LHCP 2023 - Large Hadron Collider Physics Conference
22-26 May 2023, Belgrade, Serbia

Jet substructure measurements in heavy-ion collisions

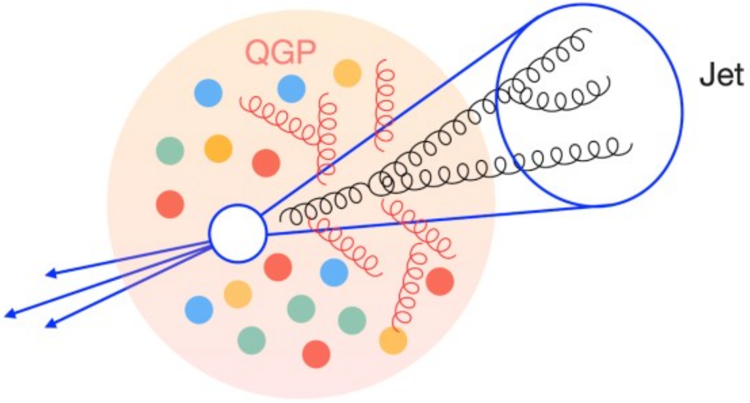
Róbert Vértesi
vertesi.robert@wigner.hu

for the **ALICE, CMS and ATLAS** collaborations

This work has been supported by the Hungarian NKFIH OTKA FK131979 and K135515
as well as the NKFIH 2021-4.1.2-TÉT-2022-00007 grants

Jets to probe the quark–gluon plasma

- **Jet quenching**: jets are modified in the quark-gluon plasma created in ultra-relativistic heavy-ion collisions



https://www.int.washington.edu/node/776

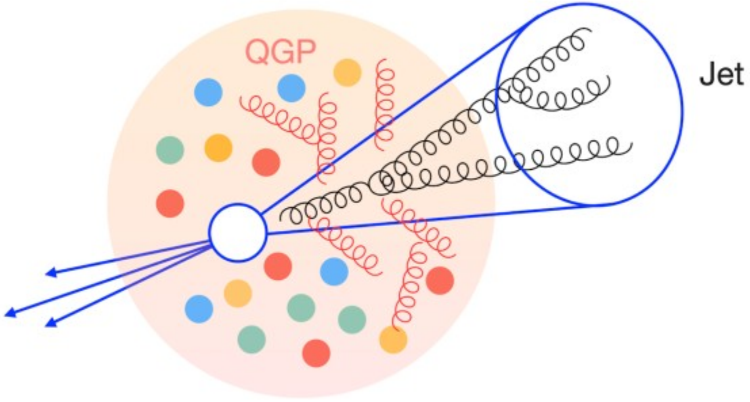
Jets to probe the quark–gluon plasma

- **Jet quenching**: jets are modified in the quark-gluon plasma created in ultra-relativistic heavy-ion collisions

- How does a color charge lose energy?

- What (angular) **length scales** can the QGP resolve?
  When do partons interact coherently?

- Signature of point-like scattering?
  Is there an emergent structure such as **quasi-particles** in the plasma?



https://www.int.washington.edu/node/776

Jets to probe the quark–gluon plasma

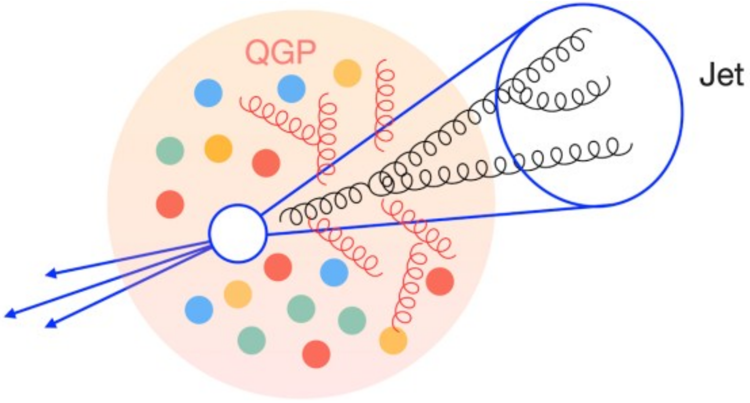
- **Jet quenching**: jets are modified in the quark-gluon plasma created in ultra-relativistic heavy-ion collisions

- How does a color charge lose energy?

- What (angular) **length scales** can the QGP resolve?
  When do partons interact coherently?

- Signature of point-like scattering?
  Is there an emergent structure such as **quasi-particles** in the plasma?

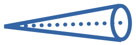
- Systematic study with **jets and their substructure**
  => constrain models for QGP dynamics



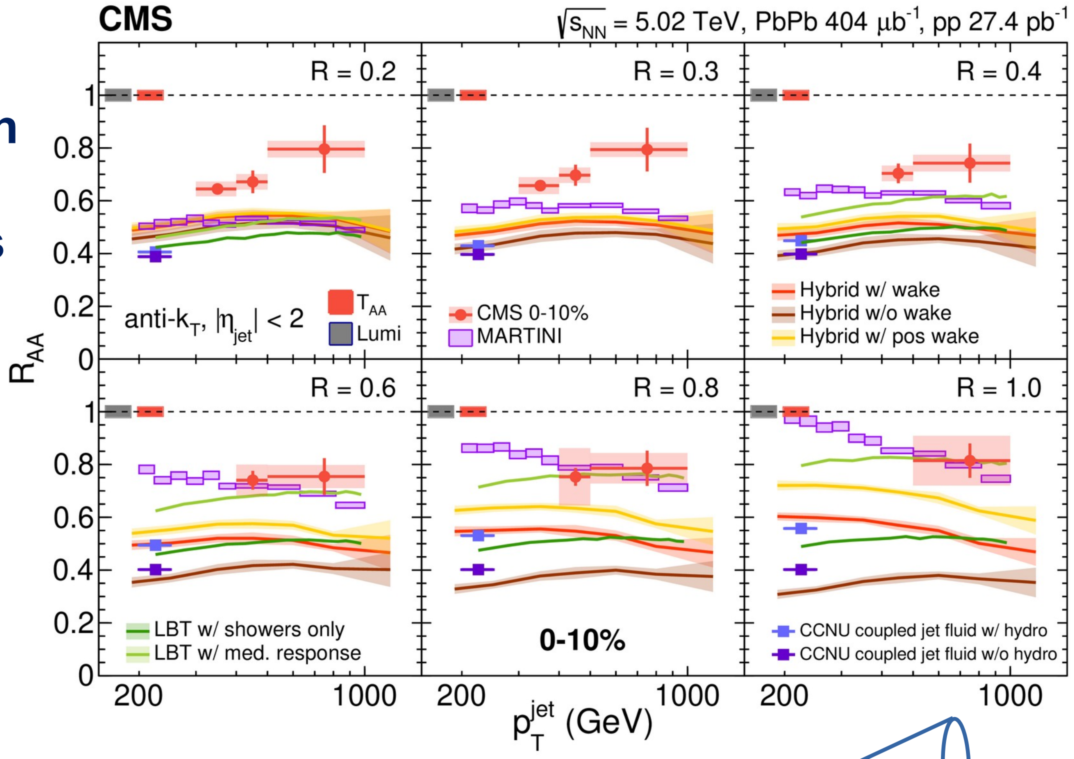
https://www.int.washington.edu/node/776

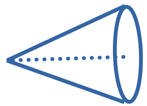
Large-R jets (CMS)

- First measurement of large-radius jets in Pb-Pb
- **Substantial suppression at high momenta from small to large radii in central Pb-Pb collisions**
- Sensitivity to energy loss mechanism as well as medium response
- **Tension with models**
  => Analysis of jet substructure to explore physics in details



JHEP 05 (2021) 284

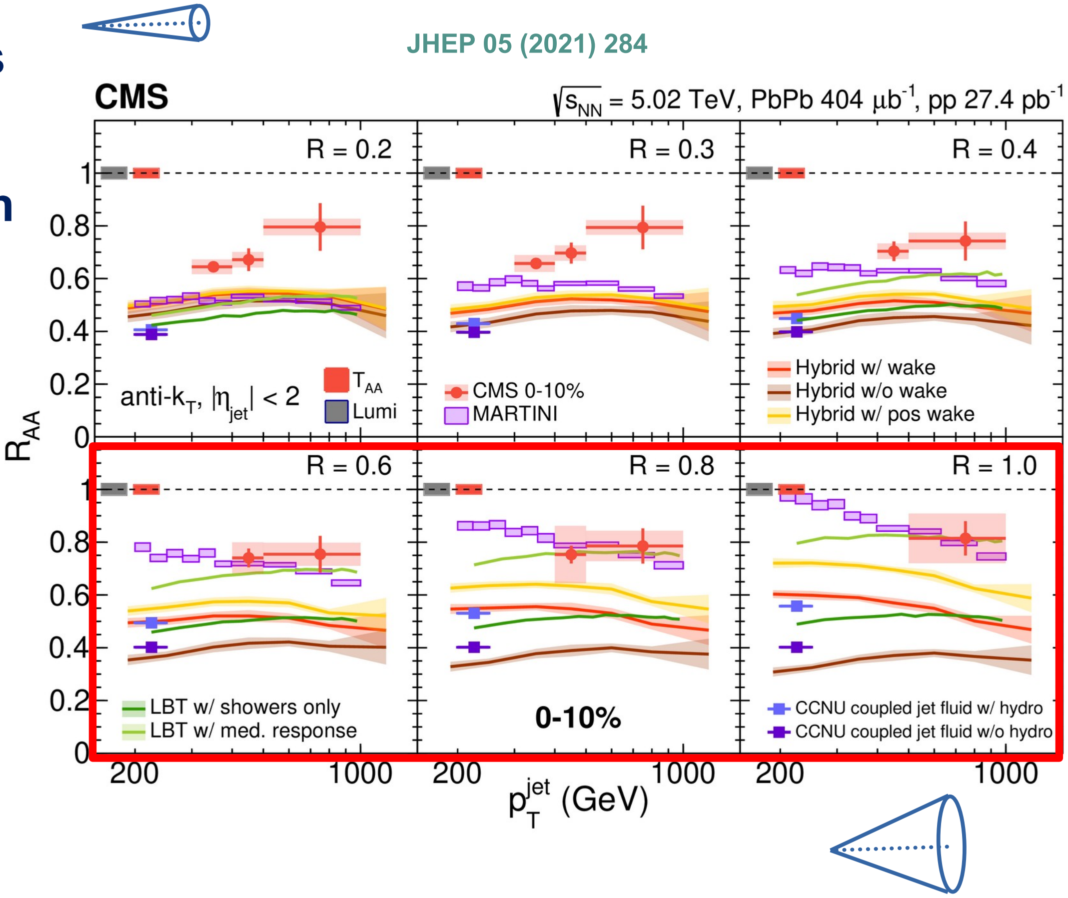




Large-R jets (CMS)

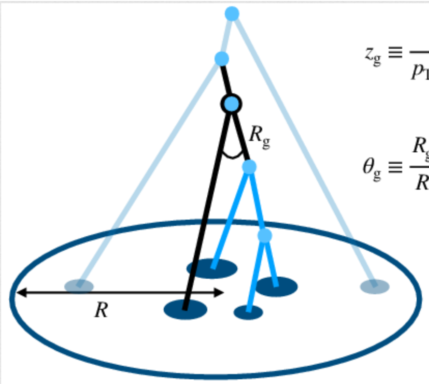
- First measurement of large-radius jets in Pb-Pb
- **Substantial suppression at high momenta from small to large radii in central Pb-Pb collisions**
- Sensitivity to energy loss mechanism as well as medium response
- **Tension with models**
  => Analysis of jet substructure to explore physics in details

JHEP 05 (2021) 284



Jet grooming

- **Grooming**: access to the hard parton structure of a jet
  - Remove large-angle soft radiation: mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations

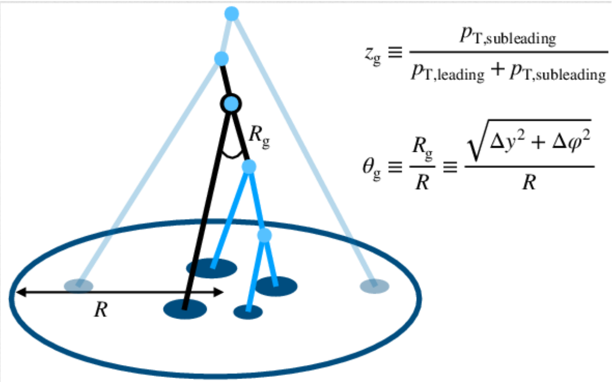


$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

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

Jet grooming

- **Grooming**: access to the hard parton structure of a jet
  - Remove large-angle soft radiation: mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations



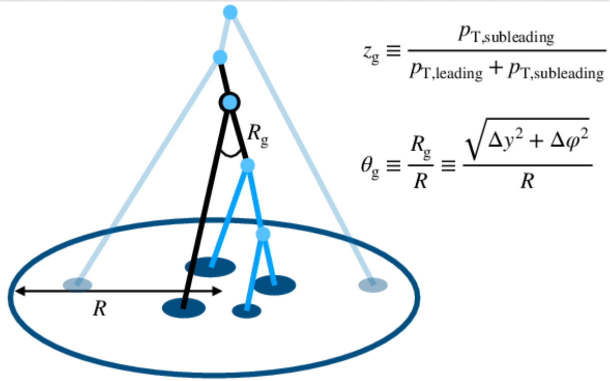
- **Soft-drop grooming**

  Larkoski et al., JHEP 05 (2014) 146
  - Recluster a jet with Cambridge-Aachen algorithm (angular ordered)
  - Iteratively remove soft branches not fulfilling SD condition $z > z_{cut}\theta^{\beta}$

$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \qquad \theta = \frac{\Delta R_{12}}{R}$$

Jet grooming

- **Grooming**: access to the hard parton structure of a jet
  - Remove large-angle soft radiation: mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations



- **Soft-drop grooming**:
  Larkoski et al., JHEP 05 (2014) 146
  - Recluster a jet with Cambridge-Aachen algorithm (angular ordered)
  - Iteratively remove soft branches not fulfilling SD condition $z > z_{\mathrm{cut}}\theta^{\beta}$

$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \qquad \theta = \frac{\Delta R_{12}}{R}$$

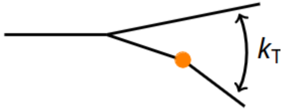
- **Dynamical grooming**
  Mehtar-Tani et al., PRD 101.034004
  - Recluster the jet with the Cambridge-Aachen algorithm
  - Look for the hardest splitting

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A\ seq.}} \left[z_i (1 - z_i) p_{T,i} \left(\frac{\theta_i}{R} \right)^a \right]$$

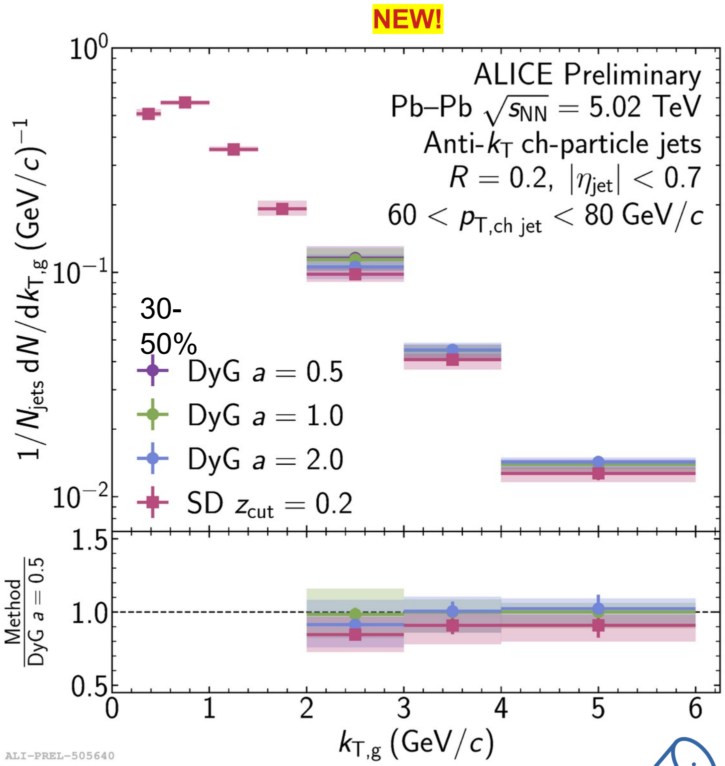
  - $a = 0.5$ more symmetrical, narrow splitting
  - $a = 1$ splitting with largest $k_T \sim \kappa^{(1)} p_T$
  - $a = 2$ shortest formation time splitting, $t_f^{-1} \sim \kappa^{(2)} p_T$

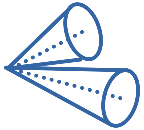
Hardest-k_T splitting (ALICE)

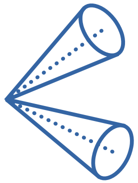
- **High-k_T emissions can be a signature of point-like scattering**



  - First measurement with dynamical grooming in Pb+Pb collisions
  - Soft-drop grooming with z_{cut} = 0.2
  - Grooming methods converge toward high-k_T

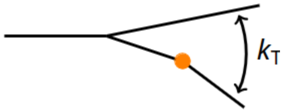






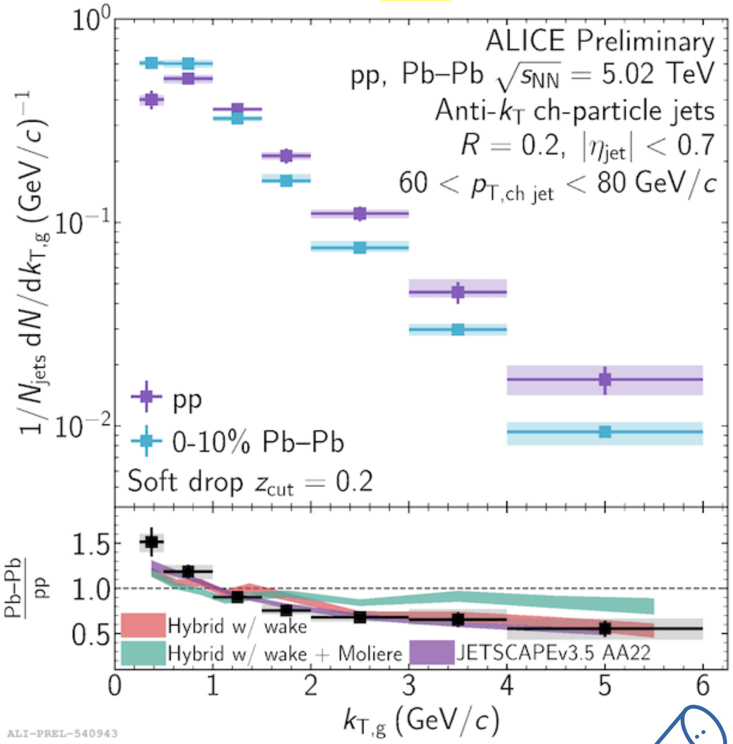
Hardest-k_T splitting (ALICE)

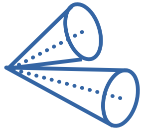
- **High-k_T emissions can be a signature of point-like scattering**

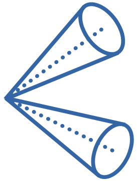


  - First measurement with dynamical grooming in Pb+Pb collisions
  - Soft-drop grooming with z_{cut} = 0.2
  - Grooming methods converge toward high-k_T
- No clear enhancement at high-k_T
- **Model without Molière scattering describes data better**

NEW!



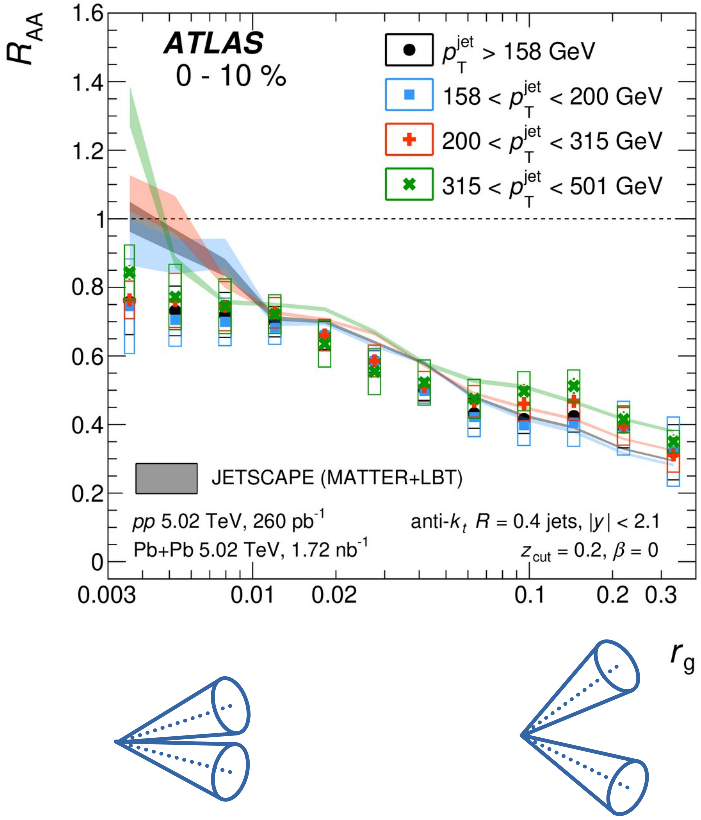




SD-groomed radius (ATLAS)

- Jets with wider opening angle lose significantly more energy
  - Jets with large r_g are approximately twice as suppressed than at small r_g
    => Narrowing of jets

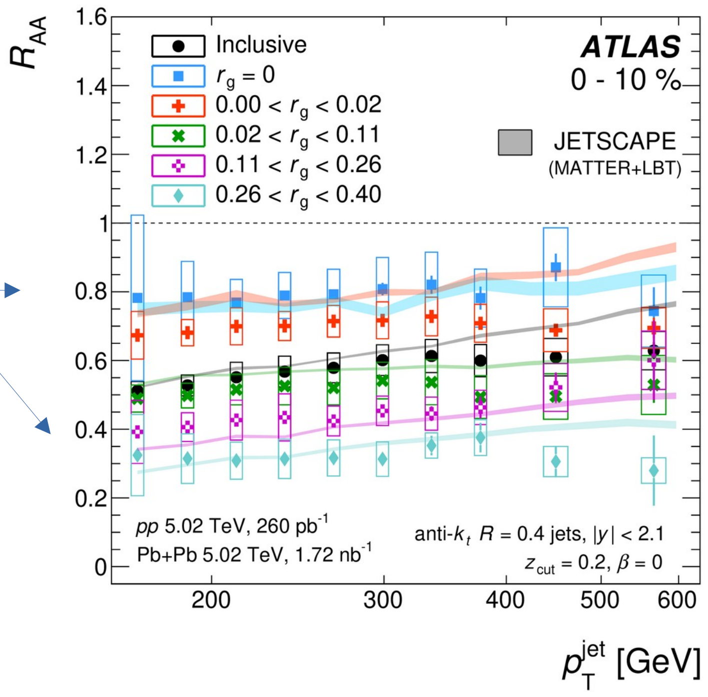
arXiv:2211.11470

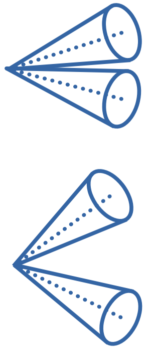


SD-groomed radius (ATLAS)

- Jets with wider opening angle lose significantly more energy
  - Jets with large r_g are approximately twice as suppressed than at small r_g
- The suppresion does not depend strongly on p_T, regardless of r_g
  - ***p_T*-dependence of inclusive jets from change of *r_g* distribution**
  - qualitatively consistent with jet quenching from coherence

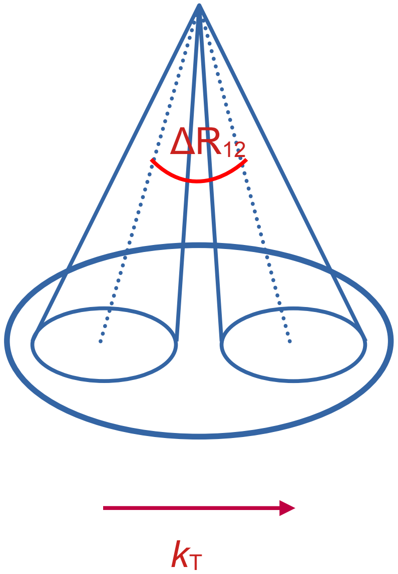
arXiv:2211.11470





Jet reclustering

- Small-radius (R=0.2) jets are reconstructed with the anti-k_T algorithm
- A p_T^{jet}>35 GeV/c threshold is applied
- The remaining jets are reconstructed into large-radius (R=1.0) jets
- The small-R jets are reclustered using the k_T algorithm to determine angular separation and splitting parameter



$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}$$

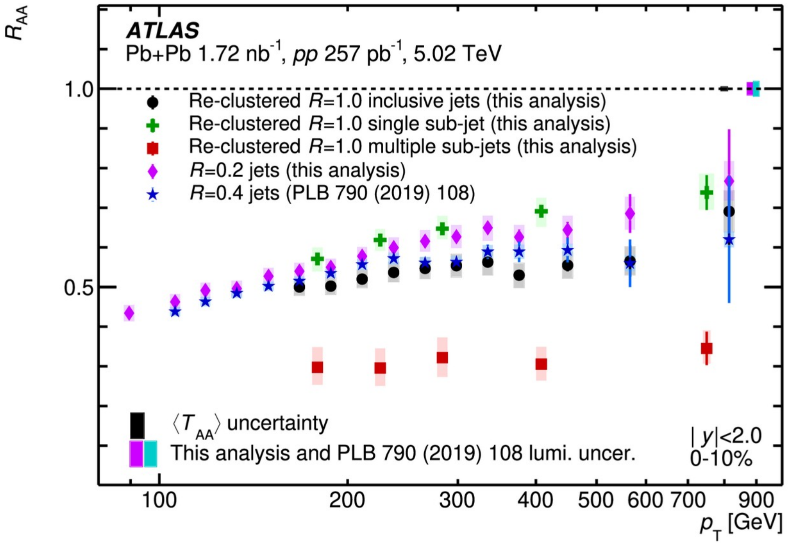
$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12} \quad \sim k_T$$

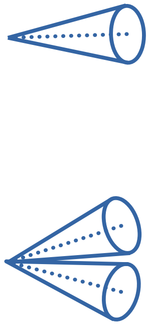
Reclustered large-radius jets (ATLAS)

- Reclustered *R*=1 jets are slightly more suppressed than smaller-radii inclusive jets

- **Significant difference in the quenching of large-radius jets having single sub-jet and those with more complex substructure**

arXiv:2301.05606 NEW!

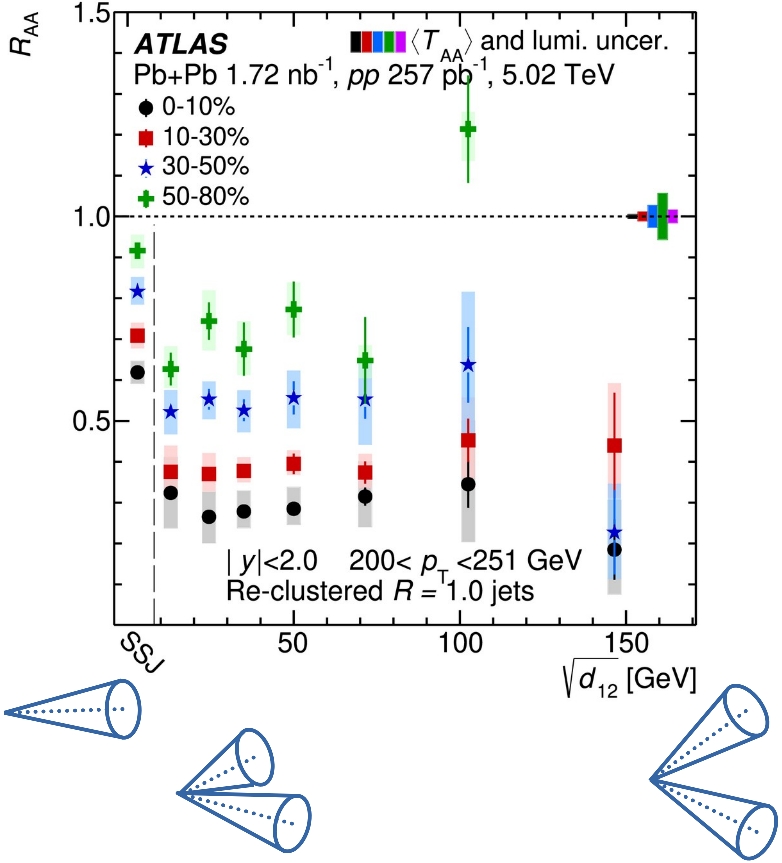




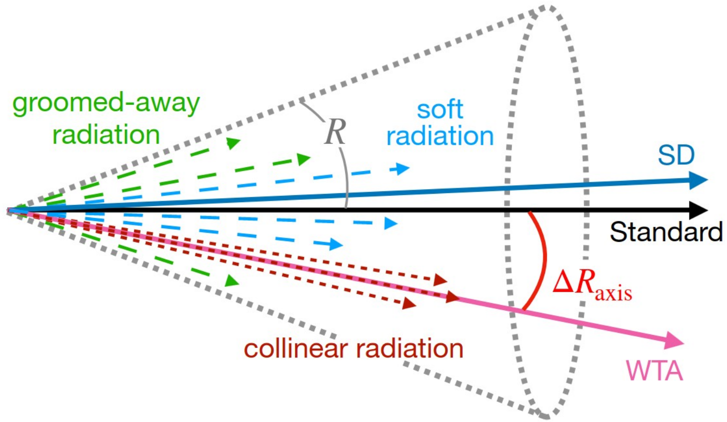
Reclustered large-radius jets (ATLAS)

- Reclustered R=1 jets are slightly more suppressed than smaller-radii inclusive jets
- **Significant difference in the quenching of large-radius jets having single sub-jet and those with more complex substructure**
- No pronunced dependence on $\sqrt{d_{12}} \sim k_T$ separation
- => supports **decoherence beyond a critical splitting angle**

arXiv:2301.05606 NEW!



Jet axis differences



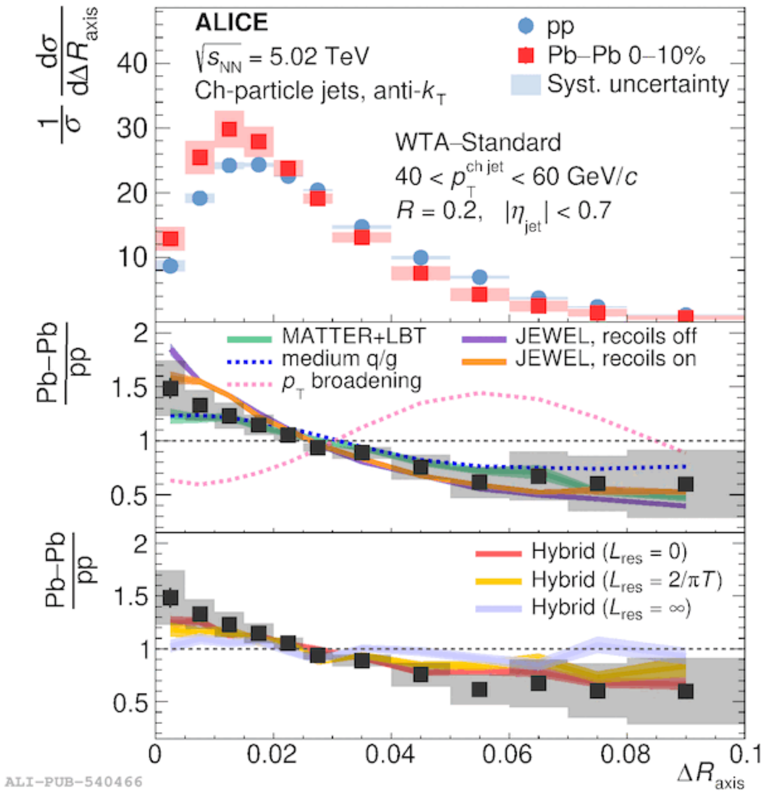
$$\Delta R_{\mathrm{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$$

- **Standard axis**: formed by the sum of pseudo-jet four-momenta in the clusterization with E-scheme
- **Soft-Drop groomed jet axis**: sum of four-momenta of constituents accepted by the SD grooming
- **Winner-takes-all axis**: recluster with CA algorithm, always combine prongs in direction of the stronger one
  => insensitive to soft radiation

Jet axis difference (ALICE)

arXiv:2303.13347 **NEW!**

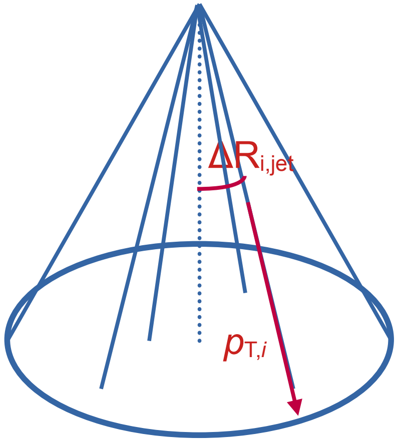
- Narrowing in heavy-ion collisions compared to the vacuum
- Sensitivity to medium resolution length: comparison to the Hybrid model
  J. Casalderrey-Solana, JHEP 10 (2014) 019
  - **Measurement favors incoherent energy loss**
- Intra-jet p_T broadening model does not describe data trend



Generalized jet angularities and jet mass

- **Angularities:** class of observables that depend on both the longitudinal and angular properties of jet splittings

$$\lambda_\alpha^\kappa = \sum_{i\in\mathrm{jet}} z_i^\kappa \theta_i^\alpha \qquad z_i = \frac{p_{\mathrm{T,i}}}{p_{\mathrm{T,jet}}} \quad \theta_i = \frac{\Delta R_{i,\mathrm{jet}}}{R}$$



- IRC-safe observables for $\kappa = 1$, $\alpha > 0$
  => Theoretically accessible in the vacuum case
- Generalization of existing jet properties with continously tunable parameters
  - Jet girth λ_1^1
  - Jet thrust λ_2^1
  - **Jet mass:** related to jet thrust $\lambda_2^1 = \left(\frac{m}{Rp_\mathrm{T}}\right)^2 + \mathcal{O}[(\lambda_2^1)^2]$

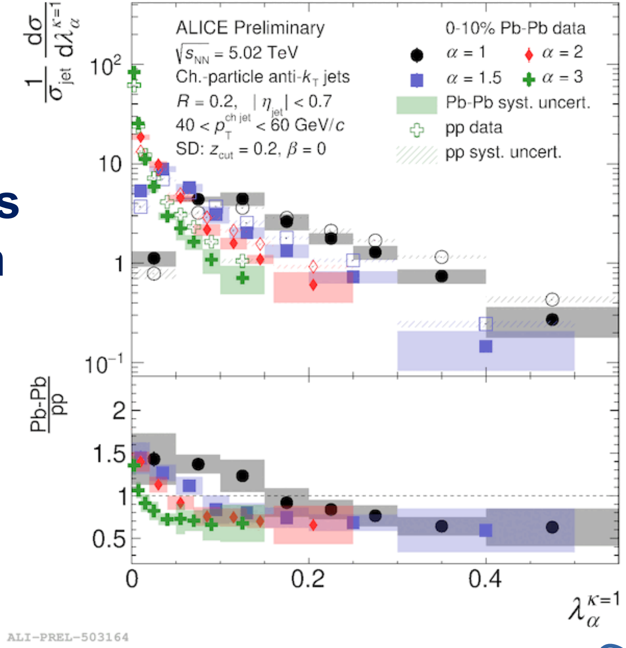
Kang et al., JHEP 1804 (2018) 110

Generalized jet angularities (ALICE)

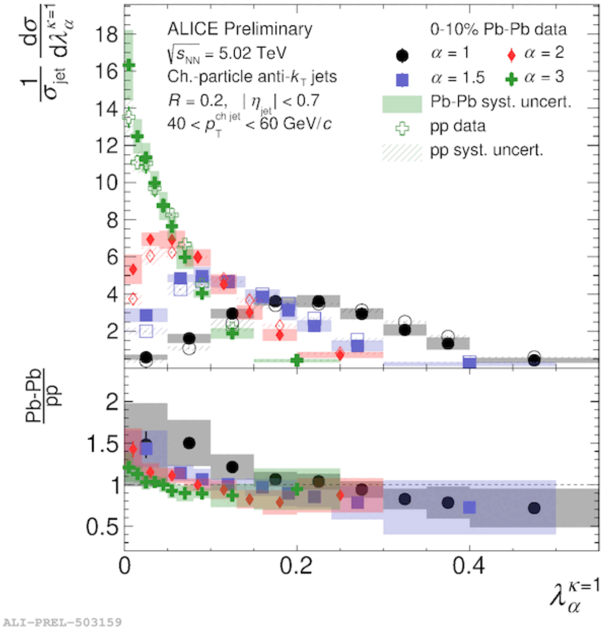
$$\lambda_{\alpha}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\alpha}$$

- **Groomed and ungroomed generalized jet angularities** reveal effect of soft radiation
- Shift toward lower angularities
  => **Narrowing of jets** for both the groomed and ungroomed case

groomed



ungroomed



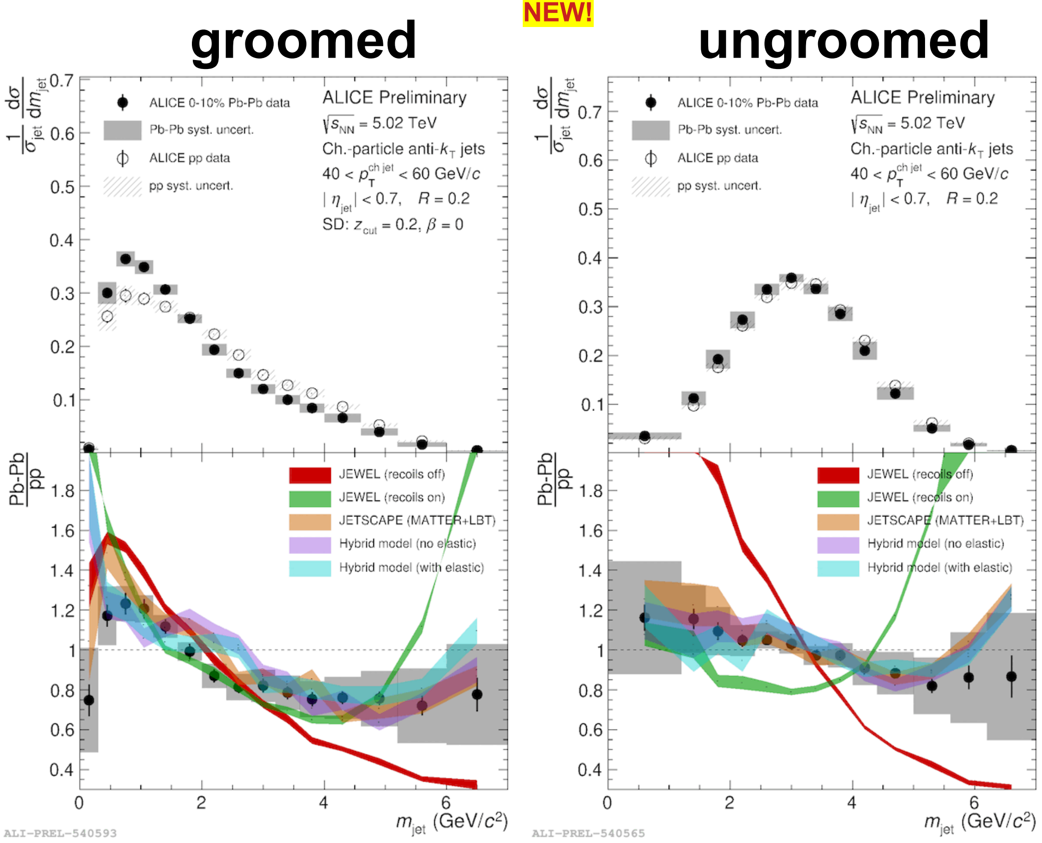
Jet mass (ALICE)

- **Jet mass related to thrust**

$$m_{\text{jet}} \sim z\theta^2$$

- Shift towards lower masses => **Narrowing of jets**
  - Several models describe jet quenching
- **Grooming enhances sensitivity to modification of jet fragmentation**
  - Modification of the jet core?

NEW!

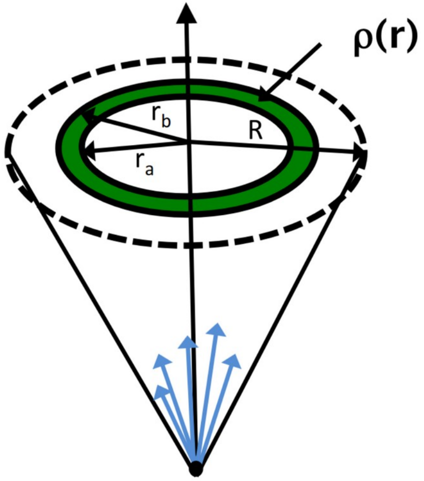


Jet shapes

- Jets clustered with anti-k_T using the E-scheme
- Axis calculated using WTA algorithm
- Jet shapes defined as

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\mathrm{jets}}} \frac{\sum_{\mathrm{jets}} \sum_{\mathrm{tracks} \in (\mathrm{r_a}, \mathrm{r_b})} p_{\mathrm{T}}^{\mathrm{ch}}}{\sum_{\mathrm{jets}} \sum_{\mathrm{tracks} \in \mathrm{r} \leq 1} p_{\mathrm{T}}^{\mathrm{ch}}}$$

- **Complementary information to groomed substructure** measurements
- Sensitive to soft radiation, background needs to be under control



CMS, JHEP 06 (2012) 160

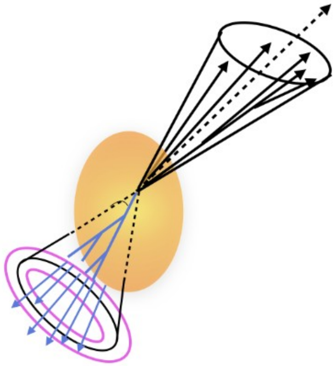
Dijet shapes (CMS)

- Back-to-back dijet shapes

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\frac{\sum_{\mathrm{jets}}\sum_{\mathrm{tracks}\in(\mathrm{r_a},\mathrm{r_b})} p_{\mathrm{T}}^{\mathrm{ch}}}{\sum_{\mathrm{jets}}\sum_{\mathrm{tracks}\in\mathrm{r}\leq 1} p_{\mathrm{T}}^{\mathrm{ch}}}$$

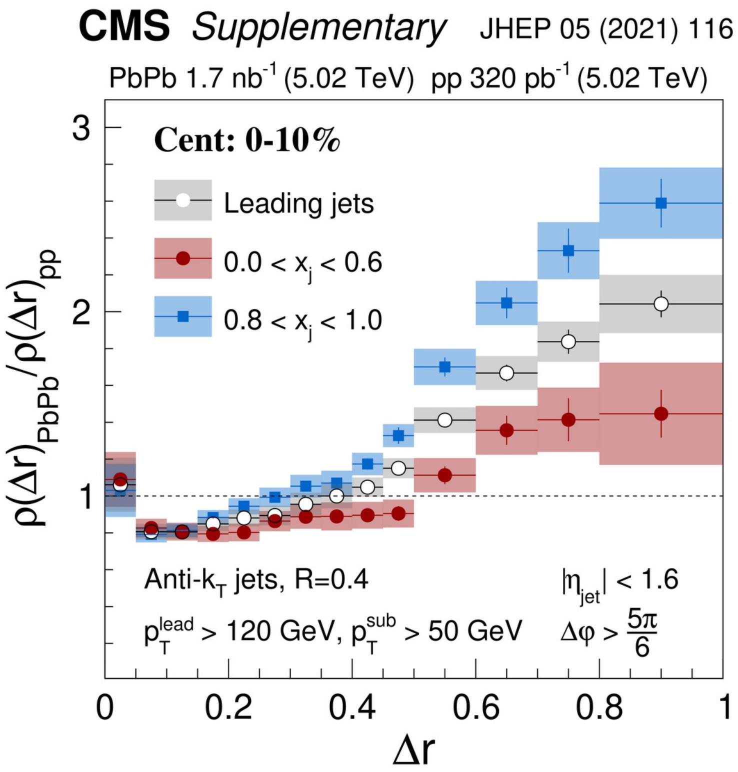
- in terms of momentum imbalance

$$x_j = p_{\mathrm{T}}^{\mathrm{subleading}} / p_{\mathrm{T}}^{\mathrm{leading}}$$



- Leading jets:
  - **redistribution of energy from small angles** w.r.t. the jet axis **to larger angles**
  - Stronger for balanced jets => path length dependence

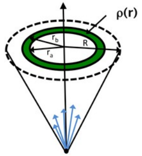
JHEP 05 (2021) 116



b-jet shapes (CMS)

- First study of jet shapes in HI collisions

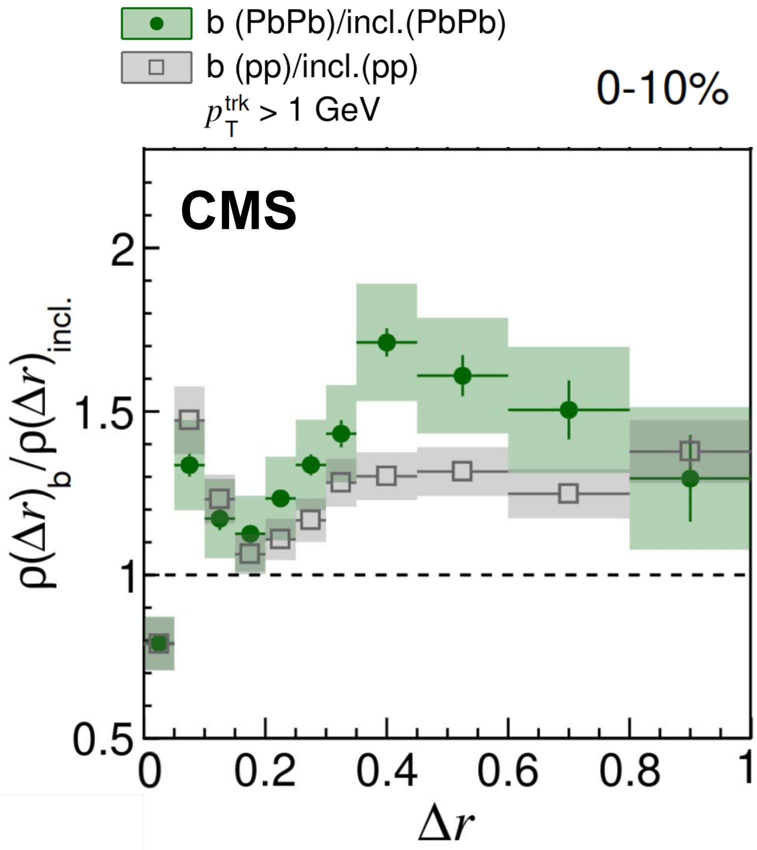
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\frac{\sum_{\mathrm{jets}}\sum_{\mathrm{tracks}\in(\mathrm{r_a},\mathrm{r_b})} p_{\mathrm{T}}^{\mathrm{ch}}}{\sum_{\mathrm{jets}}\sum_{\mathrm{tracks}\in\mathrm{r}\leq 1} p_{\mathrm{T}}^{\mathrm{ch}}}$$



- Low-Δr depletion of b-jets
- **=> consistent with a dead-cone**

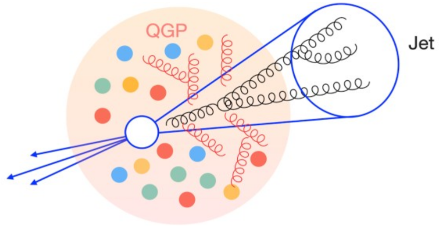
- High-Δr enhancement of b-jet shapes compared to inclusive jets, stronger in HI than in pp collisions
- **=> increased medium response to the propagation of a heavier quark**

arXiv:2210.08547



Summary

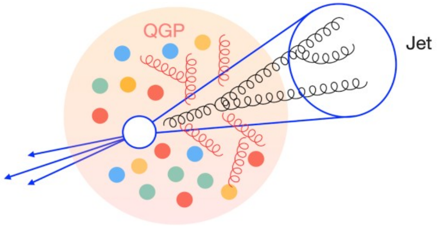
- **Jet substructure in heavy-ion collisions:
  a rapidly evolving area with lots of new measurements**



https://www.int.washington.edu/node/776

Summary

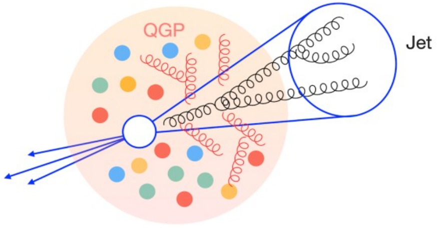
- **Jet substructure in heavy-ion collisions:**
  a rapidly evolving area with lots of new measurements
- **A tiny selection of the new results was shown**
  - No clear evidence for point-like scattering centers
  - Jet suppression strongly dependent on jet substructure
  - General narrowing of the jet core
  - Pathlength-dependent modification patterns
  - Increased medium response to a heavier quark



https://www.int.washington.edu/node/776

Summary

- **Jet substructure in heavy-ion collisions: a rapidly evolving area with lots of new measurements**
- **A tiny selection of the new results was shown**
  - No clear evidence for point-like scattering centers
  - Jet suppression strongly dependent on jet substructure
  - General narrowing of the jet core
  - Pathlength-dependent modification patterns
  - Increased medium response to a heavier quark



https://www.int.washington.edu/node/776

- **Increased sensitivity and new observables with the advent of Run 3**
  - Energy-energy correlators, photon-tagged systems, v_2 with substructure etc...
  - Extended heavy-flavor measurements

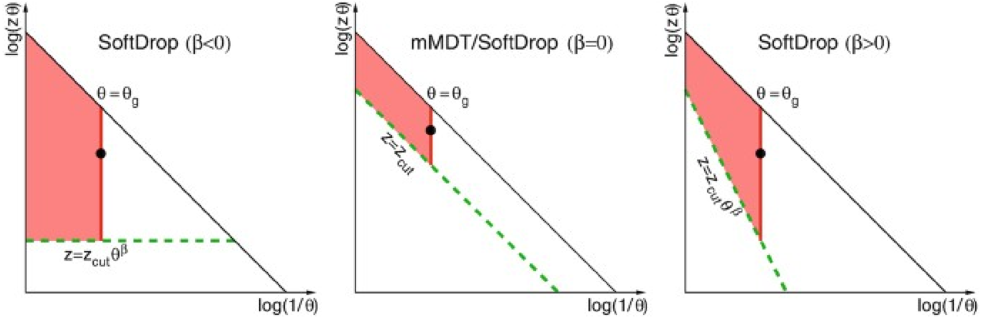
Thank you!

Lund planes

- **Soft drop grooming**

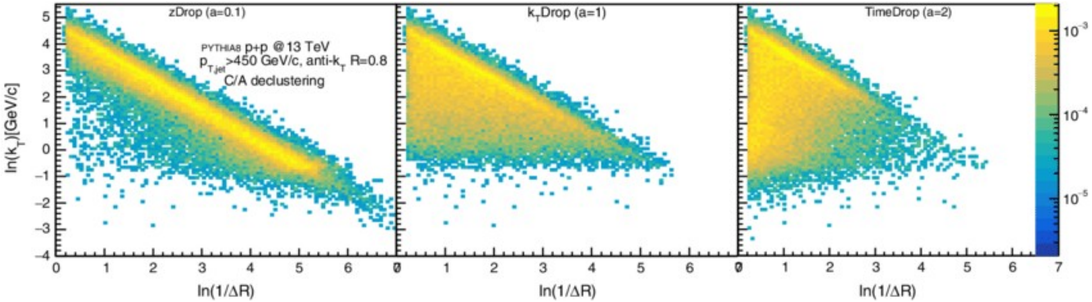
$$z > z_{\text{cut}}\theta^{\beta}$$

$$z = \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} \qquad \theta = \frac{\Delta R_{12}}{R}$$



- **Dynamical grooming**

$$\kappa^{(a)} = \frac{1}{p_{\mathrm{T}}} \max_{i \in \mathrm{C/A\ seq.}} \left[z_i (1 - z_i) p_{\mathrm{T},i} \left(\frac{\theta_i}{R} \right)^{a} \right]$$



Reclustered large-radius jets (ATLAS)

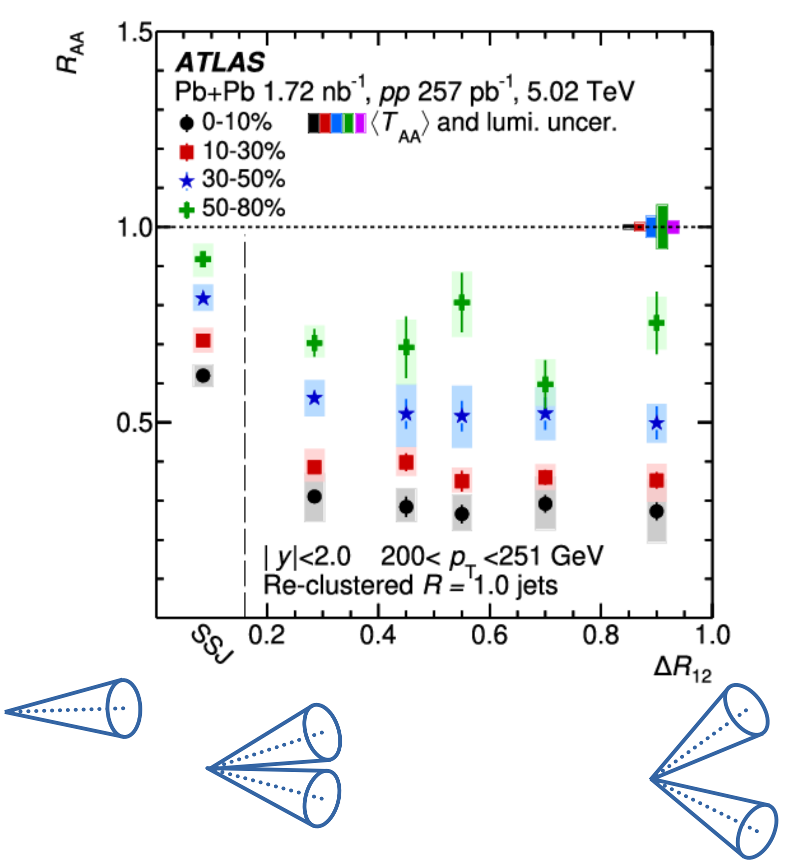
- Reclustered R=1 jets are slightly more suppressed than smaller-radii inclusive jets

- **Significant difference in the quenching of large-radius jets having single sub-jet and those with more complex substructure**

- No pronunced dependence on ΔR_{12} separation

- => supports **decoherence beyond a critical splitting angle**

arXiv:2301.05606



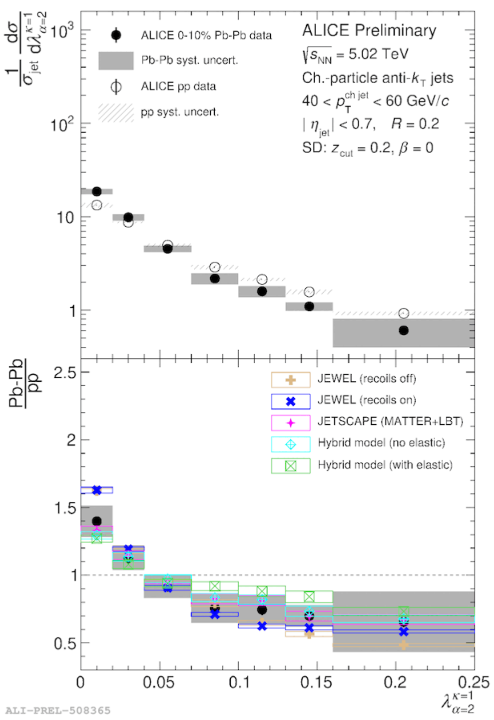
Generalized jet angularities α=2 (ALICE)

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

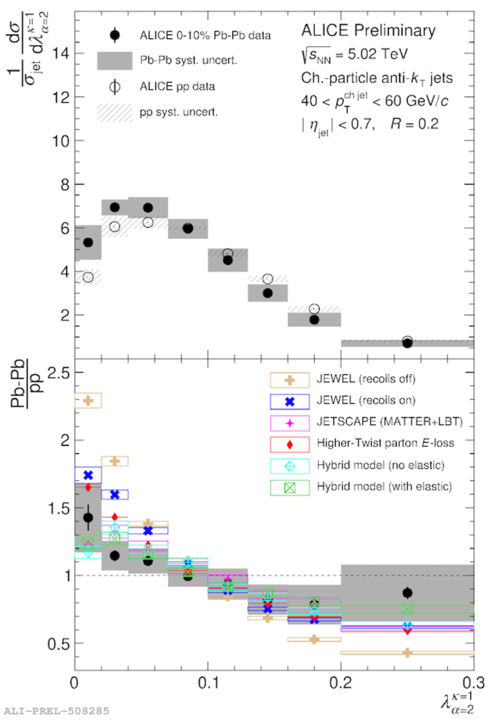
- **Groomed and ungroomed generalized jet angularities** reveal effect of soft radiation

- Shift toward lower angularities
  => **Narrowing of jets** for both the groomed and ungroomed case

groomed



ungroomed



Dijet shapes (CMS)

- Back-to-back dijet shapes

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\rm jets}}\frac{\sum_{\rm jets}\sum_{{\rm tracks}\in(r_a,r_b)} p_T^{\rm ch}}{\sum_{\rm jets}\sum_{{\rm tracks}\in r\leq 1} p_T^{\rm ch}}$$

- in terms of momentum imbalance

  $x_j = p_T^{subleading} / p_T^{leading}$
- Subleading jets
  - redistribution of energy from small angles w.r.t. the jet axis to larger angles
  - In unbalanced jets, fragmentation pattern consistent with a third jet