Disentangling quark and gluon jets in the Breit frame

Felix Ringer

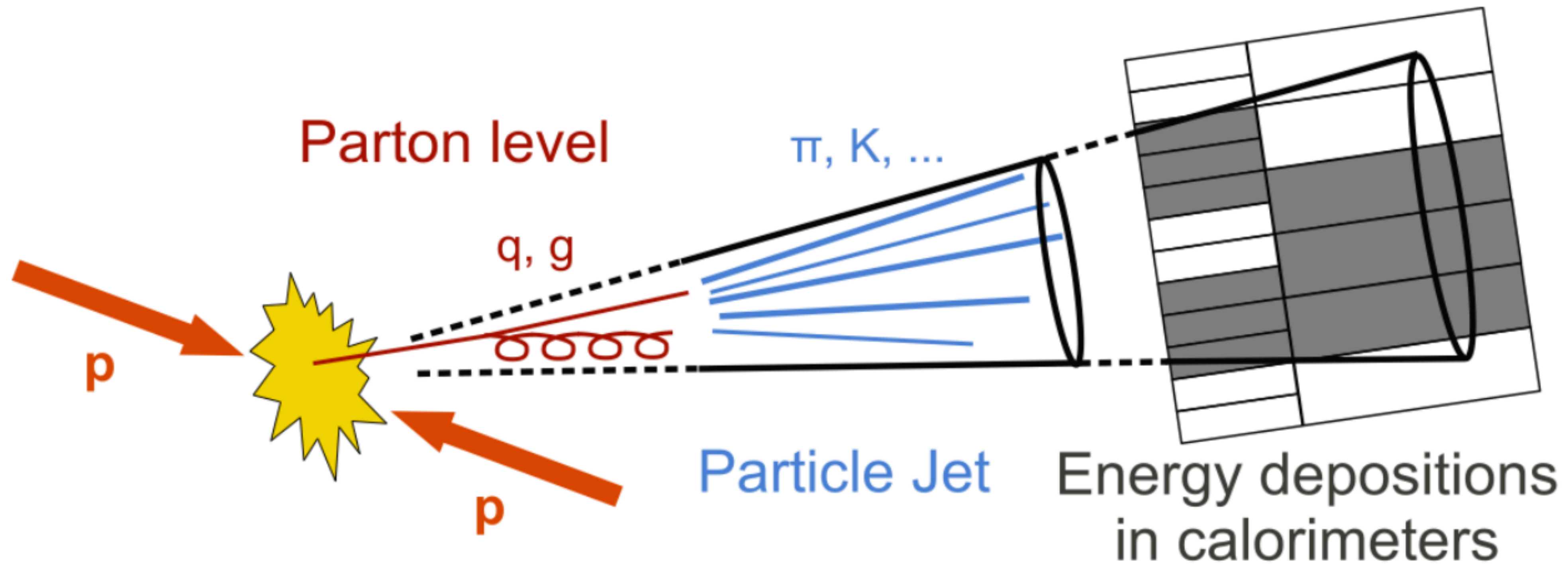
In collaboration with Alexis NieMiera, Kyle Lee, Nobuo Sato, Richard Whitehill

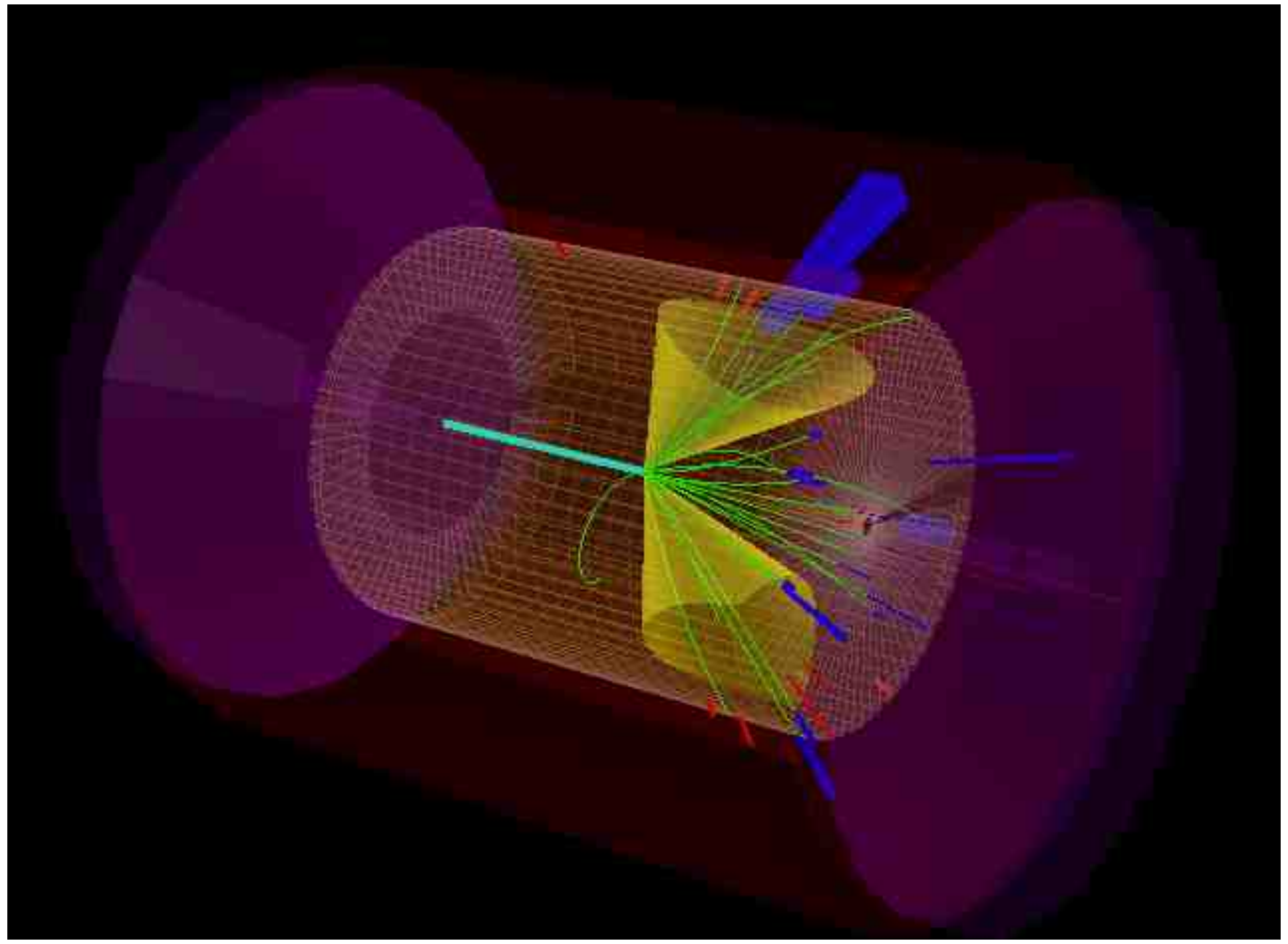
Physics Opportunities at an Electron-Ion Collider XI
Florida International University, Miami, 02/28/2025

Stony Brook University

EIC jet physics

- Direct signature of high-energy quarks & gluons
- Relevant for hadron structure, cold nuclear matter effects, etc.
- Clean EIC environment
- Versatile jet reconstruction algorithms & frame dependence

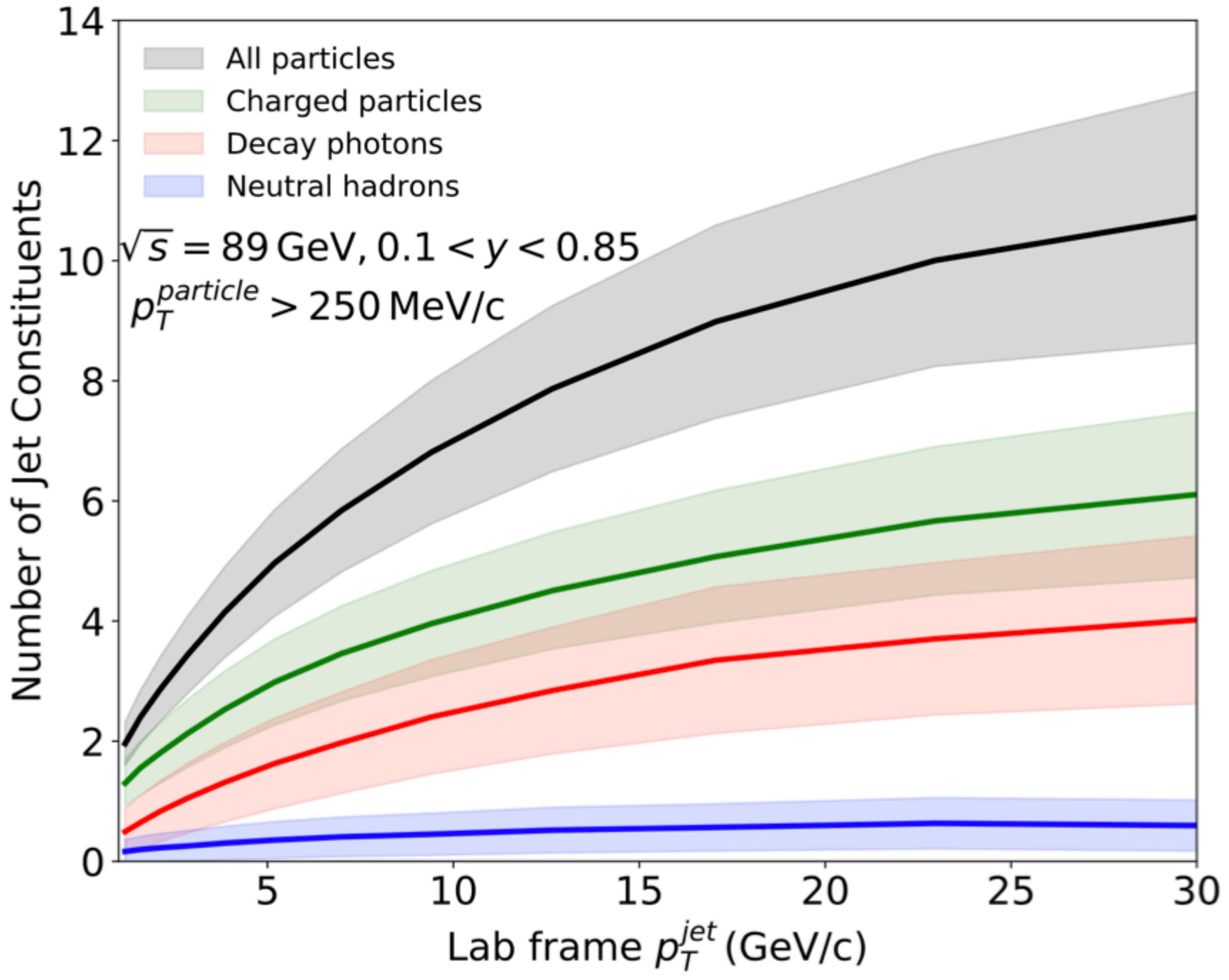




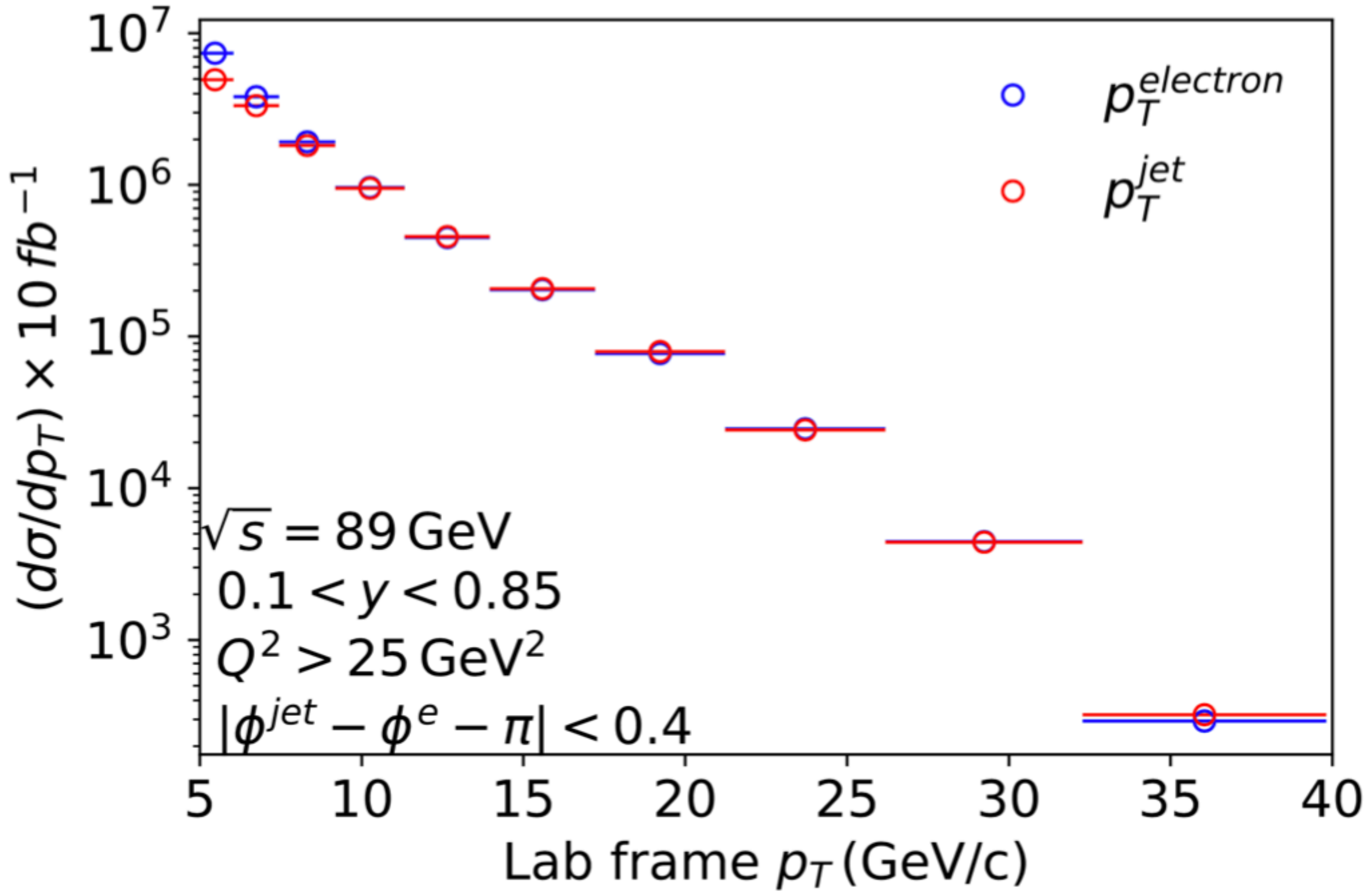
see also Ivan Vitev, Roli Esha and Brian Page's talks

Nature of jets at the EIC

Particle #

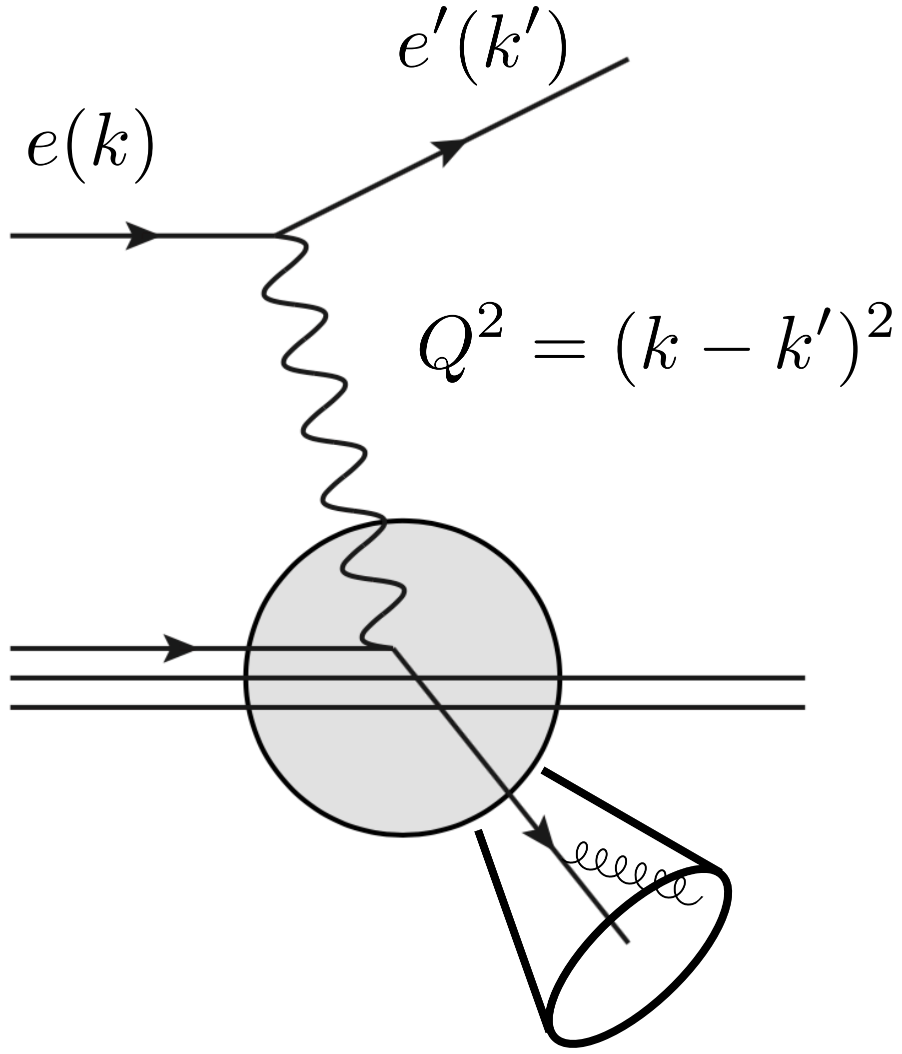


Transverse momentum



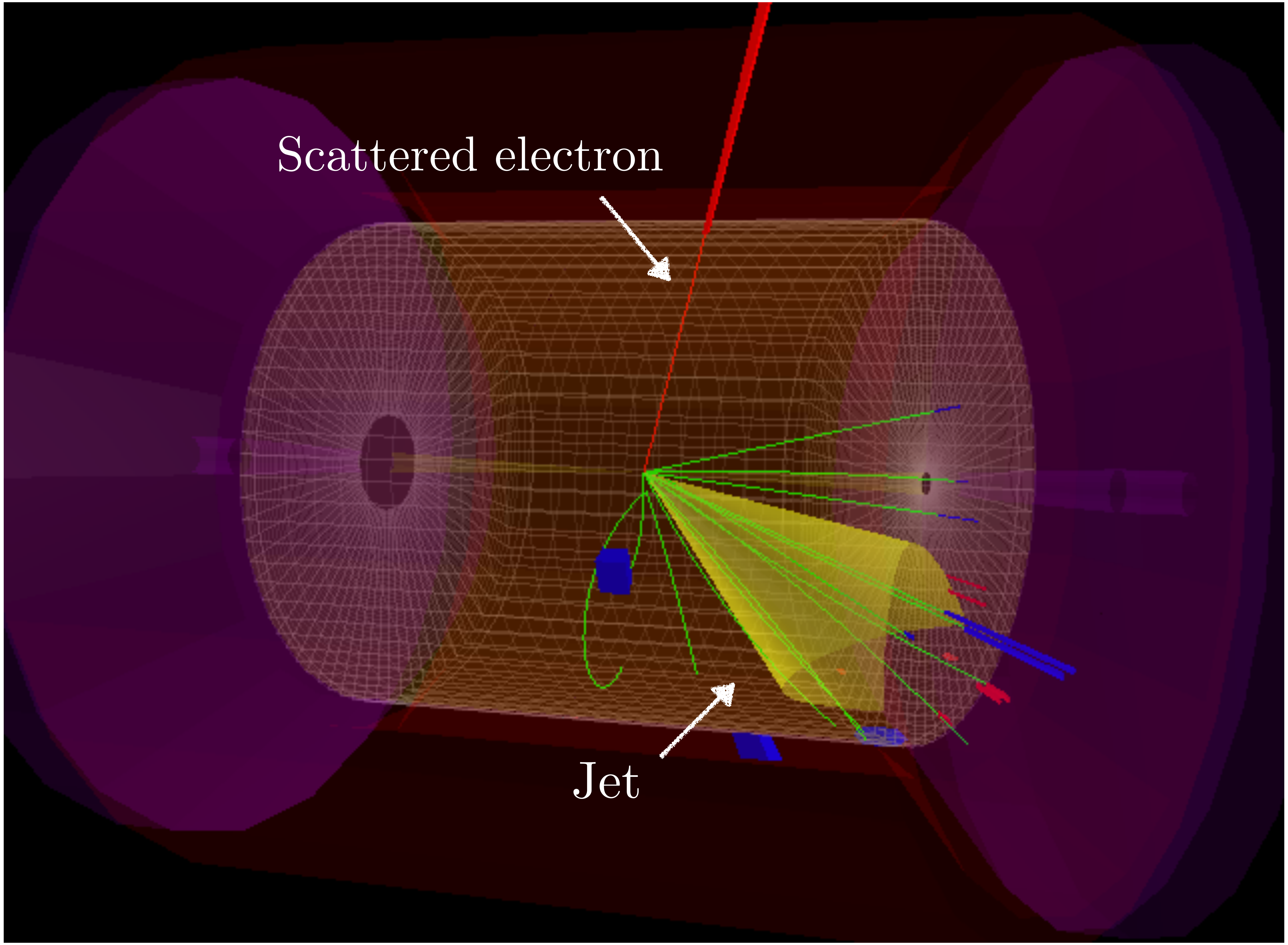
Two “natural” hard scales

- Jet transverse momentum p_T
- Photon virtuality Q^2



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

Laboratory frame



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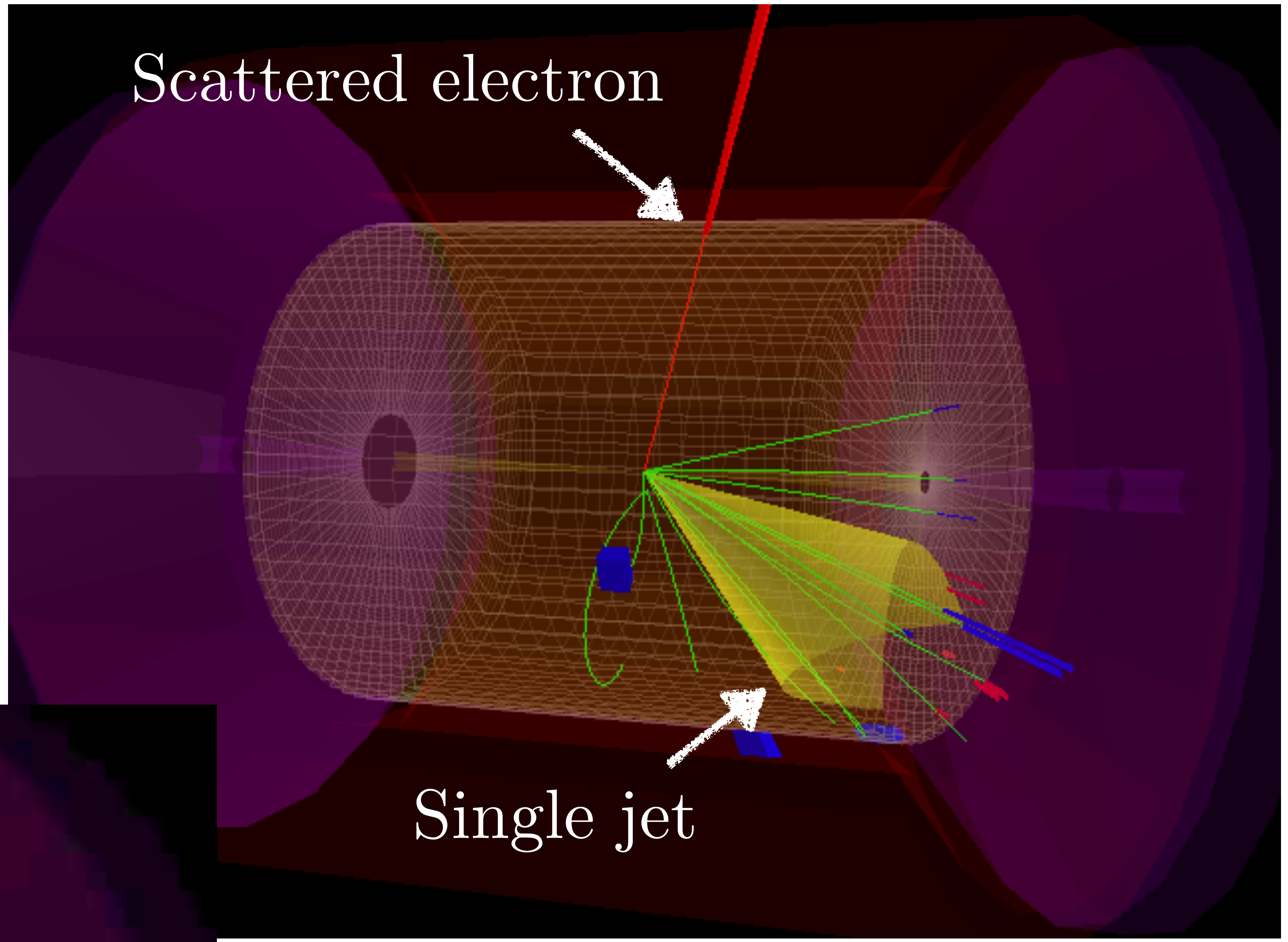
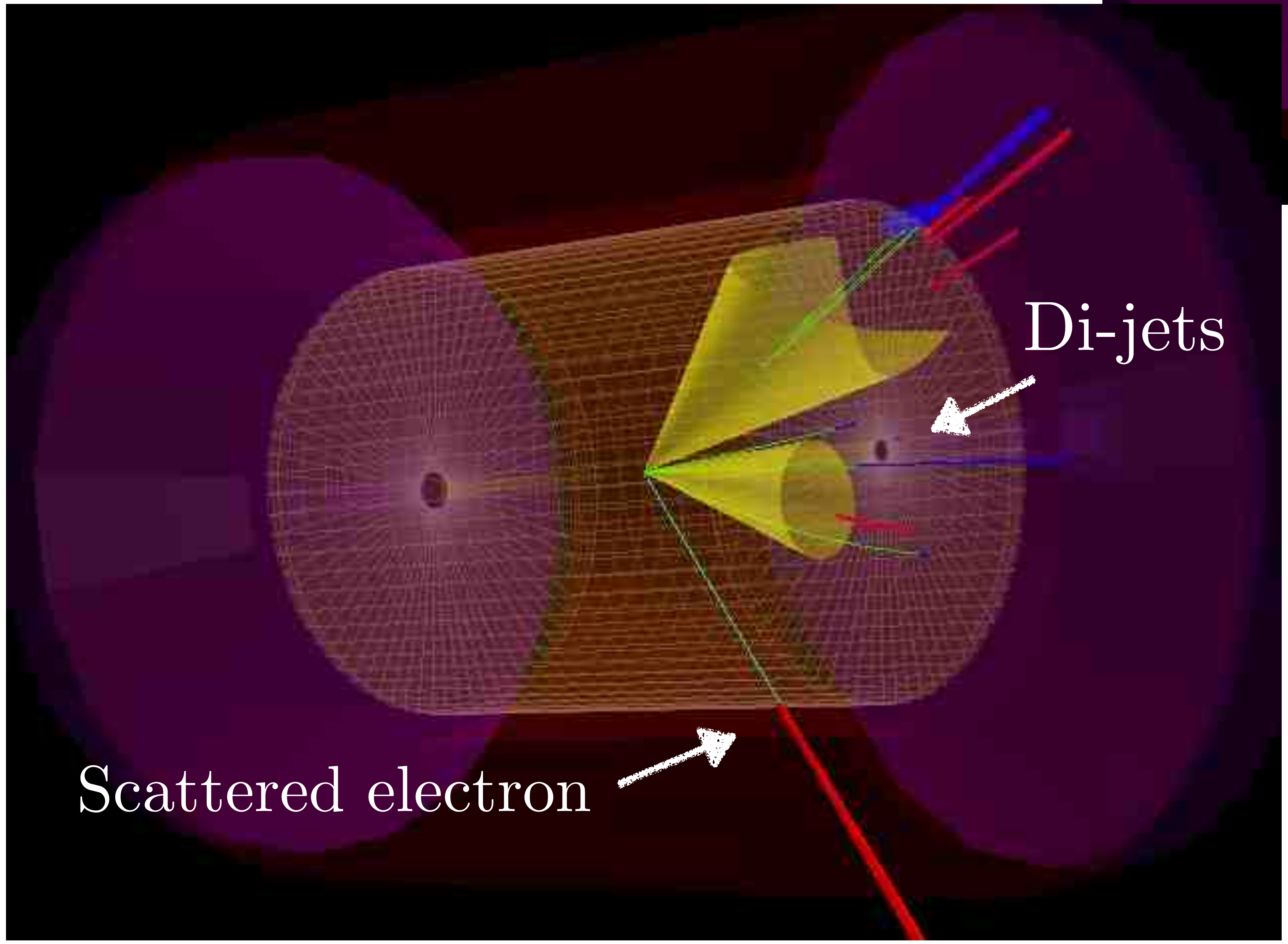
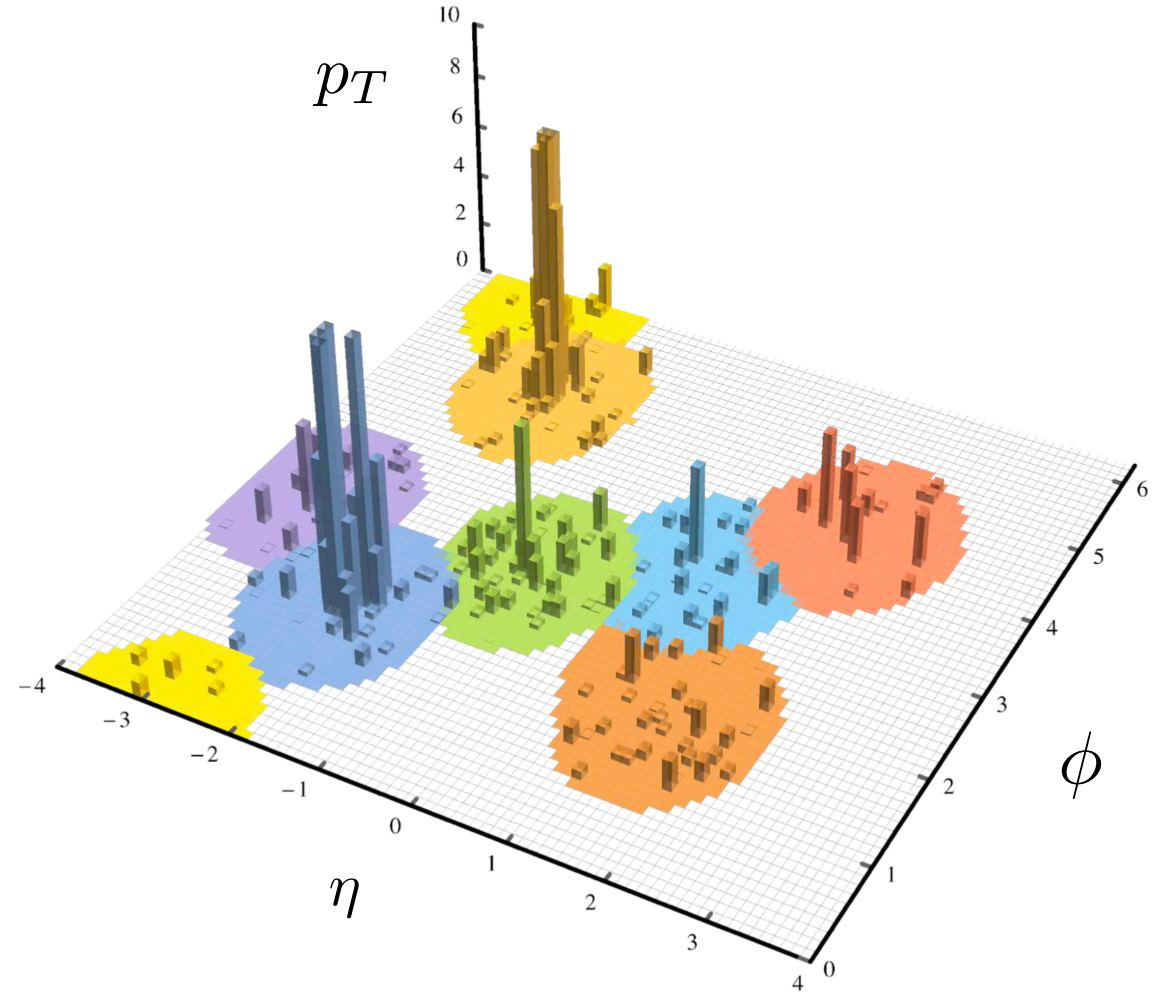




- Cf. proton-proton: jets vs. Z+jet
- Different quark/gluon fractions

Jet algoritms



Longitudinal algorithm

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 algorithm

Angles and energies

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

e^+e^- or Breit frame

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

Frame & jet algorithm dependence

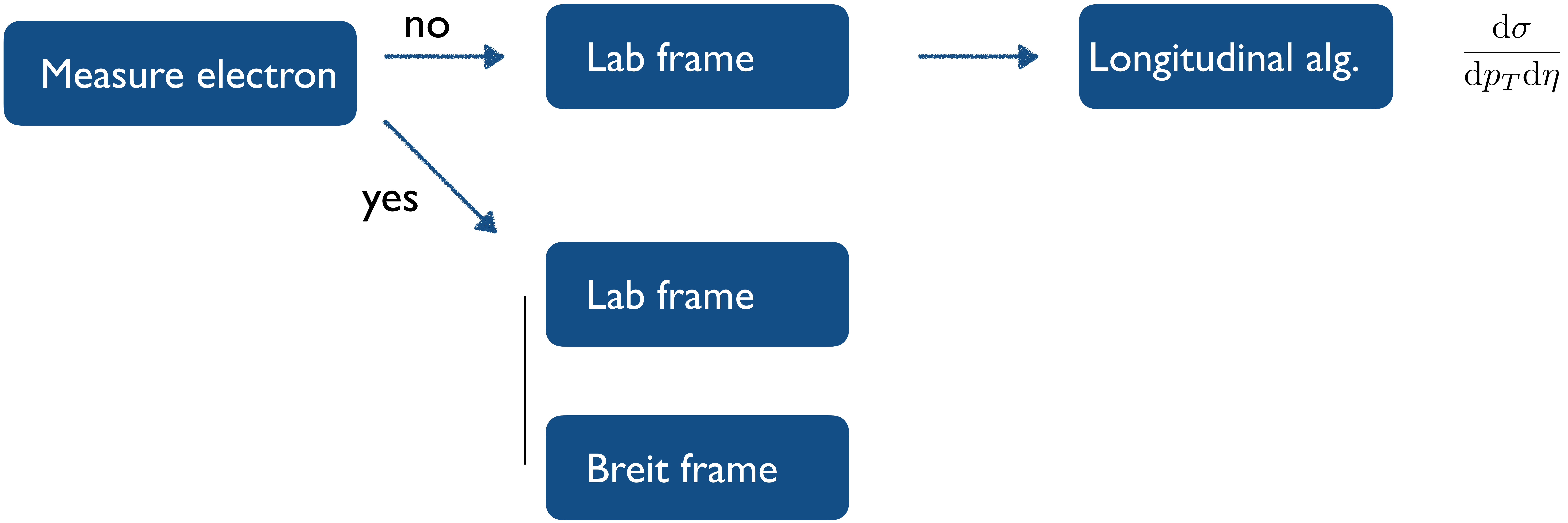
Measure electron → no → Lab frame → Longitudinal alg. $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta}$

e.g. twist-3 Vogelsang et al.

Q^2 small or large

see also asymmetric Centauro algorithm Makris et al.

Frame & jet algorithm dependence



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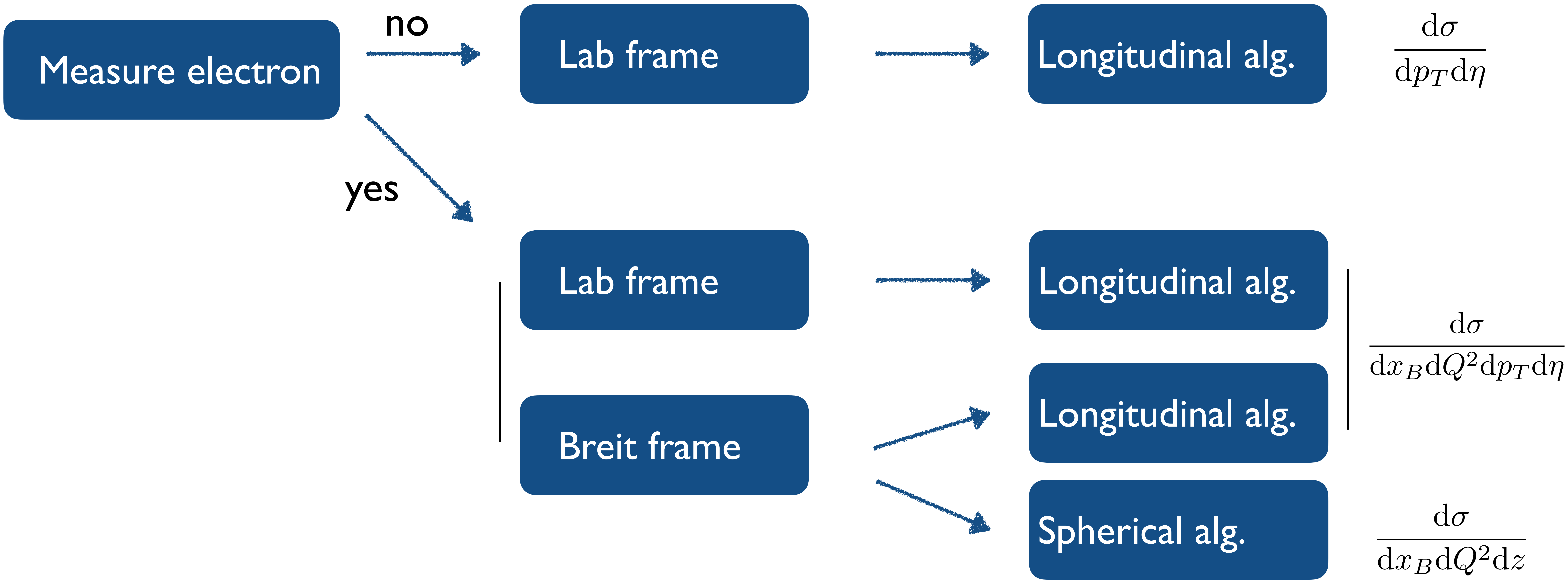

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Frame & jet algorithm dependence

Q^2 small or large

see also asymmetric Centauro algorithm Makris et al.

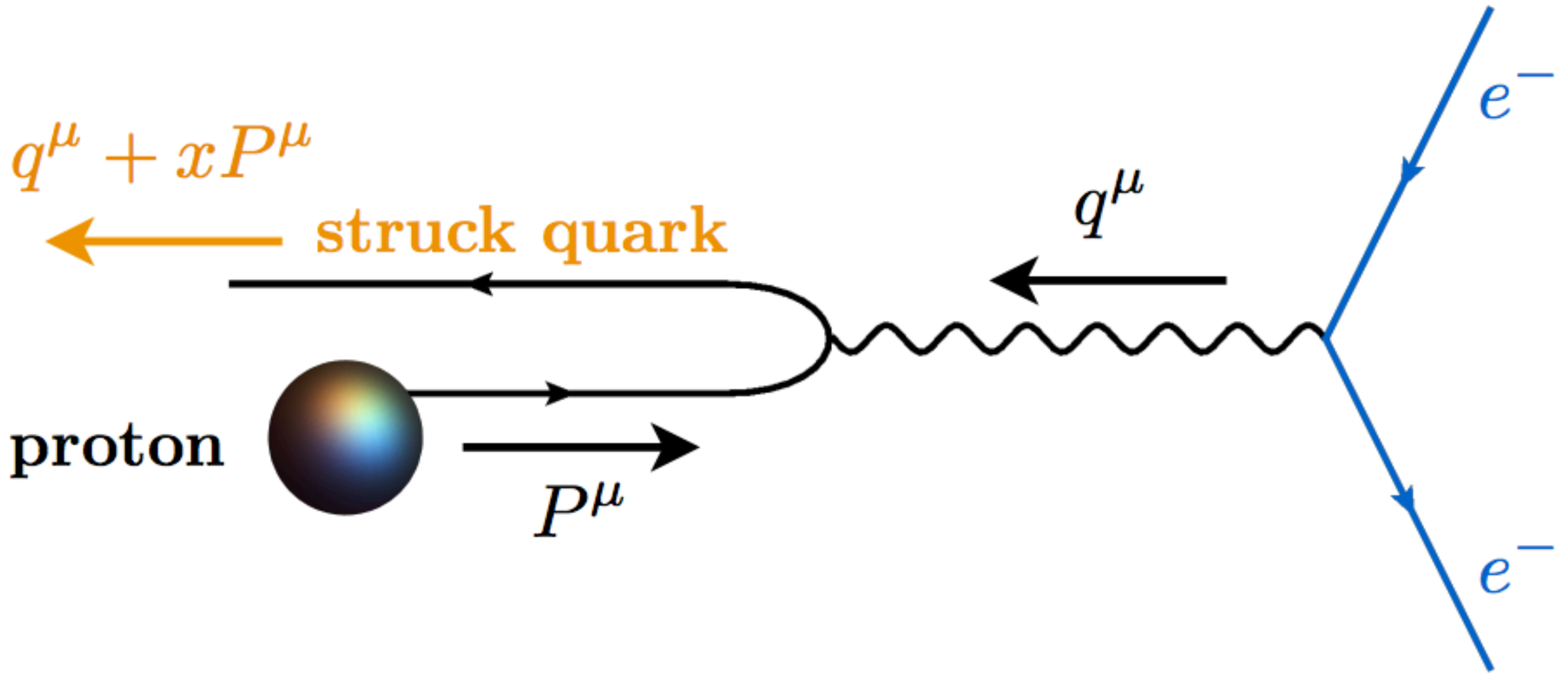
* *Fixed order Daleo, Sassot `05; Gehrmann, Vogt, et al. `18*

Algorithm dependence

Breit frame

Spherically invariant algorithm (E_i, θ_{ij})

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



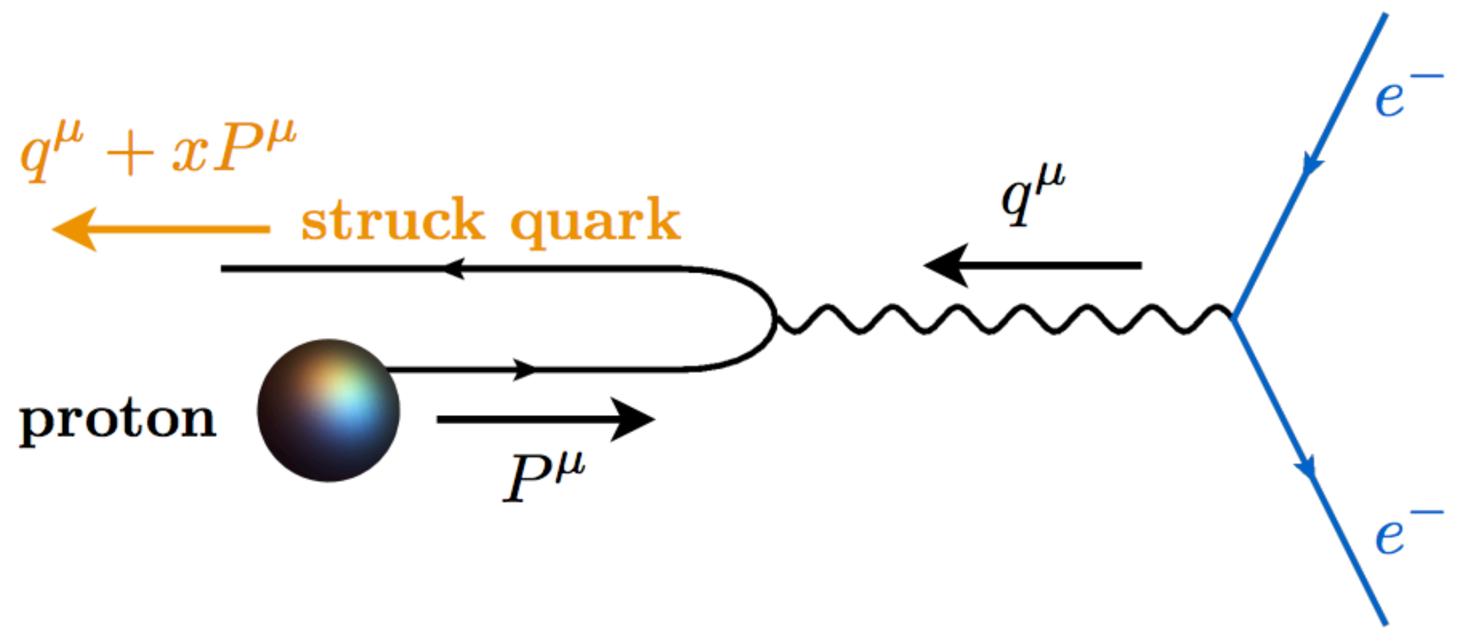
- Collinear jet function, resummation of $\ln R$ $\quad J_b \sim \delta(1-z) + \alpha_s f_b(z) + \mathcal{O}(\alpha_s^2)$
- Quark jets dominate
- Gluon contribution -1% to -3%

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})

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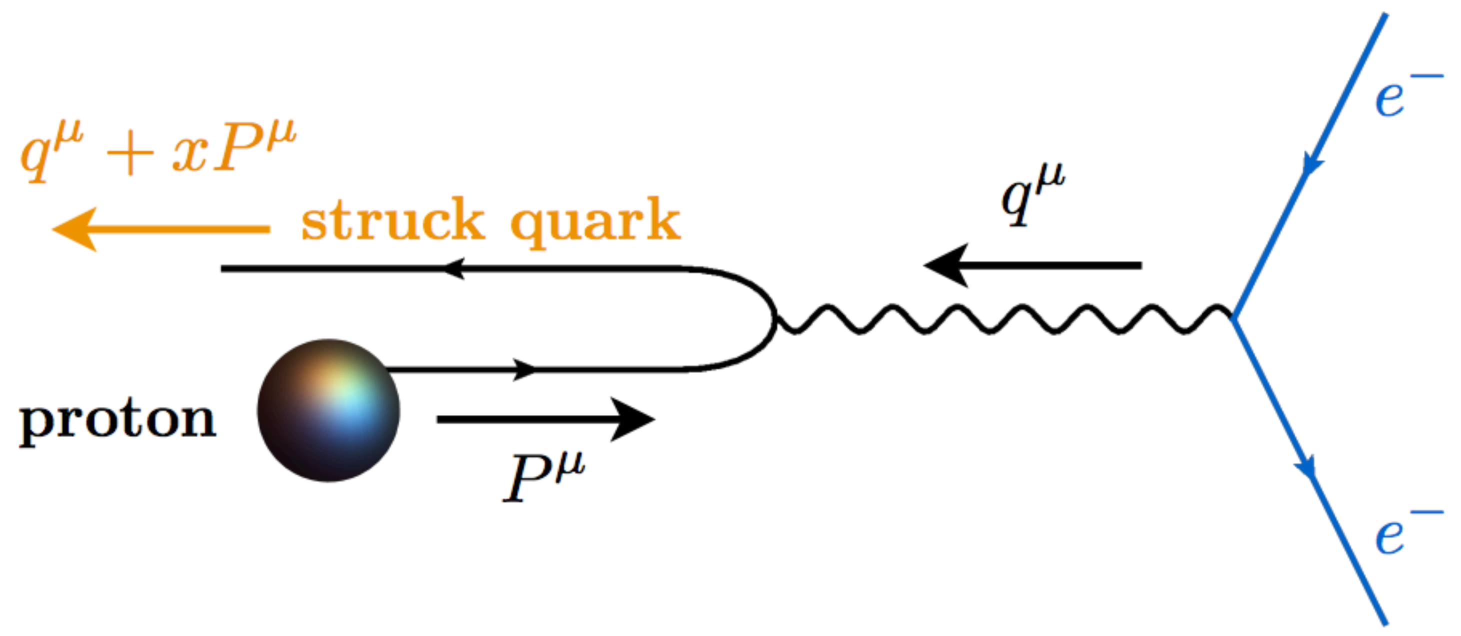

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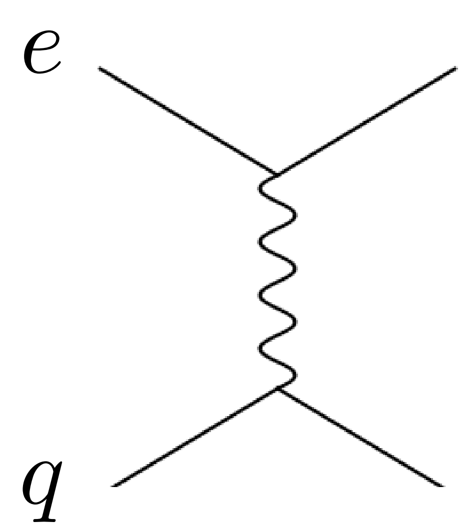
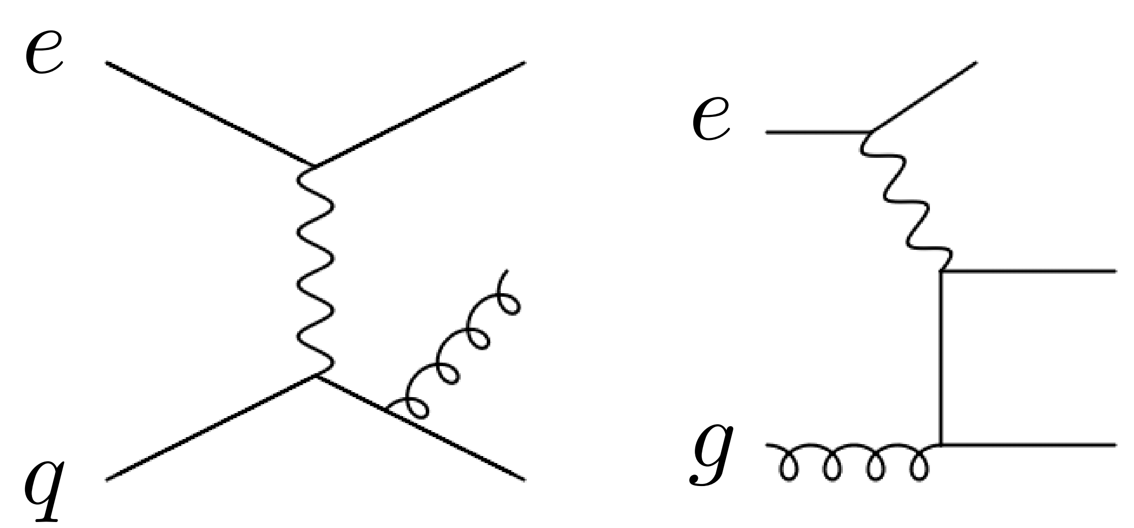
Leading order



vs.



Algorithm dependence

Breit frame

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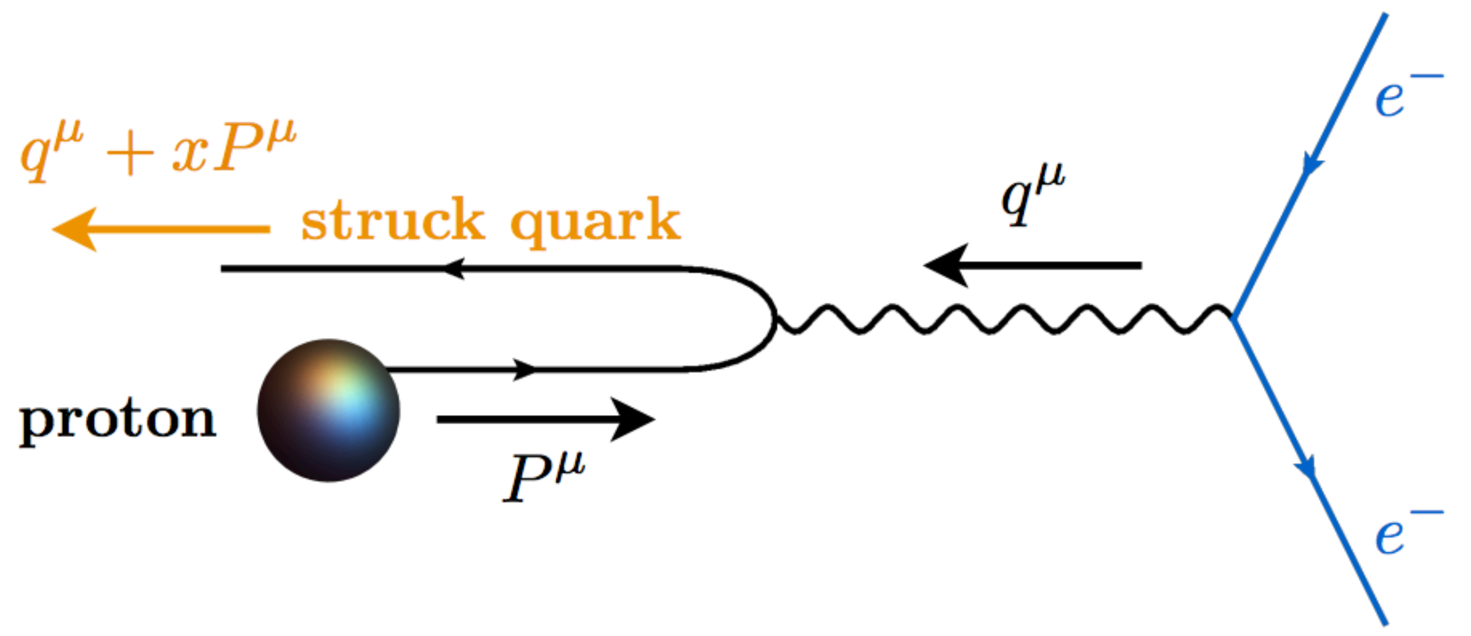

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$$\frac{\mathrm{d}\sigma^{\mathrm{LI}}}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}p_T \mathrm{d}\eta} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b$$

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

Jet substructure

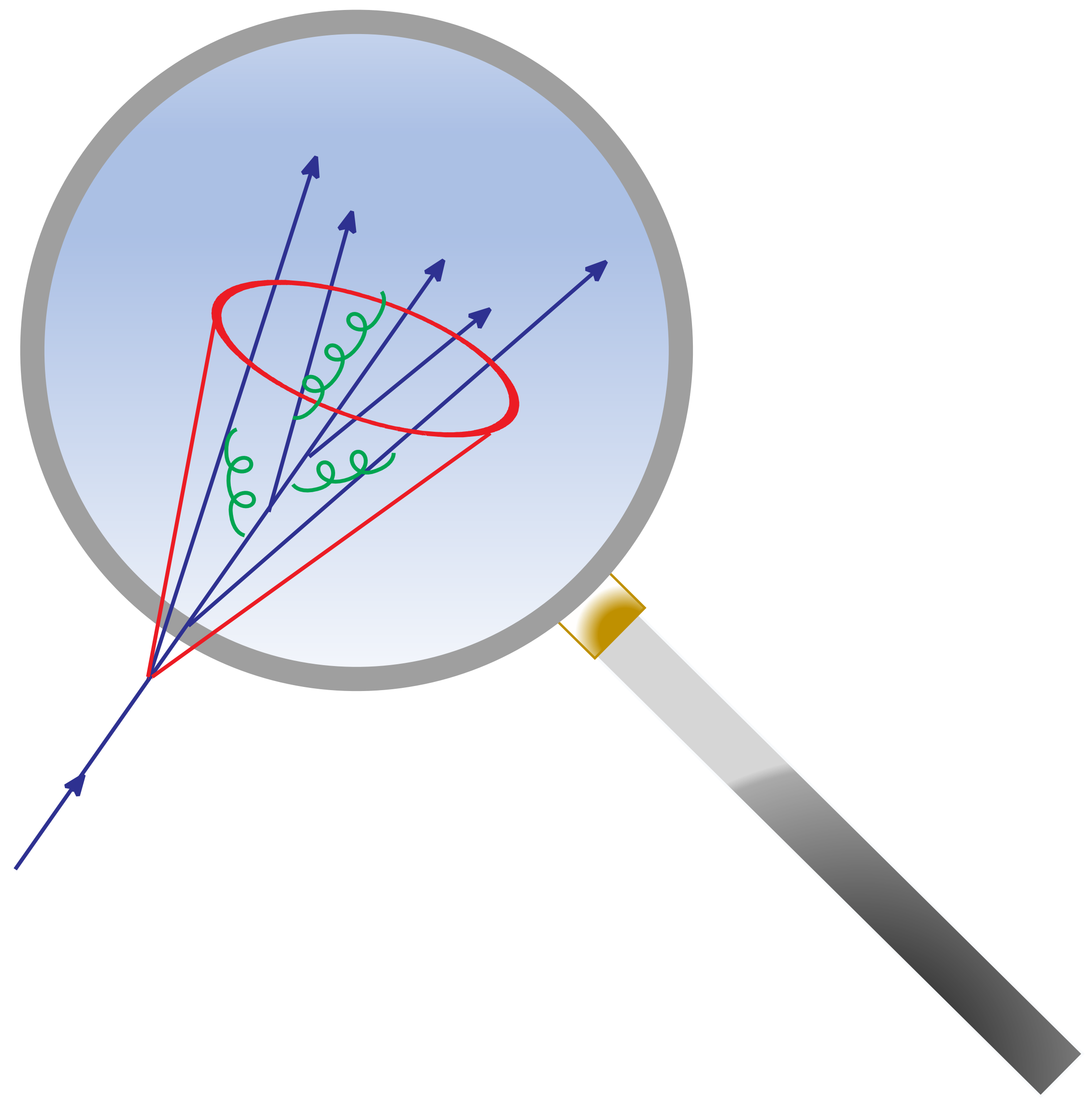
Breit frame

Spherically invariant algorithm (E_i, θ_{ij})

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

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

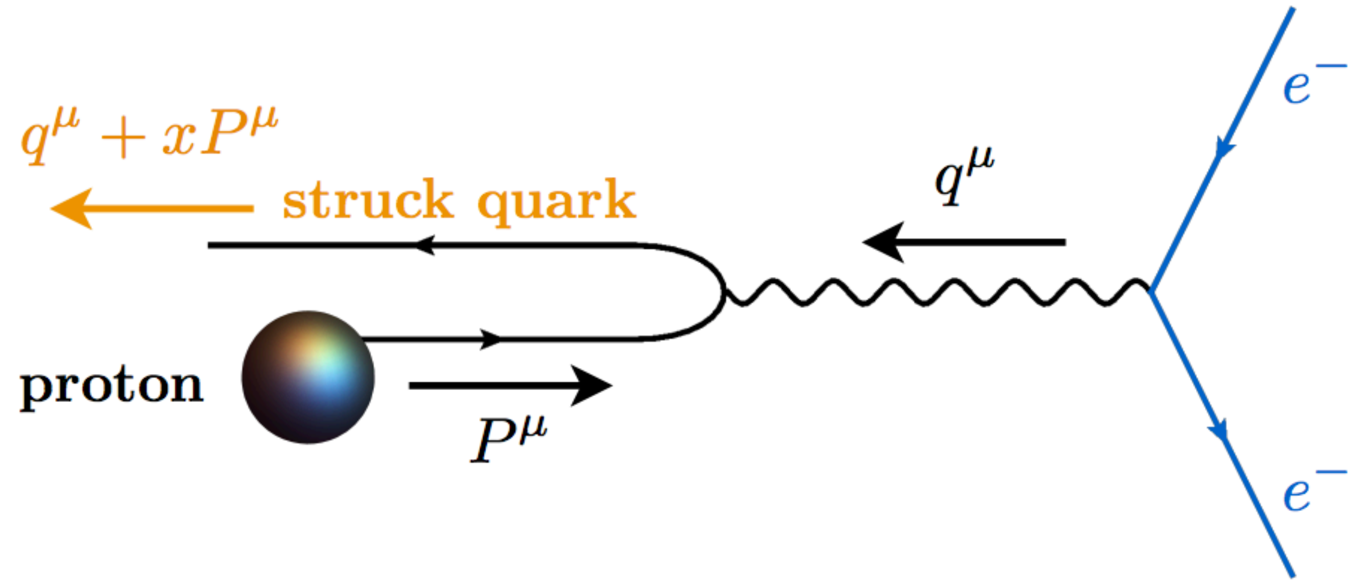
$$\frac{\mathrm{d}\sigma^{\mathrm{LI}}}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}p_T \mathrm{d}\eta \mathrm{d}\tau} \sim \sum_{ab} f_a \otimes \tilde{H}_{ab} \otimes J_b(\tau)$$

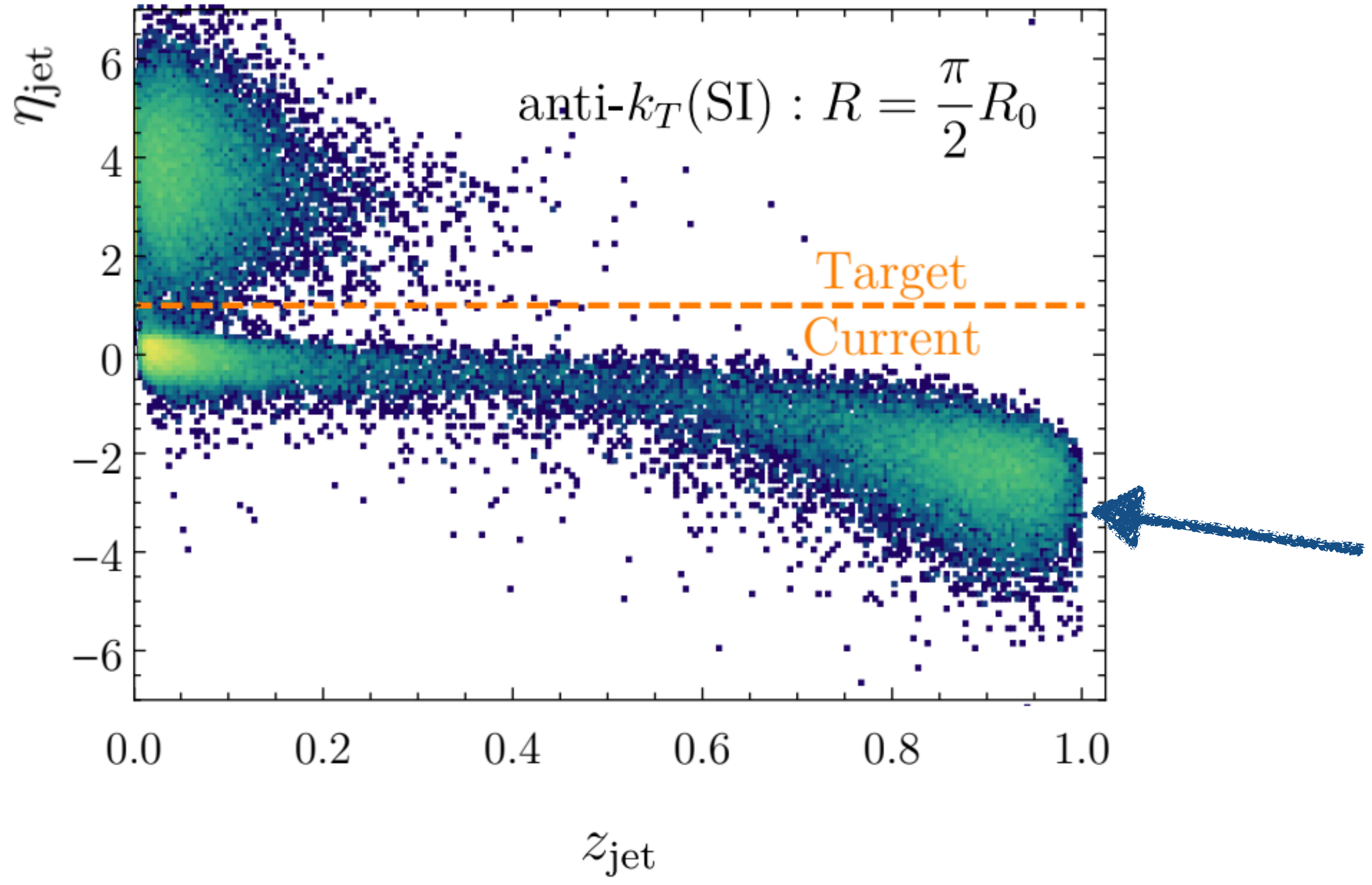


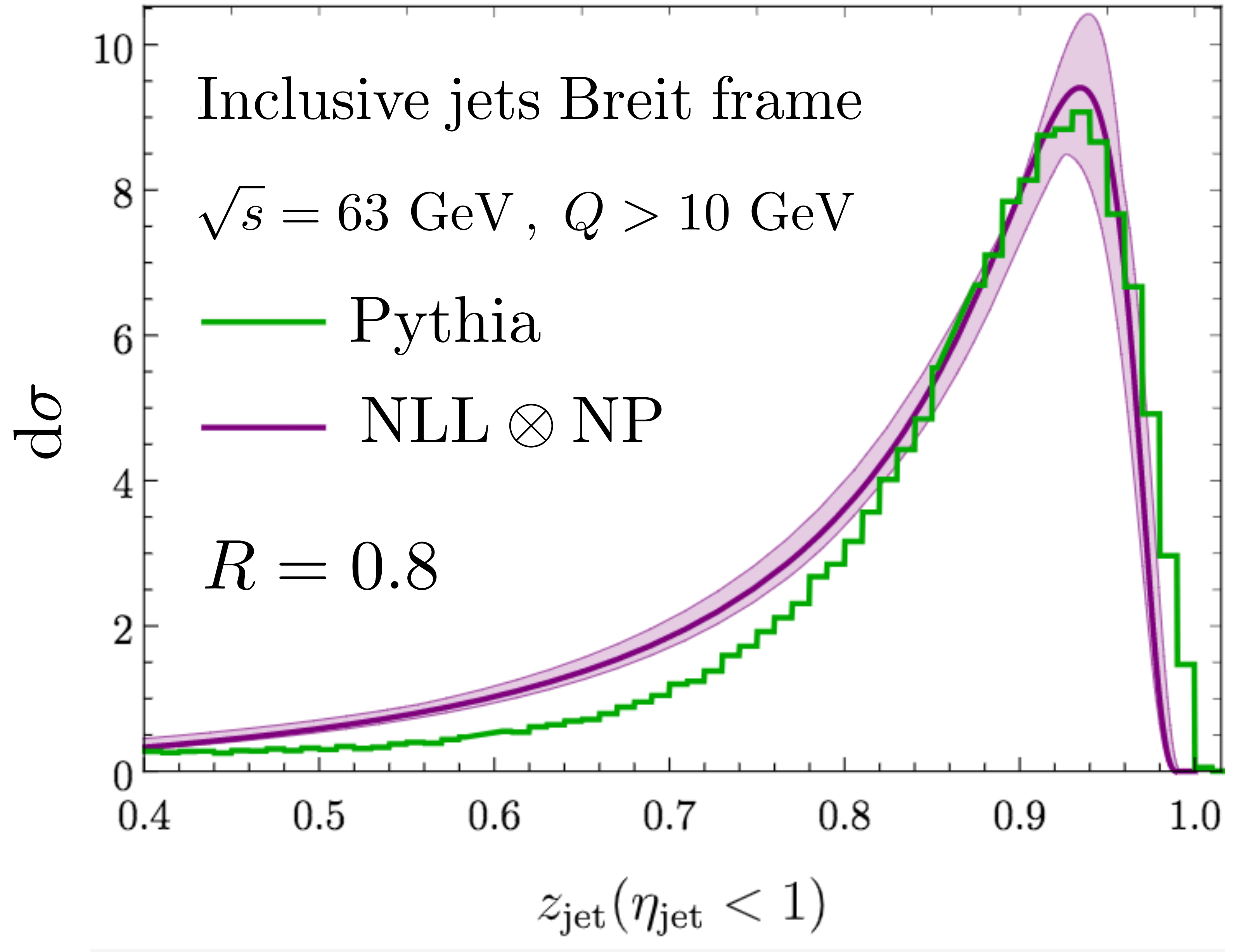
- Different than in proton-proton both are on equal footing!
- Systematically study quark/gluon differences *NieMiera, Lee, FR, Sato, Whitehill - in preparation*

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





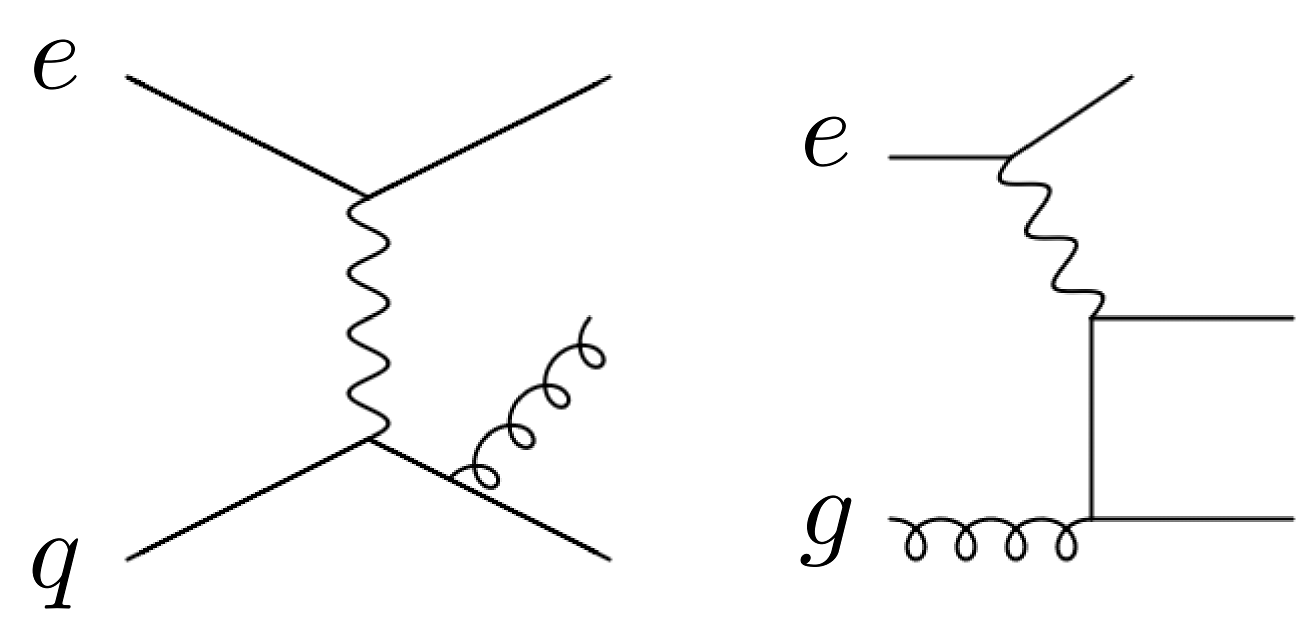


Arratia, Makris, Neill, FR, Sato `18

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

$$\frac{d\sigma}{dx_B dQ^2 dp_T d\eta} \sim \sum_{ij} \int_{e^{\eta}\frac{p_T}{\sqrt{S}}}^{\frac{e^{2\eta}}{1+e^{2\eta}}} \frac{dy}{1-y} \int_0^{1-\frac{y}{1-y}e^{-2\eta}} \frac{dz}{1-z}\, f_i(\xi)\, J_j(\zeta)\, H_{ij}(x_B, Q^2, y, z)$$

with $\xi = \frac{Q^2(1-y)(1-z) + Sye^{-2\eta}}{(Q^2+S)\,(1-y)(1-z)}$ $\qquad \zeta = \frac{e^{\eta} p_T}{\sqrt{S}y}$

cf. Daleo, de Florian, Sassot `05
Daleo, Sassot `05
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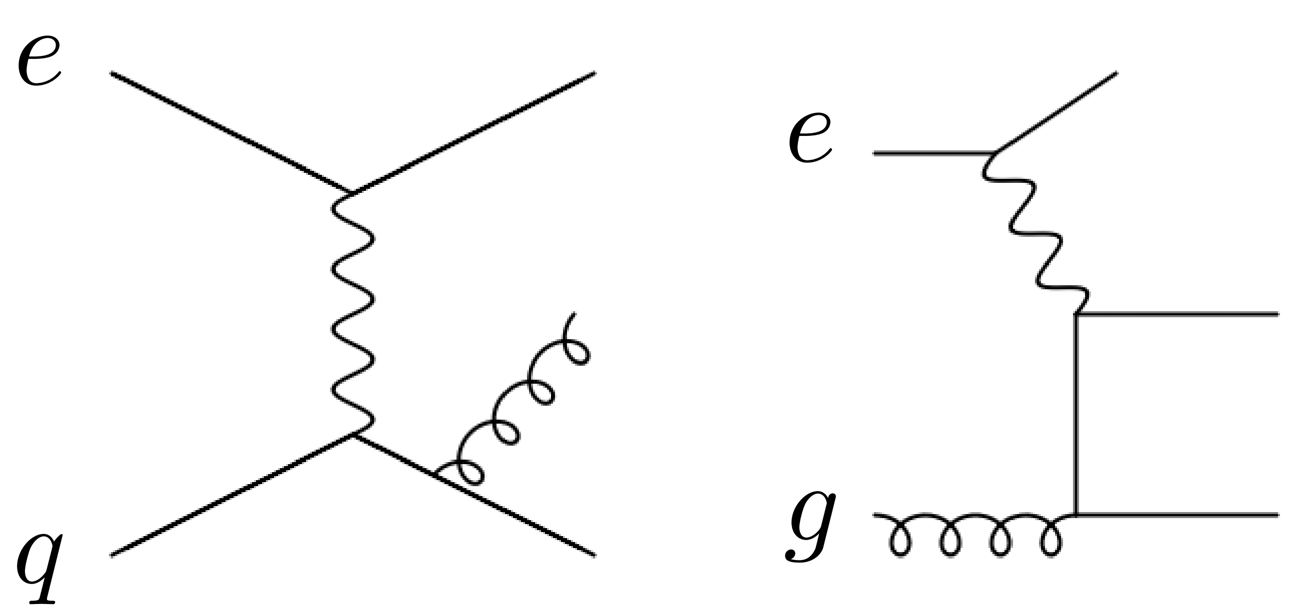


Breit frame jets - II

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

- Longitudinally invariant jet algorithm

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}p_T \mathrm{d}\eta} \sim \sum_{ij} \int_{y_0}^{y_1} dy \int_0^{z_1(y)} dz\, J_j(y_0/y)\, \mathcal{H}_{ij}(x_B, Q^2, y, z)$$

Breit frame jets - II

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

- Longitudinally invariant jet algorithm

$$\frac{d\sigma}{dx_B dQ^2 dp_T d\eta} \sim \sum_{ij} \int_{y_0}^{y_1} dy \int_0^{z_1(y)} dz\, J_j(y_0/y)\, \mathcal{H}_{ij}(x_B, Q^2, y, z)$$

$J_j(y_0/y \to 1)$

Integrable but divergent

Breit frame jets - II

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

- Longitudinally invariant jet algorithm

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}p_T \mathrm{d}\eta} \sim \sum_{ij} \int_{y_0}^{y_1} dy \int_0^{z_1(y)} dz\, J_j(y_0/y)\, \mathcal{H}_{ij}(x_B, Q^2, y, z)$$

$$= \sum_{ij} \int_{y_0}^{y_1} dy \left[\int_0^{z_1(y)} dz\, \mathcal{H}_{ij}(x_B, Q^2, y, z) - \int_0^{z_1(y_0)} dz\, \mathcal{H}_{ij}(x_B, Q^2, y_0, z) \right] J_j(y_0/y)$$

$$+ \sum_{ij} \int_{y_0}^{y_1} dy \int_0^{z_1(y_0)} dz\, J_j(y_0/y)\, \mathcal{H}_{ij}(x_B, Q^2, y_0, z)$$

Breit frame jets - II

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

- Longitudinally invariant jet algorithm

Evaluate using Mellin grid *cf. Stratmann, Vogelsang*

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}p_T \mathrm{d}\eta}$$

$$= \sum_{ij} \frac{1}{2\pi i} \int dN\, J(N) \int_{y_0}^{y_1} dy \left[\int_0^{z_1(y)} dz\, \mathcal{H}_{ij}(x_B, Q^2, y, z) - \int_0^{z_1(y_0)} dz\, \mathcal{H}_{ij}(x_B, Q^2, y_0, z) \right] (y_0/y)^{-N}$$

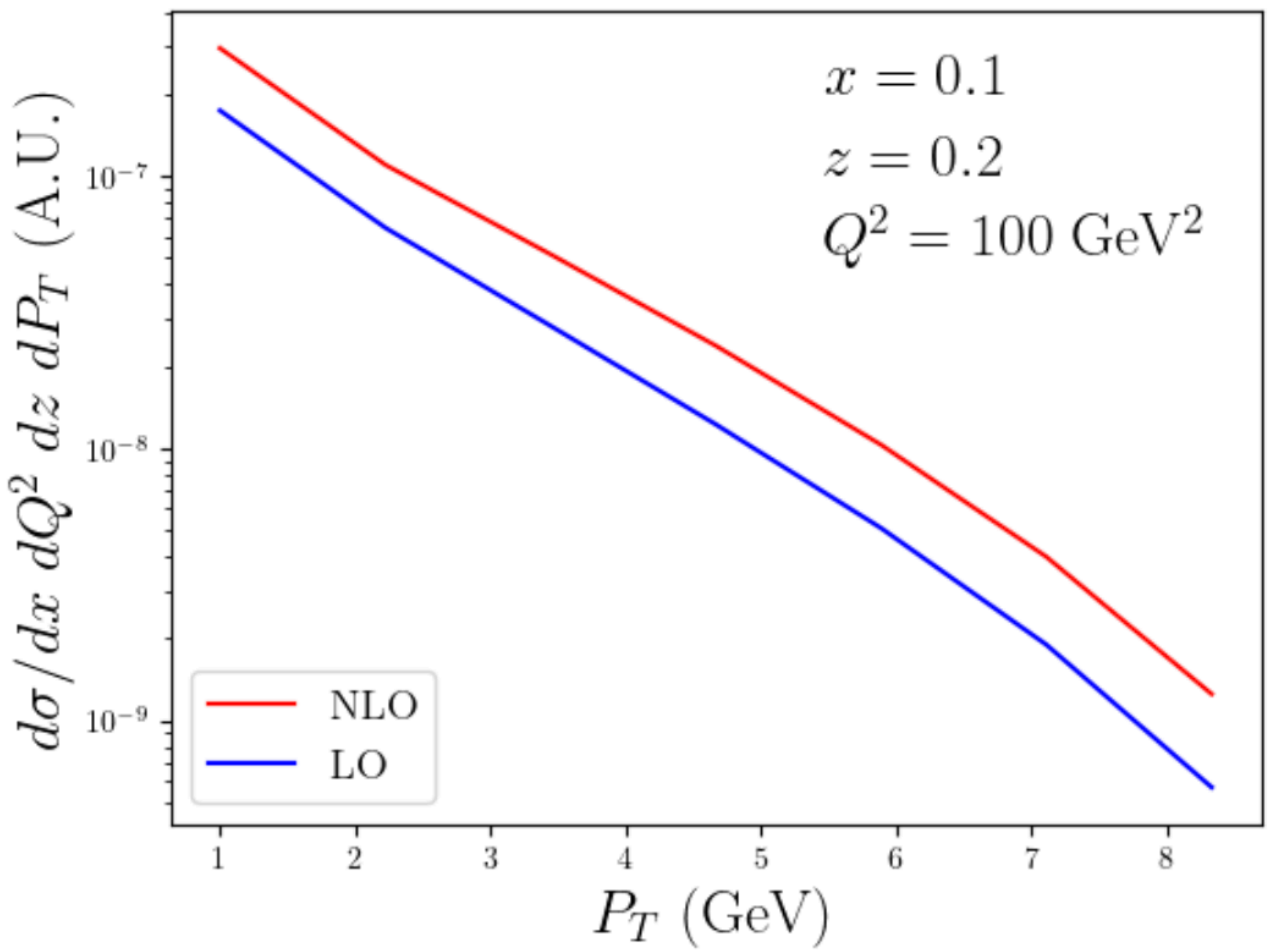
$$+ \sum_{ij} \int_{y_0}^{y_1} dy\, J_j(y_0/y) \int_0^{z_1(y_0)} dz\, \mathcal{H}_{ij}(x_B, Q^2, y_0, z)$$

Calculate analytically in Mellin space

Breit frame jets - II

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

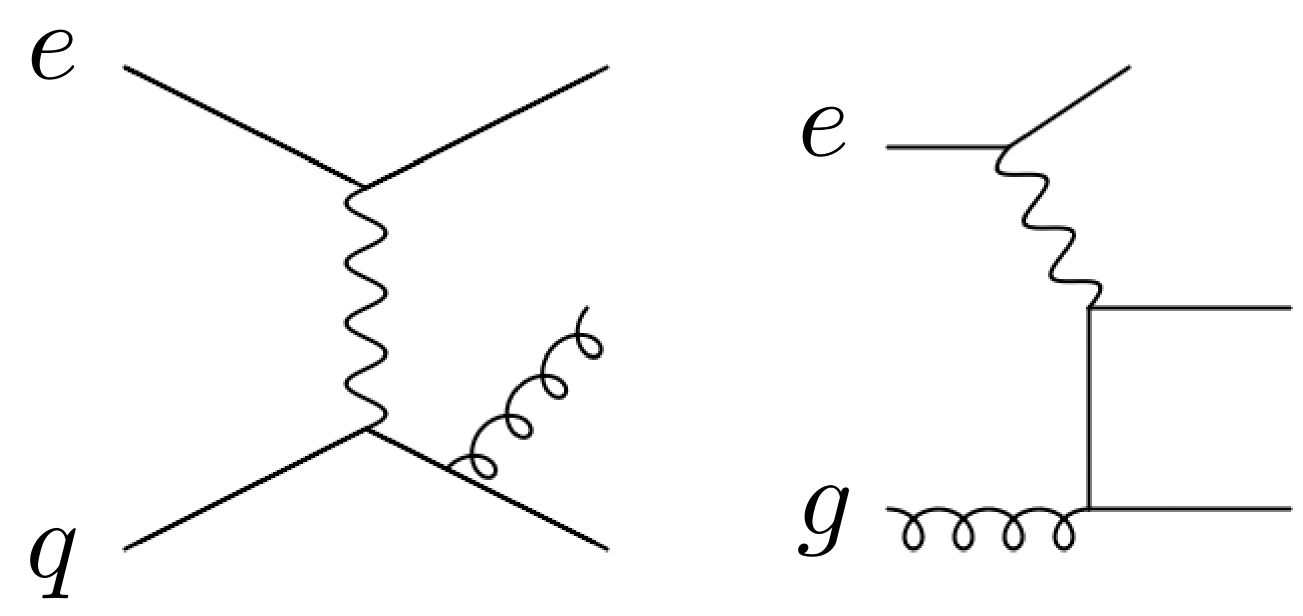
- Longitudinally invariant jet algorithm



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

$R = 0.7$

Preliminary

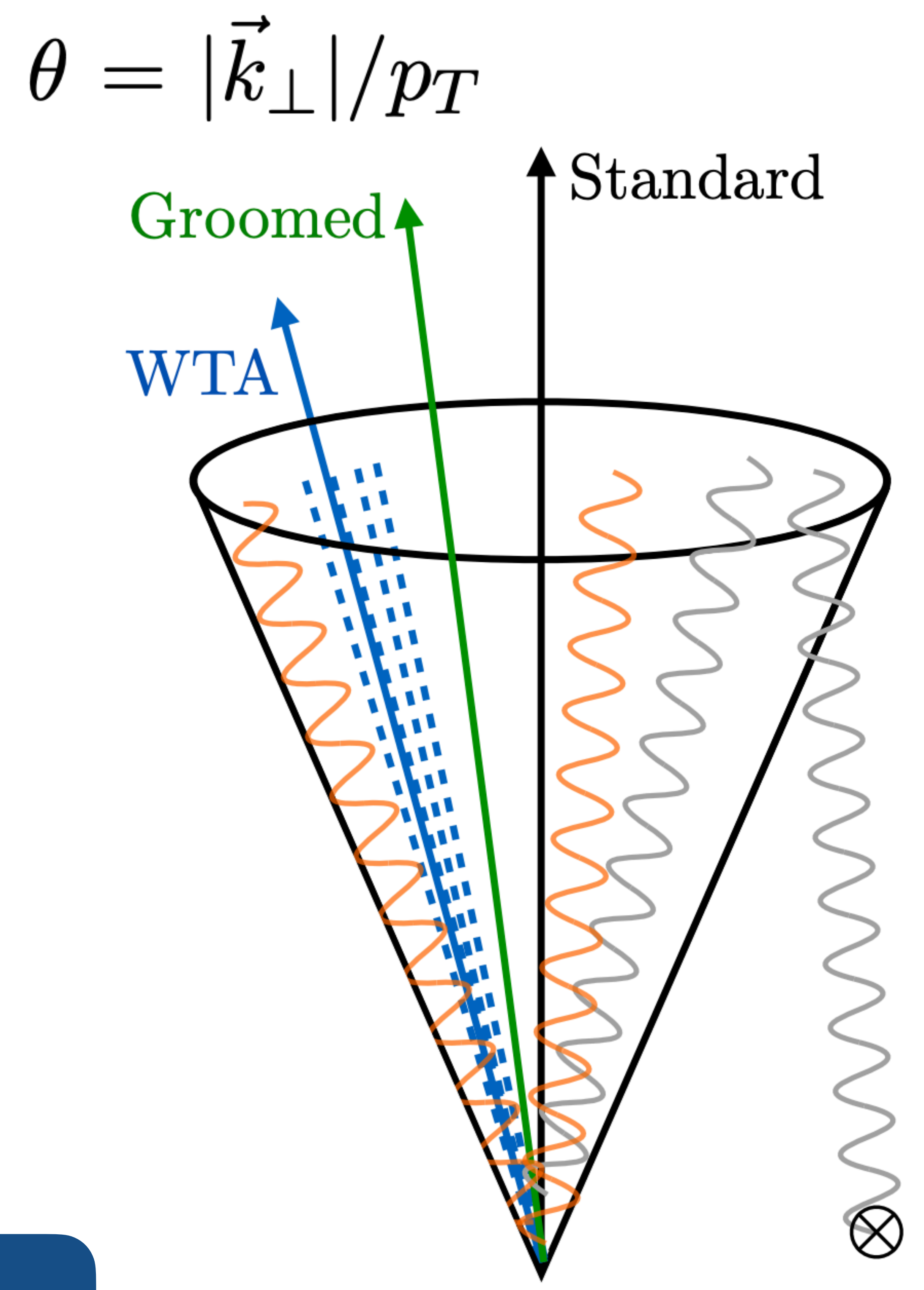


- Different functional form compared spherical algorithm
- Large higher order effects NLO + lnR resummation
- Extract quark/gluon fractions for jet substructure

Jet substructure — angles between jet axes

Cal, Neill, FR, Waalewijn `20

- 1. Standard jet axis, E-scheme $p_{12}^\mu = p_1^\mu + p_2^\mu$
- 2. Winner-Take-All (WTA)
  - Follow more energetic clustering
  - Insensitive to soft recoil



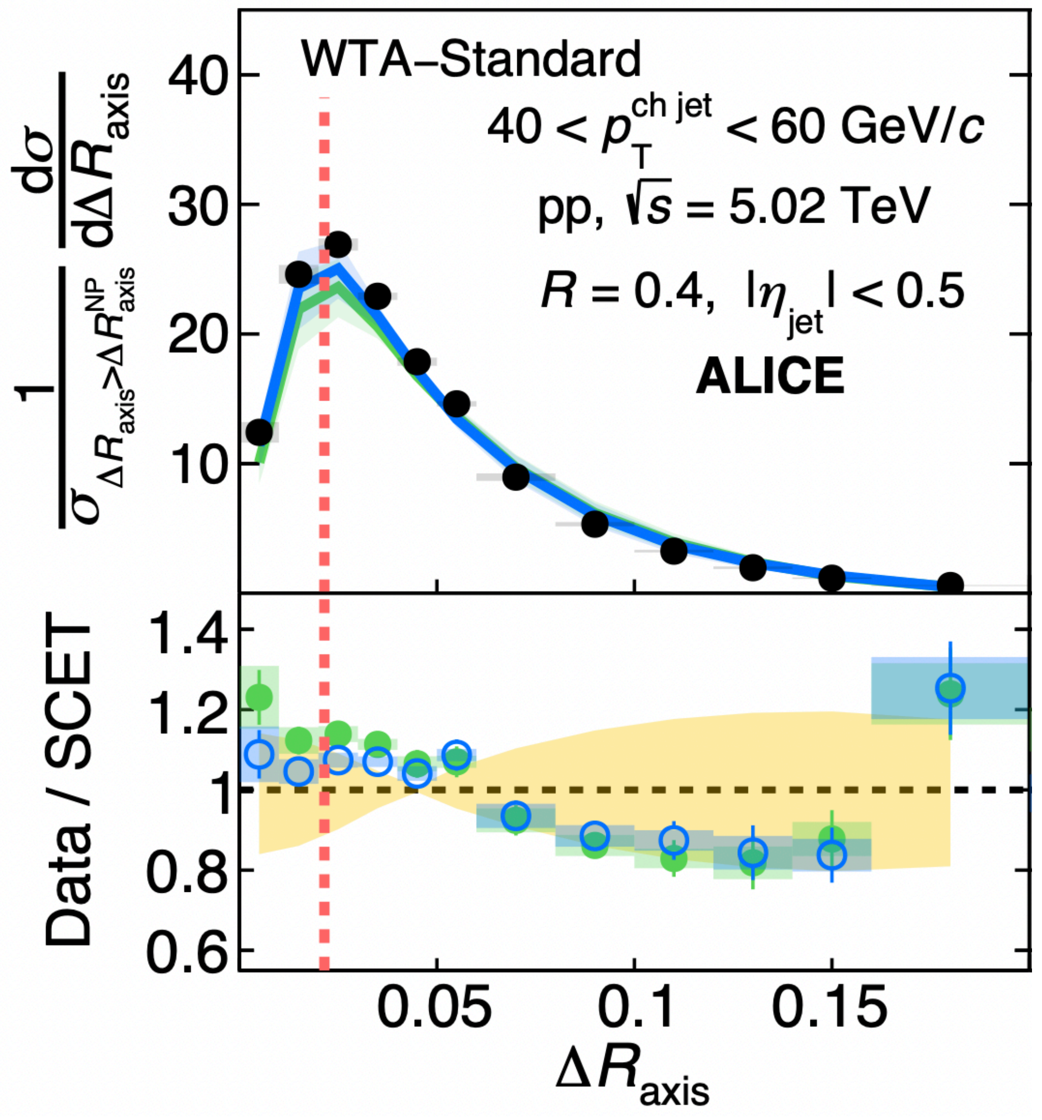
→ Relative angle between axes is IRC safe but TMD evolution

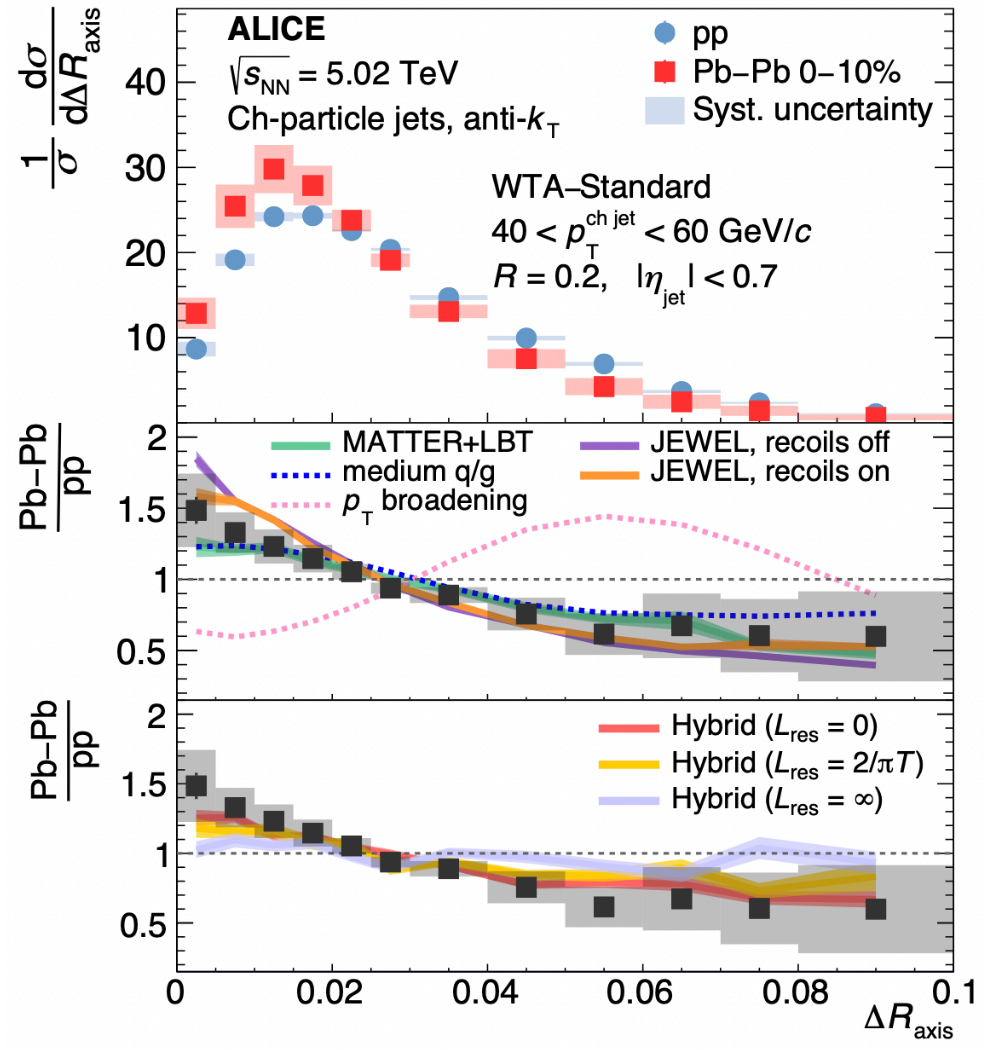
- Angle is a measure of soft physics
- Hadronization correction relatively well under control

Recent results from the LHC

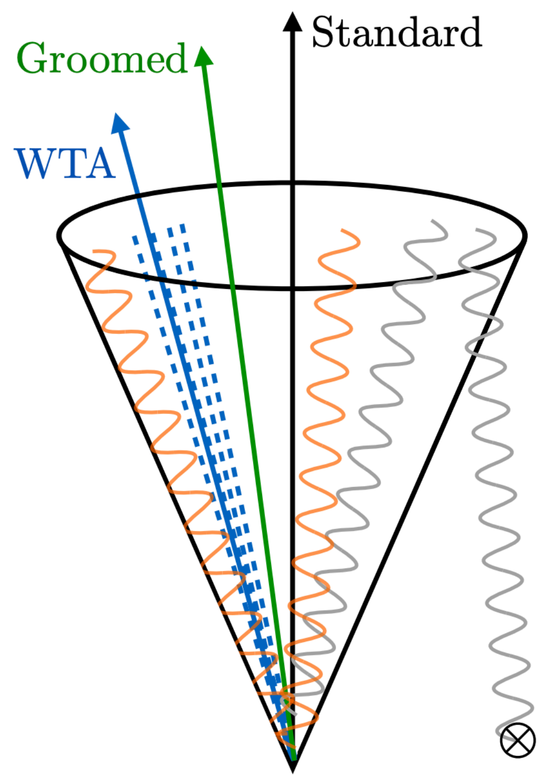
- ALICE — pp and AA

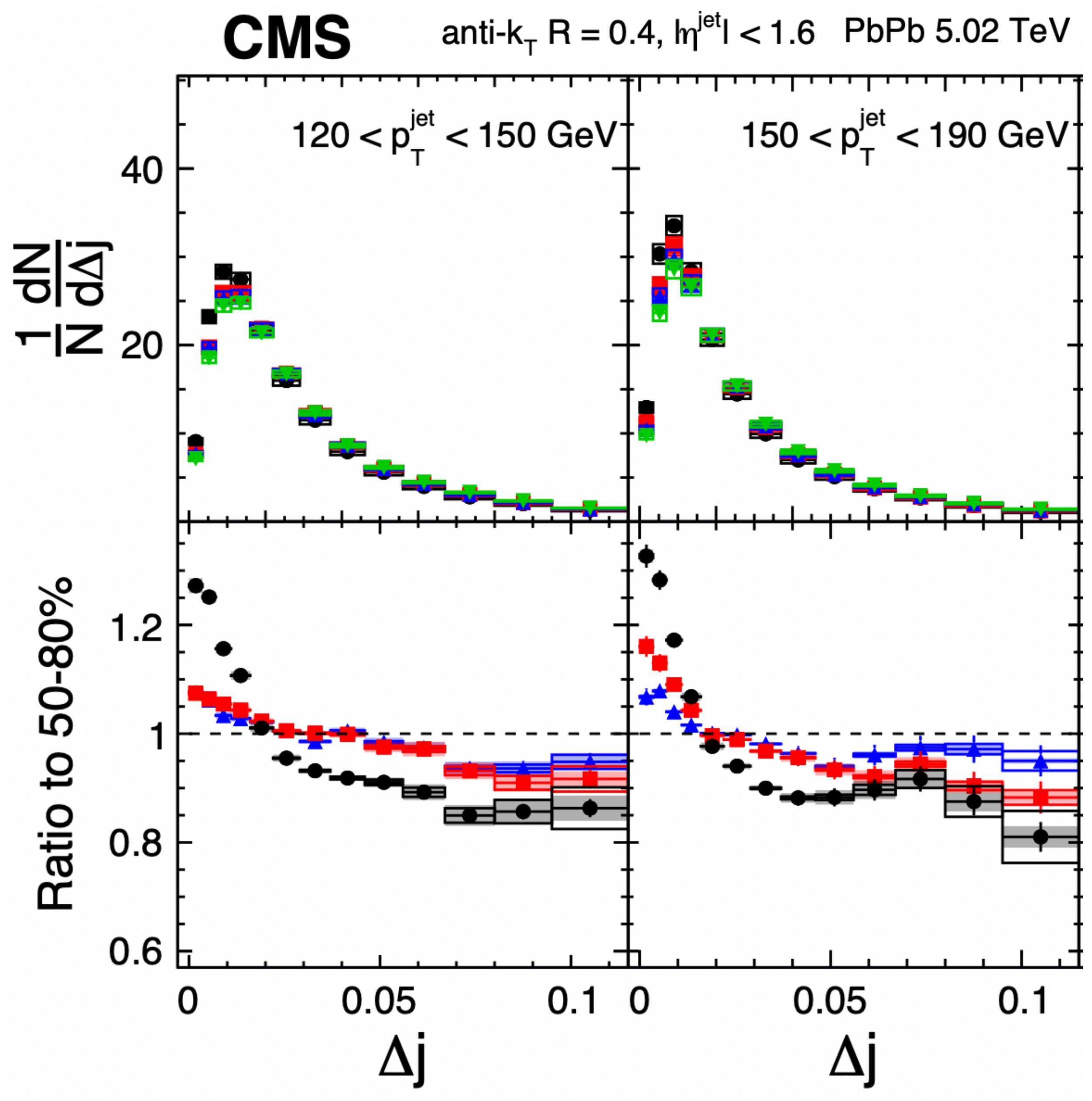
  Theory corrected to charged-particle level





- CMS — AA



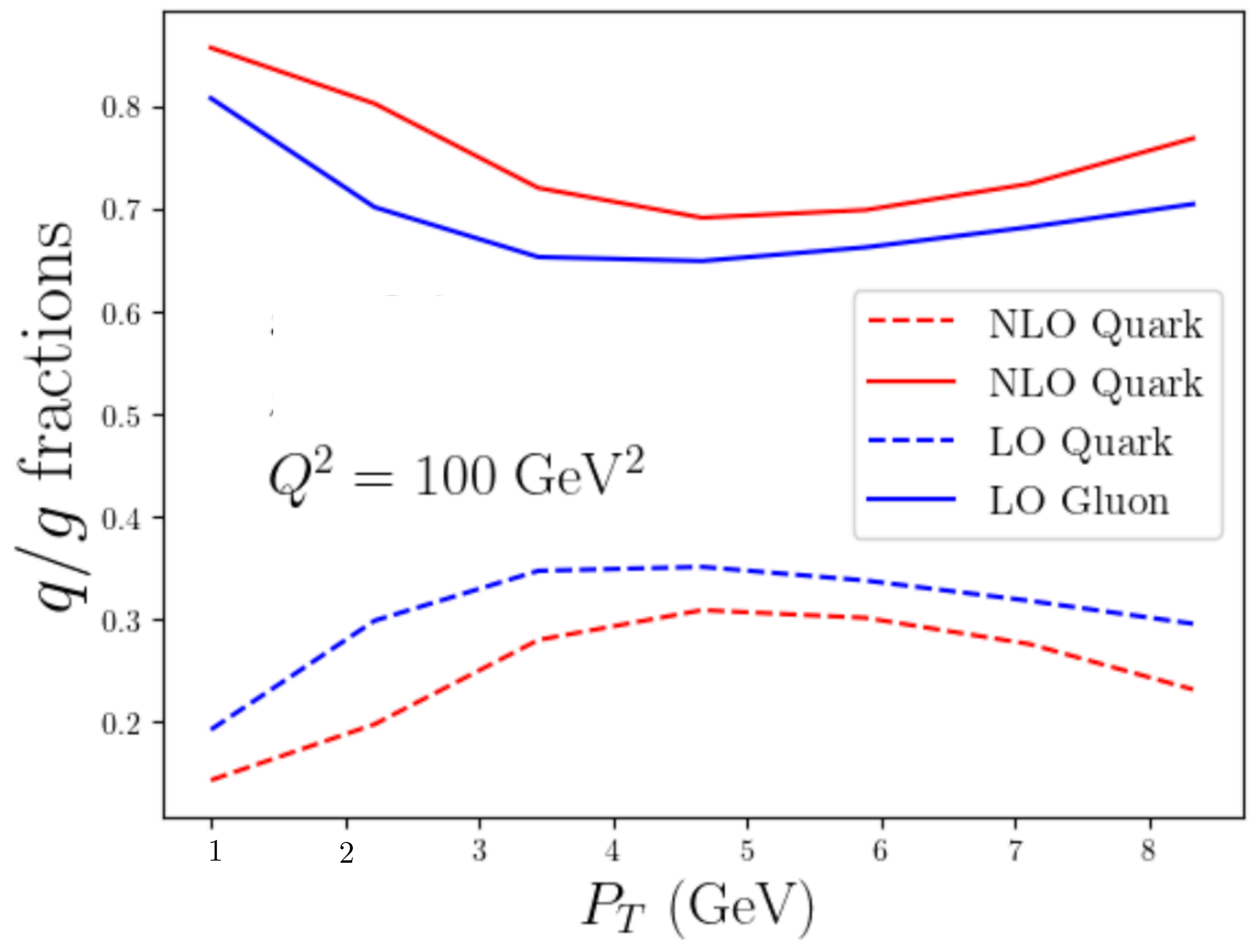


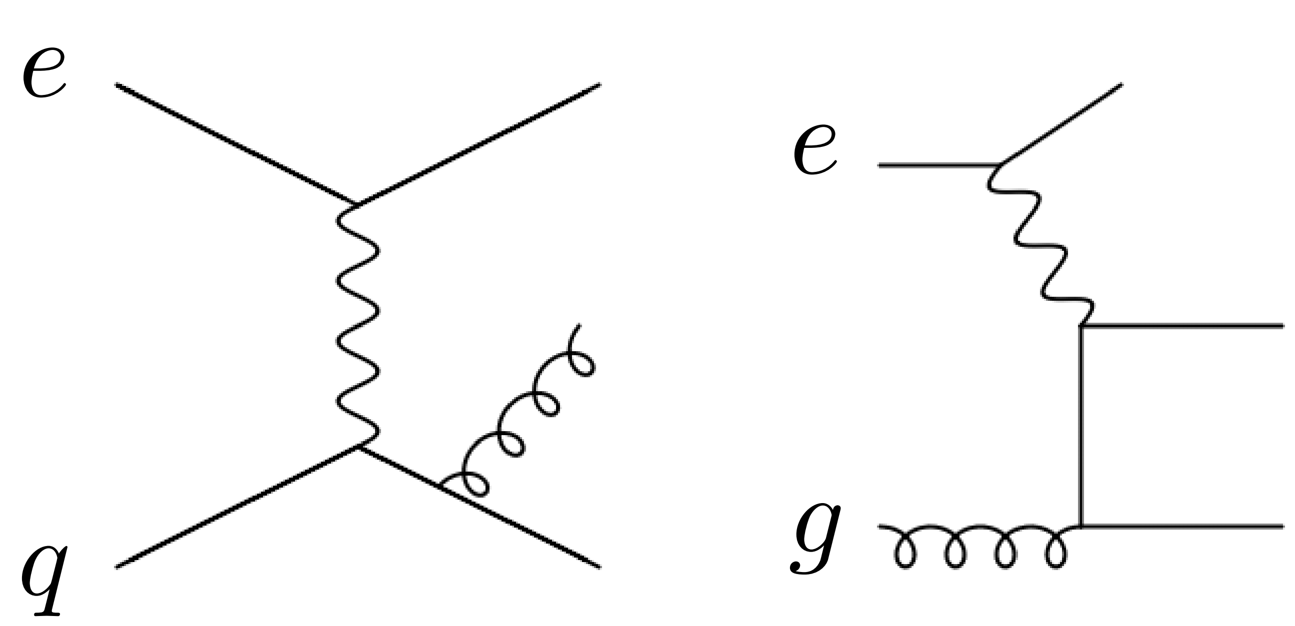
JHEP 07 (2023) 201, ALICE
PLB 849 (2024) 138412, ALICE
2502.13020, CMS

Jet substructure in the Breit frame

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

- Jet algorithm differences
  - Spherical jet algorithm: Gluon fraction around -1% to -3%
  - Longitudinal jet algorithm





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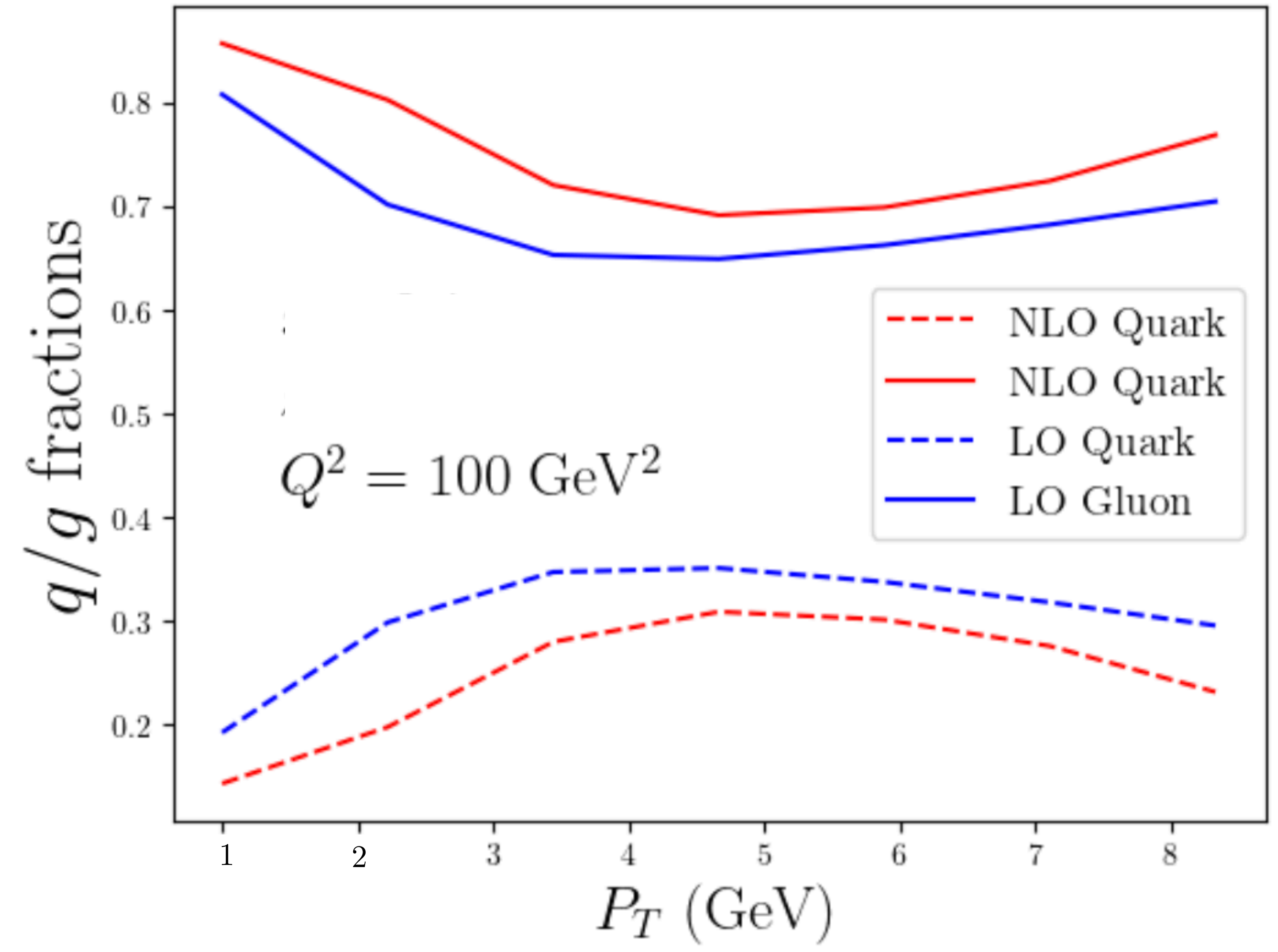
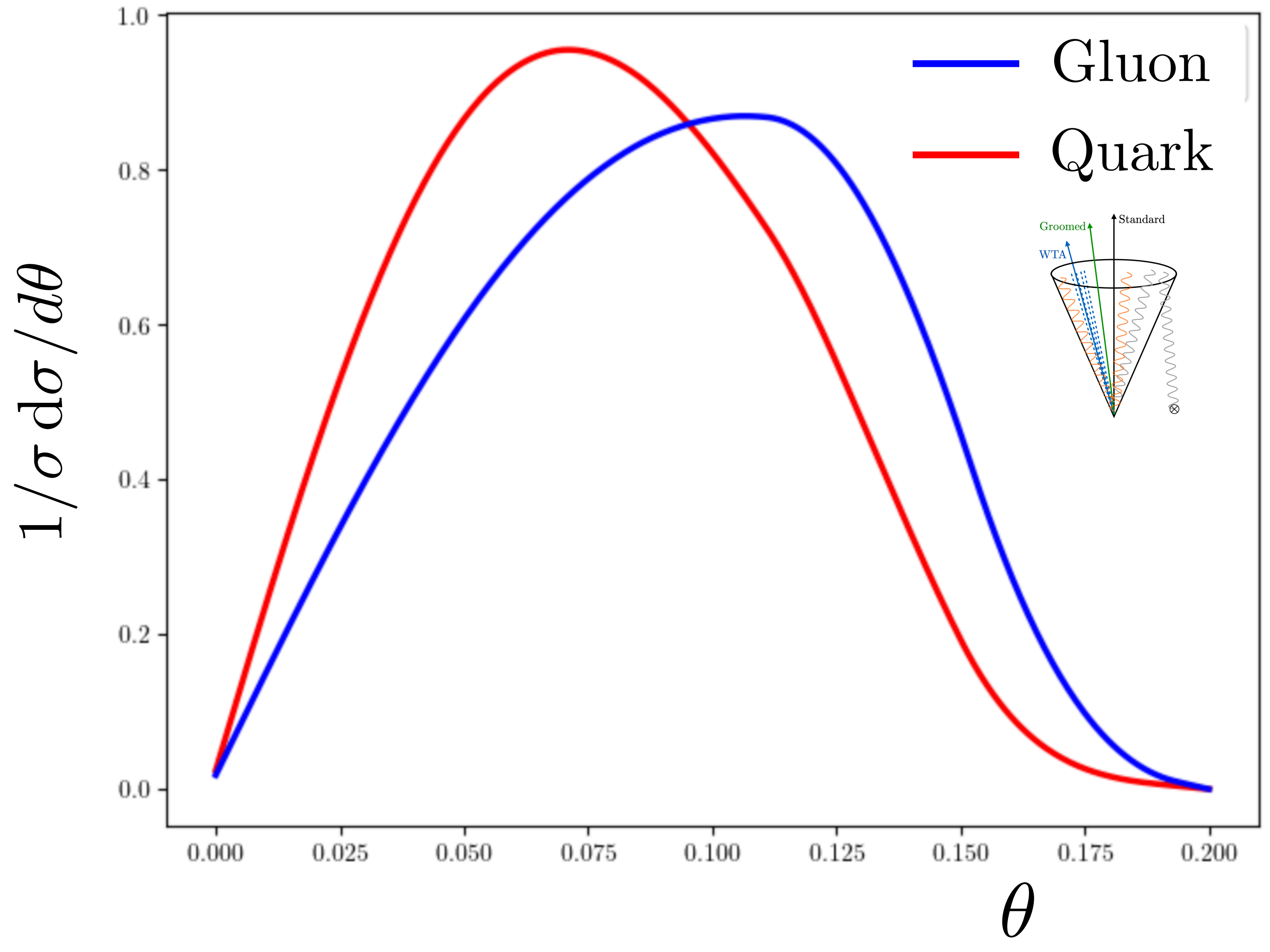
- At NLO + NLL: weighted average of quark/gluon jet substructure

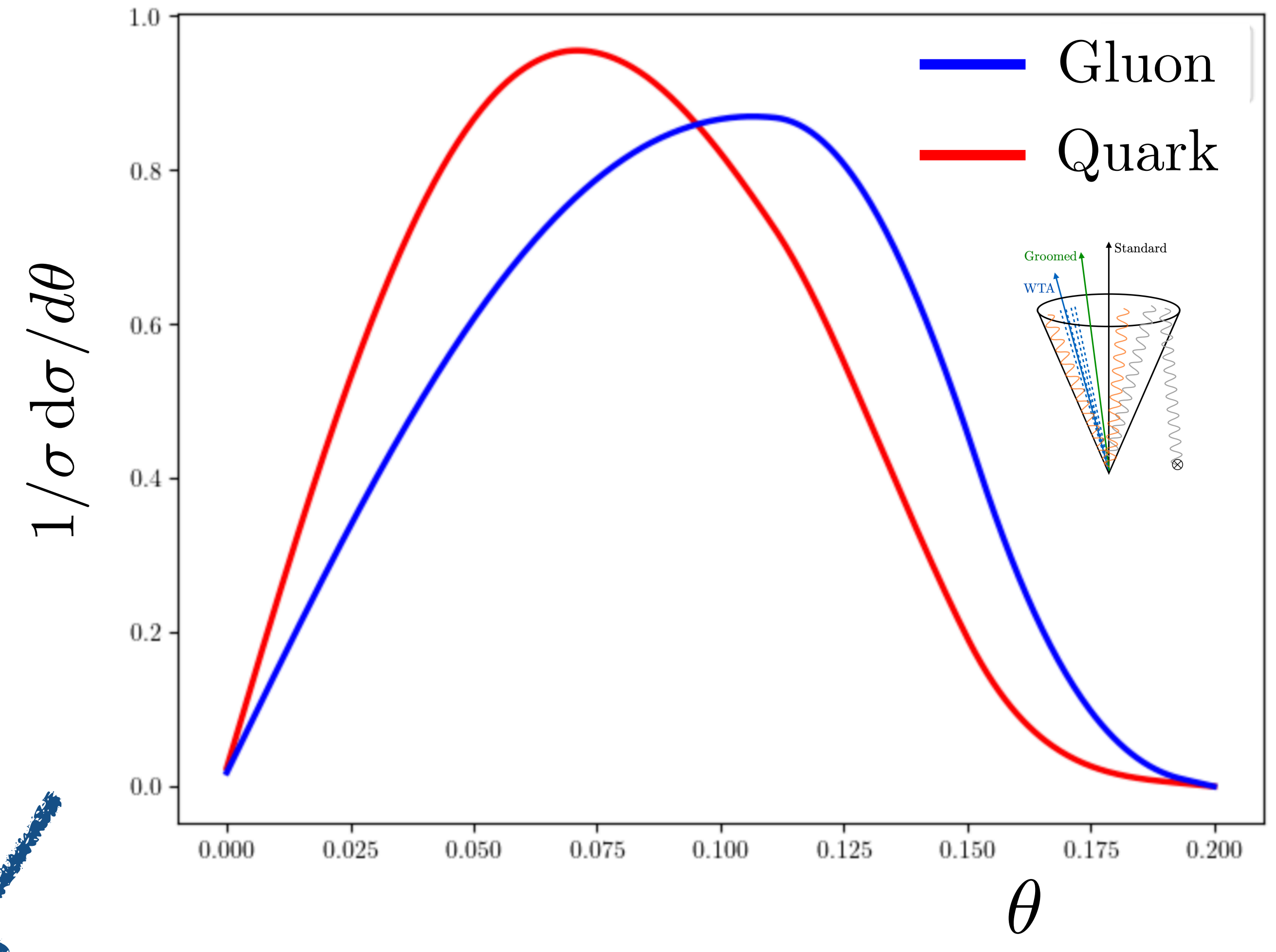




Angle between jet axes for EIC kinematics

Jet substructure in the Breit frame

- At NLO + NLL: weighted average of quark/gluon jet substructure



NieMiera, Lee, FR, Sato, Whitehill
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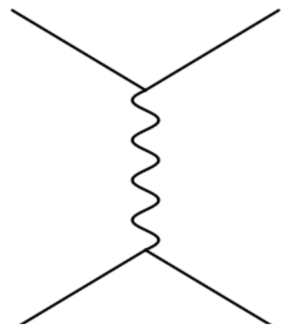
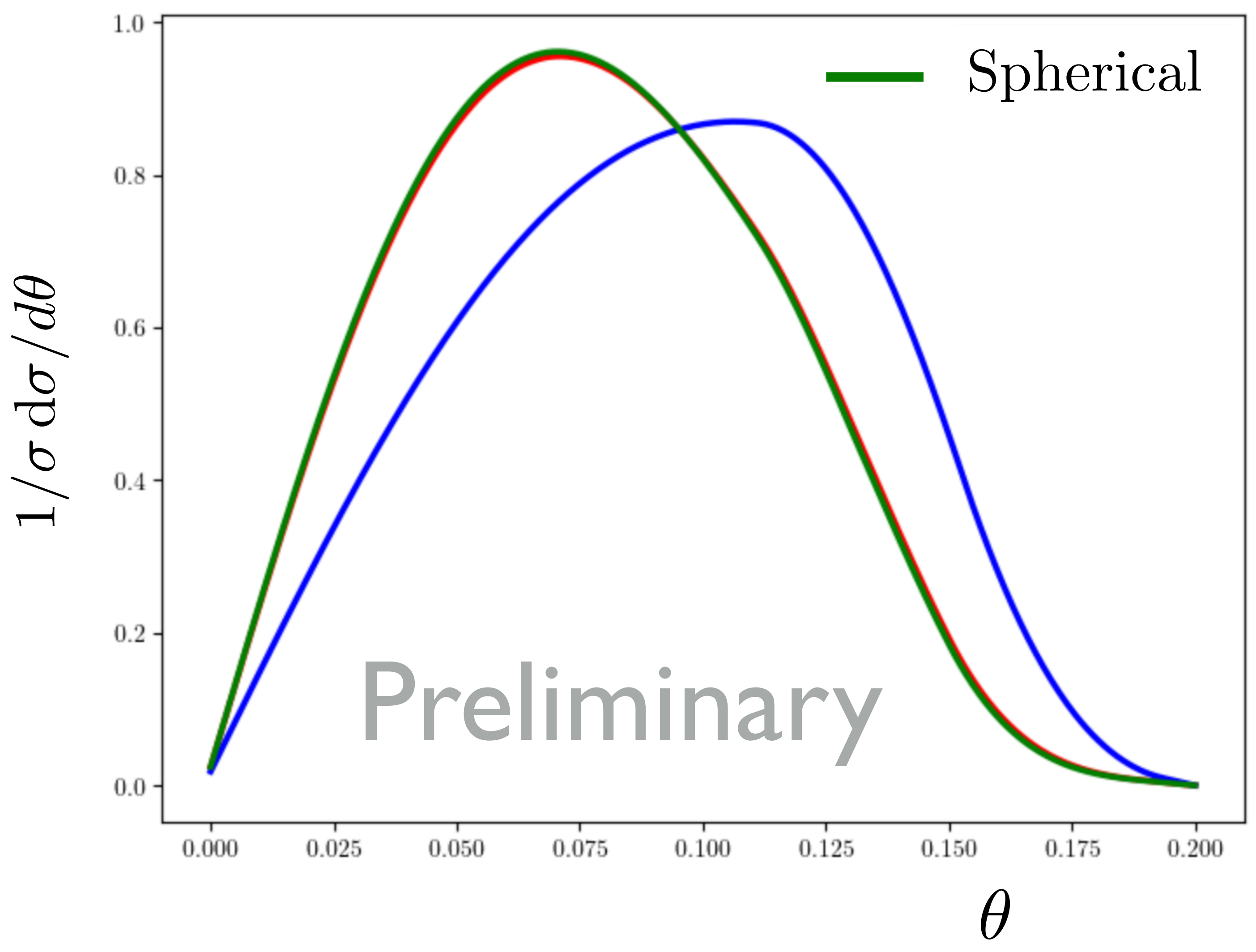
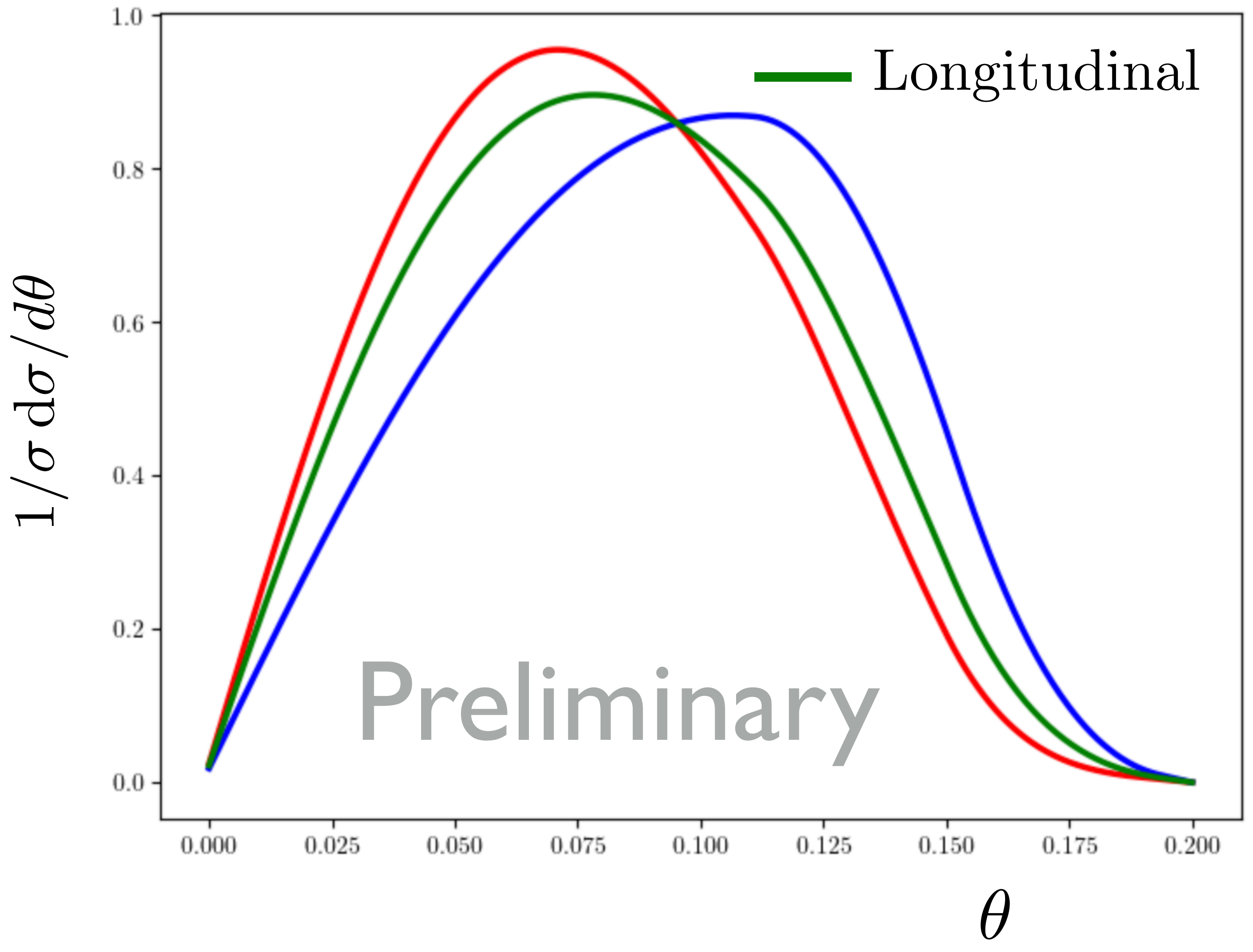
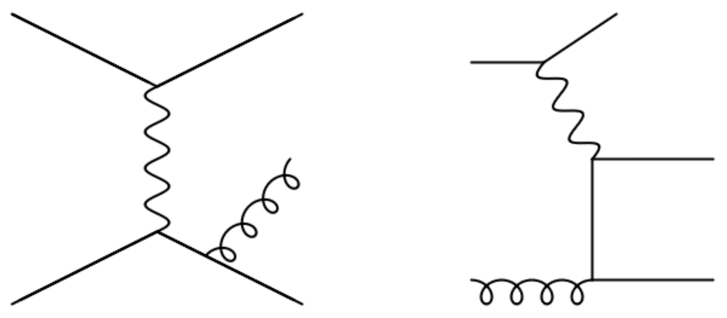
Angle between jet axes for EIC kinematics



Spherical







Longitudinal

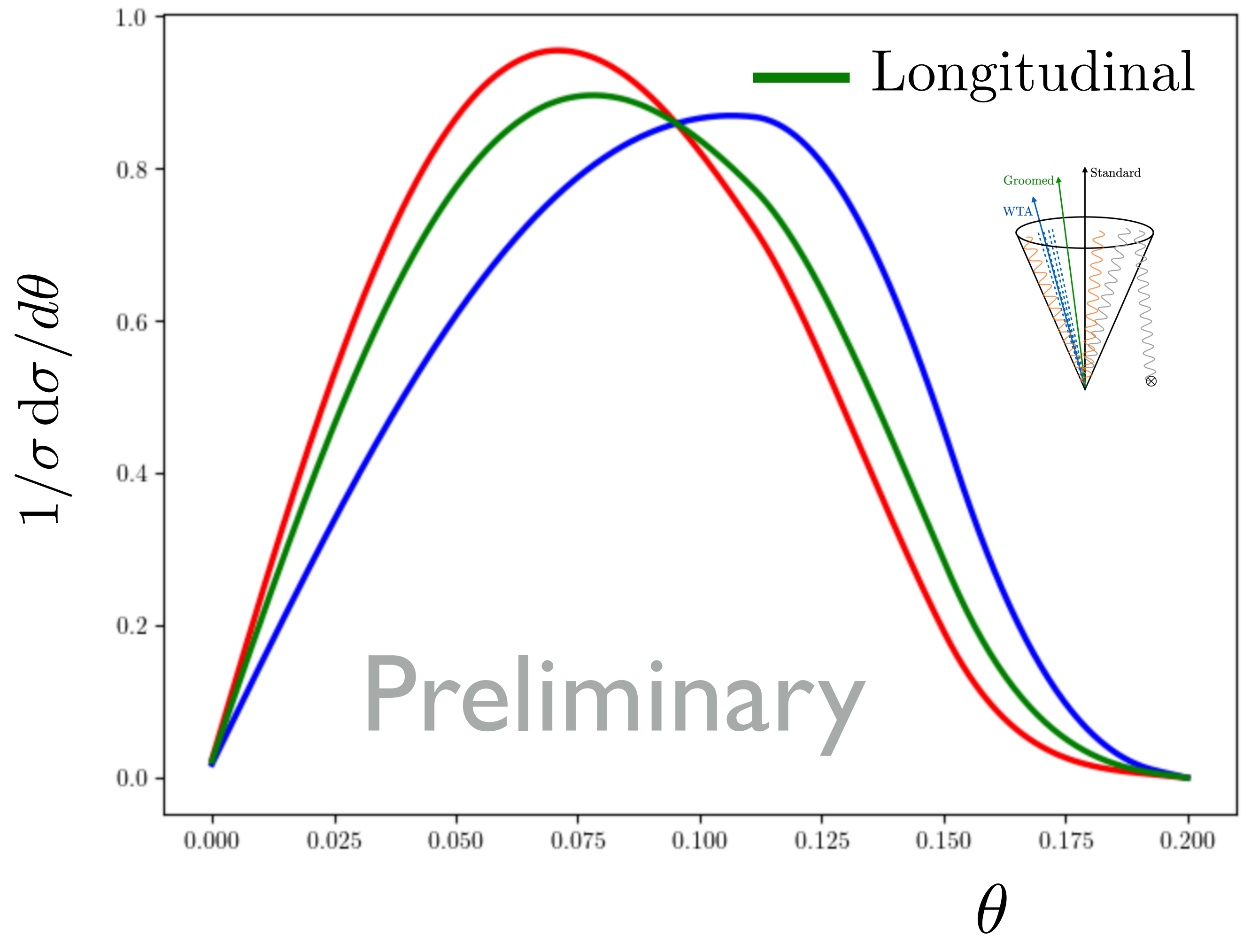
Frame & jet algorithm dependence

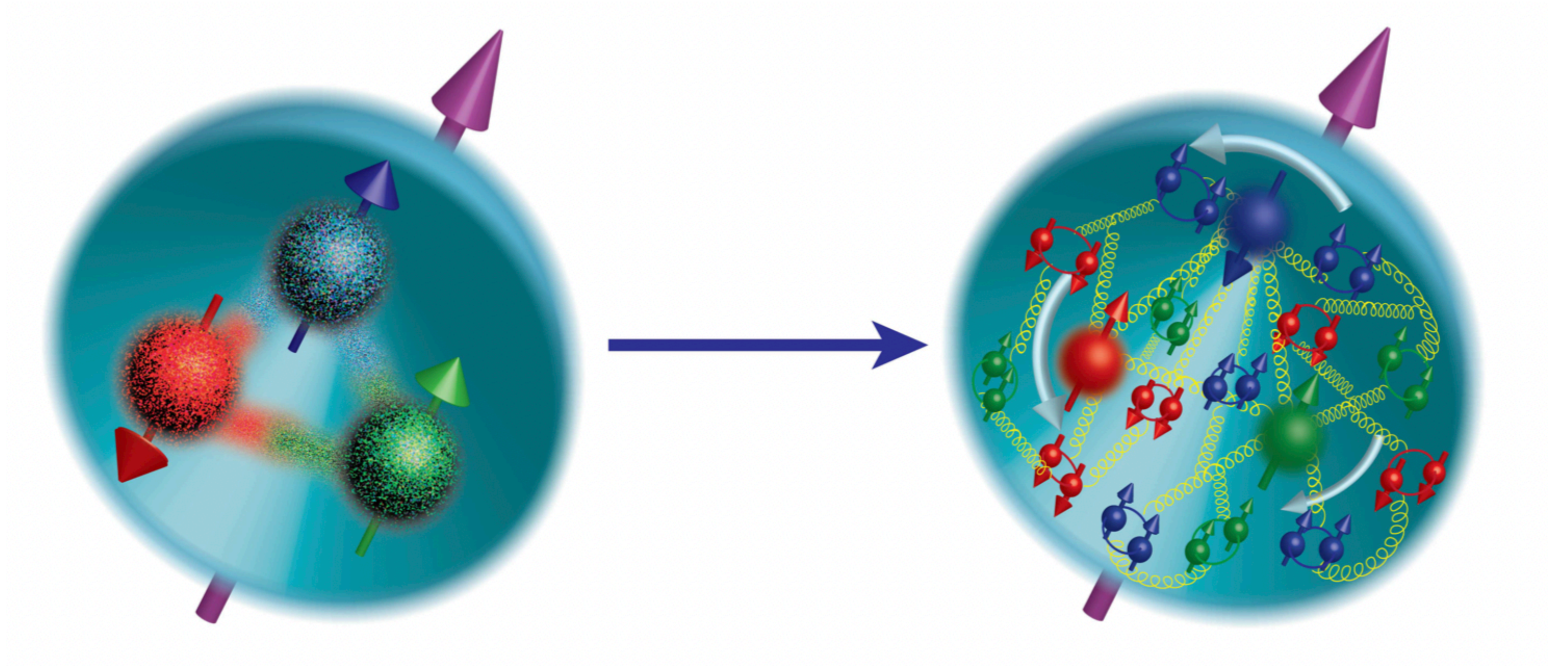
Q^2 small or large

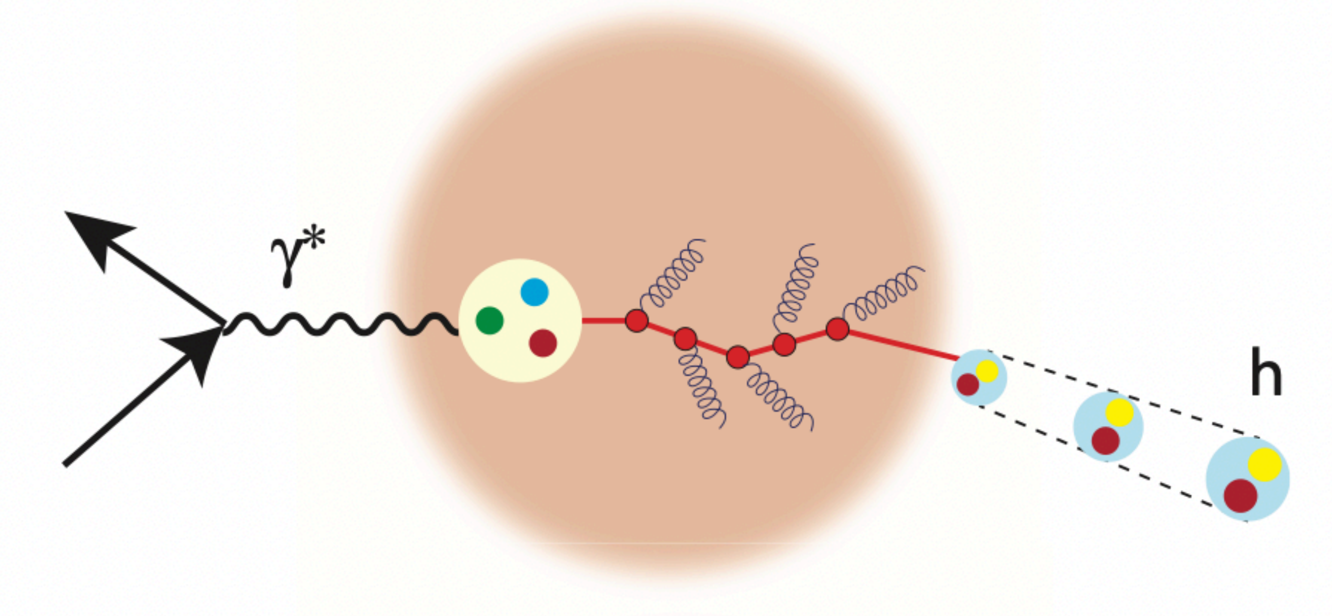
see also asymmetric Centauro algorithm Makris et al.

Summary

- Jets can be versatile tools at the EIC
- Algorithm and frame dependence
- Baseline for PDFs, spin physics, Cold Nuclear Matter, etc.
- HERA measurements?





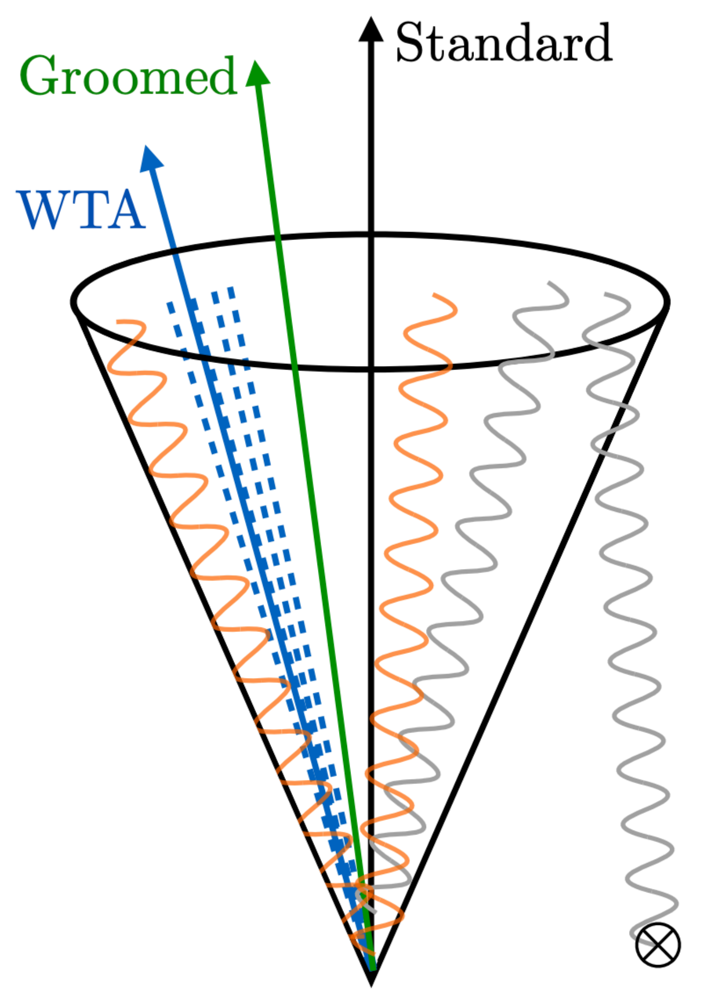


Jet substructure — angles between jet axes

Cal, Neill, FR, Waalewijn `20

- **Jet production** $pp \to \text{jet} + X$

$$\frac{\mathrm{d}\sigma^{pp\to\text{jet}\,X}}{\mathrm{d}\eta\mathrm{d}p_T\mathrm{d}k_\perp} = f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes_z \mathcal{G}_c(z,k_\perp) + \mathcal{O}(R^2)$$



- Angle between Standard & WTA axes

$$\tilde{\mathcal{G}}_i^{\text{ST,WTA}}(k_\perp, p_T R, \alpha_s(\mu)) \overset{\text{NLL}'}{=} \tilde{H}_i(p_T R,\mu) \int \mathrm{d}^2\vec{k}'_\perp C_i(k'_\perp,\mu,\nu) \int \mathrm{d}^2\vec{k}''_\perp S_i^{\text{G}}(\vec{k}_\perp - \vec{k}'_\perp - \vec{k}''_\perp, \mu, \nu R) \times S_i^{\text{NG}}\left(\frac{k''_\perp}{p_T R}\right)$$

Collinear Soft Non-global

TMD factorization, SCET_{II}, but IRC safe; Solve numerically in b-space w/ b_* prescription

Collins, Soper, Sterman `85

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