Disentangling quark and gluon jets in the Breit frame

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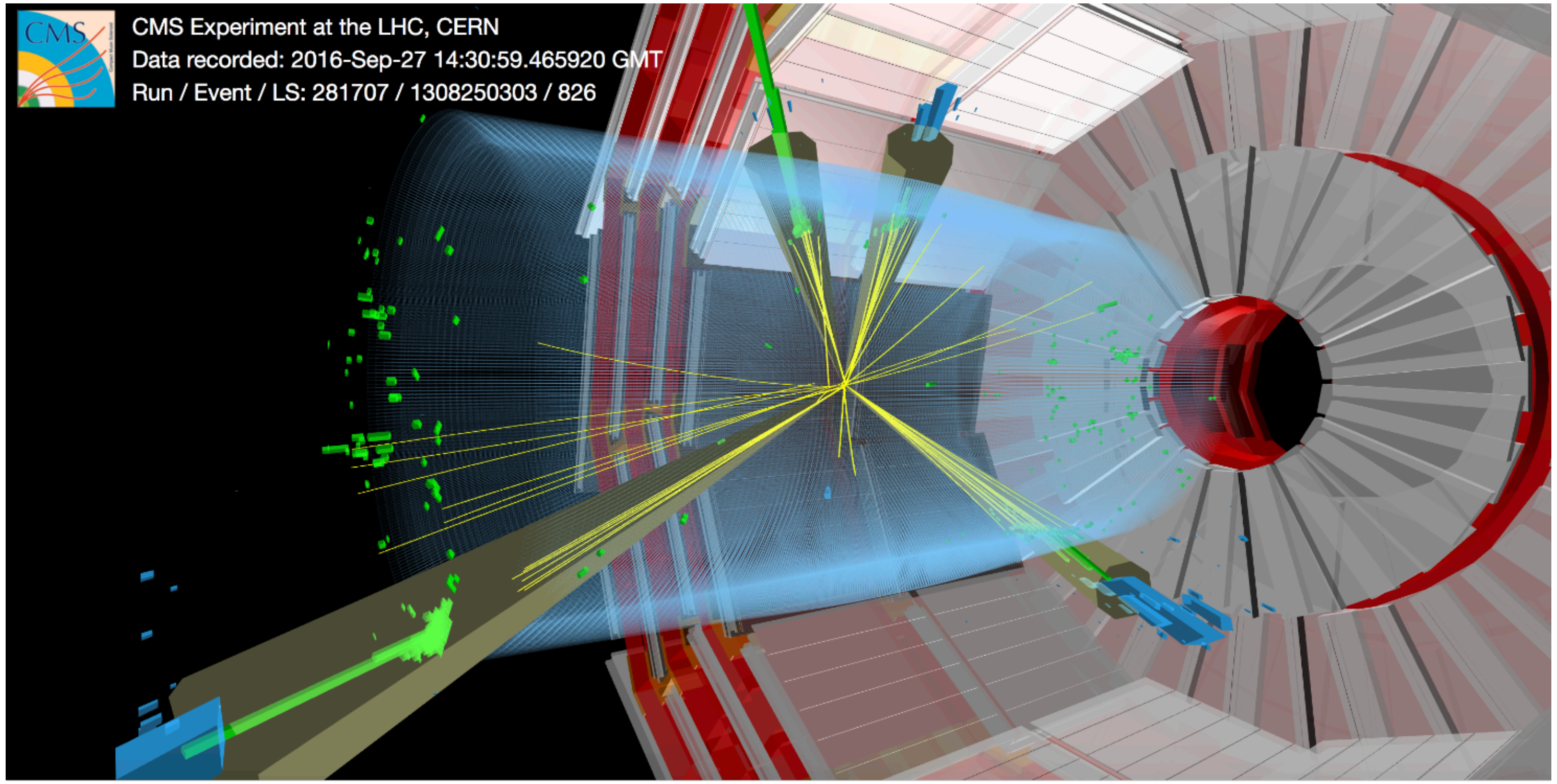
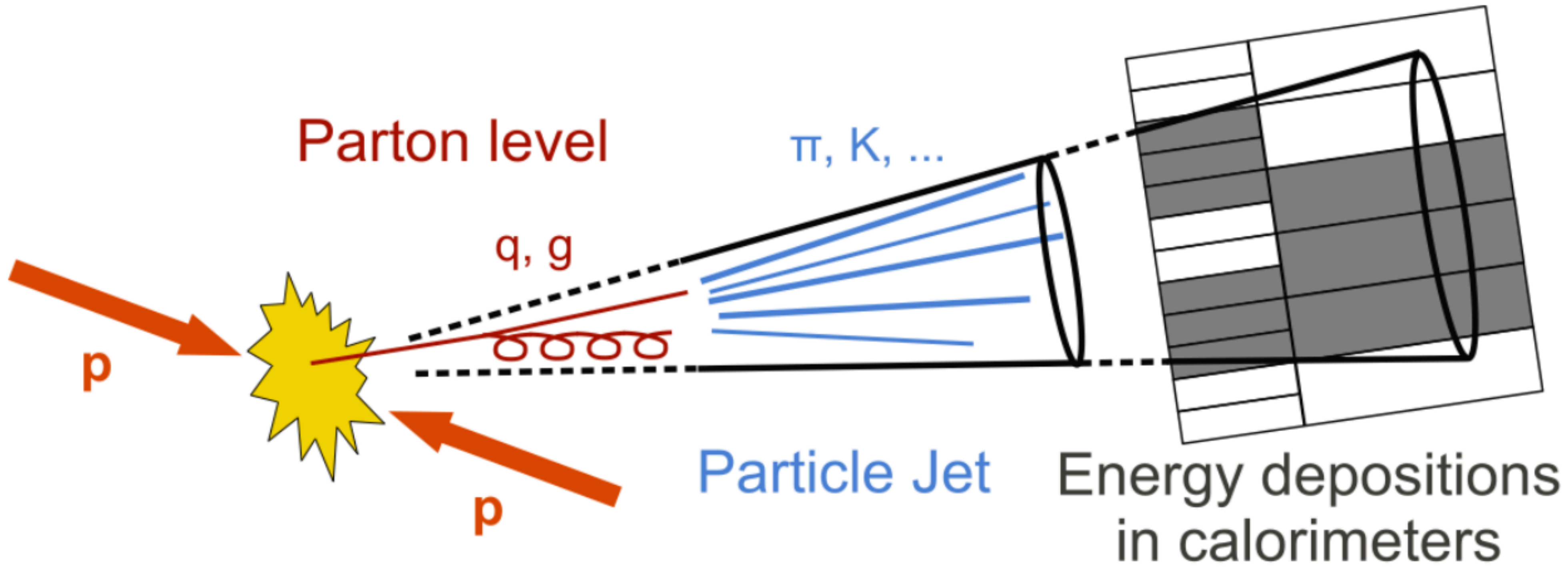
Cold Nuclear Matter Effects: from the LHC to the EIC
CFNS, 01/16/2025

Stony Brook University

Jets at collider experiments

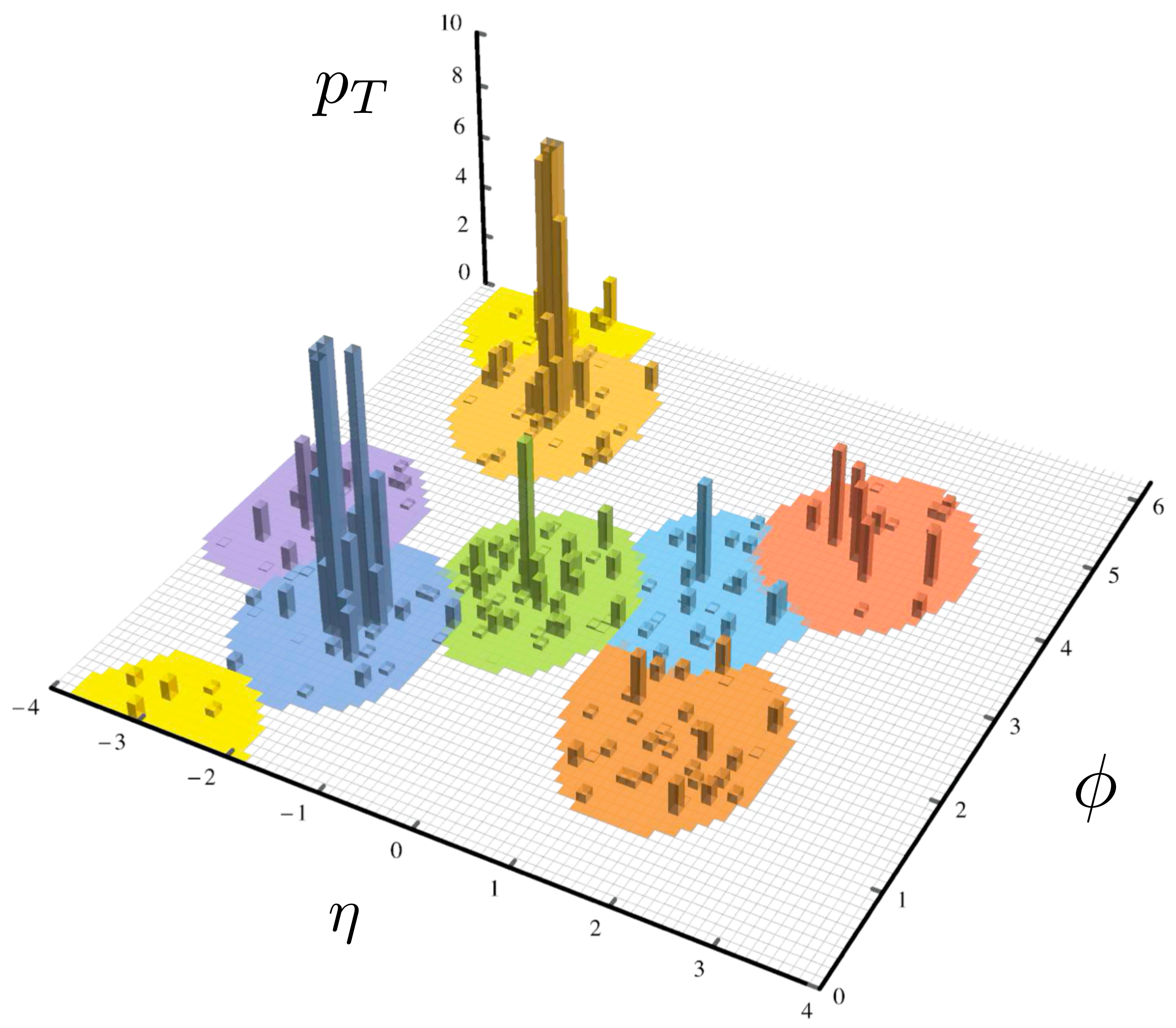
- Collimated sprays of particles
- Most direct access to high-energy quarks and gluons

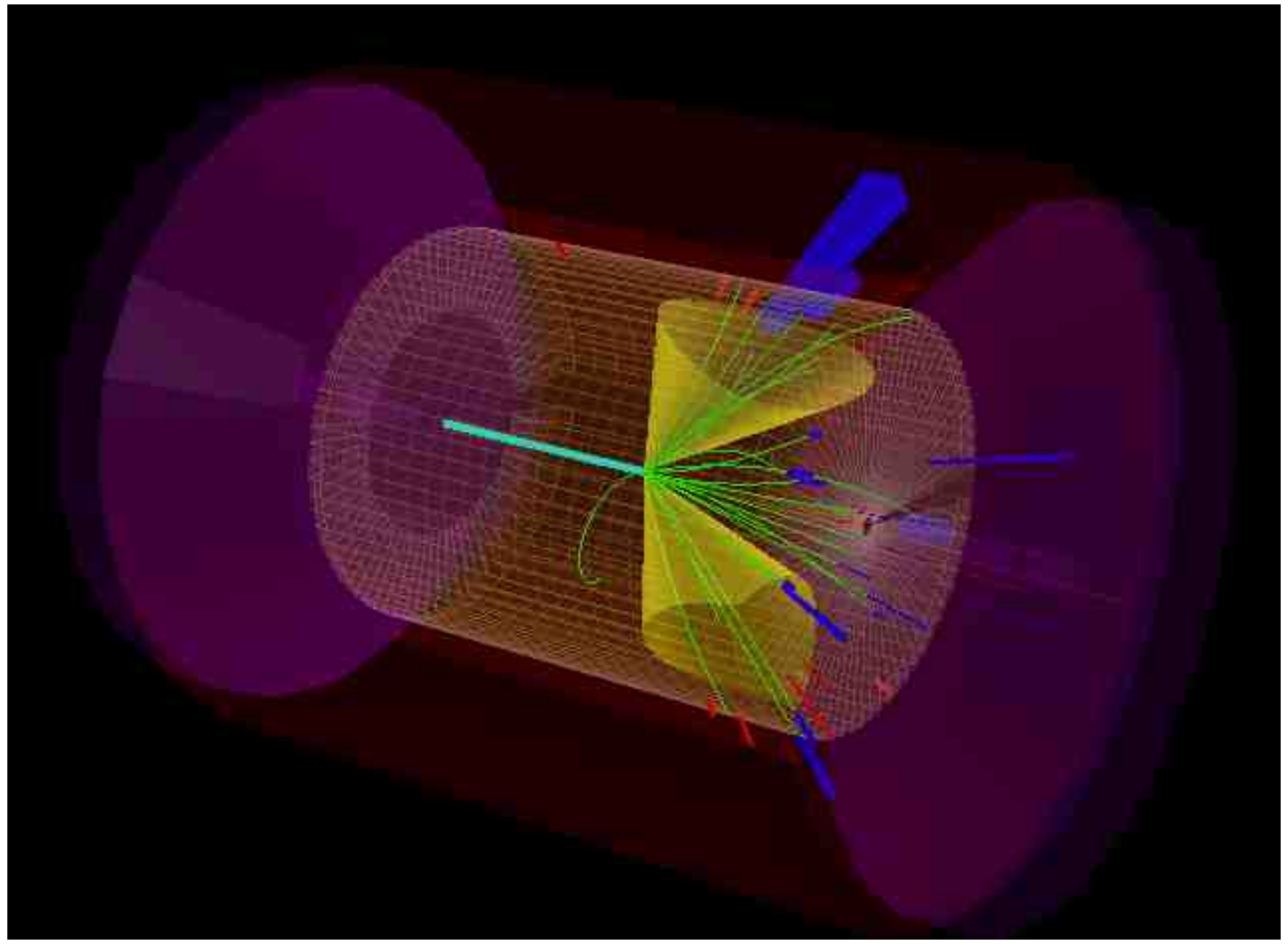




EIC jet physics

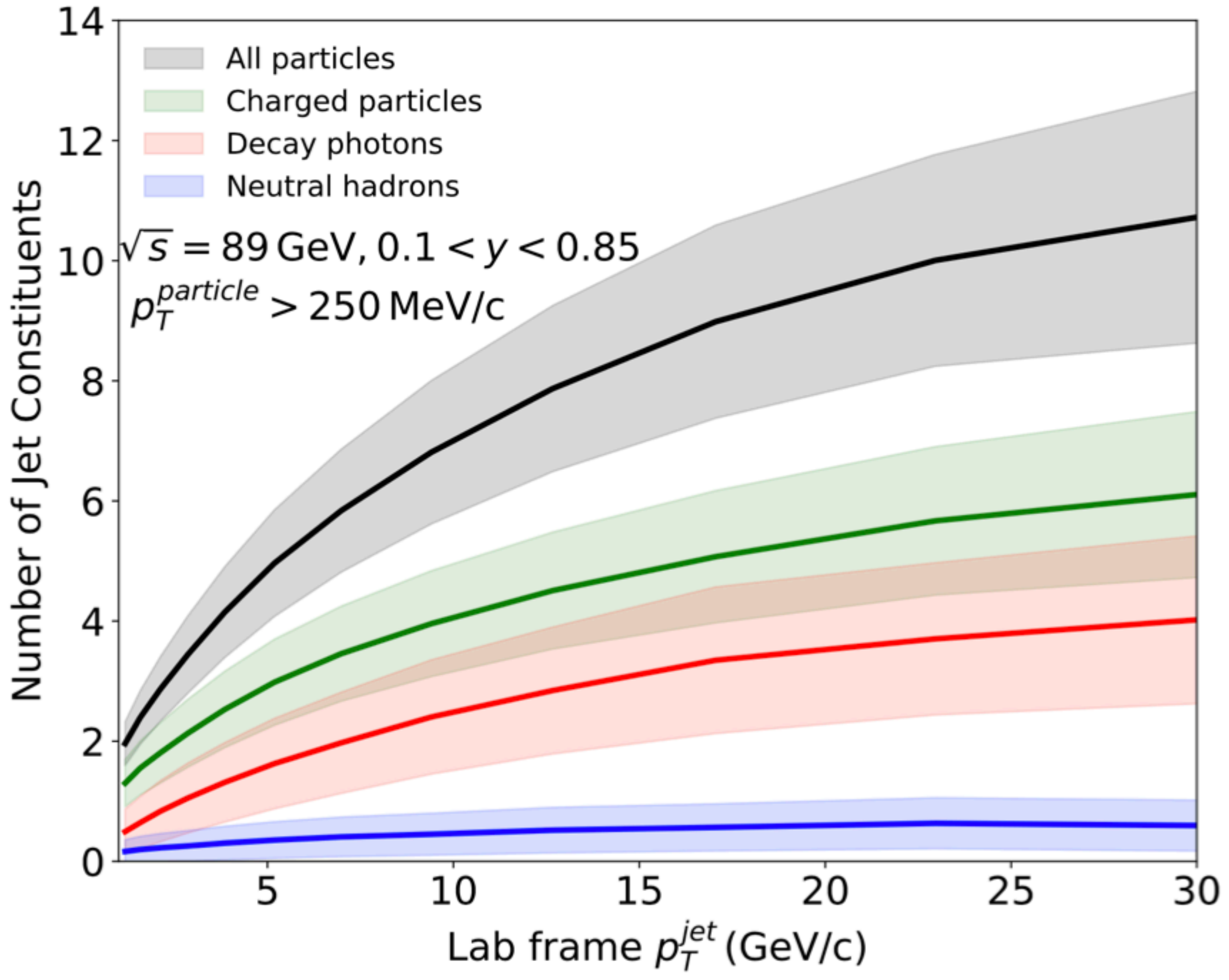
- Relevant for hadron structure, cold nuclear matter effects, etc.
- Clean EIC environment
- Jet substructure & correlations
- Versatile jet reconstruction algorithms & frame dependence



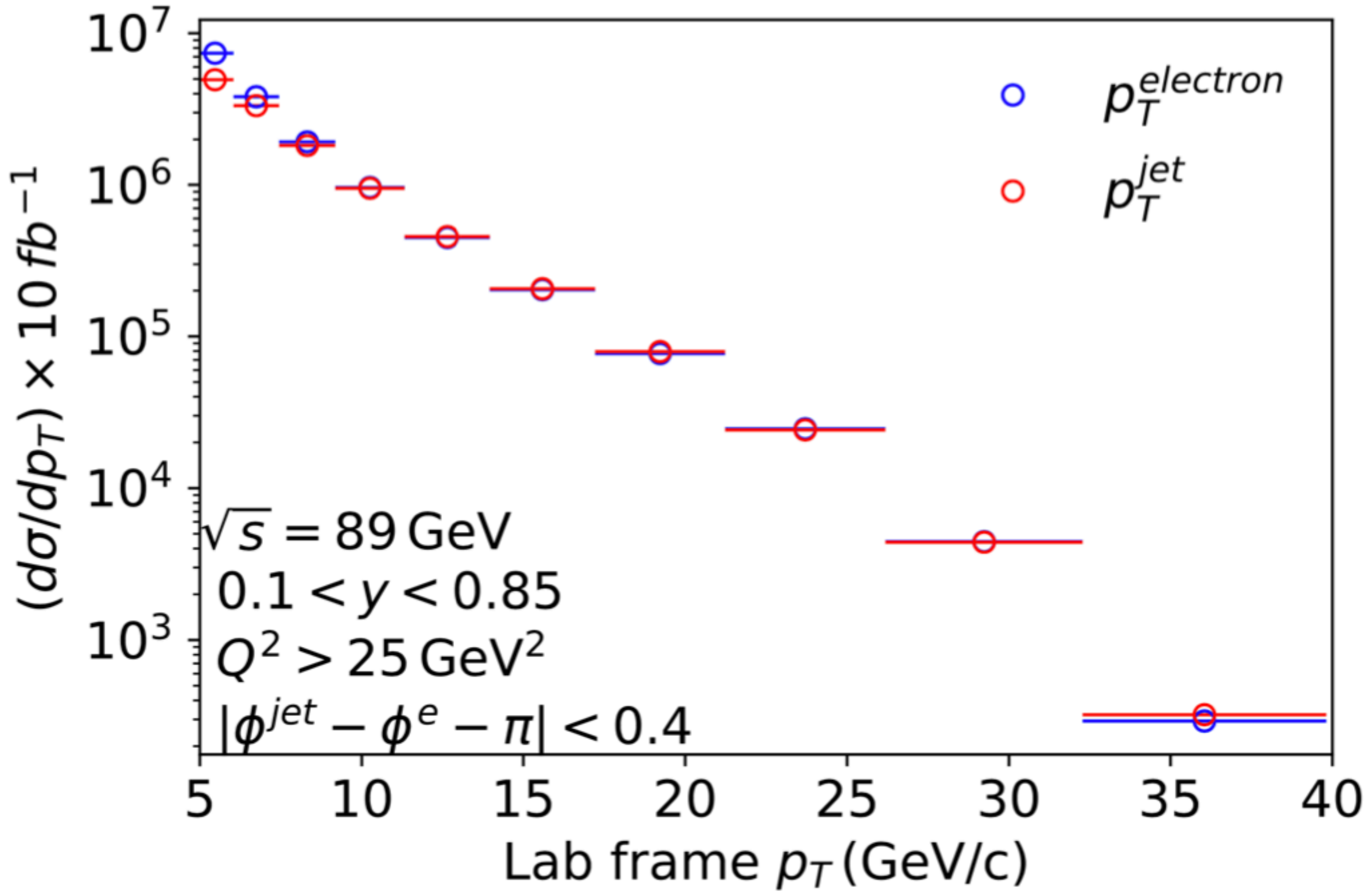


Nature of jets at the EIC

Particle #

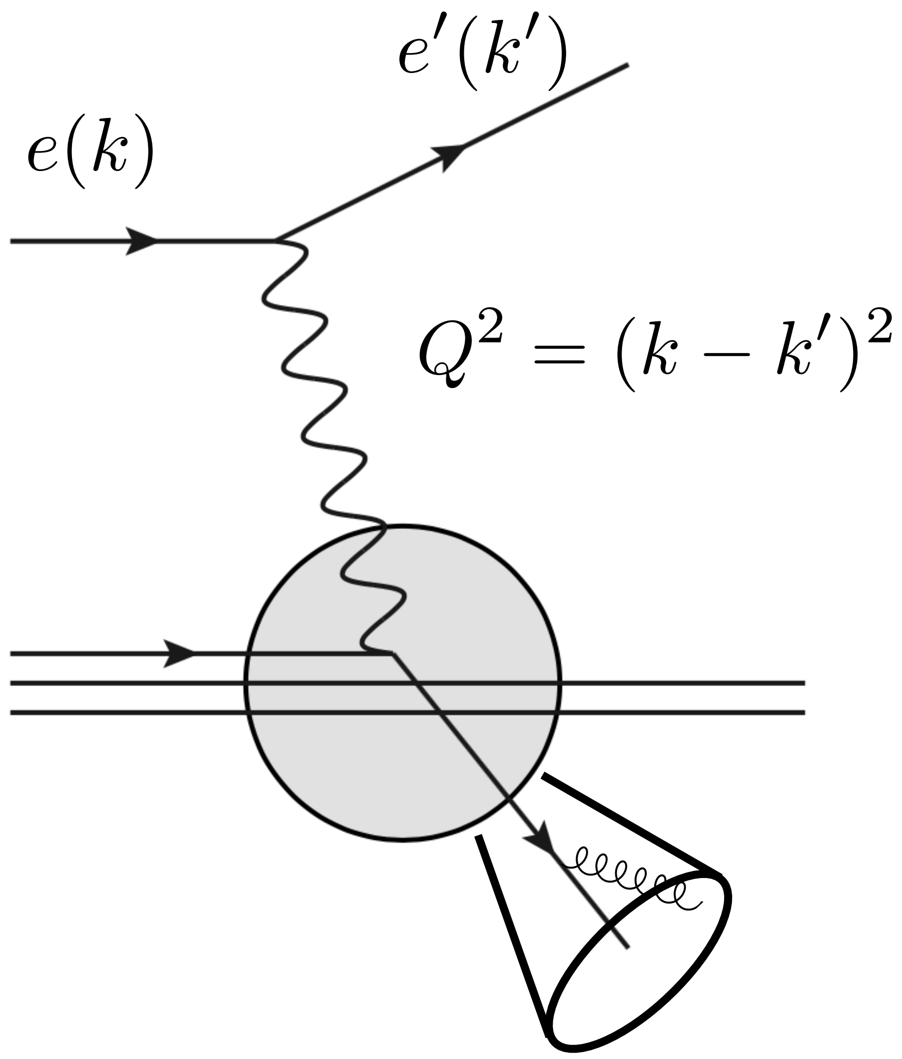


Transverse momentum



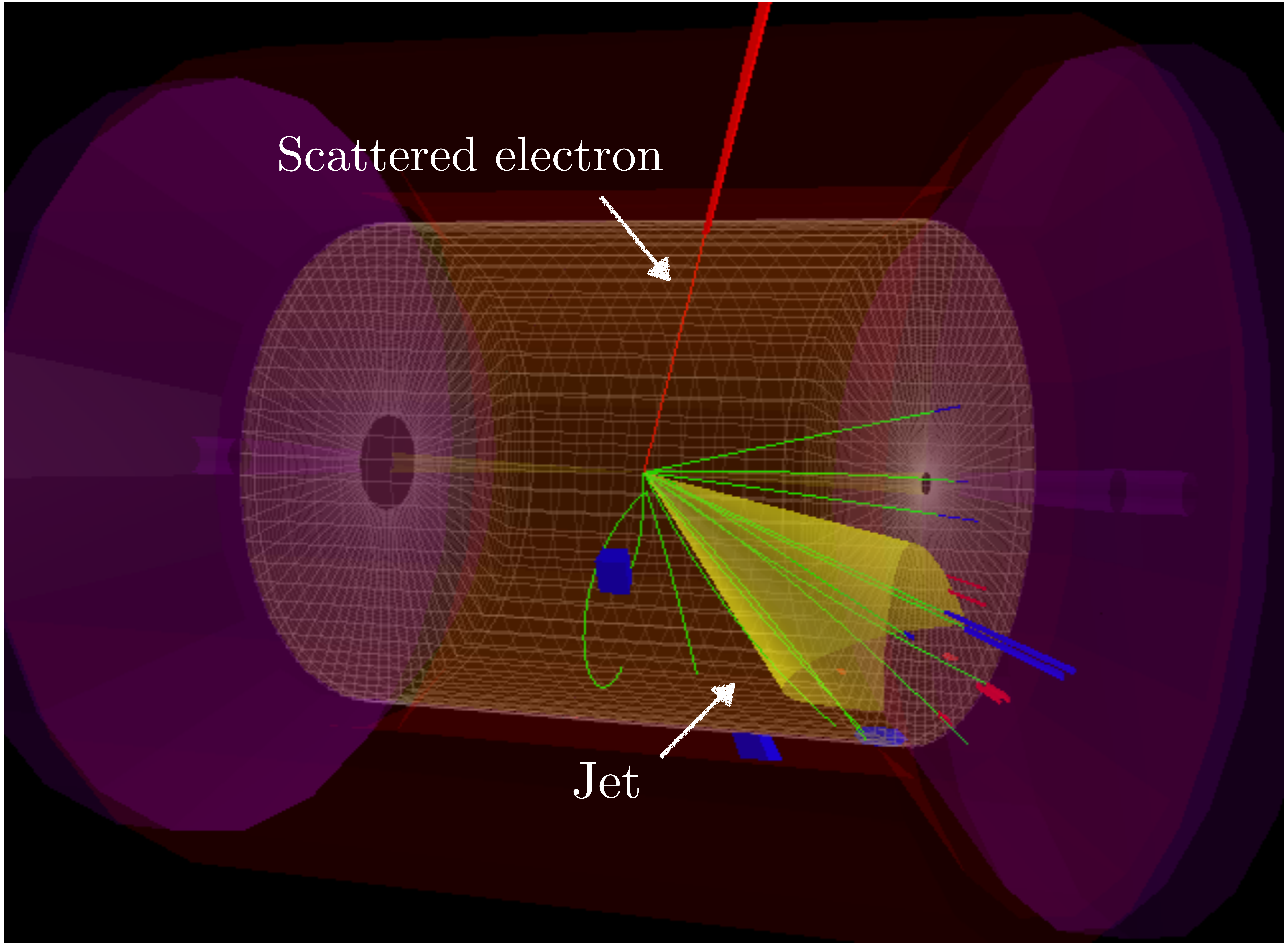
Two “natural” hard scales

- Jet transverse momentum p_T
- Photon virtuality Q^2

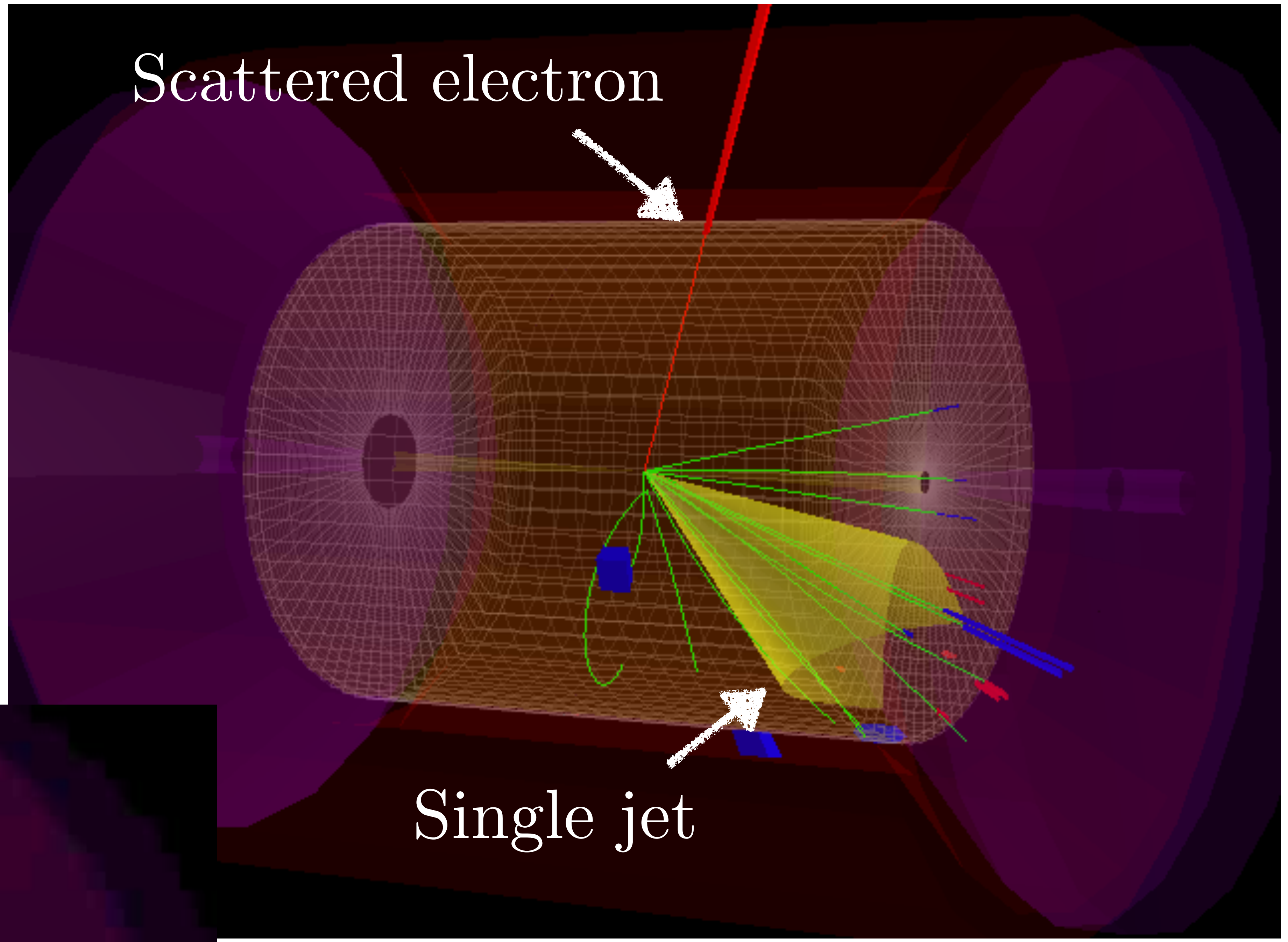


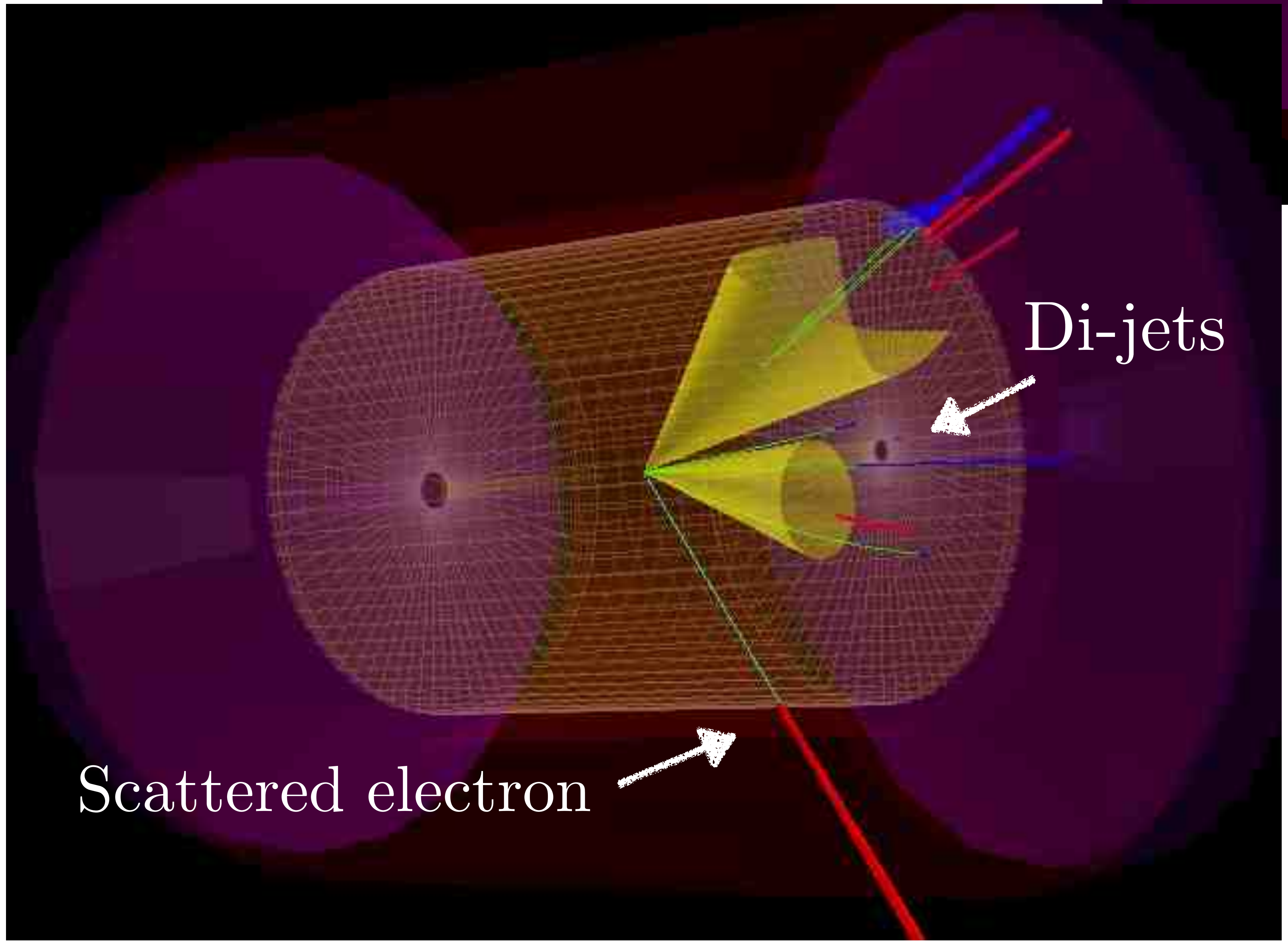
Arratia, Jacak, FR, Song `19
see also Aschenauer et al.

Laboratory frame



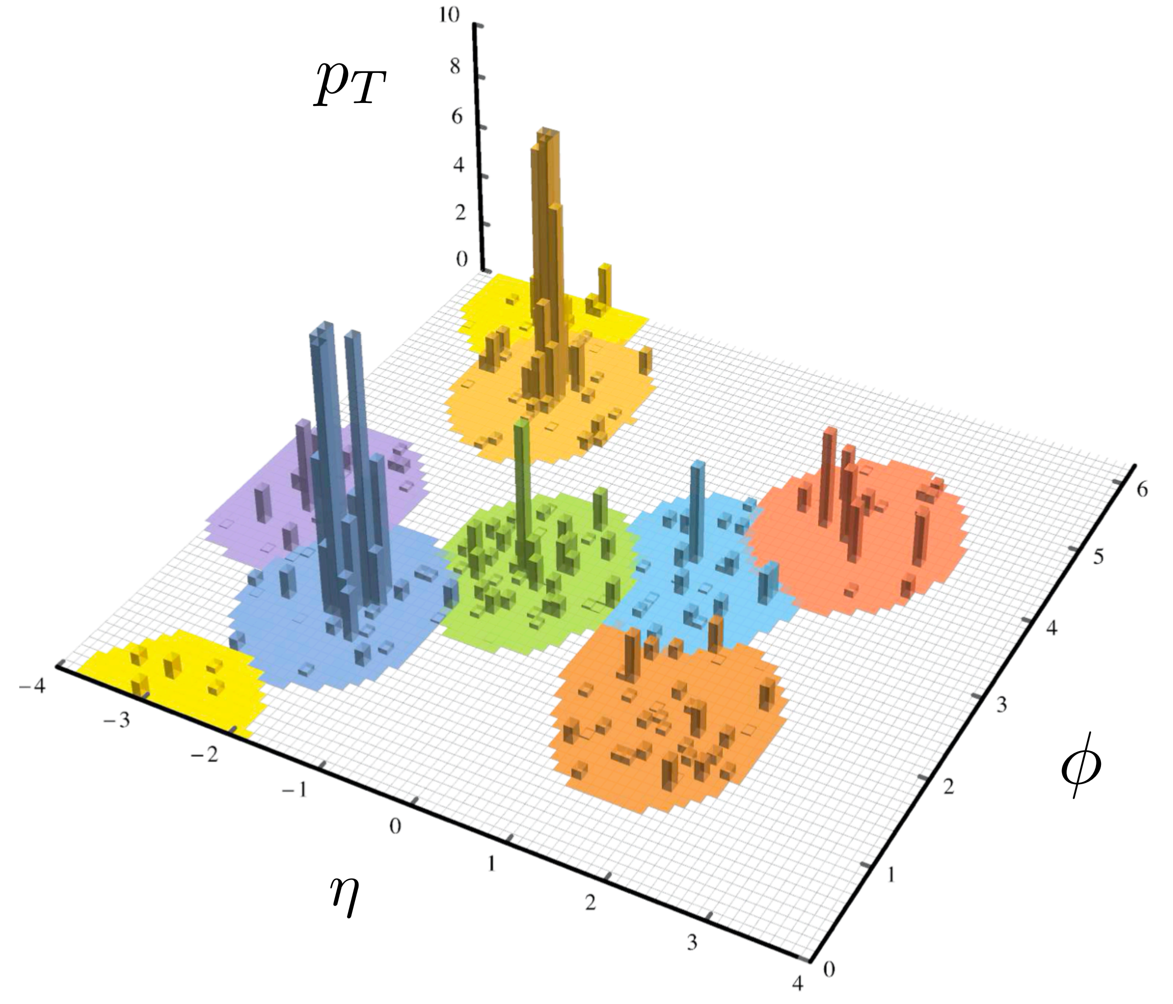
Laboratory frame





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

Jet algoritms



k_T type algorithms

Rapidity/azimuth and transverse momentum

$$d_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right)(\Delta\eta + \Delta\phi^2)^2/R^2, \quad d_{iB} = p_{Ti}^{2p}$$

Spherically symmetric

Angles and energies

see also Paul Caucal's talk

$$d_{ij} = \min\left(E_i^{2p}, E_j^{2p}\right)\theta_{ij}^2/R^2, \quad d_{iB} = E_i^{2p}$$

e^+e^- or Breit frame

ep or pp in the lab frame - clusters the beam remnants into a jet

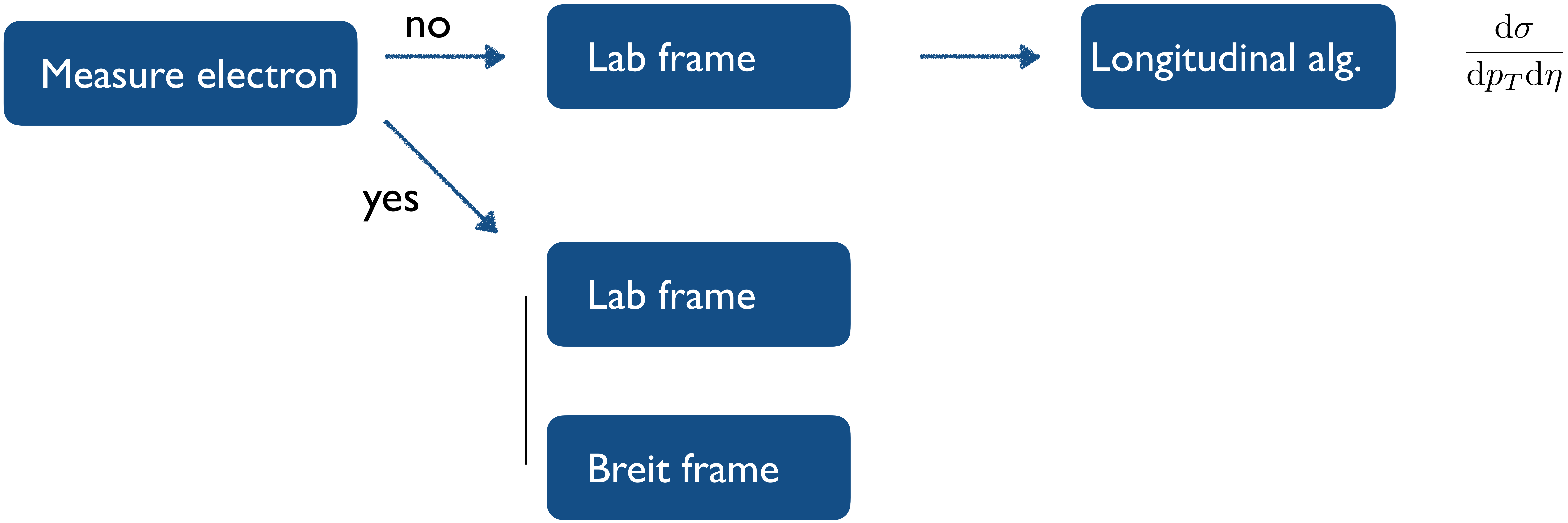
Jets - Frame & algorithm dependence

Measure electron —no→ Lab frame → Longitudinal alg. $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta}$

Q^2 small or large

see also asymmetric algorithm Makris et al.

Jets - Frame & algorithm dependence



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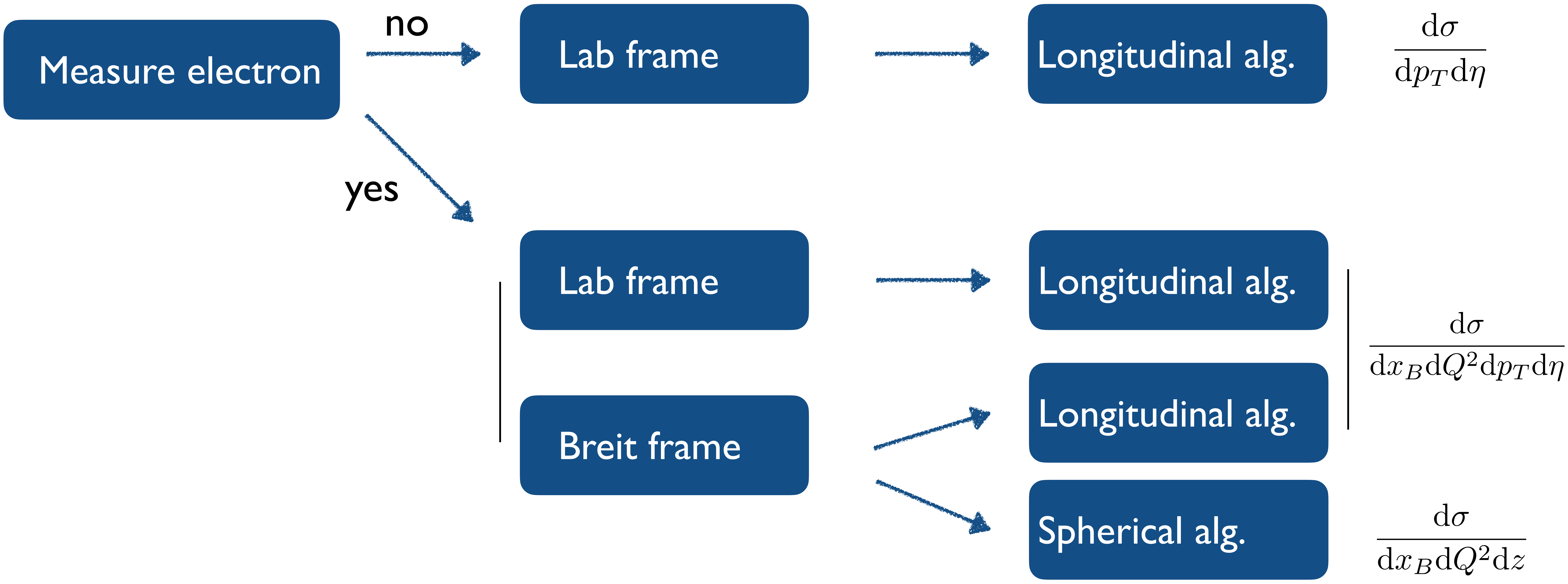
Jets - Frame & algorithm dependence



Q^2 small or large

see also asymmetric Centauro algorithm Makris et al.

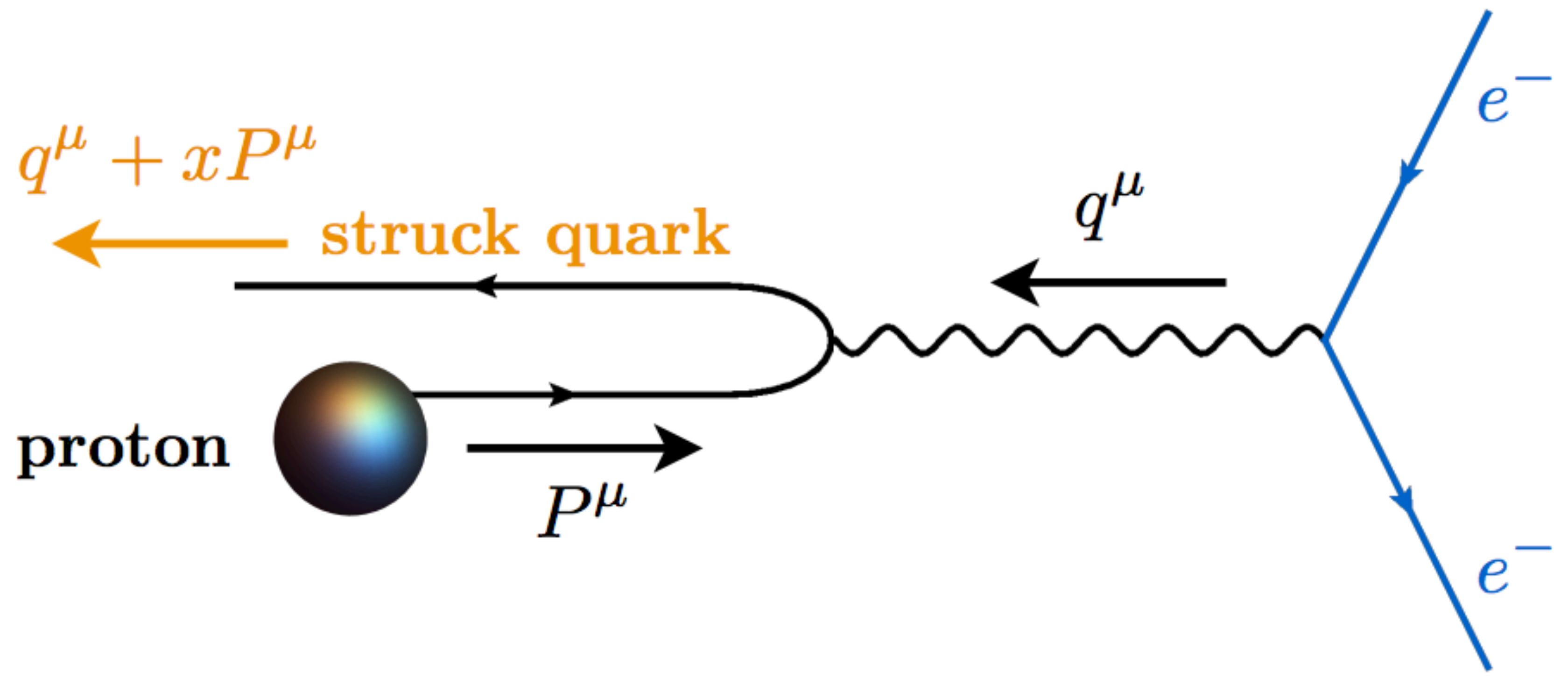
Algorithm dependence

Breit frame

Spherically invariant algorithm (E_i, θ_{ij})

$$\frac{d\sigma^{\mathrm{SI}}}{dx_B dQ^2 dz} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

- Collinear jet function, resummation of $\ln R$
- Particularly useful for jet substructure
- Quark-jets dominate
- A few percent of gluon jets at NLO



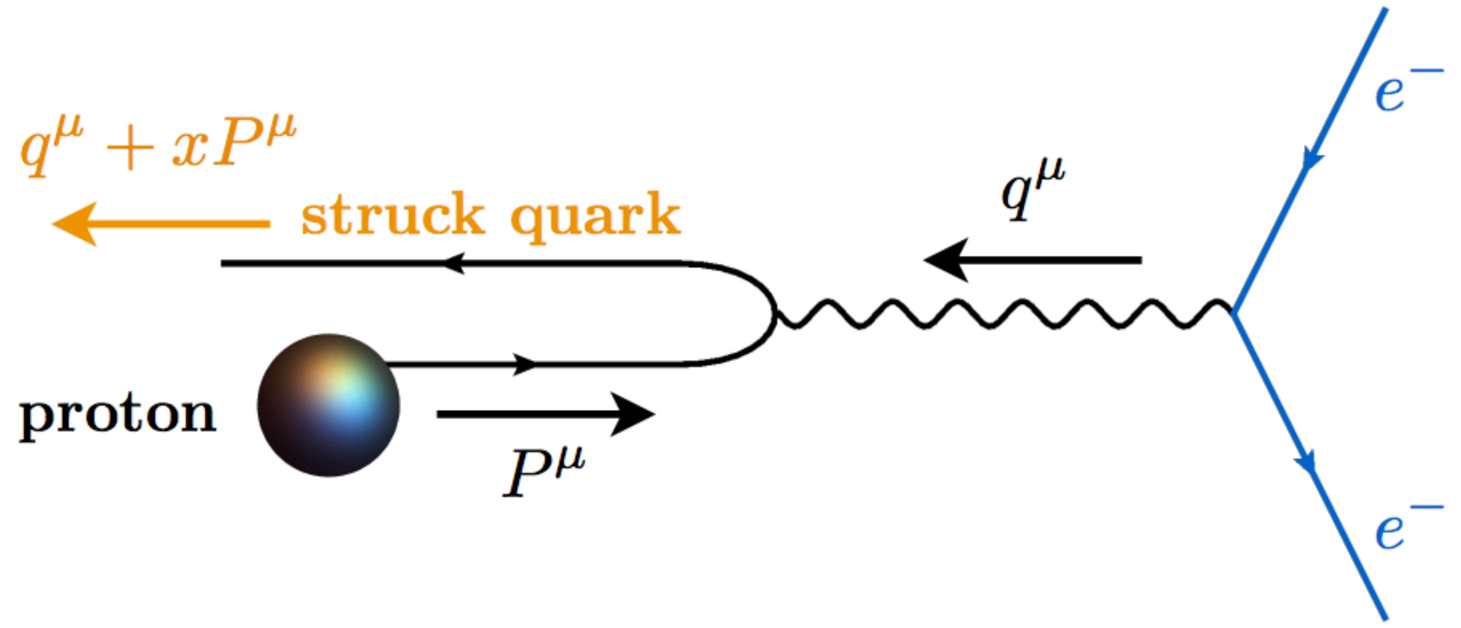
Fixed order calculations *de Florian, Borsa; Gehrmann et al.*

See Arratia, Makris, Neill, FR, Sato `20 Caucal, Iancu, Mueller, Yuan `24

Algorithm dependence

Breit frame

Spherically invariant algorithm (E_i, θ_{ij})



$$\frac{\mathrm{d}\sigma^{\mathrm{SI}}}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}z} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

Longitudinally invariant algorithm $(p_{Ti}, \Delta\eta + \Delta\phi)$

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

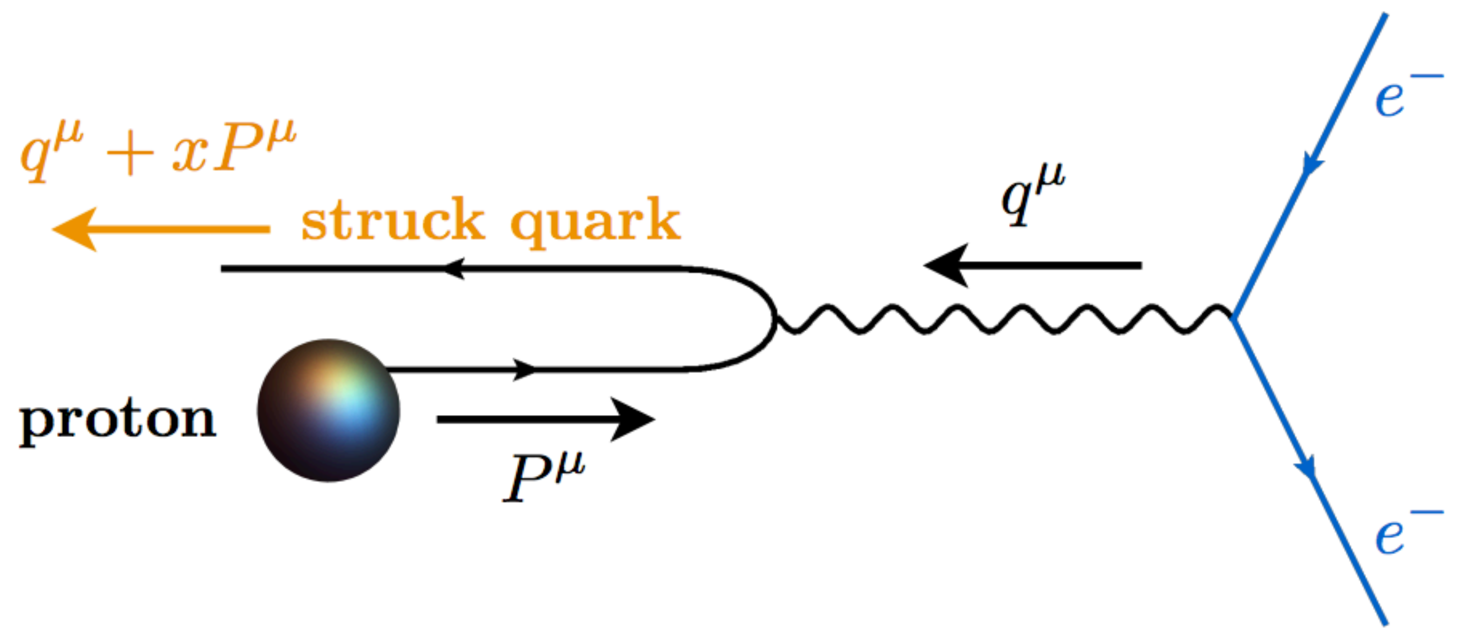
- Expect significant fraction of gluon jets

Fixed order calculations *de Florian, Borsa; Gehrmann et al.*

Algorithm dependence

Breit frame

Spherically invariant algorithm (E_i, θ_{ij})

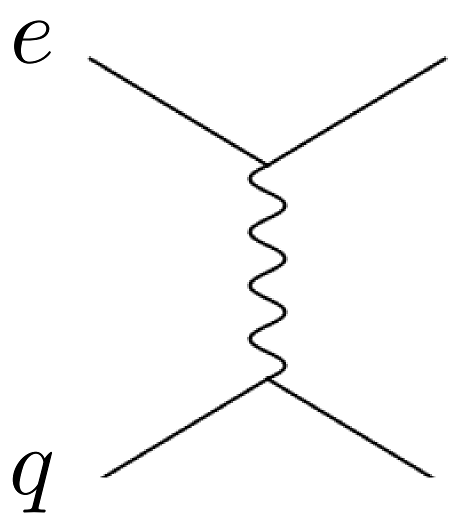


$$\frac{d\sigma^{\rm SI}}{dx_B dQ^2 dz} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b$$

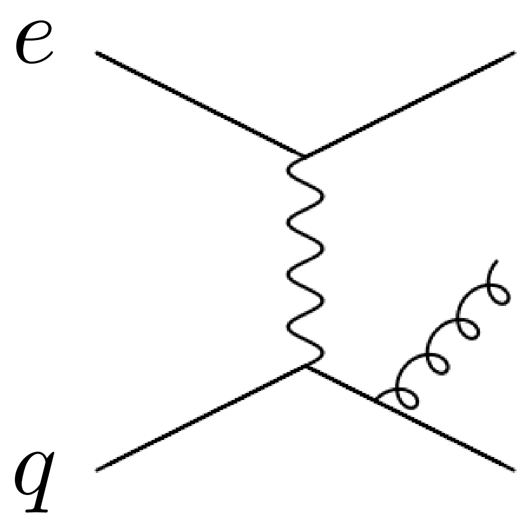
Longitudinally invariant algorithm $(p_{Ti}, \Delta\eta + \Delta\phi)$

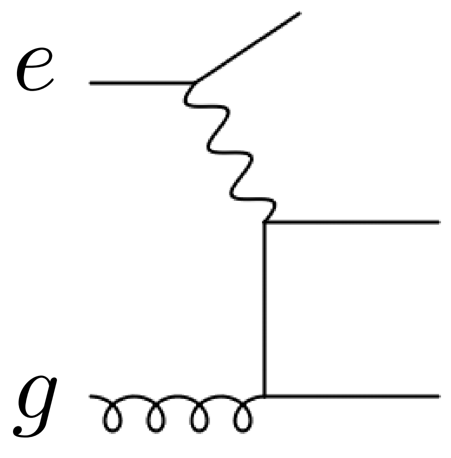
$$\frac{d\sigma^{\rm LI}}{dx_B dQ^2 dp_T d\eta} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b$$

Leading order



vs.





Algorithm dependence

Breit frame

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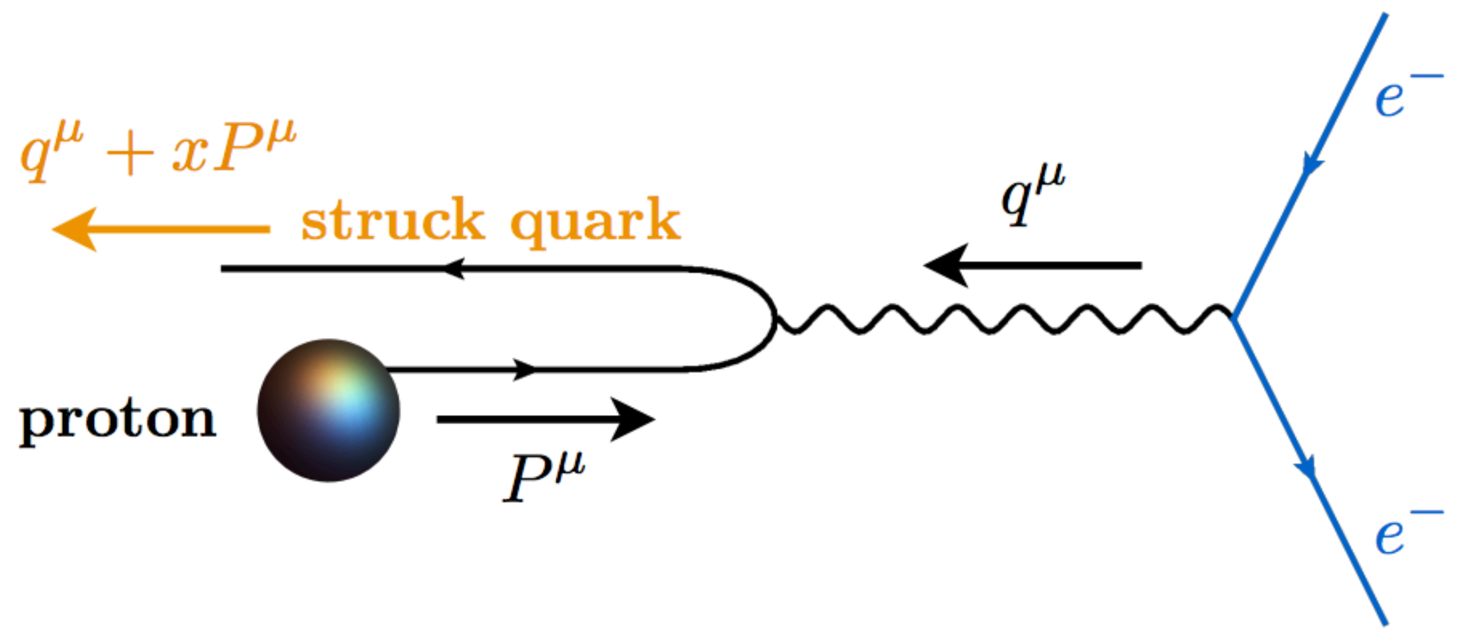

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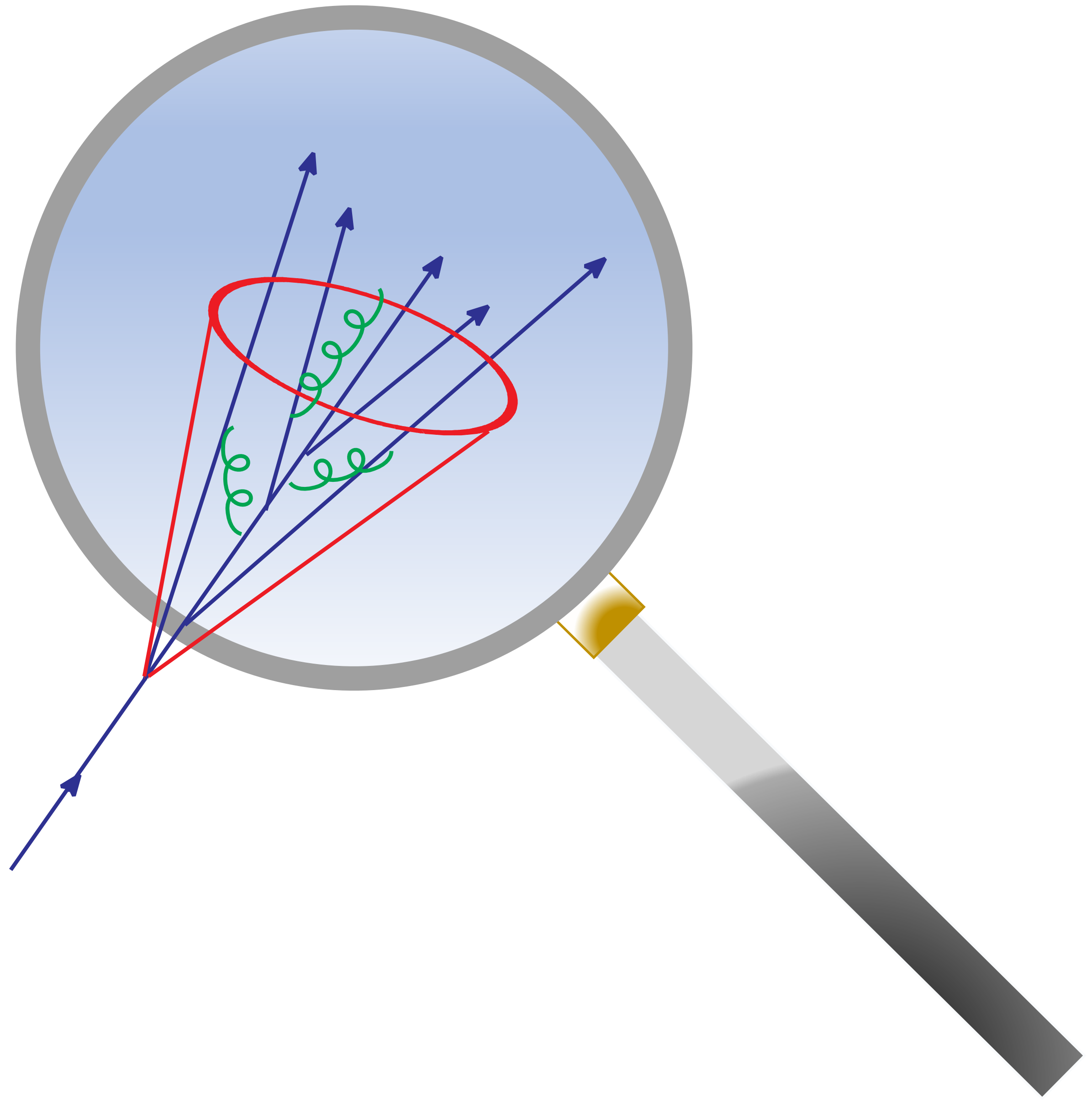
- Different than in proton-proton both are on equal footing!
- Systematically study quark/gluon differences *NieMiera, Lee, FR, Sato, Whitehill - in preparation*

Jet substructure

Breit frame

Spherically invariant algorithm (E_i, θ_{ij})

$$\frac{\mathrm{d}\sigma^{\mathrm{SI}}}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\tau} \sim \sum_{ab} f_a \otimes H_{ab} \otimes J_b(\tau)$$



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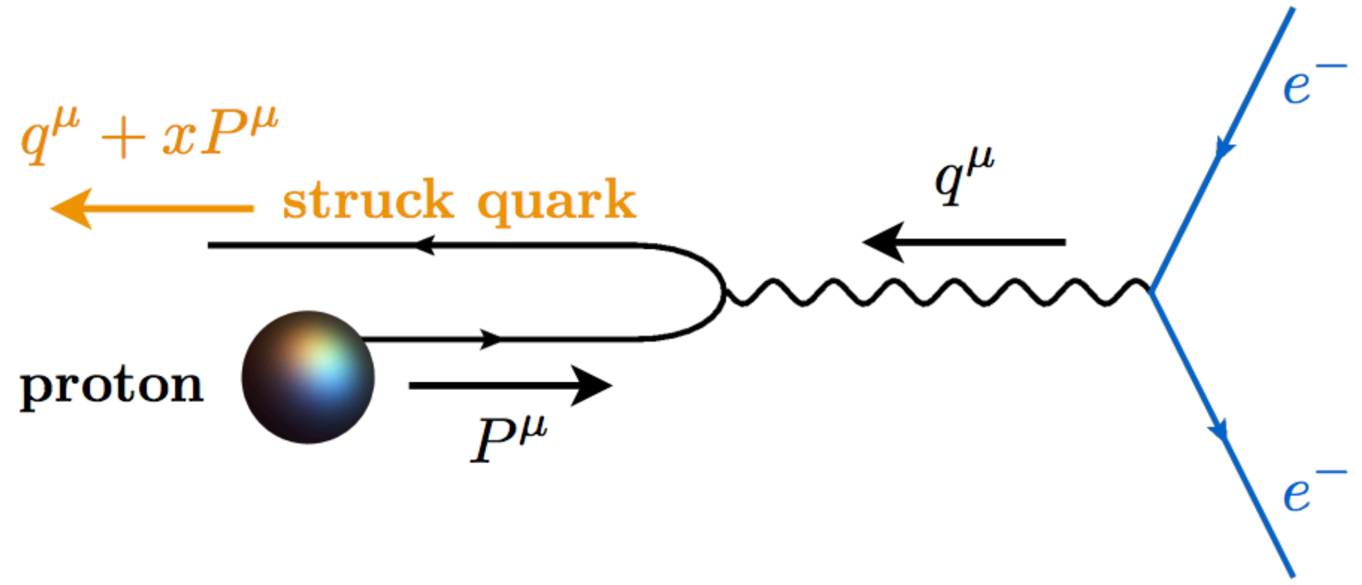
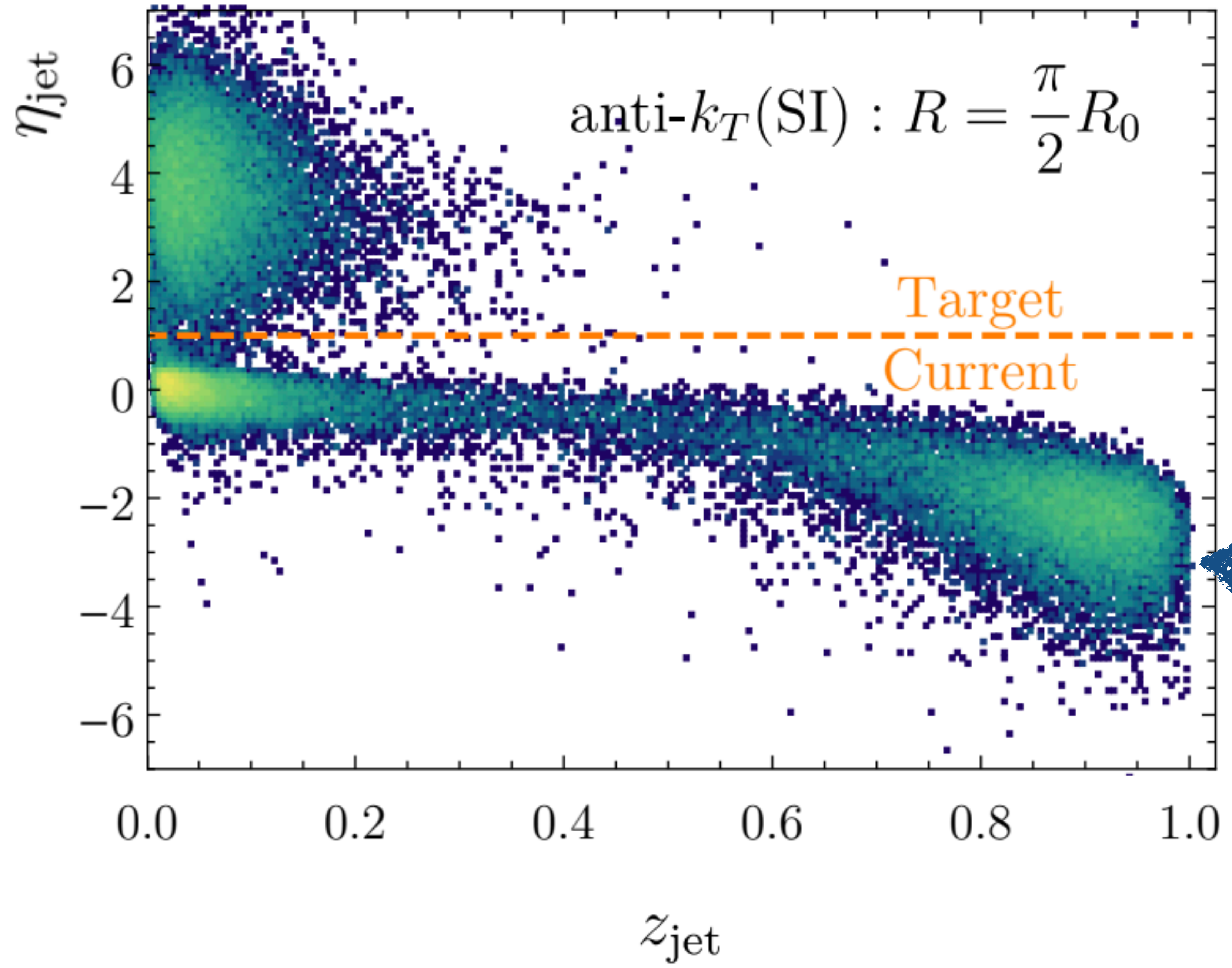
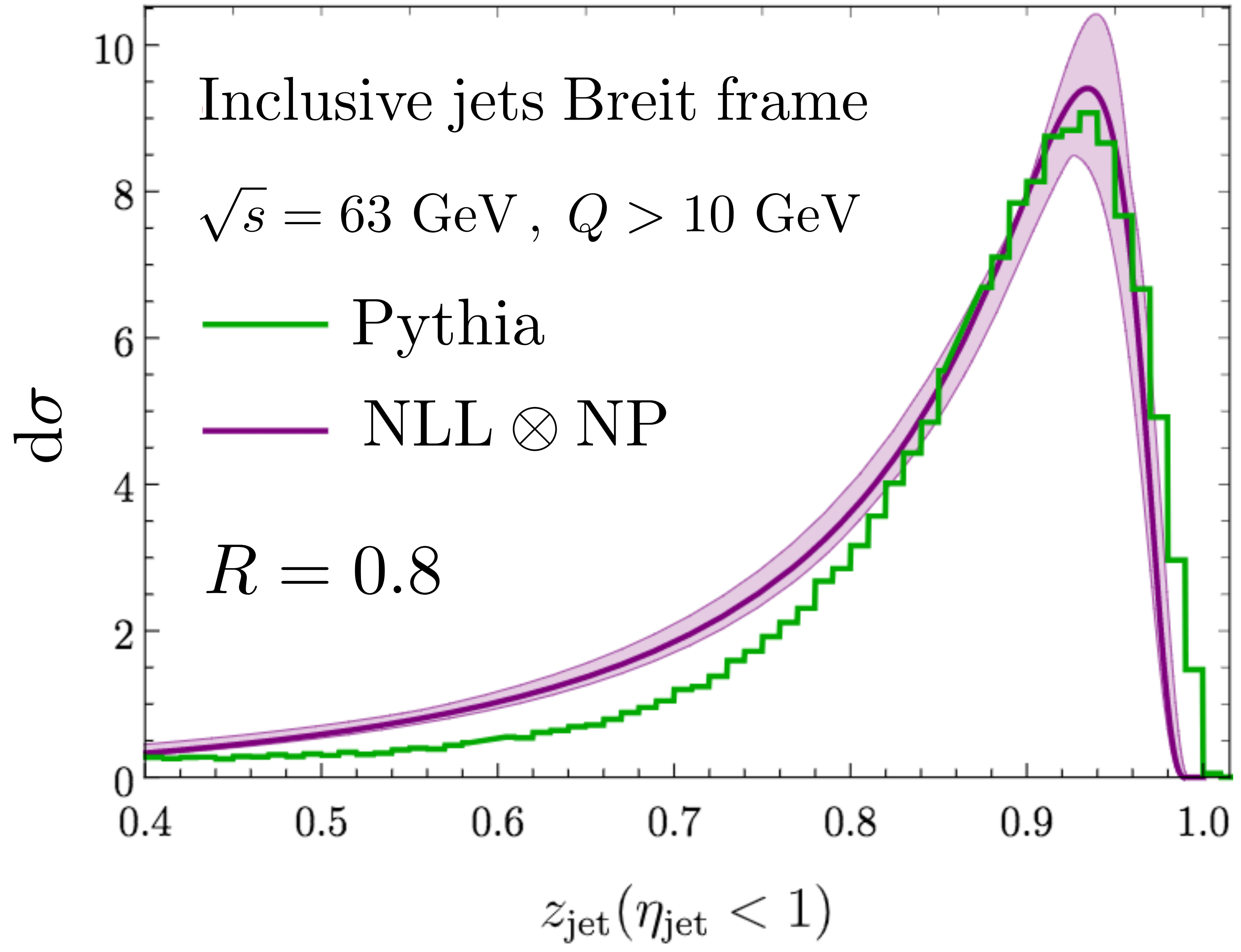
- Different than in proton-proton both are on equal footing!
- Systematically study quark/gluon differences *NieMiera, Lee, FR, Sato, Whitehill - in preparation*

Breit frame jets - I

- Spherically invariant jets (E_i, θ_{ij}) in the Breit frame
- Appears to cleanly separate the current and target fragmentation regions







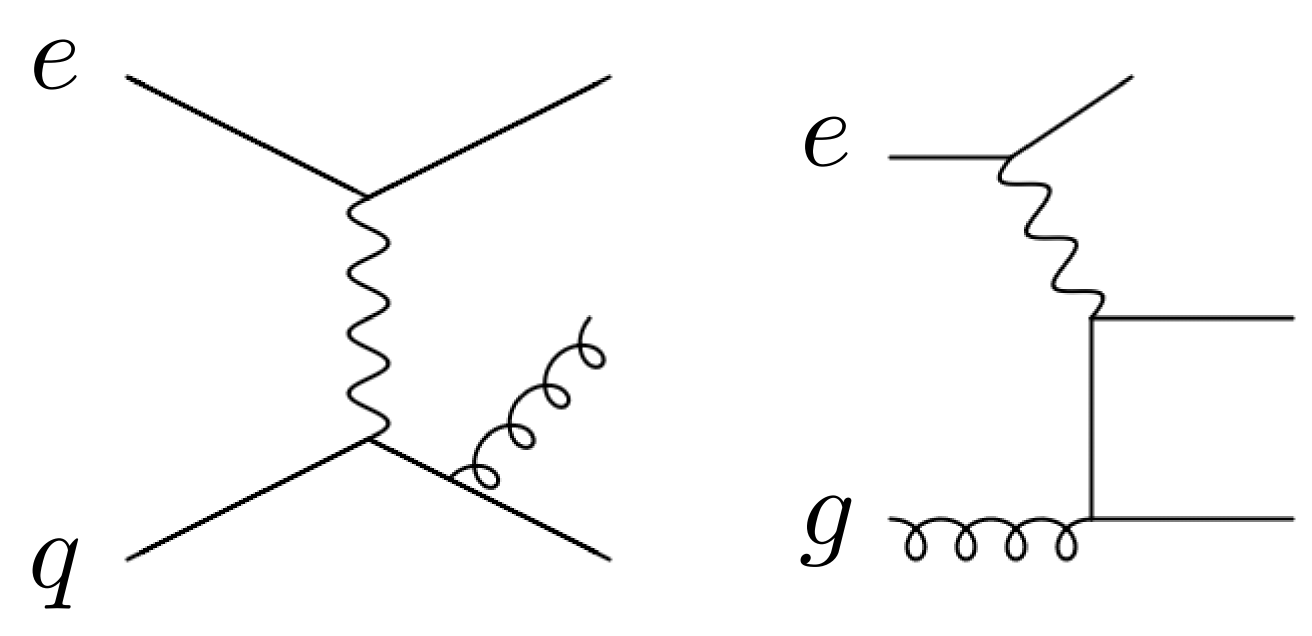
Arratia, Makris, Neill, FR, Sato `18

Can be measured at HERA?

Breit frame jets - II

- Longitudinally invariant jet algorithm

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



Hard functions known at NLO

Daleo, de Florian, Sassot `05
Wang, Gonzalez, Rogers, Sato `19

→ Use Mellin space implementation to convolve with jet functions

→ Problems due to functional form of $\mathcal{H}, J$

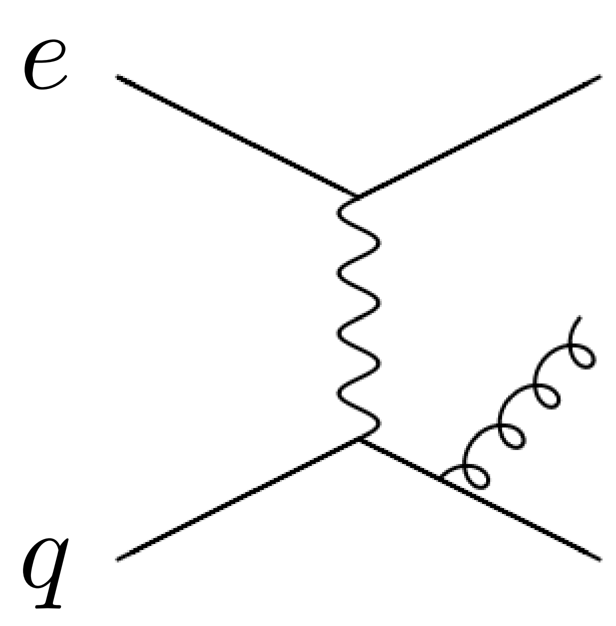
Breit frame jets - II

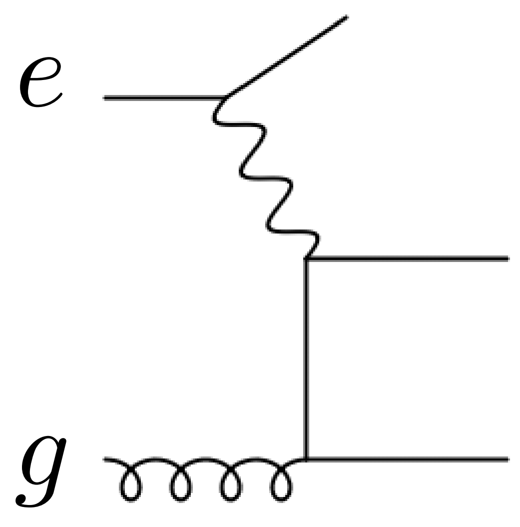
NieMiera, Lee, FR, Sato, Whitehill - in preparation

- Longitudinally invariant jet algorithm

  Via Mellin space:

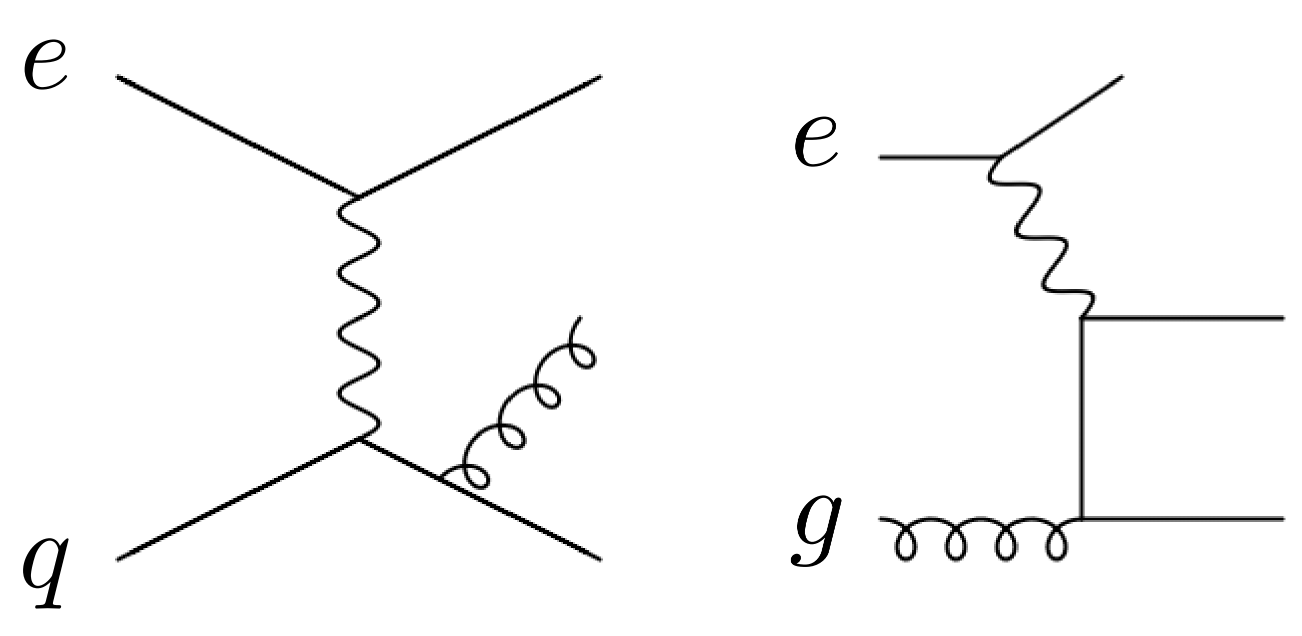
$$\int_{z_0}^{1} \mathrm{d}z\, \mathcal{H}(z) J(z)$$
$$= \int_{z_0}^{1} \mathrm{d}z\, (\mathcal{H}(z) - \mathcal{H}(1)) J(z) + \mathcal{H}(1) \int_{z_0}^{1} \mathrm{d}z\, J(z)$$





Breit frame jets - II

NieMiera, Lee, FR, Sato, Whitehill
- in preparation



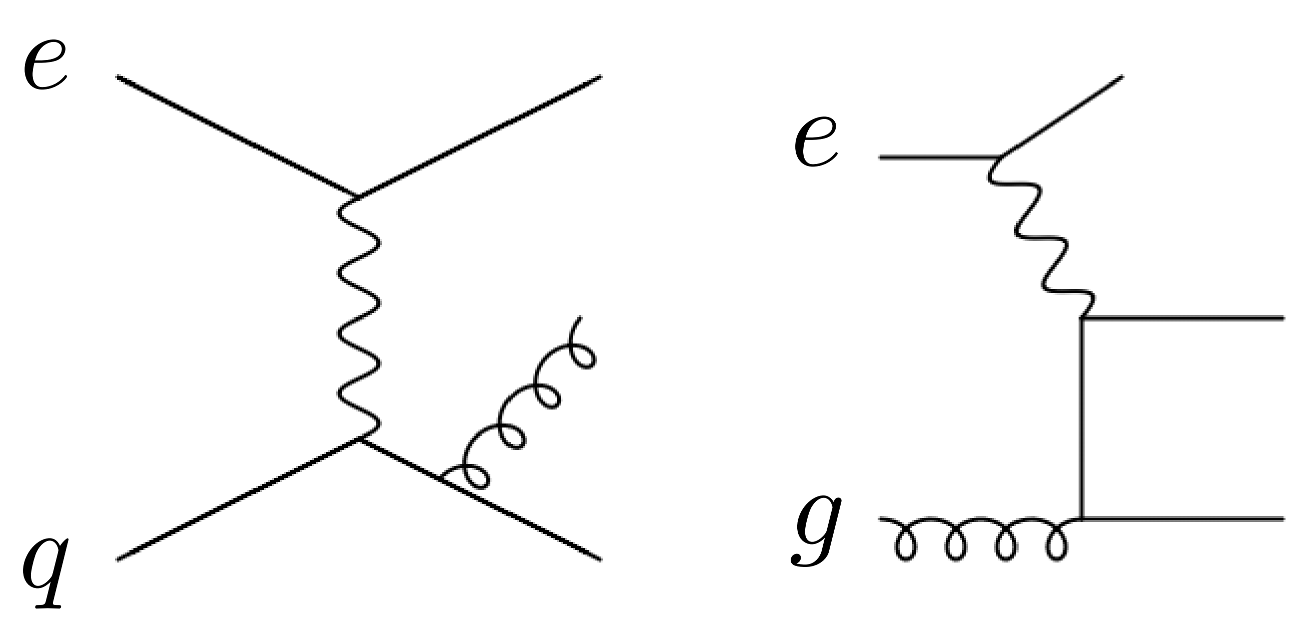
- Longitudinally invariant jet algorithm

  Via Mellin space:

$$
\begin{aligned}
&\int_{z_0}^{1} \mathrm{d}z\, \mathcal{H}(z) J(z) \\
&= \int_{z_0}^{1} \mathrm{d}z\, (\mathcal{H}(z) - \mathcal{H}(1)) J(z) + \mathcal{H}(1) \int_{z_0}^{1} \mathrm{d}z\, J(z) \\
&= \frac{1}{2\pi i} \int \mathrm{d}N J(N) \int_{z_0}^{1} \mathrm{d}z\, z^{-N} (\mathcal{H}(z) - \mathcal{H}(1)) + \mathcal{H}(1) \int_{z_0}^{1} \mathrm{d}z\, J(z)
\end{aligned}
$$

Breit frame jets - II

NieMiera, Lee, FR, Sato, Whitehill - in preparation



- Longitudinally invariant jet algorithm

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$$\int_{z_0}^{1} \mathrm{d}z\, \mathcal{H}(z) J(z)$$
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$$= \frac{1}{2\pi i} \int \mathrm{d}N J(N) \int_{z_0}^{1} \mathrm{d}z\, z^{-N} (\mathcal{H}(z) - \mathcal{H}(1)) + \mathcal{H}(1) \int_{z_0}^{1} \mathrm{d}z\, J(z)$$
$$= \frac{1}{2\pi i} \int \mathrm{d}N J(N) T(N) + \mathcal{H}(1) \int_{z_0}^{1} \mathrm{d}z\, J(z)$$

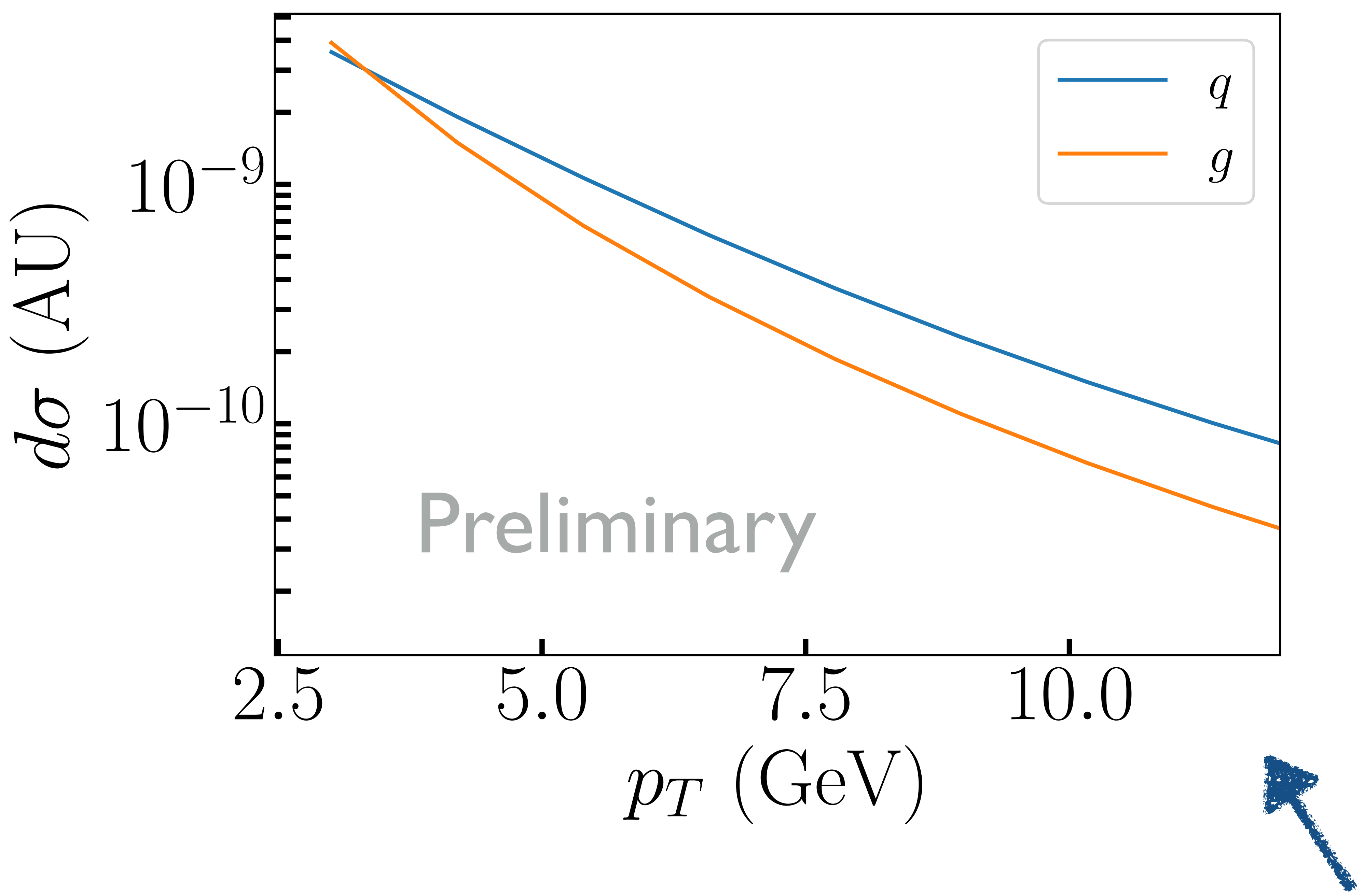
Evaluate numerically, Mellin grid

Turn into Mellin space expression

Breit frame jets - II

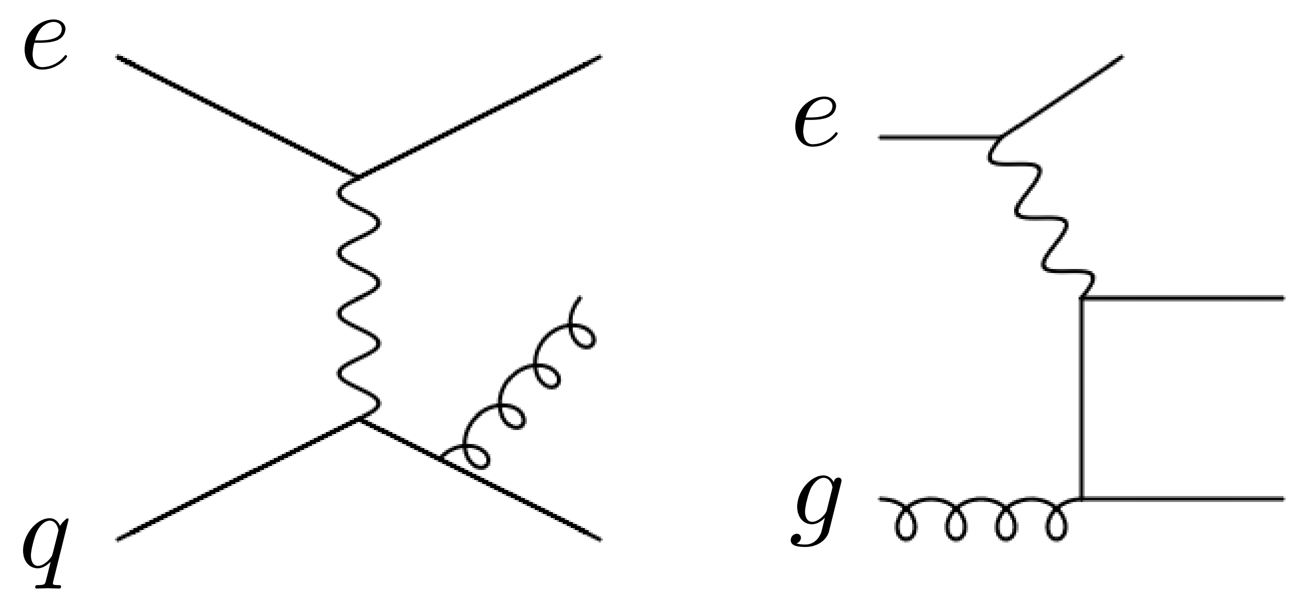
NieMiera, Lee, FR, Sato, Whitehill - in preparation

- Longitudinally invariant jet algorithm



$\sqrt{s} = 140$ GeV

$R = 0.7$

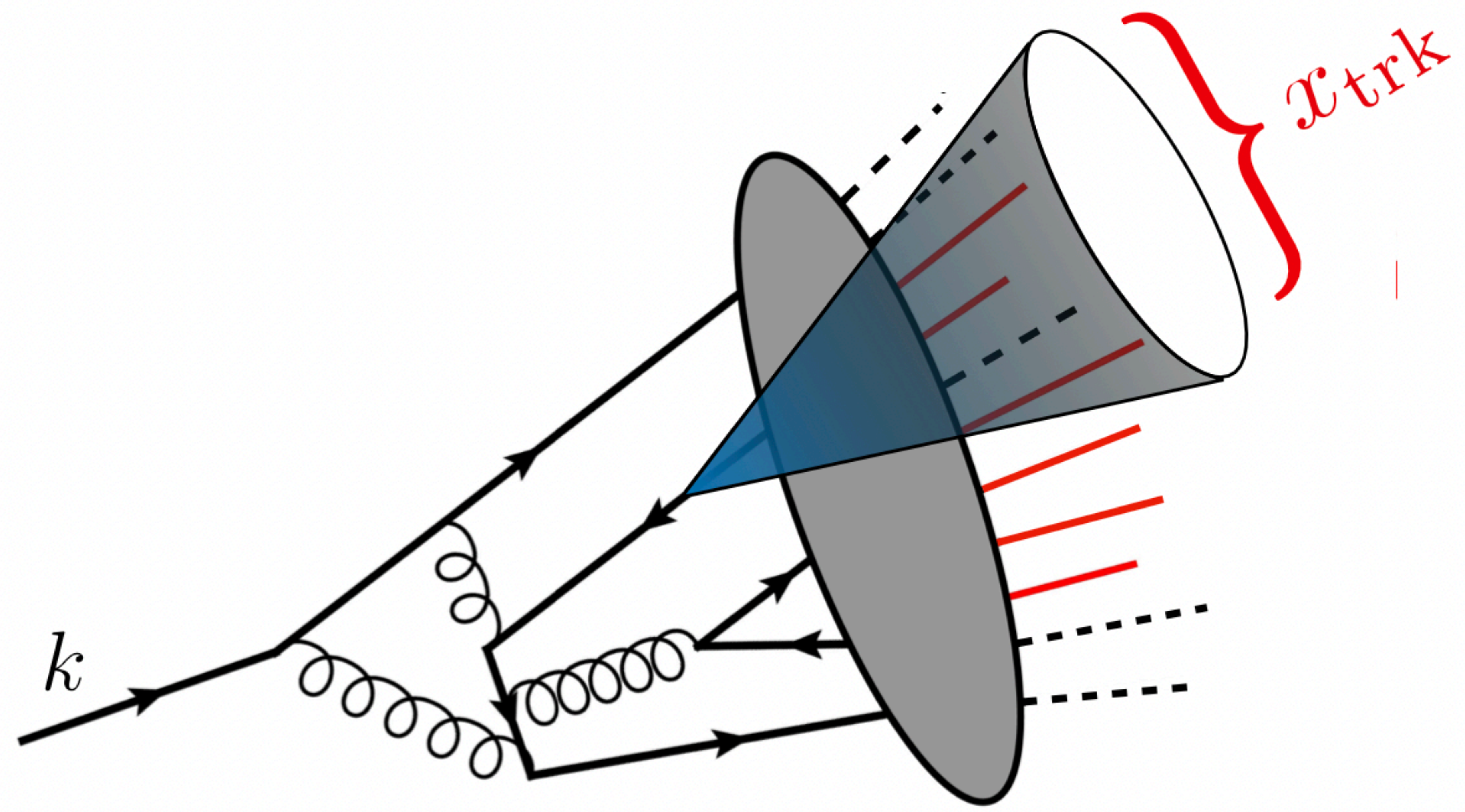


- Note the different functional form compared Breit frame jets - I even though the jet functions are the same

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



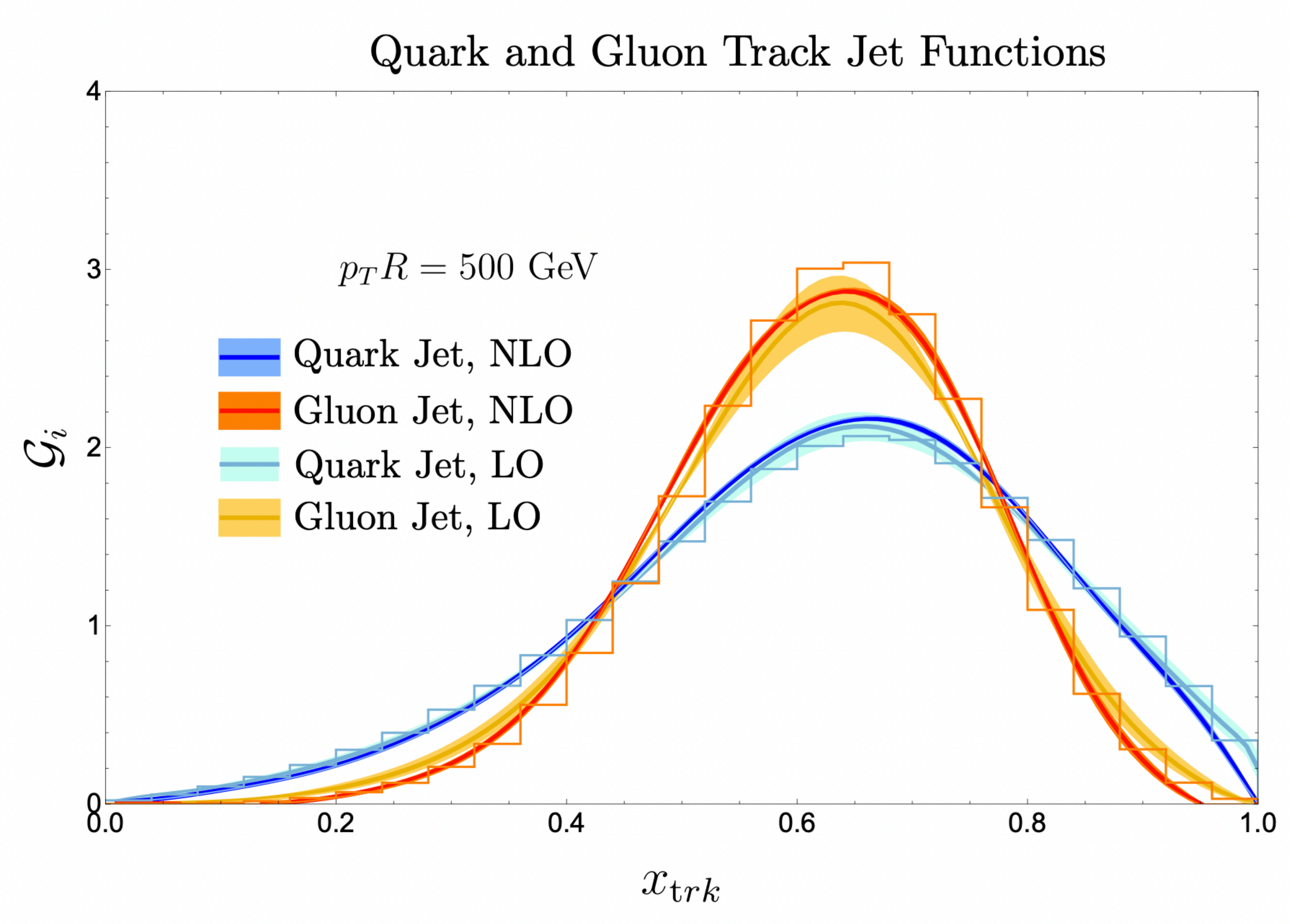
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2} T_i(x) = a_s \left[K^{(0)}_{i\to i} T_i + K^{(0)}_{i\to i_1 i_2} \otimes T_{i_1} T_{i_2} \right](x)$$
$$+ a_s^2 \left[K^{(1)}_{i\to i} T_i + K^{(1)}_{i\to i_1 i_2} \otimes T_{i_1} T_{i_2} + K^{(1)}_{i\to i_1 i_2 i_3} \otimes T_{i_1} T_{i_2} T_{i_3} \right](x)$$

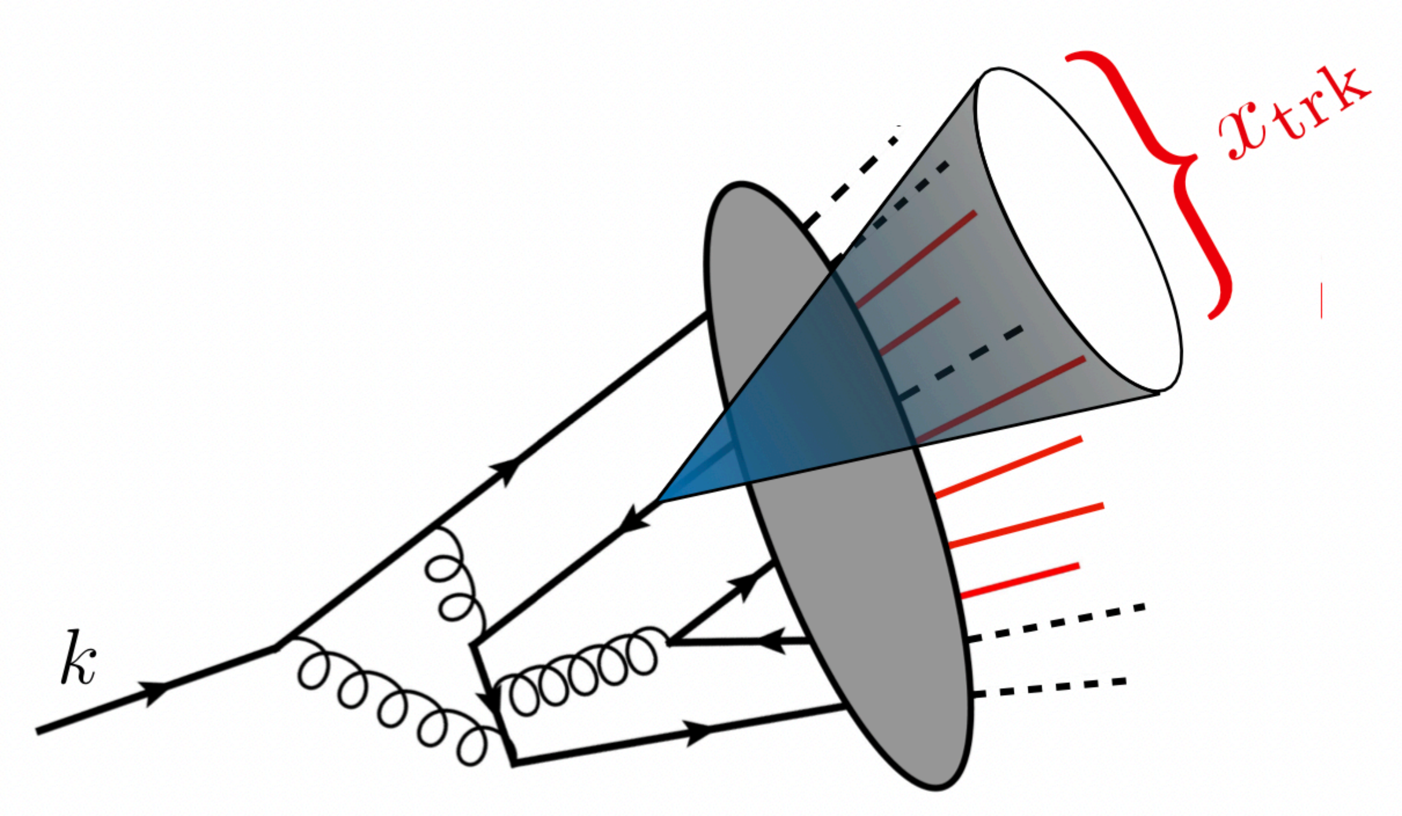
Chen, Jaarsma, Li, Moult, Waalewijn, Zhu `22

Quark gluon differences

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

- Charged particle momentum fraction of the jet



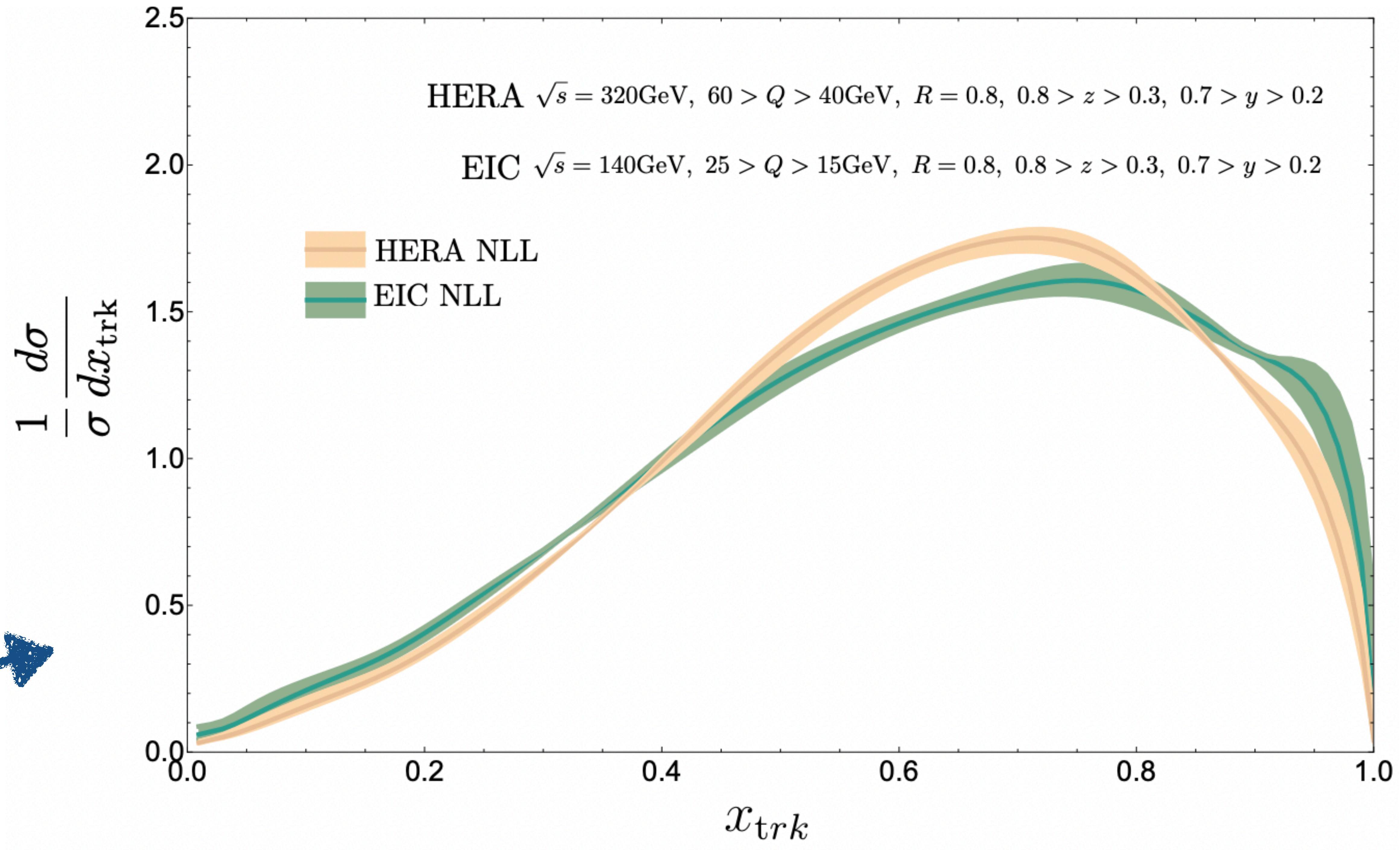


Breit frame - I: Jet substructure

Lee, Moult, FR, Waalewijn `23

- Charged particle momentum fraction of the jet
- EIC can constrain flavor dependence

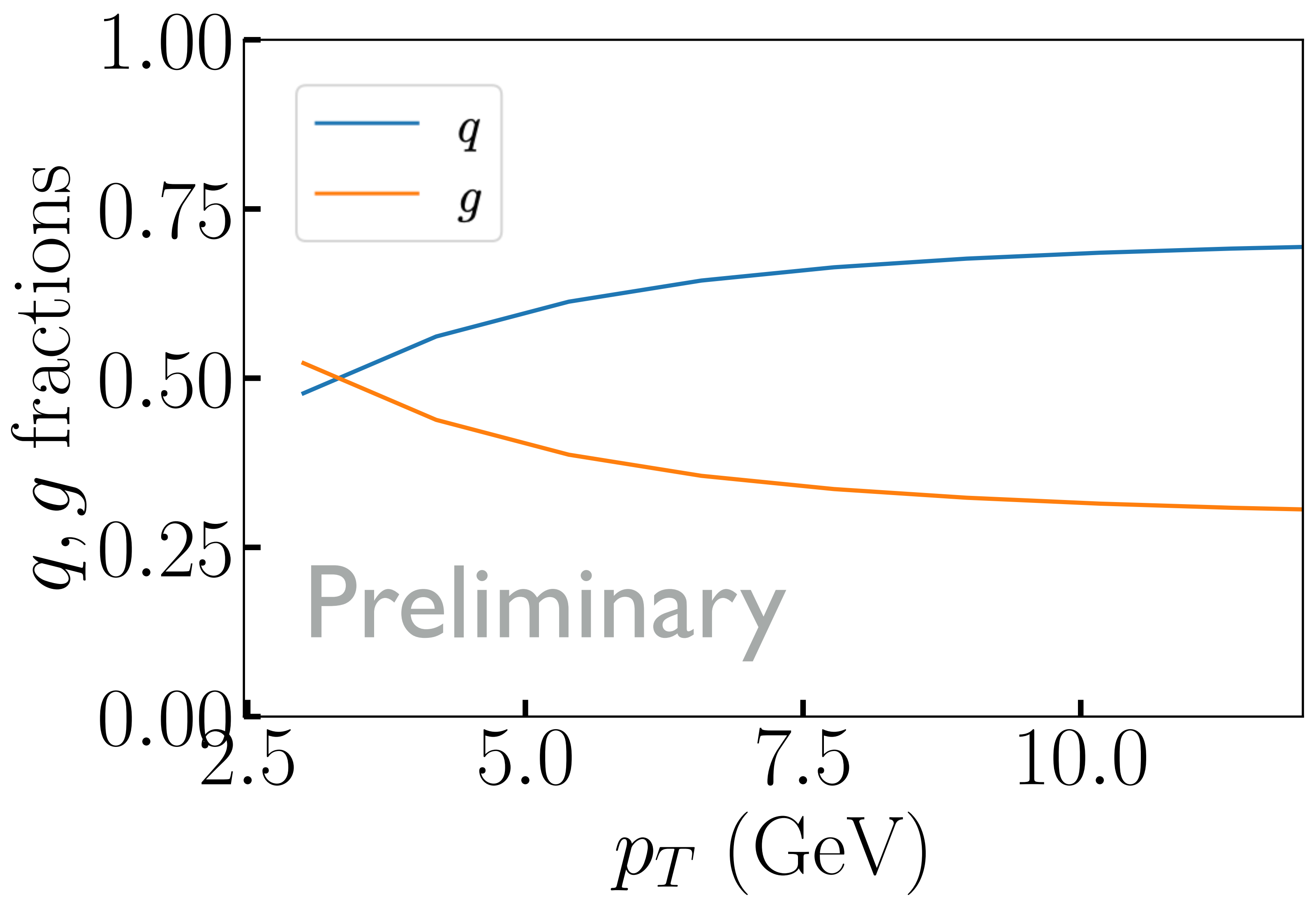
Small QCD scale uncertainty

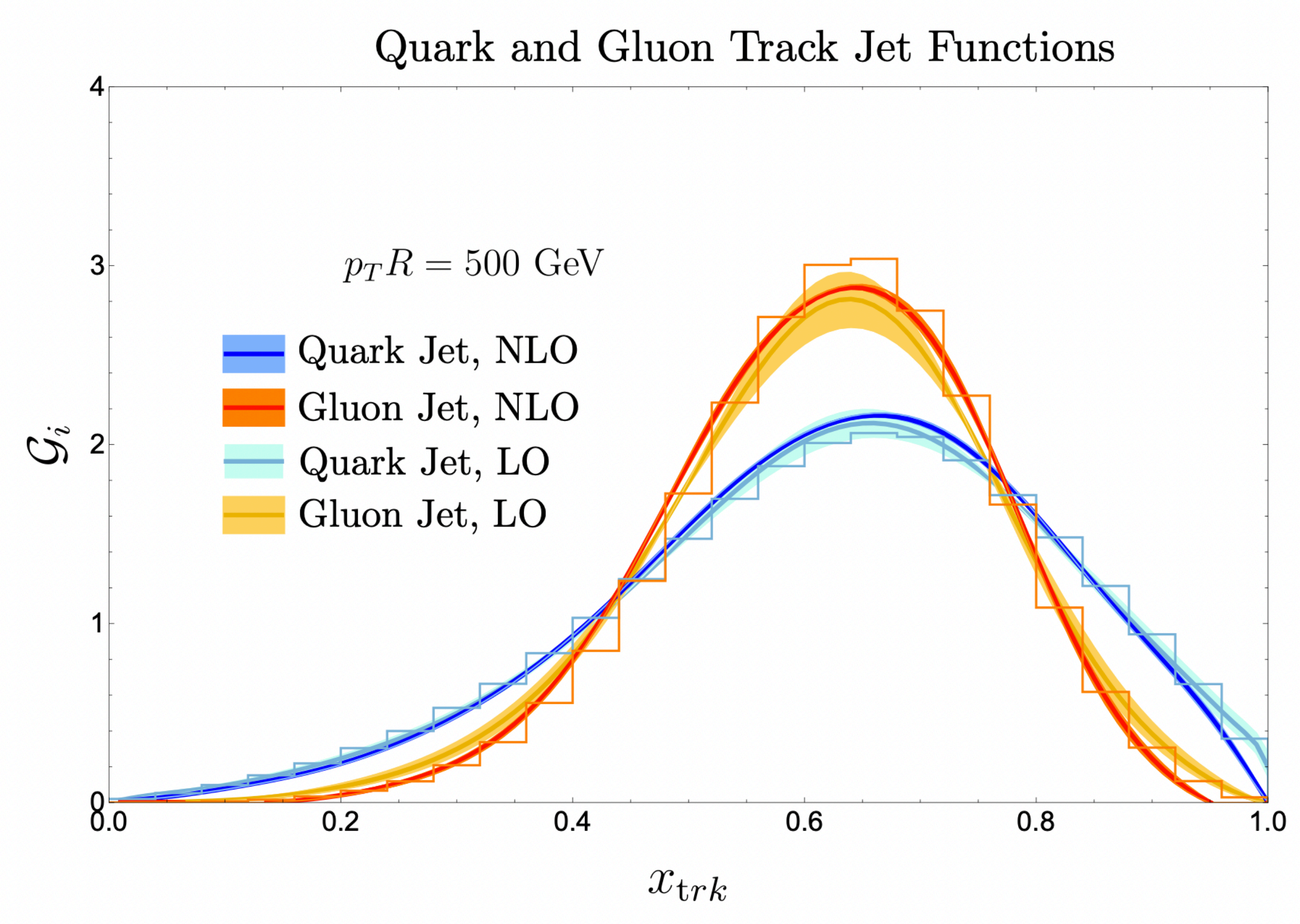


Breit frame - II: Jet substructure

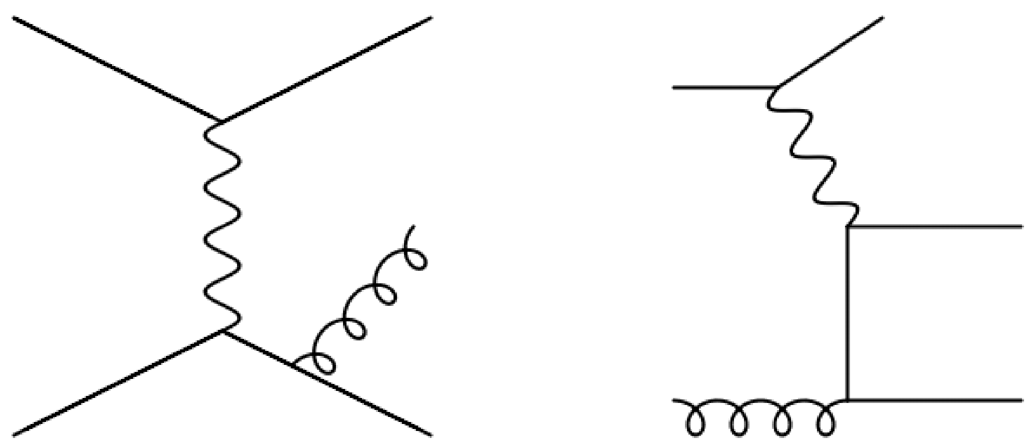
NieMiera, Lee, FR, Sato, Whitehill
- in preparation

- Significant fraction of gluon jets
- Improve understanding of low energy gluon jets
- Improve constraints on the initial state





Weighted average



Summary

- Jets will be versatile tools at the EIC
- Algorithm and frame dependence
- Clean environment at the EIC
- Study impact on hadron structure
- Disentangle Cold Nuclear Matter effects