Jet Measurements in Heavy Ion Collisions with the ATLAS Experiment

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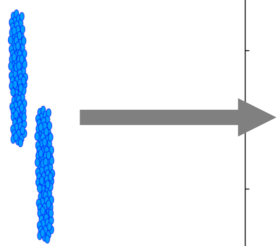
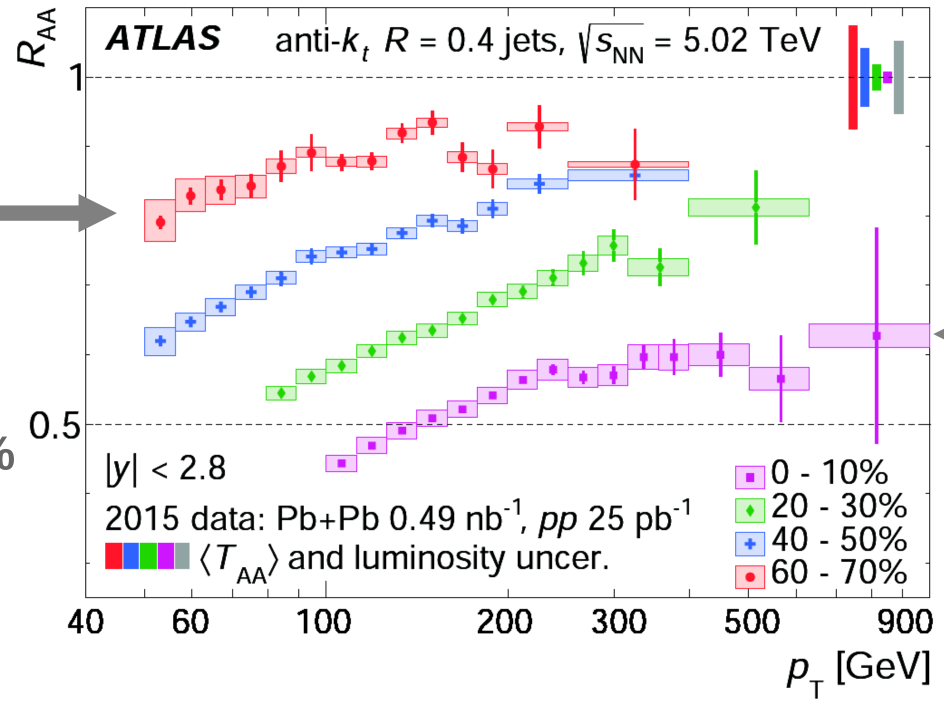
Introduction



peripheral,
e.g. 60-80%



central,
e.g. 0-10%

Pb+Pb

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

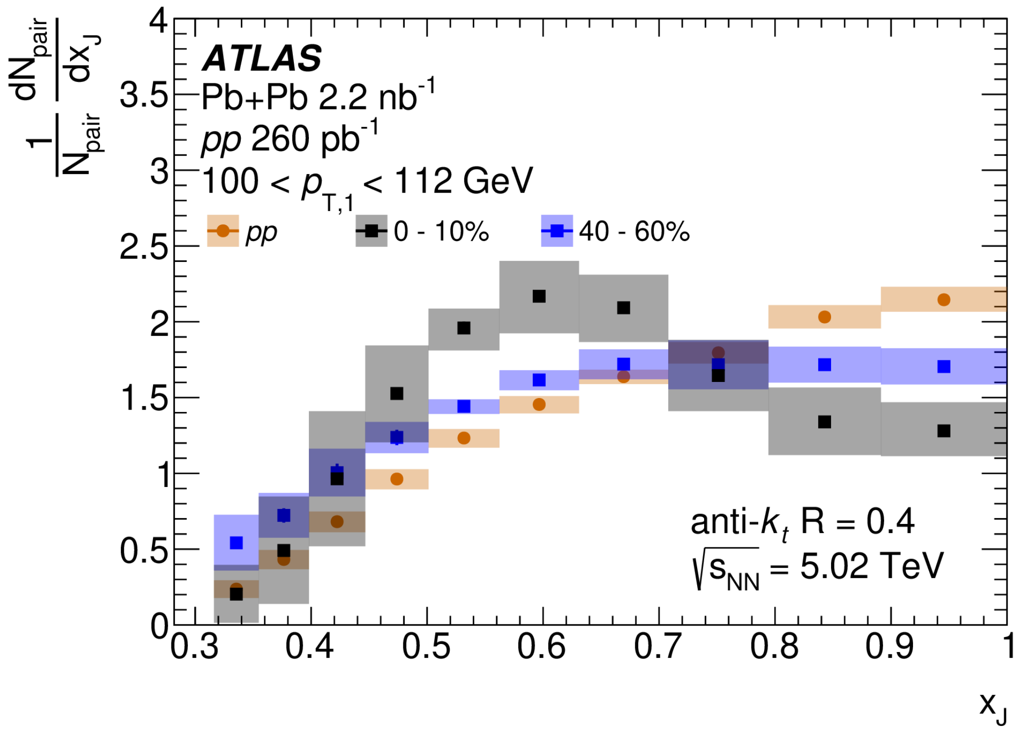
geometry — pp

Jet quenching – significant phenomenon, present also at the TeV scale!

=> need to learn details …

Dijets in Pb+Pb

- Input to better understand 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.

PRC 107 (2023) 054908

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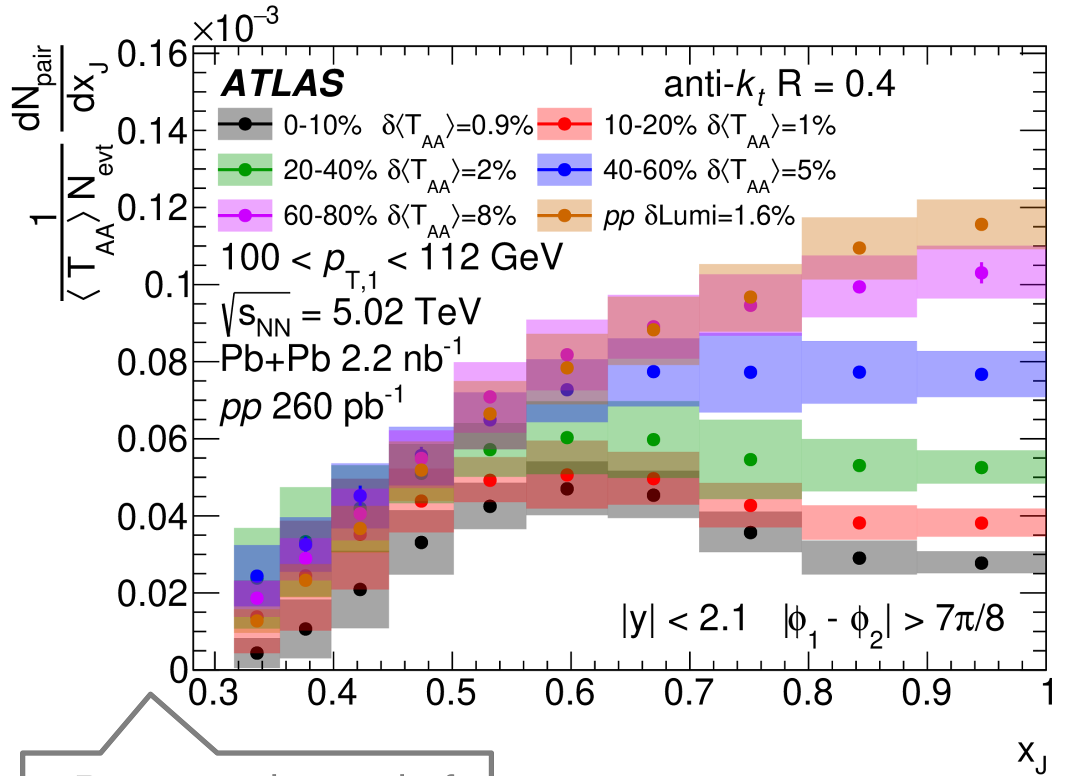


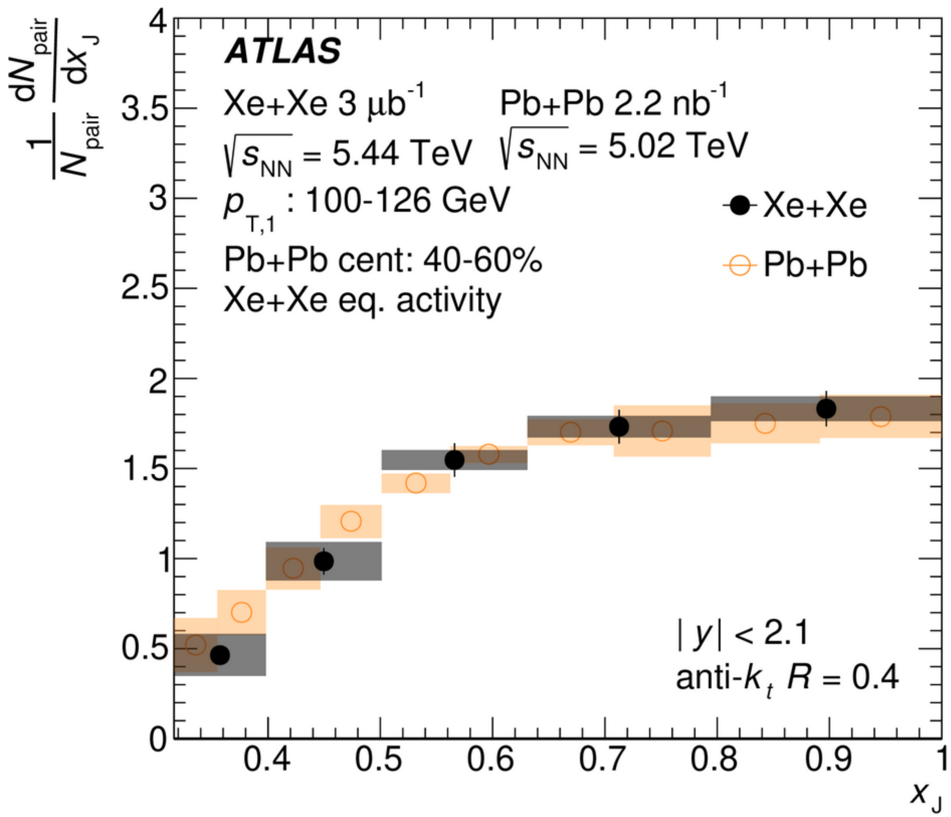
Per-event instead of dijet normalization

- 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

PRC 107 (2023) 054908

Dijets in Xe+Xe

- Input to better understand the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,leading} / p_{T,subleading}$.



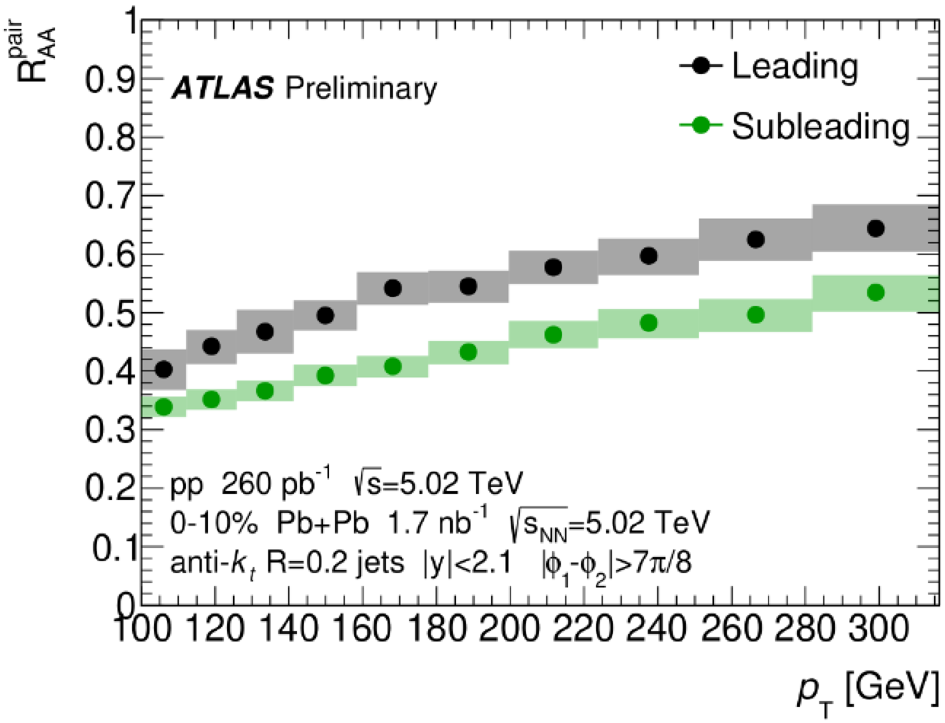
- Significant **dijet imbalance** seen in central heavy ion collisions.
- Studied also **in Xe+Xe** collisions – important to understand the system size dependence of jet quenching … similar level of jet suppression when taking into account differences in geometry and $\sqrt{s_{NN}}$

PRC 108 (2023) 024906

Radius dependence of dijet suppression

$$R_{AA}^{\mathrm{pair}}(p_{\mathrm{T},1}) = \frac{\frac{1}{N_{\mathrm{evnt}}\langle T_{\mathrm{AA}}\rangle}\int_{0.32\times p_{\mathrm{T},1}}^{p_{\mathrm{T},1}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}} \mathrm{d}p_{\mathrm{T},2}}{\frac{1}{L^{pp}}\int_{0.32\times p_{\mathrm{T},1}}^{p_{\mathrm{T},1}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}^{pp}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}} \mathrm{d}p_{\mathrm{T},2}}$$

ATLAS-CONF-2023-060



- Sub-leading jets are quenched more than leading jets.

Radius dependence of dijet suppression

$$R_{AA}^{\mathrm{pair}}(p_{\mathrm{T},2}) = \frac{\frac{1}{N_{\mathrm{evnt}}\langle T_{\mathrm{AA}}\rangle}\int_{p_{\mathrm{T},2}}^{p_{\mathrm{T},2}/0.32}\frac{\mathrm{d}^2N_{\mathrm{pair}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\mathrm{d}p_{\mathrm{T},1}}{\frac{1}{L^{pp}}\int_{p_{\mathrm{T},2}}^{p_{\mathrm{T},2}/0.32}\frac{\mathrm{d}^2N_{\mathrm{pair}}^{pp}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\mathrm{d}p_{\mathrm{T},1}}$$

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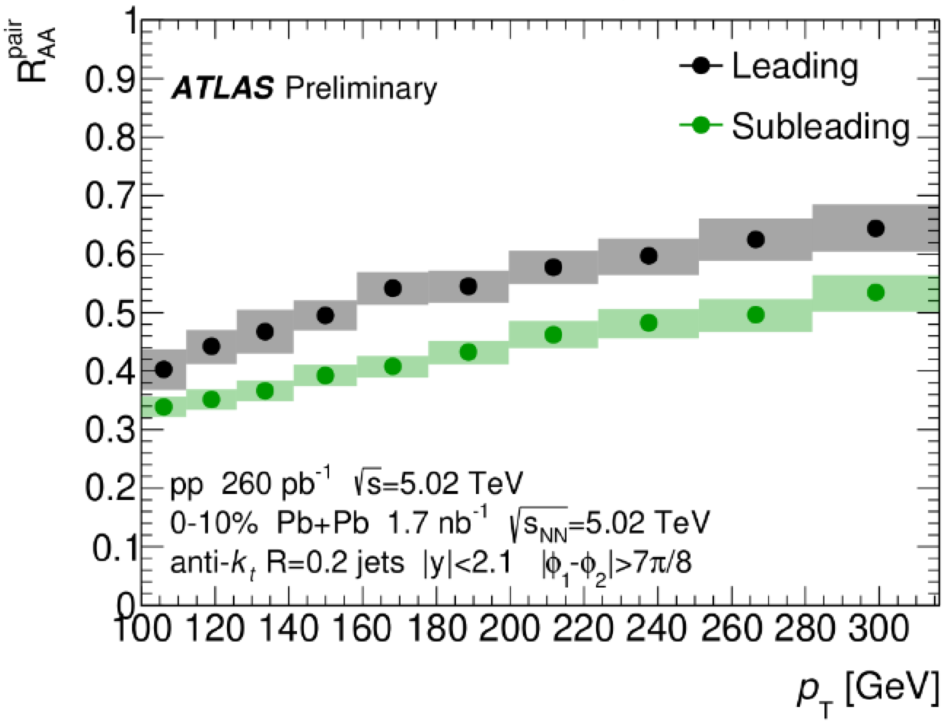

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Radius dependence of dijet suppression

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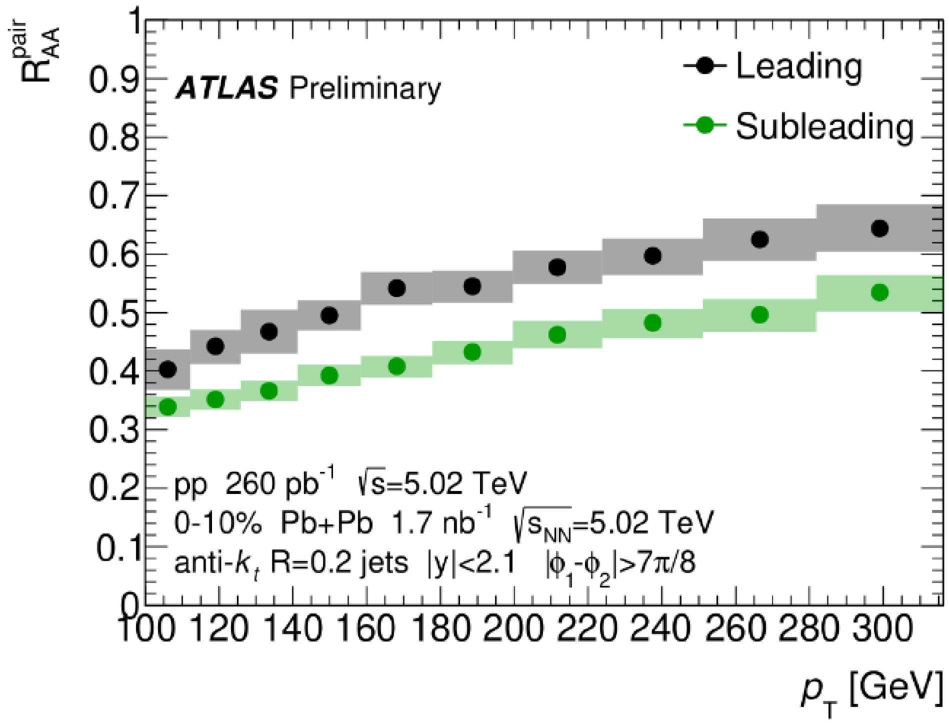
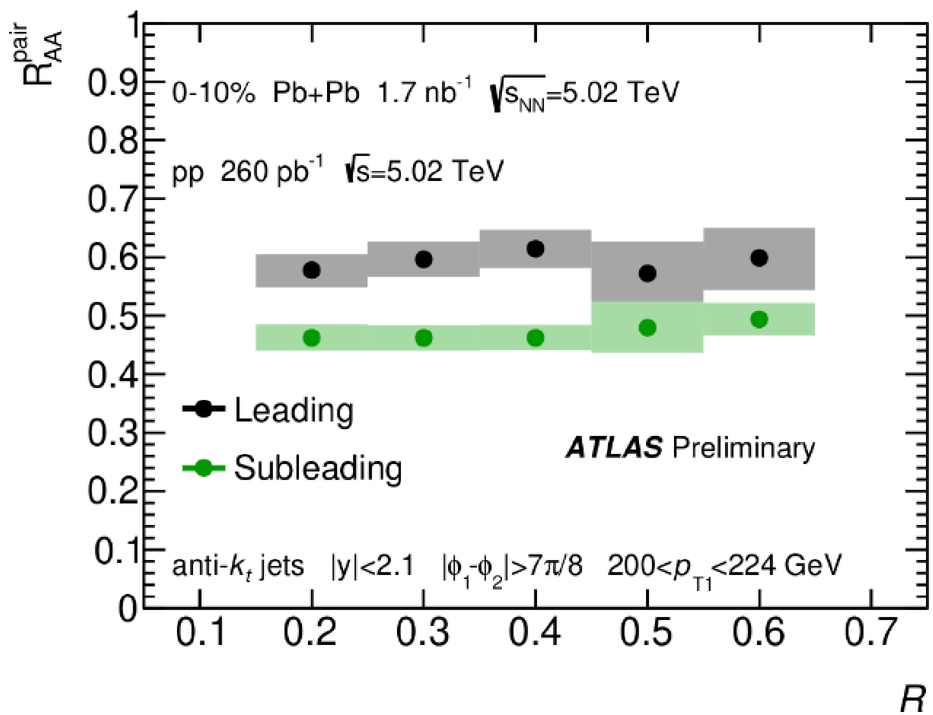
ATLAS-CONF-2023-060

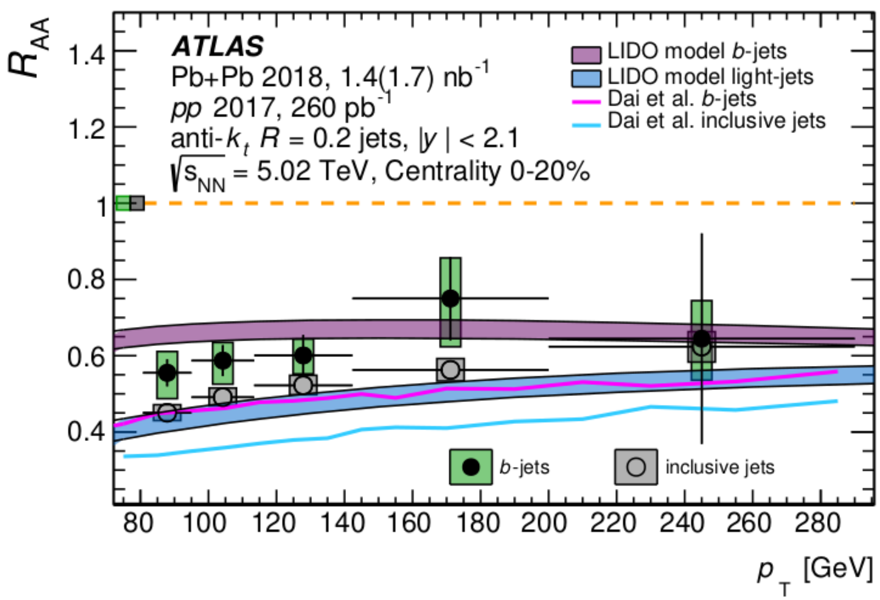


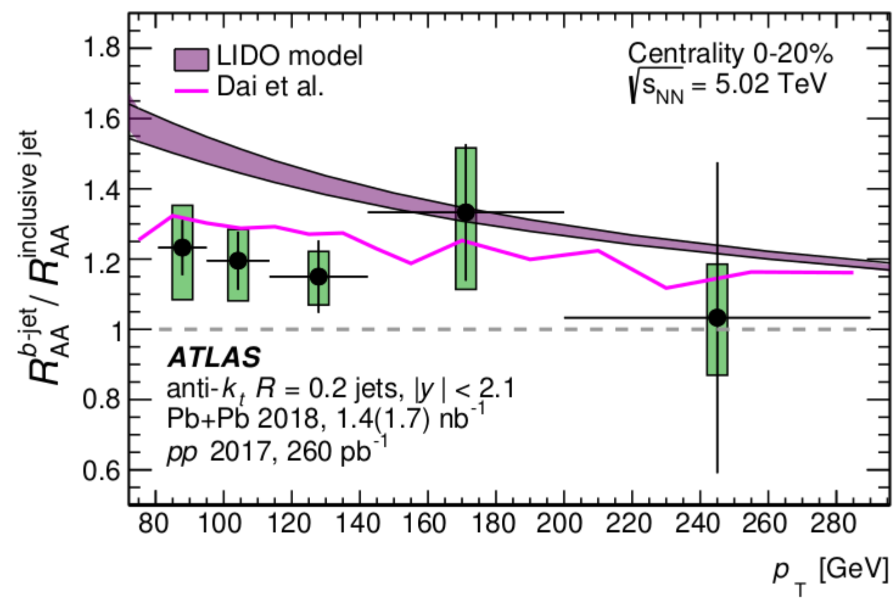


- Sub-leading jets are quenched more than leading jets.
- No significant dependence of suppression on jet radius observed.

Suppression in b-jet system

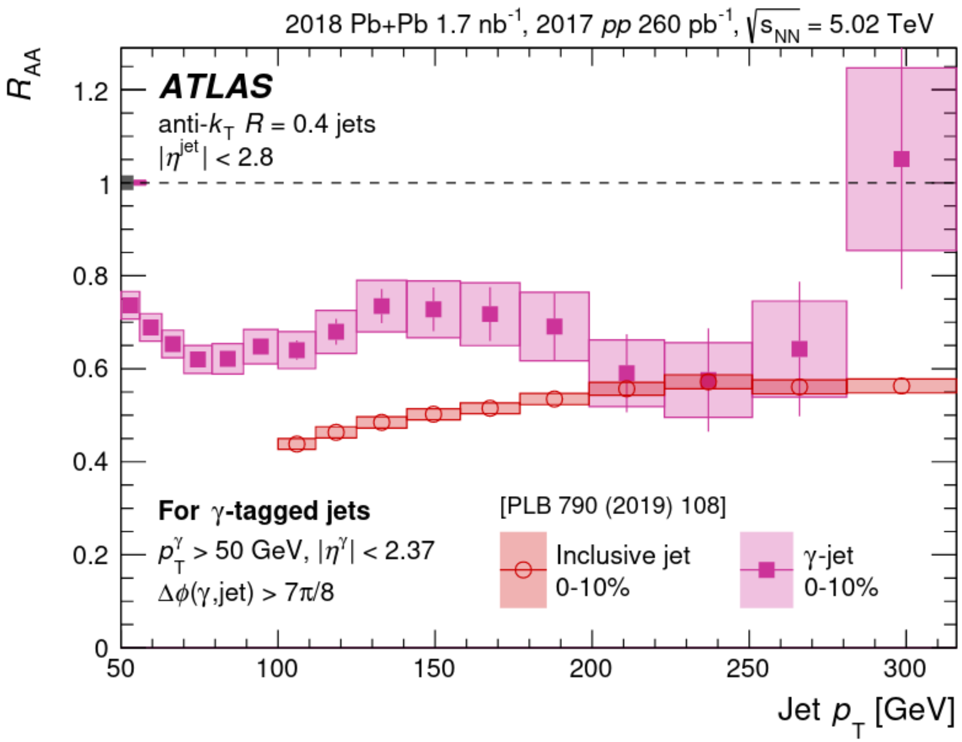
EPJC 83 (2023) 438





- b-jets: understand **parton mass** dependence of energy loss.
- Statistically limited but clearly smaller suppression of b-jets compared to inclusive jets seen.
- Clearly quantified by the double ratio.

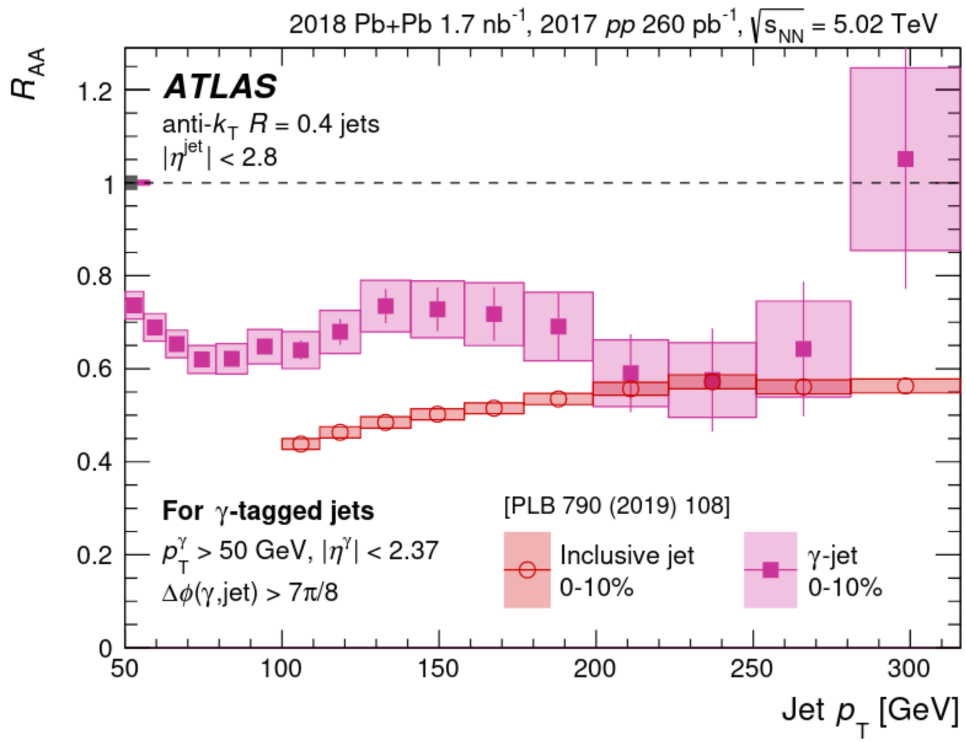
Suppression in γ-jet system

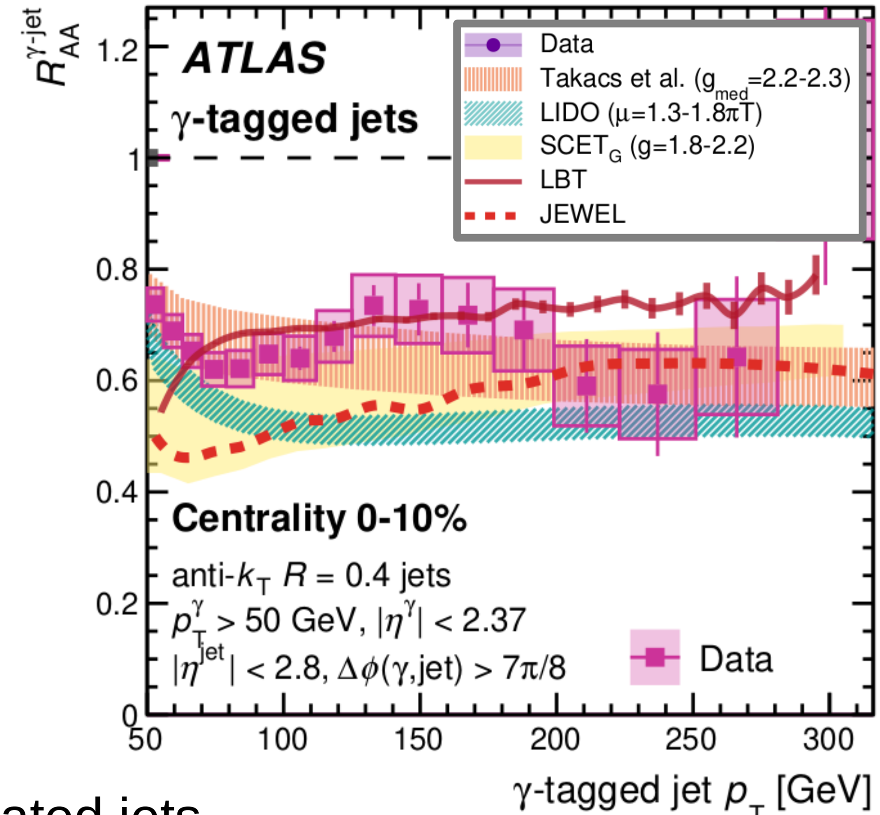


- Inclusive jets dominated by gluon-initiated jets.
- γ-jets dominated by **quark-initiated jets** => **less suppression** as expected.

PLB 846 (2023) 138154

Suppression in γ-jet system

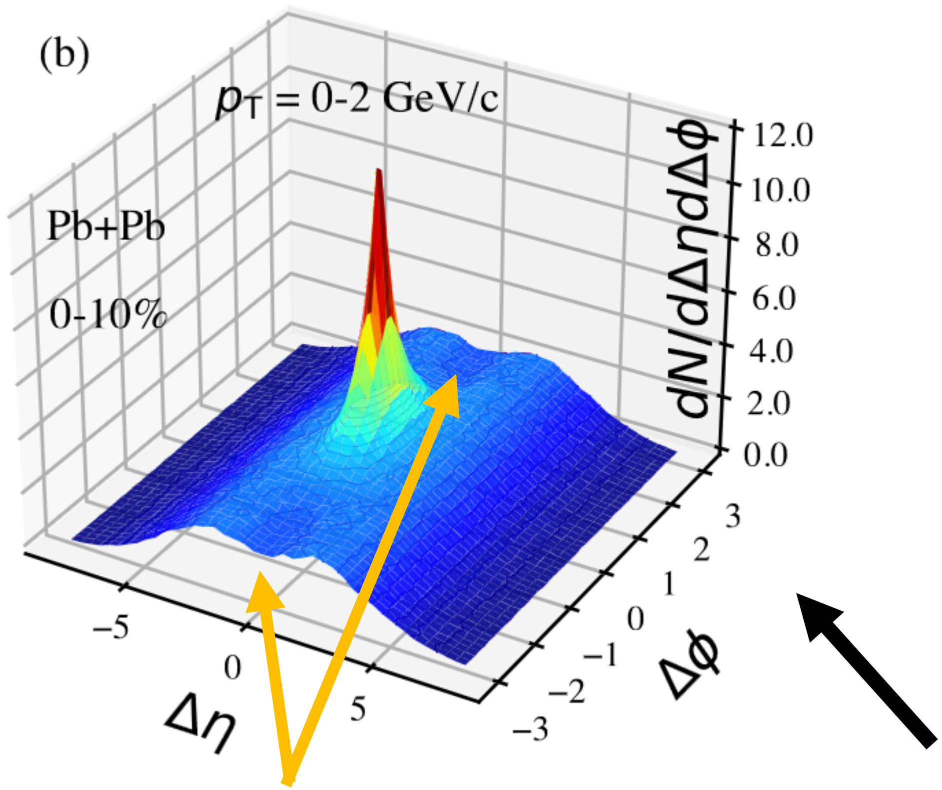




- Inclusive jets dominated by gluon-initiated jets.
- γ-jets dominated by **quark-initiated jets** => **less suppression** as expected.
- All models can be adjusted to reproduce inclusive jet R_{AA}, but none of them fully reproduces the γ-jet R_{AA} (typically **predict larger quenching**)
- Theory: impact of **color charge** & **selection bias**

PLB 846 (2023) 138154

Search for diffusion wake in γ-jet

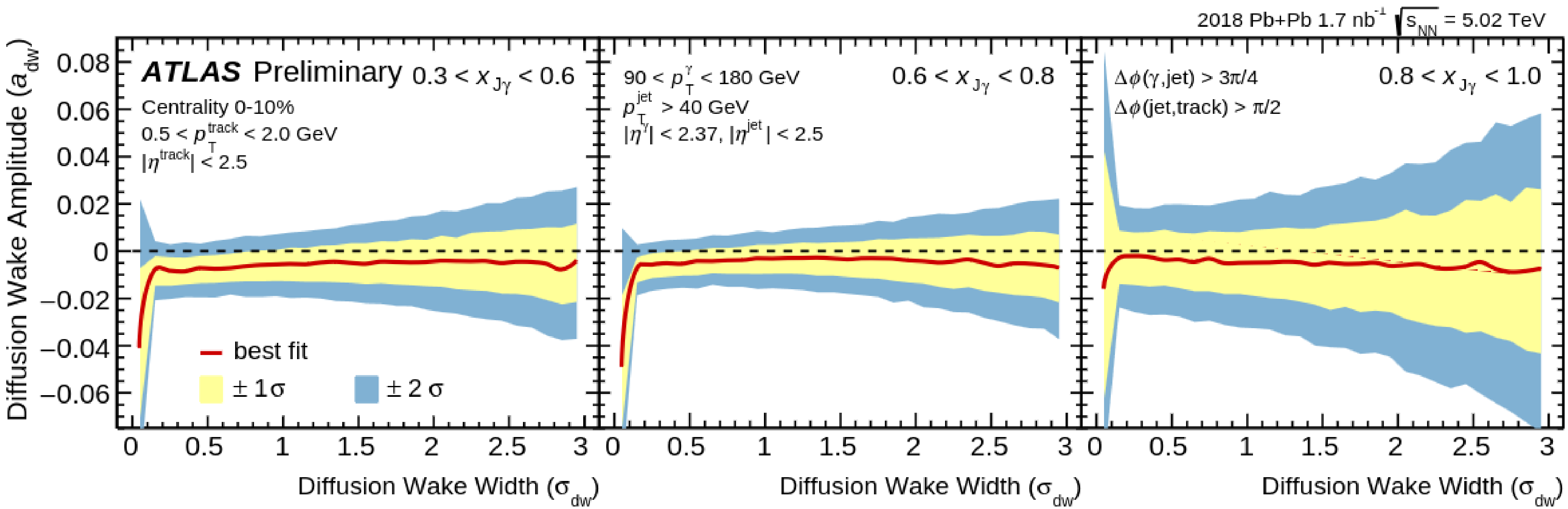


PRL 130 (2023) 5, 052301

- Jet-hadron correlations in γ-jets events **predicted** to be sensitive to a presence of **diffusion wake** (due to “holes” in the medium after partons kicked out by jet-medium interaction).

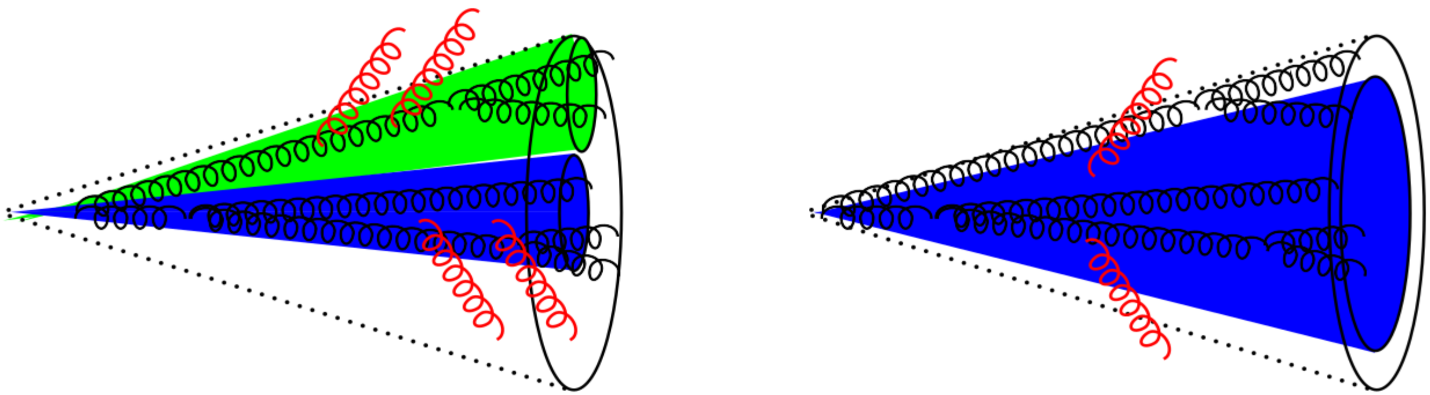
Search for diffusion wake in γ-jet

ATLAS-CONF-2023-054



- Jet-hadron correlations in γ-jets events **predicted** to be sensitive to a presence of **diffusion wake** (due to "holes" in the medium after partons kicked out by jet-medium interaction).
- Soft hadron yields divided by uncorrelated bkgr allow to fit **diffusion wake amplitude**. Evaluated as a function of $x_{J\gamma}$ (~ magnitude of energy loss).
- **No significant** diffusion wake observed. Setting limits: >0.9% modulation ruled out at 95% CL.

Jet structure and large-R jets

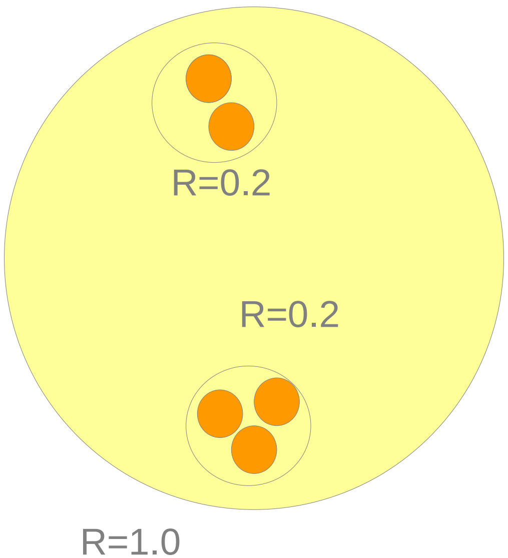


PRL 106 (2011) 122002
PLB 707 (2012) 156

- Part of the parton shower may remain unresolved due to the color coherence. Unresolved subjet **radiates as a single color charge**.
- Early, hard splittings in the parton shower are likely **not altered by the medium**.

  => measure jet suppression differentially in jet substructure.

Jet structure and large-R jets

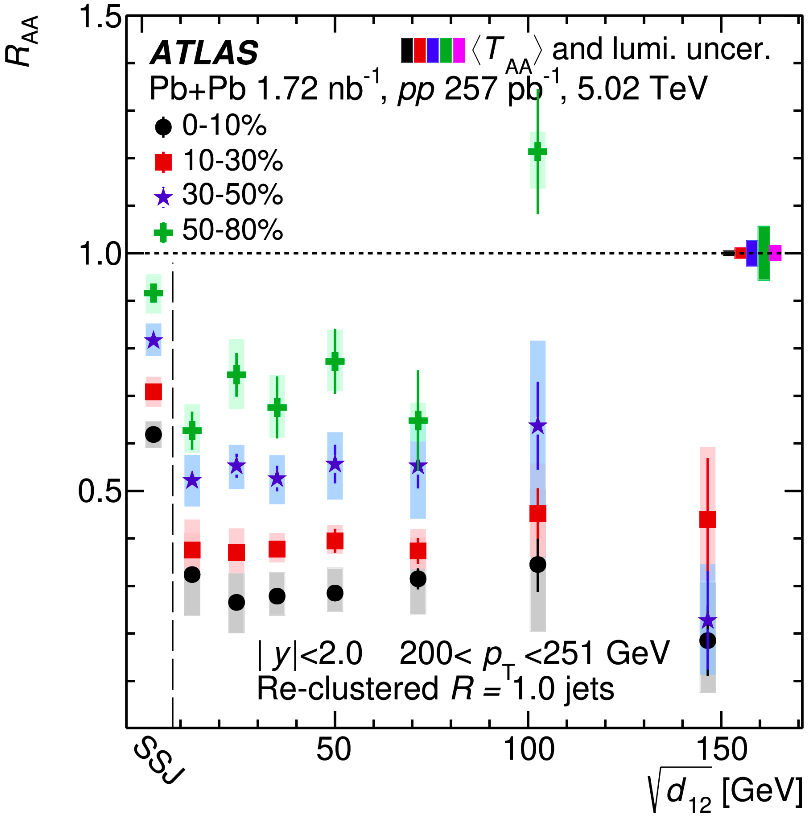


- No measurement of large-*R* jets in heavy-ion collisions done before.
- *R*=0.2 jets with p_T>35 GeV reclustered using anti-k_T *R*=1.0
  - Soft contributions removed
  - Allows to study k_T splitting scale

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

Jet structure and large-R jets

PRL 131 (2023) 172301



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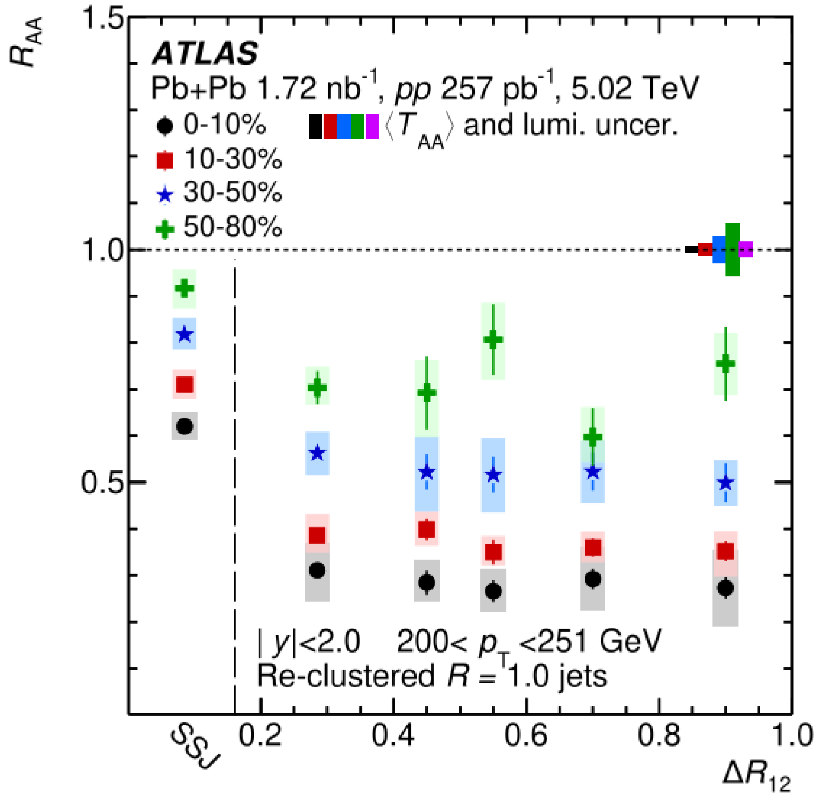
- Large-*R* jets with single sub-jet suppressed **significantly less** (consistent with color coherence picture).

- Large-*R* jets with multiple sub-jets: R_{AA} values consistent with **constant**.

Jet structure and large-R jets

PRL 131 (2023) 172301



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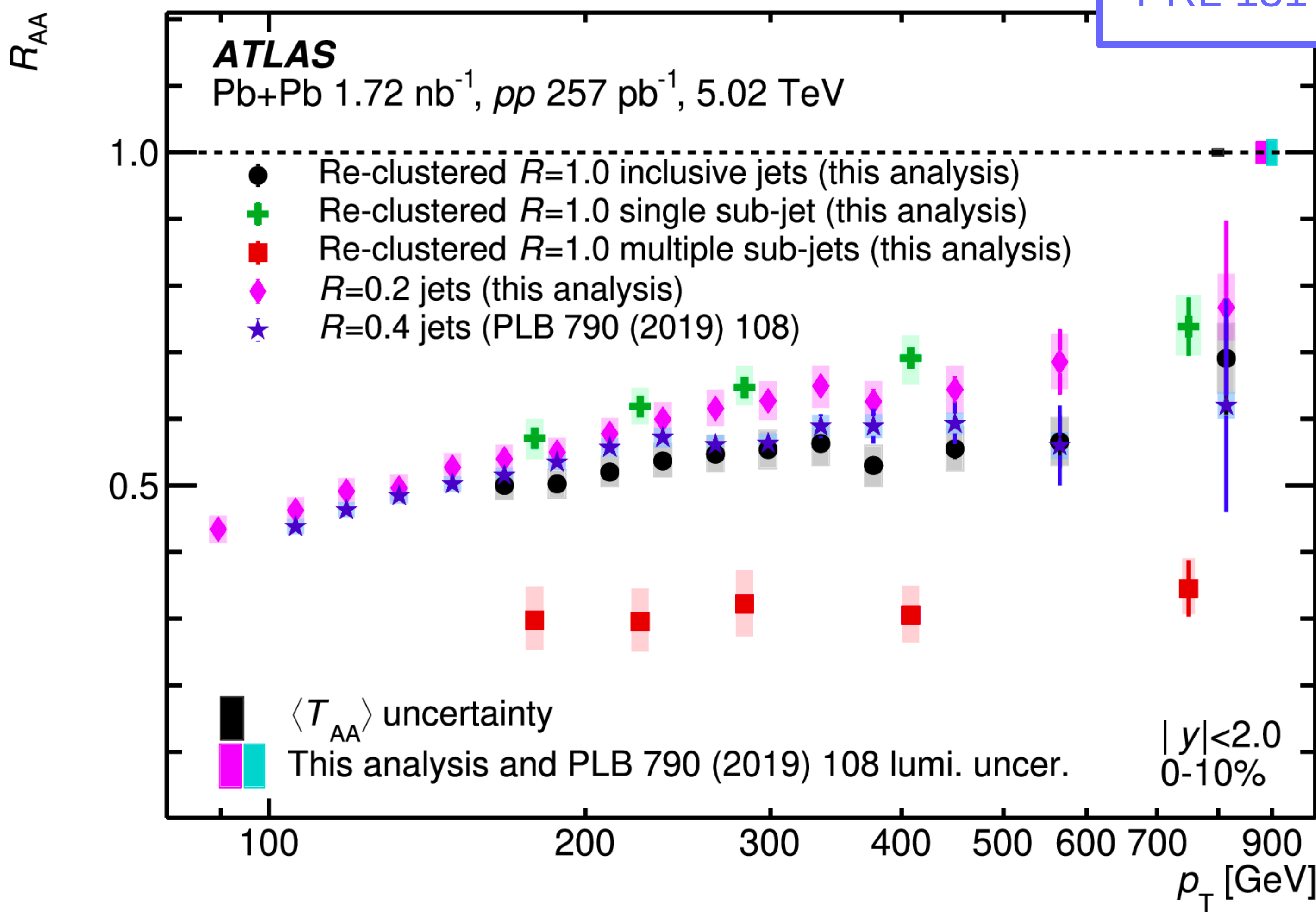
- Large-*R* jets with single sub-jet suppressed **significantly less** (consistent with color coherence picture).
- Large-*R* jets with multiple sub-jets: R_{AA} values consistent with **constant.**
- Similar picture obtained for ΔR_{12} too.

Jet structure and large-R jets

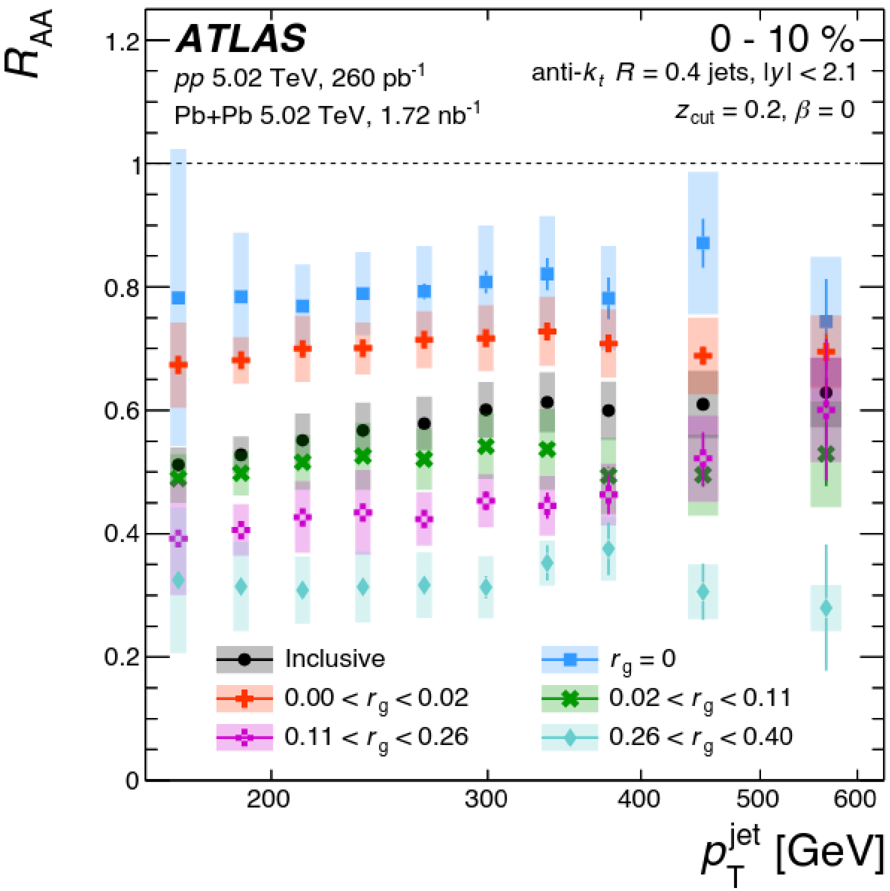
PRL 131 (2023) 172301



Single sub-jet vs. multiple sub-jets vs. R=0.4 jets and R=0.2 jets.

Jet structure and R=0.4 jets

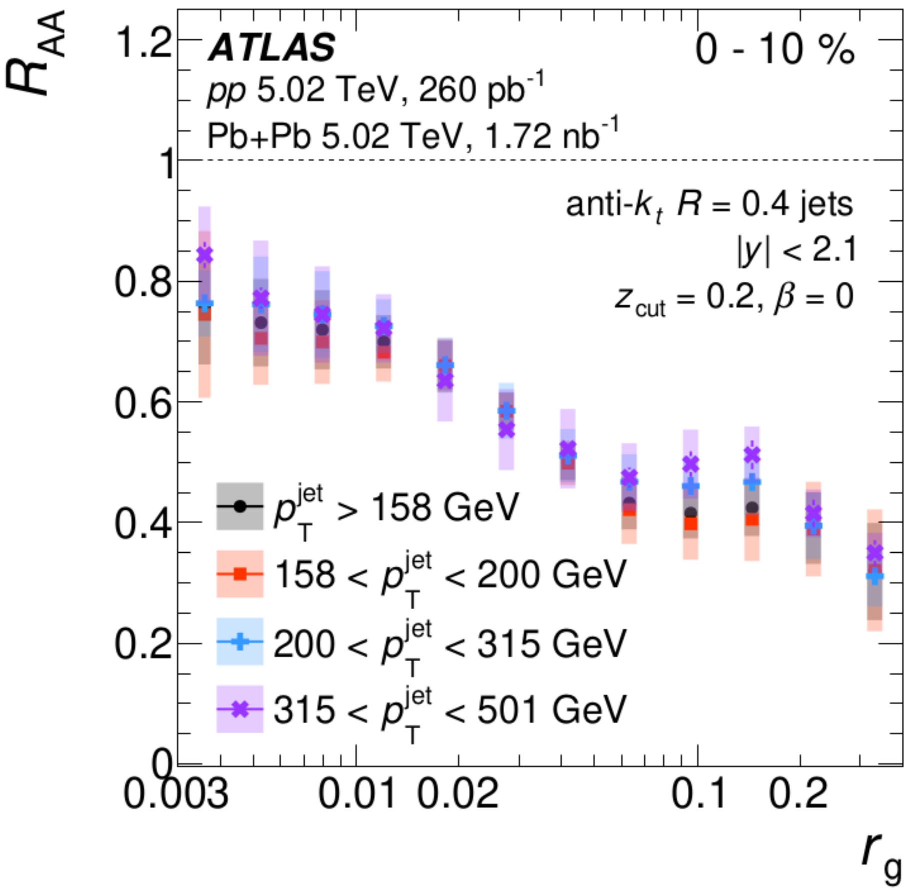
PRC 107 (2023) 054909



- Similar measurement done also for R=0.4 jets with soft-drop.
- Uses track-to-calo matching to access finer angular structure of subjets.
- 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.

Jet structure and R=0.4 jets

PRC 107 (2023) 054909



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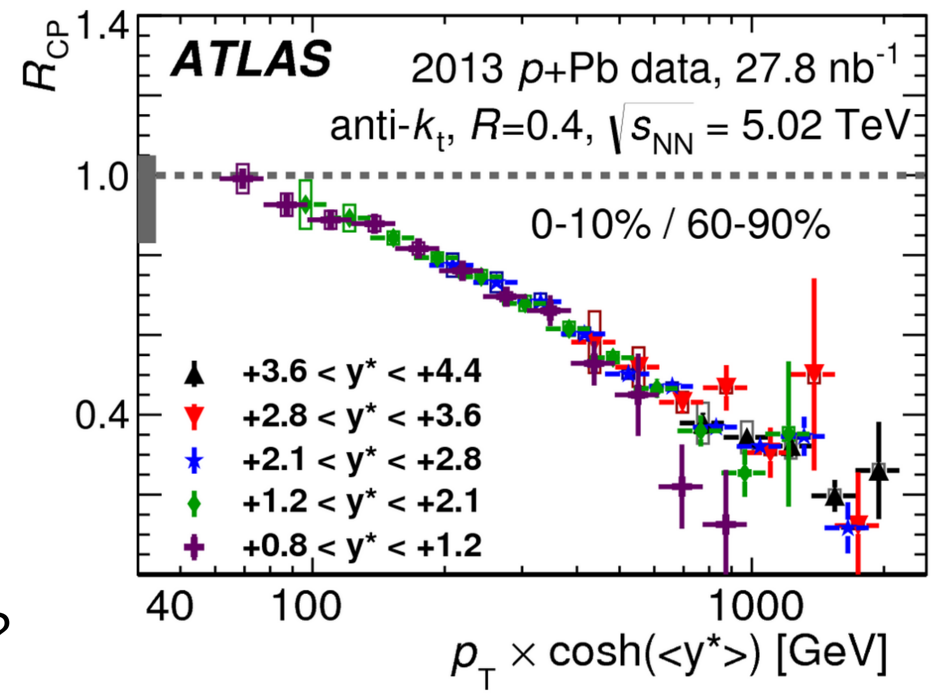
- Suppression **larger for jets with larger angle** as expected from the coherence picture.

Dijets in p+Pb

- Input to better understand R_{CP} in p+Pb:
  - different from unity
  - scales with jet energy in proton-going direction
- Possible origin of these features...
  - proton “being smaller” at high x (color transparency)?
  - gluon saturation in Pb?
  - centrality bias?
  - something else?

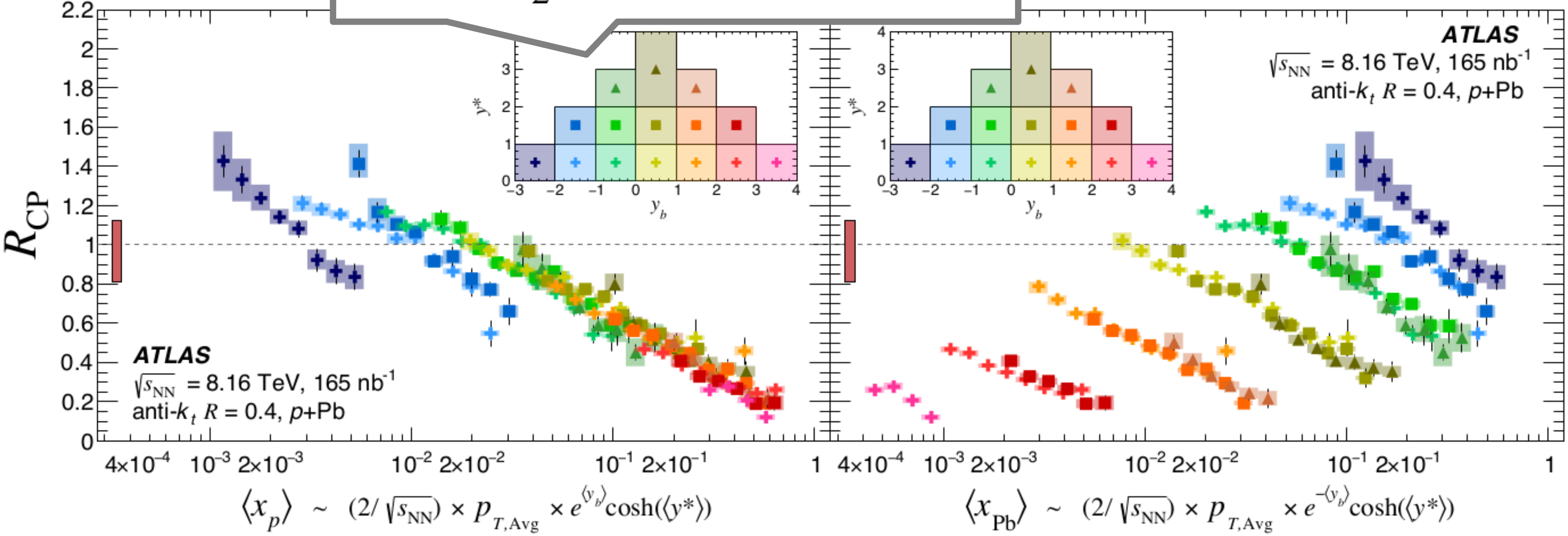
PLB 748 (2015) 392



Dijets in p+Pb

$$y^* = \frac{|y_1^{\text{c.m.}} - y_2^{\text{c.m.}}|}{2} \qquad y_b = \frac{y_1^{\text{c.m.}} + y_2^{\text{c.m.}}}{2}$$

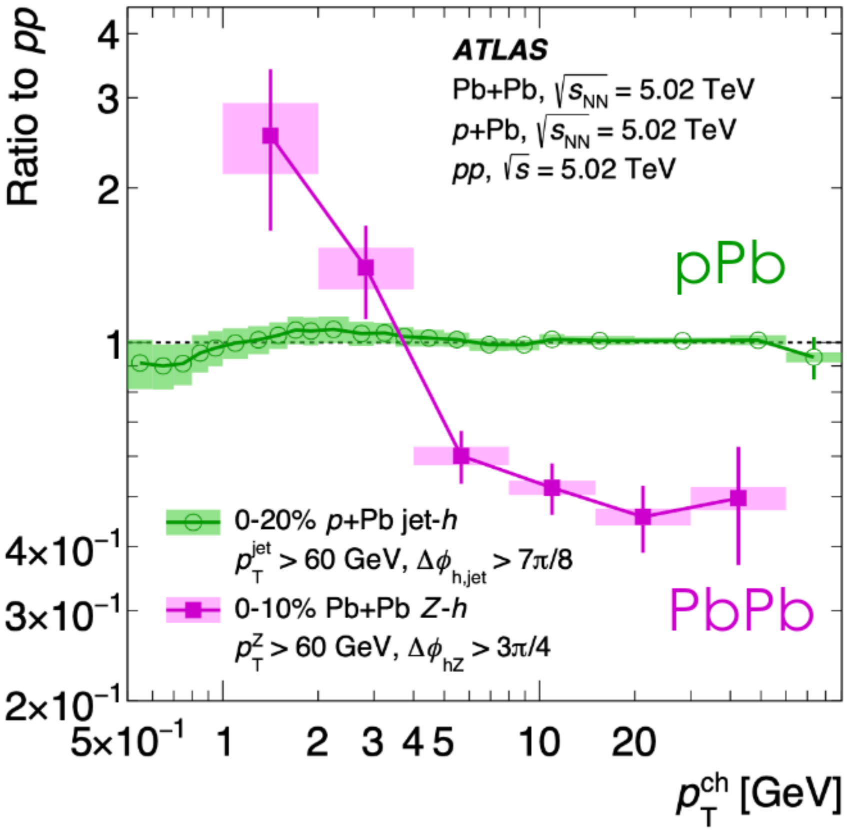
PRL 132 (2024) 102301



- Clear scaling seen **in x_p** for the **valence quark** dominated region (further insight also by not shown x_F scaling).
- No scaling seen in x_{Pb} => saturation should not be driving mechanism of observed R_{CP}.
- Important input for understanding **color fluctuations in proton**.

Jet quenching in small systems?

PRL 131 (2023) 072301



- Significant elliptic flow present in p+Pb and high mult. pp collisions is a pointer to **collectivity** => search for jet quenching in small collision systems.
- Measured p+Pb to pp ratio of **yields of hadrons** produced opposite the jet.
- **No evidence of quenching** in p+Pb seen.

Summary

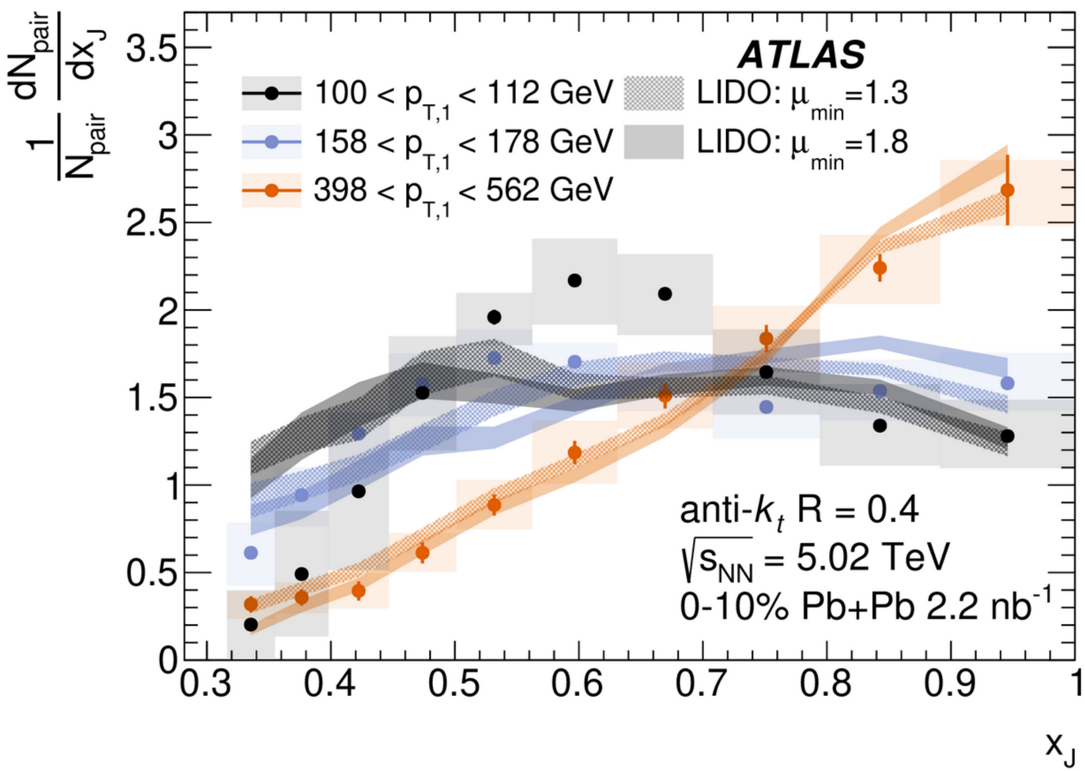
- In the dijet system, production of balanced jets is suppressed.
  Dijet suppression does not show significant dependence on jet radius.
- Significantly smaller suppression of jets in γ-jet and b-jet systems than in inclusive jet system.
- No signal of diffusion wake observed in γ-jet events.
- Large-R jets with single sub-jet suppressed significantly less then jets with more complex topologies as expected from a presence of color coherence effects.
- Scaling seen in R_{CP} of dijets in p+Pb connected with valence quarks in proton.
- No quenching seen in p+Pb environment.
- Find more here:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

This work was supported by ERC-CZ grant LL2327

Backup slides

Dijets in Pb+Pb

- Input to better understand the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,leading} / p_{T,subleading}$.

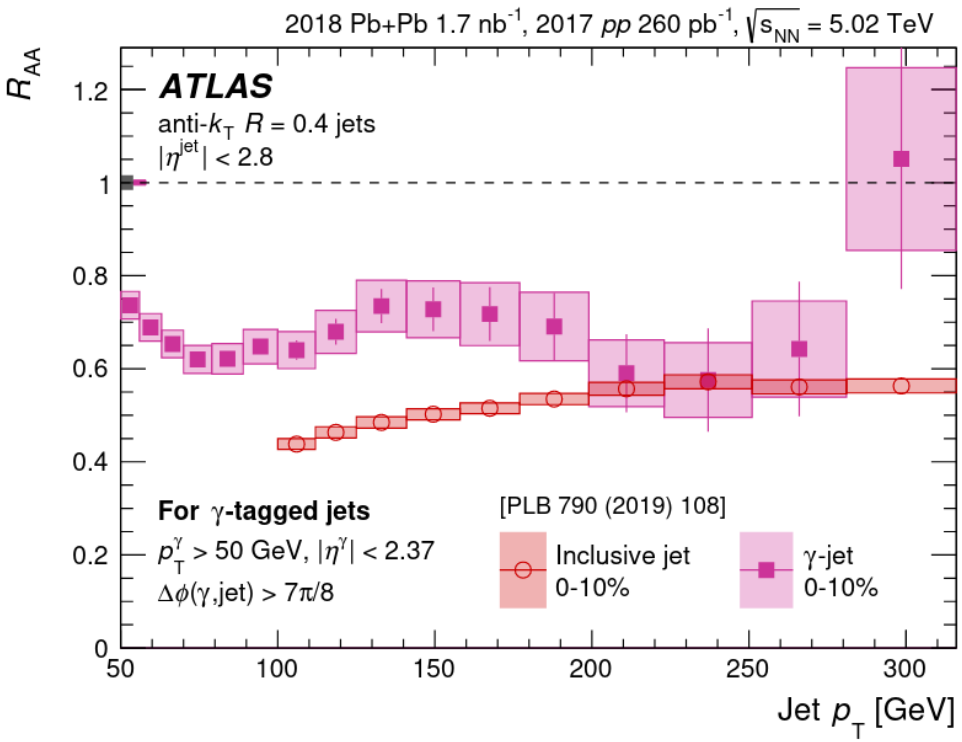


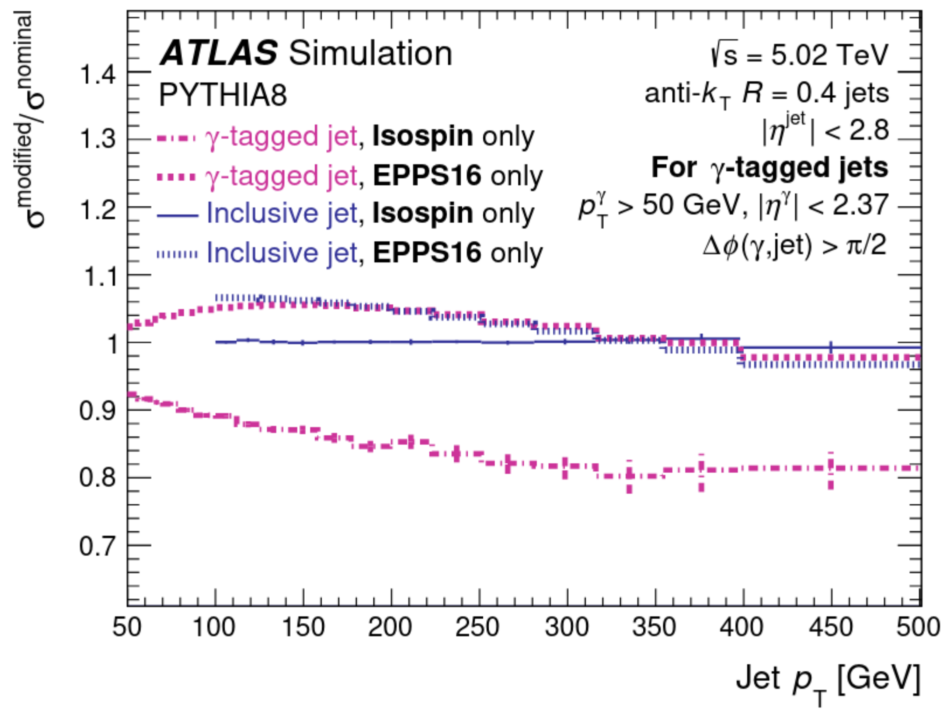
- Significant **dijet imbalance** seen in central heavy ion collisions.
- LIDO: one of **models** implementing radiative energy loss – prediction not in perfect agreement => can learn more details

PRC 107 (2023) 054908

Suppression in gamma-jet system

PLB 846 (2023) 138154

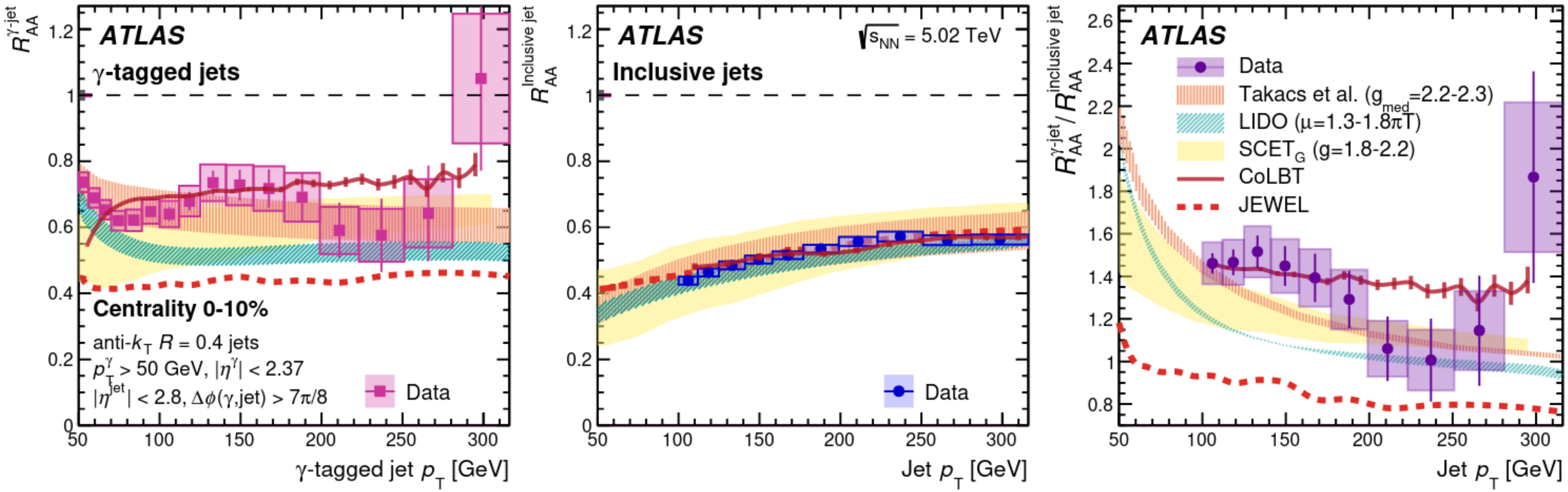




- Right:
  - Inclusive jets dominated by gluon-initiated jets.
  - Photon-jet system dominated by **quark-initiated jets** => **less suppression** as expected.
- Left: the difference cannot be explained as a consequence of isospin and nuclear-PDFs effect.

Suppression in γ-jet system

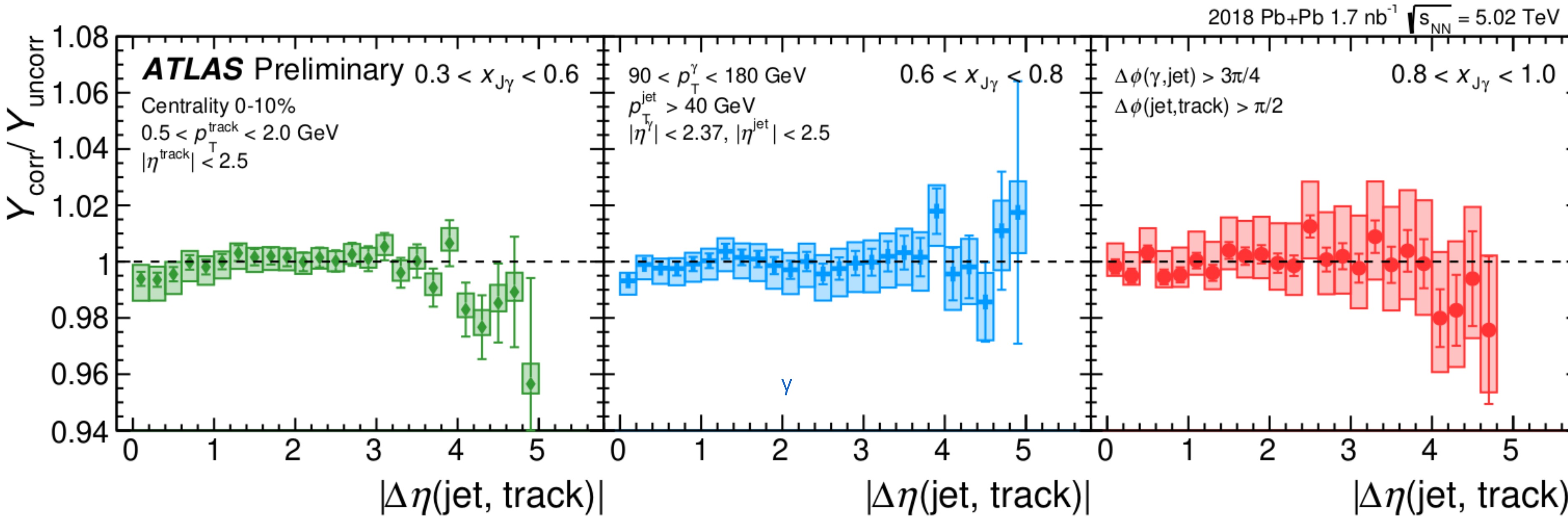
PLB 846 (2023) 138154



- 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 photon is not).

Search for diffusion wake in γ-jet

ATLAS-CONF-2023-054



$$Y_{\rm corr} = \frac{1}{N^{\gamma-\rm jet}} \frac{d^2 N^{\rm jet-track}}{d\Delta\eta\, d\Delta\phi}$$

$$a_0 + a_{\rm dw} e^{-|\Delta\eta(\rm jet,track)|^2/(2\sigma_{\rm dw}^2)}$$

- Diffusion wake amplitude (a_{dw}) then fitted for a given diffusion wake width (σ_{dw}) and $x_{J\gamma}$ => negative a_{dw} (as expected) but consistent with 0 within 1σ.
- CoLBT-hydro prediction not excluded.

Dijets in p+Pb

- Variables:

$$p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2} \qquad y_{\mathrm{b}} = \frac{y_1^{\mathrm{c.m.}} + y_2^{\mathrm{c.m.}}}{2} \qquad y^* = \frac{|y_1^{\mathrm{c.m.}} - y_2^{\mathrm{c.m.}}|}{2}$$

…. allowing to approximate:

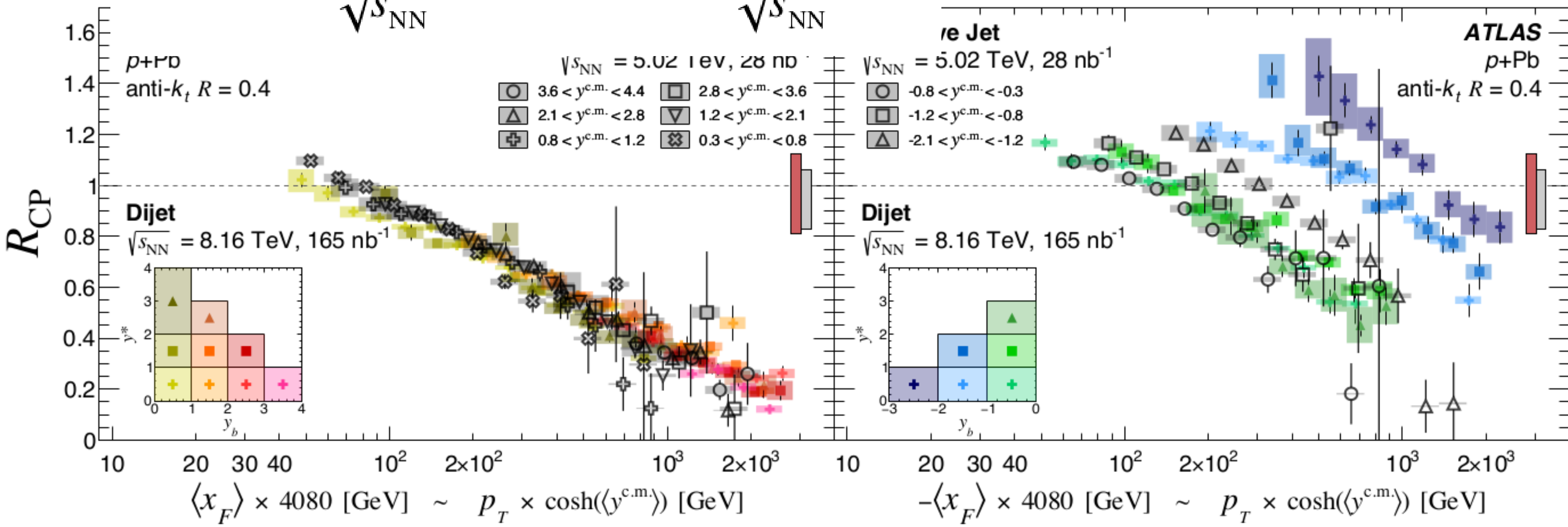
$$x_p \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{y_b} \cosh(y^*)$$

$$x_{\mathrm{Pb}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_b} \cosh(y^*)$$

Dijets in p+Pb

PRL 132 (2024) 102301

$$x_F = \frac{2m_T \times \sinh y^{c.m.}}{\sqrt{s_{NN}}} \sim \pm \frac{2p_T \times \cosh y^{c.m.}}{\sqrt{s_{NN}}}$$



- Very good agreement between dijet and inclusive jet results in positive y_b and y^* region.

$$x_F = \frac{2m_T \times \sinh y^{c.m.}}{\sqrt{s_{NN}}} \sim \pm \frac{2p_T \times \cosh y^{c.m.}}{\sqrt{s_{NN}}}$$

- Another evidence that the scaling behavior is connected with **parton configuration of the proton**.
- Important input for understanding **color fluctuations in proton**.

Recently published papers

- HION-2019-09 – Large-R jets yields and substructure in Pb+Pb and pp at 5.02 TeV
- HION-2019-02 – Dijet Asymmetry in Pb+Pb and pp collisions at 5.02 TeV
- HION-2018-24 – b-jets in Pb+Pb and pp at 5.02 TeV
- HION-2021-09 – Jet substructure and suppression
- HION-2018-28 – Dijet asymmetry in 5.44 TeV Xe+Xe
- HION-2022-14 – Photon-tagged jet RAA in 5 TeV PbPb
- HION-2023-05 – Dijet cross-section measurement in 8.16 TeV p+Pb collisions