Nuclear matter effects on jet production at electron-ion colliders

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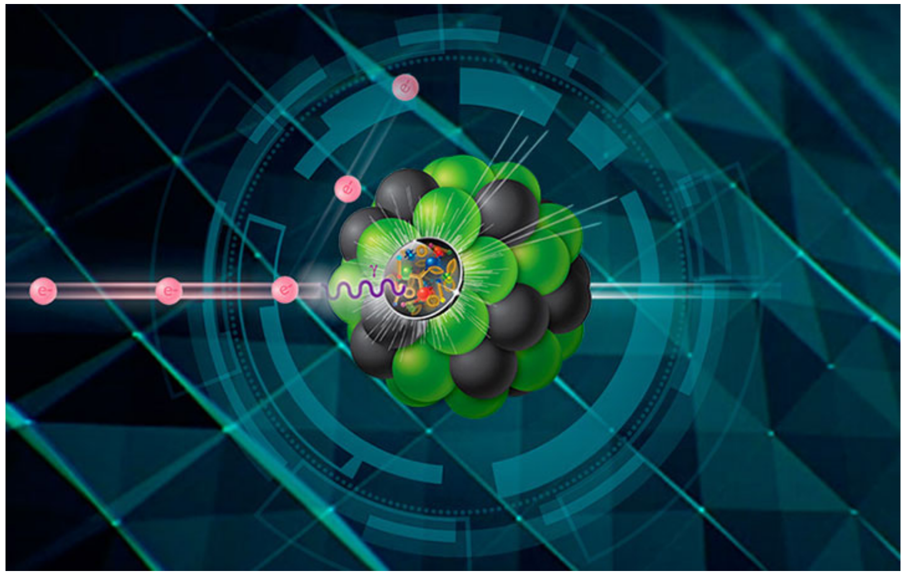
Based on the work: arXiv: 2010.05912
In collaboration with Ivan Vitev

J&HF Working Group meeting, 10/19/2020

Introduction

Use jets as precision probes at EIC to get better Understanding of QCD and nucleon



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

Jet 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

Majority of studies have focused on electron-proton reactions

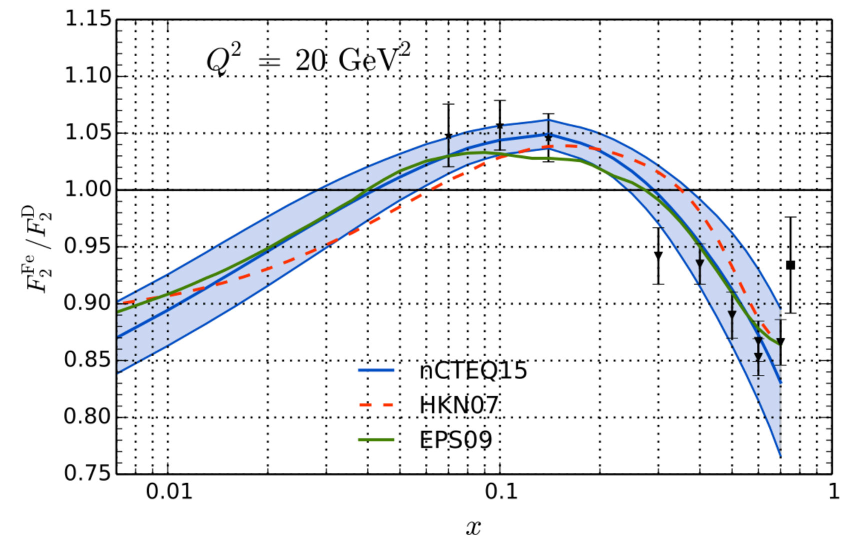
For this to work we present the nuclear effects in election-ion collisions.

to idetify kinematic region where nuclear matter effect is relative large
to disentangle the effects from nuclear PDFs and final state interaction

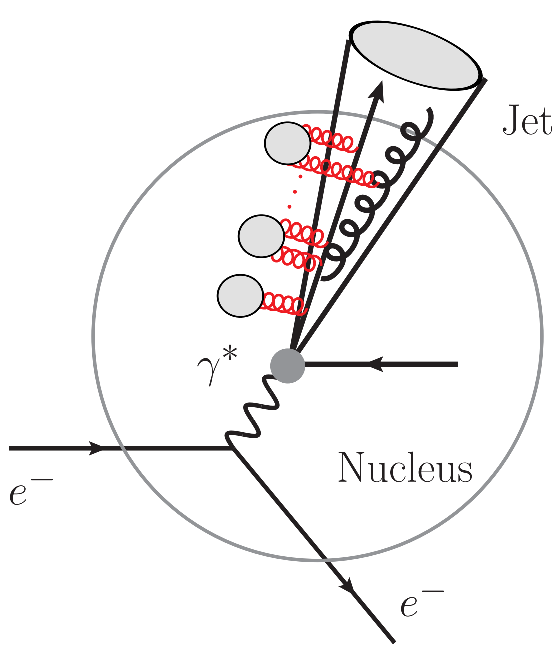
Nuclear Effects

Initial-state effects: parton desisties are different between proton and nuclear, which can be included through global-fit nuclear PDFs

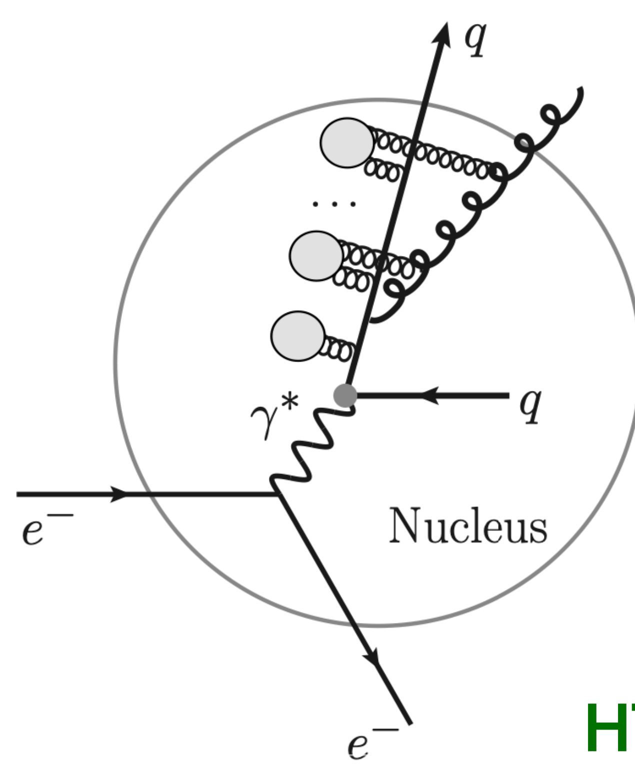
$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

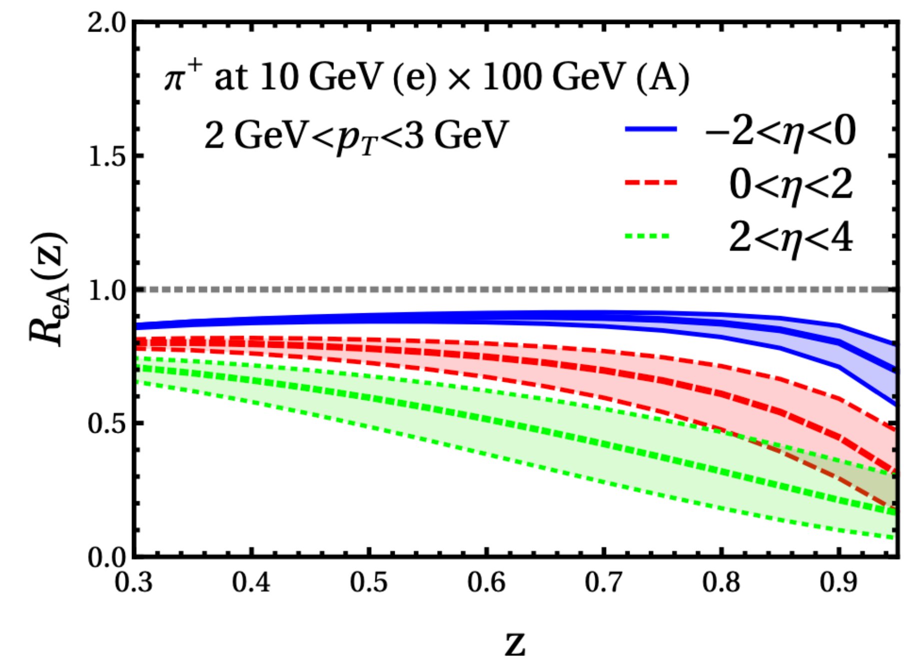


Final State effects from interactions between jet and nuclear matter



in-medium parton showers for Jet





HTL, Liu, Vitev, arXiv:2007.10994

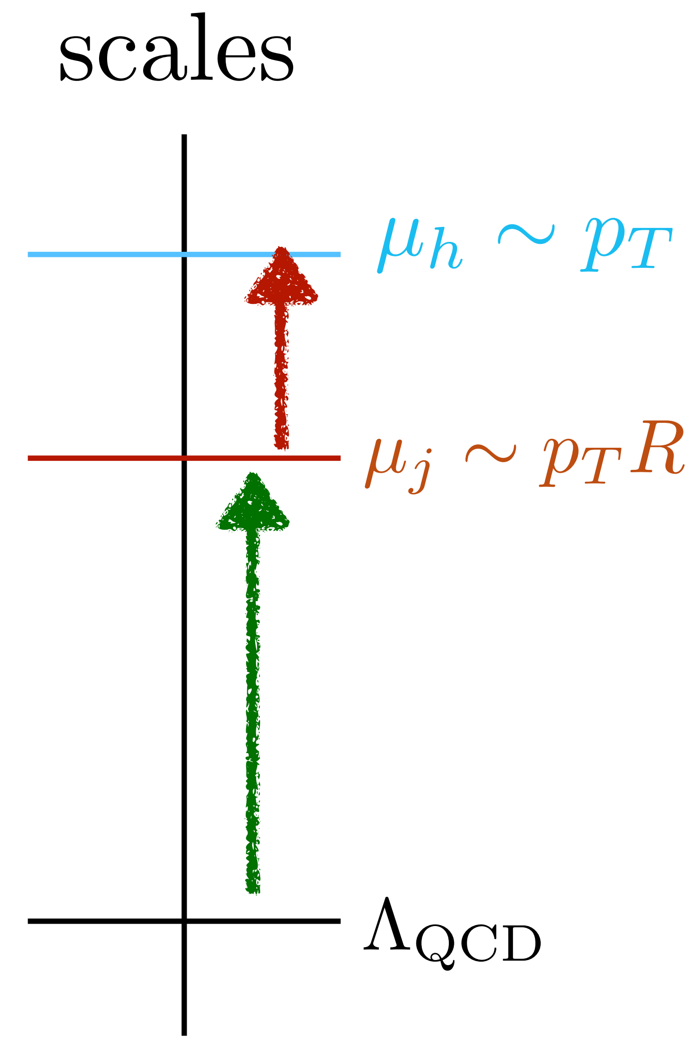
in-medium parton showers for Hadron

Inclusive jet cross section

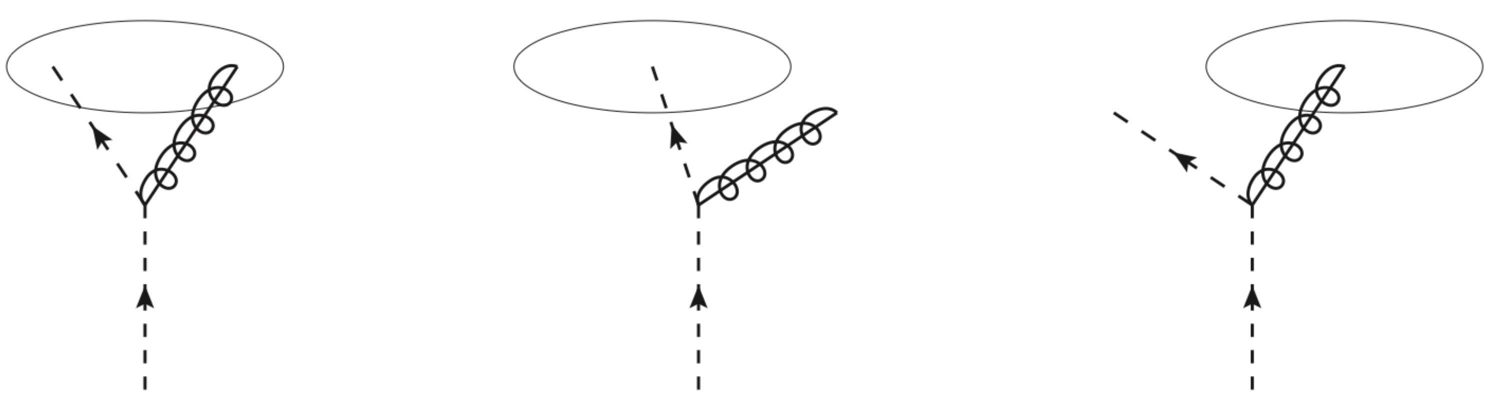
Semi-inclusive Jet Function

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

$$E_J \frac{d^3\sigma^{lN\to jX}}{d^3P_J} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f_{i/N}(x,\mu) \times \hat{\sigma}^{i\to f}(s,t,u,\mu) J_f(z, p_T R, \mu)$$



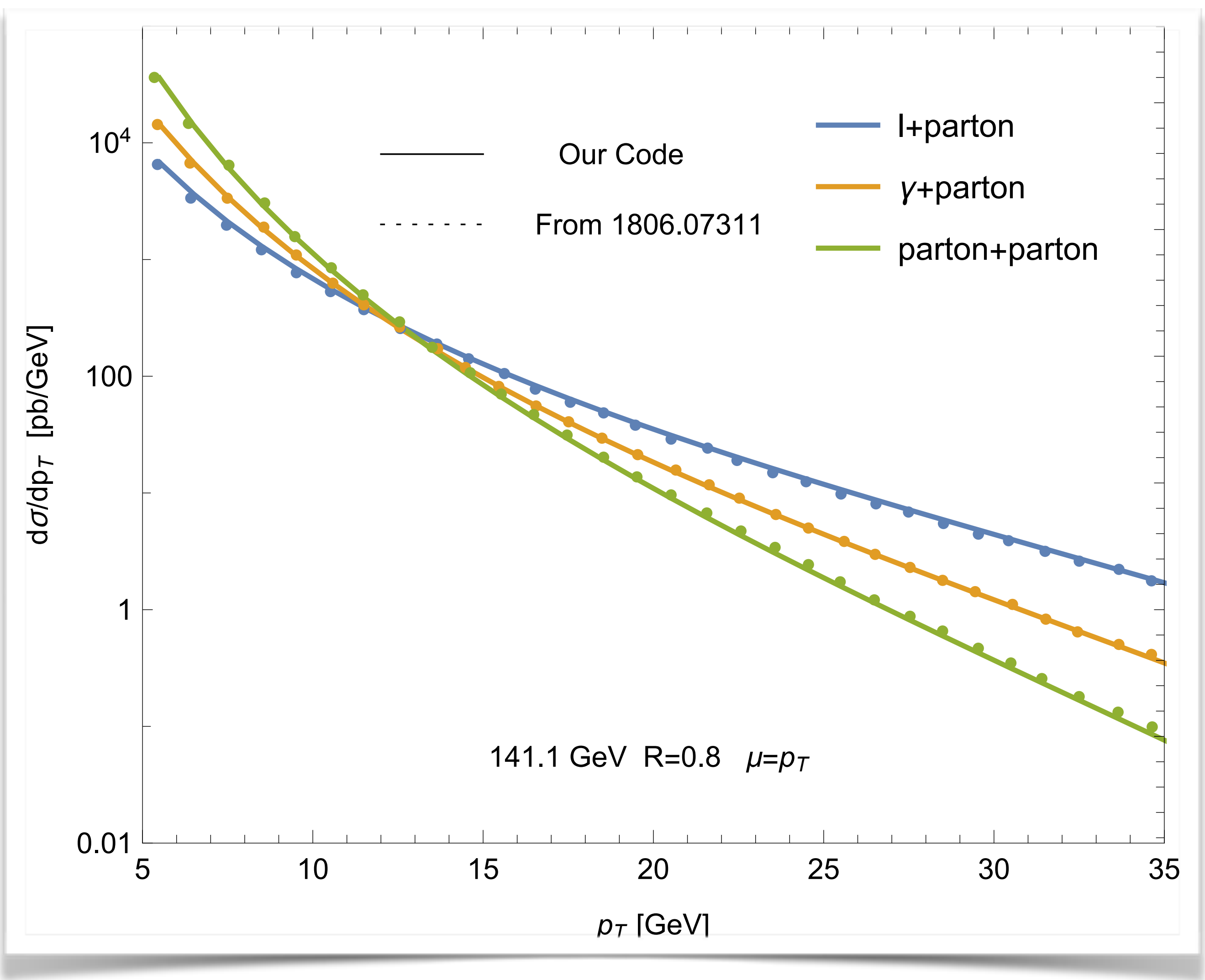
Hard part: arXiv:1505.06415
Jet Function: arXiv:1606.06732



Contribution to the semi-inclusive quark jet function

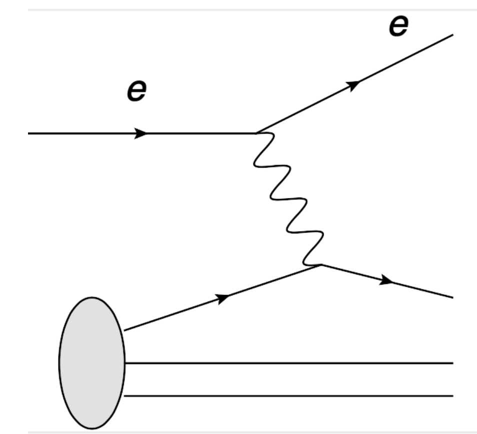
Comparision with NLO results

Comparison between NLO and factorized cross section

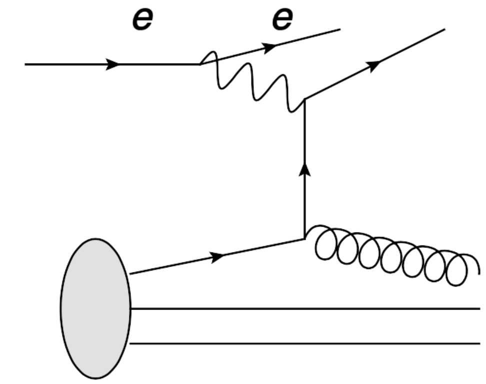


NLO results from
Boughezal, Petriello, Xing, arXiv:1806.07311

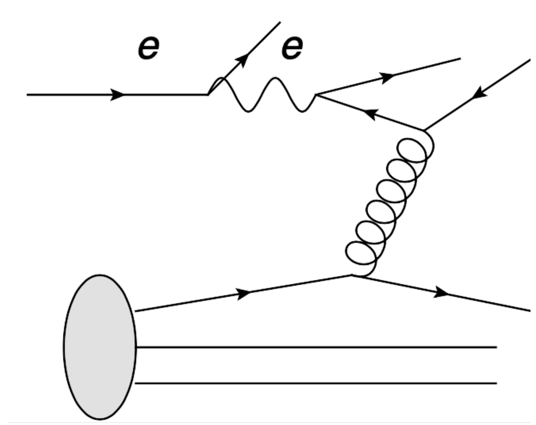
Large Q



Small Q
Photon PDF
from lepton



Small Q
Quark PDF from
lepton

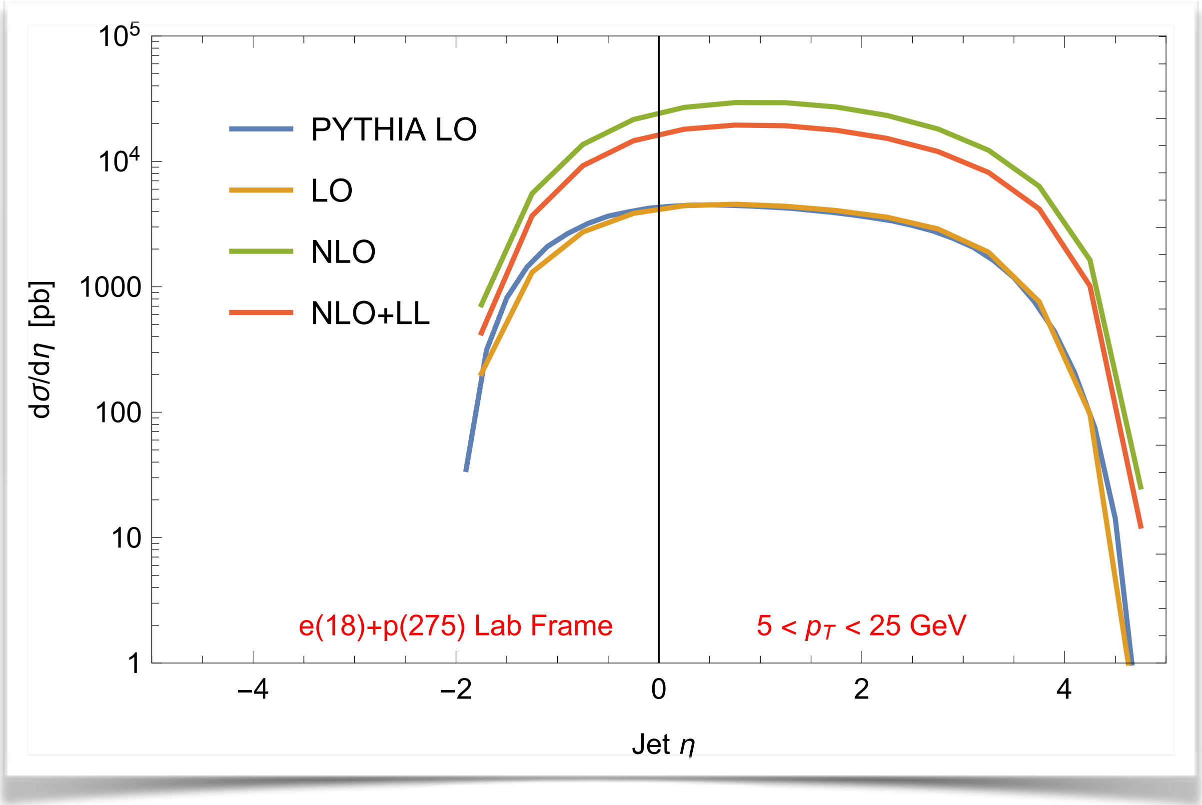


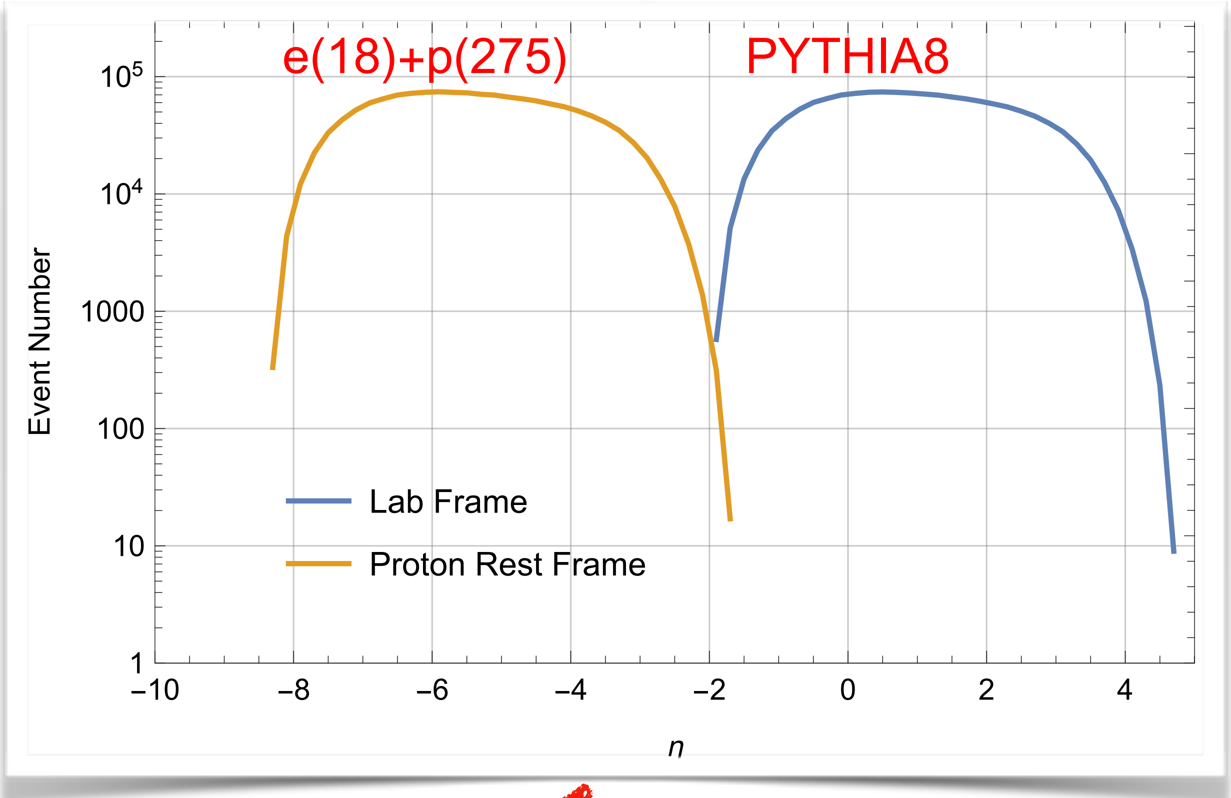
Resolved

Large Corrections from photon production and unresolved contribution in small p_T

Inclusive jet cross section

Jet Rapidity distributions





LL means $\ln R$ Resummed jet function

From Lab to the proton rest frame

- ☑ In total, Large corrections from LO to NLO
- ☑ Resummation reduced the cross section
- ☑ In the nuclear rest frame, the lower energy partons receive larger medium corrections.

Final-state Nuclear Matter Effects

Effective Lagrangian in SCET with medium-induced interaction

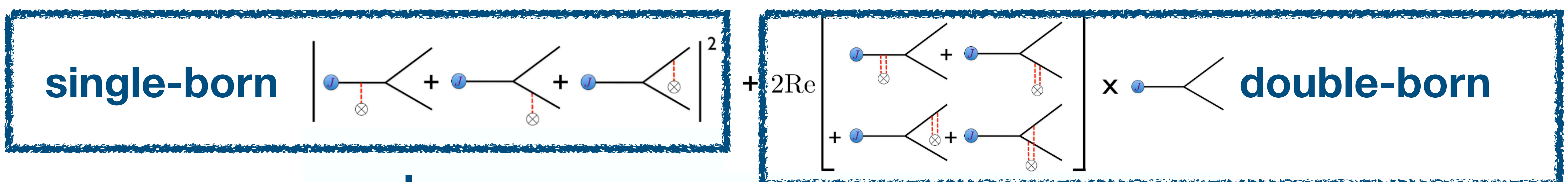
Ovanesyan, Vitev, arXiv: 1103.1074

$$\mathcal{L}_{\mathrm{SCET_G}}\left(\xi_n, A_n, A_G\right) = \mathcal{L}_{\mathrm{SCET}}\left(\xi_n, A_n\right) + \mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, A_G\right)$$

$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, A_G\right) = \sum_{p,p'} \mathrm{e}^{-i(p-p')x}\left(\bar{\xi}_{n,p'}\Gamma^{\mu,a}_{\mathrm{qqA_G}}\frac{\bar{n}}{2}\xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}}\left(A^c_{n,p'}\right)_\lambda\left(A^b_{n,p}\right)_\nu\right)A_{\mathrm{G}\mu,a}(x)$$

Medium-induced parton splitting kernels

Ovanesyan, Vitev, arXiv:1109.5619



real

virtual

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

Integration over medium size.

Non-trivial $k_\perp$ and x dependence

Final-state Nuclear Matter Effects

Medium corrections to collinear branching kernel

$$f_{i\to jk}^{\mathrm{med}}\left(z,\mathbf{k}_\perp\right)=\frac{dN_{i\to jk}^{\mathrm{med}}}{d^2\mathbf{k}_\perp dz}$$

These splitting kernels capture the medium effects on the full collinear shower dynamic

The total collinear splitting kernel is

$$f_{i\to jk}^{\mathrm{tot}}\left(z,\mathbf{k}_\perp\right)=f_{i\to jk}^{\mathrm{vac}}\left(z,\mathbf{k}_\perp\right)+f_{i\to jk}^{\mathrm{med}}\left(z,\mathbf{k}_\perp\right)$$

In analogy to SiJFs in vacuum, medium correction to NLO jet function is

$$J_q^{\mathrm{med}}\left(z,p_TR,\mu\right)=\left[\int_{z(1-z)p_TR}^{\mu}d^2\mathbf{k}_\perp f_{q\to qg}^{\mathrm{med}}\left(z,\mathbf{k}_\perp\right)\right]_+ +\int_{z(1-z)p_TR}^{\mu}d^2\mathbf{k}_\perp f_{q\to gq}^{\mathrm{med}}\left(z,\mathbf{k}_\perp\right)$$

Light jet: Kang, Ringer, Vitev, arXiv:1606.06732
Heavy flavor jet: HTL, Vitev, arXiv:1811.07905

Final-state Nuclear Matter Effects

Medium corrections to collinear branching kernel

$$f^{\mathrm{med}}_{i\to jk}\left(z,\mathbf{k}_\perp\right) = \frac{dN^{\mathrm{med}}_{i\to jk}}{d^2\mathbf{k}_\perp dz}$$

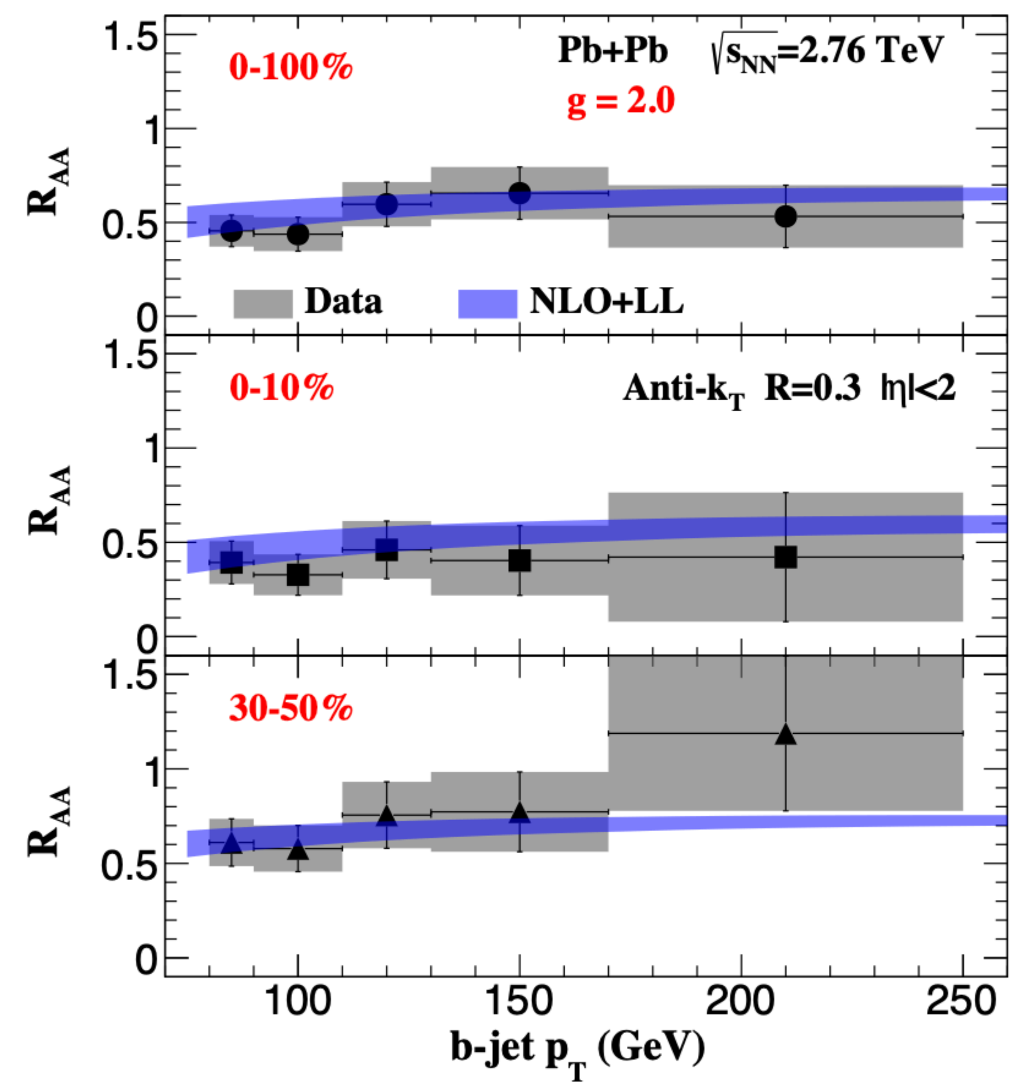
These splitting kernels capture the medium effects on the full collinear shower dynamic

The total collinear splitting kernel is

$$f^{\mathrm{tot}}_{i\to jk}\left(z,\mathbf{k}_\perp\right) = f^{\mathrm{vac}}_{i\to jk}\left(z,\right.$$

In analogy to SiJFs in vacuum, medium corr

$$J^{\mathrm{med}}_q\left(z,p_T R,\mu\right) = \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f^{\mathrm{med}}_{q\to qg}\left(z,\mathbf{k}_\perp\right)\right]$$



Light jet: Kang, Ringer, Vitev, arXiv:1606.06732
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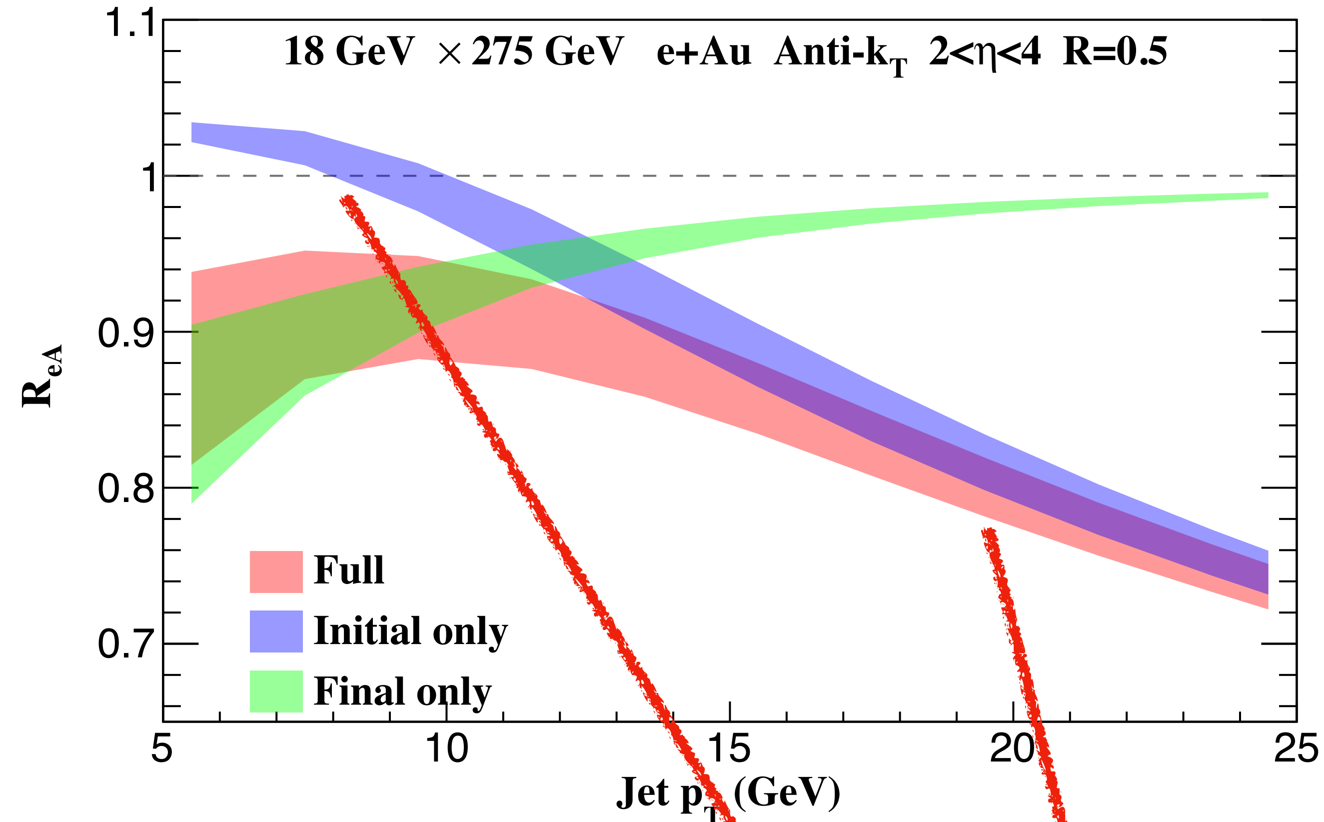
Inclusive jet cross section

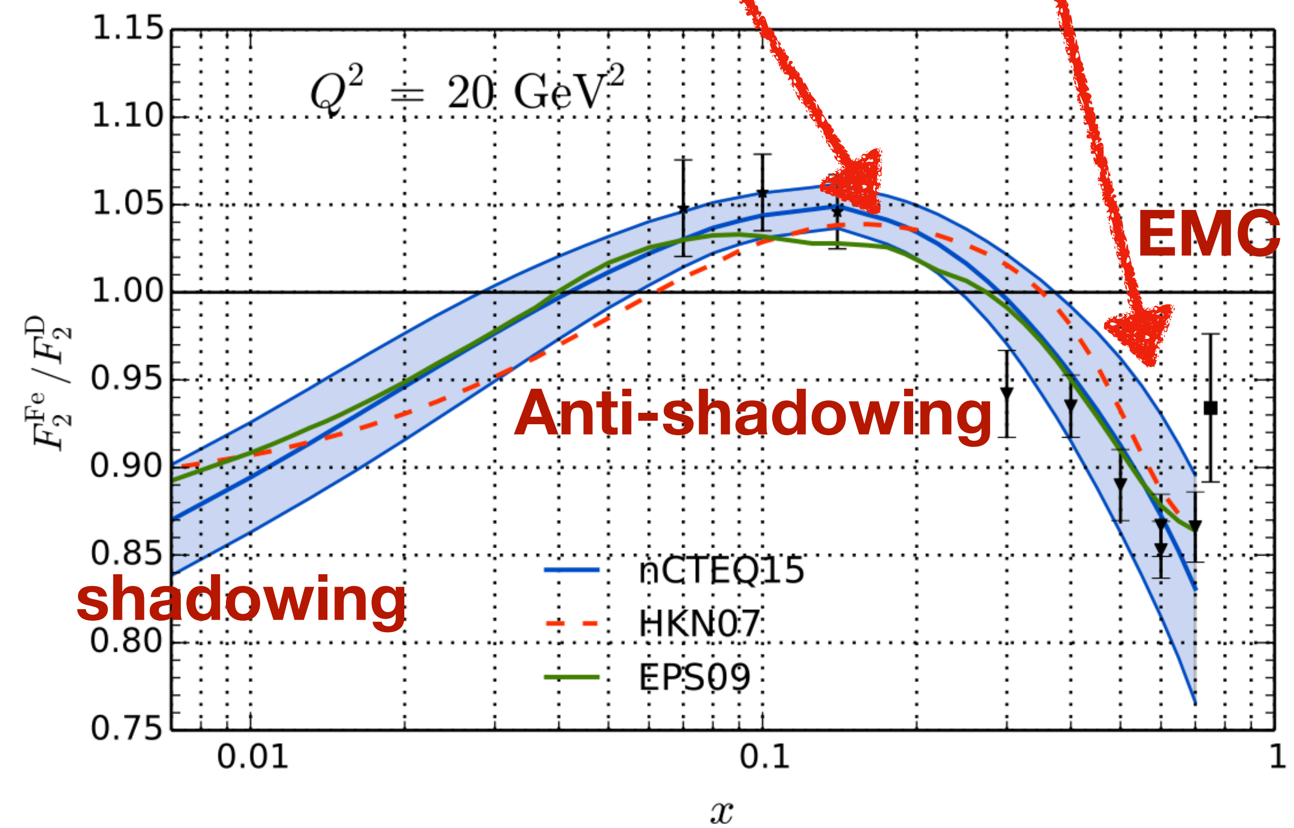
The forward pronon/nucleus going rapidity region 2< η <4 produce the largest nuclear effects.

Modifications defined as

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

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





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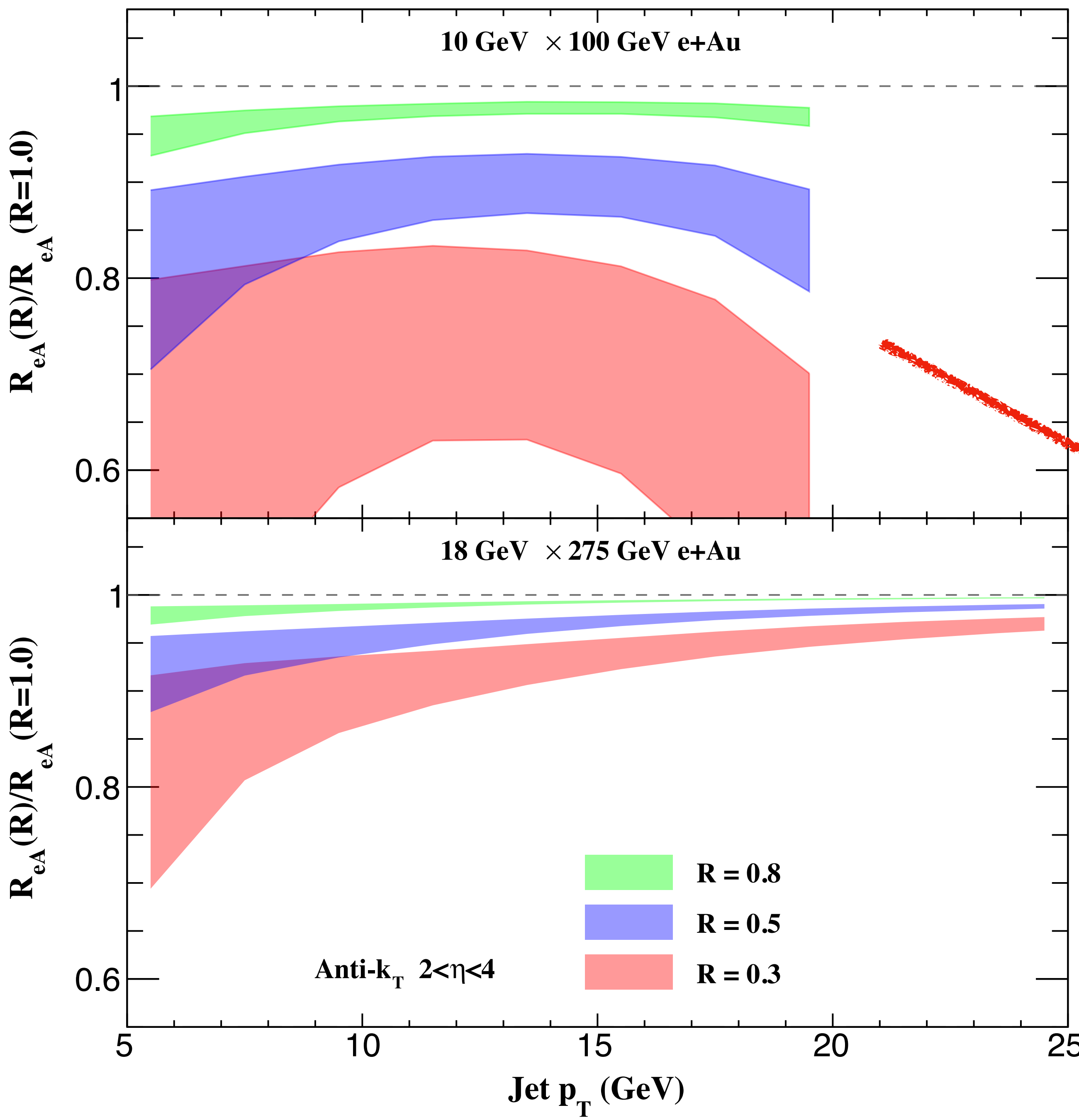

Essential reduce the role of nPDFs and enhance the effects due to final-state interactions

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

enhanced by the steeper pT spectra near the phase space boundry

- **Suppression is more significant for smaller jet radii**
- **Final State effects decreasing with p_T increasing**

Jet Charge

Jet Charge

Defined as the transverse momentum weighted sum of the charges

Definition $$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^\kappa} \sum_{\text{i}\in\text{jet}} Q_i \left(p_T^i\right)^\kappa$$ **Larger κ, smaller charge**

The quark jet charge can be derived in SCET from the collinear factorization formula for measuring a hadron inside a jet

$$\langle Q_{\kappa,q}\rangle = \boxed{\frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \exp\left[\int_{1\text{GeV}}^{\mu} \frac{d\mu'}{\mu'} \frac{\alpha_s(\mu')}{\pi} \tilde{P}_{qq}(\kappa)\right]} \boxed{\tilde{D}_q^Q(\kappa)}$$

Perturbative

scale and R dependence

Non-Perturbative

only depends on κ

Krohn, Schwartz, Waalewijn, arXiv:1209.2421
Waalewijn arXiv:1209.3019

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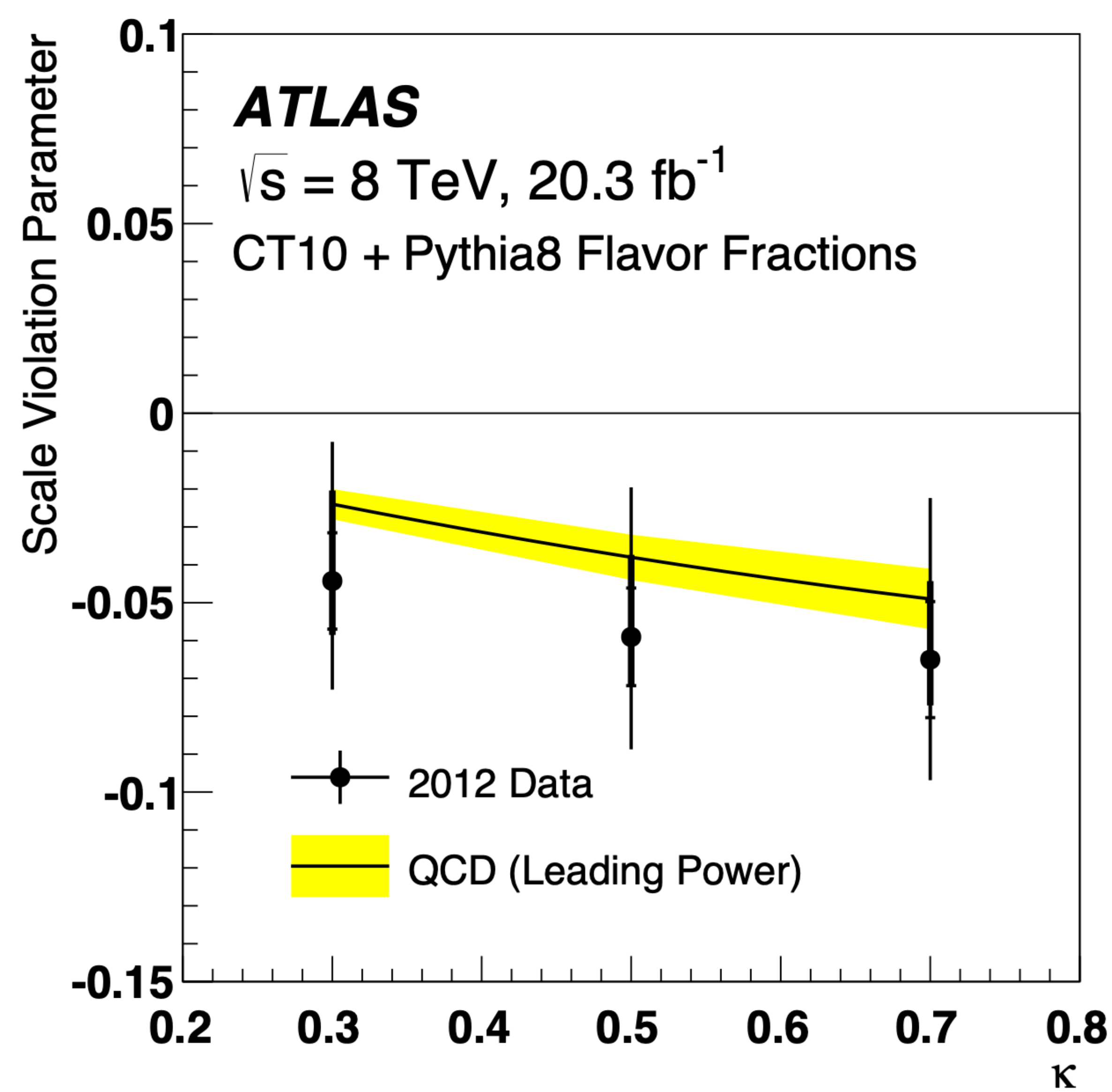
Perturbative

scale and R dependence



Krohn, Schwartz, Waalewijn, arXiv:1209.2421
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Jet charge in SCET

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- The perturbative part contains the dependence on the jet algorithm

$$\widetilde{\mathcal{J}}_{ij}(E,R,\kappa,\mu) = \int_0^1 \mathrm{d}z\, z^\kappa \mathcal{J}_{ij}(E,R,z,\mu)$$

Matching the jet function to fragmentation function

- The non-perturbative part can be related to fragmentation functions

from weighted-definition of jet charge

$$\widetilde{D}_q^h(\kappa,\mu) = \int_0^1 \mathrm{d}z\, z^\kappa D_q^h(z,\mu)$$

sum over all the hadrons in the jet

$$\widetilde{D}_q^Q(\kappa,\mu) = \sum_h Q_h \widetilde{D}_q^h(\kappa,\mu)$$

the evolution equation

$$\mu\frac{d}{d\mu}\tilde{D}_q^Q(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\tilde{P}_{qq}(\kappa)\tilde{D}_q^Q(\kappa,\mu)$$

Krohn, Schwartz, Waalewijn, arXiv:1209.2421
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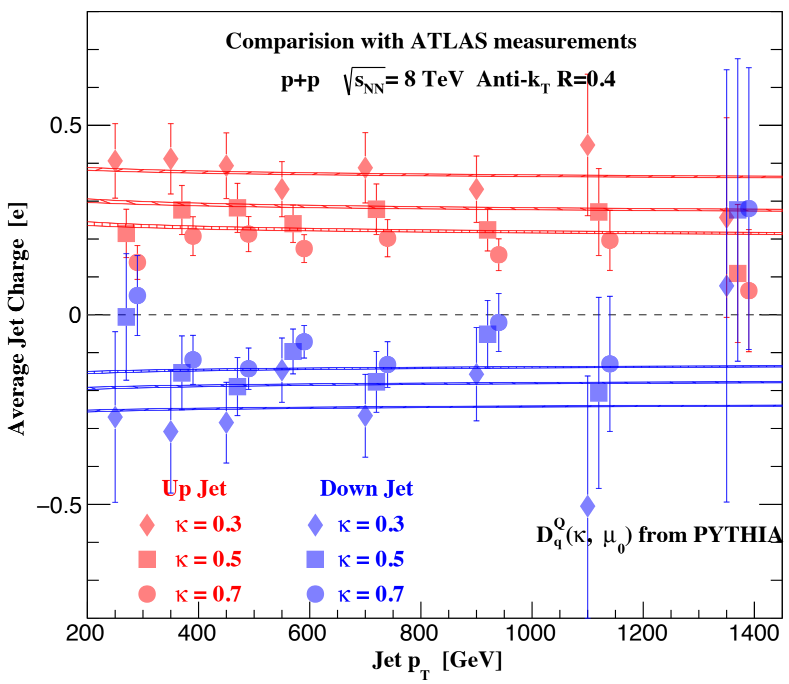

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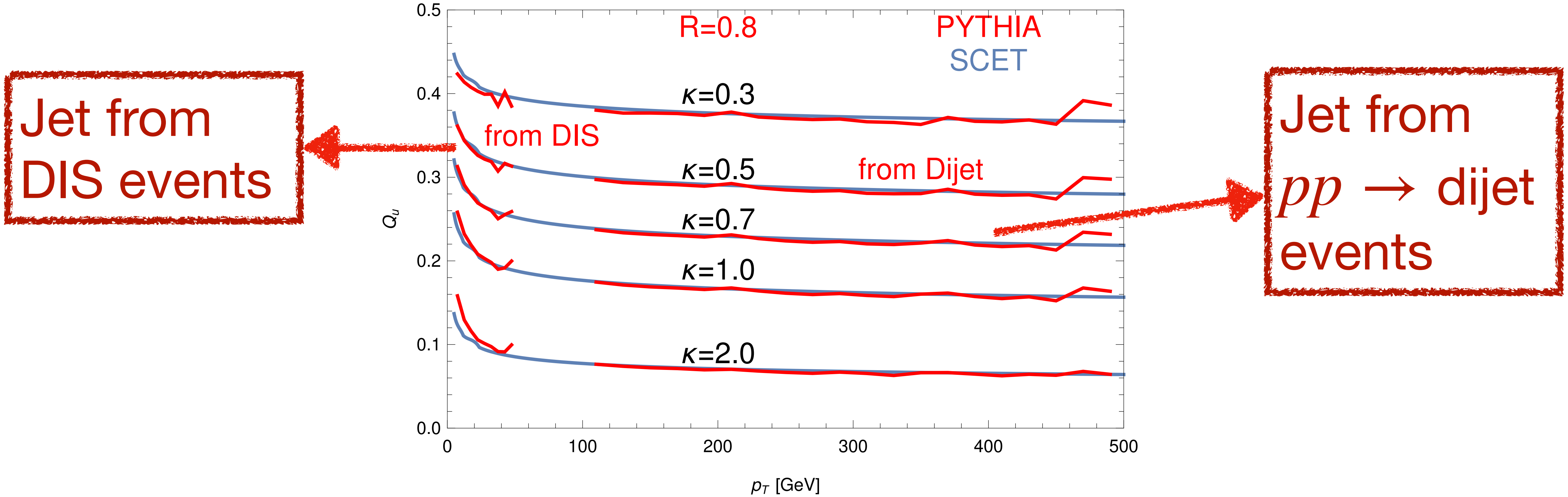
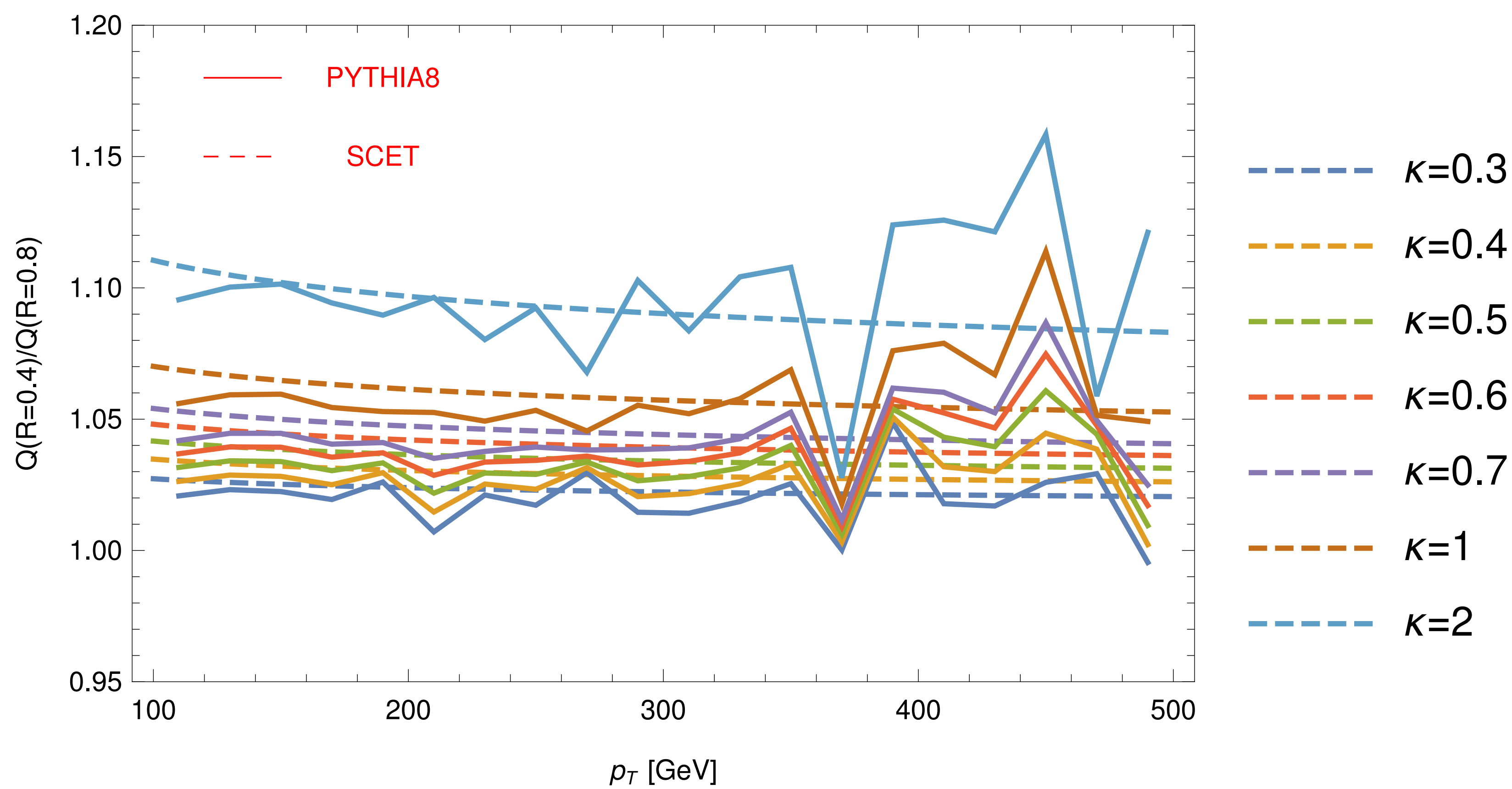
Jet Charge



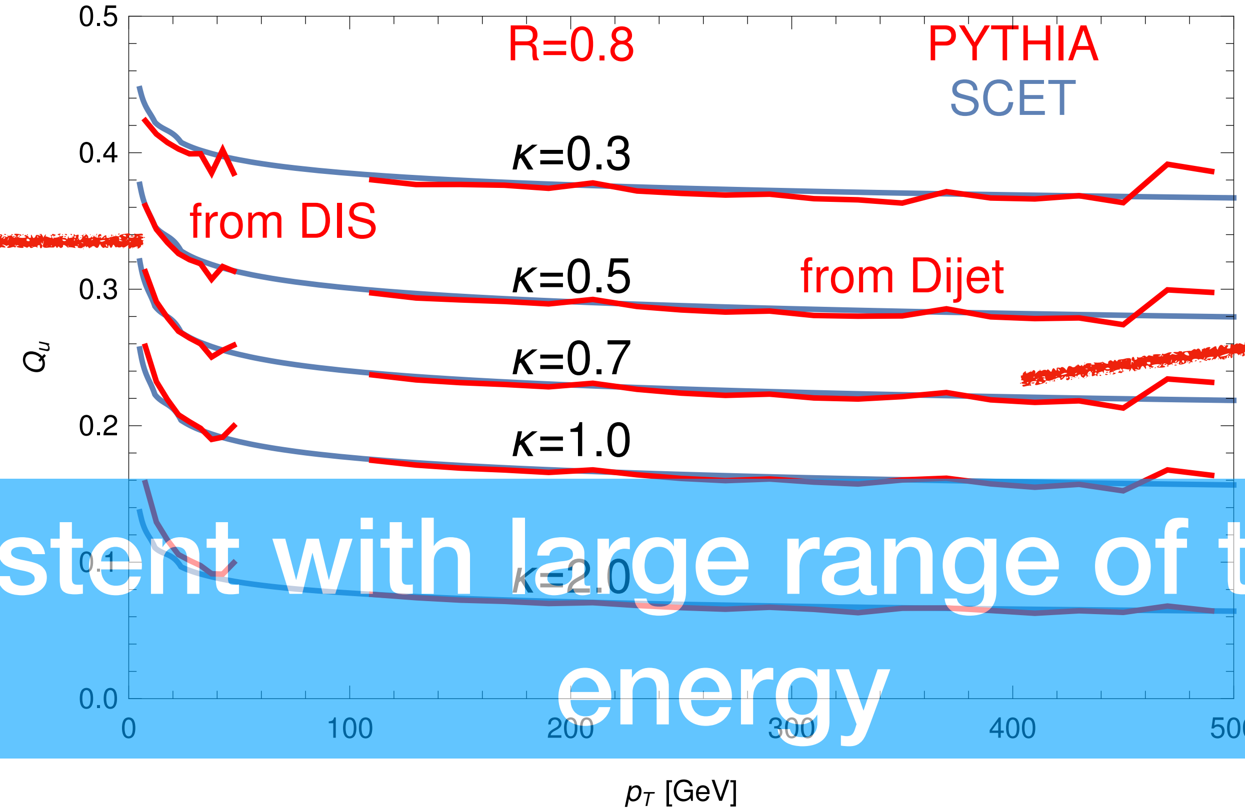
Jet from
DIS events
0.5
0.4
0.3
0.2
0.1
0.0
Q_u
R=0.8
PYTHIA
SCET
κ=0.3
from DIS
κ=0.5
from Dijet
κ=0.7
κ=1.0
κ=2.0
0
100
200
300
400
500
p_T [GeV]
Jet from
$pp \to$ dijet
events



1.20
1.15
1.10
1.05
1.00
0.95
Q(R=0.4)/Q(R=0.8)
PYTHIA8
SCET
100
200
300
400
500
p_T [GeV]
κ=0.3
κ=0.4
κ=0.5
κ=0.6
κ=0.7
κ=1
κ=2

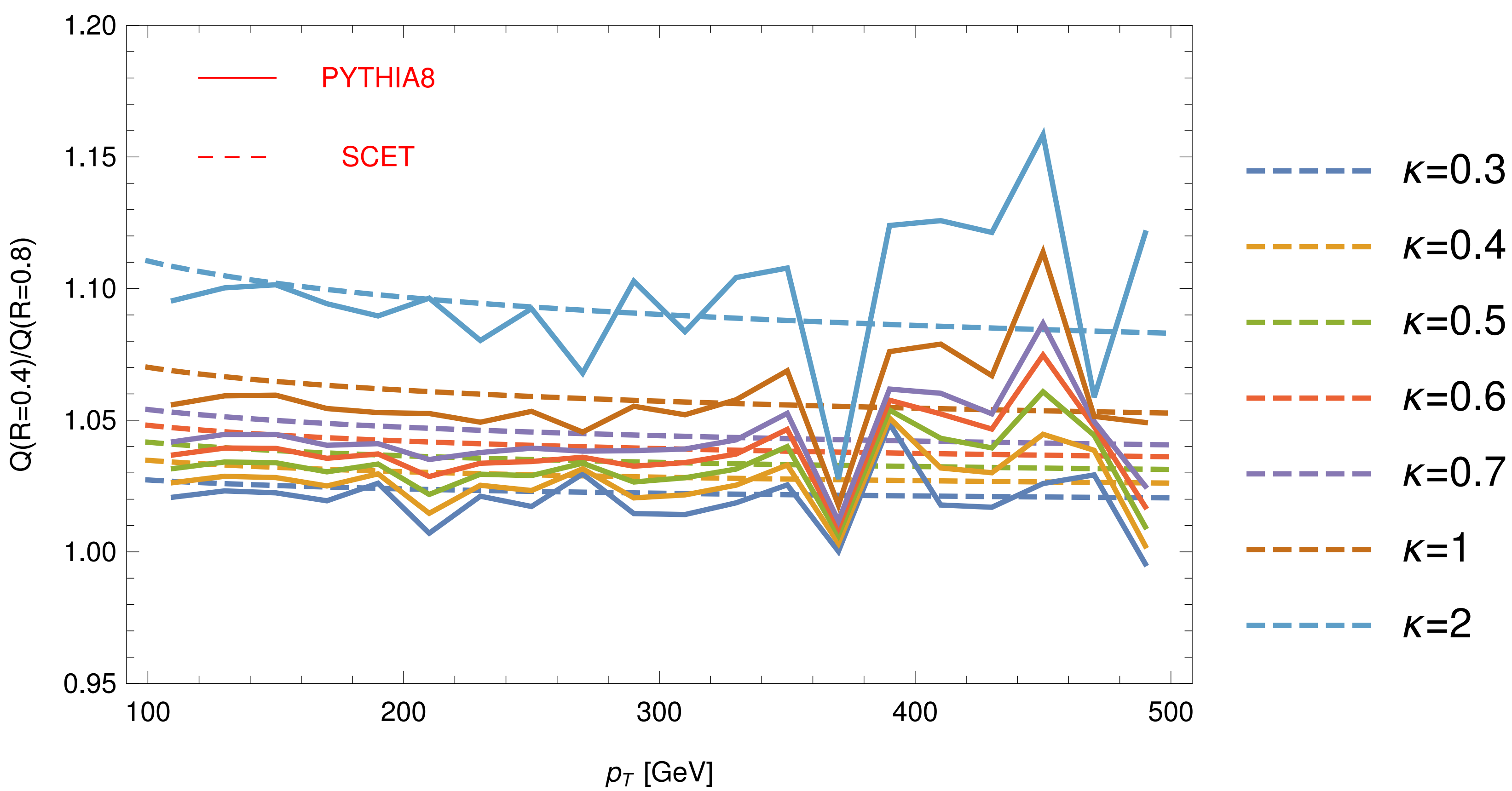
Jet Charge

Jet from DIS events



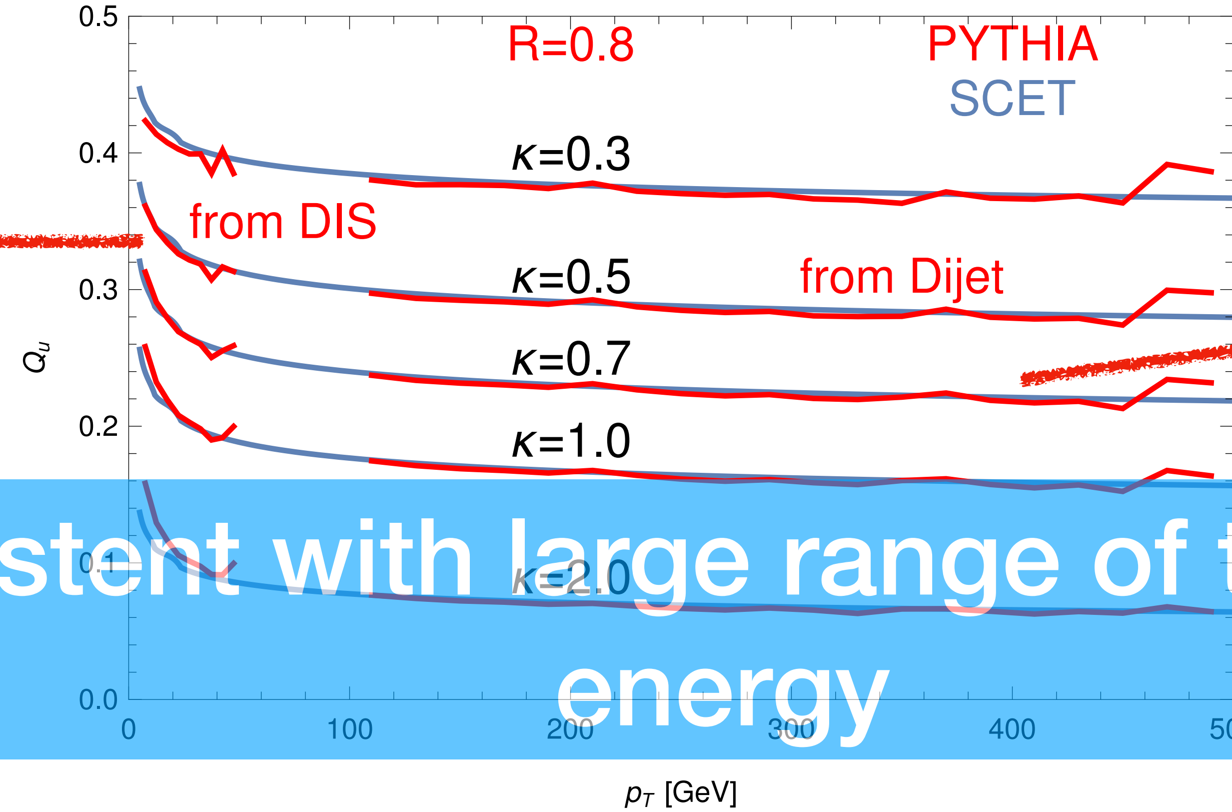
Jet from $pp \to$ dijet events

Consistent with large range of transverse energy



Jet Charge

Jet from DIS events



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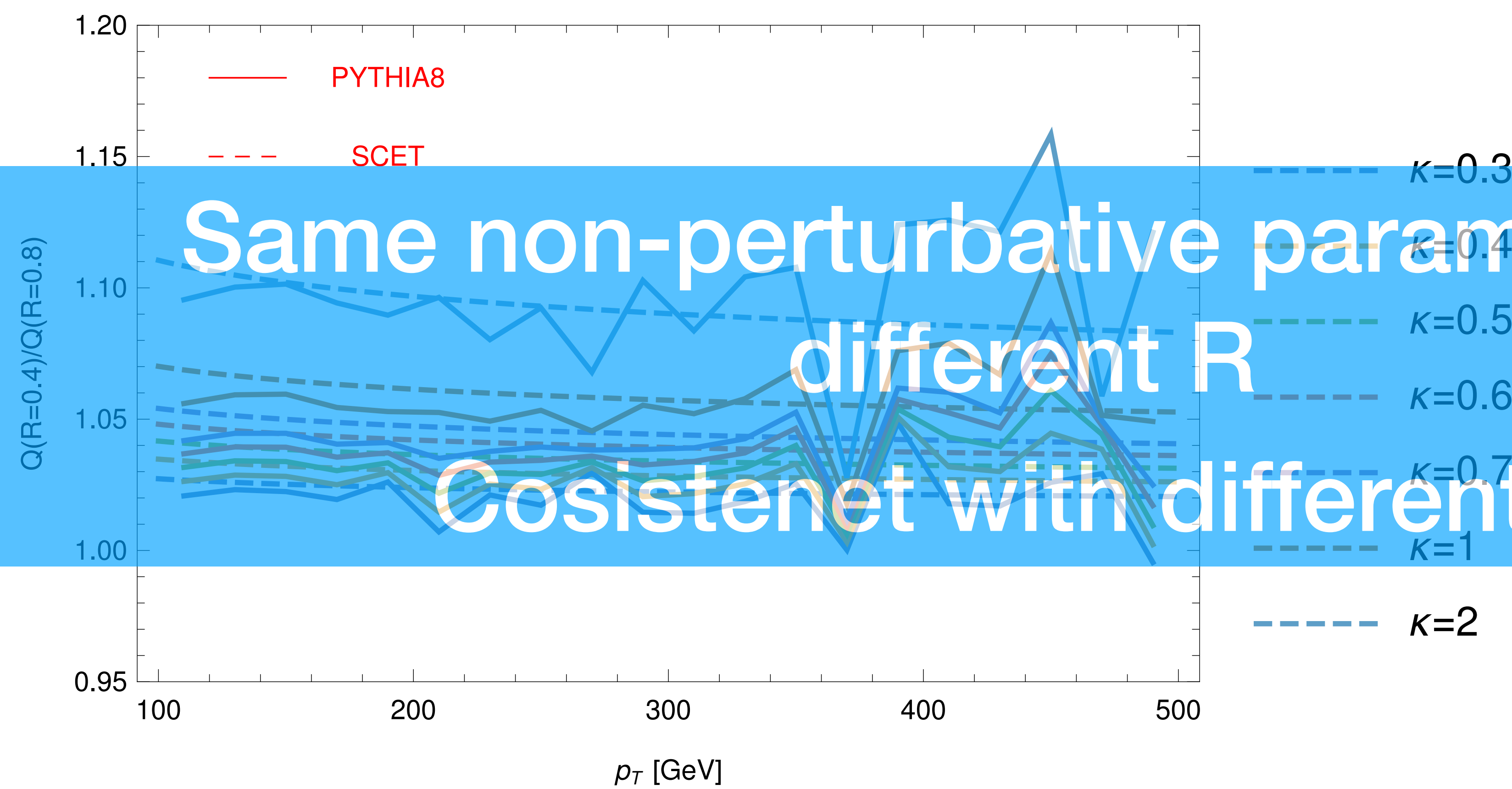


Same non-perturbative parameter for different R

Cosistenet with different κ

Nuclear Matter Effects

Jet charge in heavy-ion collisions

HTL, Vitev, arXiv:1908.06979

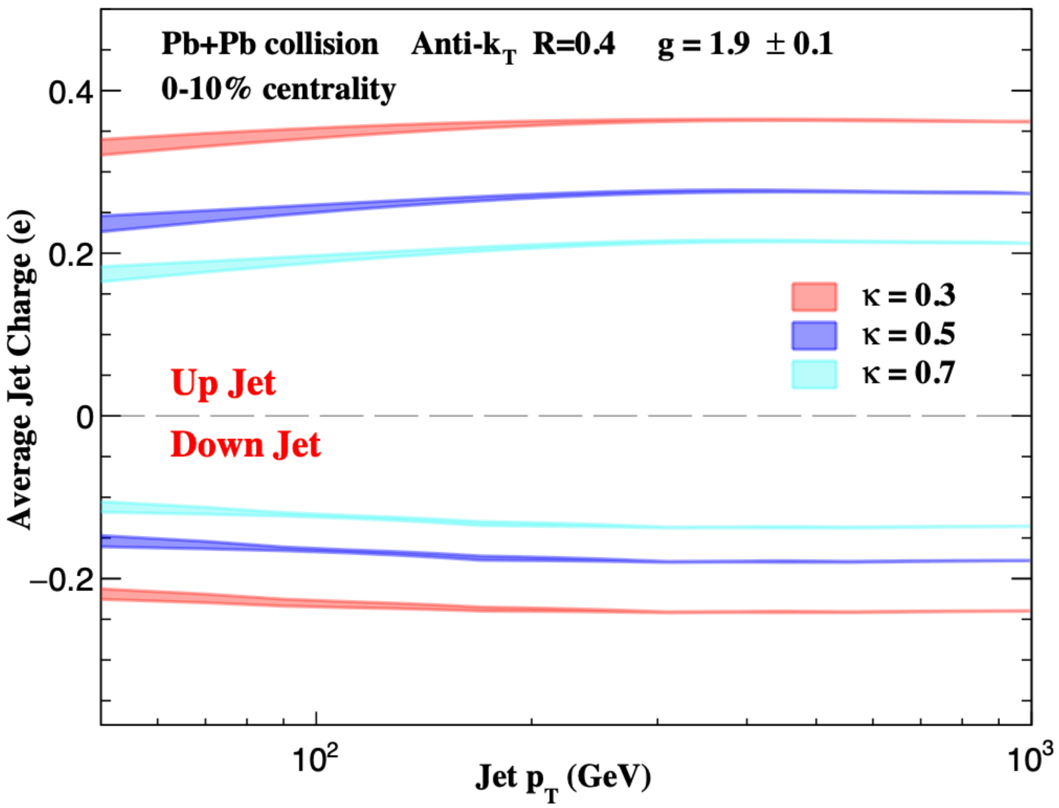
Evolution in Medium

$$\langle Q_{q,\kappa}^{\mathrm{eA}}\rangle = \langle Q_{q,\kappa}^{\mathrm{ep}}\rangle \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'}\frac{\alpha_s(\mu')}{2\pi^2}(2\pi\mu'^2)\tilde{f}_{qq}^{\mathrm{med}}(\kappa,\mu')\right]$$

$$\times\left(1+\tilde{\mathcal{J}}_{qq}^{\mathrm{med}} - J_q^{\mathrm{med}}\right) + \mathcal{O}(\alpha_s^2)$$

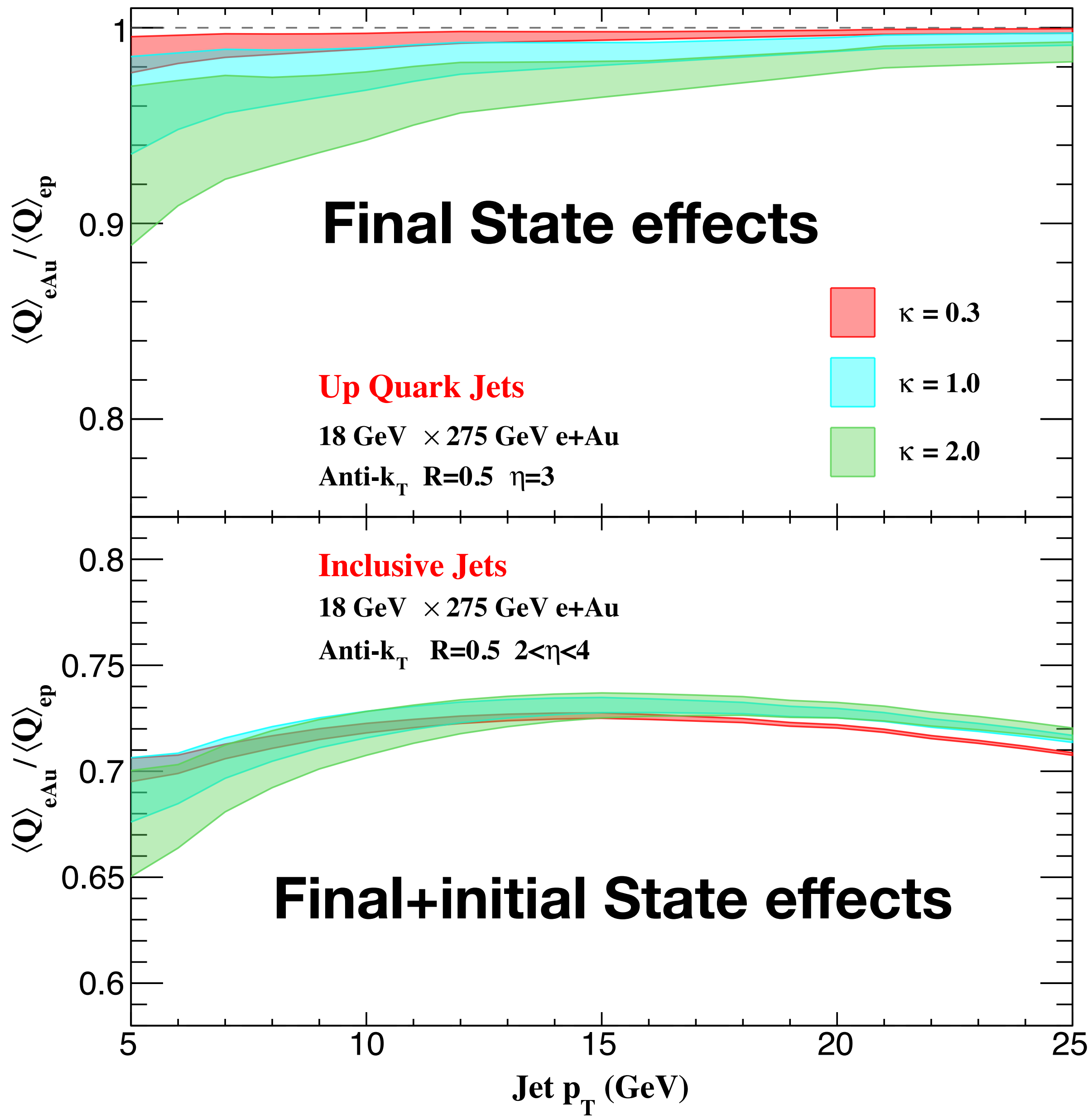
Fixed order corrections to Jet Function

In Heavy-Ion Collisions



- ❑ For charge of a given jet flavor, only finial state effects matter
- ❑ For inclusive jet, the fraction of jet flavors plays an important role

Jet Charge



In geneneral, final state effects are small

Larger correction for larger κ

At LO, approximately

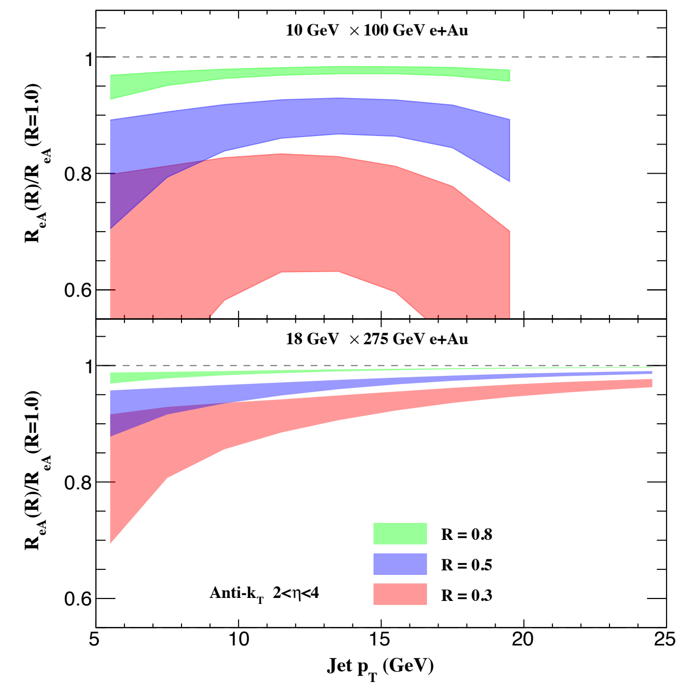
$$\langle Q_\kappa \rangle = (f_u - f_{\bar{u}}) \langle Q_\kappa^u \rangle + (f_d - f_{\bar{d}}) \langle Q_\kappa^d \rangle$$

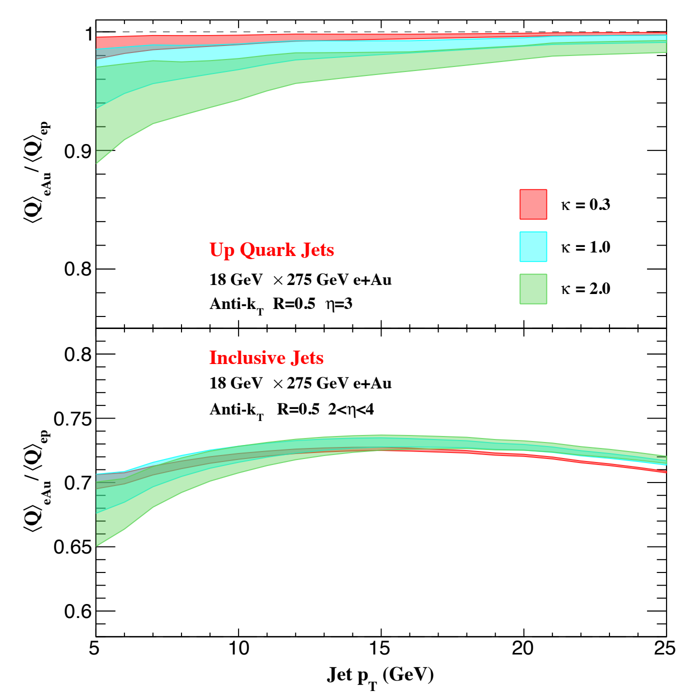
Cancellation between u and d jet

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

Conclusion

- we investigated the nuclear matter effect for jet production at EIC
- we presented theoretical predictions for the inclusive jet cross section and average jet charge at EIC
- we discussed how to disentangle the initial state effect and final state effect at EIC





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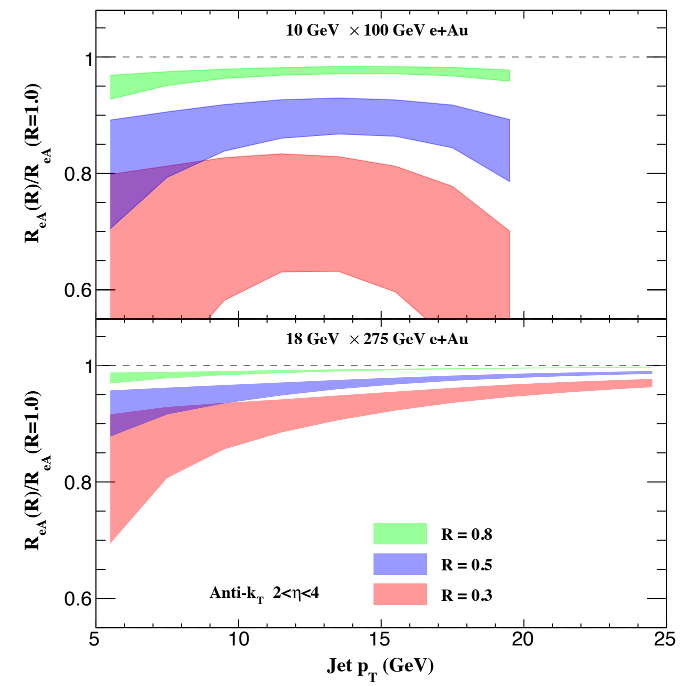
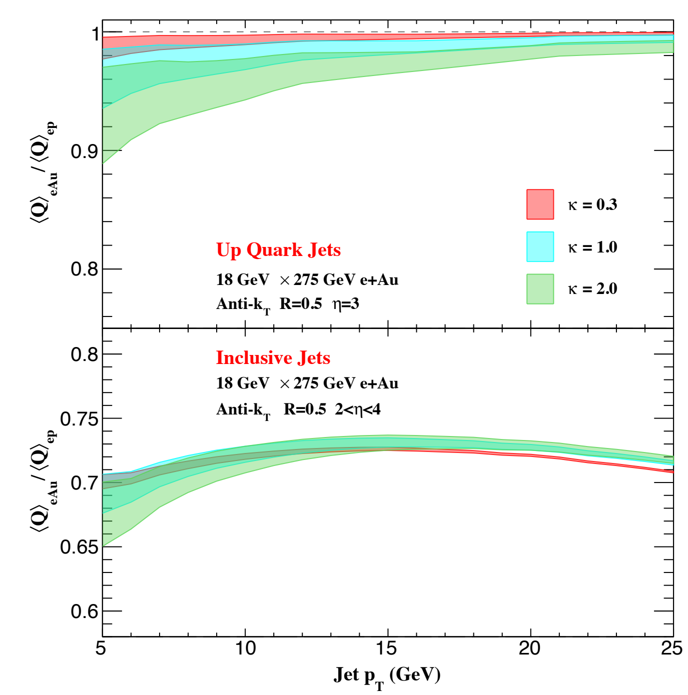


Understand the nuclear matter effects

Extract the flavor information and constrain the nuclear PDFs.



Thank you!