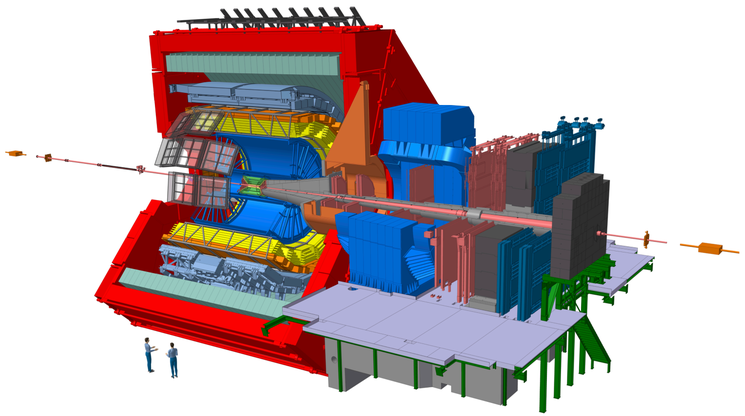
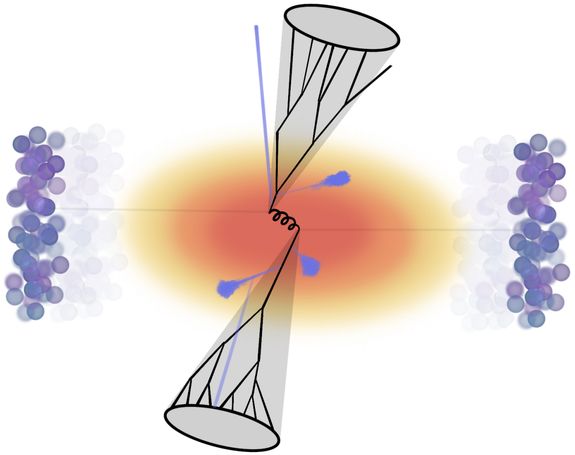
Jet angularity and fragmentation measurements in heavy-ion collisions with ALICE



James Mulligan
Lawrence Berkeley National Lab

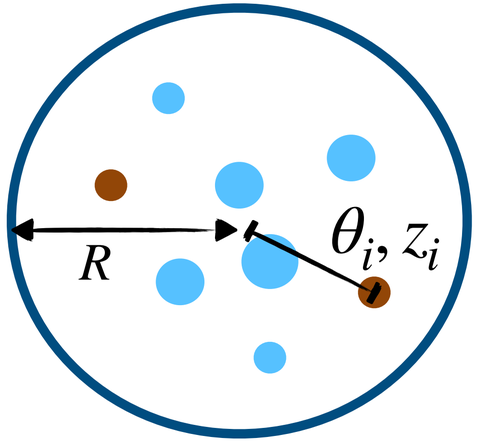
on behalf of the ALICE Collaboration



Quark Matter 2022
Kraków, Poland
April 6, 2022

Modification of jet fragmentation

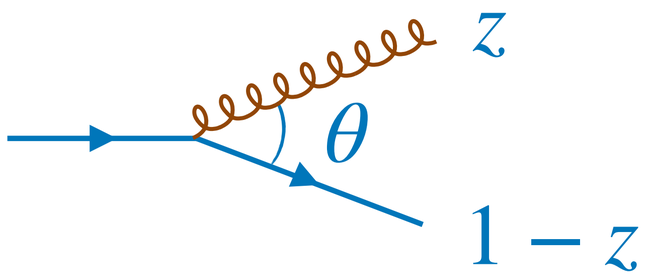
We know jets experience "energy loss" — but what is their fragmentation pattern?



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

$$z_i = \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}$$

How can we relate this to theoretically calculable quantities?



→ **Jet substructure**:

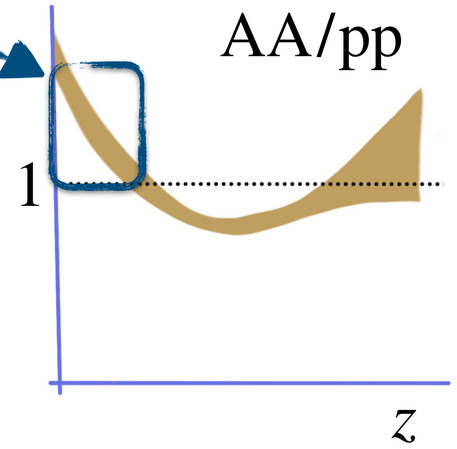
- Calculable in pQCD — no fragmentation functions needed
- Corrected for background and detector effects — direct comparison to theory

What do we know about z and θ?

Momentum

Longitudinal momentum of hadrons in jets is softened: $D(z)$

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



Little-to-no modification in jet core: z_g

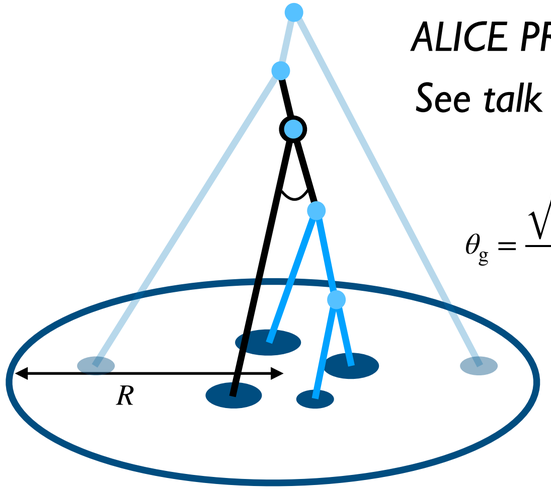
ALICE PRL 128 (2022) 10, 102001

Angle

Jet core is narrowed: θ_g

ALICE PRL 128 (2022) 10, 102001

See talk by H. Bossi Thursday 18:10



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

But there are key open questions:

- Girth/mass puzzle
- Large-z behavior

→ **This talk**

The girth-mass puzzle

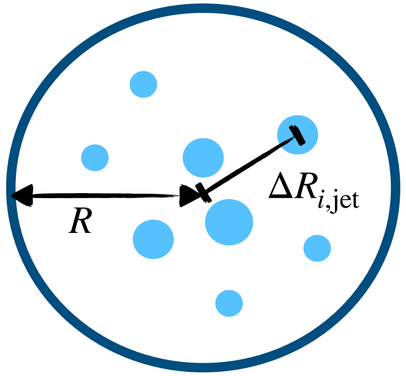
Jet angularities

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

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

$$\theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

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



The girth-mass puzzle

Jet angularities

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

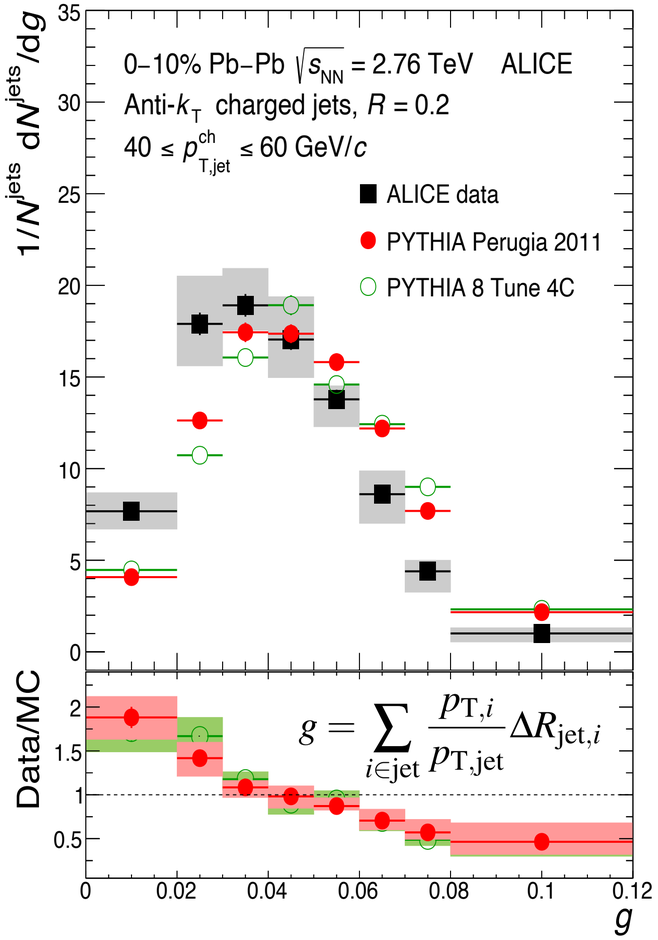
$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

Note: $\lambda_2 = \left(\frac{m}{p_T}\right)^2 + \mathcal{O}\left(\lambda_2^2\right)$

Why is the girth modified, but the mass not significantly modified?

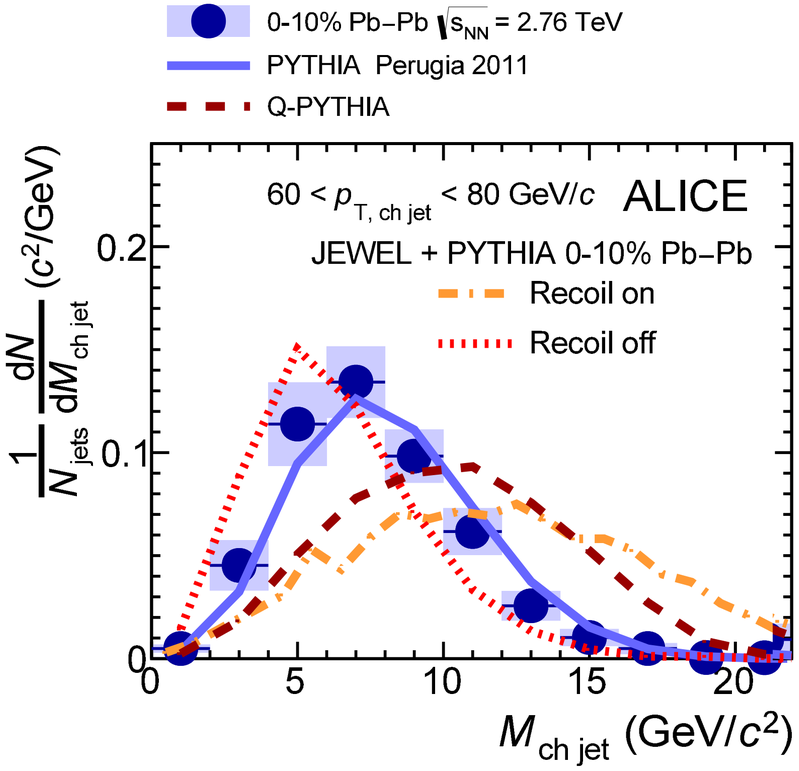
Jet girth (λ_1)

ALICE JHEP 10 (2018) 139



Jet mass ($\sim \lambda_2$)

ALICE PLB 776 (2018) 249
CMS JHEP 10 (2018) 161



Jet angularities — pp

Perform systematic measurement to map the girth-mass transition:

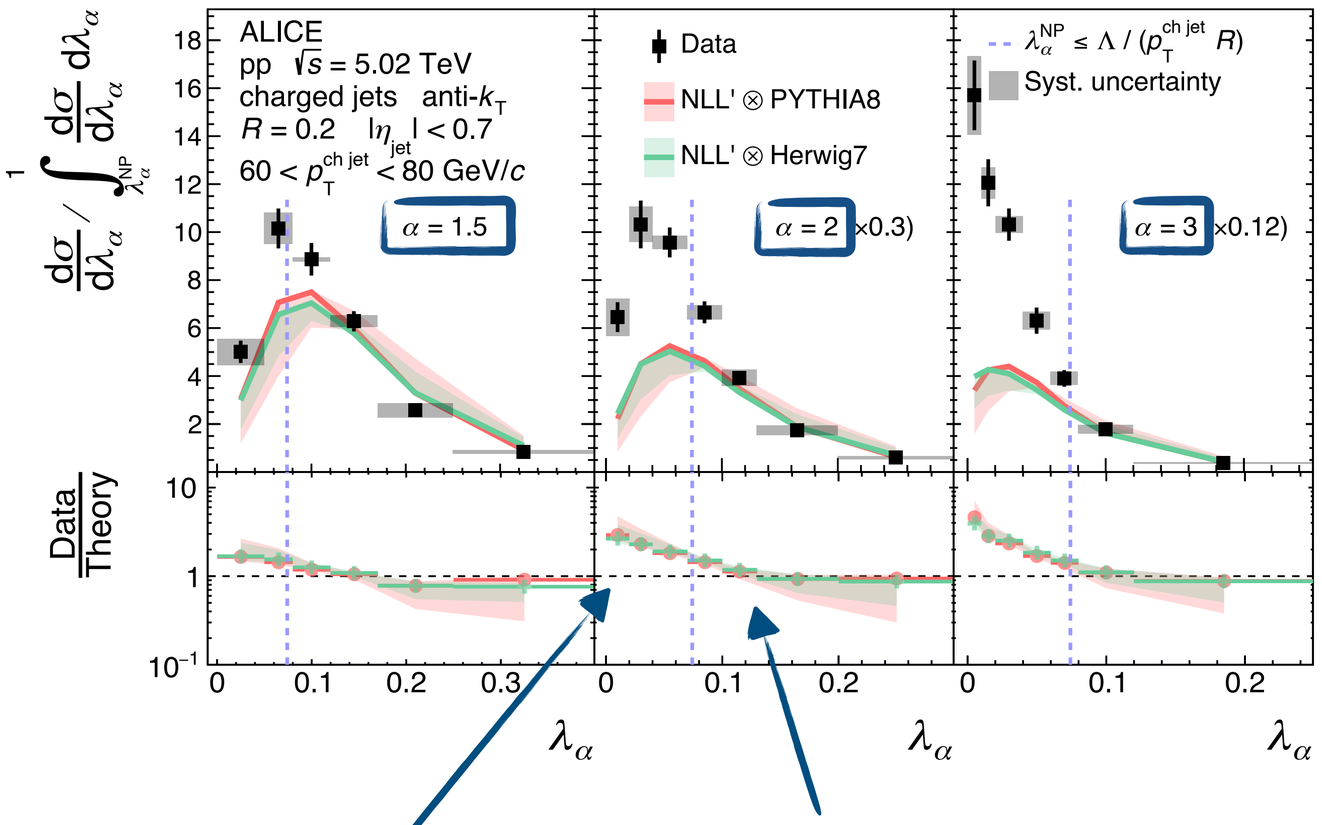
- Generalize observable:

$$g, m \rightarrow \lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha \quad \text{for } \alpha = 1, 1.5, 2, \ldots$$

- Groomed vs. ungroomed
- Multiple R

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

arXiv 2107.11303



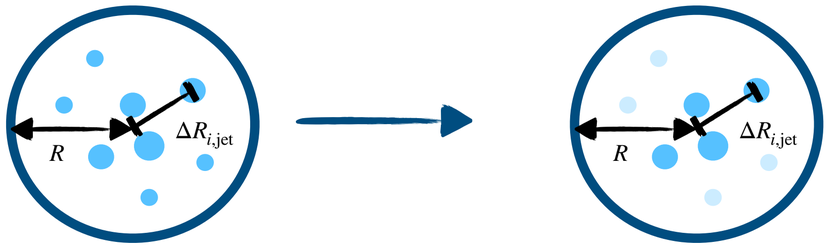
Small λ_α: Non-perturbative

Larger λ_α: Good agreement with pQCD calculations

Kang, Lee, Ringer JHEP 04 (2018) 110

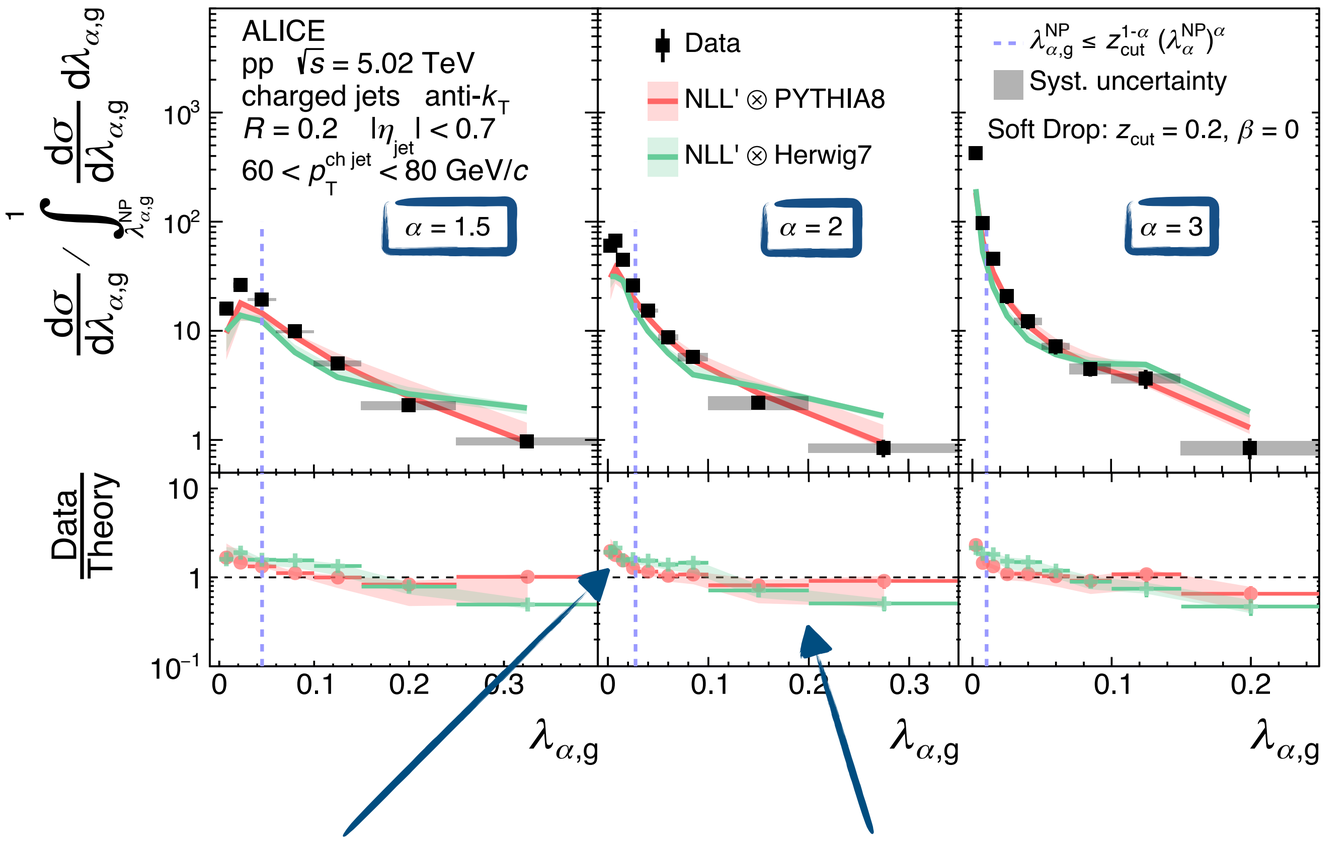
Groomed jet angularities — pp

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



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

arXiv 2107.11303



Small λ_α: Non-perturbative

Larger λ_α: Good agreement with pQCD calculations

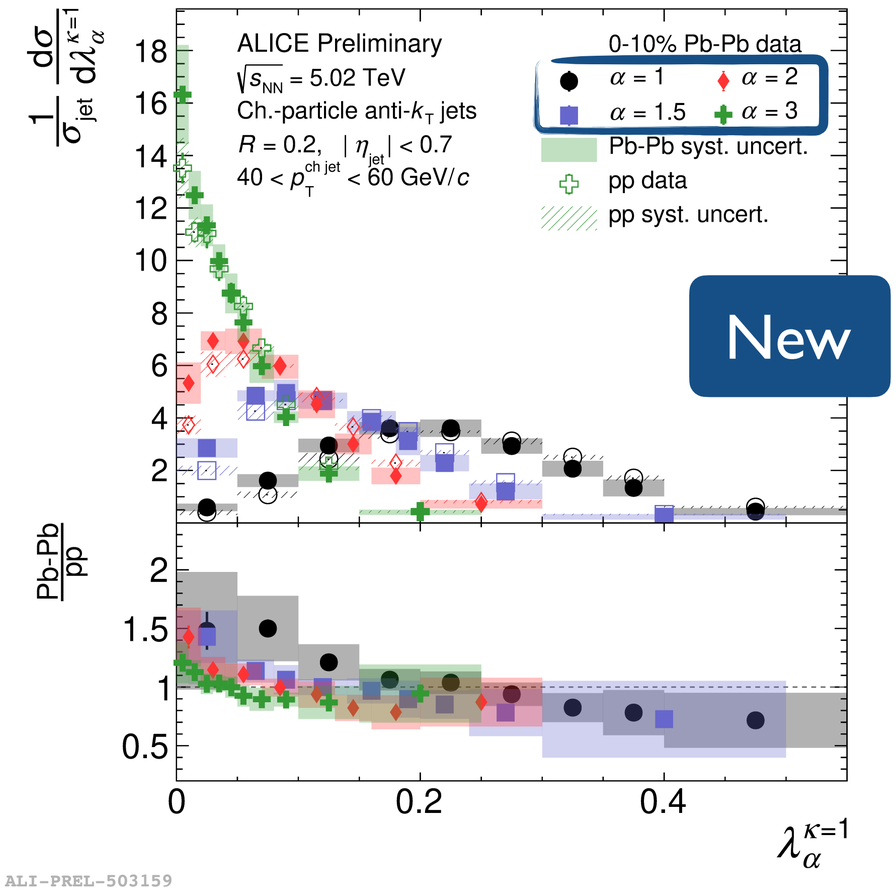
Kang, Lee, Liu, Ringer PLB 793 (2019) 41

Jet grooming recovers larger region of successful perturbative description

See also: CMS arXiv 2109.03340

Jet angularities — Pb-Pb

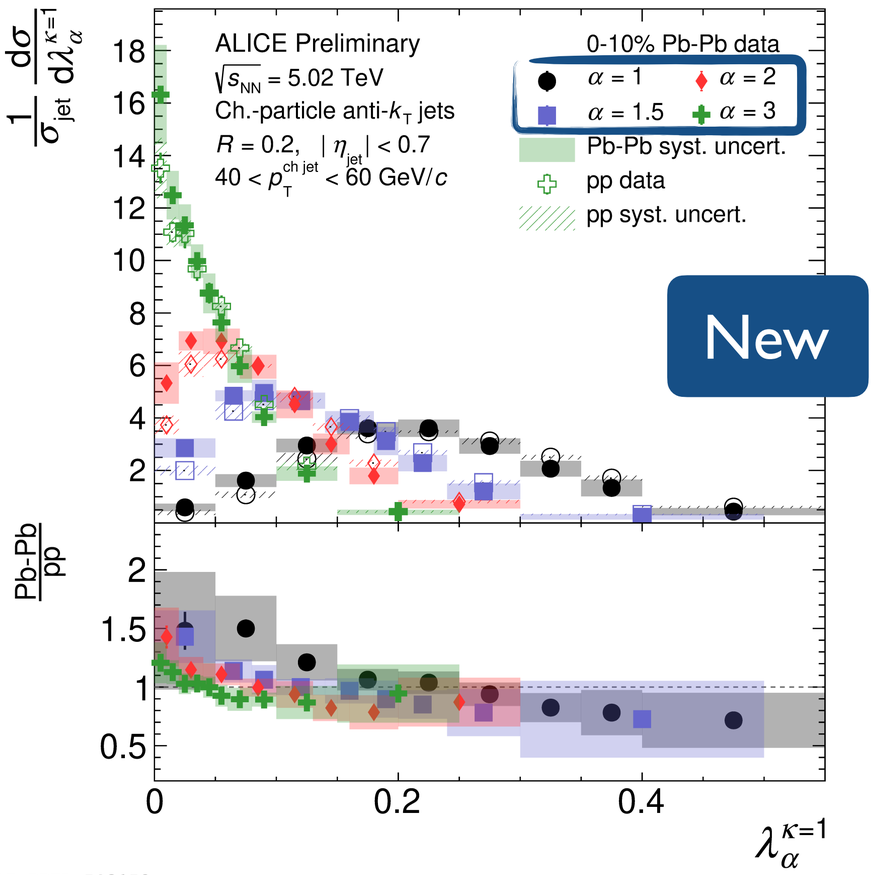
Ungroomed jet angularities



Little-to-no modification observed

Jet angularities — Pb-Pb

Ungroomed jet angularities

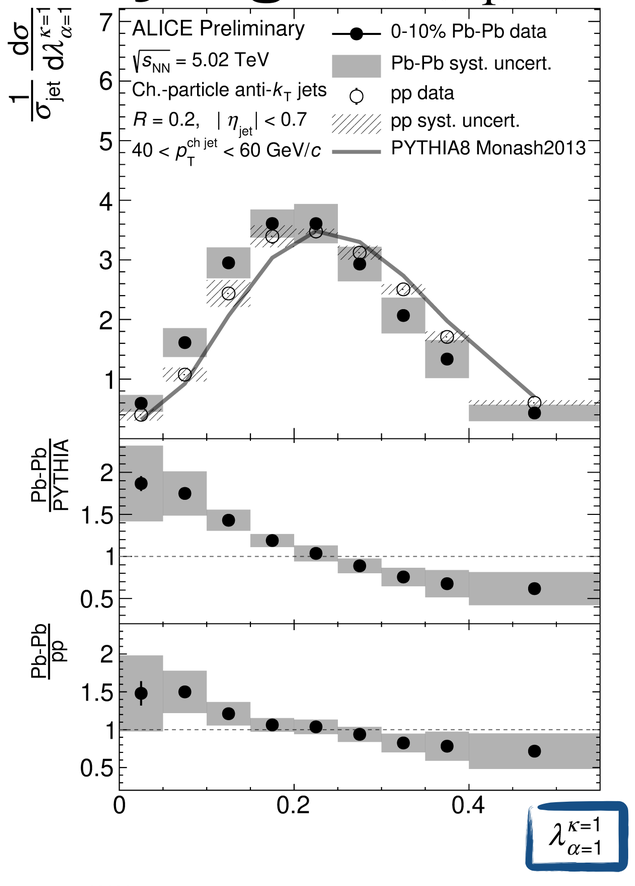


New

Measured pp baseline results in smaller modification than with PYTHIA reference

Little-to-no modification observed

Jet girth (λ_1)

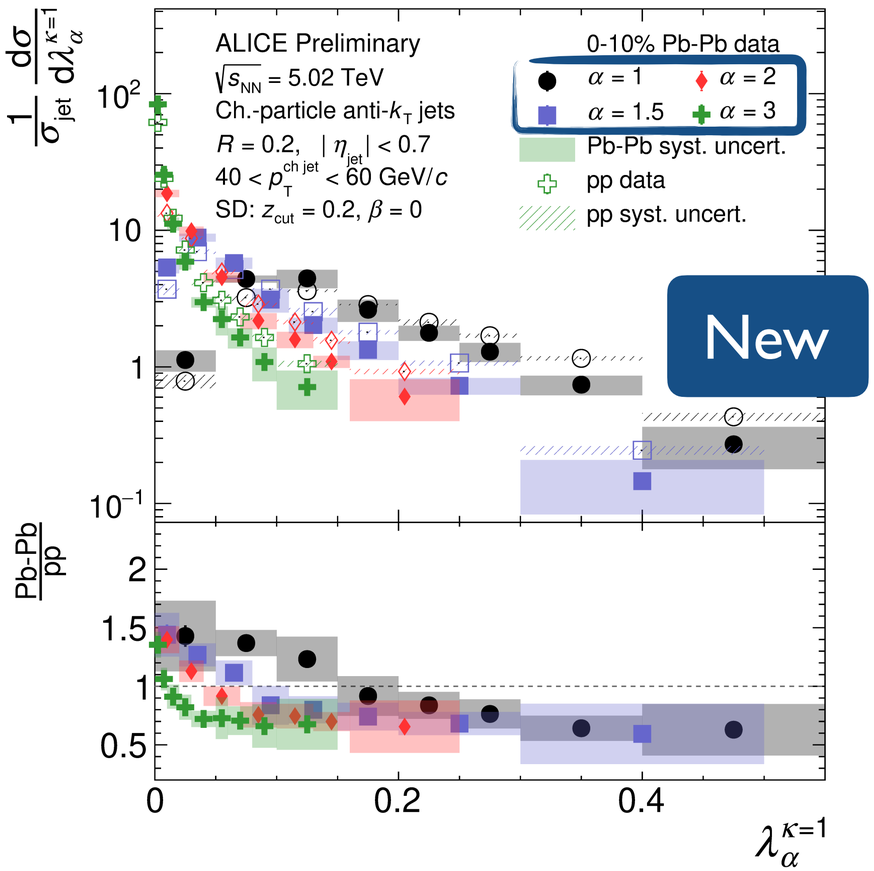


Less modification than in $\sqrt{s_{NN}} = 2.76$ TeV measurement based on PYTHIA reference

ALICE JHEP 10 (2018) 139

Jet angularities — Pb-Pb

Groomed jet angularities



Groomed angularities are modified more strongly than ungroomed angularities

Could be due to counterbalancing effects:

1. Suppression of wide jets
2. In-jet broadening

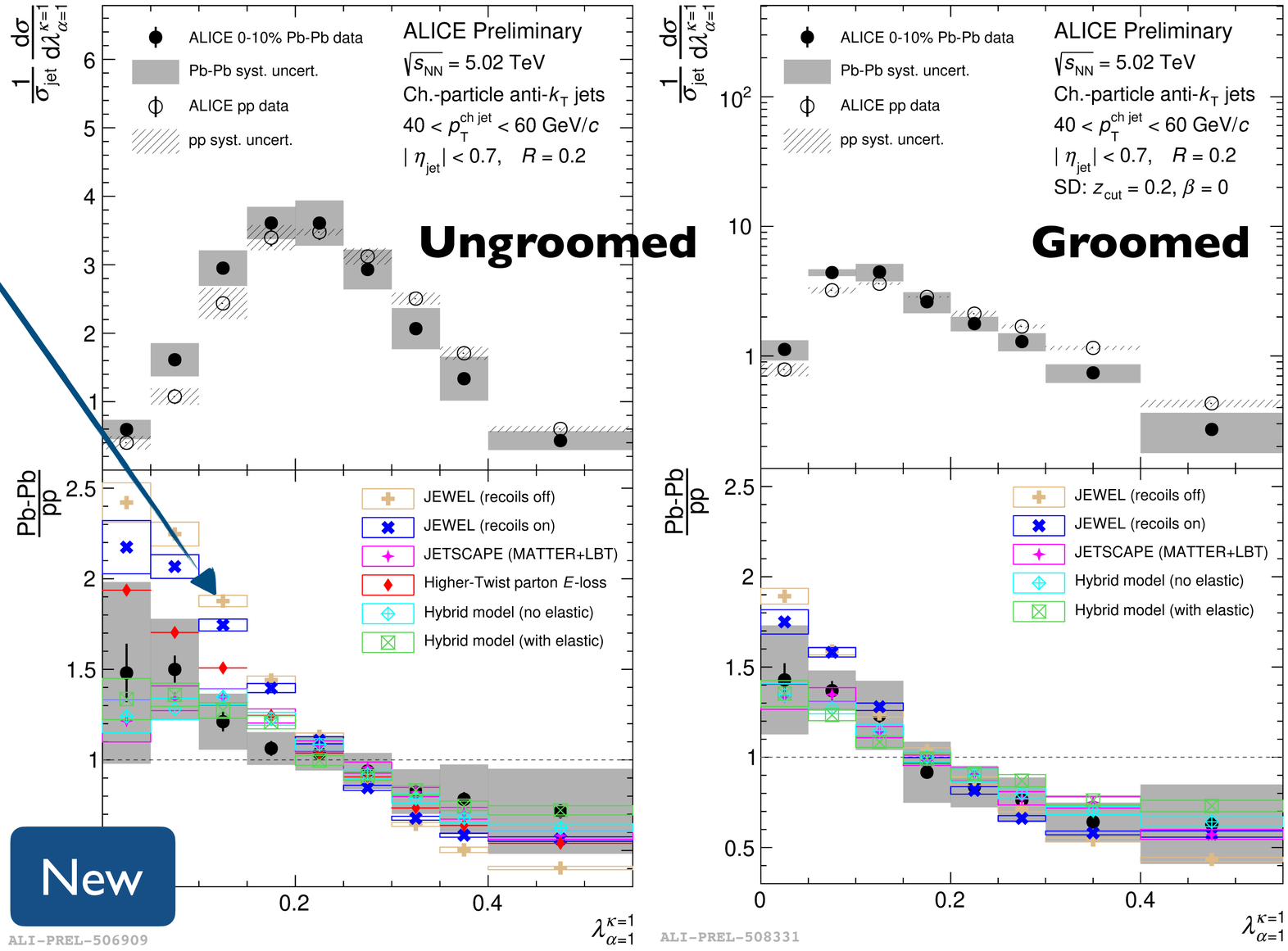
→ Jet grooming reduces (2), leaving stronger collimation effects visible

Significant modification, strong ordering in α

Jet angularities — theory comparisons

Models generally describe trends in data well, although some deviations

- JEWEL
  Zapp, EPJ C 74 2 (2014)
- JETSCAPE
  arXiv 2204.01163
- Higher Twist
  Chen, Zhang et al., CPC 45 (2021) 2, 024102
- Hybrid Model
  See Zach Hulcher, Tues 18:30



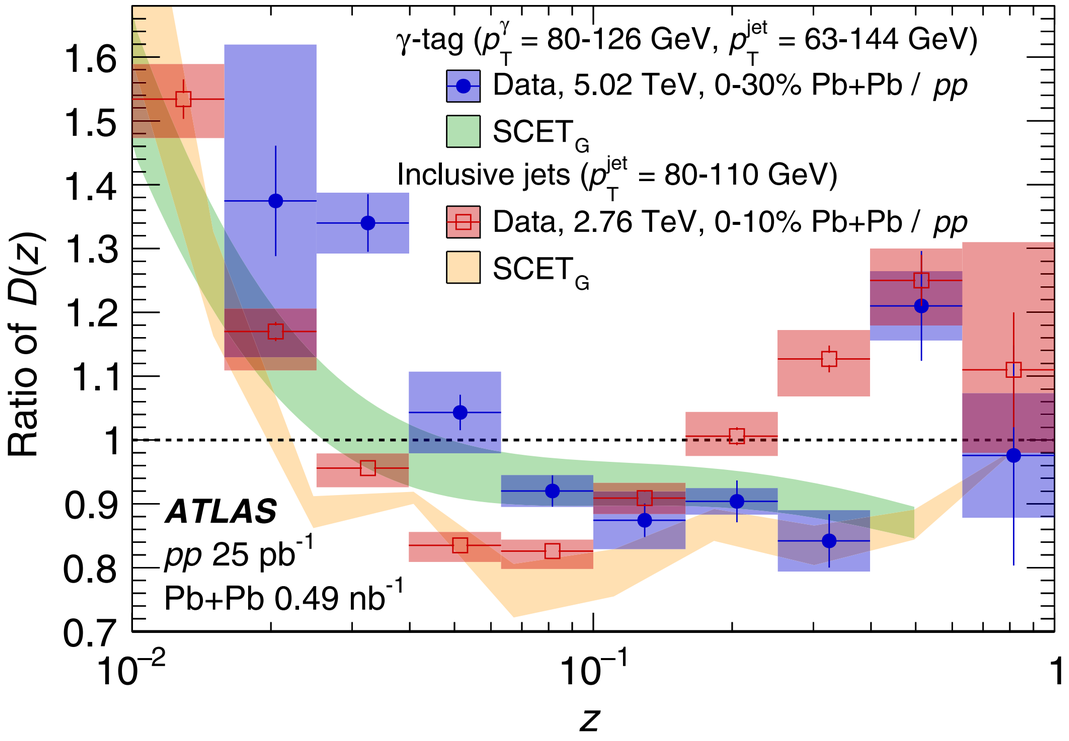
New

Additional α, p_T available:
https://alice-figure.web.cern.ch/node/21570

From hadron z to subjet z_r

Hadrons in jets → **Subjets in jets**

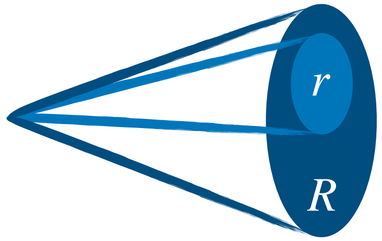
ATLAS PRL 123 042001 (2019)



See also: CMS PRC 90, 024908 (2014)

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



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

- Probe higher z than hadron fragmentation measurements
- Opportunity to test universality of jet fragmentation functions

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

parton → subjet parton → jet

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

Subjet fragmentation — pp

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

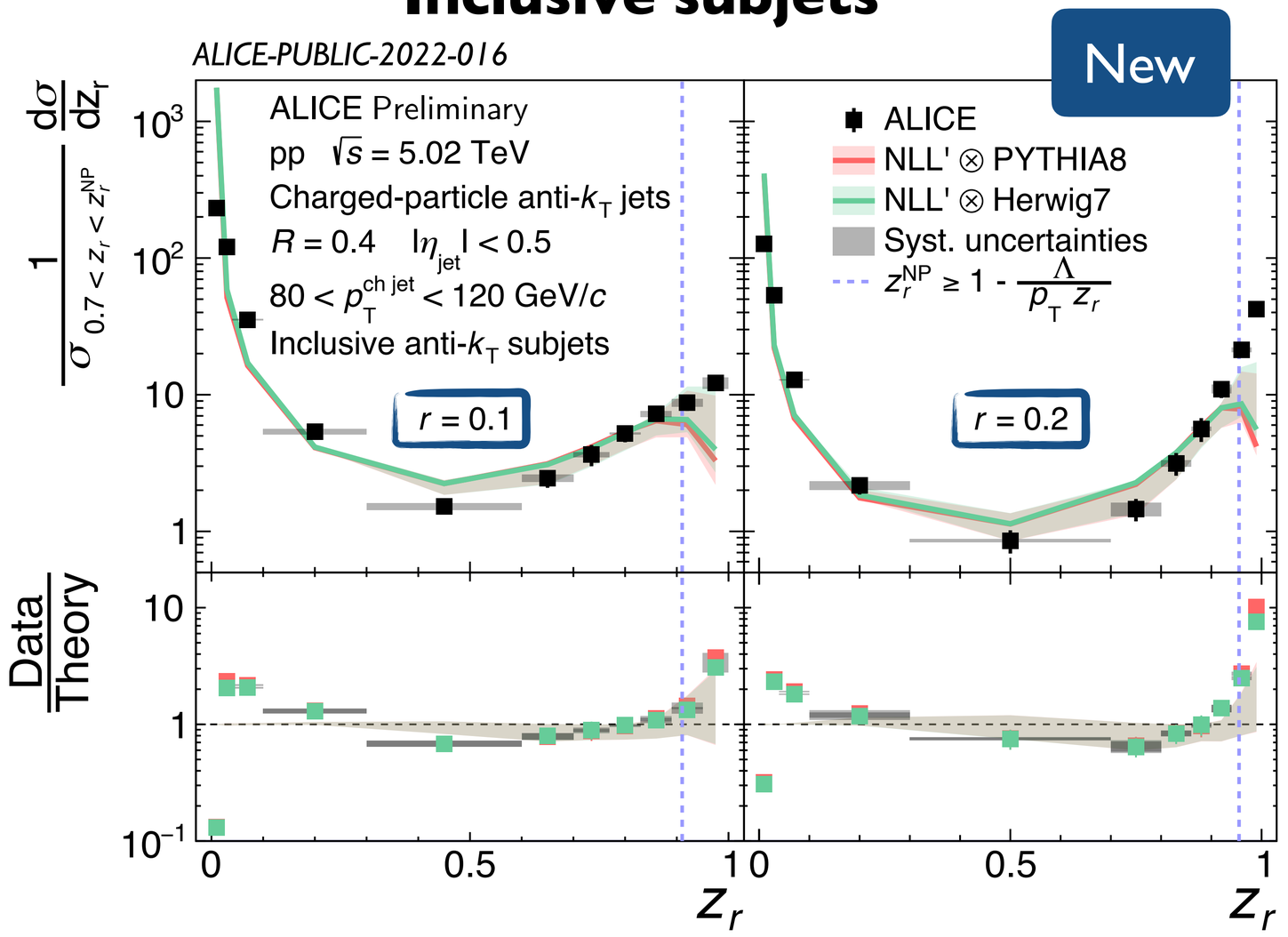
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

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

- Connection to parton-hadron duality

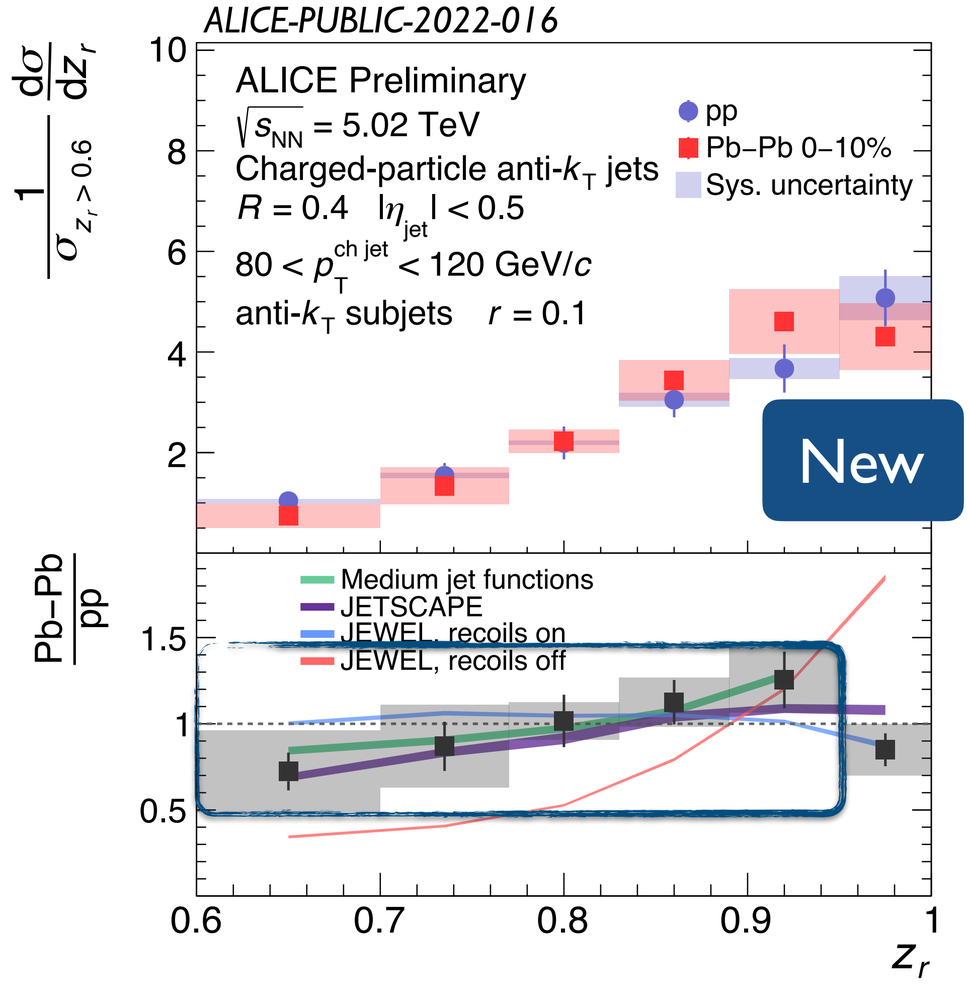
Neill, Ringer JHEP 06 (2020) 086
Neill JHEP 03 (2021) 081

Inclusive subjets



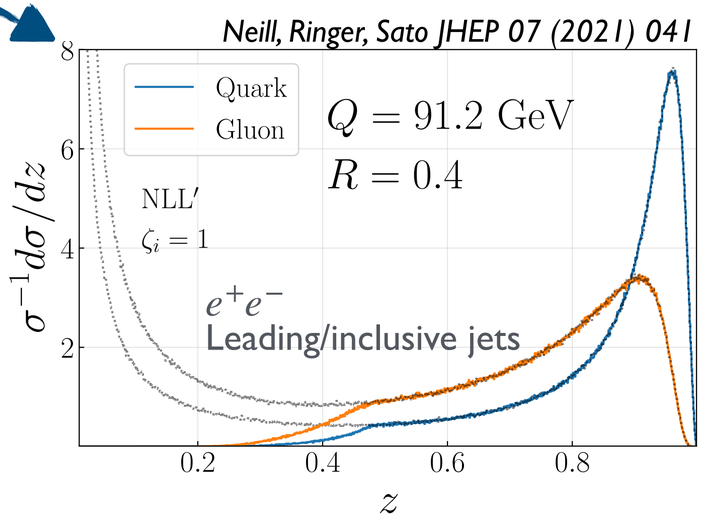
Subjet fragmentation — Pb-Pb

Leading subjets



Hint of hardening distribution at intermediate z_r

- Large quark-gluon differences in vacuum
- Competing effects
  - Gluon suppression → larger z_r
  - Soft radiation → smaller z_r



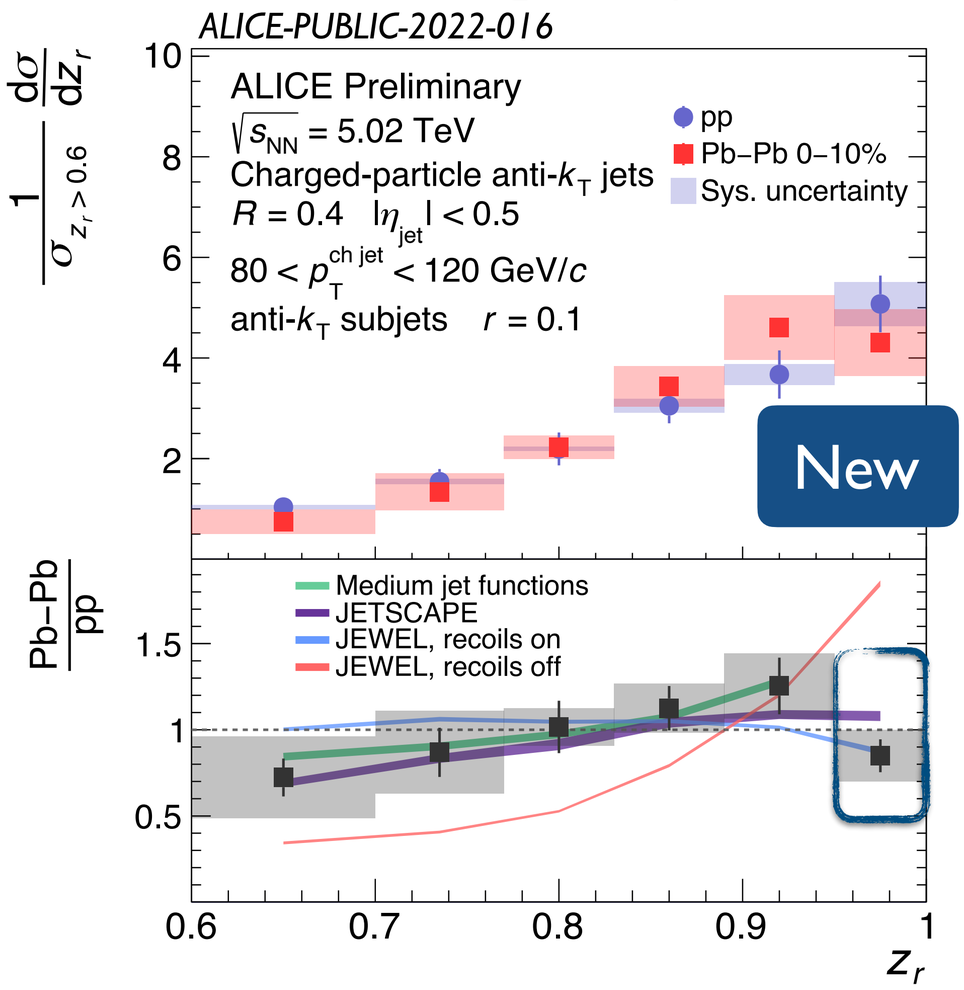
Well-described by most theoretical predictions

→ Consistent with universality of jet fragmentation in QGP

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

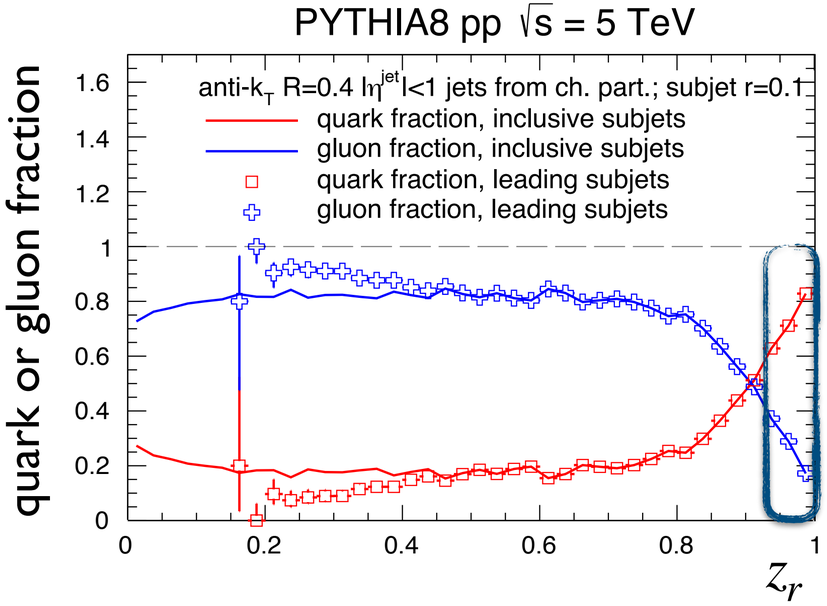
Subjet fragmentation — Pb-Pb

Leading subjets



Turnover of ratio as $z_r \to 1$

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



New path to disentangle quenching effects

Subjet fragmentation — Pb-Pb

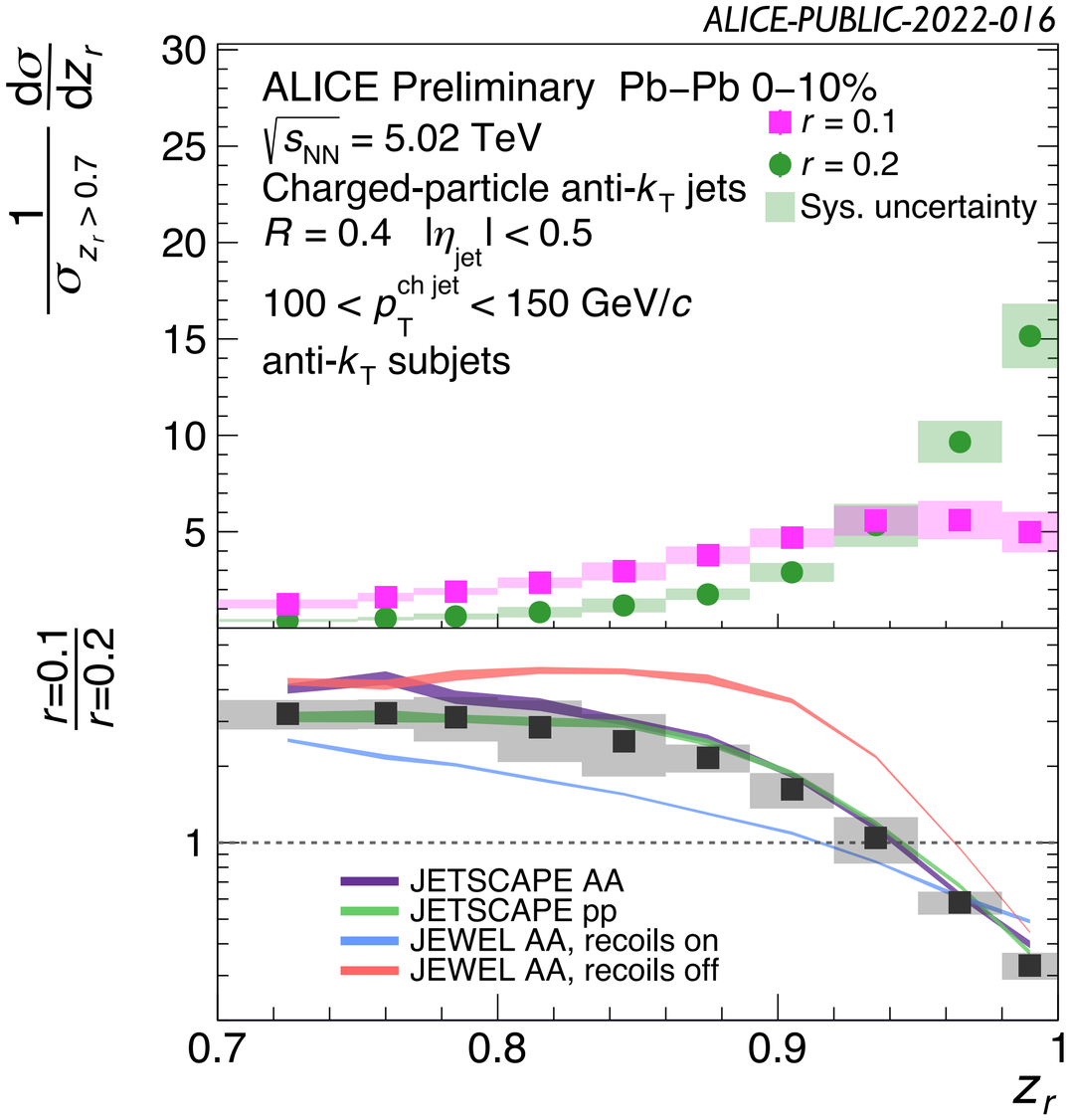
Ratio of Pb-Pb distributions for different r

- Partial cancellation of systematic uncertainties

Models capture general trend, but quantitatively disagree with data

- Note self-normalization condition

Measured data indicates broader jets at large z_r than models



Summary

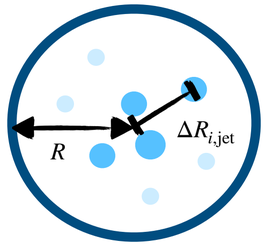
By measuring carefully chosen observables…

- Calculable in proton-proton collisions
- Corrected for background and detector effects

…we are producing an emerging picture of the jet fragmentation pattern

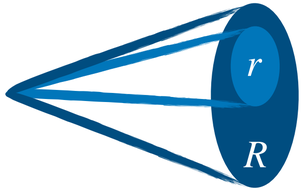
New measurements of groomed and ungroomed jet angularities

- Insight into girth/mass puzzle
- Systematic measurement for Bayesian inference of medium properties



New measurements of subjet fragmentation distributions

- Access large z_r region — quark-gluon separation using substructure
- Universality tests of jet fragmentation in QGP



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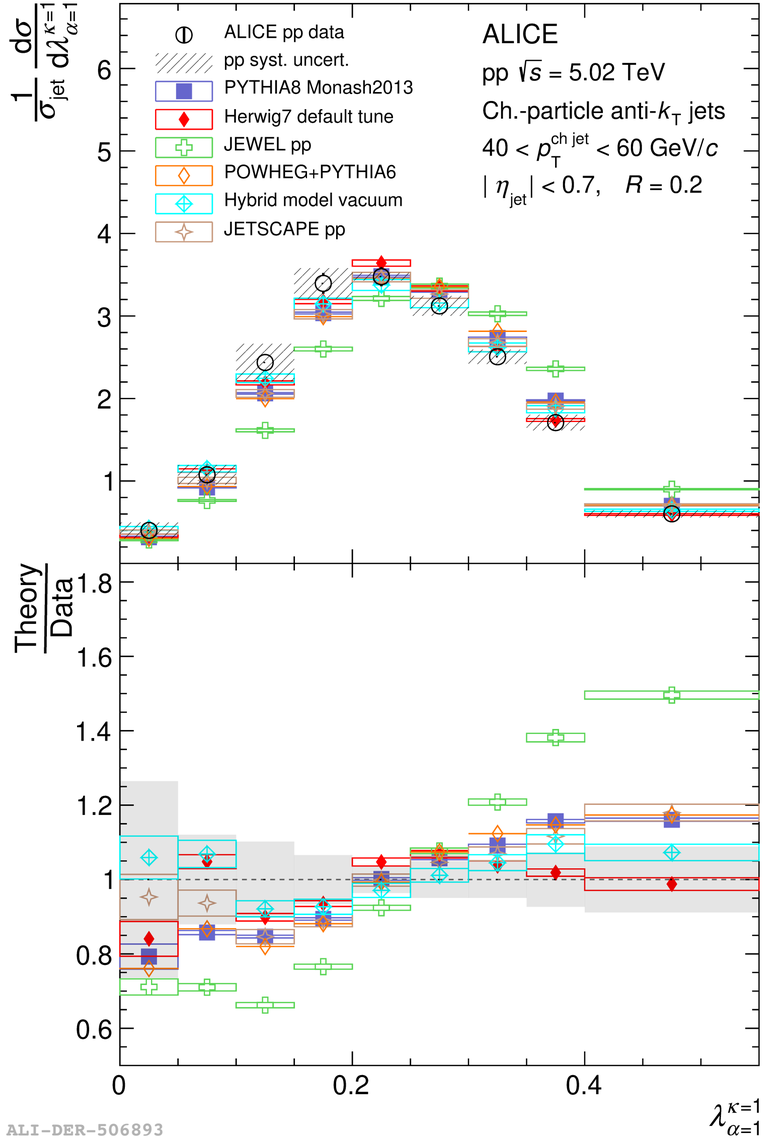
Jet angularities in Pb-Pb



pp distribution

Pb-Pb distribution

Deviations in pp baseline can induce disagreement in Pb-Pb/pp ratio