Jet measurements at the EIC

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RHIC & AGS Annual users meeting, BNL — 10/22/2020

The Electron-Ion Collider

January 9, 2020

- High luminosity

  $10^{33-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Center-of-mass energy

  $\sqrt{s} = 20 - 140\ \mathrm{GeV}$

- Highly polarized beams
- Electron-proton/nucleus collisions


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Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

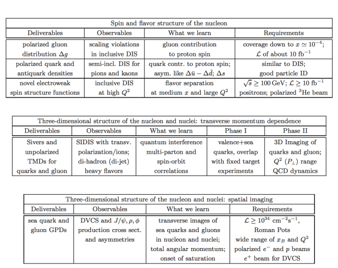
JANUARY 9, 2020

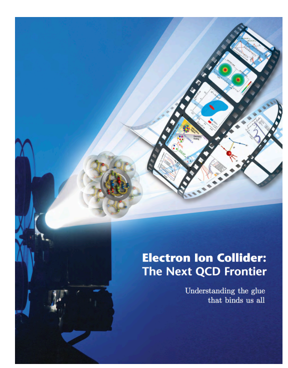
Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

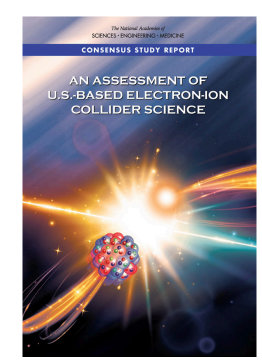
WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

Tables of golden measurements





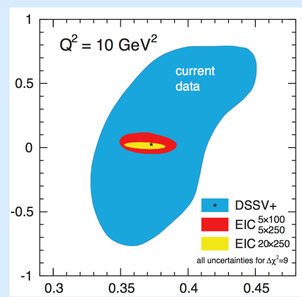


… 2010 2015 2018 2020

The EIC science program

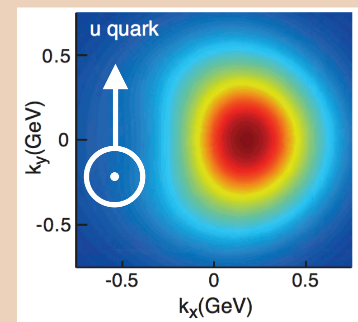
- The spin and mass of the proton
- Parton distribution functions

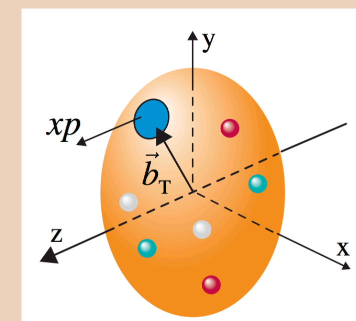
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)$$



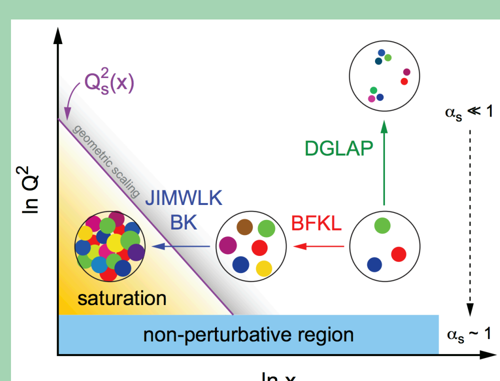
- 3D imaging

Transverse momentum (TMDs) and position (GPDs)

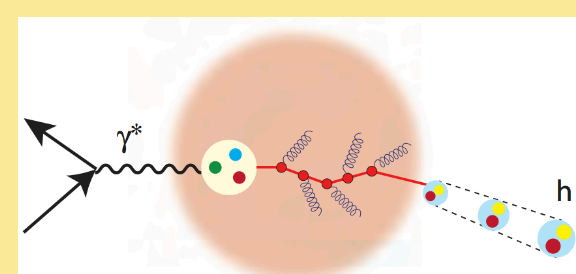




- Small-x and saturation



- Hadronization
- Nuclear modification in eA collisions

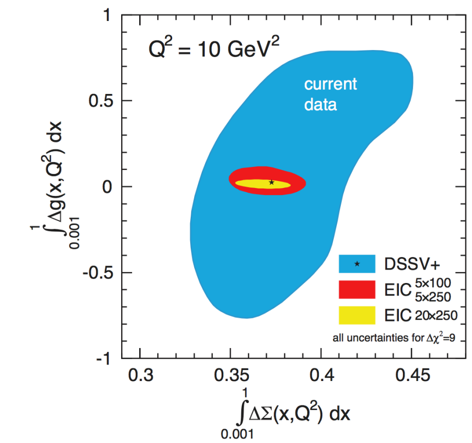


The EIC science program with jets

Jets as tools to realize the EIC science goals — Recent publications

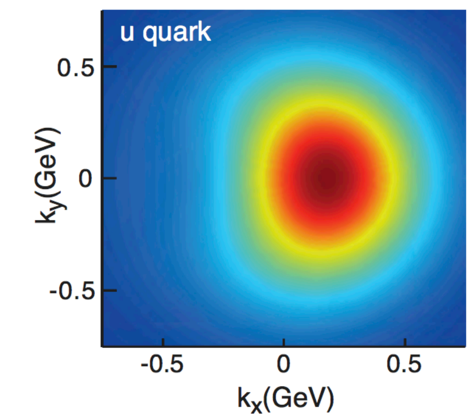
- The spin of the proton, PDFs

  Hinderer, Schlegel, Vogelsang `15, `17, Abelof, Boughezal, Liu, Petriello `16, Boughezal, Petriello, Xing `18, Aschenauer, Chu, Page `19, Guzey, Klasen `18, `20, Borsa, Florian, Pedron `20, `20, Arratia, Furletova, Hobbs, Olness, Sekula `20



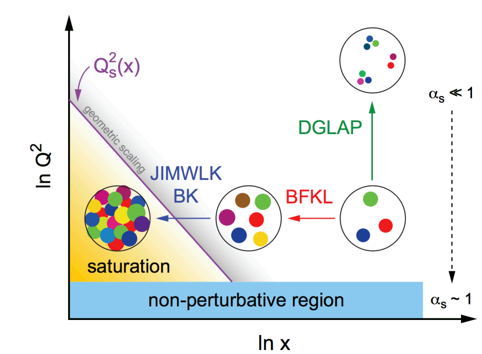
- 3D nucleon/nucleus tomography

  Zheng, Aschenauer, Lee, Xiao, Yin `18, Liu, FR, Vogelsang, Yuan `19, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `19, Hatta, Mueller, Ueda, Yuan `19, Arratia, Kang, Prokudin, FR `20, Kang, Liu, Mantry, Shao `20, Castillo, Echevarria, Makris, Scimemi `20



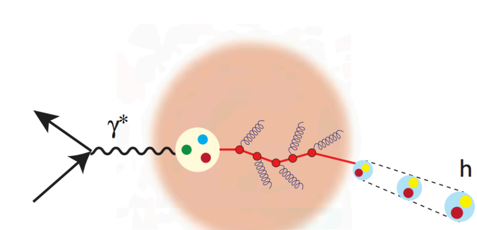
- Saturation, a new form of gluon matter

  Hatta, Xiao, Yuan `17, Salazar, Schenke `19, Roy, Venugopalan `19, Kang, Liu `19 Kolbe, Roy, Salazar, Schenke, Venugopalan `20

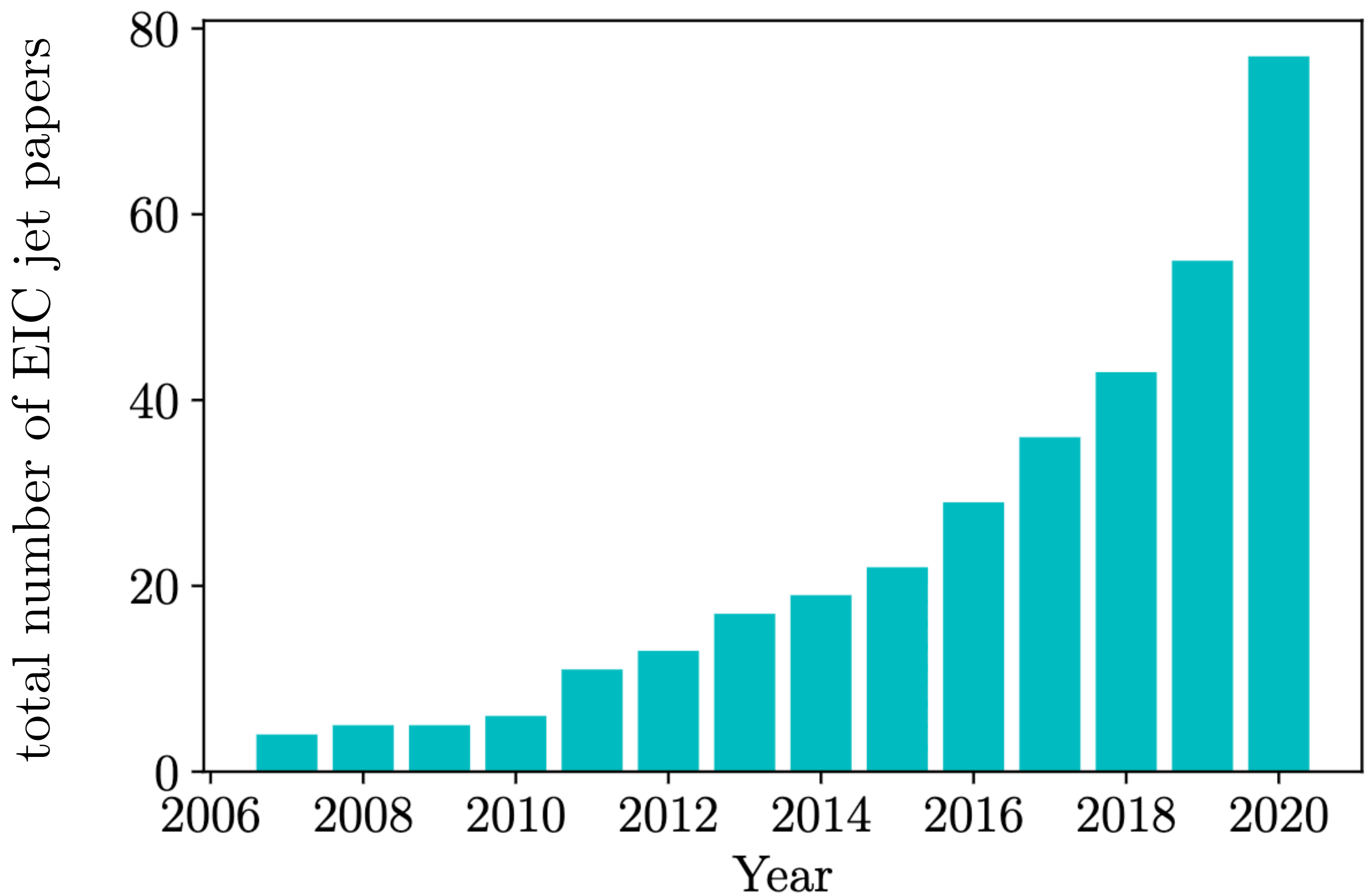


- Hadronization and quarks and gluons in the nucleus

  Klasen, Kovarik `18, Aschenauer, Lee, Page, FR `19, Qin, Wang, Zhang `19, Arratia, Song, FR, Jacak `19, Li et al. `20, Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk `20, Li, Vitev `20



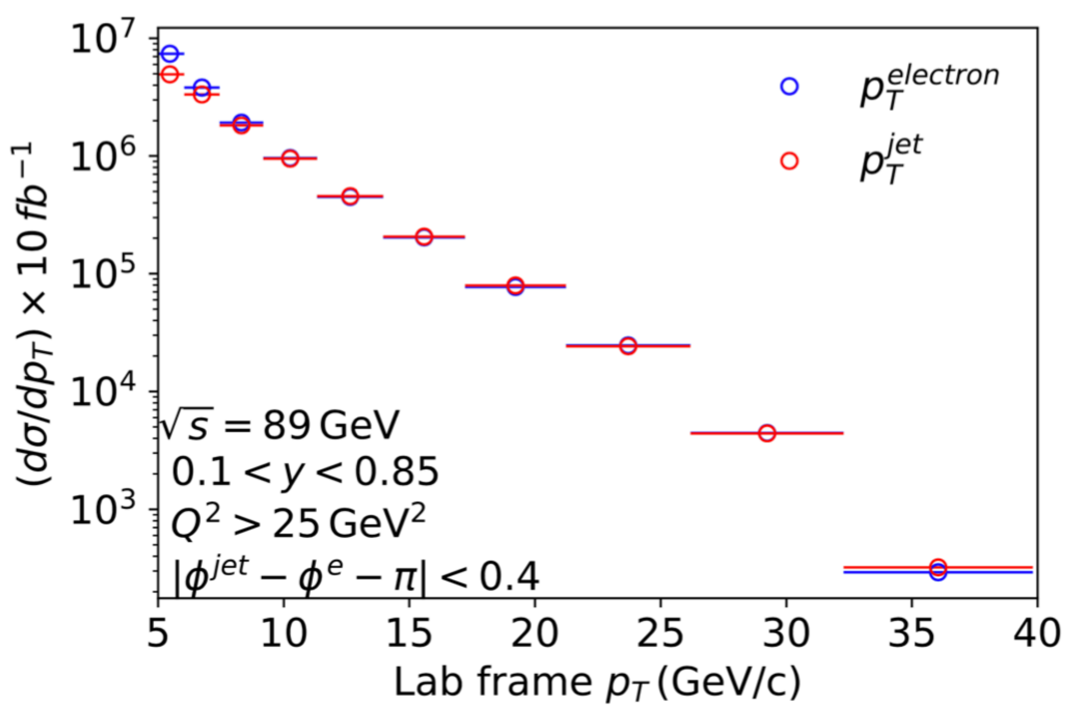
The EIC science program with jets



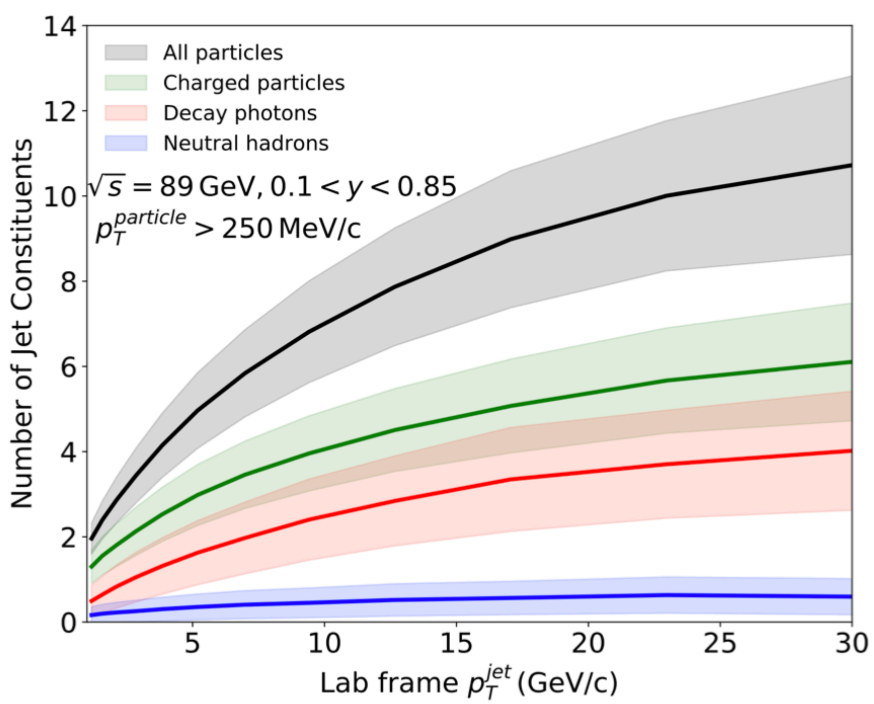
- There have been many new developments recently!
- Prominently featured in the EIC Yellow Report

Jets at the EIC

Jet transverse momentum



Number of particles



Relatively low energies, need good control of hadronization corrections

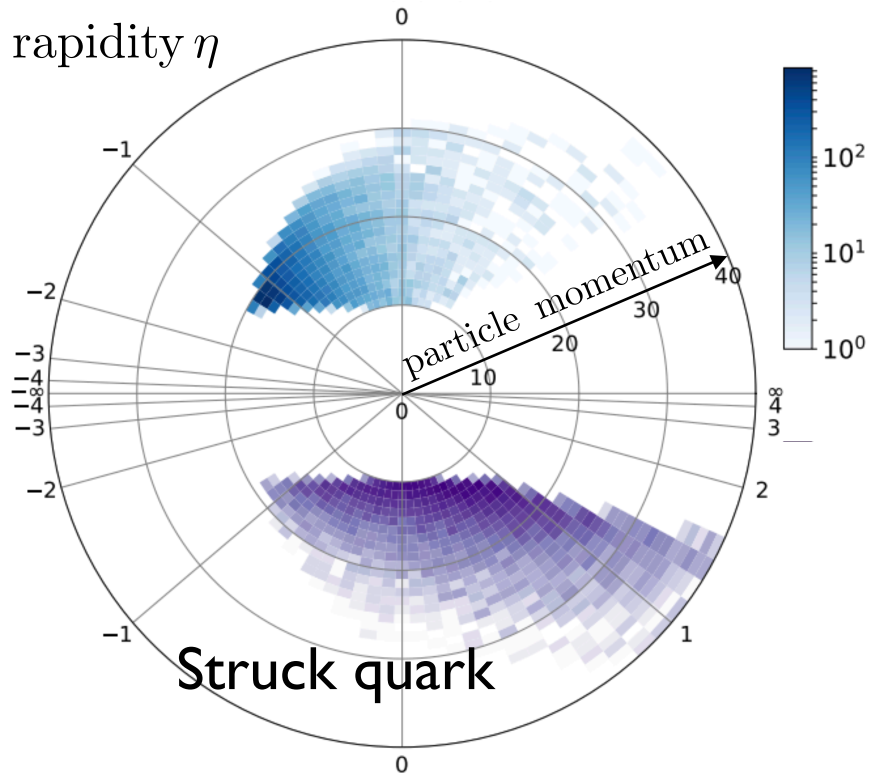
Clean environment — no Multi Parton Interactions (MPI)

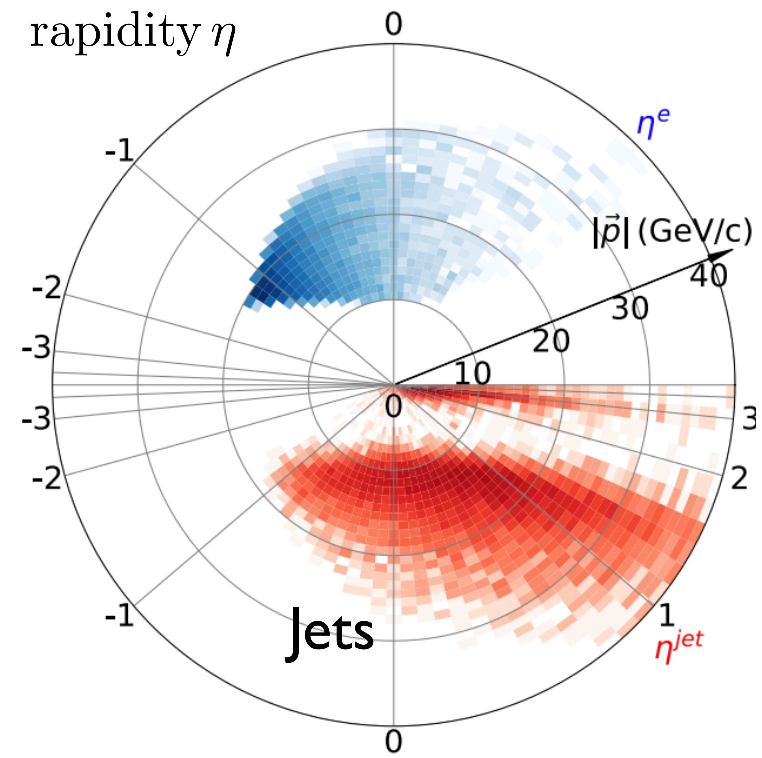
Jets at the EIC

$Q^2 > 100\ \mathrm{GeV}^2,\ \sqrt{s} = 89\ \mathrm{GeV}$

$10 < p_T^e < 30\ \mathrm{GeV},\ 0.1 < y < 0.85$

initial proton →





- Jets are excellent proxies of parton level kinematics
- Clean separation of current & target fragmentation (UE)
- Complementary to observables with hadrons

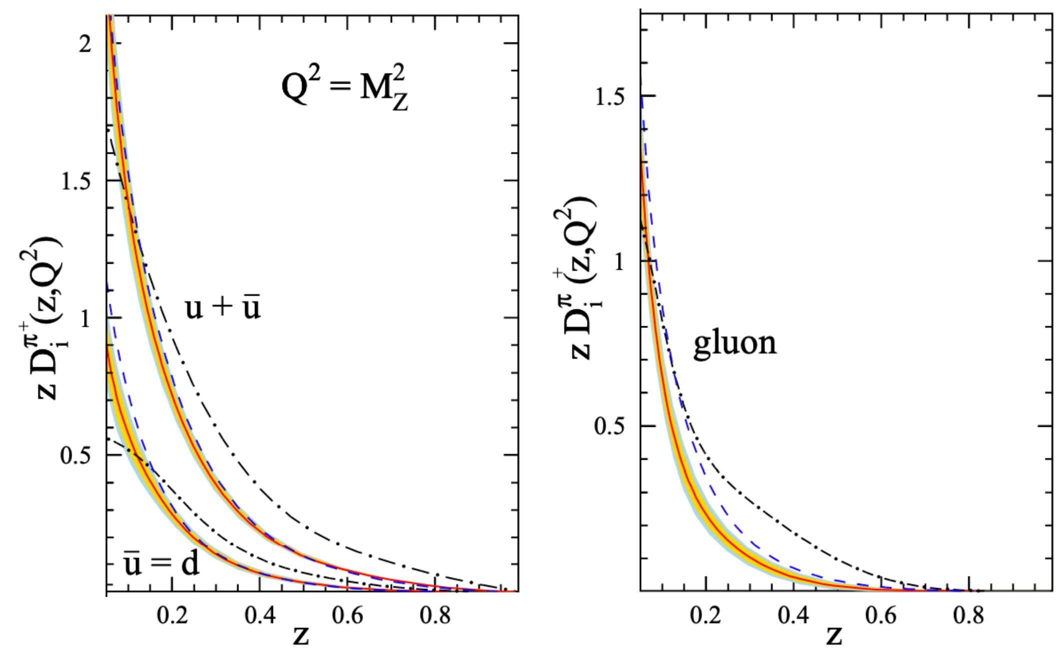
Laboratory frame Pythia 8

Arratia, Jacak, FR, Song `19
see also Aschenauer, Chu, Page `19

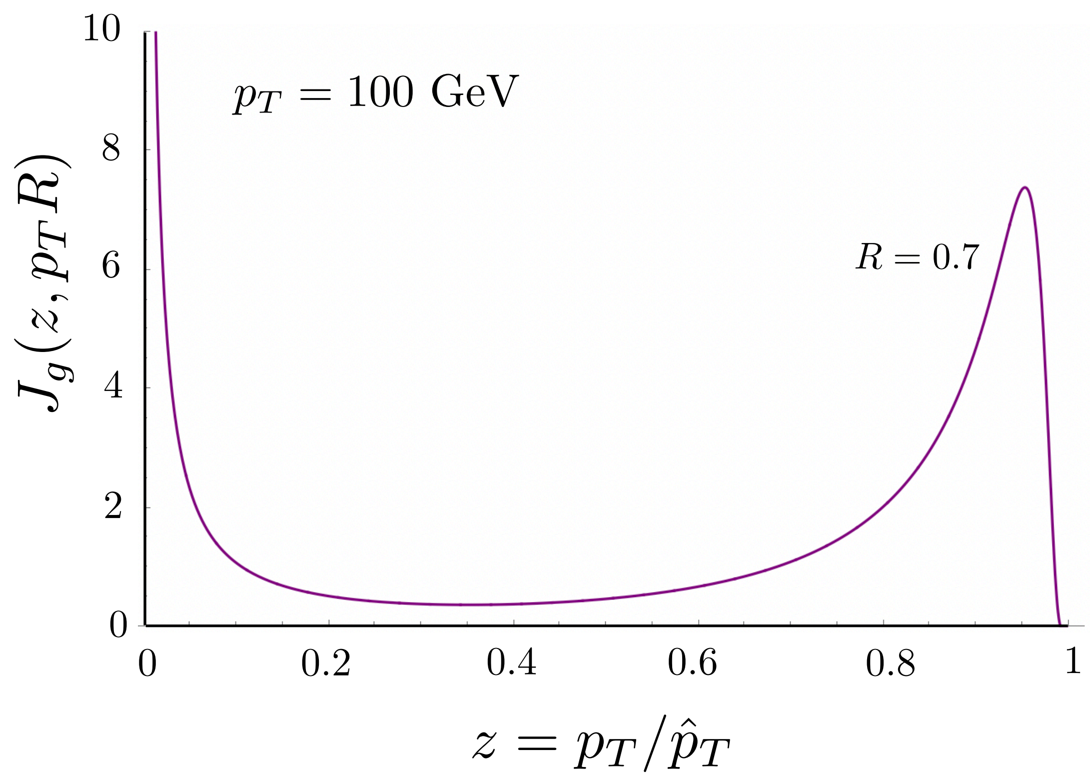
The QCD fragmentation process

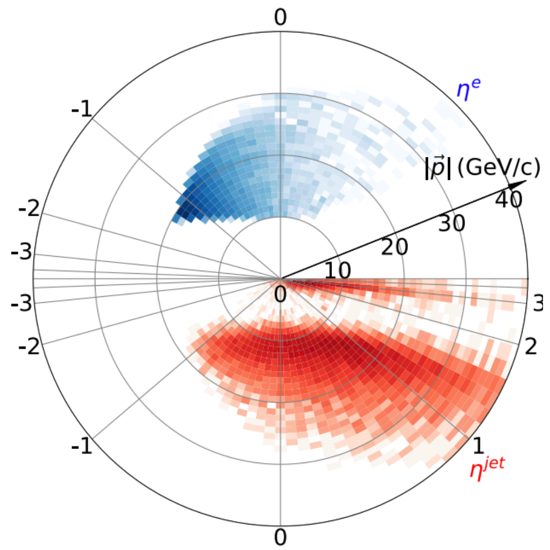
- Fragmentation functions

de Florian, Epele, Hernandez-Pinto, Sassot, Stratmann `15



- Jet functions





Kang, FR, Vitev `16
Dai, Kim, Leibovich `17
Neill, FR, Sato `20

Outline

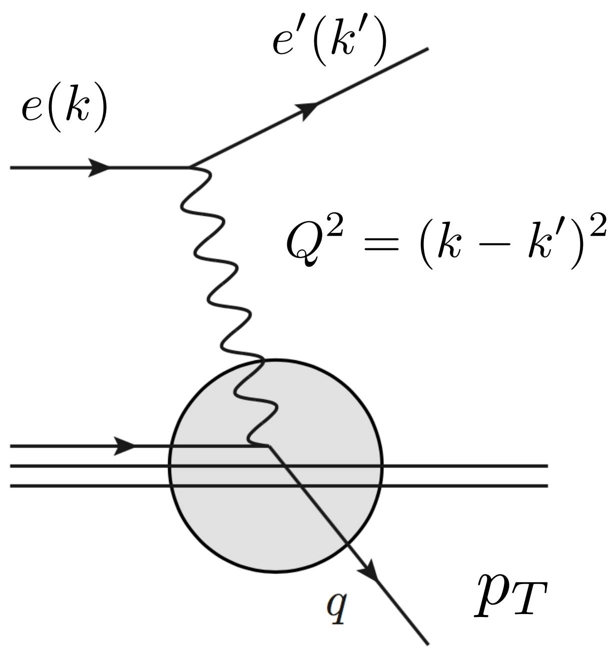
- Introduction
- Inclusive and leading jets
- TMDs measurements with jets
- Hadronization and cold nuclear matter
- Conclusions

Jet clustering and frame dependence

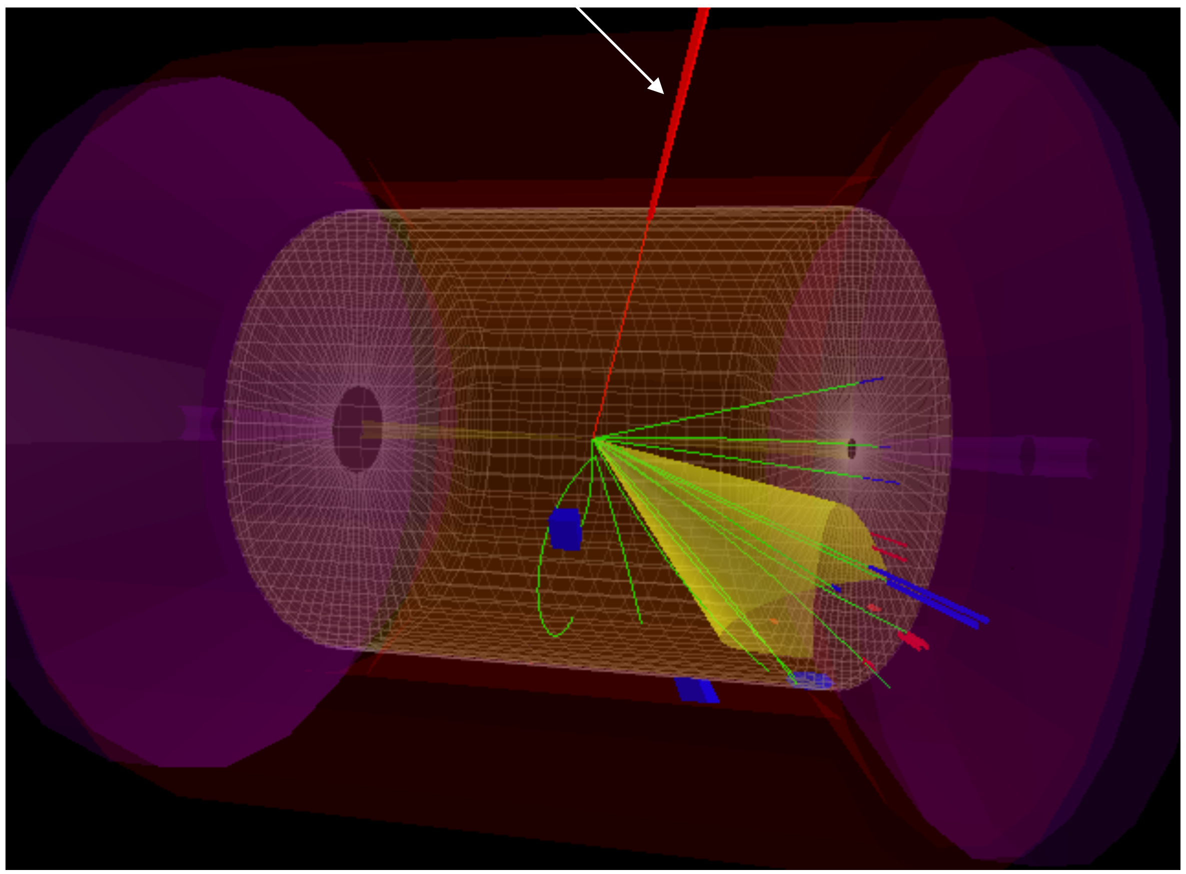
- **Laboratory frame**

Can measure two variables

- Jet transverse momentum p_T
- Photon virtuality Q^2



Leading electron Q^2

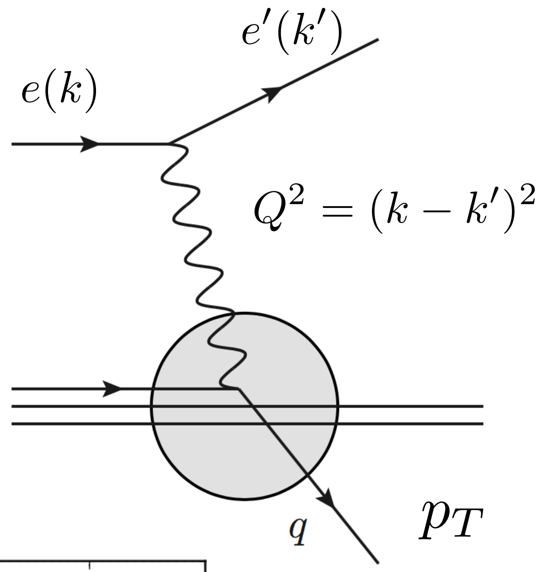


- Cluster jets in the laboratory frame η, ϕ
- Leading-order $eq \to eq$

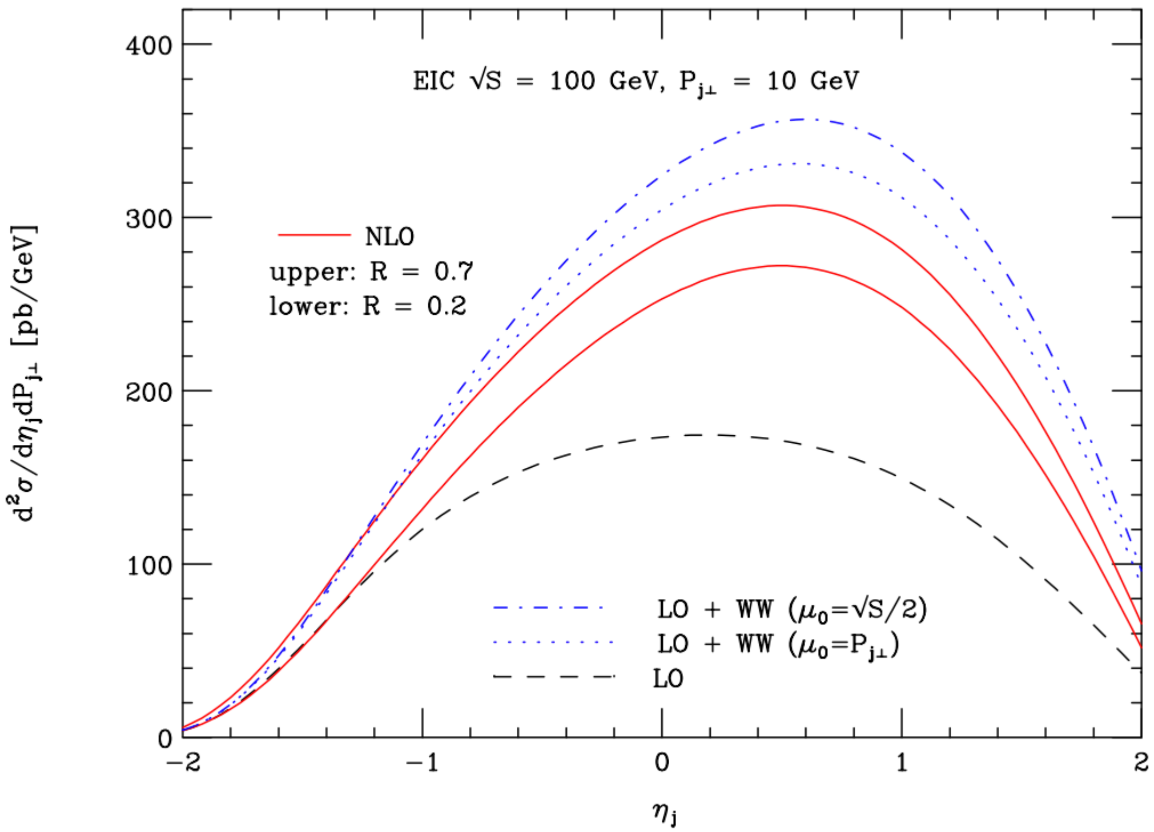
Jet clustering and frame dependence

- **Laboratory frame**

Measure only p_T, close analogy to $pp \to \text{jet} + X$

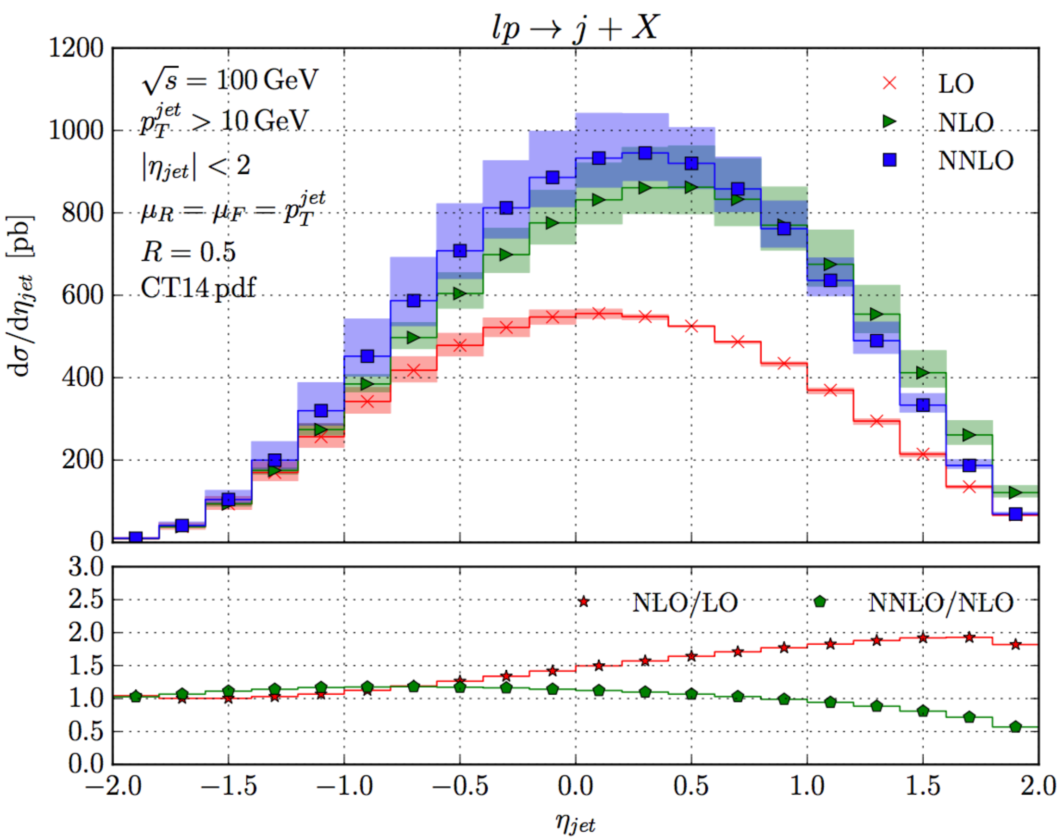


NLO



Hinderer, Schlegel, Vogelsang `15

NNLO



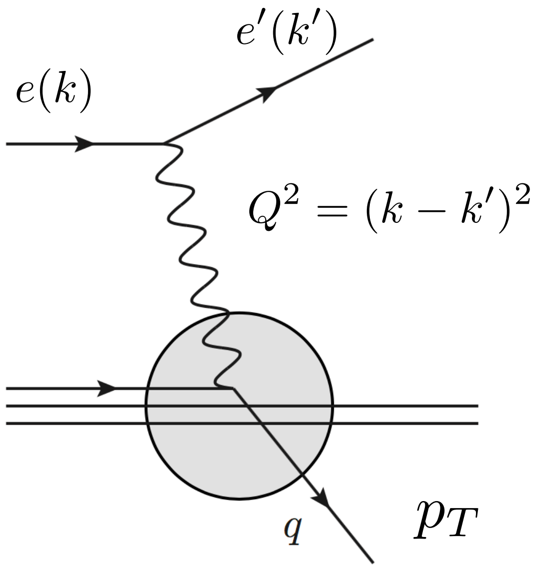
Abelof, Boughezal, Liu, Petriello `16

Jet clustering and frame dependence

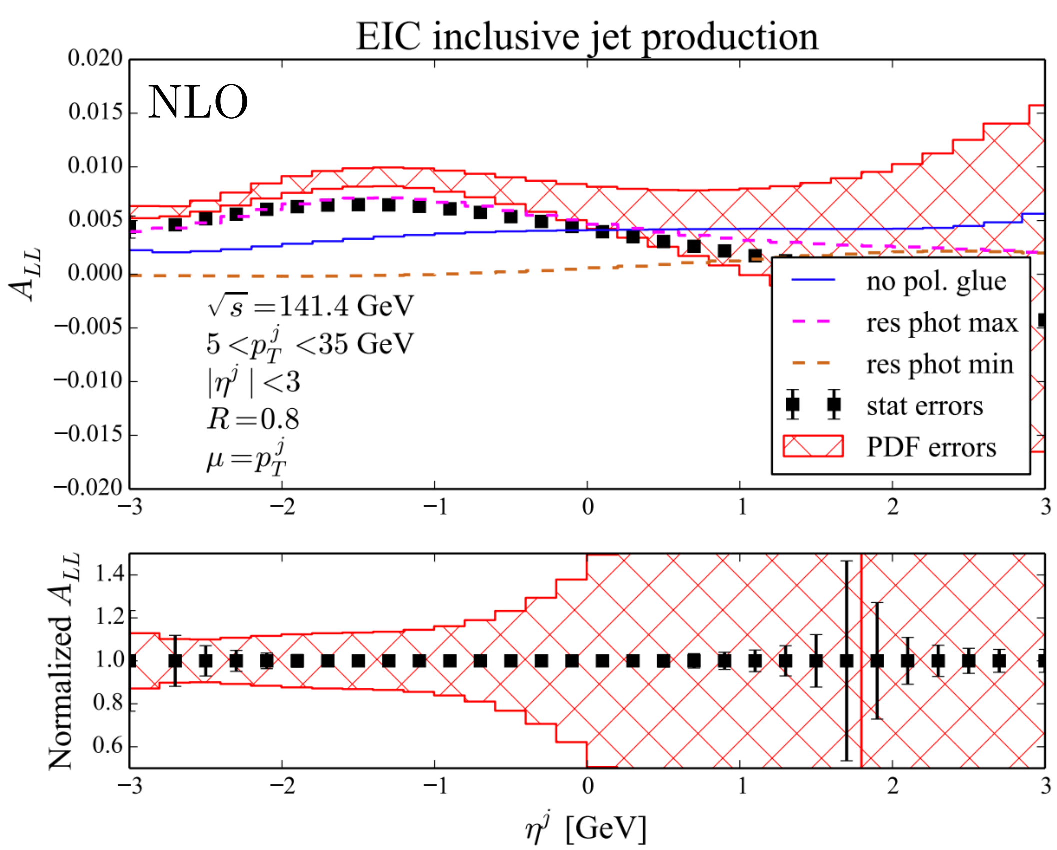
- **Laboratory frame**

Measure only p_T, close analogy to $pp \to \text{jet} + X$

Double longitudinal spin asymmetries $\Delta q_i\,,\ \Delta g$

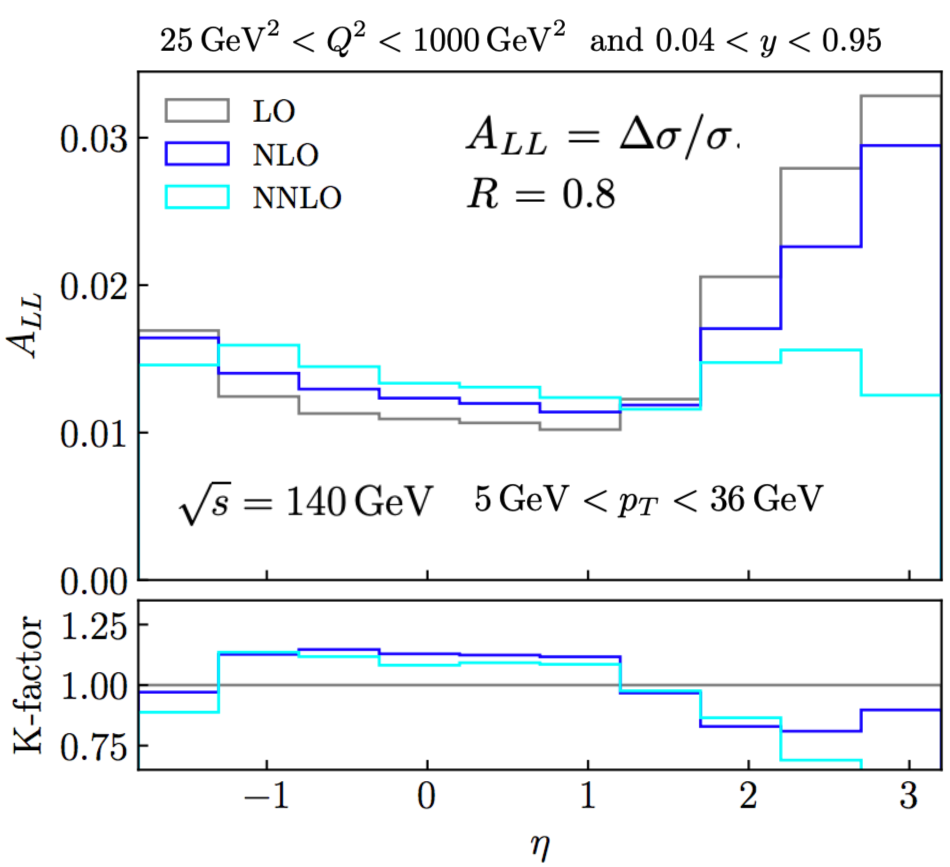


$\vec{e} + \vec{p} \to \text{jet} + X$



Boughezal, Petriello, Xing `18
see also Hinderer, Schlegel, Vogelsang `17

$\vec{e} + \vec{p} \to e + \text{jet} + X$

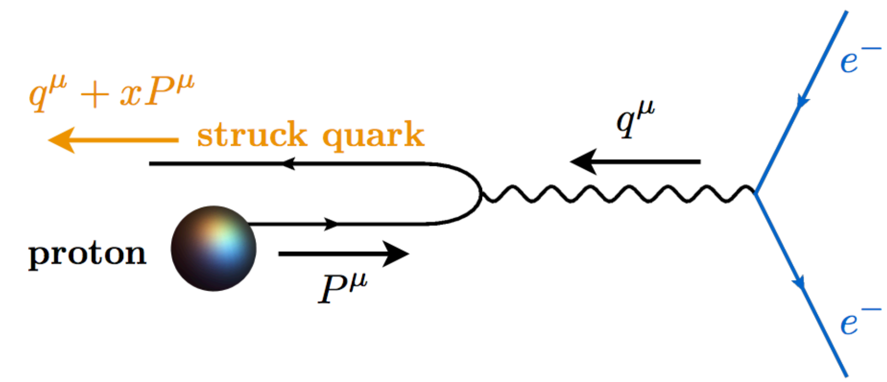


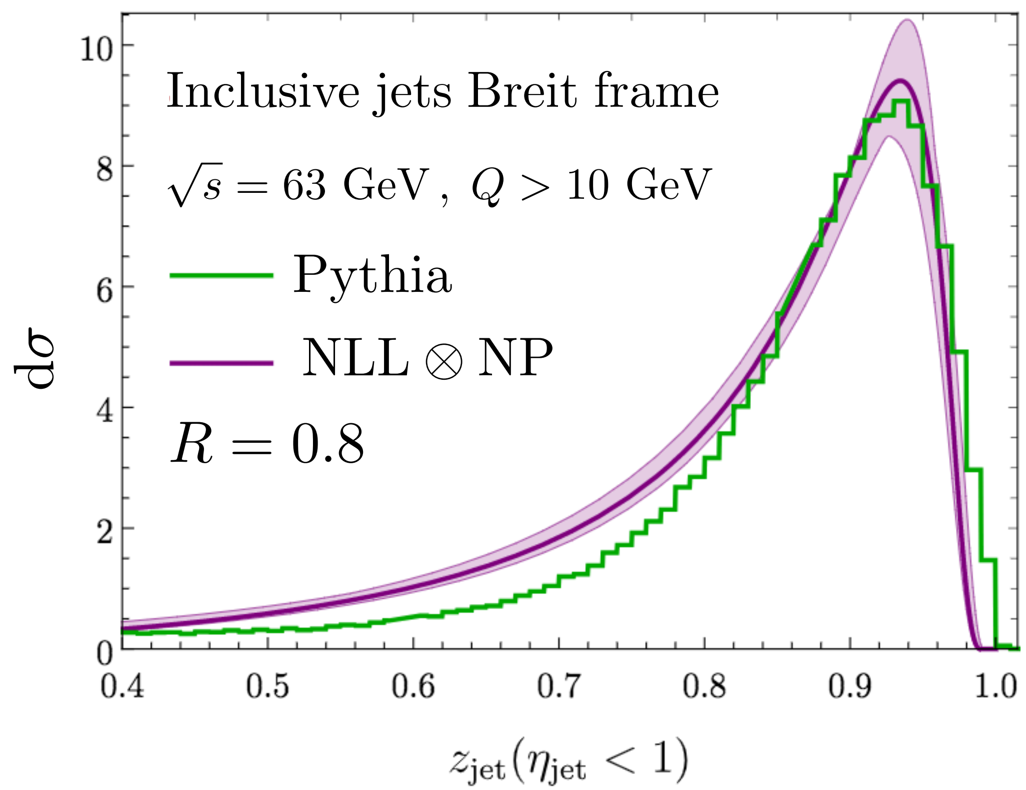
Borsa, Florian, Pedron `20

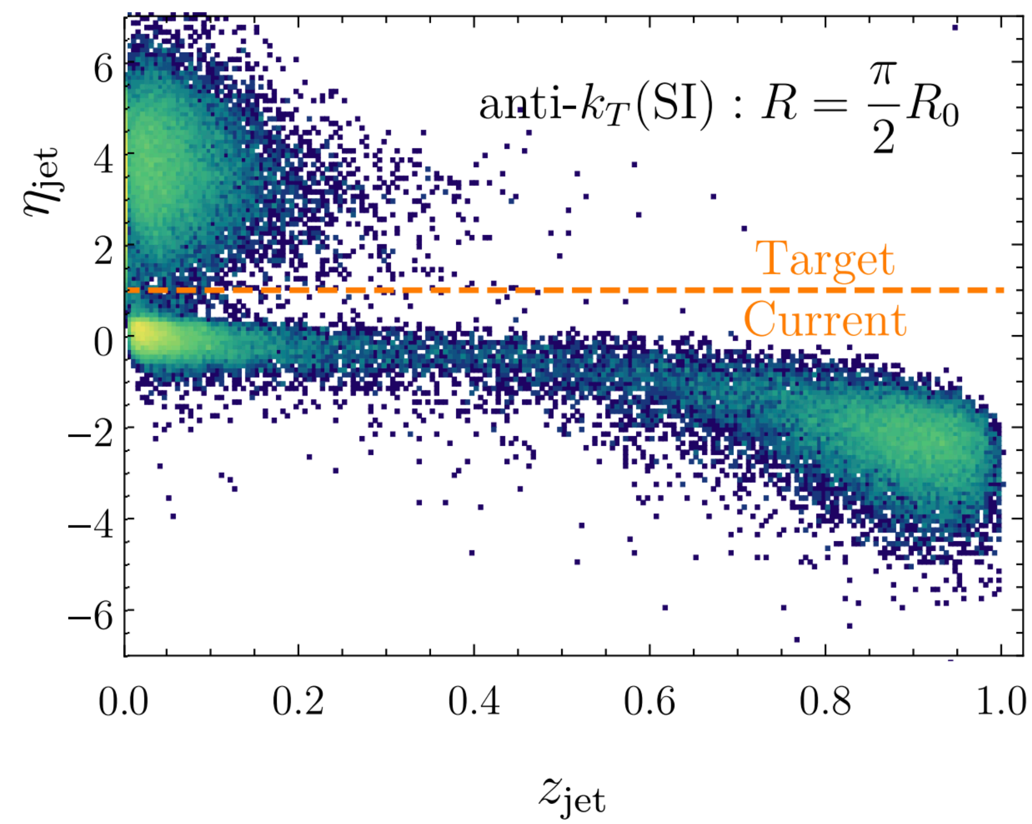
Jet clustering and frame dependence

Arratia, Makris, Neill, FR, Sato `20

- **Breit frame**
  - Photon virtuality Q^2
  - Jet **energy** $z_{\rm jet} = \dfrac{P\cdot p_{\rm jet}}{P\cdot q} \simeq p^-_{\rm jet}/Q$





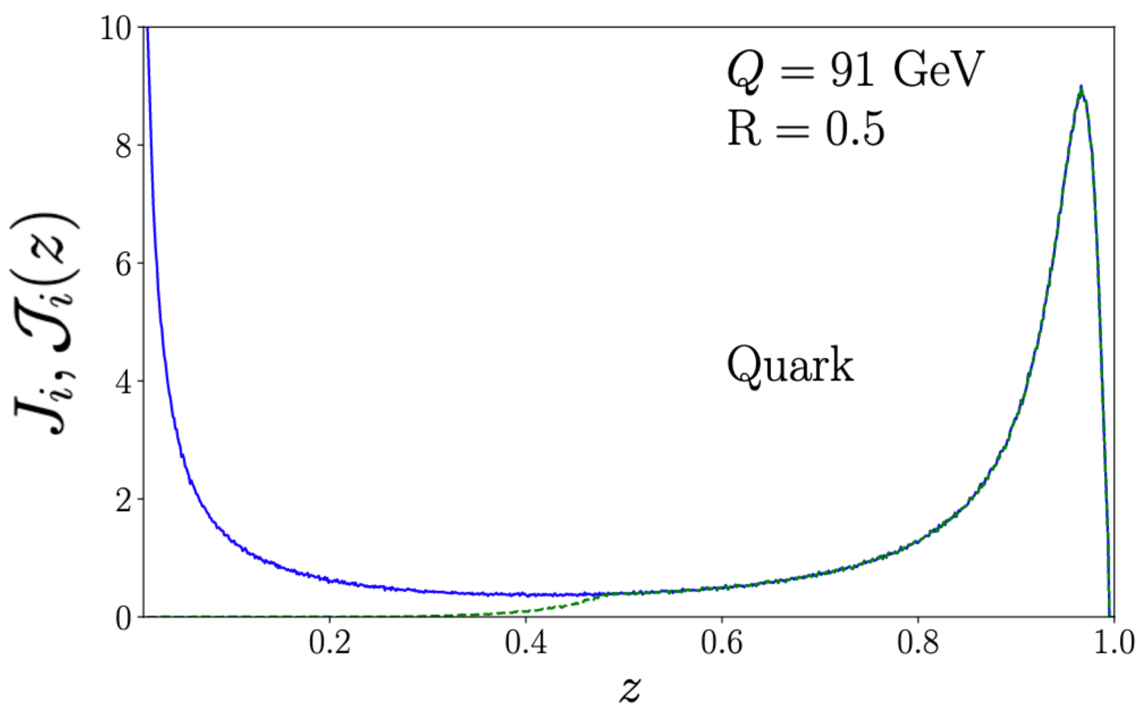


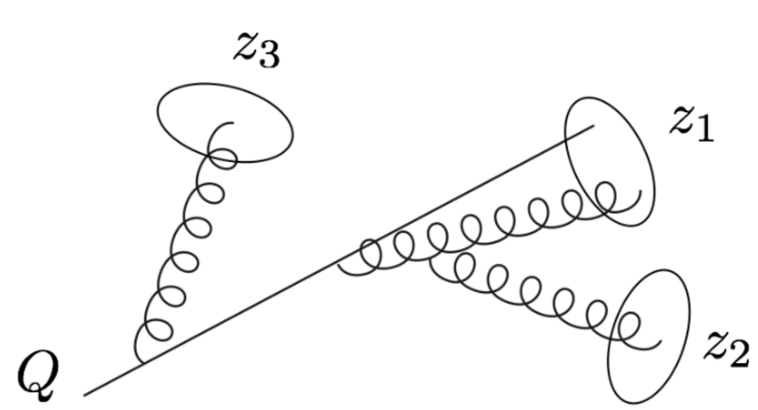
- Reconstruct jets which enclose the Breit frame beam axis
- Starting point for Breit frame TMD-jet studies

Leading jets

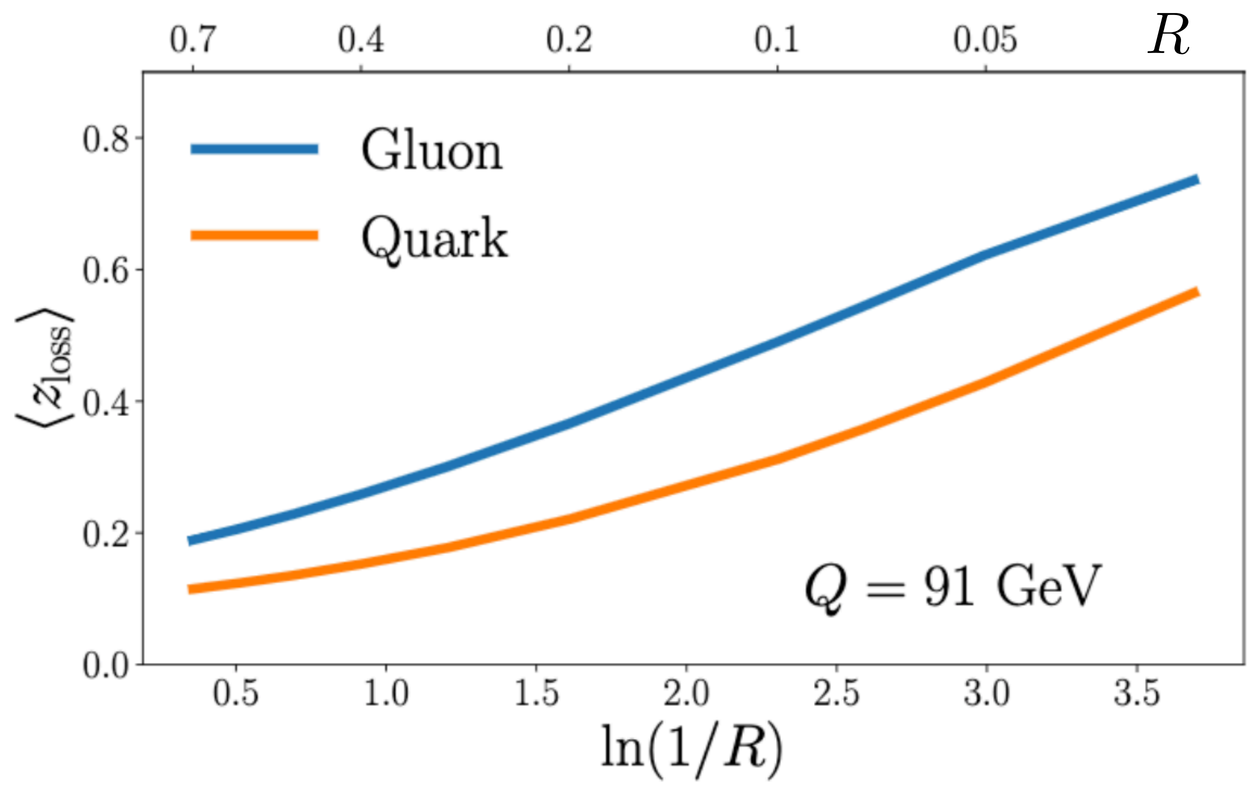
Neill, FR, Sato `20

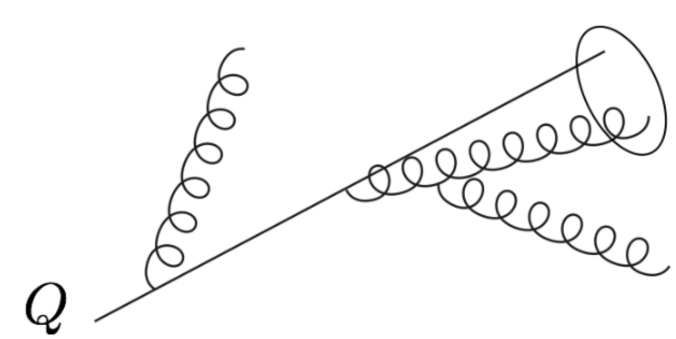
- **Inclusive vs. leading jets**





- **The average energy loss**





Outline

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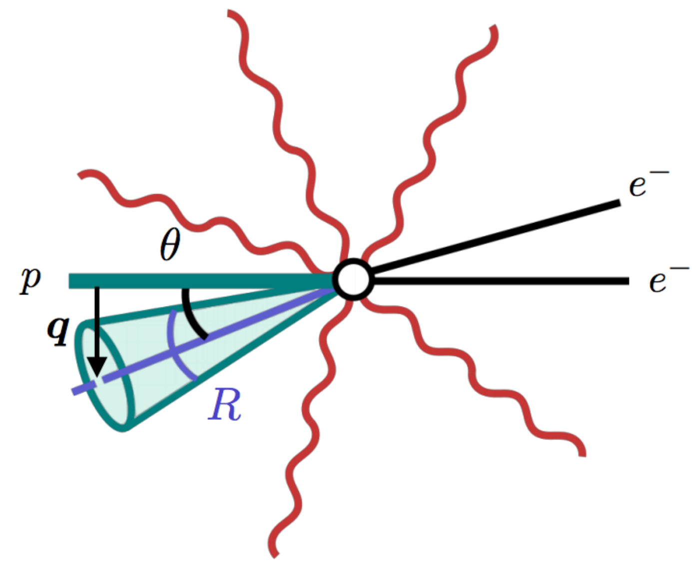
- Hadronization and cold nuclear matter
- Conclusions

TMD-jet observables

Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `18, `19
Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi `20

- Semi-Inclusive Deep Inelastic Scattering
- Breit frame jet reconstruction $e + p \to e + \mathrm{jet} + X$

$$\boldsymbol{q} = \frac{\boldsymbol{P}_J}{z} + \boldsymbol{q}_{\mathrm{in}} \qquad z = 2E_J/Q$$



$$\frac{\mathrm{d}\sigma_{ep\to eJX}}{\mathrm{d}Q^2\mathrm{d}x\mathrm{d}z\mathrm{d}\boldsymbol{q}} = \sum_q H_{\mathrm{DIS}}\, f_q(x,\boldsymbol{q}) \otimes_{\boldsymbol{q}} J_q(z,\boldsymbol{q},R)$$

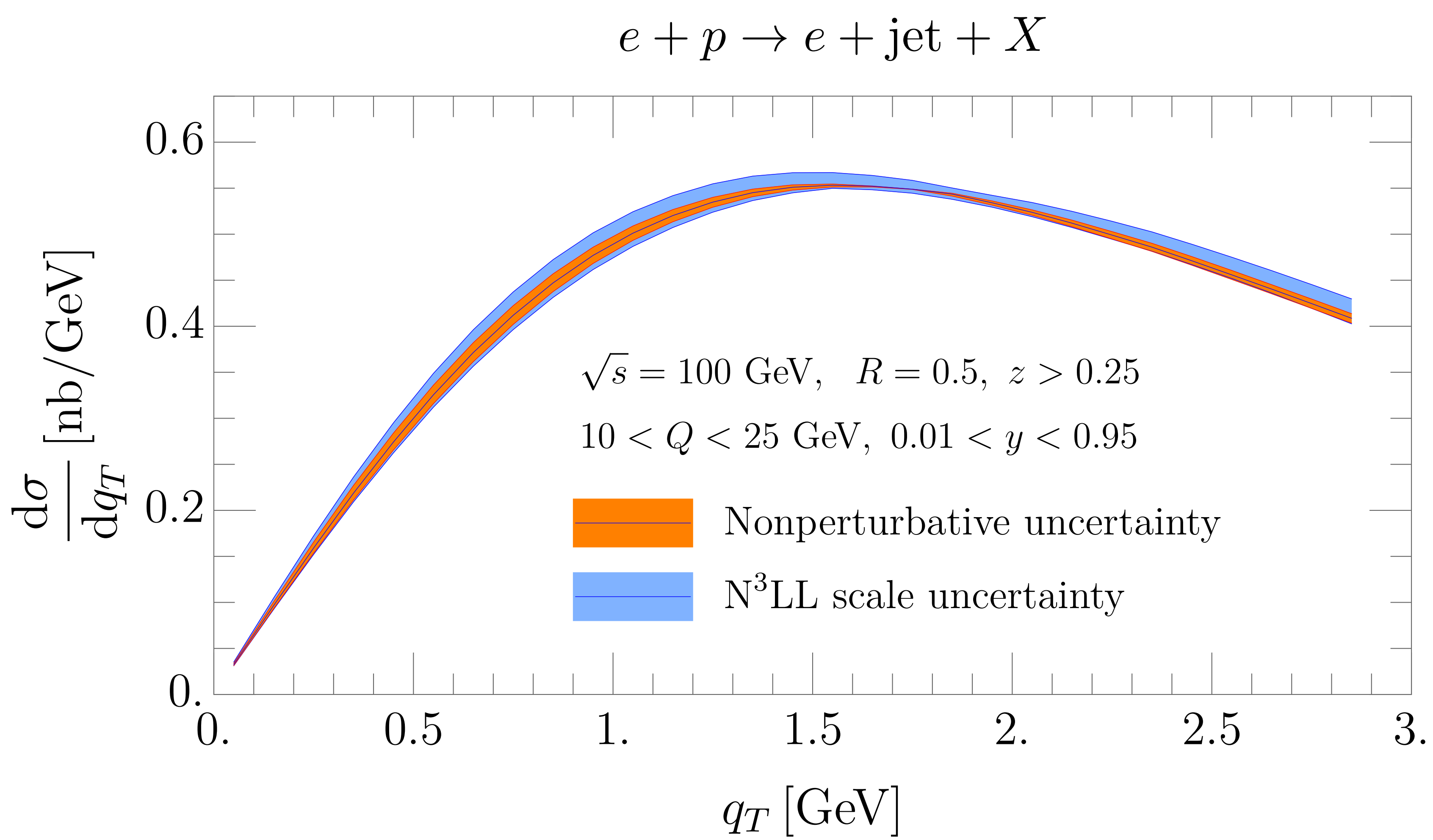
Perturbative TMD jet function

- Sensitivity to TMD PDF **only**
- Winner-take-all (WTA) jet axis

TMD-jet observables

Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `18, `19
Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi `20

- Semi-Inclusive Deep Inelastic Scattering
- Breit frame jet reconstruction

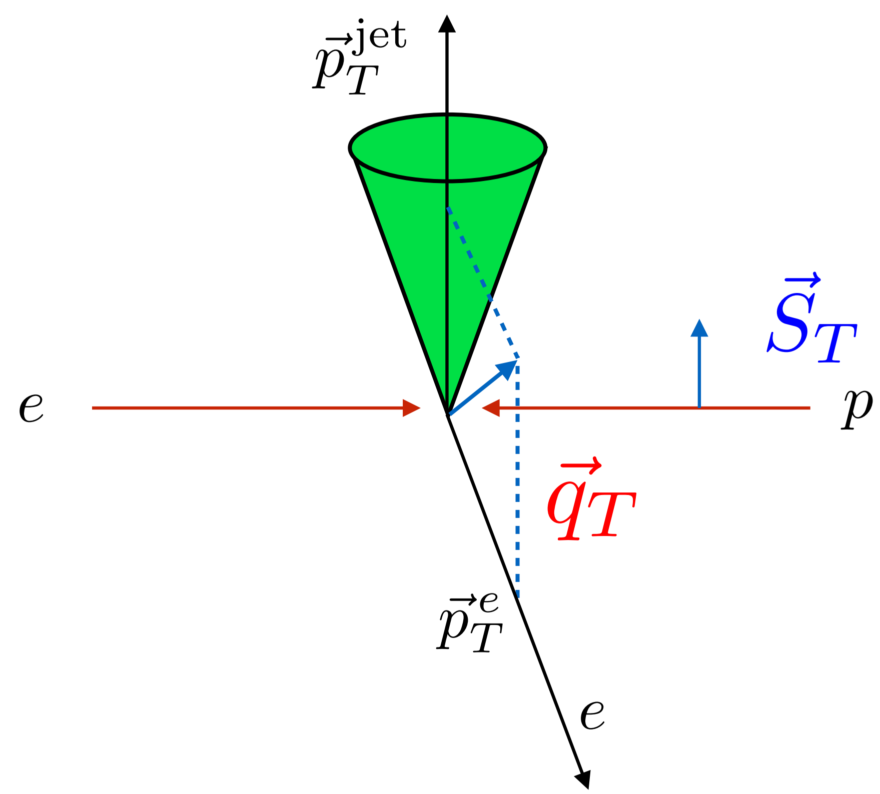


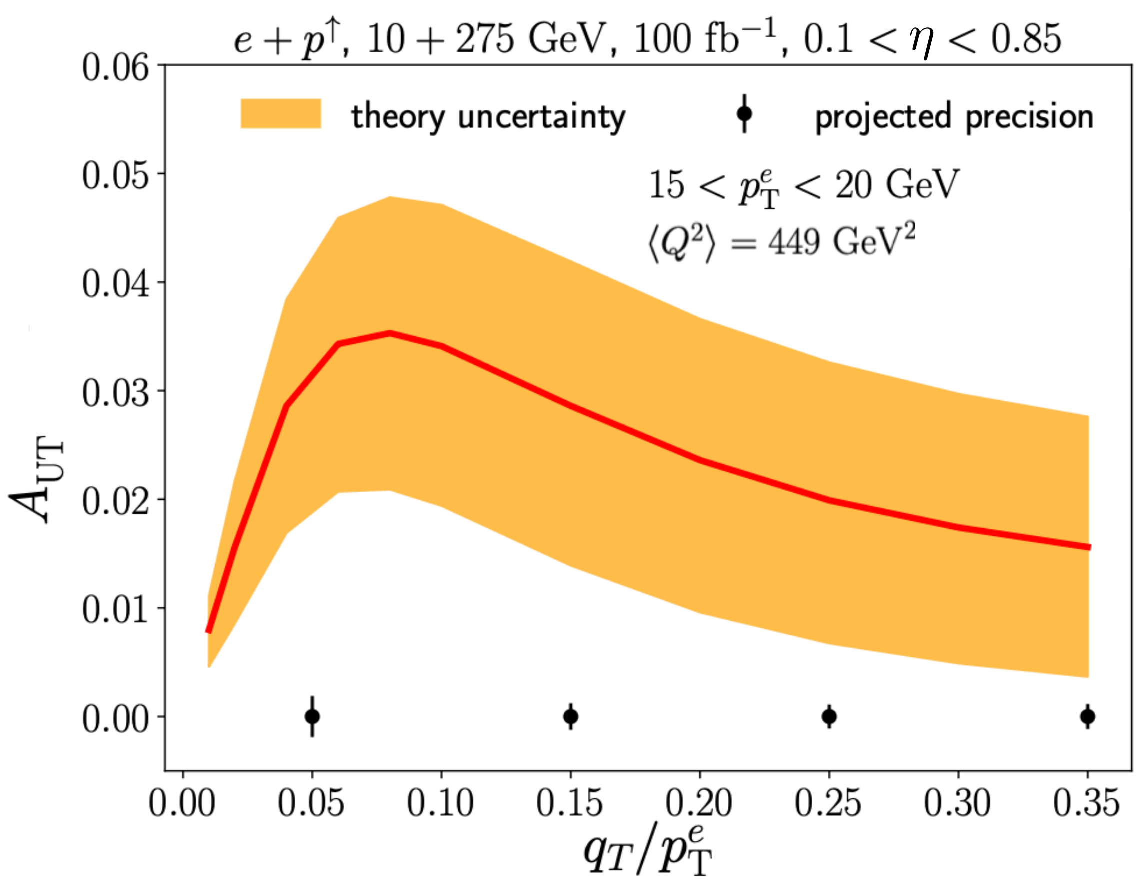
WTA-axis

Electron-jet correlations

Liu, FR, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, FR `19

- Measure the electron-jet imbalance $\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}$
- Sensitivity to TMD PDFs **only**
- Sivers asymmetry $\sigma(\vec{S}_T) - \sigma(-\vec{S}_T)$





- Test of the predictive power of QCD — di-jet processes at RHIC

Electron-jet correlations - flavor sensitivity

- Measure the electron-jet imbalance $\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\rm jet}$

Liu, Kang, Mantry, Shao `20

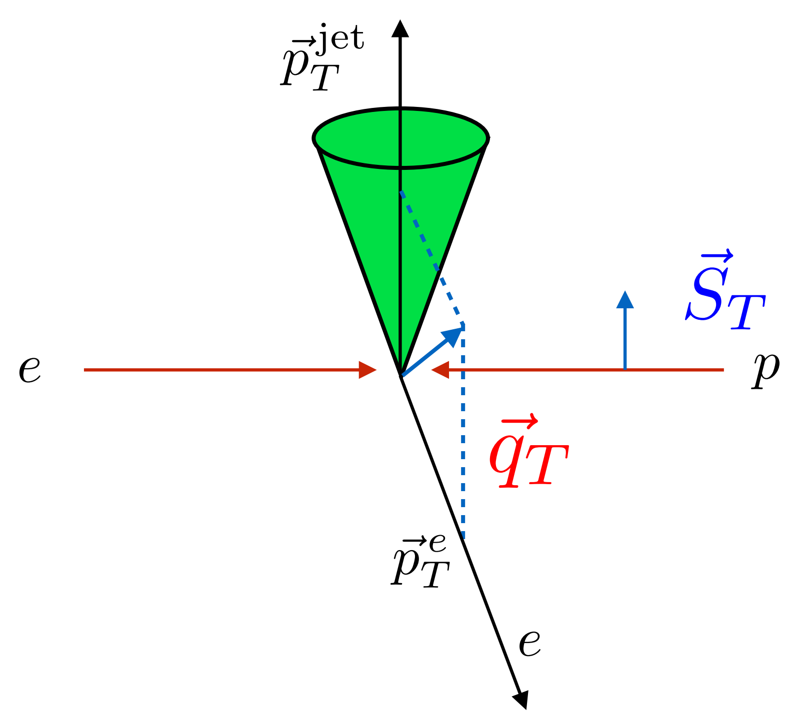
- and the jet charge

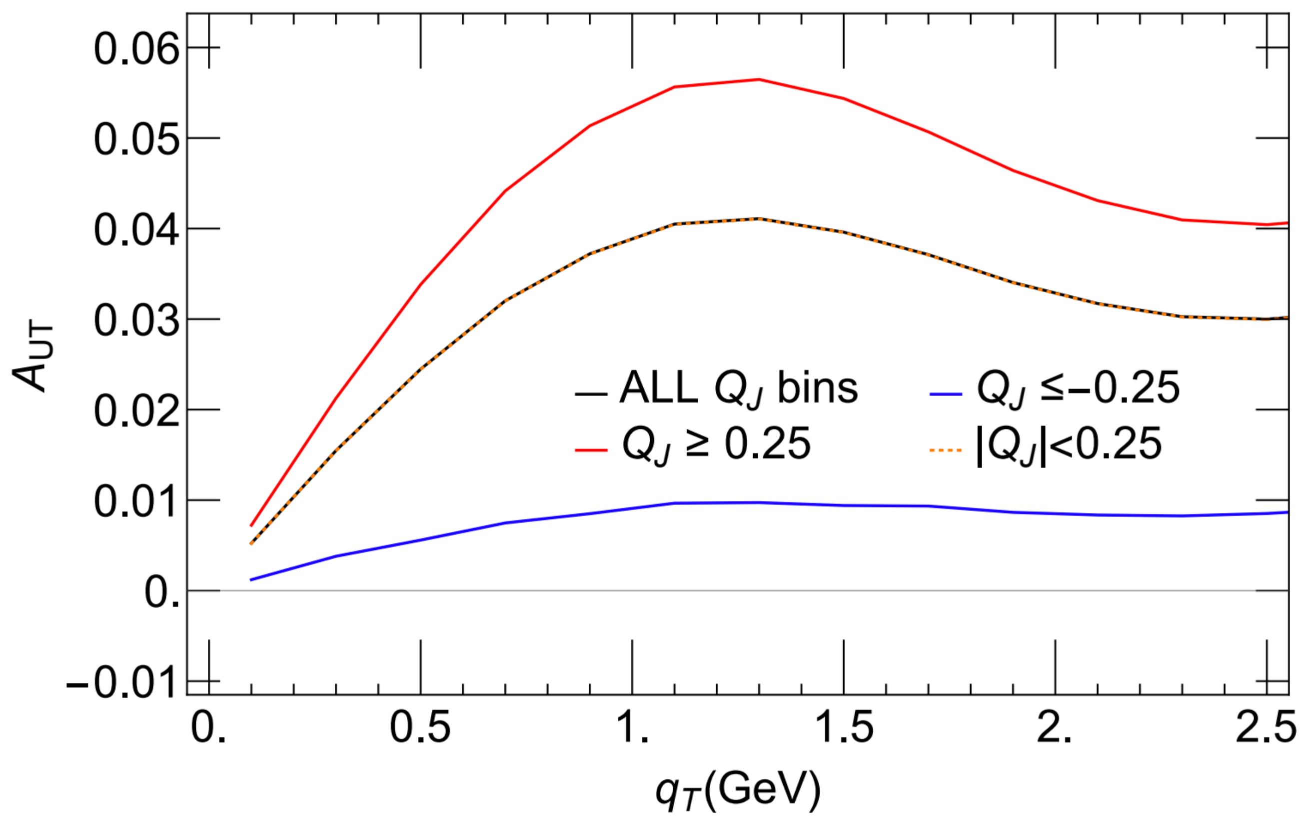
$$Q_\kappa^i = \sum_h Q_\kappa^h \equiv \sum_{h\in \rm jet} z_h^\kappa Q_h$$

Field, Feynman `78

(weighted sum of charges)

- Jet charge tagging avoids large cancellation between different quark flavors $\sigma(\vec{S}_T) - \sigma(-\vec{S}_T)$





see also Krohn, Lin, Schwartz, Waalewijn `12, Waalewijn `12, RHIC measurements

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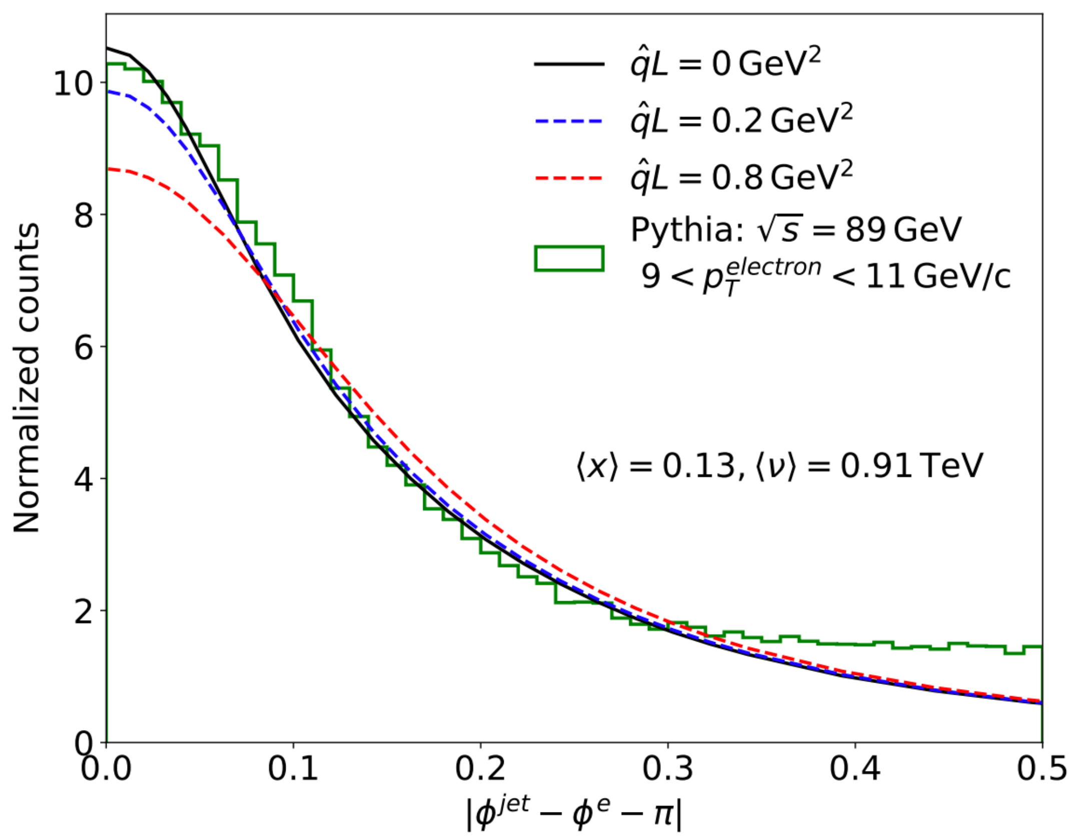
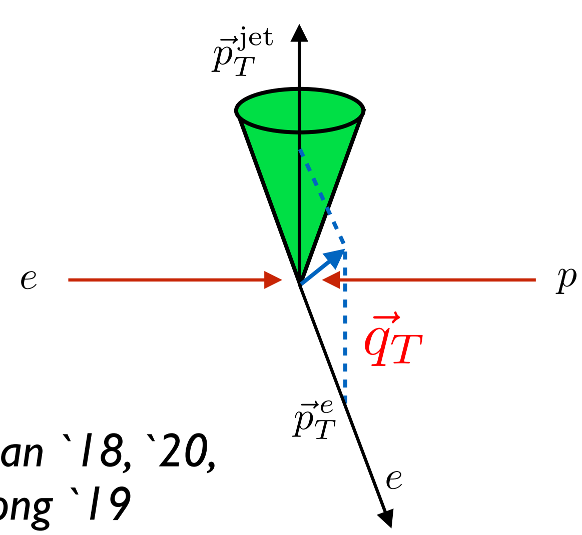
Probes of cold nuclear matter effects in eA

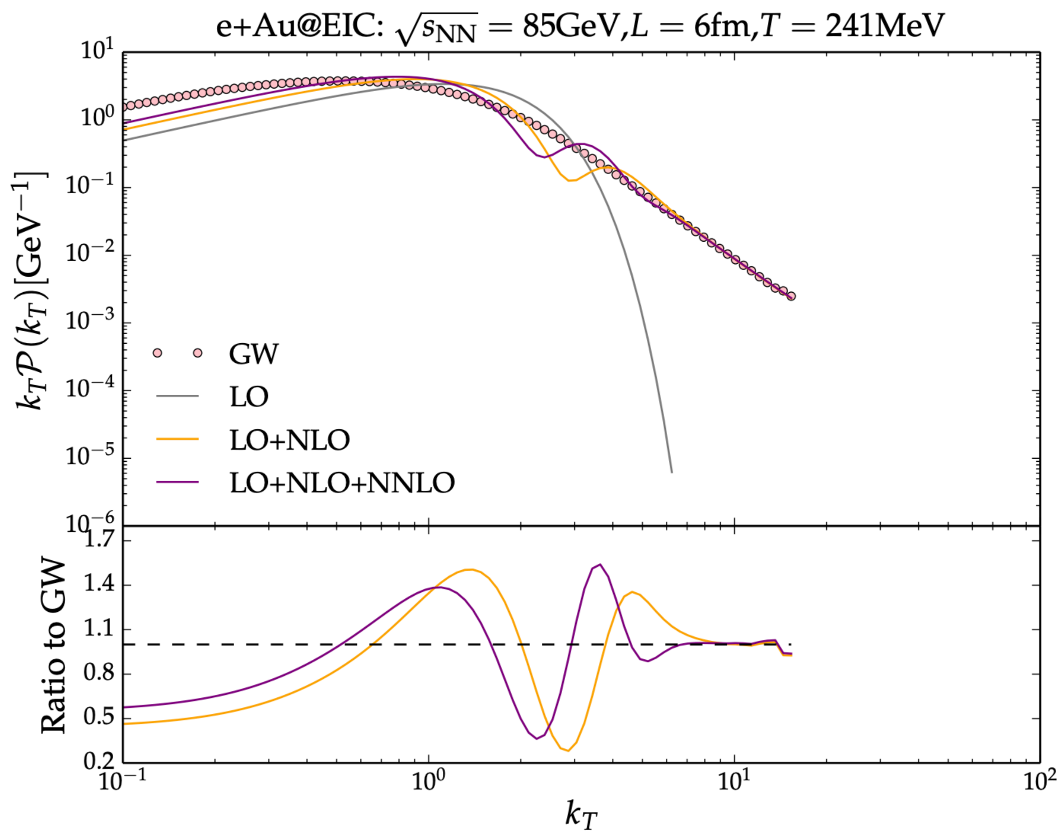
- **Electron-jet correlations**





Liu, FR, Vogelsang, Yuan `18, `20,
Arratia, Jacak, FR, Song `19

- **Transverse momentum broadening**



GW - Gyulassy Wang

$\mathcal{P}(\boldsymbol{k}, L)$ Probability distribution

Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk `20

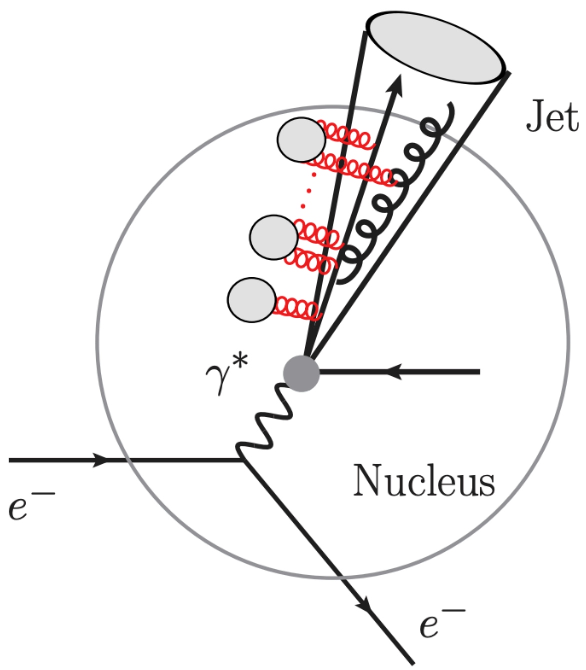
Probes of cold nuclear matter effects

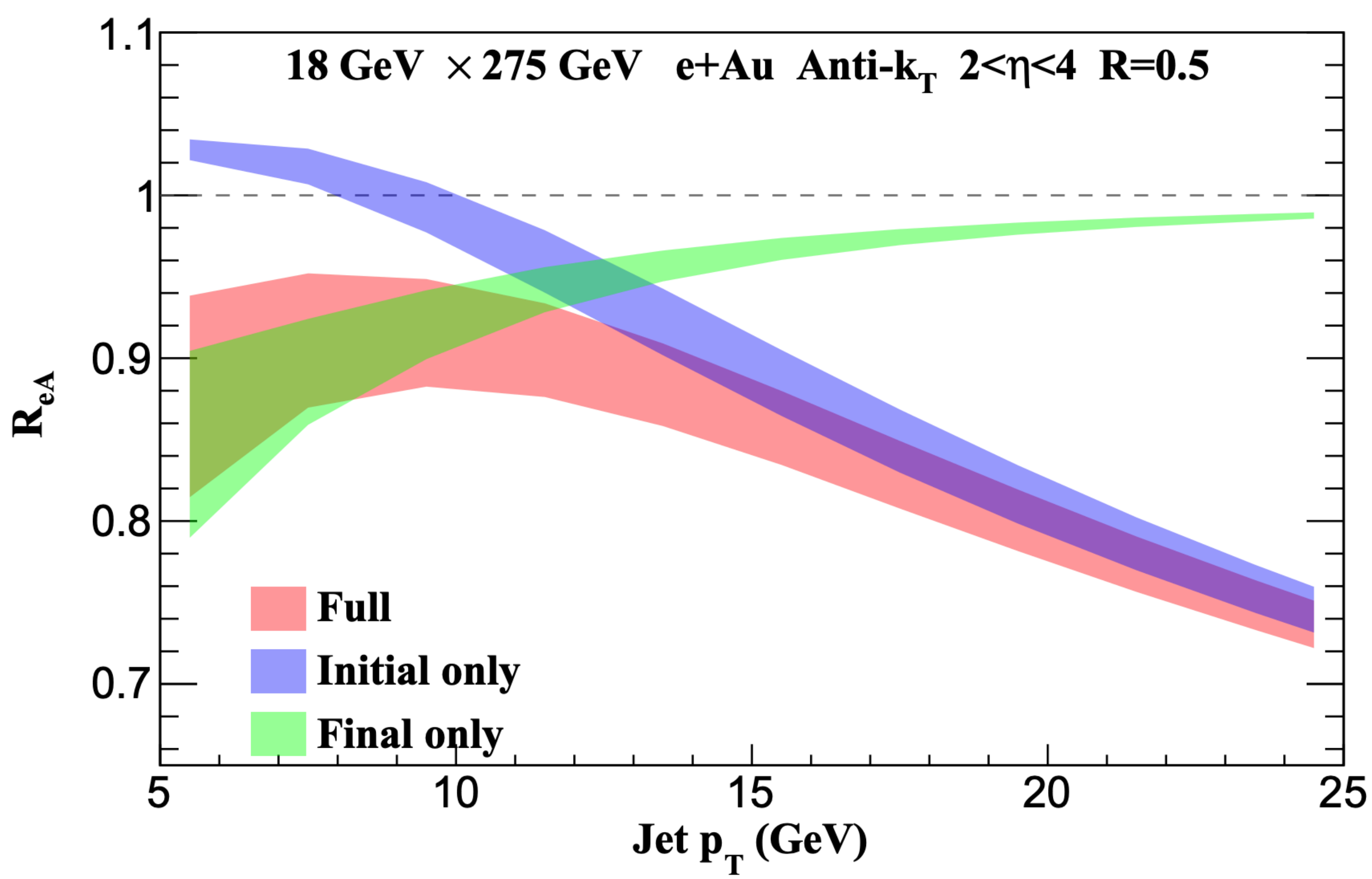
Li, Vitev `20

- Inclusive jet production $e + A \to e + \text{jet} + X$

Medium modified jet function approach

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

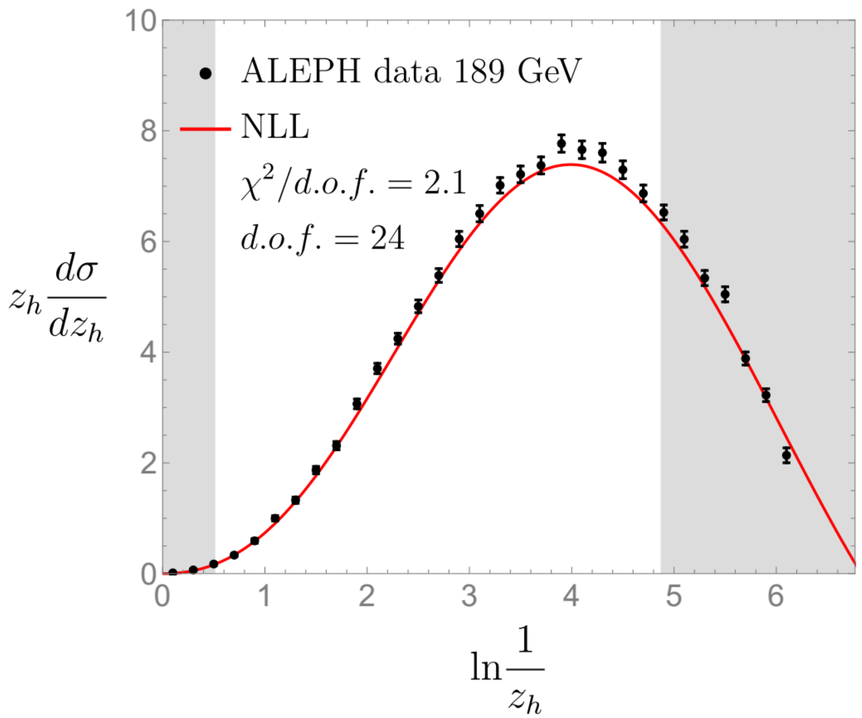


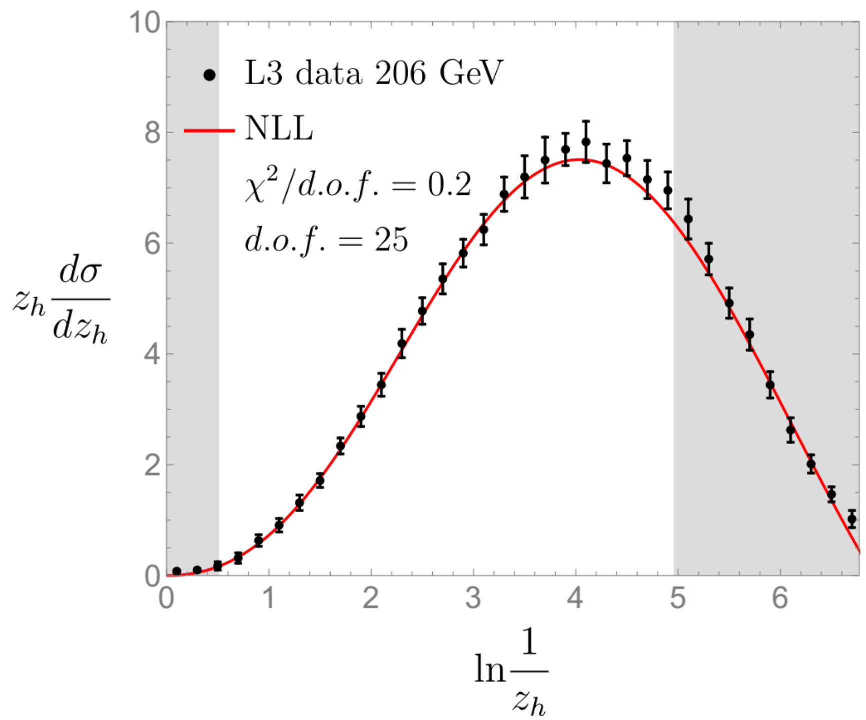


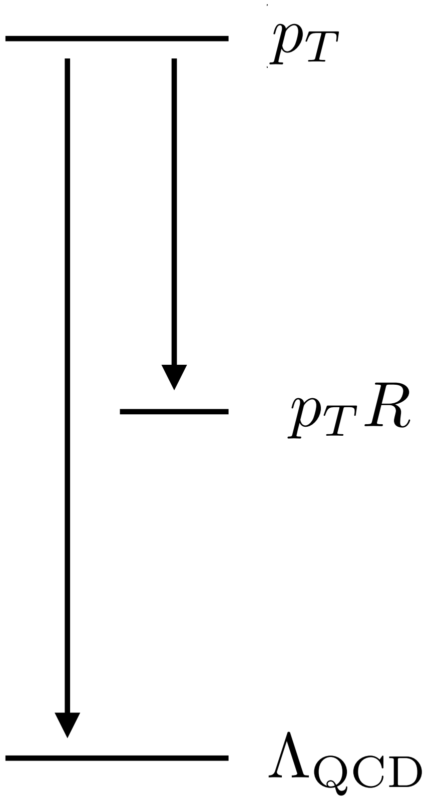
Do we need to measure jets at the EIC?

Neill `20

- Evolve jet functions to a nonperturbative scale (~1 GeV ~ Λ_{QCD})
- Small-z resummation + Local parton hadron duality
- The only fitted parameter is the cutoff scale (& partly the normalization)







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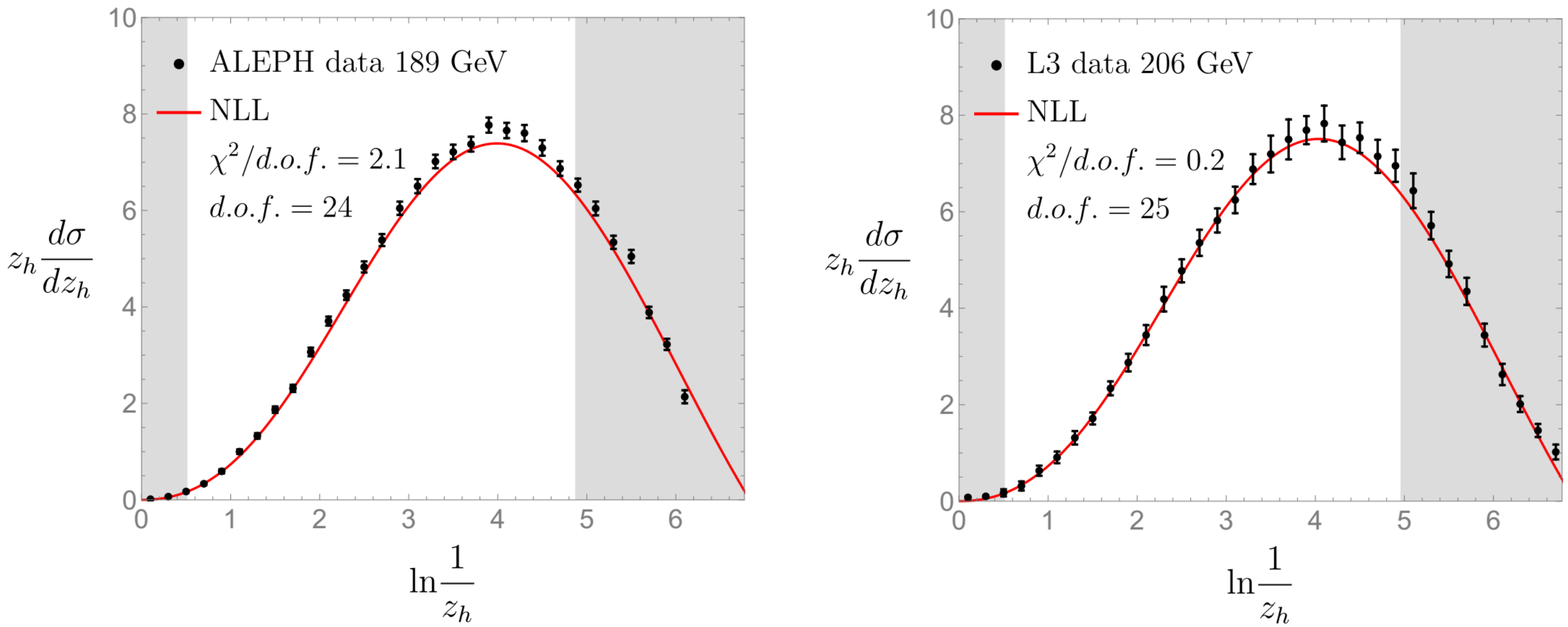

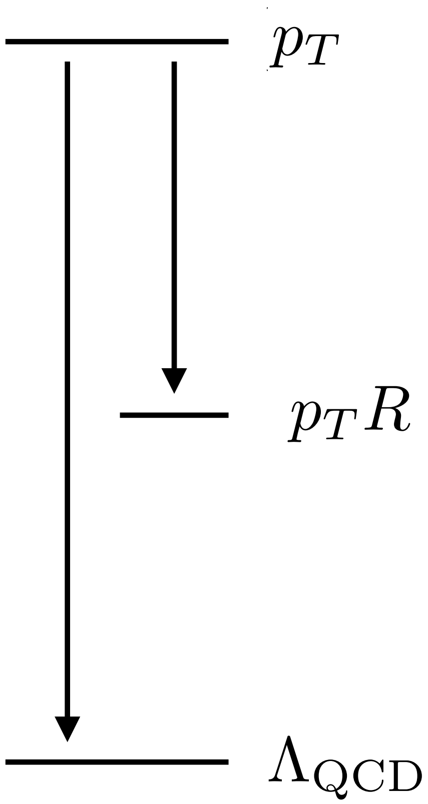

... this suggests

- Hadrons are simply jets with a nonperturbative radius
- The more fundamental objects are jets/jet functions
- Most of the QCD fragmentation process is perturbative — do we still need fragmentation functions?

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- Introduction
- Inclusive and leading jets
- TMDs measurements with jets
- Hadronization and cold nuclear matter
- Conclusions

Conclusions

- Growing field of jet physics at the EIC
- Relevant for all parts of the EIC science program
- Jet physics part of the EIC Yellow Report
- Potential impact on detector design
- Many new opportunities
- STAR, sPHENIX, HERA

https://indico.bnl.gov/event/8066/overview