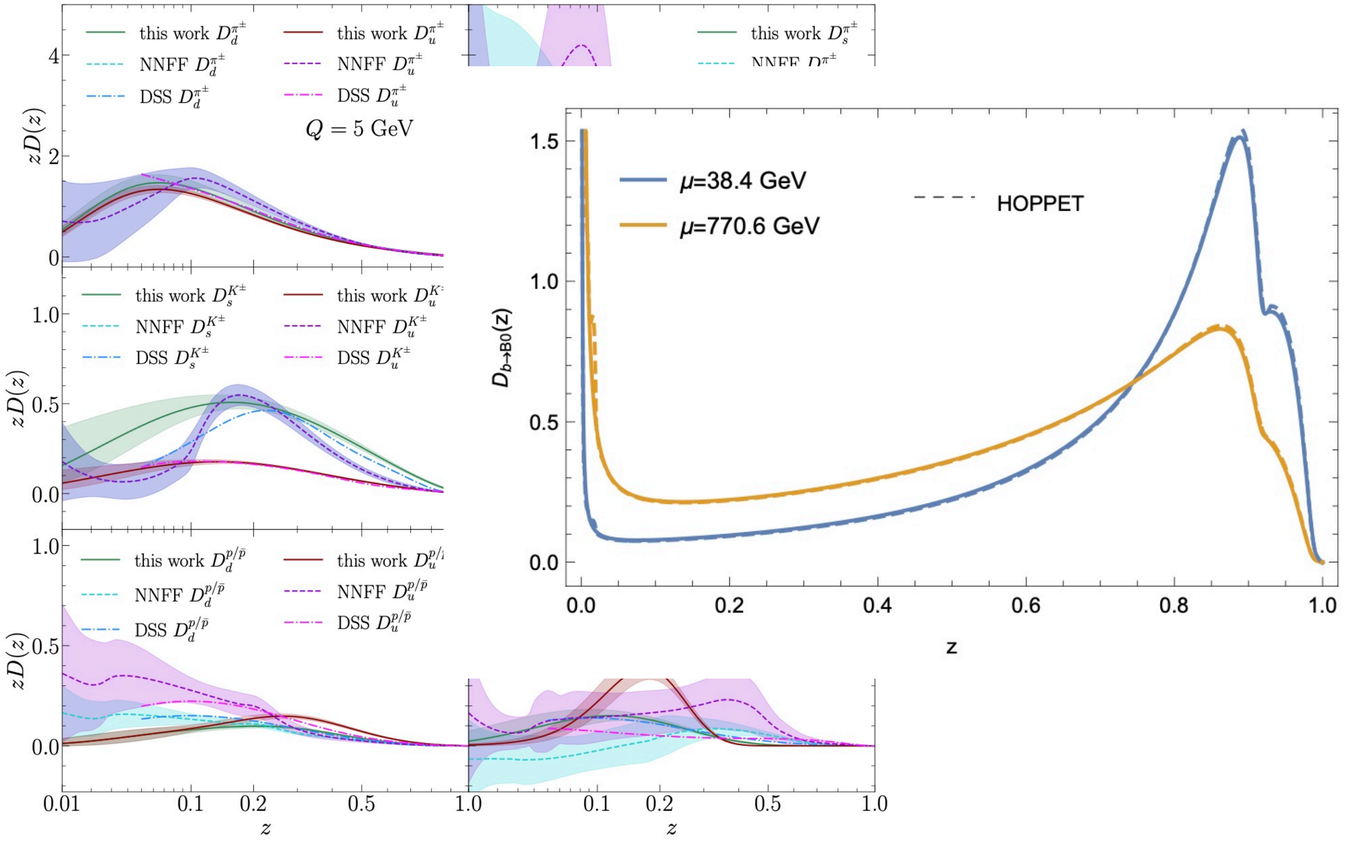

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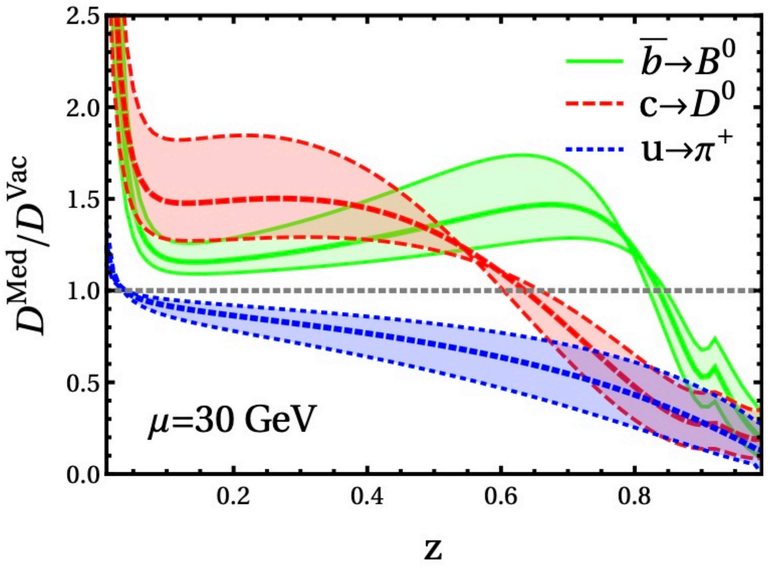

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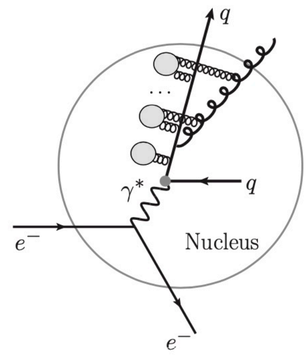
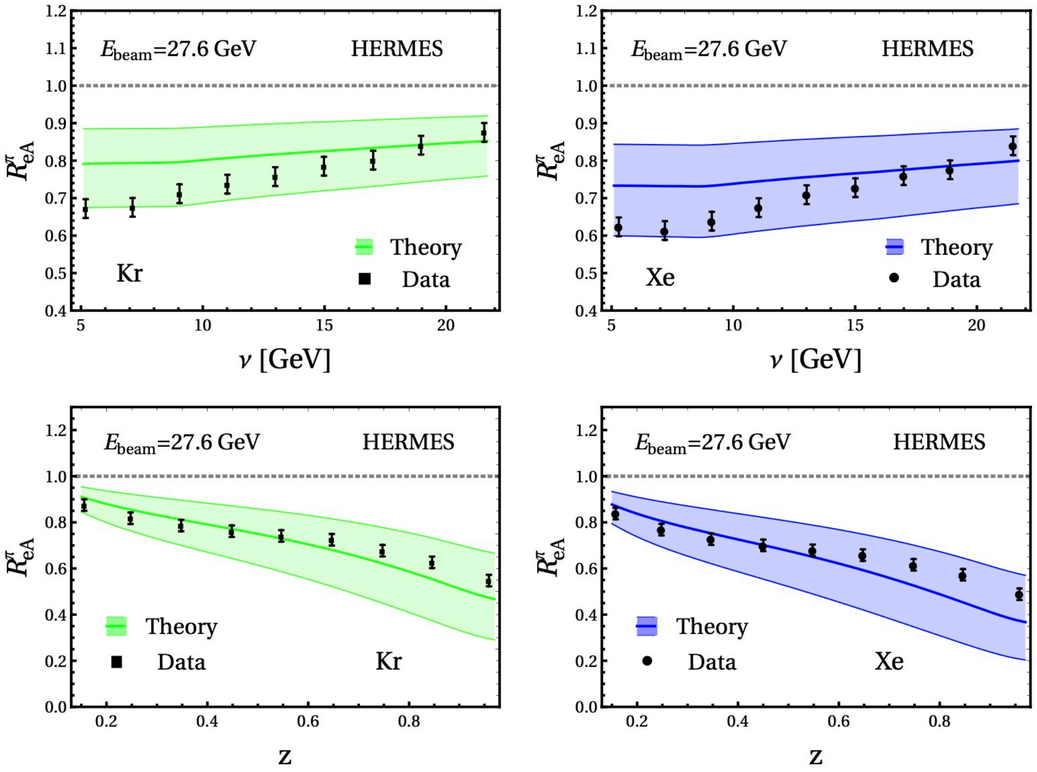
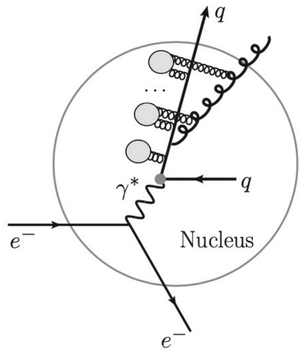


HTL, Liu, Vitev, arXiv:2007.10994

Electron-Ion Collisions

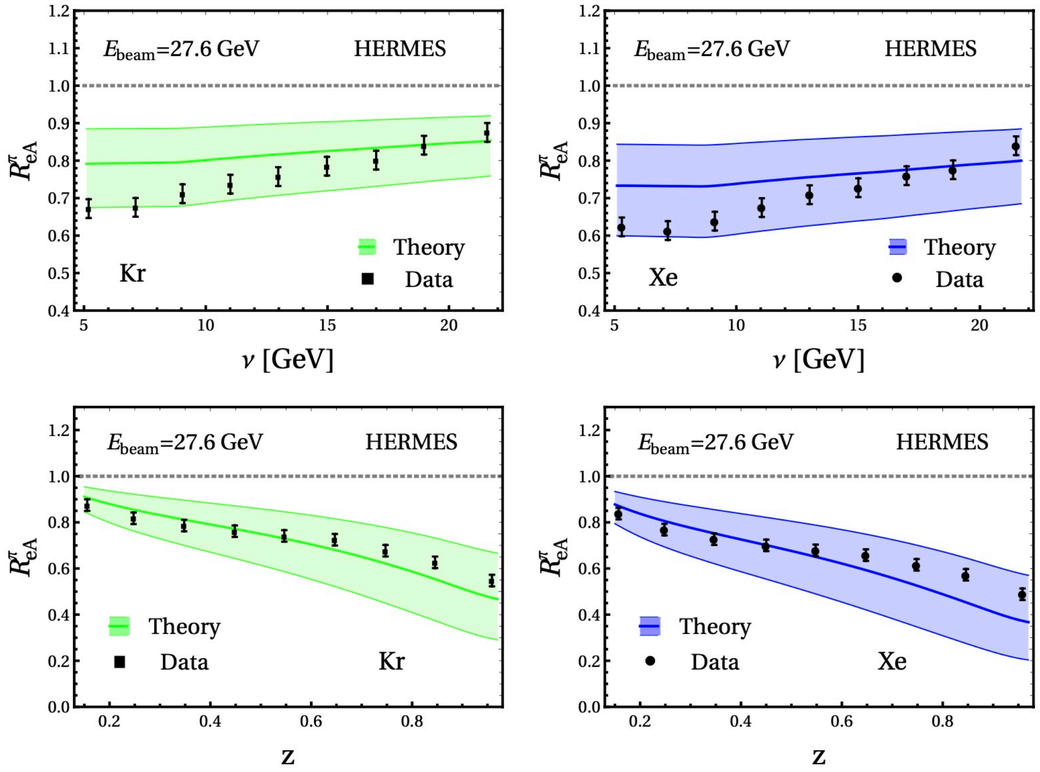




Compare our calculations with HERMES measurements

HTL, Liu, Vitev, arXiv:2007.10994

Electron-Ion Collisions



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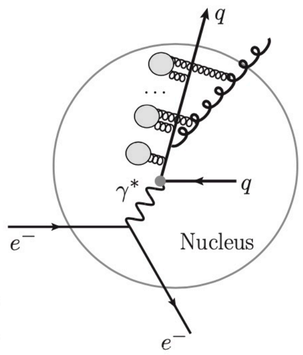
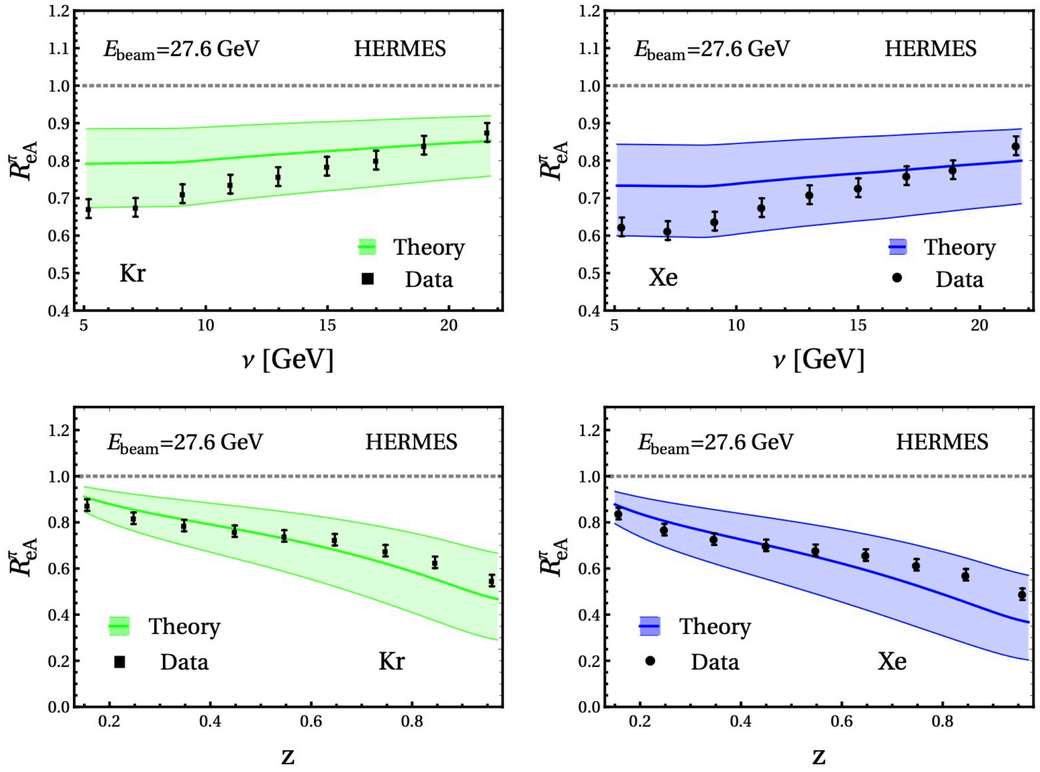


Energy		5 GeV×40 GeV		10 GeV×100 GeV		18 GeV×275 GeV	
p_T^h [GeV]		[2,3]	[5,6]	[2,3]	[5,6]	[2,3]	[5,6]
π^+	LO	5.3×10^6	2.4×10^4	1.4×10^7	3.0×10^5	2.9×10^7	9.6×10^5
	NLO	1.1×10^7	6.9×10^4	2.8×10^7	6.1×10^5	5.6×10^7	1.9×10^6
D^0	LO	1.4×10^6	3.2×10^3	8.6×10^6	9.0×10^4	3.1×10^7	6.6×10^5
	NLO	3.7×10^6	8.5×10^3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

HTL, Liu, Vitev, arXiv:2007.10994

Electron-Ion Collisions



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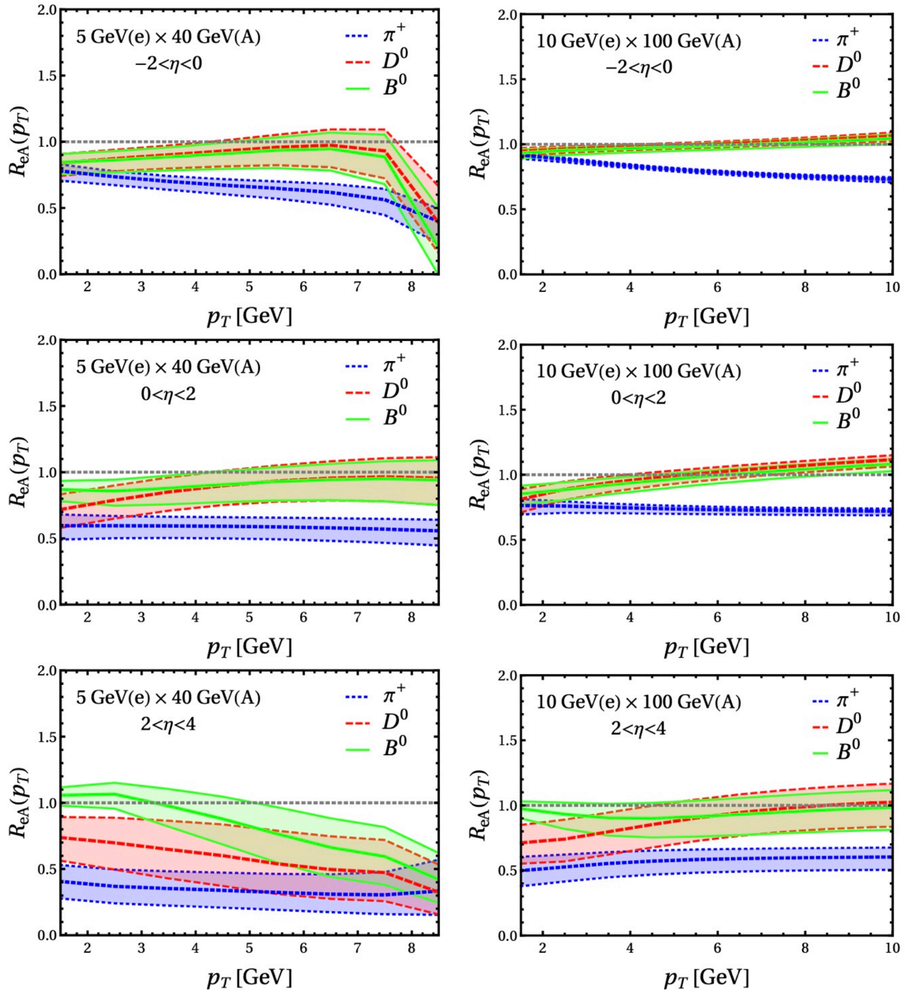

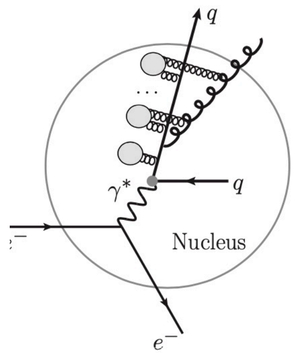

Conclusion

- Investigated nuclear matter corrections to light and heavy flavor jet production at EIC
- Presented the method to separate the initial and final state effects
- Discussed the Centrality-dependent modification
- Discussed nuclear matter corrections to hadron production at EIC
- Briefly discussed using the EEC to probe nuclear structure

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Thank you!