

Jet substructure and correlations in hadronic final states from ALICE

James Mulligan

Lawrence Berkeley National Laboratory



LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

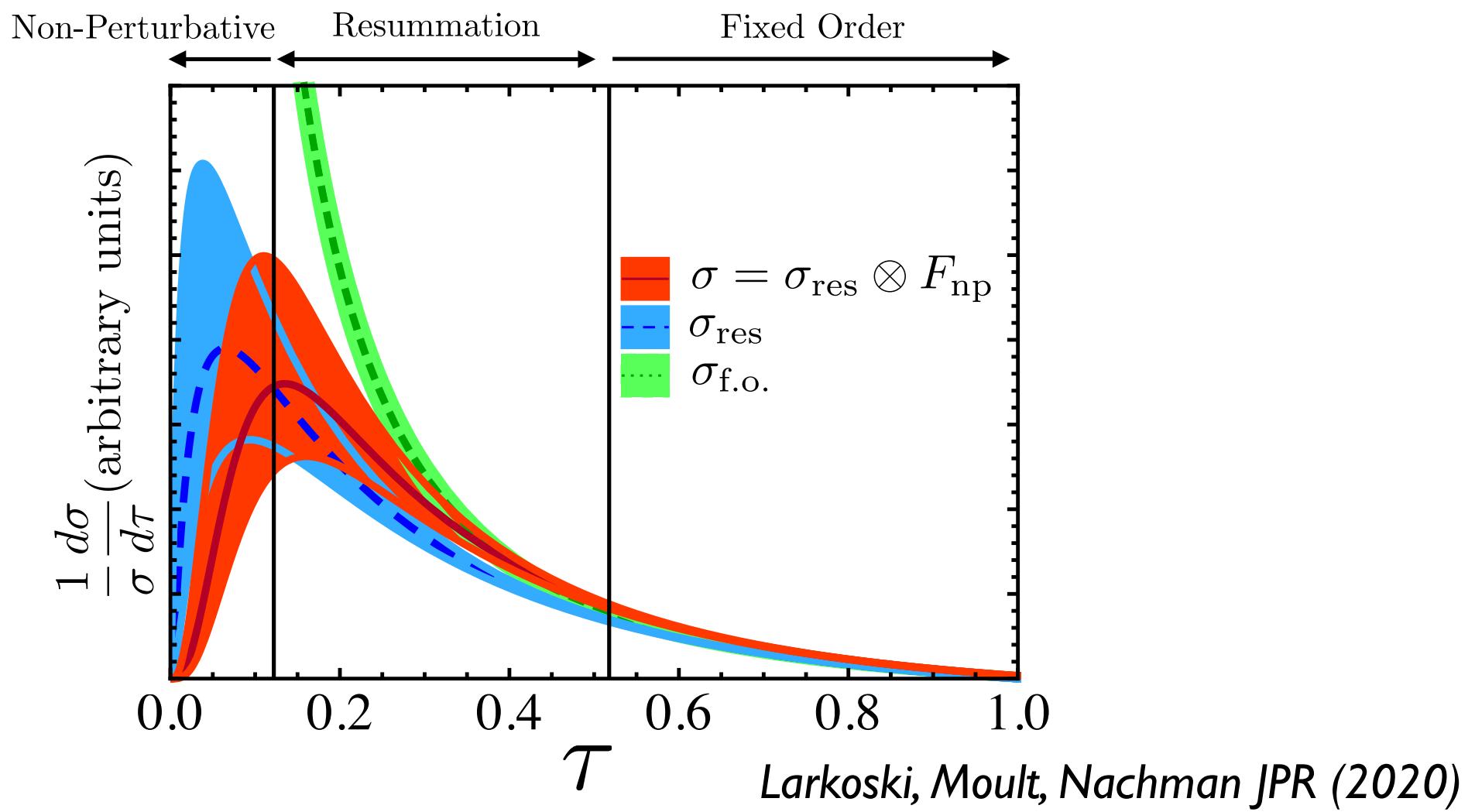
7-12 June 2021

~~Paris (France), Sorbonne Université~~

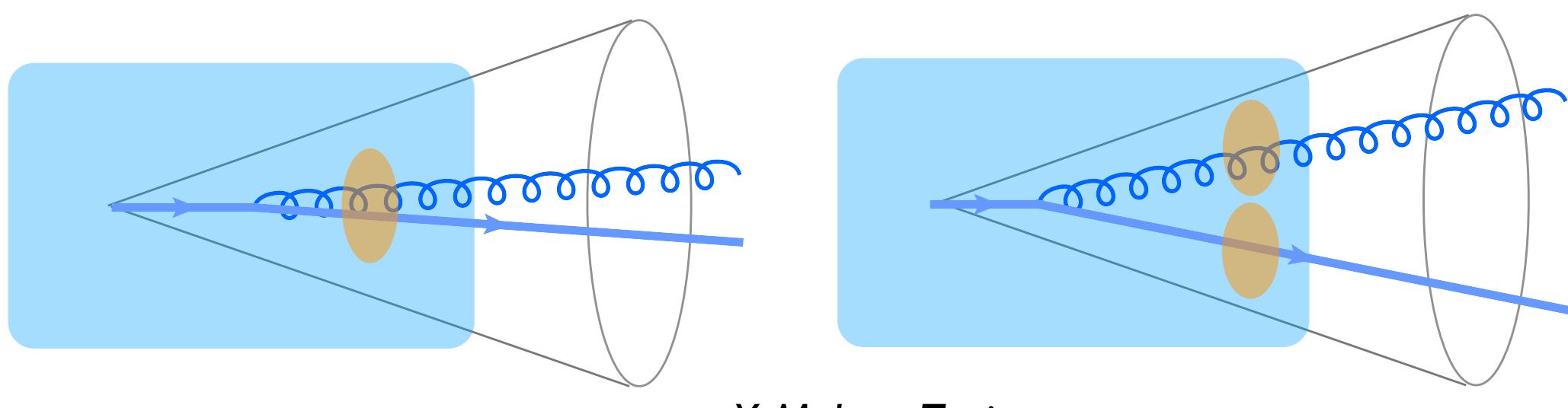
~~(IN2P3/CNRS/IRFU/CEA)~~

Jets to study QCD

- Understanding validity of perturbative vs. nonperturbative physics

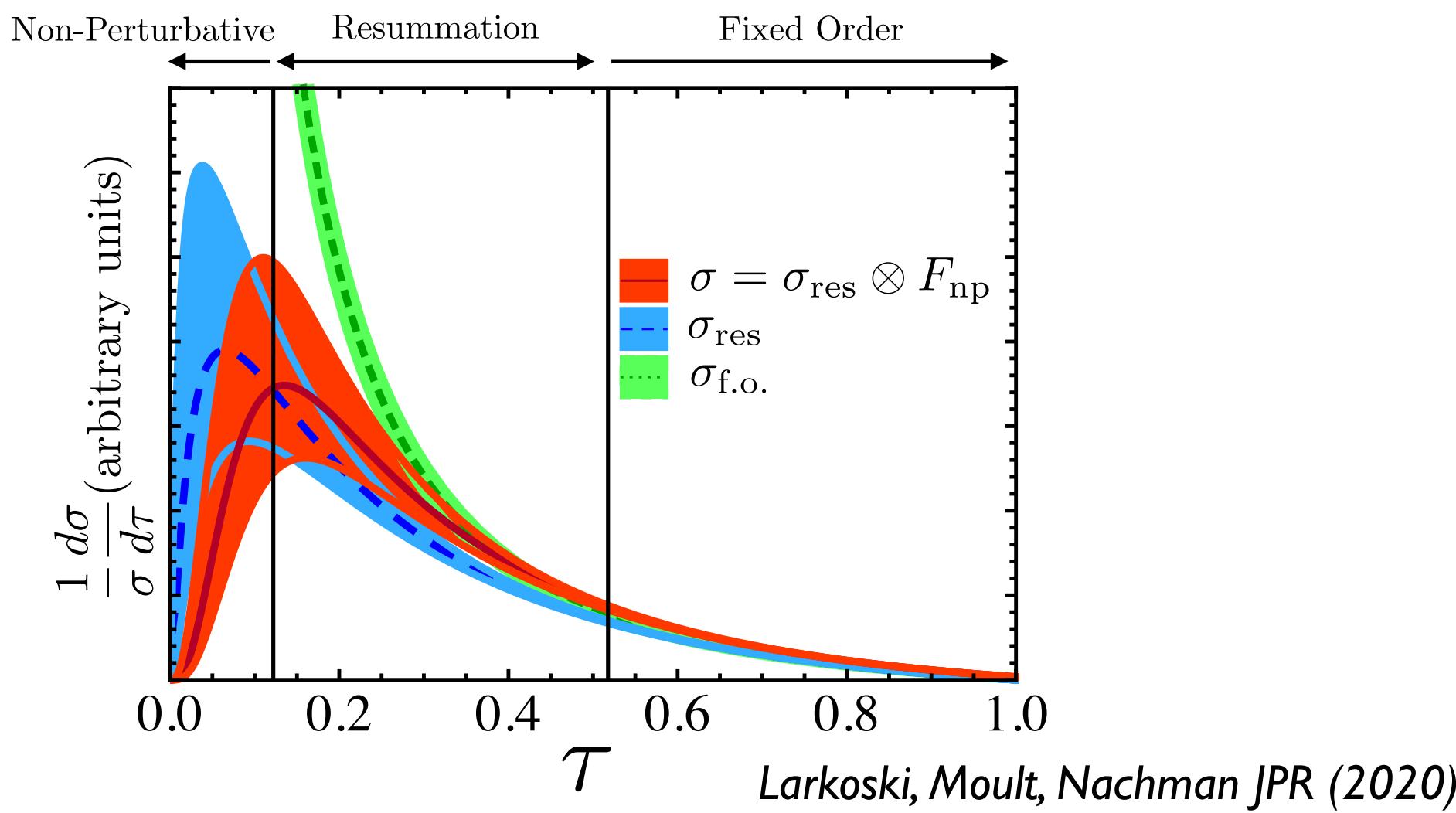


- Probes of quark-gluon plasma

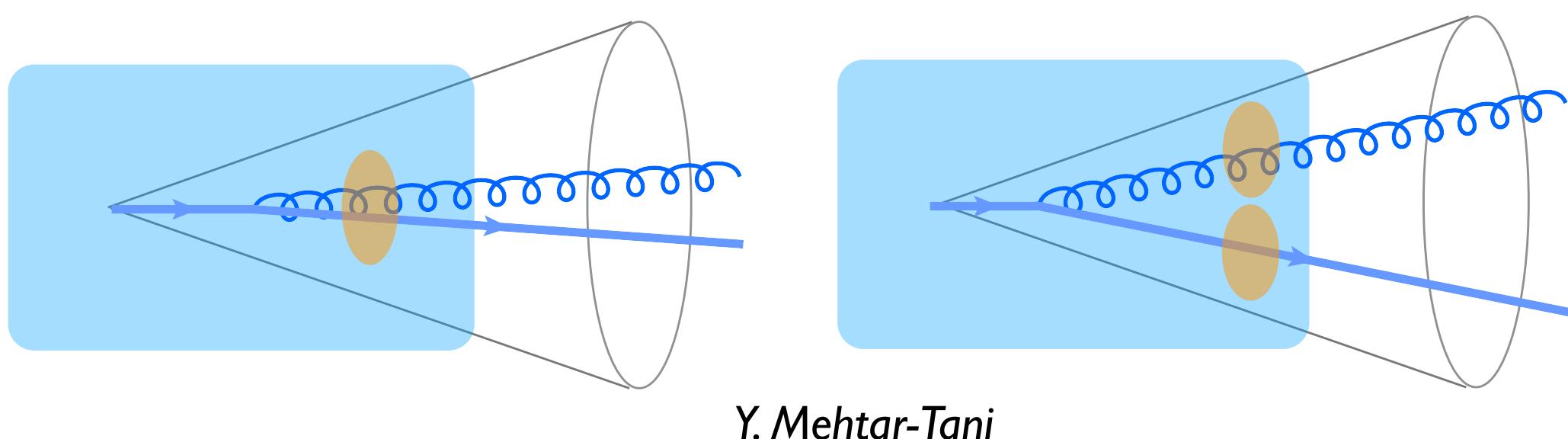


Jets to study QCD

- Understanding validity of perturbative vs. nonperturbative physics

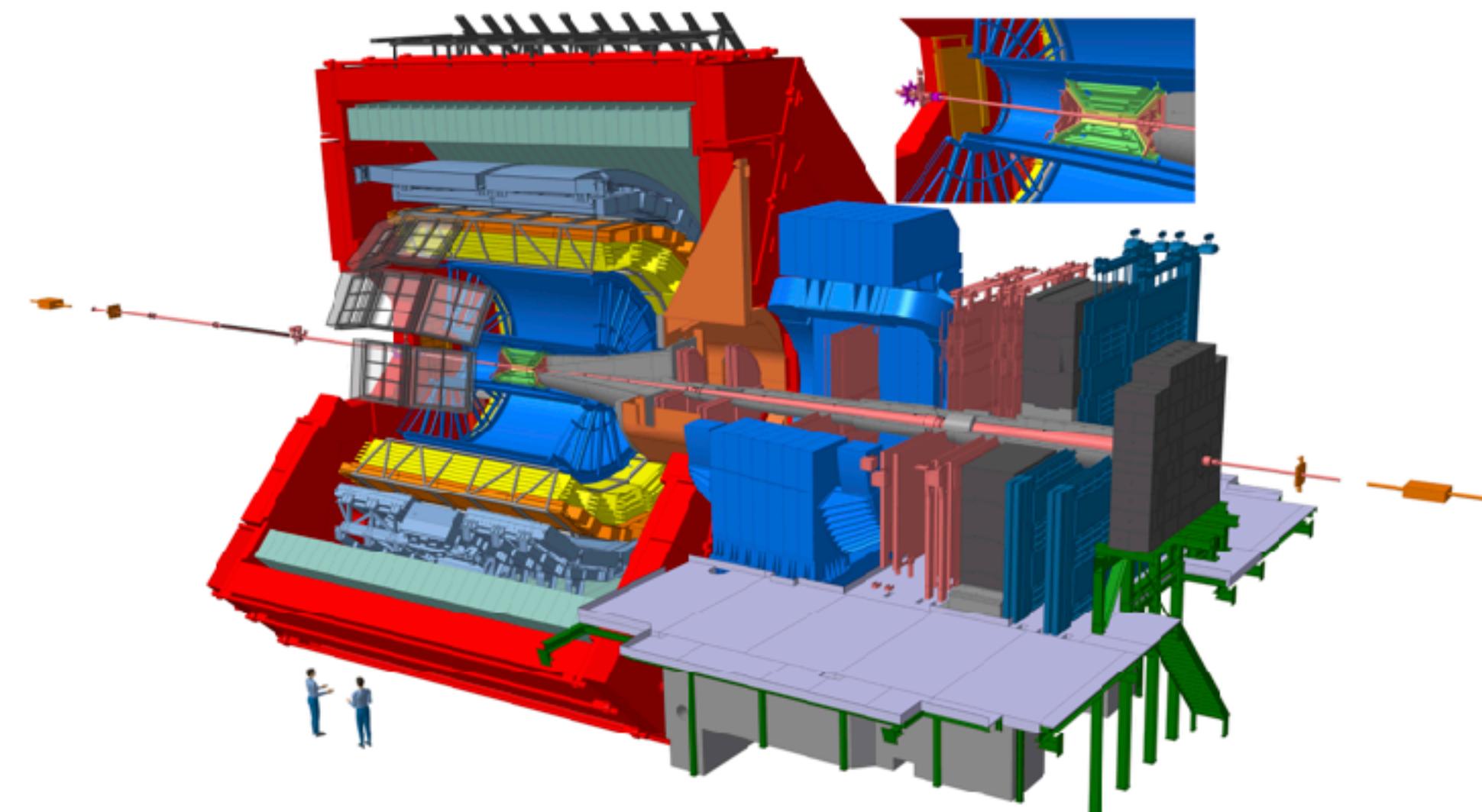


- Probes of quark-gluon plasma



ALICE reconstructs jets at midrapidity with a high-precision tracking system (ITS+TPC) and EMCal

- $p_{T,\text{jet}} \approx 20 - 200 \text{ GeV}/c$
- $|\eta| < 0.9$



Charged particle jets

- High-precision spatial resolution to resolve particles
- **Ideal for jet substructure measurements**

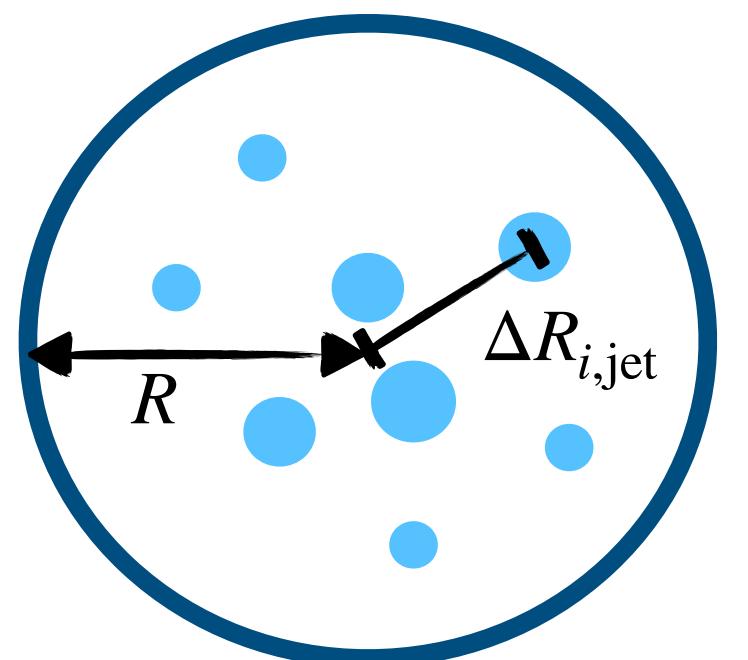
Full jets (charged tracks + EMCal π^0, γ)

- More direct comparison to theory

Jet angularities — pp

Class of IRC-safe observables:

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



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

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

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

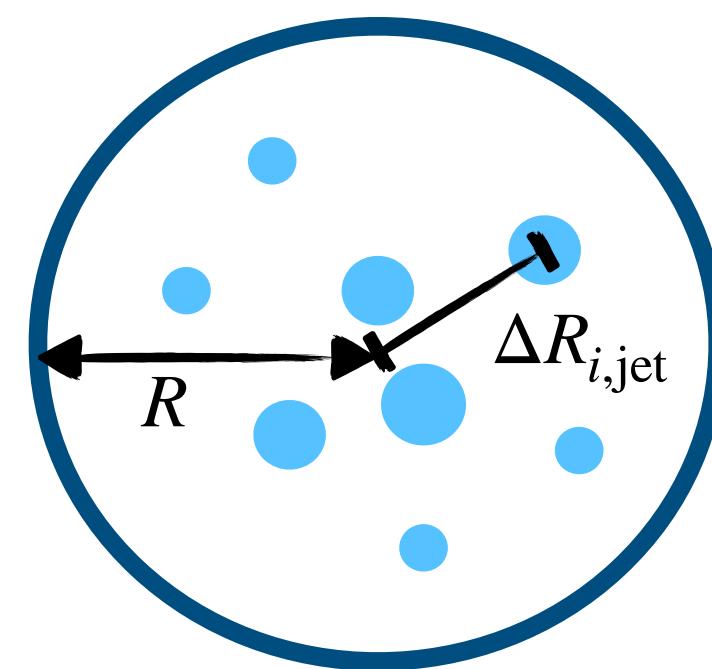
Almeida, Lee, Perez, Sterman, Sung, Virzi PRD 79 (2009)
 Larkoski, Thaler, Waalewijn JHEP 129 (2014)

...

Jet angularities — pp

Class of IRC-safe observables:

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



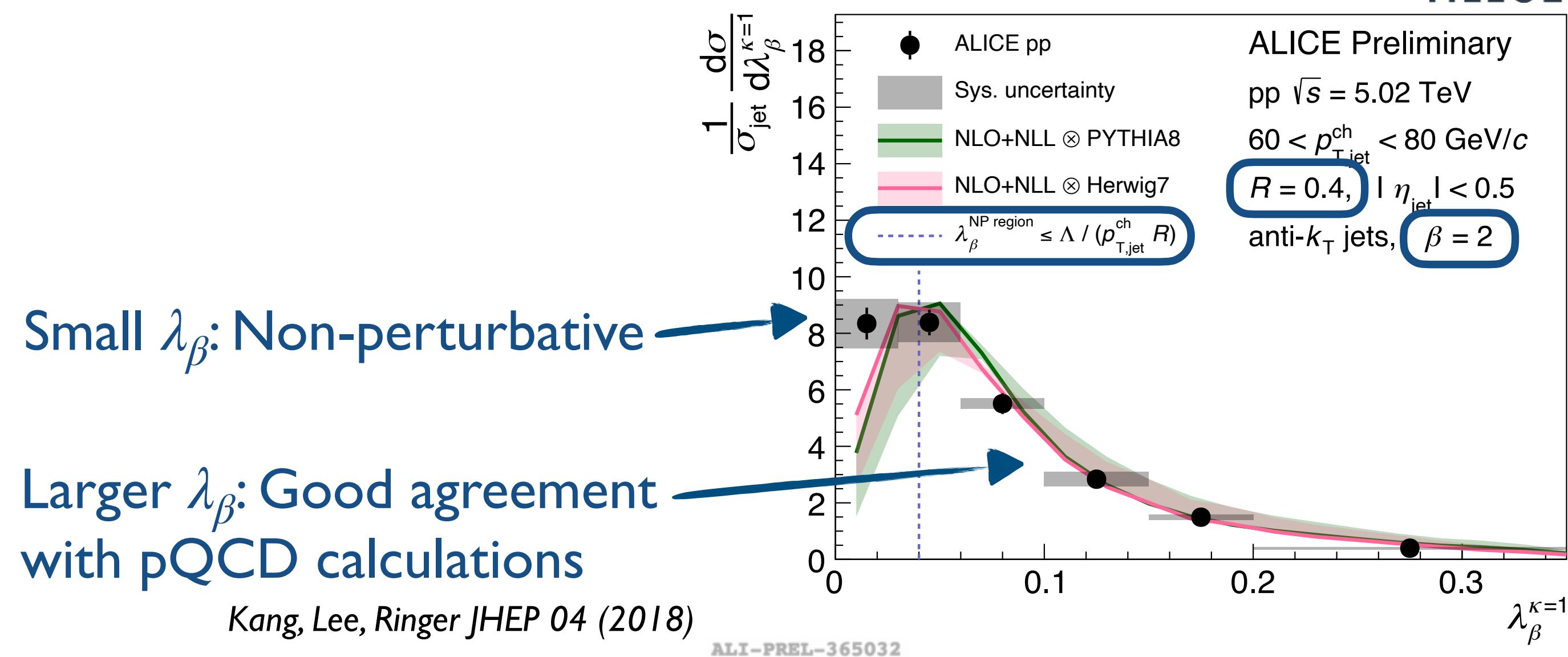
$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

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

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

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

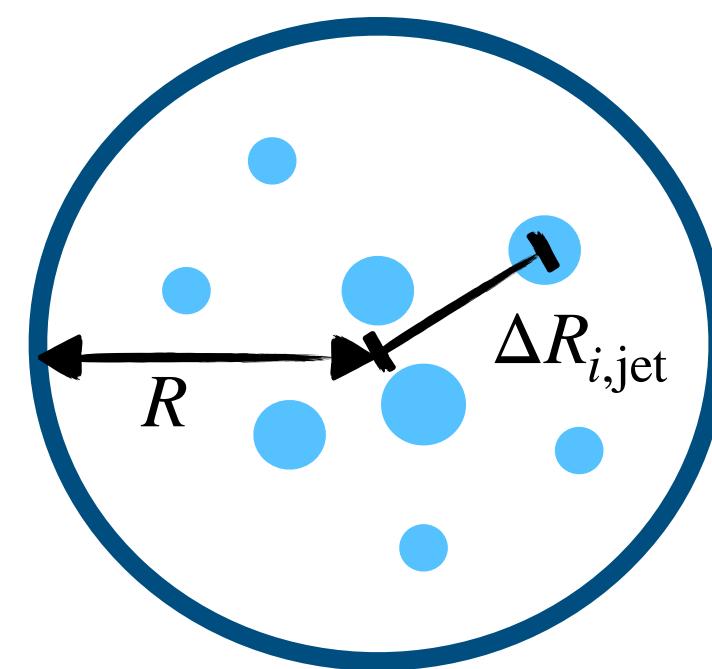
...



Jet angularities — pp

Class of IRC-safe observables:

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



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

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

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

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

Larkoski, Thaler, Waalewijn JHEP 129 (2014)

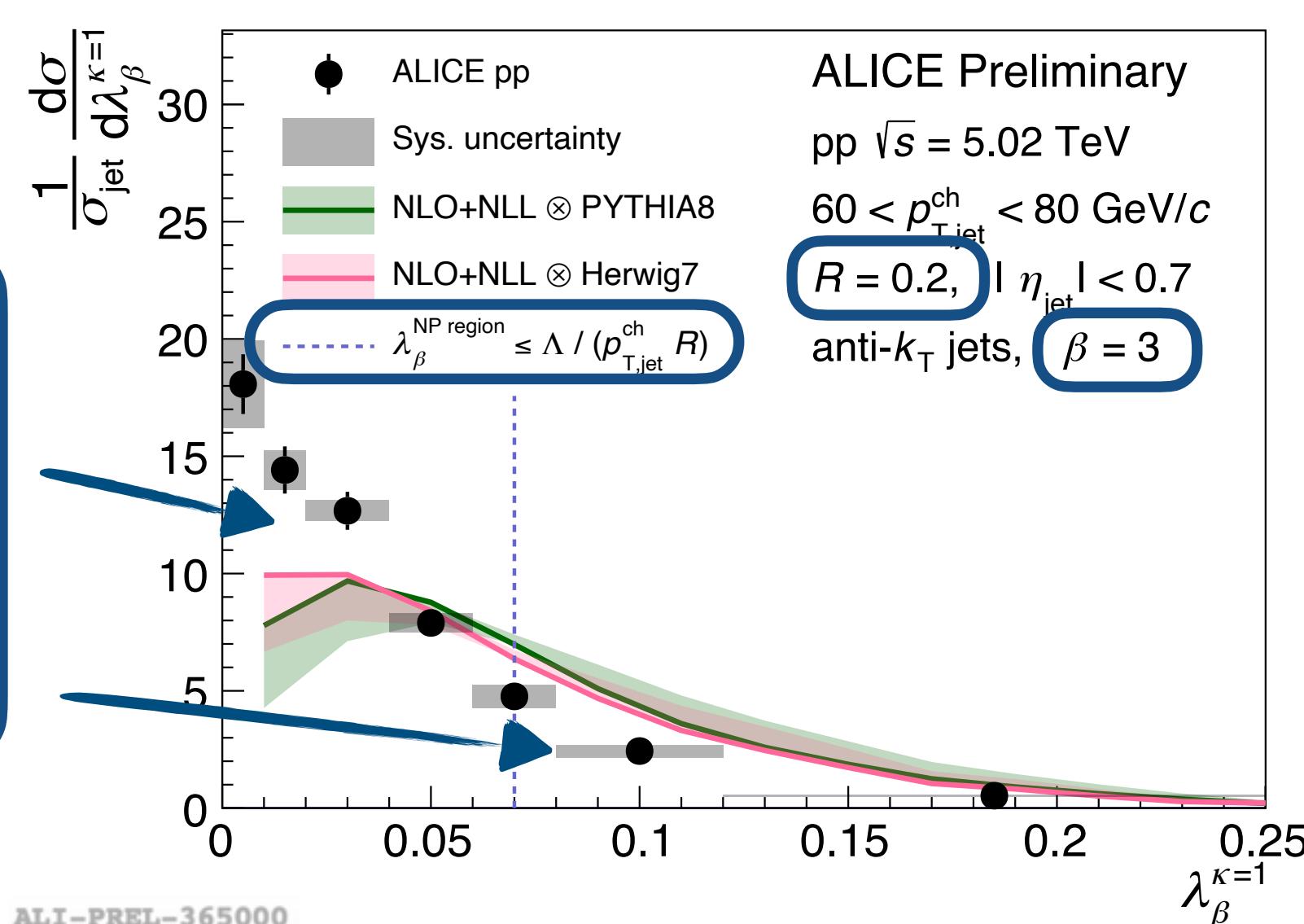
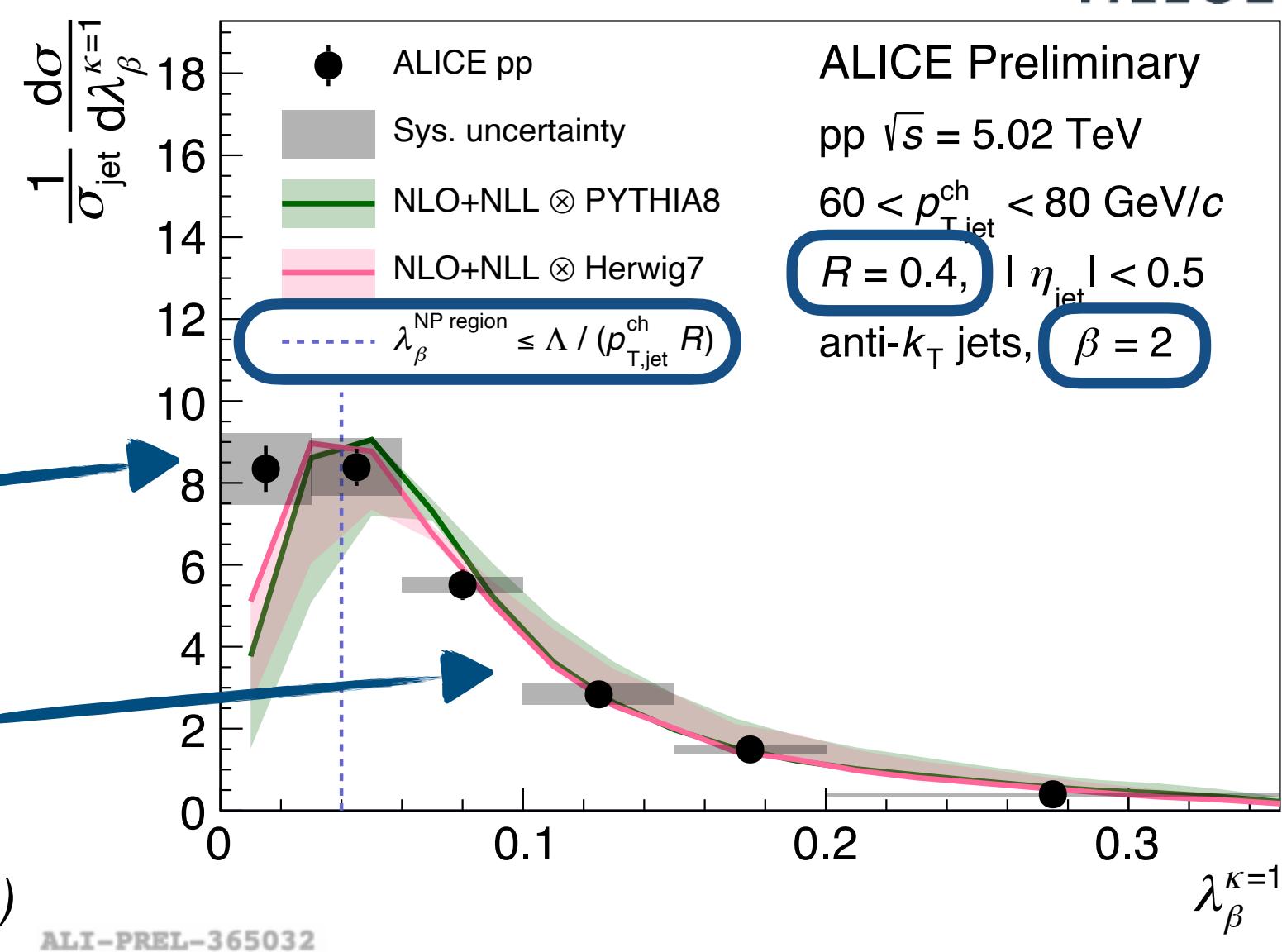
...

Small λ_β : Non-perturbative

Larger λ_β : Good agreement with pQCD calculations

Kang, Lee, Ringer JHEP 04 (2018)

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

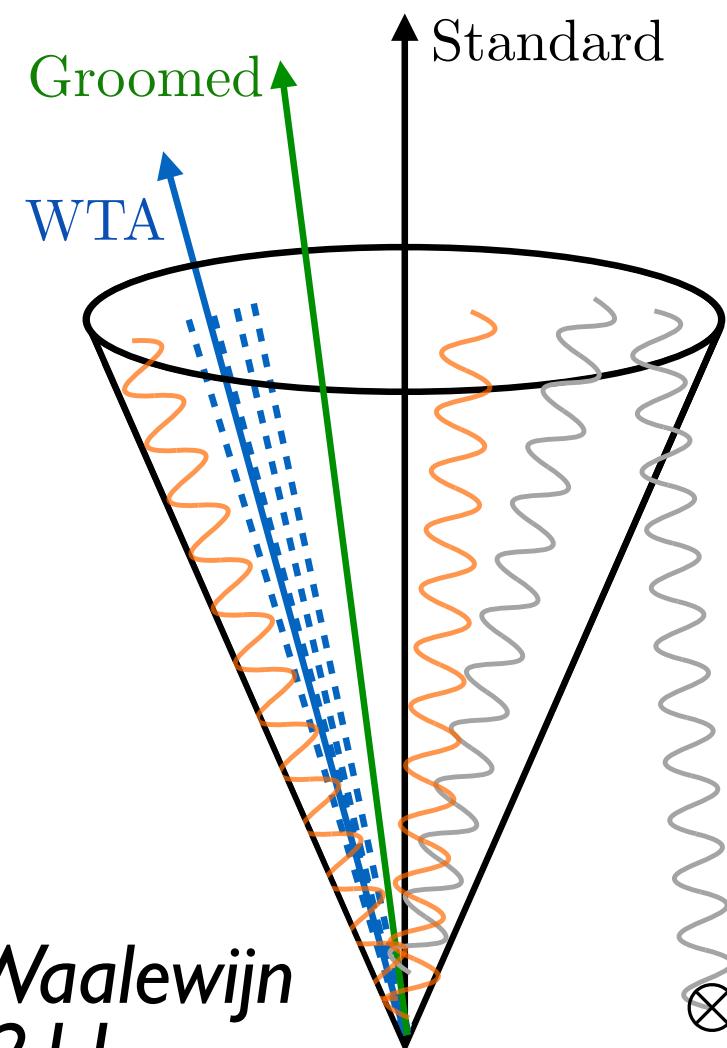


Jet axis differences — pp

Measure angular difference between different jet axes:

$$\Delta R_{\text{axis}} = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

- Standard axis: E -scheme recombination
- Soft Drop axis: Standard axis of groomed jet
- Winner-Take-All axis: WTA recombination scheme



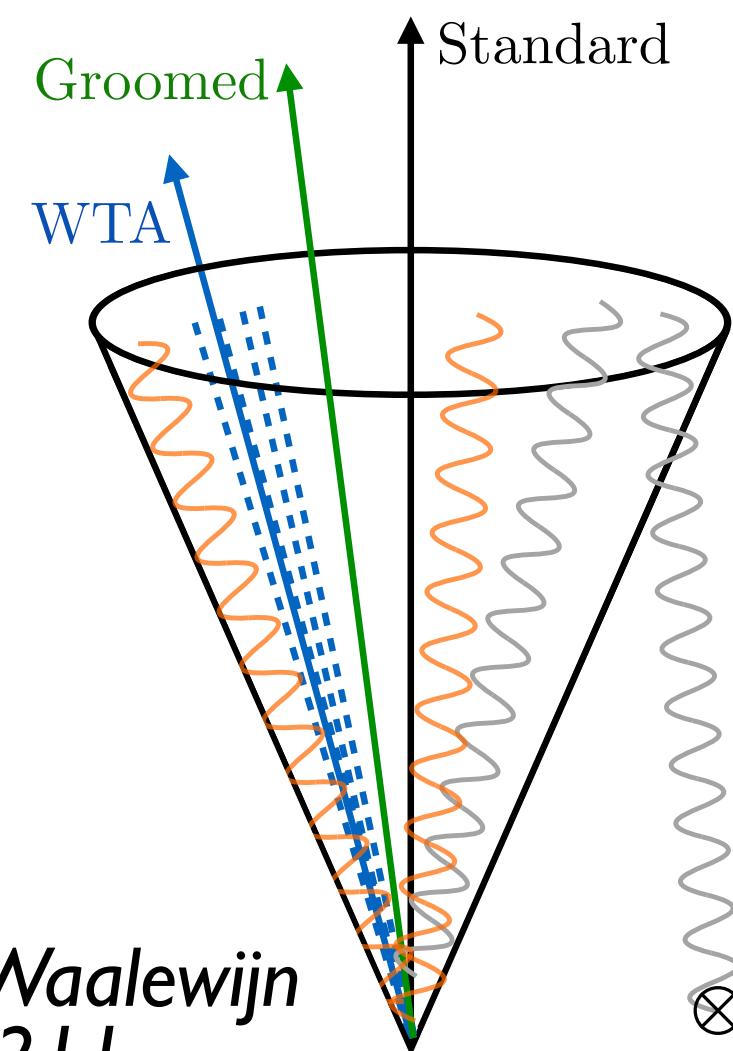
Cal, Neill, Ringer, Waalewijn
JHEP 04 (2020) 211

Jet axis differences — pp

Measure angular difference between different jet axes:

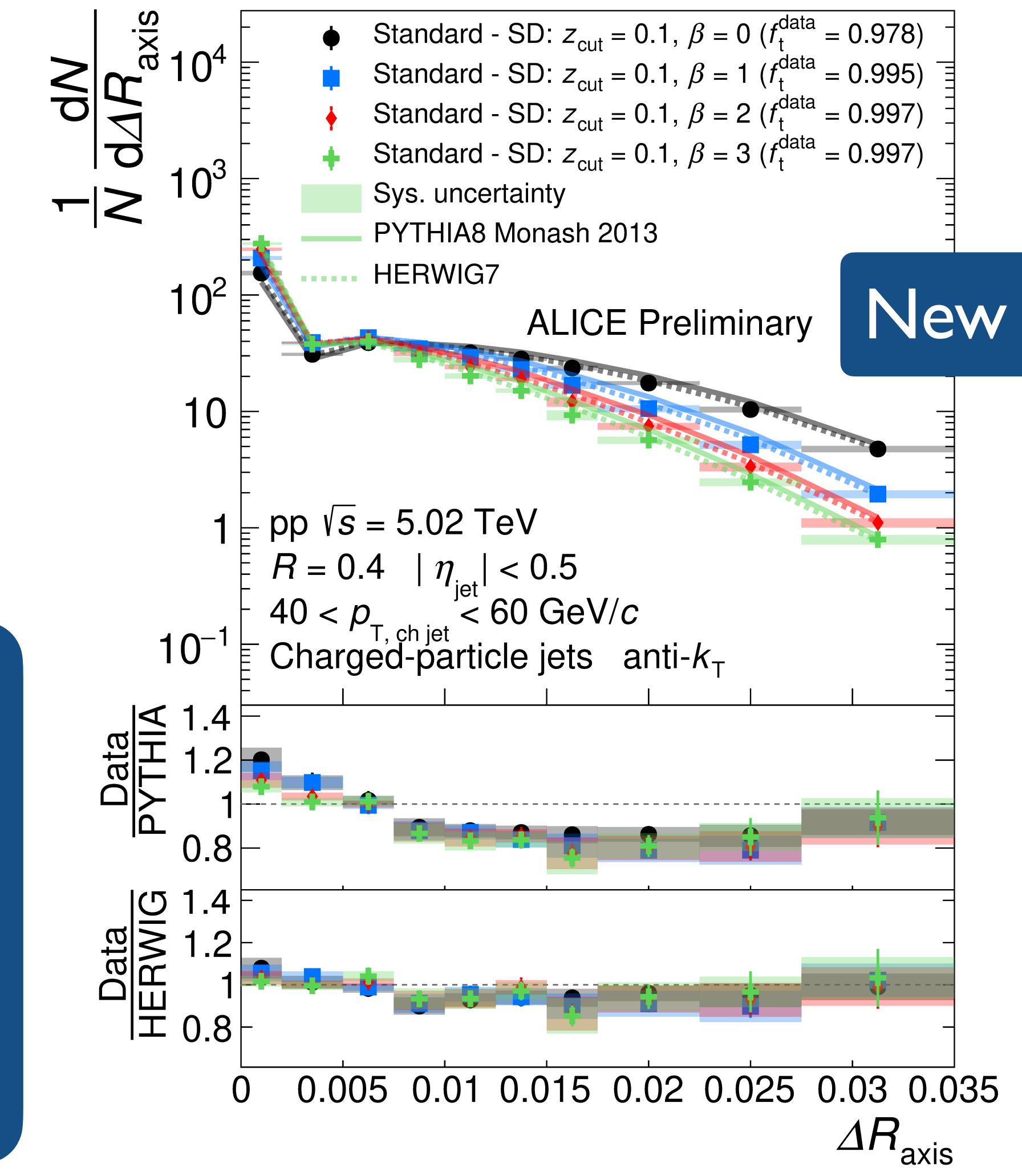
$$\Delta R_{\text{axis}} = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

- Standard axis: E -scheme recombination
- Soft Drop axis: Standard axis of groomed jet
- Winner-Take-All axis: WTA recombination scheme



Standard - SoftDrop

- Small absolute difference
- Stronger grooming → larger ΔR_{axis}

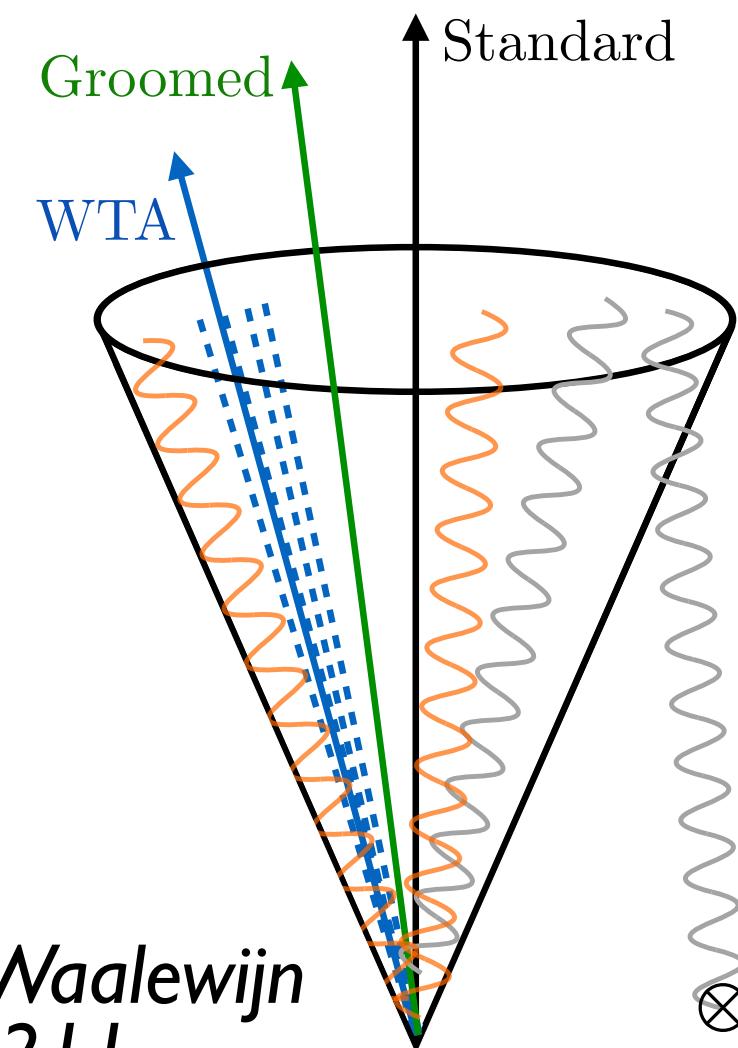


Jet axis differences — pp

Measure angular difference between different jet axes:

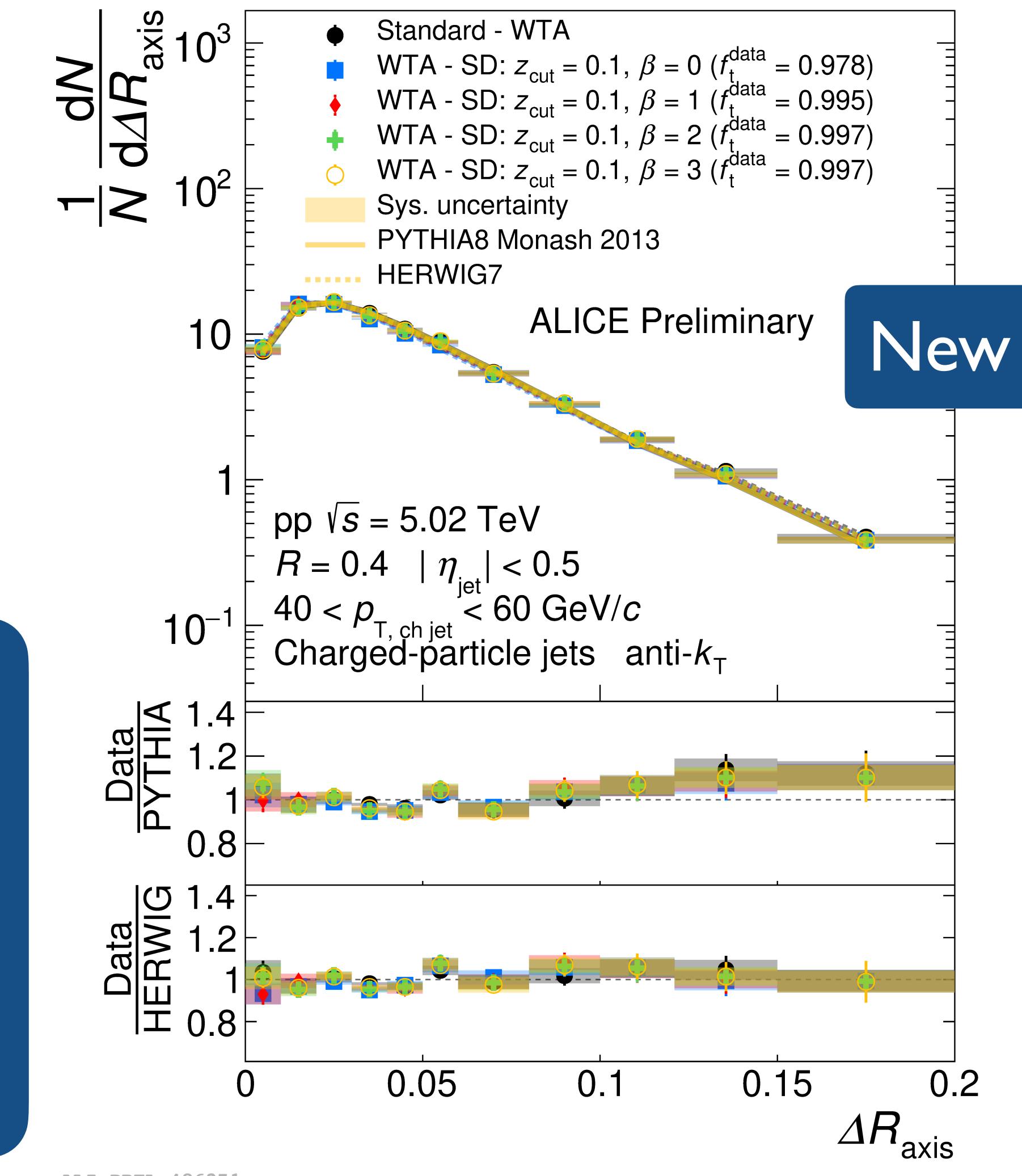
$$\Delta R_{\text{axis}} = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

- Standard axis: E -scheme recombination
- Soft Drop axis: Standard axis of groomed jet
- Winner-Take-All axis: WTA recombination scheme



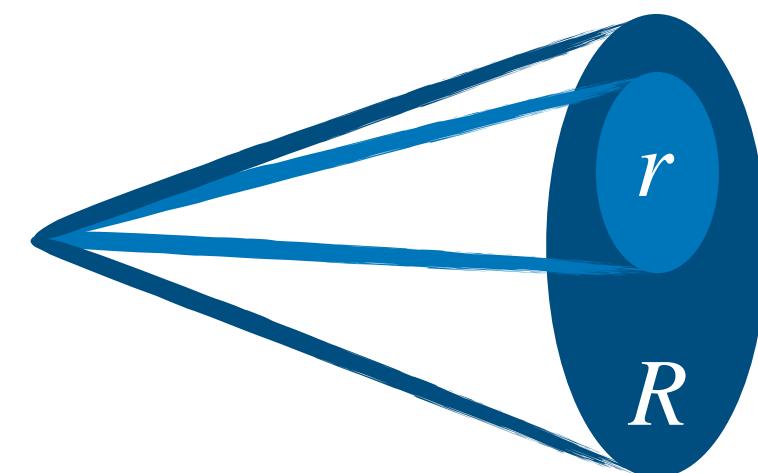
WTA - Standard/SD

- Large absolute difference
- Negligible dependence on grooming condition



Subjet fragmentation — pp

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



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

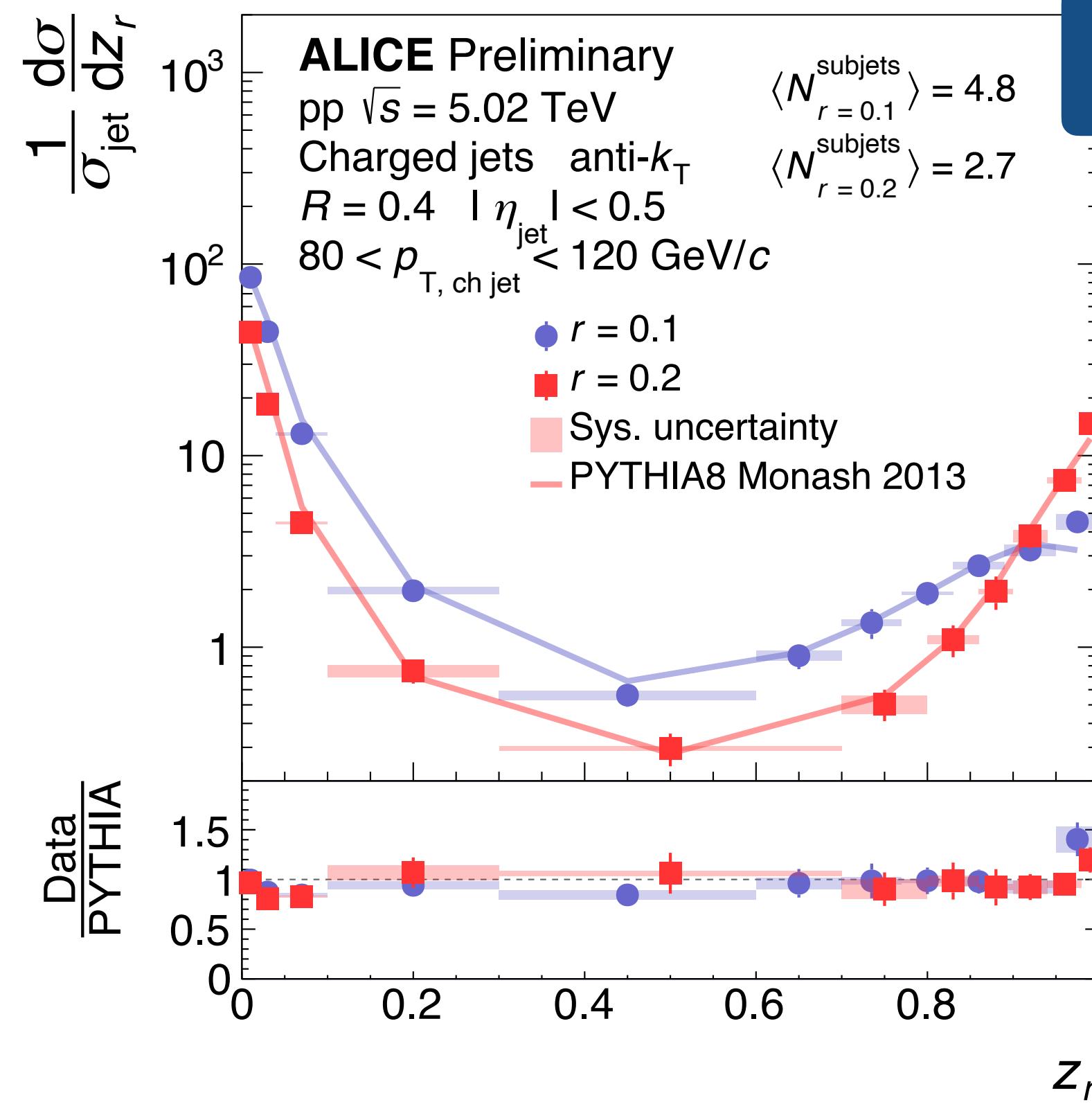
We can then measure either the *inclusive subjets* or the *leading subjets*

Generally good agreement with PYTHIA

- Disagreement at large- z_r
 - threshold resummation?
 - hadronization?

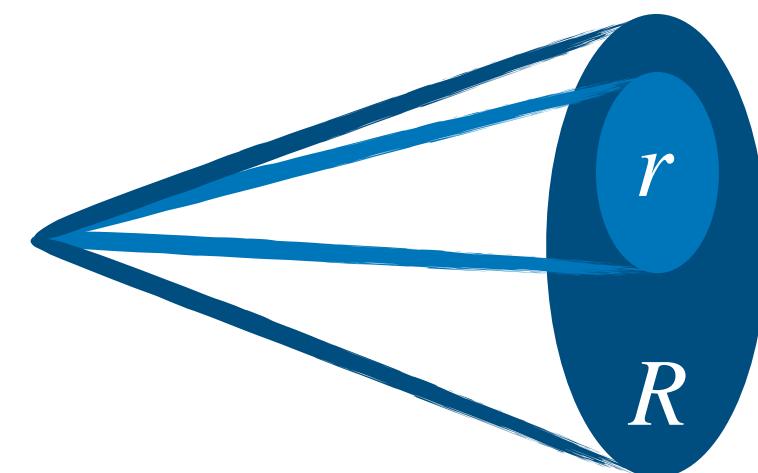
Neill, Ringer, Sato 2103.16573
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

Inclusive subjets



Subjet fragmentation — pp

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



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

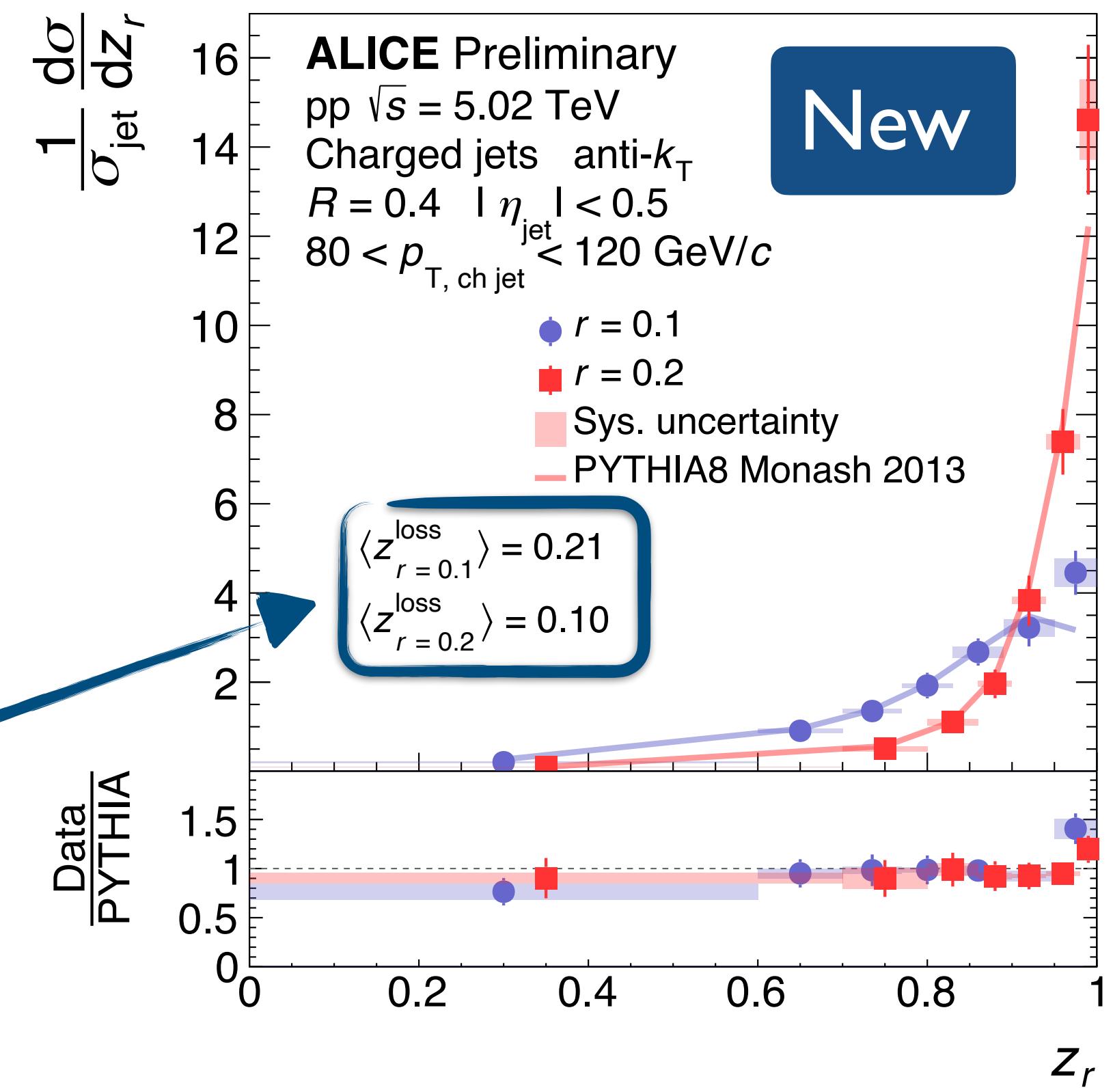
We can then measure either the *inclusive subjets* or the *leading subjets*

We can compute the “energy loss” outside of the leading subjet:

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

Neill, Ringer, Sato 2103.16573
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

Leading subjets

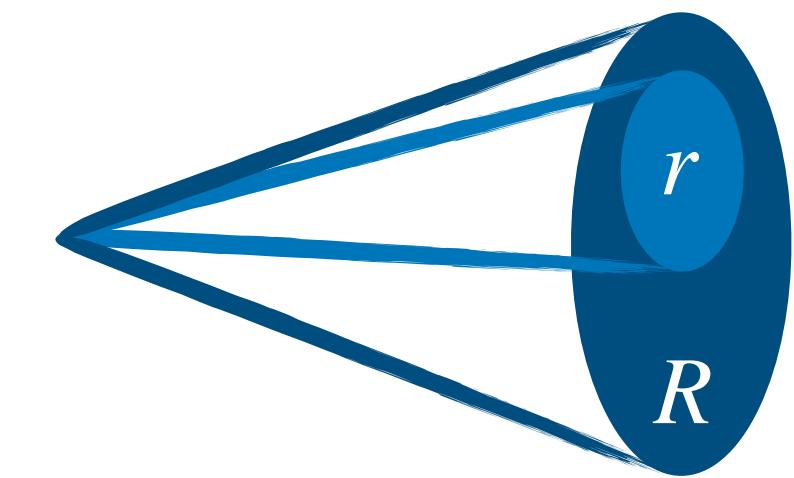


Subjet fragmentation — Pb-Pb



Measure subjets in heavy-ion collisions to probe jet quenching

See also: Caucal, Iancu, Mueller, Soyez *JHEP* 10 (2020) 204
Apolinario, Milhano, Ploskon, Zhang *EPJC* 78 (2018) 6, 529



Can probe much higher z than hadron fragmentation measurements

CMS PRC 90 (2014) 2 024908
ATLAS PRL 123 (2019) 4 042001

Opportunity to test universality of jet fragmentation functions

$$J_{r,\text{med}}(z) = J_{\text{med}}(z)$$


parton → sujet parton → jet

Subjet fragmentation — Pb-Pb

Measure subjets in heavy-ion collisions to probe jet quenching

No significant modification observed

Well-described by theoretical predictions

- JETSCAPE

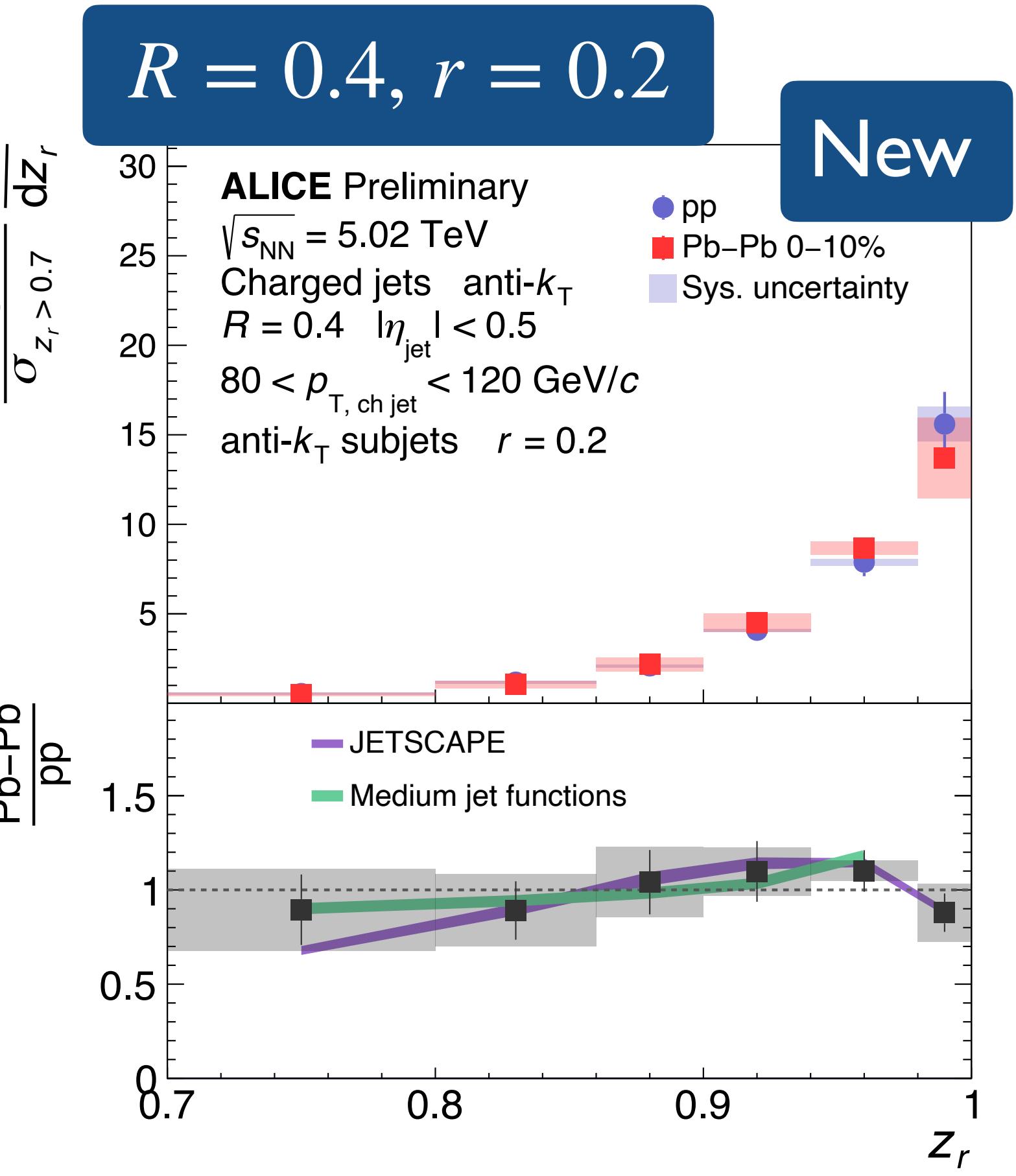
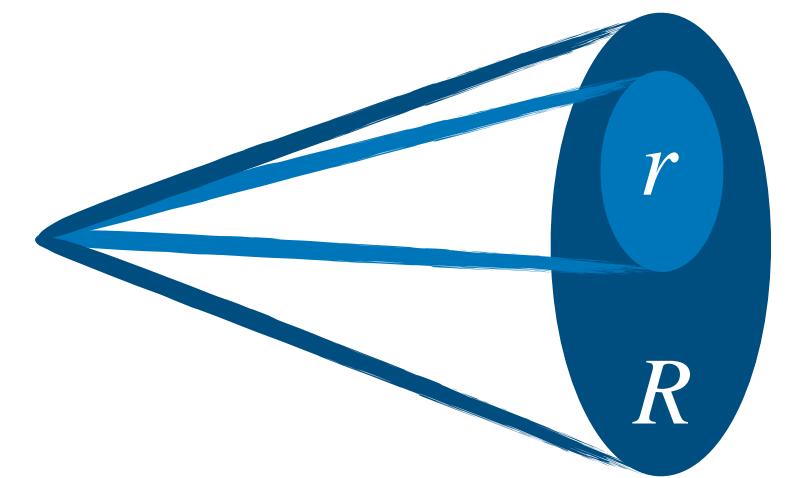
JETSCAPE Collaboration 1903.07706

- In-medium jet functions

Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25

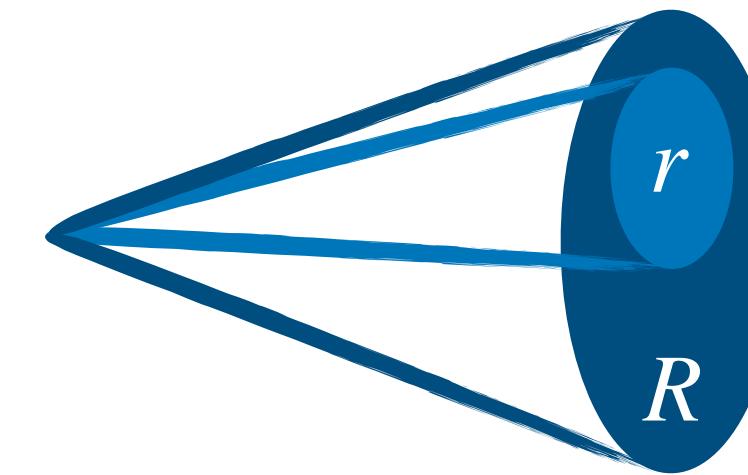
Neill, Ringer, Sato 2103.16573

Kang, Ringer, Waalewijn JHEP 07 (2017) 064



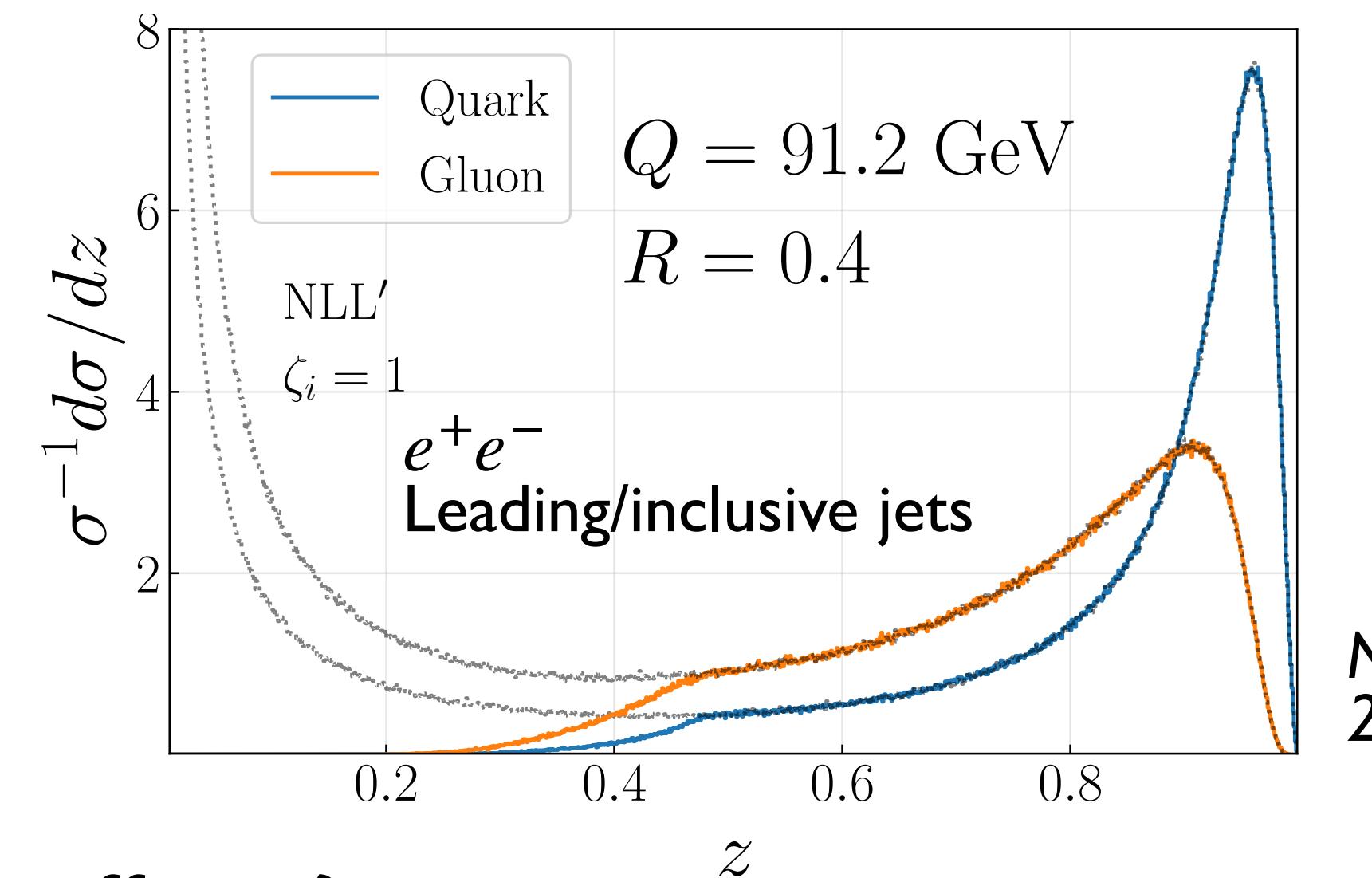
Subjet fragmentation — Pb-Pb

Measure subjets in heavy-ion collisions to probe jet quenching



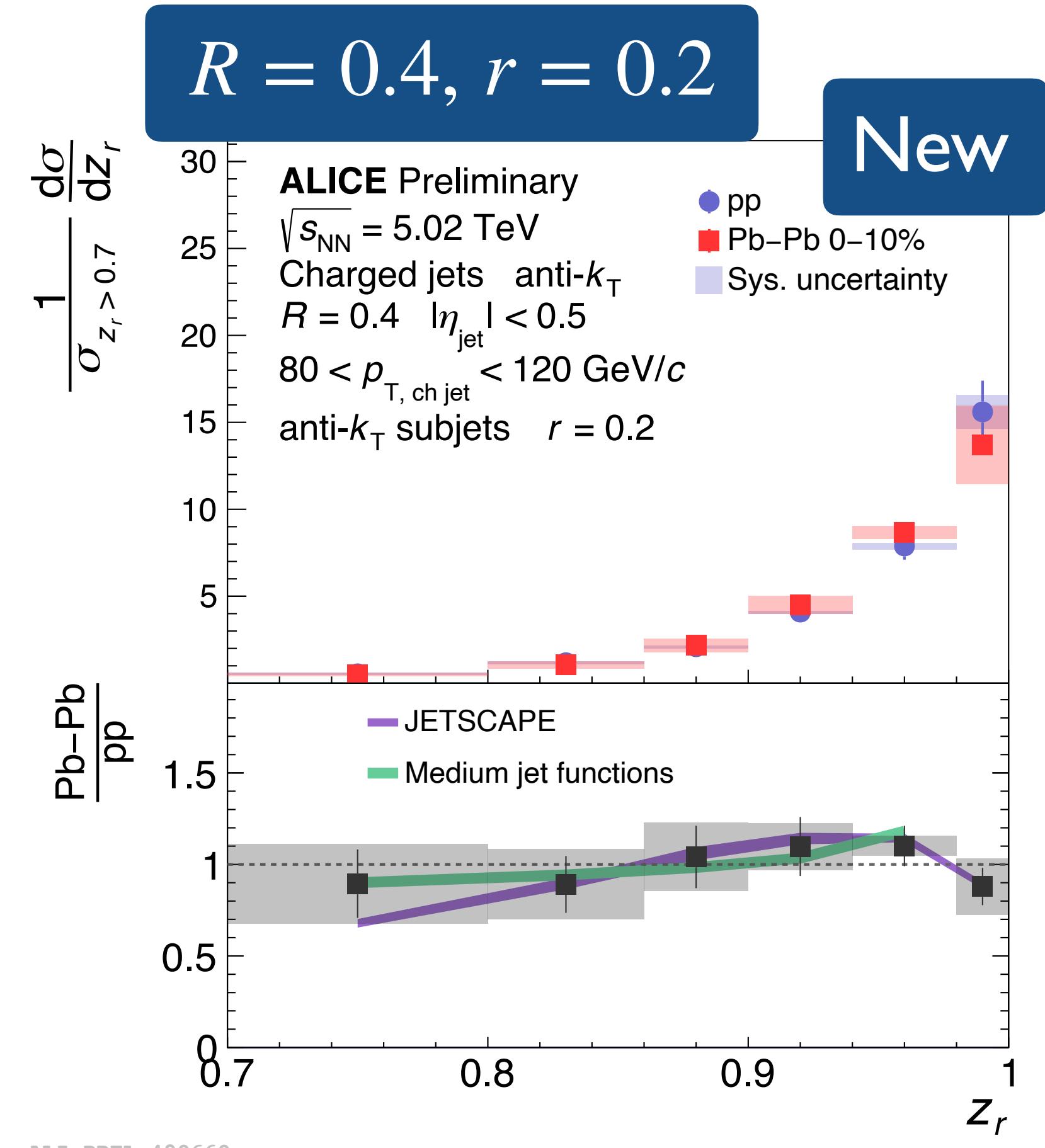
No significant modification observed

Not trivial — there are large quark-gluon differences in vacuum



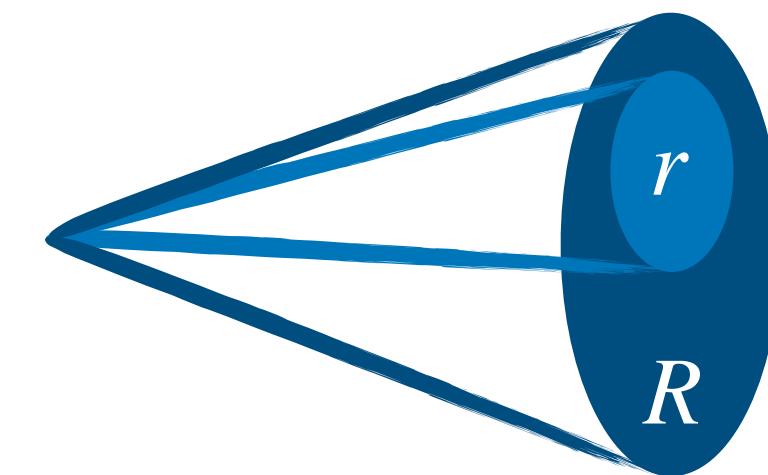
Competing effects?

- Gluon suppression \rightarrow larger z_r
- Soft radiation \rightarrow smaller z_r



Subjet fragmentation — Pb-Pb

Measure subjets in heavy-ion collisions to probe jet quenching



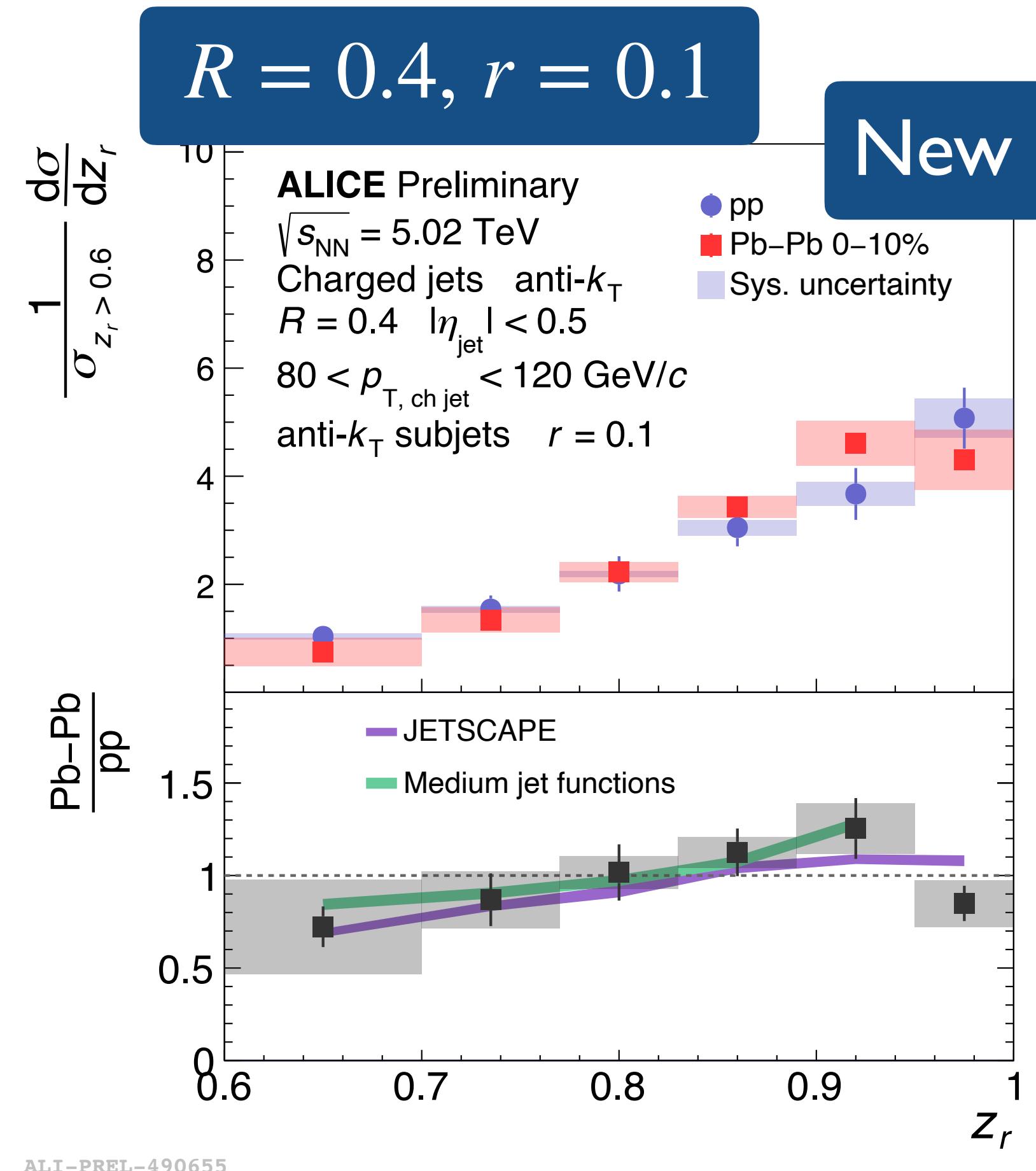
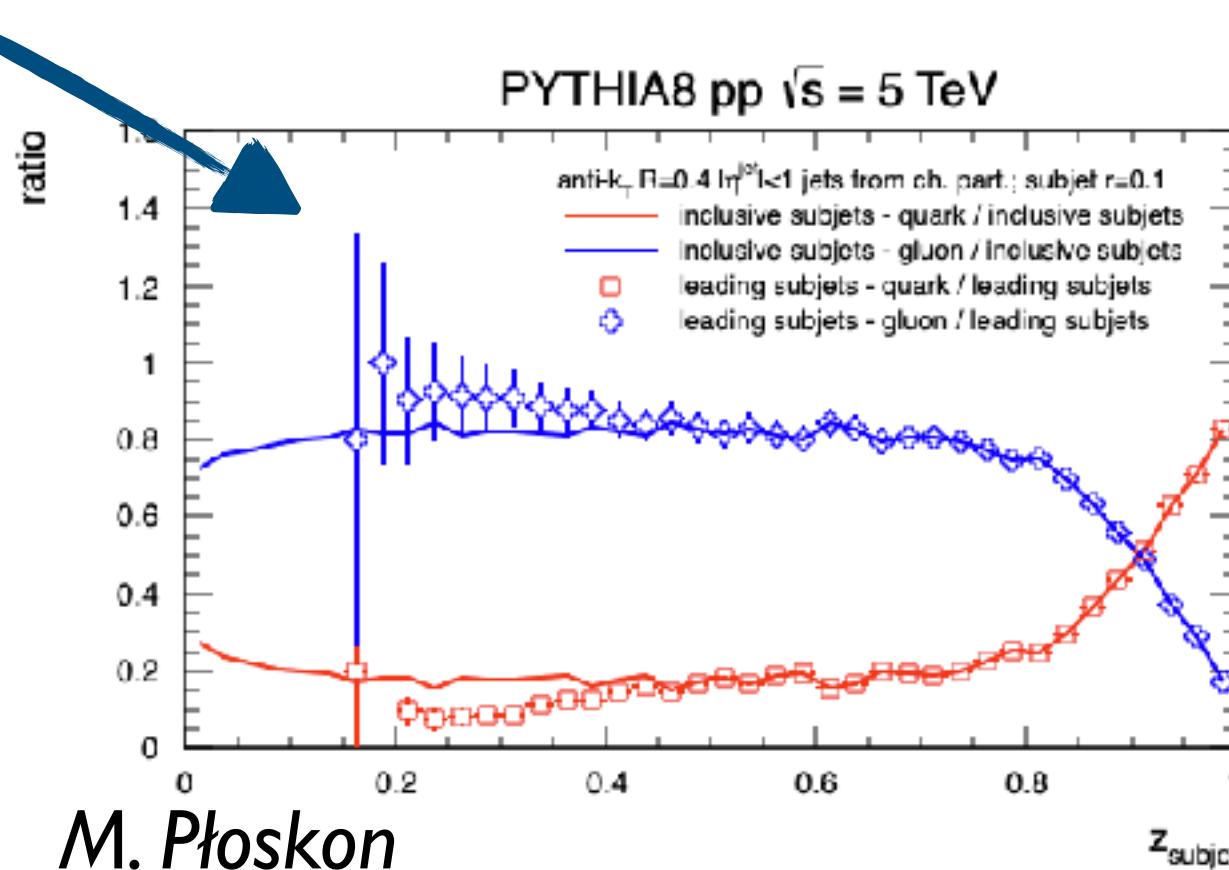
→ Study the r -dependence

Hint of hardening distribution at intermediate z_r

- q/g effect? Similar to θ_g

Hint of suppression as $z_r \rightarrow 1$

- At $z_r \rightarrow 1$, the sample becomes closer to purely quark jets!
- Expose soft medium induced emissions

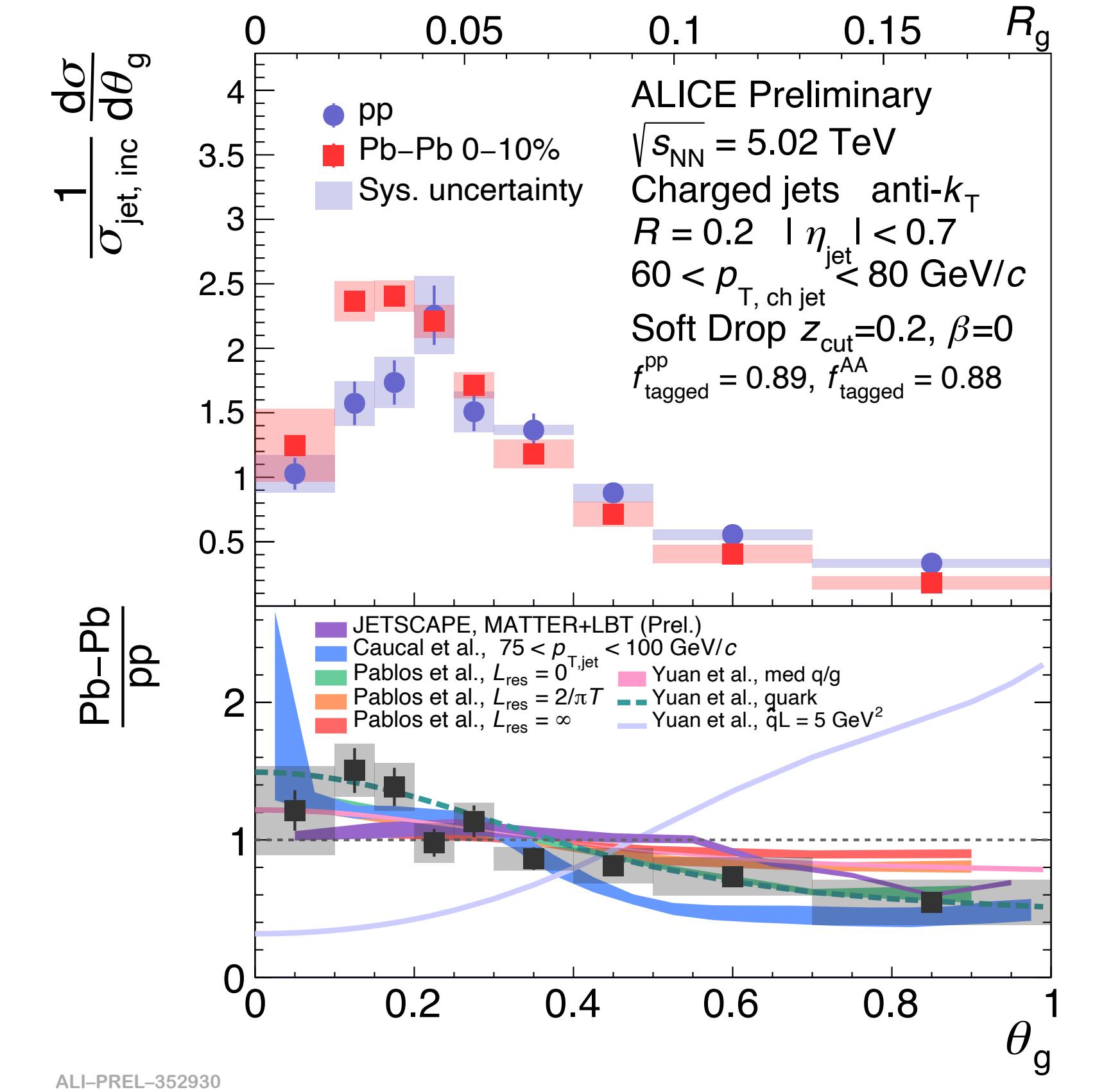
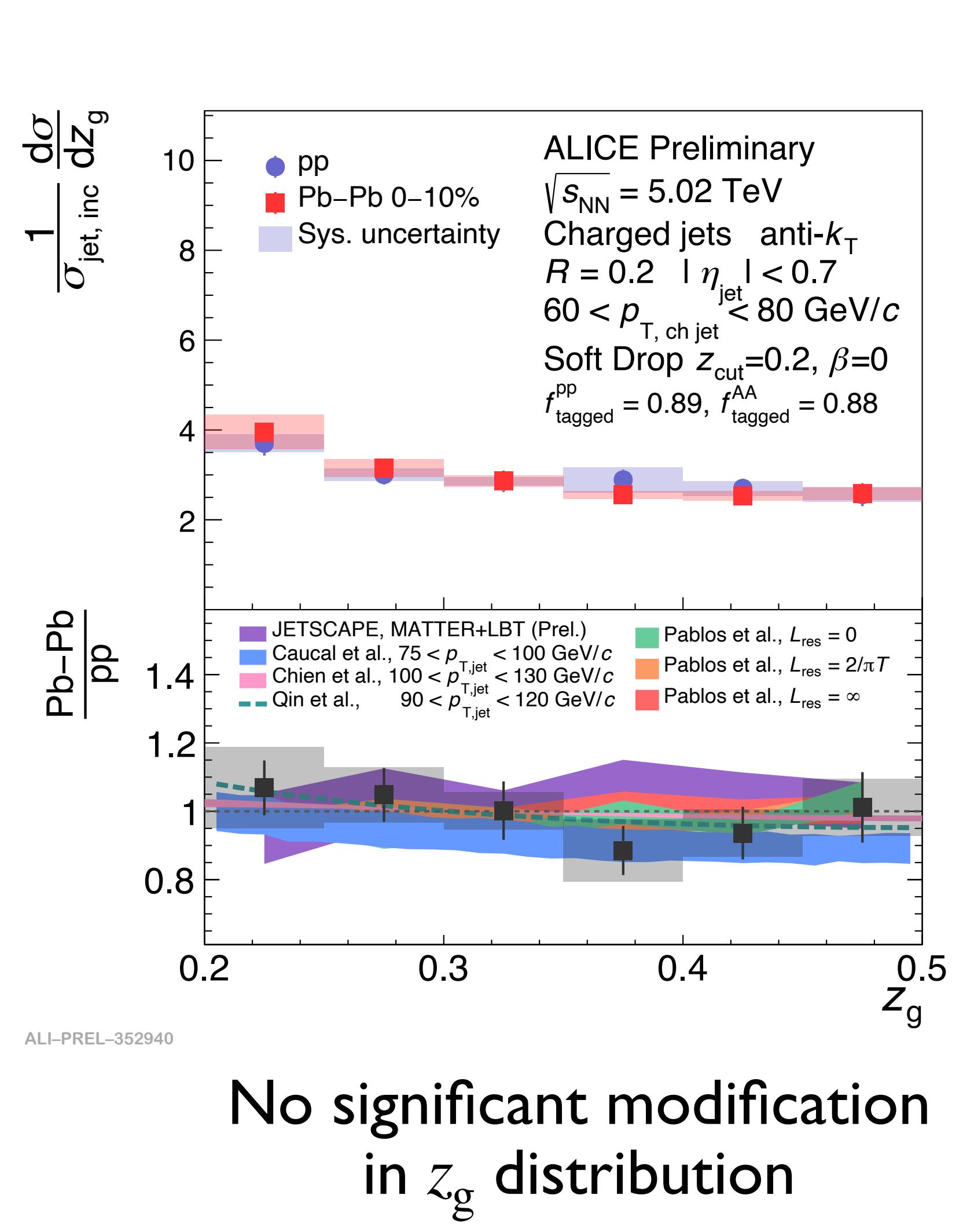
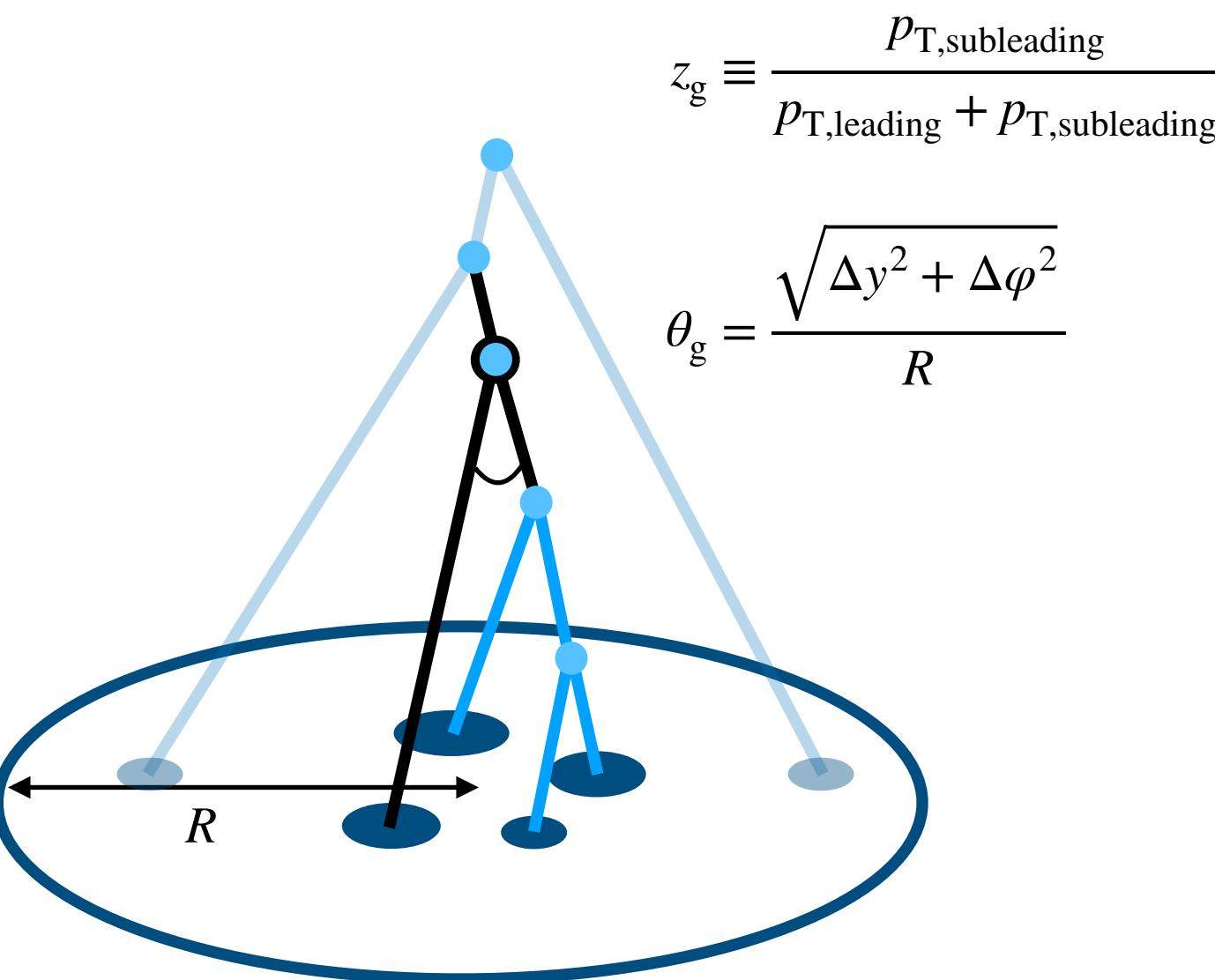


Groomed jet substructure

ALICE-PUBLIC-2020-006



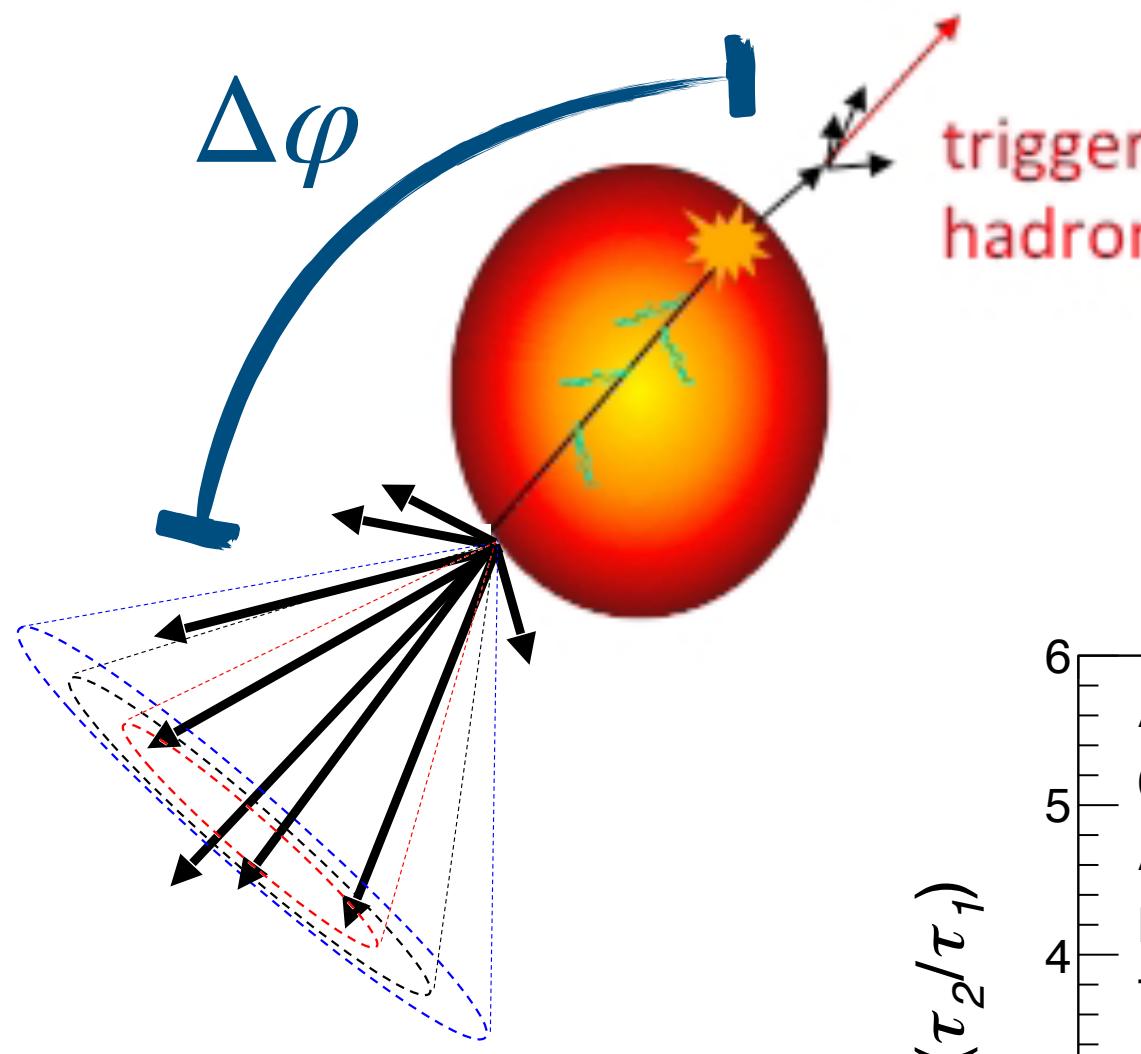
How is the hard jet
substructure modified
in heavy-ion collisions?



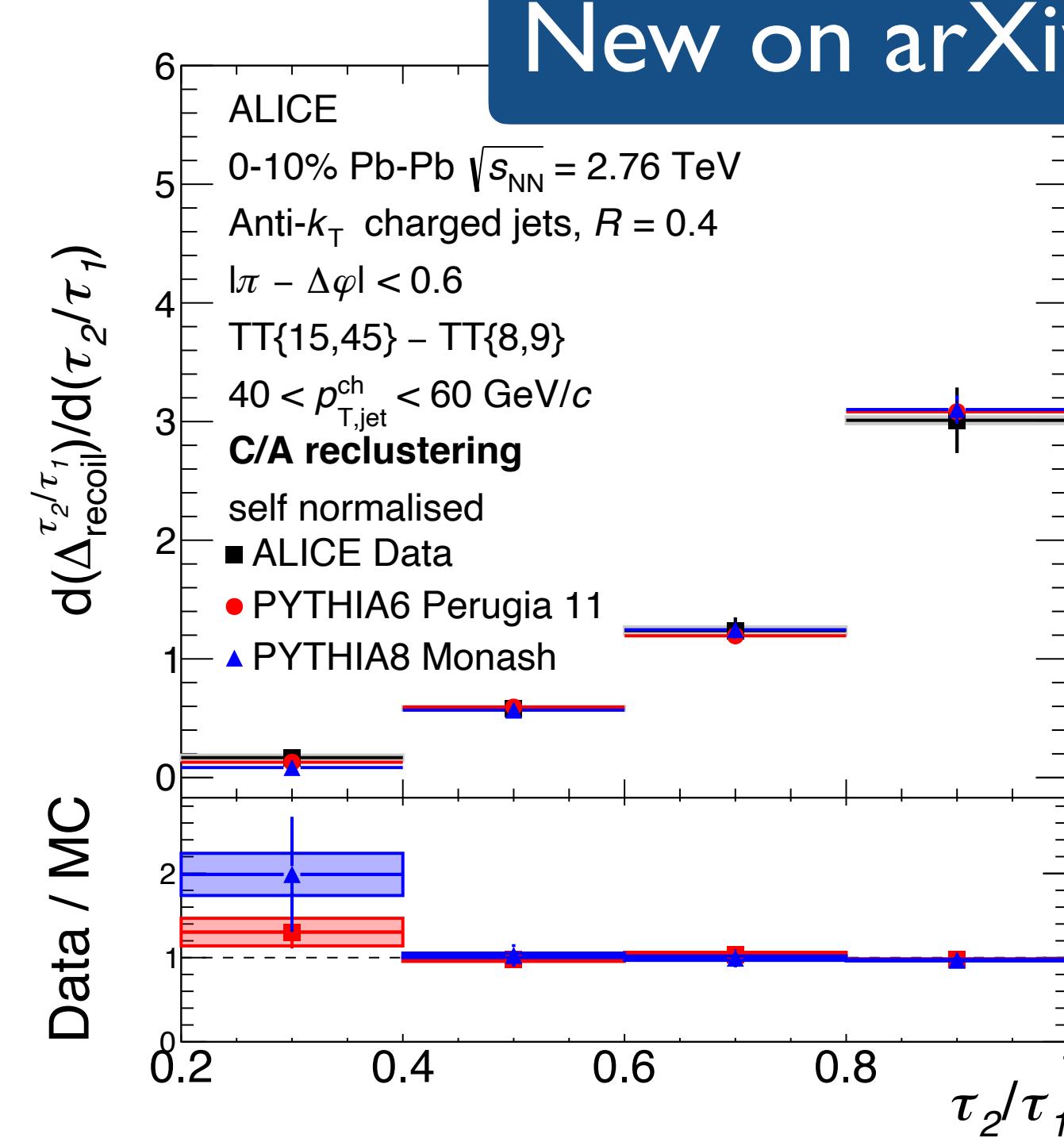
N-subjettiness

2105.04936

Substructure of recoiling jet in semi-inclusive hadron-jet coincidence



Small τ_2/τ_1 :
“2-prongy”
Large τ_2/τ_1 :
“1-prongy”



$$\tau_N = \frac{1}{p_{T,\text{jet}} \times R} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k})$$

$$\Delta_{\text{recoil}}^{\tau_2/\tau_1} = \left| \frac{1}{N_{\text{trig,Sig}}} \frac{d^2N}{dp_{T,\text{jet}}^{\text{ch}} d\tau_2/\tau_1} \right|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - \left| \frac{1}{N_{\text{trig,Ref}}} \frac{d^2N}{dp_{T,\text{jet}}^{\text{ch}} d\tau_2/\tau_1} \right|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}$$

No strong modification of “pronginess”
of jets in heavy-ion collisions

Medium-induced emissions are not
hard enough to produce a new prong
Similar to z_g being unmodified?

Summary

ALICE measurements of jet substructure in proton-proton collisions are providing new tests of our first-principles understanding of QCD

- Jet angularities, jet axis differences, subjet fragmentation, ... and more not shown!
- Explore the transition from the perturbative to nonperturbative regimes
 - Provides crucial insight for reference to heavy-ion collisions

ALICE measurements of jet substructure and jet correlations in heavy-ion collisions are producing an emerging picture of jet quenching phenomenology

- Hard splitting not strongly modified — z_g, τ_N
- Collimation/filtering of wide jets — θ_g
- Medium-induced soft splitting can be exposed in region dominated by quark jets — z_r

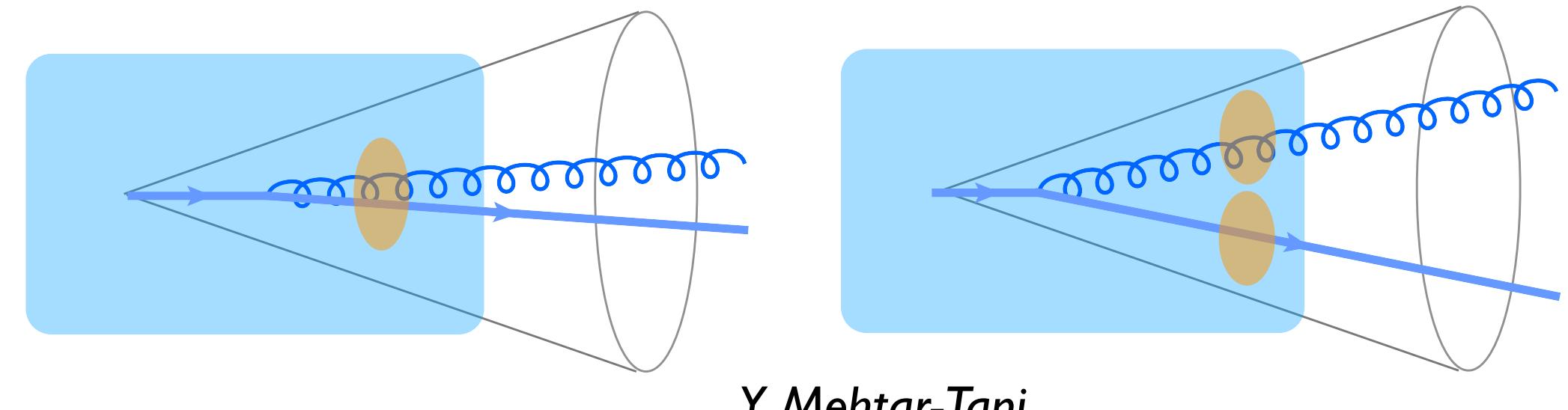
backup

Jet substructure in heavy-ion collisions



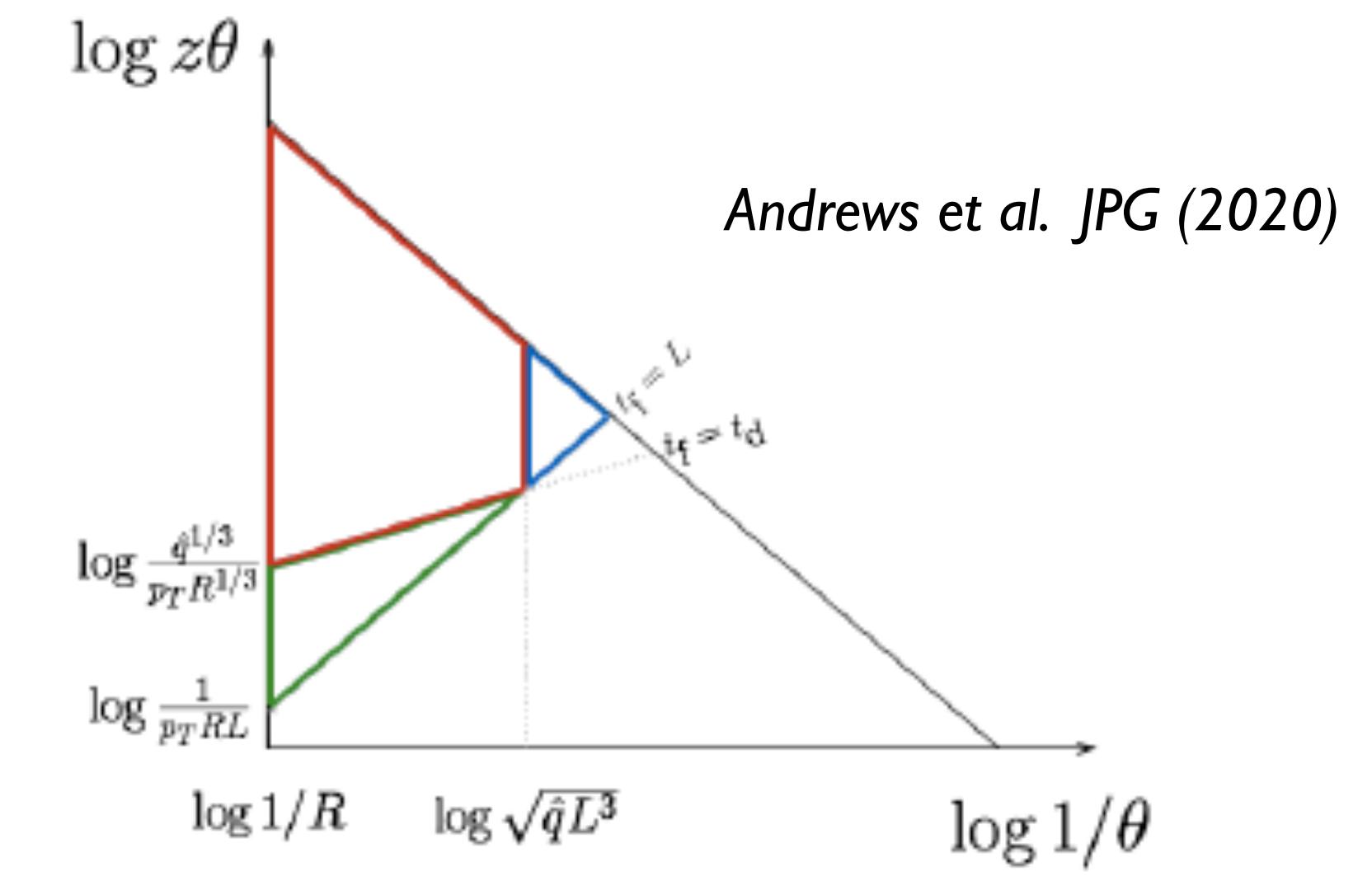
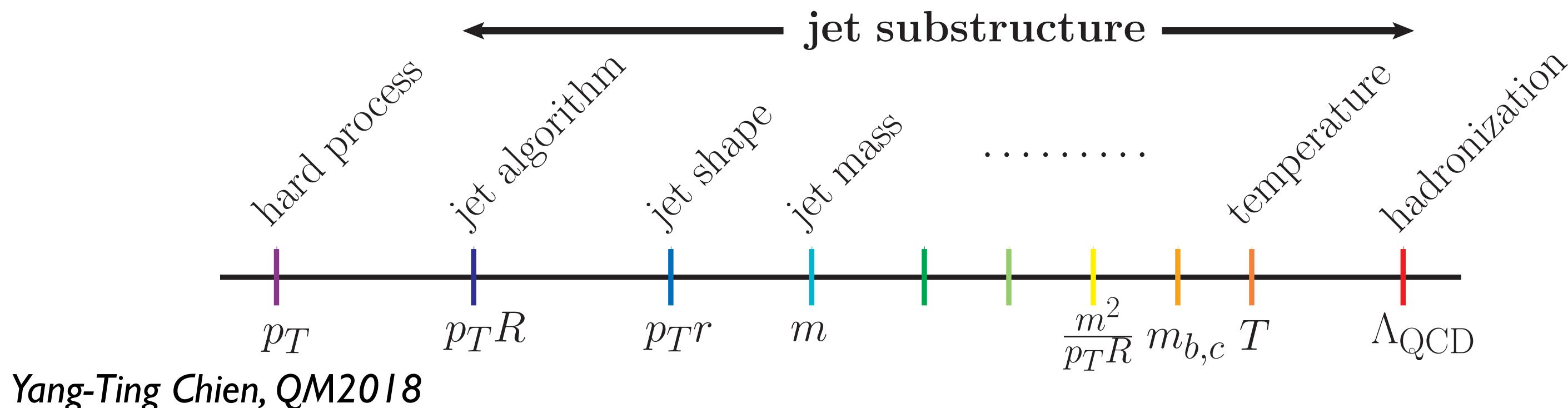
There are many simultaneous unknowns in jet quenching theory:

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



Jet substructure is an appealing tool to disentangle these

- Target specific regions of phase space

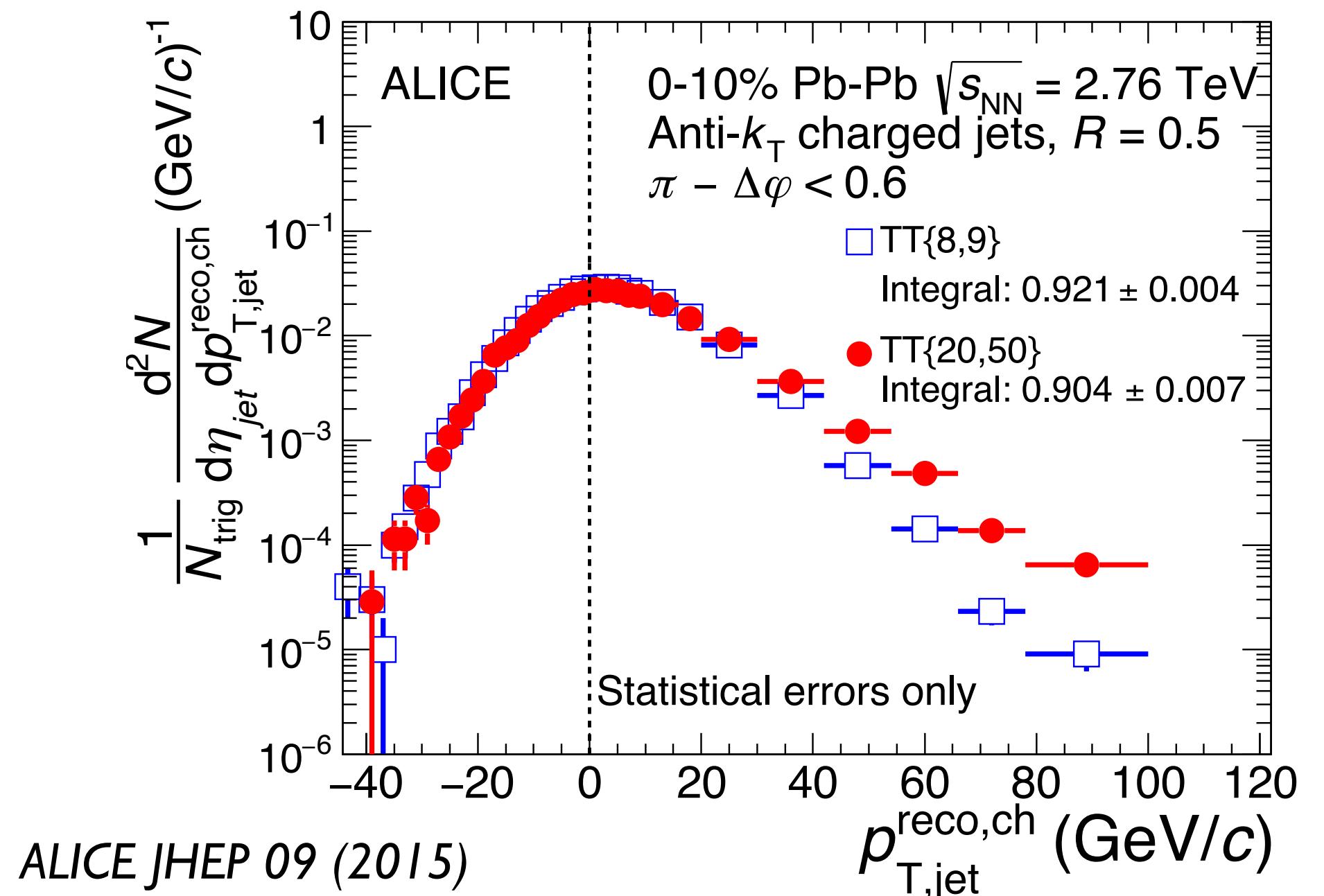


Experimental challenge: Background

Ensemble observables

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

Ungroomed angularity, mass, N-subjettiness, ...



Object tagging

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

Groomed observables, leading subjets, ...

