Jet and grooming algorithms at the future Electron-Ion-Collider

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In this talk:

Asymmetric jet clustering in deep-inelastic scattering

arXiv: 2006.10751

In collaboration with:

M. Arratia, D. Neill, F. Ringer,
N. Sato

Grooming algorithms for DIS: example 1-jettiness

arXiv 2101.02708

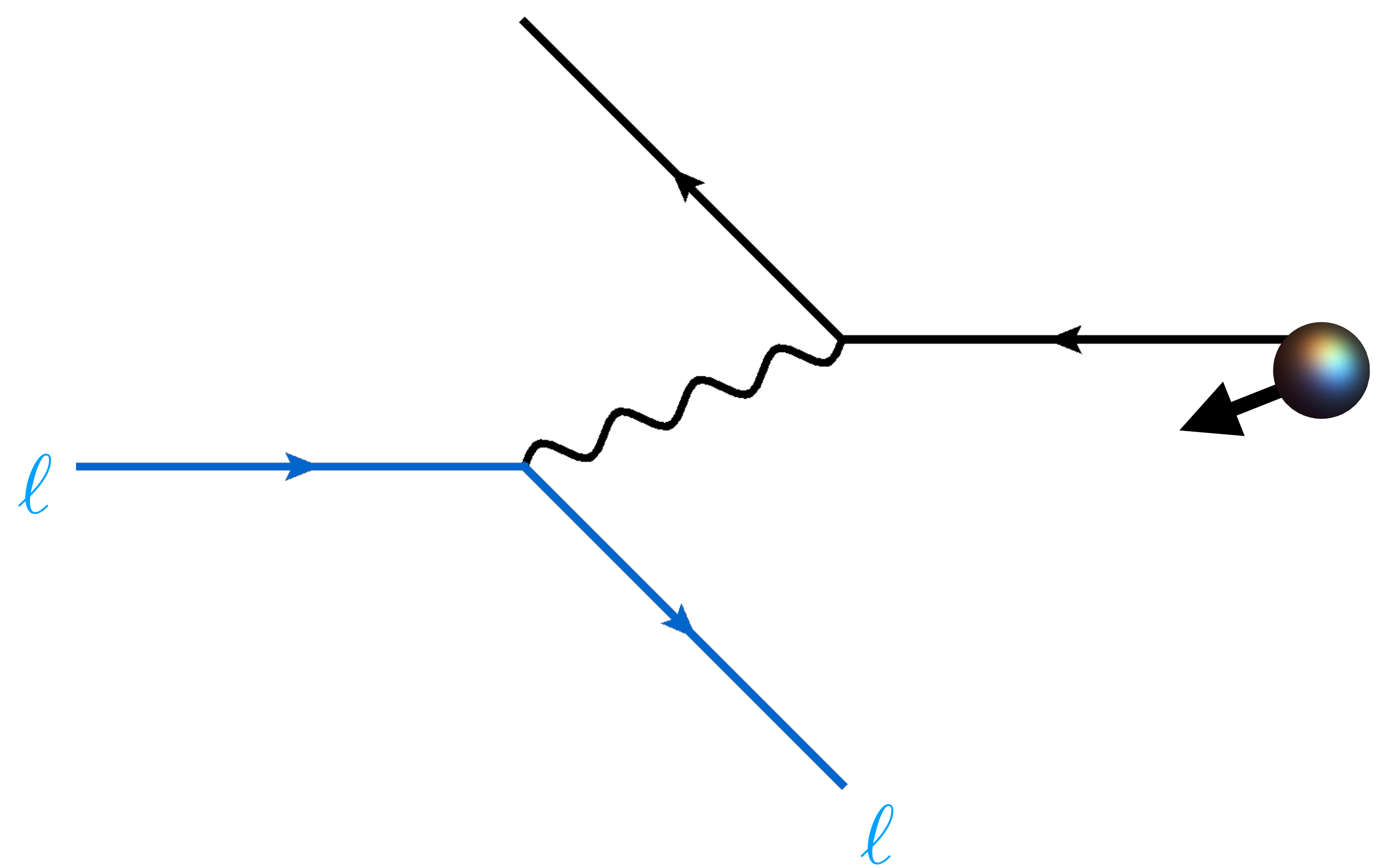
Introduction to jets (Brief and basic)

Jet algorithms (Part 1)

Event grooming and substructure (Part 2)

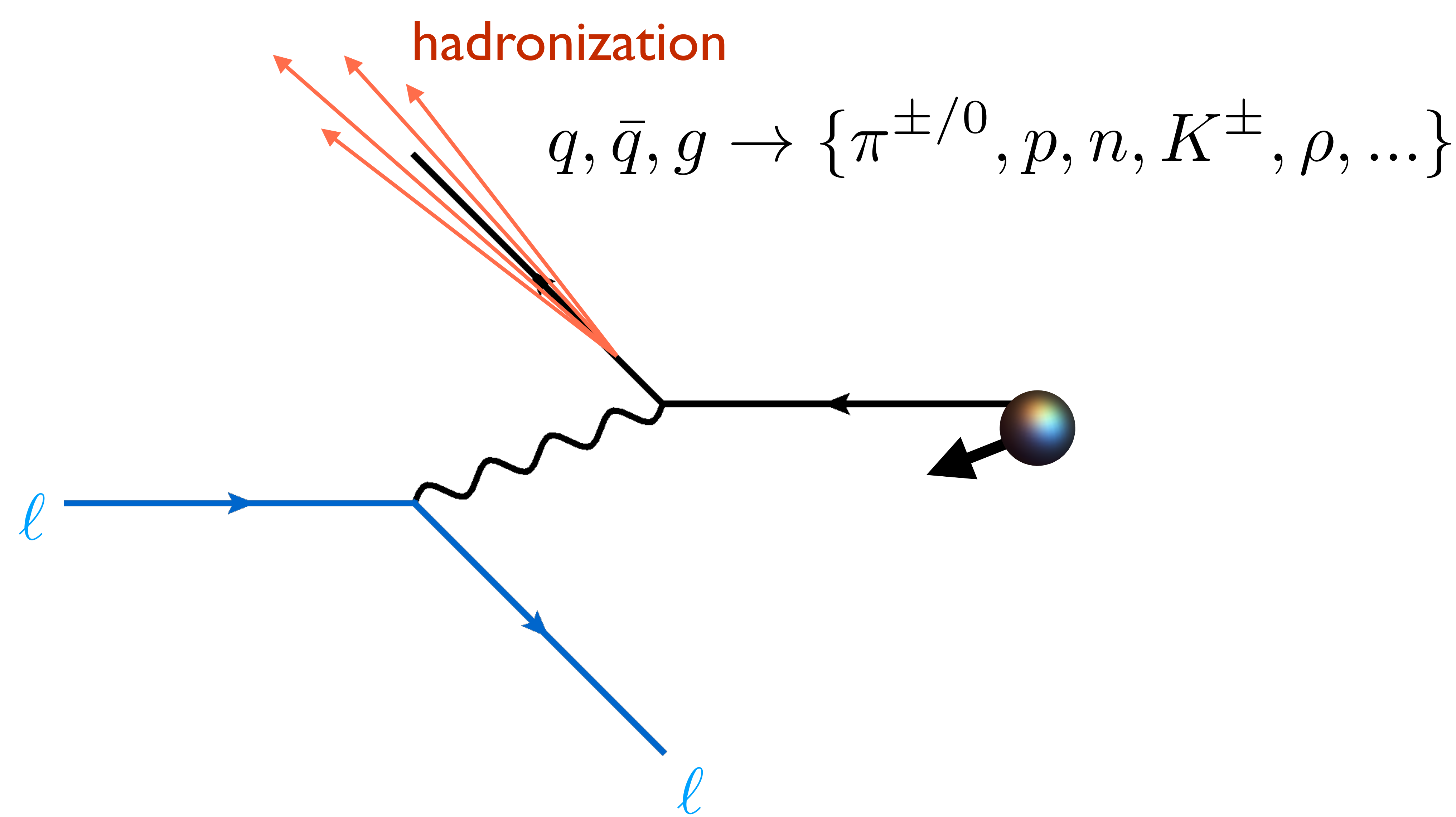
Jets as proxies for partons

deep inelastic scattering



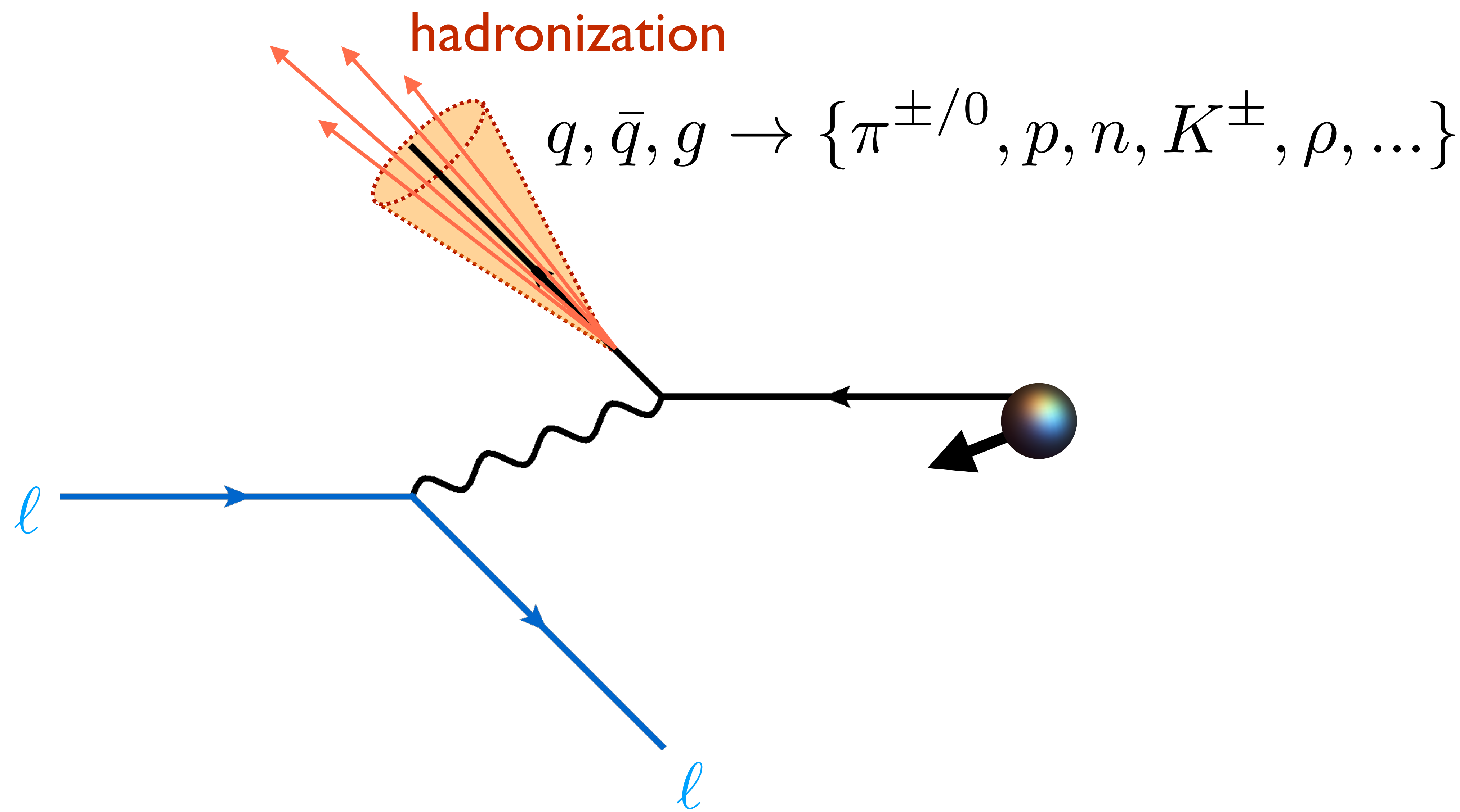
Jets as proxies for partons

deep inelastic scattering



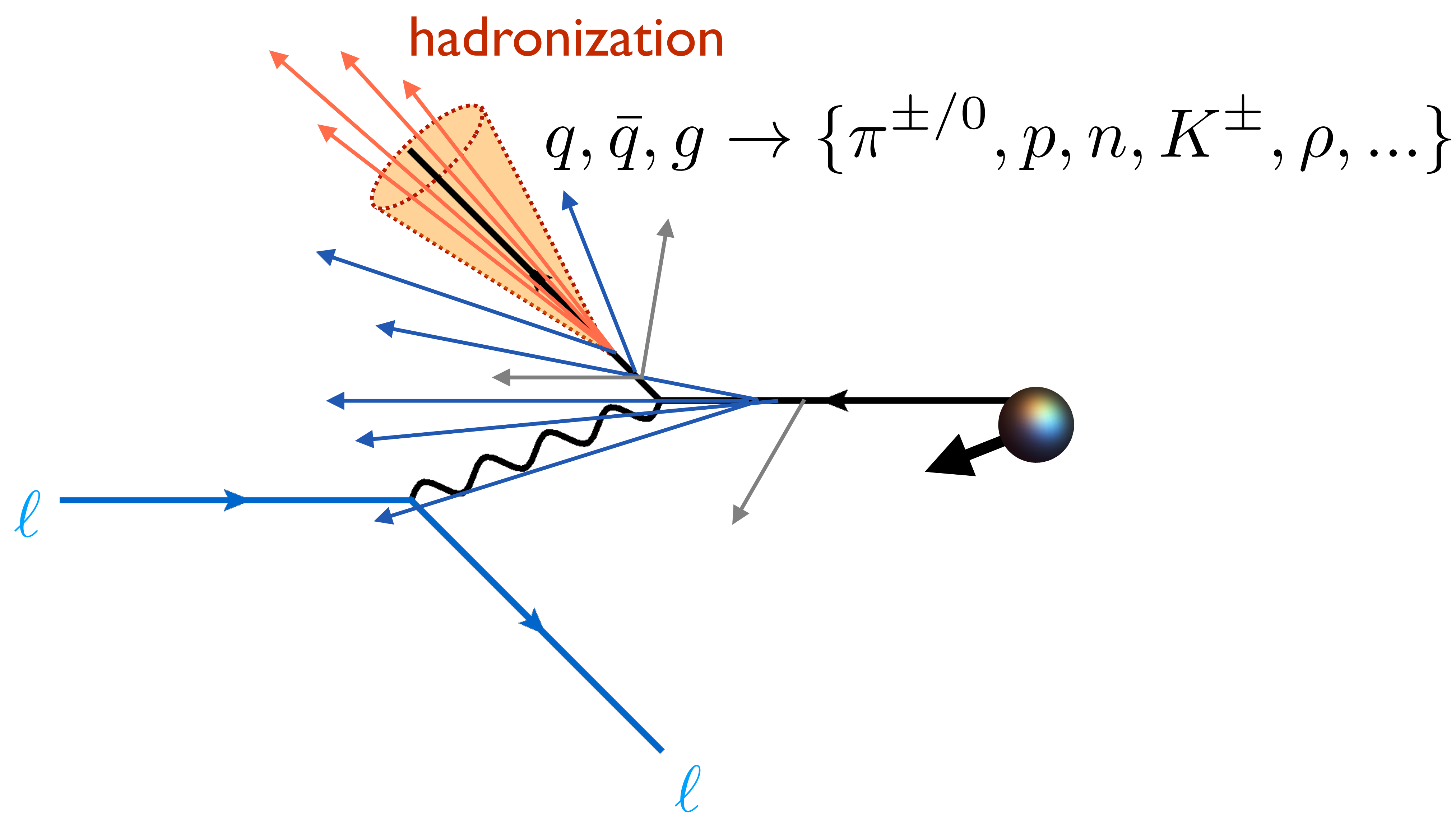
Jets as proxies for partons

deep inelastic scattering



Jets as proxies for partons

deep inelastic scattering

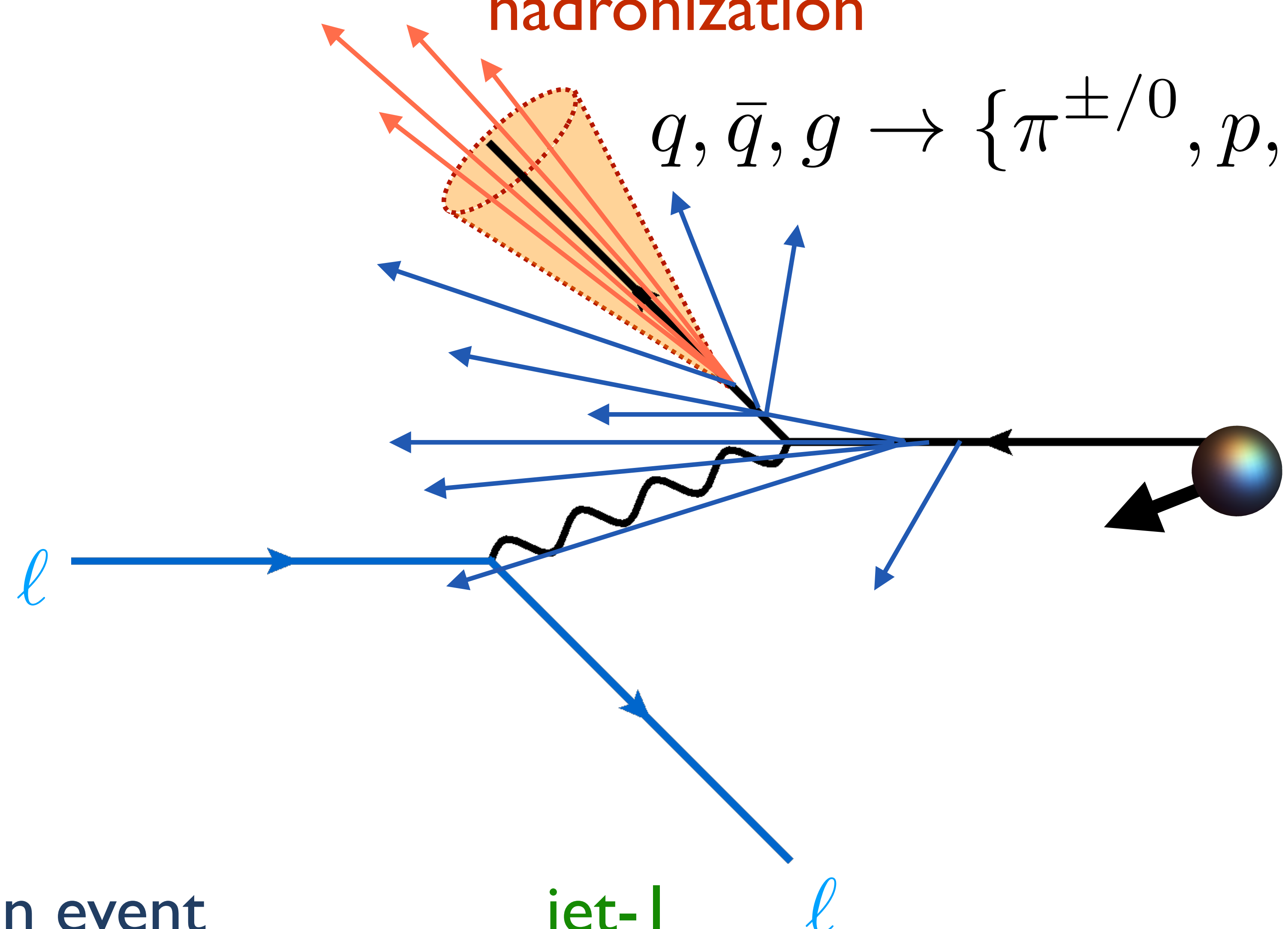


Jets as proxies for partons

deep inelastic scattering

hadronization

$$q, \bar{q}, g \to \{\pi^{\pm/0}, p, n, K^{\pm}, \rho, ...\}$$



Jet algorithms:
Algorithmic, reproducible, processes that **define** the jet

IR-safe definitions of jets

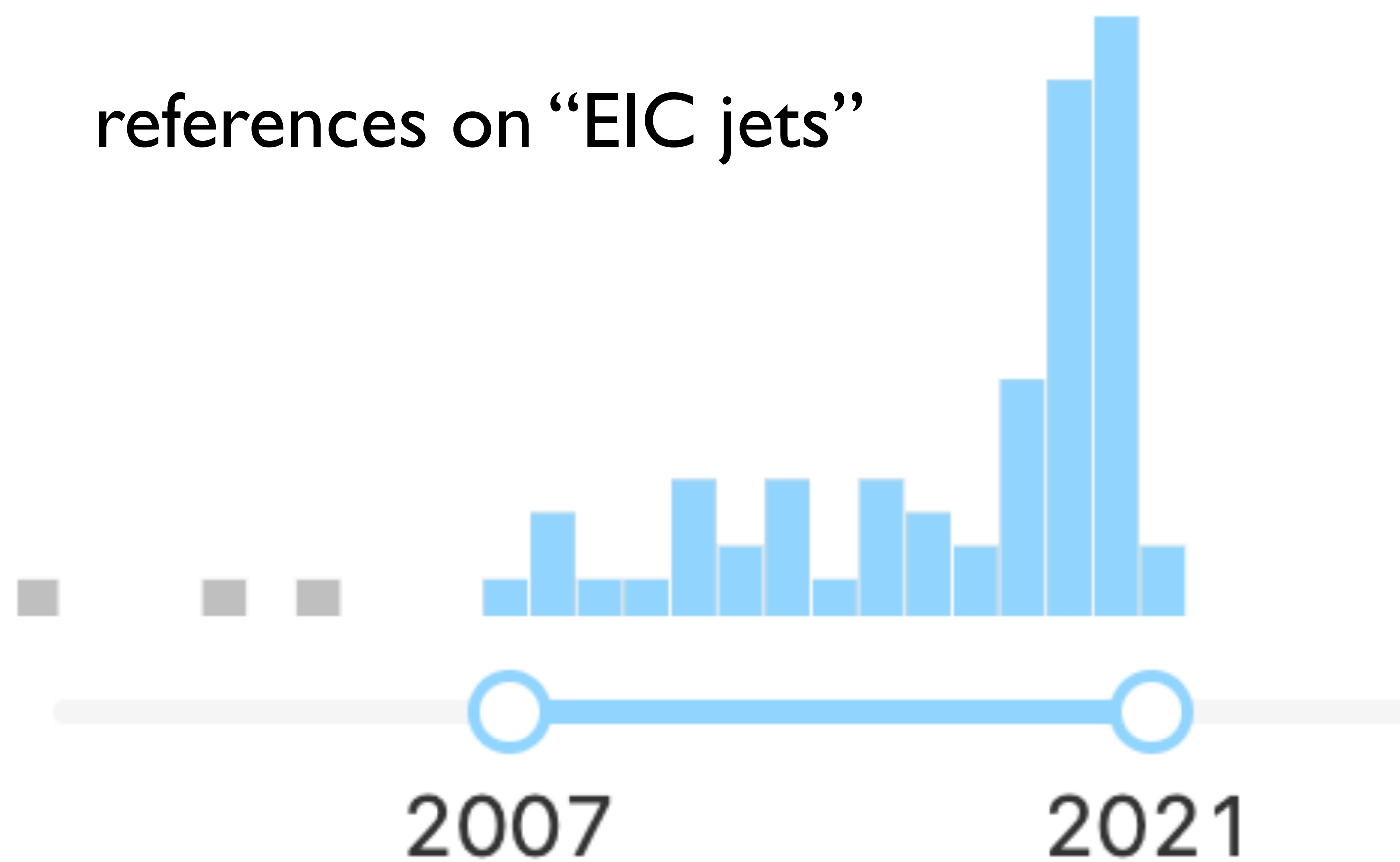
All particles in event — jet-1 — jet-2

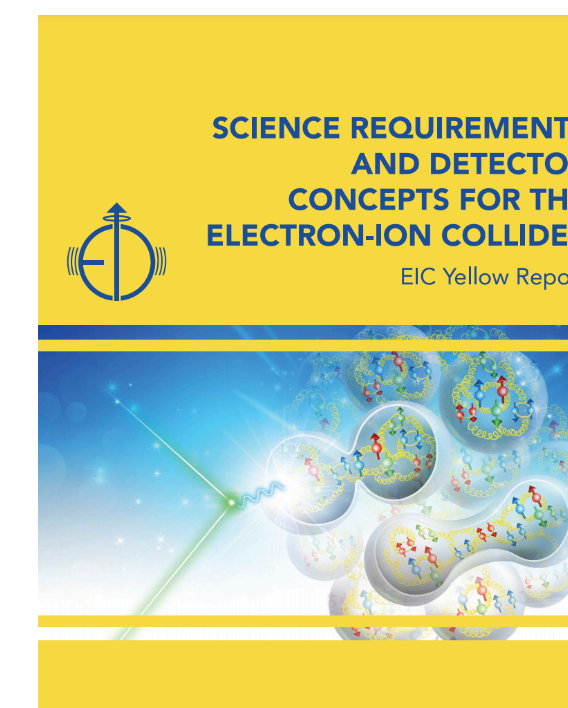
$$p_1, p_2, p_3, \ldots p_n \to \{p_1, p_2, p_3, \ldots\}_{\text{jet-1}}, p_i, p_{i+1}, \ldots \{p_k, p_{k+1}, ..\}_{\text{jet-2}}$$

Jets at Electron-Ion-Collider (EIC)

Source: inspirehep.net

references on “EIC jets”





http://www.eicug.org/web/content/yellow-report-initiative

Application of jets at EIC

Extraction of strong-coupling: multi-jet rates, event shapes, jet substructure,…

Hadronic structure: Jet-TMDs, in-jet fragmentation, multi-jet rates, diffractive processes,…

Nuclear matter probes: Jet substructure, jet rates and jet quenching,…

Hadronization: Jet substructure, in-jet fragmentation, jet energy loss,…

Introduction to jets (Brief and basic)

Jet algorithms (Part 1)

Event grooming and substructure (Part 2)

The kT-type algorithms

1. Evaluate distance:

$$d_{ij} = \min[k_{Ti}^{2p}, k_{Tj}^{2p}] \frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

"particle"-"particle"

$$d_{iB} = k_{Ti}^{2p}$$

"particle"-"beam"

2. Merge "nearest"

3. Repeat

Anti-kT: p = -1

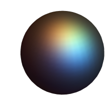
arXiv:0802.1189 (M. Cacciari, G. P. Salam and G. Soyez)

Selectors (e.g. $p_T > 20$ GeV)

Final set of jets

Breit Frame kinematics

$n^\mu = (1, 0, 0, +1) \qquad \bar{n}^\mu = (1, 0, 0, -1)$

<u>Proton</u> 

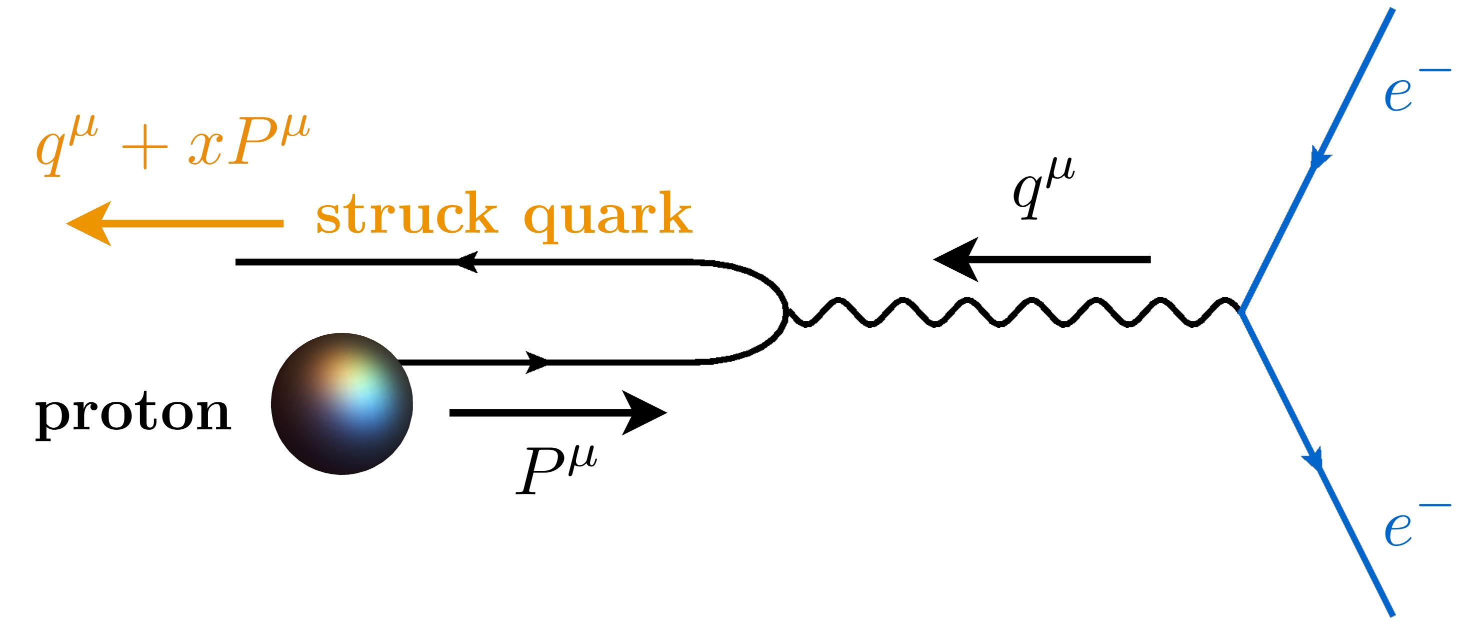
$$P^\mu = \frac{Q}{2x_B} n^\mu$$

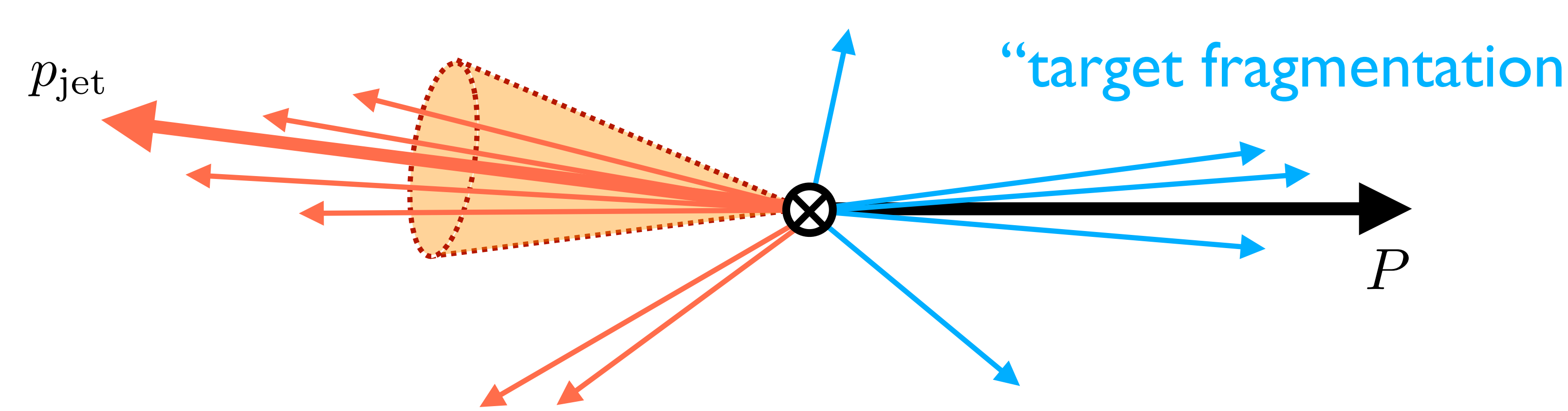
<u>Photon</u>

$$q^\mu = \frac{Q}{2}(n^\mu - \bar{n}^\mu)$$

<u>Struck quark</u>

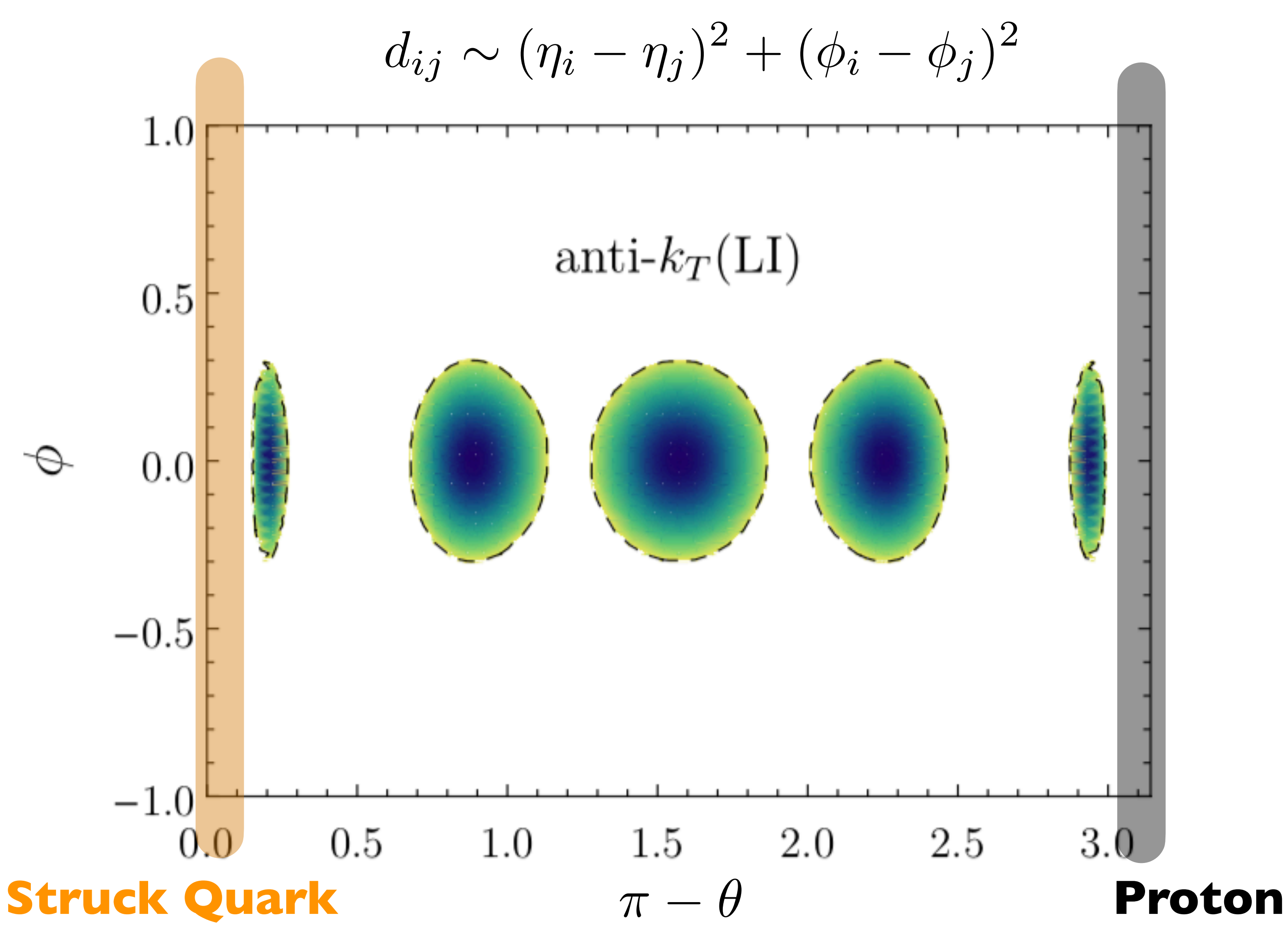
$$p^\mu = q^\mu + xP^\mu = \frac{Q}{2}\bar{n}^\mu$$

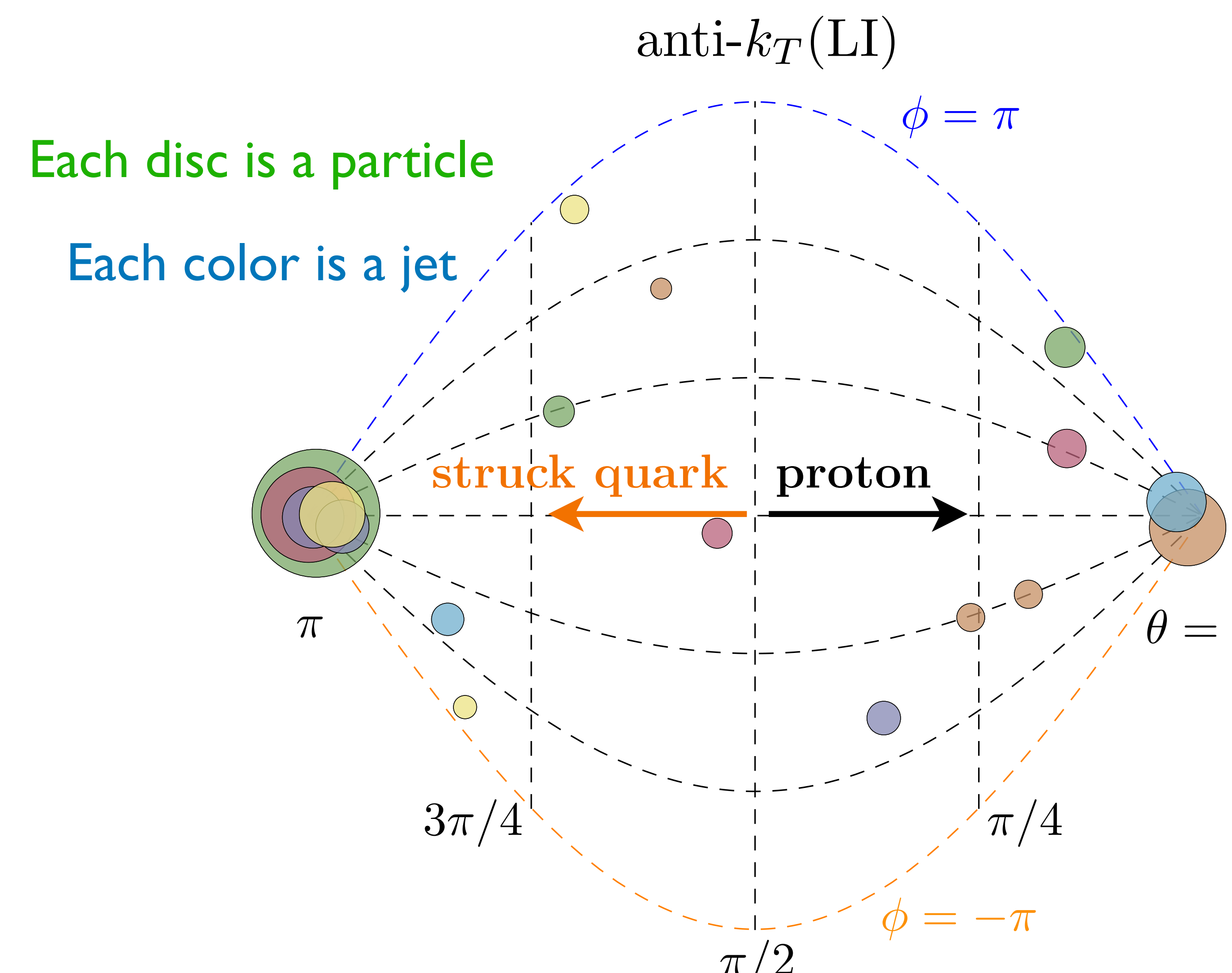




Longitudinally invariant algorithms

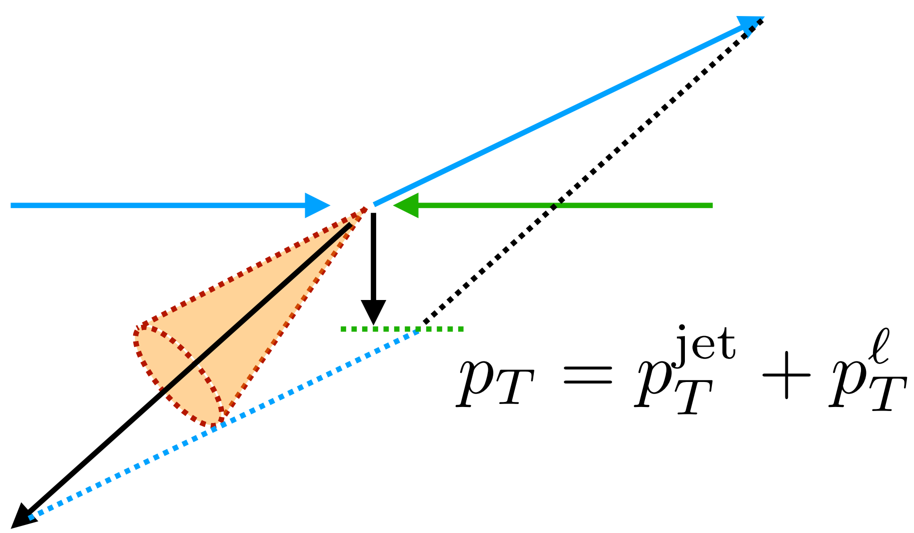
However, in Breit Frame since they cluster in the ***η-ϕ*** space,
they fail to capture jets in the very backward direction, where we are looking for one.





Universal TMDs in the Breit frame

LAB frame

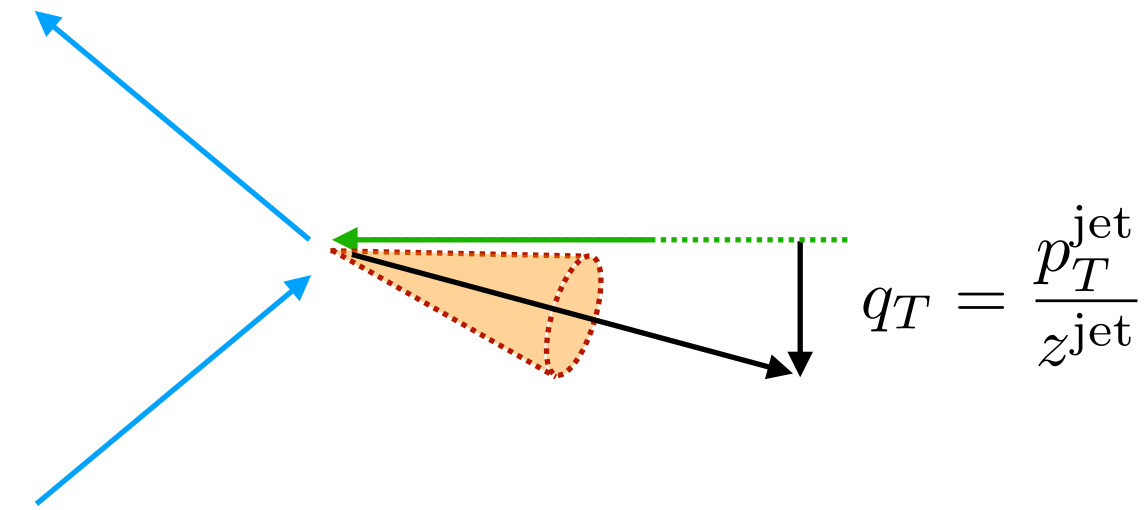


$$d\sigma \sim \Big(f(x,b)\,S_{n_1 n_2}(b)\Big)\,J(z,b)$$

Not universal

arXiv:1812.08077 (X. Liu, F. Ringer, W. Vogelsang, and F. Yuan)

Breit frame



$$d\sigma \sim \Big(f(x,b)\sqrt{S_{n\bar{n}}(b)}\Big)\Big(D(z,b)\sqrt{S_{n\bar{n}}(b)}\Big)$$

Universal

arXiv:1807.07573 (D. G.-Reyes, I. Scimemi, W. J. Waalewijn, L. Zoppi)

Also non-perturbative analysis for jet substructure observables (e.g. jet mass) is simplified in the Breit frame (work in progress)

Alternative algorithms

kT-type (SI)

Spherically invariant

$$d_{ij} = \min(E_i^{2p}, E_j^{2p}) \frac{1-\cos\theta_{ij}}{1-\cos R}$$

$$d_{iB} = E_i^{2p}$$

Similar algorithm for DIS by:
S. Catani, Y. L. Dokshitzer, and B. Webber, (1992)

Here we use: $p = -1$

Centauro

Longitudinally invariant

$$d_{ij} = \min[z_i^{2p}, z_j^{2p}](\Delta f_{ij}^2 + 2 f_i f_j (1 - \cos\Delta\phi_i j))/R^2$$

$$d_{iB} = z_i^{2p}$$

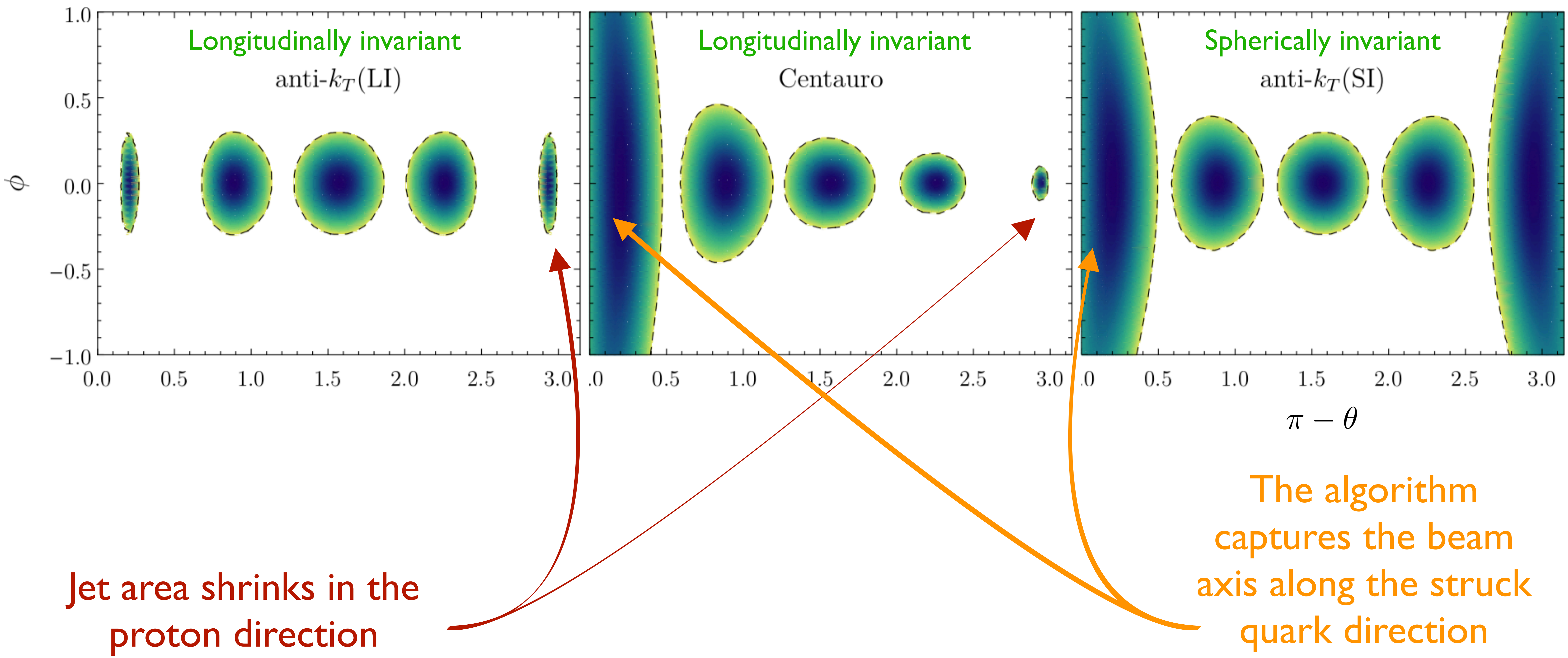
Asymmetric measure

$$f(x) = x + \mathcal{O}(x^2)$$

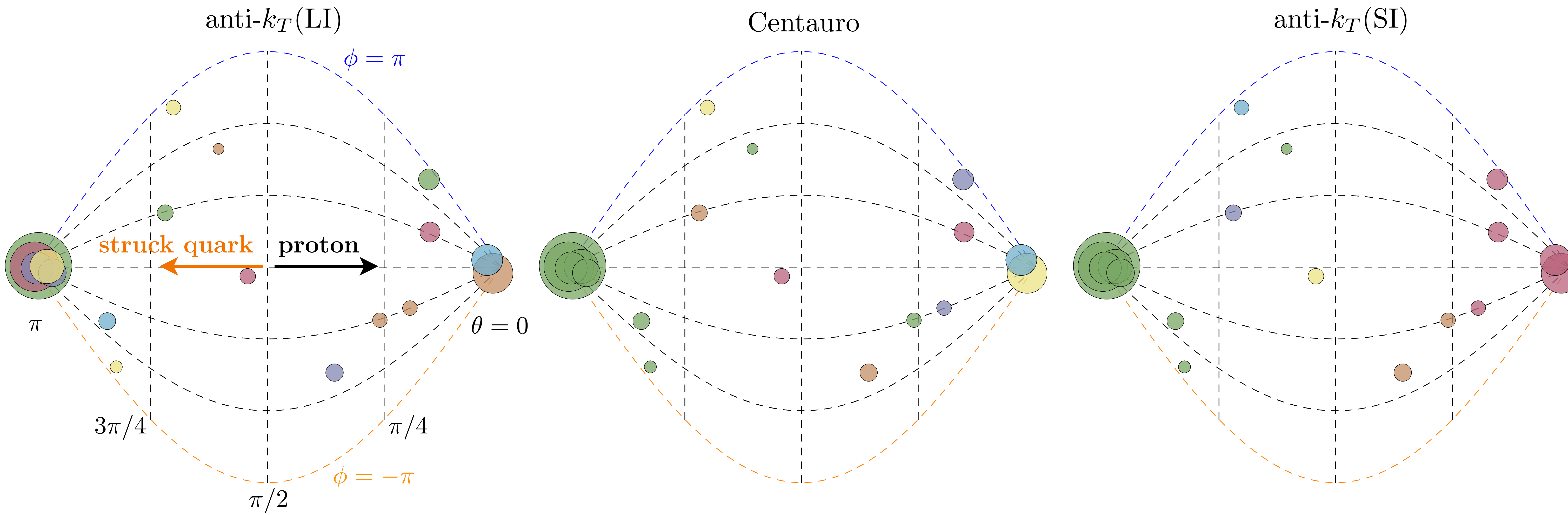
$$\bar{\eta}_i = -\frac{2Q}{\bar{n}\cdot q}\frac{p_i^{\perp}}{n\cdot p_i}$$

$$\bar{\eta}_i(\mathrm{BF}) = 2p_i^{\perp}/p_i^{+}$$

Centauro: a hybrid algorithm



Clustering



Longitudinally invariant
Symmetric

Longitudinally invariant
Asymmetric

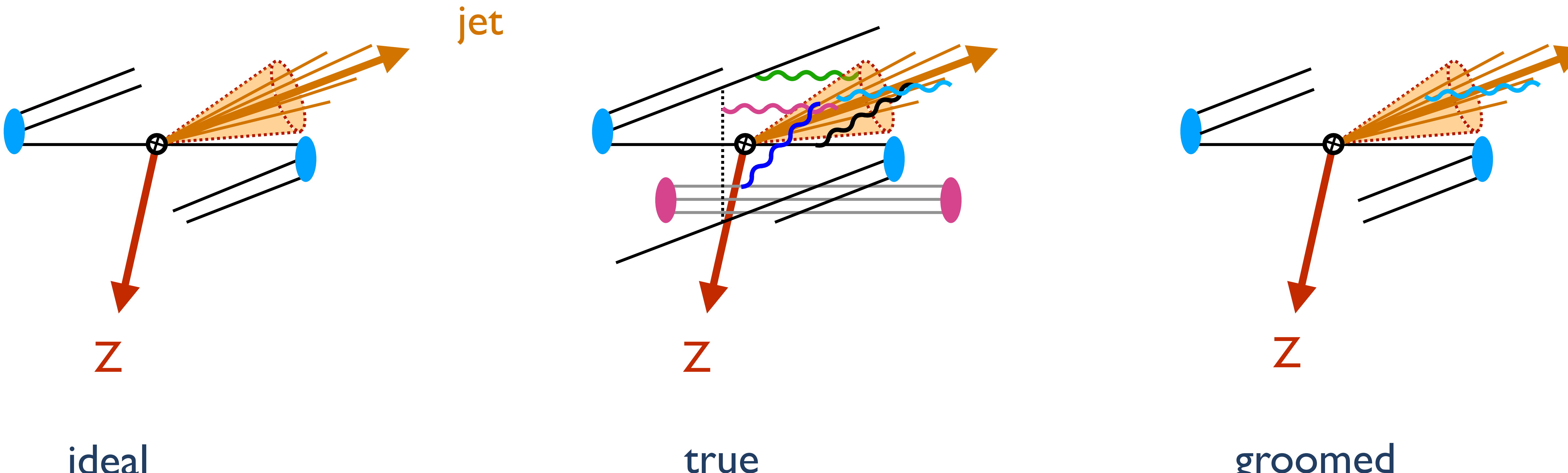
Spherically invariant
Symmetric

Introduction to jets (Brief and basic)

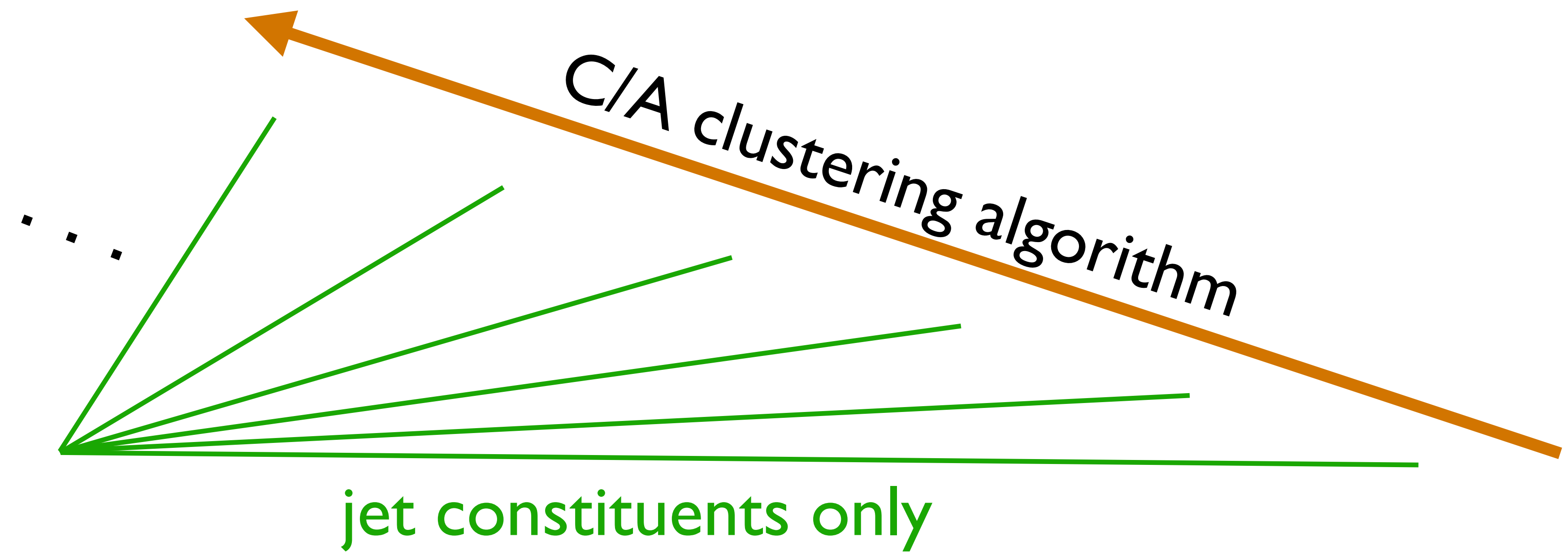
Jet algorithms (Part 1)

Event grooming and substructure (Part 2)

Jet grooming



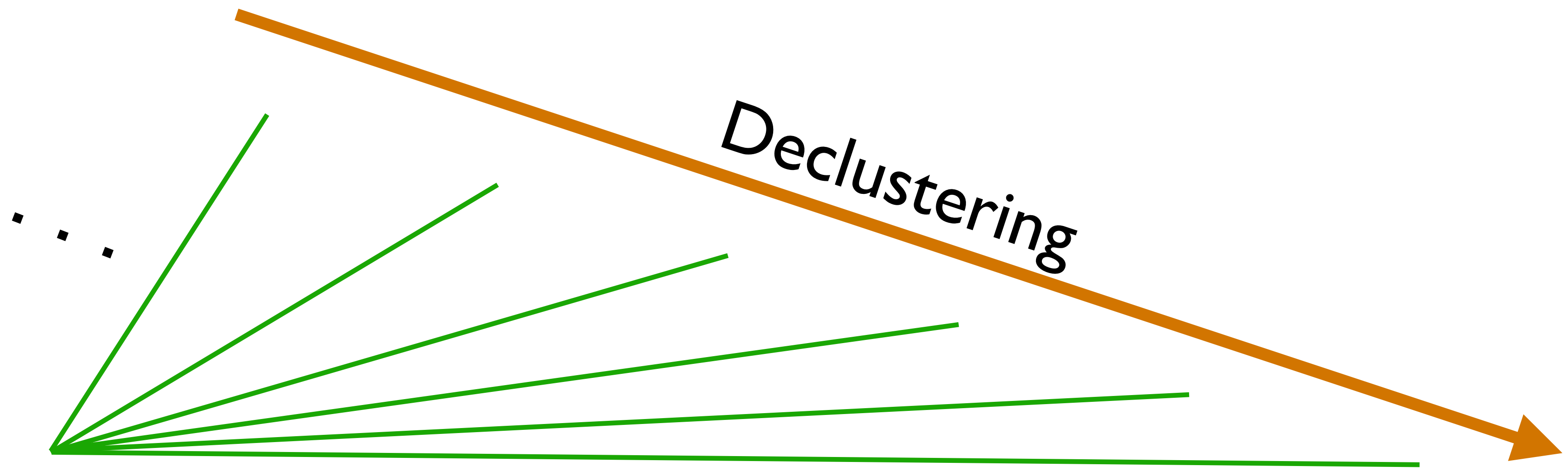
mMDT



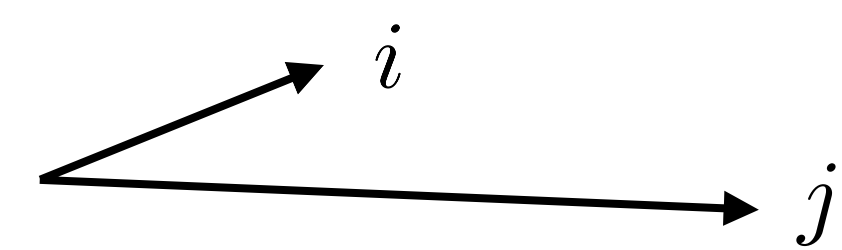
- The algorithm is imposed only on the jet constituents
- Particles closer in angle get clustered first
- Record clustering history in each step (example coming soon)

arXiv:1307.0007 (M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam)

mMDT



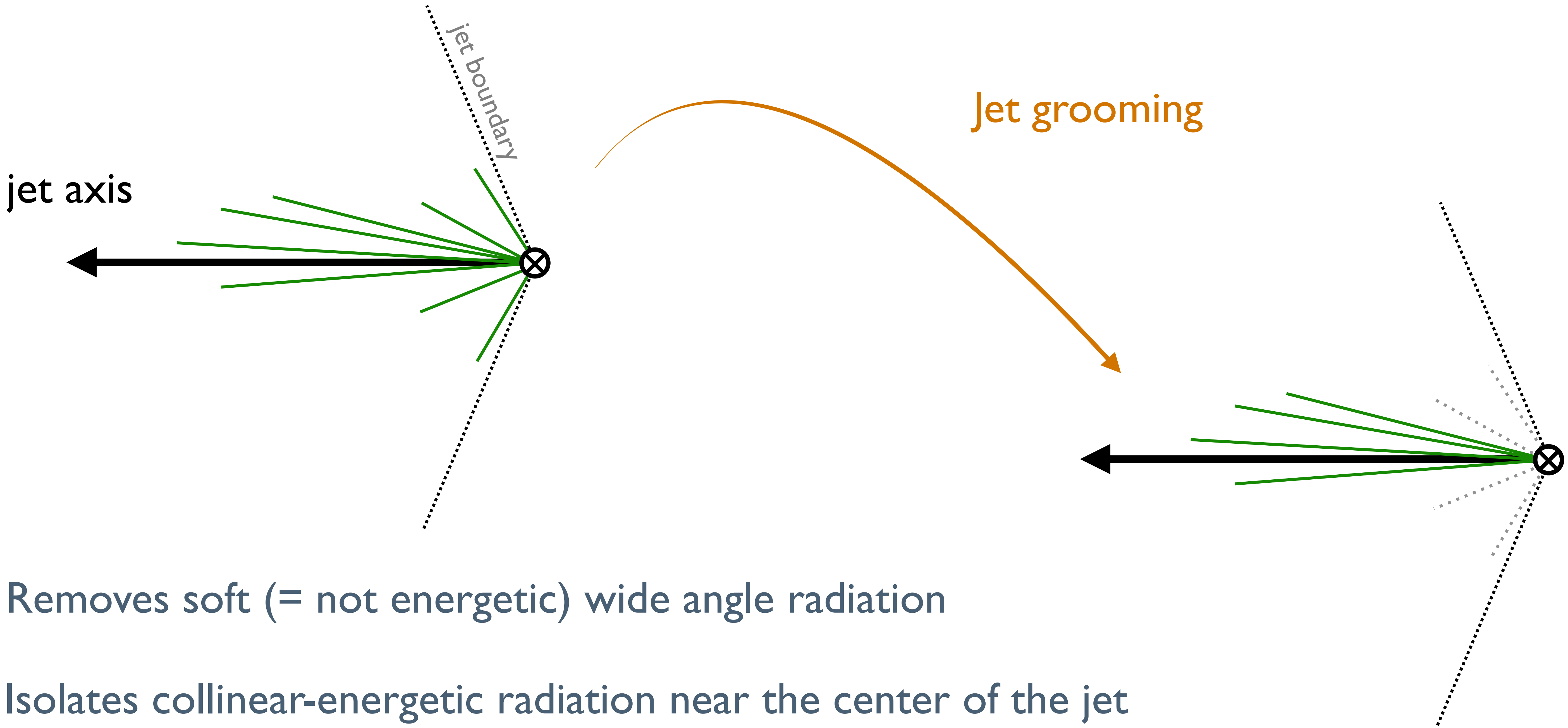
$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{\rm cut}$$



True
Stop. Remaining particles consist groomed jet

False
Drop the softer of the two branchings

Jet grooming



- Removes soft (= not energetic) wide angle radiation

- Isolates collinear-energetic radiation near the center of the jet insensitive to the cone/boundary

- Reduce contamination from underlying event

The grooming algorithm in DIS events

UE will not be a problem in EIC ✗

No non-global effects ✓

Handle on soft radiation ✓

Dial on non-perturbative corrections ✓

Universal FS matrix elements ✓

Low particle multiplicity !

Breit Frame kinematics

Proton

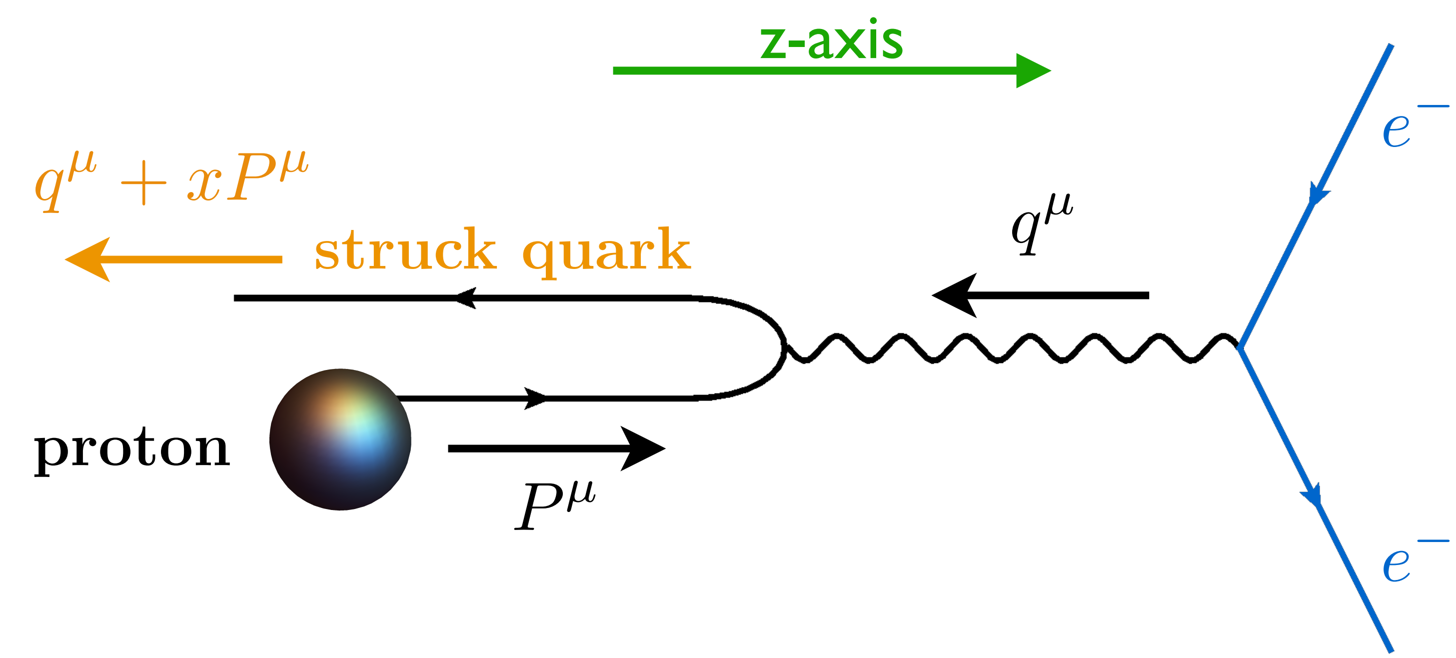
$$P^\mu = \frac{Q}{2x_B}(1,0,0,1)$$

Photon

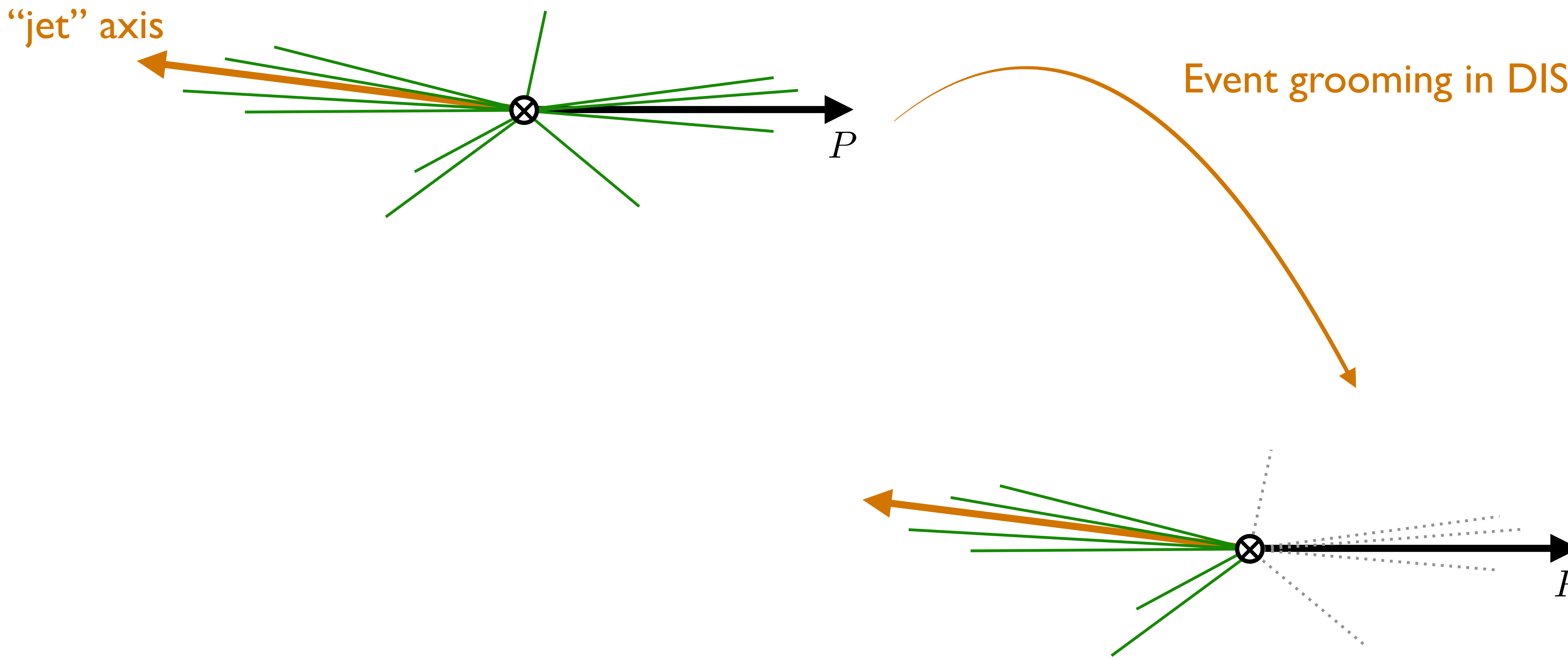
$$q^\mu = (0,0,0,-Q)$$

Struck quark

$$p^\mu = \frac{Q}{2}(1,0,0,-1)$$



Event grooming



The grooming algorithm

<u>modified MassDrop Tagger (mMDT)</u>

Centauro clustering measure, (instead of C/A) *

Modified grooming condition, (p^+ instead of p^0)

$$\frac{\min(E_i, E_j)}{E_i + E_j} > z_{\rm cut} \quad \longrightarrow \quad \frac{\min(z_i, z_j)}{z_i + z_j} > z_{\rm cut}$$

Applied to the event, (instead of jets or hemispheres)

* A similar procedure can be imposed in the Laboratory frame using C/A (L.I.)

The grooming algorithm

<u>(Step 1/2) Clustering</u>

1. For all pair of particles (i, j) calculate: $d_{ij} = (\bar{\eta}_i - \bar{\eta}_j)^2 + 2\bar{\eta}_i\bar{\eta}_j(1 - \cos(\phi_i - \phi_j))$

2. Find the smallest measure and cluster particles i and j into a single branch

3. Repeat until all particles are clustered together

The grooming algorithm

(Step 2/2) **De**Clustering: Open the clustered tree in the reverse order.
In each decluttering step there are two branches.

1. For these two branches test the condition: $$\frac{\min(z_i,\, z_j)}{z_i + z_j} > z_{\rm cut} \qquad z_i = \frac{P \cdot p_i}{P \cdot q}$$

2. If the condition is false, drop the branch with smallest z_i, and continue with the decluttering (point1) of the branch largest z_i.

3. Repeat until the condition evaluate true

Energy fraction (of particle *i*)

Definition

$$z_i = \frac{P \cdot p_i}{P \cdot q}$$

Boundaries

$$z_i(\text{Breit frame}) = p_i^+/Q$$

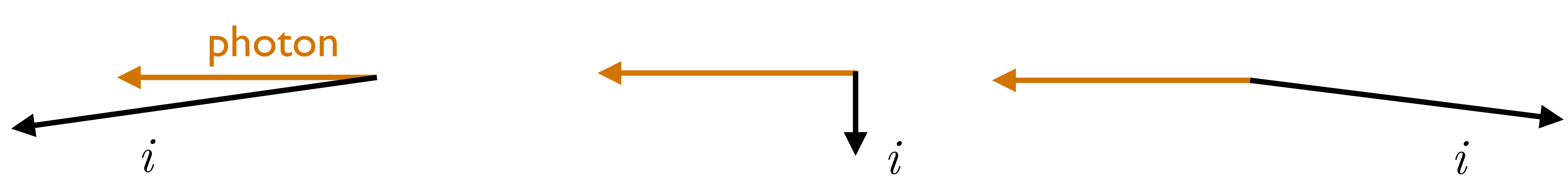
$$z_i \geq 0$$

$$z_i < 1$$

$$\sum_{i \in \text{event}} z_i = 1$$

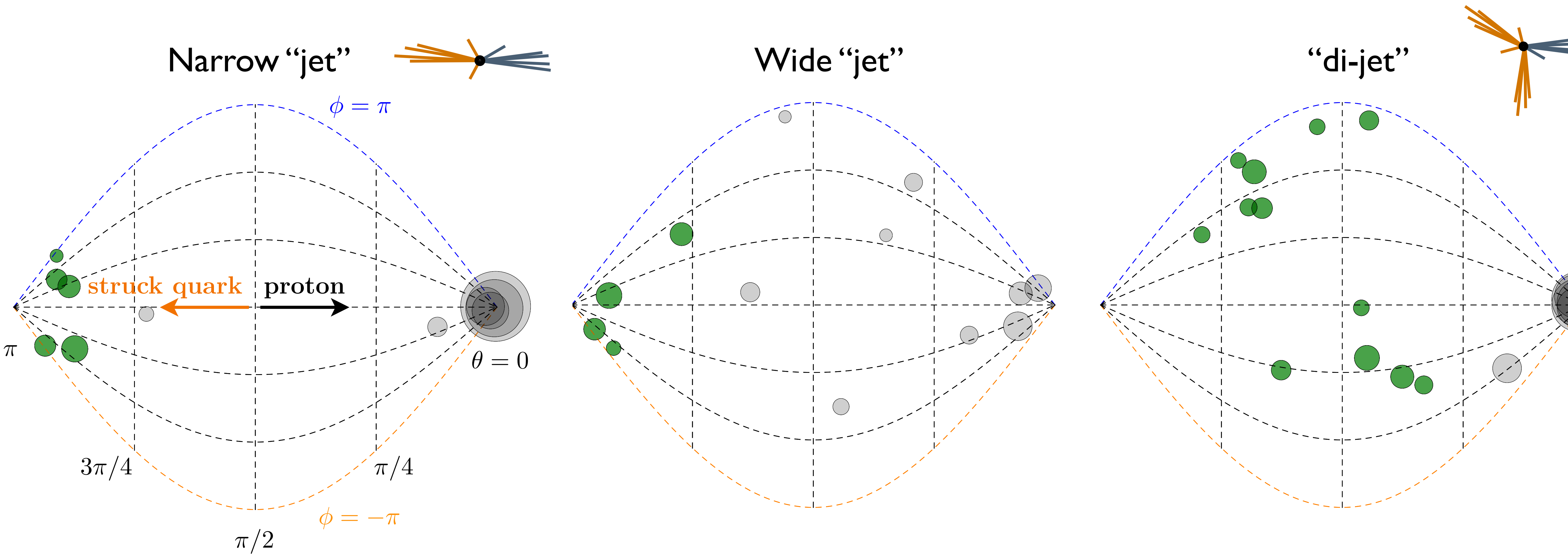
Limits (geometric interpretation in the Breit frame)

$z_i \sim 1$ | $z_i \ll 1$ | $z_i \ll 1$



collinear | soft | anti-collinear

The grooming algorithm



Each disc is a particle: = Pass Grooming

= Fail Grooming

PYTHIA 8 : $\sqrt{s} = 63$ GeV

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

$Q > 10$ GeV

Applications for EIC

Event-shape observables in ep

Dynamics and interplay of perturbative QCD and hadronization

Extracting QCD fundamental constants (strong coupling)

Fragmentation of heavy quarks

3D-structure of the proton (complementary to semi-inclusive DIS)

Probe to initial state (proton/nuclear) TMDs (no TMD-FFs)

Probe to final state TMDs and TMD evolution (no TMD-PDFs)

Cold nuclear matter effects

Jet substructure → Event substructure (z_g, θ_g)

Clean access to modifications from propagation in nuclear medium

Applications for EIC

Event-shape observables in ep ← Discuss next (as an example 1-jettiness/“jet”-mass)

Dynamics and interplay of perturbative QCD and hadronization

Extracting QCD fundamental constants (strong coupling)

Fragmentation of heavy quarks

3D-structure of the proton (complementary to semi-inclusive DIS)

Probe to initial state (proton/nuclear) TMDs (no TMD-FFs)

Probe to final state TMDs and TMD evolution (no TMD-PDFs)

Cold nuclear matter effects

Jet substructure → Event substructure (z_g, θ_g)

Clean access to modifications from propagation in nuclear medium

1-jettiness in DIS

$$\tau_1 = \frac{2}{Q^2} \sum_{i \in \text{event}} \min(q_B \cdot p_i,\, q_J \cdot p_i) \qquad q_B^\mu = x P^\mu \qquad q_J^\mu = \frac{Q}{2}(1, \hat{t}) \equiv \frac{Q}{2} n_J^\mu$$

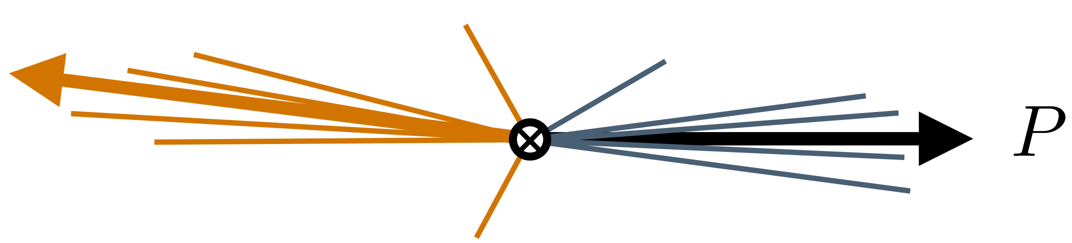
arXiv: 1004.2489 (I. W. Stewart, F. J. Tackmann, and W. J. Waalewijn)

arXiv: 1204.5469 (Z.-B. Kang, S. Mantry, J.-W. Qiu)

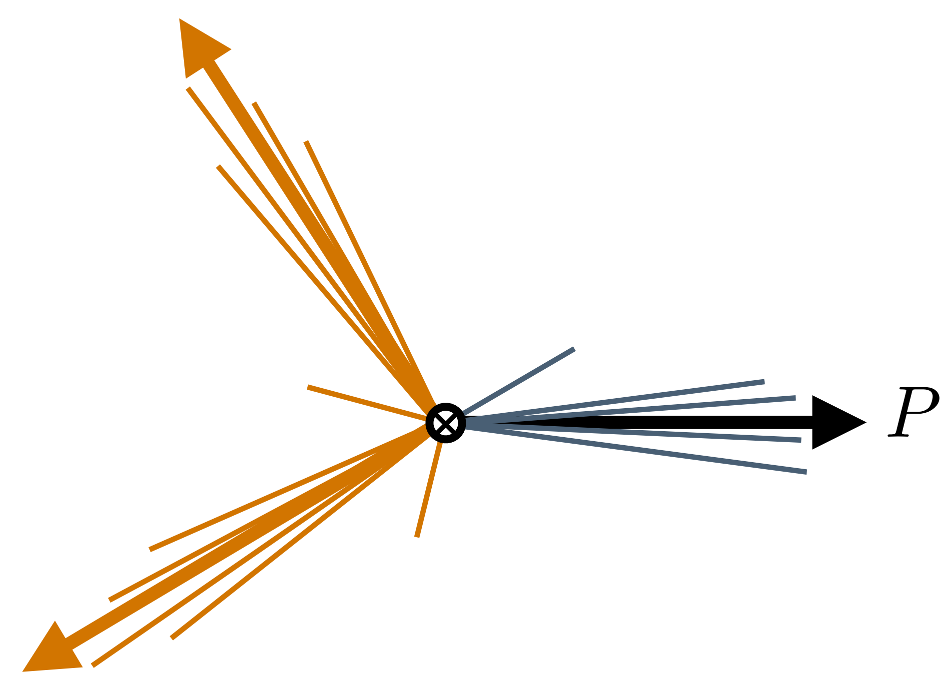
arXiv: 1303.6952 (D. Kang, C. Lee, I. W. Stewart1)

$\tau_1 \to 0 = 1$ jet
$\tau_2 \to 0 = 2$ jets
$\tau_3 \to 0 = 3$ jets
$\vdots$

Breit frame illustration:



$\tau_1 \to 0$



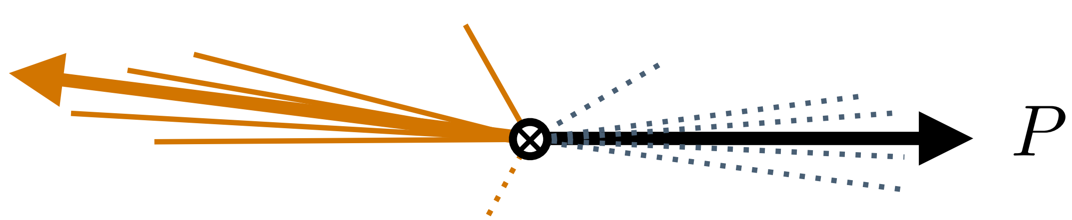
$\tau_1 \sim 1$

Groomed 1-jettiness: definition

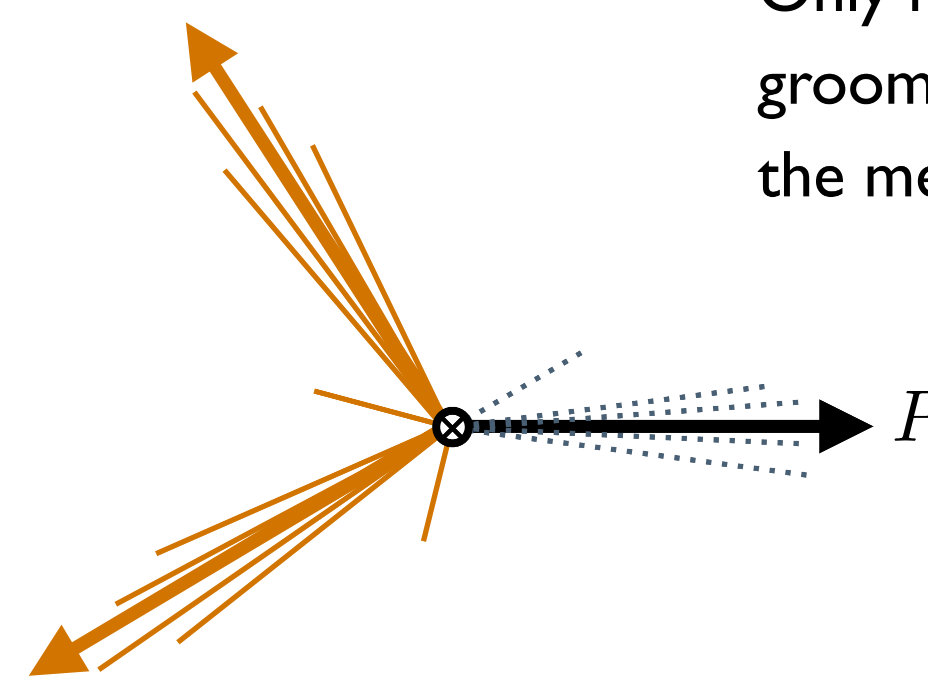
$$\tau_1 = \frac{2}{Q^2} \sum_{i \in \text{gr. ent.}} \min(q_B \cdot p_i,\, q_J \cdot p_i) \qquad q_B^\mu = x P^\mu \qquad q_J^\mu = \frac{Q}{2}(1, \hat{t}) \equiv \frac{Q}{2} n_J^\mu$$

Only radiation that passed grooming will contribute to the measurement.

Breit frame illustration:



$\tau_1 \to 0$



$\tau_1 \sim 1$

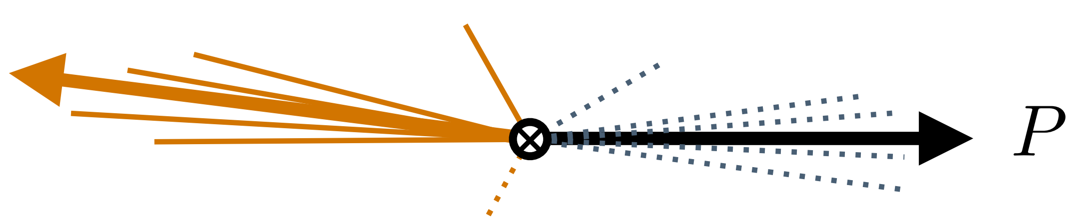
Groomed invariant-mass: definition

$$m_{\text{gr.}}^2 = \Big(\sum_{i \in \text{gr. ent.}} p_i^\mu \Big)^2$$

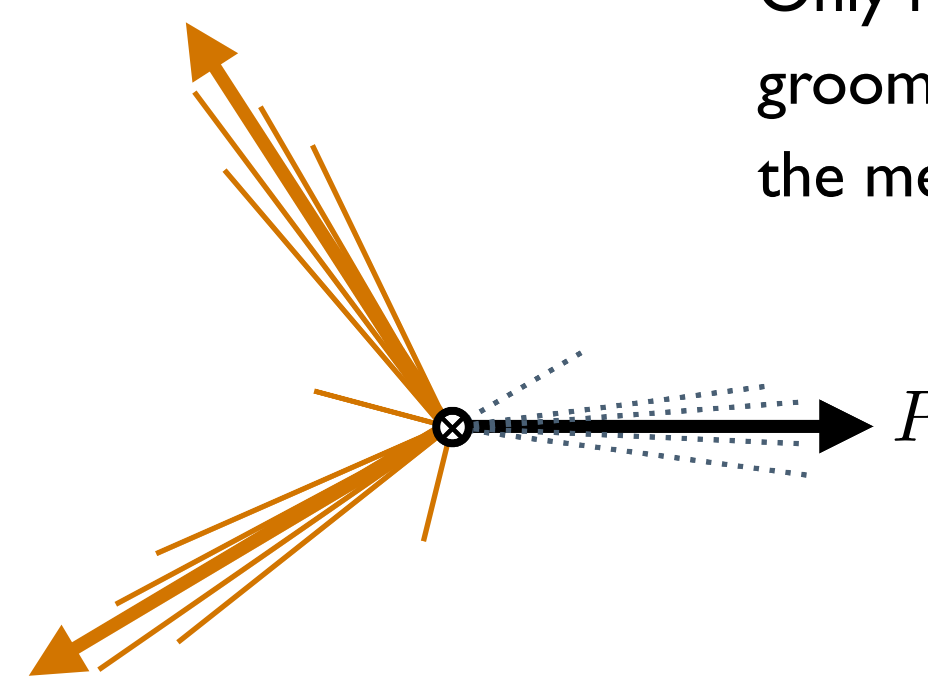
No hemispheres, no boundary conditions
no jet definitions.

Only radiation that passed grooming will contribute to the measurement.

Breit frame illustration:



$m_{\text{gr.}}^2/Q^2 \to 0$



$m_{\text{gr.}}^2/Q^2 \sim 1$

Groomed invariant-mass: definition

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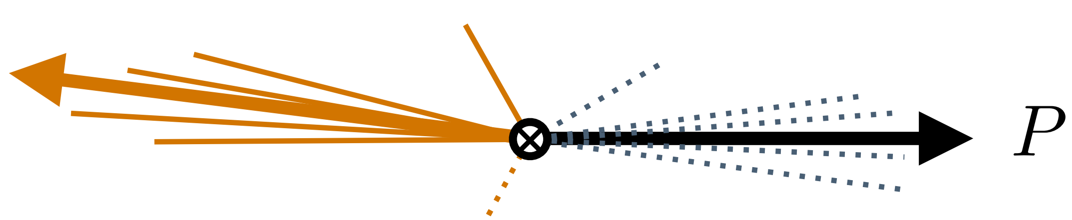
Breit frame illustration:



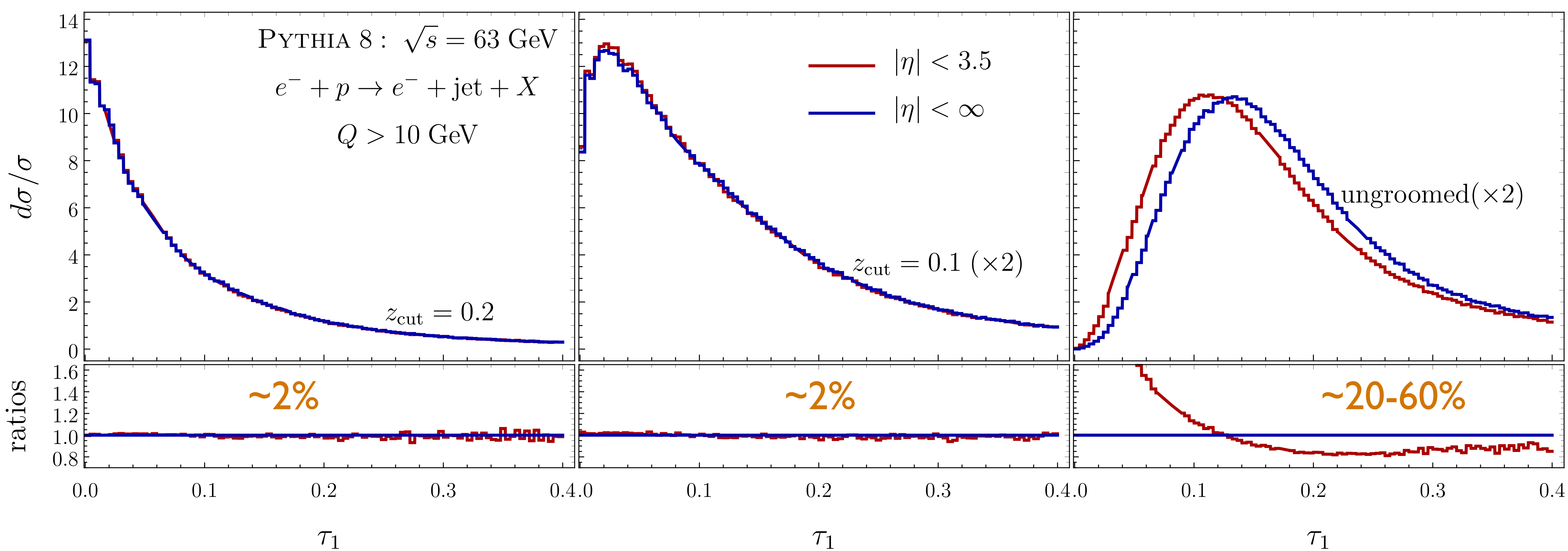
$m^2_{\text{gr.}}/Q^2 \to 0$

In the back-to-back limit the two observables are related:

$$m^2_{\text{gr.}} = Q^2 \tau_1 + \mathcal{O}(\tau_1^2)$$

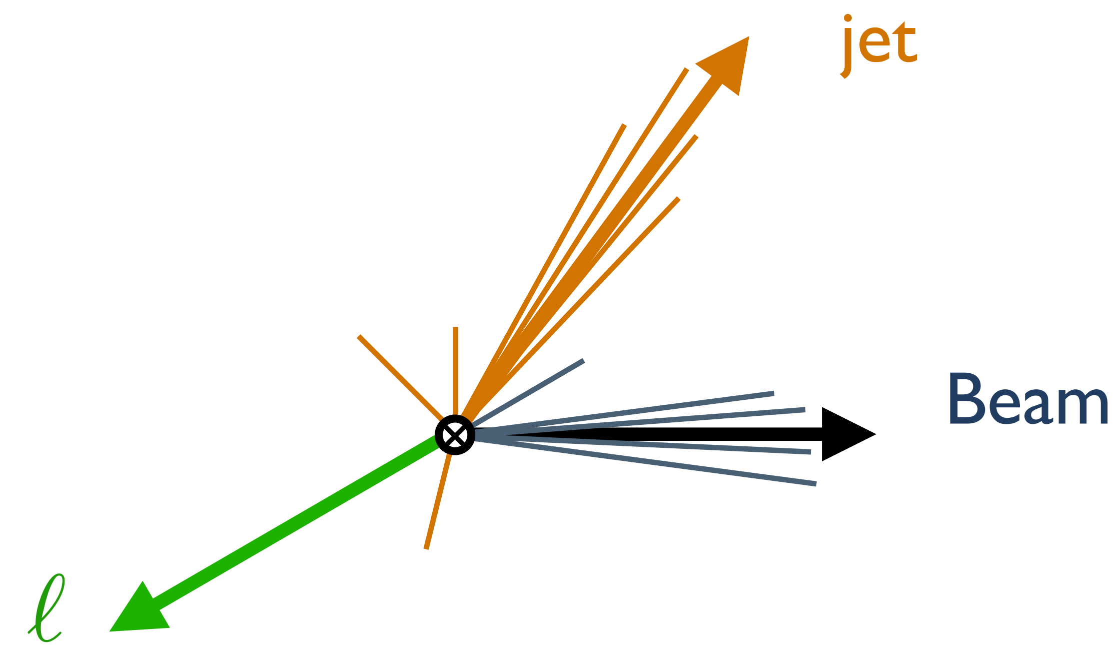
Groomed 1-jettiness: Simulations

The groomed observable
is mostly insensitive to the rapidity
cutoff imposed in the laboratory frame

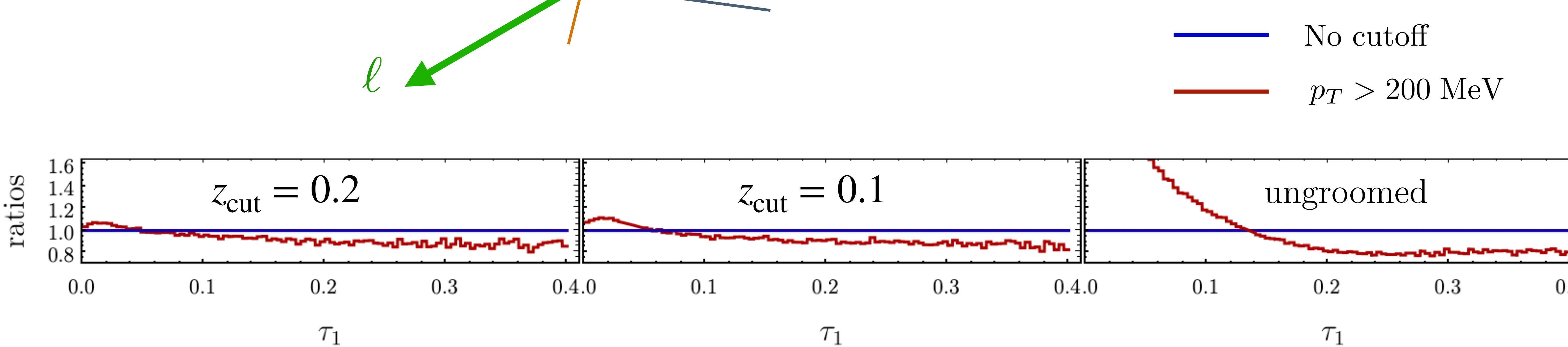


Groomed 1-jettiness: Simulations

Laboratory frame illustration:

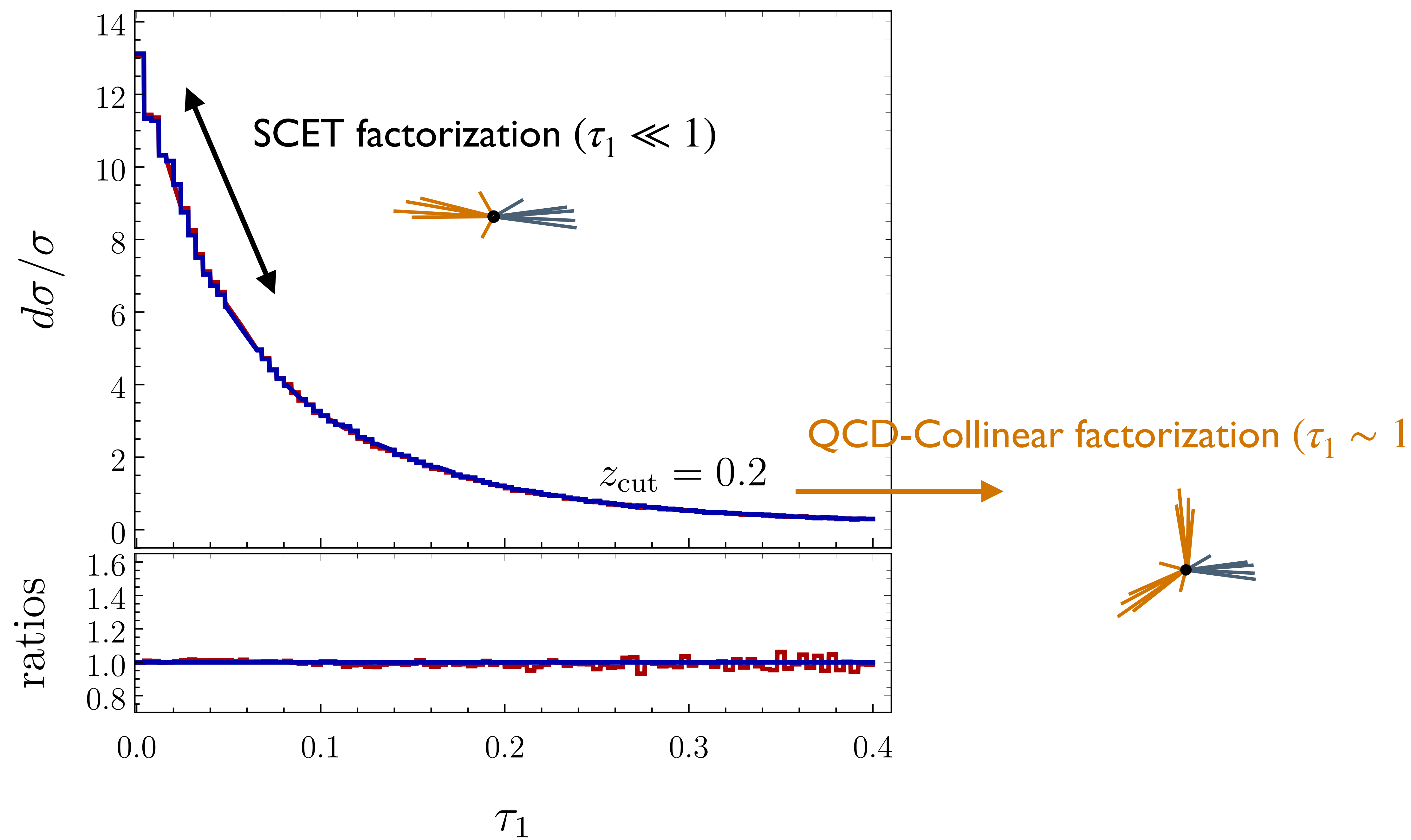


minimum particle pT threshold shows larger effect but still much smaller compared to the ungroomed case.



Groomed 1-jettiness: Factorization

SCET = Soft-Collinear Effective Theory



Groomed 1-jettiness: Factorization

$\tau_1 \ll z_{\rm cut} \ll 1$

For invariant mass: $\tau_1 \to m^2_{\rm gr.}/Q^2$

$$\frac{d\sigma}{dx dQ^2 d\tau_1} = \sigma_0(x,Q) H(Q,\mu) S(Q z_{\rm cut},\mu) \sum_f \mathcal{B}(x, Q^2 z_{\rm cut},\mu) \int_{\gamma-i\infty}^{\gamma+i\infty} du\, \frac{\exp(u\tau_1)}{2\pi i} J\Big(\frac{Q^2}{u},\mu\Big)\, \mathcal{C}\Big(\frac{Q^2}{u z_{\rm cut}},\mu^2\Big)$$

Hard
Matching between QCD and SCET

Soft
Uniform soft dynamics.
Dim-reg: scaleless up-to clustering effects

$S = 1 + \mathcal{O}(\alpha_s^2)$

"Beam"
Incoming hadron matrix element
Matched onto the PDF for:
$Q\sqrt{z_{\rm cut}} \gg \Lambda_{\rm QCD}$

Jet
Jet-mass jet function
Final-state collinear matrix element

Collinear-soft
The same as for SoftDrop (jet mass).
Mode scaling:

$$p^\mu_{cs} \sim Q z_{\rm cut}\left(\frac{\tau_1}{z_{\rm cut}}, 1, \sqrt{\frac{\tau_1}{z_{\rm cut}}}\right)$$

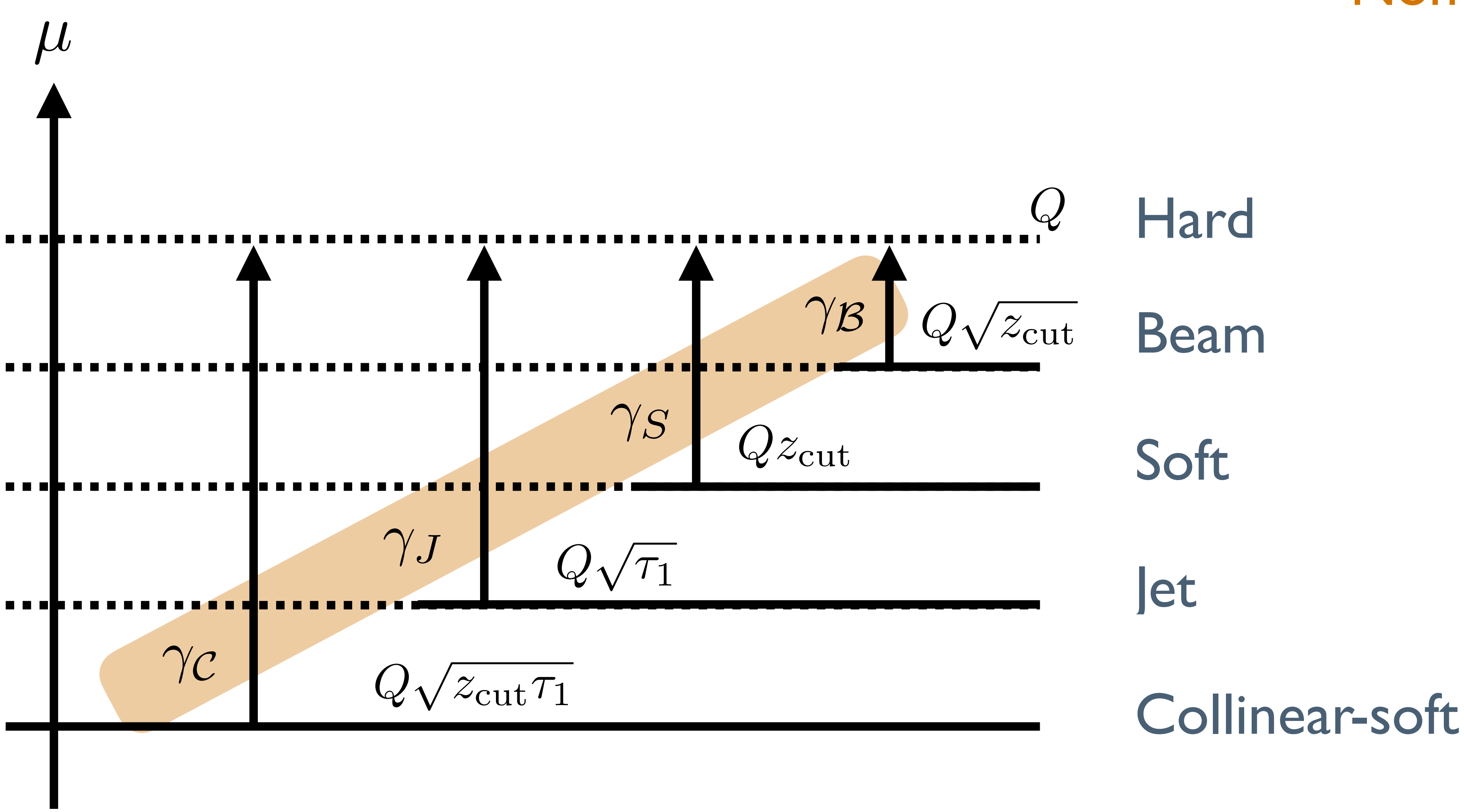
Groomed 1-jettiness: Resummation

$$\frac{d}{d\ln\mu}F(\mu) = \gamma_F(\mu)F(\mu)$$

From RG invariance of cross-section:

$$\gamma_H + \gamma_S + \gamma_{\mathcal{B}} + \gamma_J + \gamma_{\mathcal{C}} = 0$$

Non trivial check of factorization order-by-order in PT



The normalized distribution for [x,Q] bins

(1) re-scaled observable

$$e \equiv m^2_{\text{gr.}}$$

$$e \equiv Q^2 \tau_1$$

(2) normalized cross section

$$\frac{d\sigma^{\text{norm.}}}{de}(e, e_{\text{min}}, e_{\text{max}}) \equiv \left[\int_{e_{\text{min}}}^{e_{\text{max}}} de \int_{x,Q} \frac{d\sigma}{dx dQ^2 de}(e) \right]^{-1} \times \int_{x,Q} \frac{d\sigma}{dx dQ^2 de}(e)$$

(3) in terms of factorization

$$\frac{d\sigma^{\text{norm.}}}{de}(e, e_{\text{min}}, e_{\text{max}}) = \mathcal{N}(e_{\text{min}}, e_{\text{max}}, \mu) \int_{\gamma - i\infty}^{\gamma + i\infty} \frac{d\tilde{u}\ \exp(\tilde{u}e)}{2\pi i}\, J\left(\frac{1}{\tilde{u}}, \mu^2\right) \mathcal{C}\left(\frac{z_{\text{cut}}}{\tilde{u}}, \mu^2\right)$$

$$\mathcal{N}^{-1}(e_{\text{min}}, e_{\text{max}}, \mu) = \int_{e_{\text{min}}}^{e_{\text{max}}} de \int_{\gamma - i\infty}^{\gamma + i\infty} \frac{d\tilde{u}\ \exp(\tilde{u}e)}{2\pi i}\, J\left(\frac{1}{\tilde{u}}, \mu^2\right) \mathcal{C}\left(\frac{z_{\text{cut}}}{\tilde{u}}, \mu^2\right)$$

Warning: e_{min} and : e_{max} must remain within the region of validity of factorization!

NLL versus Pythia @ $\sqrt{s} = 318$ GeV

Softest scale becomes non-perturbative:

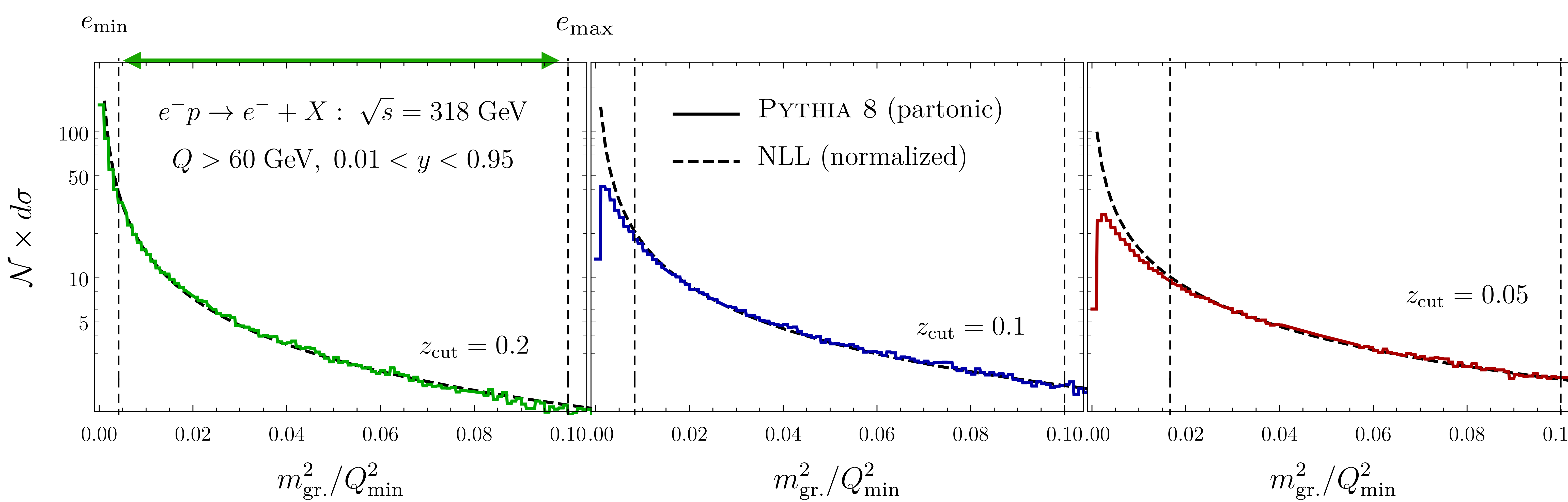
$$e_{\min} = \frac{\Lambda_{\rm NP}^2}{z_{\rm cut}}$$

Power corrections to factorization:

$$e_{\max} = 0.1$$

The effective region shrinks quickly with decreasing $z_{\rm cut}$.

This will only get worse at EIC expected energies where $Q \sim 10$ GeV



NLL versus Pythia @ $\sqrt{s} = 140$ GeV

Softest scale becomes non-perturbative:

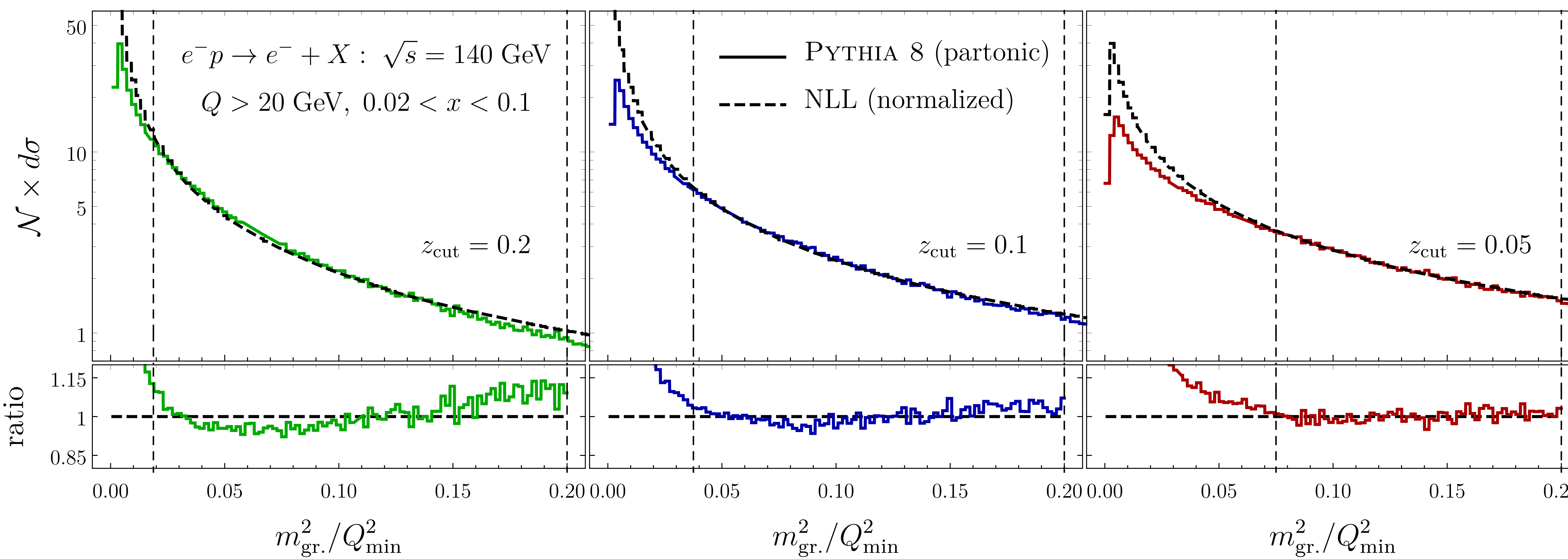
$$e_{\min} = \frac{\Lambda_{\rm NP}^2}{z_{\rm cut}}$$

Power corrections to factorization:

$$e_{\max} = 0.2$$

The effective region shrinks quickly with decreasing $z_{\rm cut}$.

This will only get worse at EIC expected energies where $Q \sim 10$ GeV

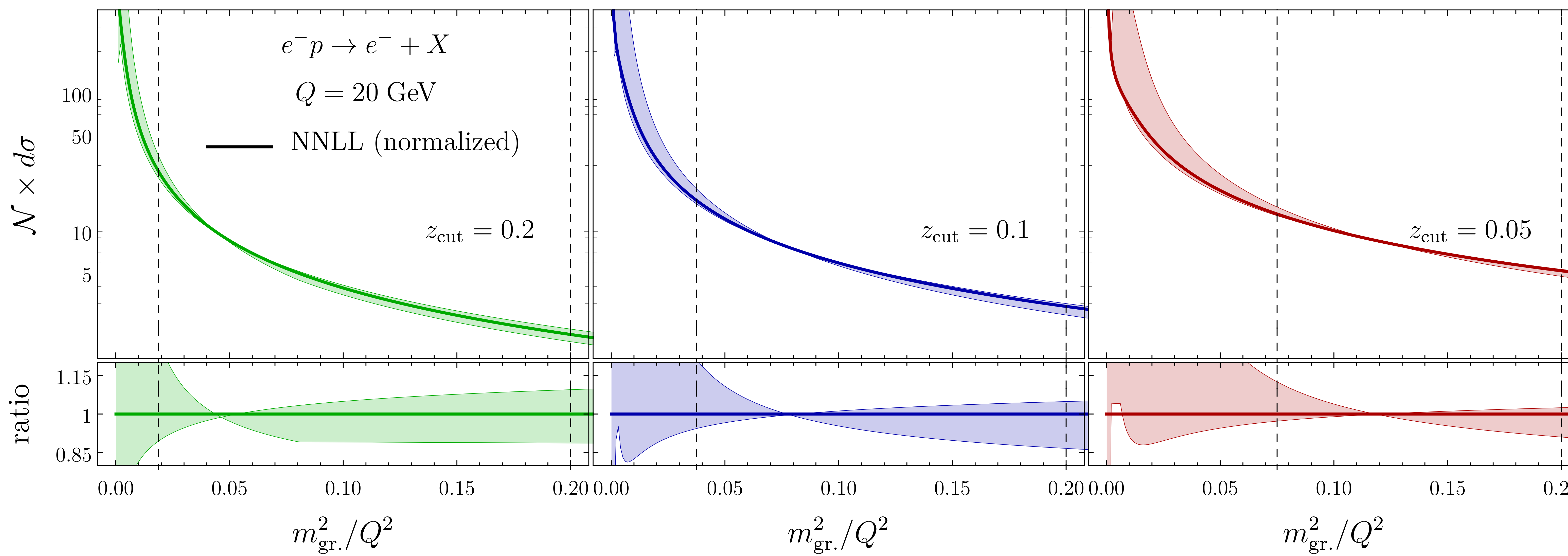


N^2LL predictions

scale variations: $\times 2 \big/ \times 0.5 \;\; (\mu_{\mathcal{J}},\ \mu_{\mathcal{C}},\ \mu = Q_{\min})$

$\Lambda_{\rm NP} = 1.4$ GeV

uncertainty = 10-20 %

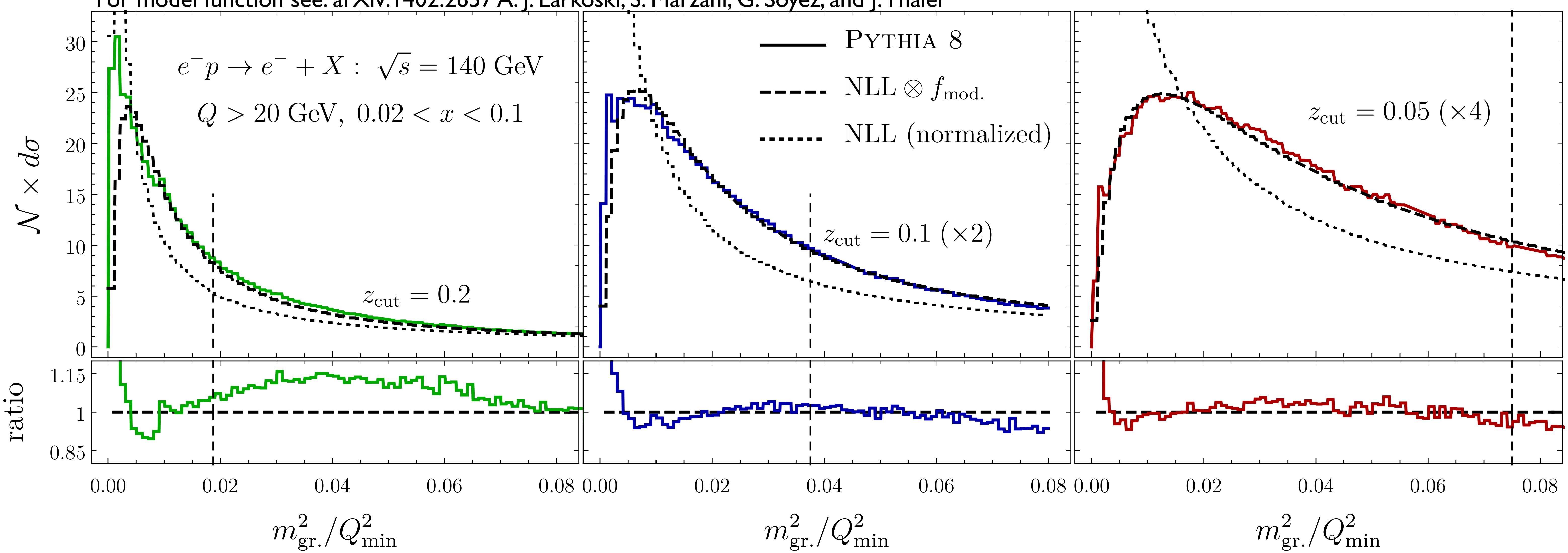


Sensitivity to hadronization effects

$$\frac{d\sigma_{\text{had.}}}{dx dQ^2 dm^2_{\text{gr.}}} = \int d\epsilon \frac{d\sigma}{dx dQ^2 dm^2_{\text{gr.}}}\left(m^2_{\text{gr.}} - \frac{\epsilon^2}{z_{\text{cut}}}\right) f_{\text{mod.}}(\epsilon)$$

$$f_{\text{mod.}}(\epsilon) = N_{\text{mod.}} \frac{4\epsilon}{\Omega^2} \exp\left(\frac{2\epsilon}{\Omega}\right)$$

For model function see: arXiv:1402.2657 A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler



Outlook

Hadronization corrections for jet mass with Centauro and anti-kT

Event (groomed) substructure studies

FastJet framework: effects of soft radiation (optimization, Grooming, WTA, e.t.c)

The necessary files can be found here:

https://github.com/miguelignacio/CentauroJetAlgorithm

Other…?

underlying principle:

utilize the asymmetric nature of the process

In this talk:

Asymmetric jet clustering in deep-inelastic scattering

arXiv: 2006.10751

In collaboration with:

M. Arratia, D. Neill, F. Ringer, N. Sato

Grooming algorithms for DIS: example 1-jettiness

arXiv 2101.02708

See also:

(Backward) energy-energy correlation (B-EEC) in DIS

arXiv: 2102.05669

In collaboration with:

H.T. Li and I. Vitev