Utrecht University

Experimental overview on groomed jet splittings

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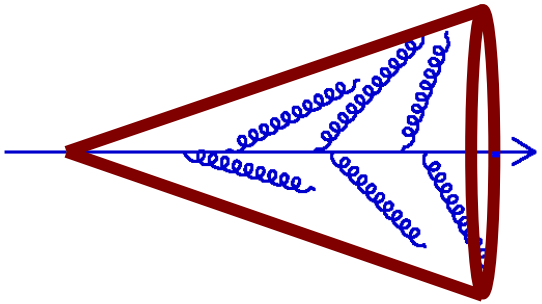
ECT*
Jet Quenching in the Quark-Gluon Plasma
June 13, 2022

What is jet substructure?

Dynamics of particles inside the jet

Two scales: angular + momentum space



Fragmentation Functions

Single hadron

Classic Jet Shapes

All hadrons

Groomed Observables

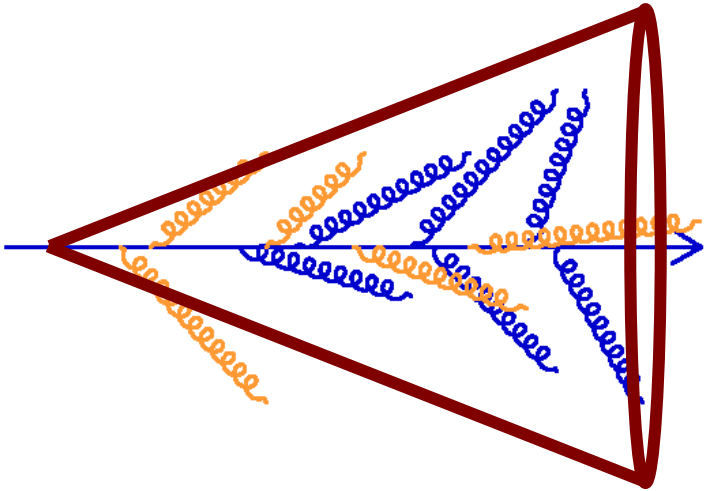
Subset of hadrons

Sketches by J. Thaler

Why jet substructure?

Structure of quenched jet different from unquenched?

- How is the parton shower modified?
- What is the exact mechanism modifying the shower?
- Can we relate shower modifications to medium properties?

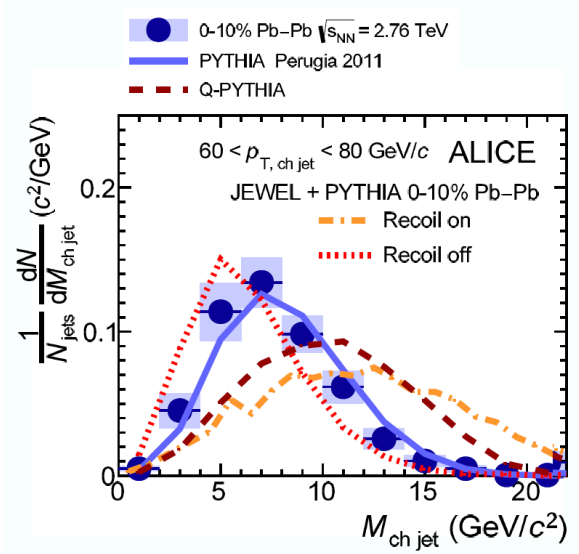


Why grooming?

We know jets loose energy

How do the medium-induced radiated gluons look like?

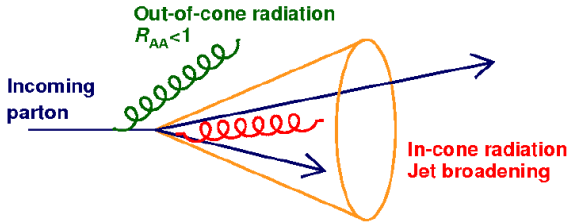
Can we disentangle competing effects?



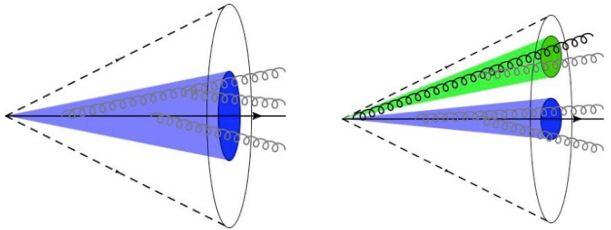
PLB 776 (2018) 249

Jet modification in hot QCD medium

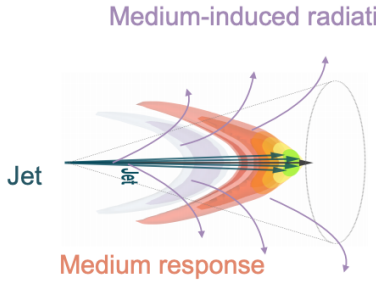
Medium-induced energy loss



Coherence effects



Medium recoil



Why grooming?

We know jets loose energy

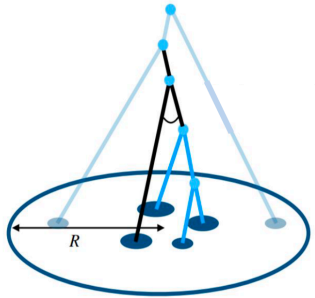
How do the medium-induced radiated gluons look like?

Can we disentangle competing effects?

Preference to use theoretically well controlled observables

- Calculable in pQCD
- Small experimental corrections

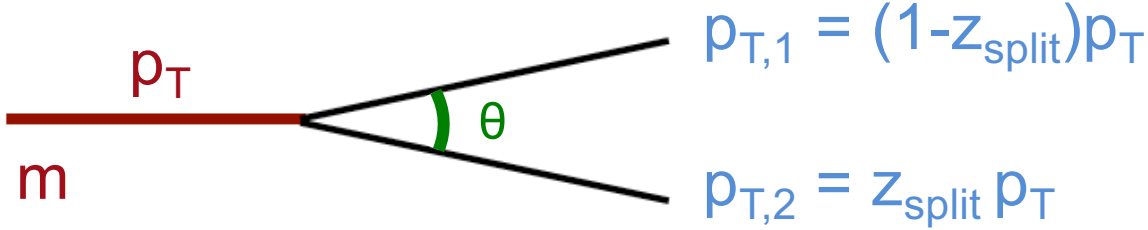
Grooming allows to select specific areas of phase space



Hard splitting as probe of medium

Idea: let a high p_T parton that splits into two other partons (antenna) propagate through the medium

Then study the influence of the medium on the antenna



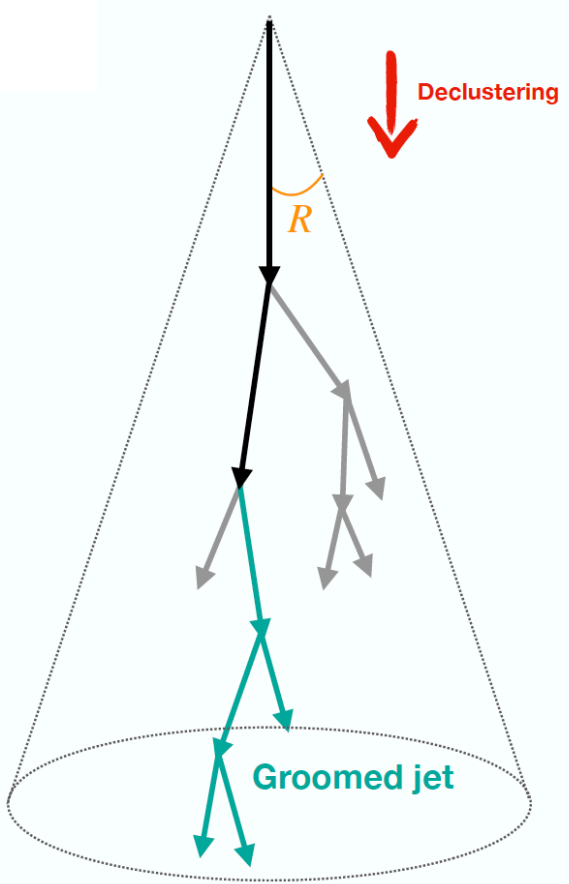
Two relevant scales:

- Opening angle between the two branches: θ
- Momentum balance between the two branches: z_{split}

Grooming recap

Order constituents in the jet

Walk back in history to identify splittings of interest



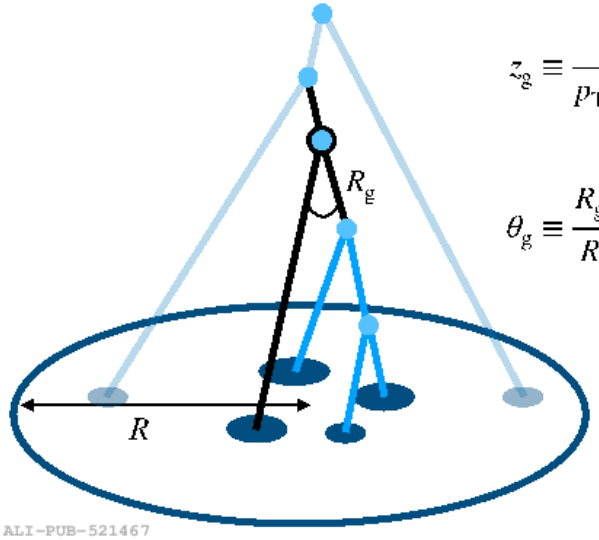
Sketch by Rey Torres

Grooming recap

Order constituents in the jet

Walk back in history to identify splittings of interest

Define your observable
- can be one specific splitting;
- but also multiple in one jet;



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

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

Splitting fraction

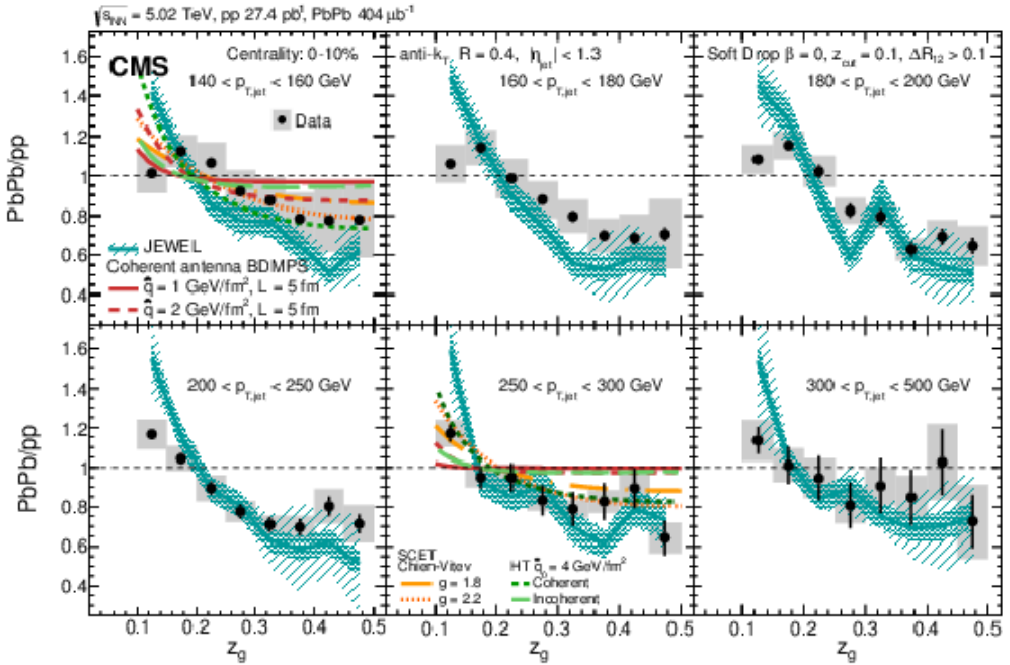
For first measurements, pp reference was smeared.

Distributions were self-normalized

Data suggested:

Splittings in quenched jets are a bit less balanced

Models capture the trend but different physics mechanisms responsible

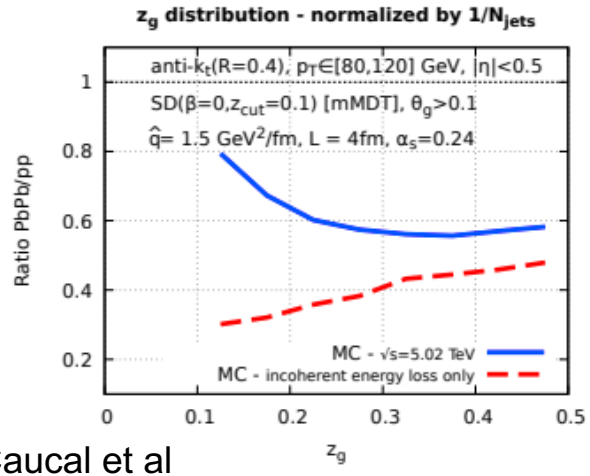


Phys. Rev. Lett. 120 (2018) 142302

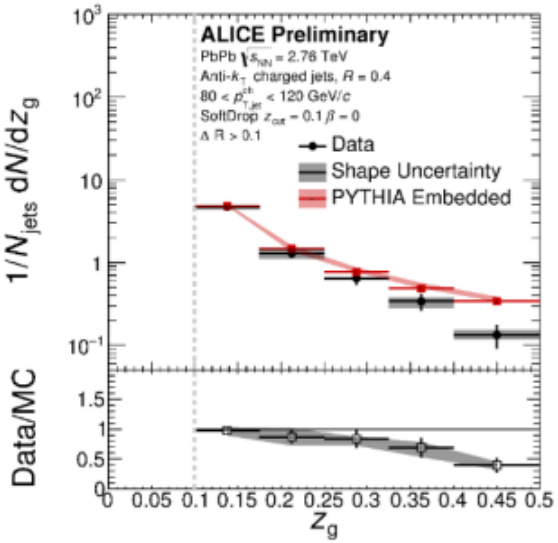
Low p_T regime

Multiple effects at play:

- Independent energy loss of the two branches from VLE
- Hard medium-induced emissions passing grooming
- Promotion of subjets due to medium response contribution

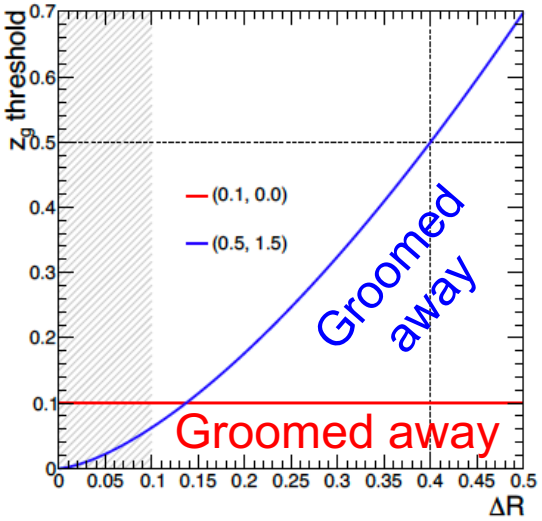


Caucal et al
JHEP 10(2019)273



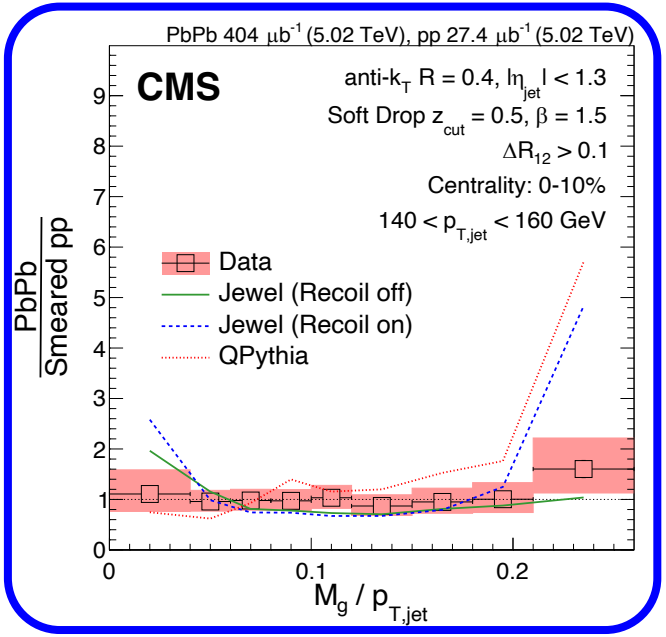
Groomed jet mass

Groomed jet mass with flat and large angle grooming



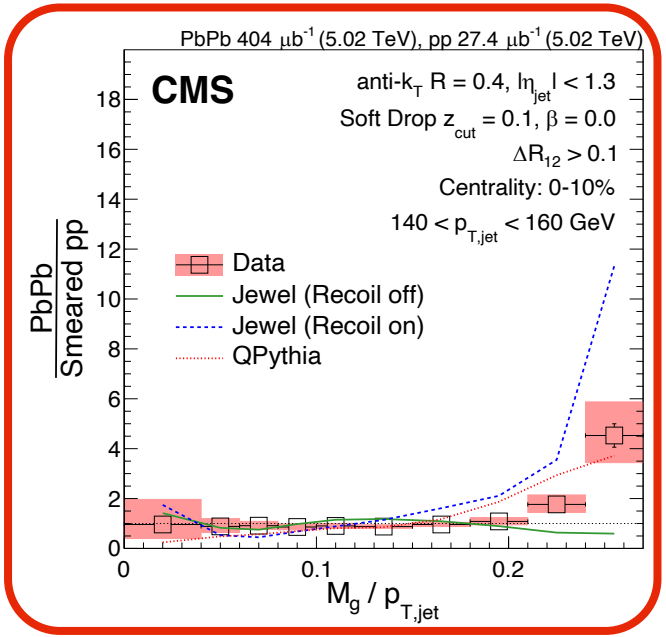
arXiv:1805:05145, JHEP

Large angle grooming



Jet core hardly affected by medium

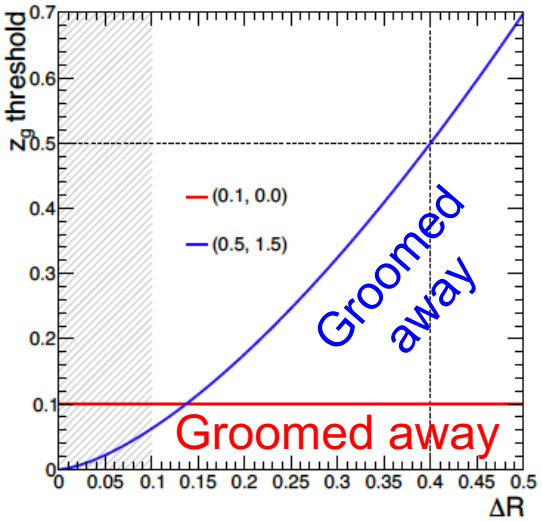
Flat grooming



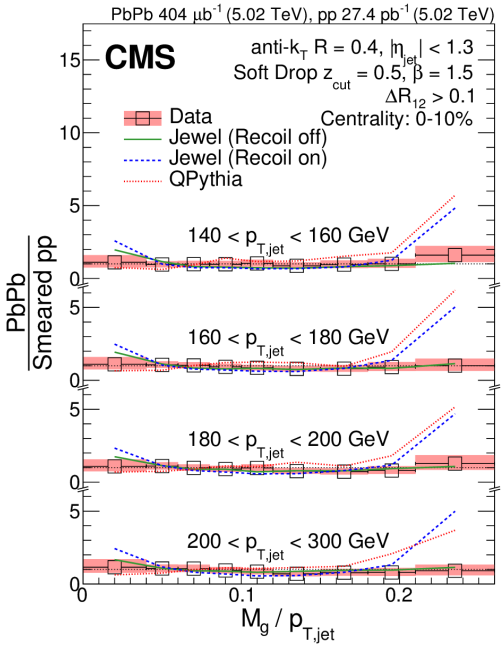
Jet quenching models do not describe large mass data

Groomed jet mass

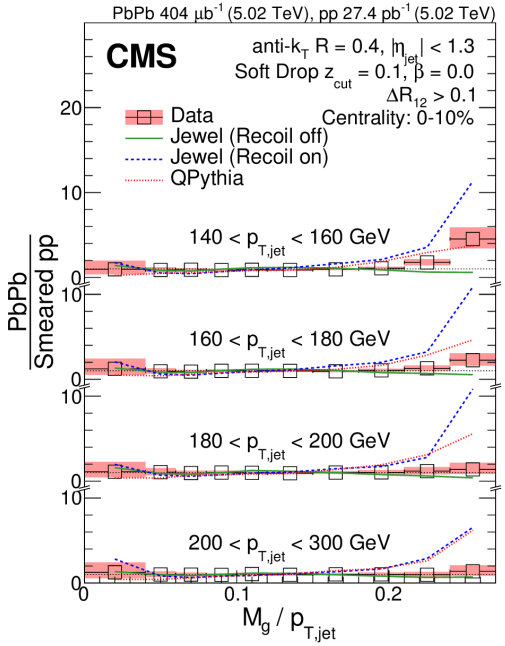
Groomed jet mass
with flat and
large angle grooming



Large angle grooming



Flat grooming

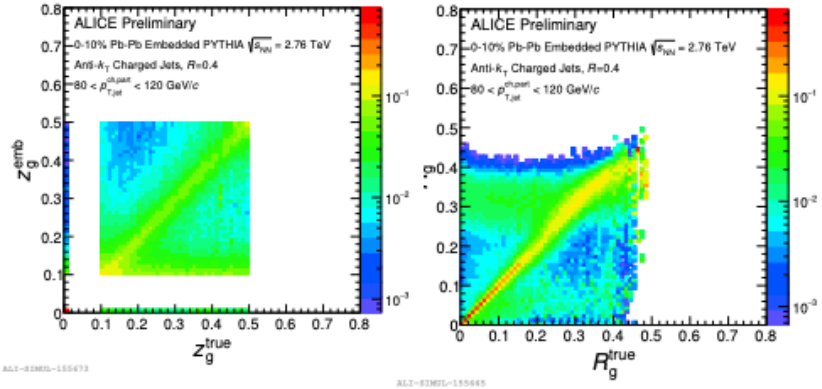


Effect for large M_g decreases for high p_T

Modification originates from small z and/or large angle

Limitations of grooming in heavy ion data

- Hard grooming selection cuts in non-trivial way into your sample
  → resolution on groomed observables is truncated at edges
- Large underlying event causes:
  - promotion of a different splitting as first passing the selection
  - UE subjets pass selection (due to upward fluctuation of background)

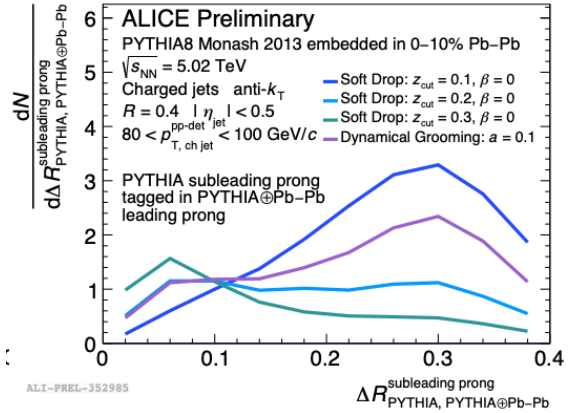


- Consequence: off-diagonal structures in response matrices
- First measurements were compared to forward folded pp and theory

Suppressing background contamination

Explored methods:

- More selective grooming



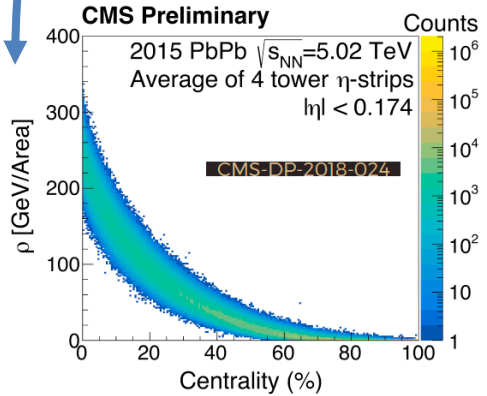
With larger z_{cut},
less misidentified splittings

See also arXiv:2006:01812

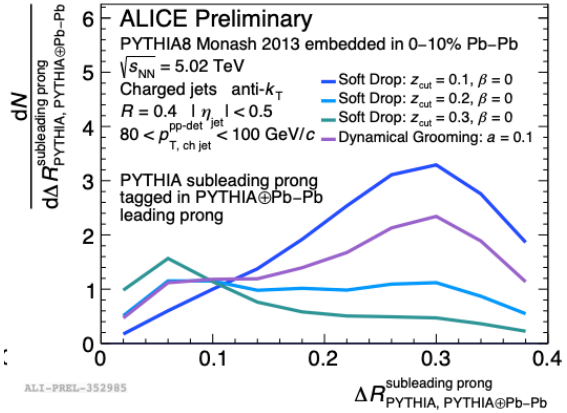
Suppressing background contamination

Explored methods:

- More selective grooming
- Less central events



Less hot medium results in less particles uncorrelated to the jet



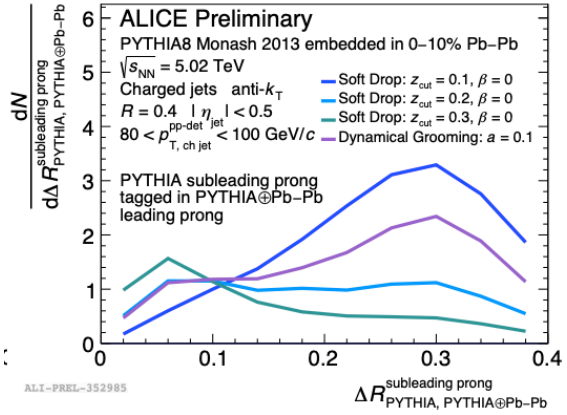
With larger z_{cut}, less misidentified splittings

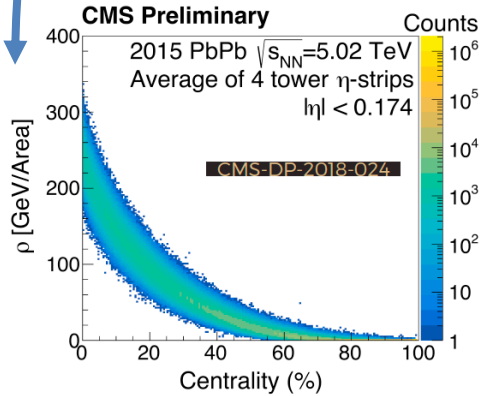
See also arXiv:2006:01812

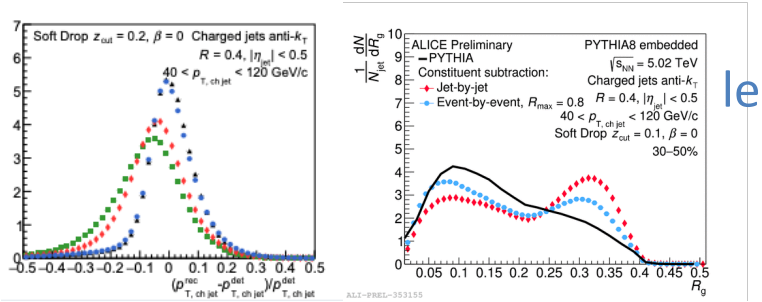
Suppressing background contamination

Explored methods:

- More selective grooming
- Less central events
- Improved background subtraction







With larger z_{cut}, less misidentified splittings

See also arXiv:2006:01812

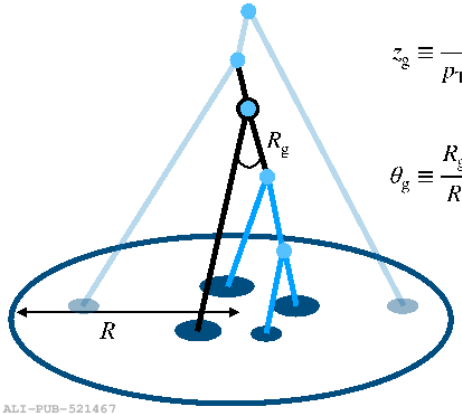
Less hot medium results in less particles uncorrelated to the jet

Unfolding possible!

Splitting fraction

Fully unfolded

With larger z_{cut} (0.2) no modification visible



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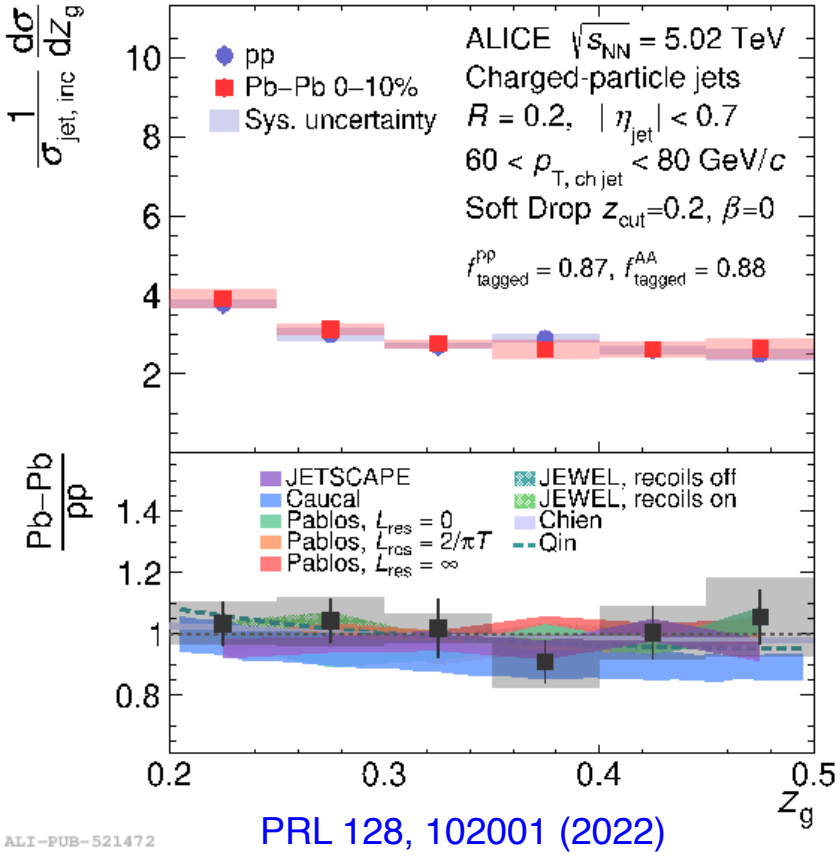
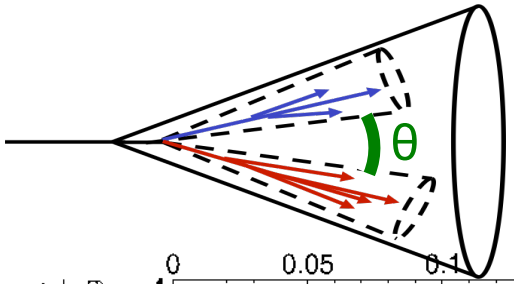
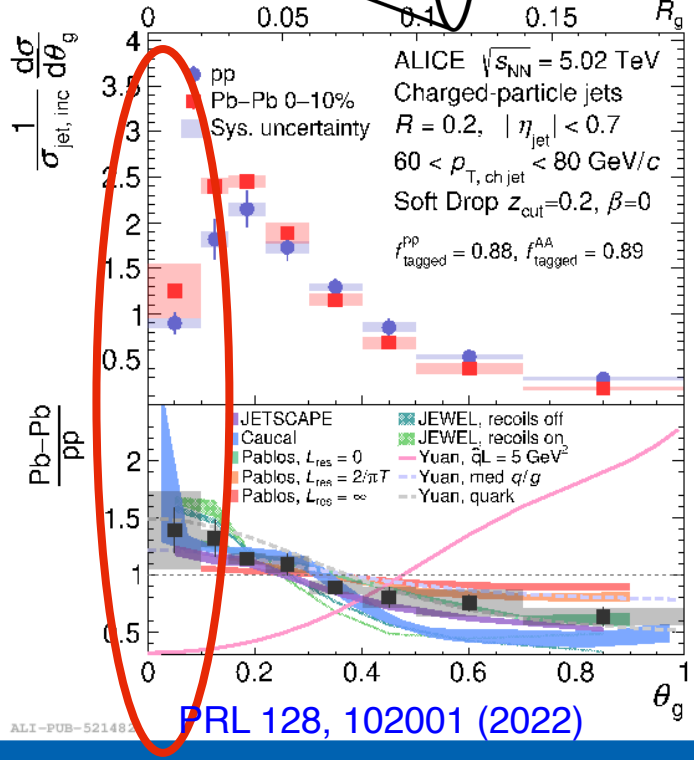


PRL 128, 102001 (2022)

Splitting angle





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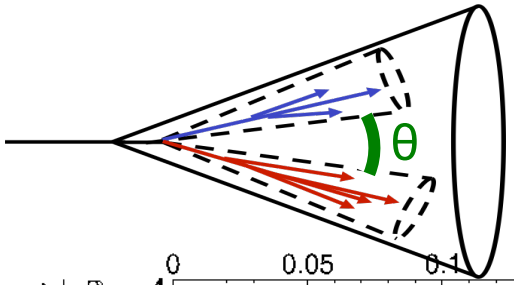
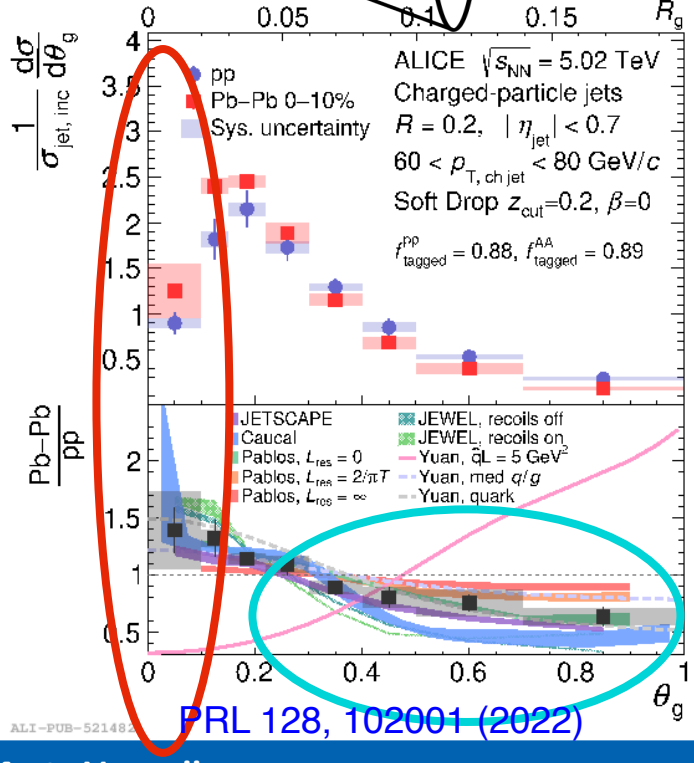
Small θ_g: less vacuum-like emitters from which energy can be radiated

→less suppression observed in data

Splitting angle

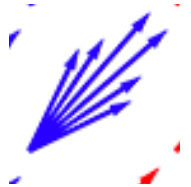




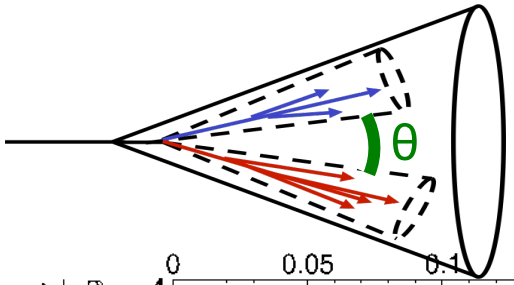
PRL 128, 102001 (2022)

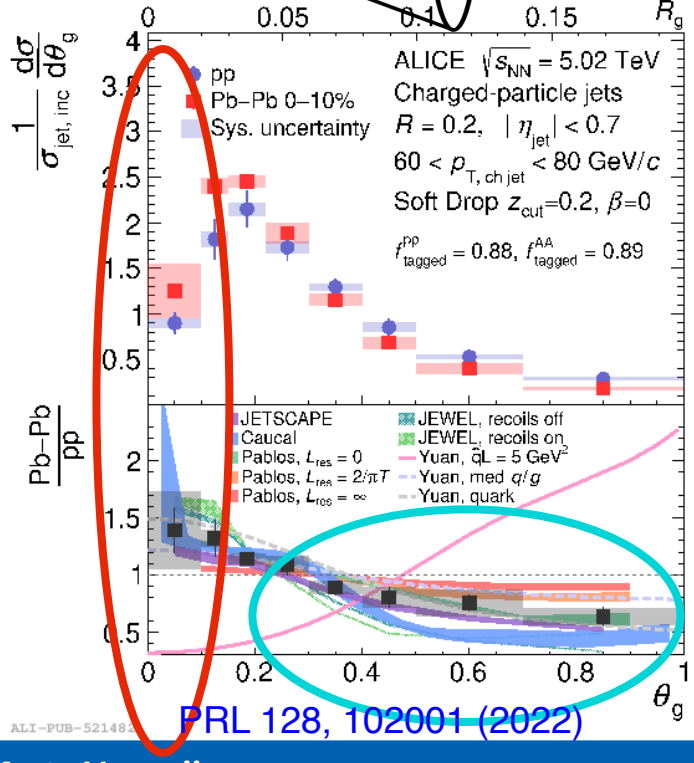
Small θ_g: less vacuum-like emitters from which energy can be radiated
→less suppression observed in data

Large θ_g : more suppressed



Splitting angle





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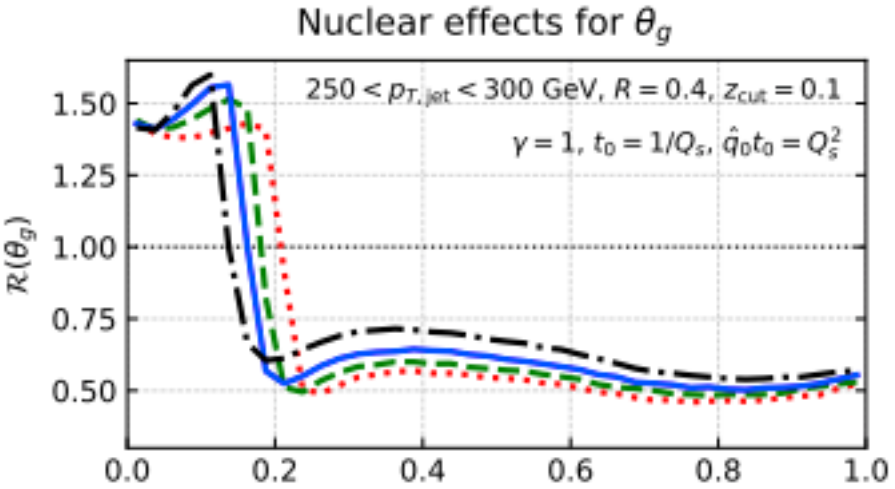
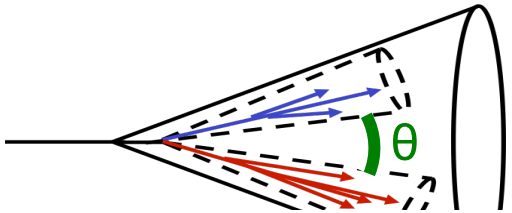
Caucal, Iancu, Soyez, 1907.04866 & 2012.01457



Jets with $\theta_g \geq \theta_c$ are suppressed while jets with $\theta_g \leq \theta_c$ are relatively enhanced.

Is ALICE seeing the critical angle?
Or is this due to the number of emitters?
Or a selection bias?

Splitting angle



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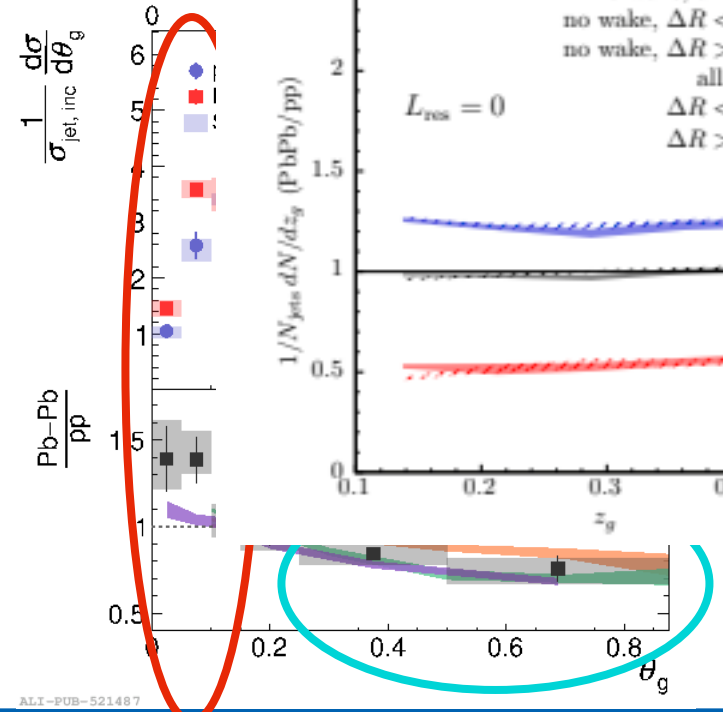
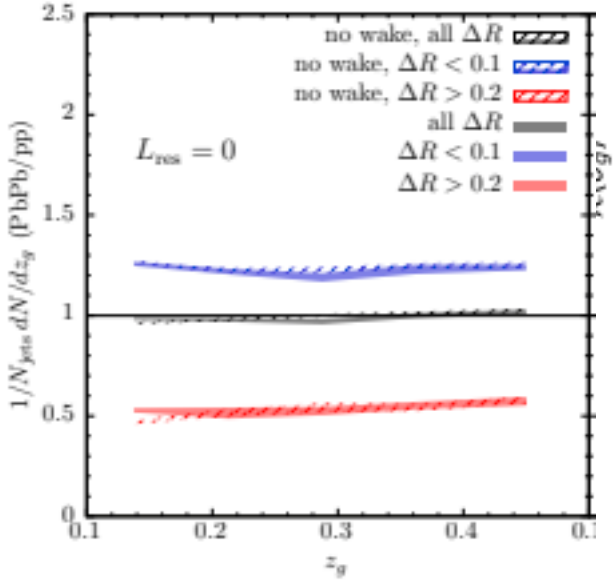
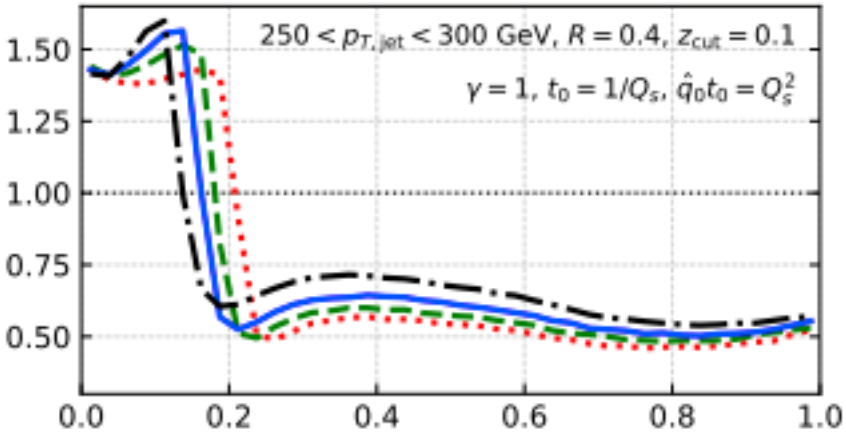




Nuclear effects for θ_g



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Is ALICE seeing the critical angle?
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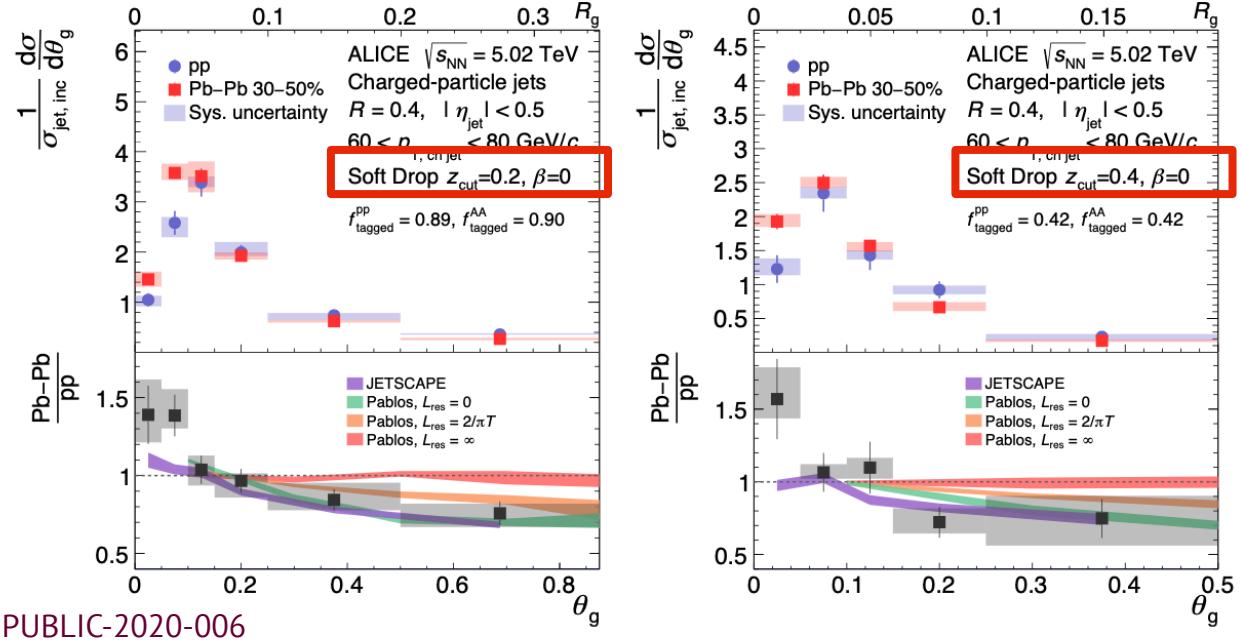
Less central events

Medium at lower temperature

Expect smaller jet quenching effects

Experimental advantage: less background particles

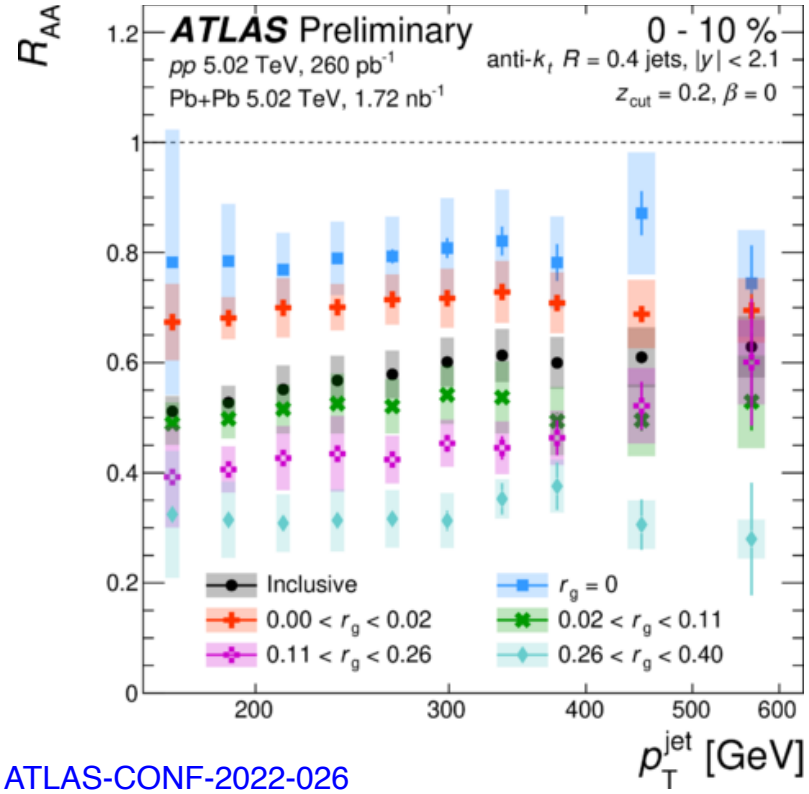


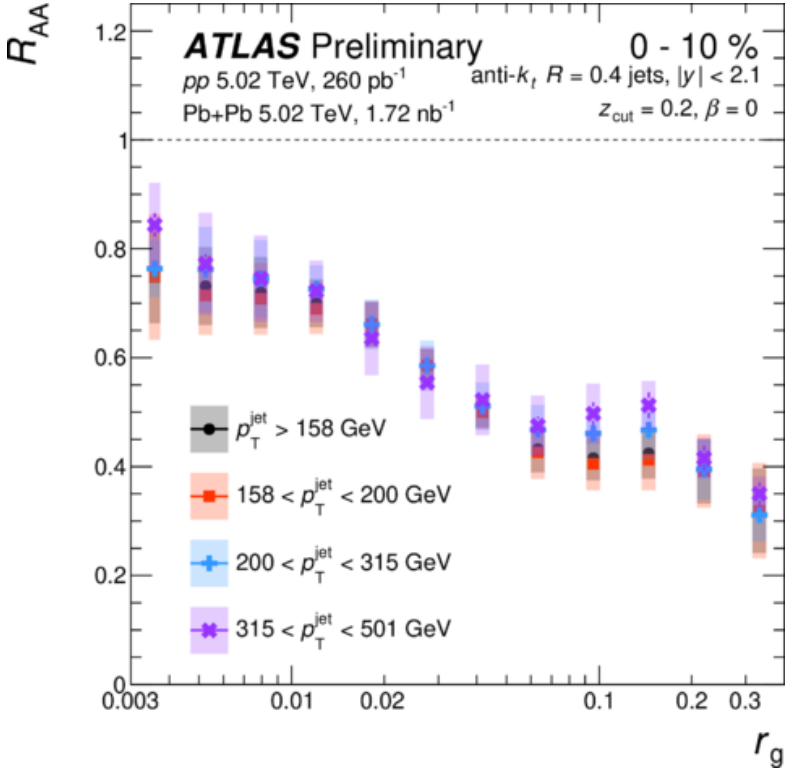
Also narrowing in less central events

Symmetric splittings (z_{cut}=0.4) show similar modification

ALICE-PUBLIC-2020-006

Suppression vs splitting angle





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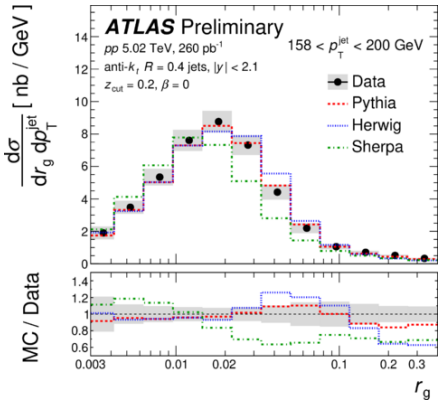
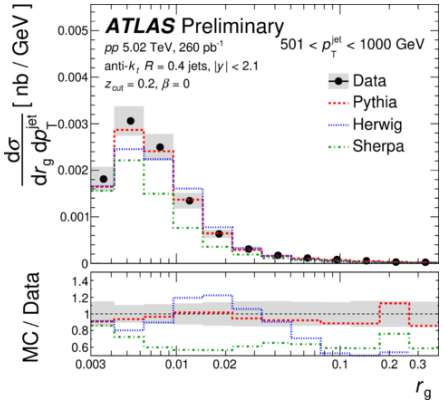
Suppression vs splitting angle

r_g decreases with p_T in vacuum

Low p_T

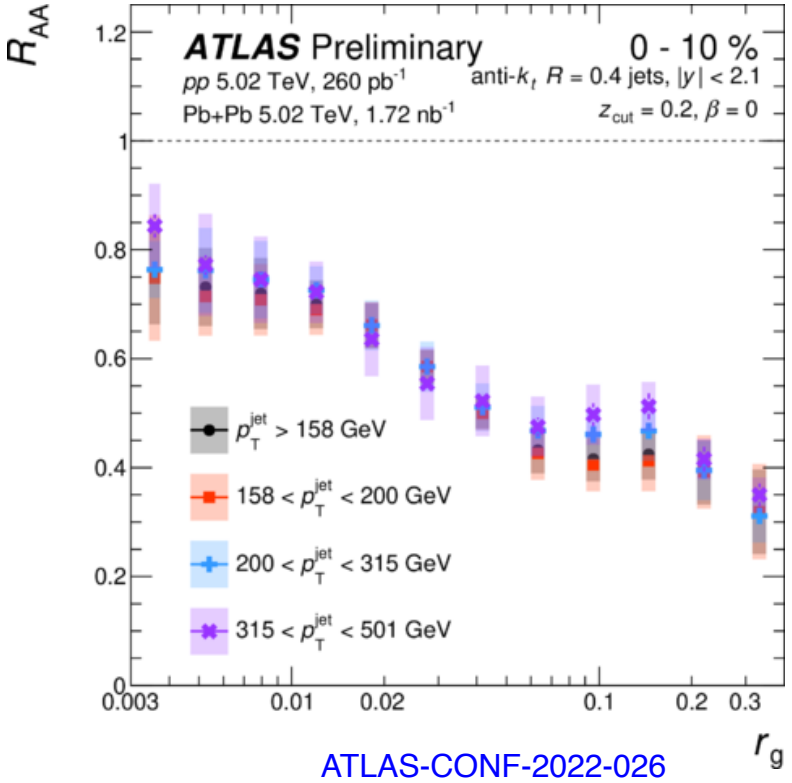


High p_T



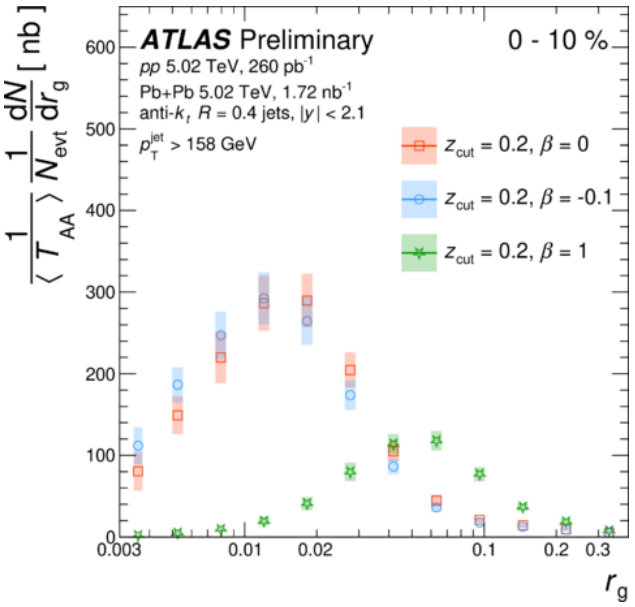
Jet p_T selection + energy loss results in observed r_g dependence

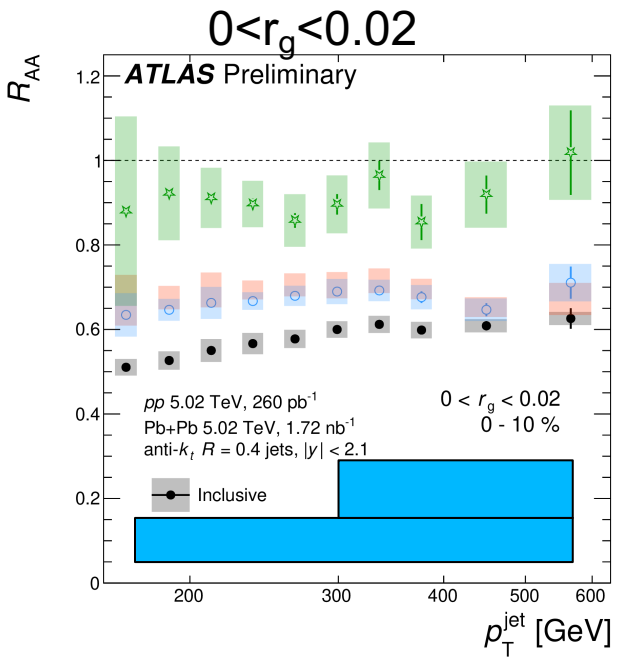
How much room remains for decoherent energy loss within the cone picture?

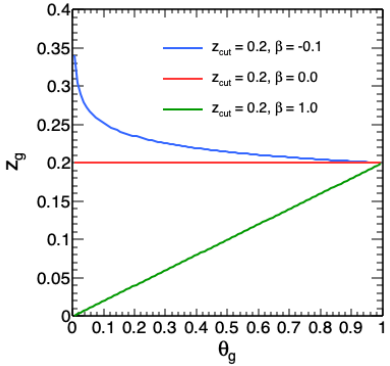


ATLAS-CONF-2022-026

Grooming strength





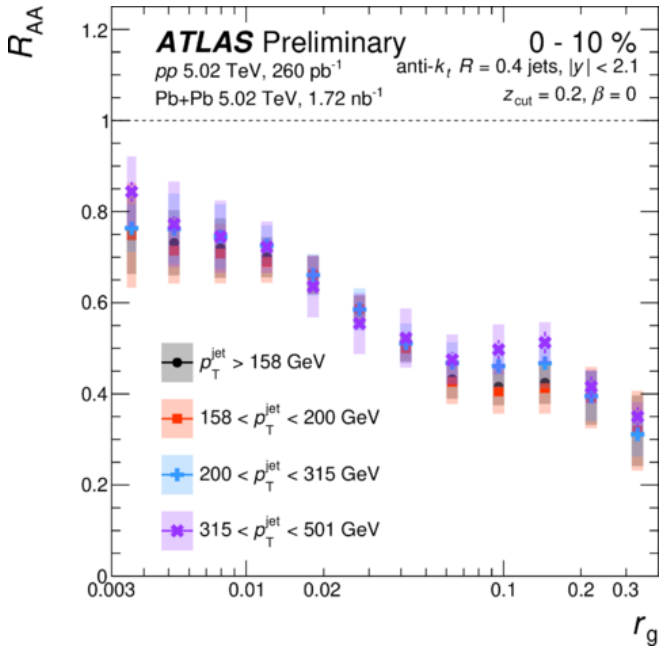


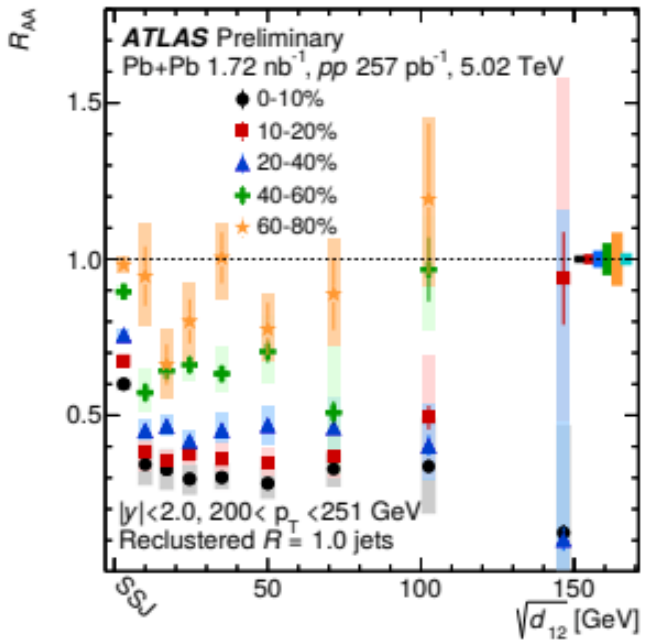
Jets with small r_g are less suppressed when more softer branches survive grooming

ATLAS-CONF-2022-026

Suppression vs opening angle

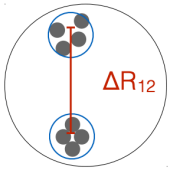
ATLAS-CONF-2022-026





ATLAS-CONF-2019-056

$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$

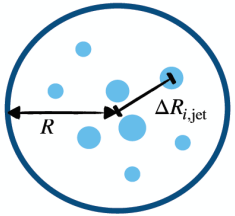


if there is only a single sub-jet (SSJ) → $\sqrt{d_{12}} = 0$

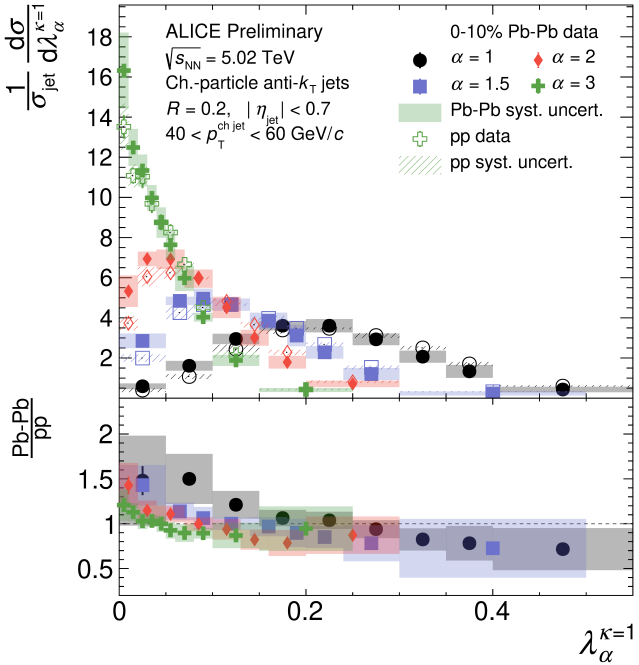
Similar suppression observed for both measurements for large splitting angle

Angularities

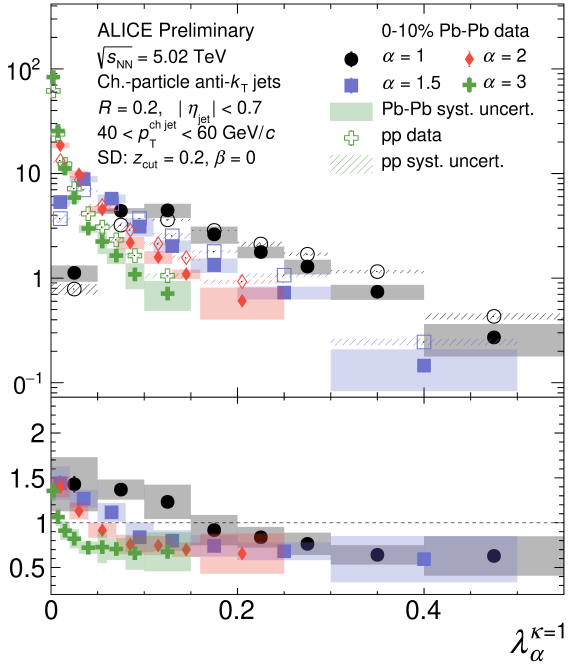
$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha \qquad z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$



Ungroomed



Groomed



Groomed angularities are modified more strongly than ungroomed angularities

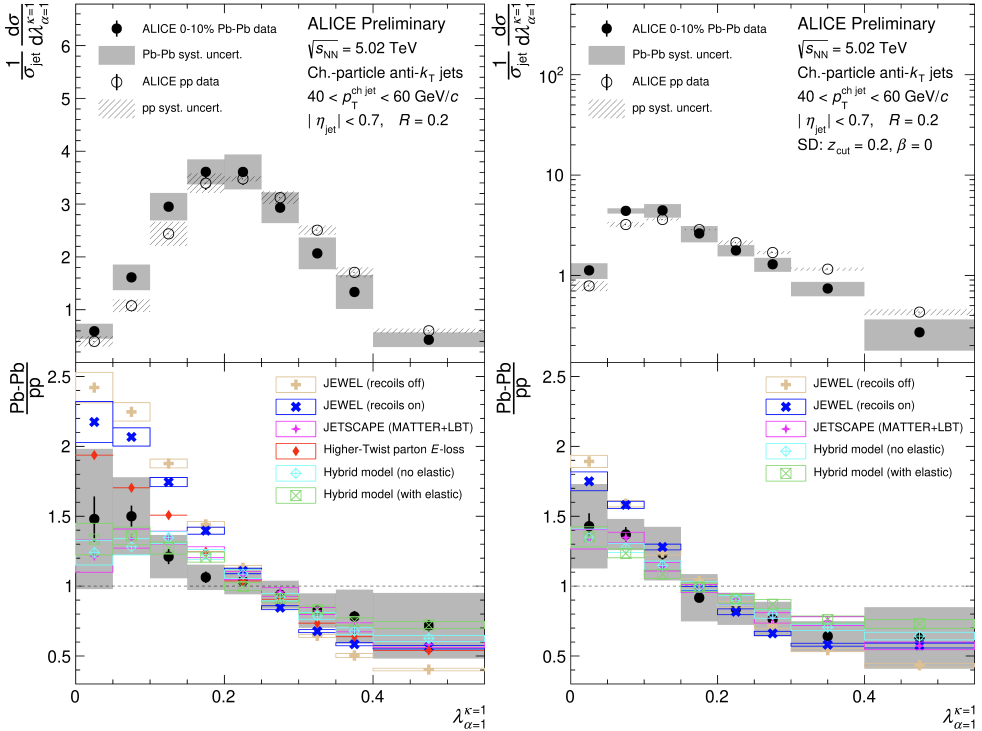
Could be due to competing effects:

1. Suppression of wide jets
2. Broadening

Jet grooming enhances collimation effects

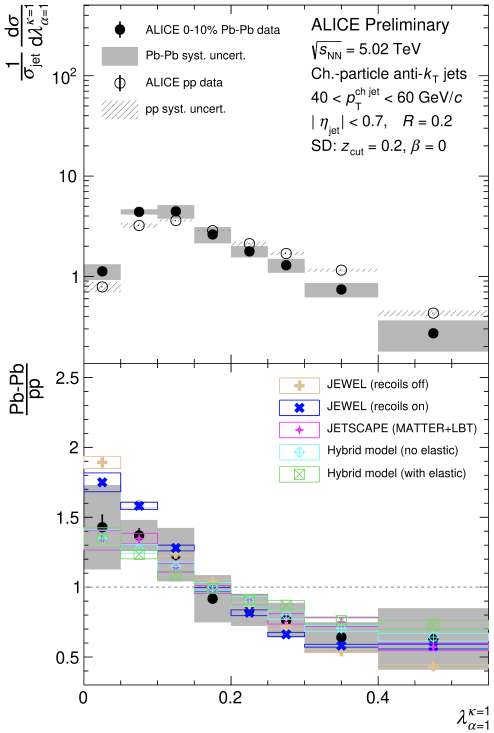
Angularities vs theory

Models describe data. Some tension for JEWEL at small λ

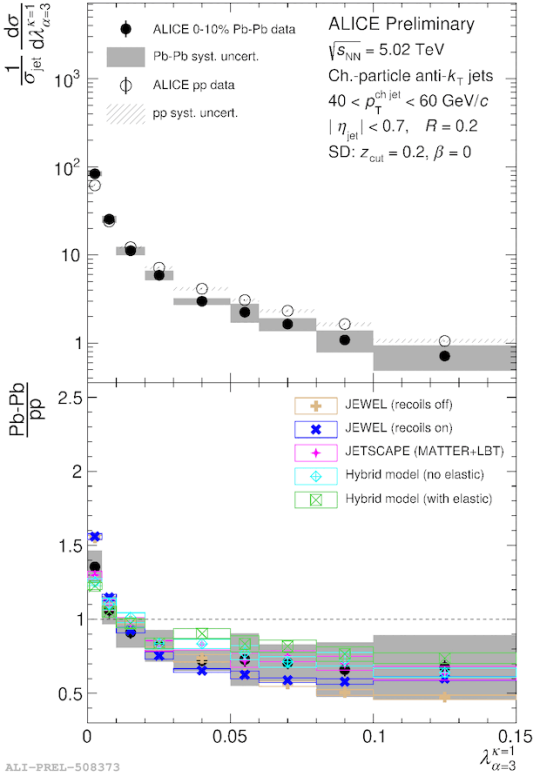


Angularities vs theory

α=1



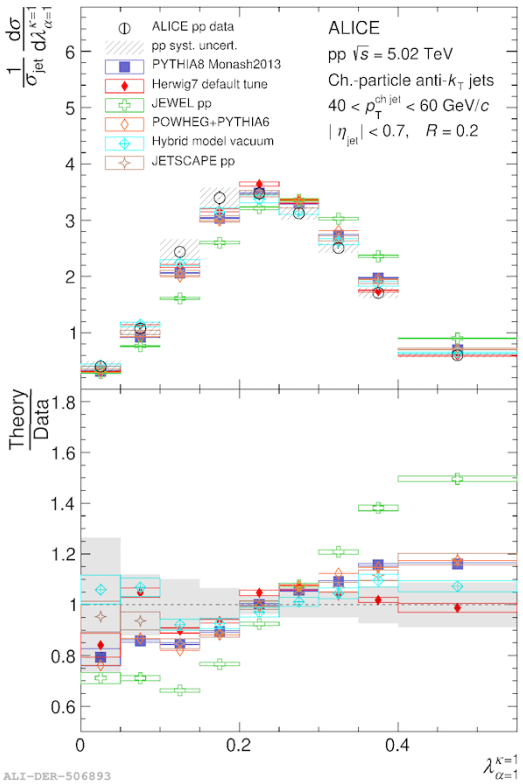
α=3



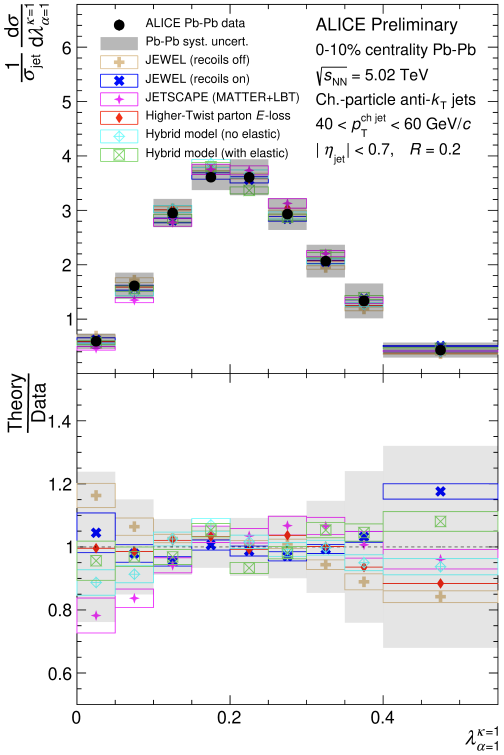
Also in the models, more pronounced modification when more weight is given to collinear radiation

Models vs data

pp



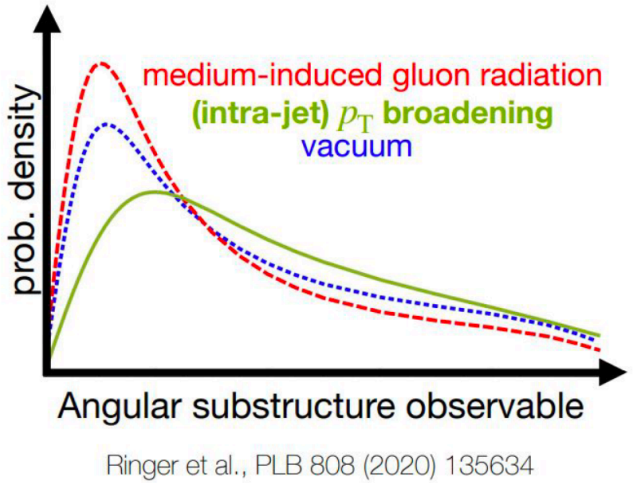
Pb-Pb



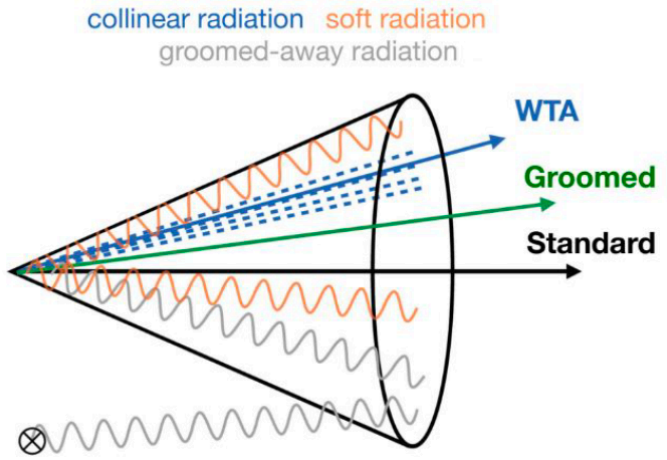
Large variation in models when comparing the distribution directly

- JEWEL pp baseline is off and causes the disagreement with data in PbPb-to-pp ratio

Jet axes as substructure



Ringer et al., PLB 808 (2020) 135634

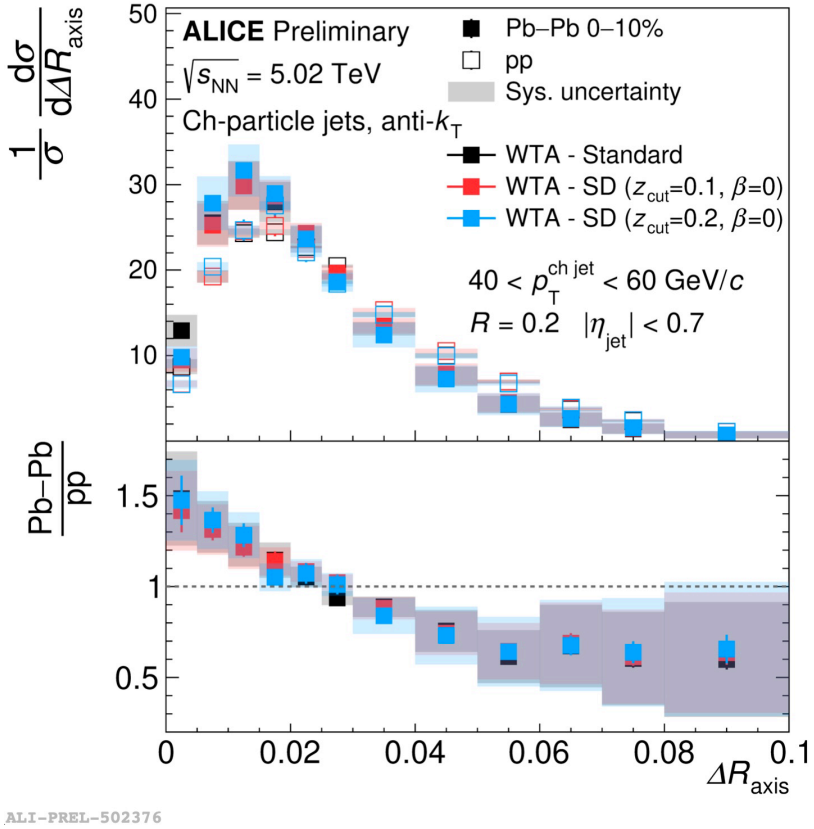


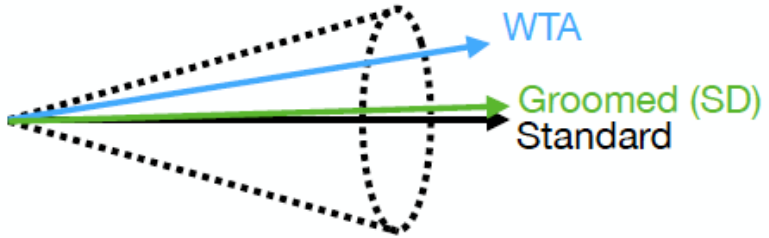
Use pointing direction of jets to study
- Medium-induced radiation
- p_T broadening

→ Study their interplay

Observable: angle between jet axes
- Standard ungroomed axis
- Groomed axis
- Winner-takes-all axis

Jet axes as substructure

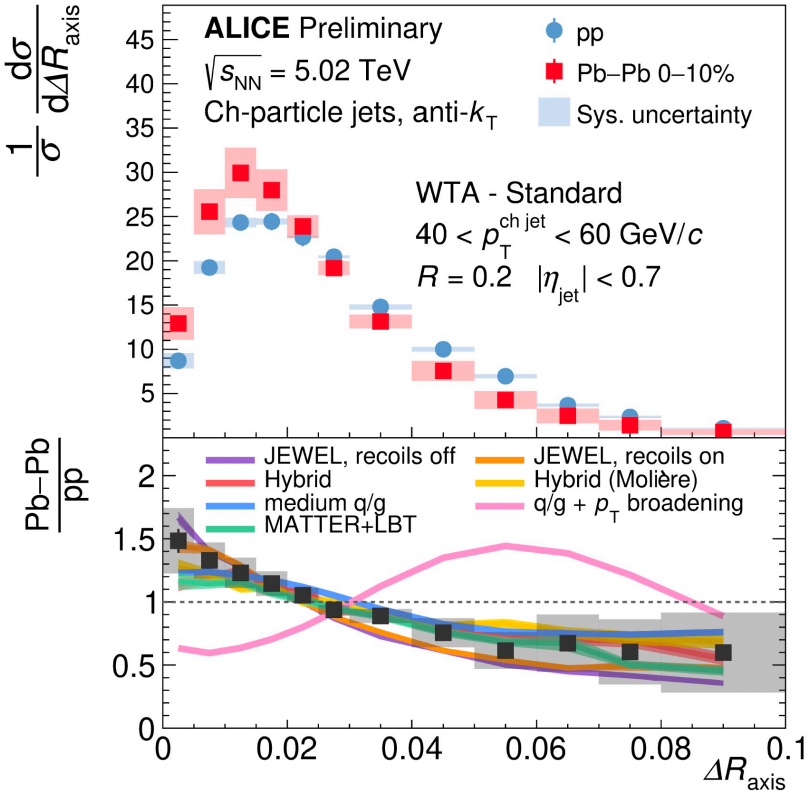


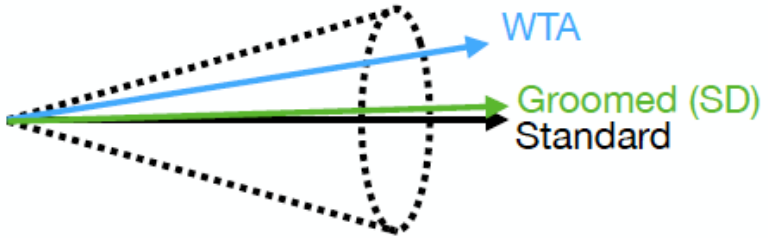


Grooming hardly moves the jet axis

Narrowing effect also visible for ungroomed jets

Jet axes as substructure





Narrowing effect also visible for ungroomed jets

Disagreement with p_T broadening model remains when no grooming is used

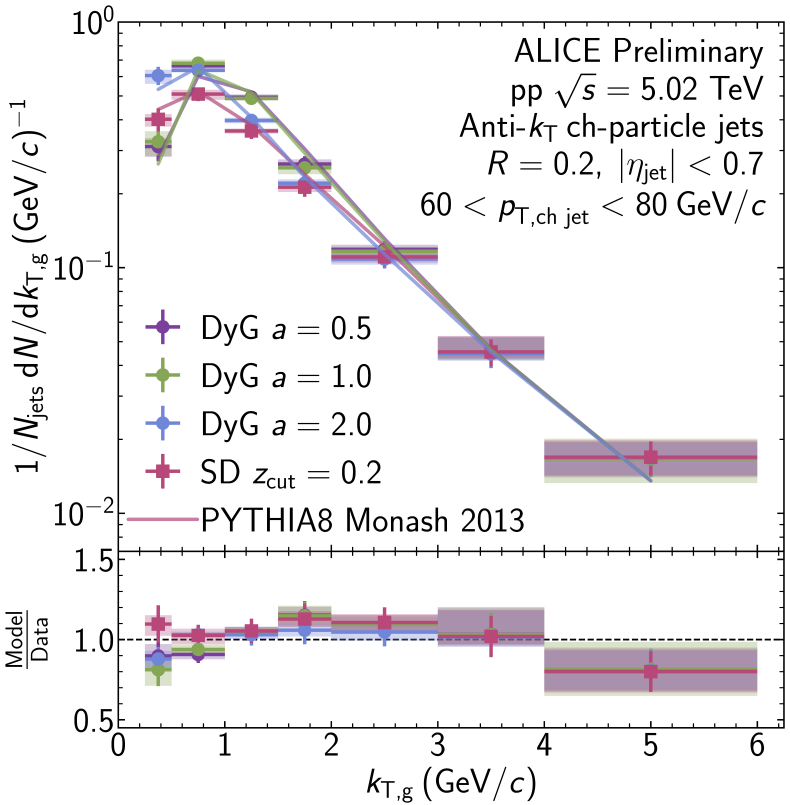
Dynamical grooming

Dynamical grooming

- Find hardest split in tree
- Grooming cutoff depends on jet properties
- Parameter a can be used to change hardness measures

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in C/A} \; z_i(1 - z_i) \; p_{T,i} \; \left(\frac{\Delta R_i}{R}\right)^a$$

Hardest k_T



Mehtar-Tani et al., Phys. Rev. D. 101.034004

Dynamical grooming

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- Find hardest split in tree
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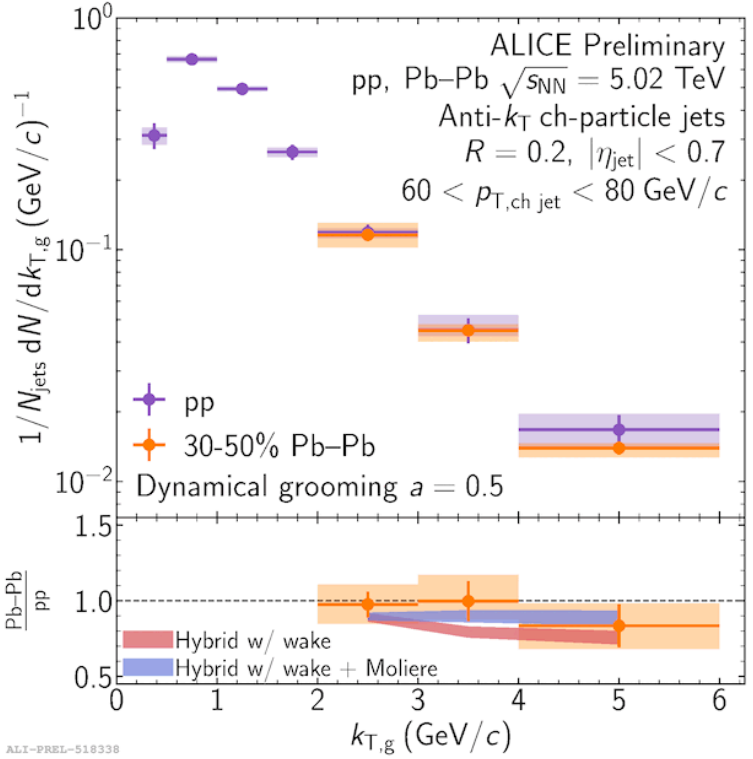
a=0.5



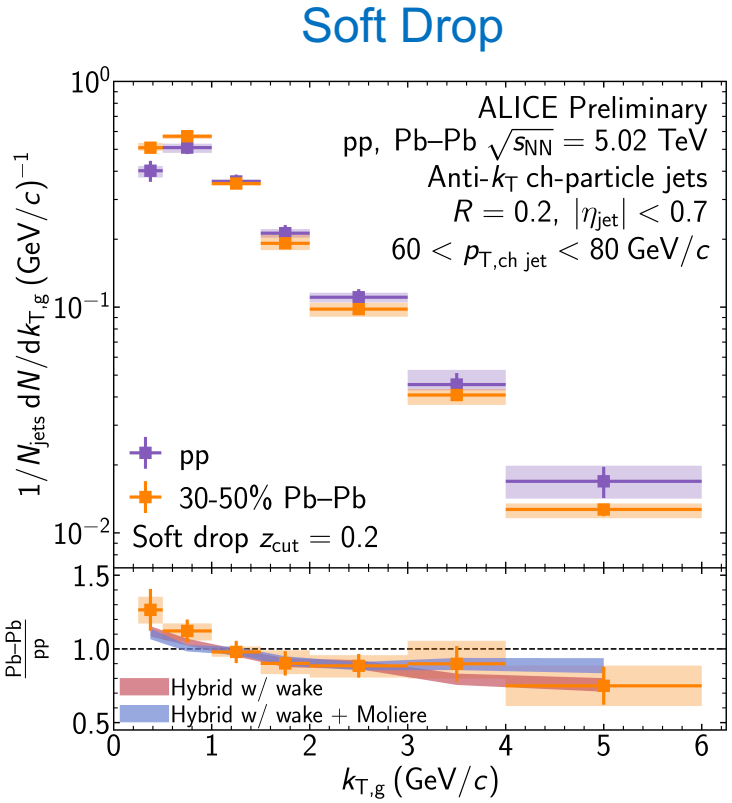
Mehtar-Tani et al., Phys. Rev. D. 101.034004

k_T modification

Dynamical grooming

- Find hardest split in tree
- Grooming cutoff depends on jet properties
- Parameter a can be used to change hardness measures

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in C/A} \; z_i(1 - z_i) \; p_{T,i} \; \left(\frac{\Delta R_i}{R}\right)^a$$



Mehtar-Tani et al., Phys. Rev. D. 101.034004

k_T modification

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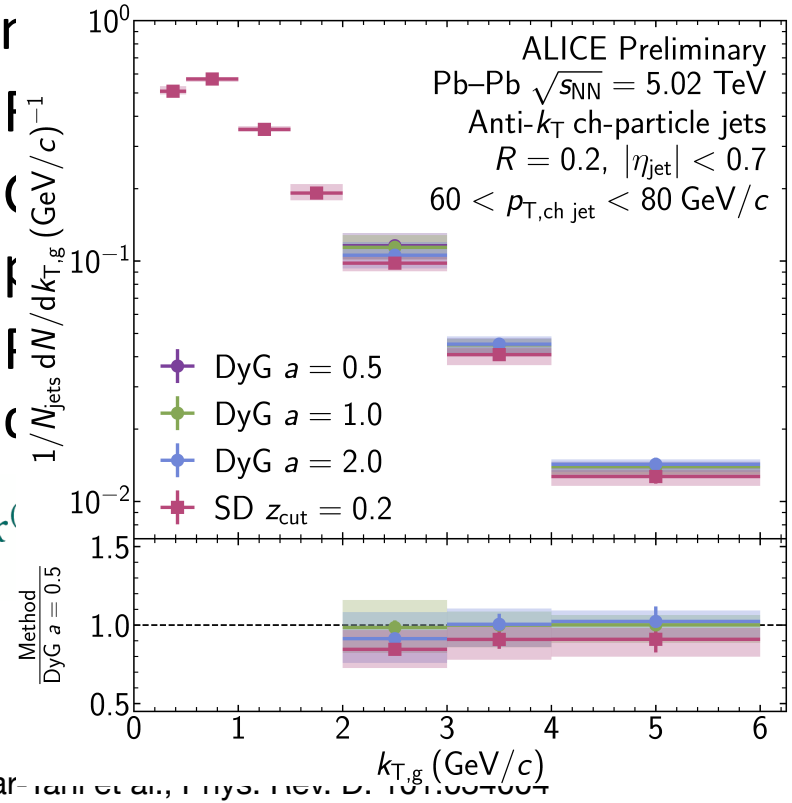
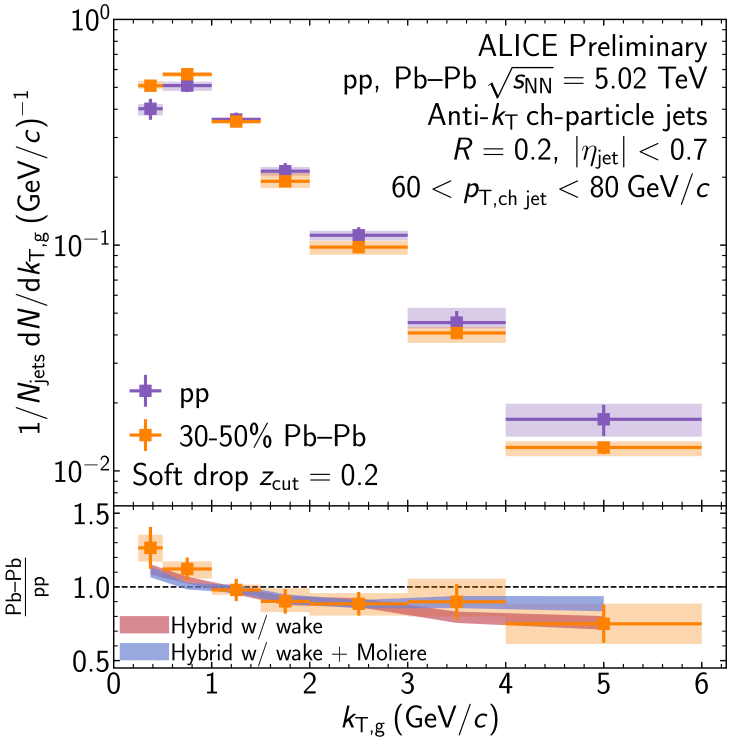
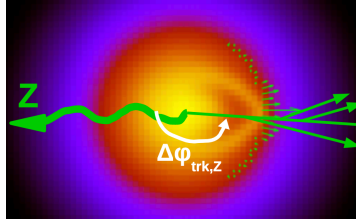


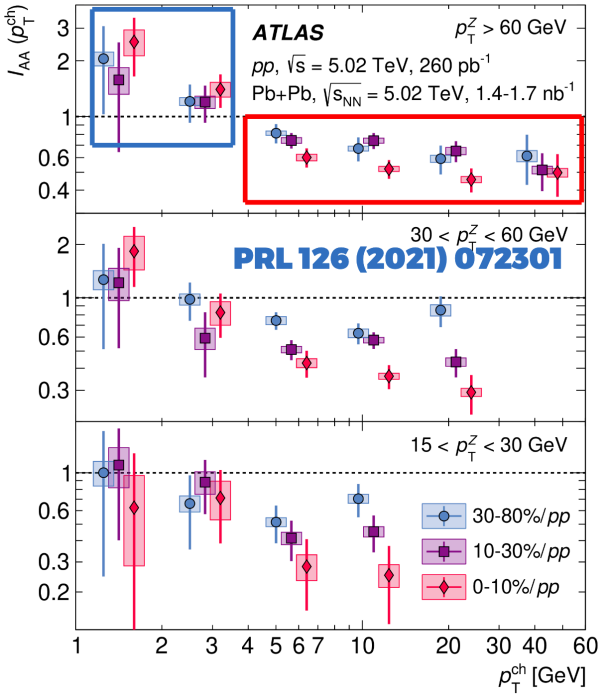
Soft Drop

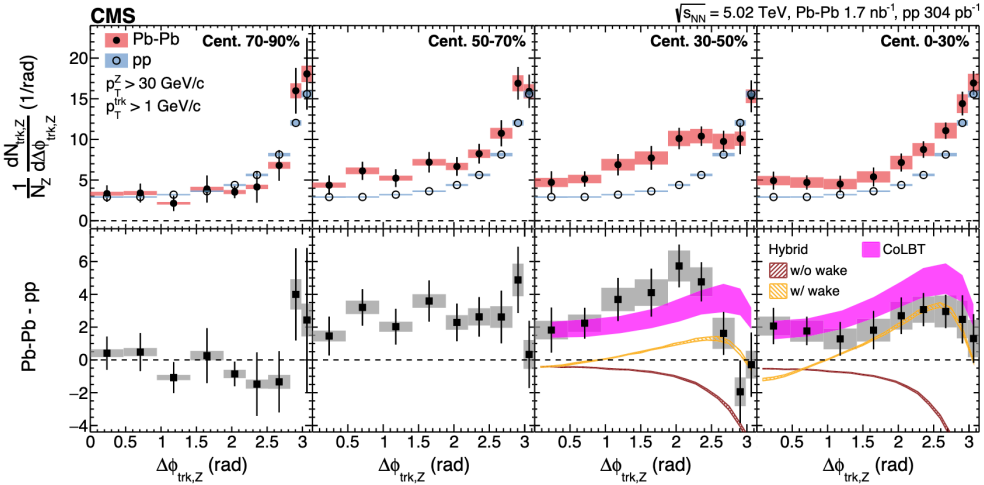


Mehtar-Tani et al., Phys. Rev. D. 101:034004

Z-hadron







CMS PRL 128 (2022)122301

Summary

Jets are never simple.

And even more complicated when traversing a quark-gluon plasma.

Making progress on understanding in-medium parton shower

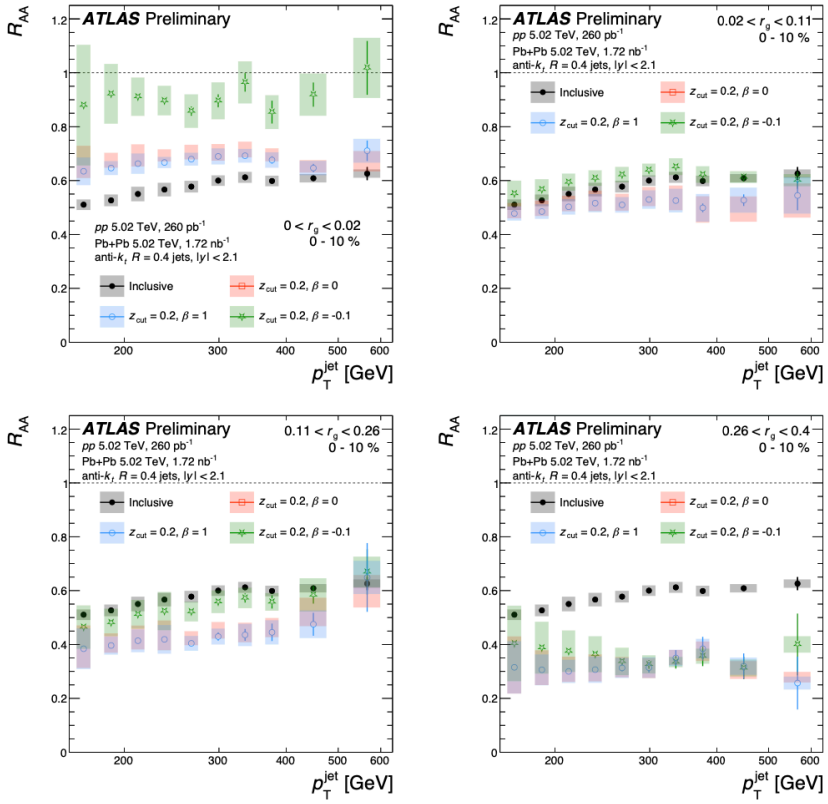
→ This leads to more accurate extraction of QGP properties (transport coefficient $\hat{q}$, (de)coherence angle θ_c, …)

But there are open questions

- Role of medium response? Resolution scale of QGP? Quasi-particles?

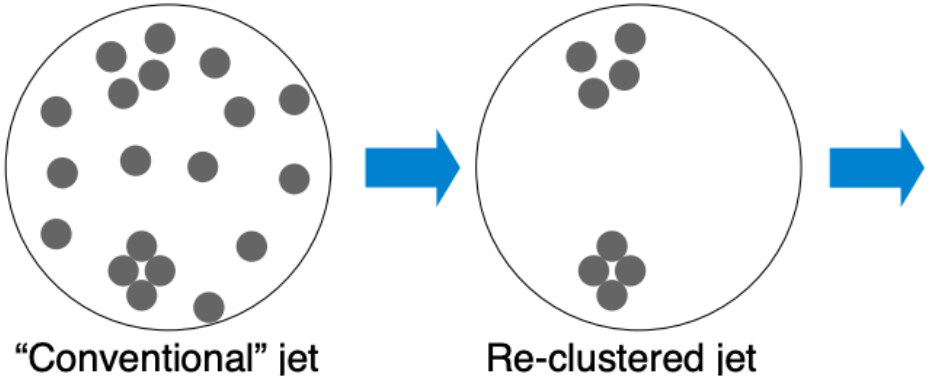
Summary

Grooming strength



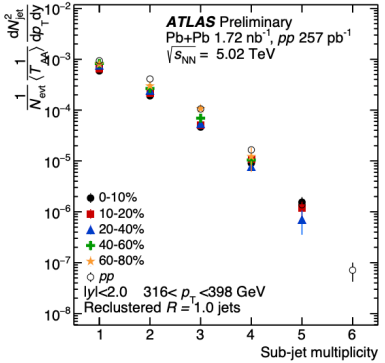
The ATLAS way

Cal. towers & UE subtraction → R=0.2 jets anti-k_t jets $p_T > 35$ GeV → re-clustering with anti-k_t R=1.0 → Sub-jets → re-clustering with k_t algorithm → Splitting scale $\sqrt{d_{12}}$



Different jets than the conventional R=1.0.

Trimming & 35 GeV threshold remove soft components.



ATLAS-CONF-2019-056

Slide taken from A. Sickles at Hard Probes 2020