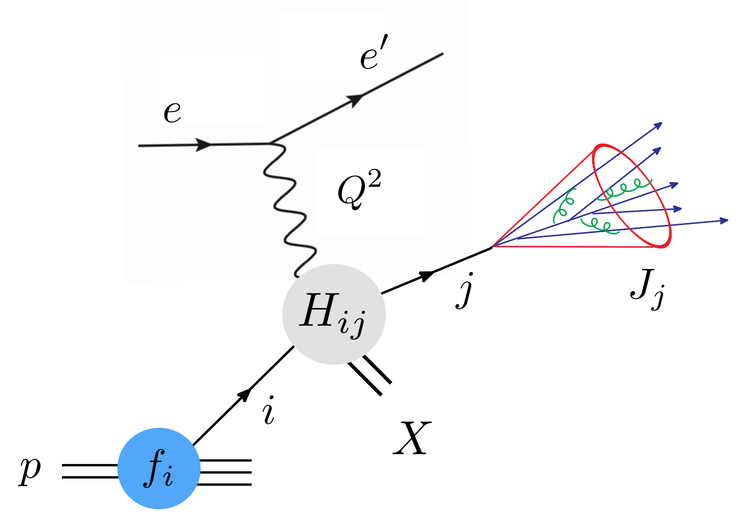
Exploring the transition from perturbative to non-perturbative QCD at the LHC

James Mulligan
University of California, Berkeley

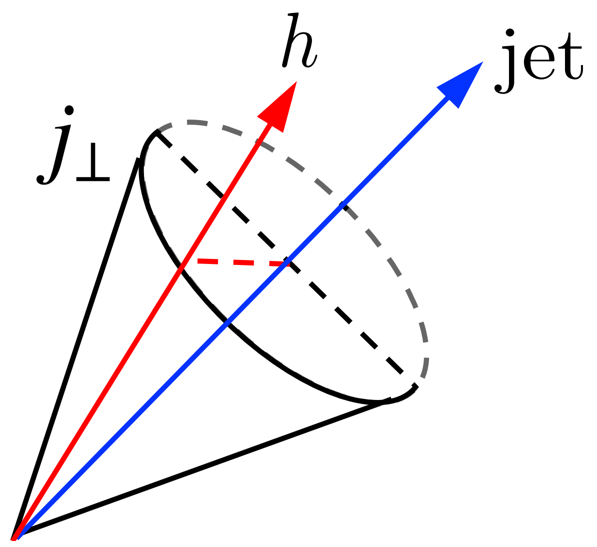
Jet Physics: From RHIC/LHC to EIC
Stony Brook University
June 30, 2022

The Zoo of Jet Observables

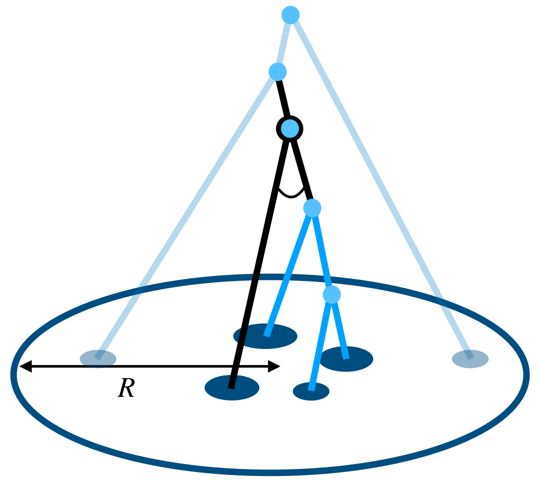
Inclusive jet cross-section



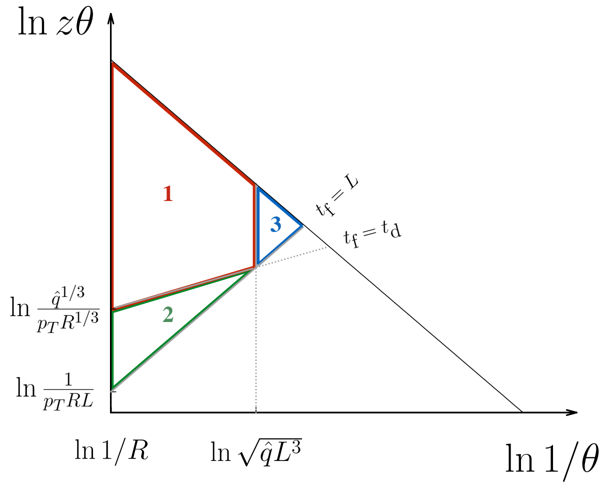
Hadron-in-jet distributions



Groomed jet substructure



Lund plane

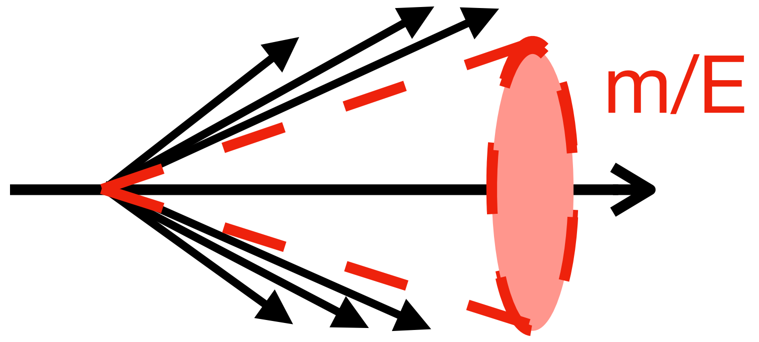


Jet charge

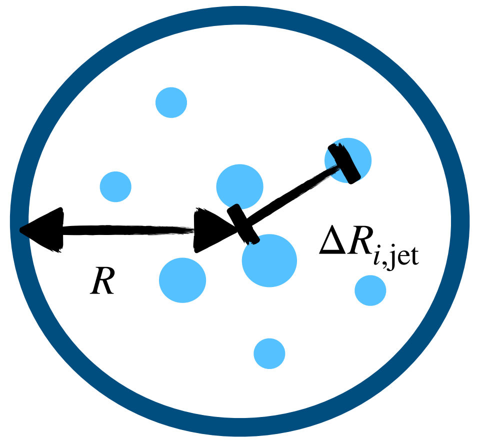
$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_i Q_i (p_{\mathrm{T}}^i)^{\kappa}$$

...

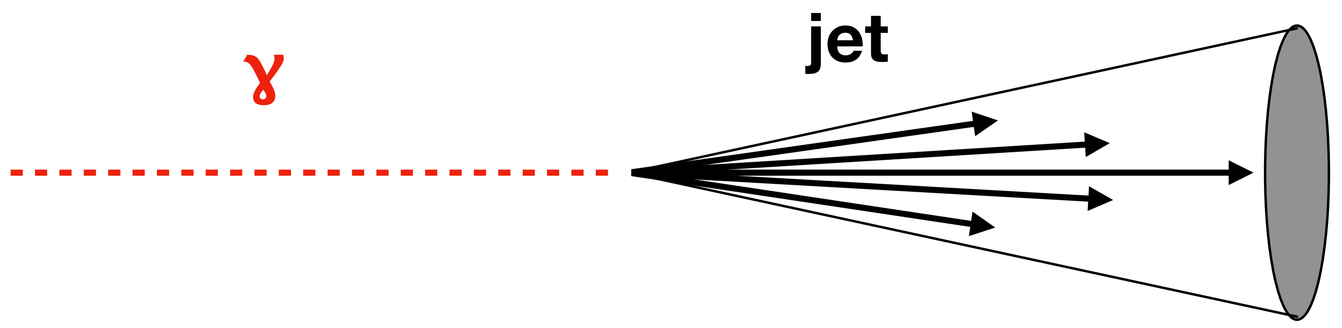
Heavy flavor jets



Jet angularities



EW-tagged jets



With great flexibility…comes great responsibility

Perturbative vs. Non-perturbative QCD

(1) Cannot test perturbative accuracy if non-perturbative contribution is not under control

- This requires comparison of data to analytical calculation — not a tuned MC!

Perturbative vs. Non-perturbative QCD

(1) Cannot test perturbative accuracy if non-perturbative contribution is not under control

- This requires comparison of data to analytical calculation — not a tuned MC!

(2) Jet quenching: Need theoretical control of pp baseline in order to understand perturbative vs. non-perturbative modification

- This requires comparison of data to analytical calculation — not a tuned MC!

Perturbative vs. Non-perturbative QCD

(1) Cannot test perturbative accuracy if non-perturbative contribution is not under control

- This requires comparison of data to analytical calculation — not a tuned MC!

(2) Jet quenching: Need theoretical control of pp baseline in order to understand perturbative vs. non-perturbative modification

- This requires comparison of data to analytical calculation — not a tuned MC!

(3) Ultimately: seek first-principles understanding of non-perturbative physics

- Scaling laws; new observables; real-time dynamics; …

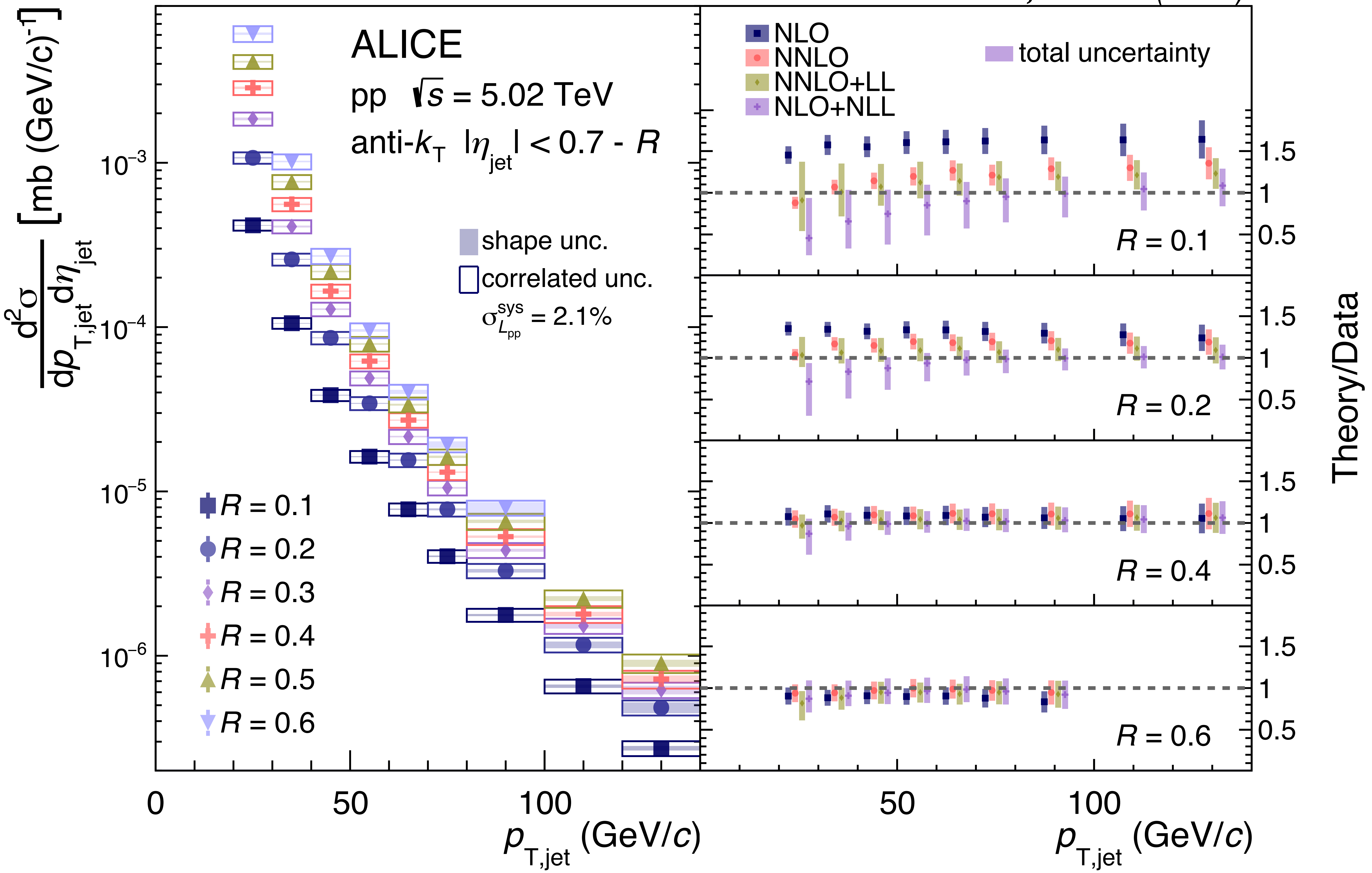
See talks by Moult, Lee, Sterman, Ringer, …

Inclusive jet cross-section

At small R, perturbative calculations begin to differ

- NNLO important
- Resummation important

PRC 101, 034911 (2020)



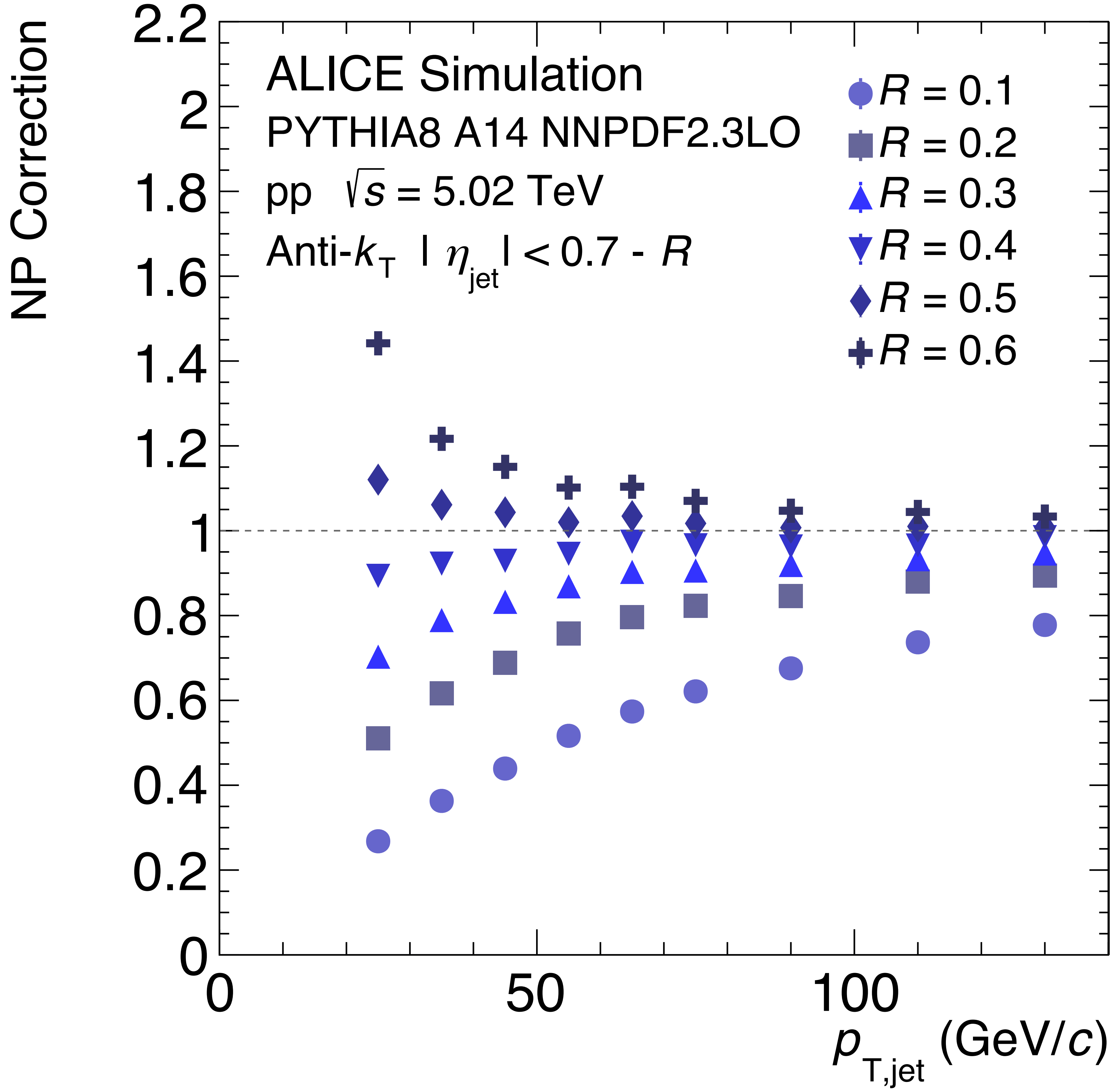
Inclusive jet cross-section

At small R, perturbative calculations begin to differ

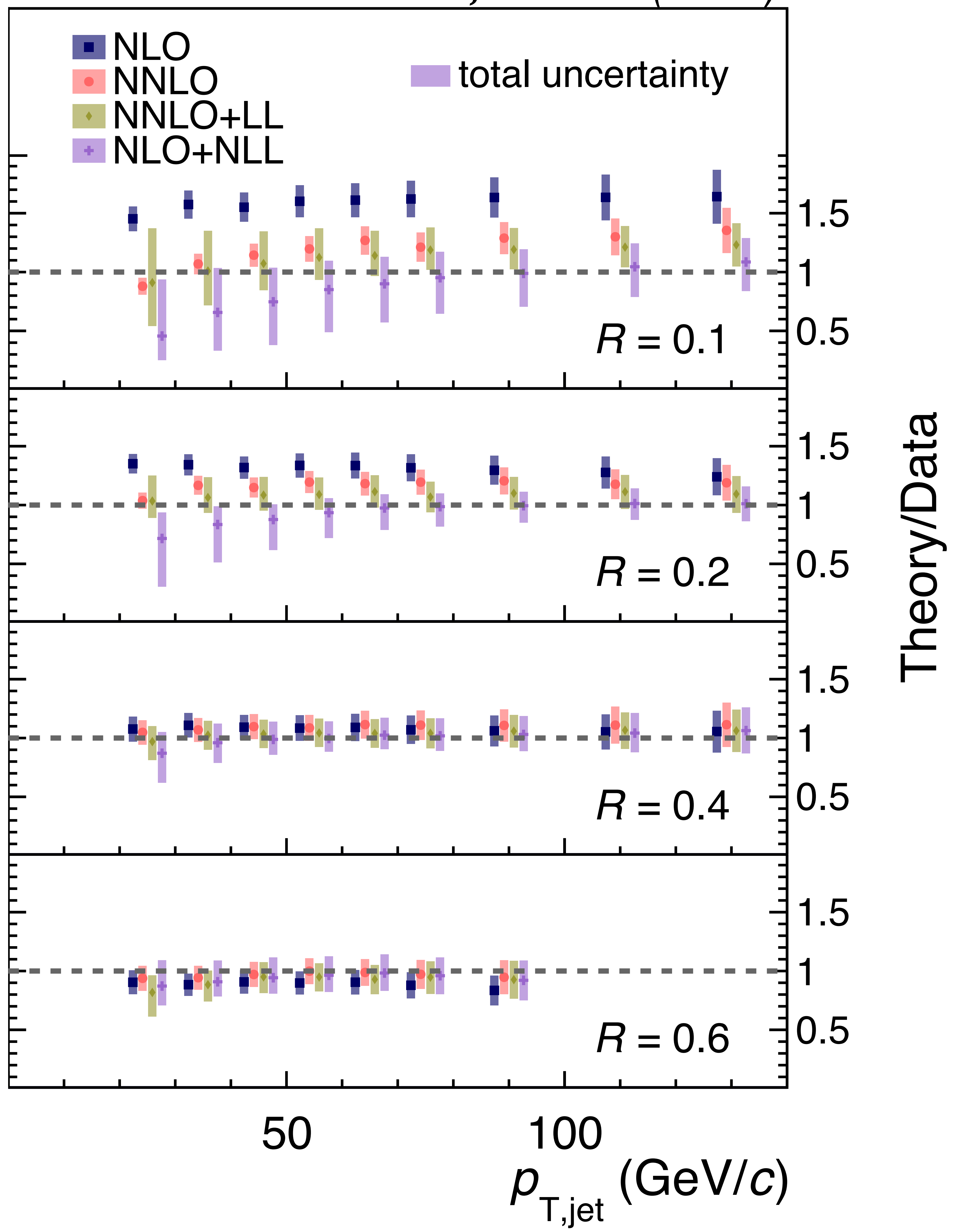
- NNLO important
- Resummation important

Non-perturbative effects become large at low p_T

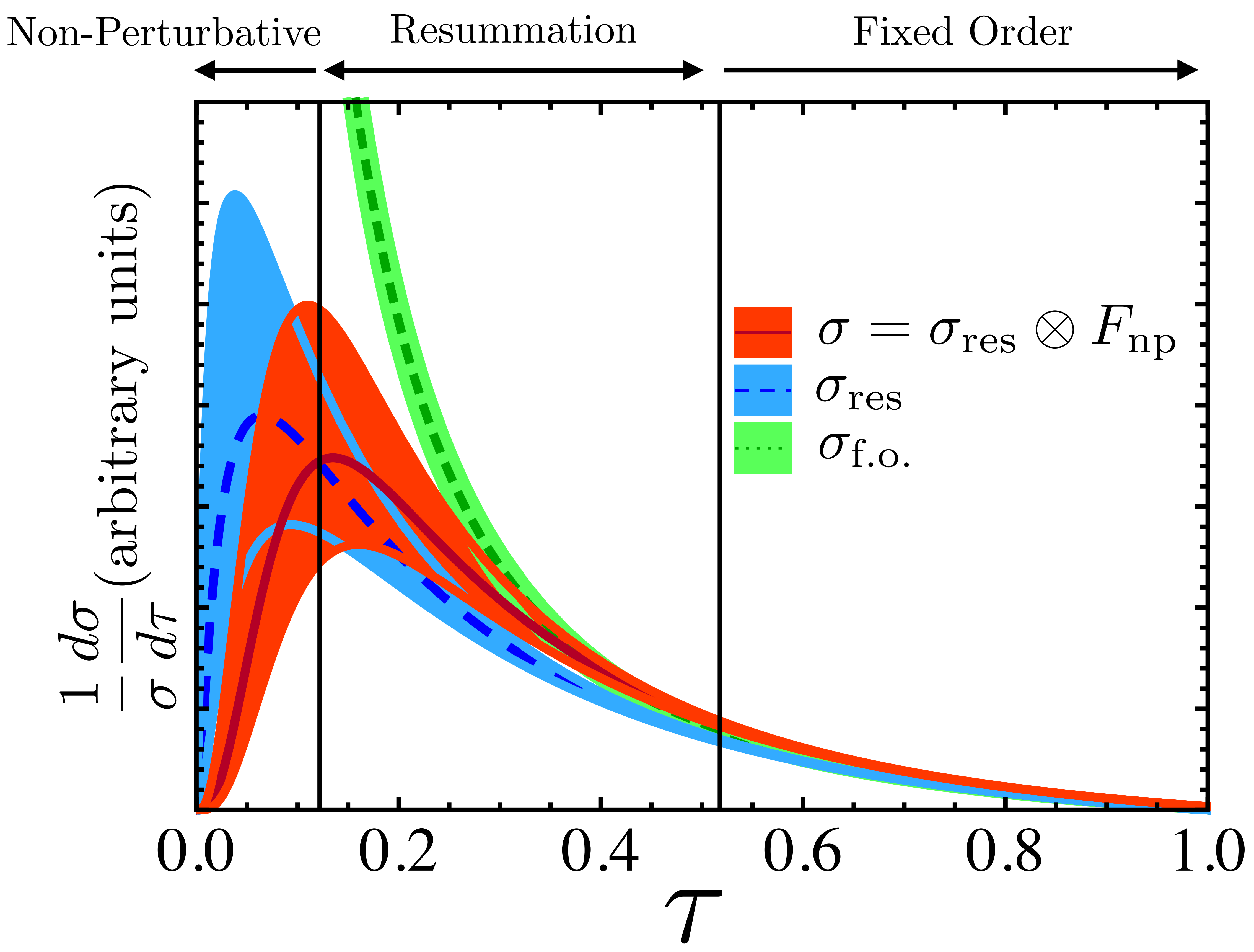
- Major challenge to interpreting data-theory comparison



PRC 101, 034911 (2020)

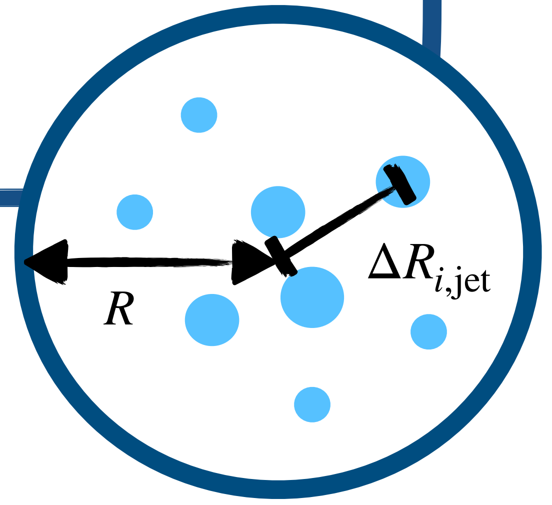


Jet substructure in proton-proton collisions



Larkoski, Moult, Nachman JPR 841 1 (2020)

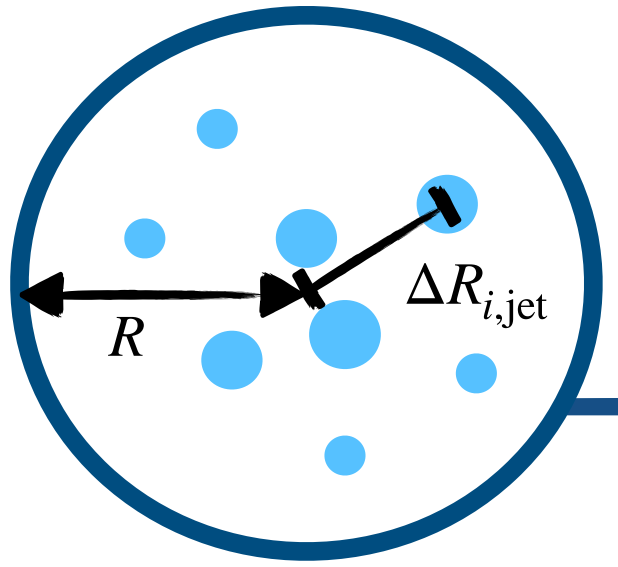
Jet substructure observables are sensitive to **specific regions** of QCD radiation phase space



Each observable has:

- Fixed-order regime — $\mathcal{O}\left(\alpha_s^n\right)$
- Resummation regime — large logarithms to all orders in α_s (e.g. $\alpha_s^n \ln^{2n} R$)
- Non-perturbative regime

Example 1: Jet angularities



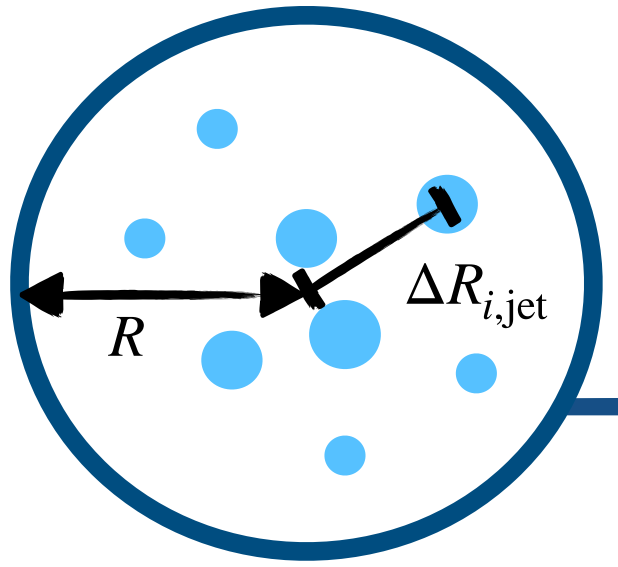
$$\lambda_\alpha \equiv \sum_{i \in \mathrm{jet}} z_i \theta_i^\alpha$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\mathrm{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\mathrm{jet}}}{R}$$

Parameter $\alpha > 0$ systematically varies weight of collinear radiation

Almeida, Lee, Perez, Sterman, Sung, Virzi PRD 79 (2009) 074017
Larkoski, Thaler, Waalewijn JHEP 11 (2014) 129
…

Example 1: Jet angularities



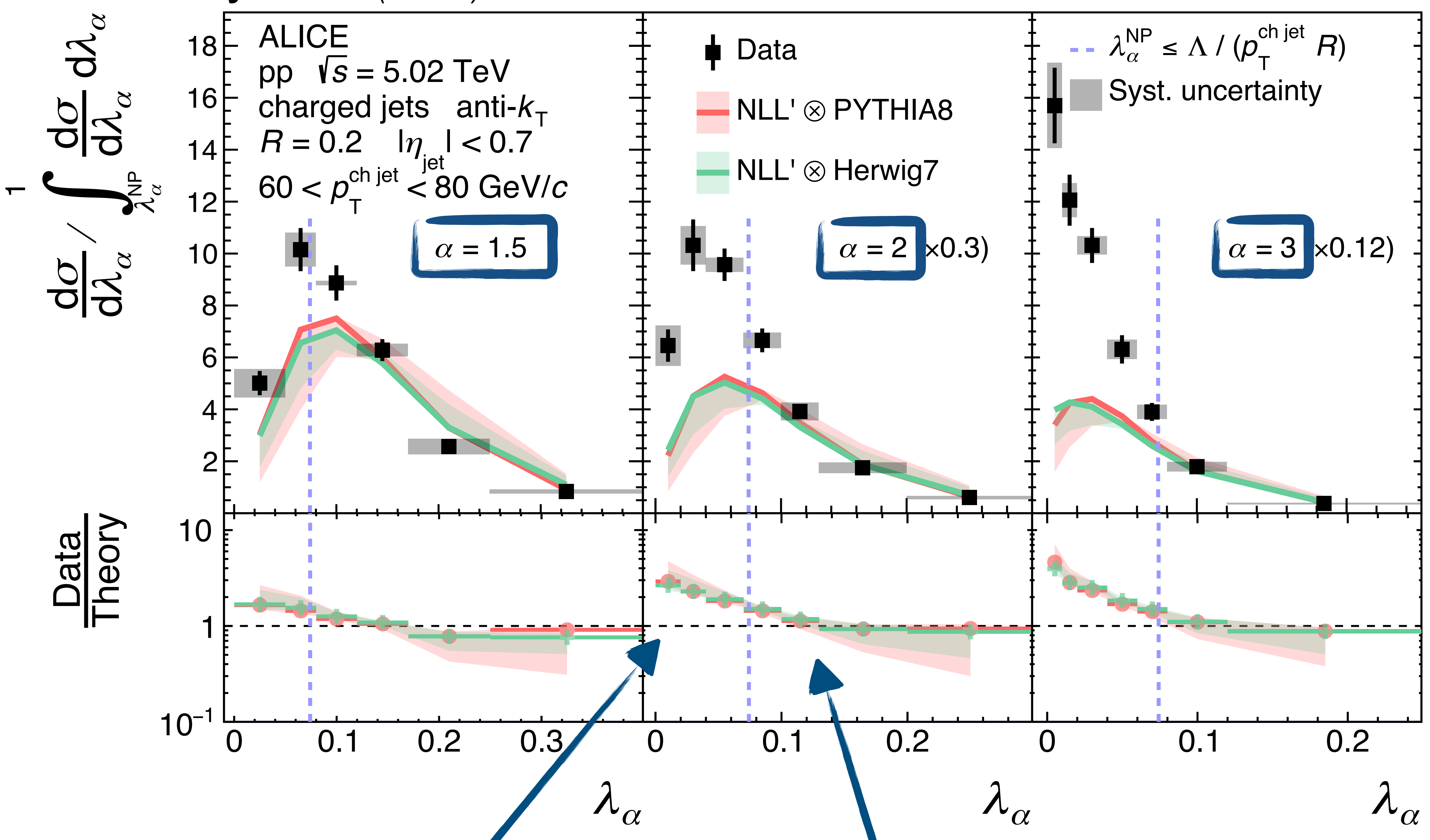
$$\lambda_\alpha \equiv \sum_{i \in \mathrm{jet}} z_i \theta_i^\alpha$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\mathrm{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\mathrm{jet}}}{R}$$

Parameter $\alpha > 0$ systematically varies weight of collinear radiation

Measurement is described by pQCD in perturbative regime — with expected breakdown in nonperturbative regime

JHEP 05 (2022) 061



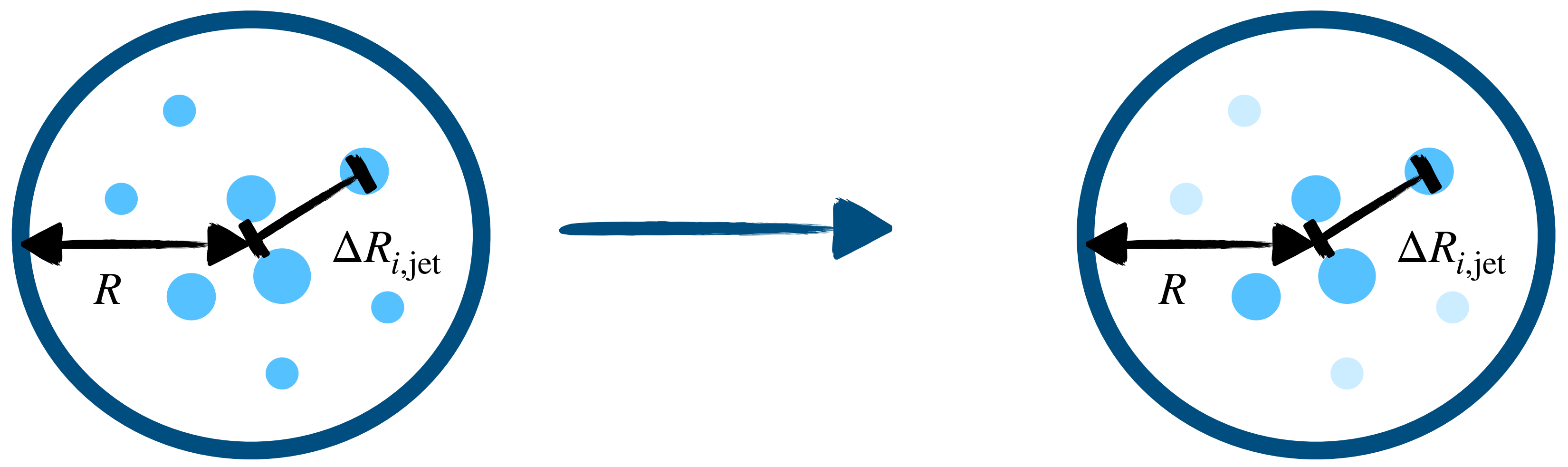
Small λ_α: Non-perturbative

Larger λ_α: Good agreement with pQCD calculations

Kang, Lee, Ringer JHEP 04 (2018) 110

Groomed jet angularities — pp

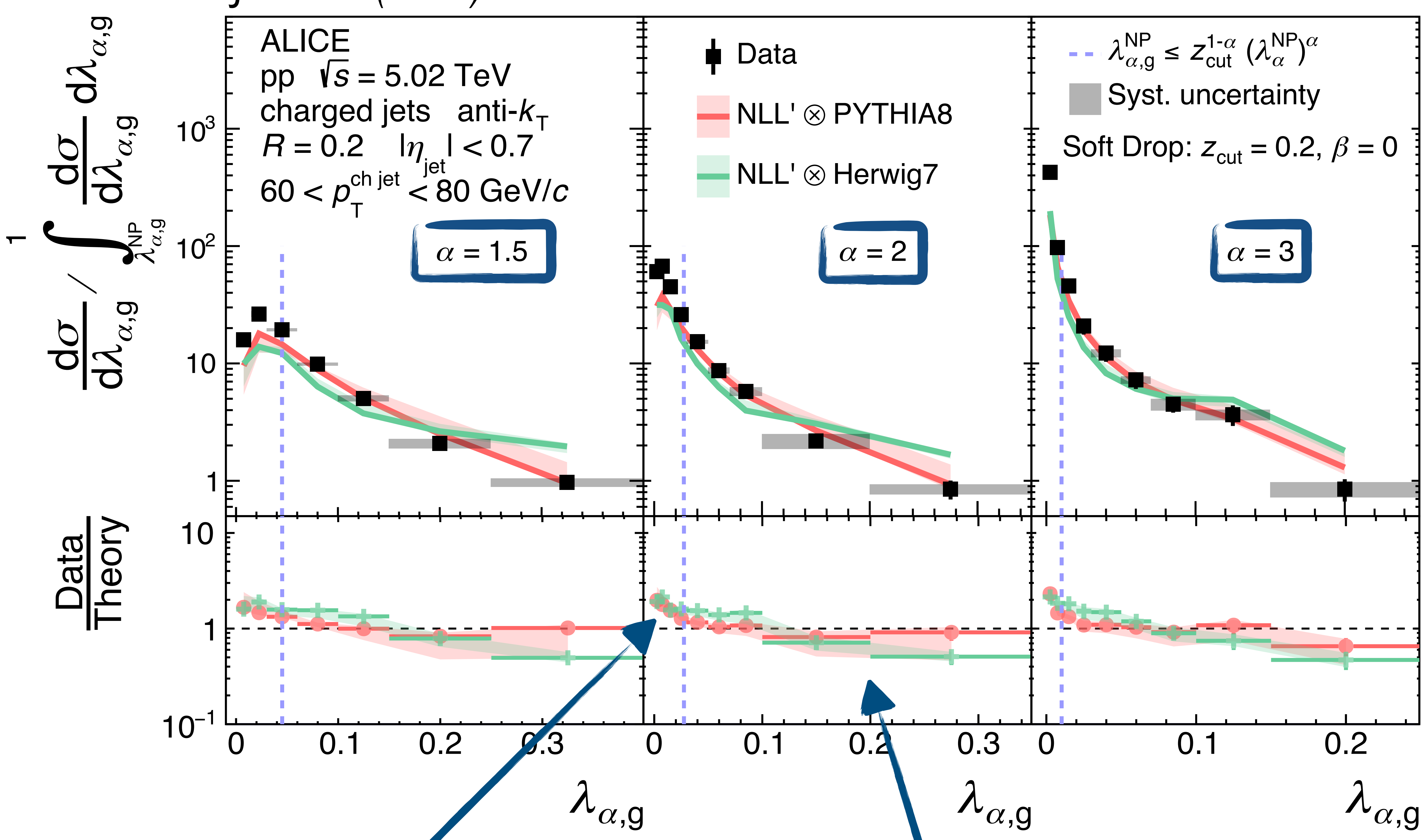
Apply grooming procedure to remove low-energy, wide-angle radiation



$$\lambda_{\alpha,\mathrm{g}} \equiv \sum_{i \in \text{groomed jet}} z_i \theta_i^{\alpha}$$

Jet grooming recovers larger region of successful perturbative description

JHEP 05 (2022) 061



Small λ_α: Non-perturbative

Larger λ_α: Good agreement with pQCD calculations

Kang, Lee, Liu, Ringer PLB 793 (2019) 41

See also: CMS arXiv 2109.03340

Jet angularities — pp

Non-perturbative shape function $F(k)$ to describe hadronization and underlying event effects

$$\frac{d\sigma}{d\lambda_\alpha} = \int F(k) \frac{d\sigma^{\text{parton-level}}}{d\lambda_\alpha}\left(\lambda_\alpha - \frac{k}{p_T^{\text{jet}} R}\right) dk$$

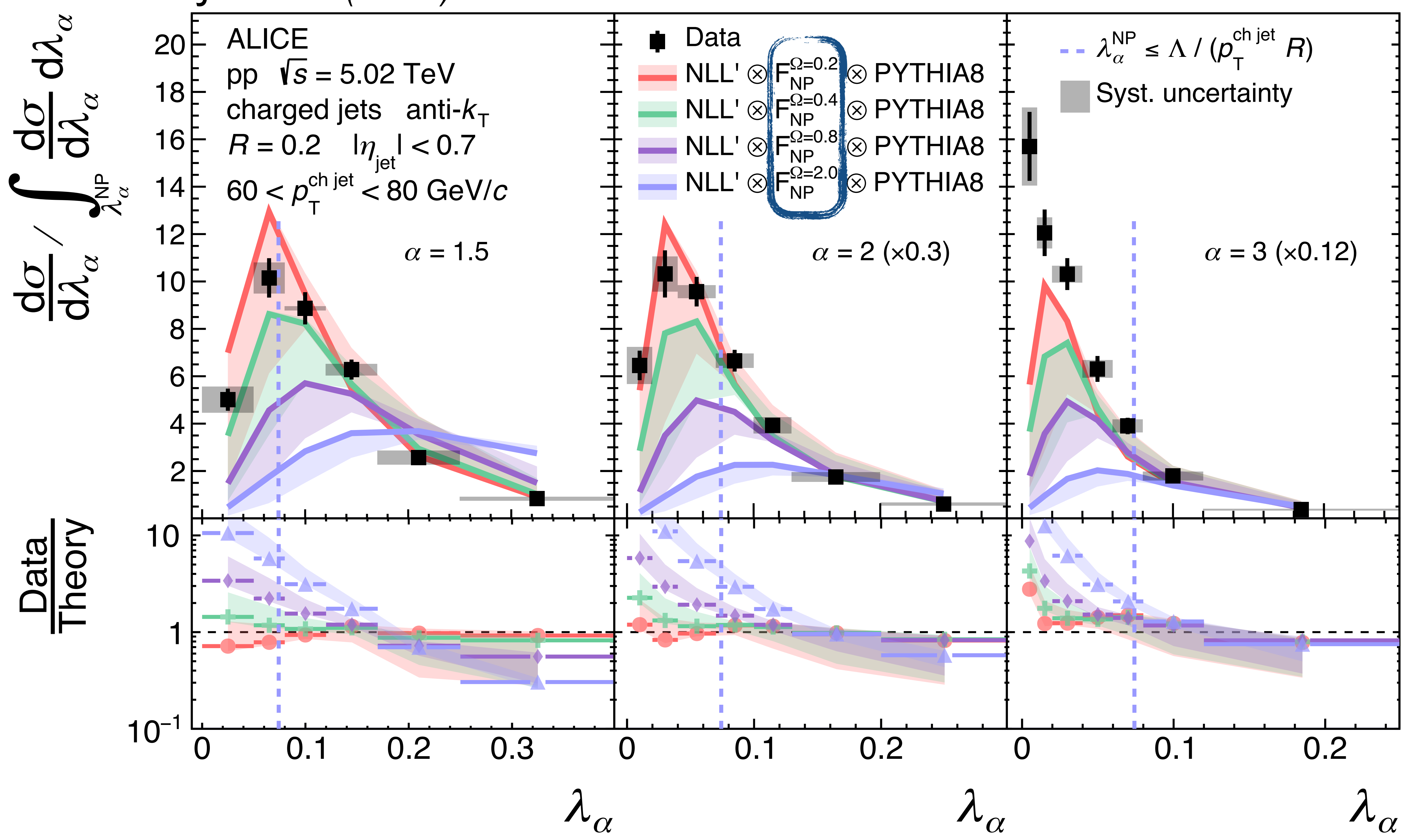
$$F(k) = \frac{4k}{\Omega_\alpha^2} \exp\left(-\frac{2k}{\Omega_\alpha}\right)$$

Test predicted scaling of $F(k)$ with α

$$\Omega_\alpha = \Omega/(\alpha - 1)$$

Korchemsky, Sterman Nucl. Phys. B 555 1 (1999)
Stewart, Tackmann, Waalewijn PRL 114, 092001 (2015)
Kang, Lee, Ringer JHEP 04 (2018) 110
Kang, Lee, Liu, Ringer JHEP 10 (2018) 137

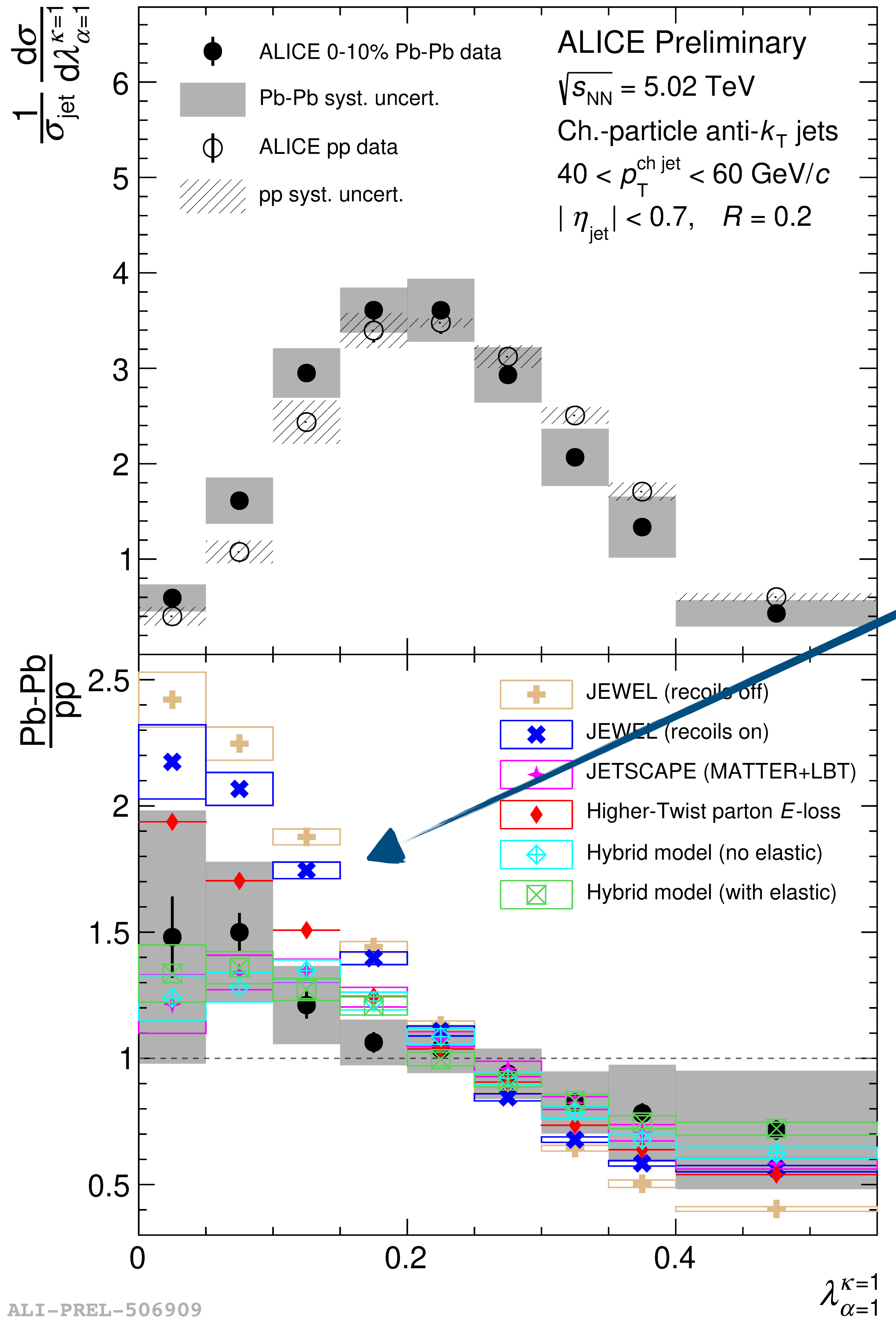
JHEP 05 (2022) 061



Universal description of data for $\Omega < 1$ GeV

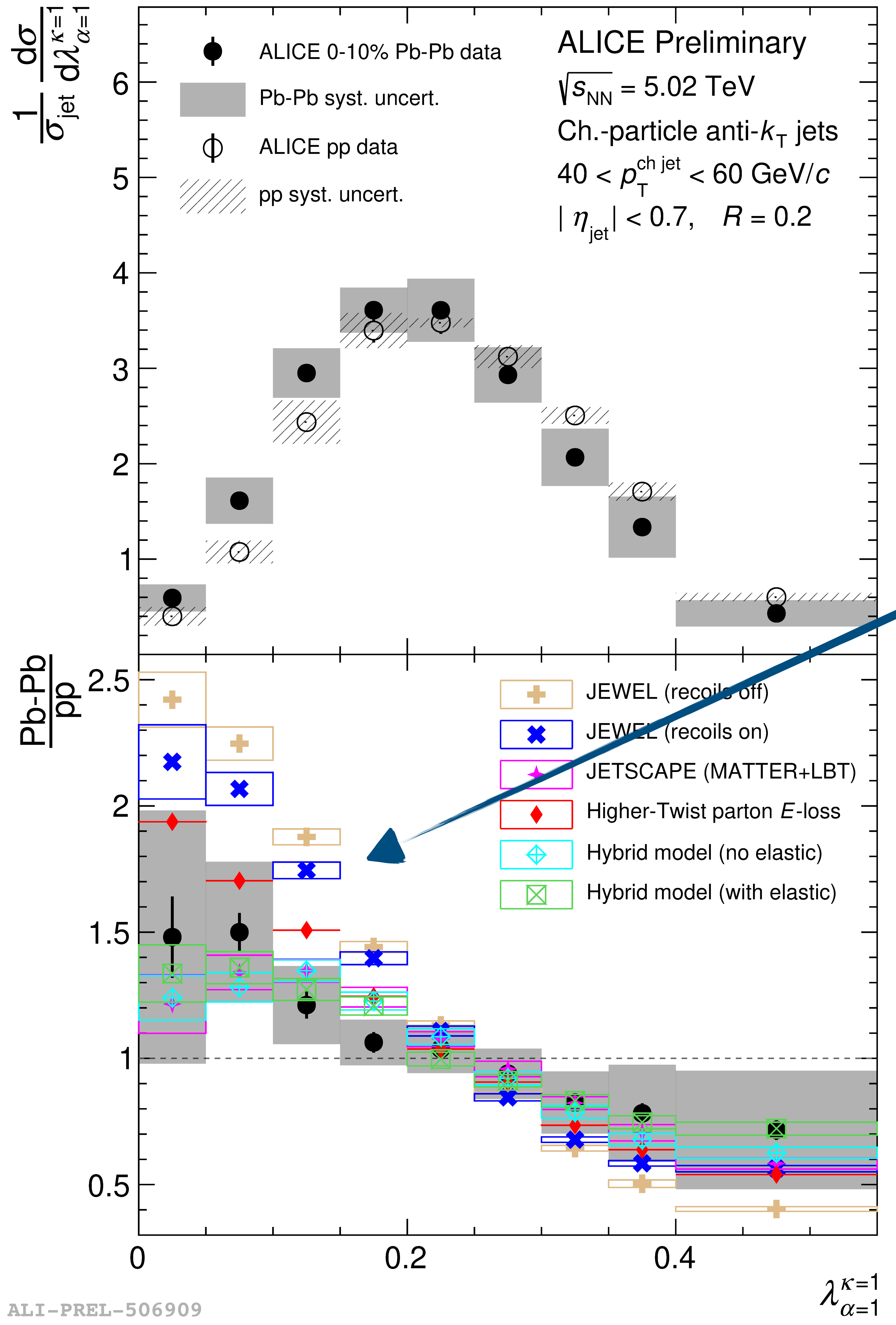
See also: Kang, Lee, Liu, Ringer JHEP 10 (2018) 137

Jet angularities — Pb-Pb

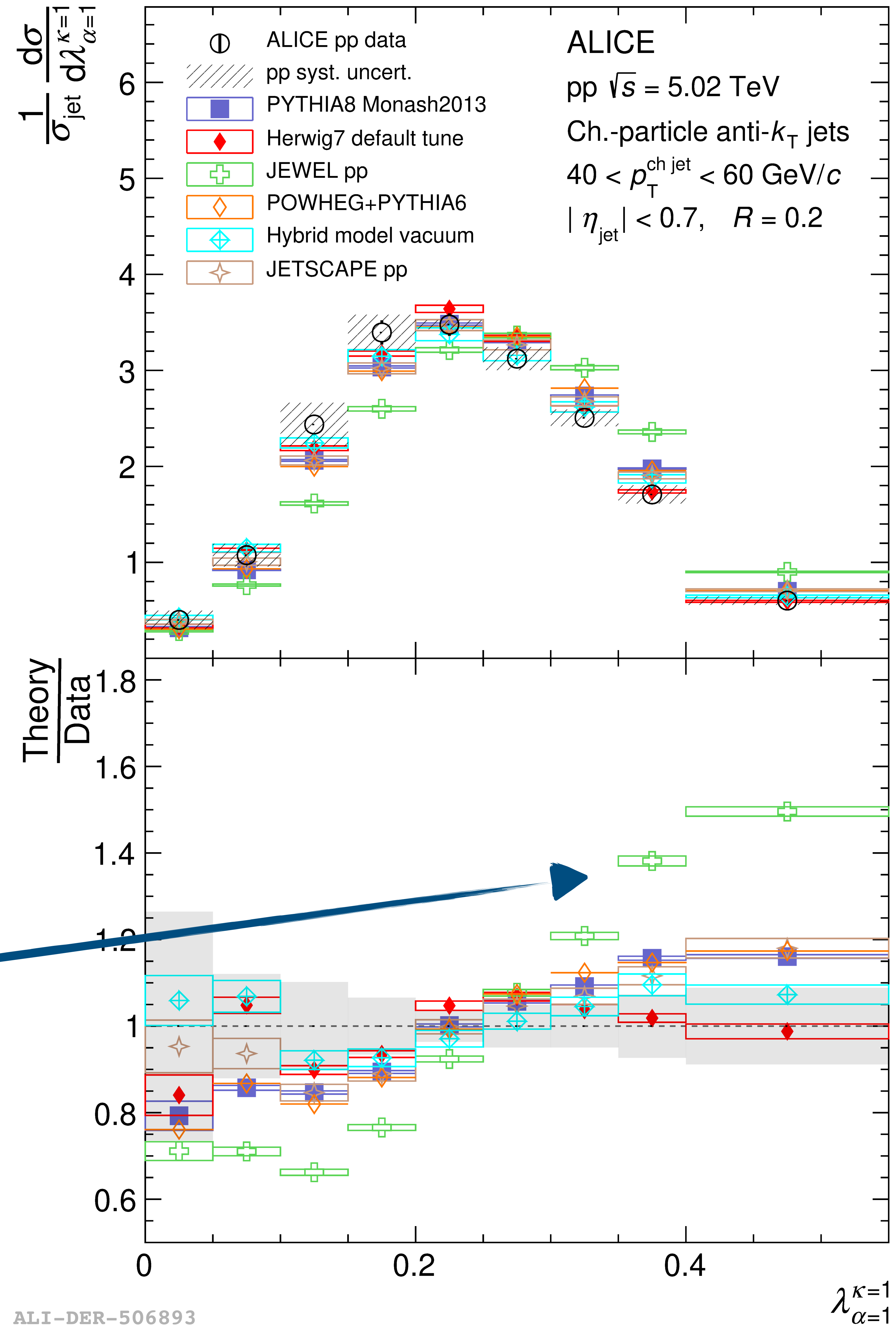


Jet quenching models generally describe trends in data well, although some deviations

Jet angularities — Pb-Pb



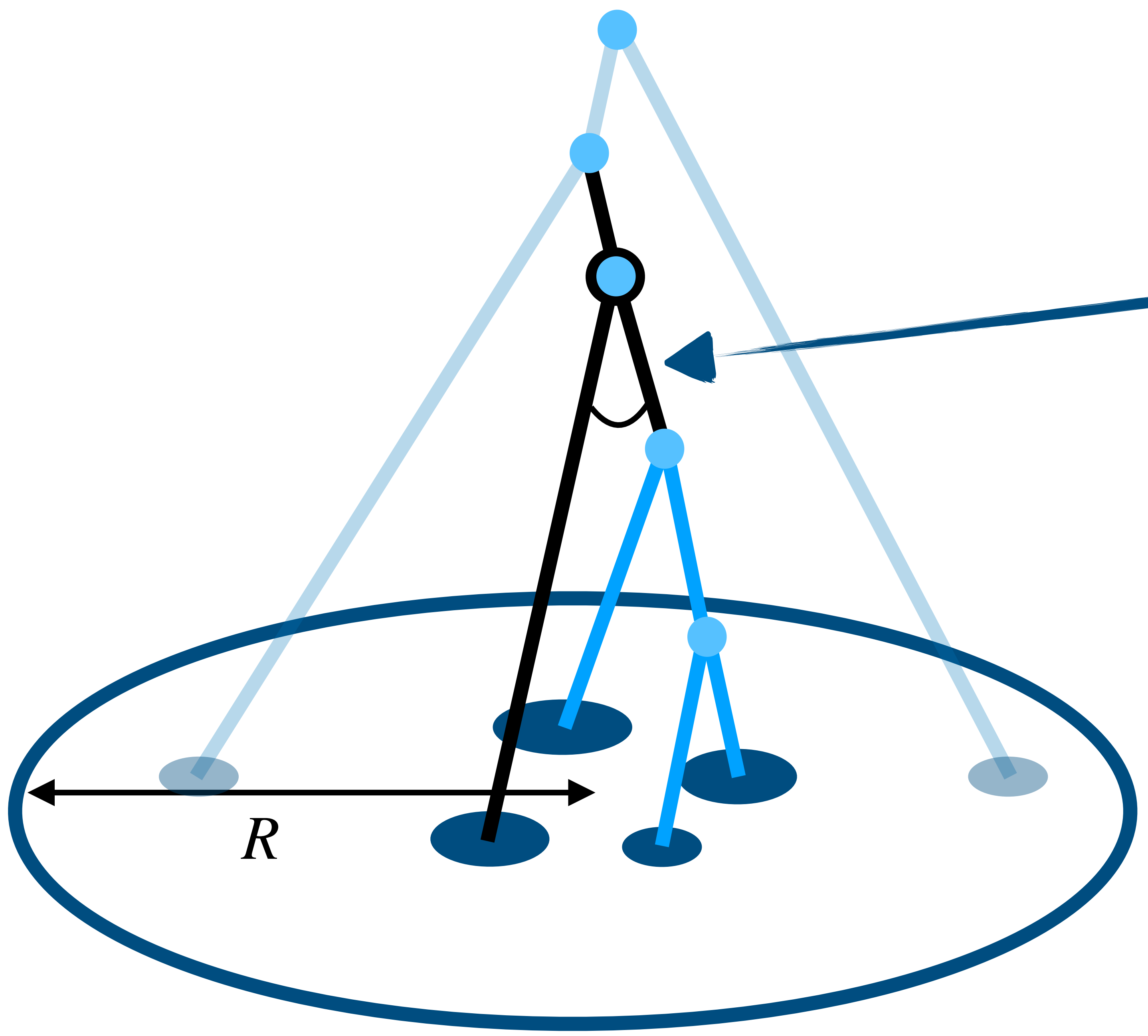
Jet quenching models generally describe trends in data well, although some deviations



However deviations in pp baseline are inducing disagreement in Pb-Pb/pp ratio!

Example 2: Groomed jet splittings

How is the perturbative core of the jet modified in heavy-ion collisions?

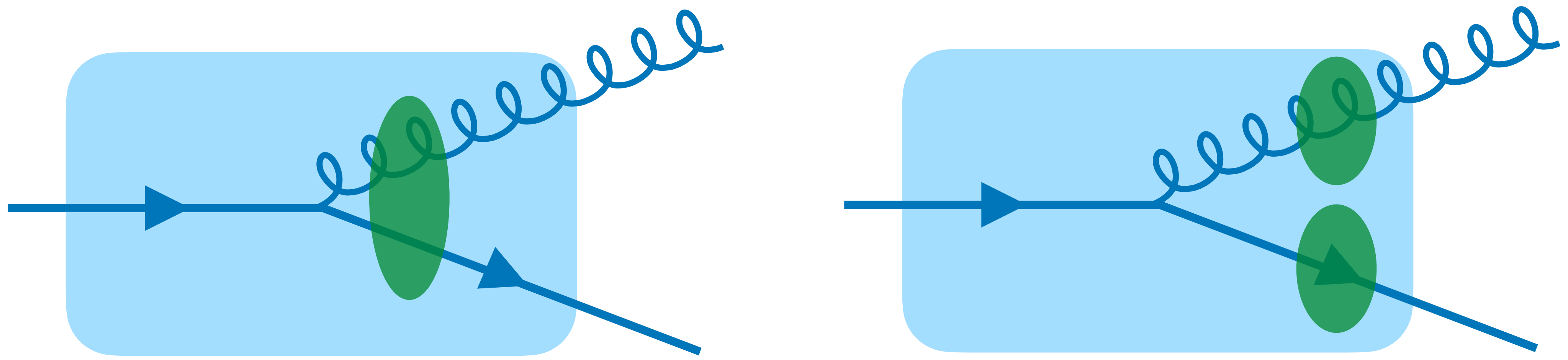


Measure the kinematics of the two prongs in the high-Q^2 jet splitting:

θ_g — angle

z_g — momentum

θ_g is sensitive to the angular resolution scale of the quark-gluon plasma

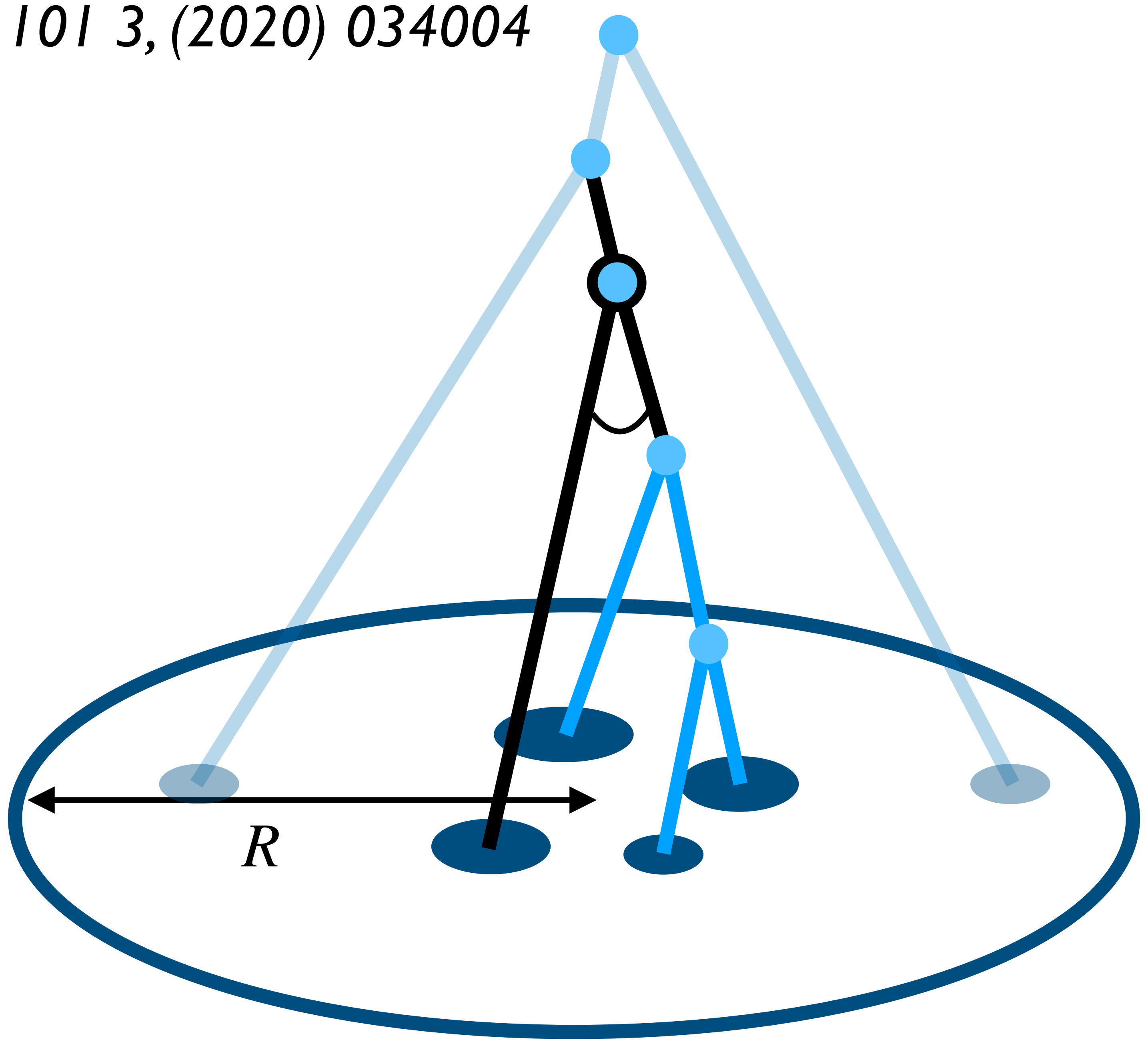


Dynamical grooming — z_g

Find splitting that *maximizes* grooming condition:

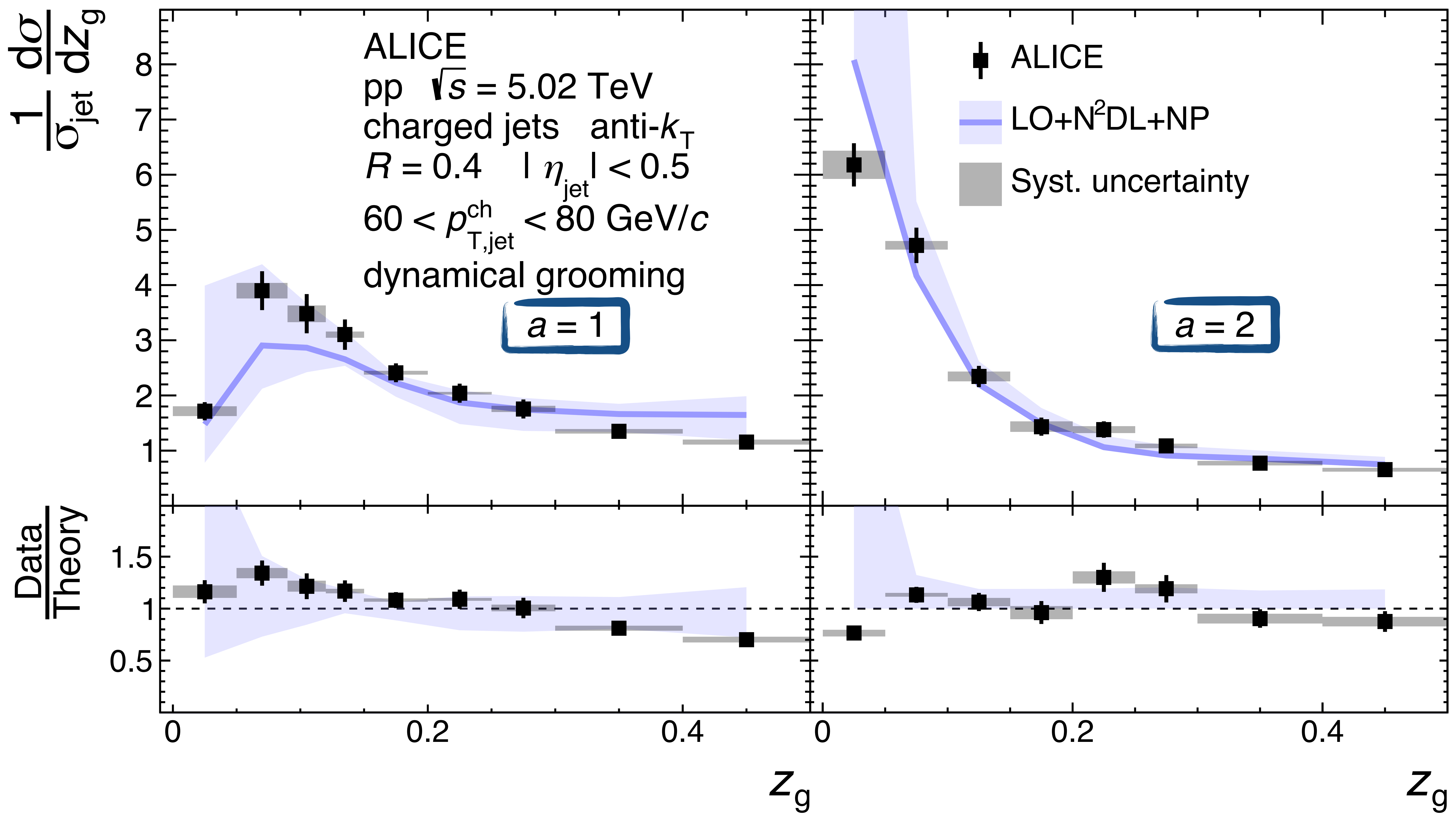
$$z_i(1-z_i)\,p_{\mathrm{T,i}}\,\theta_i^a$$

Mehtar-Tani, Soto-Ontoso, Tywoniuk
PRD 101 3, (2020) 034004



arXiv 2204.10246

pQCD calculations from:
Caucal, Soto-Ontoso, Takacs, JHEP 07 (2021) 020



MC-based non-perturbative corrections: large uncertainty at small z_g

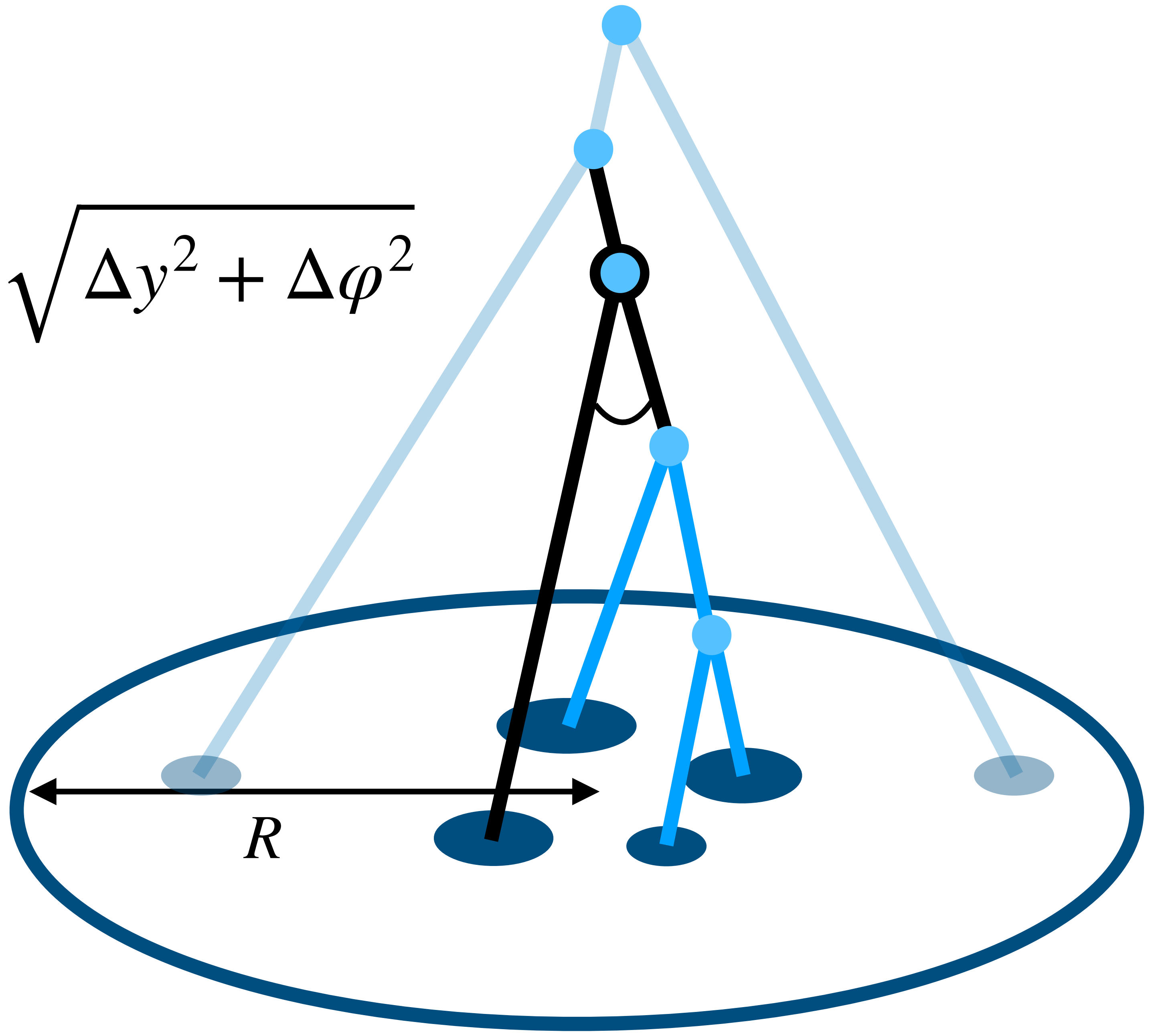
Soft Drop — r_g

Find *first* splitting that satisfies grooming condition:

$$z_i > z_{\text{cut}}\,\theta_i^{\beta}$$

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719

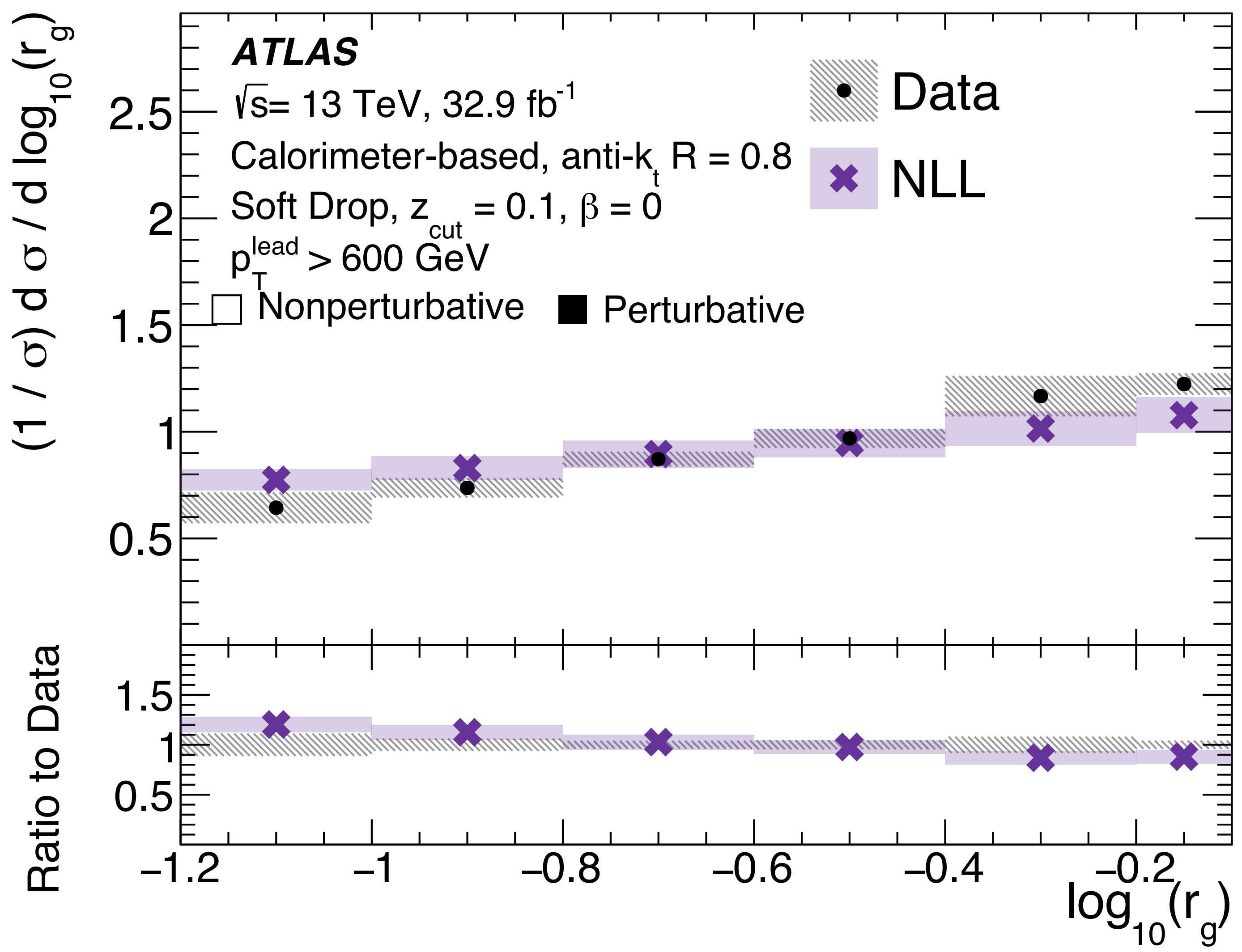
$$r_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

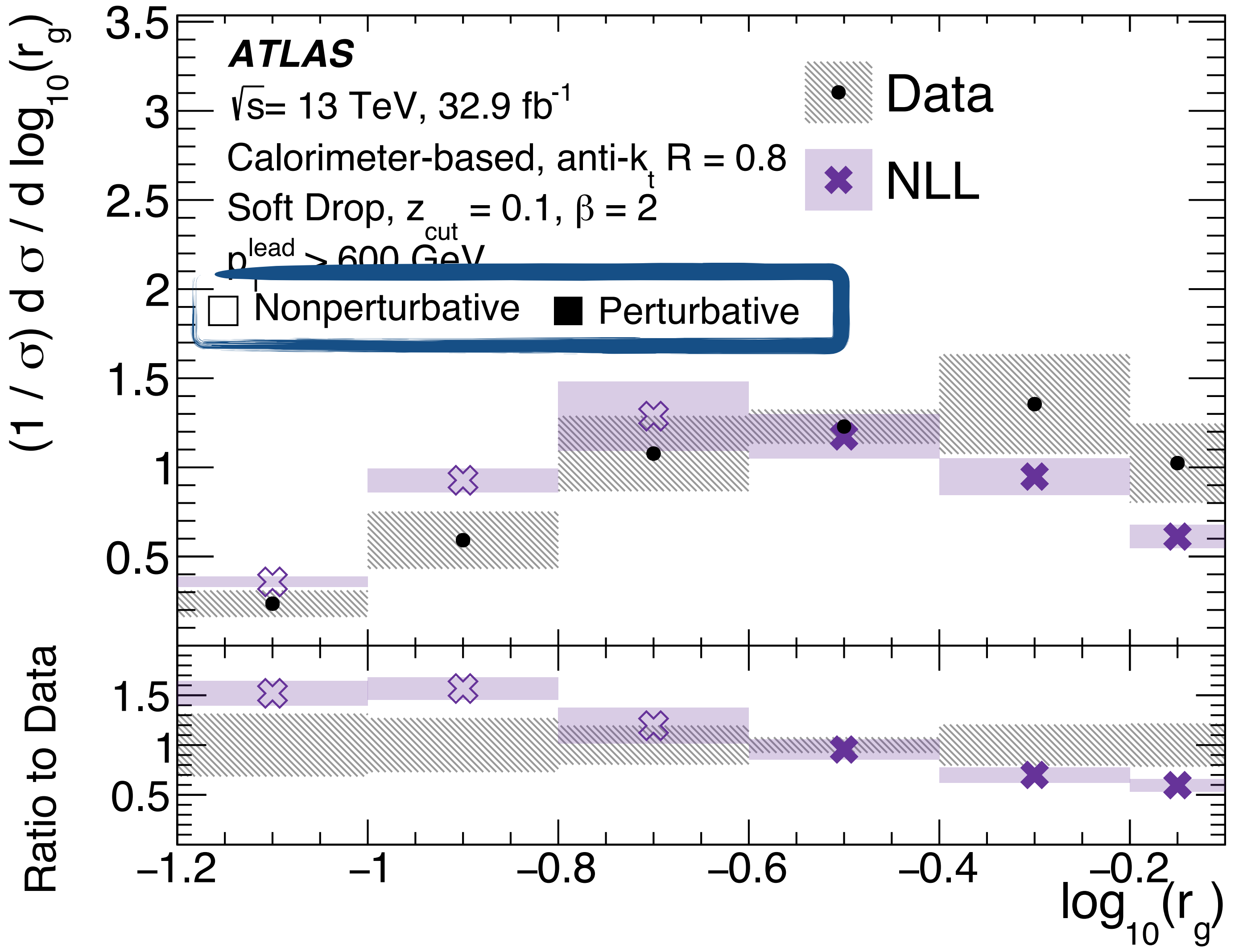


ATLAS PRD 101 (2020)

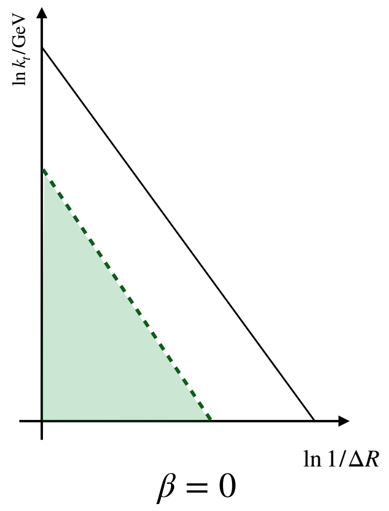
pQCD calculations from:

Kang, Lee, Liu, Neill, Ringer, JHEP 2 (2020) 054

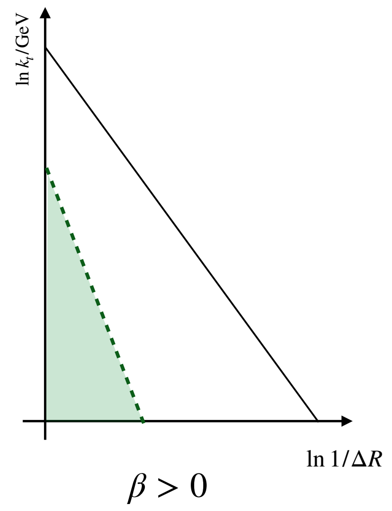




$\beta = 0$



$\beta = 2$



Less grooming → larger non-perturbative region

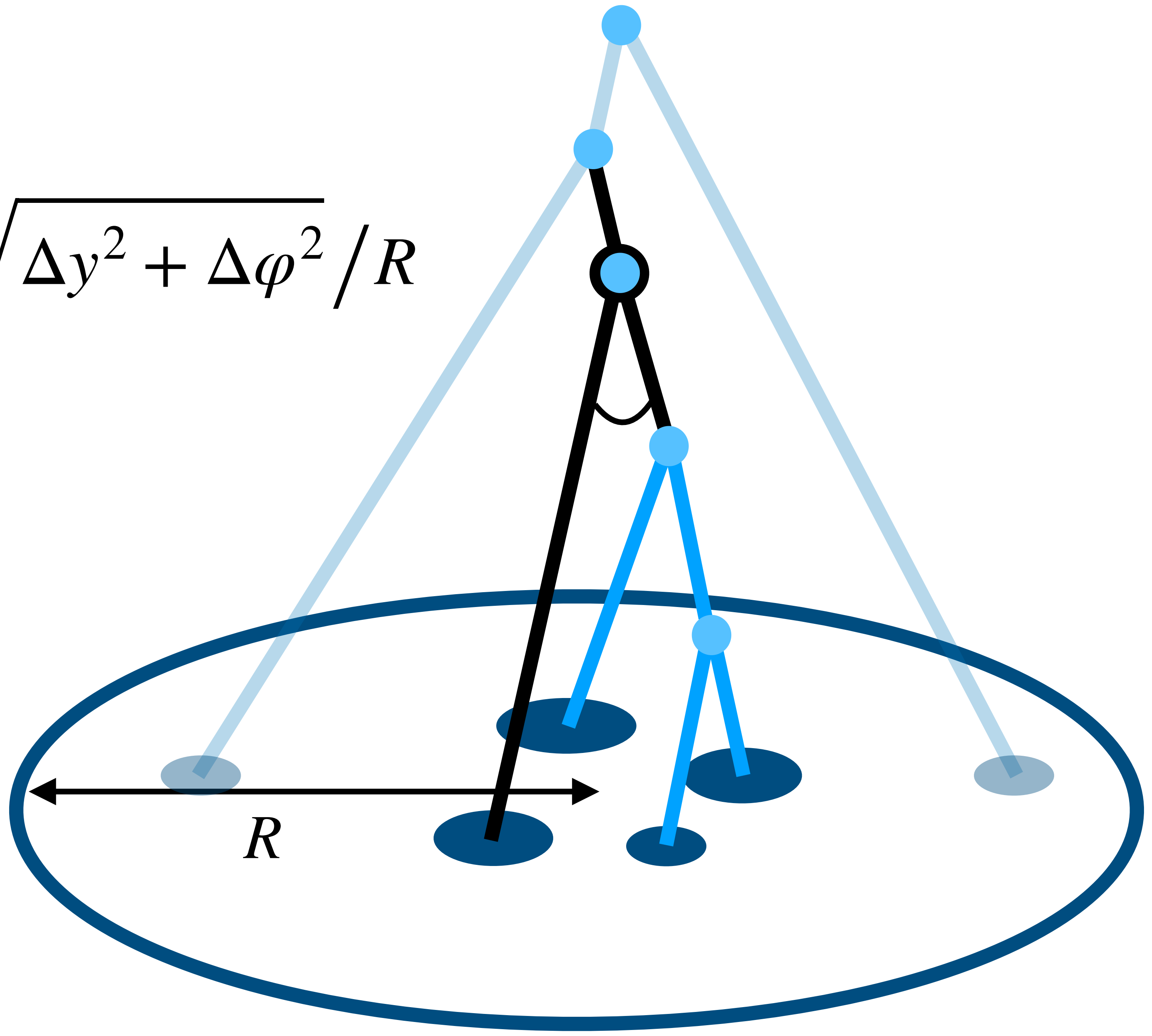
Soft Drop — θ_g

Find *first* splitting that satisfies grooming condition:

$$z_i > z_{\text{cut}}\,\theta_i^{\beta}$$

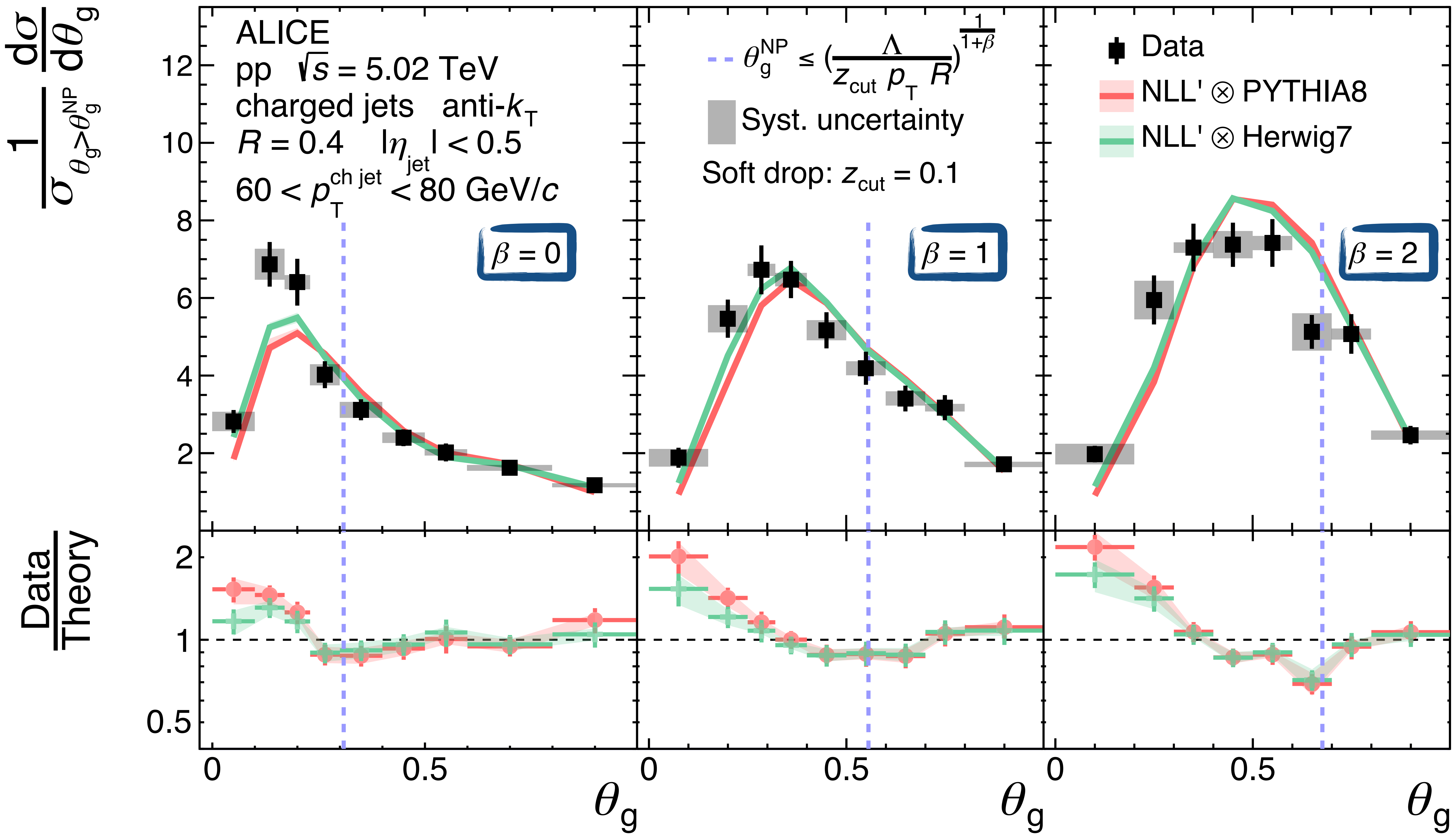
Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719

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



arXiv 2204.10246

pQCD calculations from:
Kang, Lee, Liu, Neill, Ringer, JHEP 2 (2020) 054



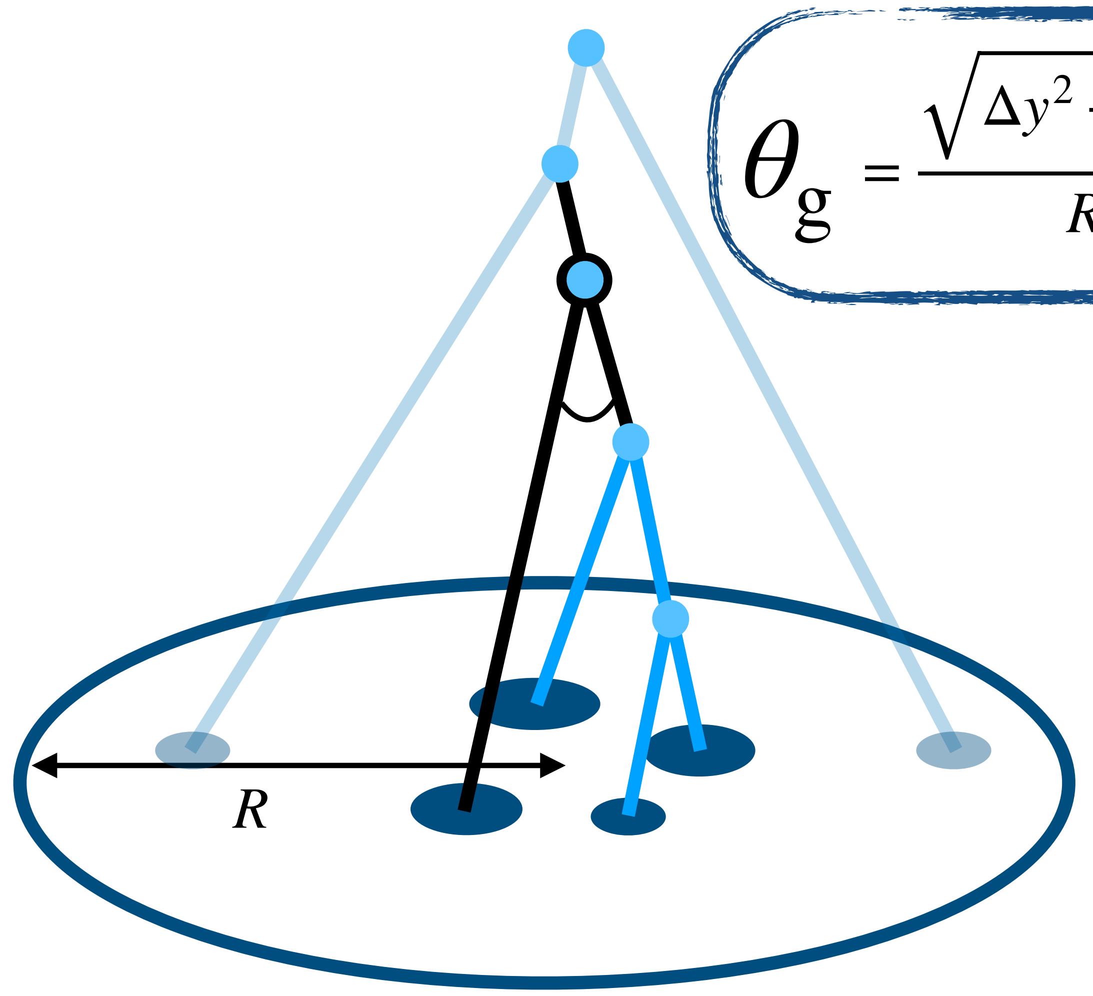
At lower jet p_T, $\beta = 2$ is highly non-perturbative!

Groomed jet radius — Pb-Pb

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

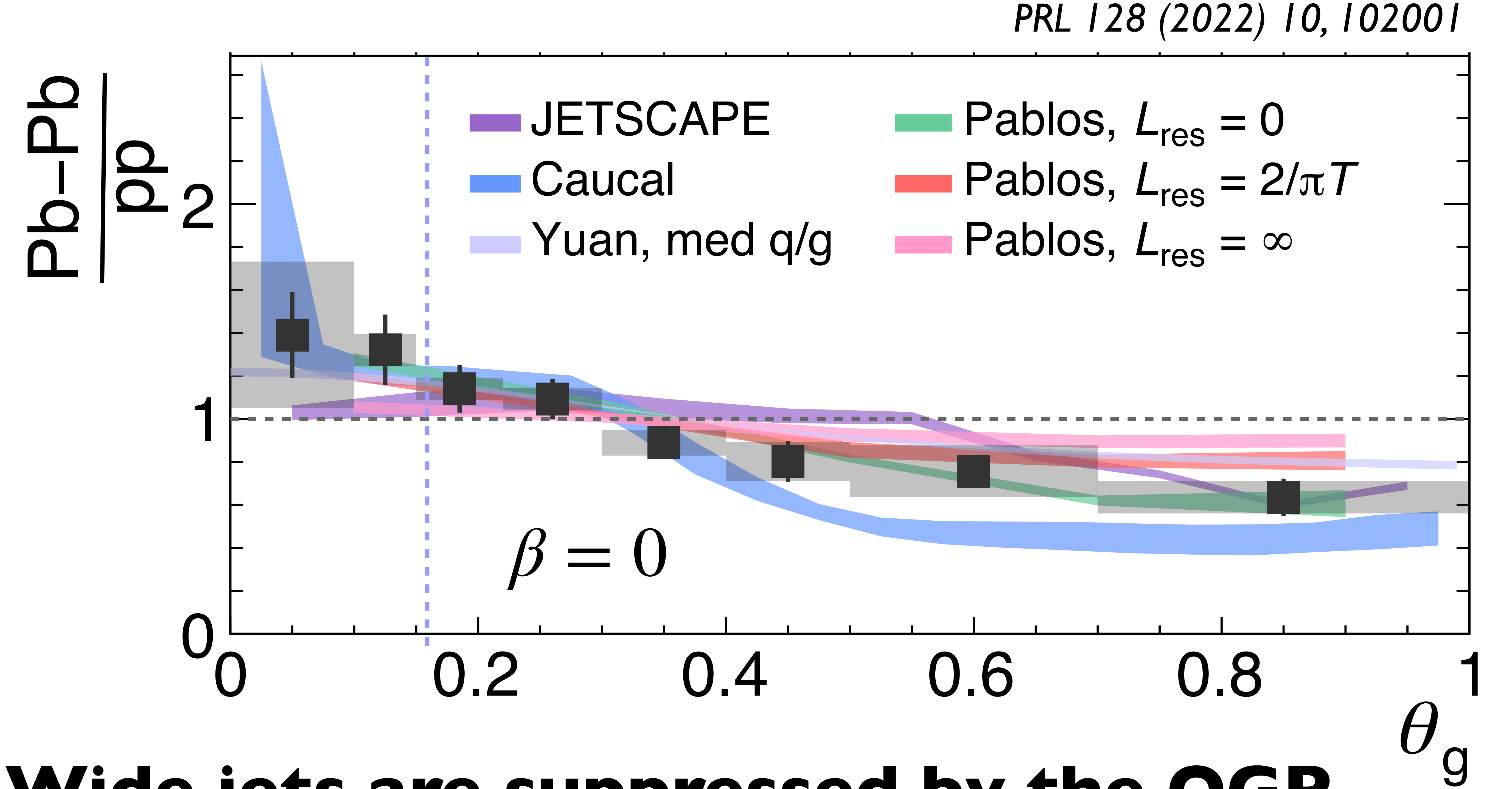
$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

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



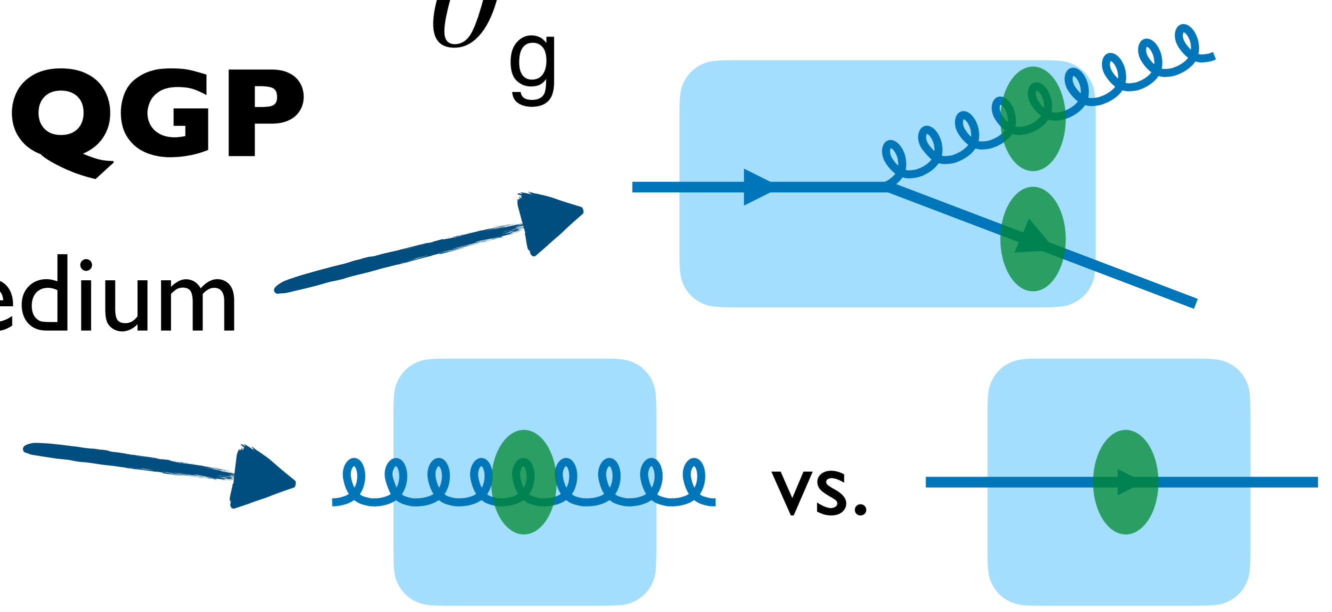
Starting point to understand jet quenching: perturbative-dominated observable

PRL 128 (2022) 10, 102001



Wide jets are suppressed by the QGP

(1) Wider splittings are resolved by the medium
(2) Suppression of gluon jets vs. quark jets



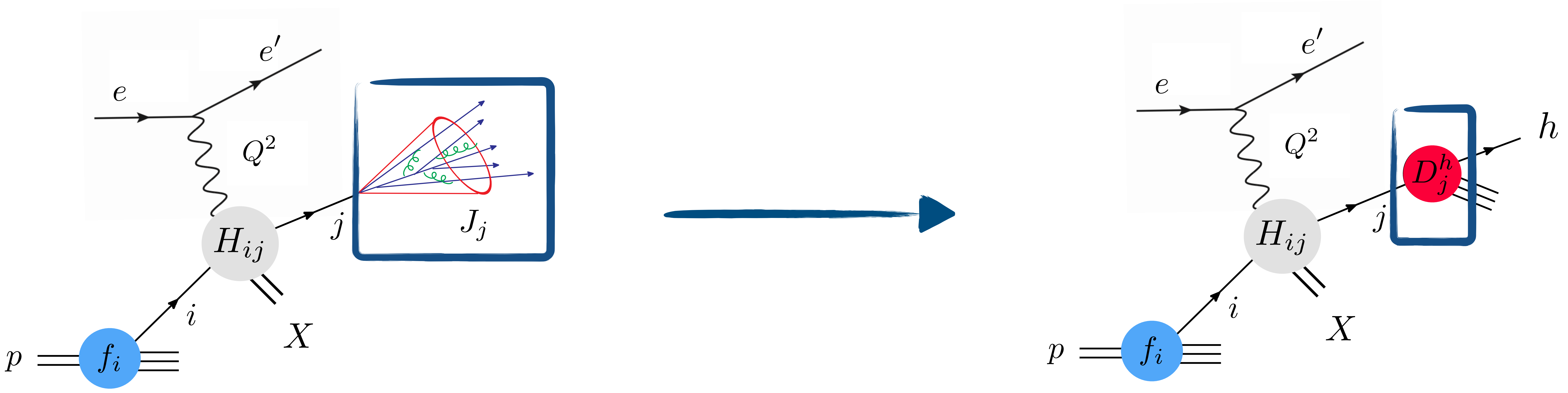
Example 3: Subjet fragmentation

Cluster inclusive jets with radius R, then recluster with anti-k_t with radius r

Neill, Ringer, Sato JHEP 07 (2021) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

$$z_{\mathrm{r}} = \frac{p_{\mathrm{T}}^{\text{ch subjet}}}{p_{\mathrm{T}}^{\text{ch jet}}}$$

Jet → hadron transition as $r \to 0$



Diagrams from Felix Ringer

Example 3: Subjet fragmentation

Cluster inclusive jets with radius R, then recluster with anti-k_t with radius r

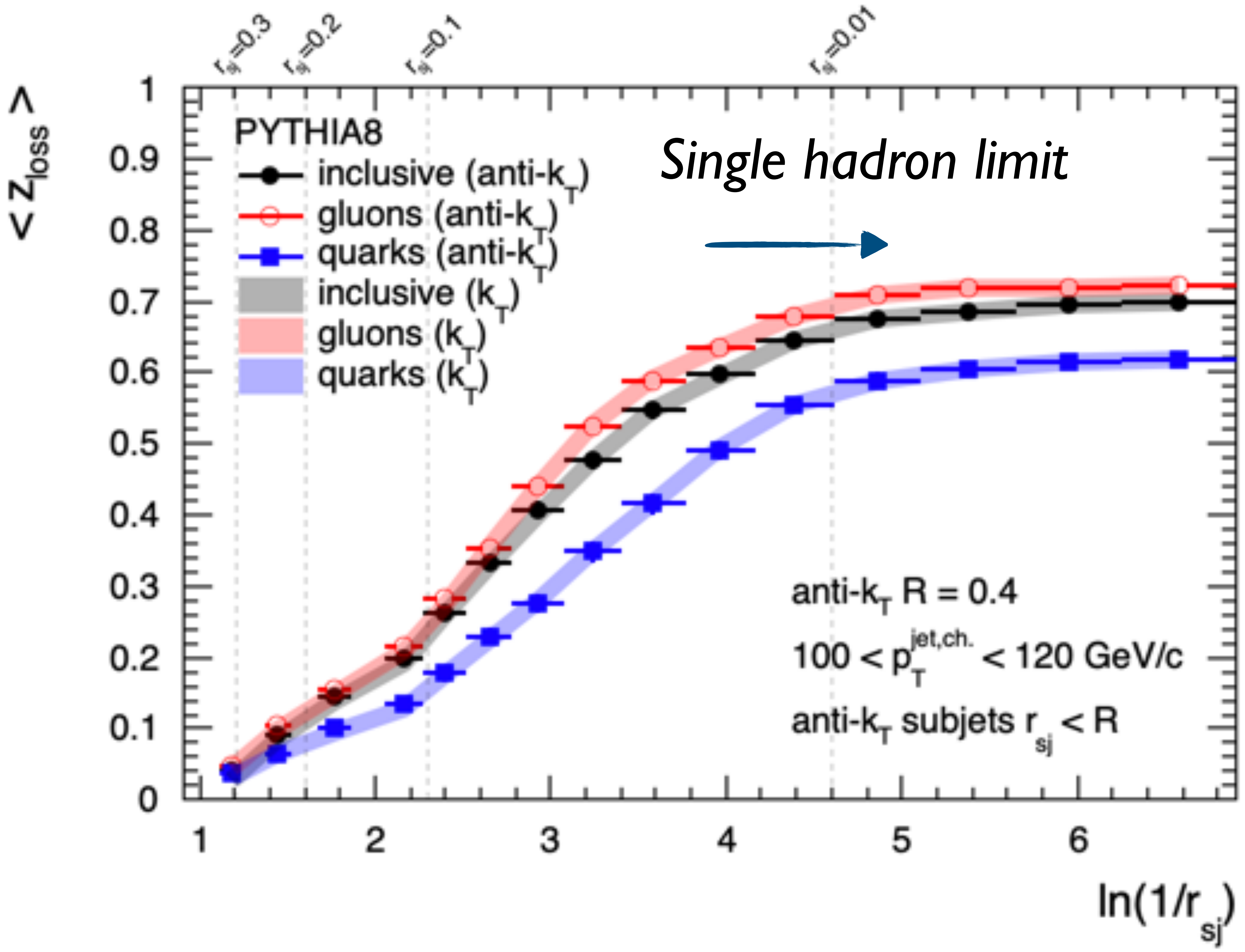
Neill, Ringer, Sato JHEP 07 (2021) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

Jet → hadron transition as $r \to 0$

Compute the "energy loss" outside of the leading subjet:

$$\langle z^{\text{loss}} \rangle = 1 - \int_0^1 dz_r \, z_r \frac{1}{\sigma} \frac{d\sigma}{dz_r}$$



Subjet fragmentation — pp

Measurements described well by pQCD in $0.1 \lesssim z_r \lesssim 0.9$

Kang, Ringer, Waalewijn JHEP 07 (2017) 064

At small z_r, the pQCD calculation fails due to lack of small z_r resummation

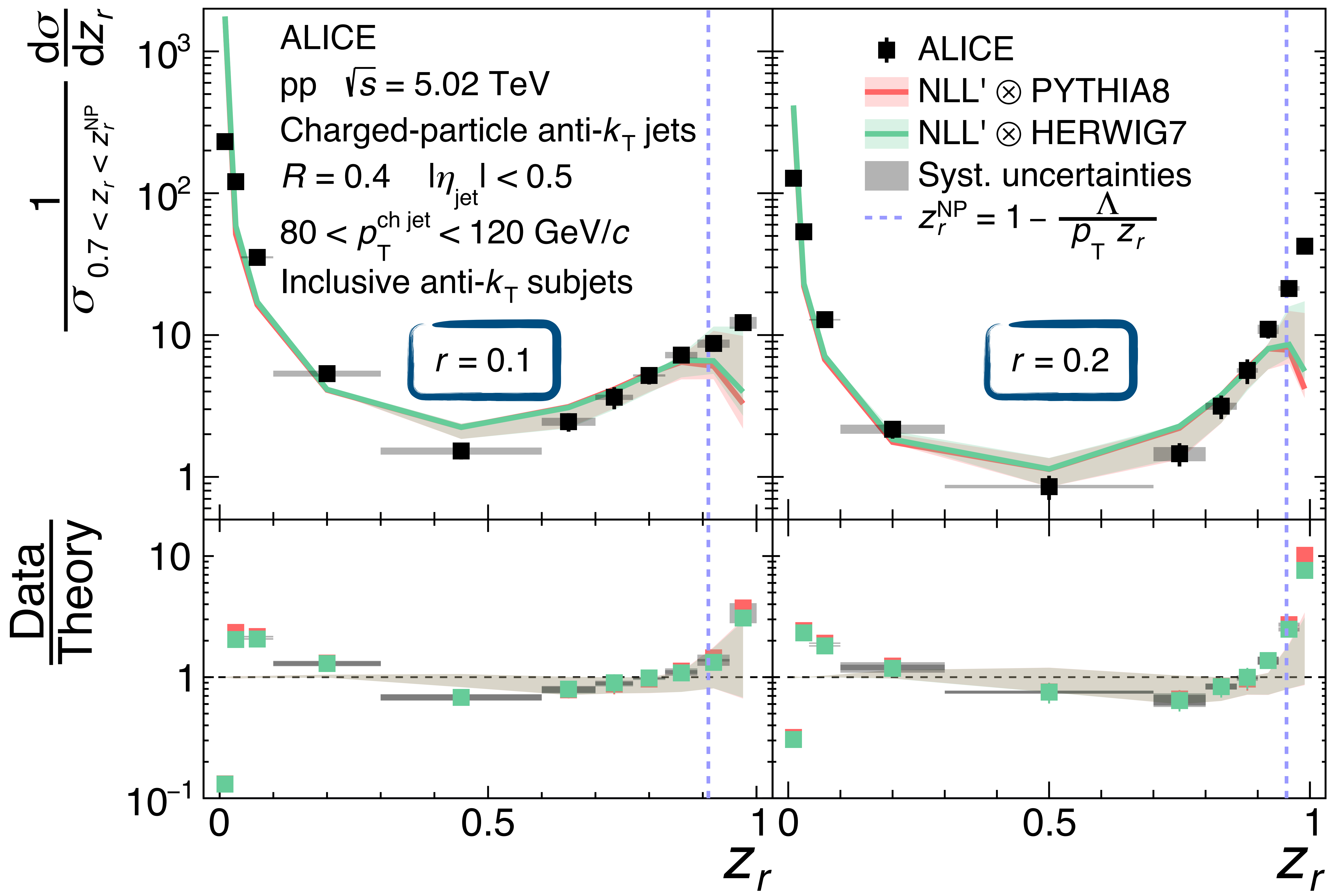
- Connection to parton-hadron duality

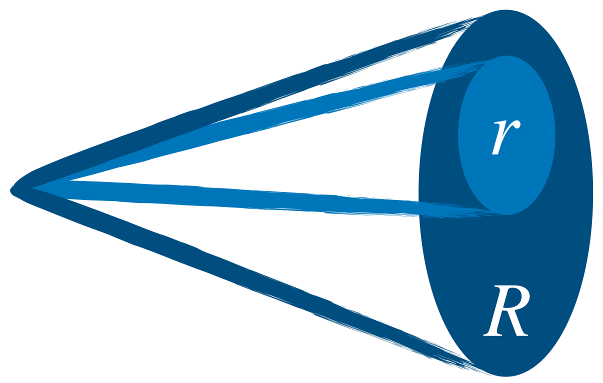
Neill, Ringer JHEP 06 (2020) 086
Neill JHEP 03 (2021) 081

At large z_r, both threshold resummation and non-perturbative physics play a role

Inclusive subjets

arXiv 2204.10270

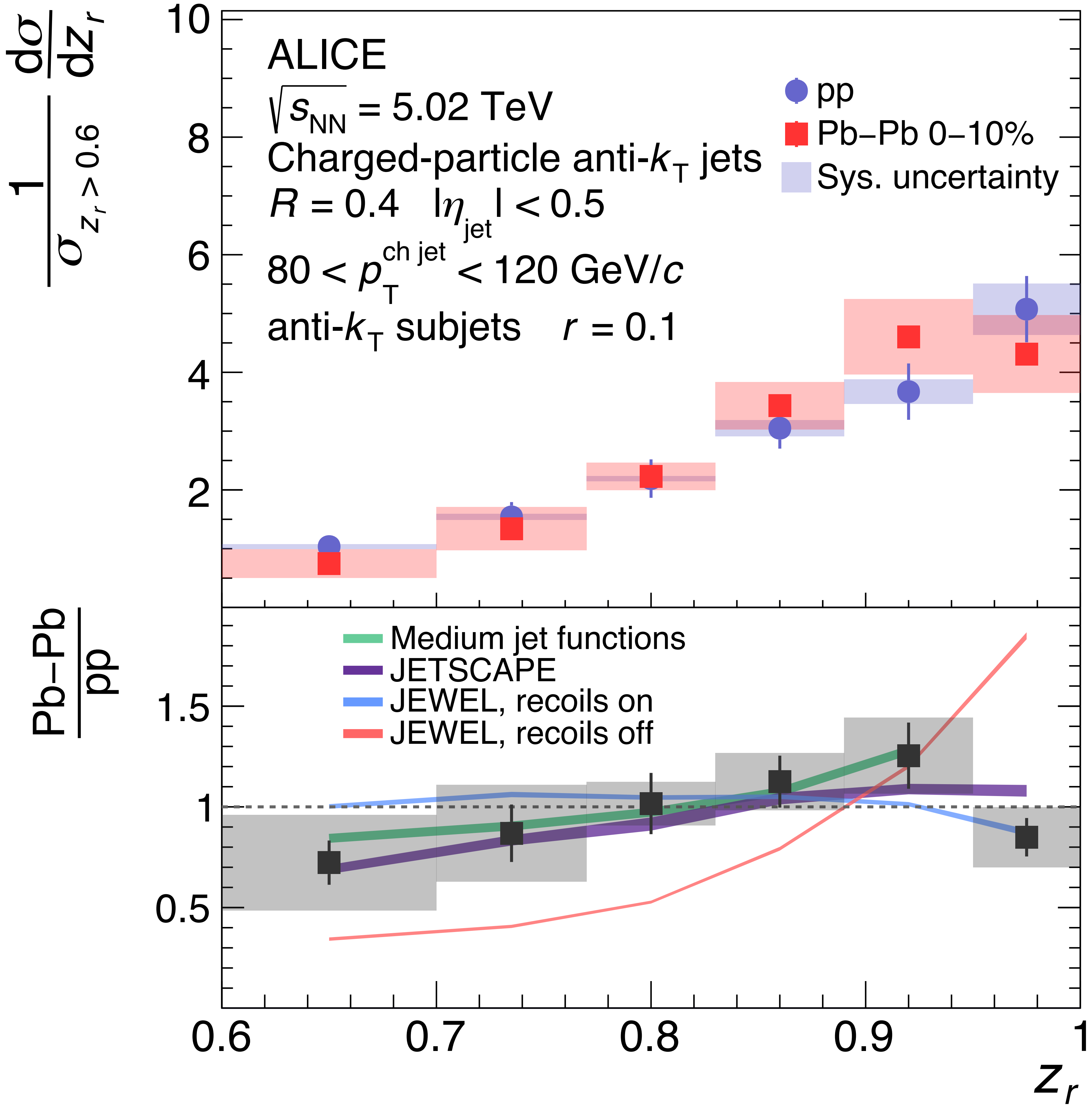


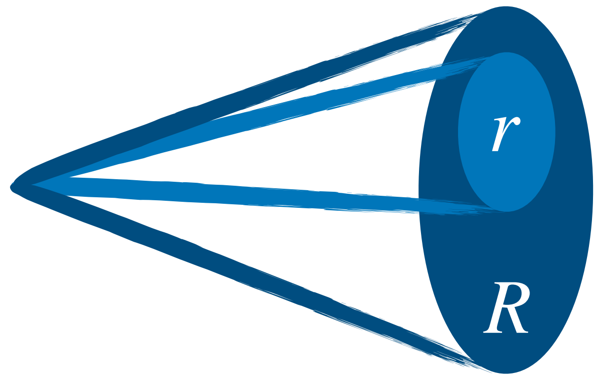


Subjet fragmentation — Pb-Pb

Leading subjets

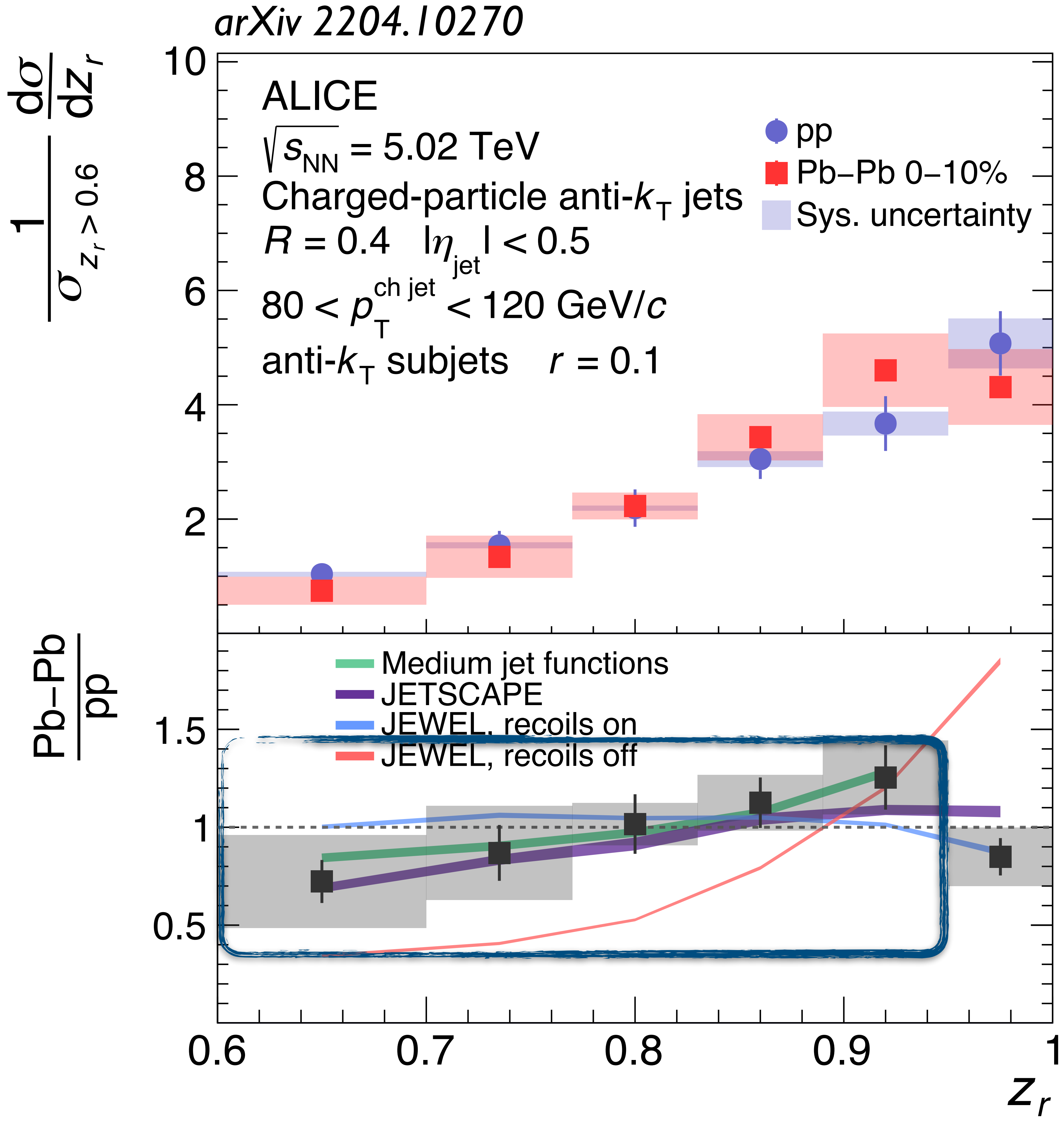
arXiv 2204.10270





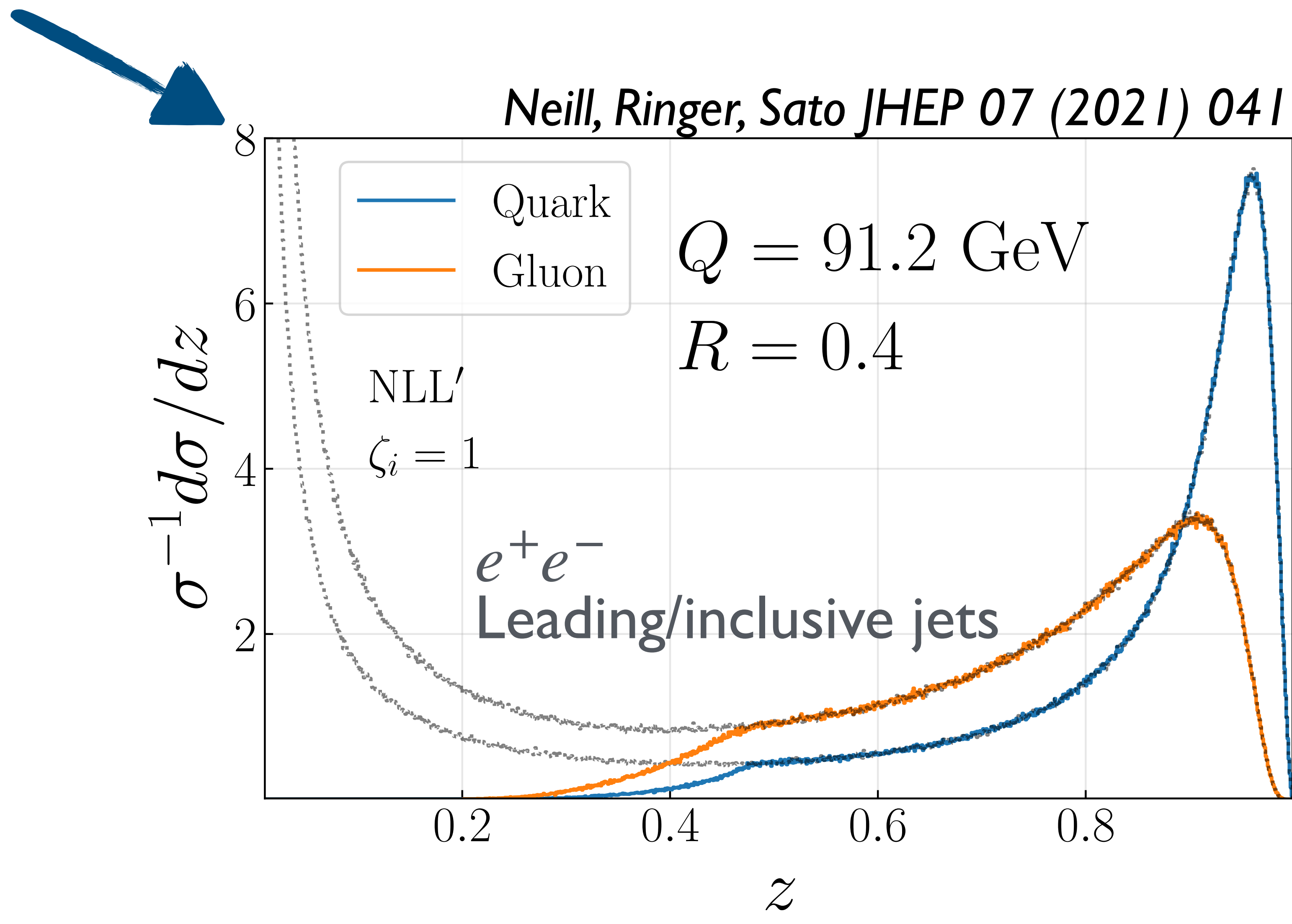
Subjet fragmentation — Pb-Pb

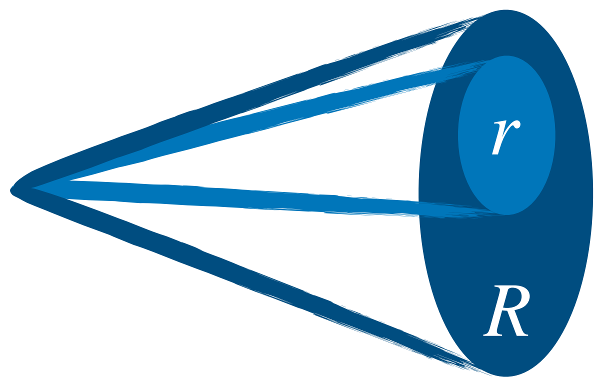
Leading subjets



Consistent with hardening of distribution at intermediate z_r

- Large quark-gluon differences in vacuum

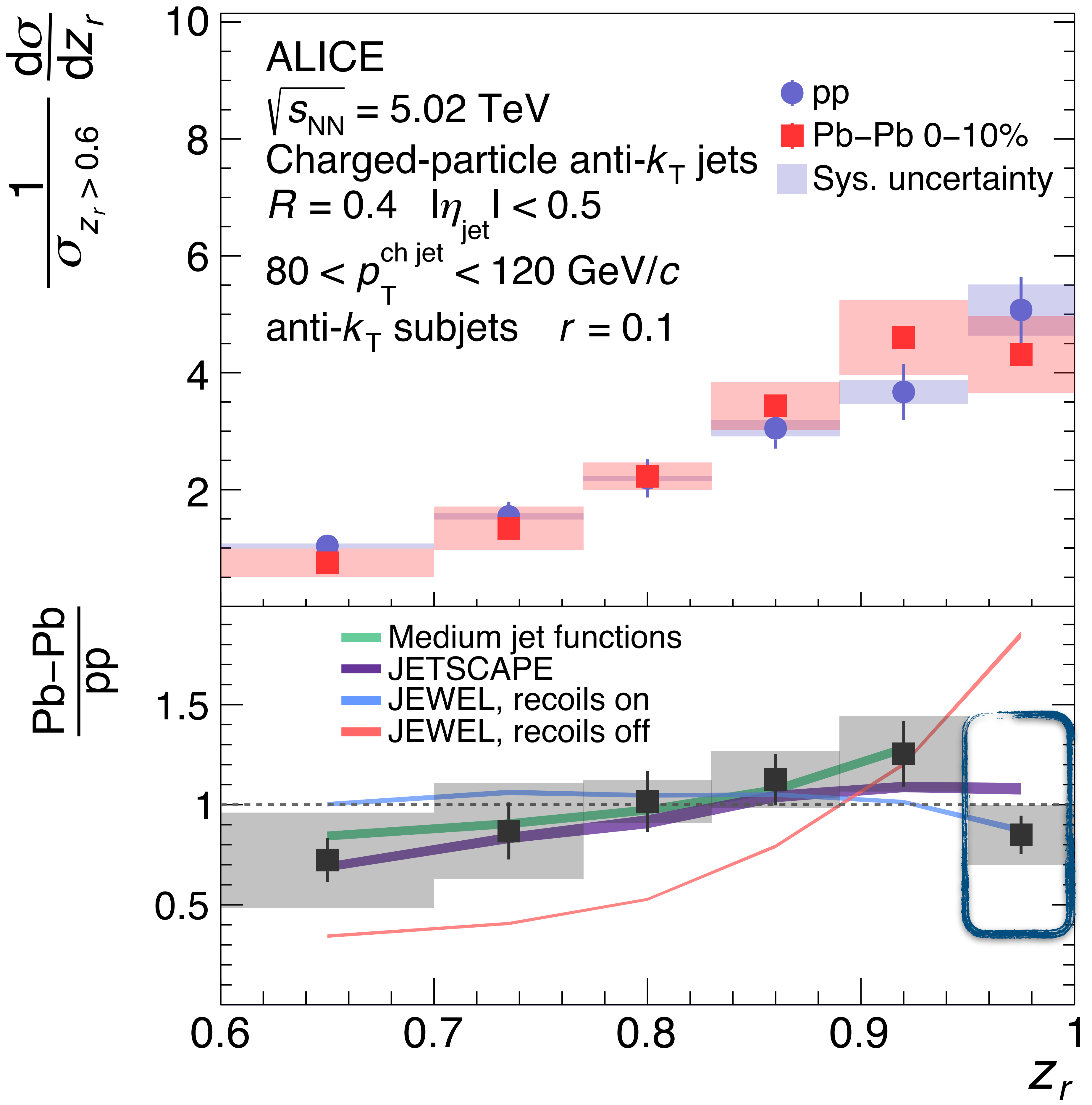




Subjet fragmentation — Pb-Pb

Leading subjets

arXiv 2204.10270

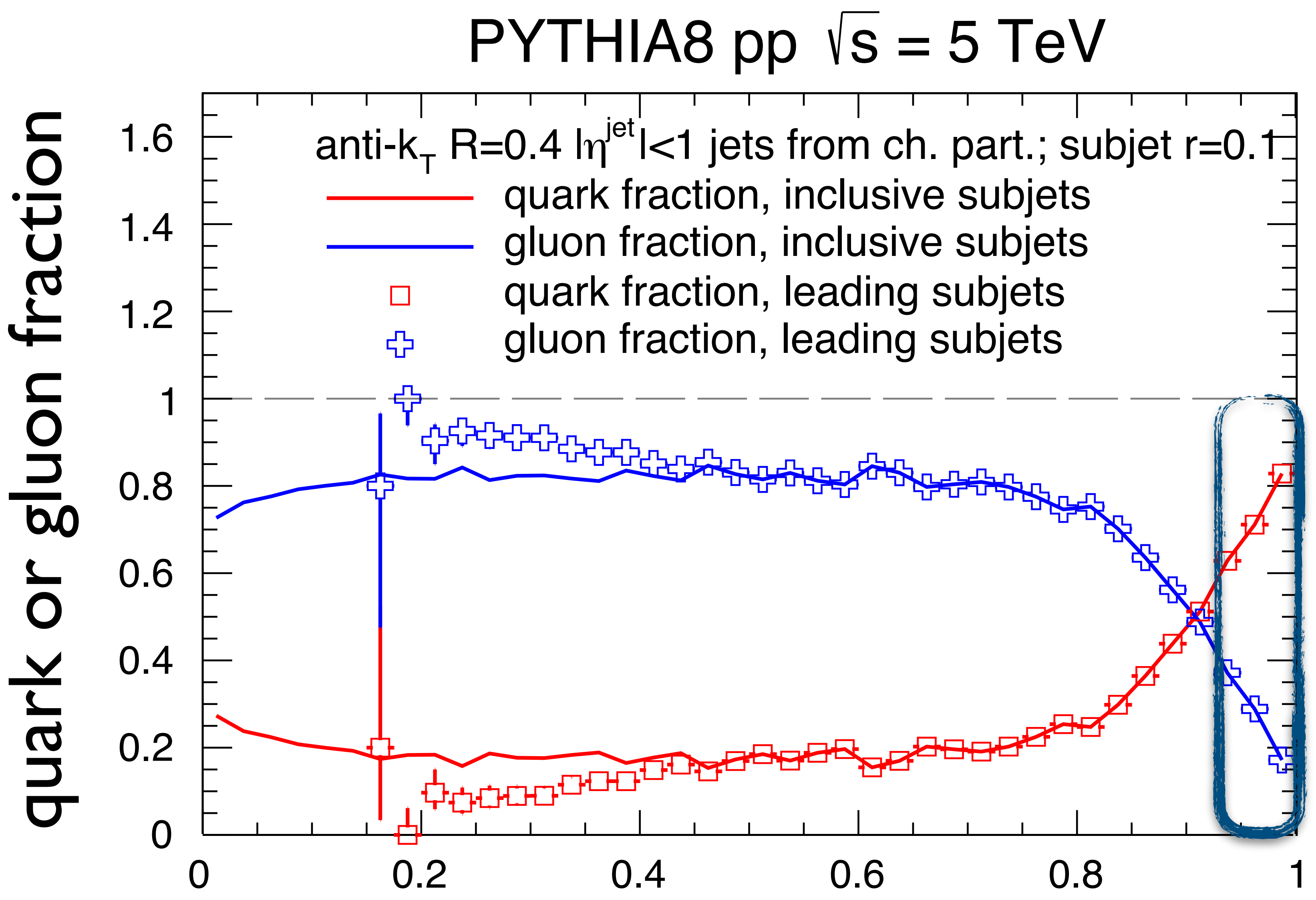


Consistent with hardening of distribution at intermediate z_r

- Large quark-gluon differences in vacuum

As $z_r \to 1$, the sample becomes closer to purely quark jets!

- Expose region depleted by soft medium induced emissions



New path to disentangle quenching effects — requires further theoretical work at large z_r

Summary

Understanding the transition from perturbative to non-perturbative QCD is crucial in order to interpret jet measurements

- Understand jet quenching effects in heavy-ion collisions
- Test accuracy of high-order perturbative calculations

Recent LHC jet substructure measurements explore the expected breakdown of perturbative calculations in the non-perturbative regime

- (i) Jet angularities, (ii) Groomed jet splittings, (iii) Subjet fragmentation
- Provides guidance for future measurements

See talks by Moult, Lee, Sterman, Ringer, …

Will require even more attention at RHIC (sPHENIX, STAR) and EIC