Jets at the EIC

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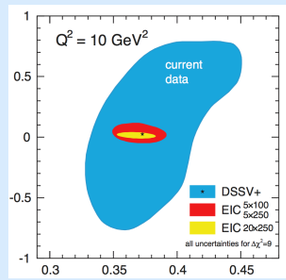
EIC opportunities for Snowmass — 01/27/2021

The EIC science program

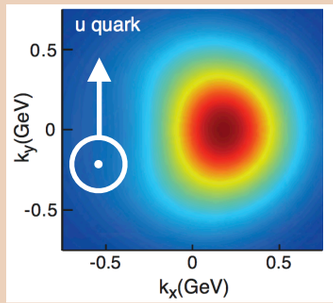
- The spin and mass of the proton
- Parton distribution functions

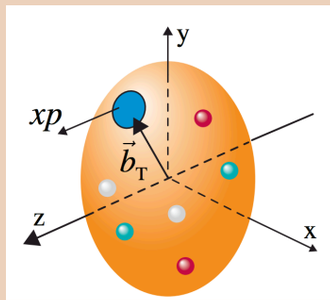
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)$$



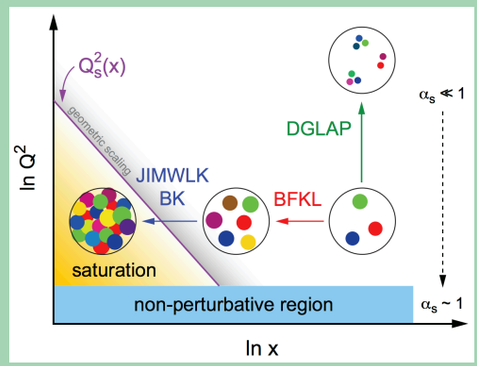
- 3D imaging

  Transverse momentum (TMDs) and position (GPDs)

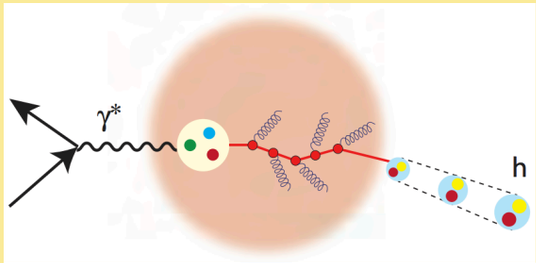




- Small-x and saturation

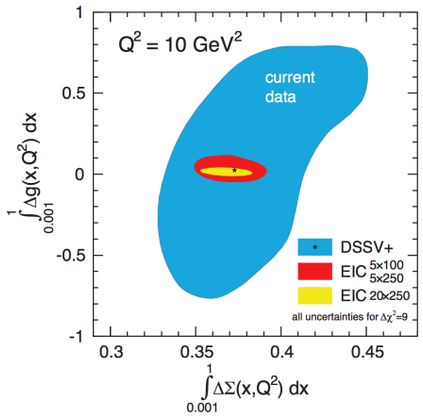


- Hadronization
- Nuclear modification in eA collisions



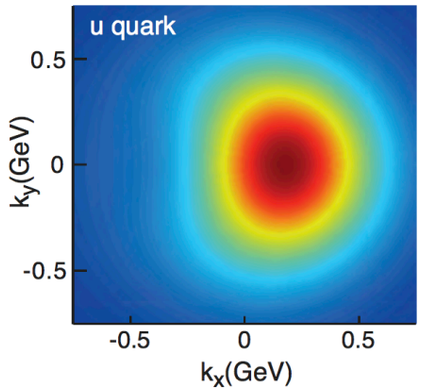
The EIC science program with jets

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



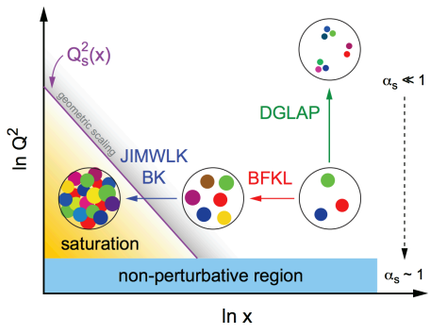
- Collinear factorization, spin

  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



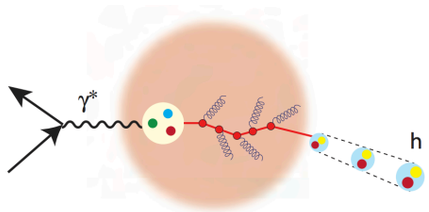
- 3D nucleon/nucleus tomography

  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, Makris `21



- Saturation, a new form of gluon matter

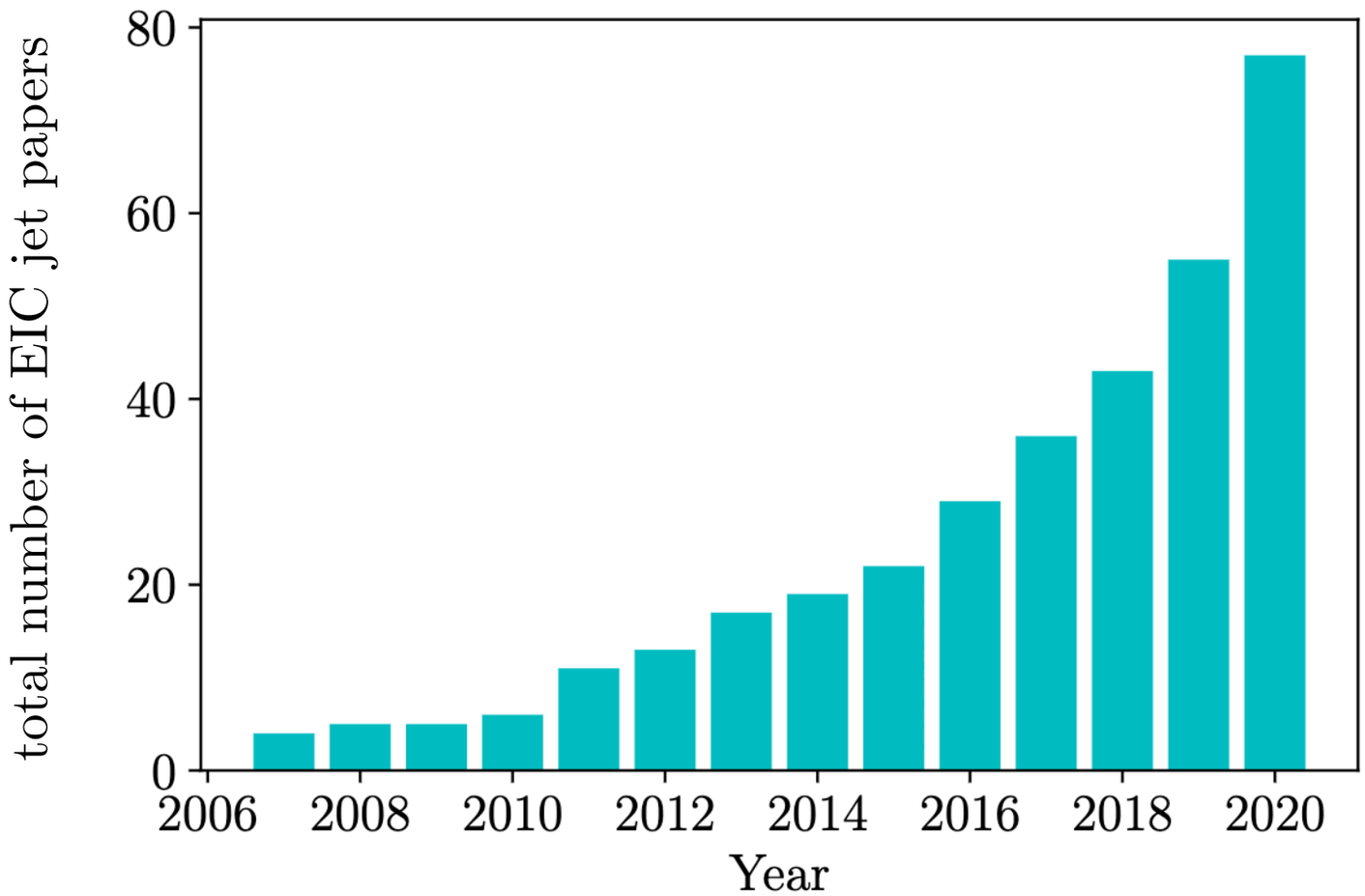
  Hatta, Xiao, Yuan `17, Salazar, Schenke `19, Roy, Venugopalan `19, Kang, Liu `19 Kolbe, Roy, Salazar, Schenke, Venugopalan `20



- 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

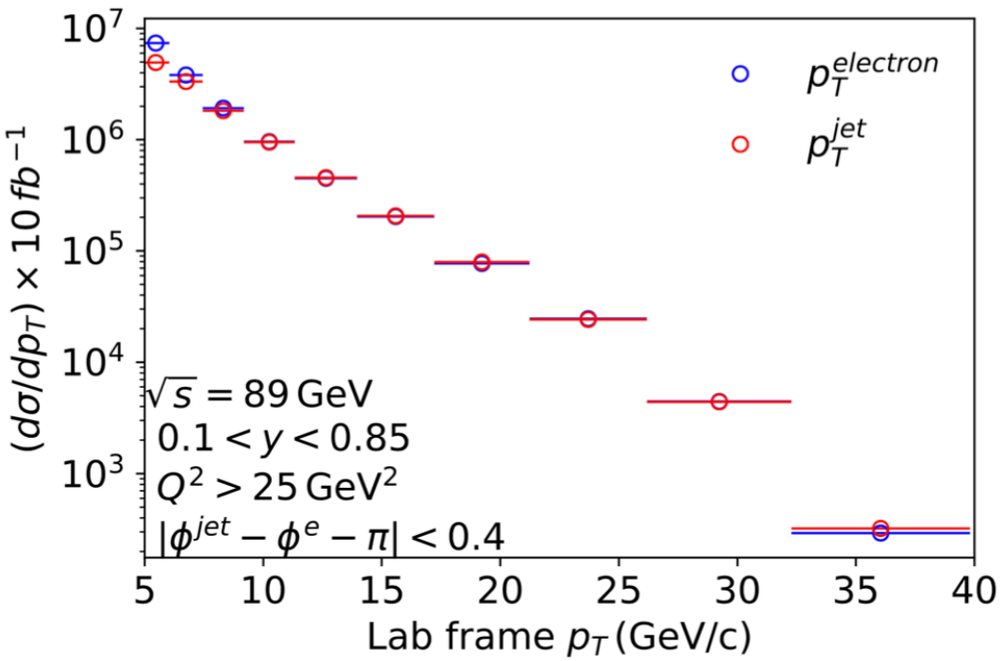
The EIC science program with jets



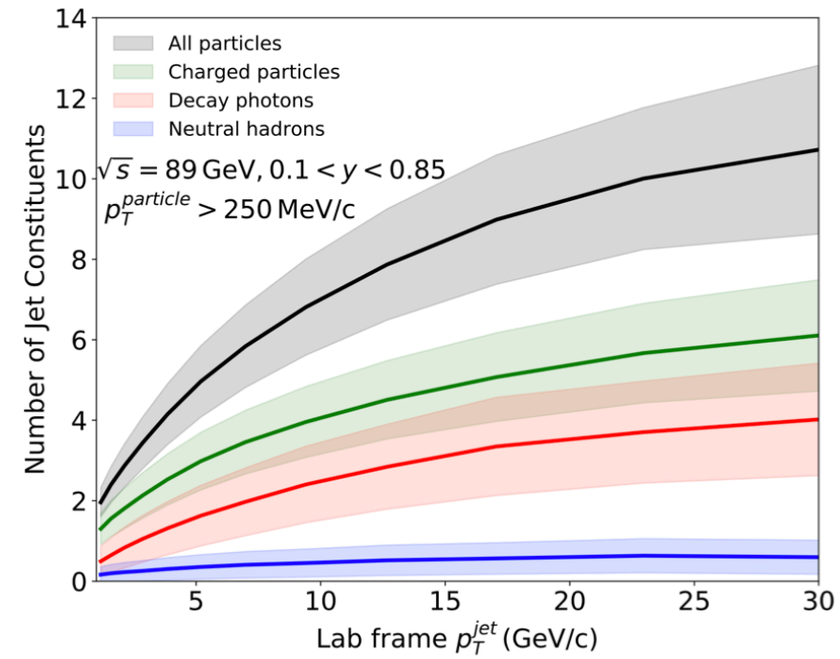
- There have been many new developments recently!

Jets at the EIC

Jet transverse momentum



Number of particles



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

Jets are excellent proxies of parton level kinematics

Clean separation of current & target fragmentation (UE)

Relatively low energies, need good control of hadronization corrections

Clean environment — no Multi Parton Interactions (MPI)

Outline

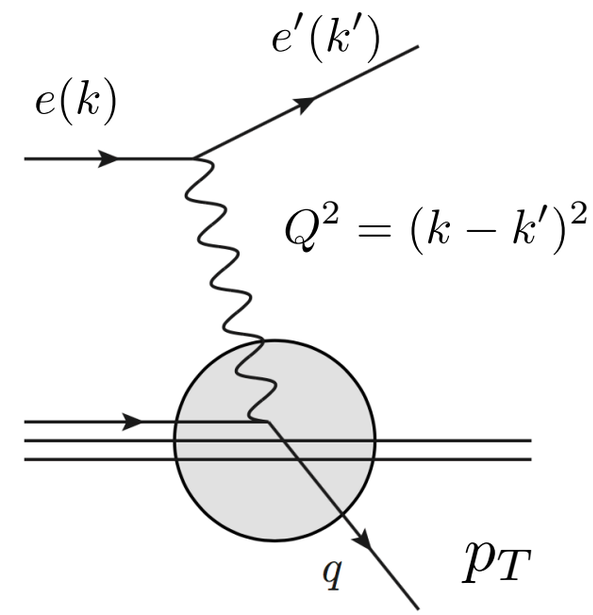
- Introduction
- Inclusive and leading jets
- TMD PDFs with jets
- Jet substructure
- Conclusions

Jet clustering and frame dependence

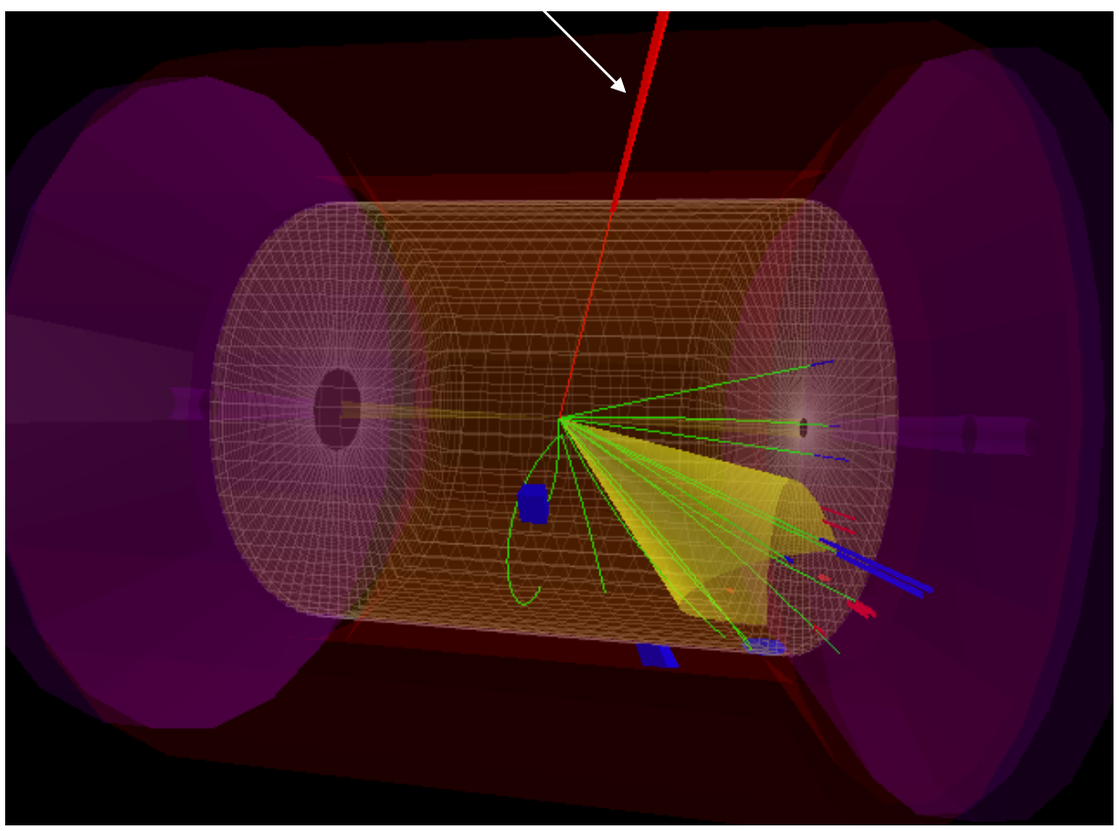
- **Laboratory frame**

Can measure two variables

- Jet transverse momentum p_T
- Photon virtuality Q^2

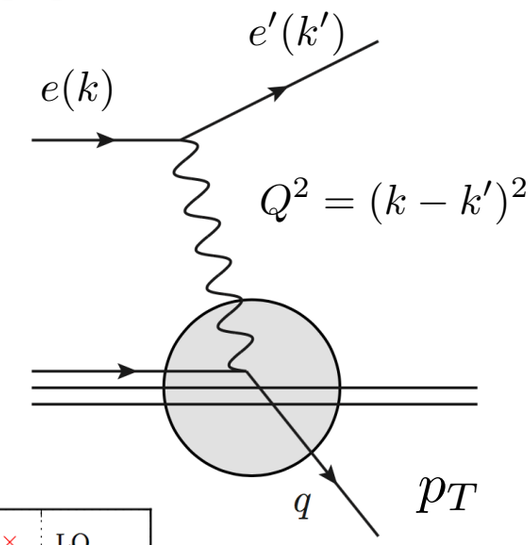


Leading electron Q^2



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

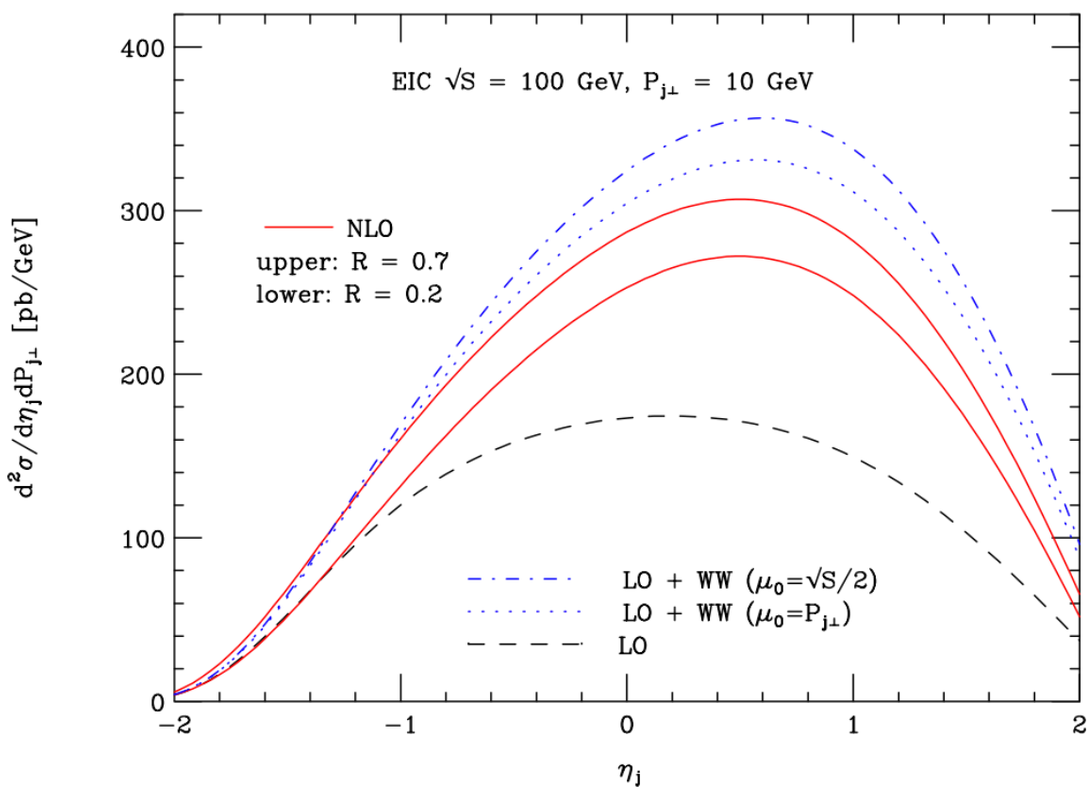
Jet clustering and frame dependence



- **Laboratory frame**

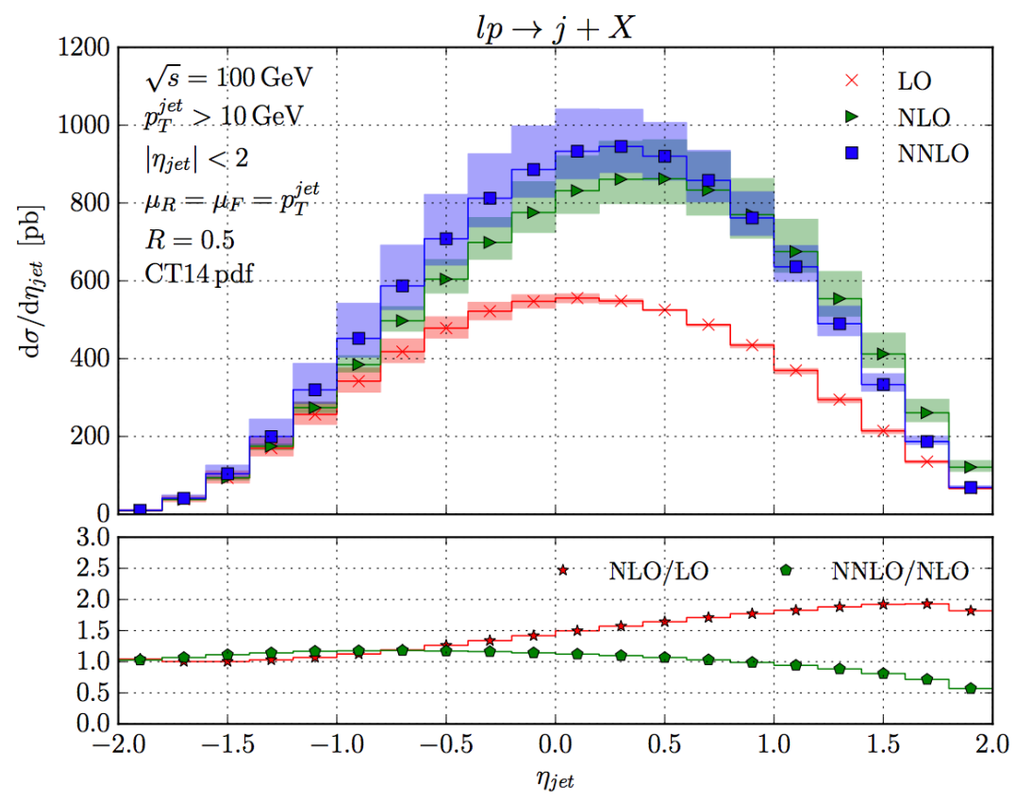
e.g. measure only p_T, close analogy to $pp \to \text{jet} + X$

NLO



Hinderer, Schlegel, Vogelsang `15

NNLO



Abelof, Boughezal, Liu, Petriello `16

Polarized case *Boughezal, Petriello, Xing `18*
Hinderer, Schlegel, Vogelsang `17
Borsa, Florian, Pedron `20

see talk by Frank Petriello

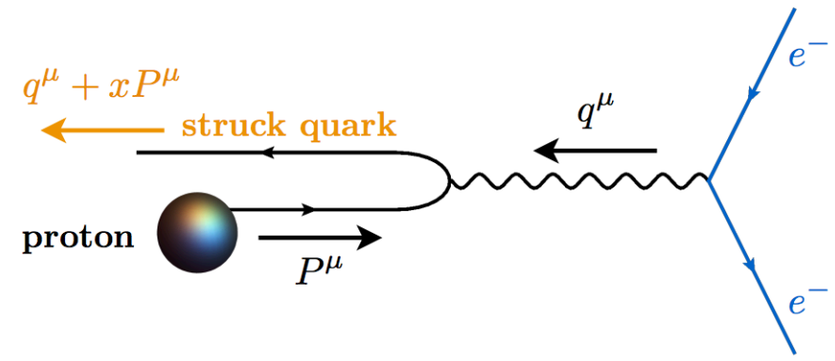
Jet energy relative to a reference scale

Arratia, Makris, Neill, FR, Sato `20

- Measure jet energy with respect to the photon virtuality Q^2

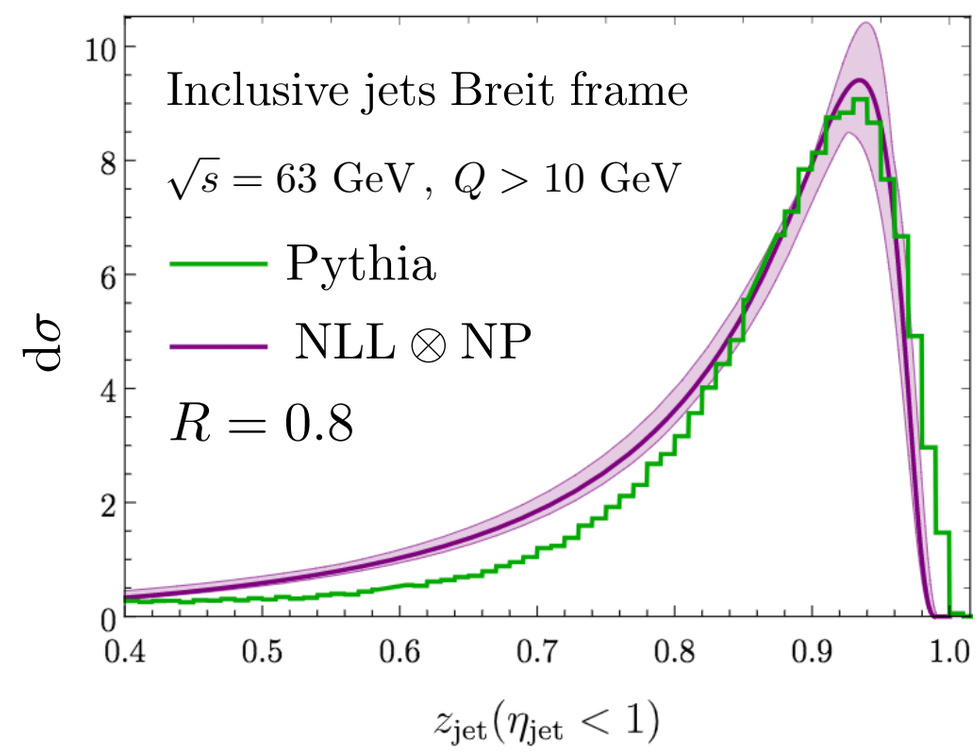
- Jet **energy** $z_{\rm jet} = \dfrac{P \cdot p_{\rm jet}}{P \cdot q} \simeq p^-_{\rm jet}/Q$

$$0 < z_{\rm jet} < 1$$



- Reconstruct jets which enclose the Breit frame beam axis

- Spherically invariant or Centauro jet algorithm



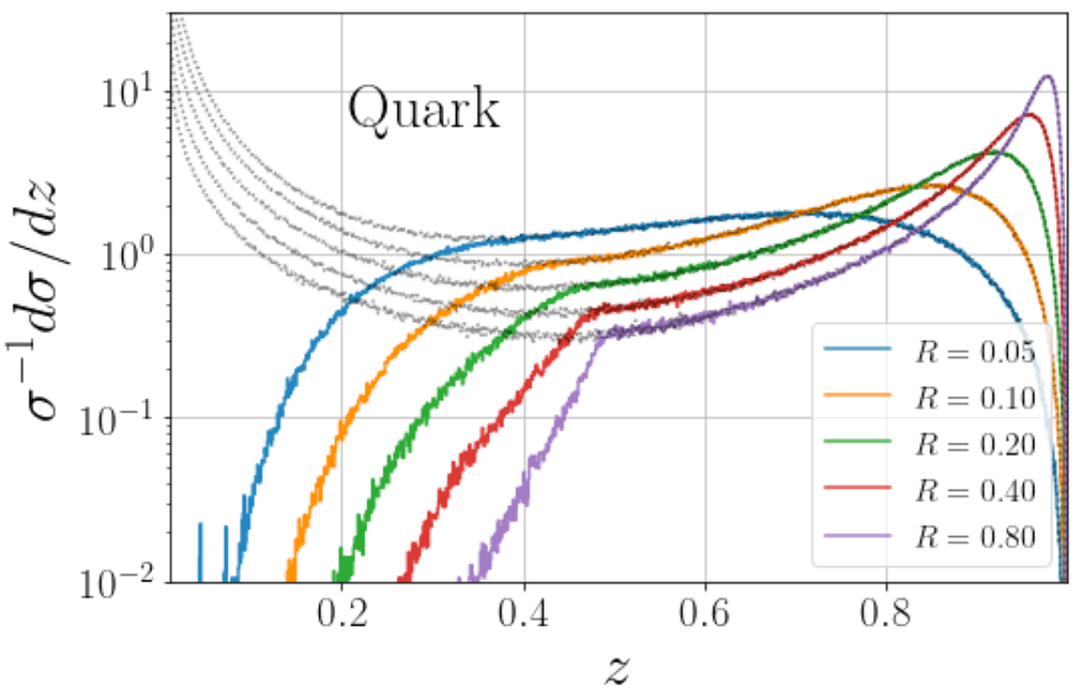
Unique opportunity at the EIC/ep scattering!

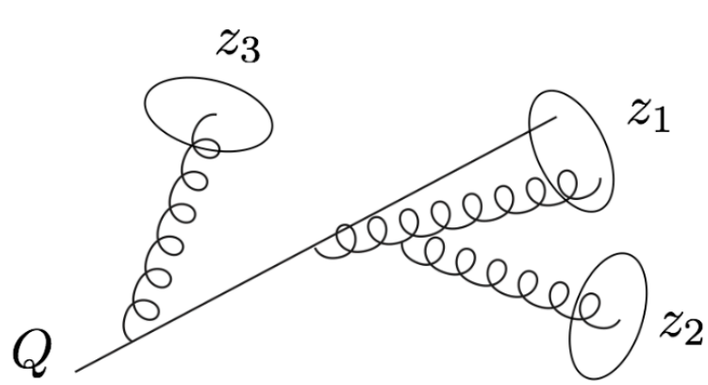
(There are alternative observables for pp and e^+e^-)

Leading jets and energy loss

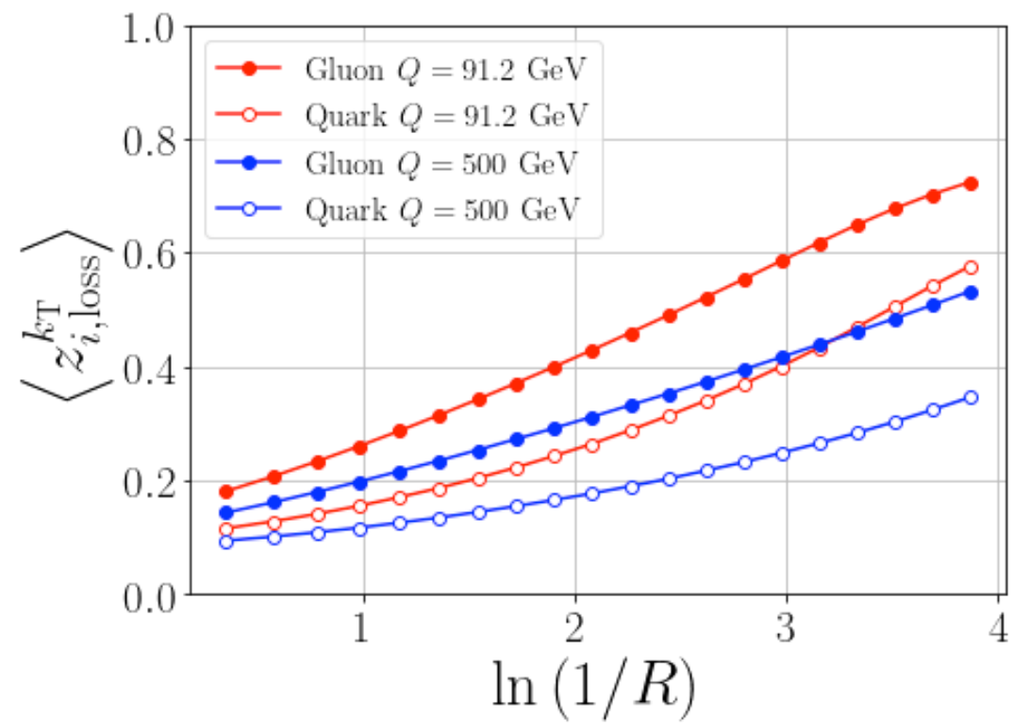
Neill, FR, Sato `21

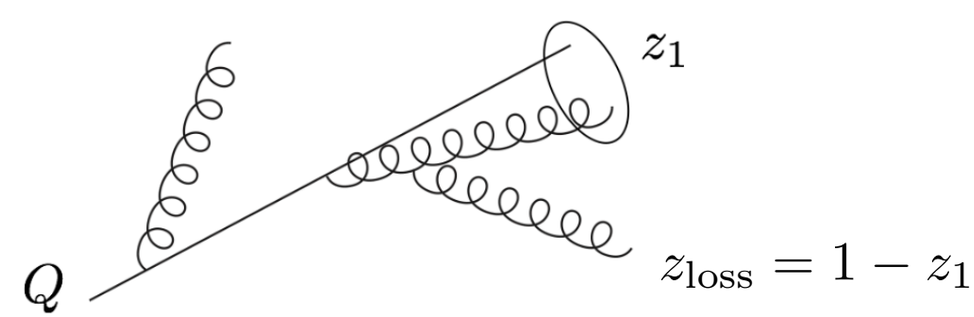
- **Inclusive vs. leading jets**





- **The average energy loss**



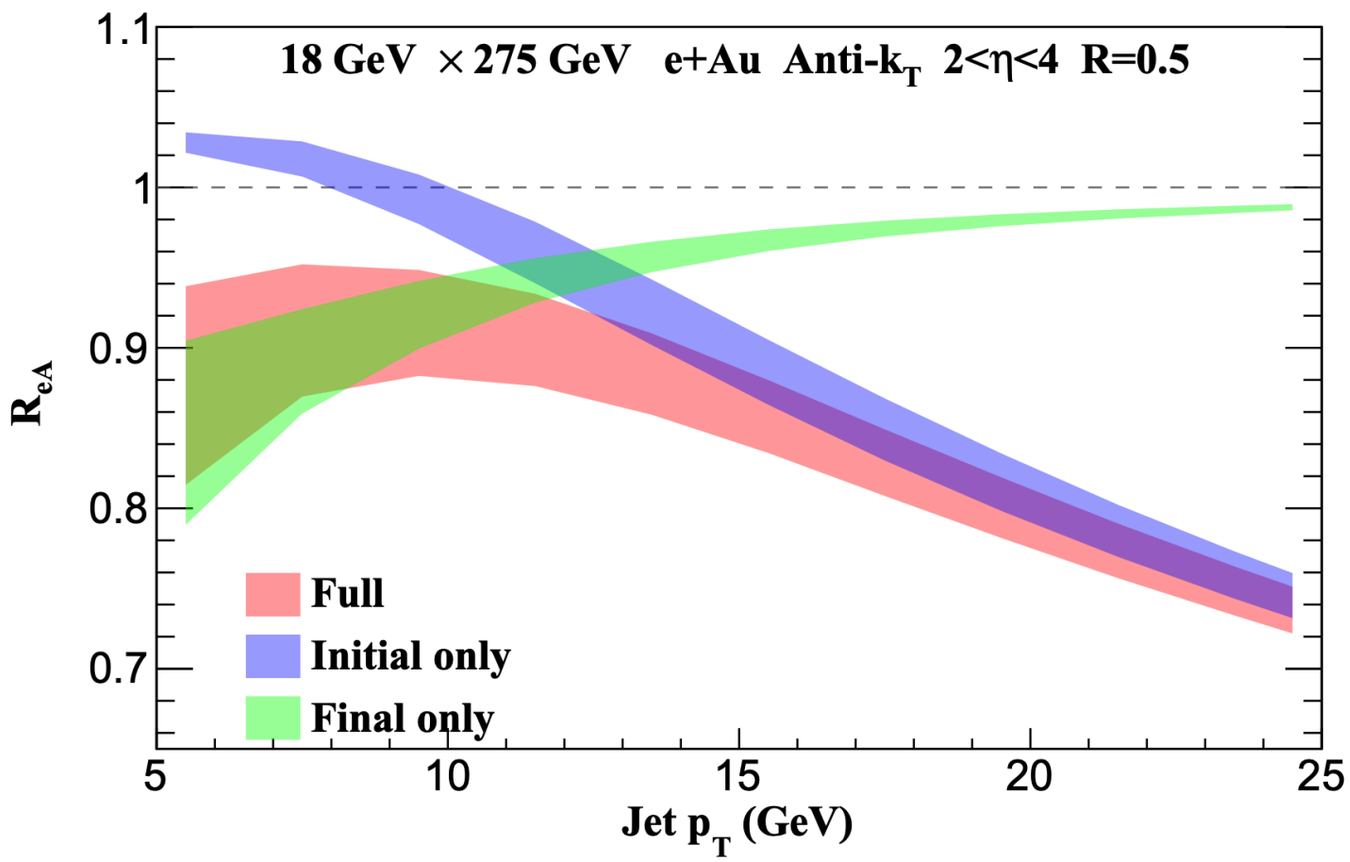


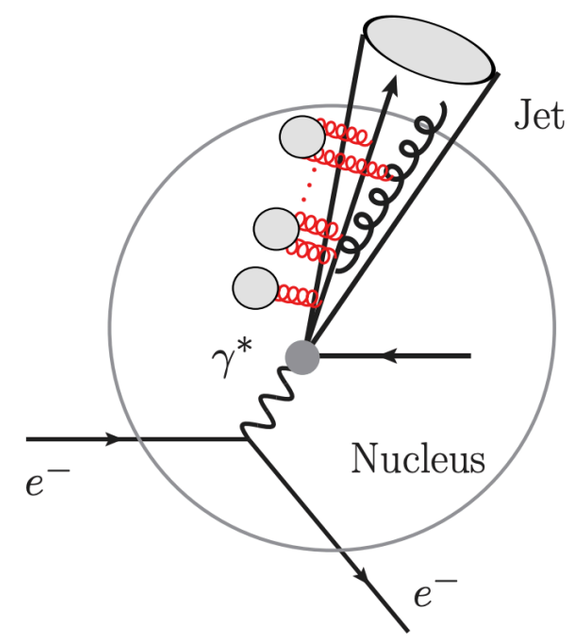
see talk by Nobuo Sato

Jets as probes of cold nuclear matter effects

Li, Vitev `20

- Inclusive jet production $e + A \to e + \text{jet} + X$
- Medium modified jet function approach $J_q^{\text{med}}(z, p_T R, \mu)$





see also e.g. Zhang, Qin, Wang `19, `20
Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk `20

see talk by Haitao Li

Outline

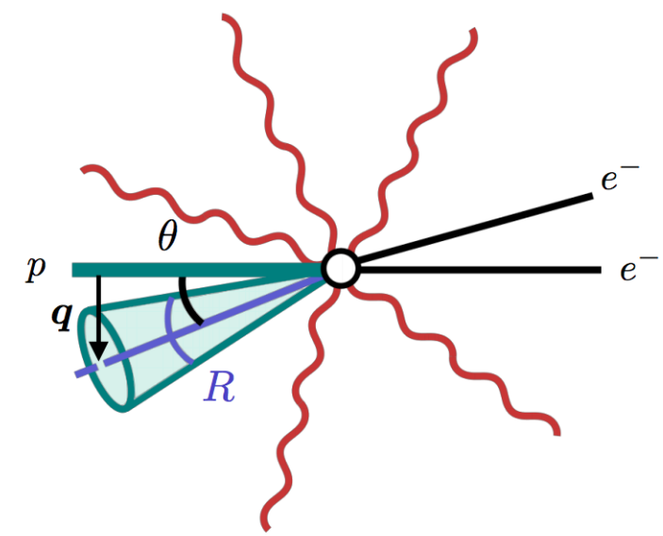
- Introduction
- Inclusive and leading jets
- TMD PDFs with jets
- Jet substructure
- Conclusions

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

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



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

Perturbative TMD jet function

- **Decorrelation** of TMD PDFs and FFs
- Winner-take-all (WTA) jet axis

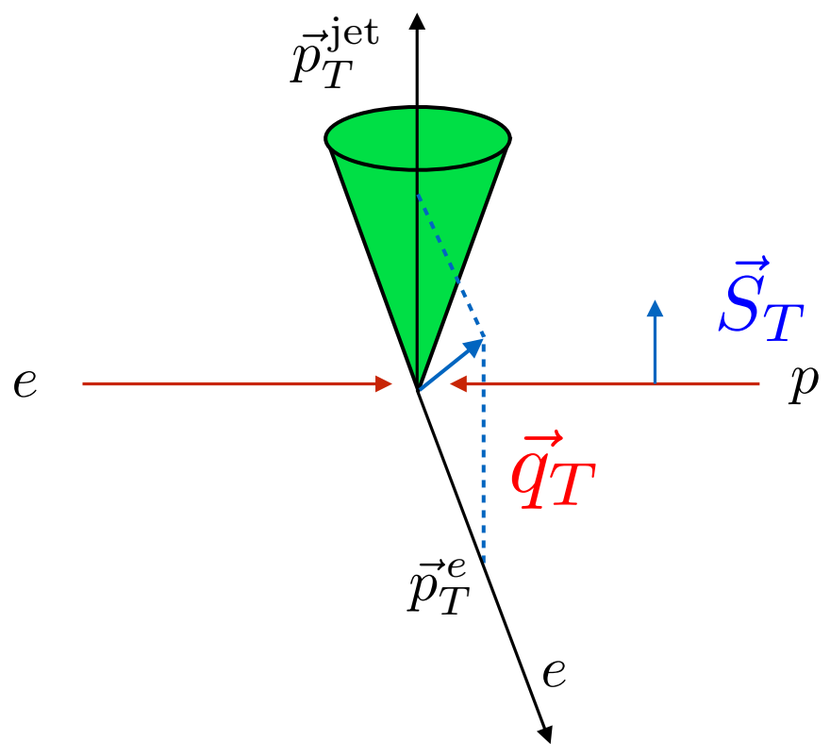
- Gluon TMDs with dijets in the Breit frame

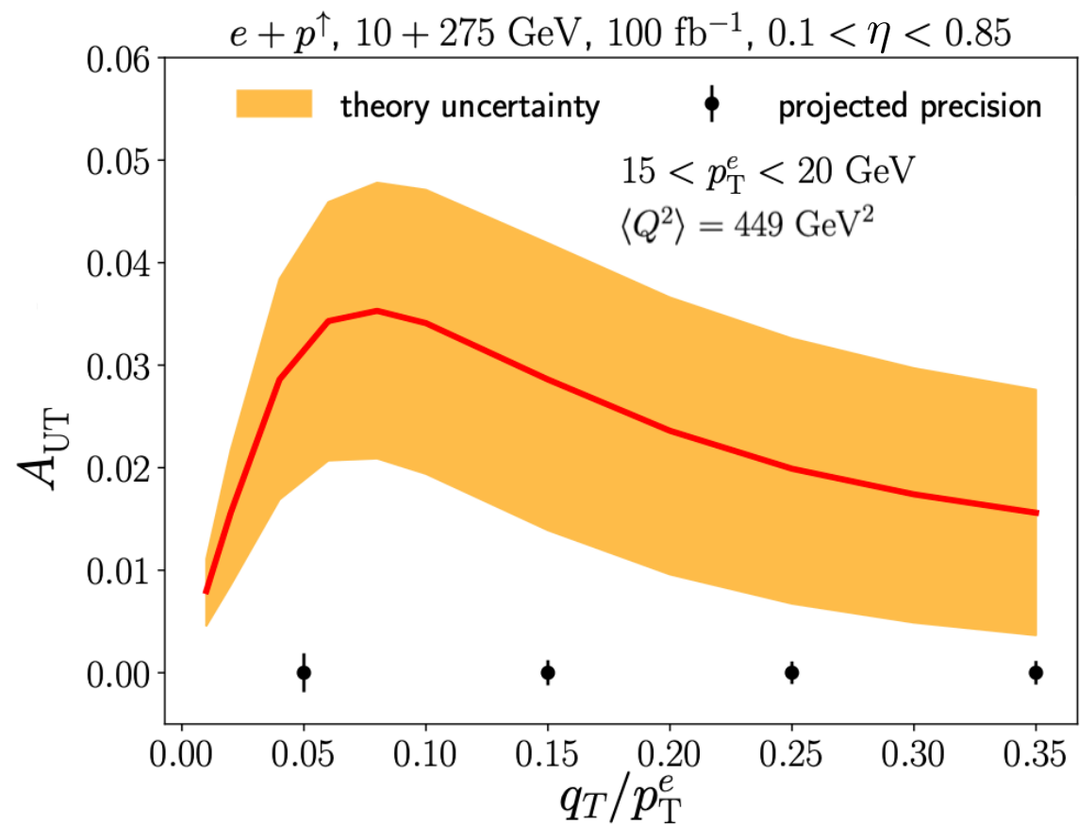
see Zheng, Aschenauer, Lee, Xiao, Yin `18
Castillo, Echevarria, Makris, Scimemi `20
Kang, Reiten, Shao, Terry `20

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

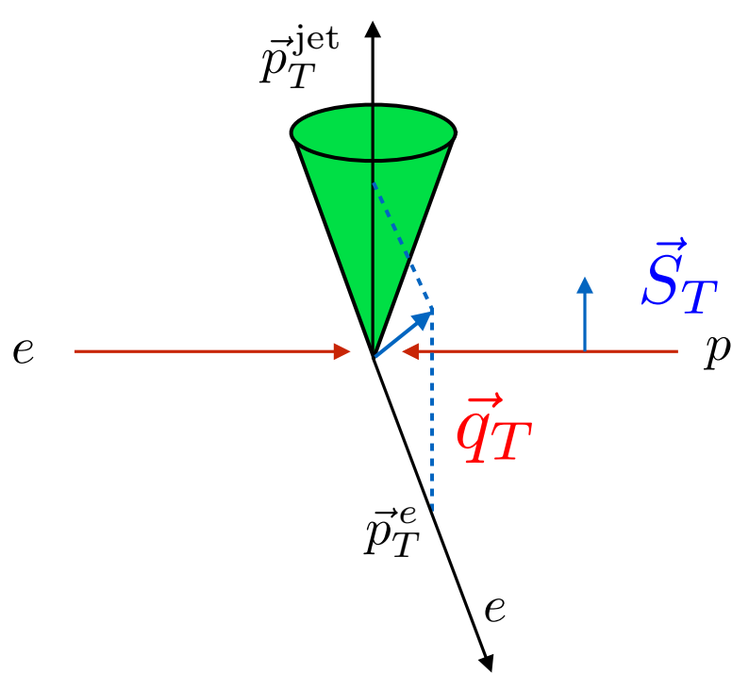
Electron-jet correlations - flavor sensitivity

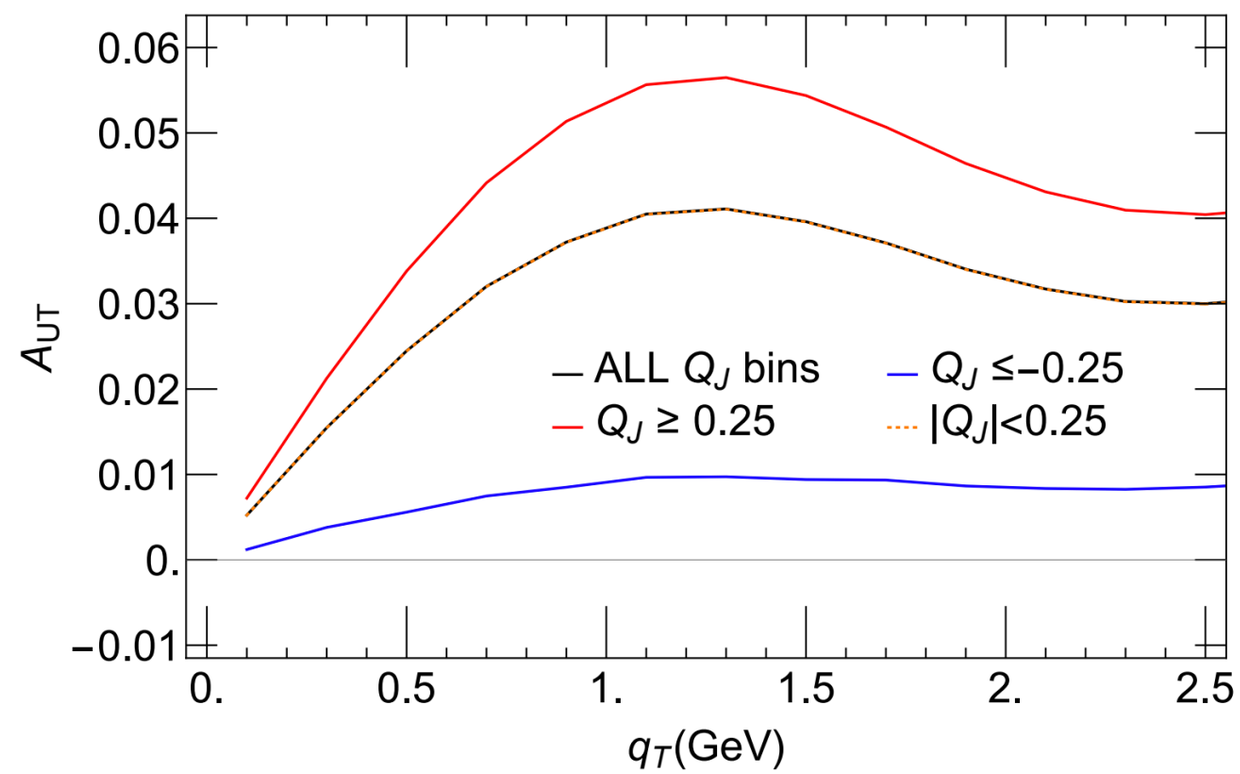
- Measure the electron-jet imbalance $\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}$ *Liu, Kang, Mantry, Shao `20*

- and the jet charge $$Q_\kappa^i = \sum_h Q_\kappa^h \equiv \sum_{h\in\mathrm{jet}} z_h^\kappa Q_h$$ *Field, Feynman `78*

(weighted sum of charges)

- Jet charge tagging can avoid 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

Extracting TMD PDFs using the thrust axis

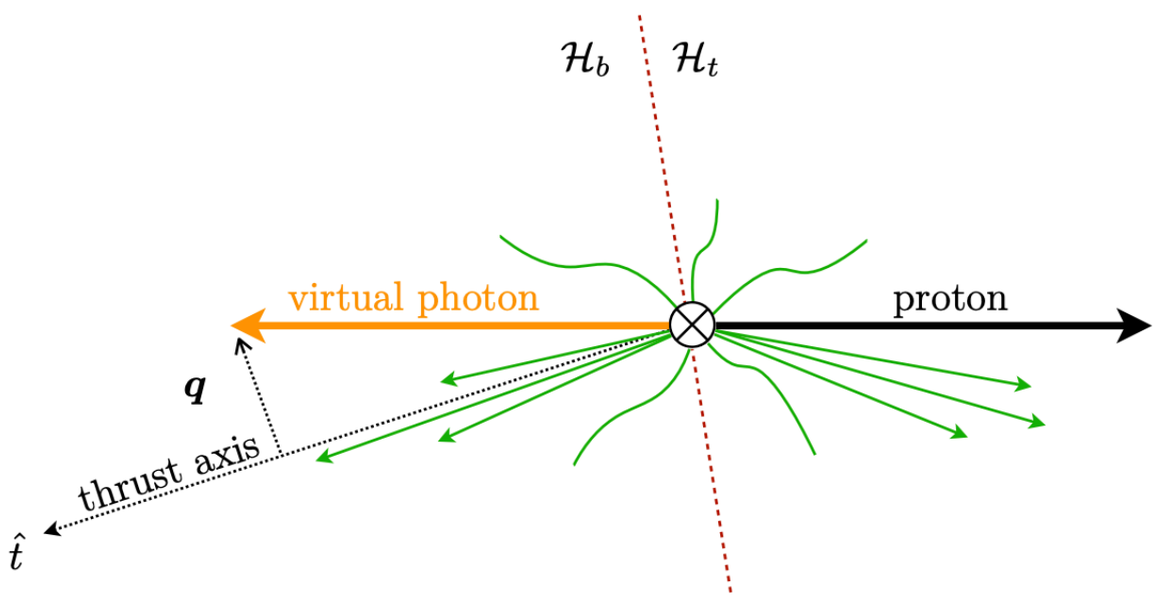
- Measure the electron-jet imbalance

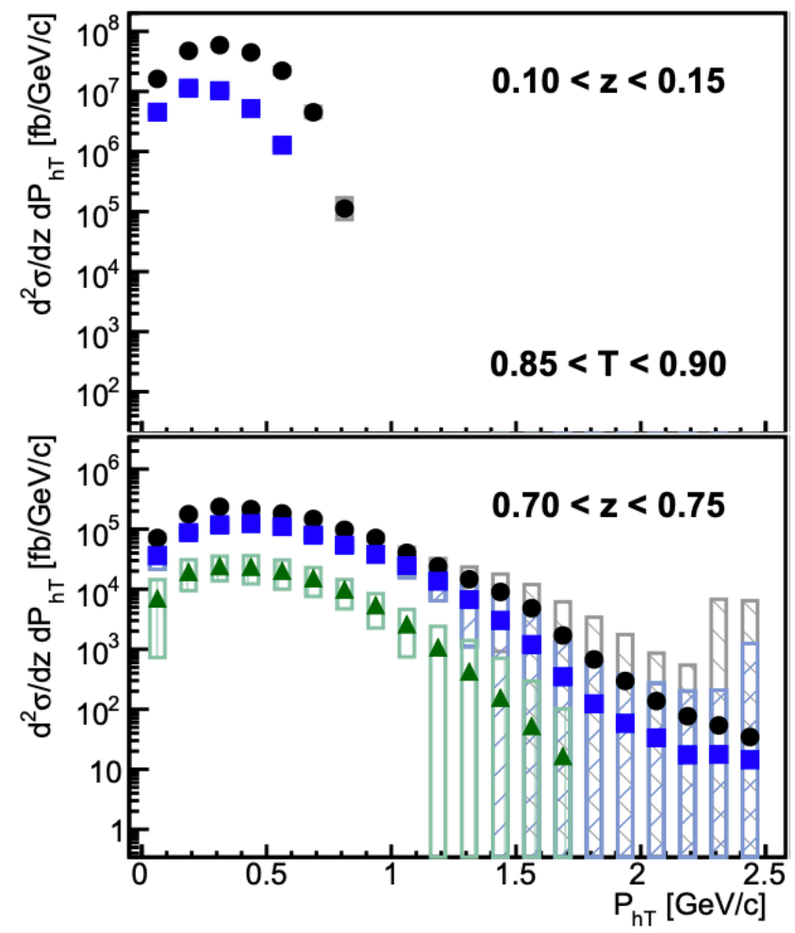
Makris, Ringer, Waalewijn `20

- Connection to the recent BELLE measurement of thrust and TMD fragmentation

BELLE Collaboration, Seidl et al. `19

$$\tau_{\rm DIS} = \min_{\hat{t}} \frac{1}{Q} \sum_i \min\{n \cdot p_i, n_t \cdot p_i\}$$





see also Kang, Mantry, Qiu `12
Kang, Lee, Stewart `13
Boglione, Simonelli `20
Kang, Shao, Zhao `20

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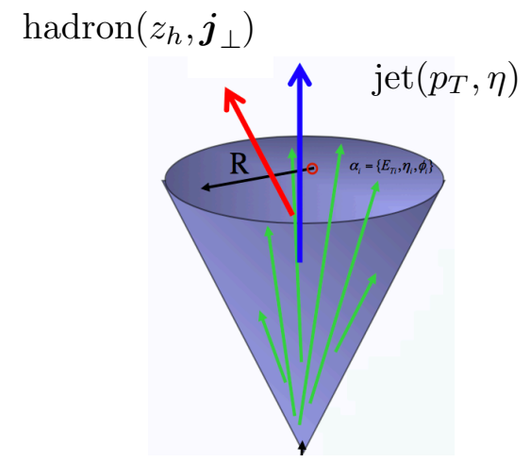
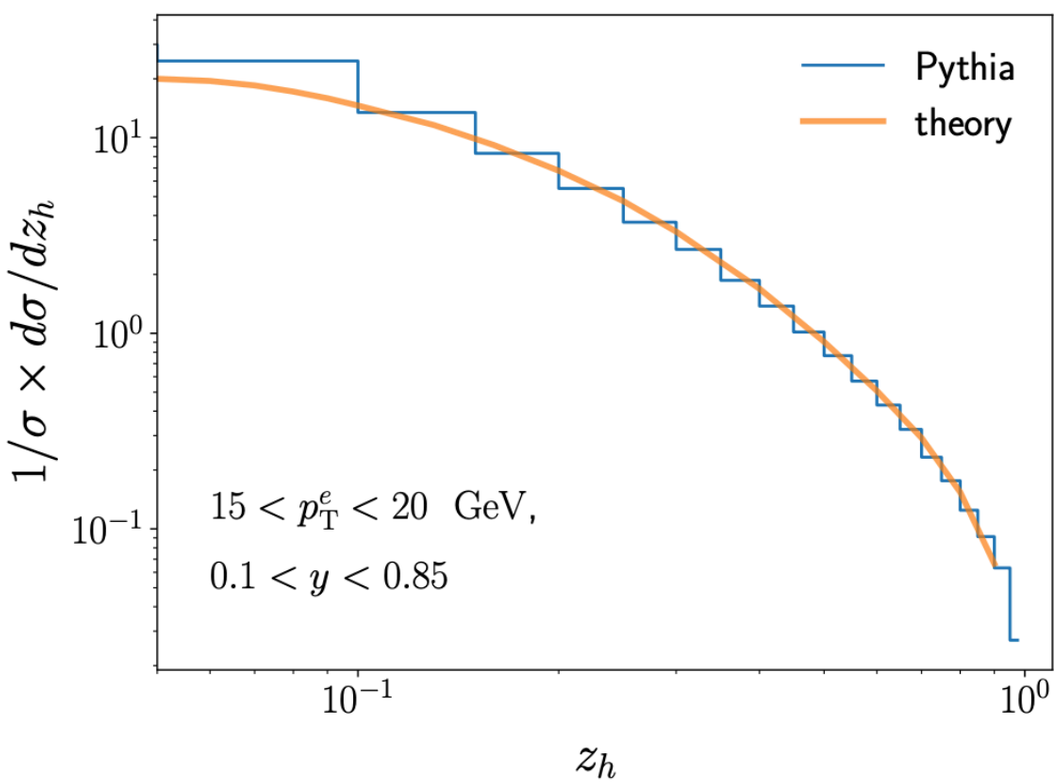
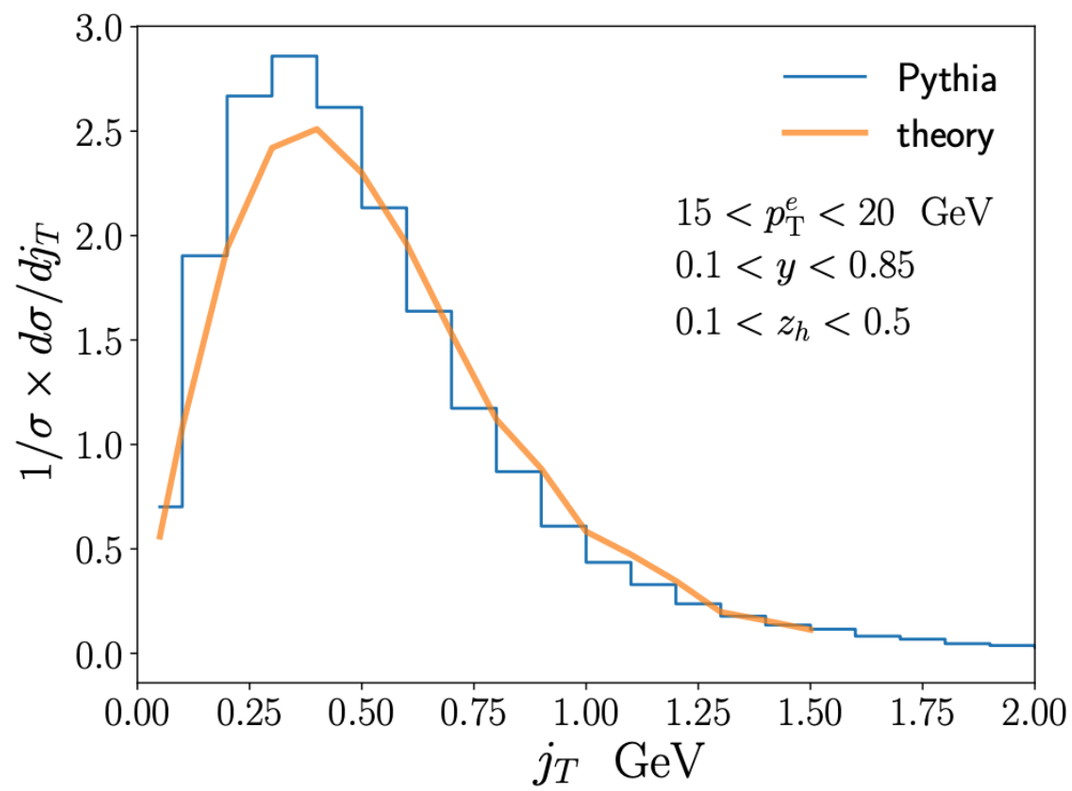
Hadron-in-jet fragmentation

Arratia, Kang, Prokudin, FR `20

- Hadron-in-jet measurement
- Longitudinal z_h and transverse momentum $\vec{j}_T$
- TMD FF **decorrelated** from TMD PDF $\mathcal{O}(R^2)$







Measure collinear FF at small z_h

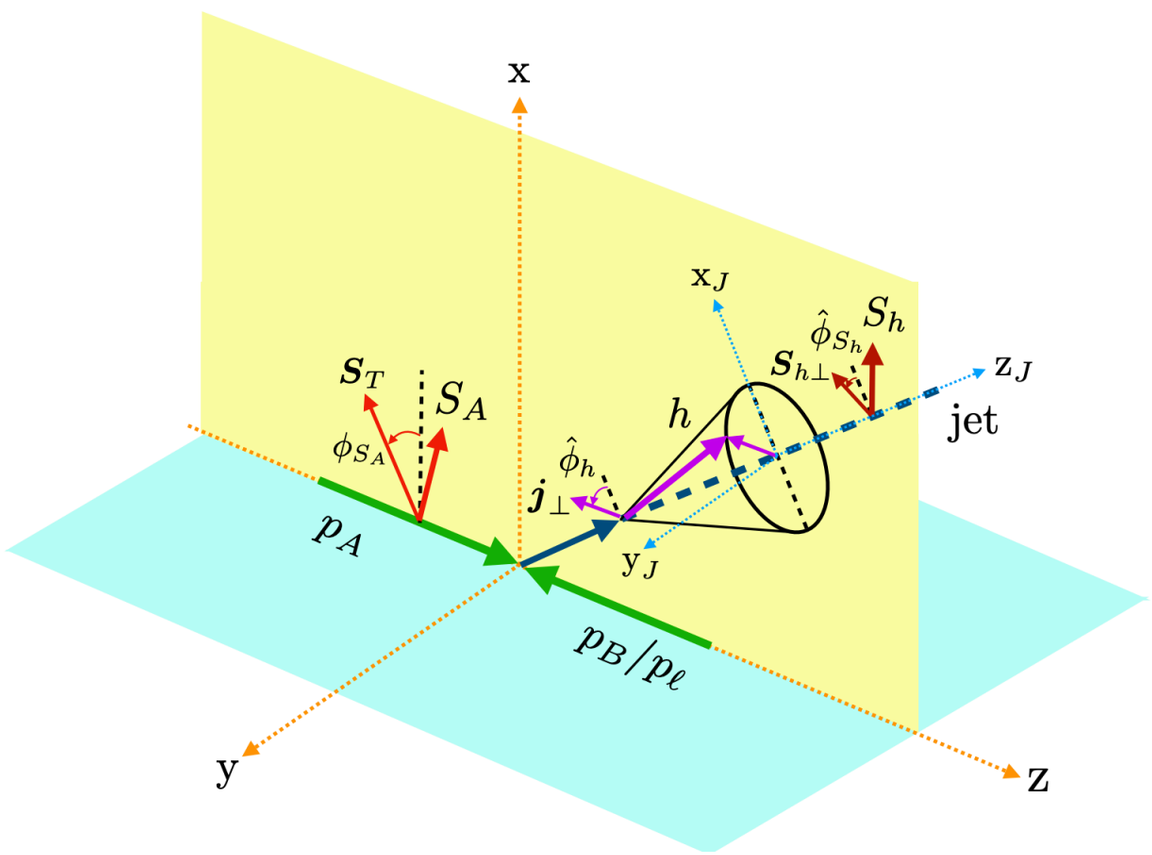
In SIDIS limited to $z_h > 0.2$

see also Procura, Stewart `10
Kaufmann, Mukherjee, Vogelsang `15
Bain, Makris, Mehen `16
Kang, Liu, FR, Xing `17

Hadron-in-jet fragmentation

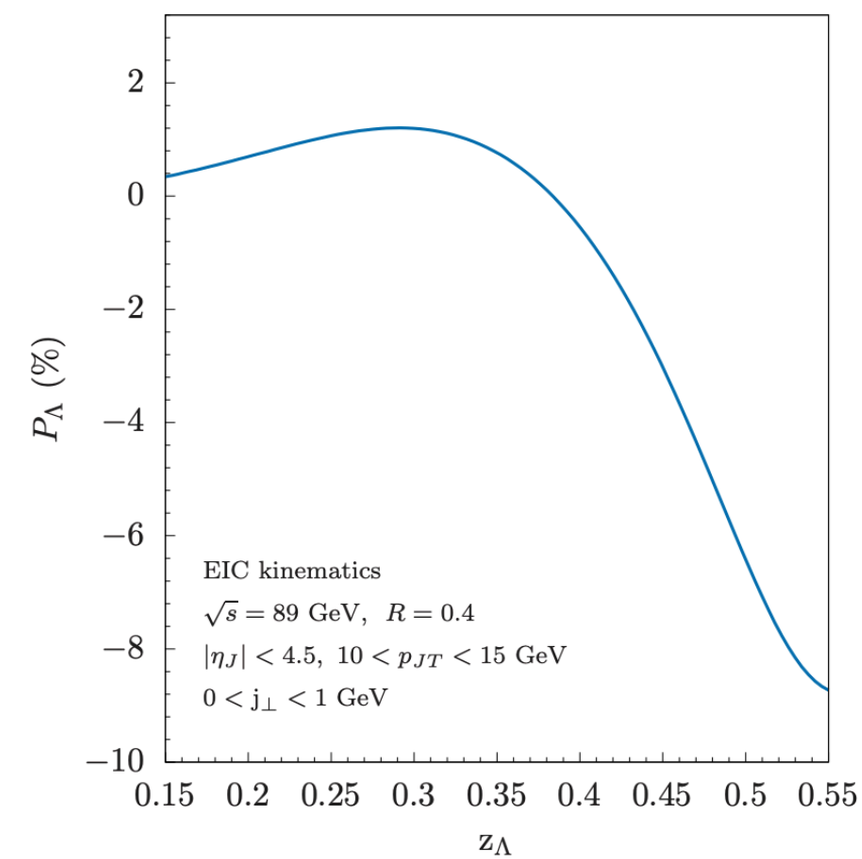
Kang, Lee, Zhao `20

- Hadron-in-jet measurement
- Longitudinal z_h and transverse momentum $\vec{j}_T$
- Including polarization



Lambda - transverse polarization

$ep \to (\text{jet} + \Lambda^\uparrow) + X$

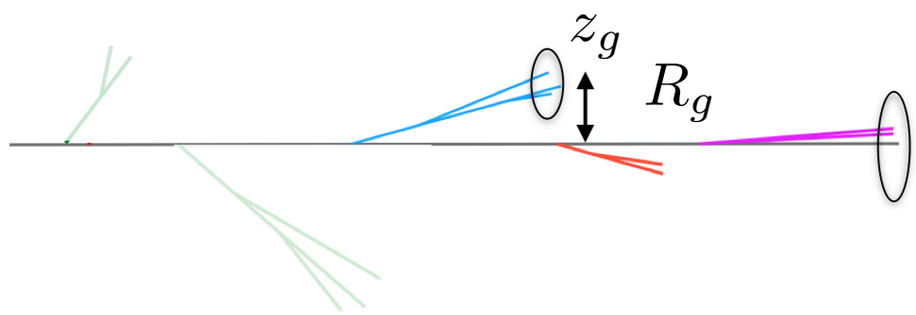


see talk by Kyle Lee

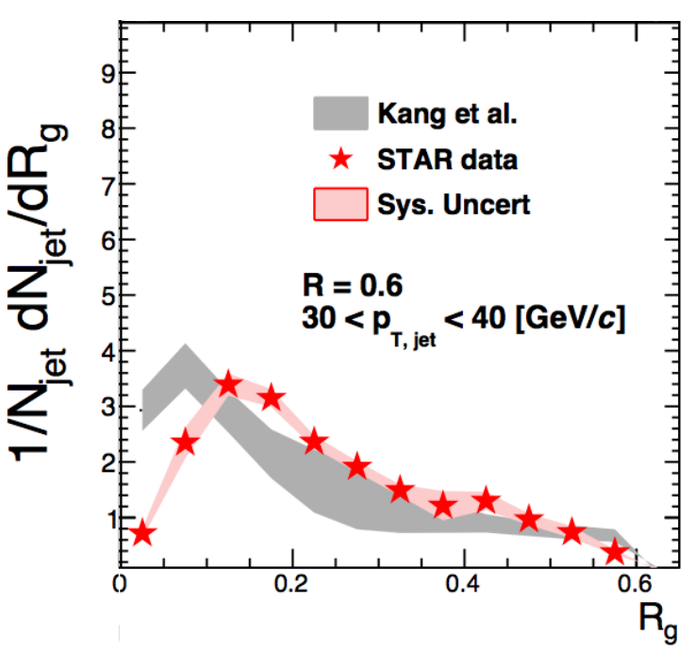
Groomed jet substructure

- Direction connection to results from RHIC and LHC

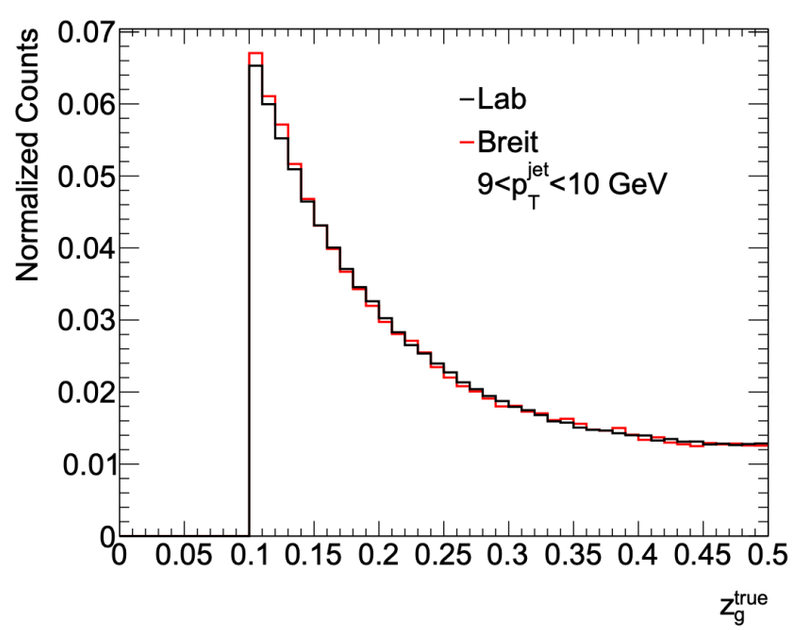
Dasgupta, Fregoso, Marzani, Salam `13
Larkoski, Marzani, Soyez, Thaler `14
Larkoski, Thaler `15

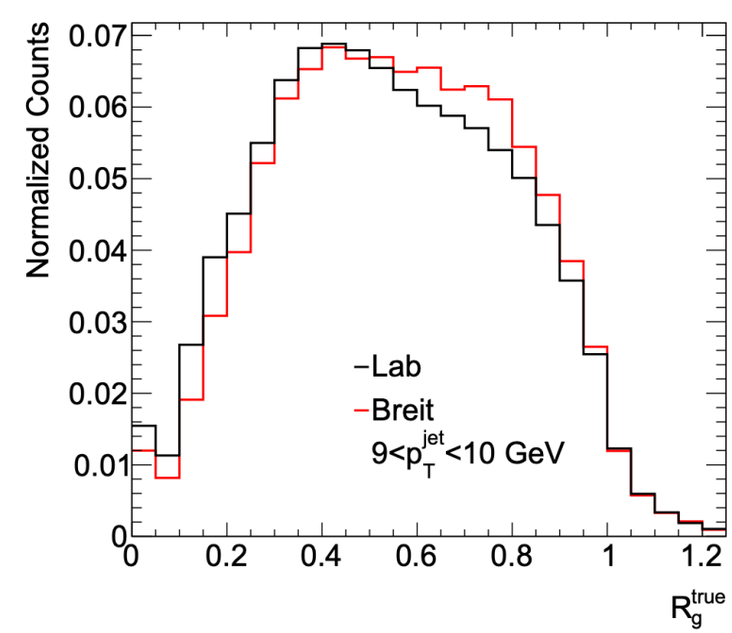


STAR, PLB 811 (2020) 135846



EIC *Fitzgerald, Osborn, EIC YR, `20*





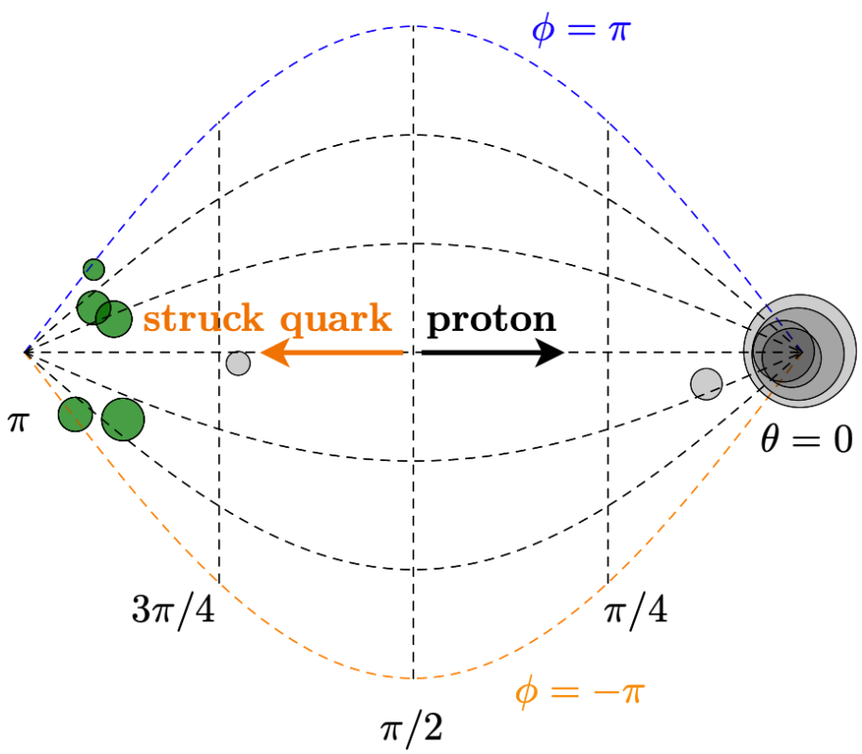
see also ALICE, ATLAS, CMS

see talk by Ben Nachman

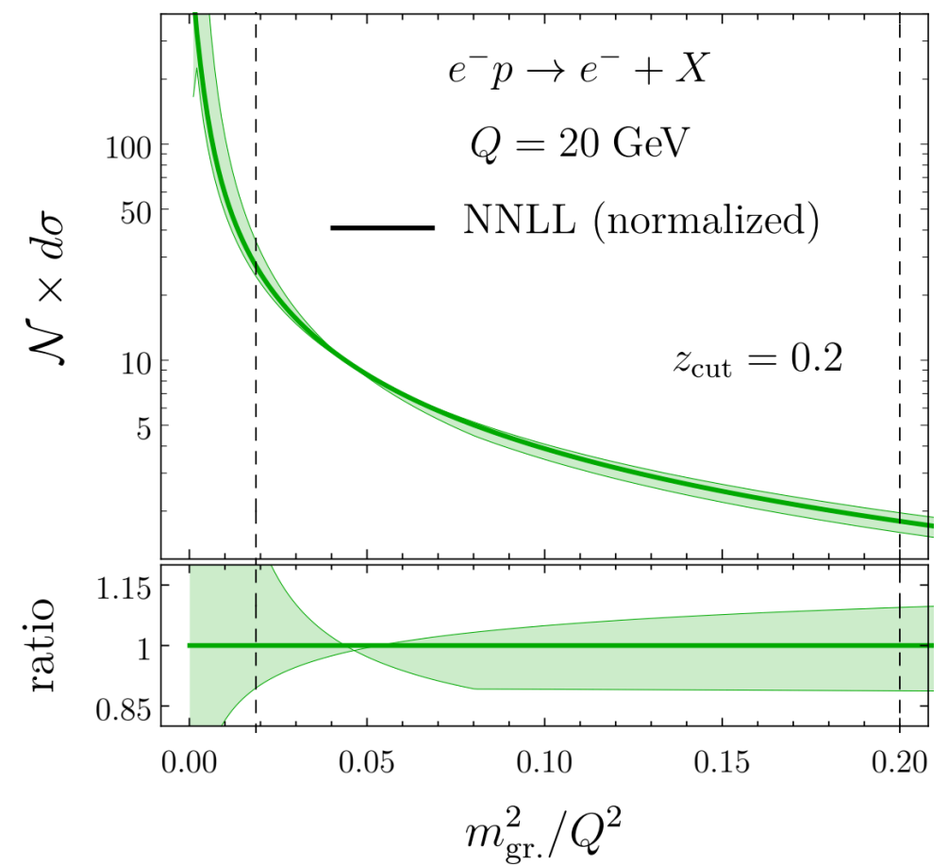
Groomed event shapes in DIS

Makris `21

- Event wide clustering and grooming
- Breit frame, Centauro distance metric
- Grooming removes the contribution from beam remnants



PYTHIA 8 $\sqrt{s} = 63$ GeV $Q \sim 10$ GeV



Groomed event mass in DIS at NNLL

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Conclusions

- Growing field of jet physics at the EIC
- Jets are relevant for all aspects of the EIC science program
- Direction connection to RHIC & LHC physics (pp & AA), BELLE