Jet physics at the EIC

Felix Ringer

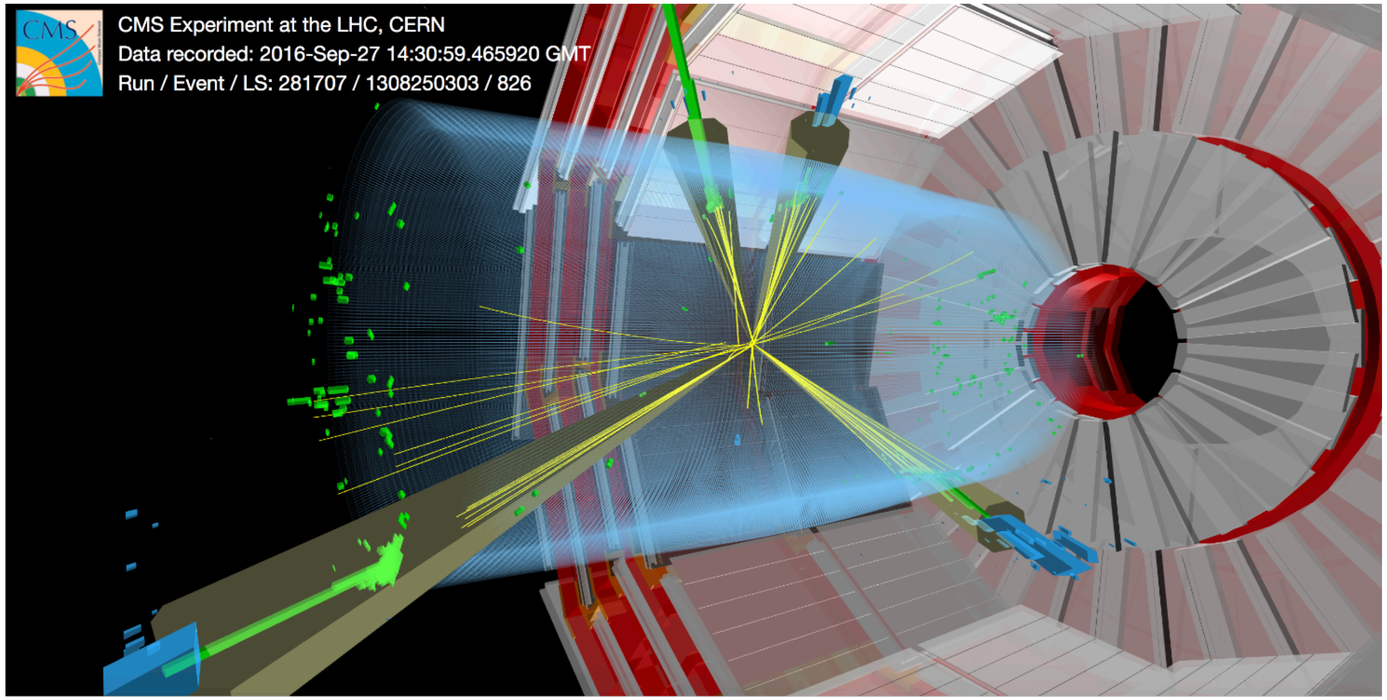
RHIC/AGS Annual Users' Meeting `24

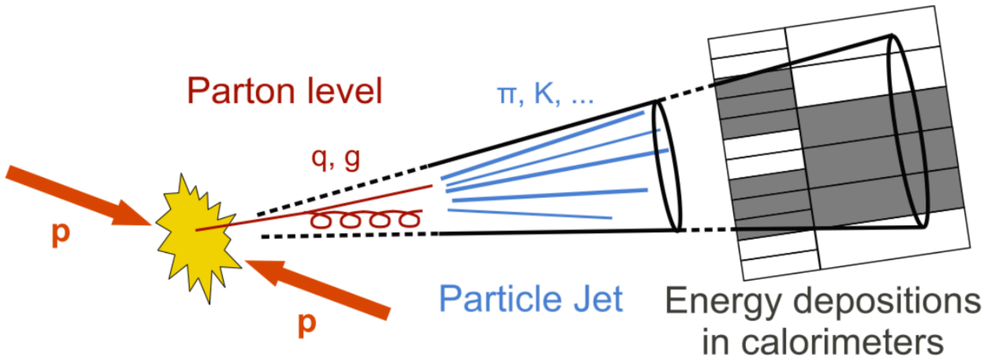
OLD DOMINION UNIVERSITY

Jefferson Lab

Jets at collider experiments

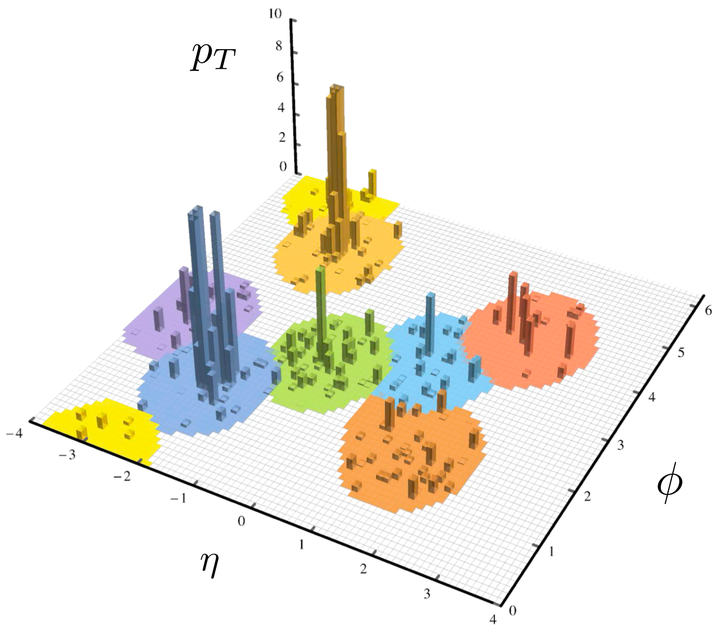
- Collimated sprays of particles
- Most direct access to high-energy quarks and gluons

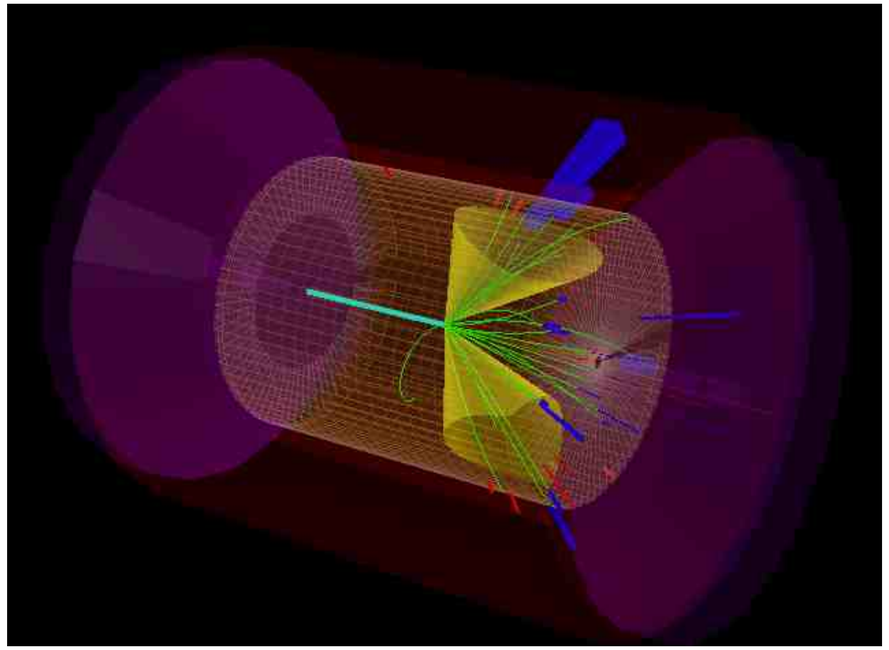




EIC jet physics

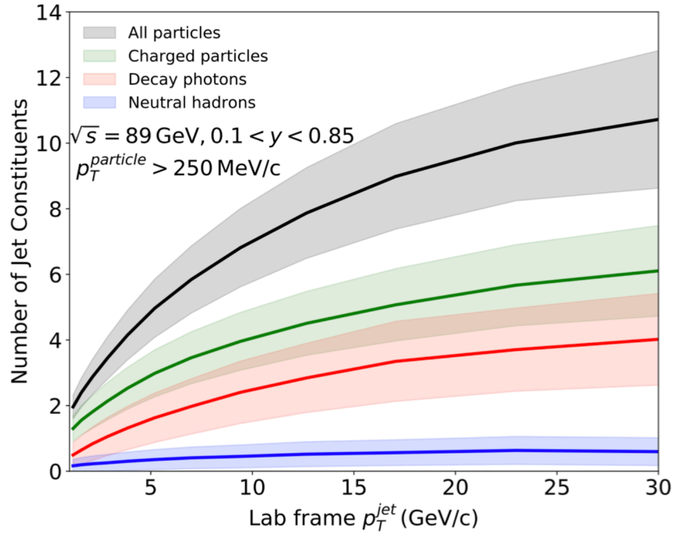
- Relevant for hadron structure, hadronization, etc.
- Clean EIC environment
- Jet substructure & correlations
- Versatile jet reconstruction algorithms & frame dependence



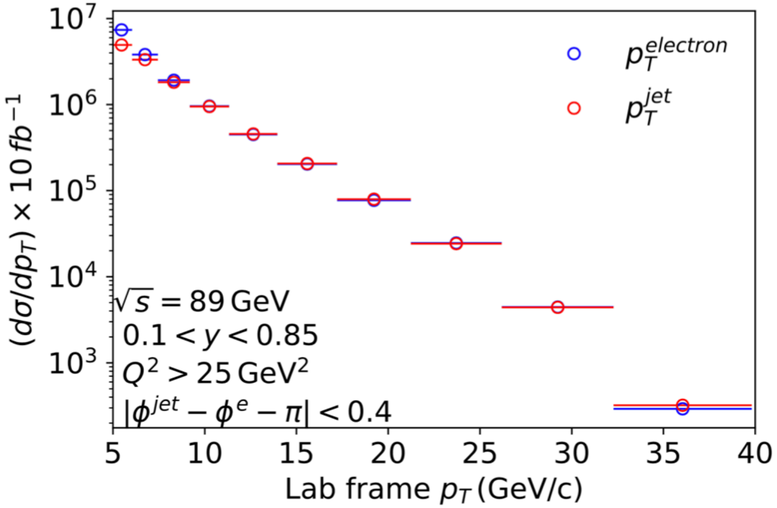


Nature of jets at the EIC

Particle #

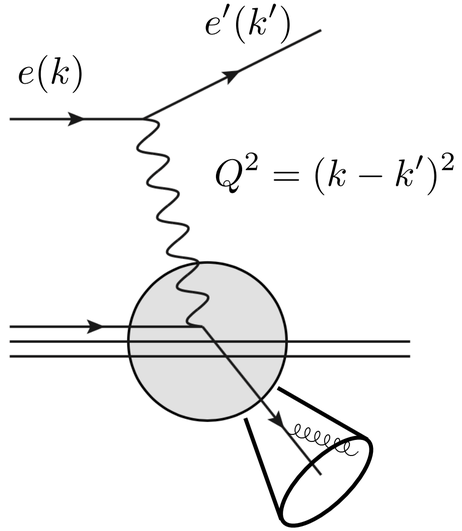


Transverse momentum



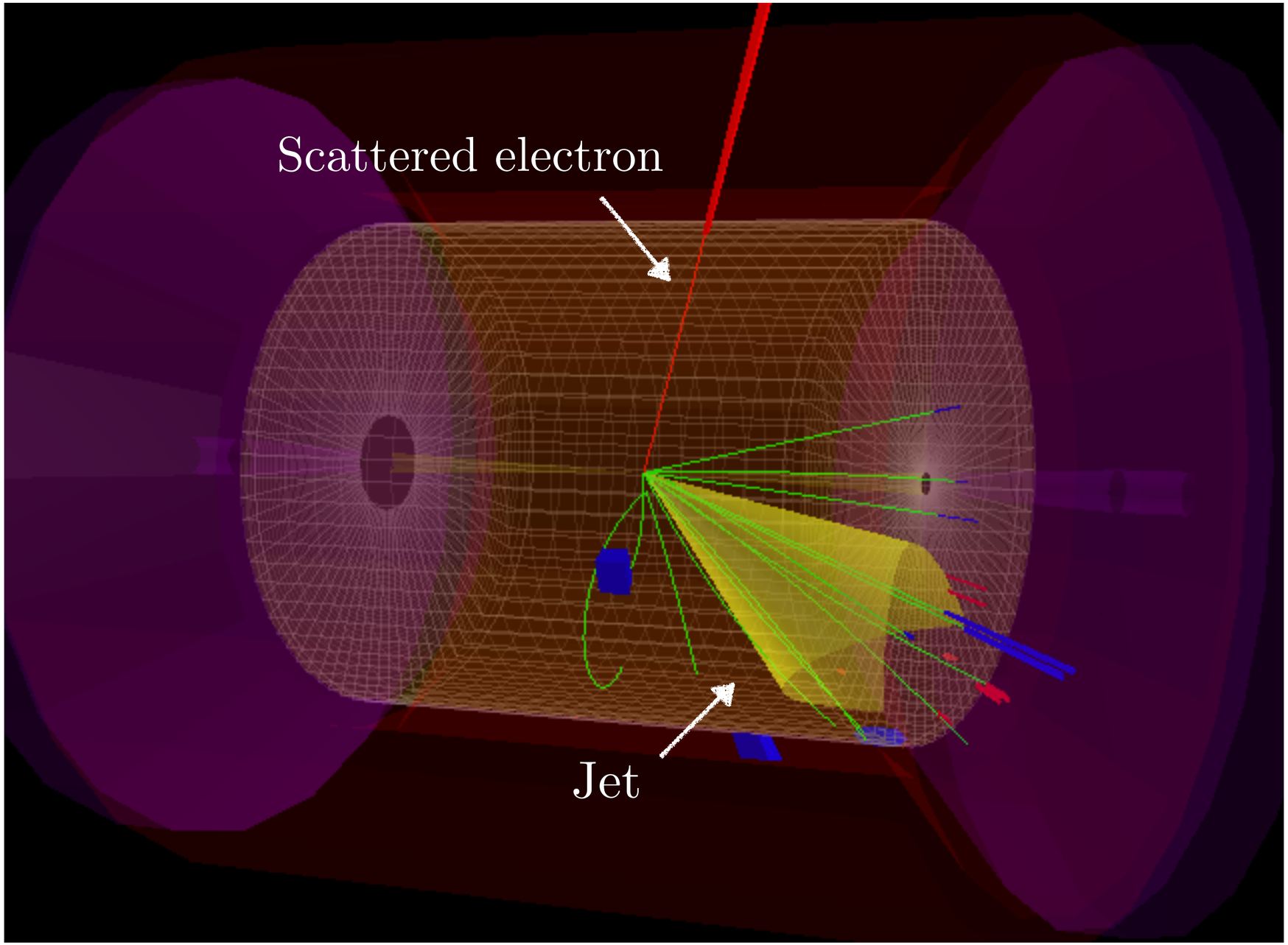
Two "natural" hard scales

- Jet transverse momentum p_T
- Photon virtuality Q^2

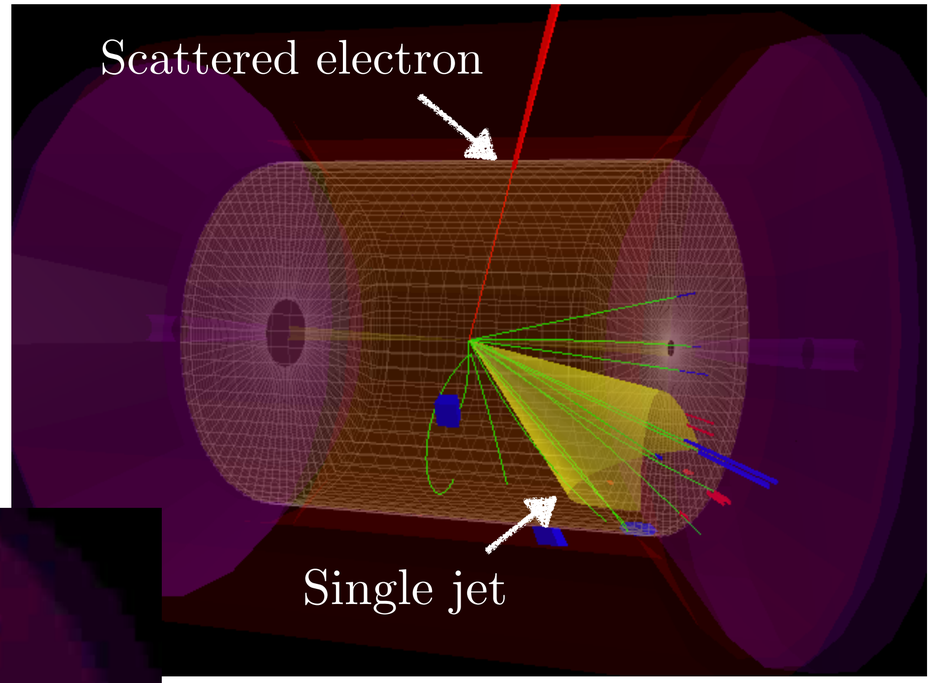


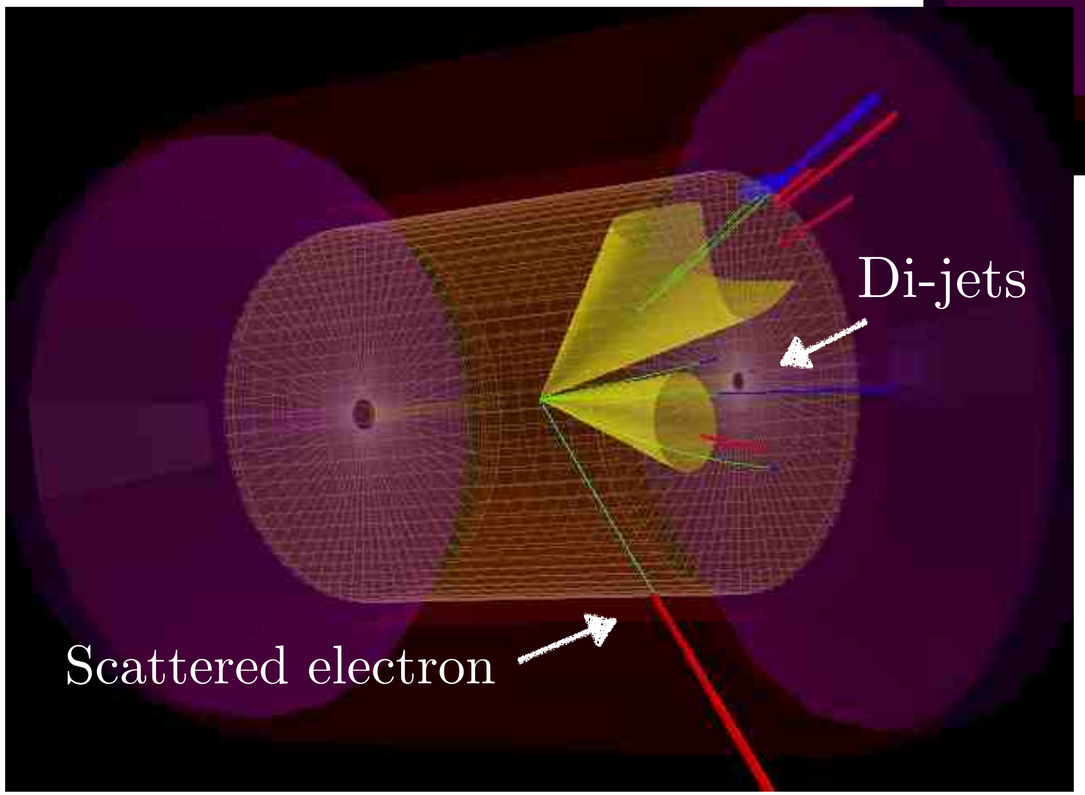
Arratia, Jacak, FR, Song `19
see also Aschenauer et al.

Laboratory frame



Laboratory frame





- Cf. proton-proton: jets vs. Z+jet
- Different quark/gluon fractions

Frame dependence

Lab frame

QCD factorization

$$\frac{\mathrm{d}\sigma^{\mathrm{Lab}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

- Analogous to a fragmentation function
- Quark-jets dominate

Frame dependence

Lab frame

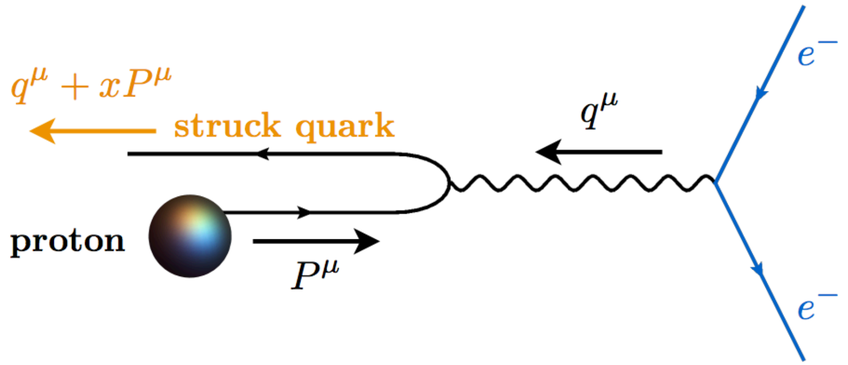
QCD factorization

$$\frac{\mathrm{d}\sigma^{\mathrm{Lab}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

Breit frame

Rotate and boost

$$\frac{\mathrm{d}\sigma^{\mathrm{Breit}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b$$

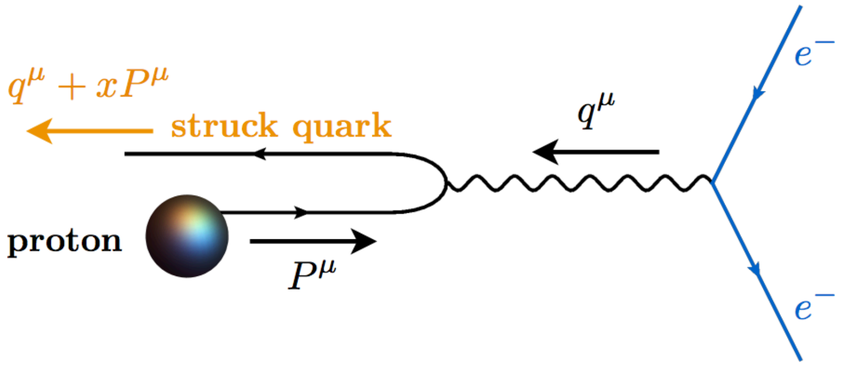


Frame dependence

Lab frame

QCD factorization

$$\frac{\mathrm{d}\sigma^{\mathrm{Lab}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

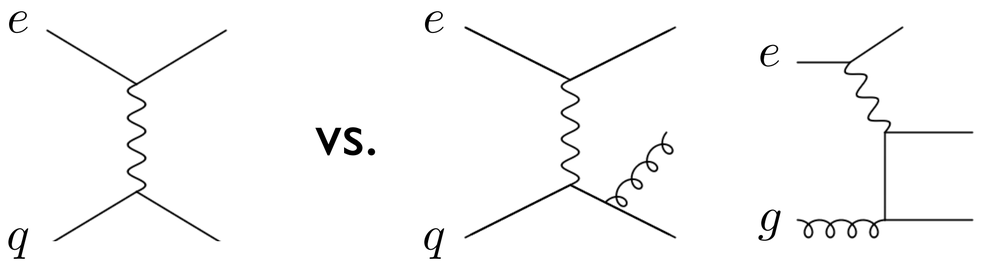


Breit frame

Rotate and boost

$$\frac{\mathrm{d}\sigma^{\mathrm{Breit}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b$$

Leading order



Frame dependence

Lab frame

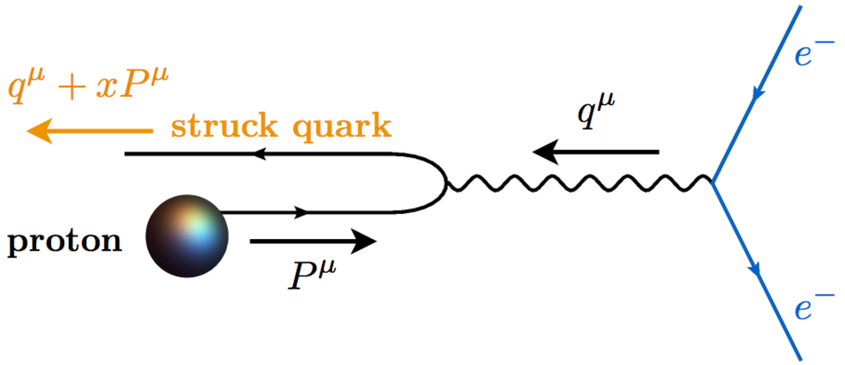
QCD factorization

$$\frac{\mathrm{d}\sigma^{\mathrm{Lab}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

Breit frame

Rotate and boost

$$\frac{\mathrm{d}\sigma^{\mathrm{Breit}}}{\mathrm{d}Q^2\mathrm{d}\eta\mathrm{d}p_T} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b$$



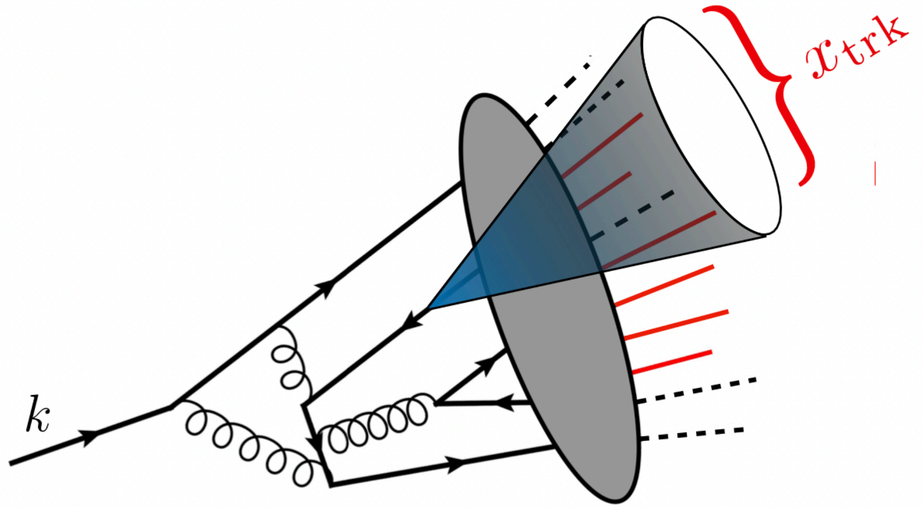
- Different than in proton-proton both are on equal footing!
- Systematically study quark/gluon differences

NieMiera, Lee, FR, Sato
- in preparation

Lab-frame jet substructure

Krohn, Schwartz, Lin, Waalewijn `12
Lee, Moult, FR, Waalewijn `23

- Charged particle momentum fraction of the jet
- Track functions related to multi-hadron fragmentation functions
- Probe of multi-parton and non-linear QCD dynamics



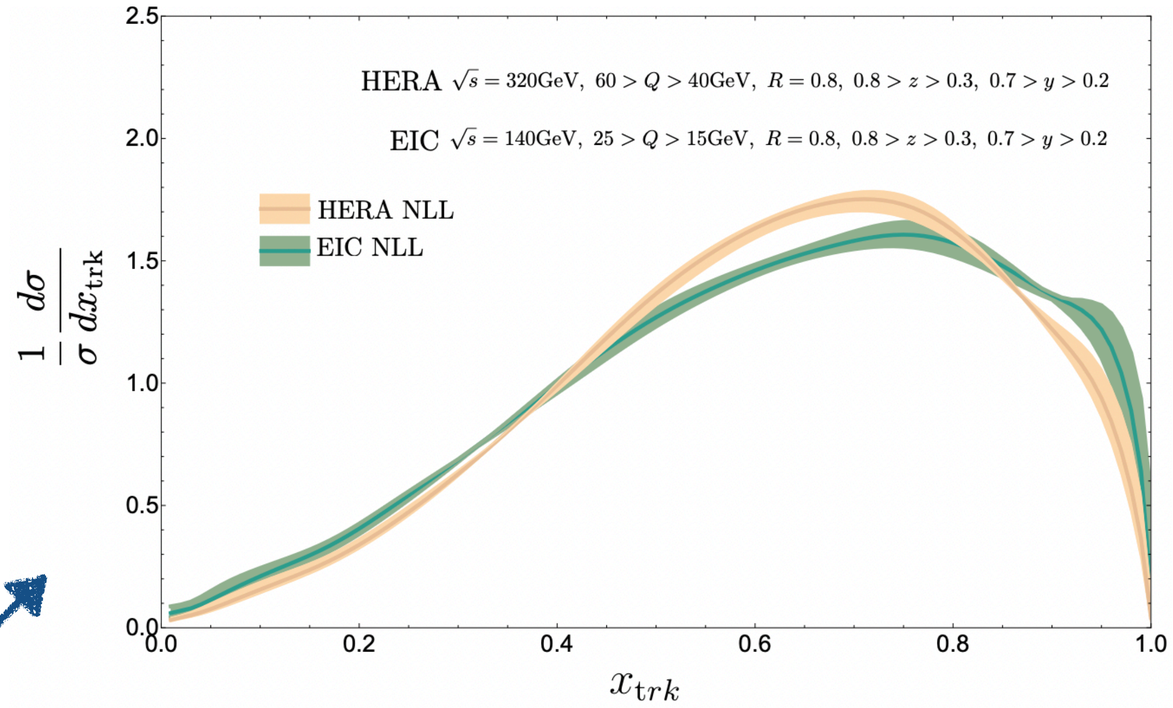
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}T_i(x) = a_s\left[K^{(0)}_{i\to i}T_i + K^{(0)}_{i\to i_1 i_2}\otimes T_{i_1}T_{i_2}\right](x)$$
$$+ a_s^2\left[K^{(1)}_{i\to i}T_i + K^{(1)}_{i\to i_1 i_2}\otimes T_{i_1}T_{i_2} + K^{(1)}_{i\to i_1 i_2 i_3}\otimes T_{i_1}T_{i_2}T_{i_3}\right](x)$$

Chen, Jaarsma, Li, Moult, Waalewijn, Zhu `22

Lab-frame jet substructure

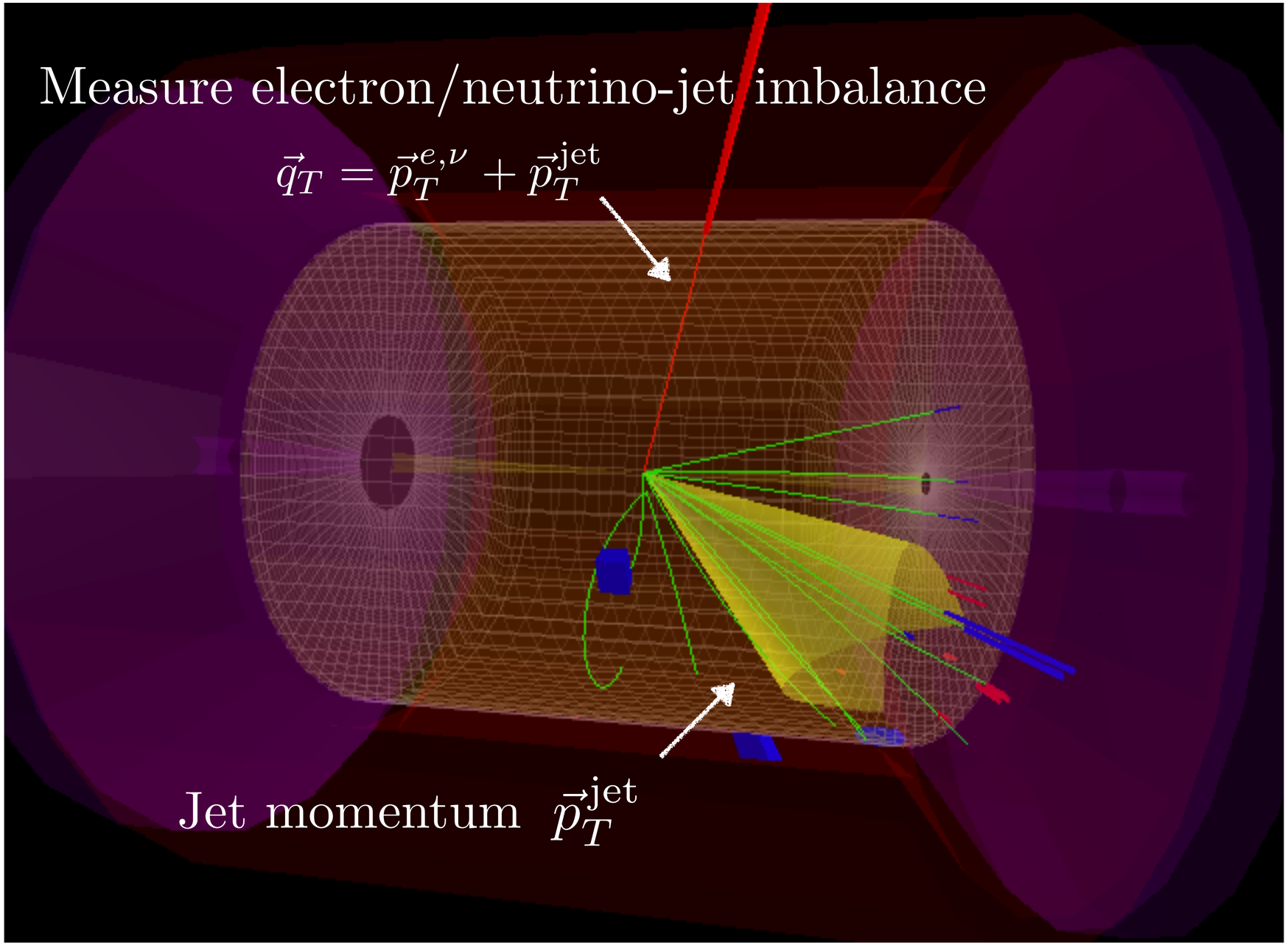
Lee, Moult, FR, Waalewijn `23

- Charged particle momentum fraction of the jet
- Track functions related to multi-hadron fragmentation functions
- EIC can constrain flavor dependence



Small QCD scale uncertainty

Laboratory frame



Electron-jet correlations

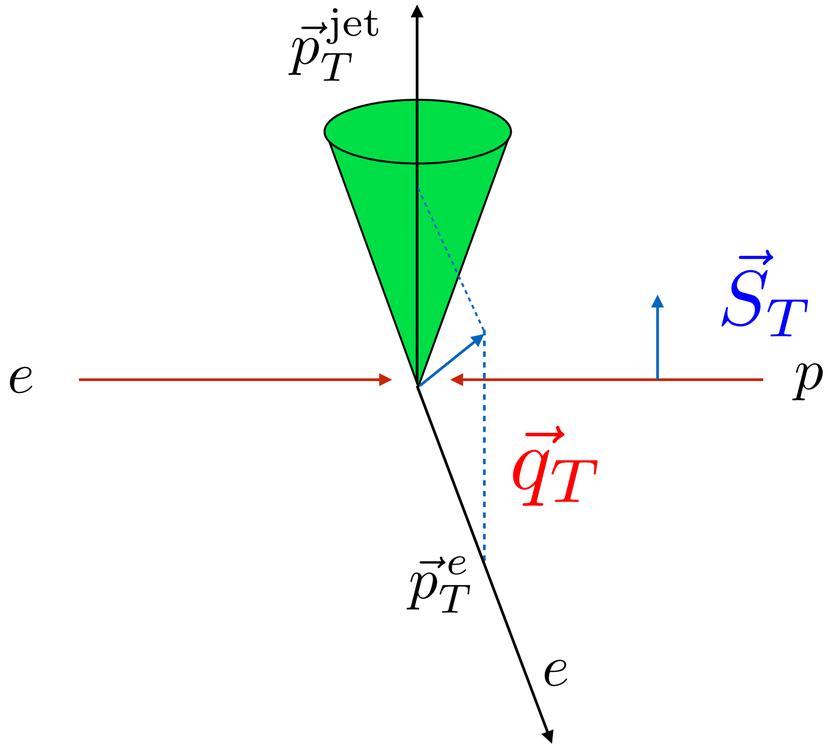
- Electron-jet imbalance at the EIC

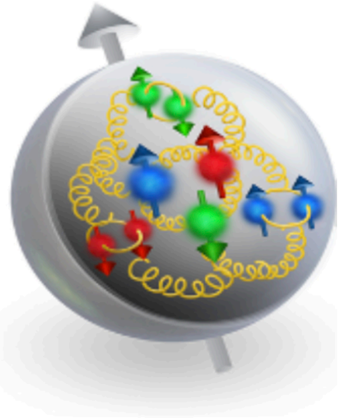
$$\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}$$

- Sensitivity to TMD PDFs but no TMD FF
- TMD factorization

$$F_{UU} = \sigma_0 \, H_q(Q,\mu) \sum_q e_q^2 \, J_q(p_T^{\mathrm{jet}} R, \mu)$$

$$\times \int \frac{\mathrm{d}^2 \vec{b}_T}{(2\pi)^2} \, e^{i \vec{q}_T \cdot \vec{b}_T} \, f_q^{\mathrm{TMD}}(x, \vec{b}_T, \mu) \, S_q(\vec{b}_T, y_{\mathrm{jet}}, R, \mu)$$





see also Boer, Vogelsang `05
Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `18, `19

Spin-dependent electron-jet correlations

- Electron-jet imbalance at the EIC

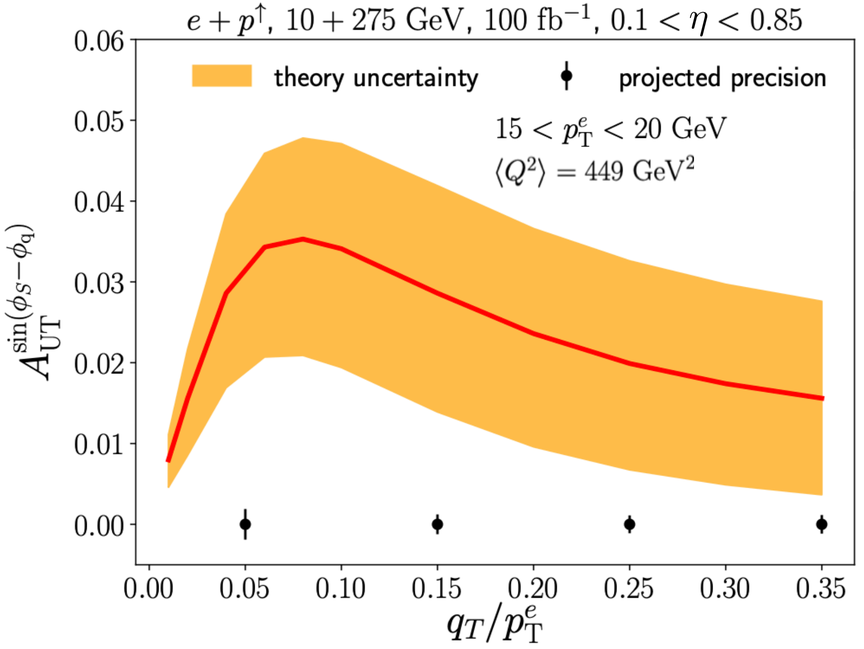
$$\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}$$

- Sensitivity to TMD PDFs but no TMD FF
- TMD factorization

$$F_{UU} = \sigma_0 \, H_q(Q,\mu) \sum_q e_q^2 \, J_q(p_T^{\mathrm{jet}} R, \mu)$$

$$\times \int \frac{\mathrm{d}^2 \vec{b}_T}{(2\pi)^2} \, e^{i \vec{q}_T \cdot \vec{b}_T} \, f_q^{\mathrm{TMD}}(x, \vec{b}_T, \mu) \, S_q(\vec{b}_T, y_{\mathrm{jet}}, R, \mu)$$

- Sensitivity to the Sivers function

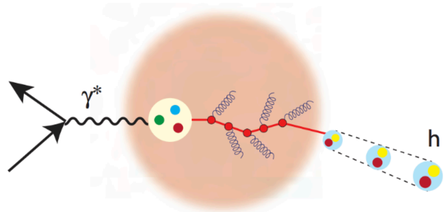


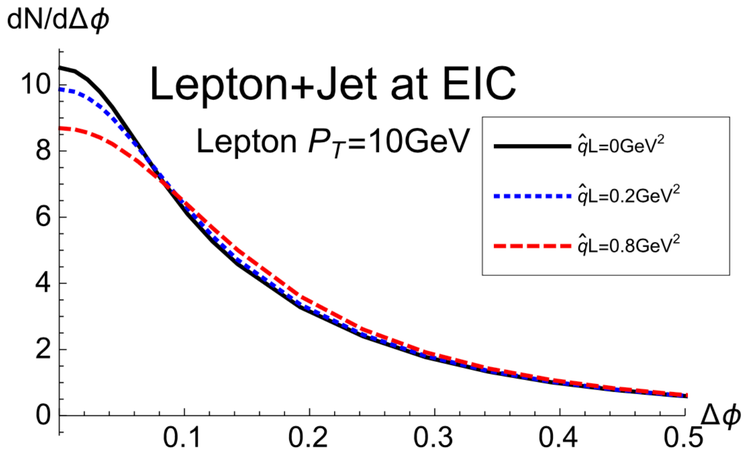
Liu, FR, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, FR`20
H1, PRL 128 (2022) 13, 132002

Electron-jet correlations in eA

- Constrain cold nuclear matter effects
- Broadening

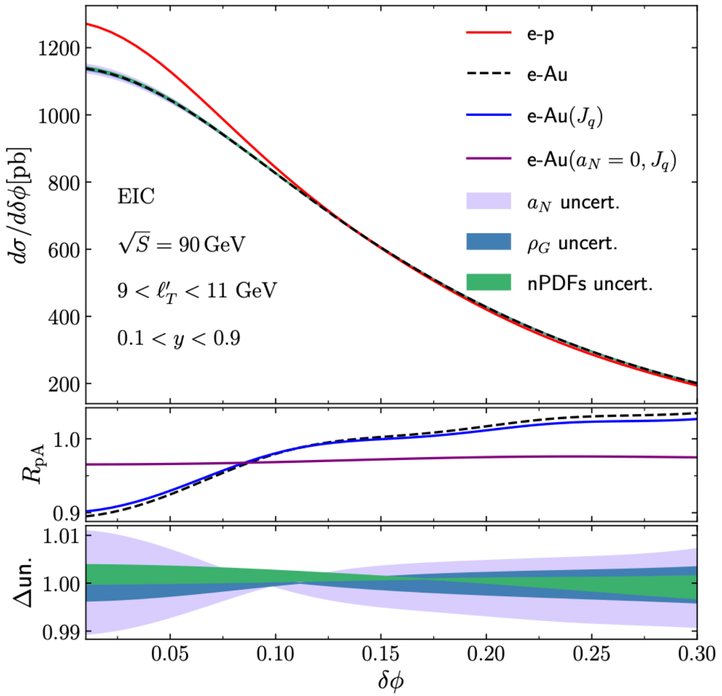
Standard jet axis





Liu, FR, Vogelsang, Yuan `18

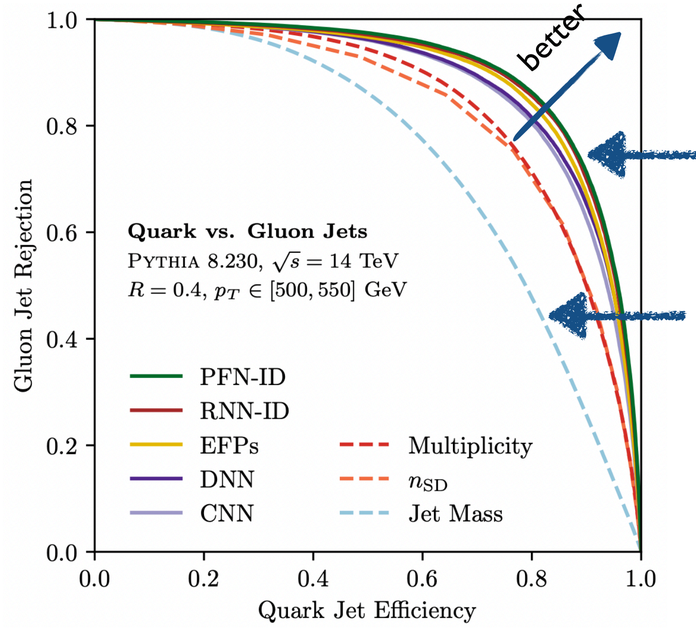
- Winner-take-all jet axis
- Forward scattering in the medium



Feng, Ke, Shao, Terry `23

ML-based jet classification

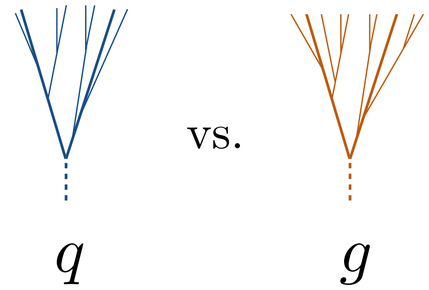
- E.g. quark vs. gluon jet classification
- LHC vs. EIC



AI/ML

Traditional observable

Komiske, Metodiev, Thaler `19



Deep set architecture

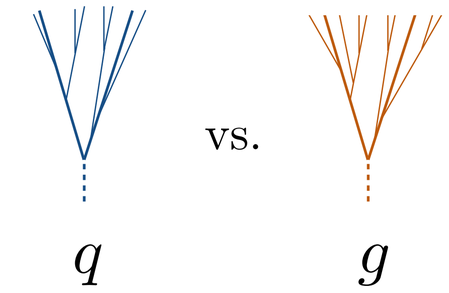
$$f(p_1, \ldots, p_M) = F\left(\sum_{i=1}^{M} \Phi(p_i)\right)$$

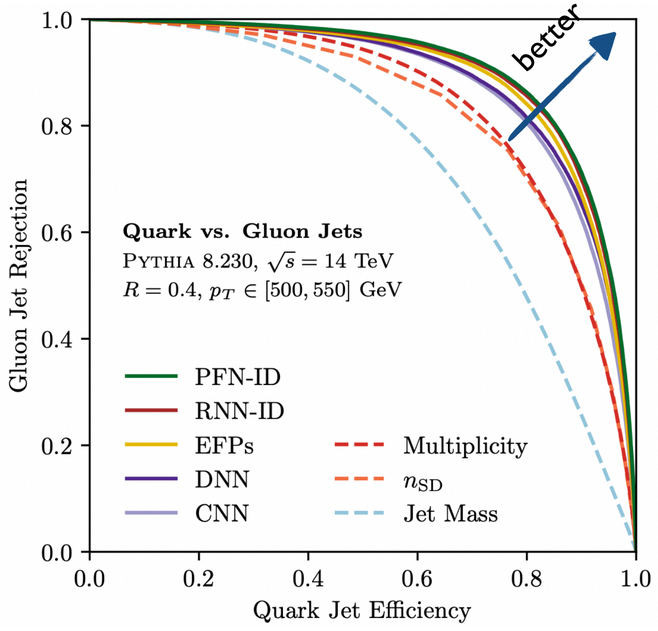
see also Hannah Bossi's talk

ML-based jet classification

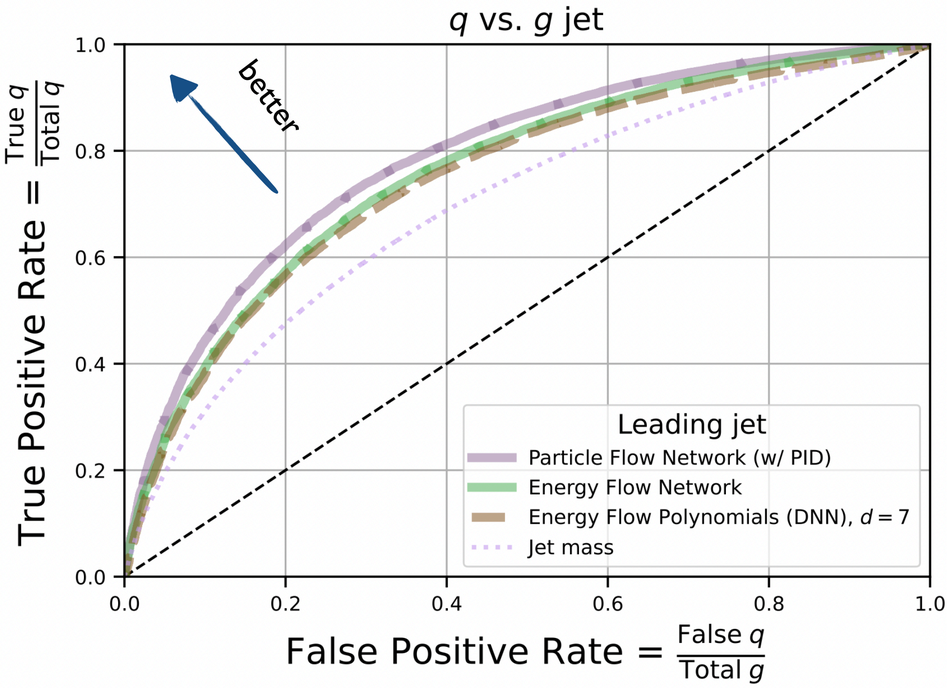
Lee, Mulligan, Ploskon, FR, Yuan `22

- E.g. quark vs. gluon jet classification
- LHC vs. EIC





Komiske, Metodiev, Thaler `19



ML-based jet classification

Lee, Mulligan, Ploskon, FR, Yuan `22

- E.g. quark vs. gluon jet classification
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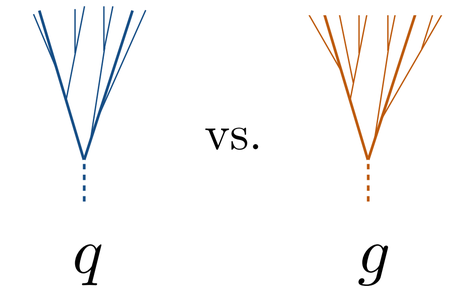
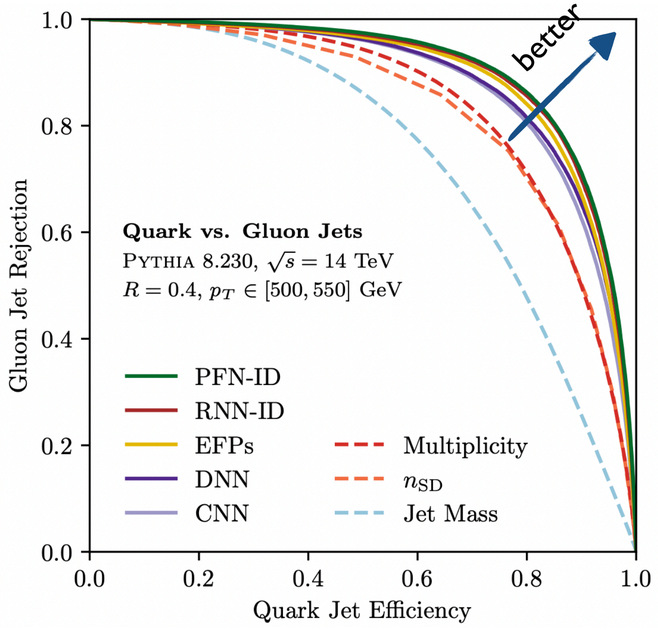
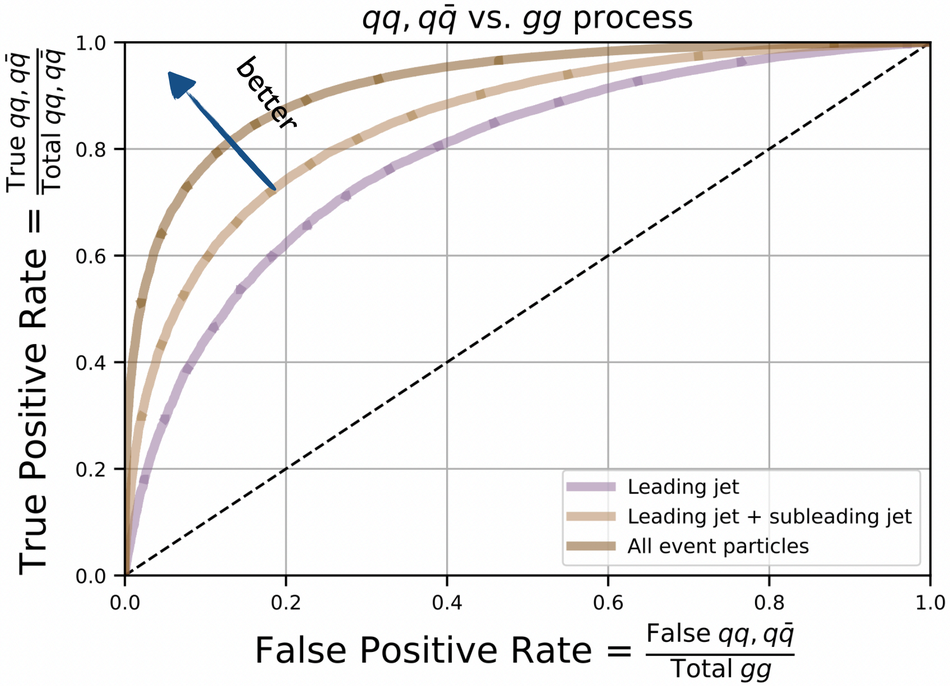


Full event information



Komiske, Metodiev, Thaler `19



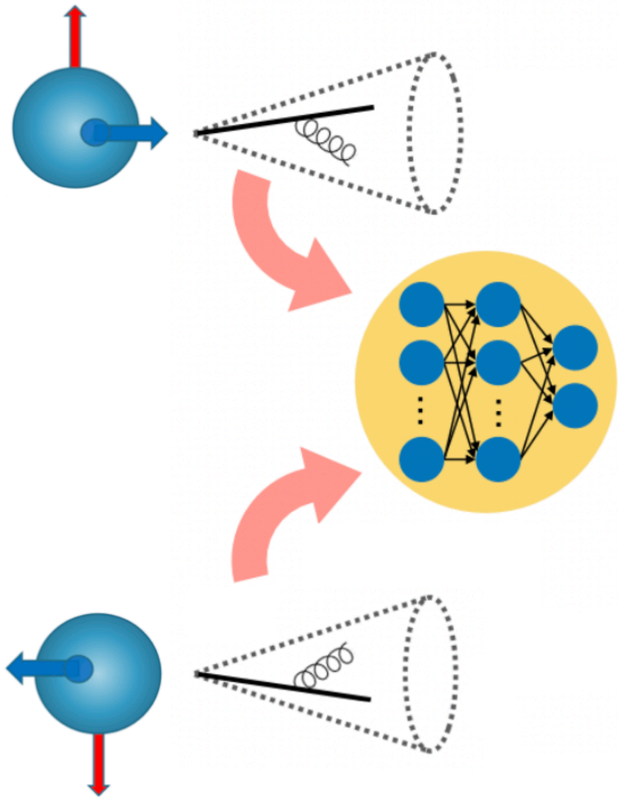
ML for spin physics

Lee, Mulligan, Ploskon, FR, Yuan `22

- How can we apply these techniques to spin-dependent observables?

1. Supervised machine learning
2. Train on data e.g. $A_{UT} = \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}}$

- Reformulate regression task as classification problem $\max_{\theta} |A_{UT}(\theta)|$



→ Upper limit on what can possibly be achieved

→ Identify new observables

Summary

- Jets will be versatile tools at the EIC
- Can take advantage of the EIC's clean environment, high luminosity, etc.
- New recent calculations such as jets in eA
- Exploration of ML-based classification, generative modeling