Jet substructure measurements with the ALICE experiment

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HUN REN wigner

ALICE

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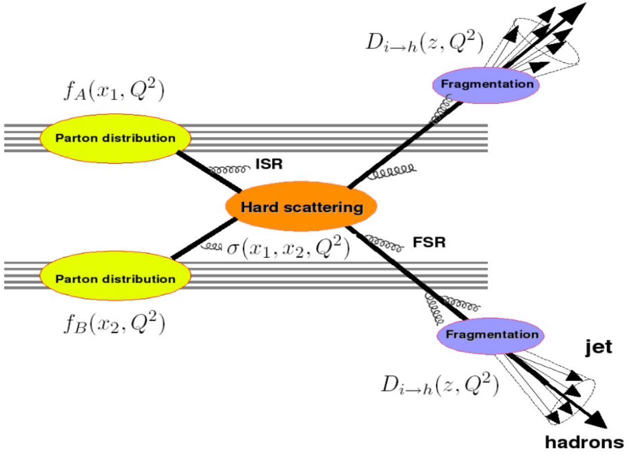
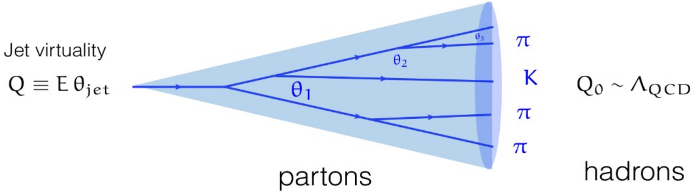
Background

- **Jets:** collimated showers of particles produced by fragmentation and hadronization of hard-scattered partons.
- **Experimentally:** defined by a jet reconstruction algorithm and a jet resolution parameter R.
- An experimentally accessible **observable** to "capture" the directly unmeasurable **parton shower**.

D. d'Enterria arXiv:0902.2011





Background

- **Jets:** collimated showers of particles produced by fragmentation and hadronization of hard-scattered partons.
- **Jet substructure:** set of observables to extract information from the radiation pattern inside the jets:
- **- in vacuum:** it probes specific phase space regions of QCD radiation for jet showers.
- **- in heavy-ion collisions:** it probes quark-gluon plasma (QGP) properties.
- **In this talk:** a selection of **jet substructure measurements in ALICE** in both pp and heavy-ion collisions.

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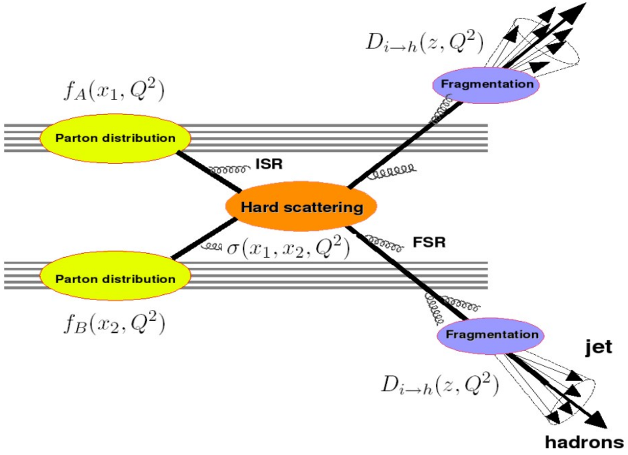
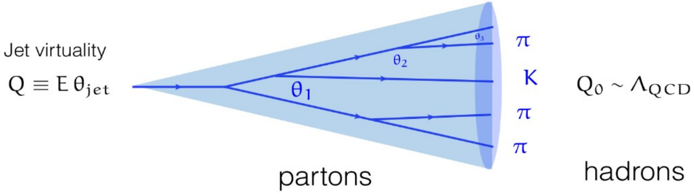
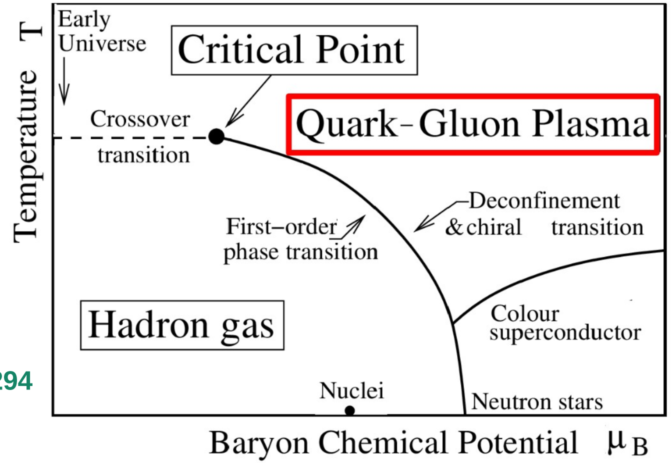


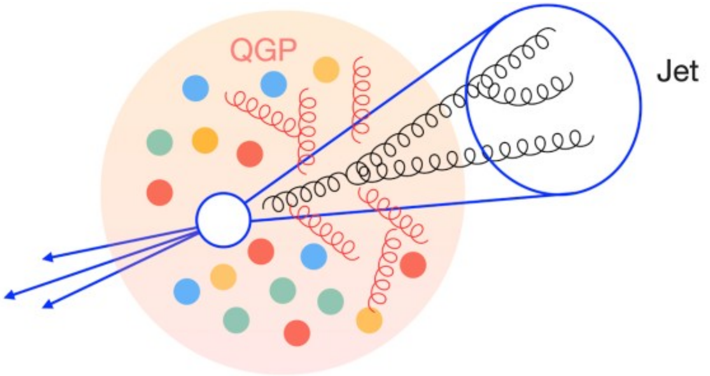


Probing the quark–gluon plasma with jets

- **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?
- **QGP in small collision systems?** Is there evidence of jet modification?
- Systematic study with jets and their substructure → constrain models for QGP dynamics

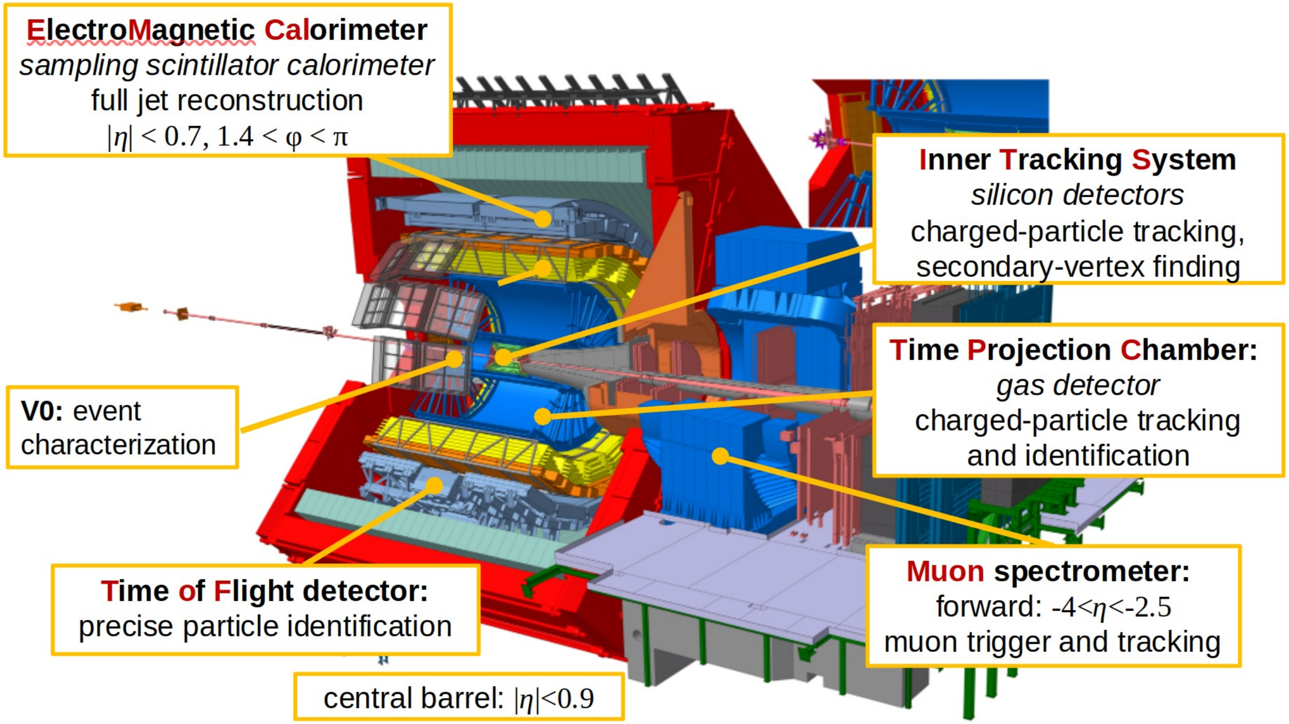


Bhalerao arXiv:1404.3294



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

The ALICE detector



More ALICE talks:

Kai Schweda:
"The ALICE Experiment at the LHC"

Róbert Vértesi:
"The ALICE 3 detector concept for LHC Runs 5 and 6 and its physics performance"

The ALICE detector has **unique capabilities for jet substructure measurements** due to the **high-precision tracking system**.

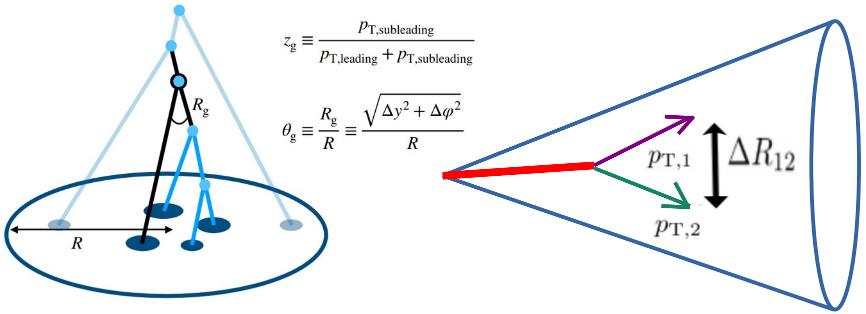
Jet grooming

- **Jet Grooming:** accesses the perturbative parton structure of the jet by removing the soft components.

  - Mitigates the influence of the underlying event and hadronization.

  - Results directly comparable with pQCD calculations.

Phys.Rev.Lett. 128 (2022) 10, 102001



$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- **Soft Drop (SD) Grooming: dynamical trimmer**

  Larkoski et al., JHEP 05 (2014) 146

  - Angular-ordered reclustering with Cambridge-Aachen (C/A) jet algorithm.
  - Iteratively removing the soft branches which do not fulfill 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

  - Reclustering jets with C/A algorithm.
  - Tagging the splitting in the angular-ordered shower with the largest κ value which is given by:

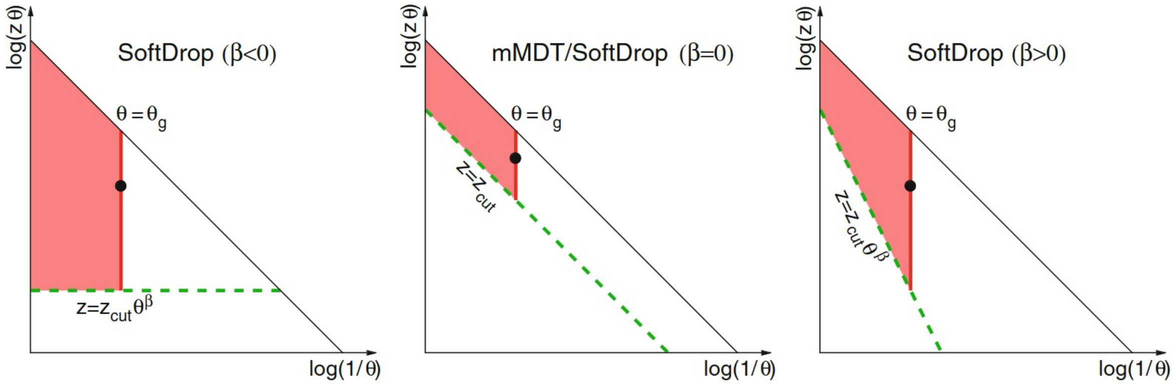
$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A\,seq.}} \left[z_i (1 - z_i) p_{T,i} \left(\frac{\theta_i}{R} \right)^a \right]$$

Lund planes

- **Soft drop grooming:**

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

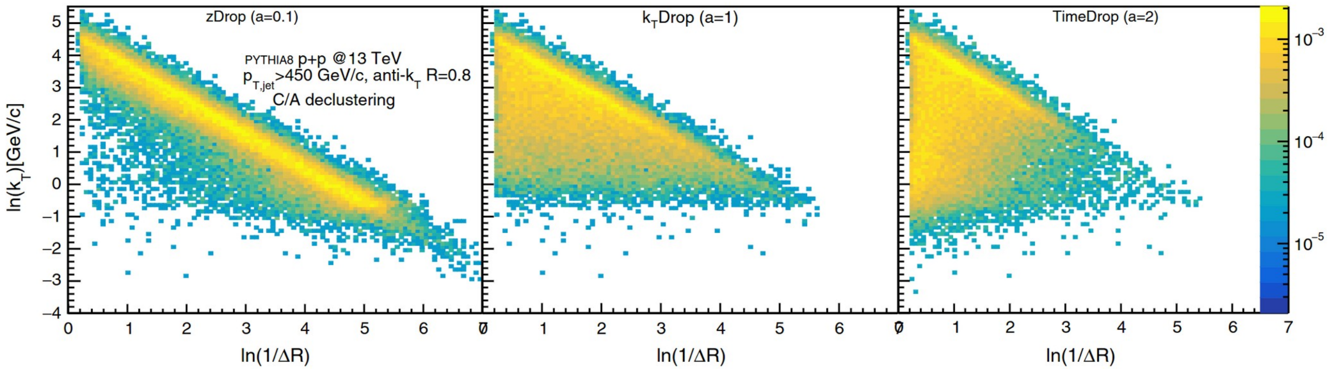
$$z = \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} \qquad \theta = \frac{\Delta R_{12}}{R}$$



S. Marzani, G. Soyez, M. Spannowsky: “Looking Inside Jets”

- **Dynamical grooming:**

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



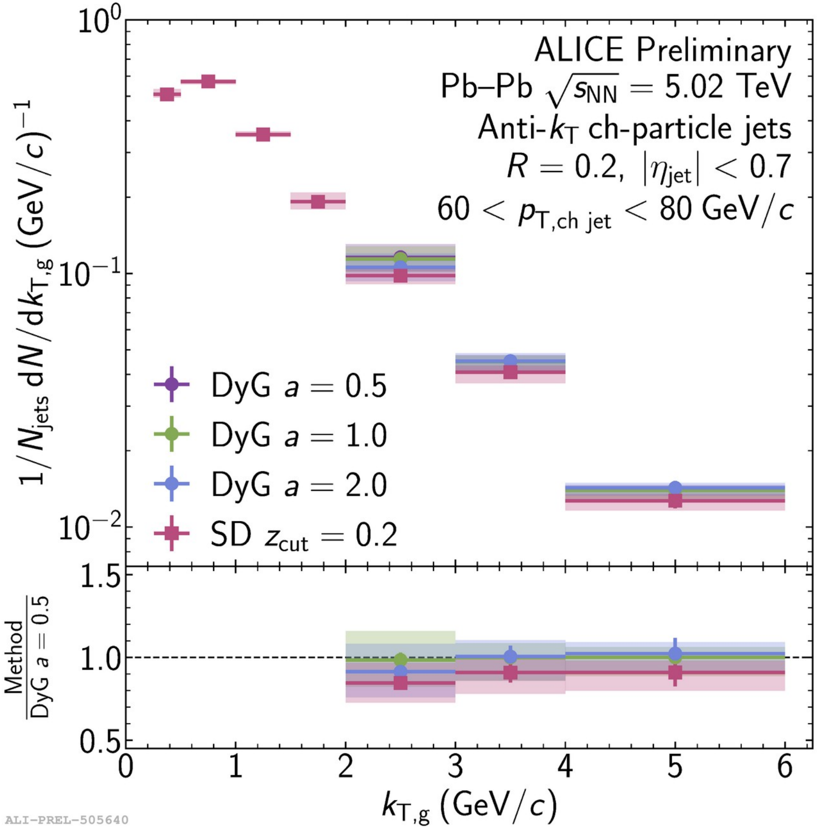
Y. Mehtar-Tani et al. Phys. Rev. D 101, 034004 (2020)

Hardest k_T jet splitting

$$k_T = p_{T,\text{subleading}} \sin \Delta R$$

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

- **Enhancement of high-k_T emissions can be a signature of point-like scattering (Molière)**
  - First measurement with dynamical grooming in Pb+Pb collisions.
  - Soft-drop grooming with $z_{cut} = 0.2$.
  - Grooming methods converge within uncertainties across all measured k_T.



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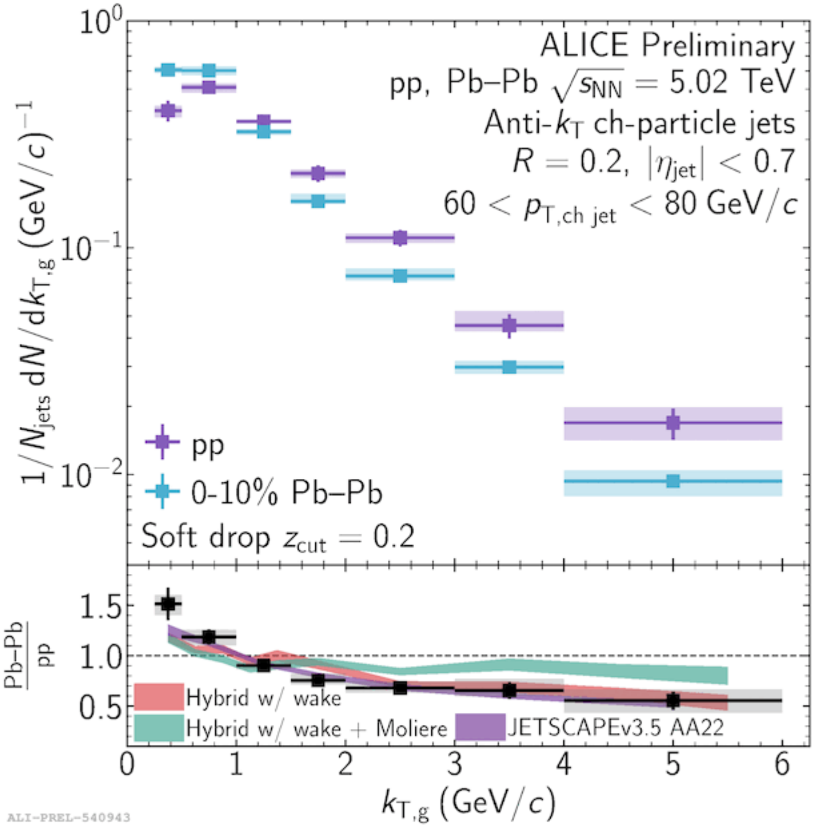
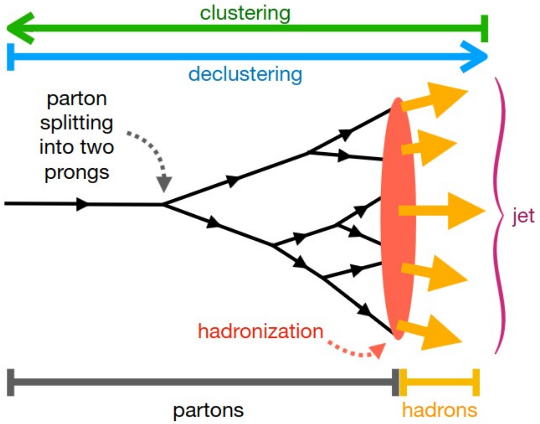
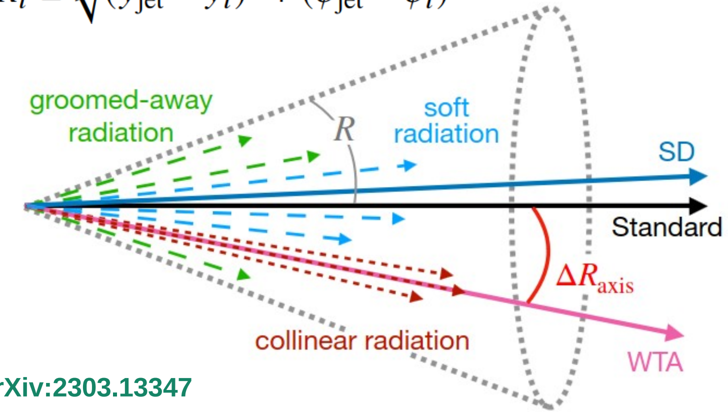
  - First measurement with dynamical grooming in Pb+Pb collisions.
  - Soft-drop grooming with z_{cut} = 0.2 .
  - Grooming methods converge within uncertainties across all measured k_T.
- No clear enhancement at high-k_T.
- **Models without Molière scattering describe the data better.**



Jet axis definitions



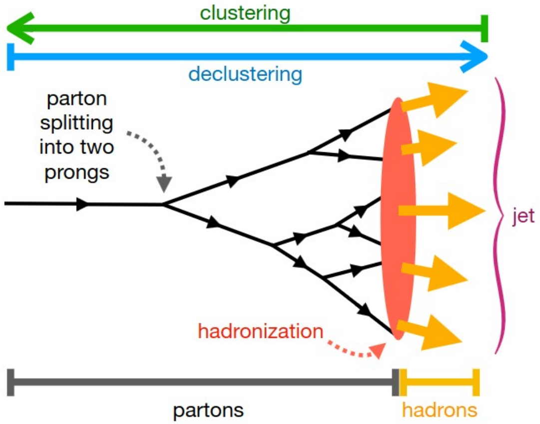
$$\Delta R_i \equiv \sqrt{(y_{\mathrm{jet}} - y_i)^2 + (\phi_{\mathrm{jet}} - \phi_i)^2}$$



arXiv:2303.13347

- **Idea:** Measure the angle between differently defined jet axes and compare it to models: allows us to differently probe the parton shower properties.

Jet axis definitions



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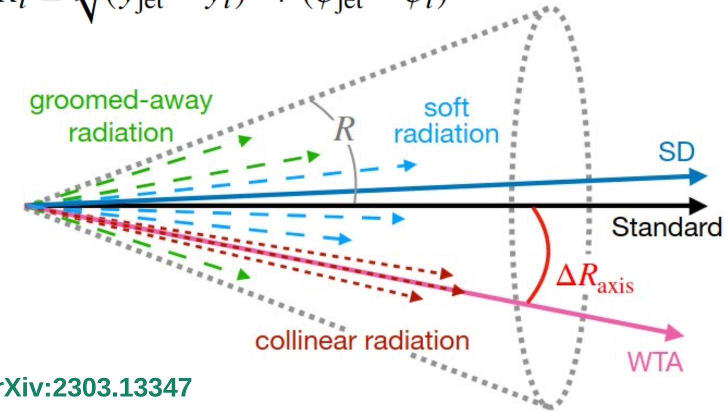


arXiv:2303.13347

- **Standard axis:** four-momentum sum of all jet constituents.

- **Soft-Drop (SD) axis**: soft wide-angle radiation is removed via the SD grooming procedure using the Cambridge-Aachen (C/A) reclustering, then the standard axis of the groomed jet is found.

- **Winner-takes-all (WTA) axis:** reclustering with C/A algorithm and WTA recombination scheme: at each step of the clustering the direction of the cluster is given by the direction of the hardest subjet, not the four-momentum sum of constituents.

  - WTA axis typically consistent with direction of hardest constituent.

  - Less sensitive to soft radiation.

Jet axis differences

- First measurement of the **angle between different jet axes** in Pb-Pb.

- Measurements at low transverse momenta

  → they can be a **sensitive probe of QGP effects** (but interpretation can be challenging).

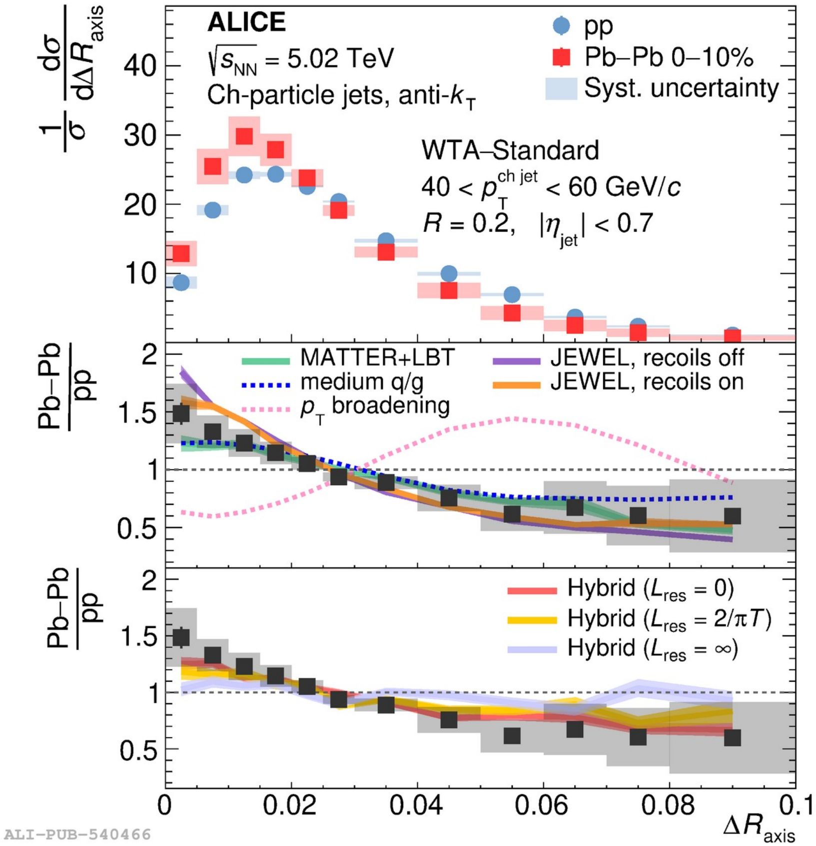
- **Narrowing in heavy-ion collisions**, compared to vacuum.

- **Sensitivity to medium resolution length.**
  - Comparison to hybrid model: measurement favors incoherent energy loss.

  J. Casalderrey-Solana JHEP 10 (2014) 019

- **Intra-jet p_T broadening model does not describe the data.**

arXiv:2303.13347

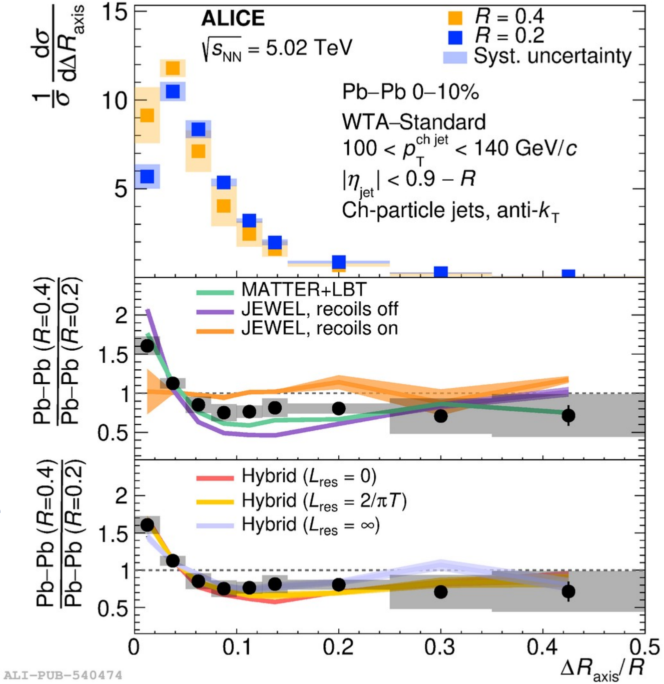


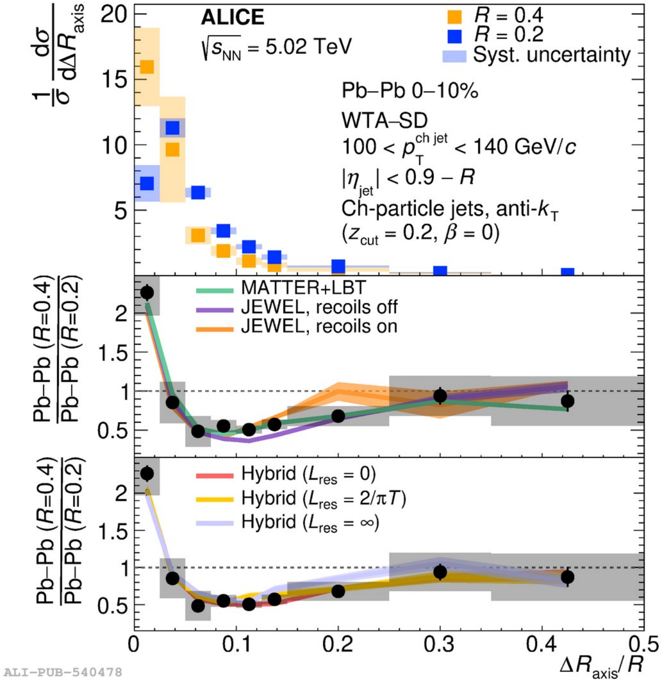
Jet axis differences

- Ungroomed WTA-Standard result is challenging to models.
- **Grooming improves the agreement** between models and data.

→ Ungroomed results capture significantly more of the the non-perturbative aspects of jet quenching.

arXiv:2303.13347



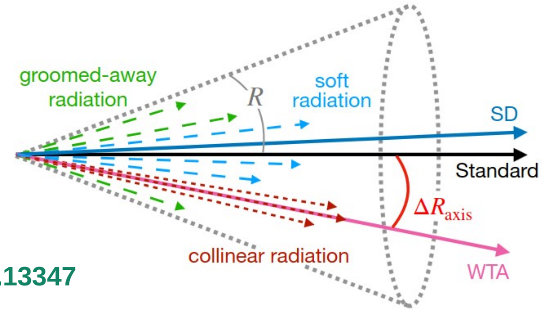


Generalized jet angularities

- **Jet angularities:** class of jet substructure observables that depend on both the momentum fraction and the angular separation of the jet constituents.

$$\lambda_\alpha^\kappa \equiv \sum_{i\in\text{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,\,jet}}}\right)^\kappa \left(\frac{\Delta R_i}{R}\right)^\alpha \equiv \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\alpha \qquad z_i = \frac{p_{\mathrm{T,i}}}{p_{\mathrm{T,jet}}} \qquad \theta_i = \frac{\Delta R_{i,\mathrm{jet}}}{R}$$

- These observables
  - are IRC-safe for $\kappa = 1$ and $\alpha > 0$ (theoretically accessible in the vacuum case),
  - can help quantify QGP related effects.
- Existing jet properties are generalized with continuously tunable parameters κ and α
  - Jet girth λ^1_1 and jet thrust λ^1_2.
  - Jet mass is related to jet thrust as $\lambda_2^1 = \left(\frac{m_{\text{jet}}}{p_{\mathrm{T,\,jet}} R}\right)^2 + O[(\lambda_2^1)^2]$



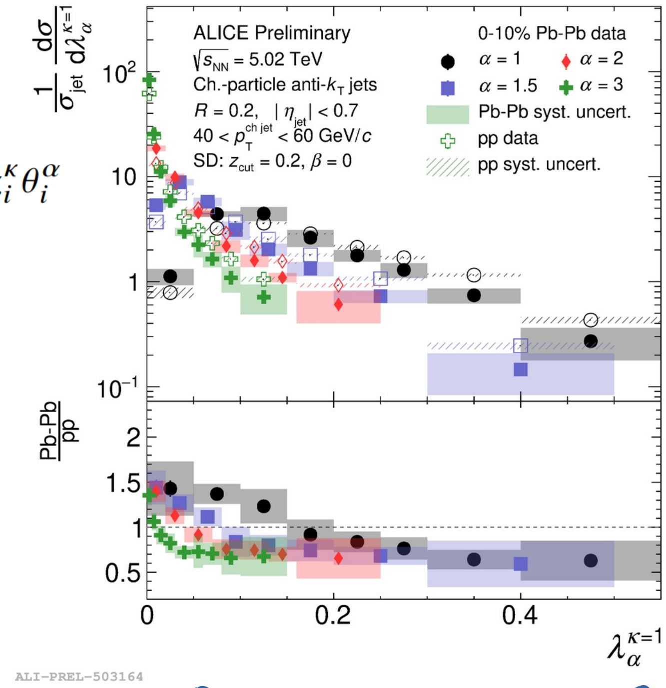
arXiv:2303.13347

- **Groomed** vs. **ungroomed** generalized jet angularities**:** provides information on the **effects of soft radiation**.

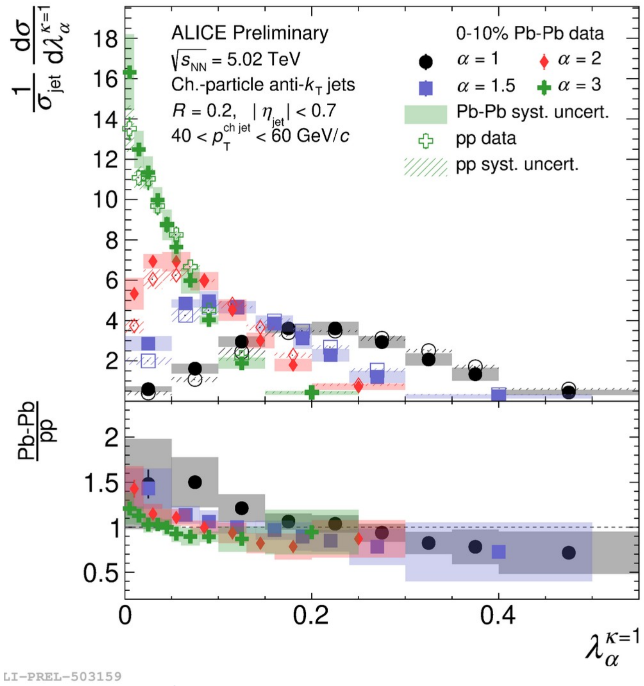
$$\lambda_\alpha^\kappa \equiv \sum_{i\in\text{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,\,jet}}}\right)^\kappa \left(\frac{\Delta R_i}{R}\right)^\alpha \equiv \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\alpha$$

- **Shift toward lower angularity values:**
  - **Jet narrowing.**
  - Both for groomed and ungroomed.

groomed



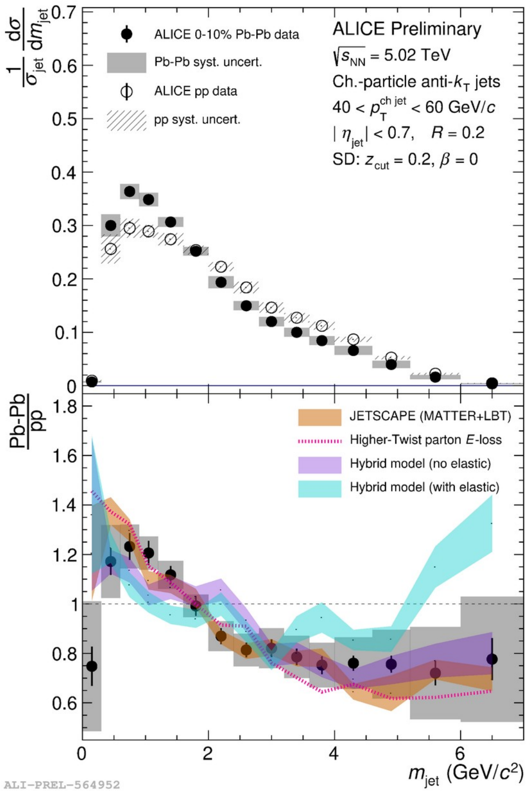
ungroomed

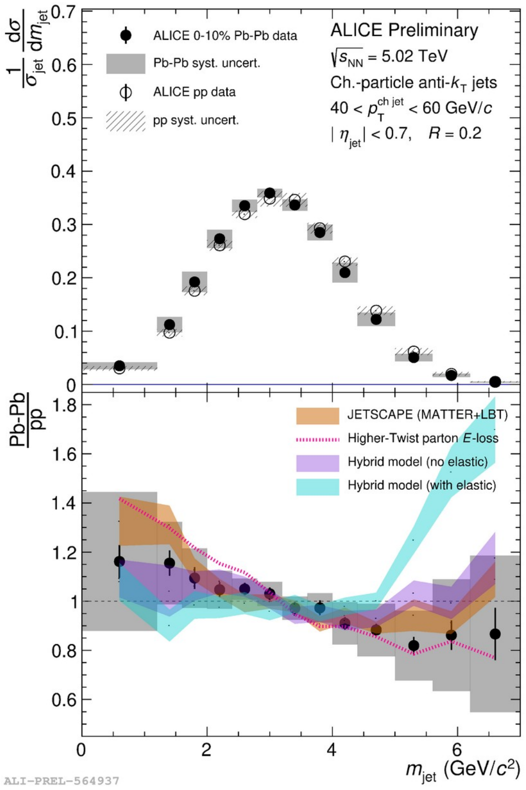


Jet mass

- **Jet mass:** $m_{\text{jet}} \equiv \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}$
- Related to **jet thrust:**
  - $m_{jet} \sim z\theta^2$
  - but not identical in physical sensitivity.
- Shift toward lower masses → **narrowing of jets**.
  - Several models describe jet quenching.
- **Grooming enhances sensitivity to modification of jet fragmentation.**
  - **Modification of jet core?**

groomed arXiv:2311.11136 **ungroomed**





- Comparing **groomed and ungroomed generalized jet angularities** reveal **effects of soft radiation**.

- Shift toward lower thrust values → **narrowing of jets**.

  - Both for groomed and ungroomed case.

- **Comparing to jet mass results:**

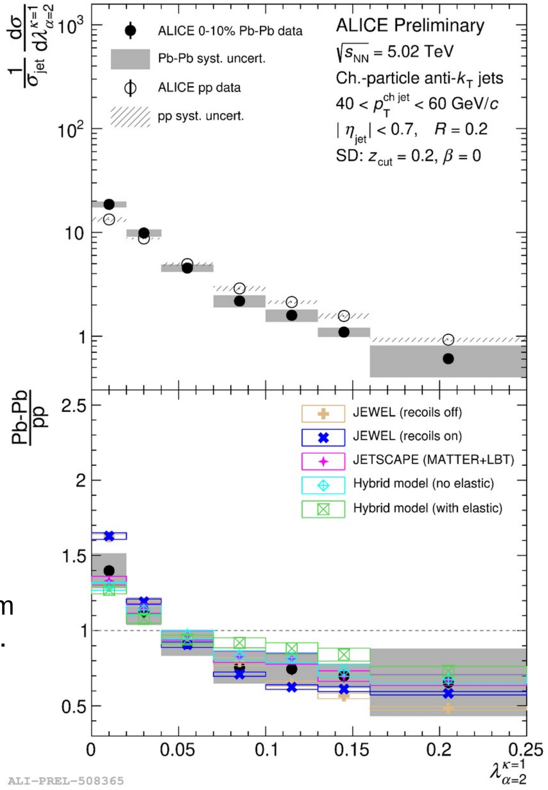
  - **Different physical sensitivity.**

Correction term might be large.

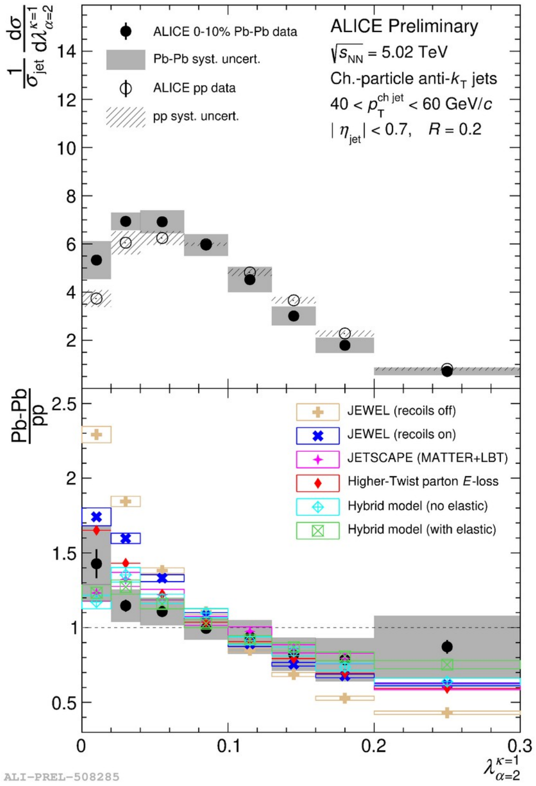
$$\text{jet thrust } \lambda_2^1 = \left(\frac{m_{\text{jet}}}{p_{\text{T, jet}} R}\right)^2 + O[(\lambda_2^1)^2]$$

arXiv:2311.11136

groomed



ungroomed



Is there QGP in small collision systems?

- **Collectivity in high-multiplicity p-p collisions:**

  - Substantial v_n, Yan-Ollitrault, PRL 112, 082301 (2014)

  - Enhancement of strange hadrons,

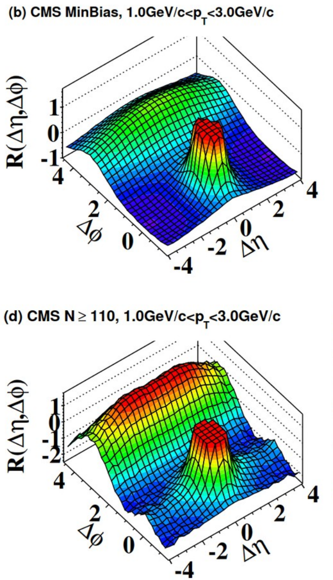
  - Ridge-like structure,

  - Intra-jet properties are promising observables, since they are sensitive to the parton shower and hadronization processes.

- **Questions arising:**

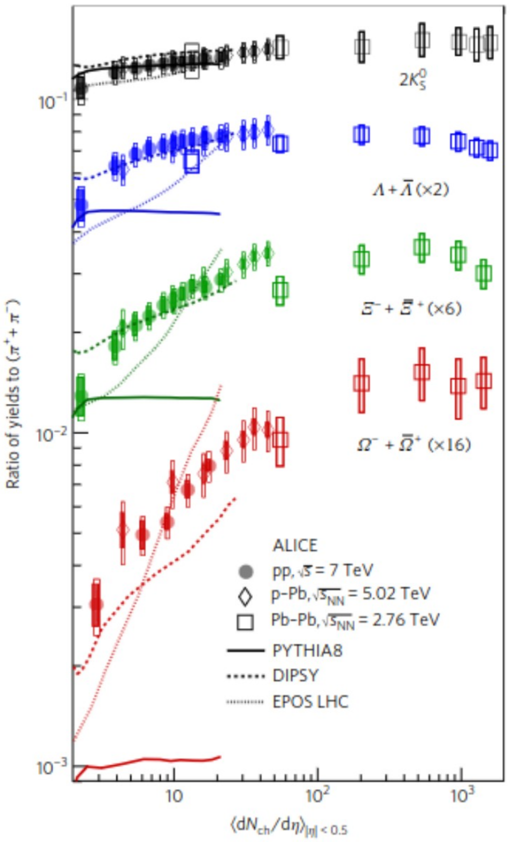
  - How do the QGP signatures evolve as a function of system size?

  - **Any evidence for jet quenching in small systems?**



CMS, JHEP 09 (2010) 091

Nature Physics 13 (2017) 535-539



Nuclear modification factor of jets

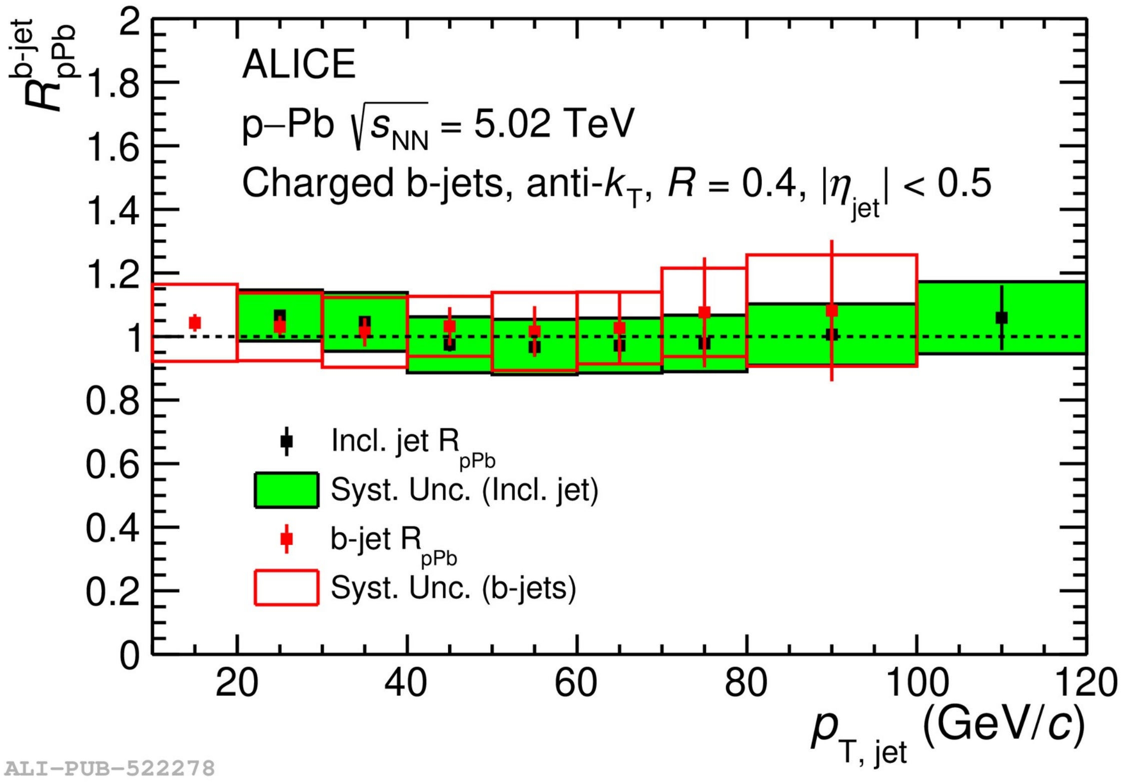
- **Inclusive and b-jets in minimum bias p-Pb:**

  - Nuclear modification factor is close to one:

  R ~ 1 → no jet quenching!

  - No flavor-dependent cold-nuclear-matter effects visible.

- **In small collision systems we have to look for a subtle modification effect.**

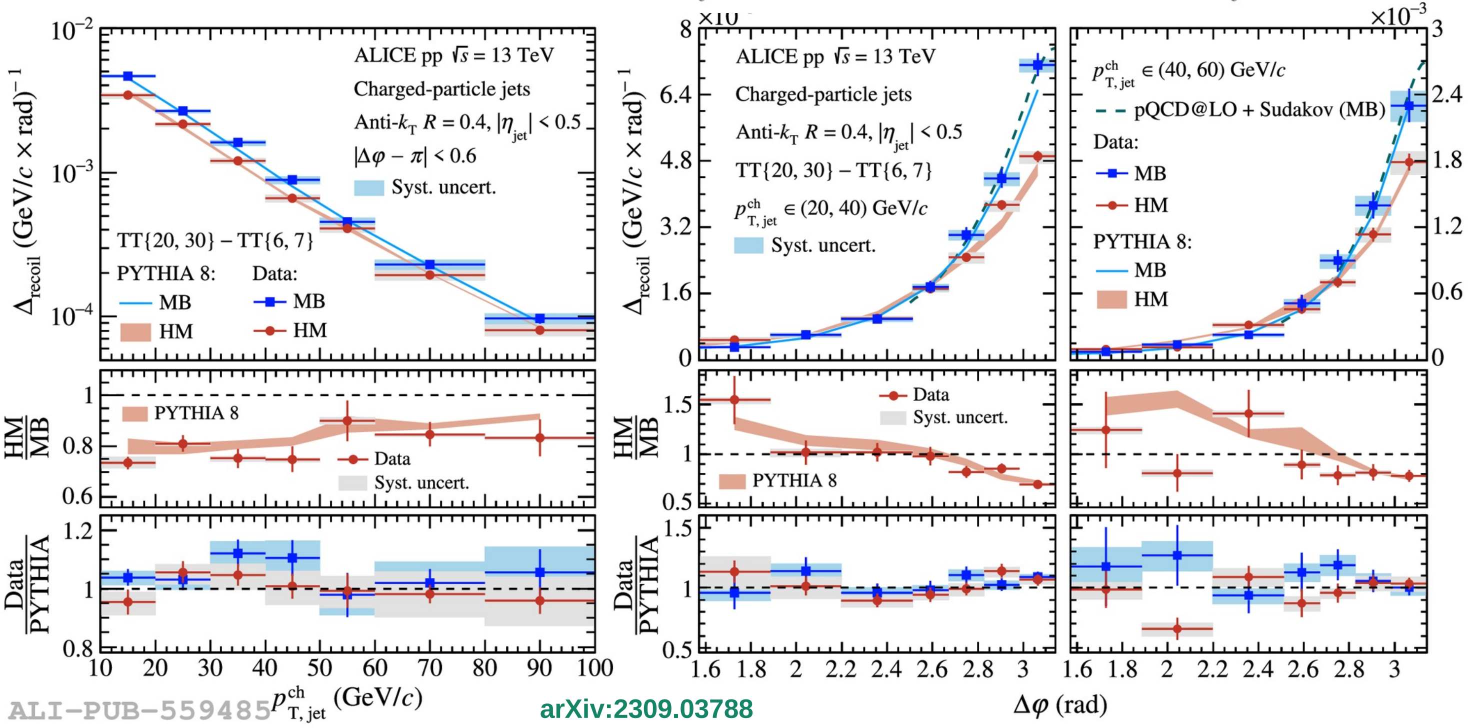


arXiv:2110.06104

Search for jet quenching in high-multiplicity pp

- **Observable:** Per trigger hadron normalized yield of correlated jets:

$$\Delta_{\mathrm{recoil}}(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{20,30\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}} - c_{\mathrm{ref}}\cdot\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{6,7\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}}$$



arXiv:2309.03788

At high-multiplicity: **Suppression of back-to-back correlation w.r.t. min-bias.**

Reproduced by PYTHIA!

- HM trigger makes it more likely to detect a high-p_T jet in V0C.

- Trigger effects can mask small jet quenching signals.

First measurement of E3C in ALICE

- **N-point projected energy correlators:**

ε → asymptotic energy flow operator T → stress-energy tensor

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta\hat{R}_L) \frac{1}{(E_{\mathrm{jet}})^N} \langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$$

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int_0^\infty dt\ r^2 n^i T_{0i}(t, r\vec{n})$$

- **Multiple advantages of E correlators:**
  - Calculable in pQCD framework.
  - IRC safe observable.
  - No need for grooming.
  - Separation of scales.

First measurement of E3C in ALICE

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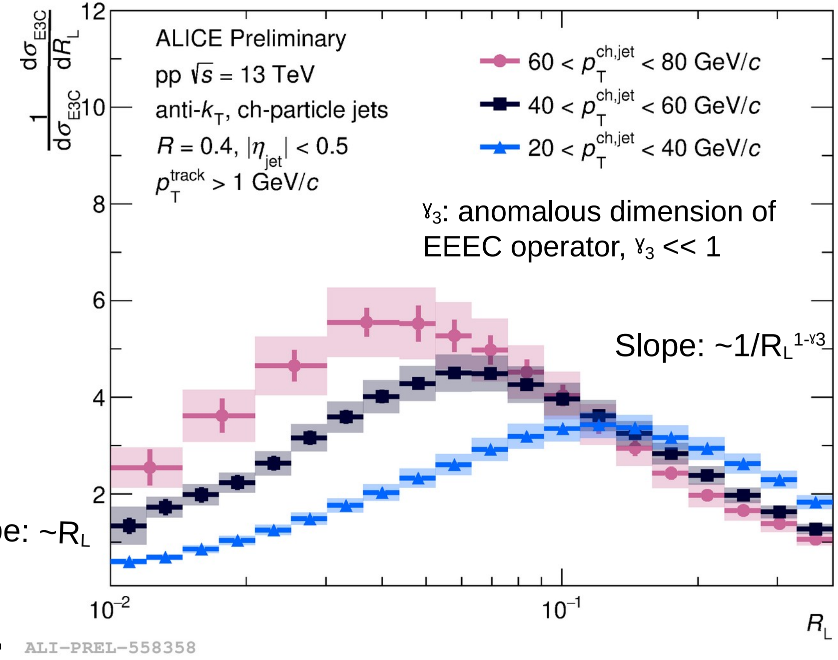
- **Energy-energy correlator (EEC):**
  - In experiment: a weighted histogram is created as a function of **R_L** (largest distance between 2 jet constituents) weighted with $p_{T,1}p_{T,2}/p_{T,\text{jet}}$.
  - Correlation between 2 jet constituents.
  - Probes the **scale dependence** of energy flow.

- **Energy-energy-energy correlator (EEEC):**
  - Provides information on shape of energy flow.
  - **Integrating out 2 of the 3 R distances gives E3C.**

First measurement of E3C at 13 TeV in ALICE:



Shows angular ordering of QCD.

First measurement of E3C/EEC in ALICE

- **N-point projected energy correlators:**

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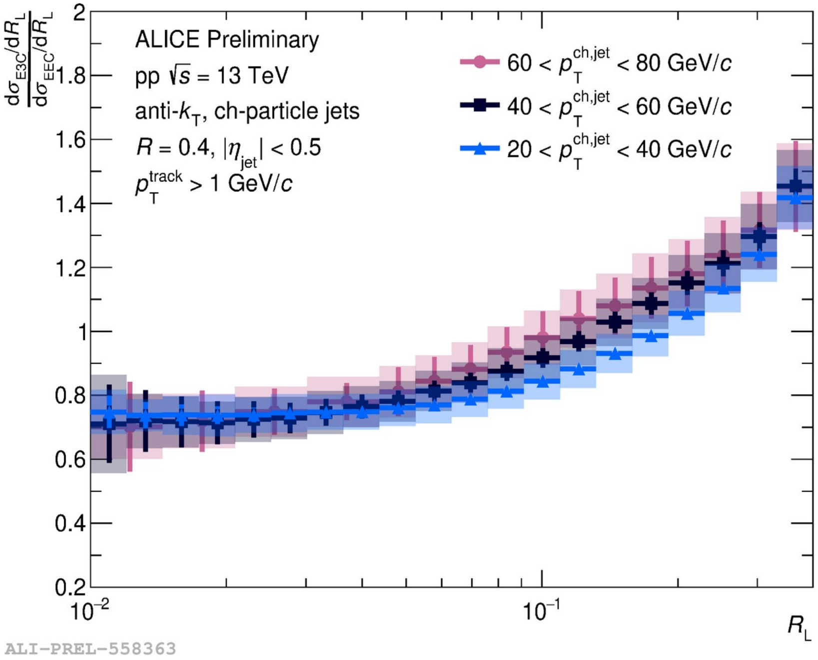
- **Measurement of E3C/EEC:**
  - non-perturbative regime: for all measured $p_{T,jet}$ bins the slope of the curves are the same.

  - perturbative regime: positive slope ($\gamma_3 > \gamma_2$), which reproduces the pQCD predictions ($\gamma_{N+1} > \gamma_N$).

  - The p_T – dependence of the slope indicates the running of the QCD coupling α_S.

First measurement of E3C/EEC at 13 TeV in ALICE:



Summary

- **Jet substructure:** a fast evolving research area with lots of new opportunities.

- A small selection was presented, with **many lessons** gained:

  - General narrowing of the jet (including the jet core) in Pb-Pb collisions,

  - No clear evidence of point-like scattering centers in the medium.

- **No evidence for jet quenching in small collision systems yet** $\rightarrow$ might be a small effect.

  - Important lesson: event selection biases can create jet quenching signatures!

- **Run 3 data provides increased sensitivity to the observables:**

  - e.g. differential energy-energy correlators, photon-tagged systems, v_2 with substructure, etc.

  - Extend heavy-flavor jet measurements.

Thank you!