Jets and Heavy Flavor at the Electron-Ion Collider

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Base on the works in collaboration
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中国高能核物理网络论坛

(High Energy Nuclear Physics in China, HENPIC)

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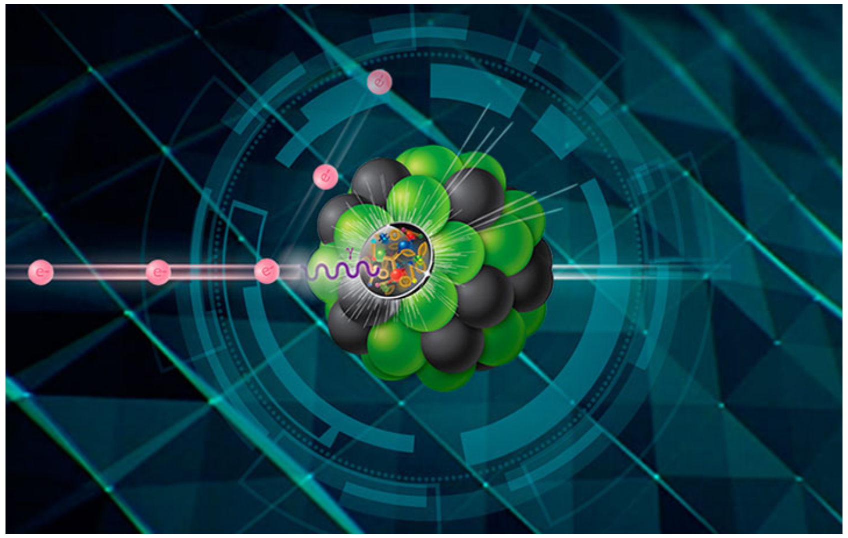
Outline

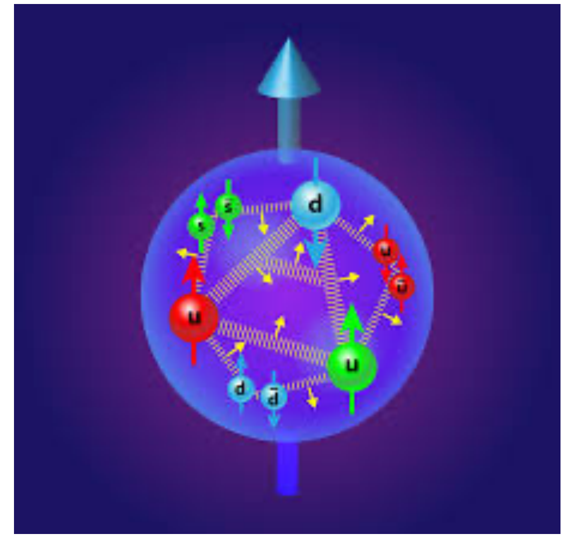
1. Introduction
2. TEEC/EEC in DIS
3. Heavy-flavor Meson production at EIC
4. Jet production at EIC
5. Conclusion

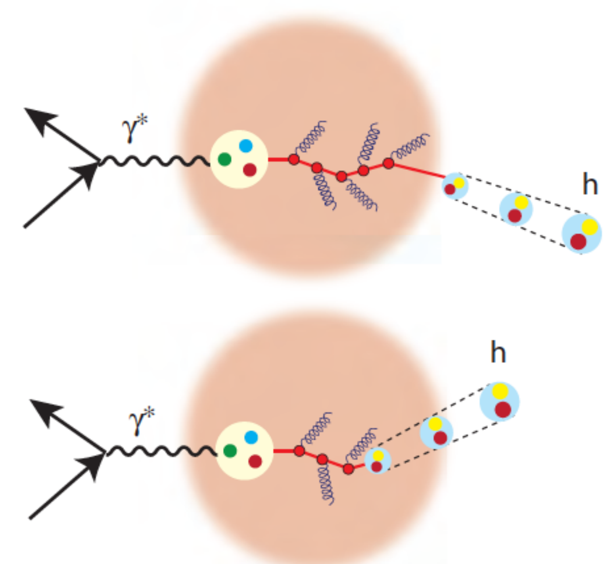
TEEC at EIC: arXiv:2006.02437; EEC at EIC: arXiv:2101.xxxxx

Mesons at EIC: arXiv:2007.10994; Jets at EIC: arXiv:2010.05912

Introduction







Use jet and hadron as precision probes at EIC to get better understanding of QCD and nucleon

- ❑ The origin of mass and the role of gluons
- ❑ The internal landscape of nucleons and nuclei, 3D tomography
- ❑ Gluon saturation
- ❑ Transport properties of large nuclei and the physics of hadronization
- ❑ …..

A lot of new developments are in the area of jets and heavy flavor at EIC

No calculations of nuclear effects in meson and jet production – a void in the e+A program.

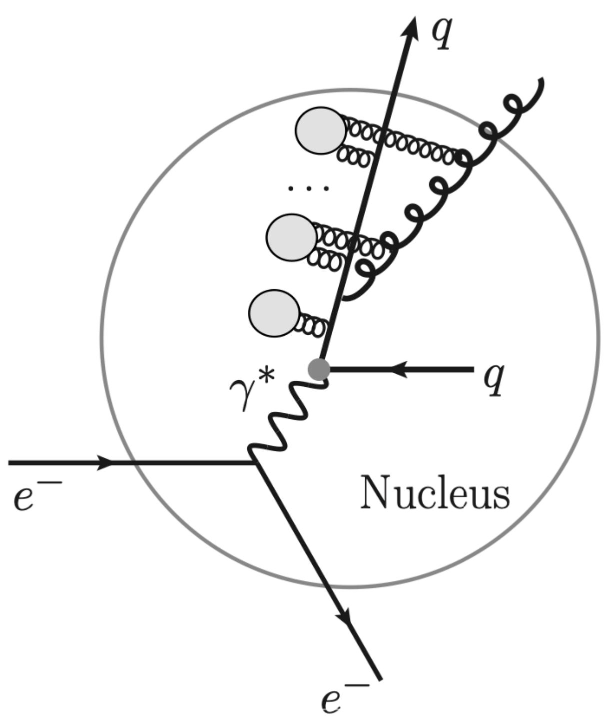
Introduction

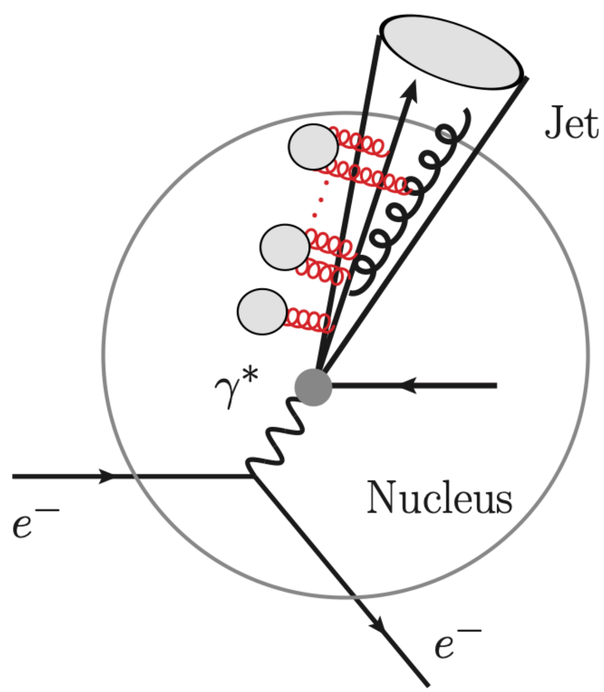
Precision study in e+p collisions

TEEC/EEC: New Event Shape variables

- measures the flow of radiation in a scattering event.
- be studied theoretically and experimentally with high precision
- be used to determinate strong coupling
- be used to study TMD physics at various colliders

Study of cold nuclear matter effect in e+A collisions





to identify kinematic region where nuclear matter effect is relative large

to disentangle the effects from nuclear PDFs and final state interaction

Building Blocks for nuclear effects

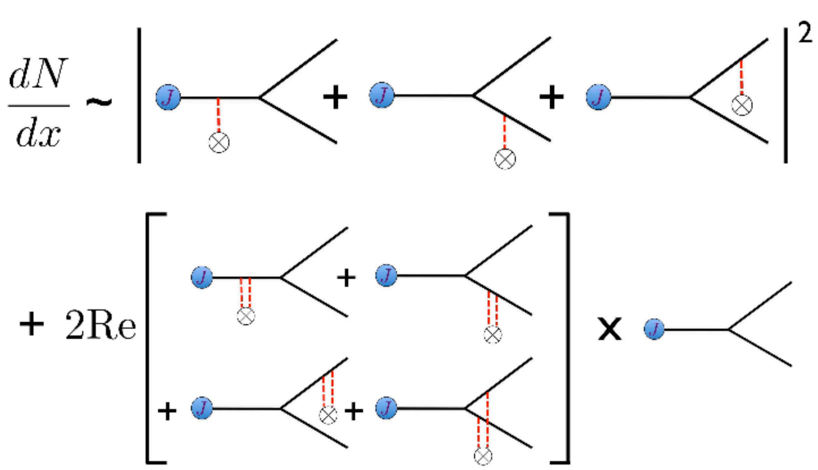
Effective Lagrangian in SCET with medium-induced interaction

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

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

Ovanesyan, Vitev, arXiv: 1103.1074

Calculated in the framework of soft-collinear effective theory with Glauber gluon interactions

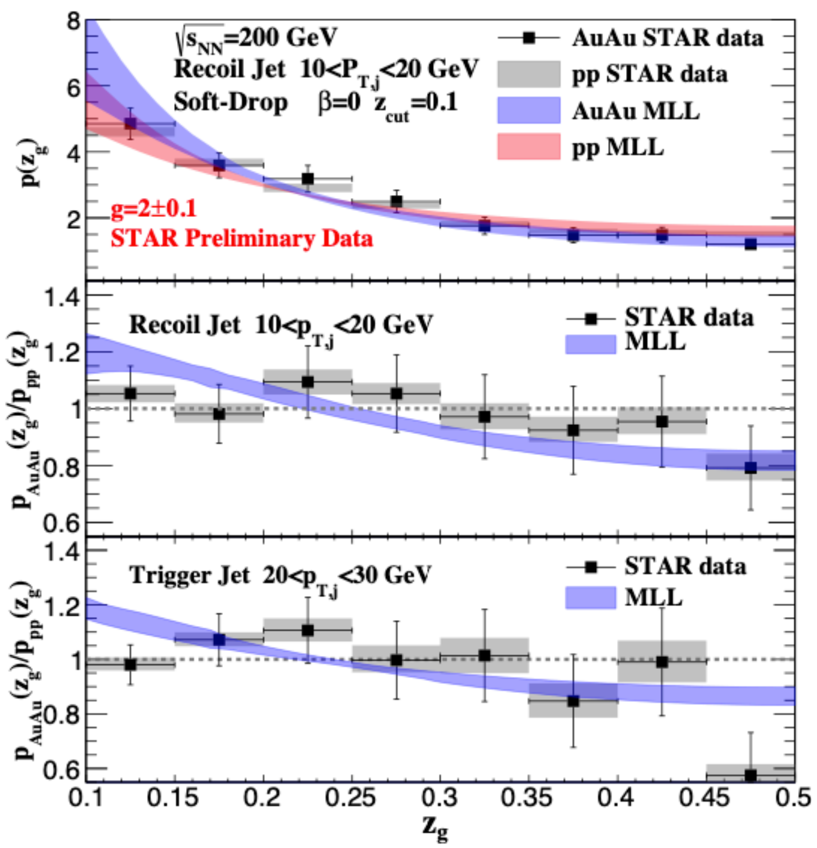


$$\left(\frac{dN^{\mathrm{med}}}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\boldsymbol{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\mathrm{med}}}{d^2\boldsymbol{q}_\perp}\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\b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

Ovanesyan, Vitev, arXiv: 1103.1074

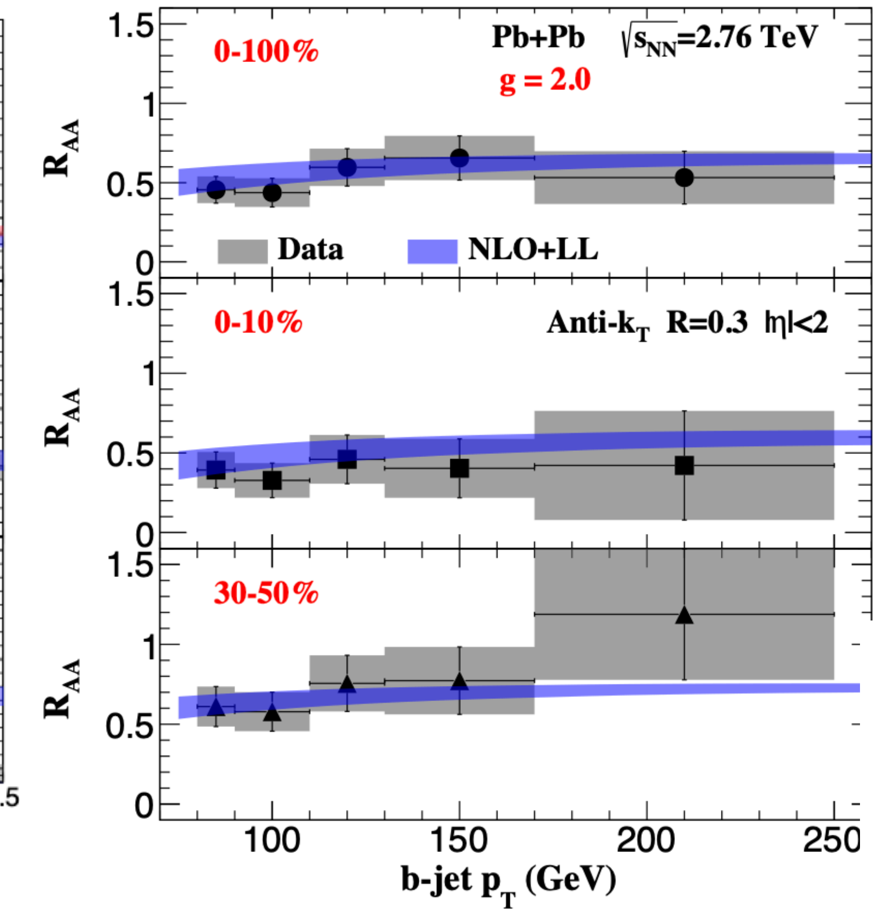
See the work arXiv:1807.03799 and 1903.0617 for the method for the calculation up to any order of opacity.

Applications in HIC



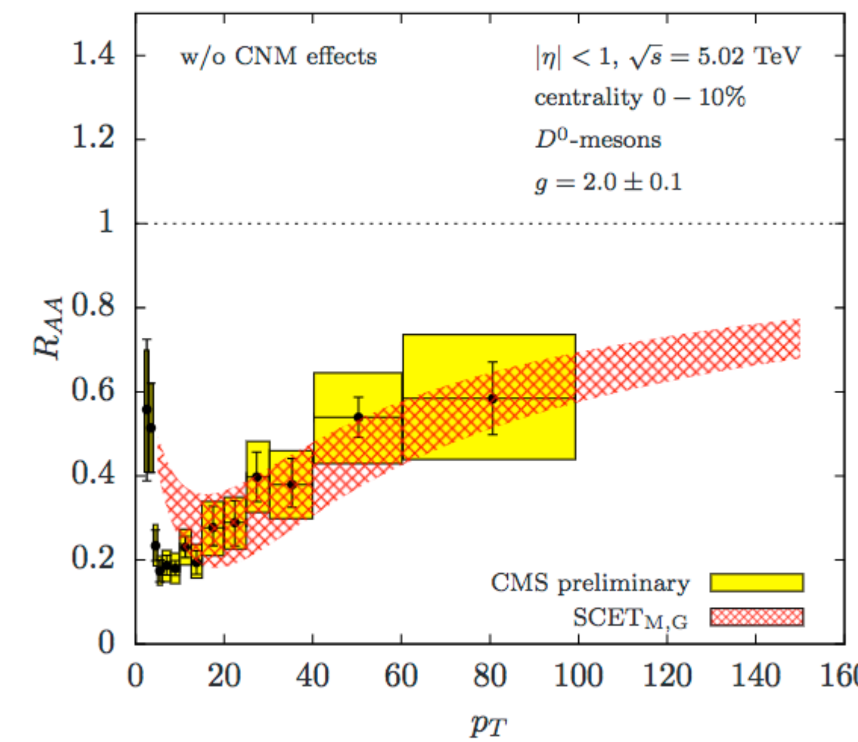
Jet z_g

HTL, Vitev, 2017



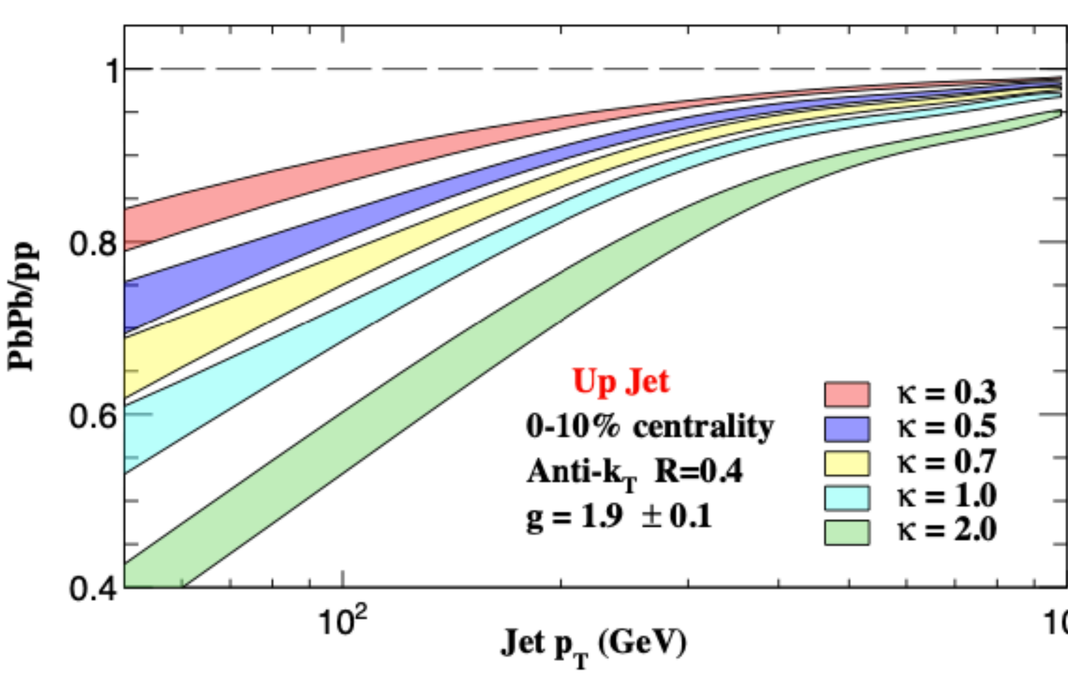
Heavy-flavor jet

HTL, Vitev, 2017



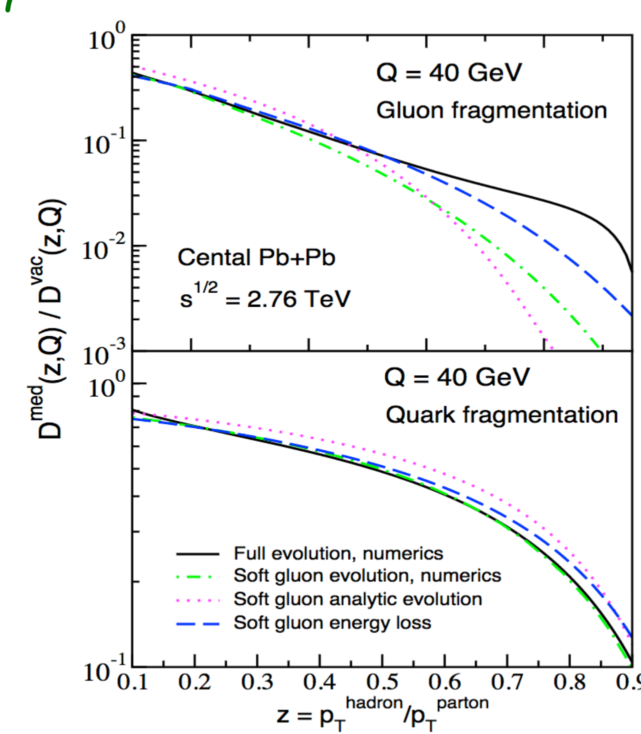
Nuclear modification factor RAA for D0 meson (massive)

Kang et al 2016



Jet Charge

HTL, Vitev, 2017



Modification of fragmentation functions for gluon and quark

Kang et al 2014

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TEEC in DIS

HTL, Vitev, Zhu, 2020

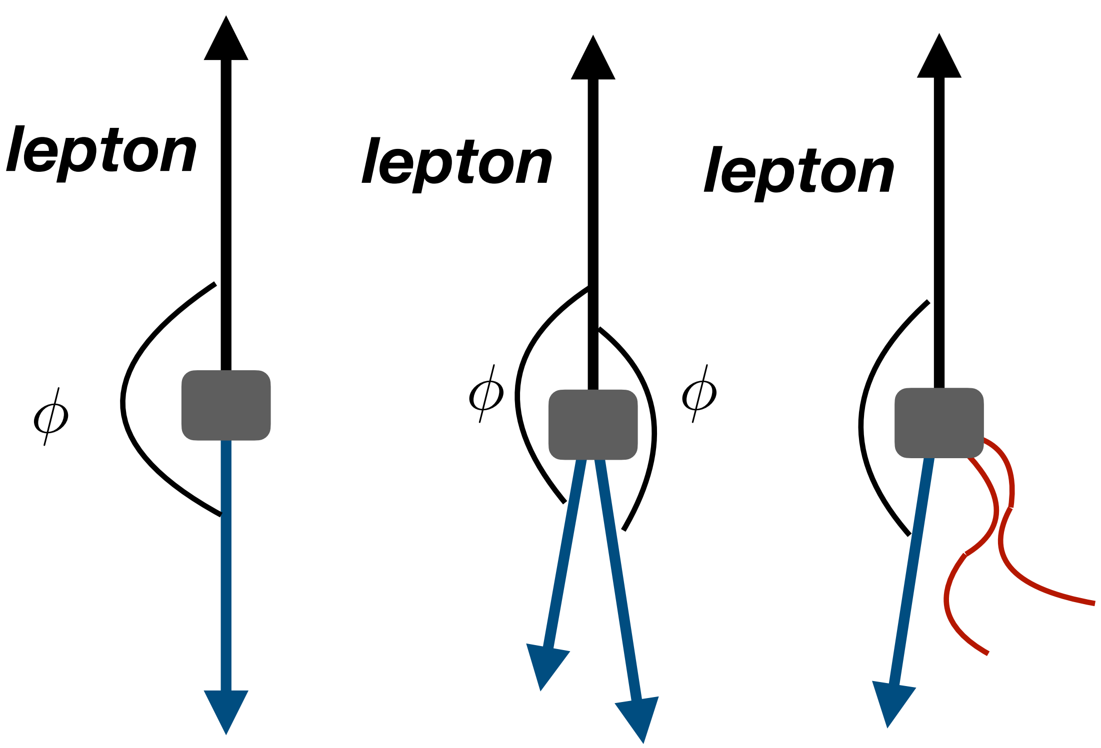
Definition

$$\mathrm{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

sum over all hadrons

energy weighted

measure azimuthal angle correlations



$$\delta(\tau)$$

$$A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$$

$$\tau = \frac{1+\cos\phi}{2}$$

Measure momentum imbalance in y direction

TEEC in DIS

HTL, Vitev, Zhu, 2020

Definition

$$\mathrm{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

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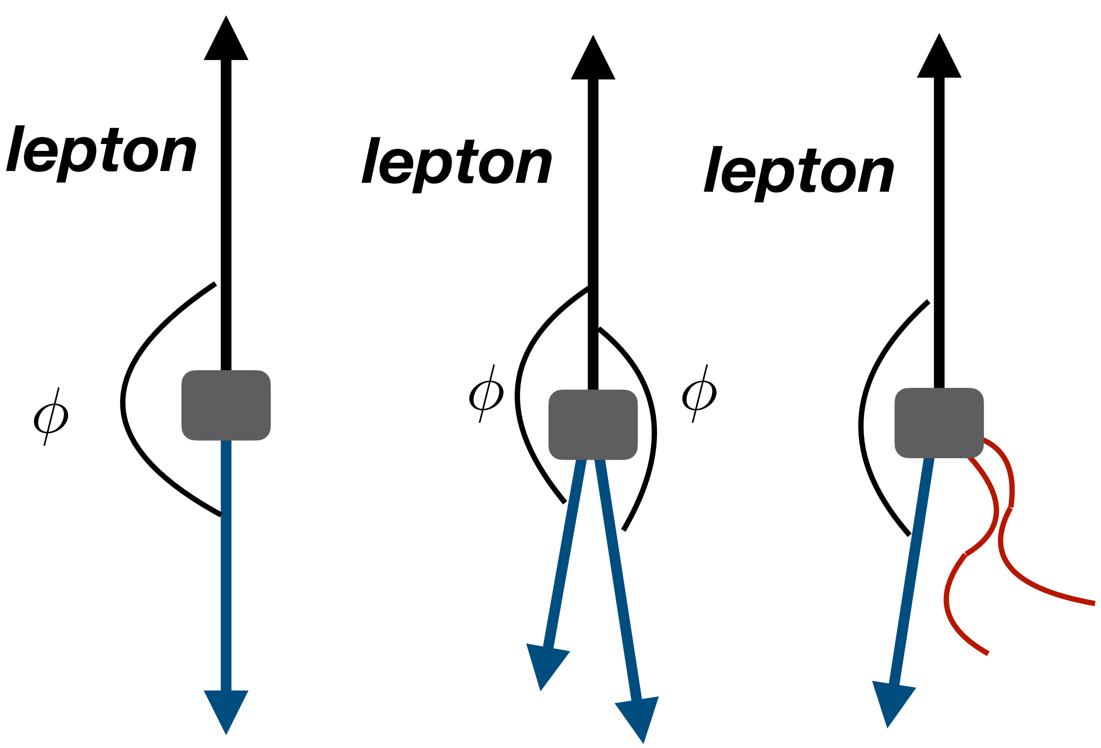


$\delta(\tau)$

$A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$

$$\tau = \frac{1+\cos\phi}{2}$$

Measure momentum imbalance in y direction

For Hadron production

TMD PDF

$$\frac{d\sigma_h}{d^2p_\perp} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int \frac{db}{2\pi} e^{ib_\perp\cdot p_\perp} f_{f/N}\left(b,\xi,\mu,\nu\right) S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right) \int \frac{dz}{z^2} F_{h/f}\left(z, b/z, E_4, \mu, \nu\right)$$

TMD soft

TMDFF

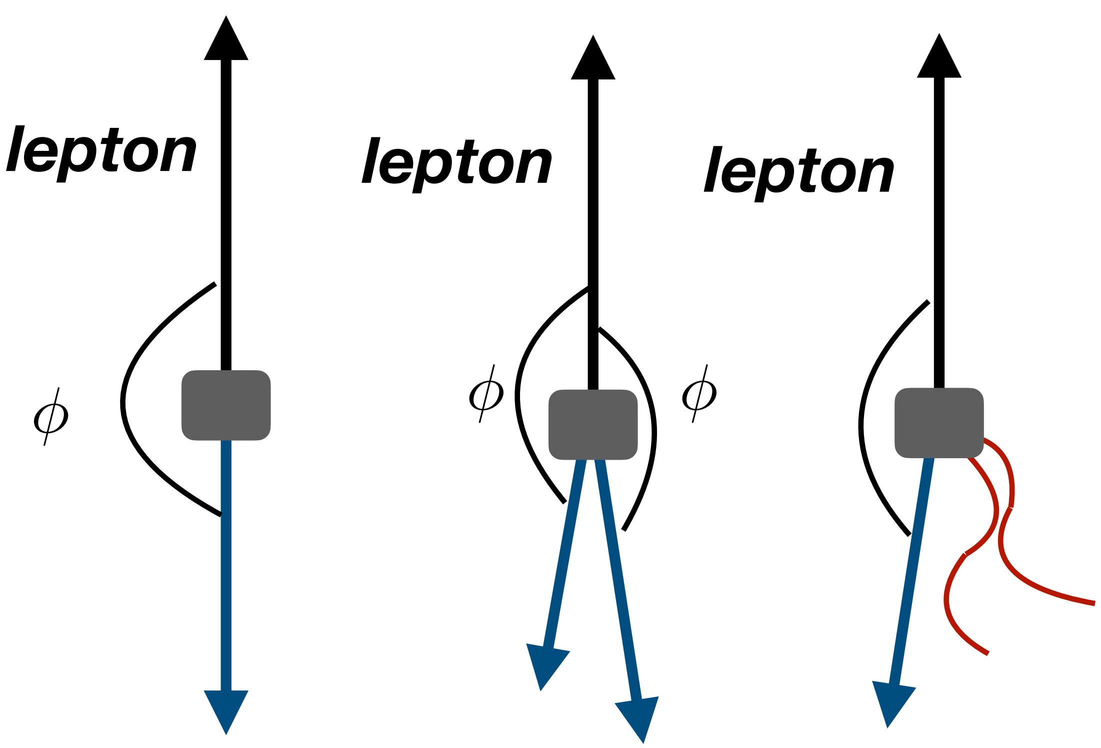
TEEC in DIS

HTL, Vitev, Zhu, 2020

Definition

$$\mathrm{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

- $\sum_a$: sum over all hadrons
- $\frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}}$: energy weighted
- $\delta(\cos\phi_{la} - \cos\phi)$: measure azimuthal angle correlations



$\delta(\tau)$ $\quad A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$

$$\tau = \frac{1+\cos\phi}{2}$$

Measure momentum imbalance in y direction

For Hadron production

$$\frac{d\sigma_h}{d^2p_\perp} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int \frac{db}{2\pi} e^{ib_\perp\cdot p_\perp} f_{f/N}(b,\xi,\mu,\nu)\, S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right) \int \frac{dz}{z^2} F_{h/f}(z, b/z, E_4, \mu, \nu)$$

- $f_{f/N}(b,\xi,\mu,\nu)$: TMD PDF
- $S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right)$: TMD soft
- $\int \frac{dz}{z^2} F_{h/f}(z, b/z, E_4, \mu, \nu)$: TMDFF

sum over all hadrons in the final state

$$\frac{d\sigma_h}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int dk_y \int \frac{db}{2\pi} e^{-ib_y\cdot k_y} f_{f/N}(b,\xi,\mu,\nu)$$
$$S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right) \sum_h \int z dz\; F_{h/f}(z, b/z, E_4, \mu, \nu)\, \delta(\tau - \tau(k_y))$$

TEEC in DIS

HTL, Vitev, Zhu, 2020

Definition $\text{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$

sum over all hadrons | energy weighted | measure azimuthal angle correlations

$$\sum_N \int_0^1 dz z F_{N/q}\left(z, b_\perp/z, \nu\right) = \sum_{i,N}\int_0^1 dz z \int_z^1 \frac{d\xi}{\xi} d_{N/i}(z/\xi)\ \mathscr{C}_{iq}\left(\xi, b_\perp/\xi, \nu\right) + \mathcal{O}\left(b_T^2\Lambda_{\text{QCD}}^2\right) = \sum_{i,N}\int_0^1 dx x \mathscr{C}_{iq}\left(x, b_\perp/\xi, \nu\right)\int_0^1 d\xi \xi d_{N/i}(\xi) + \mathcal{O}\left(b_T^2\Lambda_{\text{QCD}}^2\right)$$

The jet function is the second Mellin-Moment of the matching coefficients

$$J^q\left(b_\perp, \mu, \nu\right) = \sum_i \int_0^1 dx x \mathscr{C}_{iq}\left(x, b_\perp/x, \mu, \nu\right)$$

$\delta(\tau)$

$A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$

$$\tau = \frac{1+\cos\phi}{2}$$

Measure momentum imbalance in y direction

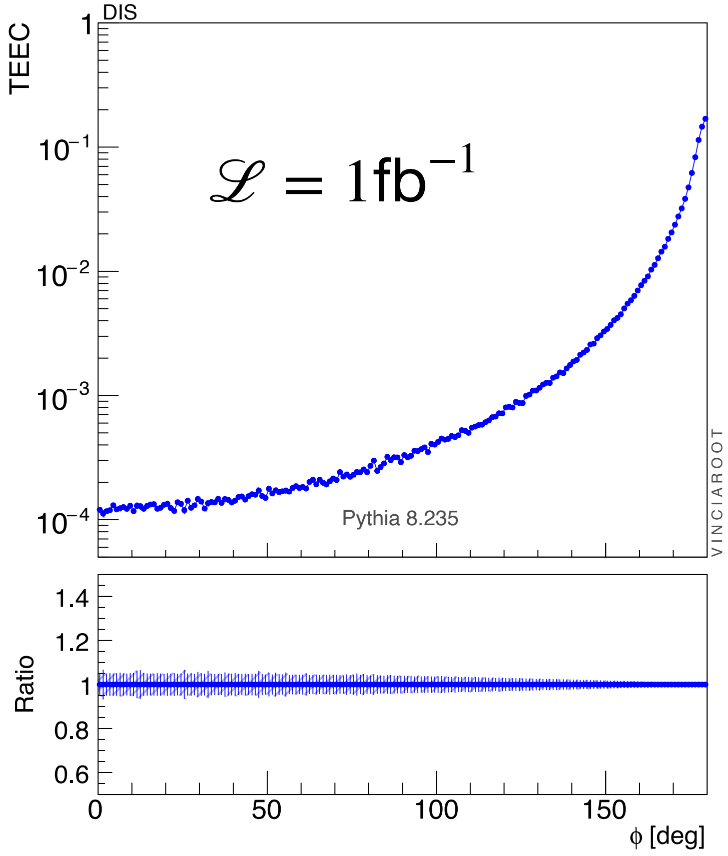
☑ **sum over all hadrons in the final state**

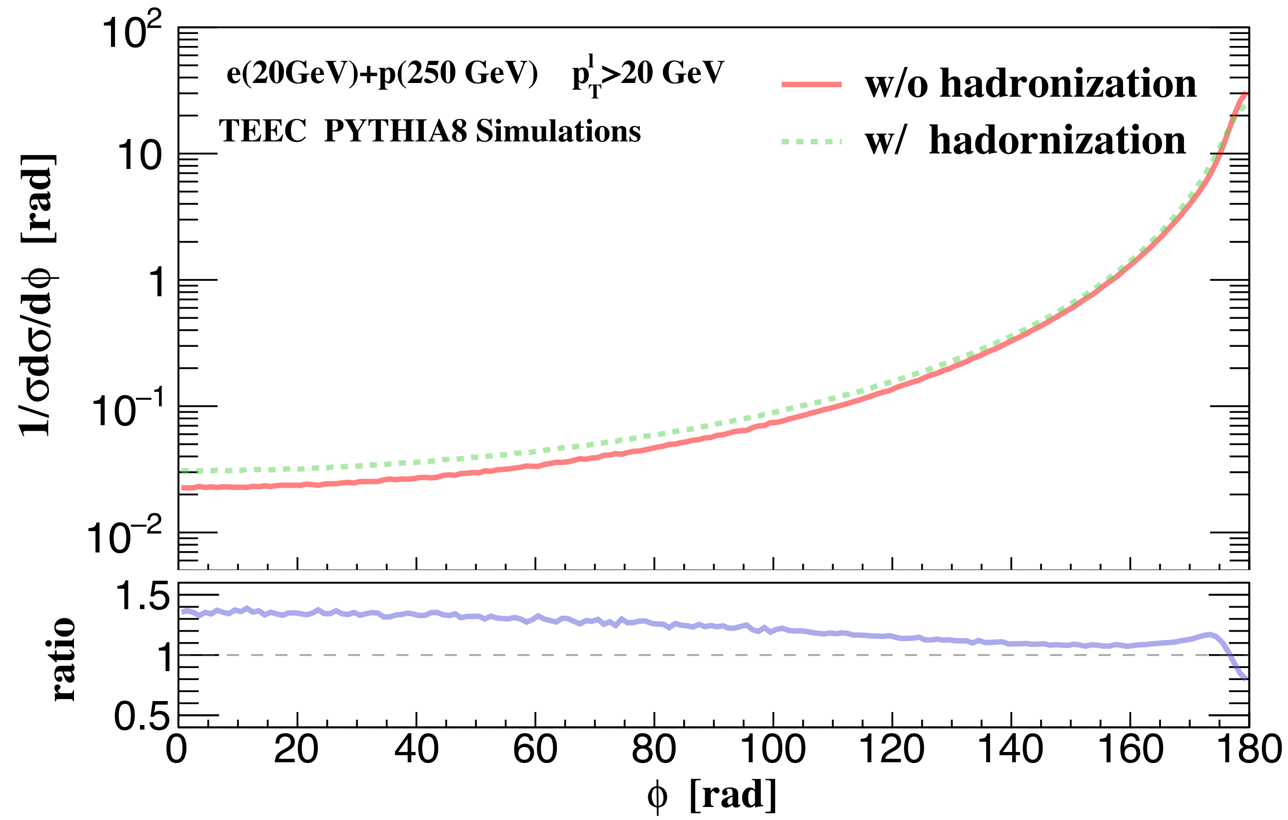
$$\frac{d\sigma_h}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu)\int dk_y \int \frac{db}{2\pi} e^{-ib_y\cdot k_y} f_{f/N}\left(b,\xi,\mu,\nu\right)$$

$$S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right)\sum_h \int z dz\ F_{h/f}\left(z, b/z, E_4, \mu, \nu\right)\delta(\tau - \tau(k_y))$$

TEEC in DIS

HTL, Vitev, Zhu, 2020



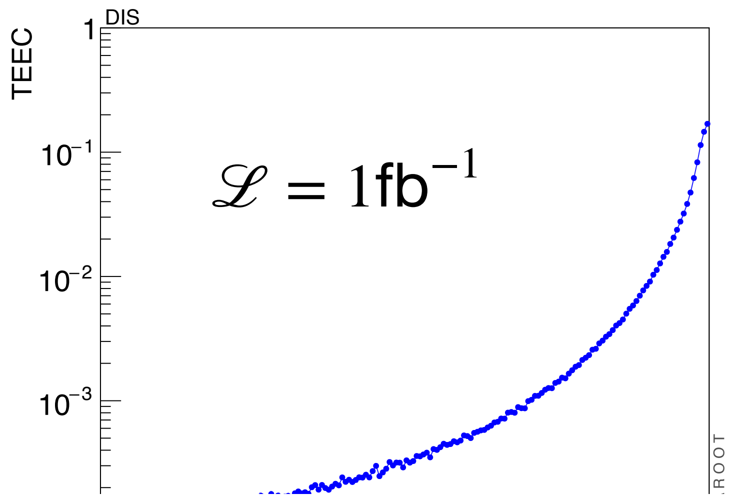


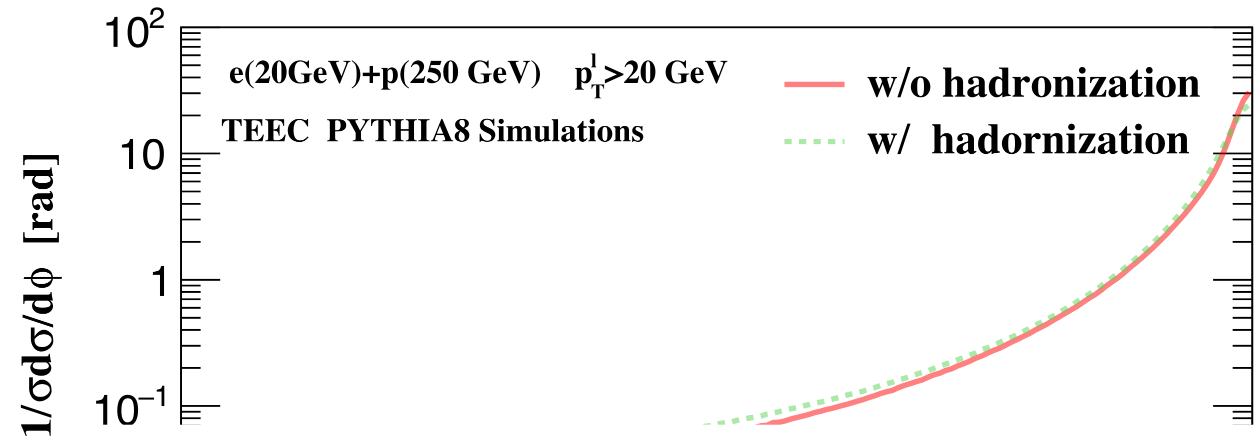
It is possible to study this observable in percent level

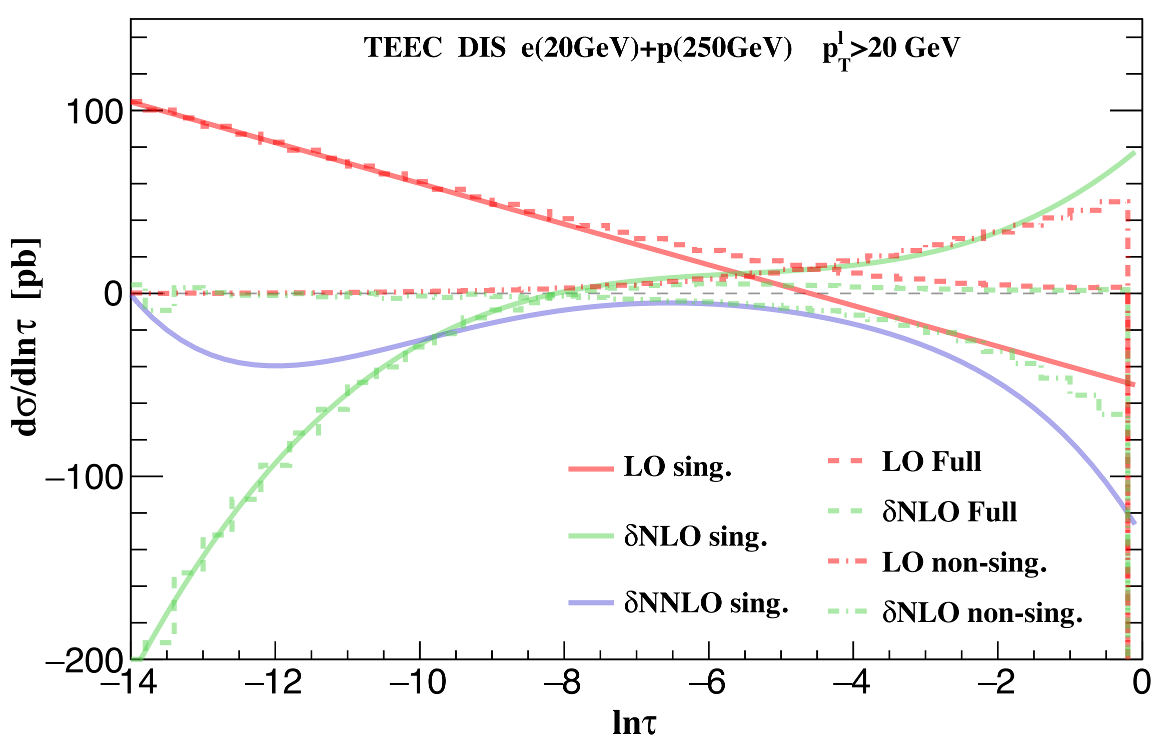
Relatively small hadronization effects

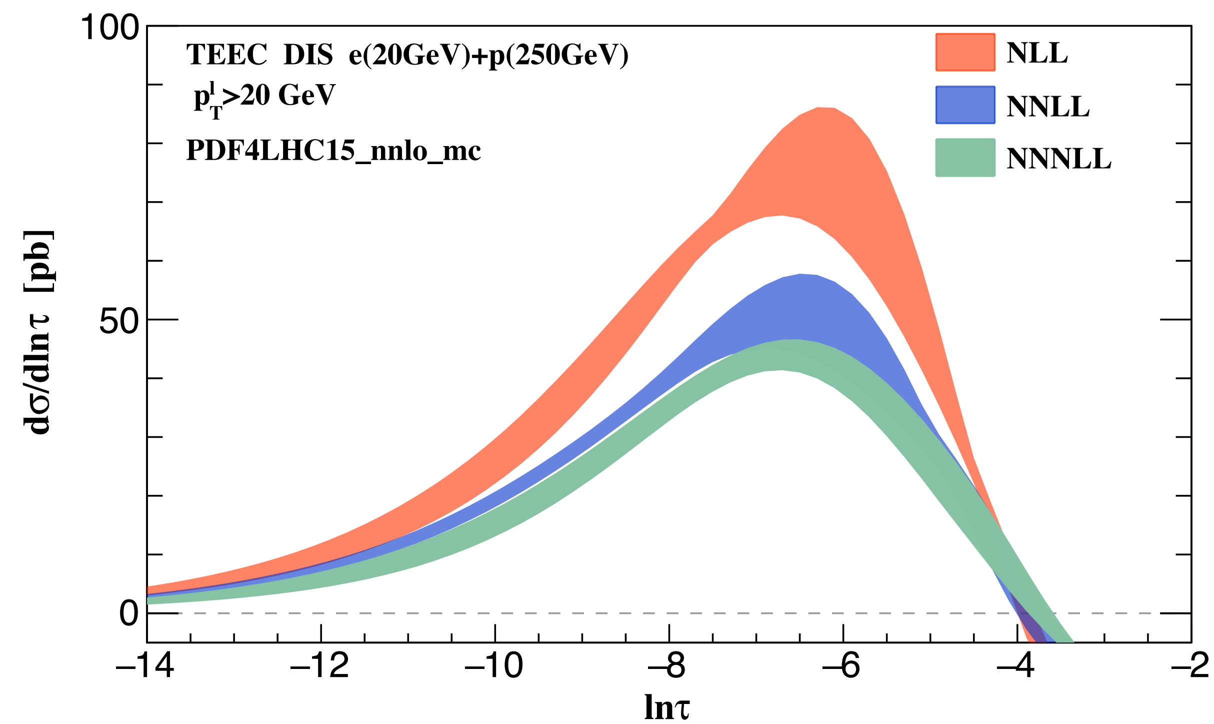
TEEC in DIS

HTL, Vitev, Zhu, 2020





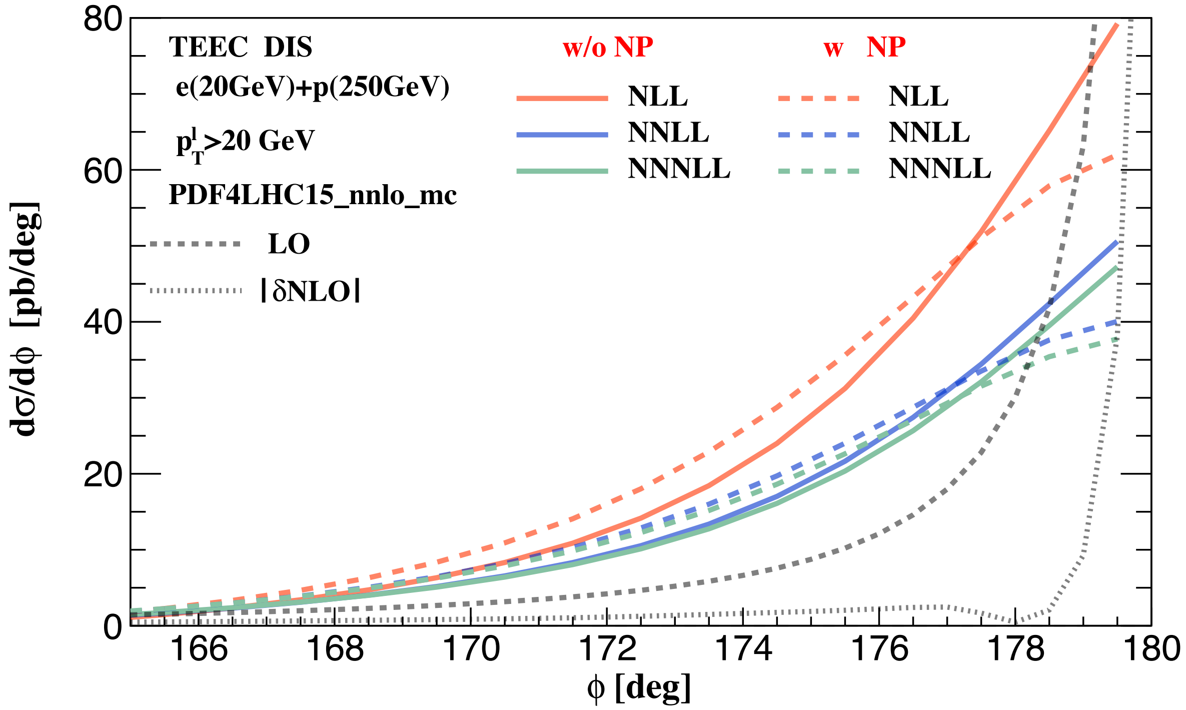




- Full control of the distributions in the back-back limit.
- We obtained singular distribution up to NNLO (three loop anomalous dimensions)
- Convergence in back-to-back limit after resummation
- Huge difference from NLL to NNLL and good perturbative convergence from NLL to NNNLL
- Reduction of scale uncertainties order by order from NLL to NNNLL

TEEC in DIS

HTL, Vitev, Ma, 2020

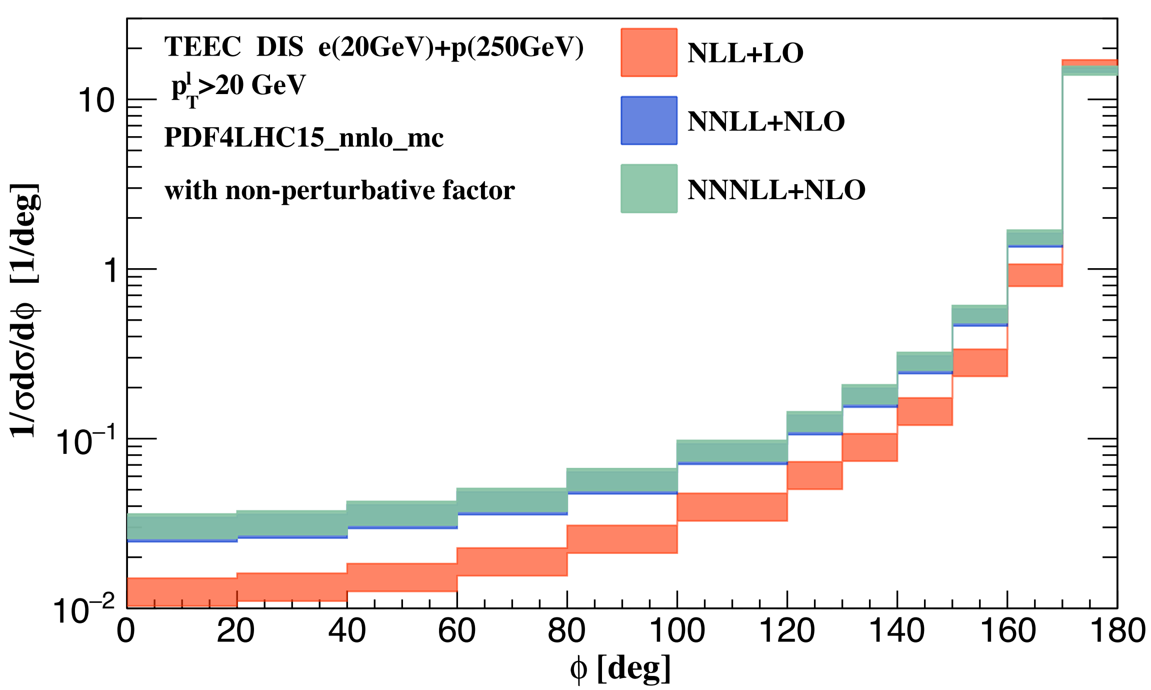


$$S_{\rm NP} = \exp\left[-0.106\, b^2 - 0.84 \ln Q/Q_0 \ln b/b^*\right]$$

NP shifts the cross section

Sizable NP effects in back-to-back limit

Nuclear matter effects are expected in this region



Prediction in full ϕ range

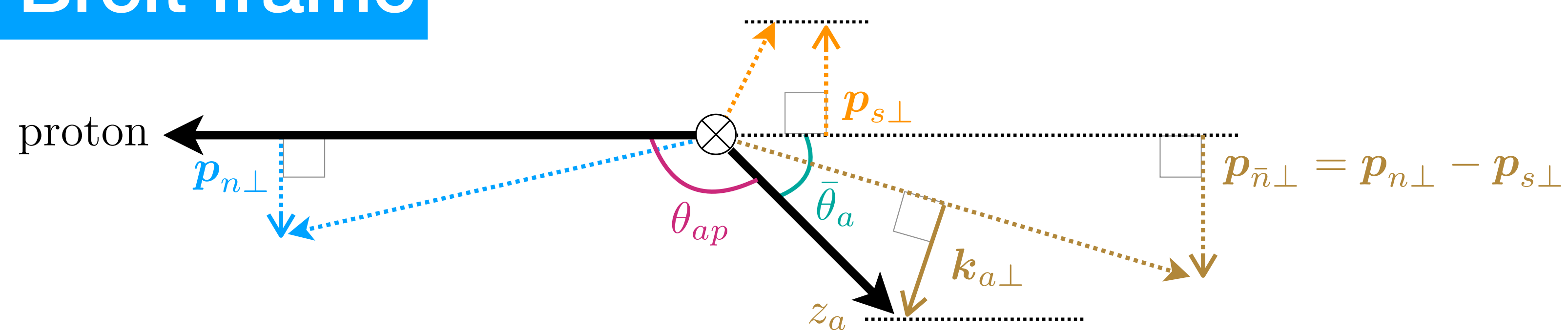
Uncertainties from fixed order are dominated

NNLO matching will improve the predictions

EEC in DIS

An extension to Breit frame

HTL, Vitev, Makris, in preparation



Sum over all the hadrons in final state

$$\text{BEEC} = \frac{1}{\sigma}\sum_a \int d\sigma(\ell + h \to \ell + a + X)\frac{P\cdot p_a}{P\cdot q}\delta(\cos\theta_{ap} - \cos\theta)$$

opening angle between hadron and proton

weight is boost invariant

For $\cos\theta \to -1$, only hadrons with small $p_\perp$ contribute: $p_T = Qz_h\sqrt{\frac{1+\cos\theta}{2}}$

EEC in DIS

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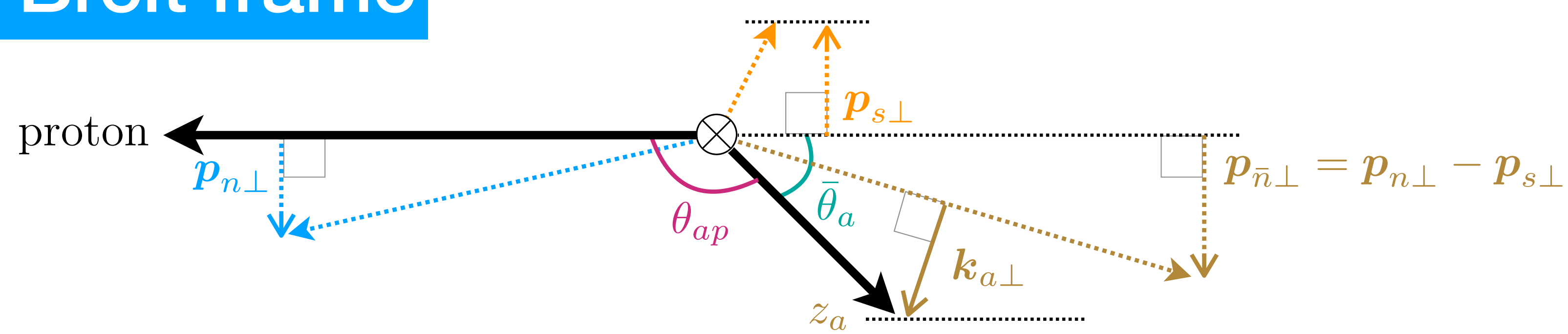

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For $\cos\theta \to -1$, only hadrons with small $p_\perp$ contribute: $p_T = Qz_h\sqrt{\frac{1+\cos\theta}{2}}$

Usual TMD factorization for hadron production can be used

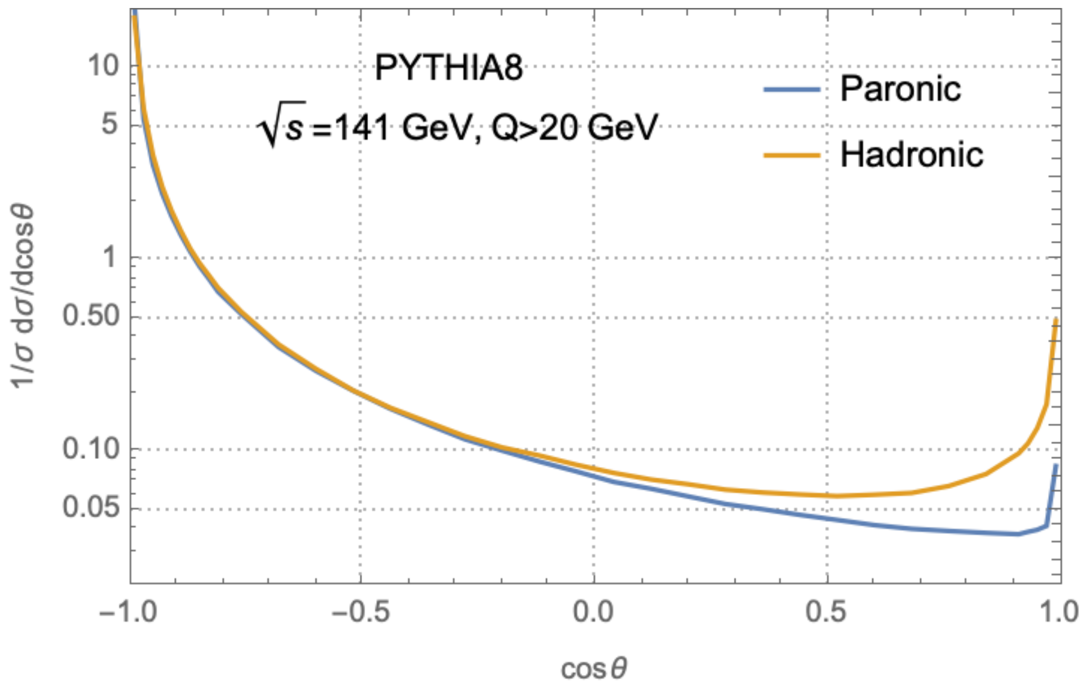
$$d\sigma \propto \text{TMDPDF} \otimes \text{Soft} \otimes \sum_{\text{hadrons}} \int dz_h z_h \times \text{TMDFF}$$

$\Rightarrow$ $d\sigma \propto$ TMDPDF $\otimes$ Soft $\otimes$ Jet

better way to connect with TMD physics

EEC in DIS

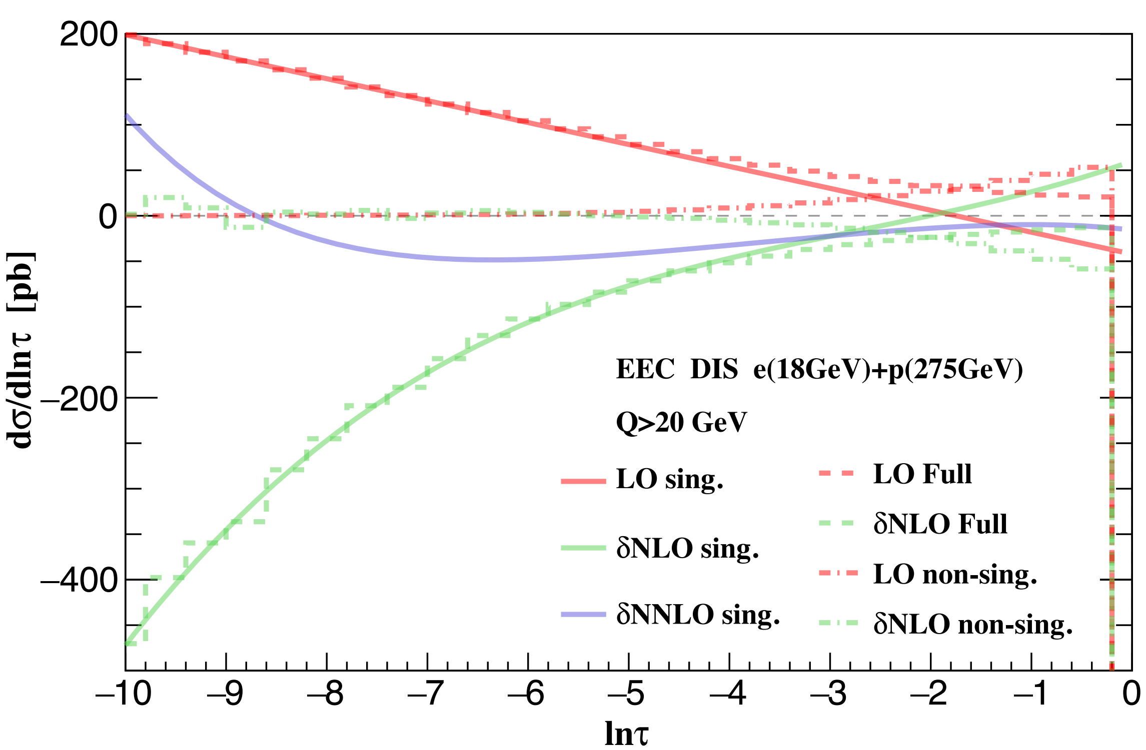
HTL, Vitev, Makris, 2101.xxxxx



In Breit frame,

Rapidity cut only changes the cross section tail region

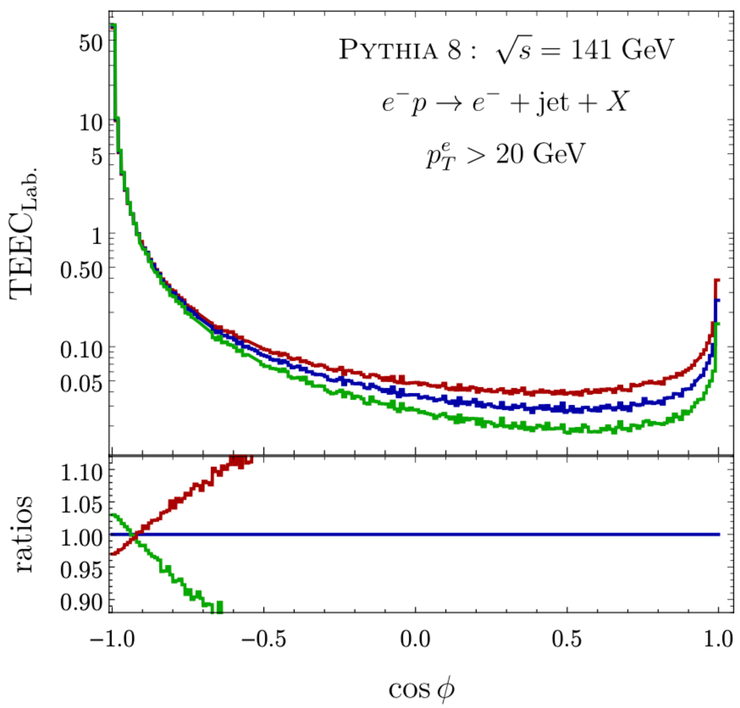
Hadronization effects are only important in the tail region

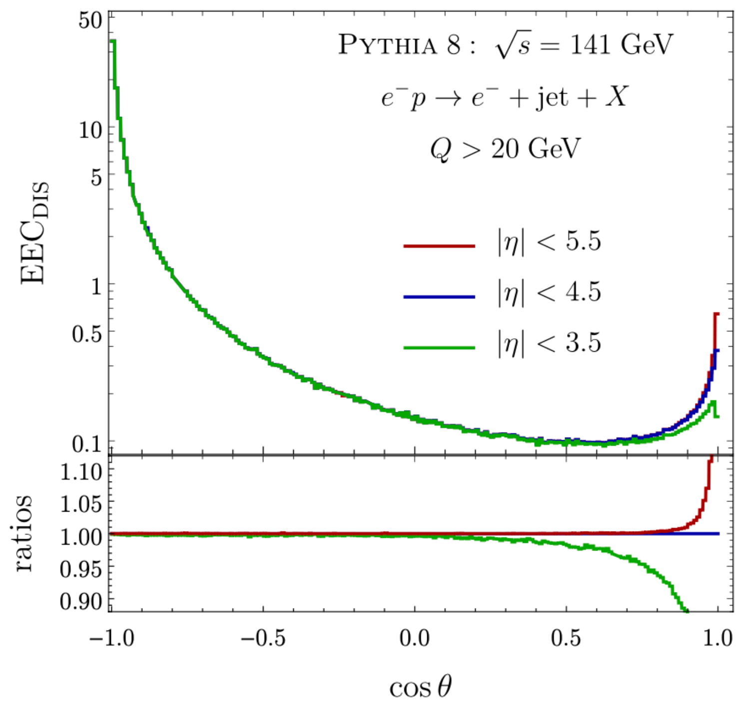


reproduce the singular behaviors

EEC in DIS

HTL, Vitev, Makris, 2101.xxxxx





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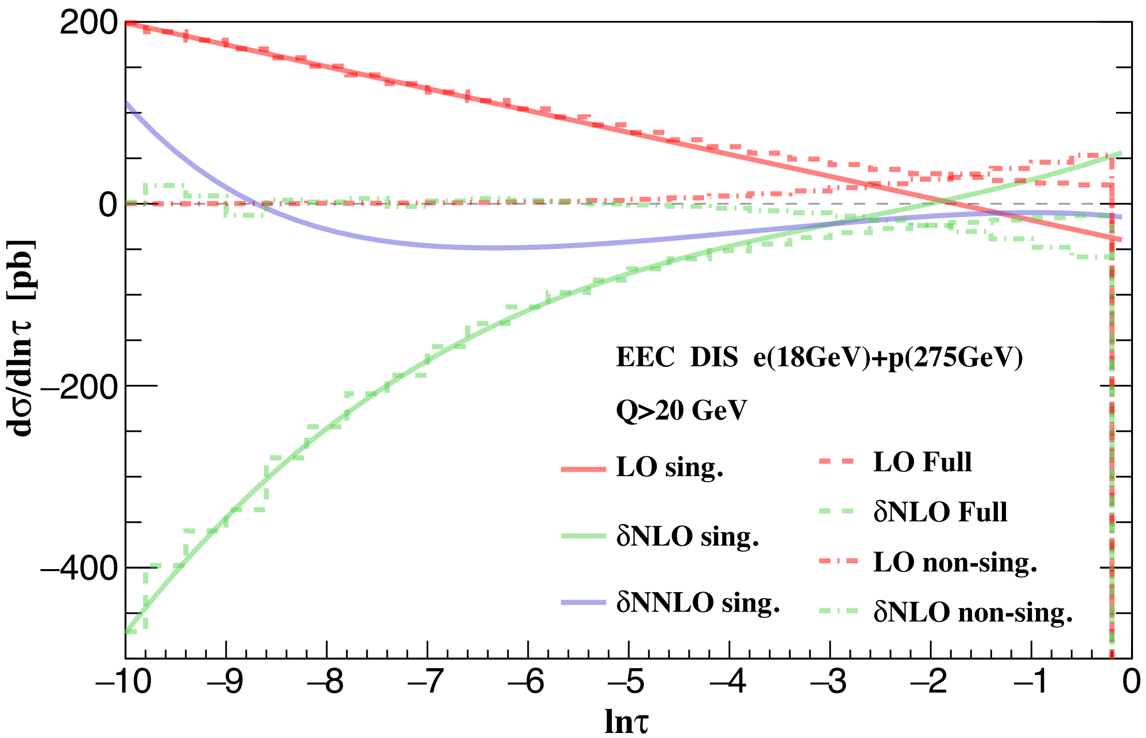
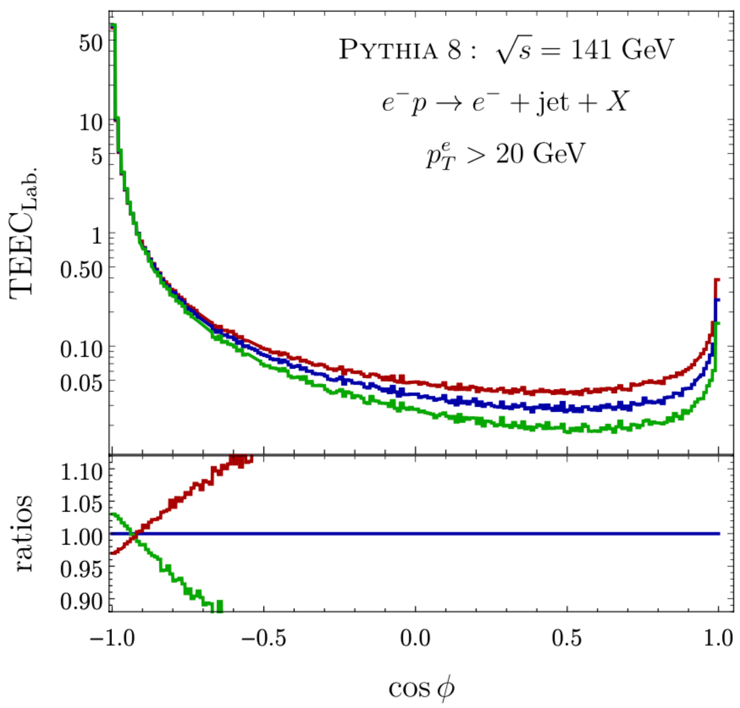
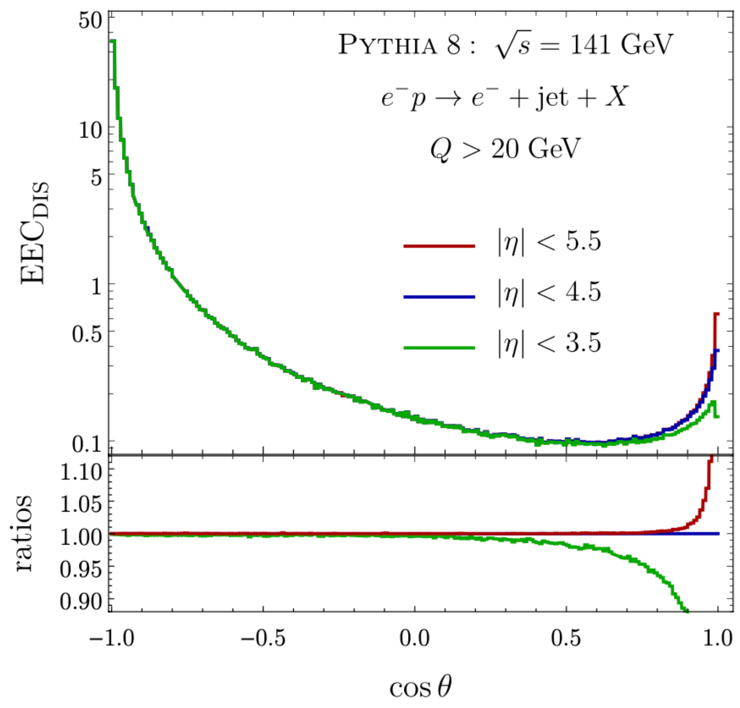


reproduce the singular behaviors

EEC in DIS

HTL, Vitev, Makris, 2101.xxxxx





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Rapidity cut only changes the cross section tail region

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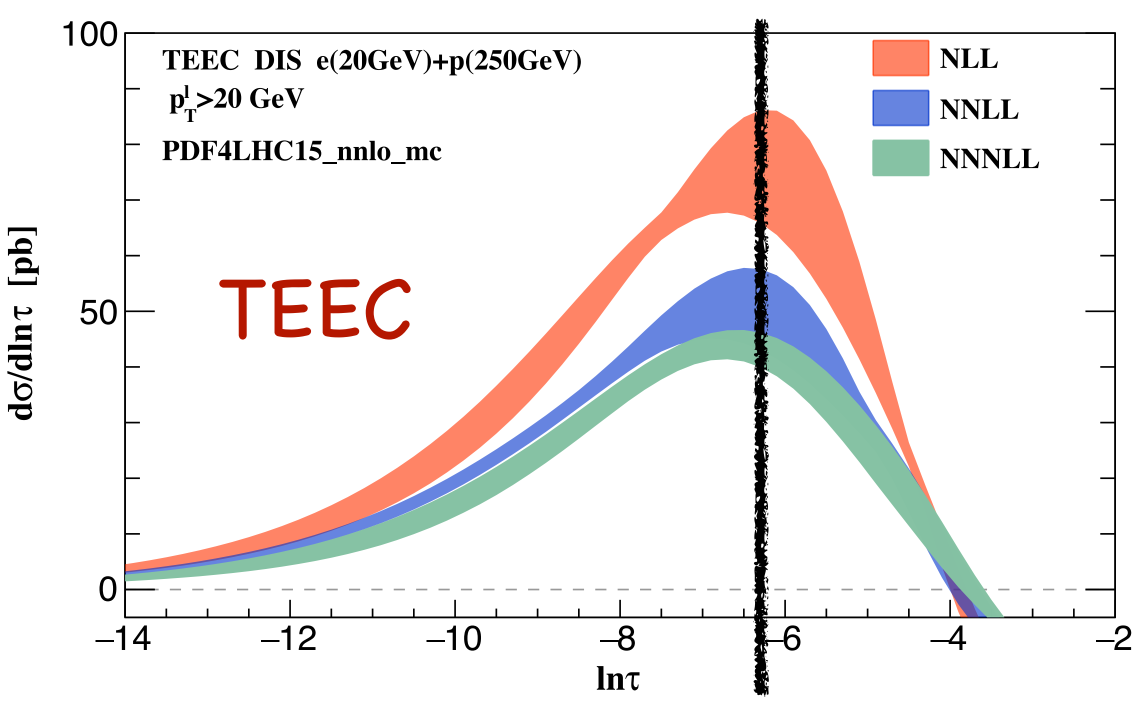
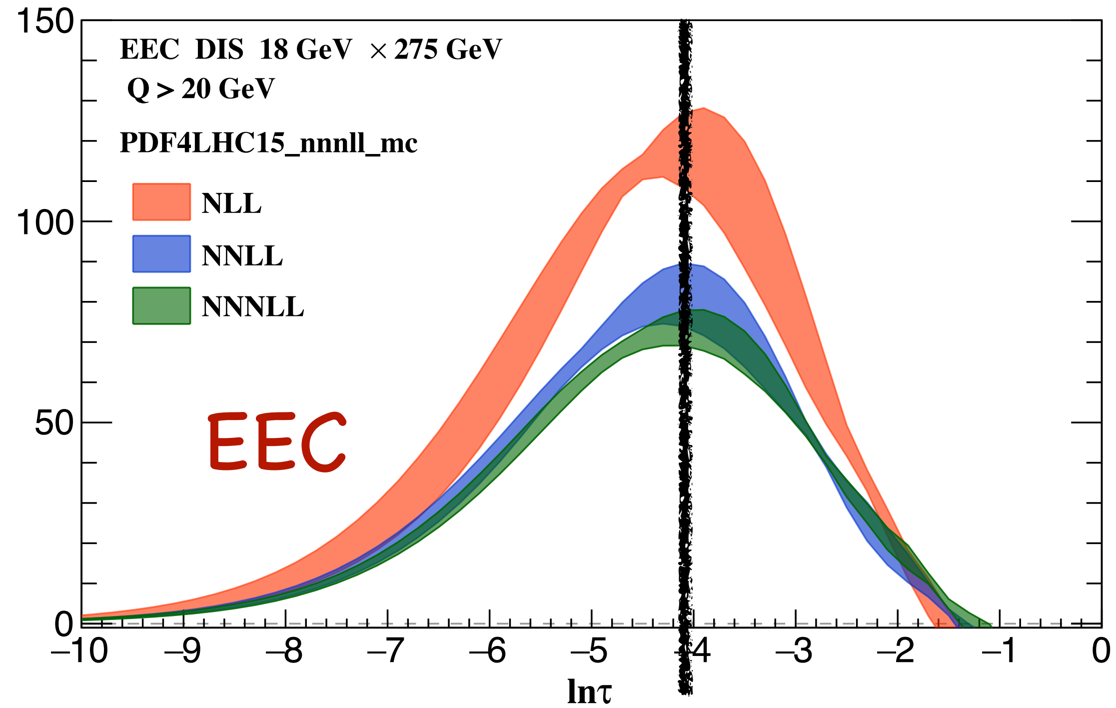
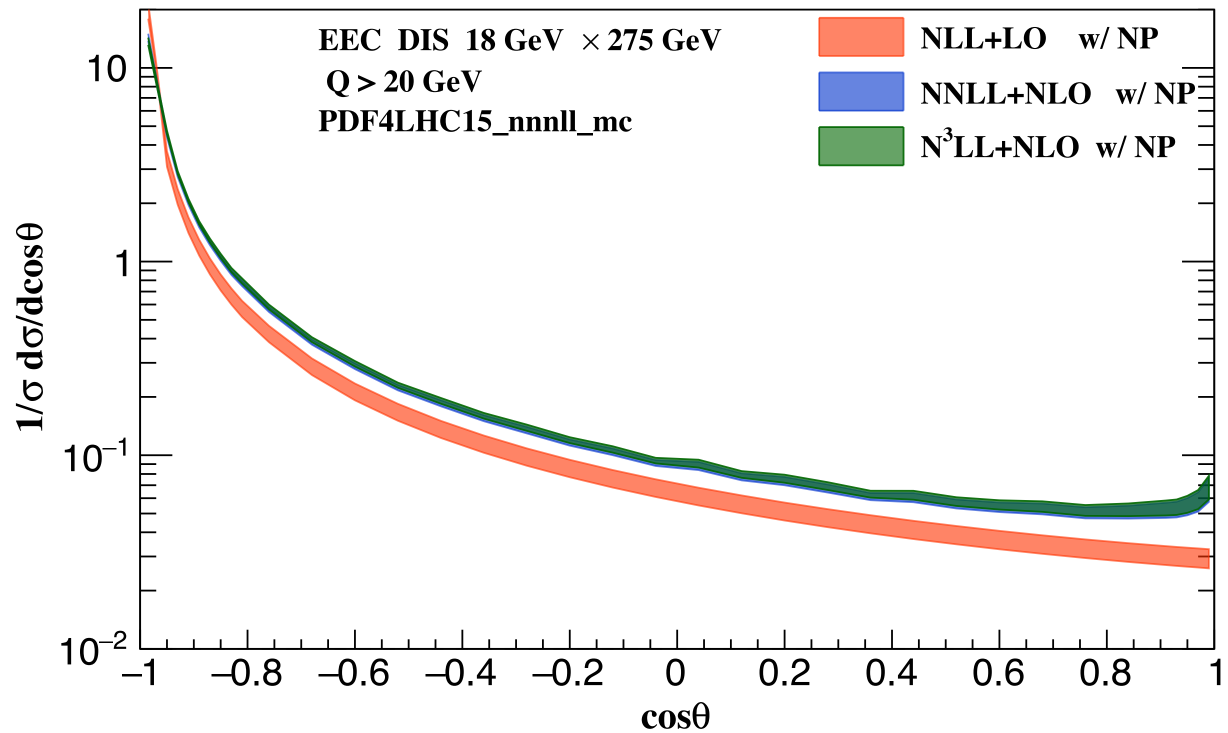
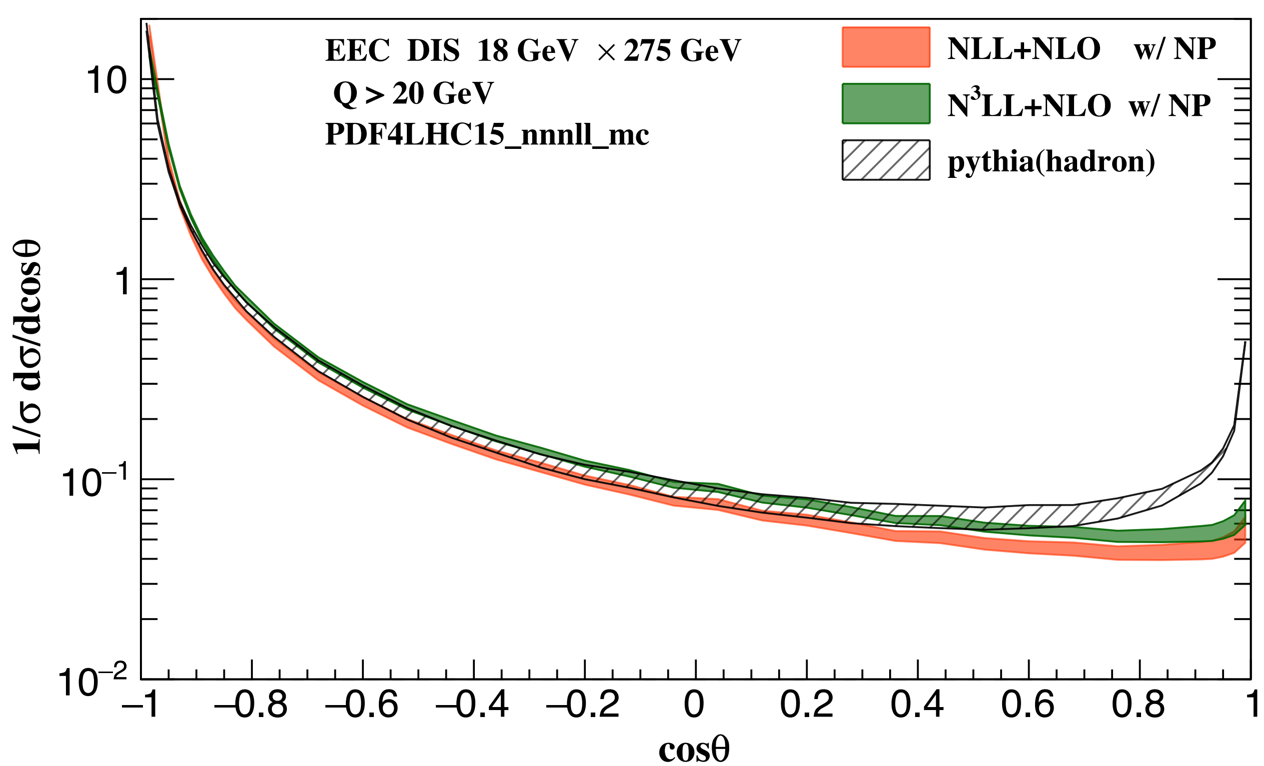




peak at larger tau, means small NP effects

EEC in DIS


EEC DIS 18 GeV × 275 GeV
Q > 20 GeV
PDF4LHC15_nnnll_mc
NLL+LO w/ NP
NNLL+NLO w/ NP
N3LL+NLO w/ NP
1/σ dσ/dcosθ
10
1
10−1
10−2
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cosθ


EEC DIS 18 GeV × 275 GeV
Q > 20 GeV
PDF4LHC15_nnnll_mc
NLL+NLO w/ NP
N3LL+NLO w/ NP
pythia(hadron)
1/σ dσ/dcosθ
10
1
10−1
10−2
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cosθ

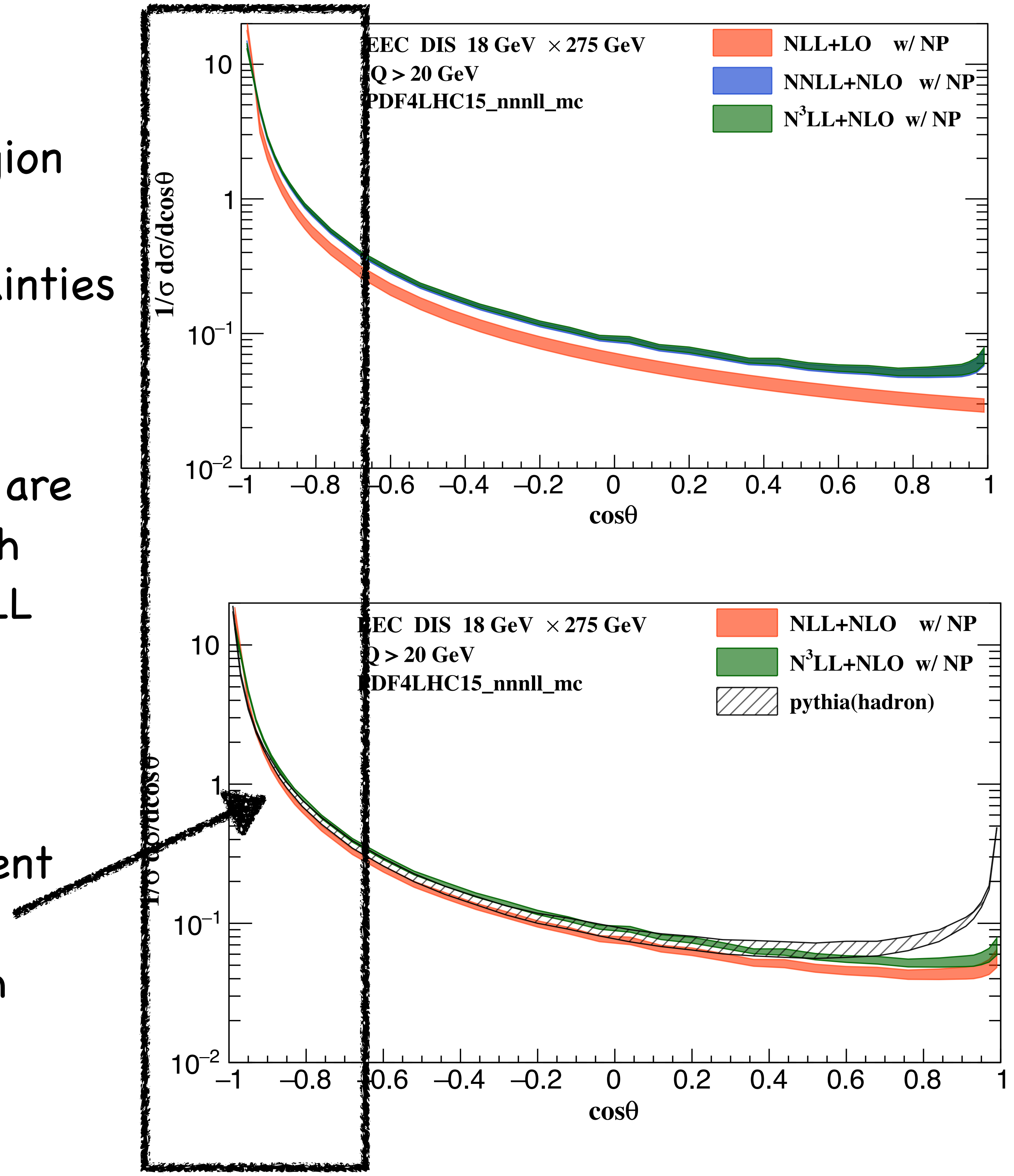
EEC in DIS

Resummation Dominant region

Scale uncertainties are reduced

Bands almost are on top of each other for NNLL +NLO and NNNLL+NLO

Slightly different with PYTHIA simulation with hadronization



EEC in DIS

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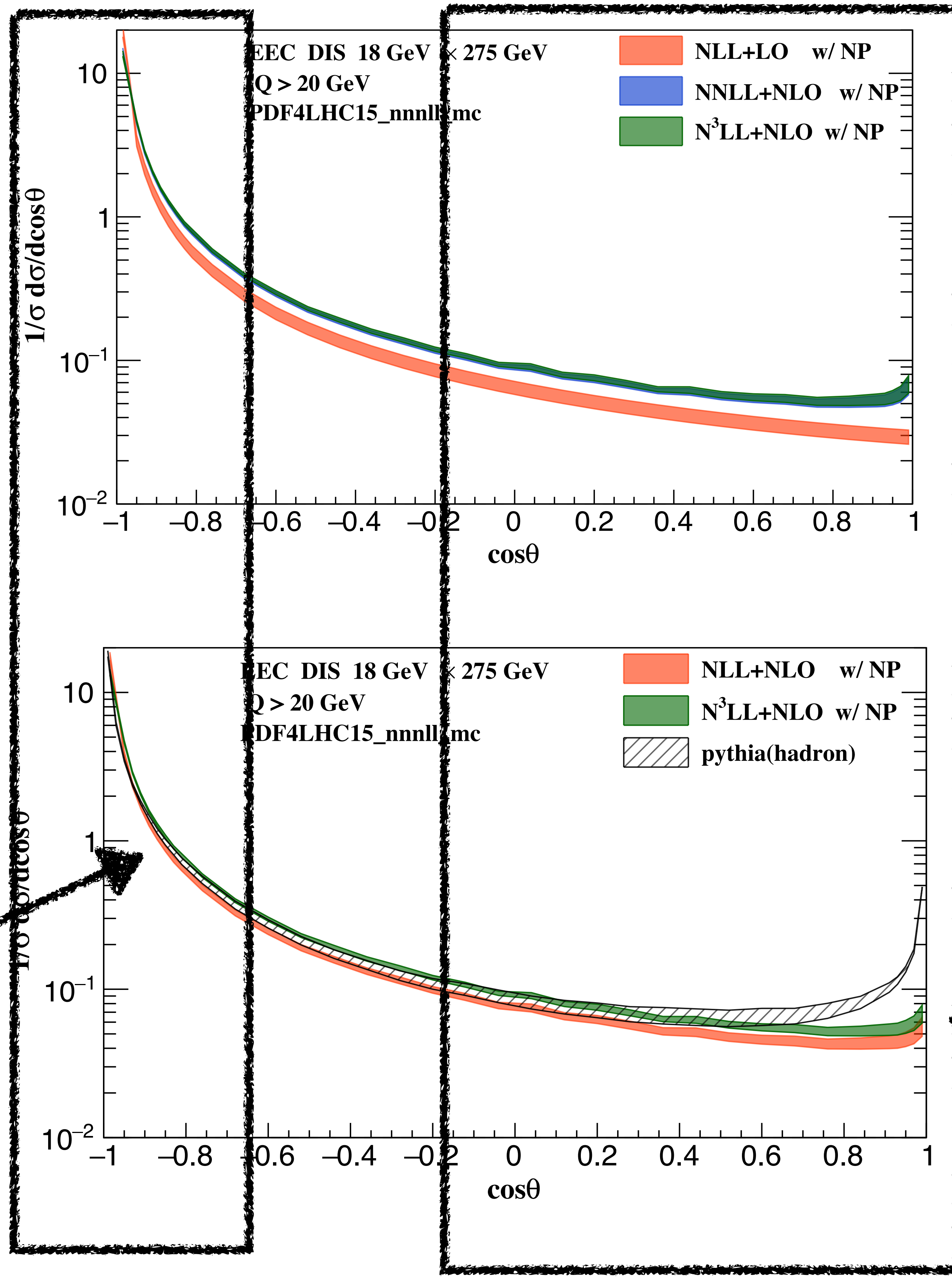

Scale uncertainties dominated by fixed order

NNLO matching would improve the predictions

Hadronization effects are only important in tail region

EEC in DIS

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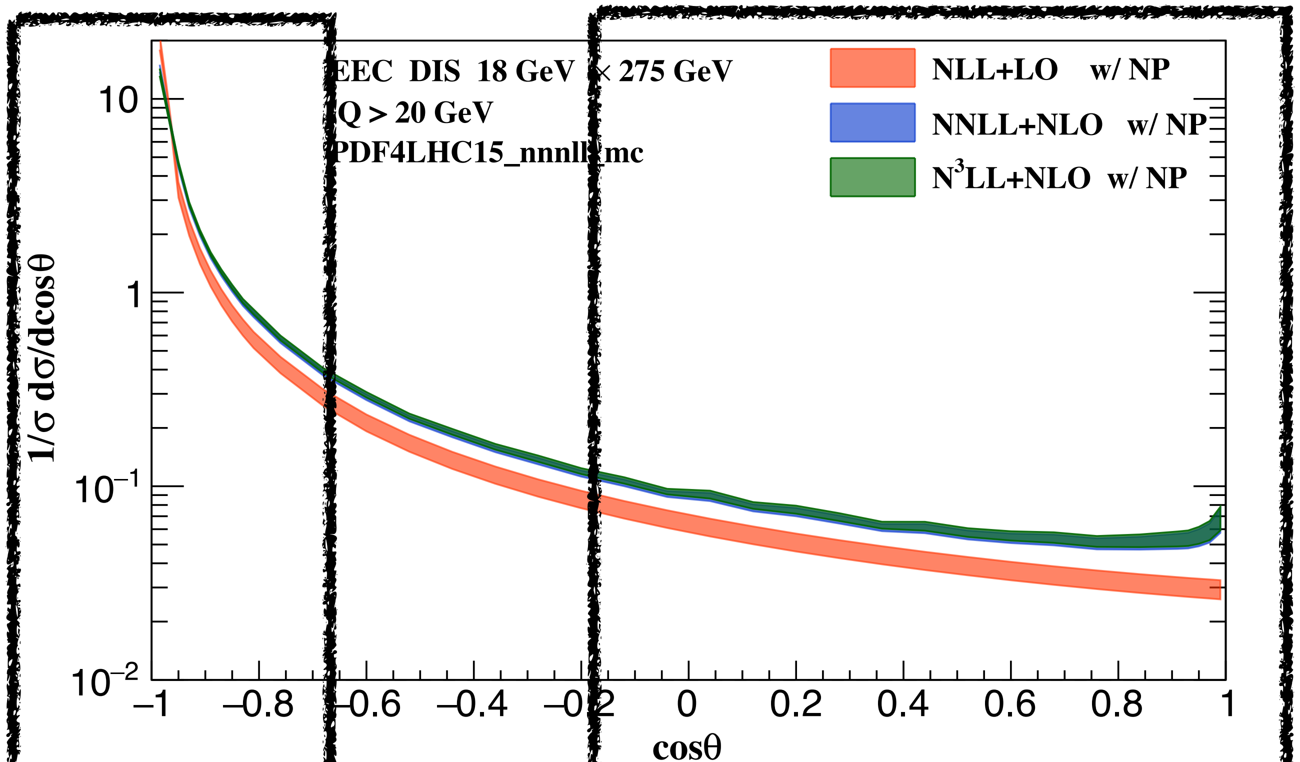

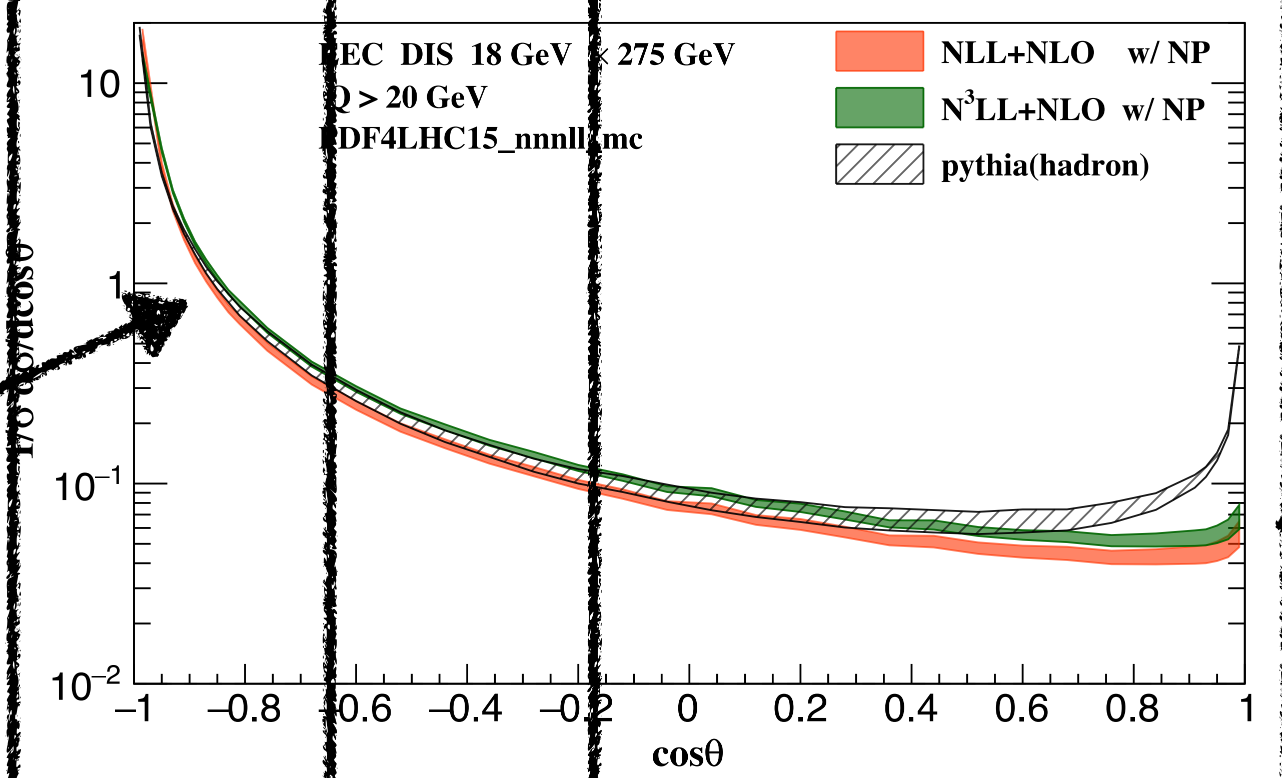

Scale uncertainties dominated by fixed order

NNLO matching would improve the predictions

Hadronization effects are only important in tail region

The highest resumed accuracy achieved to date in DIS

TEEC/EEC in DIS

Simplest definition of the event shape

$$\mathrm{TEEC} = \frac{1}{\sigma}\sum_a \int d\sigma(l + h \to l + a + X)\ \frac{E_{T,a}}{\sum_i E_{T,i}};\ \delta(\cos\phi_{al} - \cos\phi)$$

$$\mathrm{BEEC} = \frac{1}{\sigma}\sum_a \int d\sigma(\ell + h \to \ell + a + X)\ \frac{P\cdot p_a}{P\cdot q}\ \delta(\cos\theta_{ap} - \cos\theta)$$

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In principle we could sum over all hadrons in final state, or

$$\sum_a \to \sum_{a\in S}$$

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sum over charged particles, hadrons with a certain flavors, or an identified hadron,

which allows up to probe initial state flavor information

and test final state fragmentation functions

Conclusion for TEEC/EEC

- TEEC/EEC in DIS can be measured extremely accurately at the EIC.
- We study the TEEC/EEC in the framework of SCET.
- Clearly, TEEC/EEC can be used to study TMD physics at the EIC.
- Fixed-order singular distributions are available up to NNLO.
- NNNLL resummation was achieved.
- It is a great observable and fully utilizes EIC detector capabilities without any downside and uncertainty related to jet radius or jet reconstruction algorithm.

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1. Introduction
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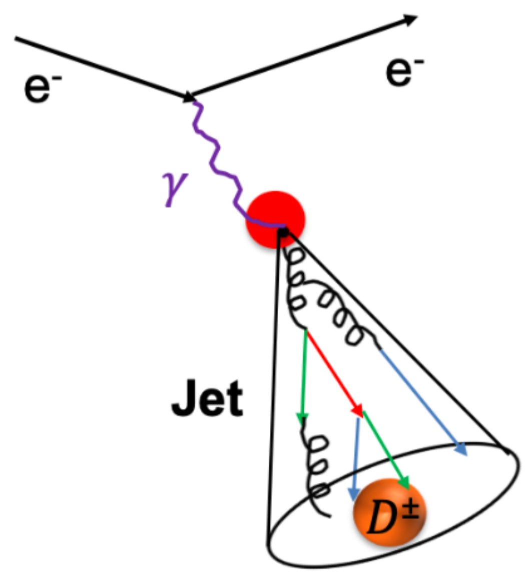
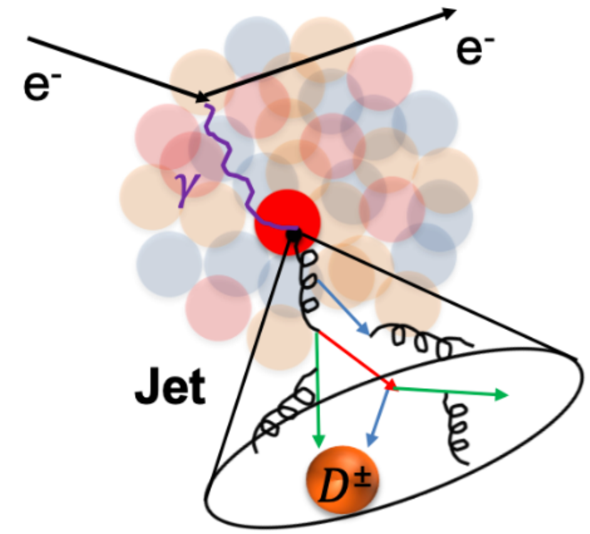
Prediction in e+p collision

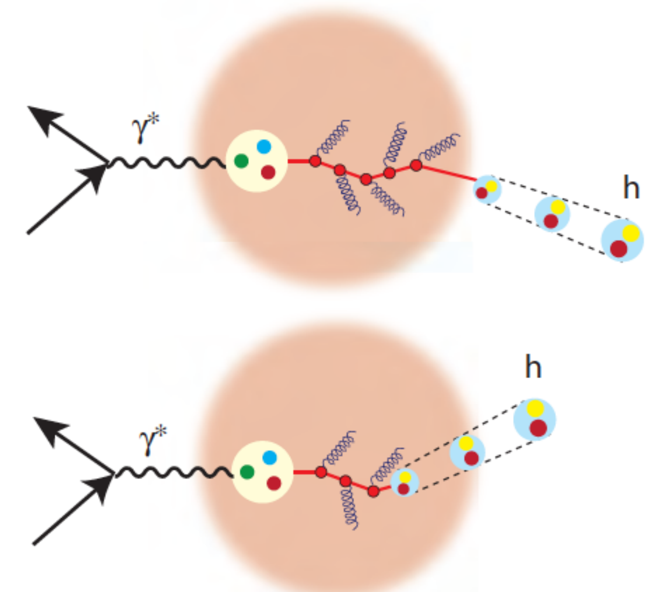
$e^- + \text{p} \rightarrow e^- + jet(D^{\pm}) + X$



$e^- + \text{Au} \rightarrow e^- + jet(D^{\pm}) + X$



energy loss and hadron absorption



NLO cross section can be factorized as

$$E_h \frac{d^3\sigma^{\ell N \to hX}}{d^3 P_h} = \frac{1}{S} \sum_{i,f} \int_0^1 \frac{dx}{x} \int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times D^{h/f}(z,\mu) \left[\hat{\sigma}^{i \to f} + f^{\gamma/\ell}_{\text{ren}}\left(\frac{-t}{s+u}, \mu \right) \hat{\sigma}^{\gamma i \to f} \right].$$

FFs

NLO hard kernel

quasi-real photon scattering

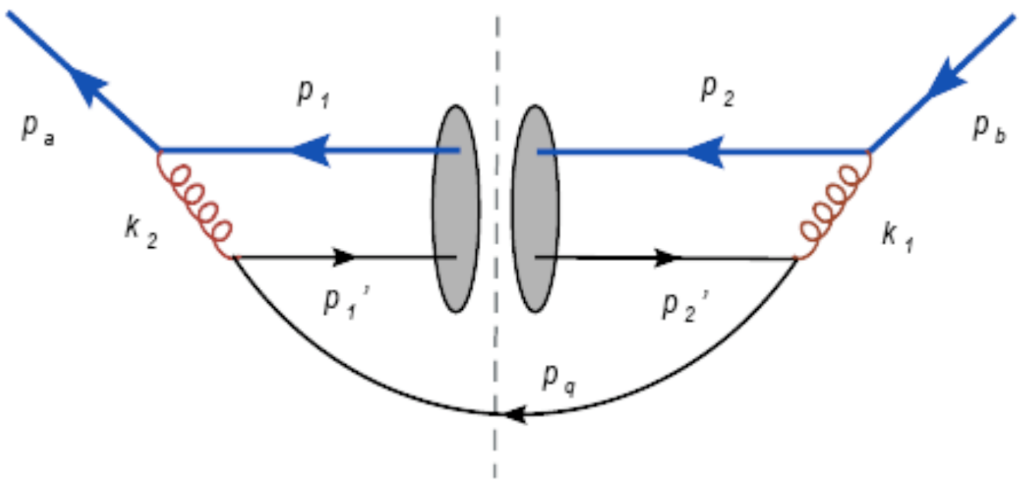
Fragmentation function: for light meson: HKNS

M. Hirai et al., '07

Partonic cross section: analytical NLO result

P. Hinderer et al., '15

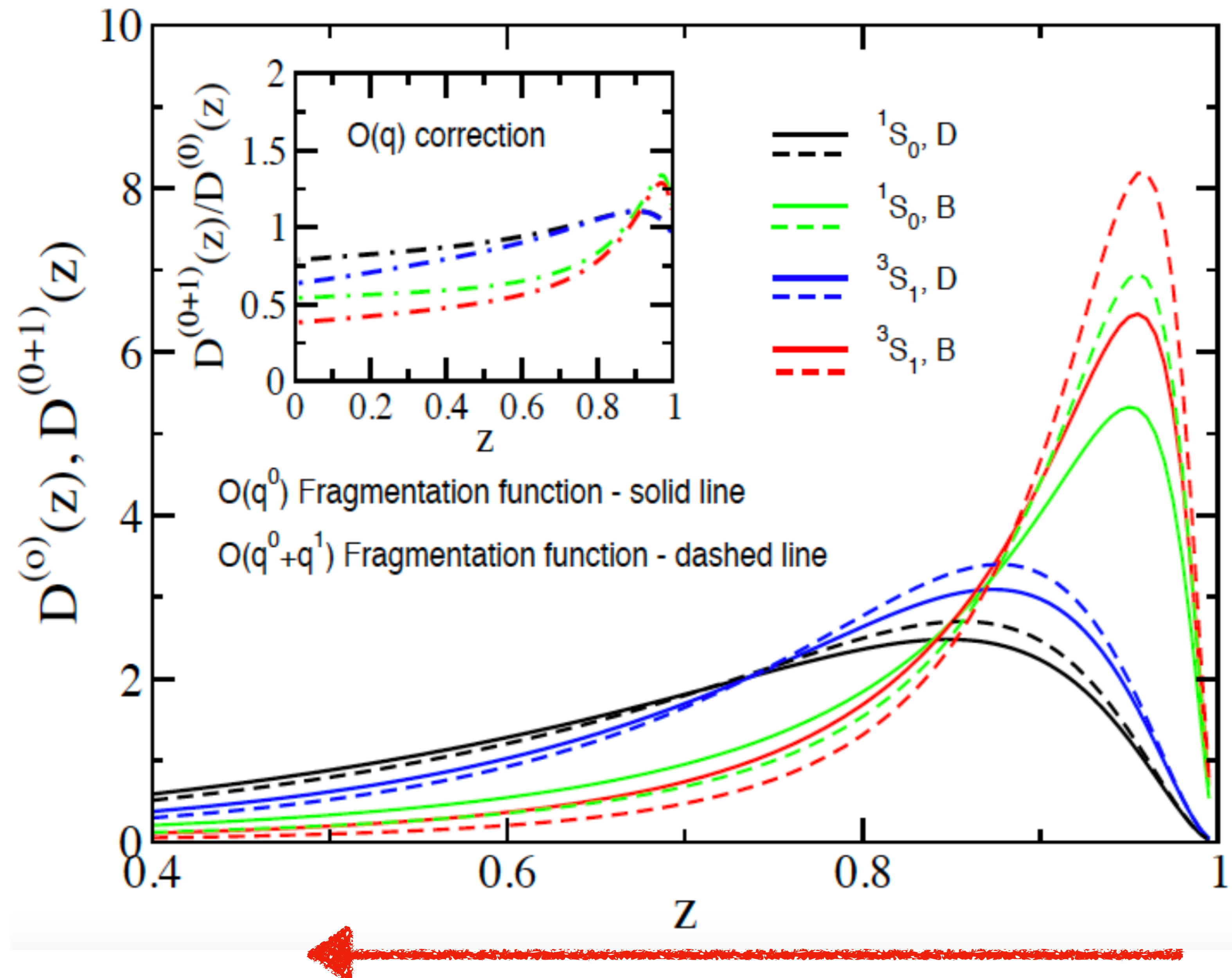
FFs for heavy flavors in vacuum



studied in HQET

Heavy quarks introduce a mass scale that allows the fragmentation function shape to be computed perturbatively

Chang et al. 1992 Braaten et al. 1994



The vacuum FFs are used as input boundary conditions to determine the FFs in Medium

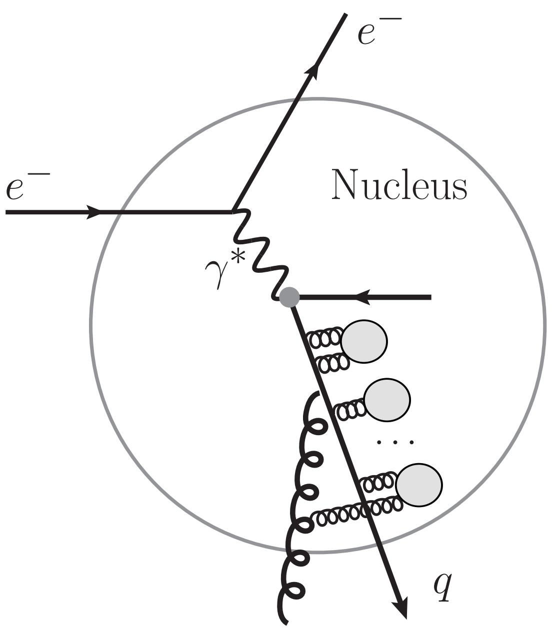
energy loss in medium would shift FF to lower z

Evolution of Fragmentation Functions

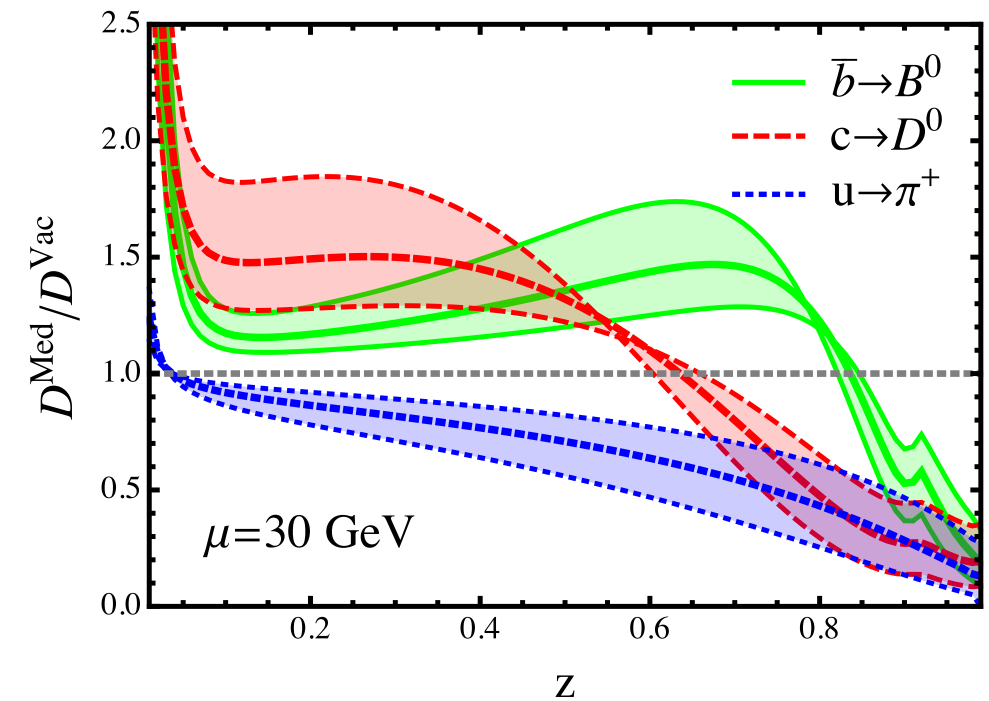
$$\frac{\mathrm{d}D_{h/q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left[P^{\mathrm{full}}_{q\to qg}(z',Q;\beta)D_{h/q}\left(\frac{z}{z'},Q\right) + P^{\mathrm{full}}_{q\to gq}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right)\right]$$

$$P_i^{\mathrm{full}}(x,\boldsymbol{k}_\perp;\beta) = P_i^{\mathrm{vac}}(x) + P_i^{\mathrm{med}}(x,\boldsymbol{k}_\perp;\beta)$$

Fragmentation Function In Medium (Au)



- In-Medium Splitting functions are derived based on SCETG
- Significant Enhancement at small z for heavy flavors



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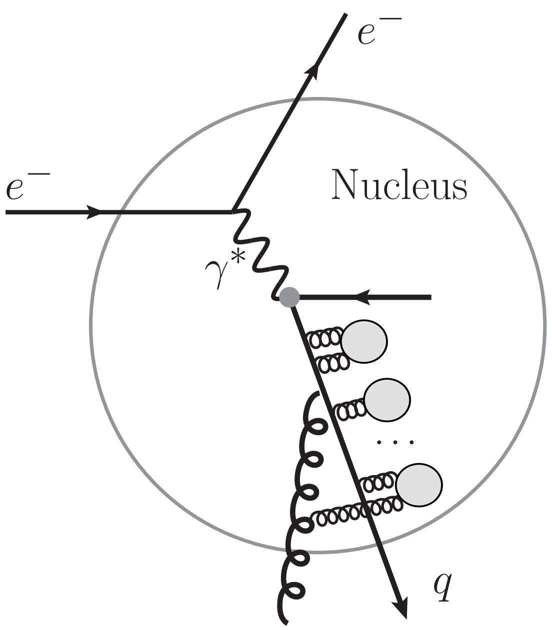

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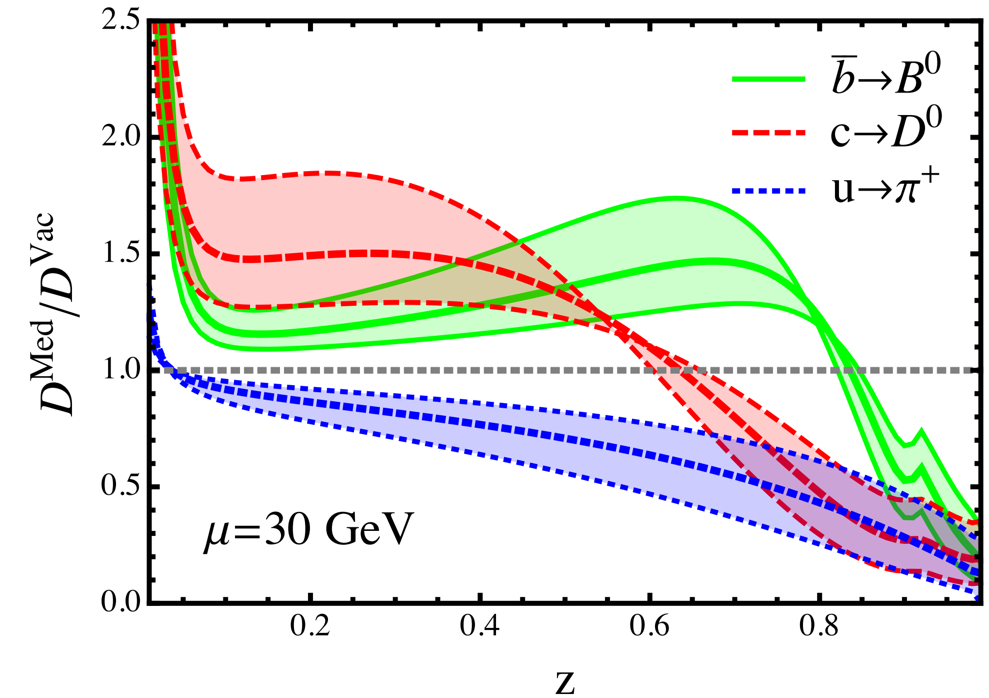
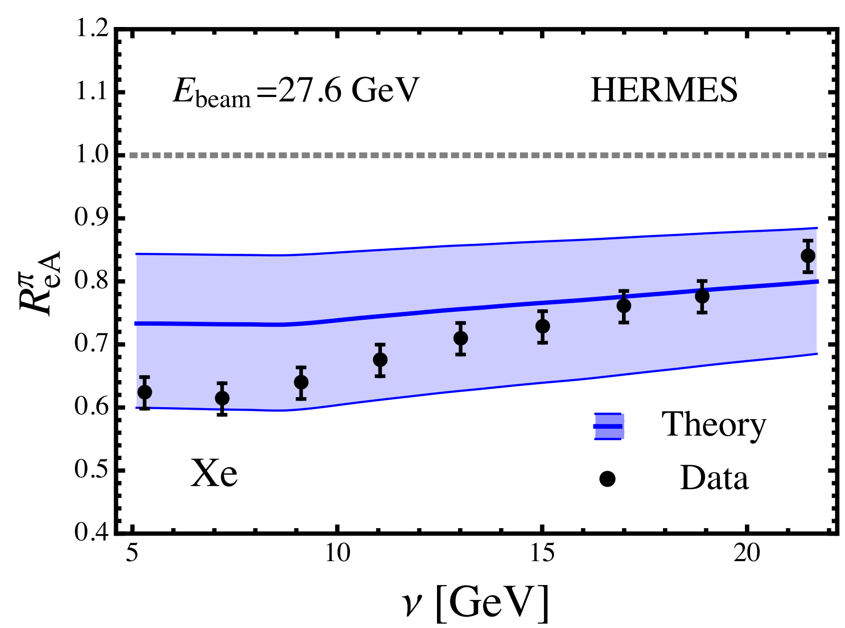
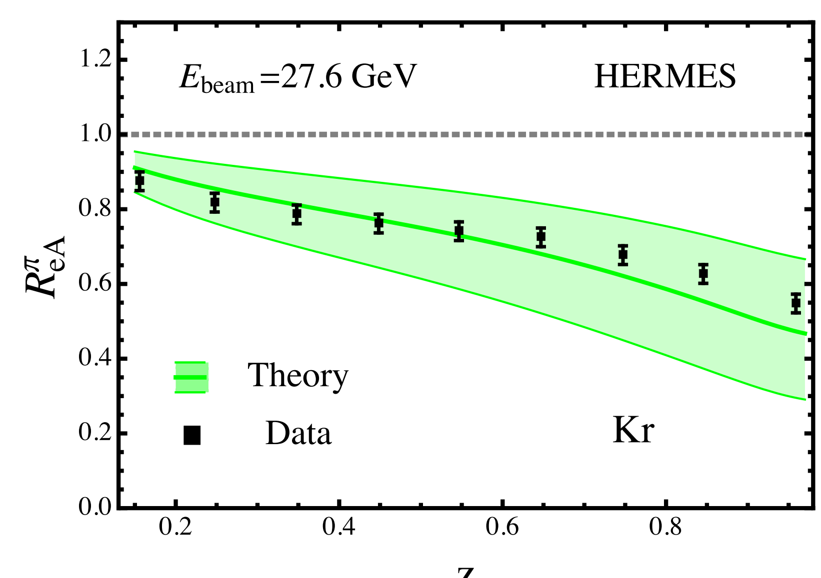


- Our description of hadronization in-medium is valid
- Transport parameter of Cold Nuclear Matter effect is constrained by HERMES

$\langle k_\perp^2\rangle/\lambda_g = 0.12\ \mathrm{GeV}^2/\mathrm{fm}$

vary it by a factor of two



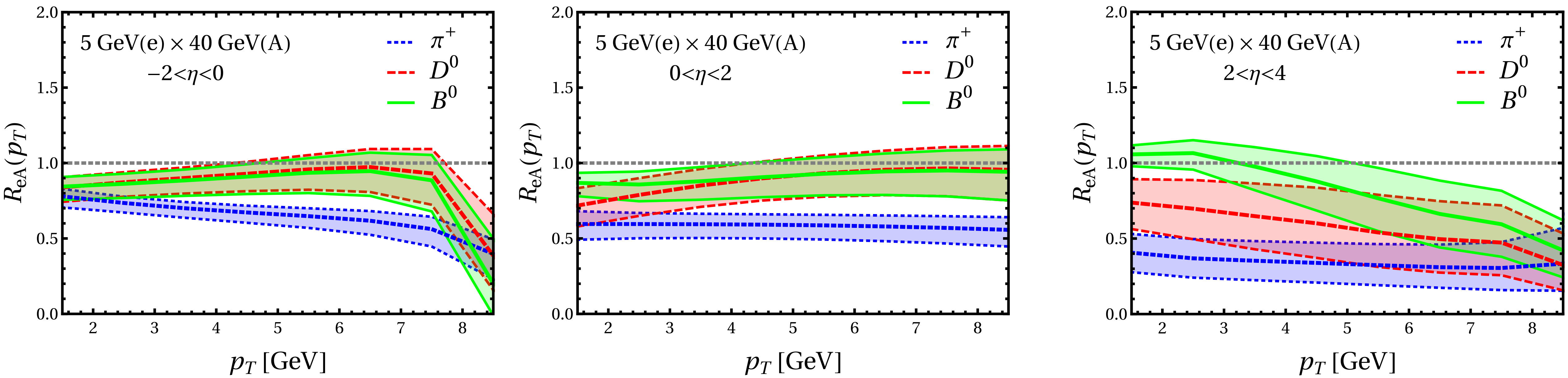


Hadron production at the EIC

To investigate nuclear medium effect, study the ratio of cross section in e+Au to the one in e+p

$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+p}}$$

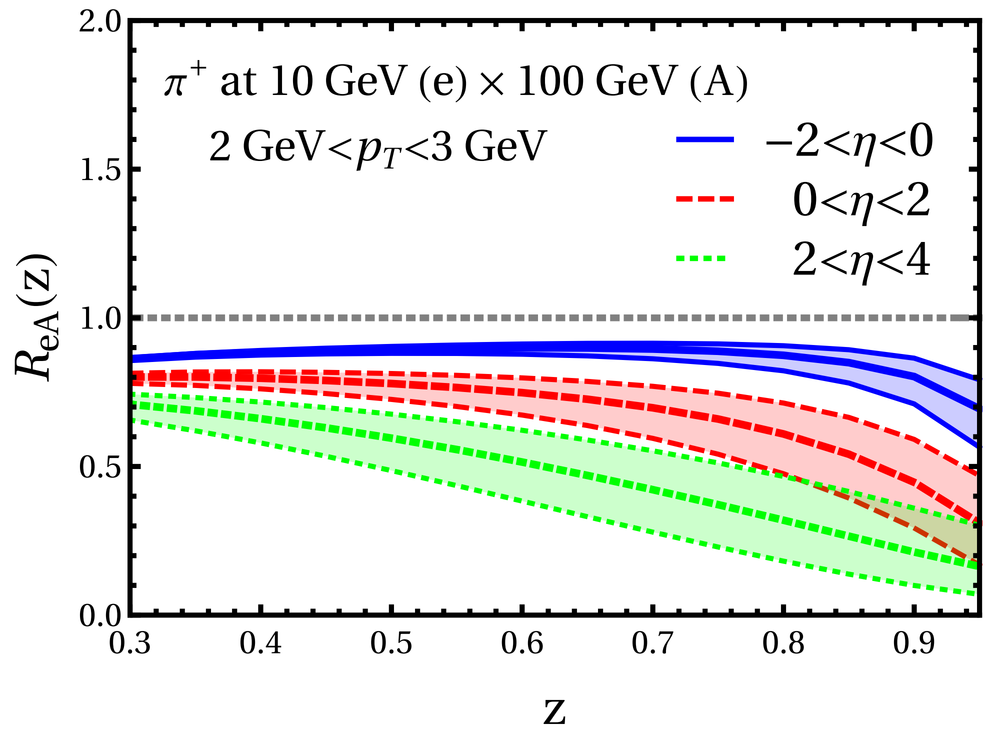
use the cross section of inclusive jet production for normalization that minimizes the effect of nuclear PDFs

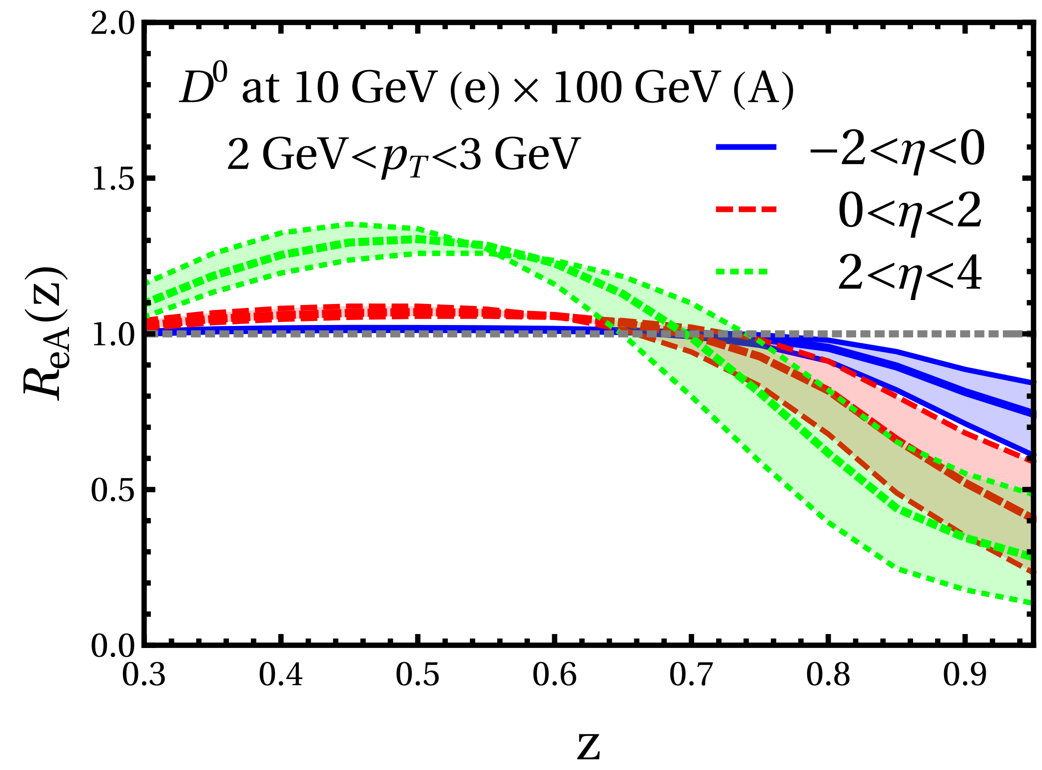


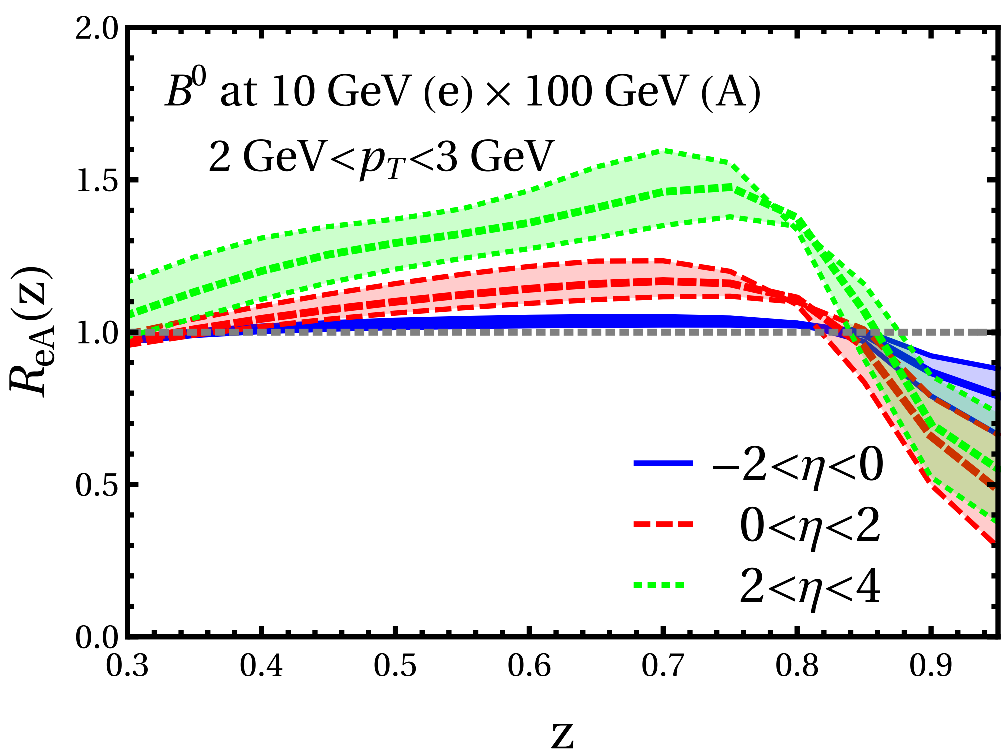
Parton in forward rapidity region has lower energy in rest frame of nuclei, resulting in larger in-medium modification

result of Landau-Pomeranchuk-Migdal (LPM) Effect

Heavy Flavor production - pT distribution







- Cold Nuclear Matter effect is more significant in forward rapidity region
- For light flavor, observe suppression, which can be as large as a factor of 2
- Suppression of light hadrons, transmission to enhancement for heavy flavor
- Study of in-medium effects benefits from more differential analysis

Conclusion for heavy-flavor meson

- Hadronization plays an important role for jet and most semi-inclusive observables and affects them qualitatively and quantitatively. Its role at the EIC is not explored yet
- Larger radiative corrections are pronounced at lower CM energies and forward rapidities
- Studies of in-medium modification benefits from more differential measurements
- The clear transition from enhancement to suppression from moderate to large values of z will be a quantitative measure of parton shower formation in large nuclei.

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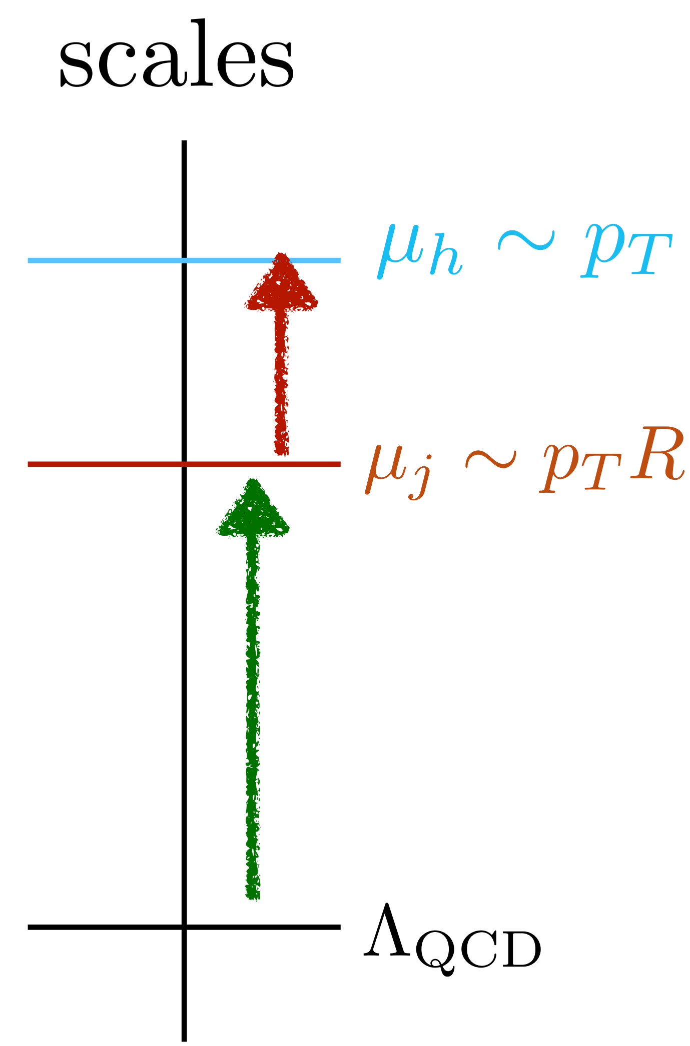
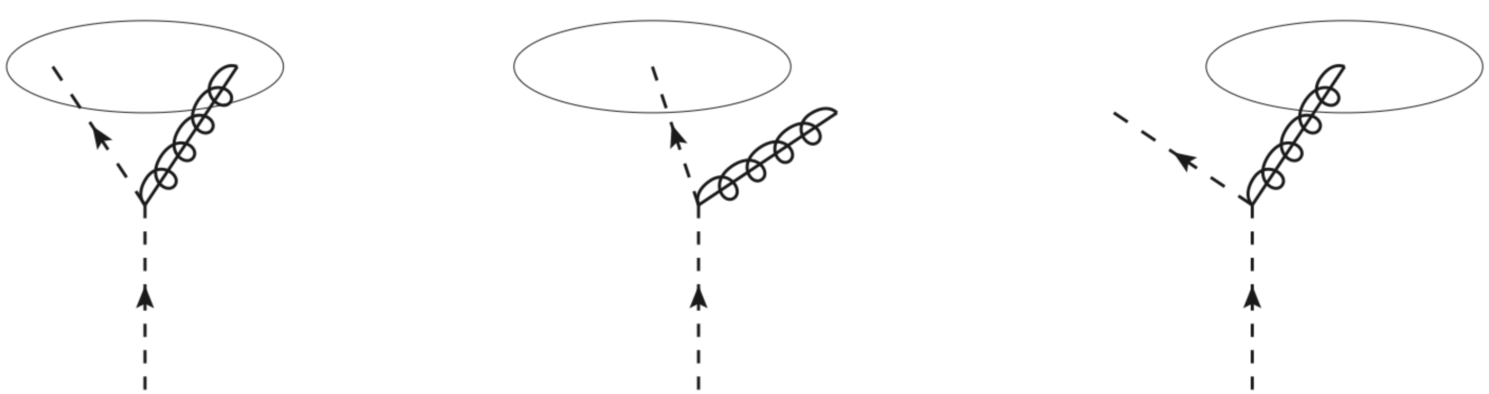
Inclusive jet cross section

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

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



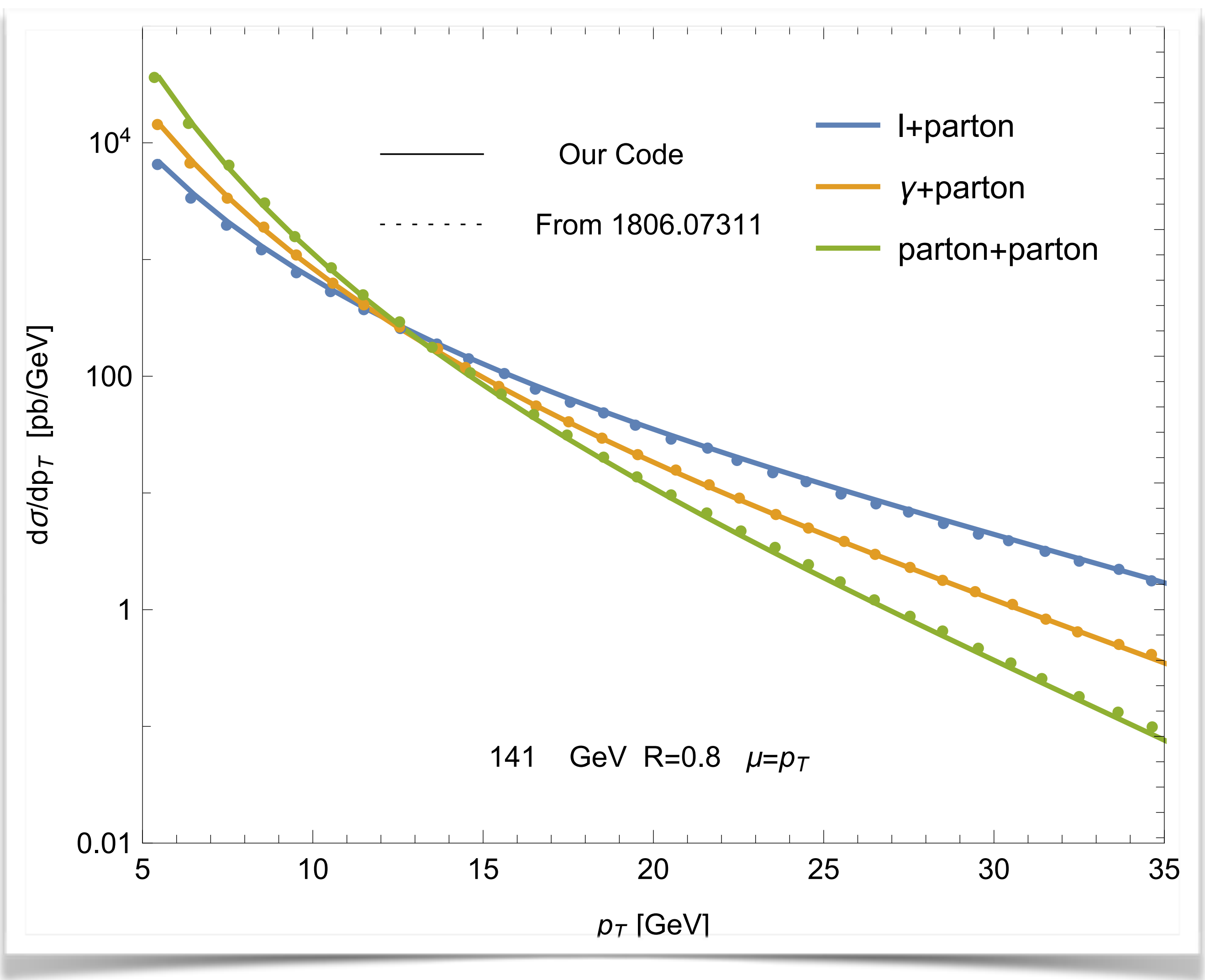
Hard part: arXiv:1505.06415
Jet Function: arXiv:1606.06732



Contribution to the semi-inclusive quark jet function

Inclusive jet cross section

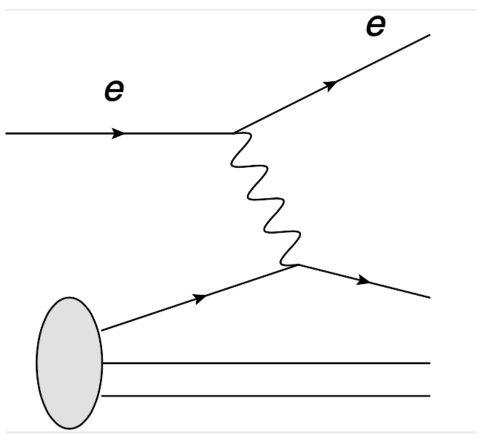
Comparison between NLO and factorized cross section



NLO results from

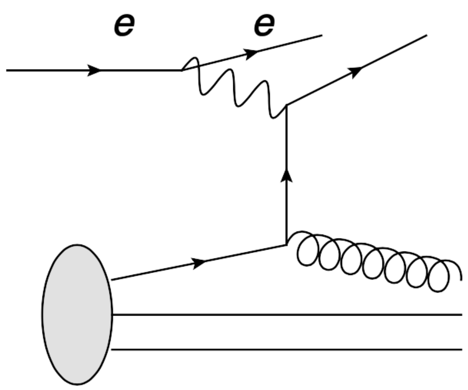
Boughezal, Petriello, Xing, arXiv:1806.07311

Large Q



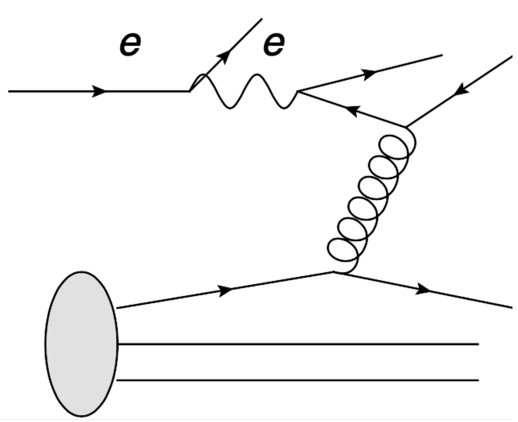
Small Q

Photon PDF from lepton



Small Q

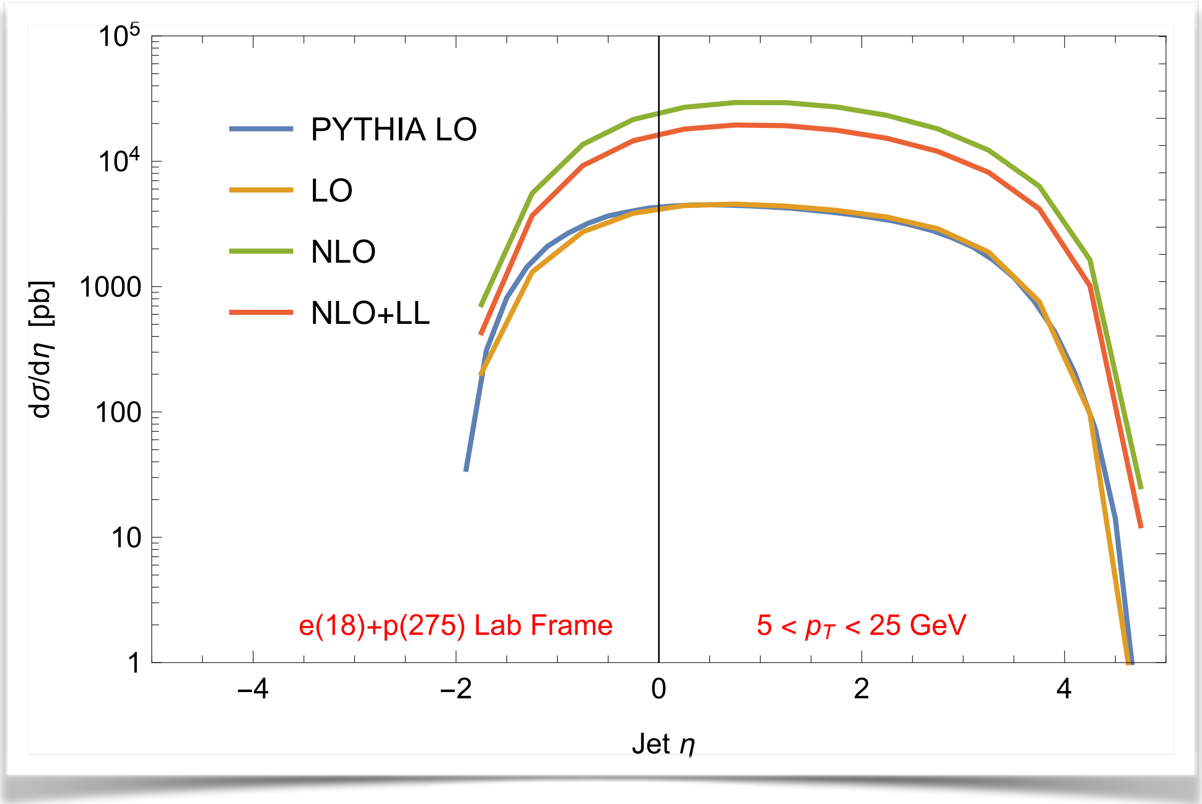
Quark PDF from lepton

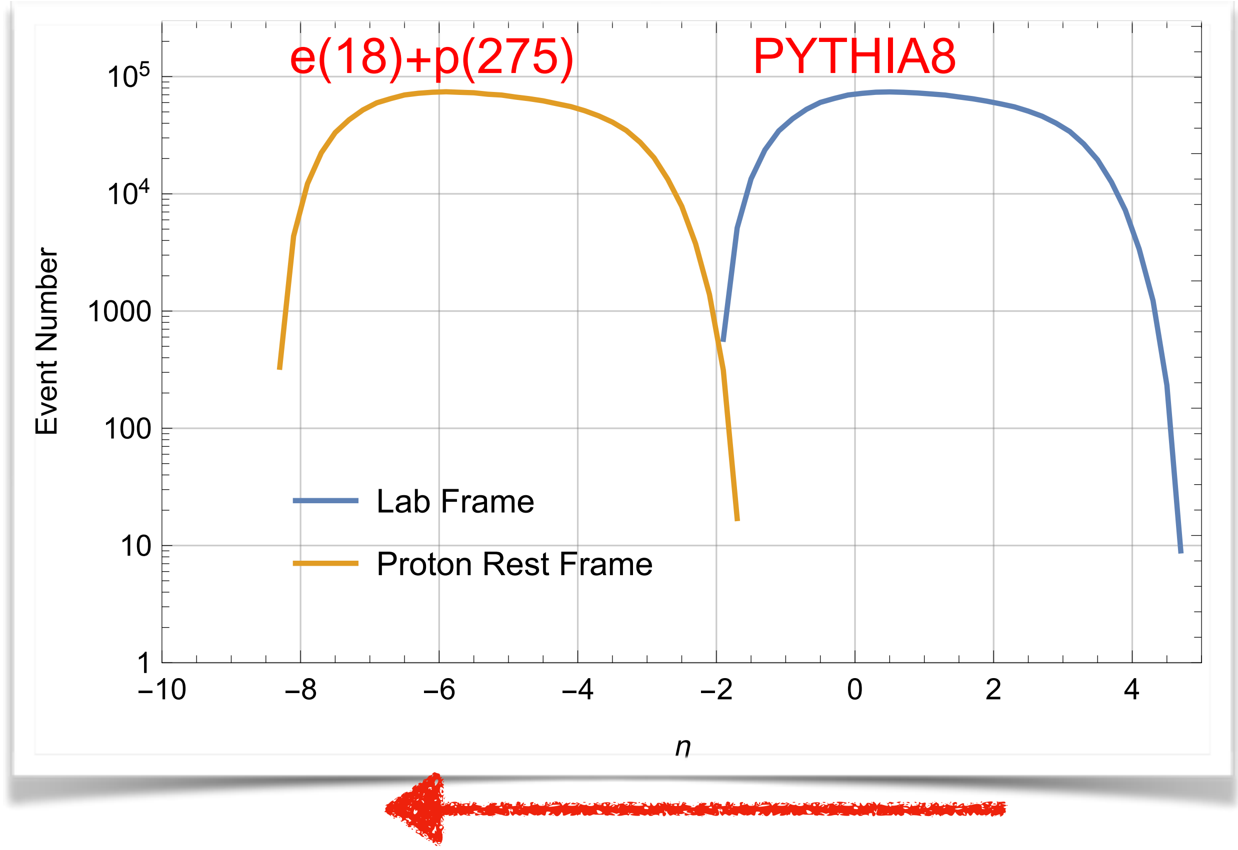


Large Corrections from photon production and unresolved contribution in small p_T

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.

Inclusive jet cross section

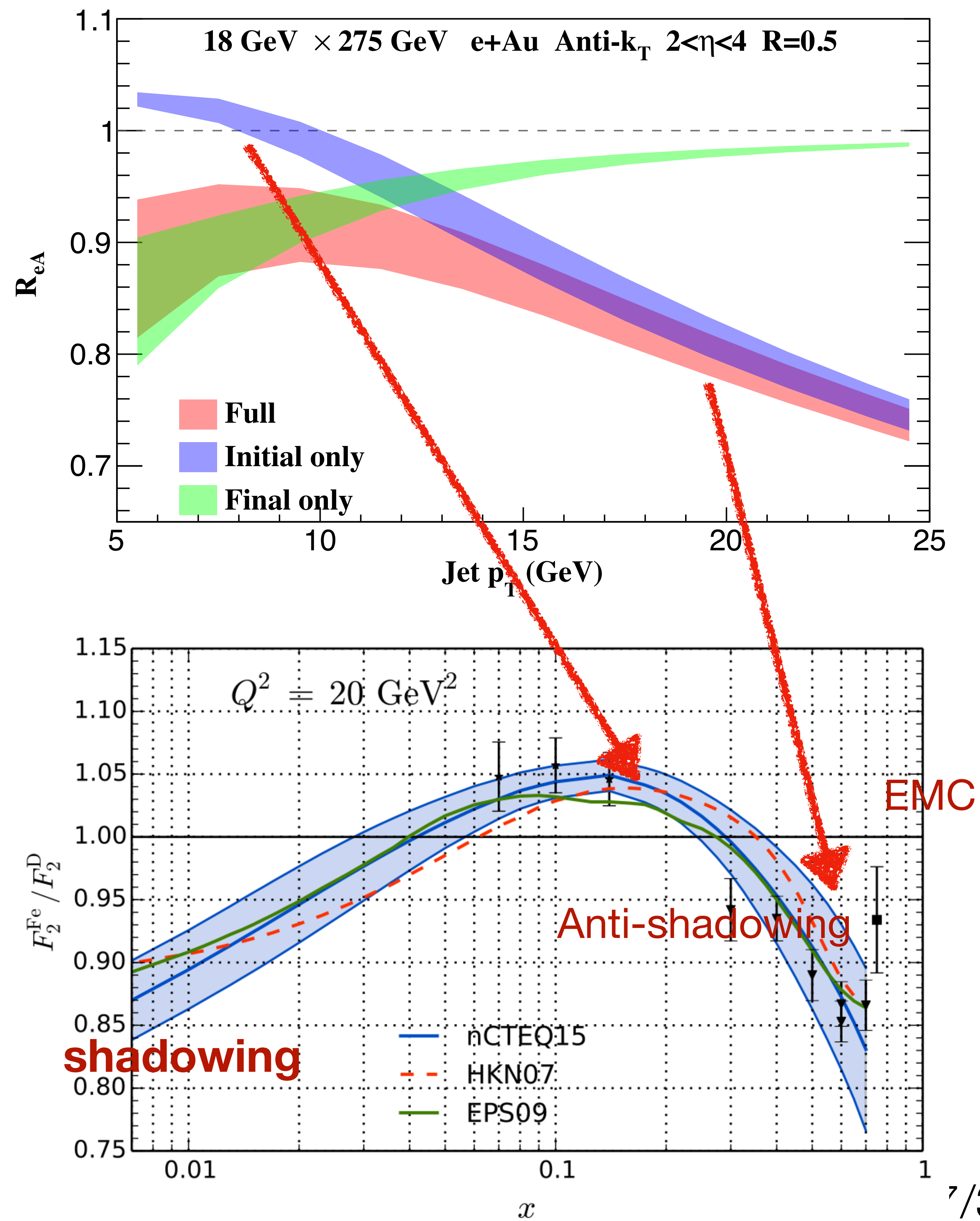
Fixed $\langle k_\perp^2 \rangle / \lambda_g = 0.12\ \mathrm{GeV}^2/\mathrm{fm}$

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

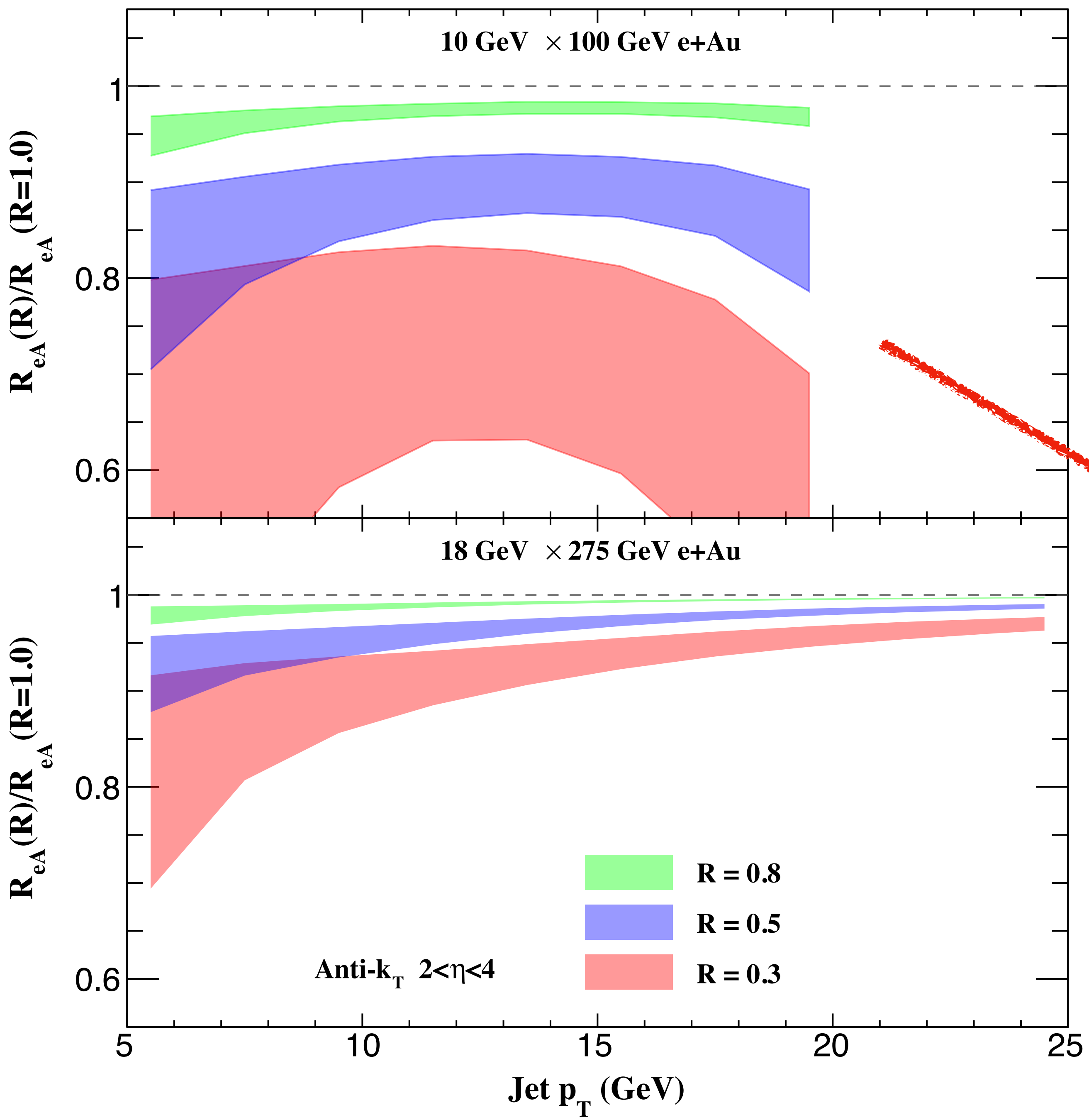
Modifications defined as

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

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



Inclusive jet cross section



Essential to 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 boundary

- Suppression is more significant for smaller jet radii
- scale uncertainties are larger for smaller p_T
- Final State effects decreasing with p_T increasing

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

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

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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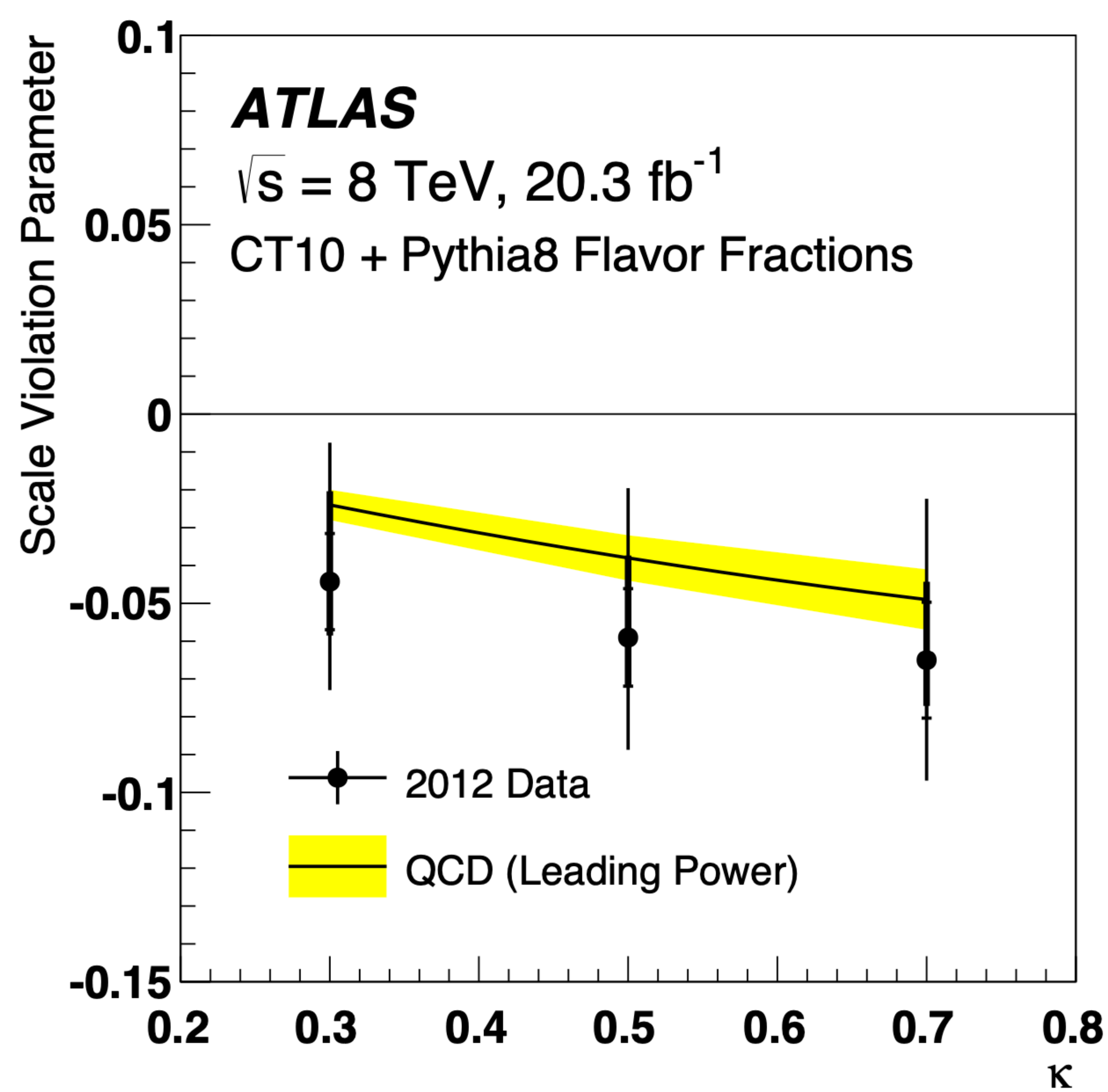
Pertur

scale and R de



Krohn, Schwartz, Wa
Waalewijn a

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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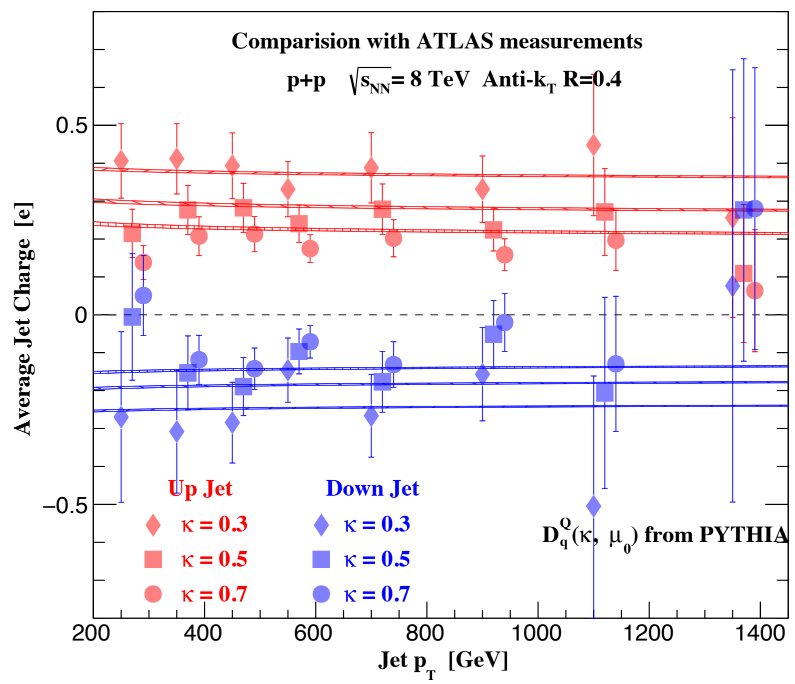

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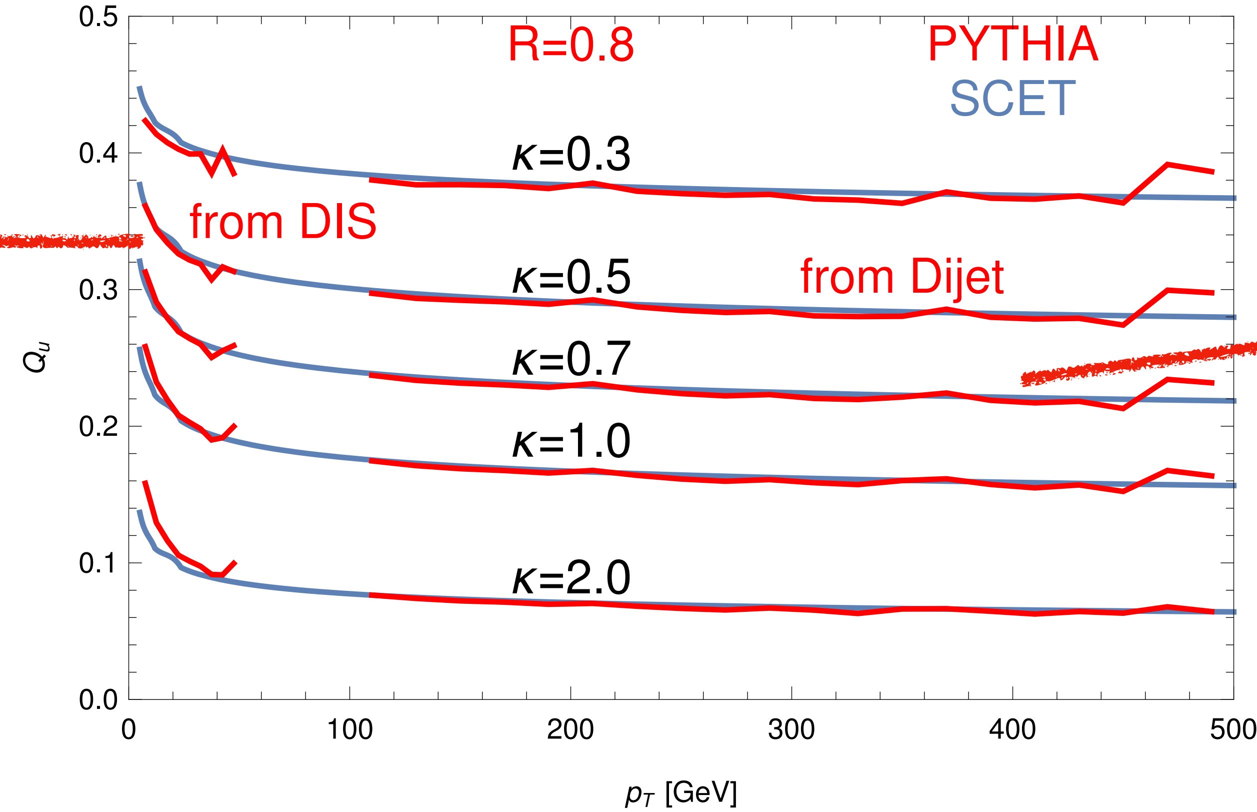
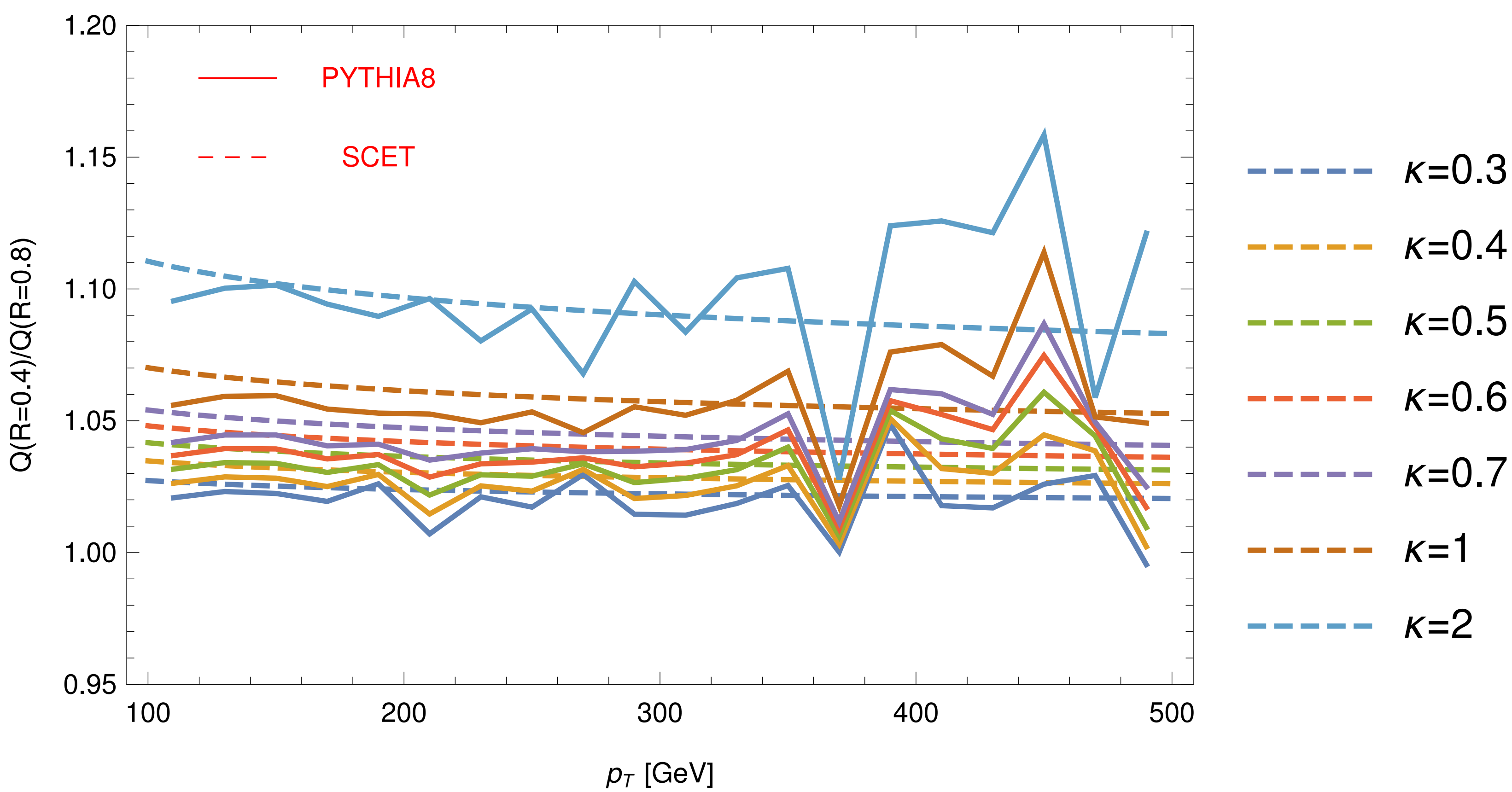
Krohn, Schwartz, Waalewijn, arXiv:1209.2421
Waalewijn arXiv:1209.3019

Jet Charge

Jet from DIS events

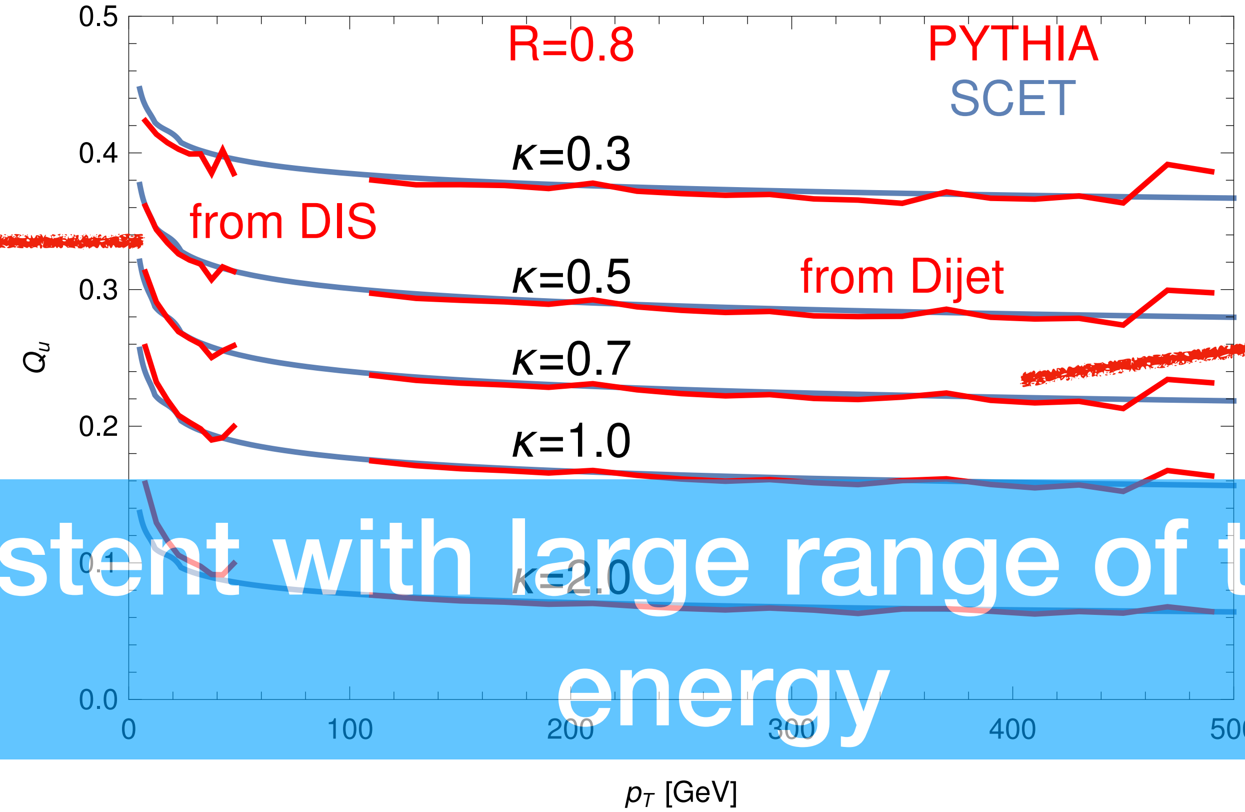


Jet from $pp \rightarrow$ dijet events



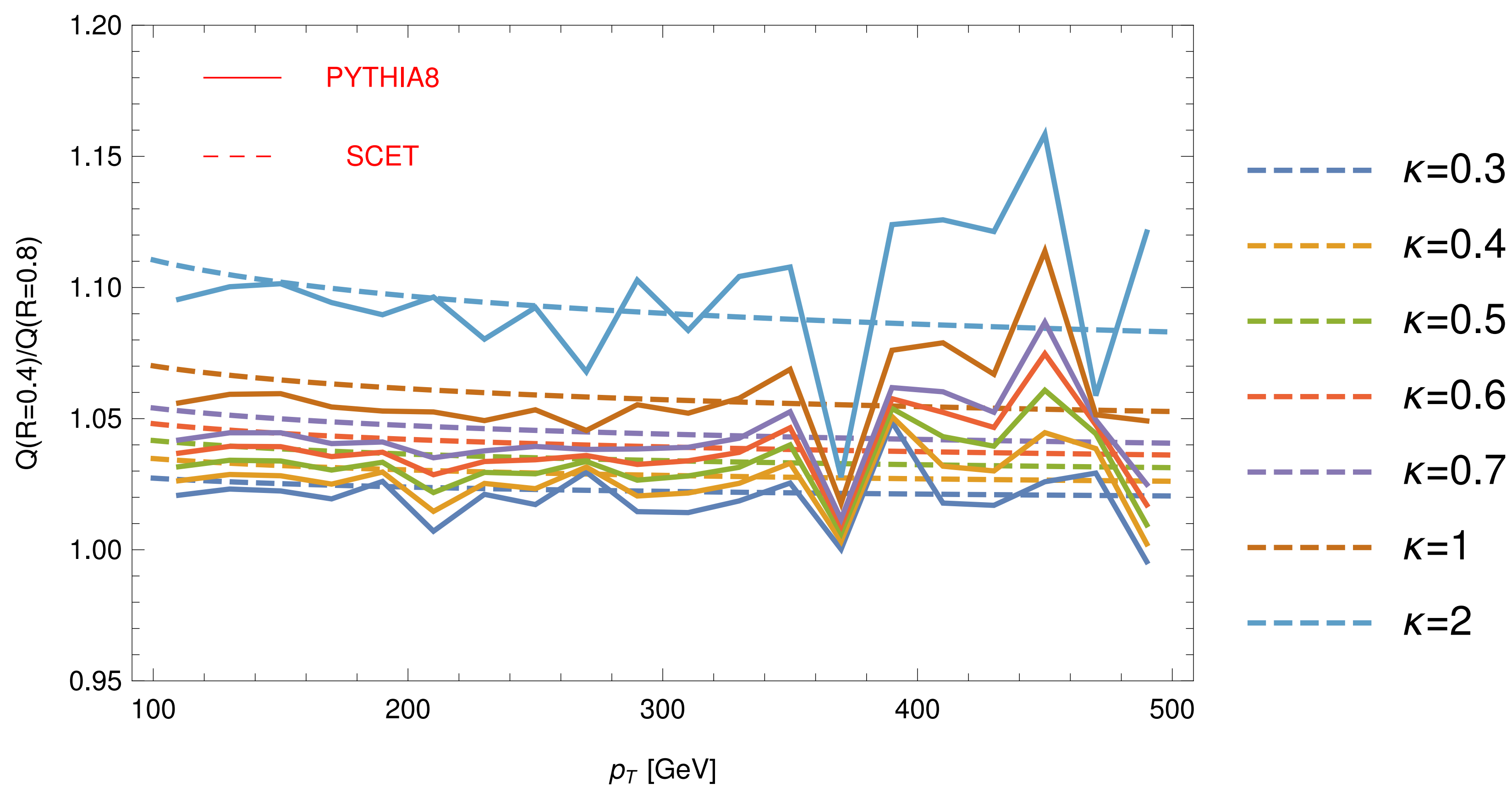
Jet Charge

Jet from DIS events

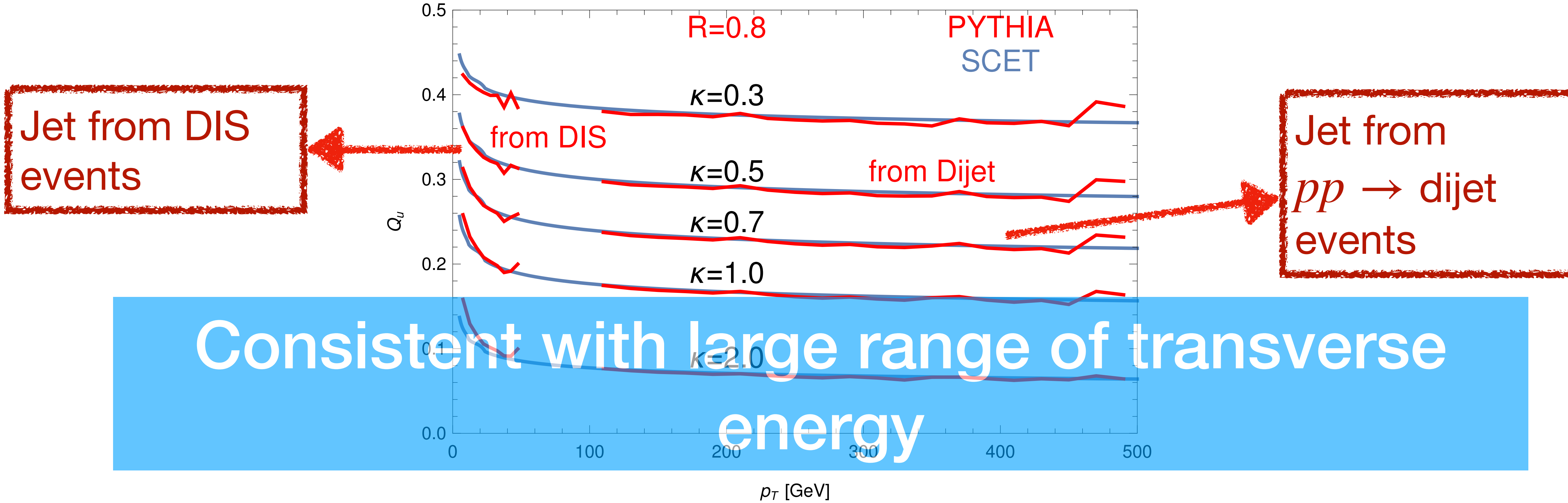


Jet from $pp \to$ dijet events

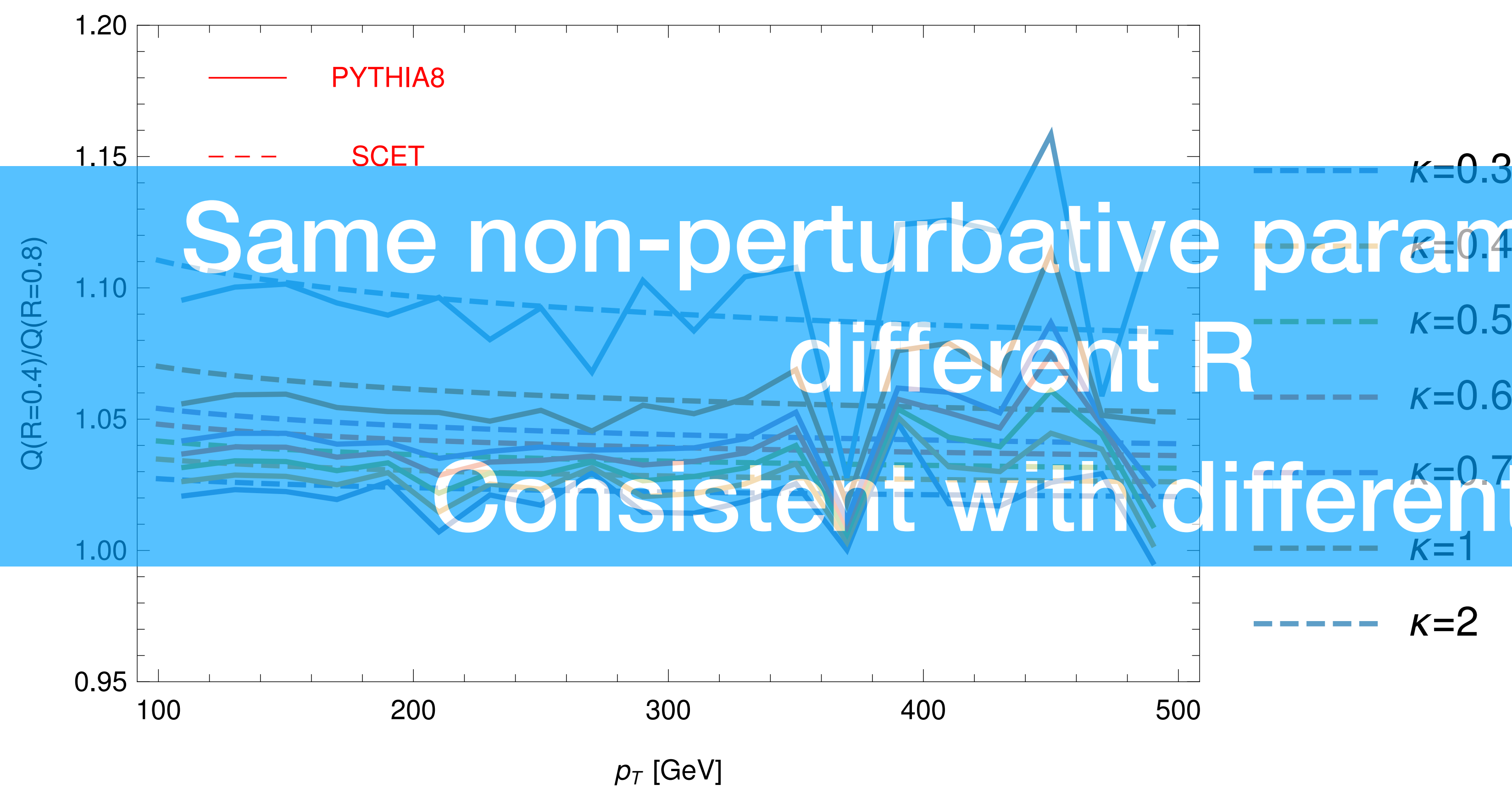
Consistent with large range of transverse energy



Jet Charge



Consistent with large range of transverse energy



Same non-perturbative parameter for different R

Consistent with different κ

Jet Charge

Jet charge with medium effects

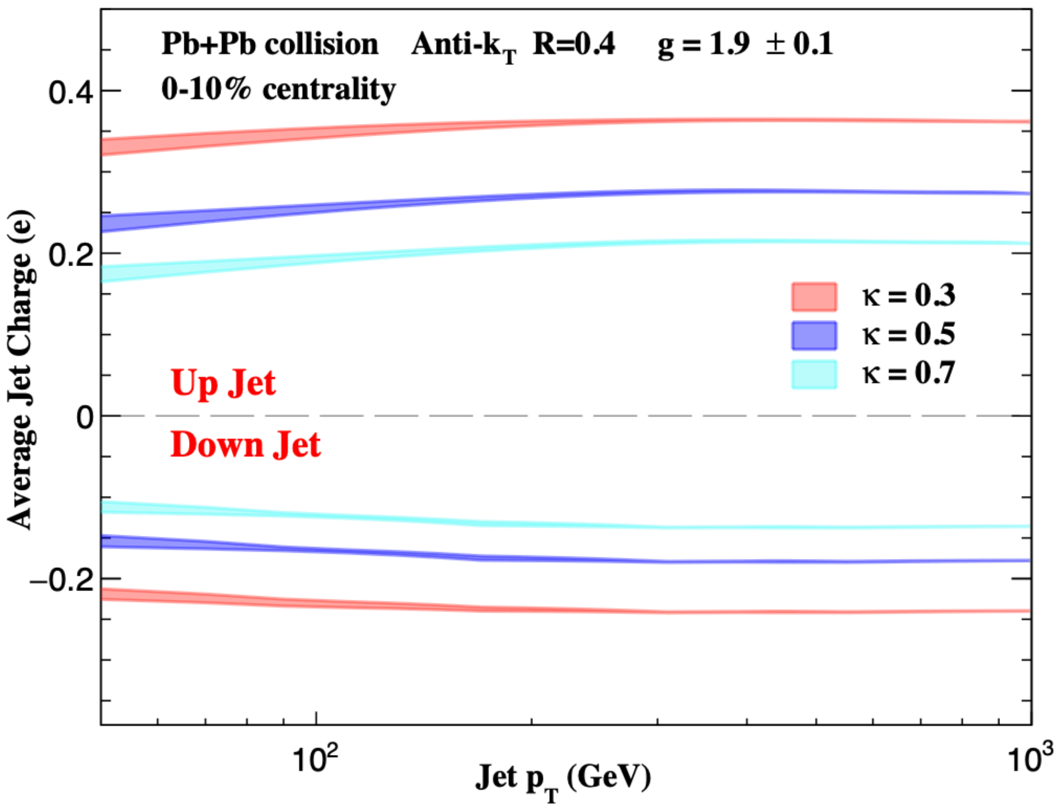
HTL, Vitev, arXiv:1908.06979

Evolution in Medium

$$\langle Q_{q,\kappa}^{\mathrm{eA}}\rangle = \langle Q_{q,\kappa}^{\mathrm{ep}}\rangle \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \frac{\alpha_s(\mu')}{2\pi^2}(2\pi\mu'^2)\tilde{f}_{qq}^{\mathrm{med}}(\kappa,\mu')\right]$$
$$\times\left(1+\tilde{\mathcal{J}}_{qq}^{\mathrm{med}} - J_q^{\mathrm{med}}\right) + \mathcal{O}(\alpha_s^2)$$

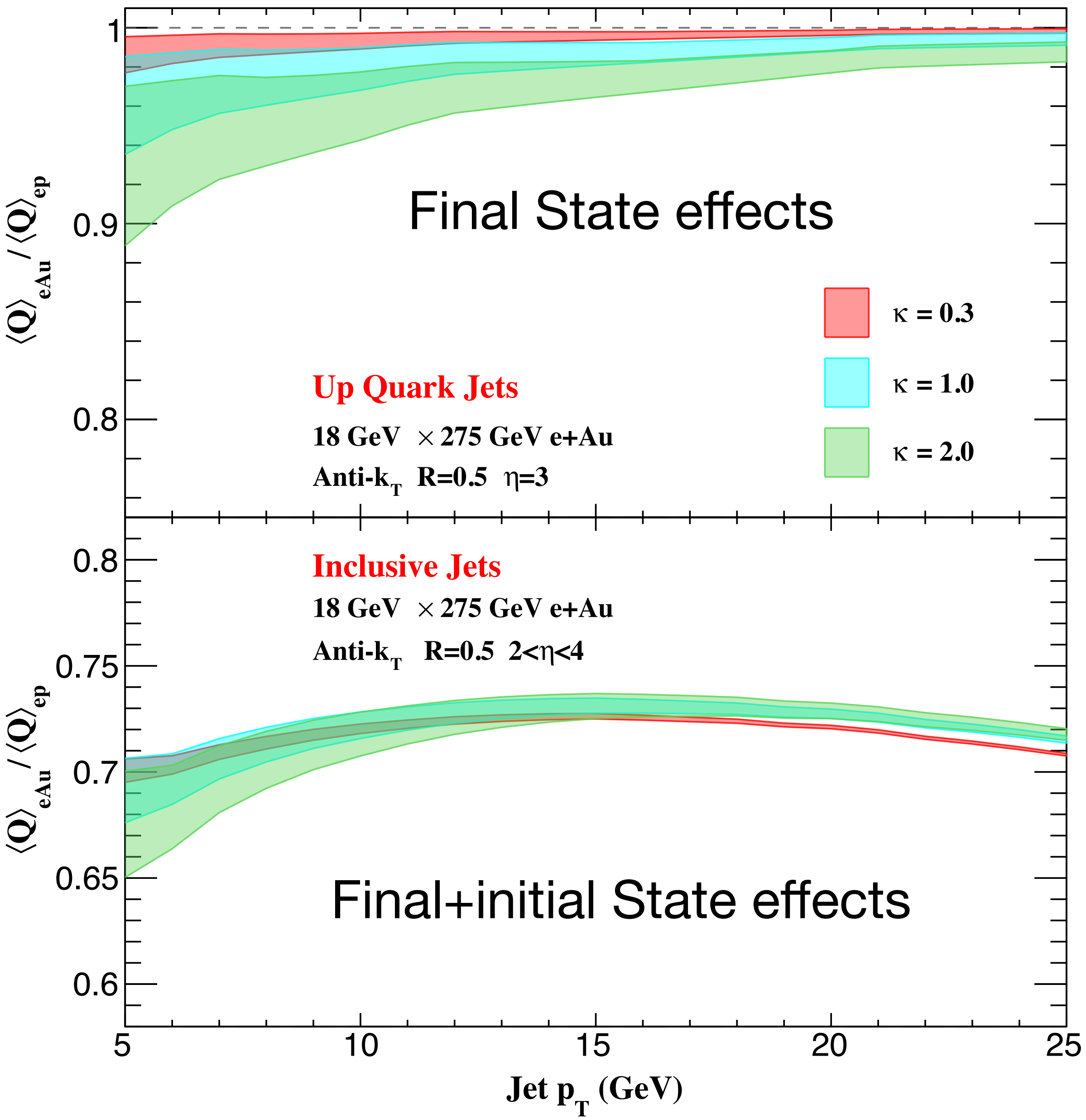
Fixed order corrections to Jet Function

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 general, final state effects are small

Larger correction for larger κ because medium induced radiation tends to be soft

At LO, approximately

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

positive charge negative charge

Cancellation between u and d jet

Initial state effects is large

Precision measurement of the charge will be an excellent way to constrain isospin effects and the up/down quark PDFs in the nucleus.

Conclusion for jet production

- We presented the nuclear matter effect for jet production at EIC
- Initial-state effects were considered via global-fit nuclear PDFs
- Final-state effects were calculated by $SCET_G$
- Modifications for the inclusive jet cross section and average jet charge at EIC are discussed
- Demonstrate how to disentangle initial-state effects and final-state effects for the inclusive jet cross section and the jet charge
- One way to disentangle final and initial state effects and to extract the flavor information

Outline

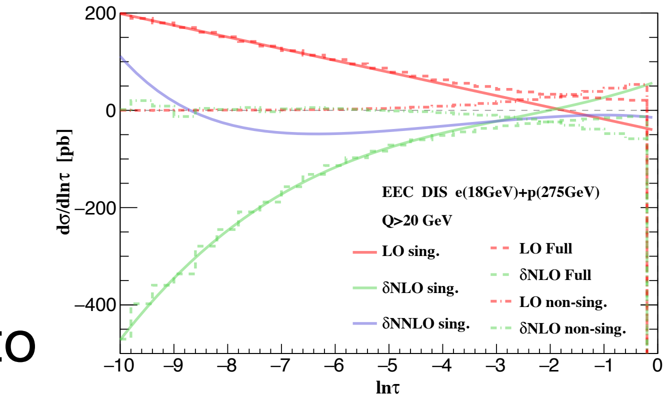
1. Introduction
2. TEEC/EEC in DIS
3. Heavy-flavor Meson production at EIC
4. Jet production at EIC
5. Conclusion

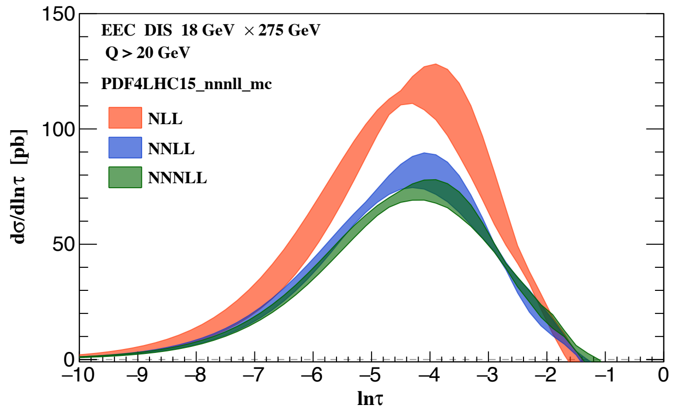
Conclusion

Precision Study in DIS

- Presented the first study of TEEC in DIS
- Introduced a new definition of EEC in DIS for a better connections to TMD physics
- Obtained the NNNLL+NLO distributions for the TEEC and EEC

Highest resumed accuracy achieved to date in DIS





Conclusion

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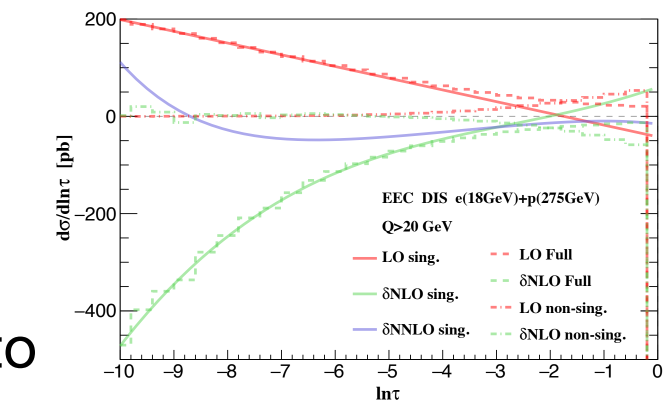
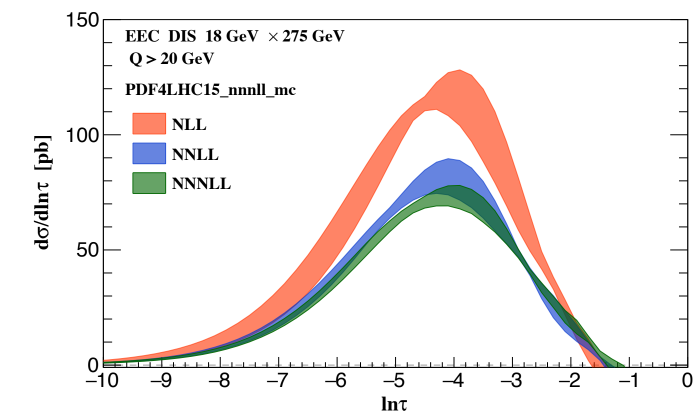
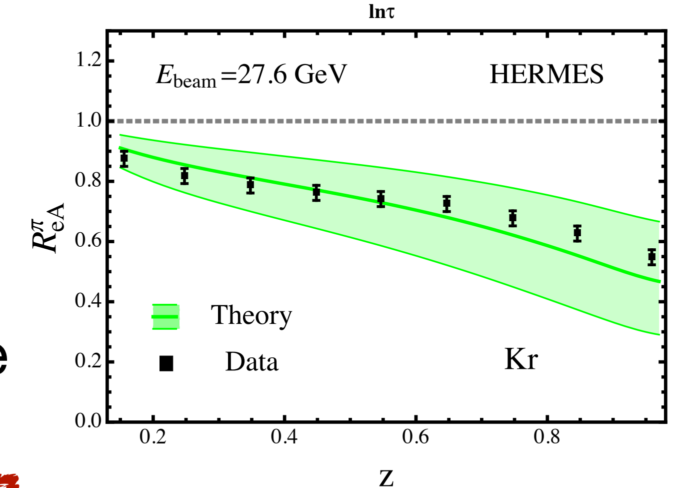
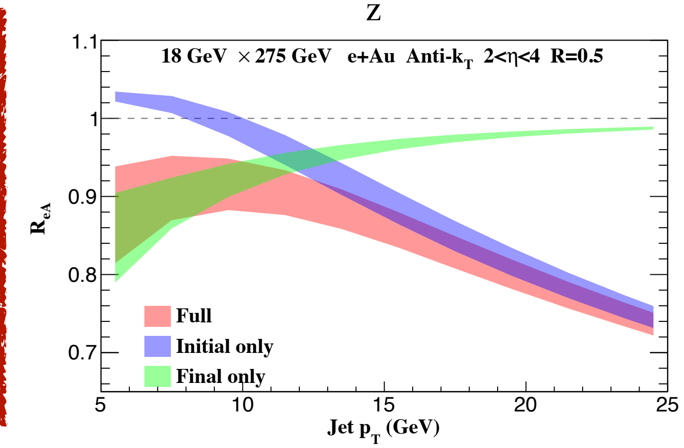




Nuclear effects at EIC

- Showed the first calculation of meson production in e+A at the EIC
- Studied nuclear effects for inclusive jet cross section and jet charge





- Identify the kinematic regions most sensitive to cold nuclear effects
- How to disentangle the initial state effect and final state effect at EIC

Thank you!