Inclusive jets and dijet suppression in heavy ion collisions

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Inclusive jet suppression

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{evnt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

Jet yield per centrality class in heavy-ion collisions

Nuclear thickness function

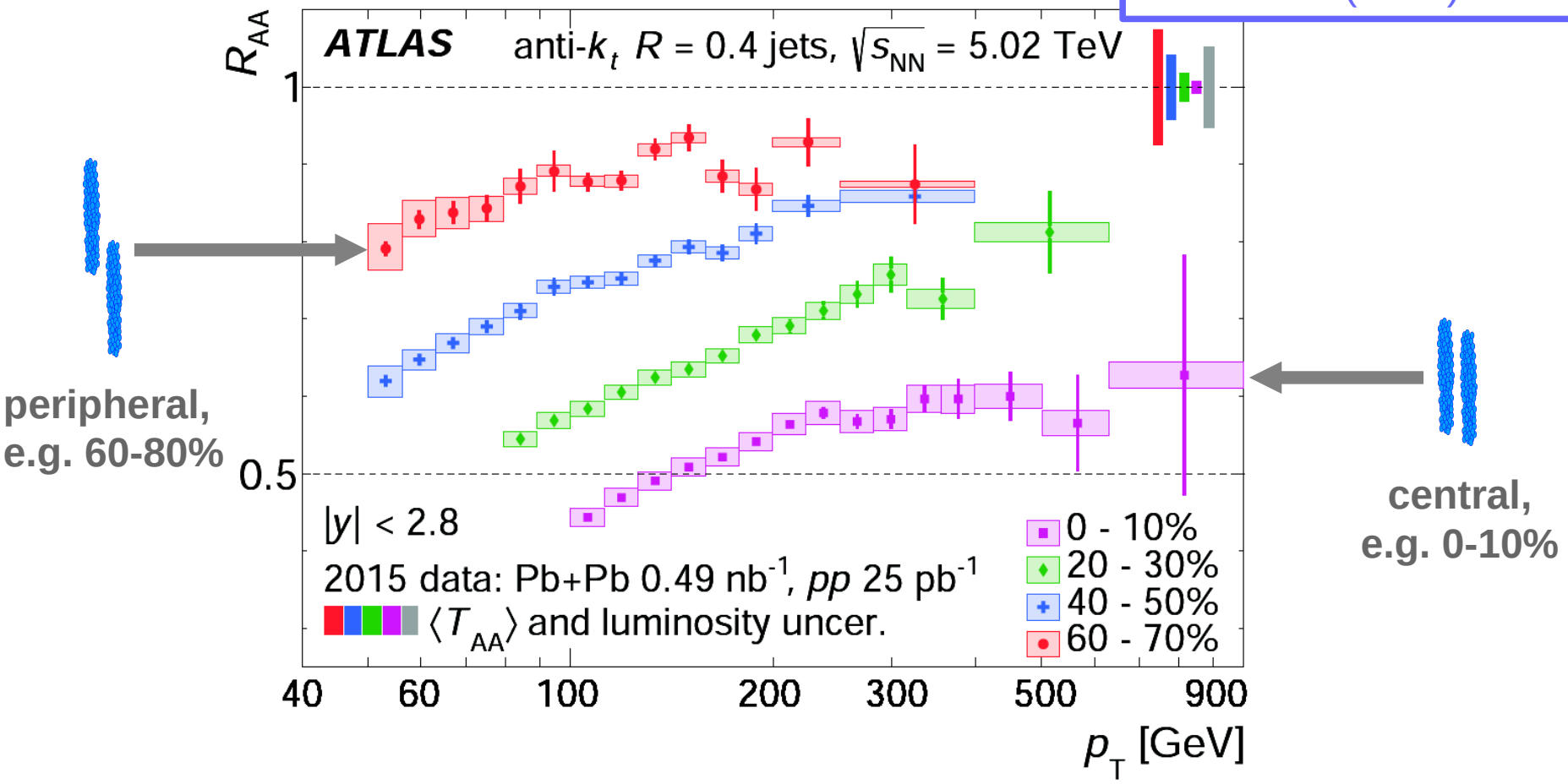
Jet cross-section in *pp* collisions

Number of expected jets per event of a given centrality

- Large **suppression of jets** seen in Pb+Pb collisions with respect to p+p collisions quantified by the nuclear modification factor, R_{AA}.
- This phenomenon is called jet quenching.
- If there was no modification of the jet yield in heavy-ion collision, then $R_{AA} = 1$.

Inclusive jet suppression

PLB 790 (2019) 108

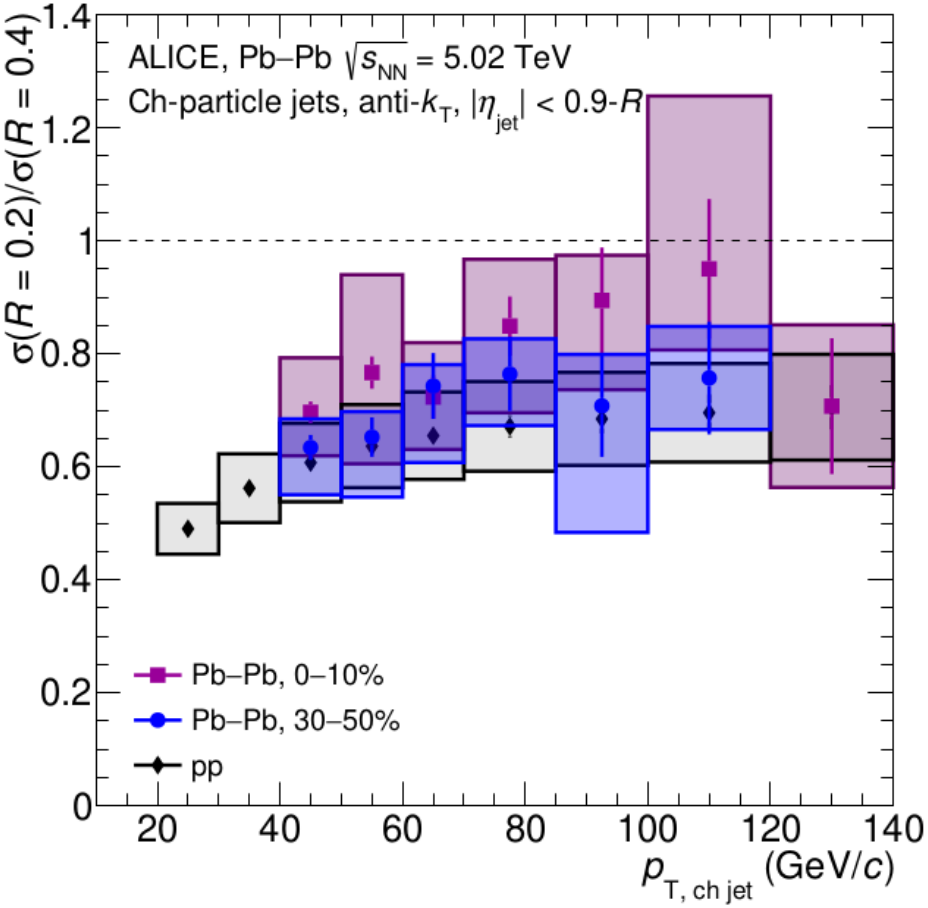


- Jet quenching – very significant, present also at the TeV scale!
- R_{AA} of Z and W is unity (modulo isospin) => jet quenching is due to the **interaction of parton shower with deconfined color charges.**

Looking at details
from the latest measurements...

Radial dependence of inclusive jet suppression

arXiv:2303.00592



- Ratio of jet cross-sections (or R_{AA}'s) for jets with different radii.
- Helps finding impact of competing effects:
  - **recovering** of in-medium radiation (=> increase)
  - larger-R jets at given p_T are **broader** => more quenched (=> decrease)
  - **vacuum** effect (decrease)
- Measured also for R=0.6 jets.

Radial dependence of inclusive jet suppression

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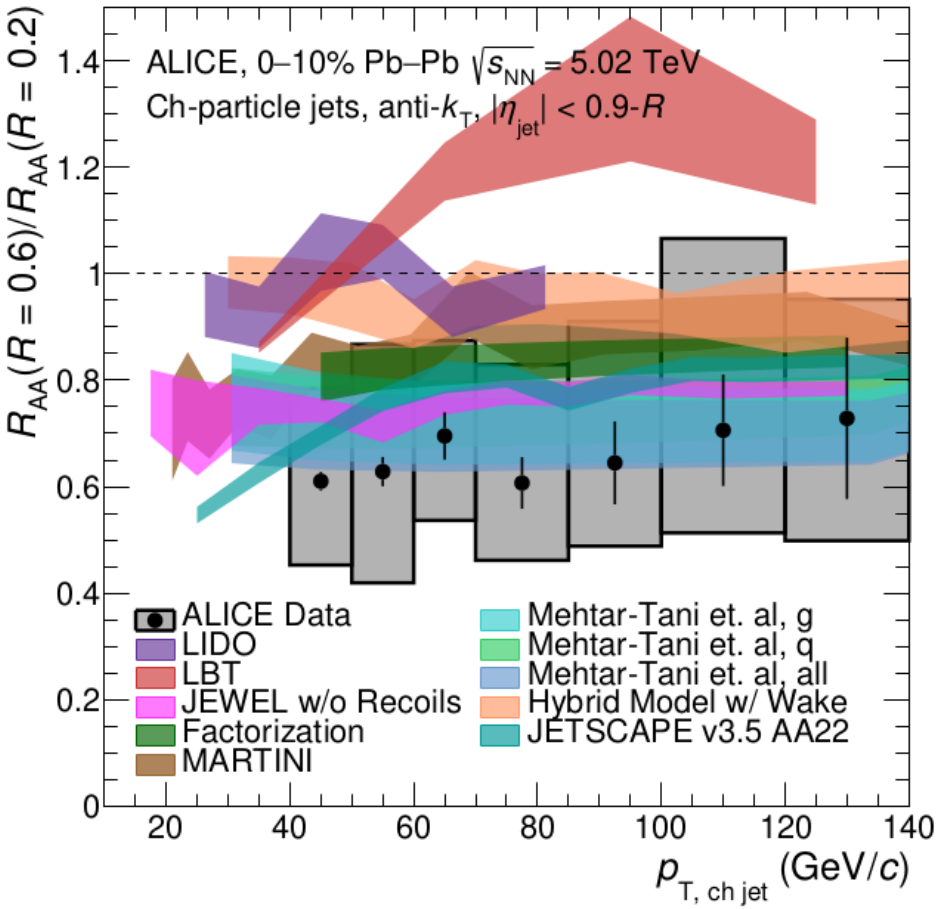

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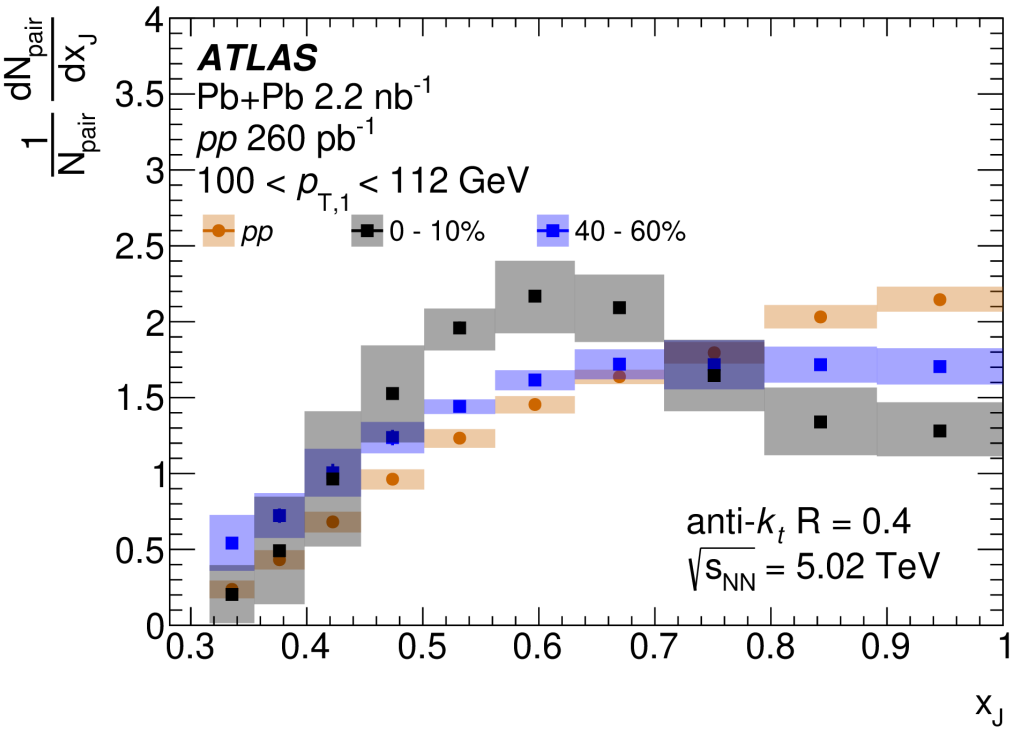
Dijet studies

- Measuring dijets allows to also study the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,\text{sub-leading}} / p_{T,\text{leading}}$.



- Significant **dijet imbalance** seen in central heavy ion collisions.

arXiv:2205.00682

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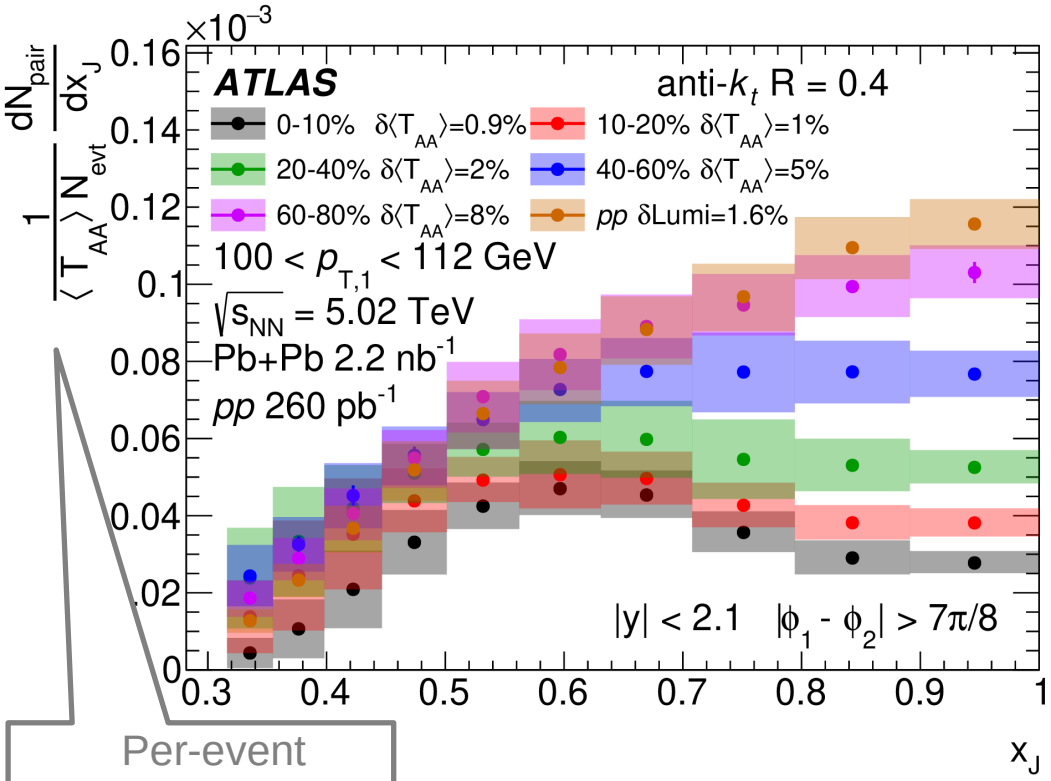

Per-event instead of dijet normalization

- Significant **dijet imbalance** seen in central heavy ion collisions.
- This imbalance is shown to be due to a **suppression of balanced** dijet topologies rather than enhancement in imbalanced topologies.

arXiv:2205.00682

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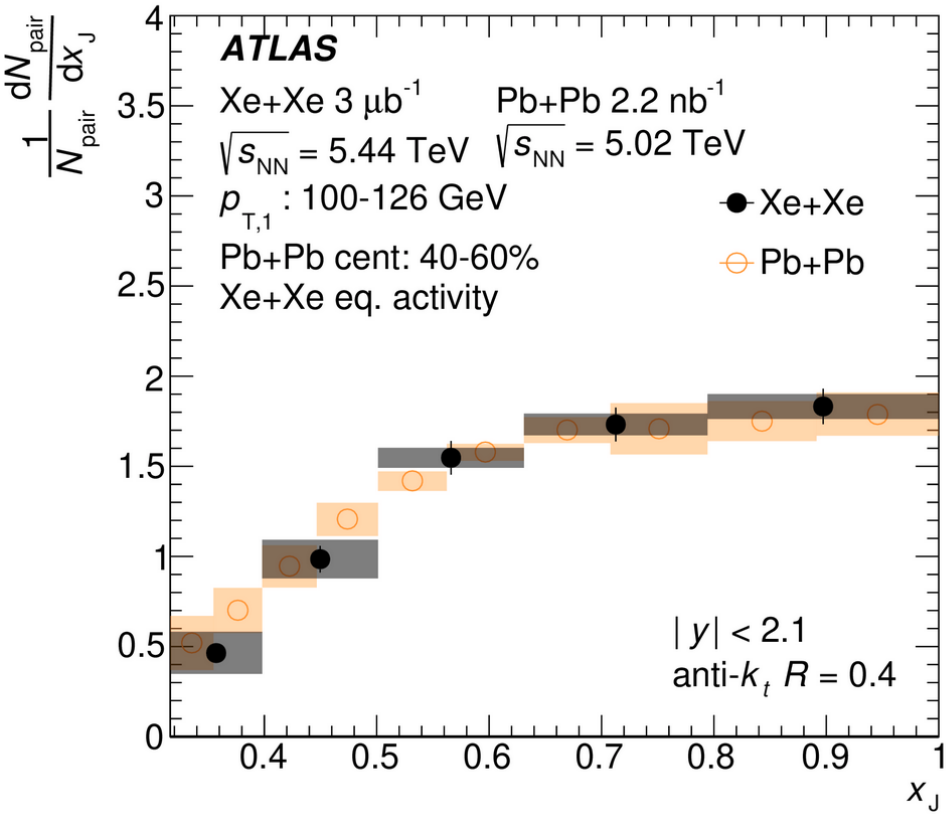
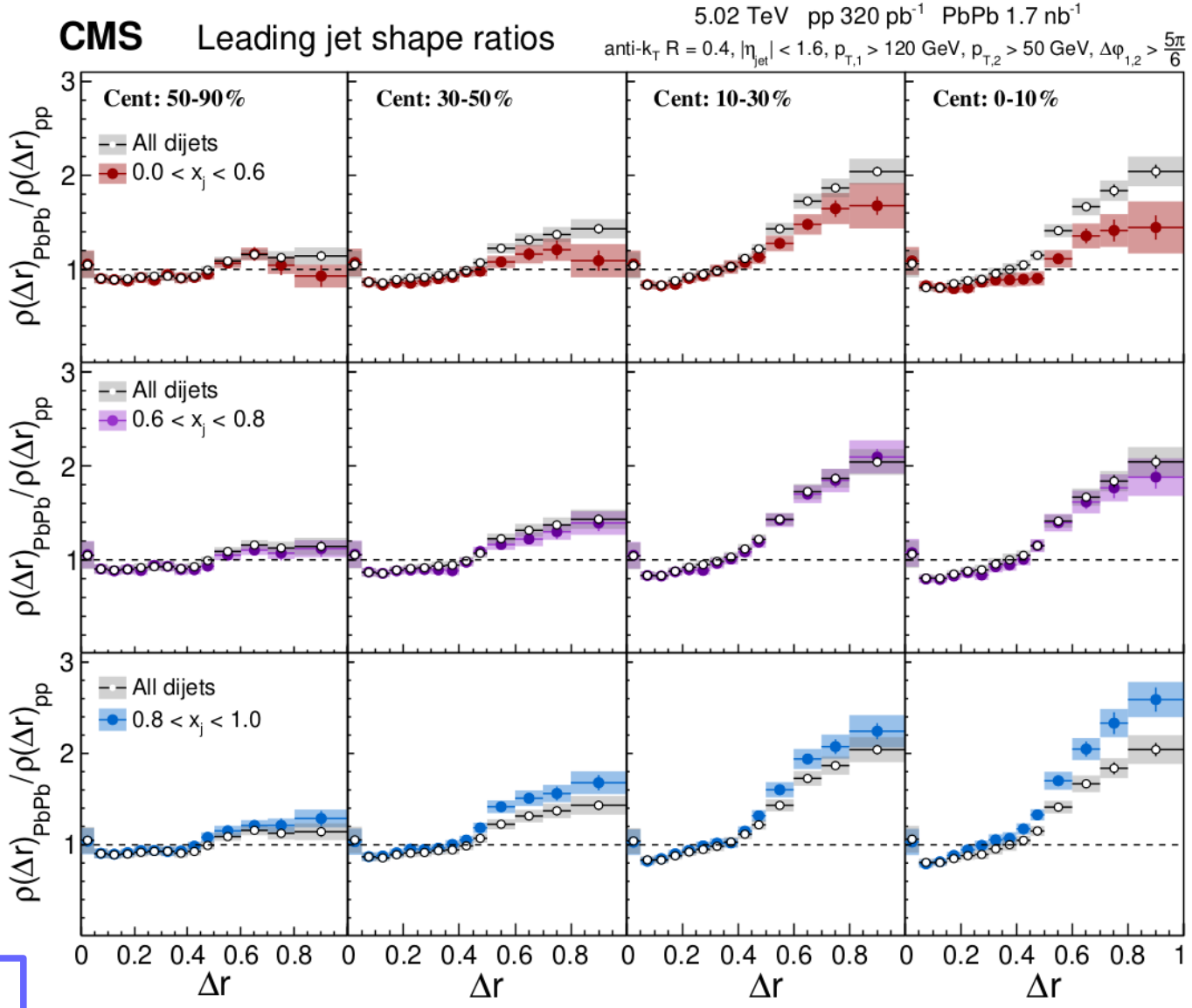


- Significant **dijet imbalance** seen in central heavy ion collisions.
- Measured **in Xe+Xe** collisions: system size dependence of jet quenching:
  - Similar level of jet suppression after taking into account differences in geometry and $\sqrt{s_{NN}}$.

arXiv:2302.03967

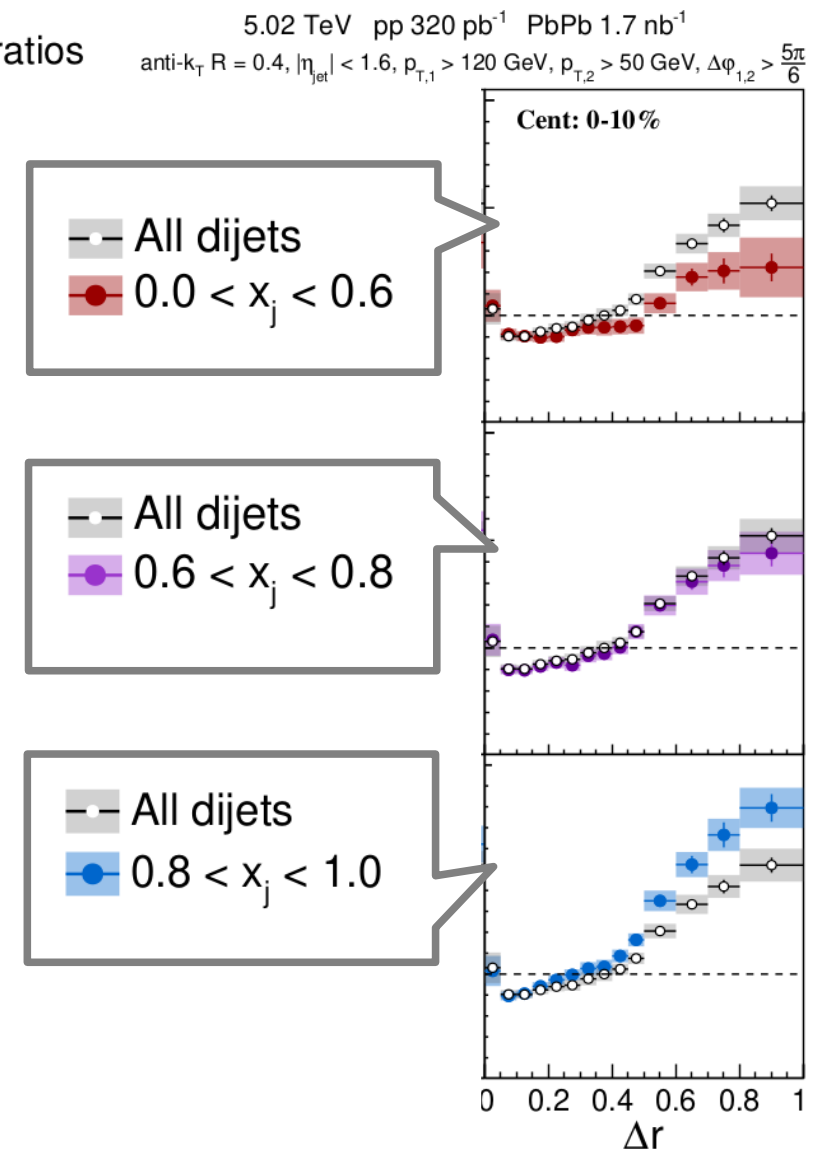
Jet shapes in dijet system

- Jet shape = flow of p_T around the jet axis



JHEP 05 (2021) 116

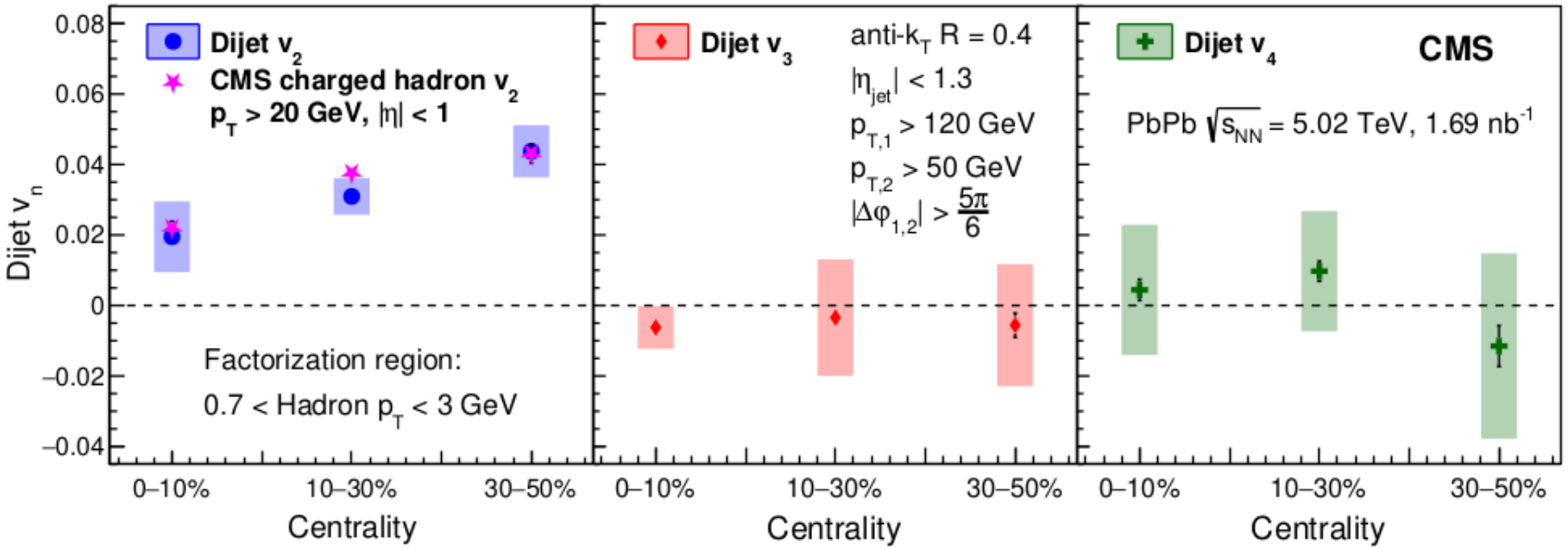
Jet shapes in dijet system



- Jet shape = flow of p_T around the jet axis.
- More energy produced outside of jets in Pb+Pb compared to pp.
- Enhancement for leading jets is larger in more balanced dijet systems.
- Consistent with geometric origin of dijet imbalance (leading jet is suppressed less for imbalanced dijets).
- Consistent with the x_J measurement.

JHEP 05 (2021) 116

Azimuthal anisotropy in dijet system

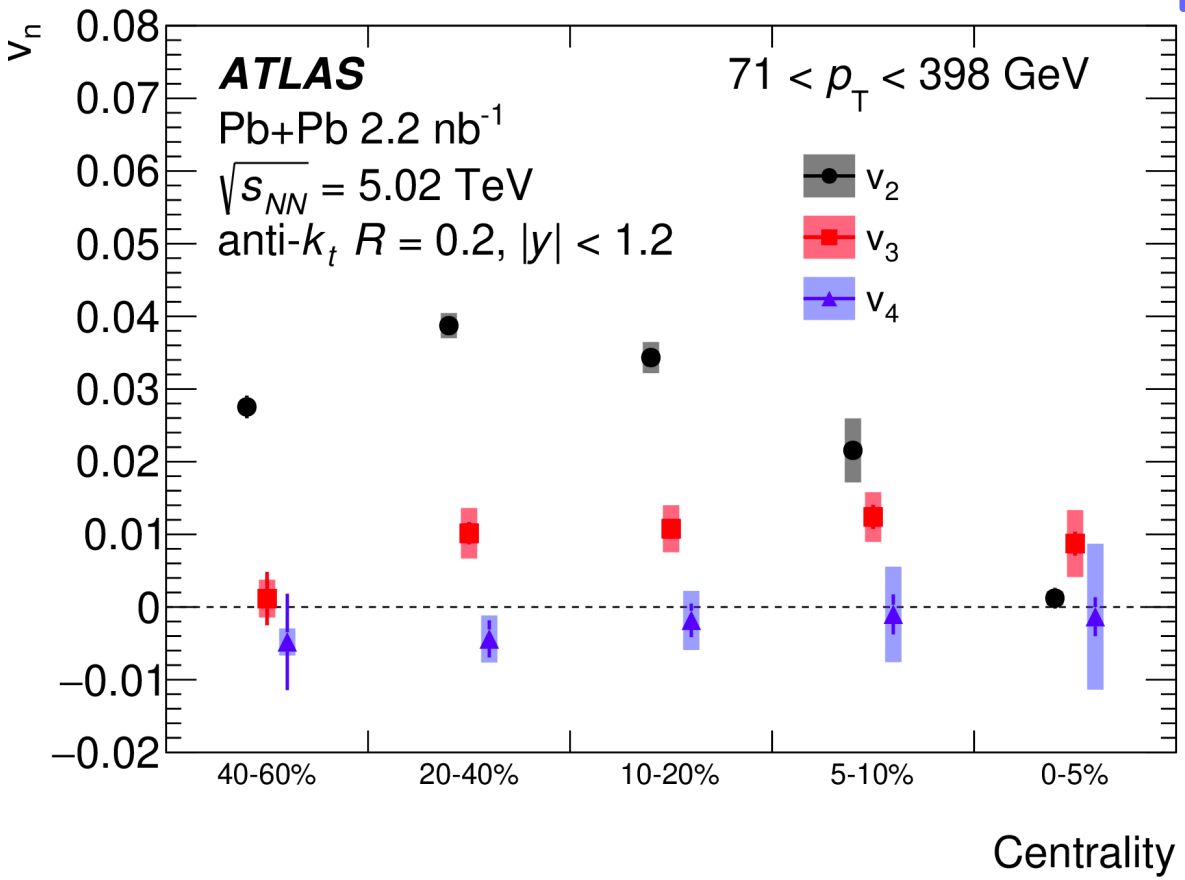


arXiv:2210.08325

- Dijet v_2 using jet-hadron correlations – resilient against long range hydro-like correlations.
- Dijet v_2>0, but dijet v_3=0 and v_4=0.
- Quantifies **path-length** dependence of the energy loss.
- Implies **no significant impact** of initial state geometry and medium density fluctuations.

Azimuthal anisotropy for inclusive jets

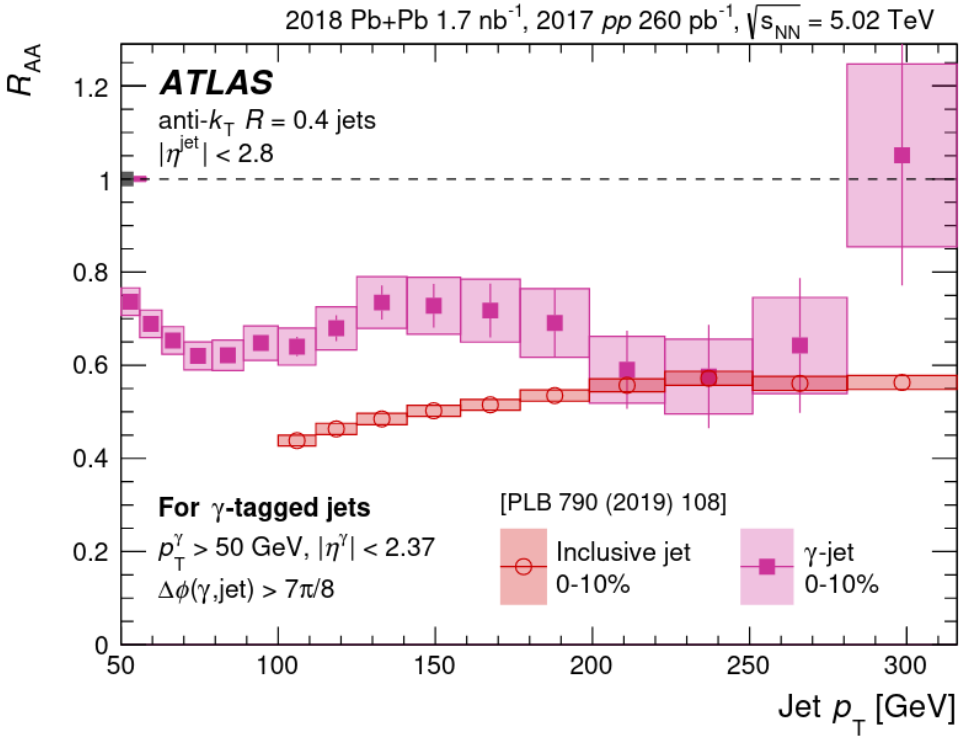
PRC 105 (2022) 064903



- Inclusive jet v_2>0 and v_3>0, v_4=0.
- Direct comparison with CMS difficult (different binning choices).

Suppression in γ-jet system

arXiv:2303.10090



- Left:
  - Inclusive jets dominated by gluon-initiated jets.
  - γ-jet system dominated by **quark-initiated jets** => **less suppression** as expected.

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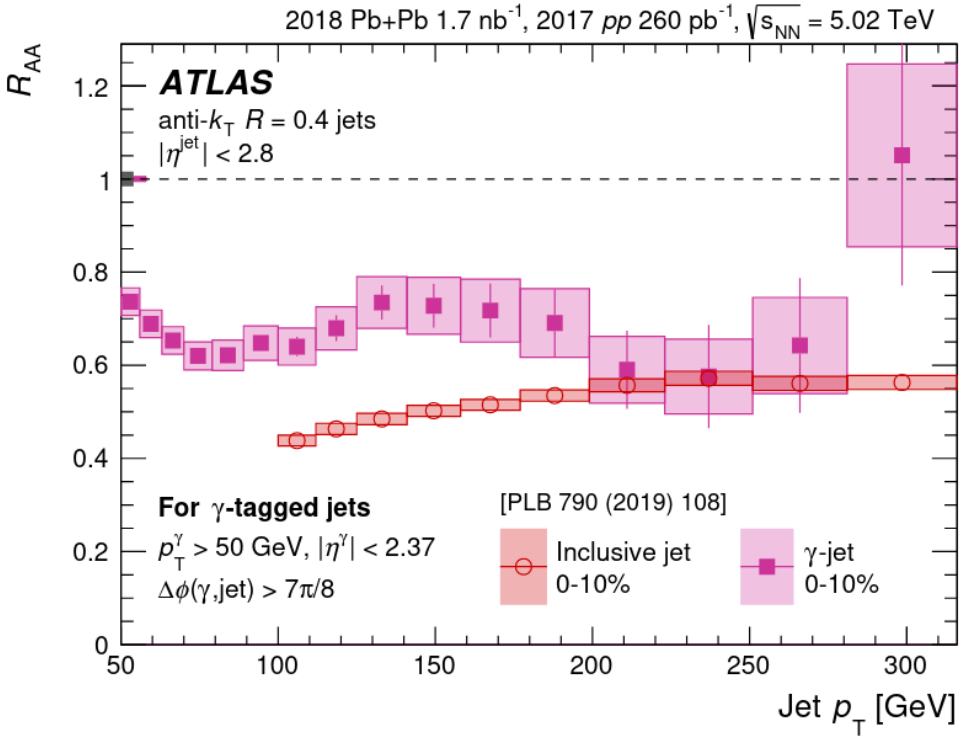
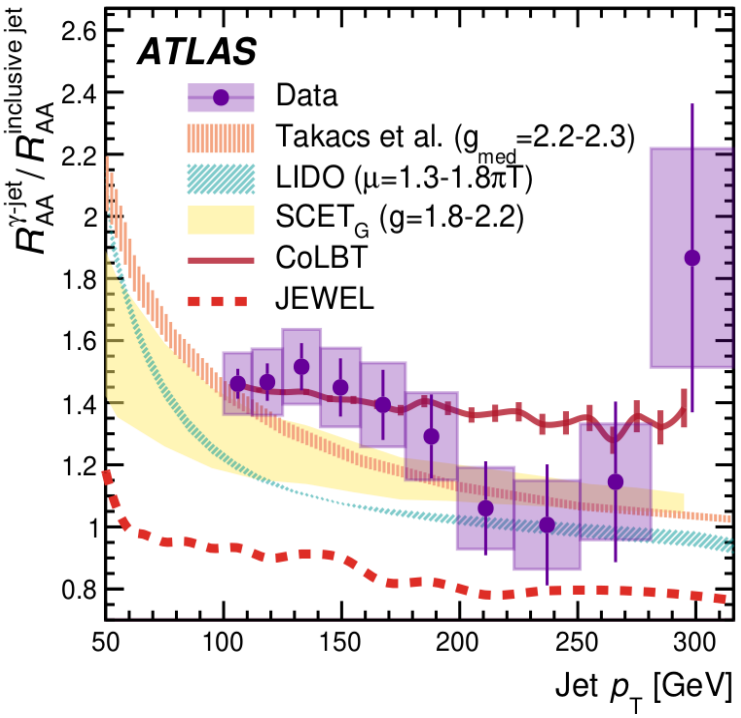
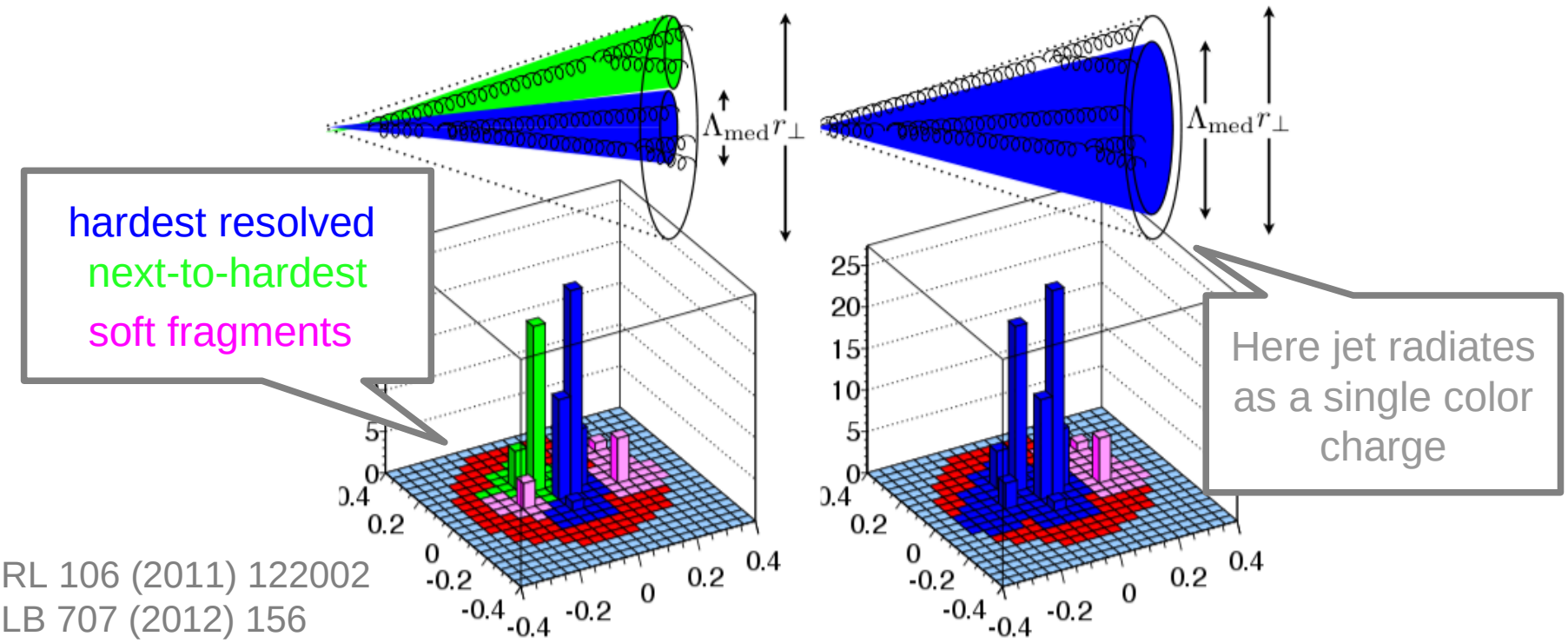




- Left: – Inclusive jets dominated by gluon-initiated jets.
  – γ-jet system dominated by **quark-initiated jets**
  => **less suppression** as expected.
- Right: γ-jet to inclusive jet ratio.
- Should help constraining the **impact of color charge** as well as impact of so called **selection bias** (γ is not quenched).

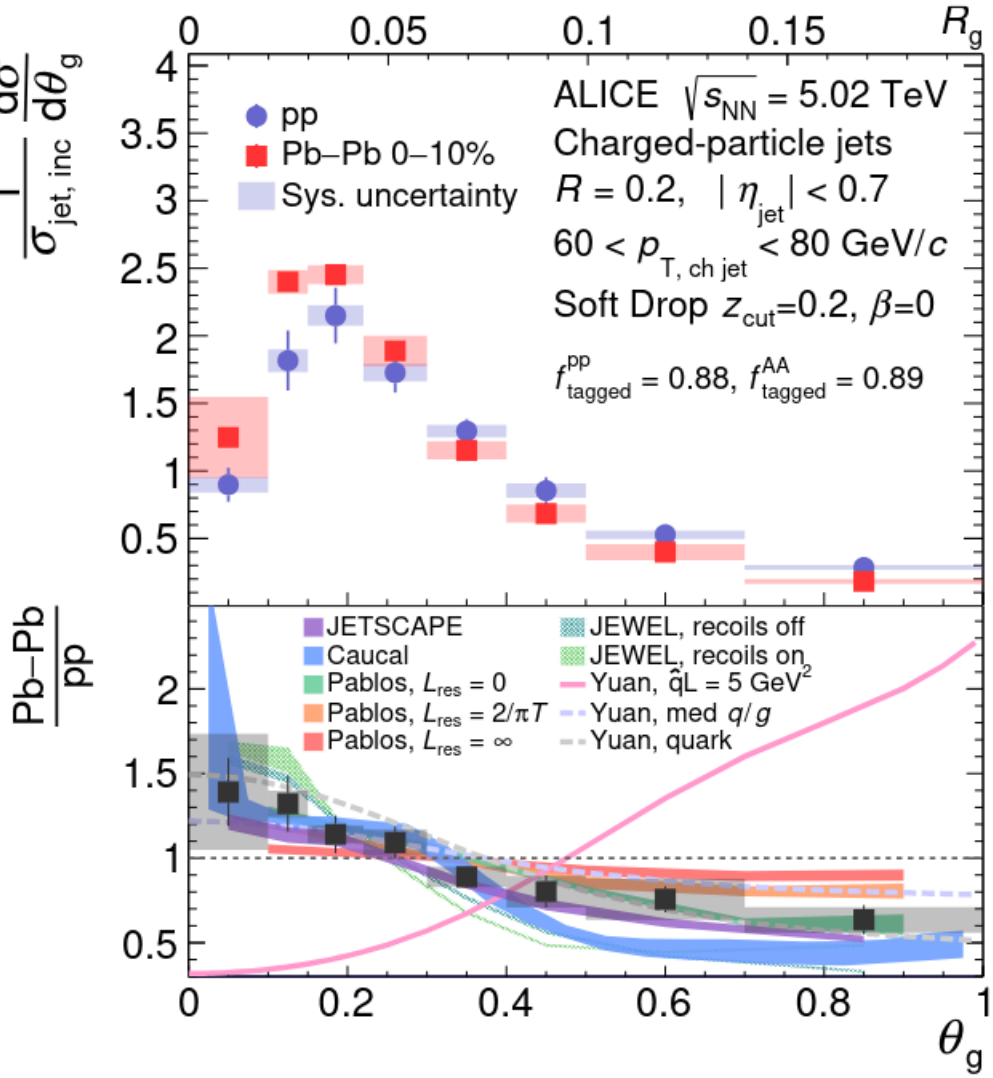
Jet sub-structure



PRL 106 (2011) 122002
PLB 707 (2012) 156

Part of the parton shower may remain unresolved due to the color coherence. Early, hard splittings in the parton shower are likely **not altered by the medium** => substructure measurements.

Jet structure: R=0.2, dσ/dθ



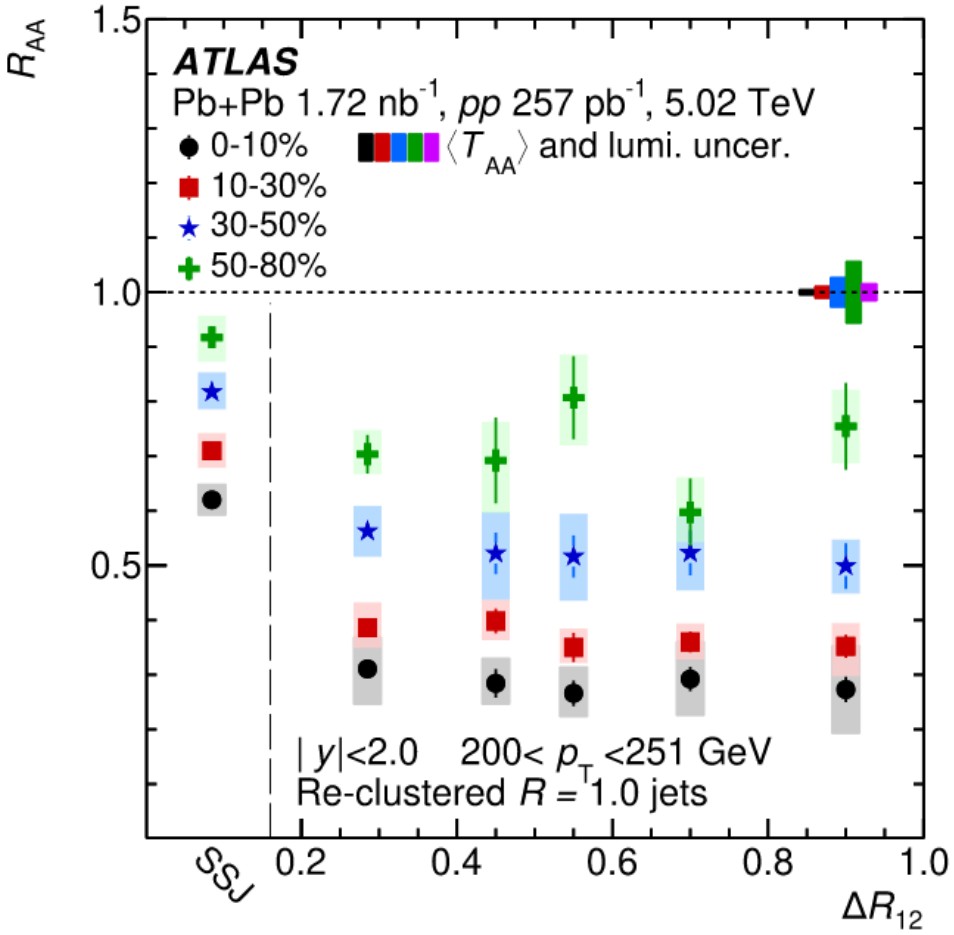
- Groomed jet radius for 0.2 jets with soft-drop.

  $R_g \sim \theta_g \sim \Delta R_{12} \equiv \theta$

- Significant **narrowing** observed in Pb+Pb.
- Two possible sources:
  - color **coherence**
  - quenching induced change in **q/g fraction**
- Also measured splitting scale or jet mass.

arXiv:2204.10246

Jet structure: R=1.0, $R_{AA}(\theta)$



- R=1.0 clustered from R=0.2 jets with p_T>35 GeV.
- R_{AA} measured differentially in substructure observable.
- R=1.0 jets with single sub-jet suppressed **significantly less** (consistent with color coherence picture).

arXiv:2301.05606

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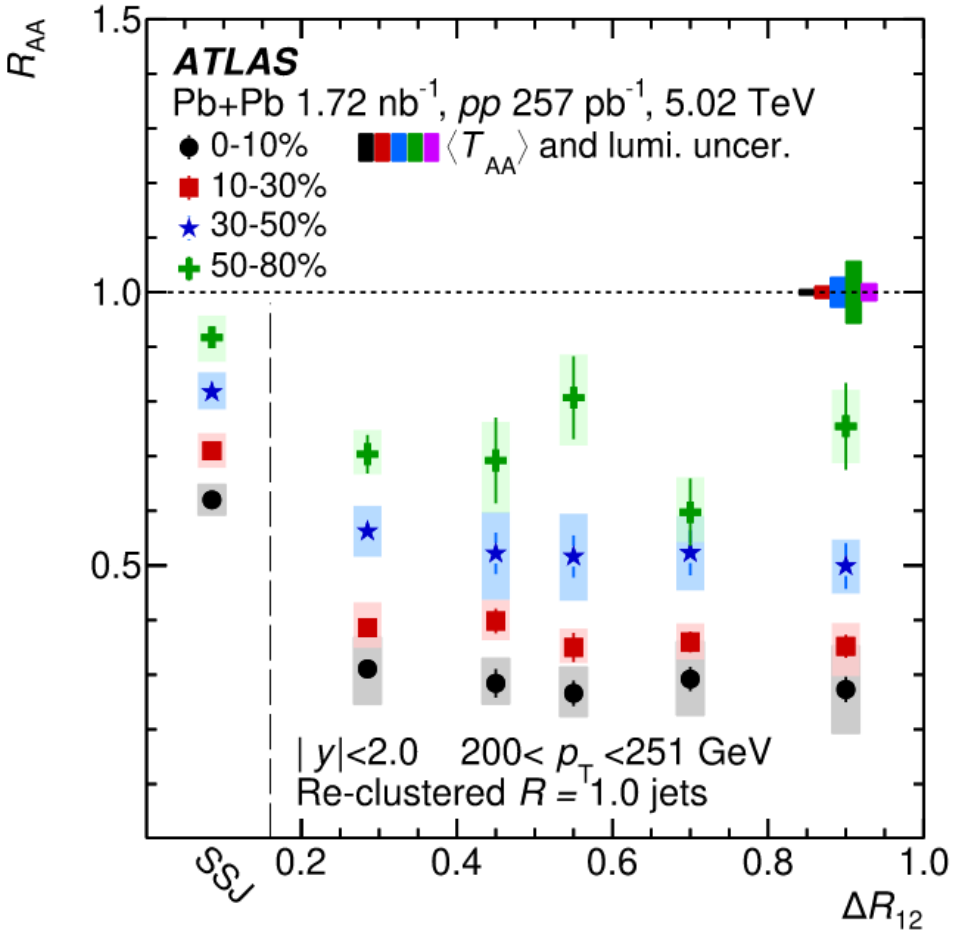

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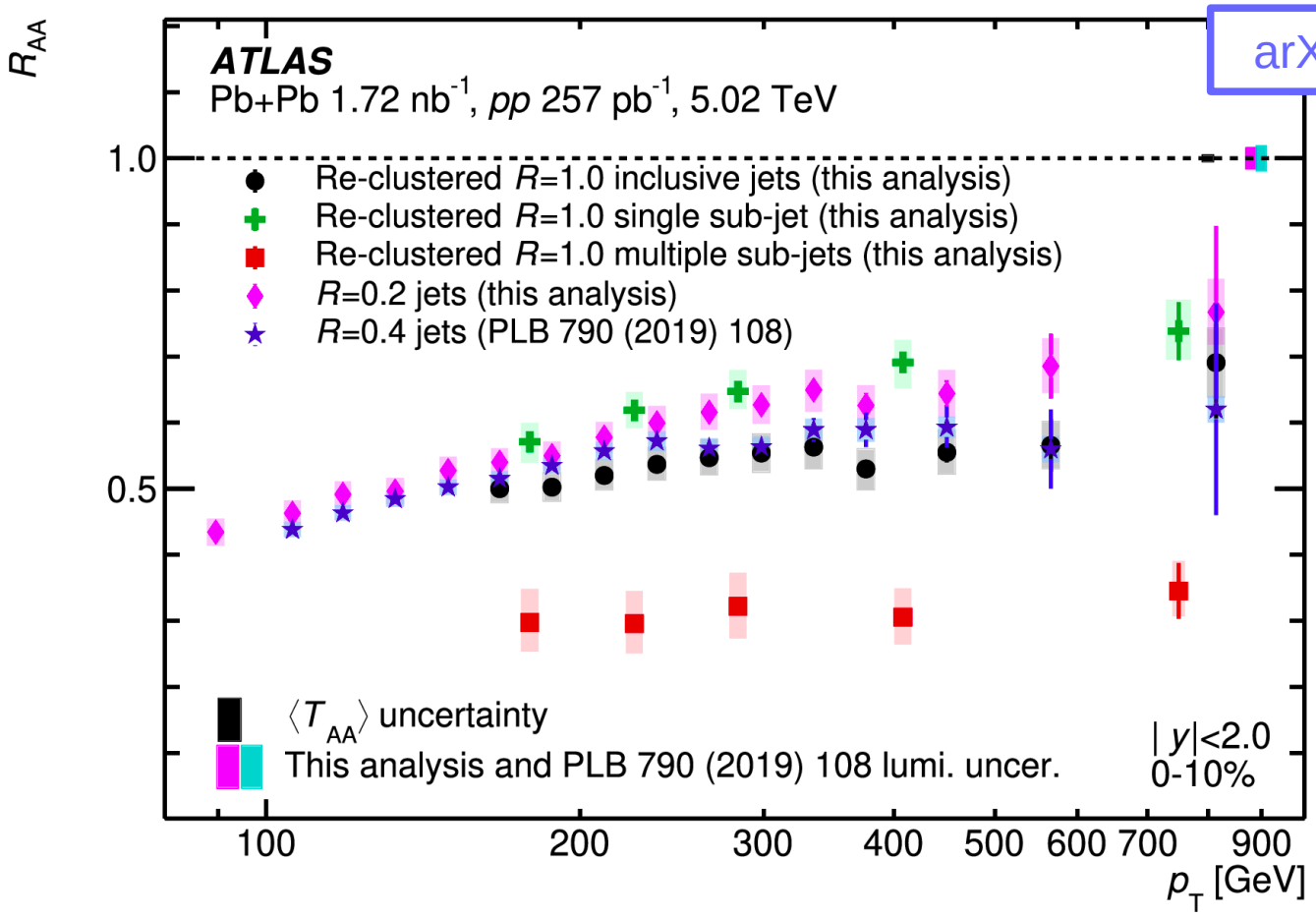
Detailed measurement for ΔR_{12}<0.4 using tracking information

arXiv:2301.05606

arXiv:2211.11470

Jet structure and large-*R* jets



arXiv:2301.05606

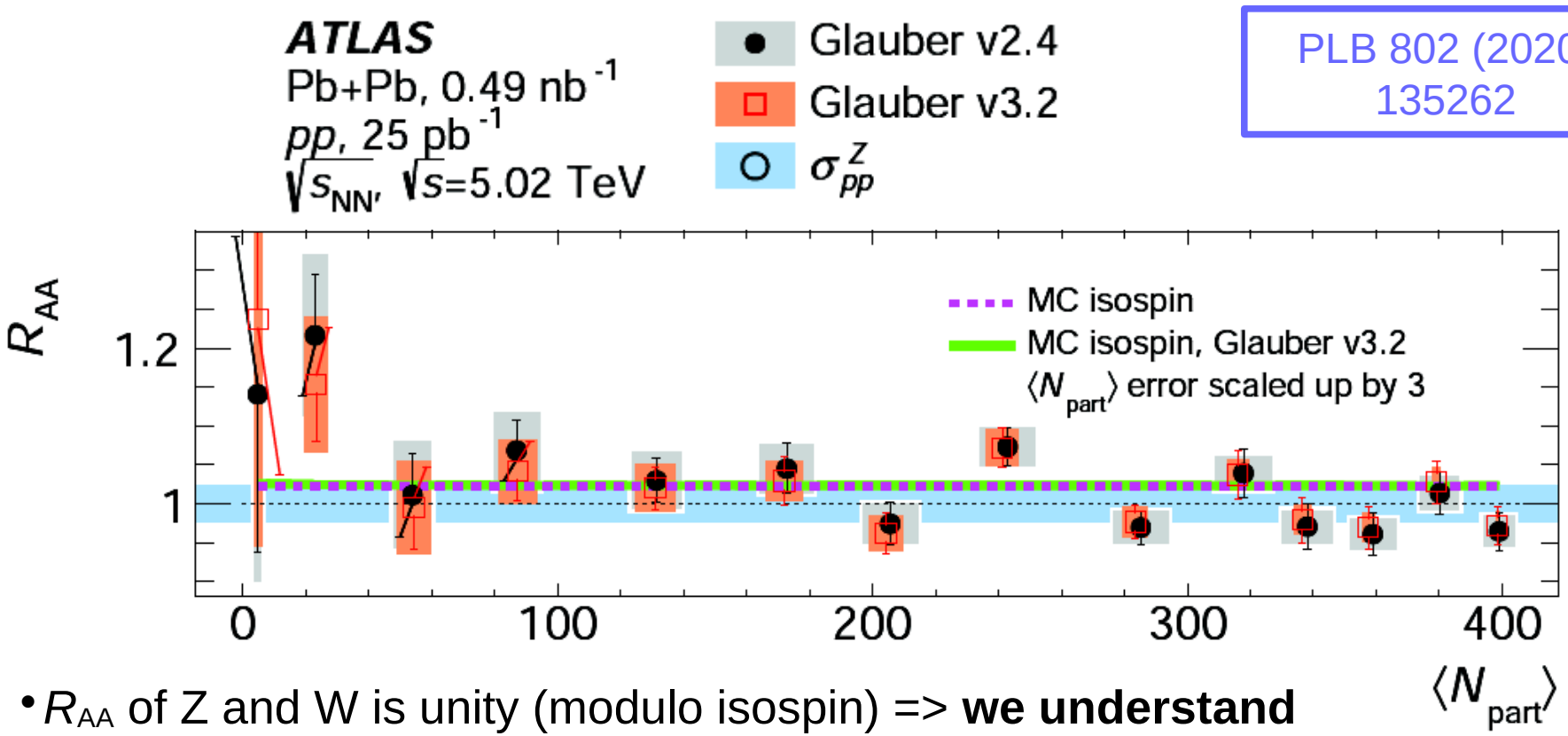
Suppression **ordering**: reclustered *R*=1.0 w/ multiple subjets >
> inclusive reclustered *R*=1.0 >
> *R*=0.4 > *R*=0.2 >
> reclustered *R*=1.0 w/ single subjets

Summary

- Inclusive jets are suppressed by a factor of two at the TeV scale.
- In the dijet system, production of balanced jets is suppressed. Enhancement of soft particle production is larger for leading jets from balanced dijets => Consistent picture of **geometry-driven** energy loss of dijets.
- Dijet and inclusive jet v_2, v_3, v_4 – understanding of path-length dependence and **role of initial state and fluctuations**.
- Significantly smaller suppression of jets in gamma-jet system – expected from the **flavor dependence** of jet quenching.
- Large-*R* jets with single sub-jet suppressed significantly less then jets with more complex topologies as expected at presence of **color coherence effects**.
- Difference between suppression of jets with **different *R*** quantified.

Back-up slides

Comparing to EW bosons

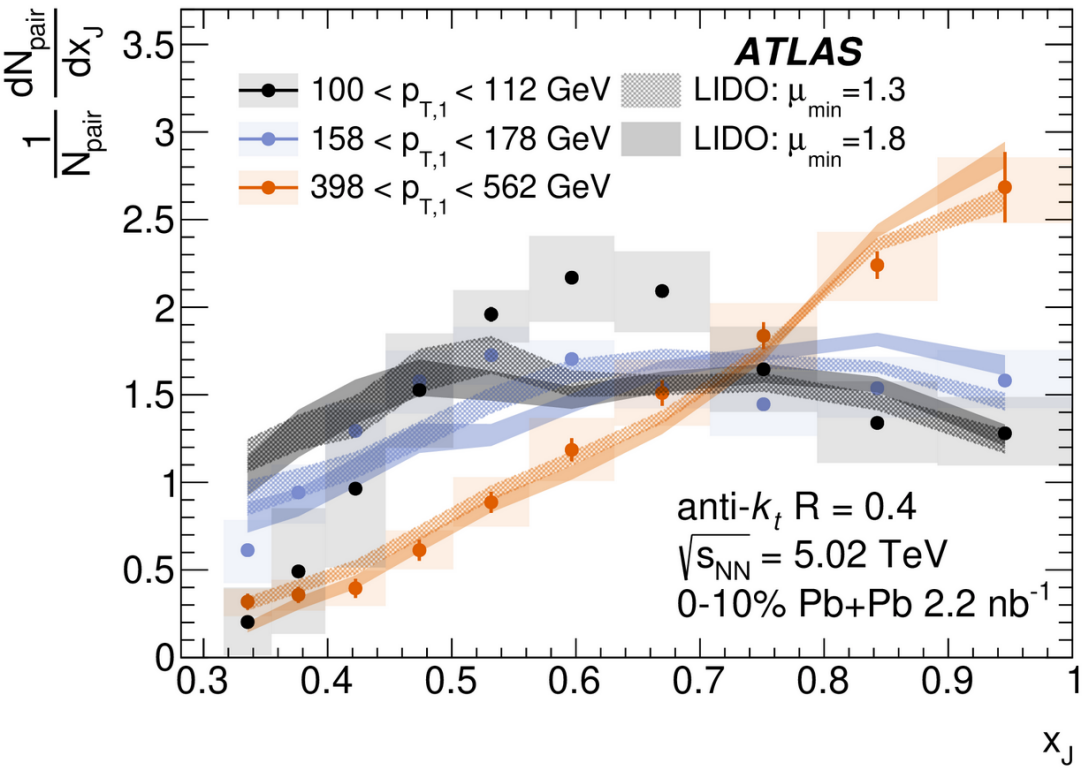


PLB 802 (2020) 135262

- R_{AA} of Z and W is unity (modulo isospin) => **we understand the geometry** of Pb+Pb collision.
- Some small deviation from unity => information about high-energy nuclear structure: **nuclear-PDFs**, **neutron skin-effect**, …
- Jet quenching – result of **final state interaction** of parton shower with deconfined medium.

Dijet studies

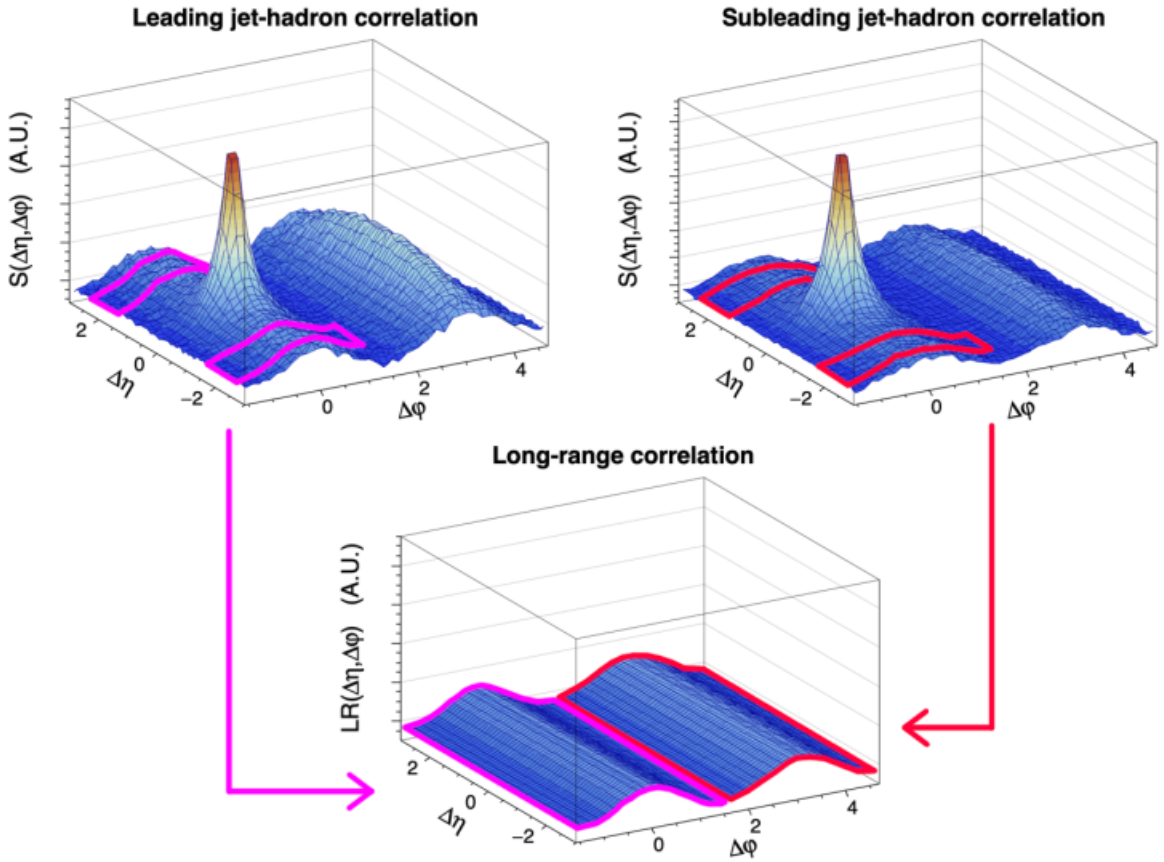
- Measuring dijets allows to also study the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,leading} / p_{T,subleading}$.



- Significant **dijet imbalance** seen in central heavy ion collisions.
- Comparison to one of radiative energy loss models => can learn more details

arXiv:2205.00682

Dijet studies

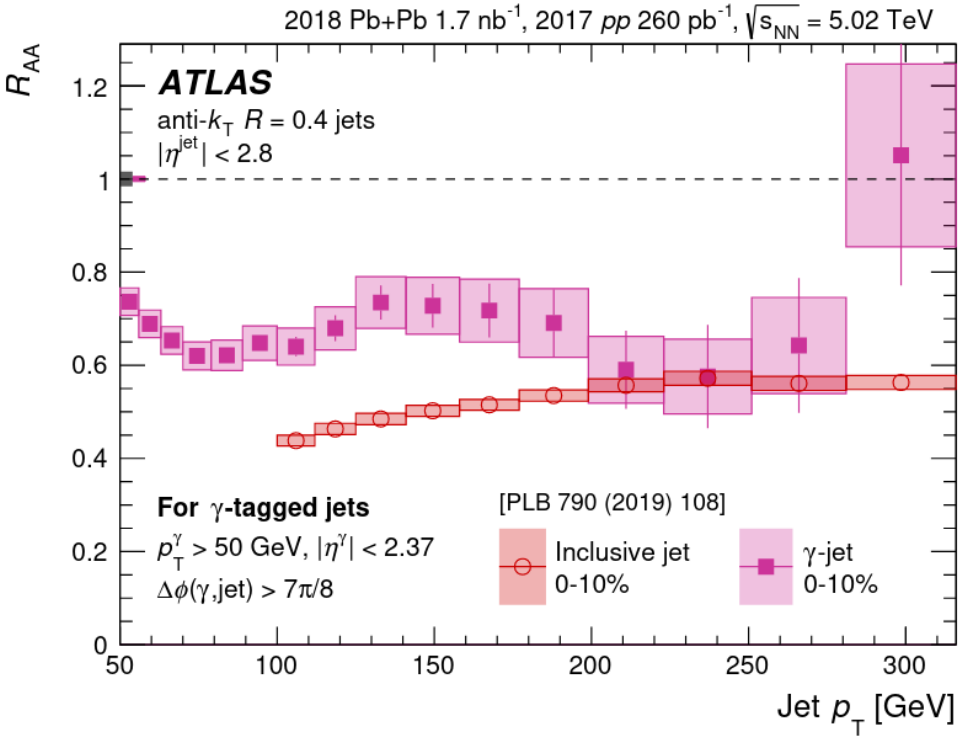


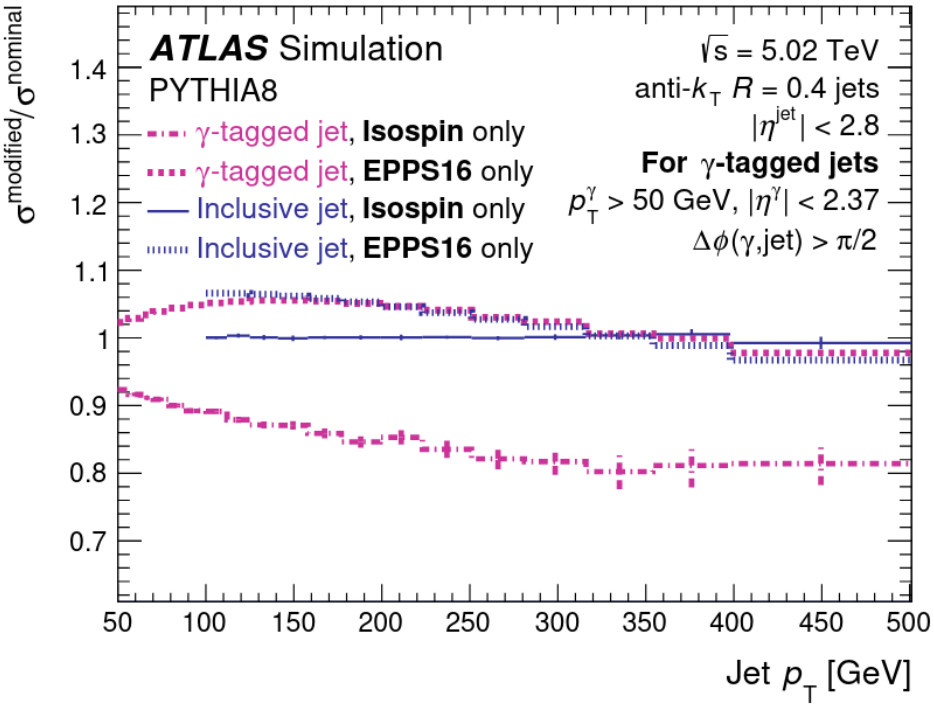
$$f_{\text{Fourier}}(\Delta\varphi) = A\left(1 + \sum_{n=1}^{4} 2V_{n\Delta}\cos(n\Delta\varphi)\right)$$

$$V_{n\Delta}^{\text{dihadron}} = v_n^{\text{trigger}} v_n^{\text{associated}}$$

Suppression in gamma-jet system

arXiv:2303.10090





- Right:
  - Inclusive jets dominated by gluon-initiated jets.
  - Photon-jet system dominated by **quark-initiated jets** => **less suppression** as expected.
- Left: the difference cannot be explained as a consequence of isospin and nuclear-PDFs effect.

Suppression in γ-jet system

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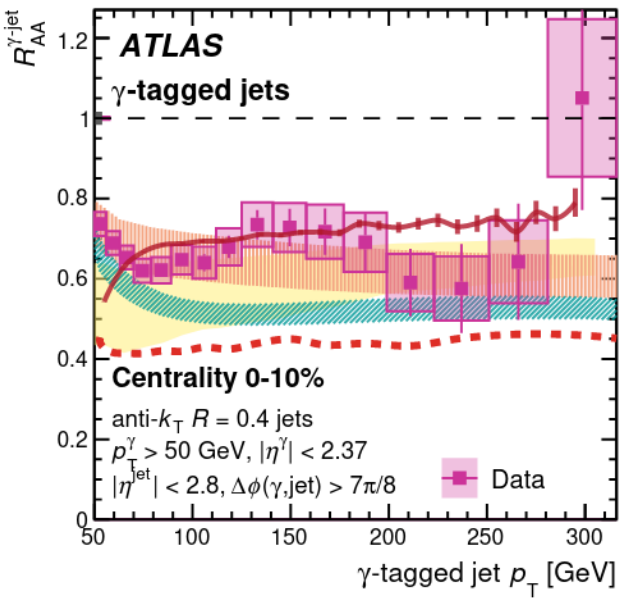
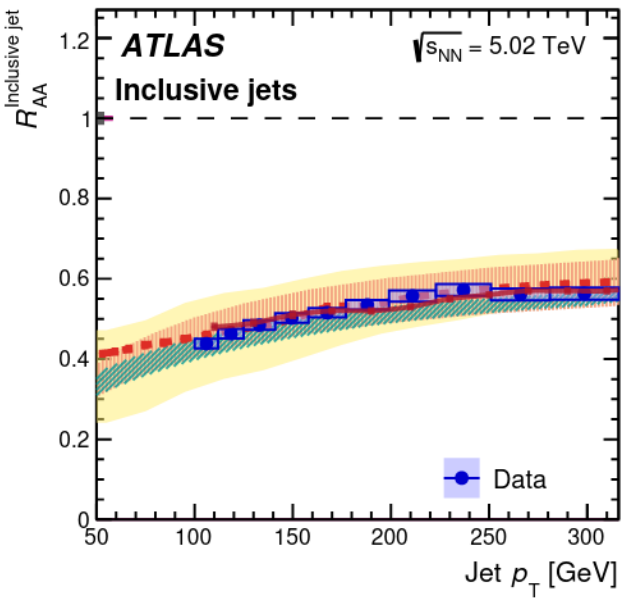
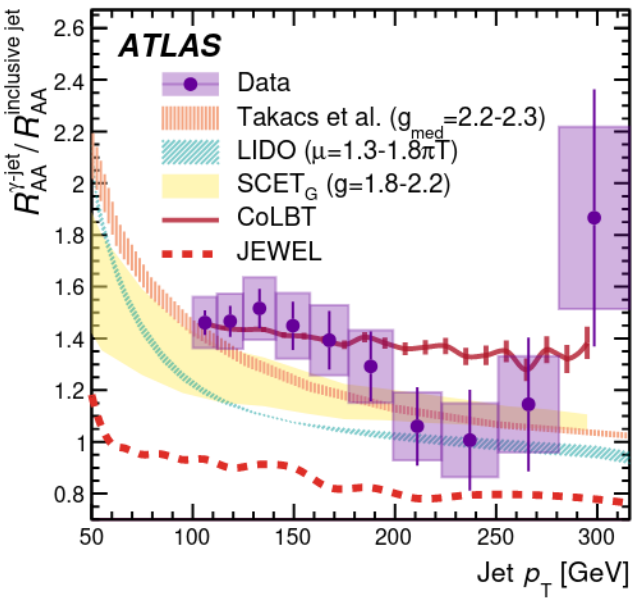


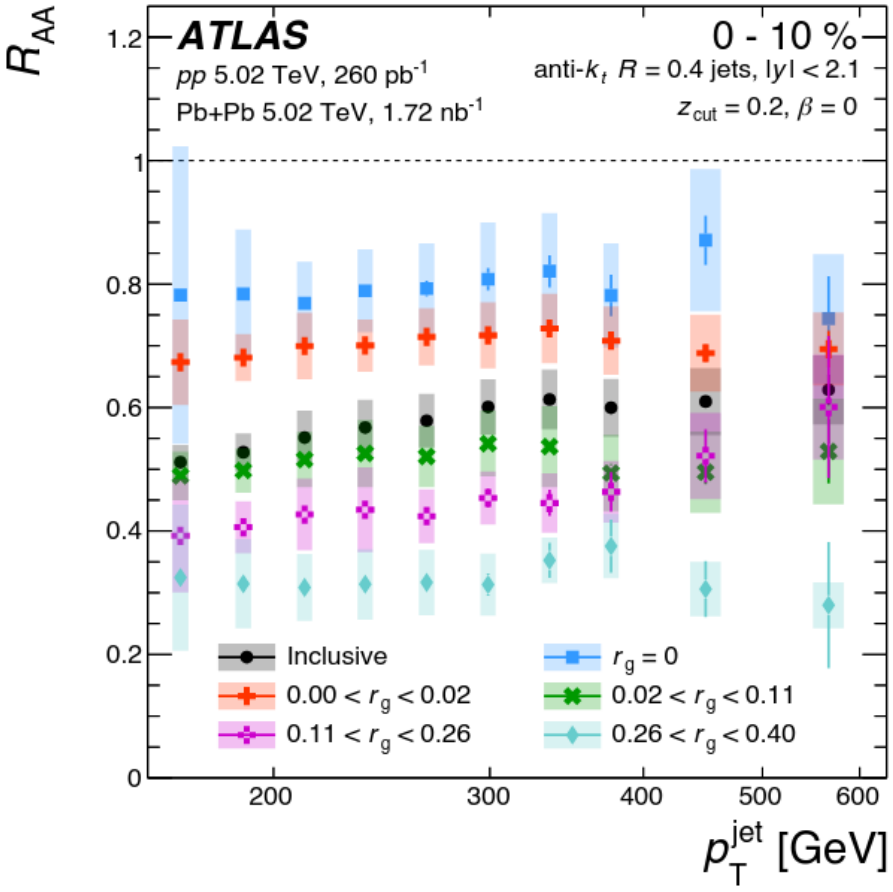




- Inclusive jets: good agreement between various models and the data.
- γ-jets: in general, **smaller suppression seen in the data** than in theory predictions.
- Should help constraining the **impact of color charge** as well as impact of so called **selection bias** (jets in dijets are quenched while gamma is not).

Jet structure and R=0.4 jets

arXiv:2211.11470



- Similar measurement done also for R=0.4 jets with soft-drop.
- Suppression measured differentially in $r_g \sim \Delta R_{12}$
- A **factor of two** difference between different r_g configurations.
- Suppression **larger for jets with larger angle** as expected from the coherence picture.