Jet substructure: from proton-proton to heavy-ion collisions

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Lawrence Berkeley National Laboratory

9th Workshop of the APS Topical Group on Hadronic Physics
April 15 2021

Jet substructure

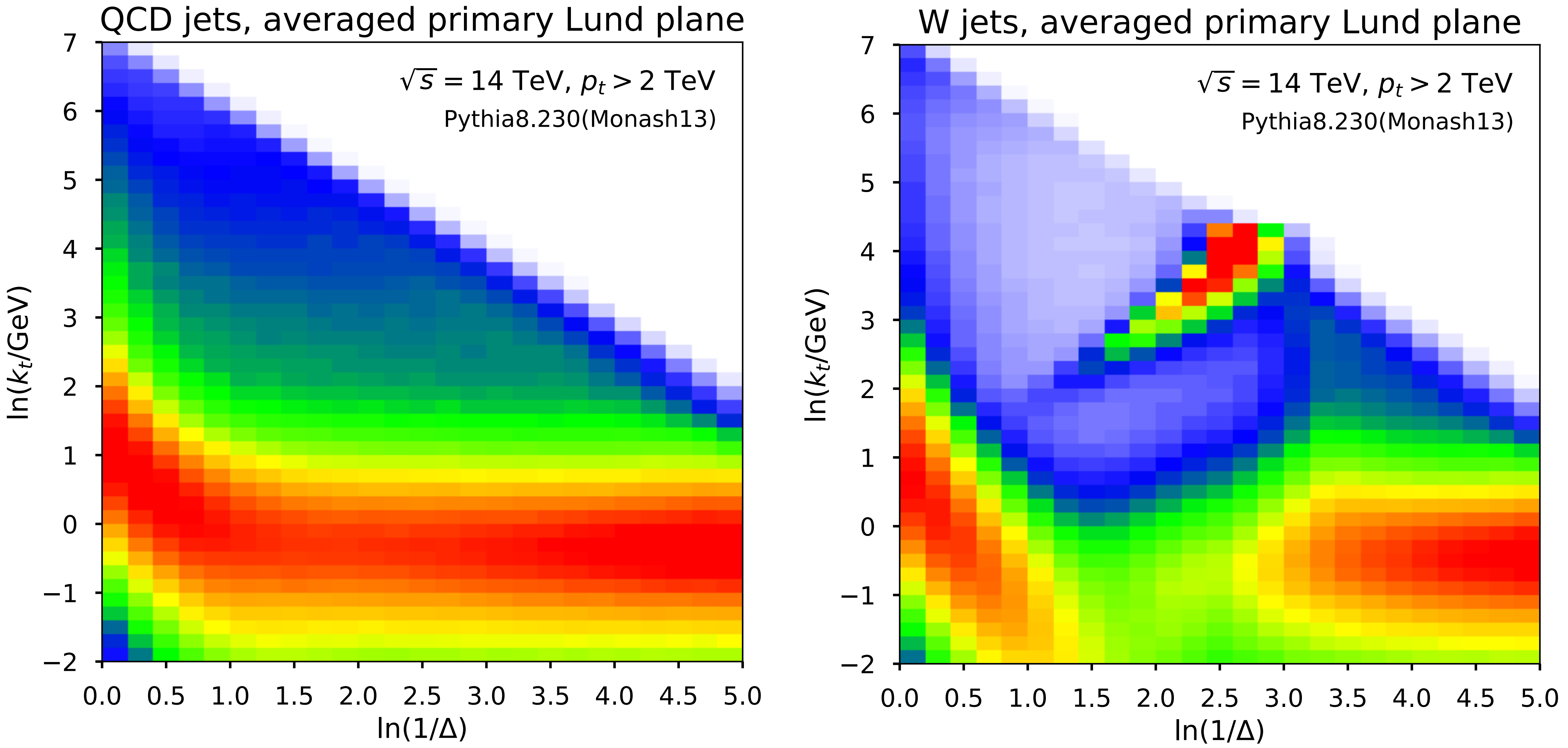
Tagging

Fundamental QCD

Jet substructure

Tagging

- Boosted objects
- Quark vs. gluon jets



Dreyer, Salam, Soyez JHEP 12 (2018) 064

Fundamental QCD

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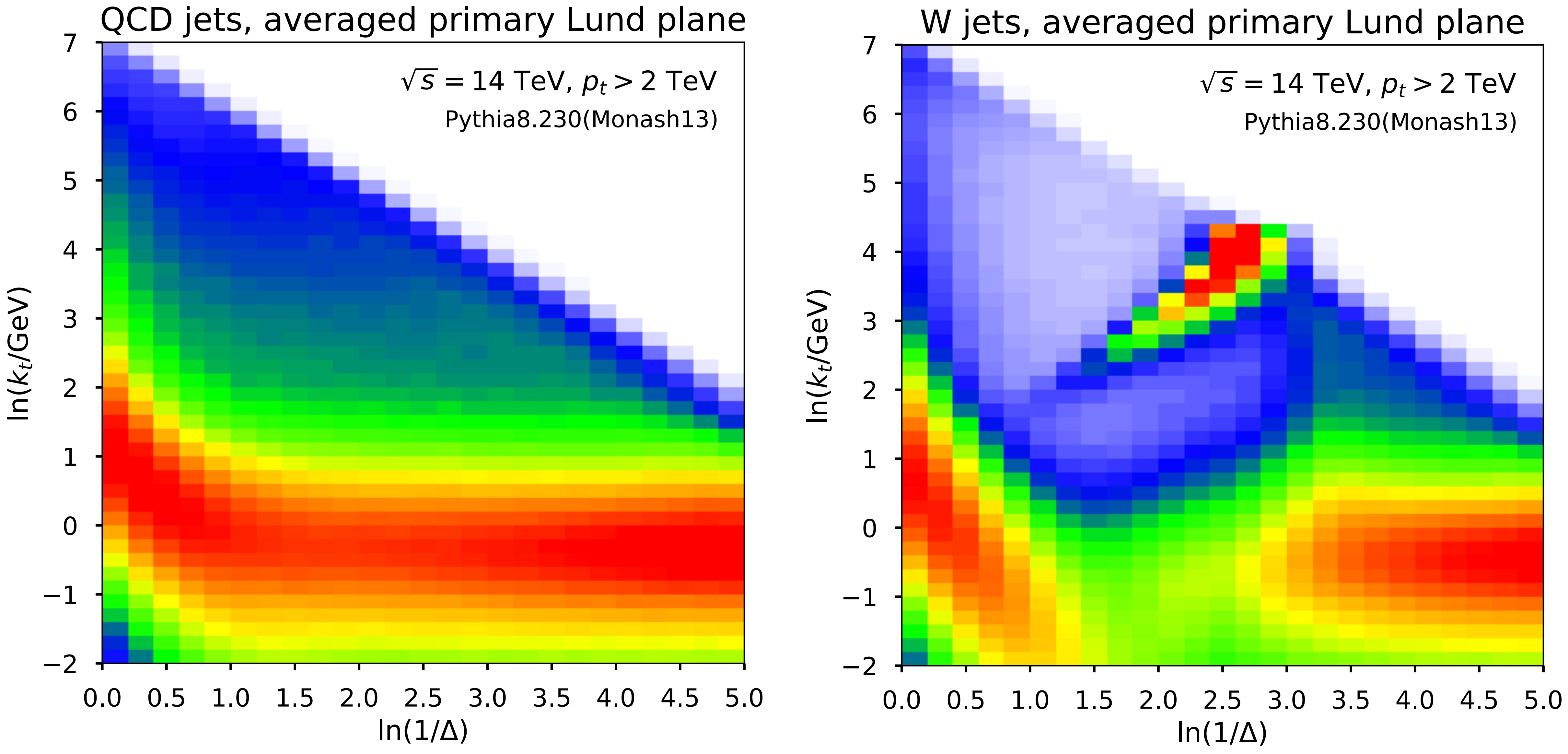
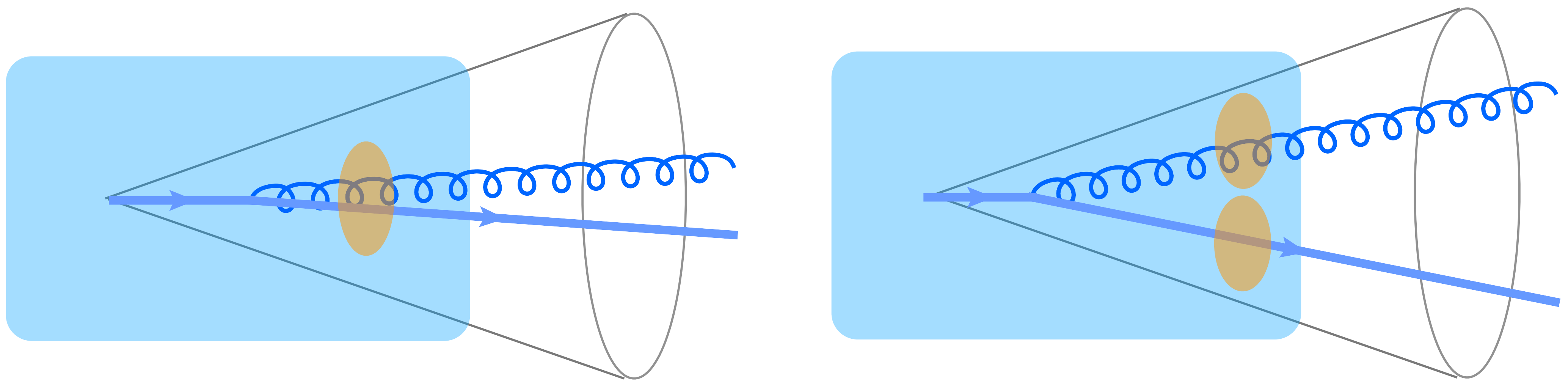


Dreyer, Salam, Soyez JHEP 12 (2018) 064

Fundamental QCD

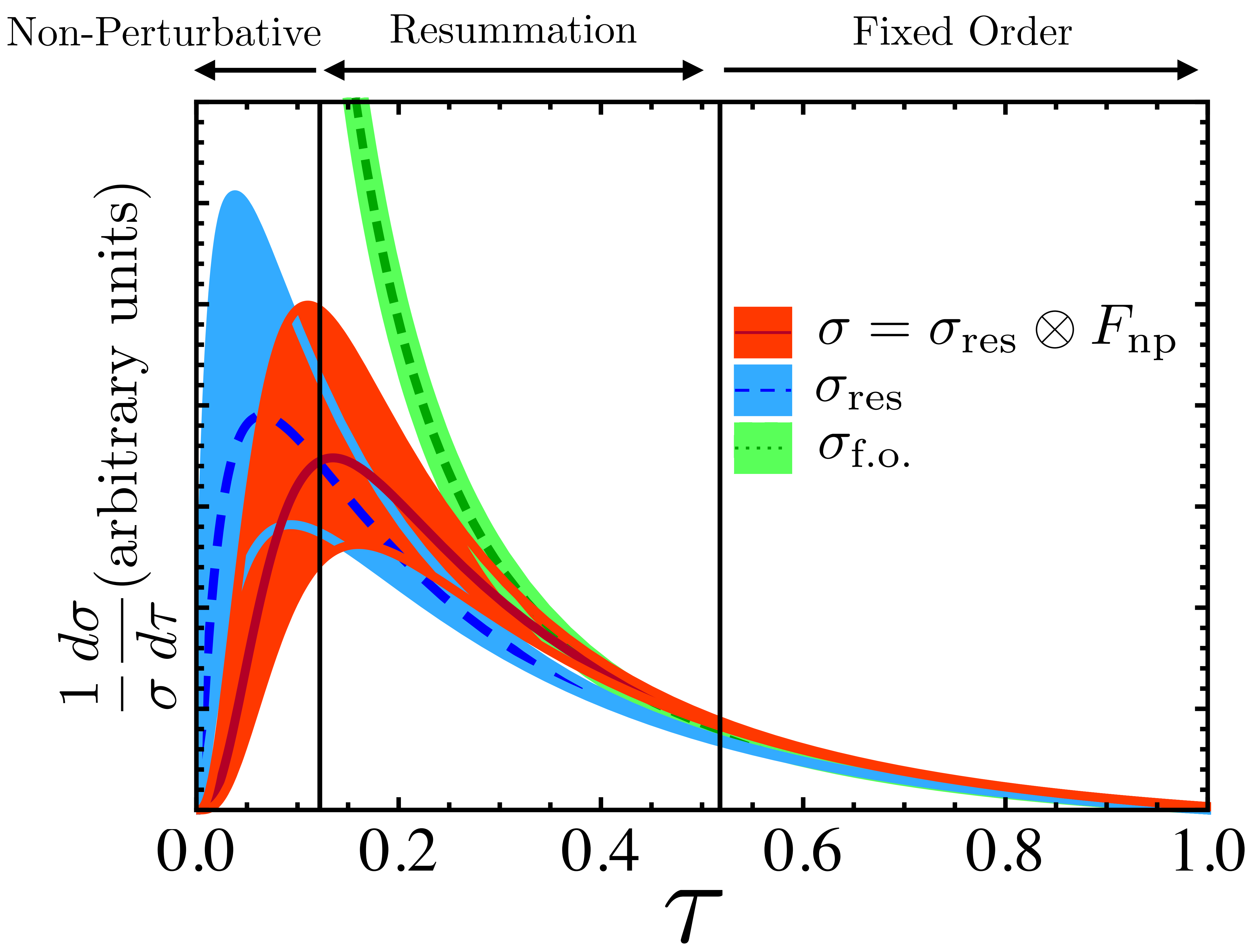
- Understanding validity of perturbative vs. nonperturbative physics
- Probes of quark-gluon plasma



Y. Mehtar-Tani

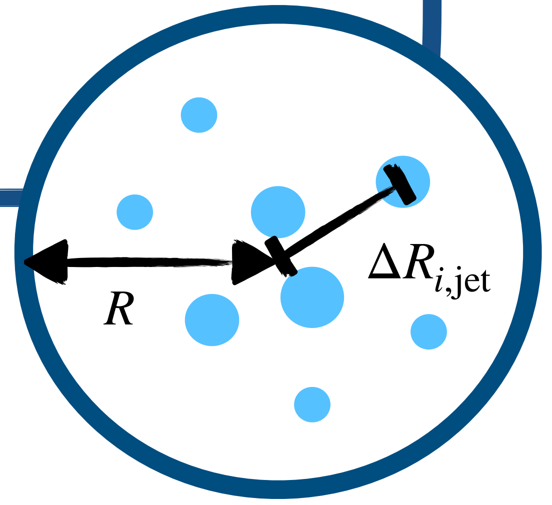
→ **This talk**

Jet substructure in proton-proton collisions



Larkoski, Moult, Nachman JPR (2020)

Jet substructure observables are sensitive to **specific regions** of QCD radiation phase space



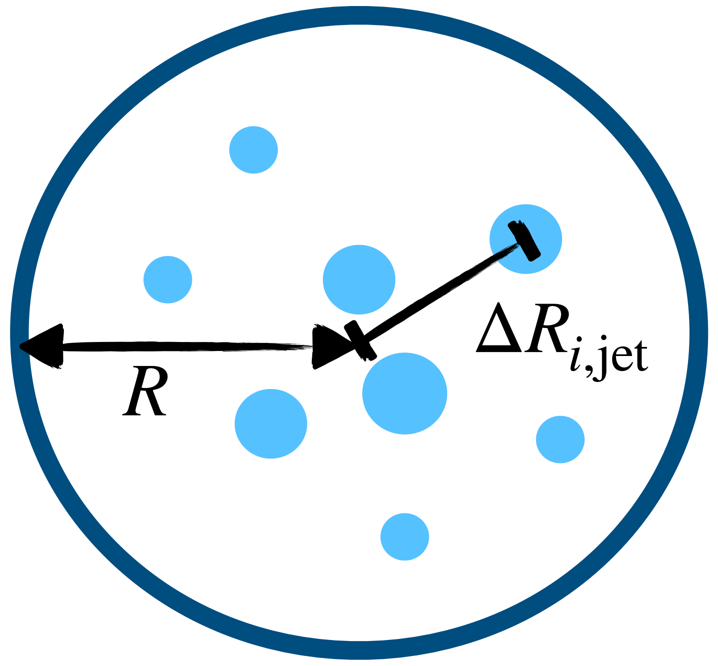
Each observable has:

- Fixed-order regime — $\mathcal{O}\left(\alpha_s^n\right)$
- Resummation regime — large logarithms to all orders in α_s
- Nonperturbative regime

Jet angularities — pp

Class of IRC-safe observables:

$$\lambda_\beta \equiv \sum_{i \in \text{jet}} z_i \theta_i^\beta$$



$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

$$\theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}, \; \Delta R_{i,\text{jet}} = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

Continuous parameter $\beta > 0$ systematically varies weight of collinear radiation

Almeida, Lee, Perez, Sterman, Sung, Virzi PRD 79 (2009)
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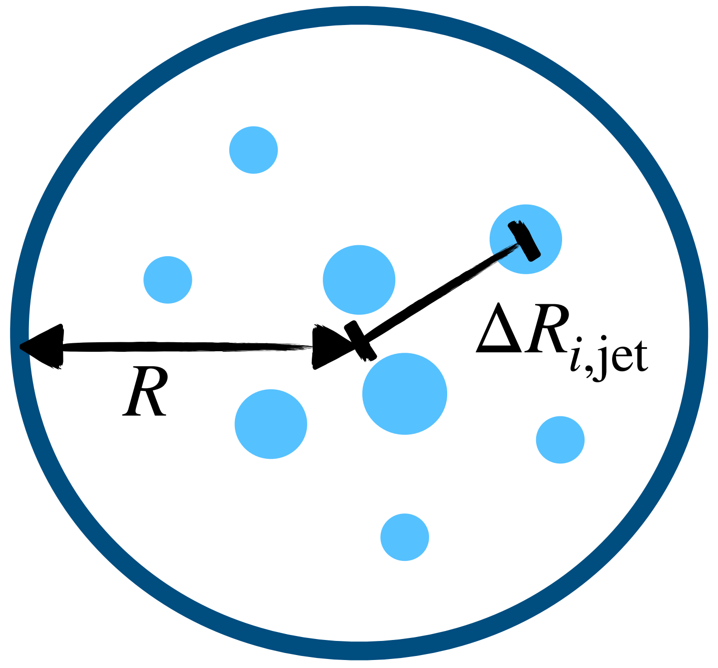

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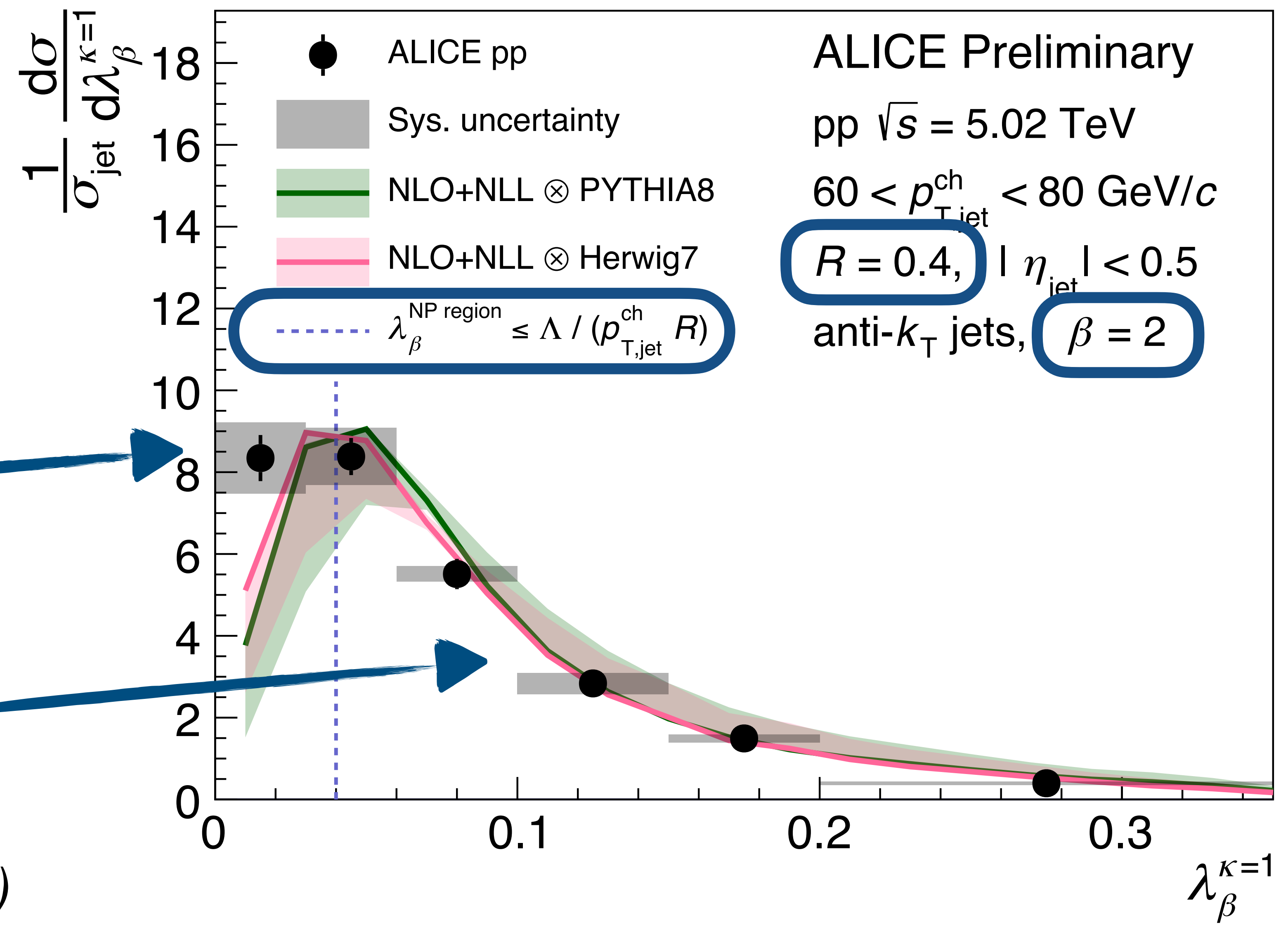
Small λ_β: Nonperturbative

Larger λ_β: Good agreement with pQCD calculations

Kang, Lee, Ringer JHEP 04 (2018)



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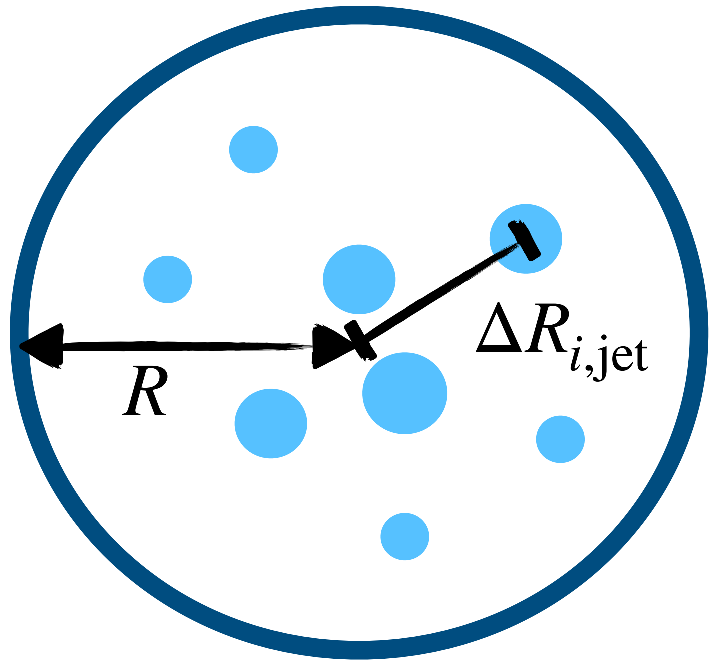

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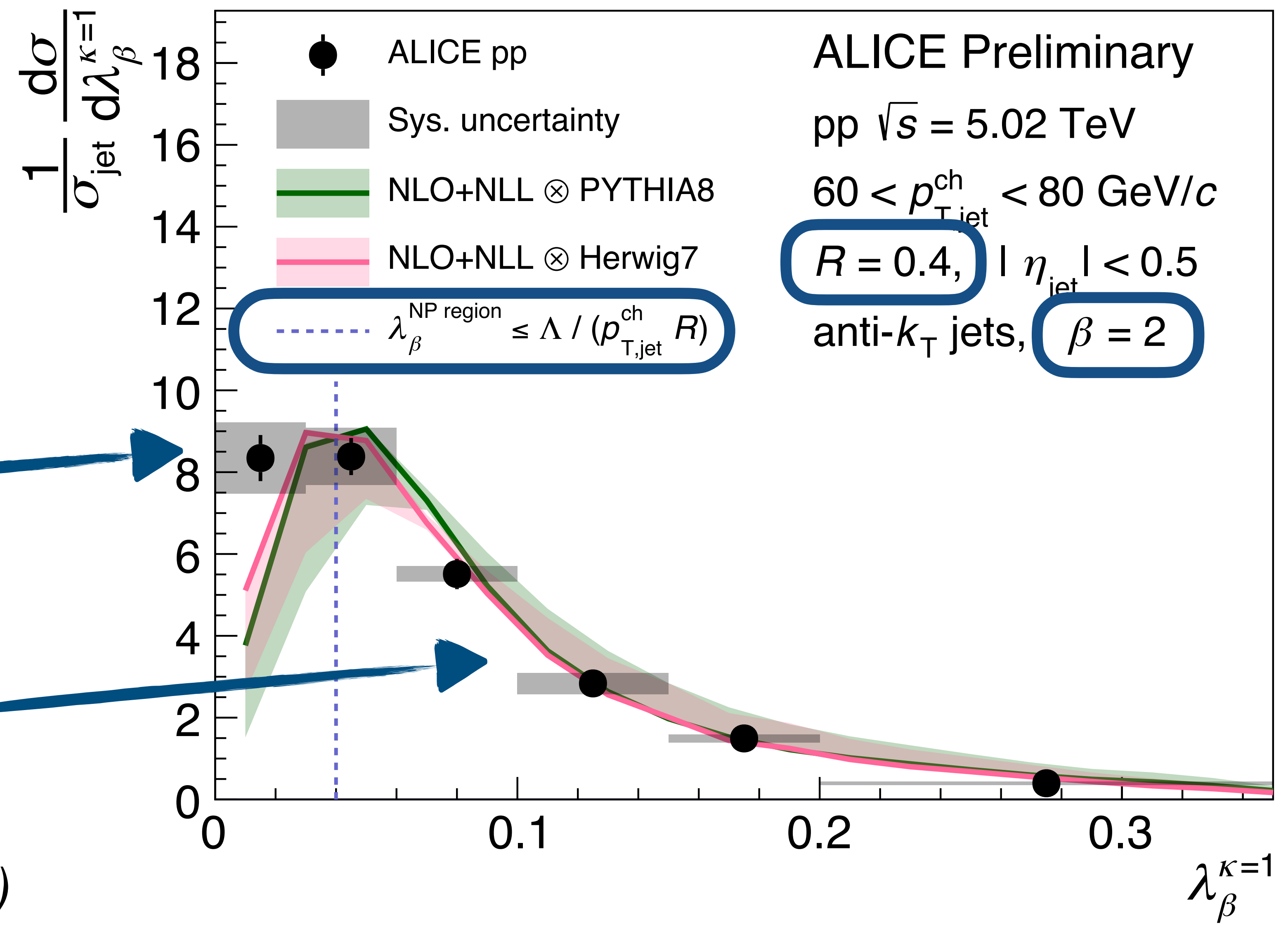
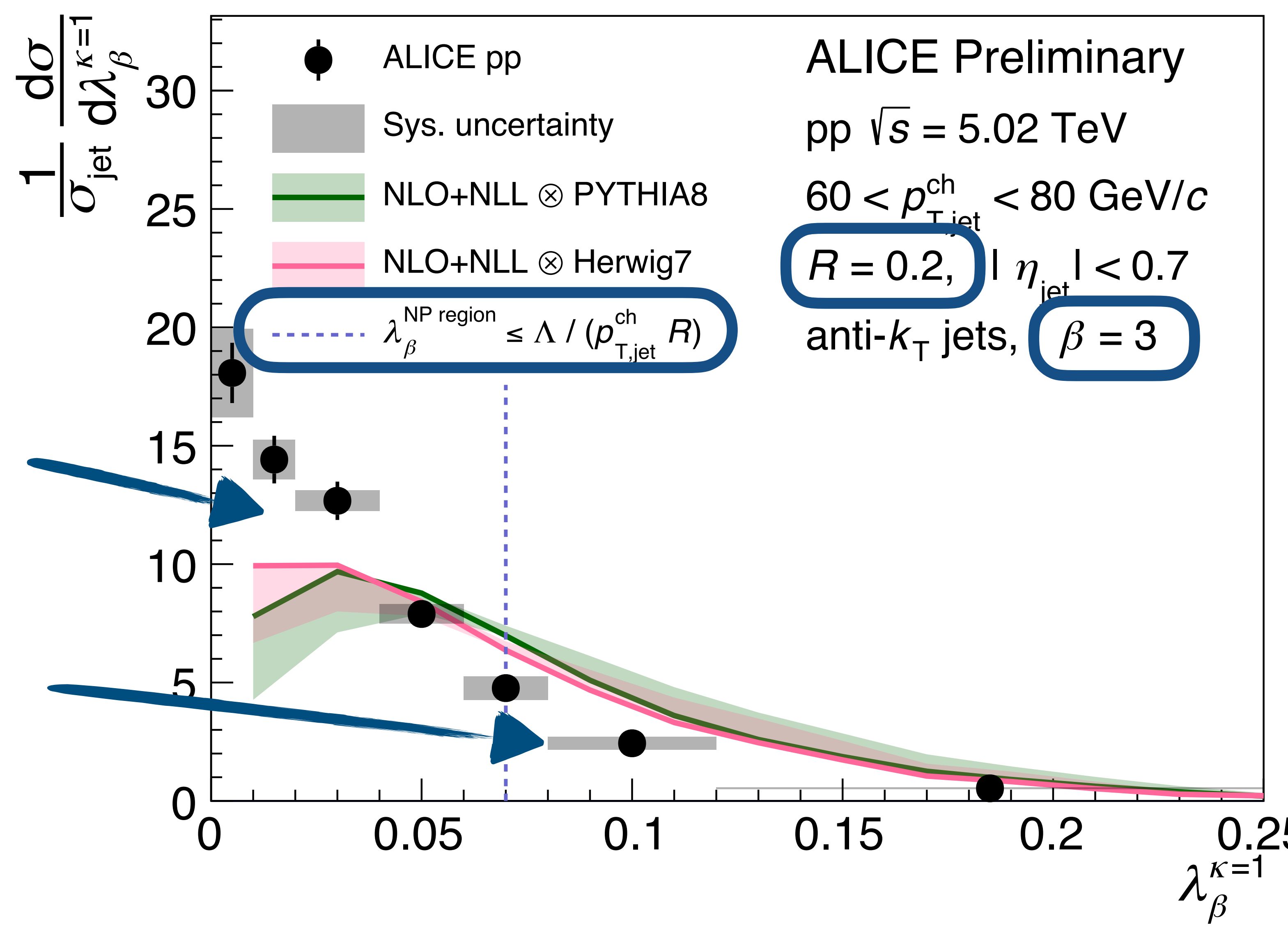
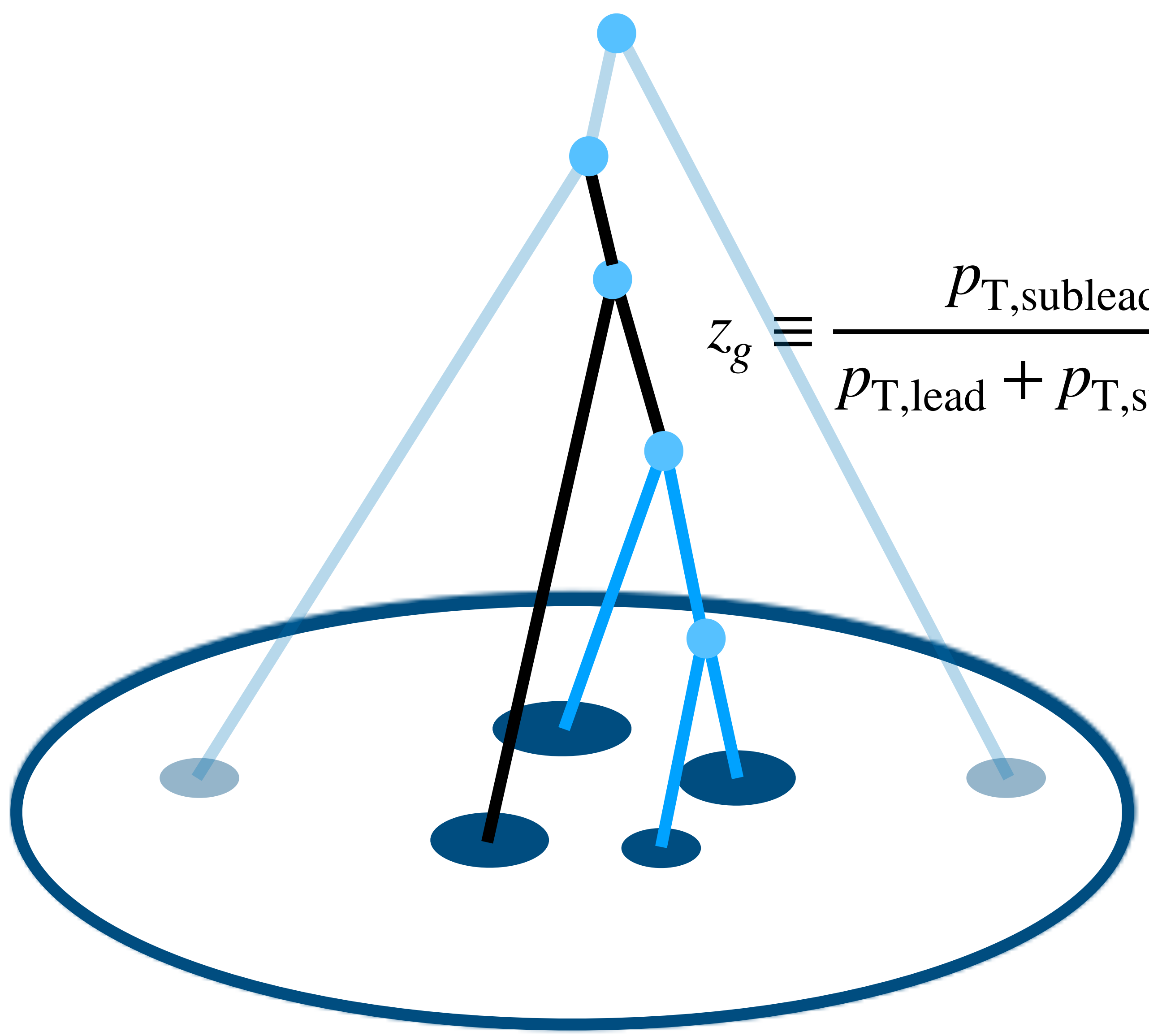




Most of the distribution can be nonperturbative, which spoils agreement in perturbative region due to self-normalization!

Groomed jet substructure — pp

Recluster and groom jet to expose hard splitting



$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Soft Drop: $z < z_{\mathrm{cut}}\theta^{\beta}$

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
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See also: Alba Soto-Ontoso, Thursday 08:00

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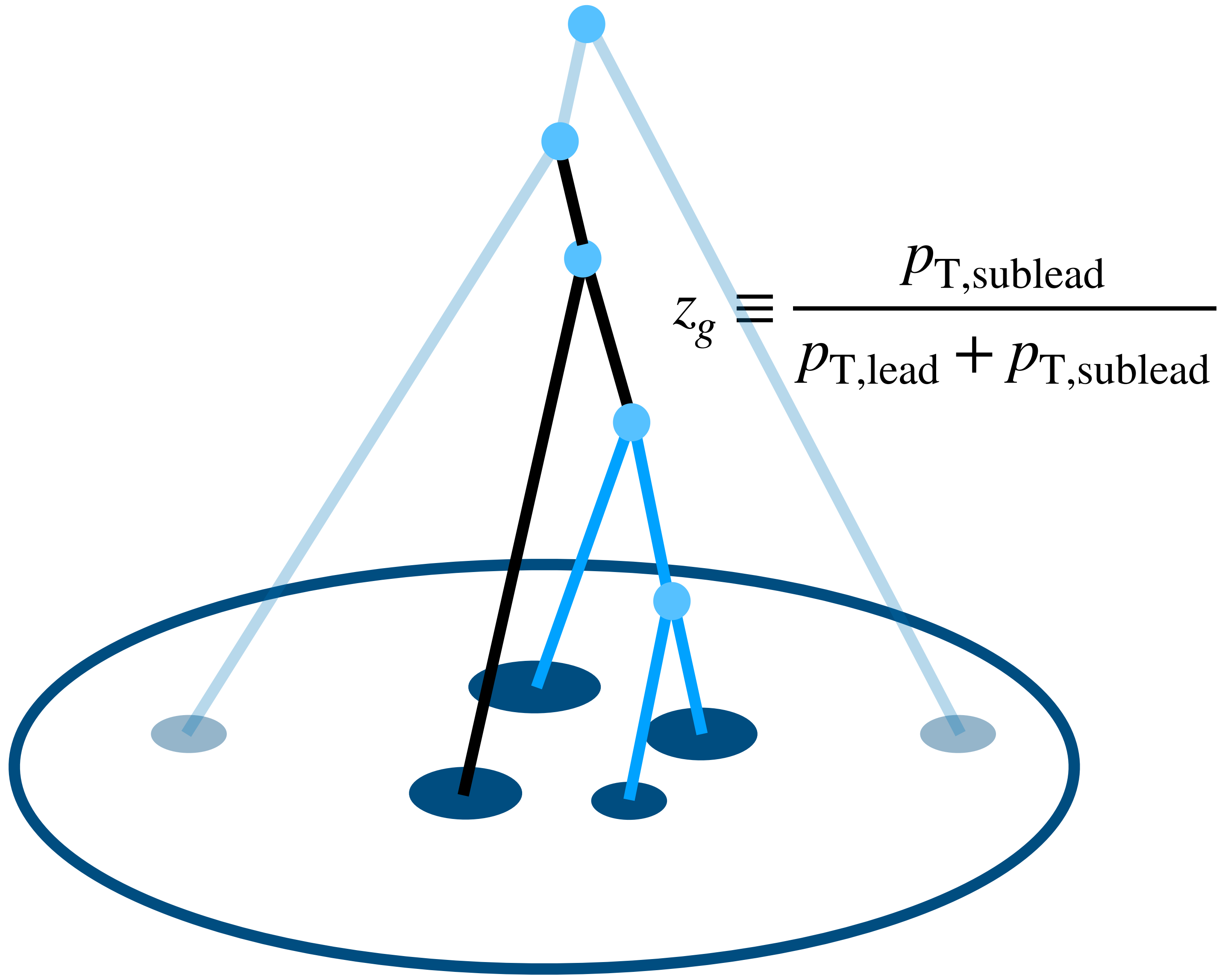

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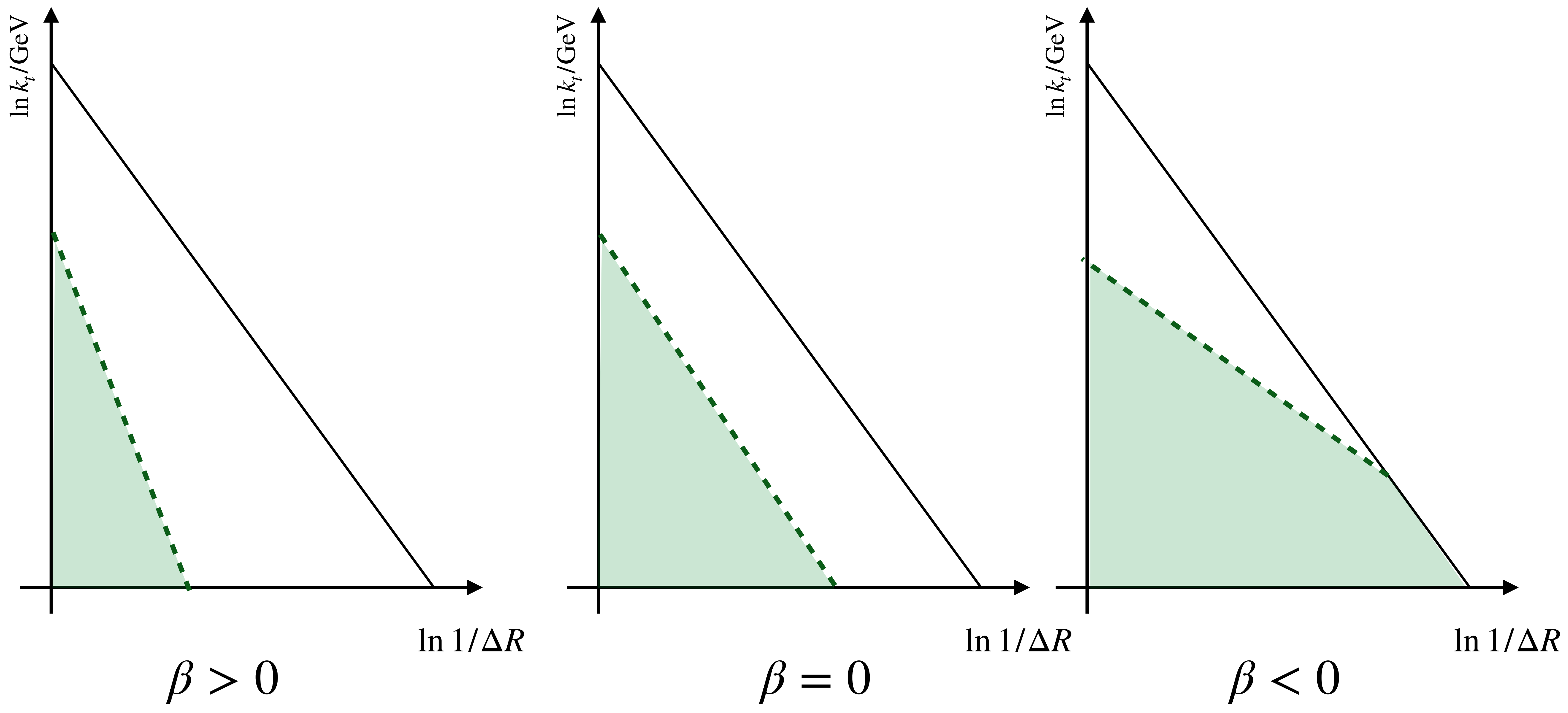
Increasing β grooms away collinear radiation less and less

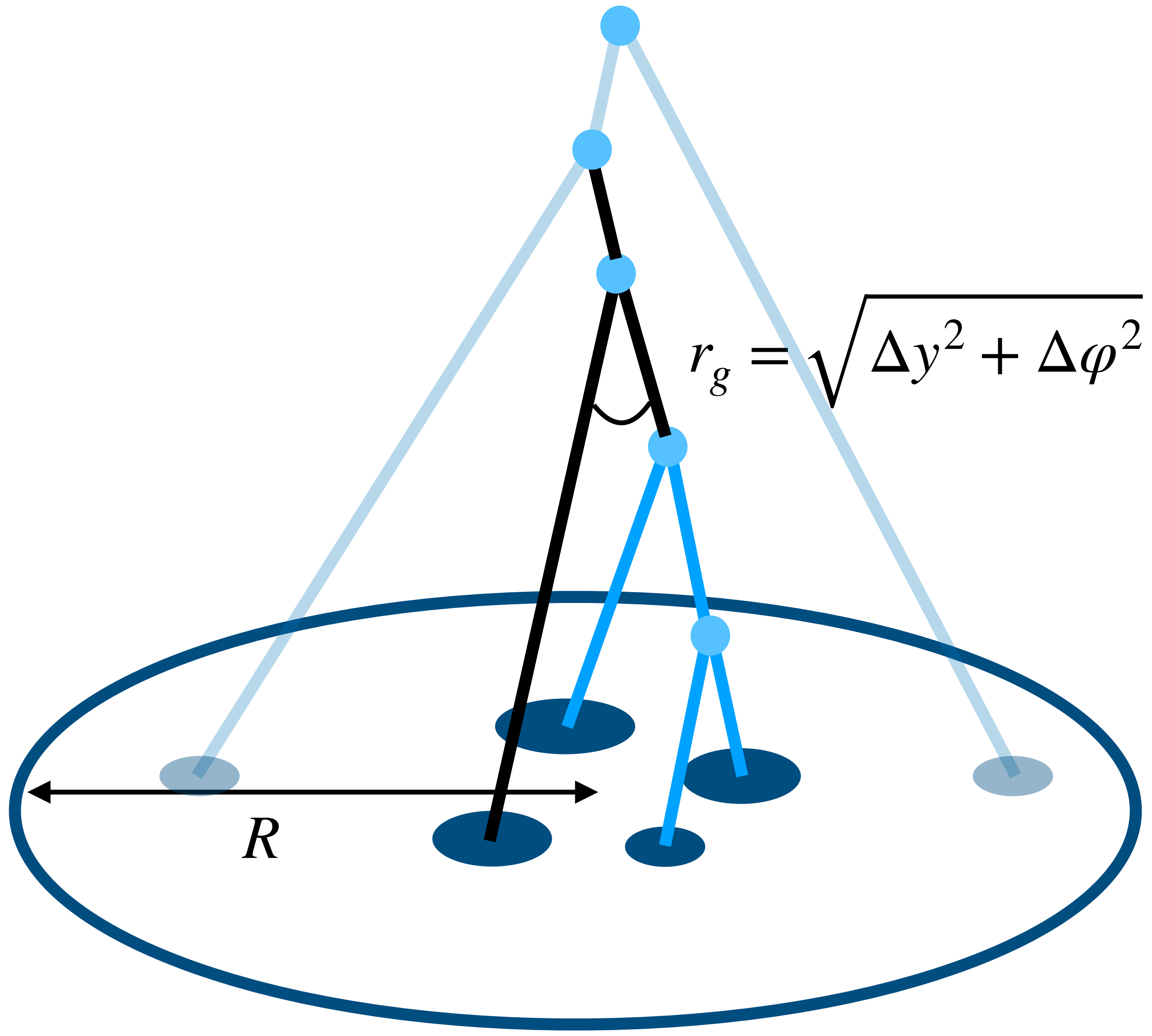


K. Tywoniuk, EMMI RRTF

Groomed jet substructure — pp

ATLAS PRD 101 (2020)

Recluster and groom jet to expose hard splitting



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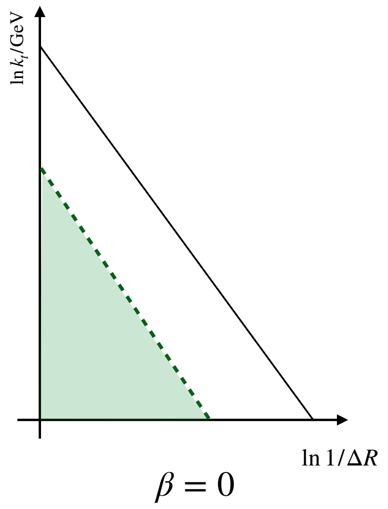
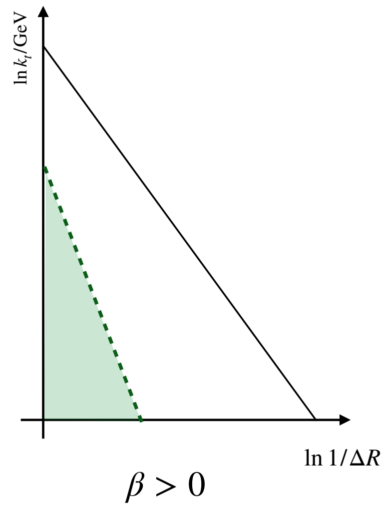
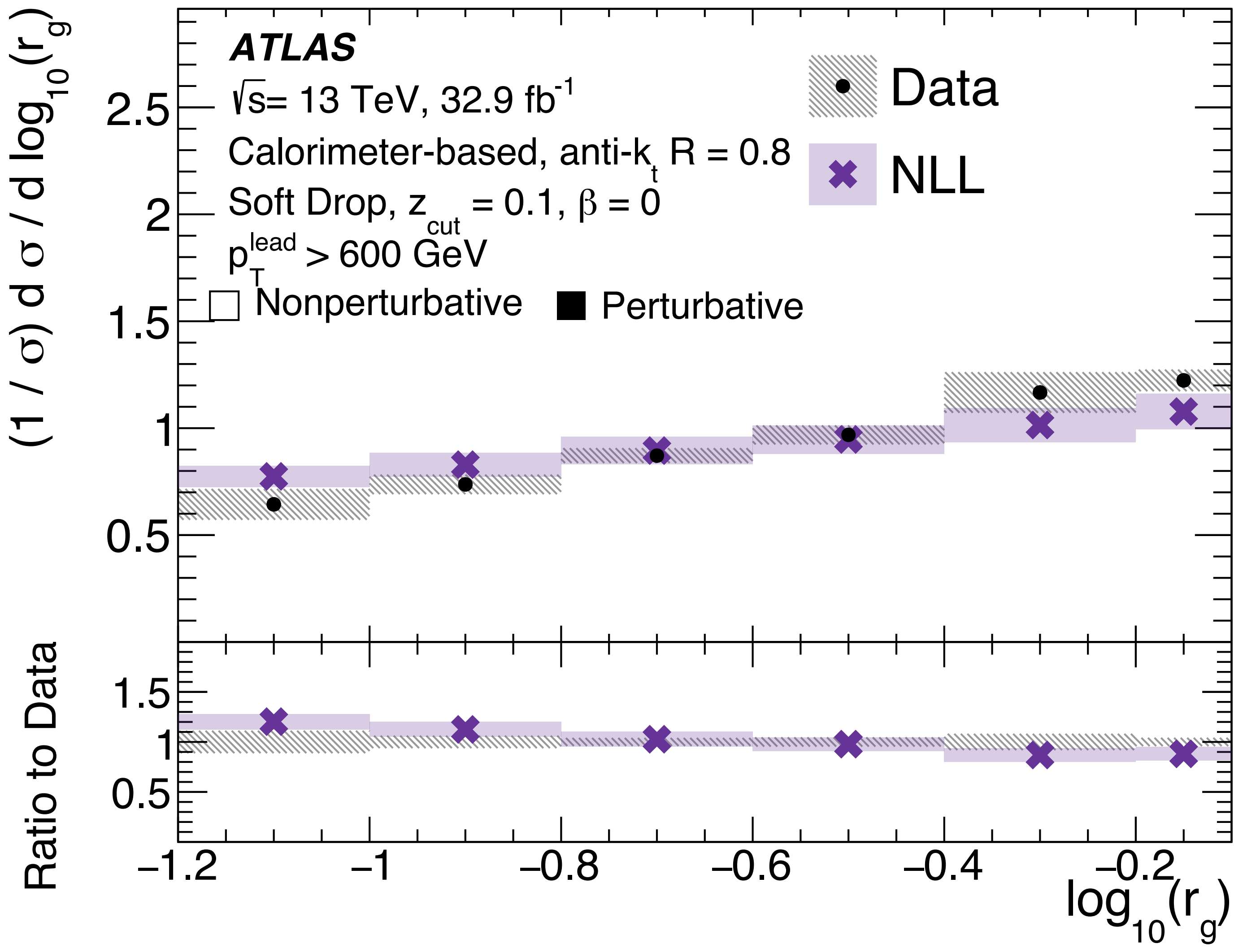
Groomed jet radius: $r_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$

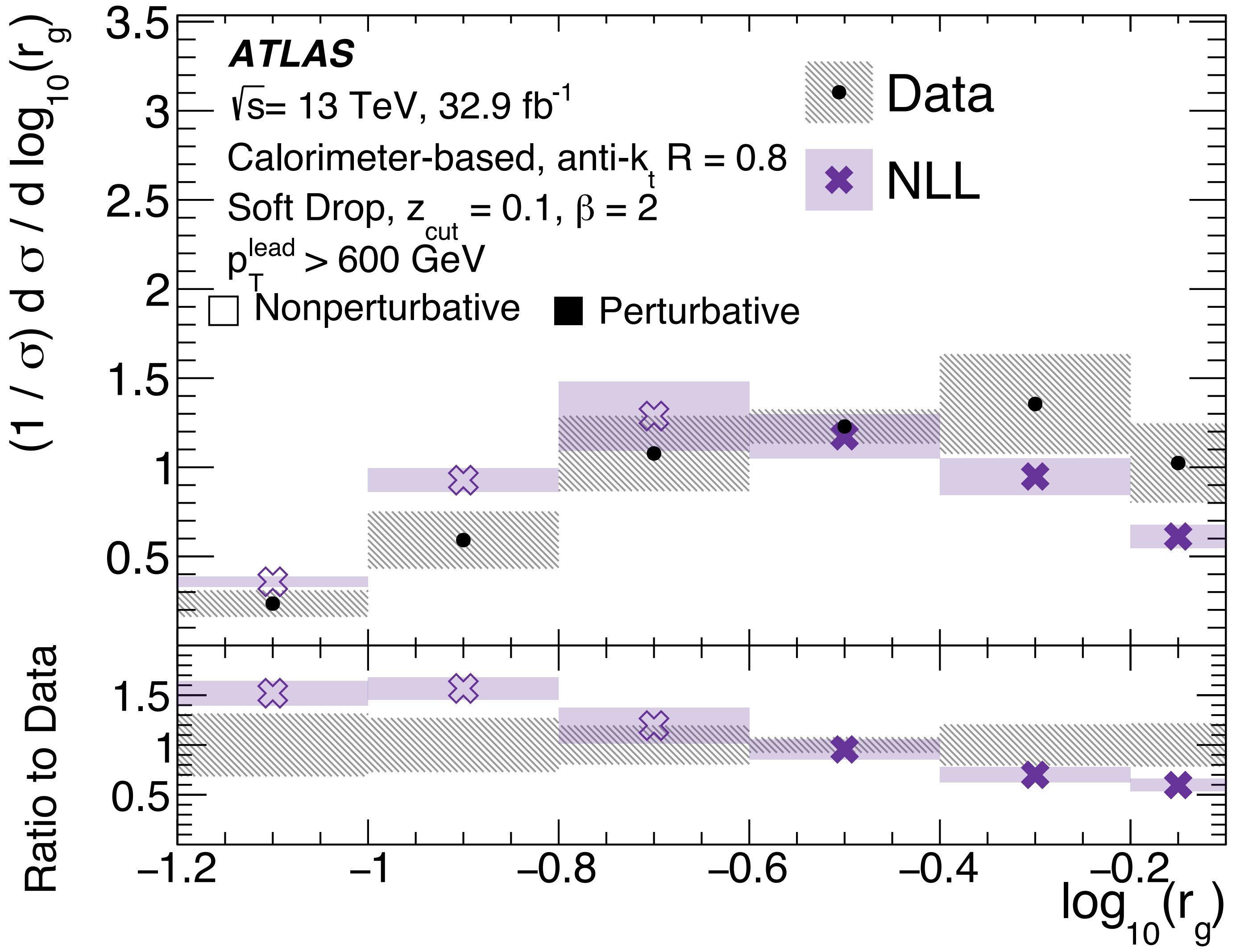
$\beta = 0$



$\beta = 2$





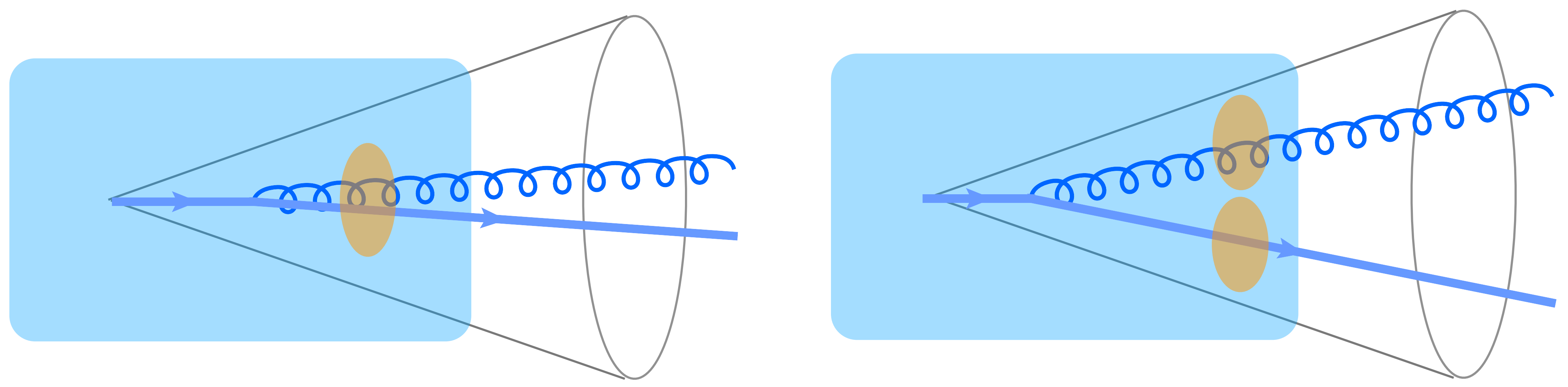


Calculations describe data best with more grooming

Jet substructure in heavy-ion collisions

There are many simultaneous unknowns in jet quenching theory:

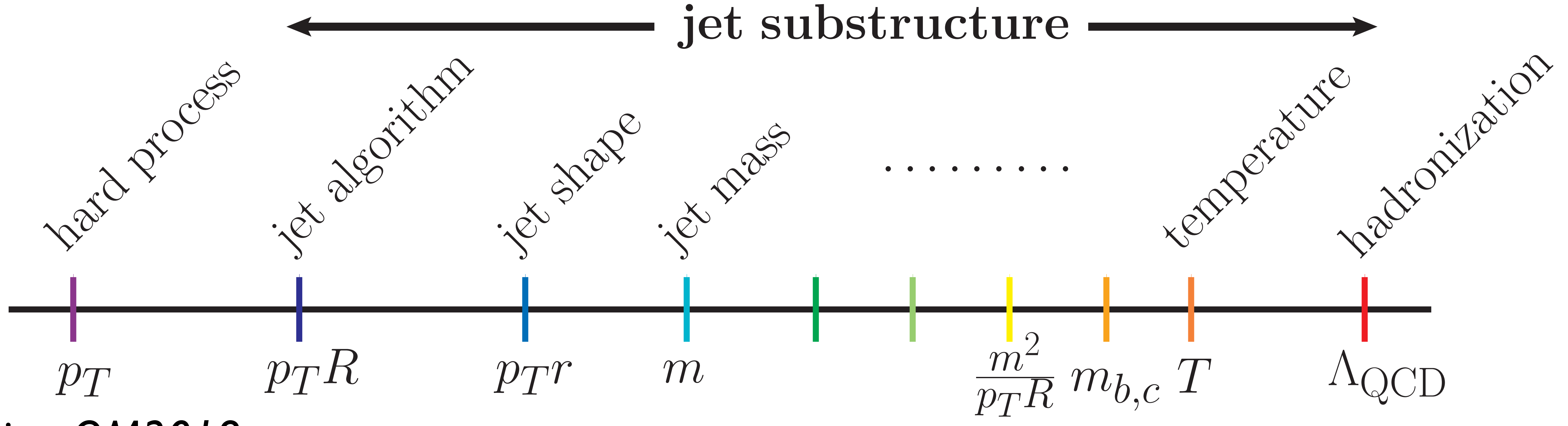
- Strongly-coupled vs. weakly-coupled interaction
- Color coherence
- Spacetime picture of parton shower
- Nature of quasiparticles
- …



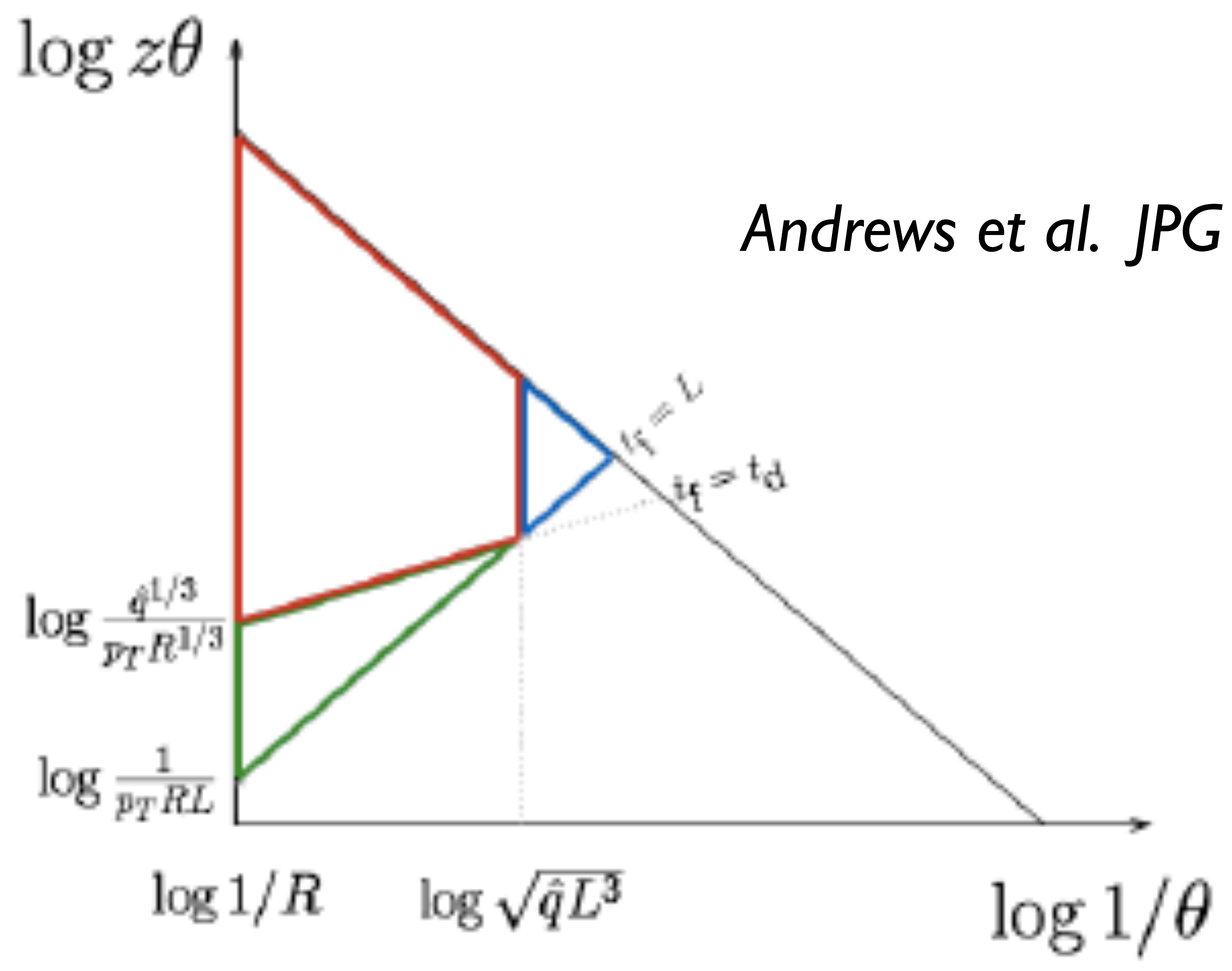
Y. Mehtar-Tani

Jet substructure is an appealing tool to disentangle these

- Target specific regions of phase space



Yang-Ting Chien, QM2018



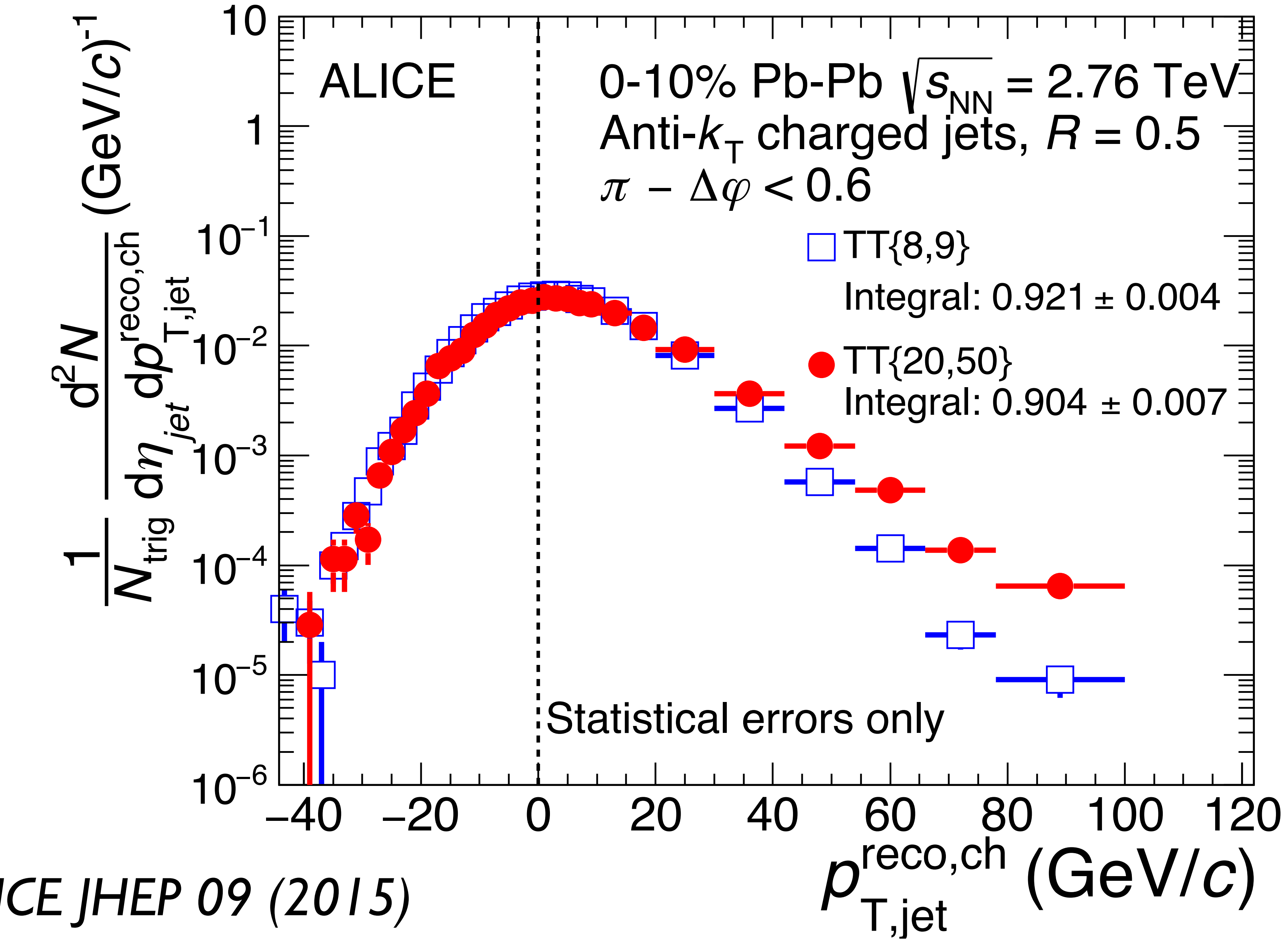
Andrews et al. JPG (2020)

Experimental challenge: Background

Ensemble observables

For observables that don't involve event-by-event tagging of objects, use ensemble-based methods

Ungroomed angularity, mass, N-subjettiness, …

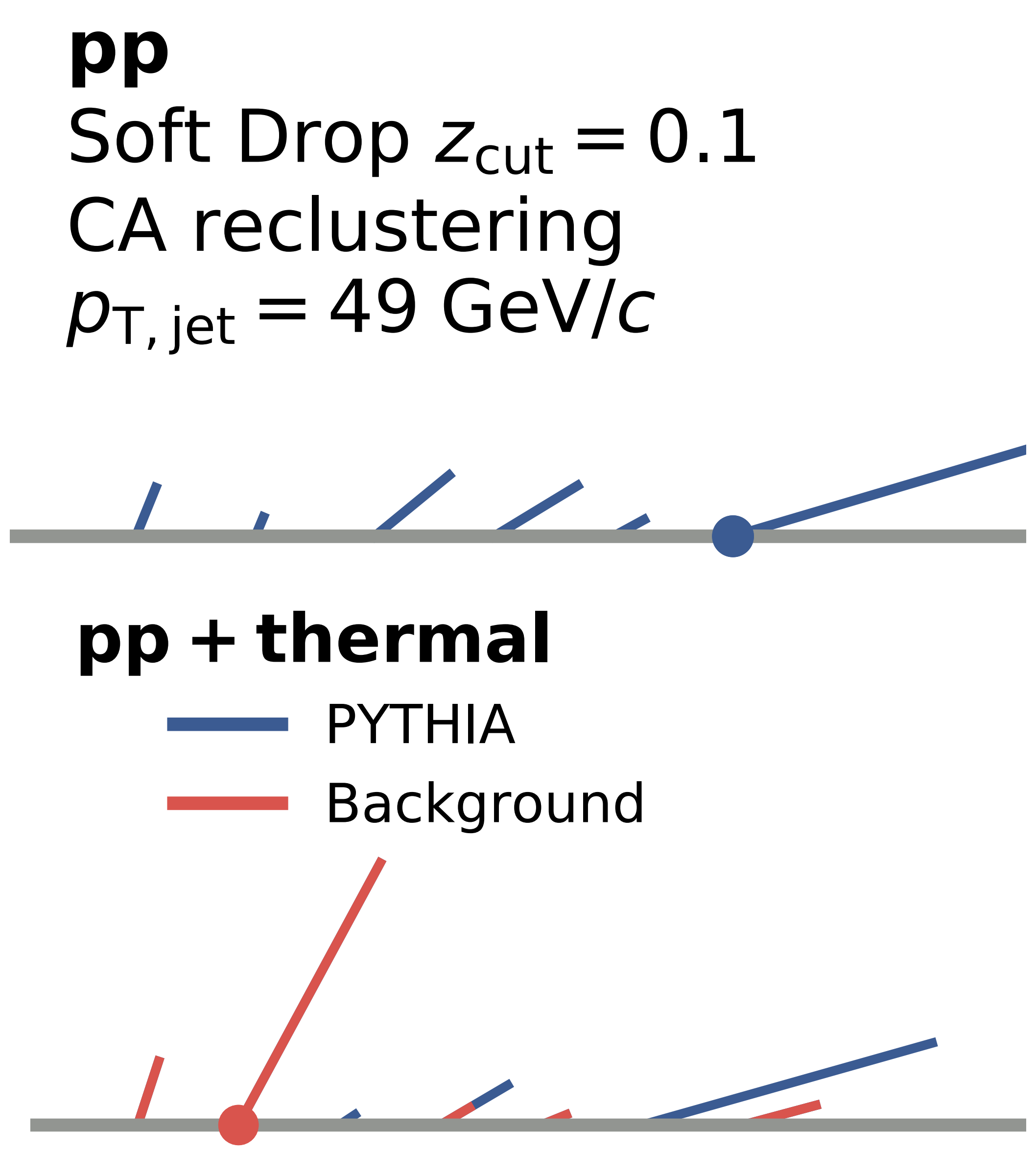


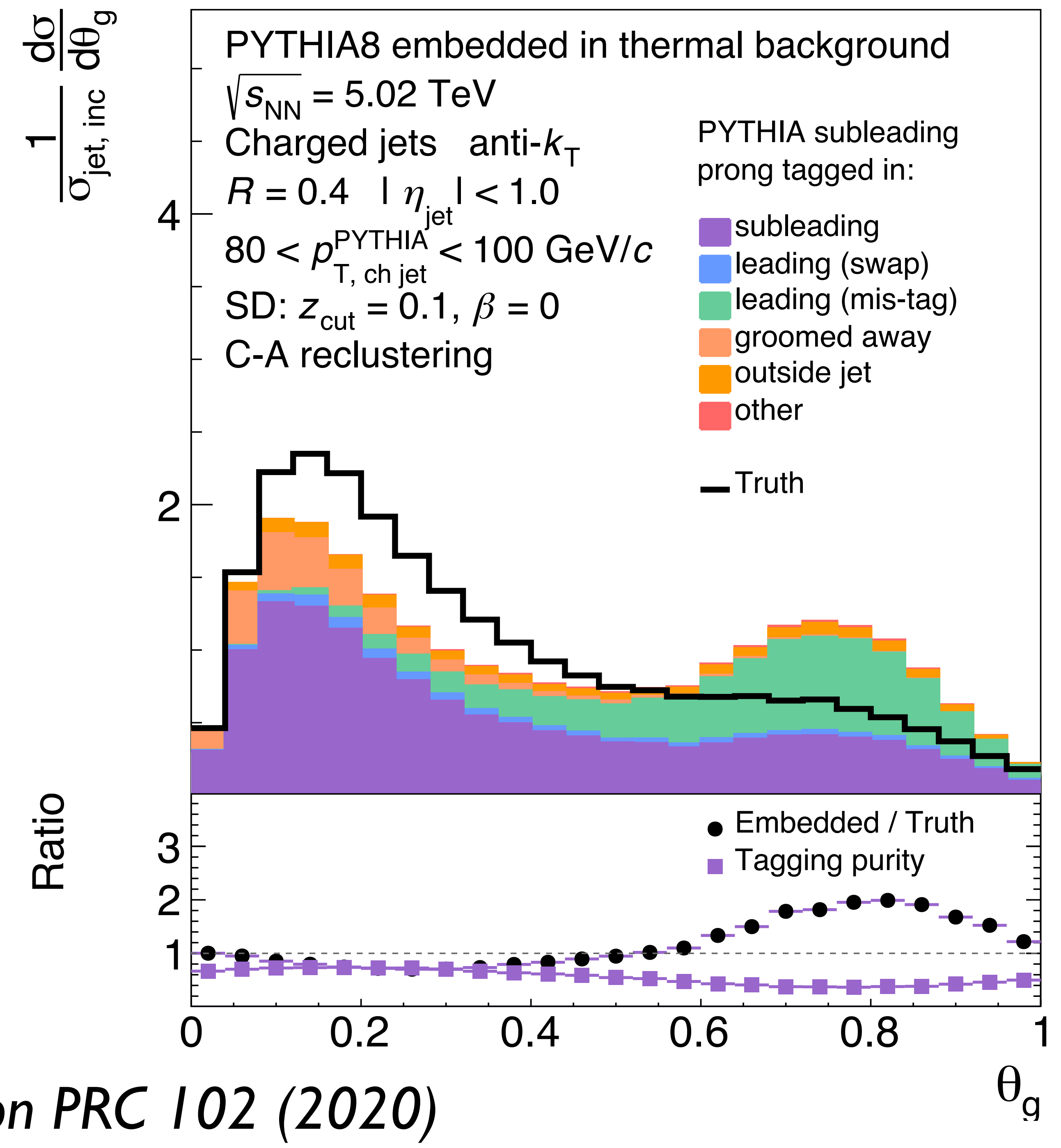
ALICE JHEP 09 (2015)

Object tagging

For observables that involve event-by-event tagging, the background can induce mis-tagging

Groomed observables, leading subjets, …

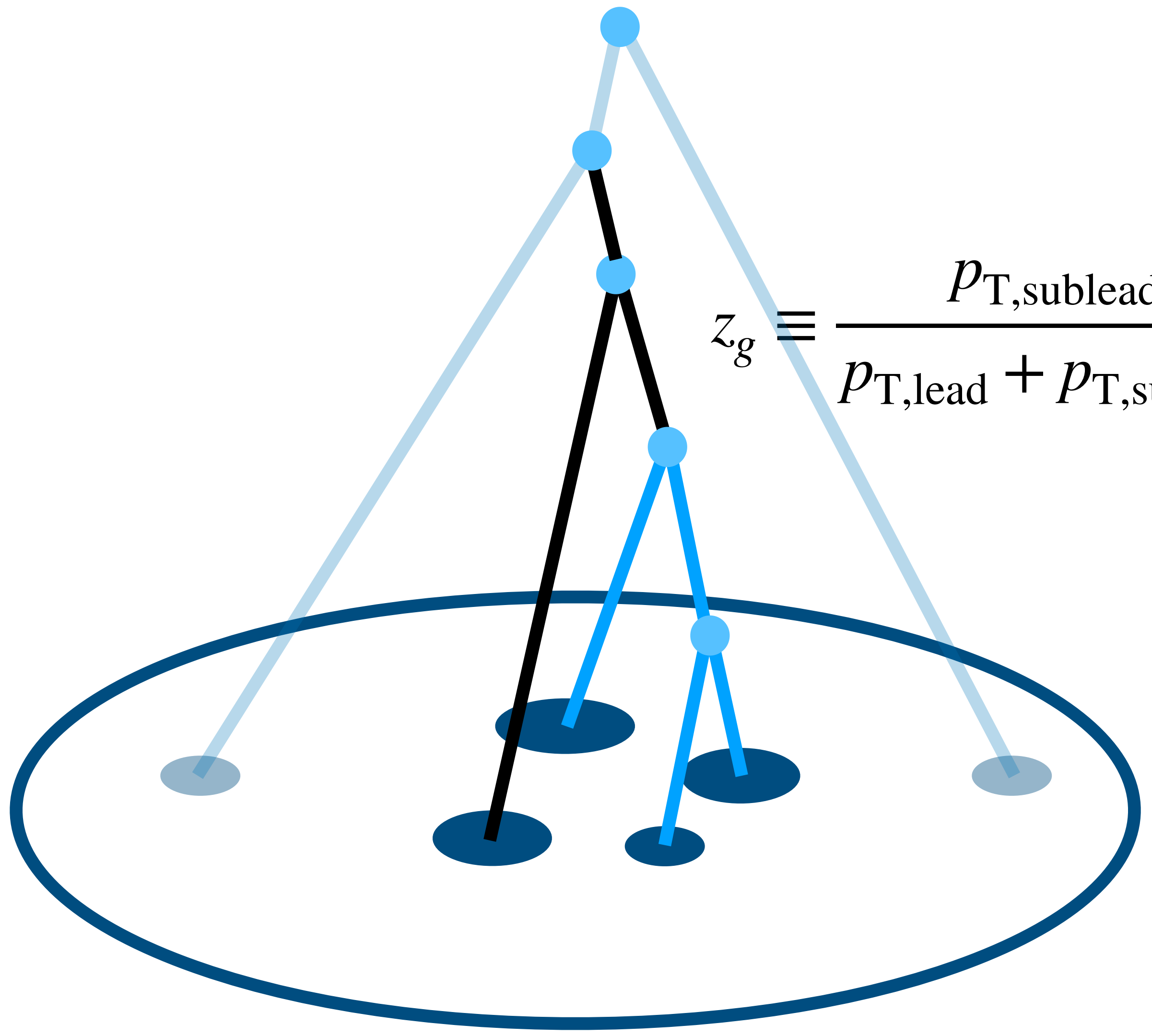




JM, Ploskon PRC 102 (2020)

Groomed jet substructure

How is the hard jet substructure modified in heavy-ion collisions?



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ALICE-PUBLIC-2020-006

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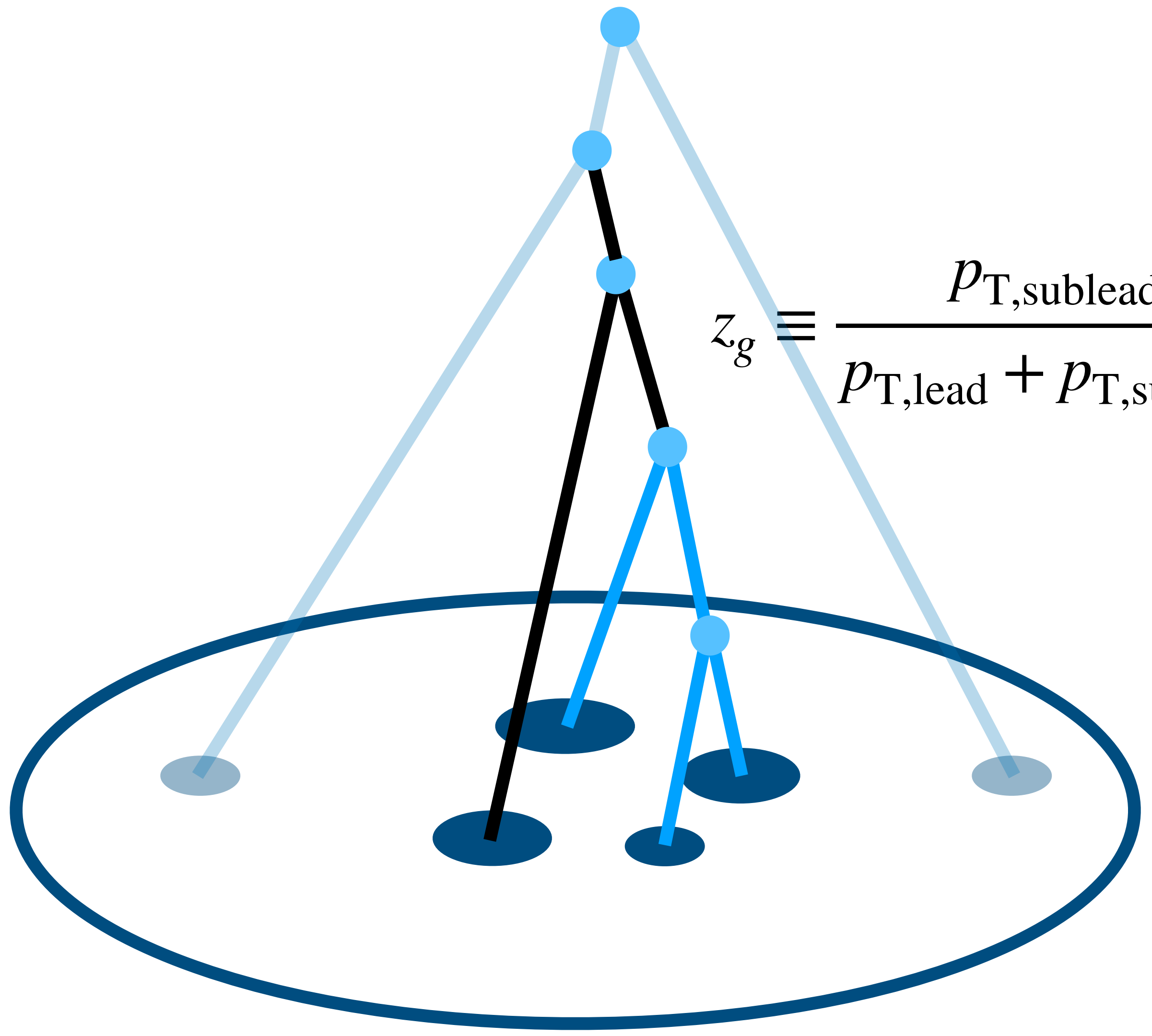

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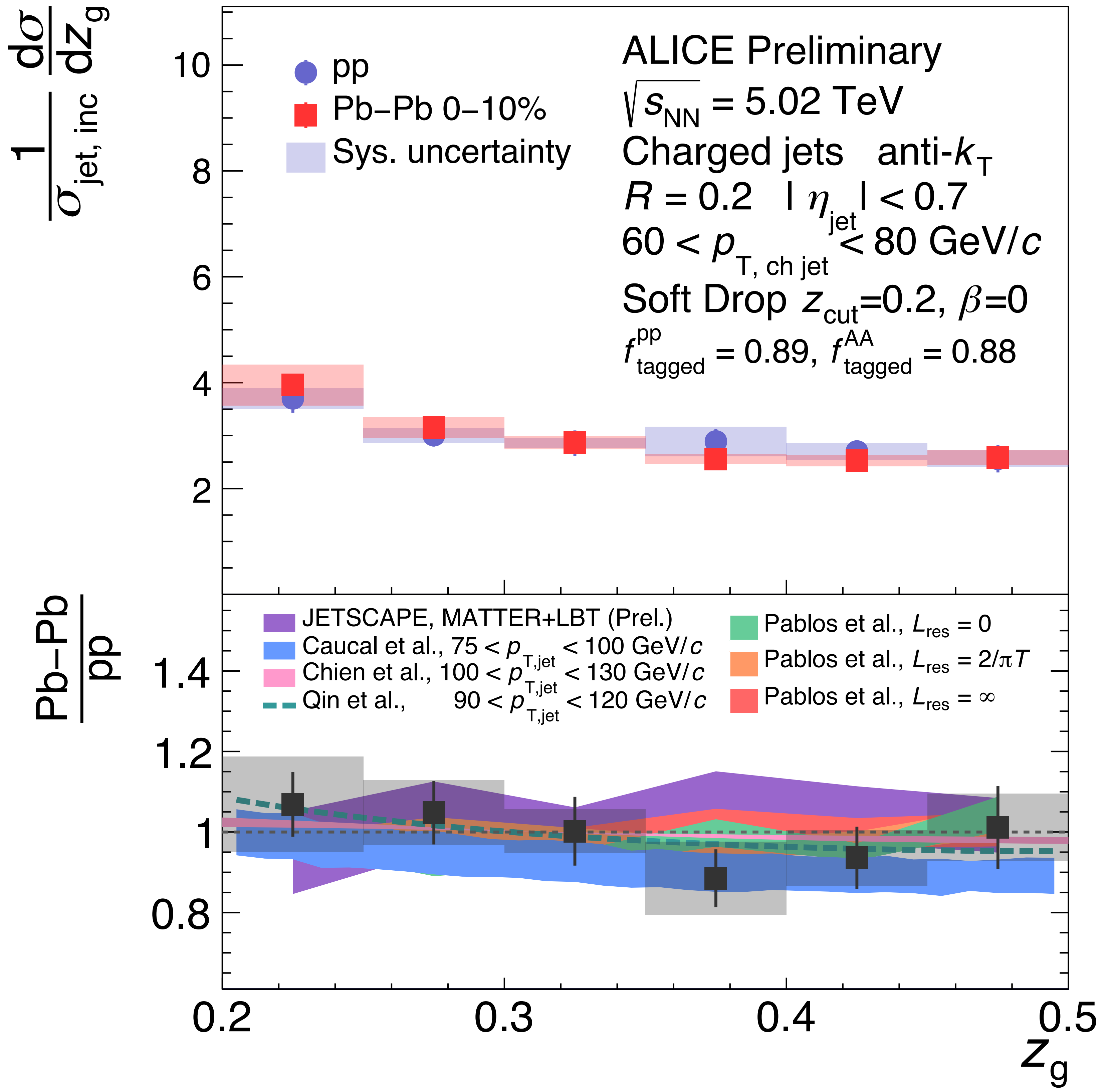

No significant modification in z_{g} distribution

Groomed jet substructure

ALICE-PUBLIC-2020-006

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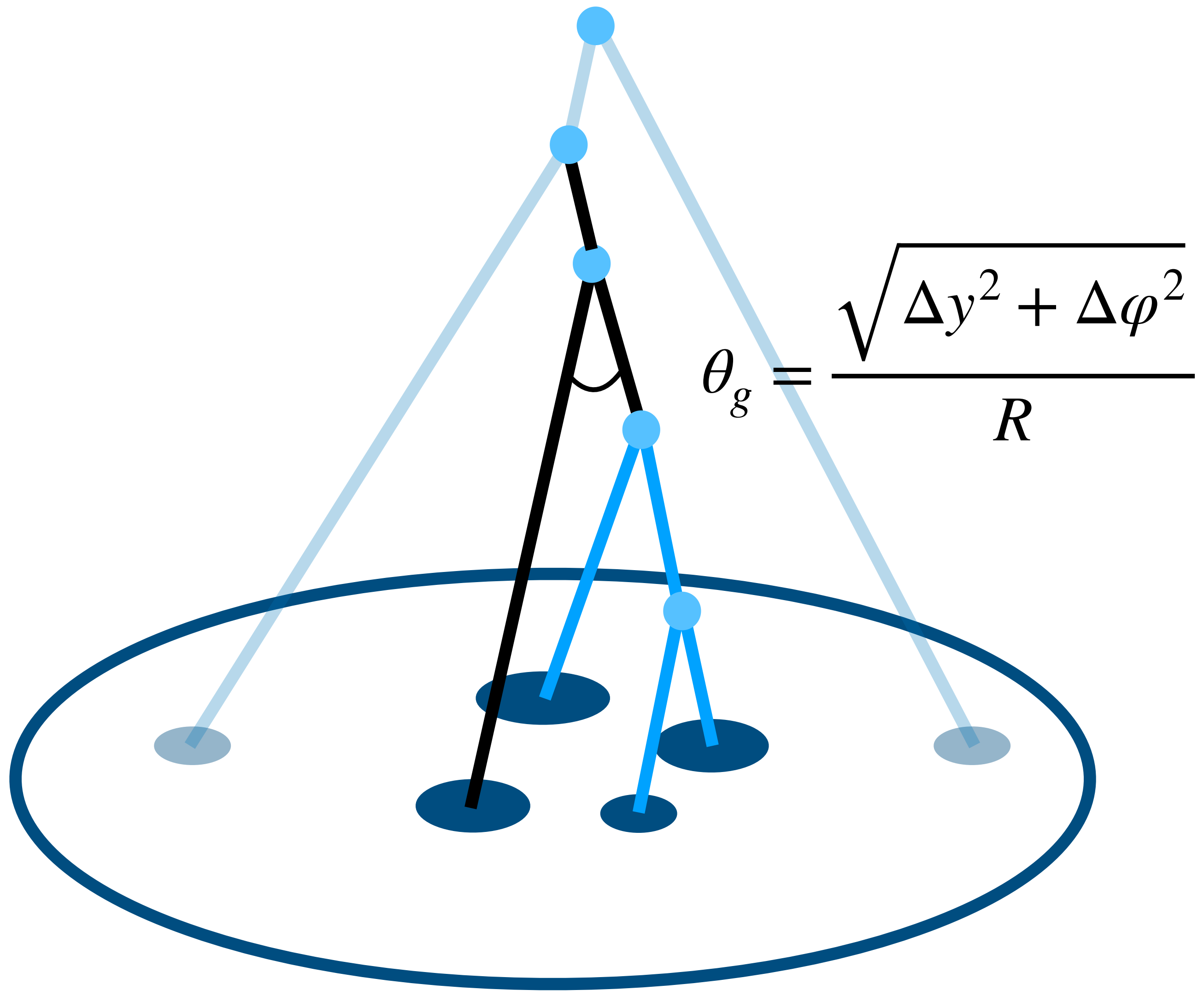
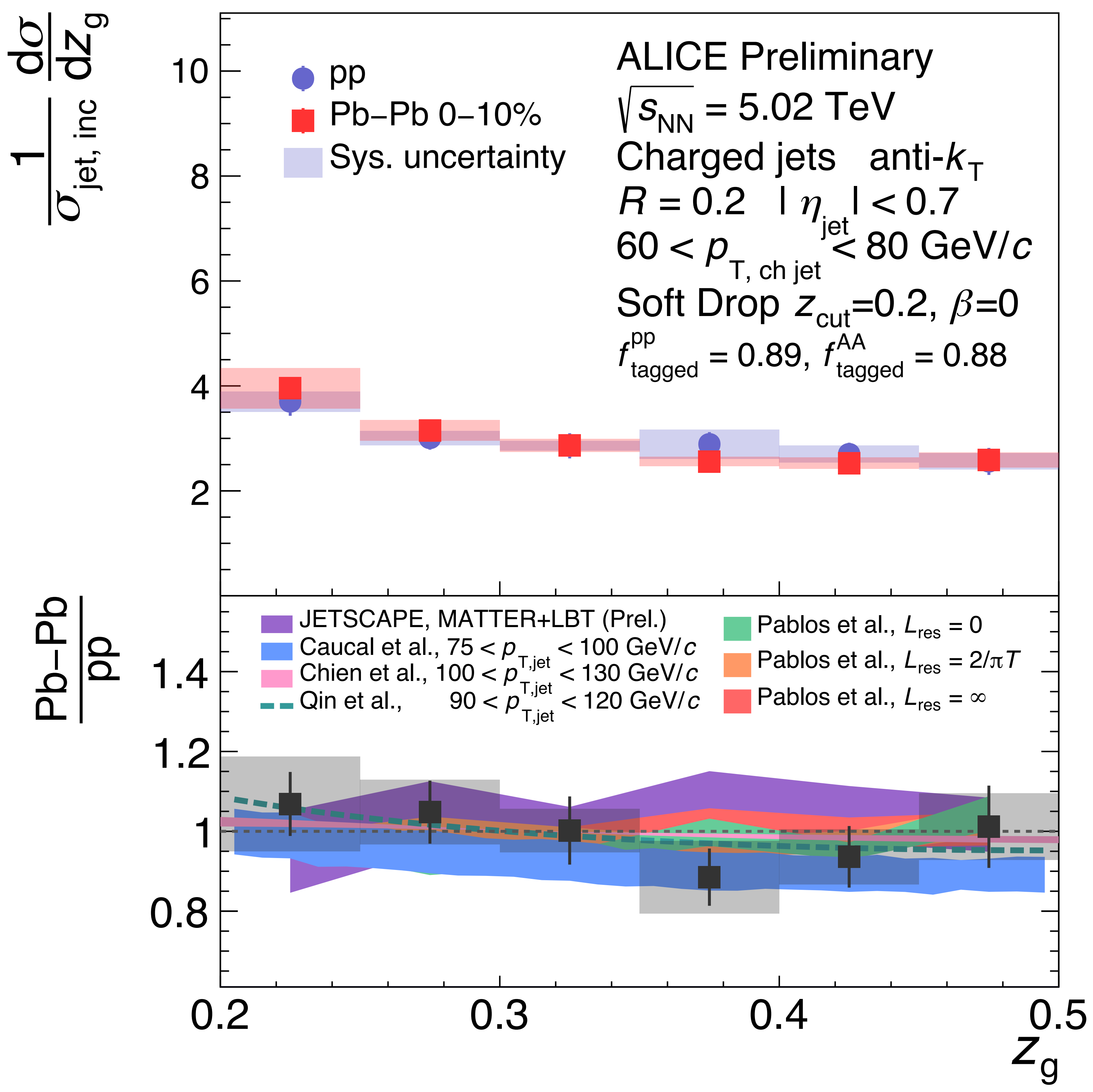


$$\theta_g = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$



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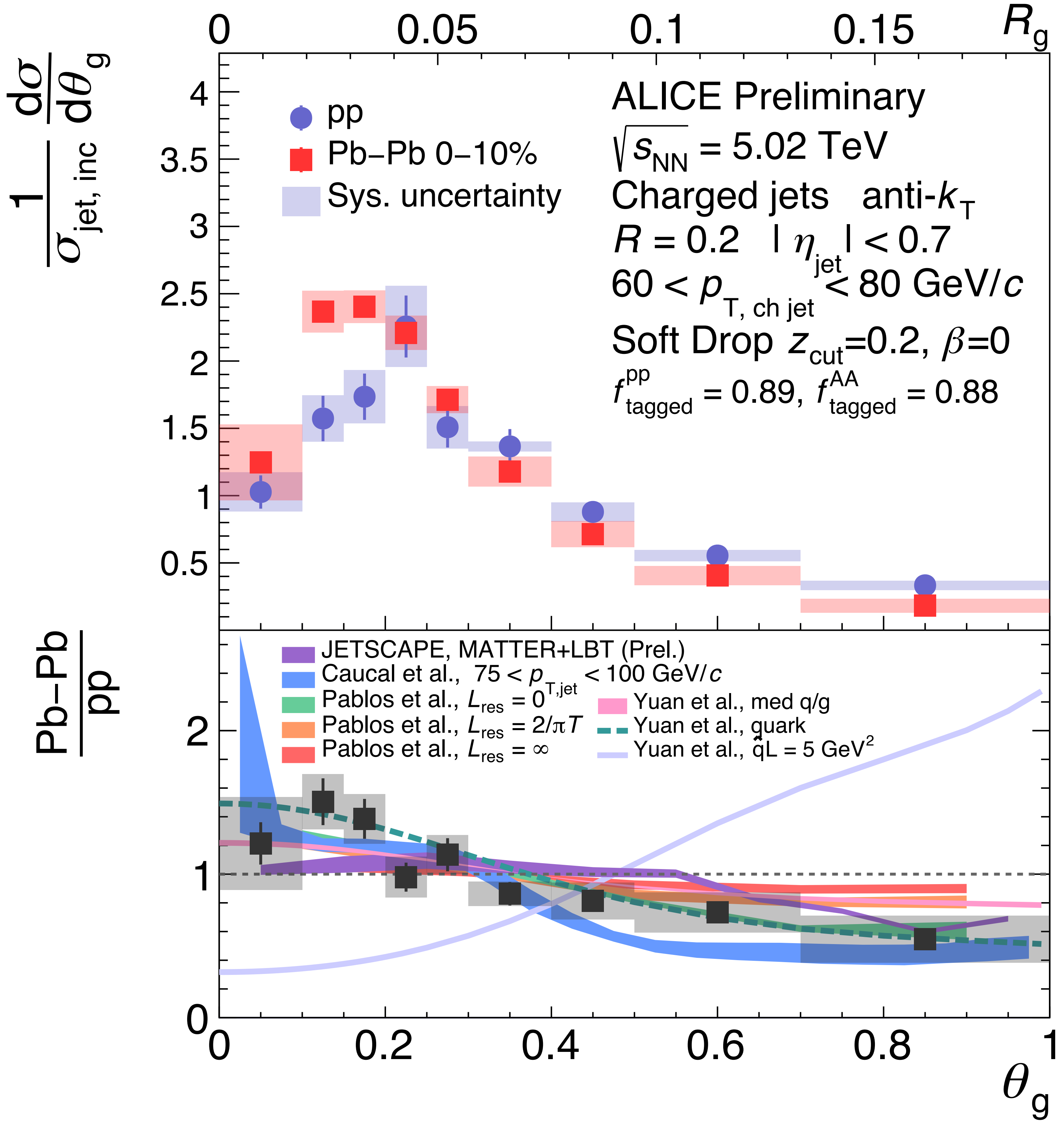
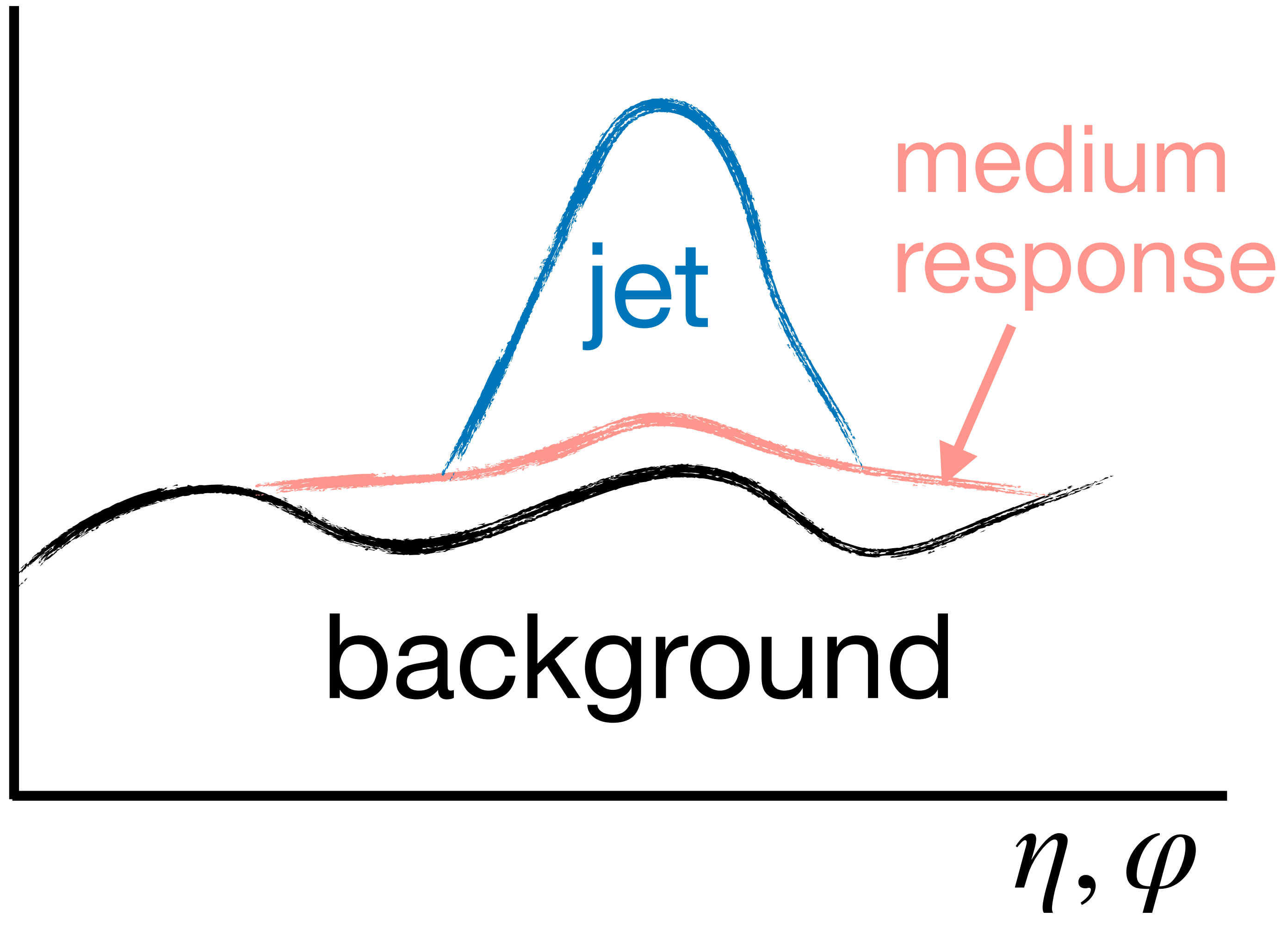


The cores of jets are narrower in Pb-Pb compared to pp collisions

Sensitive to QGP resolution length

Ungroomed jet substructure

How is the soft jet substructure modified in heavy-ion collisions?



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ATLAS PRL 123 (2019)

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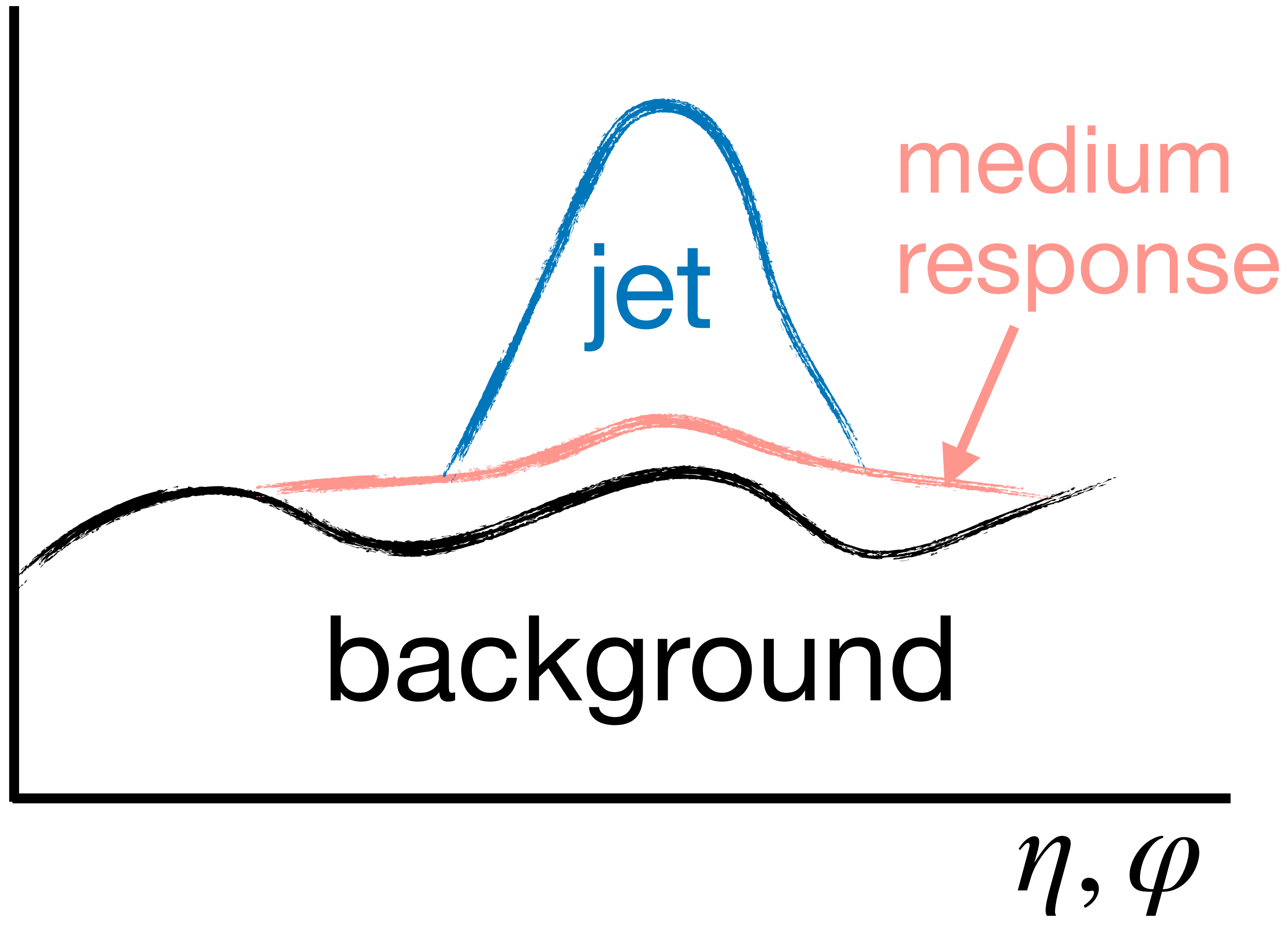
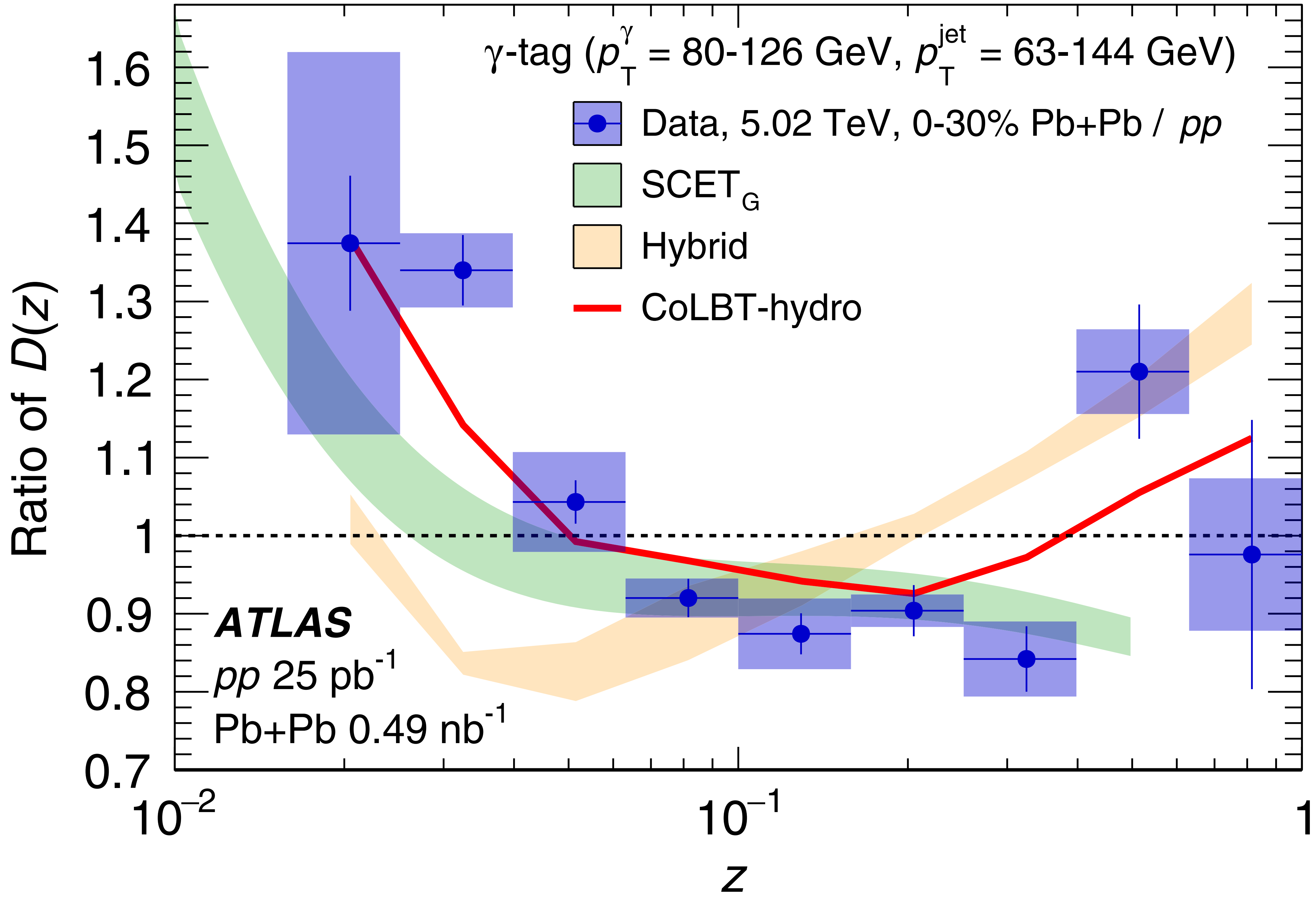


Longitudinal momentum fraction of hadrons in jets

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{ch}}}{dz}$$

$$z \equiv p_{\mathrm{T}} \cos \Delta R \; / \; p_{\mathrm{T}}^{\mathrm{jet}}$$



Simultaneous description of high-z and low-z is an open question

Ungroomed jet substructure

ALICE PLB 776 (2018)

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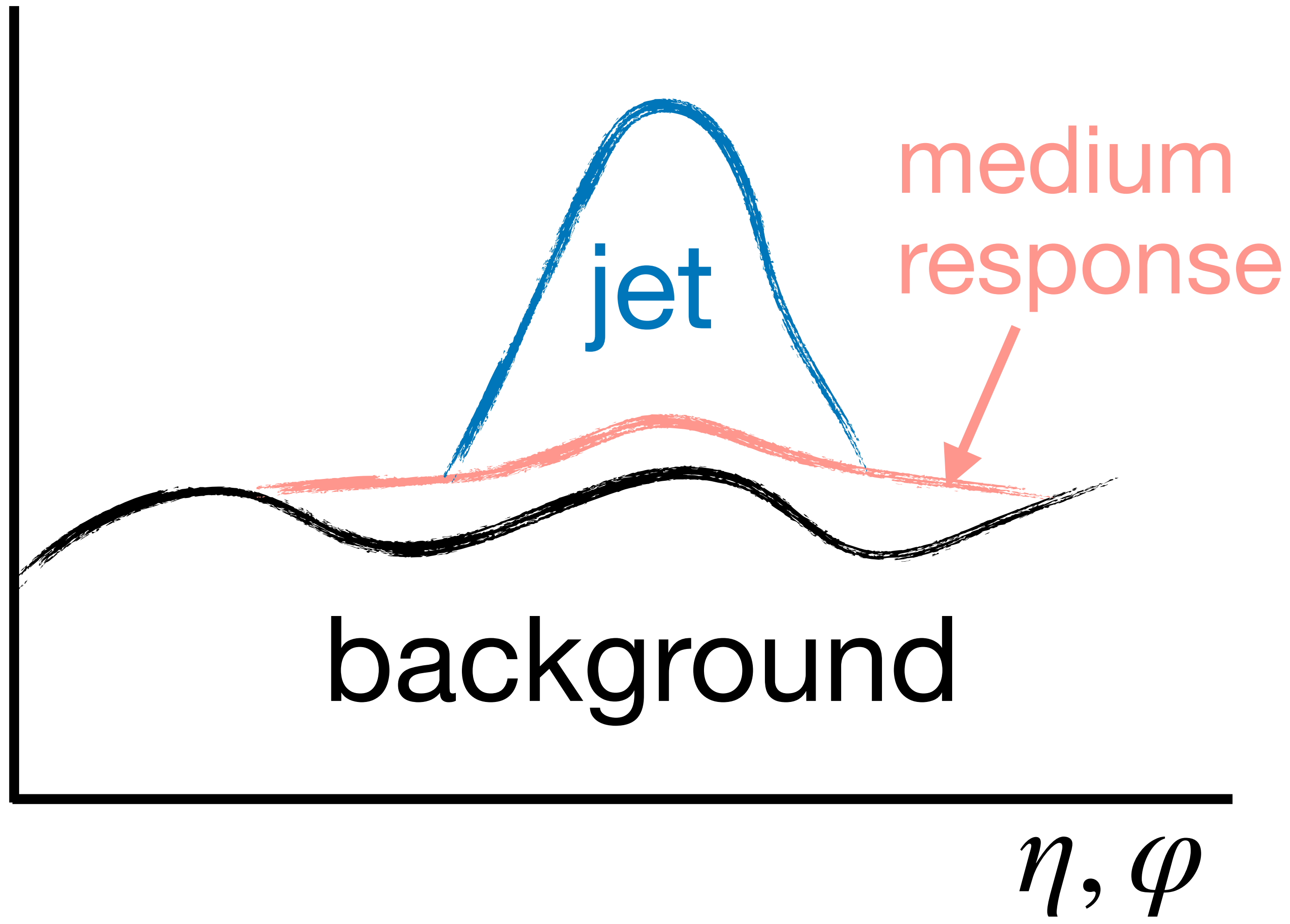
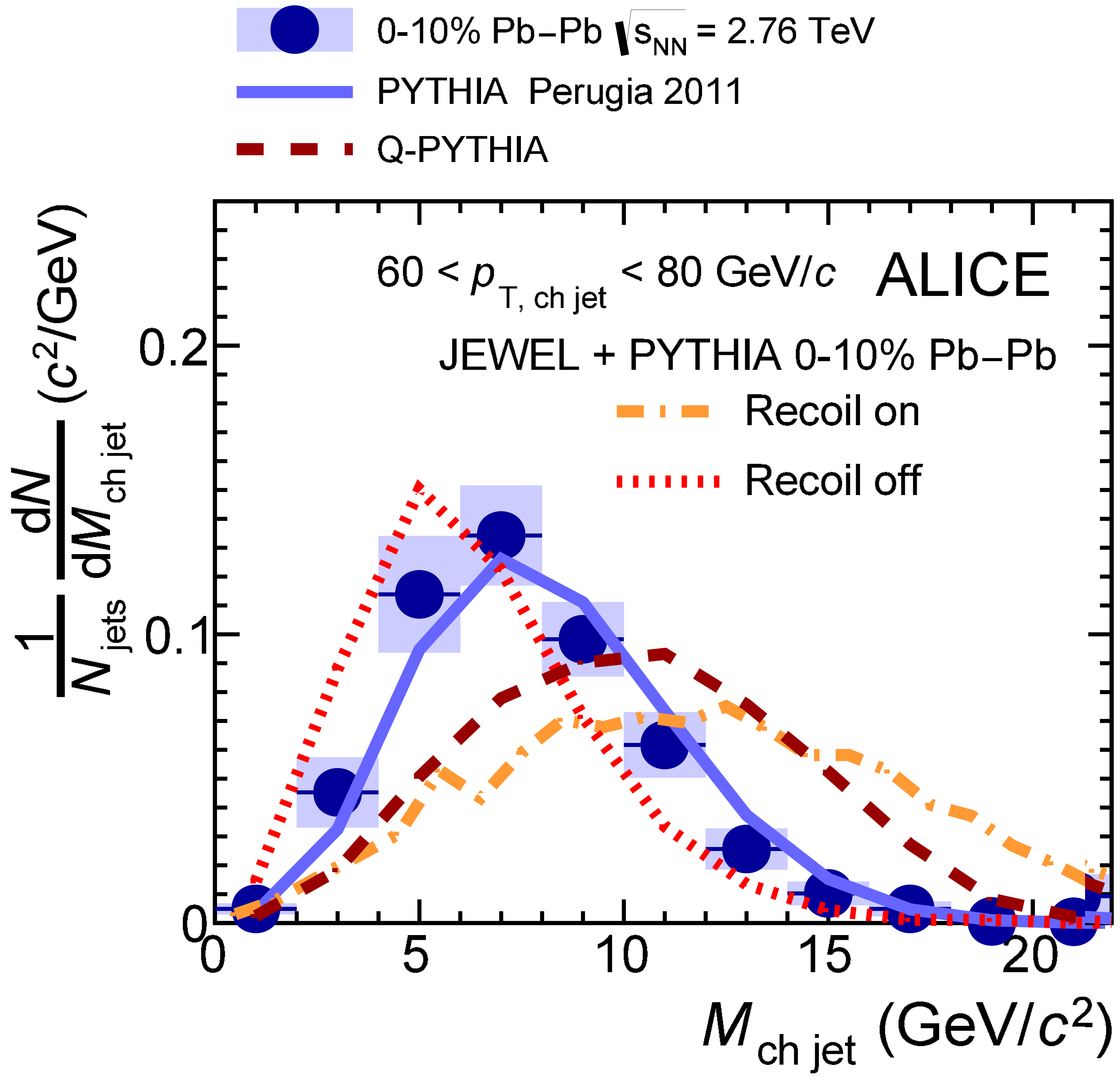


Jet mass $M = \sqrt{E^2 - p_T^2 - p_z^2}$



Poor description by models

Large impact of medium response

Outlook — jet substructure in heavy-ion collisions

Hard substructure: collimation/filtering of wide jets — splitting not strongly modified

Soft substructure: excess of soft particles, but mechanism unclear — difficult to model

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Where do we go from here?

- Theory guidance — not just "model A vs. model B" — but controlled comparisons of specific aspects within model (quark vs. gluon suppression, color coherence, medium response, …)

  JETSCAPE 1903.07706
  Casalderrey-Solana, Milhano, Pablo, Rajogopal JHEP 01 (2020)
  …

- Continue to develop new experimental techniques for background — we can do better — which will open up new, differential observables

- Global analysis is key to connect observables to QGP properties — now is the time

  JETSCAPE 2102.11337
  …

Summary

Jet substructure in proton-proton collisions is providing new tests of our first-principles understanding of QCD

- Higher-order terms in perturbative calculations
- Explore the transition from the perturbative to nonperturbative regimes
  - Provides crucial insight for reference to heavy-ion collisions

Jet substructure in heavy-ion collisions is providing flexibility to probe the quark-gluon plasma over a range of scales

- Groomed observables test well-controlled perturbative aspects
- Ungroomed observables constrain nonperturbative / medium response phenomenology
- Will play an essential role in global fits *JETSCAPE 2102.11337*

backup

Groomed jet substructure — pp

ATLAS PRD 101 (2020)

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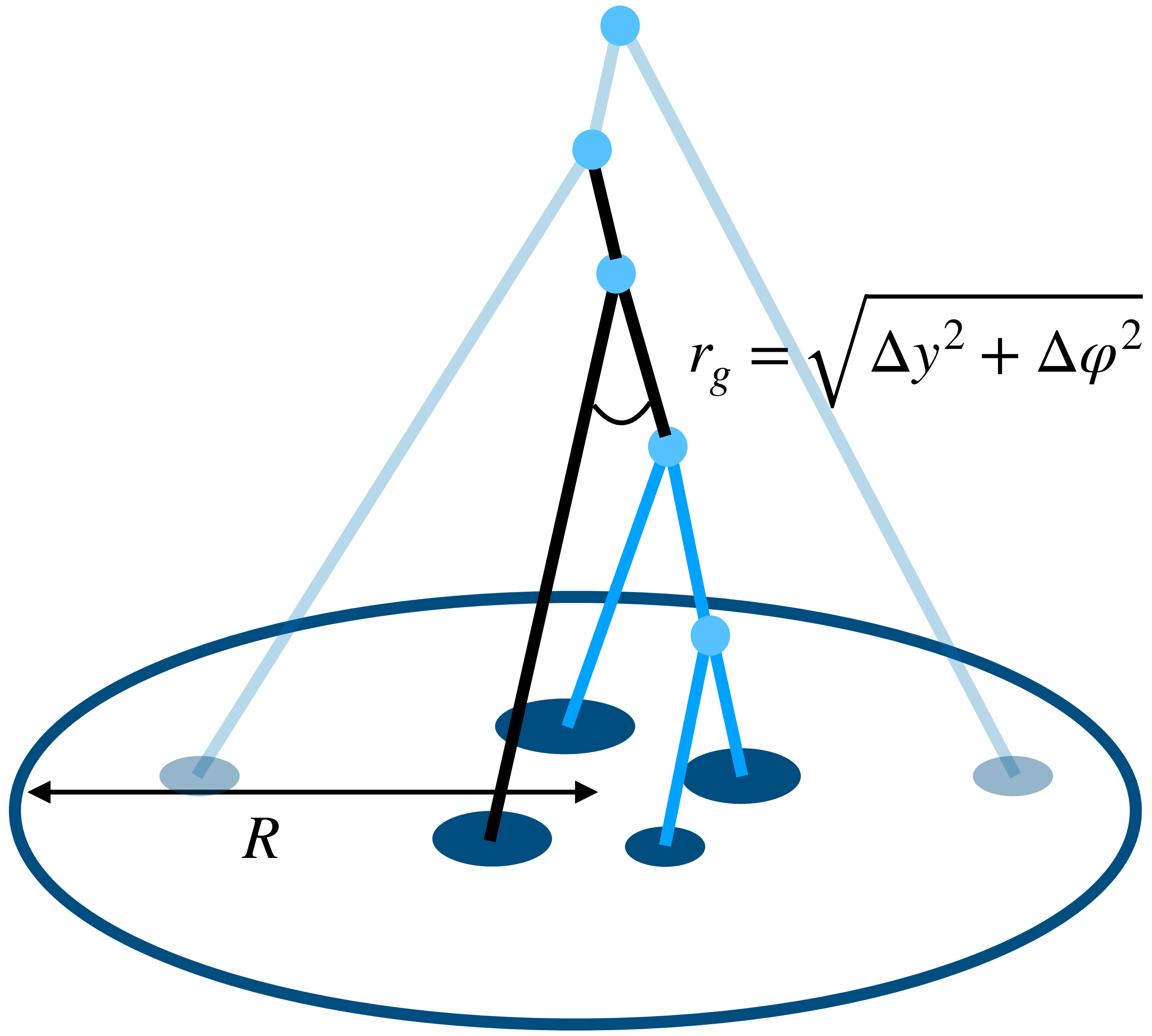

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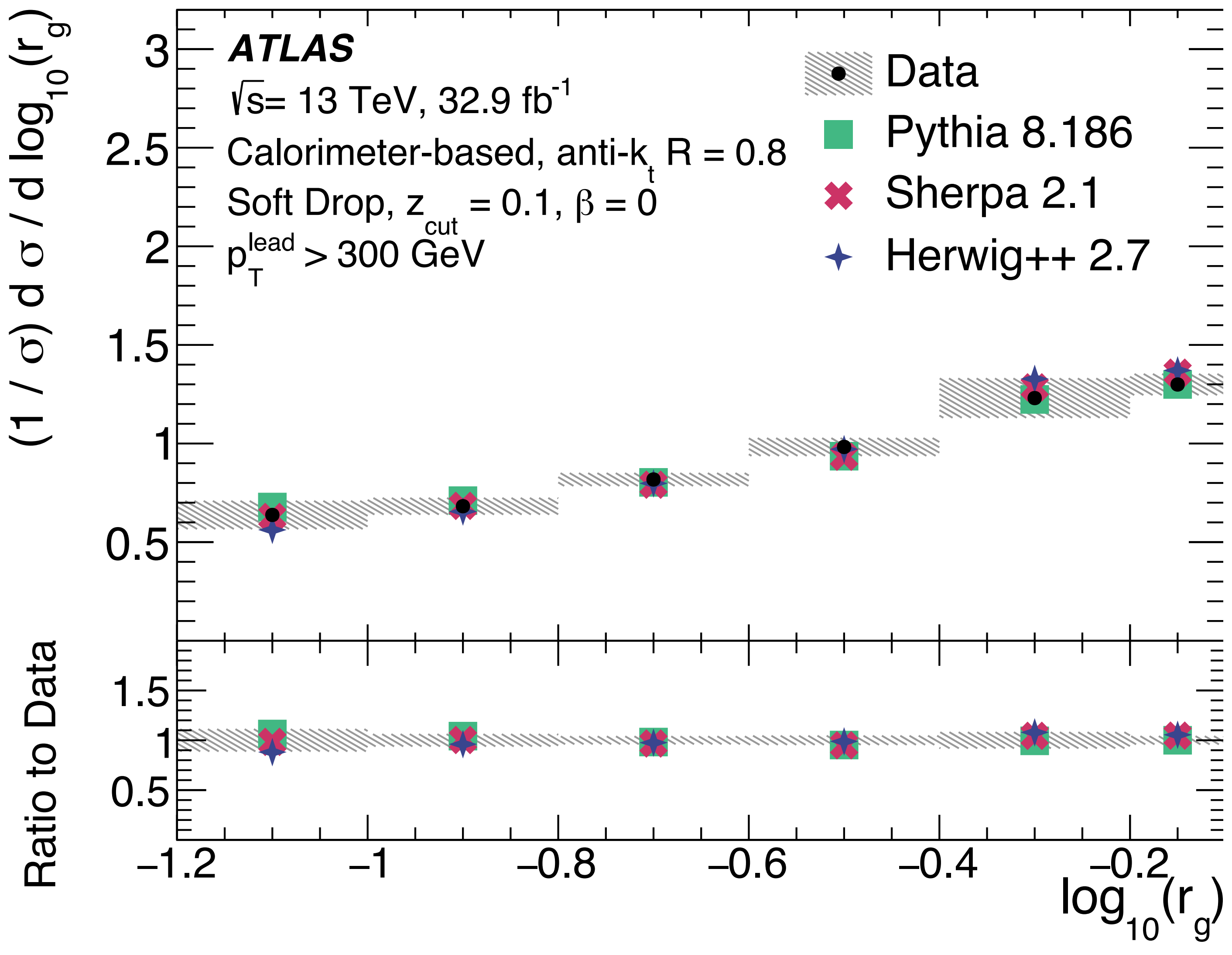
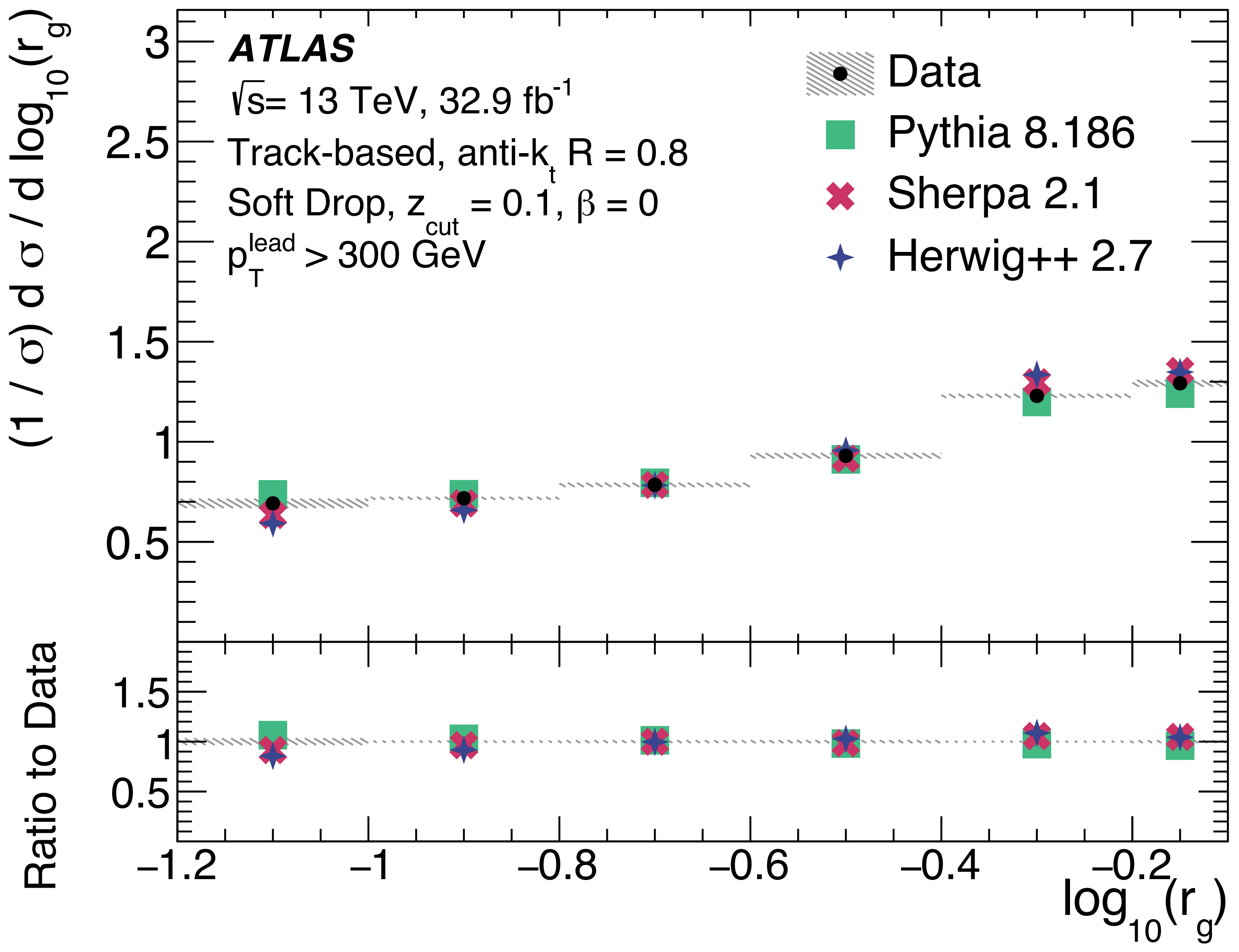
Calorimeter-based



Track-based



Track-based substructure observables can be measured with greater precision

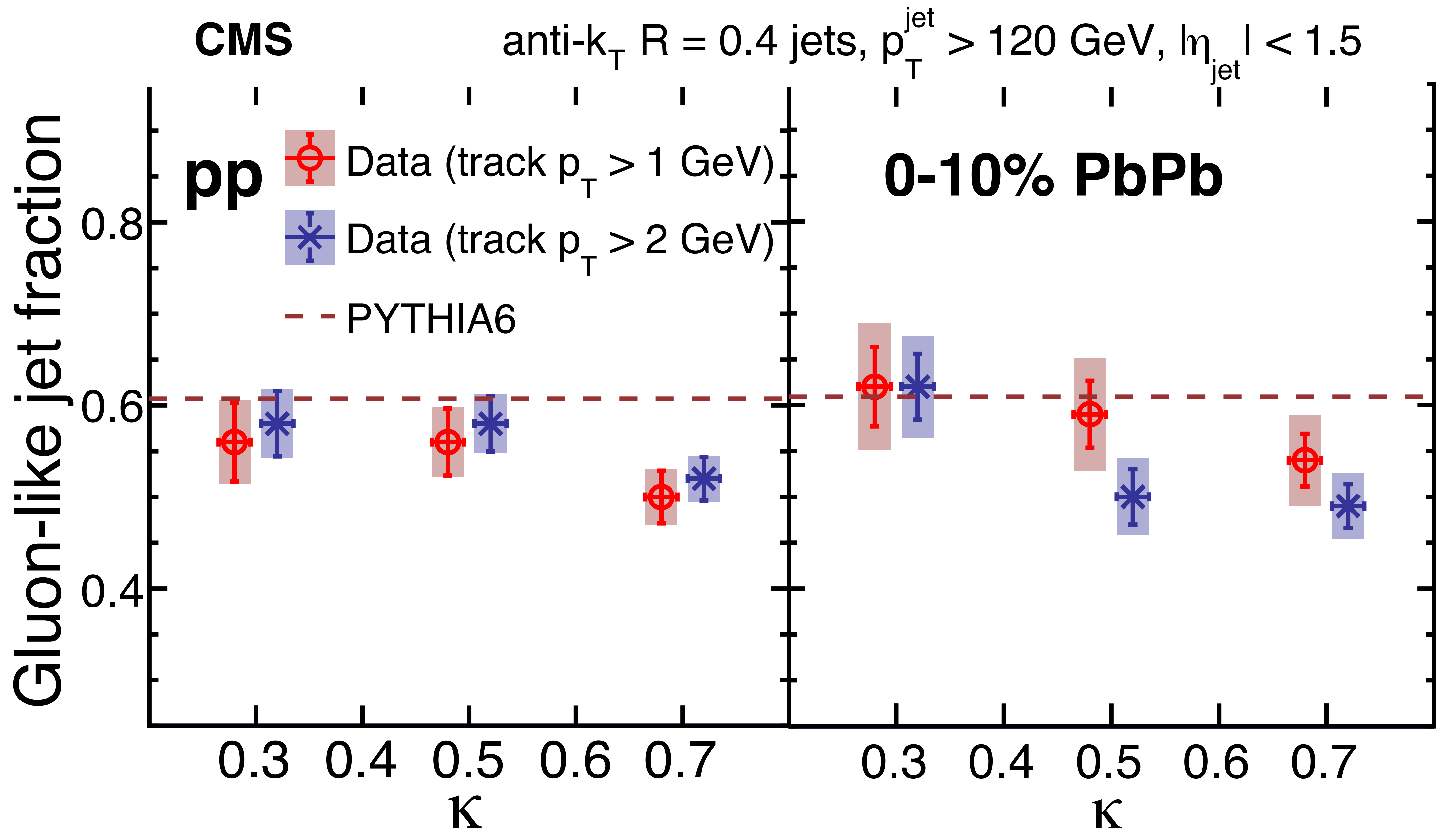
Chang, Procura, Thaler, Waalewijn PRL 111 (2013)

Ungroomed jet substructure

CMS JHEP 07 (2020)

How is the soft jet substructure modified in heavy-ion collisions?

Jet charge $$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_{i \in \mathrm{jet}} q_i {p_{\mathrm{T},i}}^{\kappa}$$



No strong modification of "gluon-like" jets

Interpretation unclear — quenching, medium response