Jet and Jet Substructure: ALICE Results

Diffraction and Low-x
Trabia, Sicily Italy
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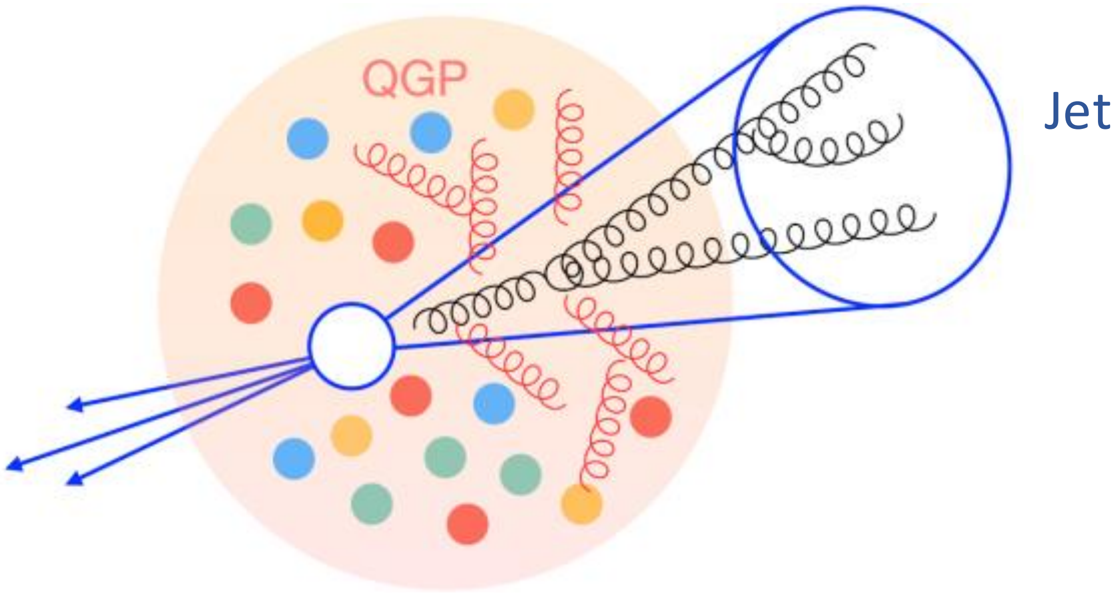
ALICE

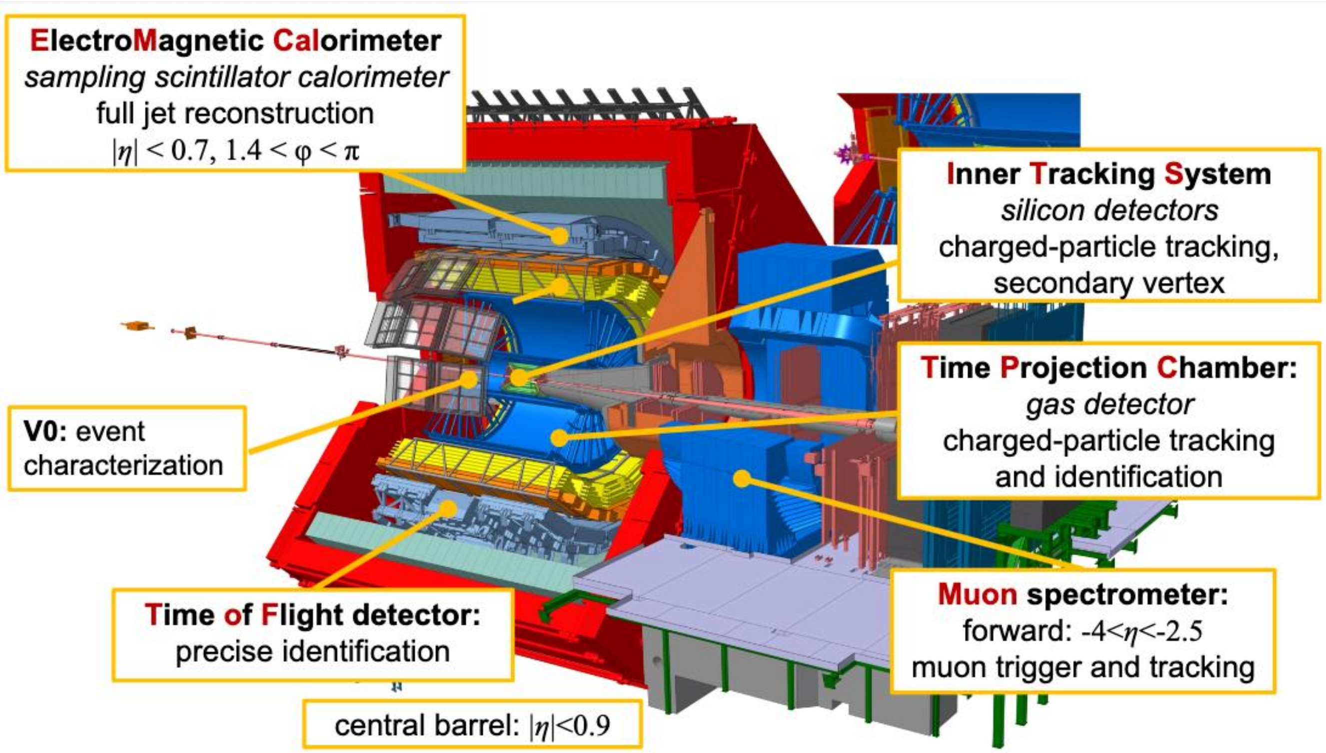
Jets and jet substructure

- Heavy-ion collisions create a deconfined phase of QCD matter - the QGP
- The QGP is too small and short-lived to be studied with external probes
- Jets are collimated sprays of particles resulting from quarks and gluons produced at high energy
- Jets are produced at the early stage of collisions, and interact strongly with the medium
  - Jets provide unique probes of the QGP at multiple scales
- Jet substructure is a set of tools to exploit information from the radiation pattern inside jets
- Jet-medium interactions manifests in different ways:
  - Energy loss – energy transport outside jet cone
  - Jet deflection via multiple soft scatters or single hard scatter
  - Jet fragmentation and substructure - insight into the microscopic modification



Jet measurement with the ALICE detector

- General purpose heavy-ion experiment at the LHC
- Coverage of central barrel: $|\eta| < 0.9$
- Excellent PID information
- High precision tracking capabilities down to 150 MeV/c
- Reconstructs jets at mid-rapidity with a high-precision tracking system (TPC and ITS) and EMCal in pp, p—Pb and PbPb collisions



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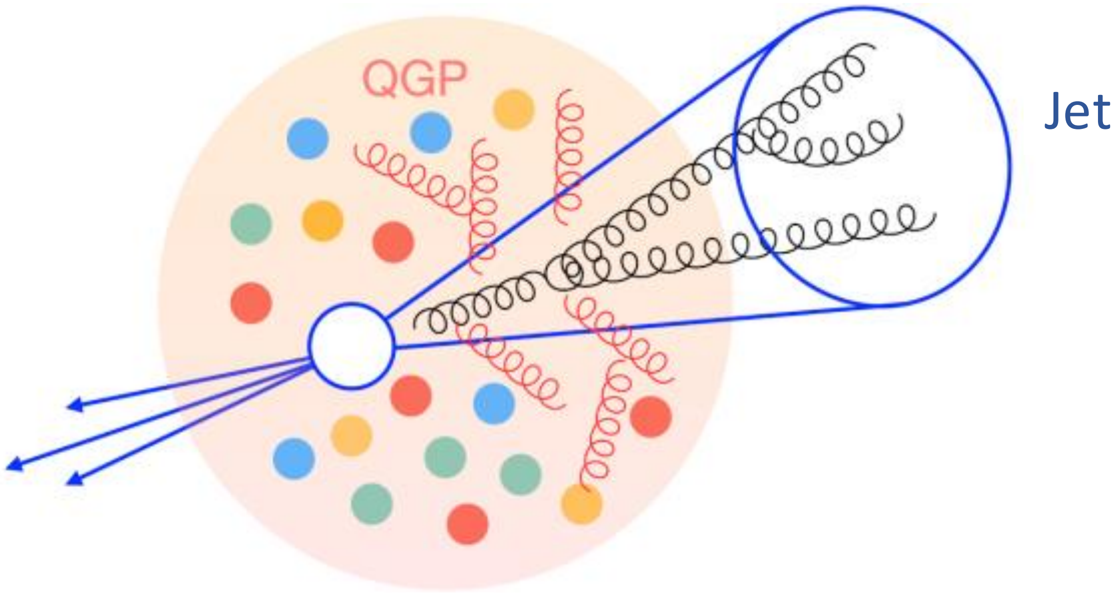
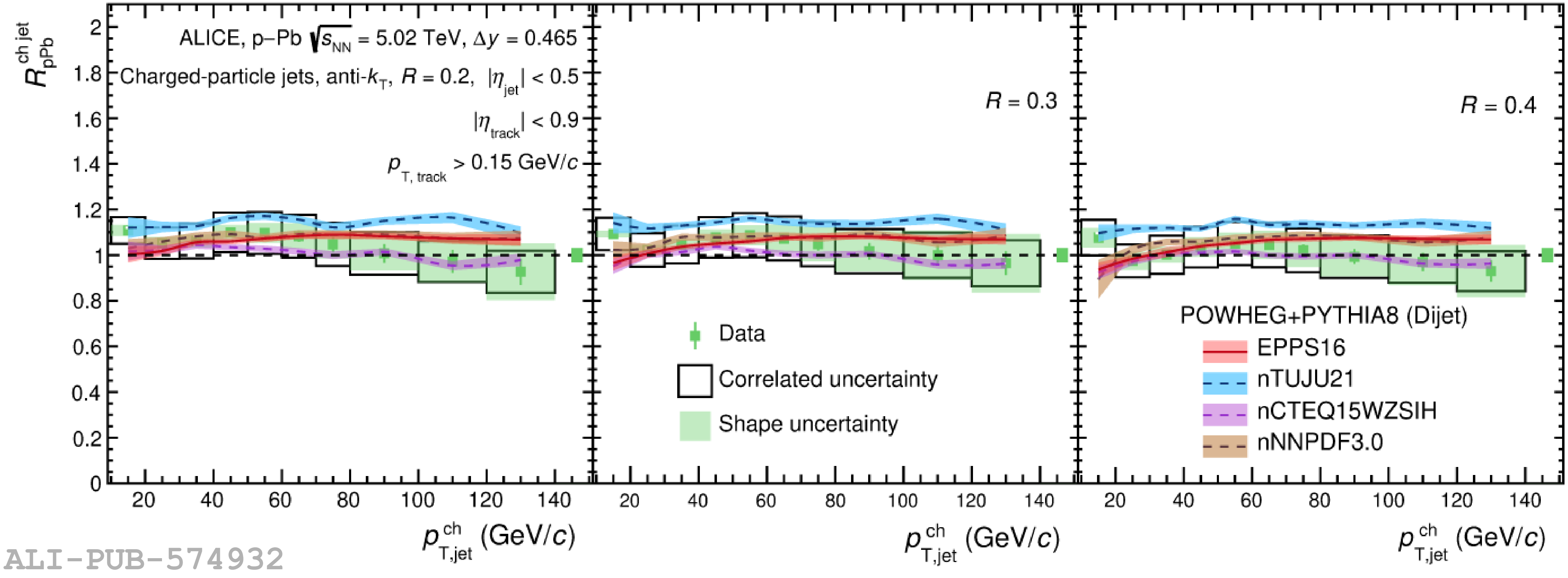


Inclusive jet R_{pPb}

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \Big/ \frac{\mathrm{d}^2\sigma_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

JHEP 05 (2024) 041



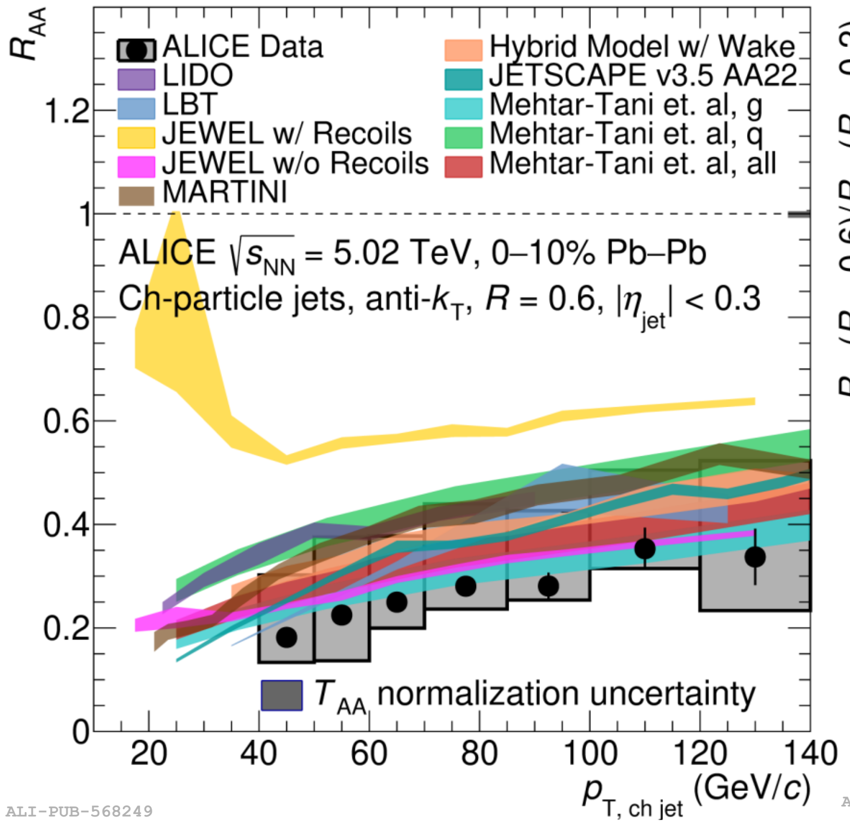
- R_{pPb} is consistent with unity – no significant modification within uncertainties
- Jet quenching, if present, is smaller than the sensitivity of the current measurement
- The NLO POWHEG+PYTHIA8 prediction describes the data within uncertainties
- Effects of nuclear-modified PDFs introduced by the nPDFs have minor impact on jet production

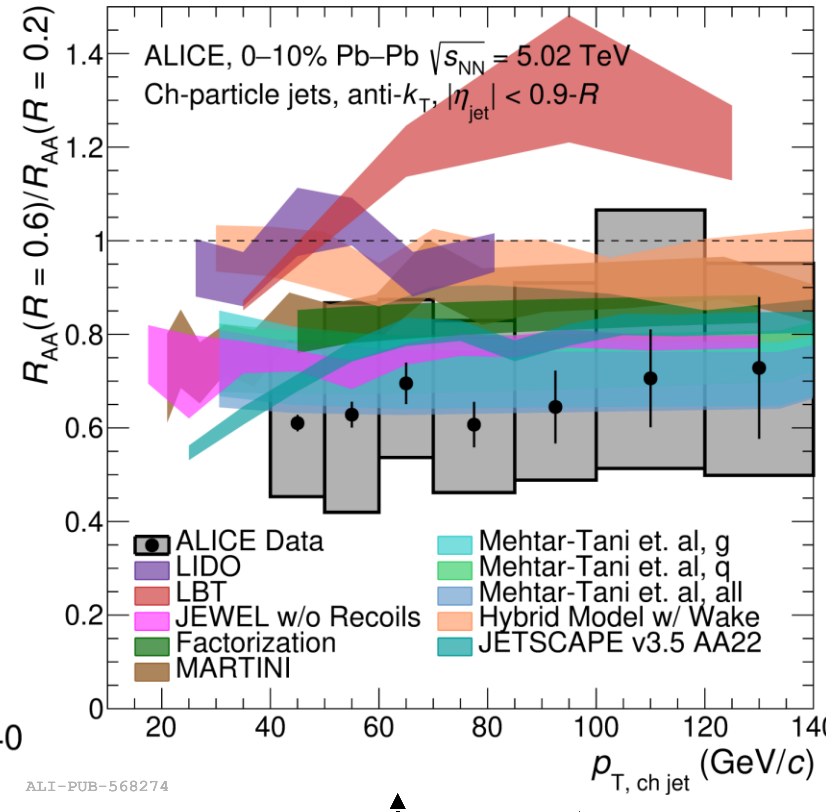
Inclusive jet R_{AA} and R dependence

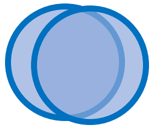
$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N_{PbPb}}{dp_T d\eta} \Big/ \frac{d^2 \sigma_{pp}}{dp_T d\eta}$$

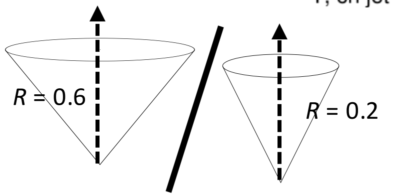
[PLB 849 (2024) 138412](PLB 849 (2024) 138412)

- New ML-based techniques allow for the extension to lower-p_T jet and large R = 0.6
  - Important since more substantial impact of quenching at low jet p_T
- R = 0.6 jets are more suppressed than R = 0.2 jets – R dependence of quenched jets
  - The jet energy is transferred mostly to soft particles, found at large angles relative to the jet axis
- Good agreement between data and model predictions









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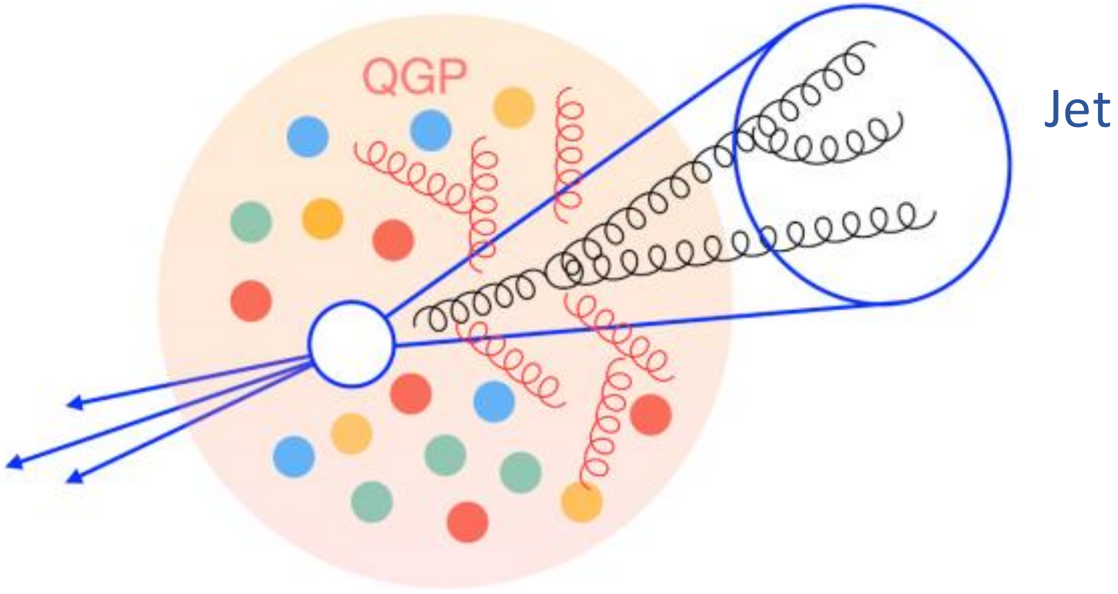
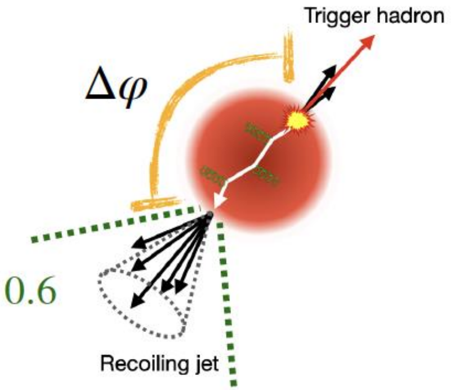


Semi-inclusive jet I_{AA}

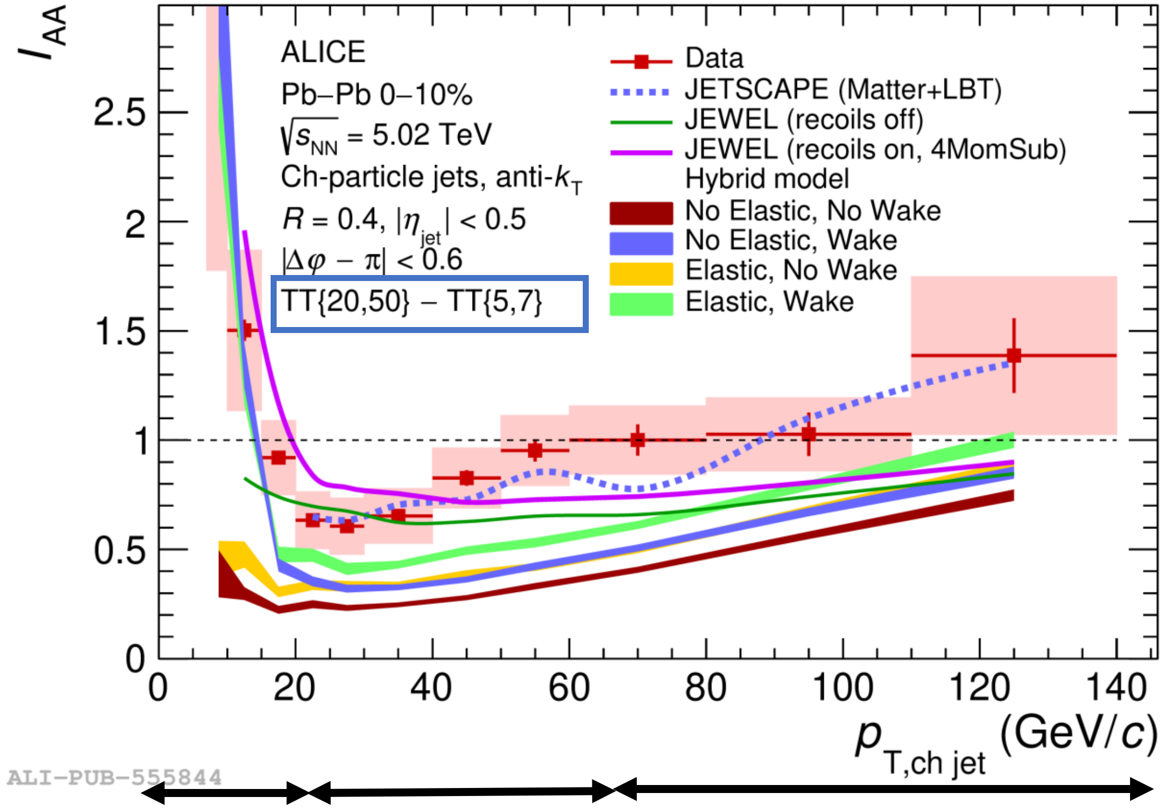
PRL 133 (2024) 022301
PRC 110 (2024) 014906

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$

$|\Delta\varphi - \pi| < 0.6$



- Measure the yield of charged-particle jets recoiling from a high-p_T trigger hadron
- Enhancement at $p_{T,jet}$ < 20 GeV/c
  - Surface bias - trigger hadrons are produced close to the edge of the QGP and escape it with little energy loss
- Suppression at 20 < $p_{T,jet}$ < 60 GeV/c
  - Jet energy loss
- Rising trend with increasing jet $p_{T,jet}$
  - Interplay of jet quenching and jet production



$p_T^{hadron} > p_{Tch}^{jet}$ $p_T^{hadron} \sim p_{Tch}^{jet}$ $p_T^{hadron} < p_{Tch}^{jet}$

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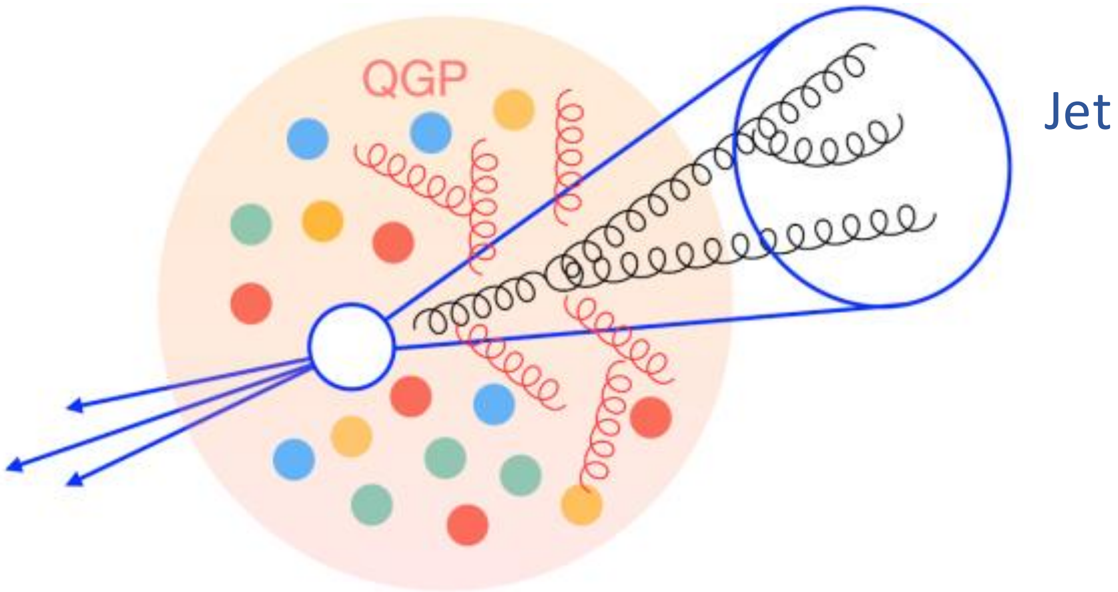
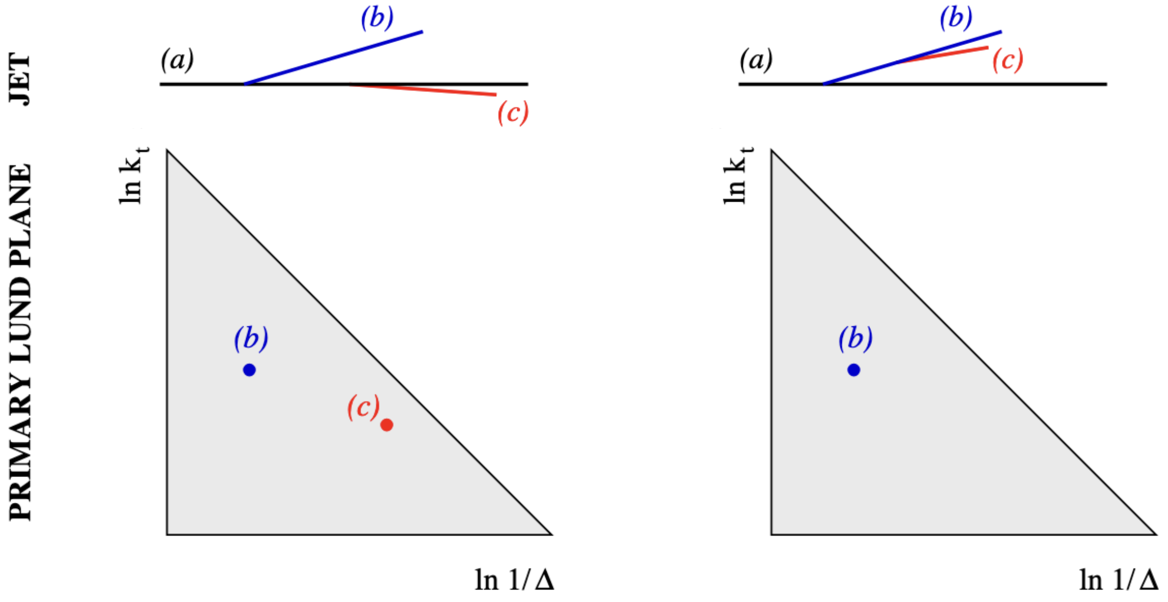


The primary jet Lund Plane

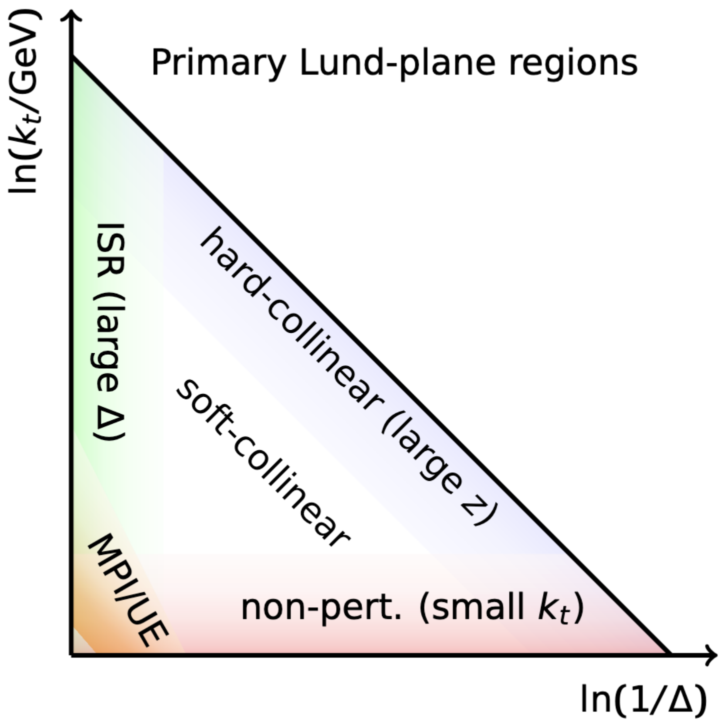


- Decluster jets using C/A algorithm by reversing the clustering to identify emissions – measure density of emissions in Lund Jet Plane

$$\Delta R = \sqrt{(\eta^{\mathrm{a}} - \eta^{\mathrm{b}})^2 + (\varphi^{\mathrm{a}} - \varphi^{\mathrm{b}})^2}$$

$$k_{\mathrm{T}} = p_{\mathrm{T,b}} \sin(\Delta R)$$

JHEP 12 (2018) 064



Lund diagram can be used to isolate regions of QCD phase space

The primary jet Lund Plane

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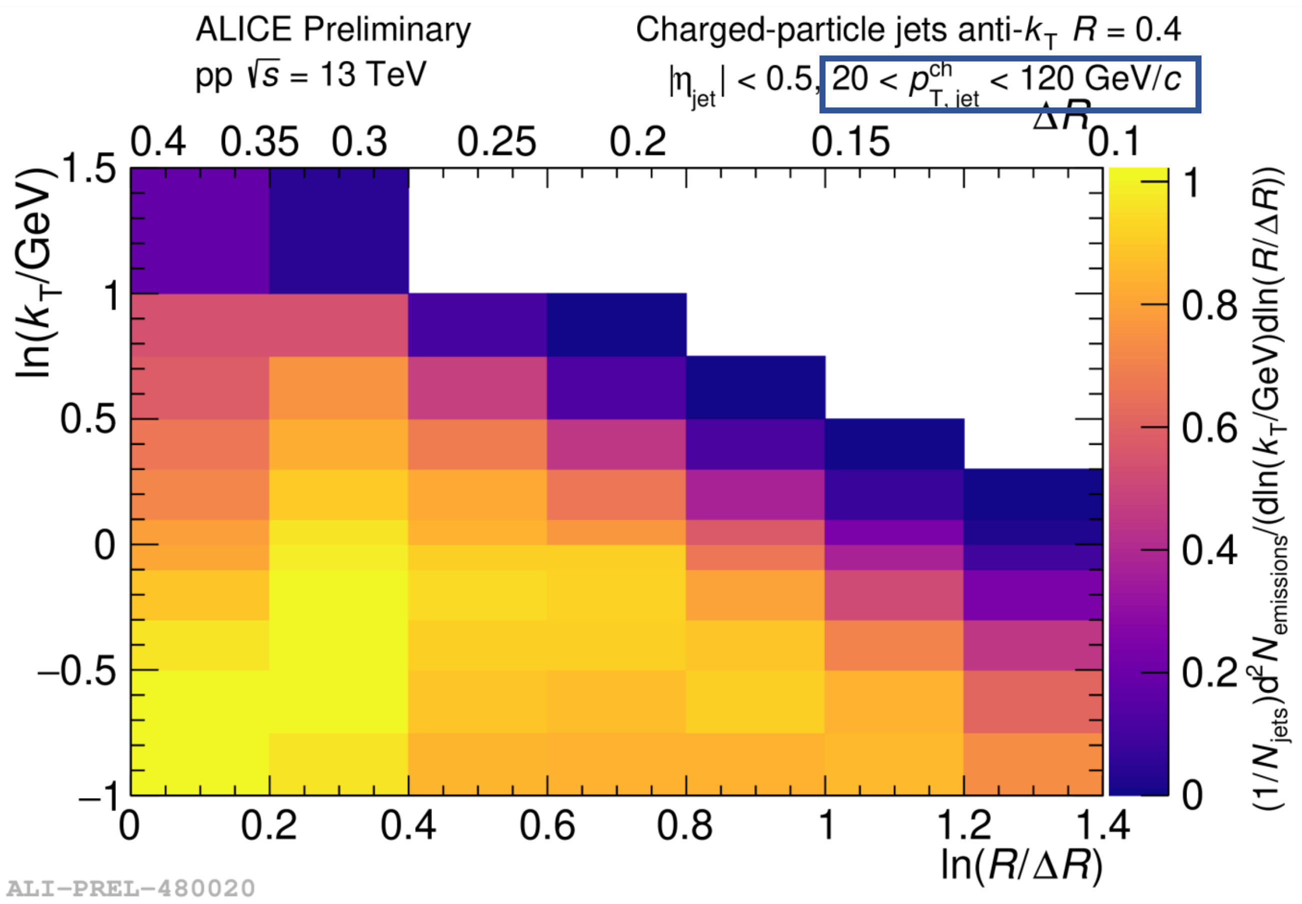

- Differentially looking at the Lund Plane in $20 < p_{T,jet} < 120$ GeV/c
- Compliments measurements by ATLAS ($p_{T,jet}$> 675 GeV, PRL 124, 2020) and CMS ($p_{T,jet}$>700 GeV, JHEP 05 (2024) 116)

The primary jet Lund Plane

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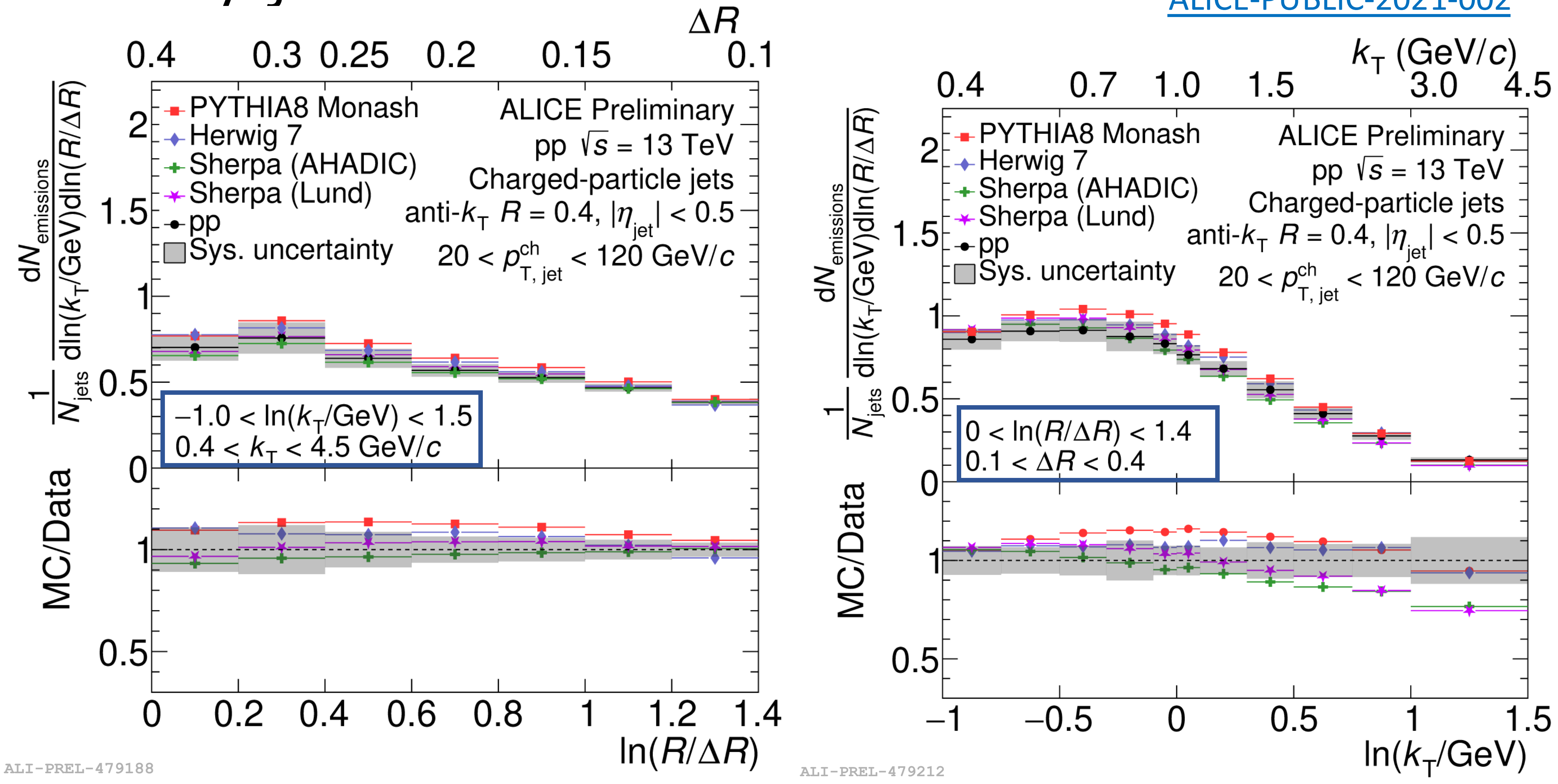


- Models reasonably describe the data within uncertainties

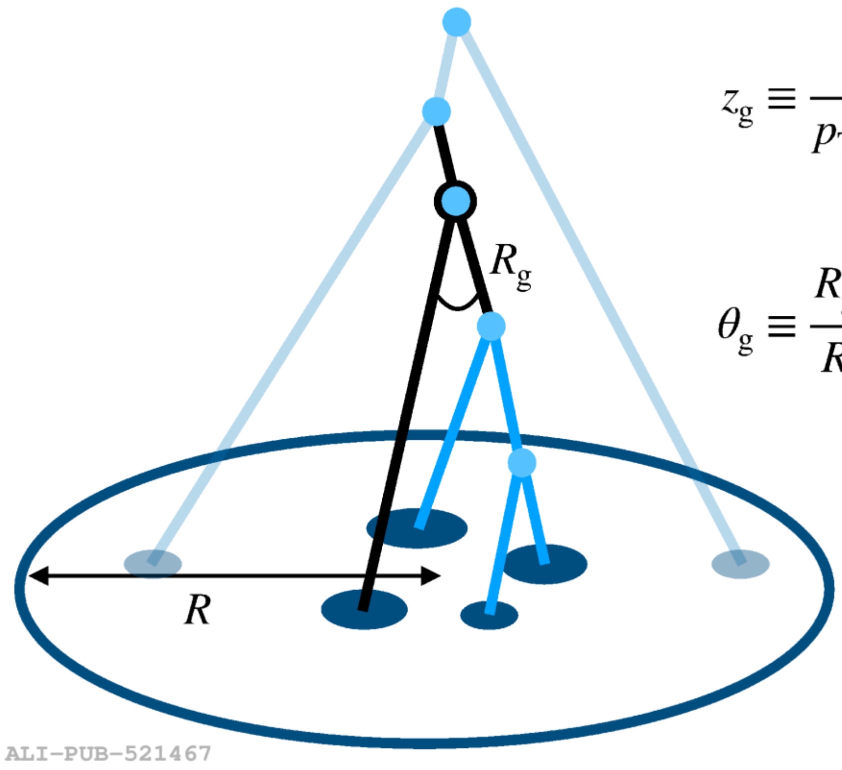
Jet grooming

PRL 128 (2022) 102001

- Jet grooming is a technique to remove soft, wide-angle radiations in vacuum, and reduce contamination from soft backgrounds in heavy-ion collisions
- **Soft drop algorithm:** select hard splittings satisfying the Soft Drop condition:

$$z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R}{R}\right)^{\beta}$$

- IRC safe – can be calculated analytically



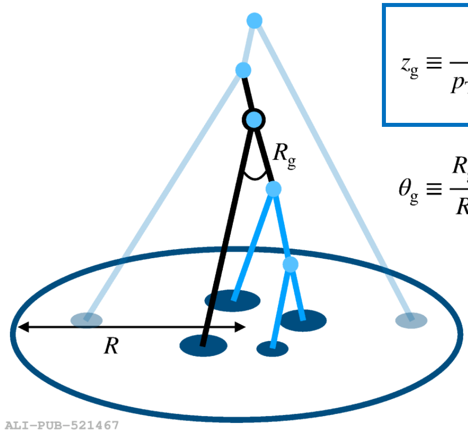
$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

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

Jet grooming

PRL 128 (2022) 102001

Jet momentum fraction, z_g



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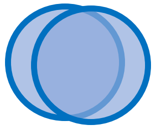
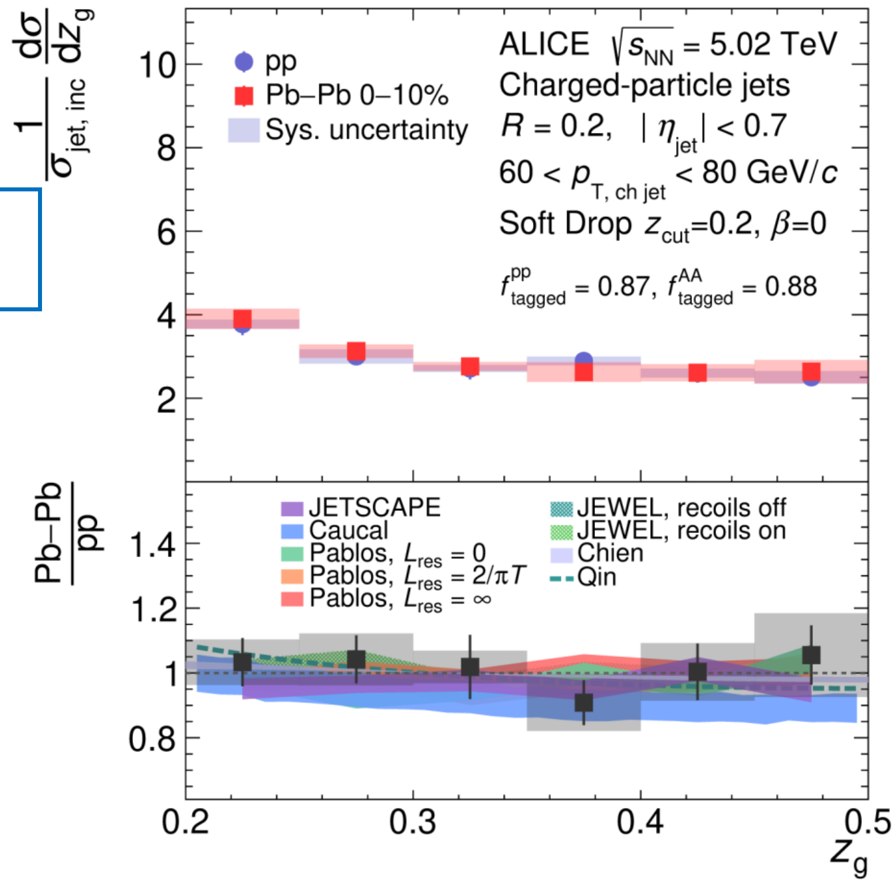
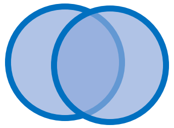
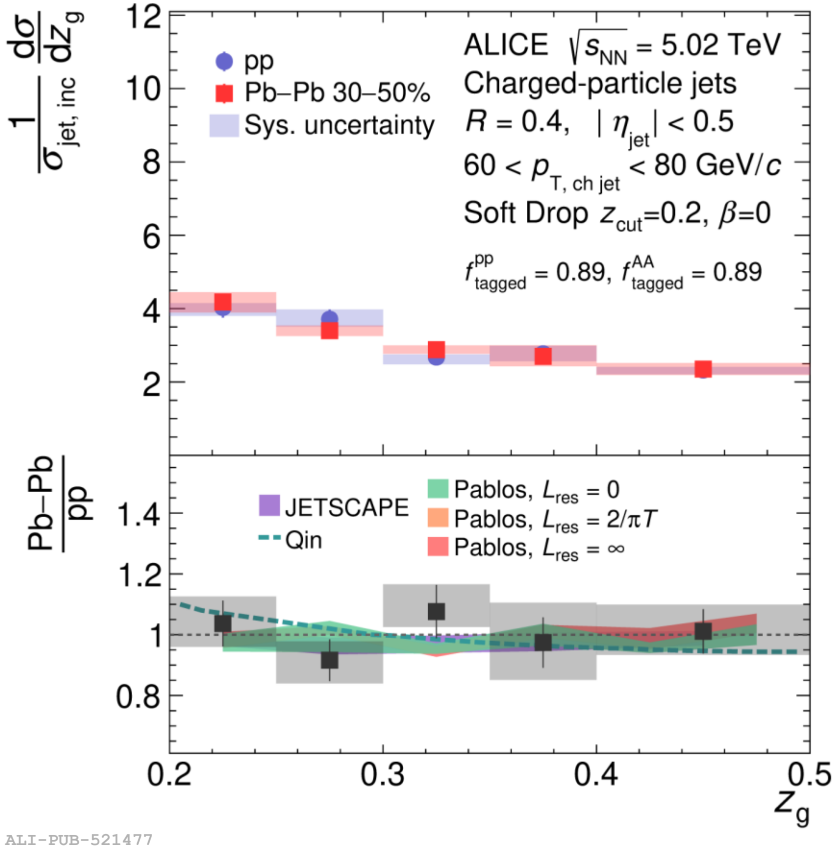






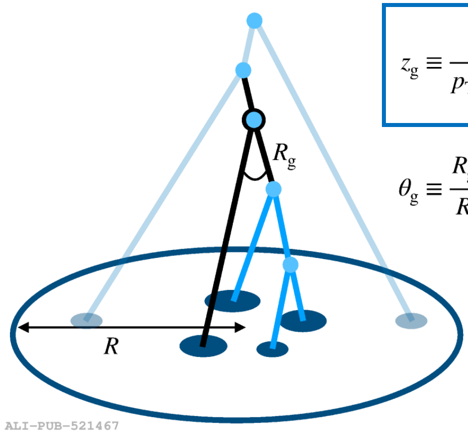


No significant modification of the jet momentum splitting fraction

Groomed D^0-tagged jets

PRL 131 (2023) 192301

Jet momentum fraction, z_g



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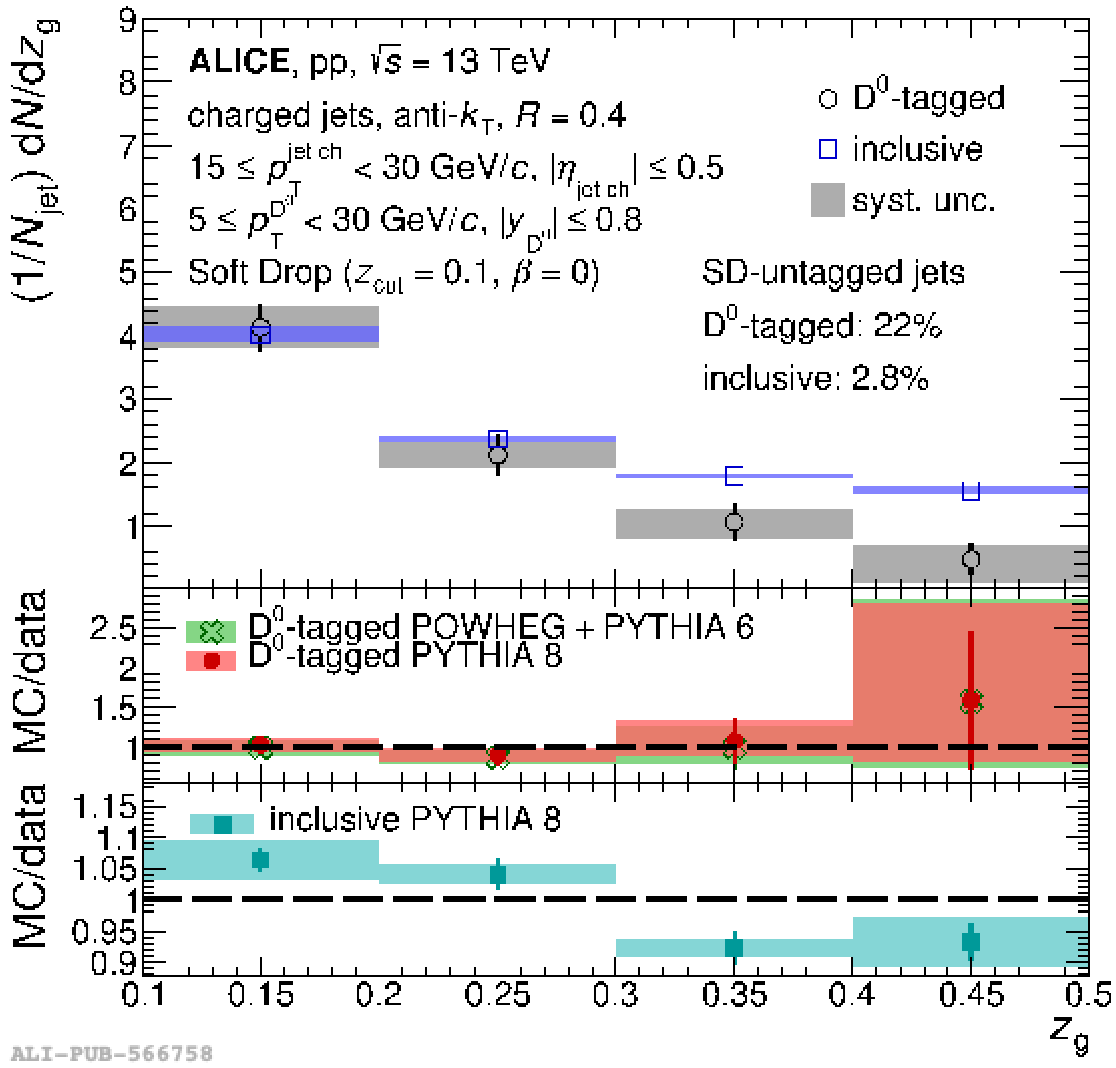
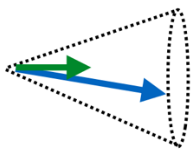
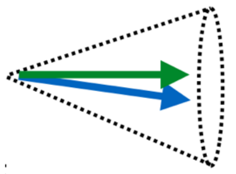
- Larger p_T asymmetry for charm jets



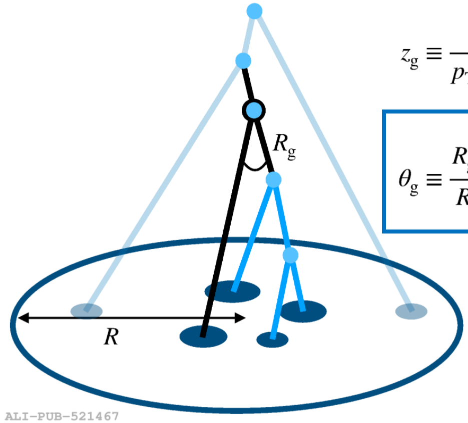




Jet grooming

PRL 128 (2022) 102001

Angular distance, θ_g



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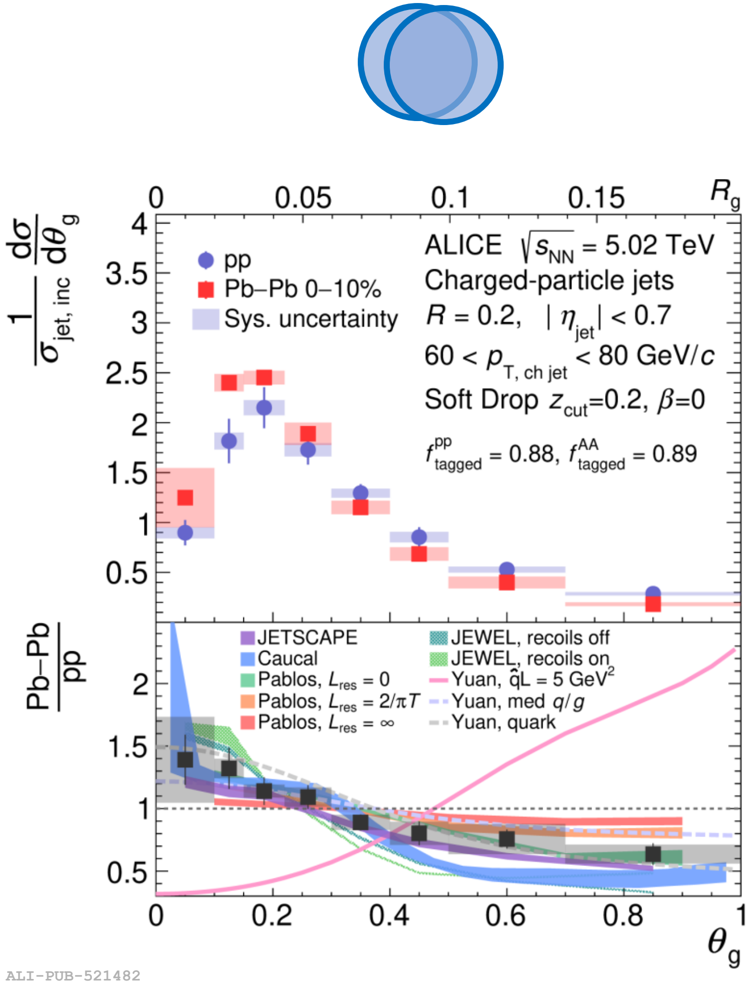
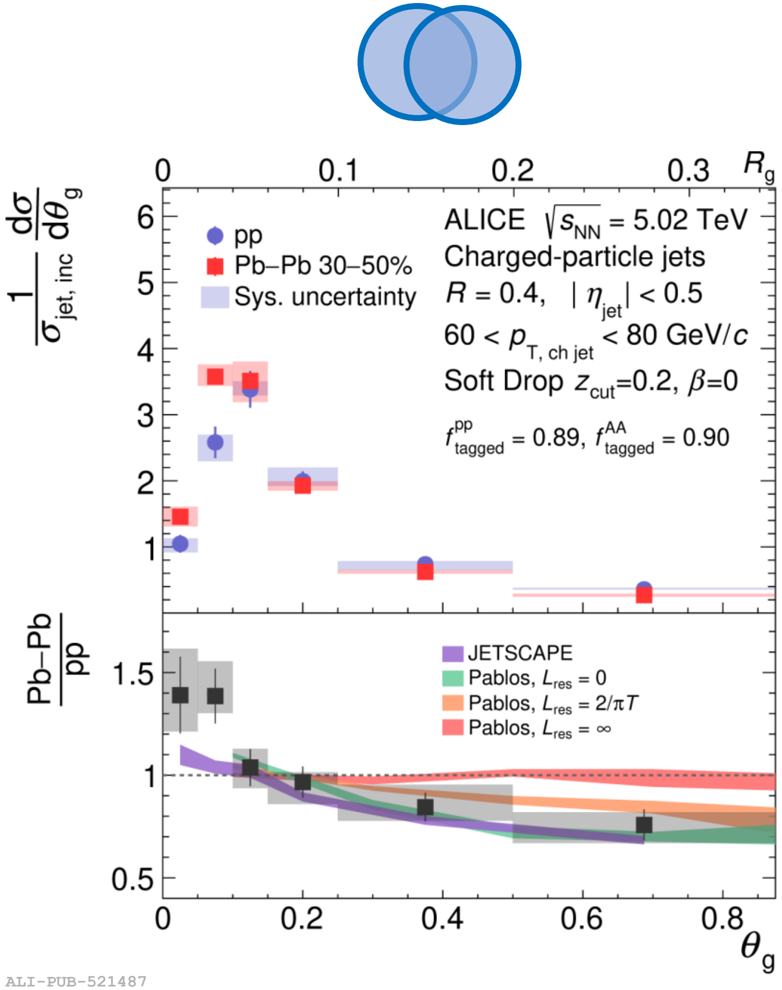




The cores of jets are narrower in Pb-Pb compared to pp collisions

Most models capture the qualitative feature of the narrowing

Generalized angularities

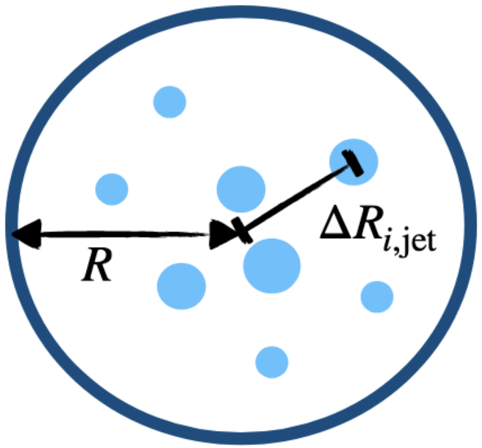
arXiv:1605.04692

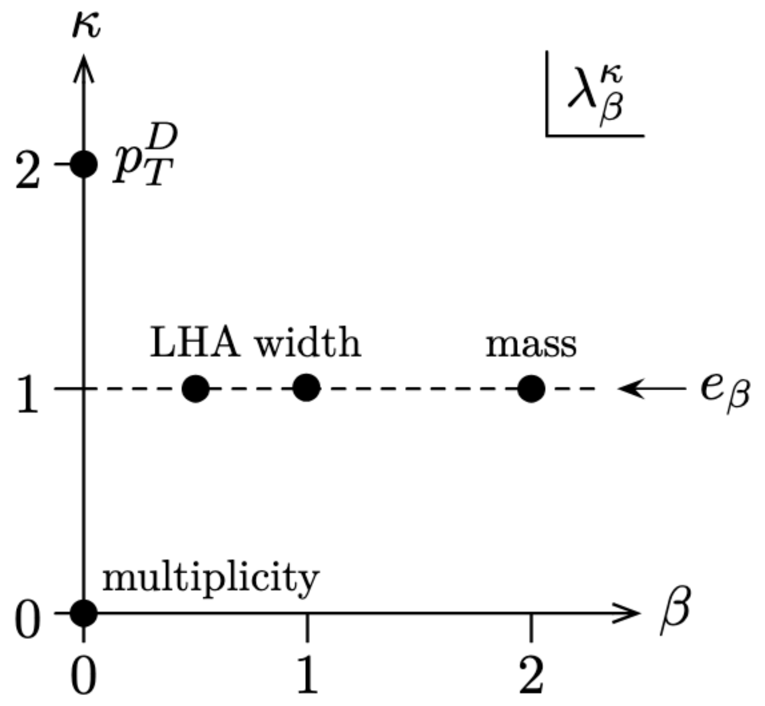
ALICE

- A set of substructure observables to probe constituents and angular distributions of jets with relative weightings κ and β

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

- IRC safe for κ = 1 and β > 0





Jet girth $= \lambda_1^1 R$

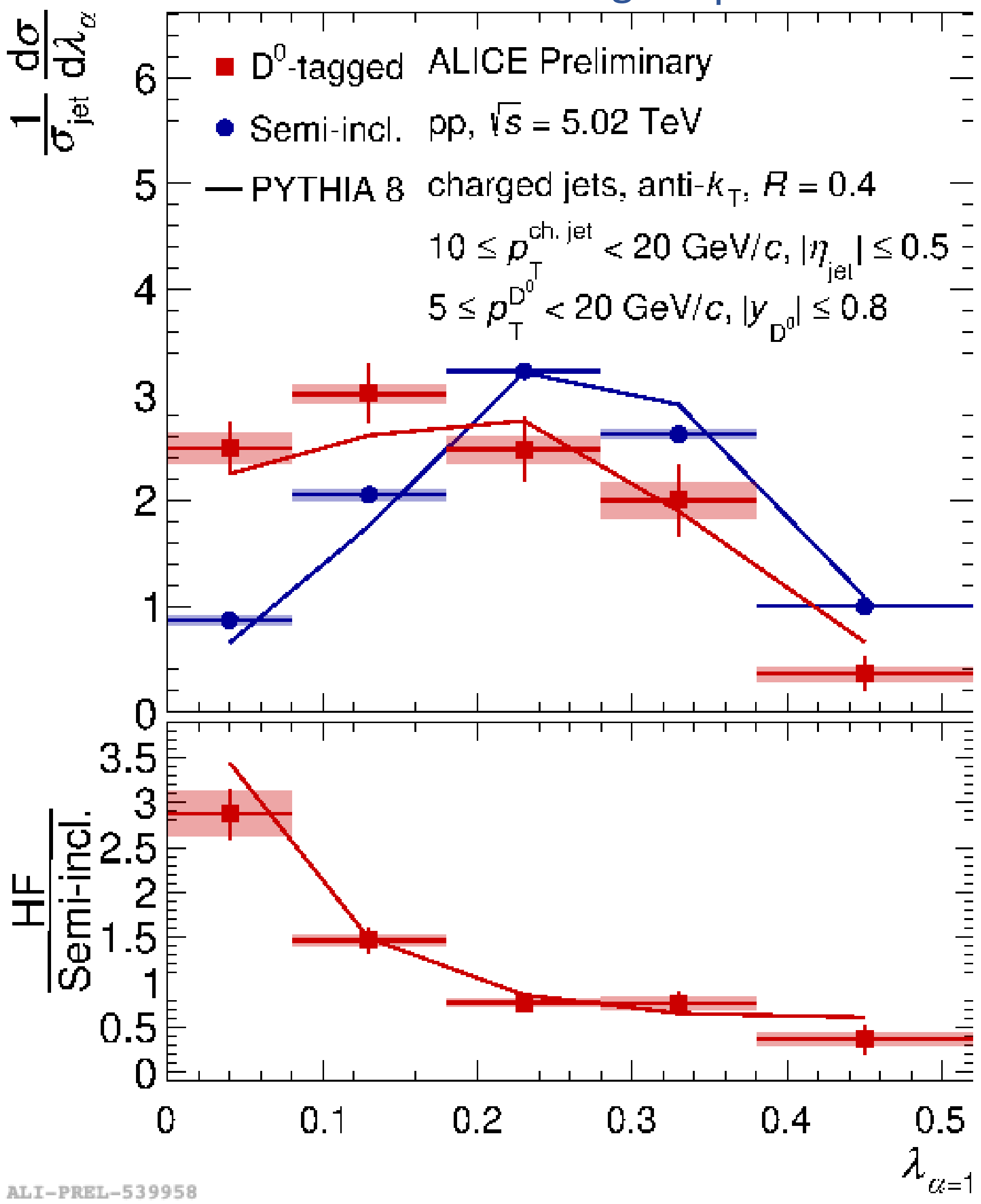
Jet thrust $= \lambda_2^1$

etc.

Generalized angularities

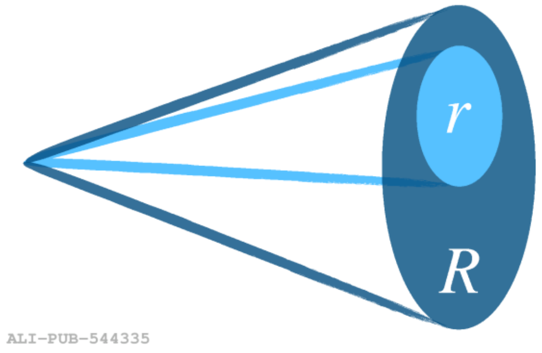
- Semi-inclusive jet girth vs D^0-tagged jet
- D^0-tagged jets have lower angularities than semi-inclusive jets
- Charm jets are more collimated than semi-inclusive jets
  - The dead cone around the charm quark - charm quark fragments less
  - The smaller color charge of quarks compared to gluons

Jet grith β = 1



Subjet fragmentation

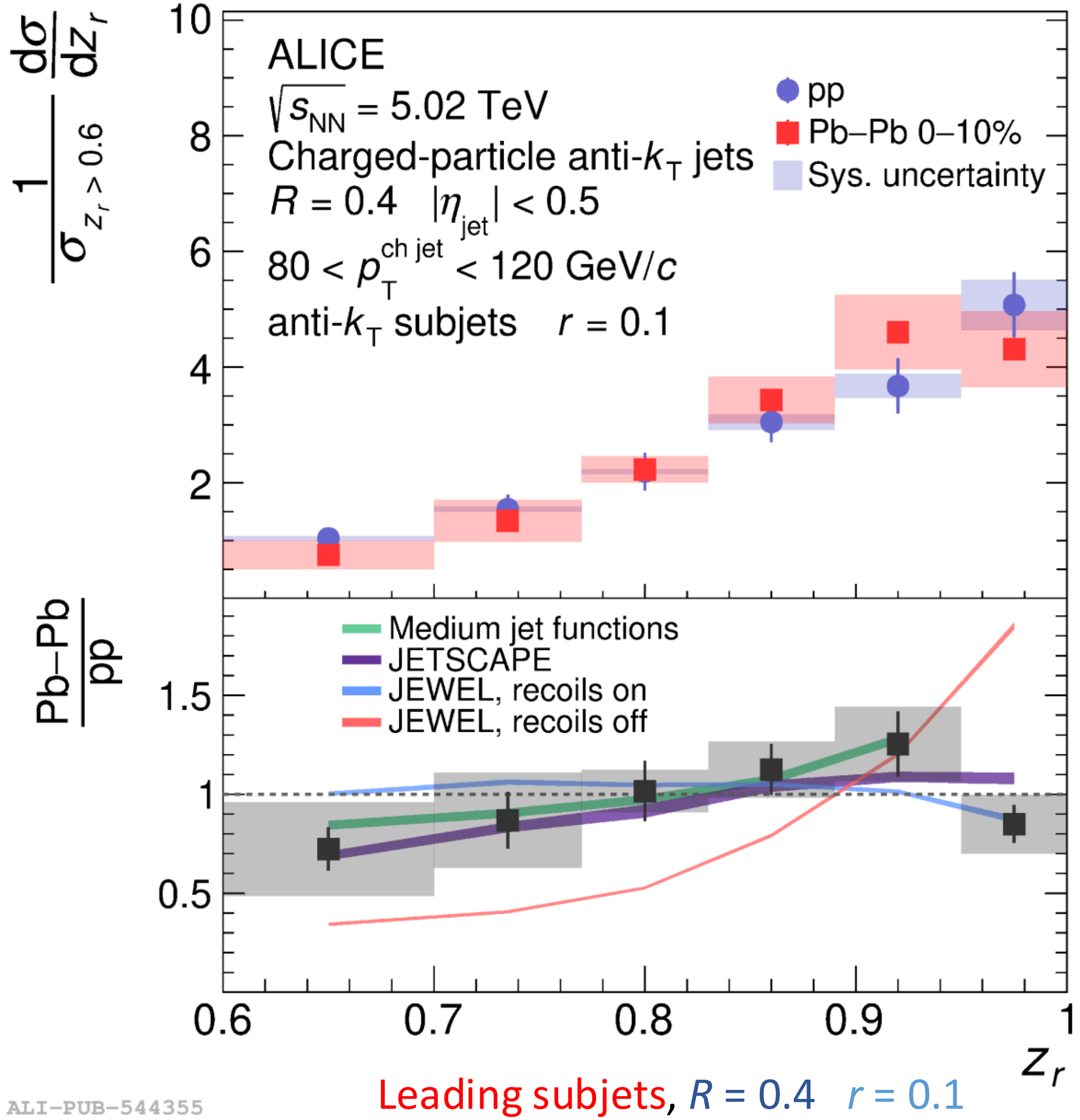
JHEP 05 (2023) 245



Cluster inclusive jets with radius R, then recluster with anti-k_T with radius $r < R$

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

- Hint of hardening at intermediate z_r and a hint of suppression as $z_r \rightarrow 1$
  - Could be due to quark/gluon differences
- Good agreement with model predictions



Leading subjets, R = 0.4 r = 0.1

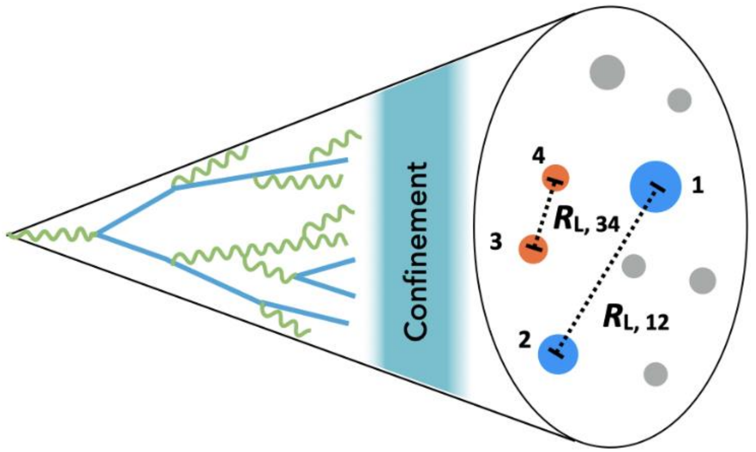
Energy-energy correlators (EEC)

- EEC probes the transition region from free quarks into hadrons
- MPI and UE suppressed by the energy weight
- Can be compared to pQCD calculation
- EEC (R_{L}) corresponds to
  - at small R_{L}: free hadrons
  - at large R_{L} : perturbative quark and gluon interactions
  - At mid R_{L} : $R_{\mathrm{L}} \propto \frac{\Lambda_{\mathrm{QCD}}}{p_{\mathrm{T}}^{\mathrm{jet}}}$

Energy weight

$$\frac{\mathrm{d}\sigma_{\mathrm{EEC}}}{\mathrm{d}R_{\mathrm{L}}} = \sum_{i,j} \int d\sigma(R'_{\mathrm{L}}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^{2}} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})$$

$$R_{\mathrm{L}} = \sqrt{\Delta\varphi_{ij}^{2} + \Delta\eta_{ij}^{2}}$$



Perturbative

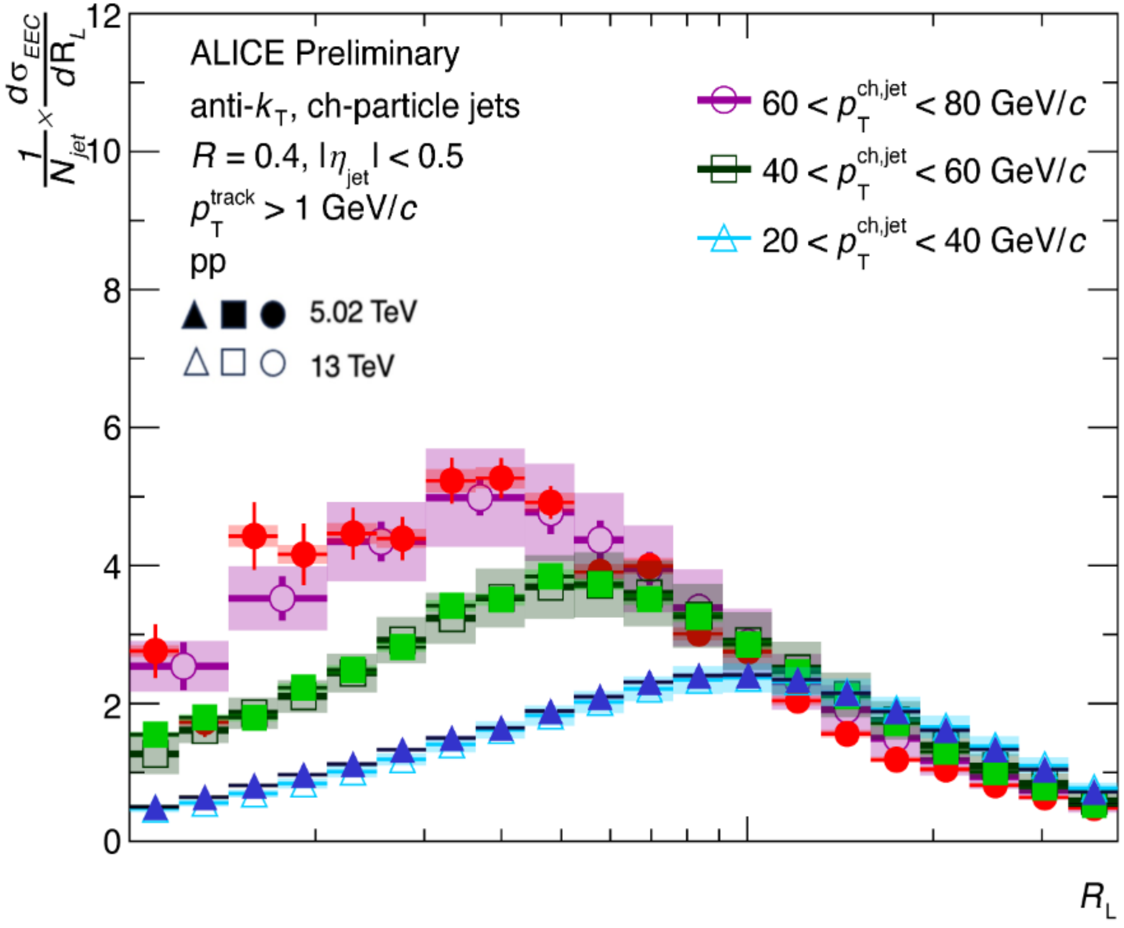
Short time scale
High energy scale

from weak to strong coupled limit

Nonperturbative (NP)

Long time scale
Low energy scale

Energy-energy correlators (EEC)



ALI-PREL-557542

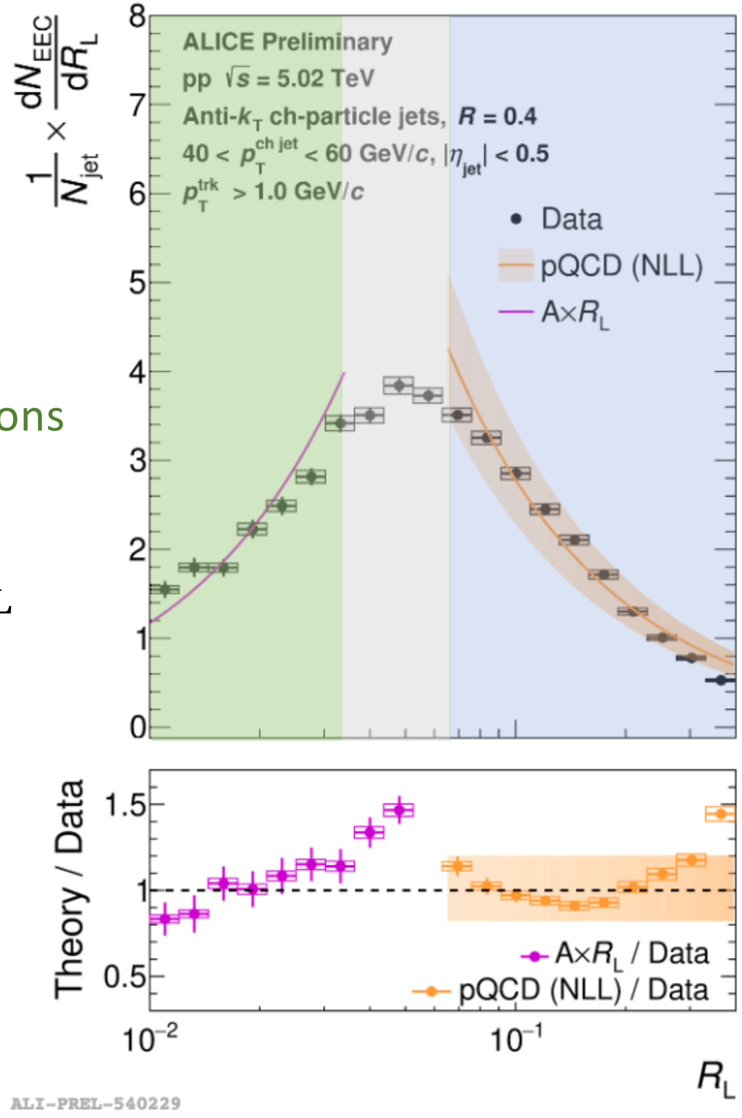
- EEC measured in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV
- No significant collision energy dependence observed
- Different scaling behavior observed in the perturbative (large R_L) and NP region (small R_L)
- Transition position shifts to lower R_L for higher jet p_T range

QCD hadronization scale

Transition

Free hadrons

$$\frac{d\sigma}{dR_L} \propto R_L$$



Quarks/gluons

pQCD scaling deviates near transition region – increasing NP effects

Summary

- ALICE has measured a diverse collection of jet and jet substructure observables useful for exploring different physics questions
- Run 3 data will focus on increasing precision
- Many more new and exciting results on the way! Stay tuned!

Recent ALICE jet measurements

- Dijet invariant mass https://alice-figure.web.cern.ch/node/16256
- Full jets in p-Pb collisions https://alice-figure.web.cern.ch/node/26208
- Jet R_{AA} using mixed-event method https://alice-figure.web.cern.ch/node/26490
- Jet energy flow within jets https://alice-figure.web.cern.ch/node/26307
- Di-jet acoplanarity in high-multiplicity JHEP 05 (2024) 229
- Fragmentation function in minimum-bias and high-multiplicity arXiv:2311.13322
- Time reclustering https://alice-figure.web.cern.ch/node/28410
- Jet axis difference JHEP 07 (2023) 201, arXiv:2303.13347
- Hardest k_T splittings https://alice-figure.web.cern.ch/node/18030
- Three-point energy correlator https://alice-figure.web.cern.ch/node/28272
- First measurements of in-jet fragmentation of charmed mesons and baryons PRD 109 (2024) 7
- Charm jets tagged with D^0 mesons JHEP 06 (2023) 133

Many recent exciting jet measurements by ALICE – this presentation only shows a few highlights

Extra slides