Brookhaven National Laboratory

Dijet Measurements in Heavy Ion Collisions

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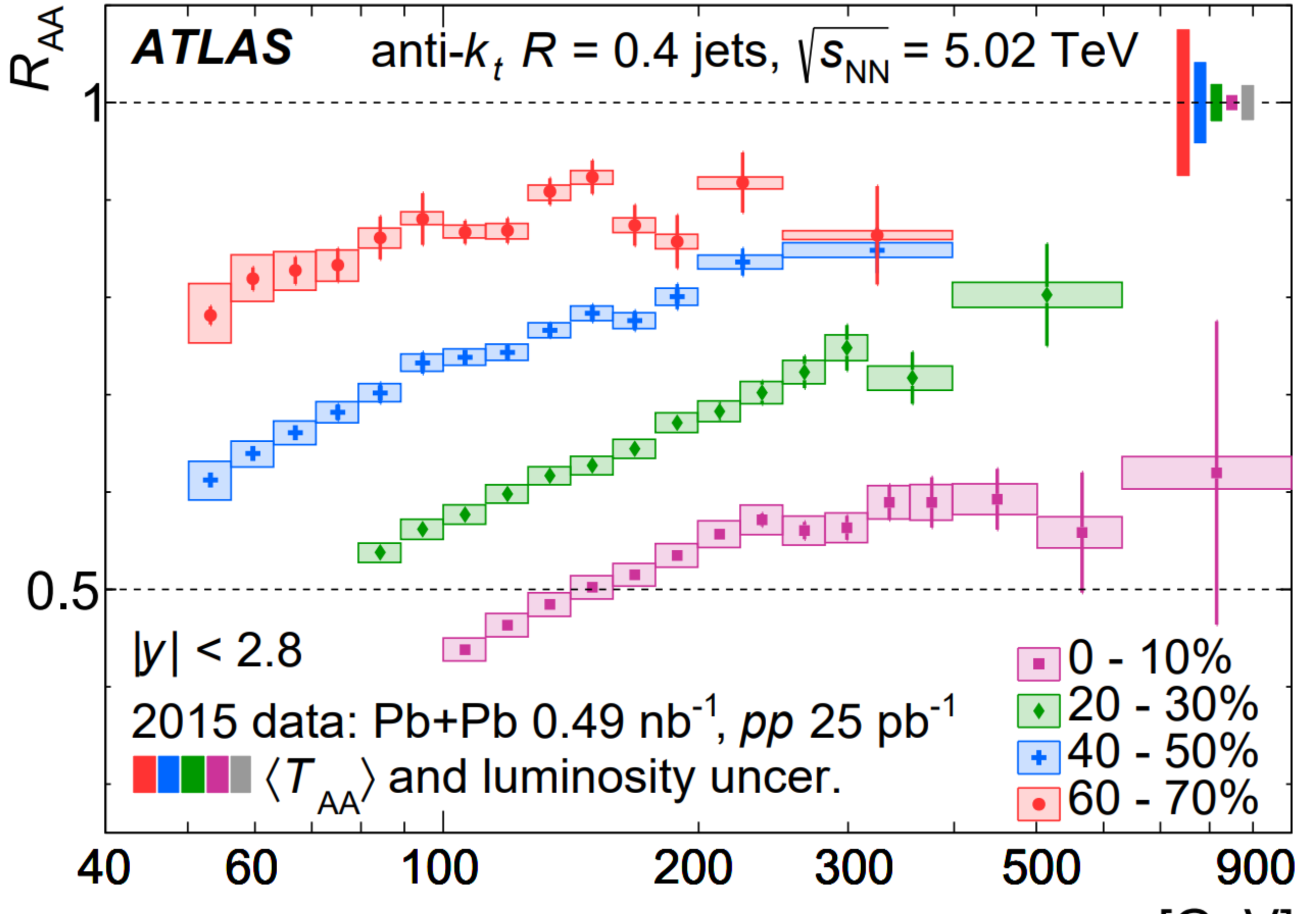
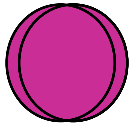
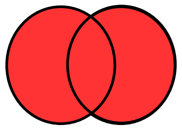
Jet quenching in heavy ion collisions

- ➢Jet constituents lose energy while traversing the Quark Gluon Plasma
  - ➢Results in phenomenon known as Jet Quenching

- ➢R_{AA} provides key evidence of jet momentum modification
  - ➢Differential measurements of jet modifications are needed to understand the mechanisms of jet energy loss

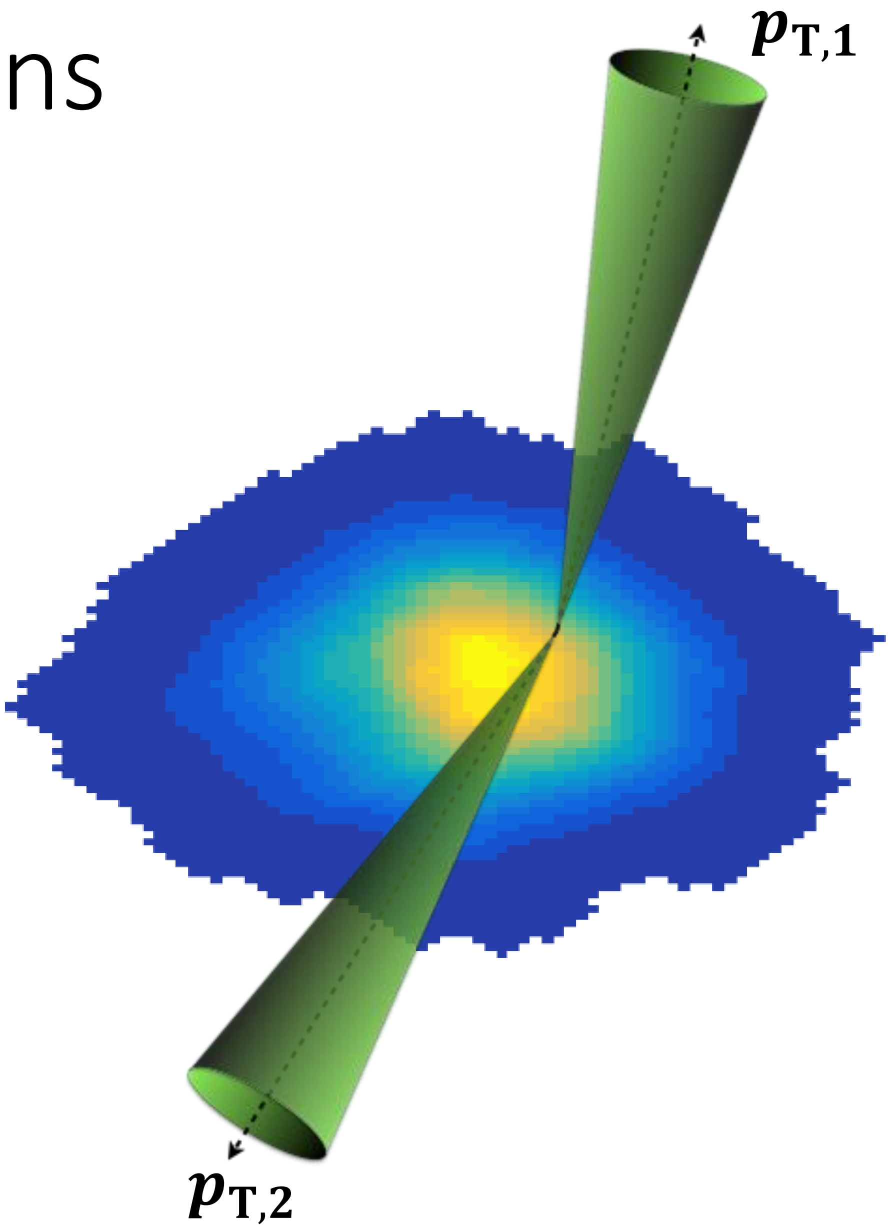



0-10%


60-70%

Dijets in heavy ion collisions

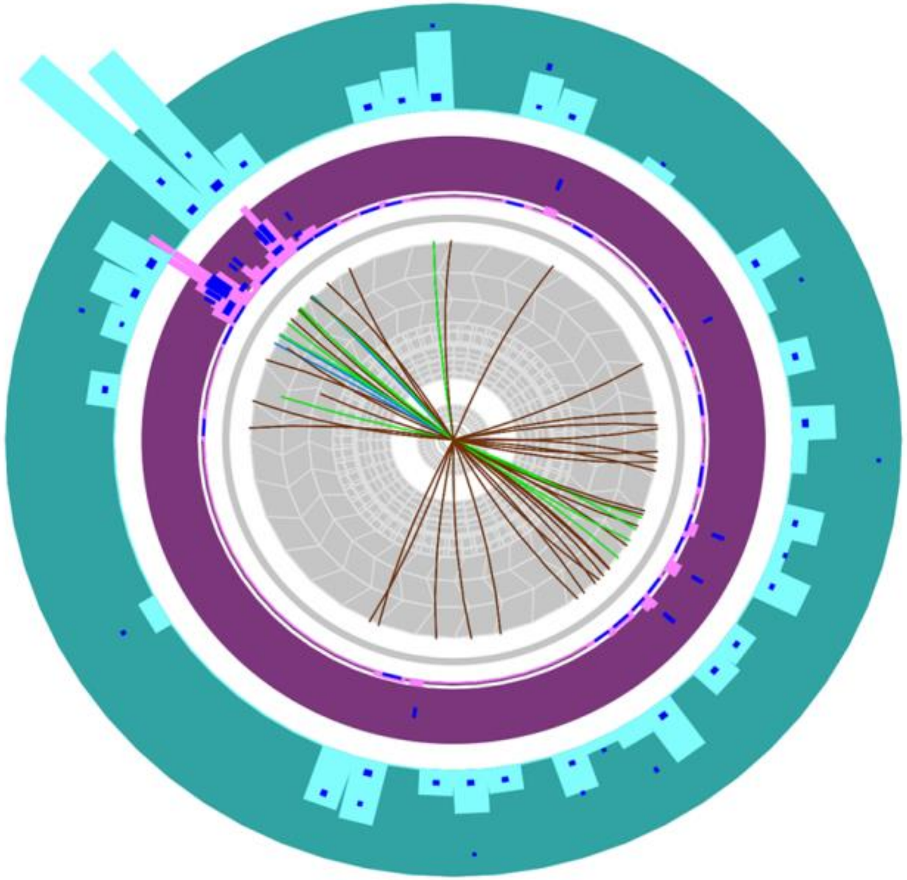
- ➢Hard scattering processes produce balanced partons
  - ➢Significant jet asymmetries observed in heavy ion collisions
- ➢Back-to-back jet pairs provide access to asymmetric energy loss
  - ➢Path length dependent energy loss
  - ➢Energy loss fluctuations

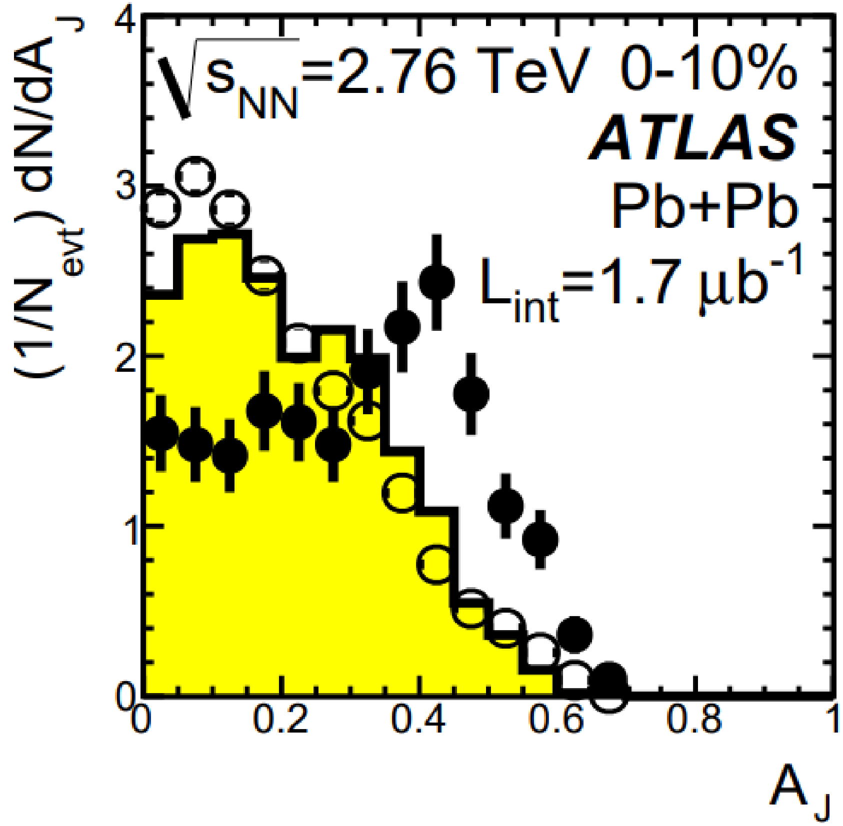


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Asymmetric energy loss

Phys.Rev.Lett.105:252303,2010





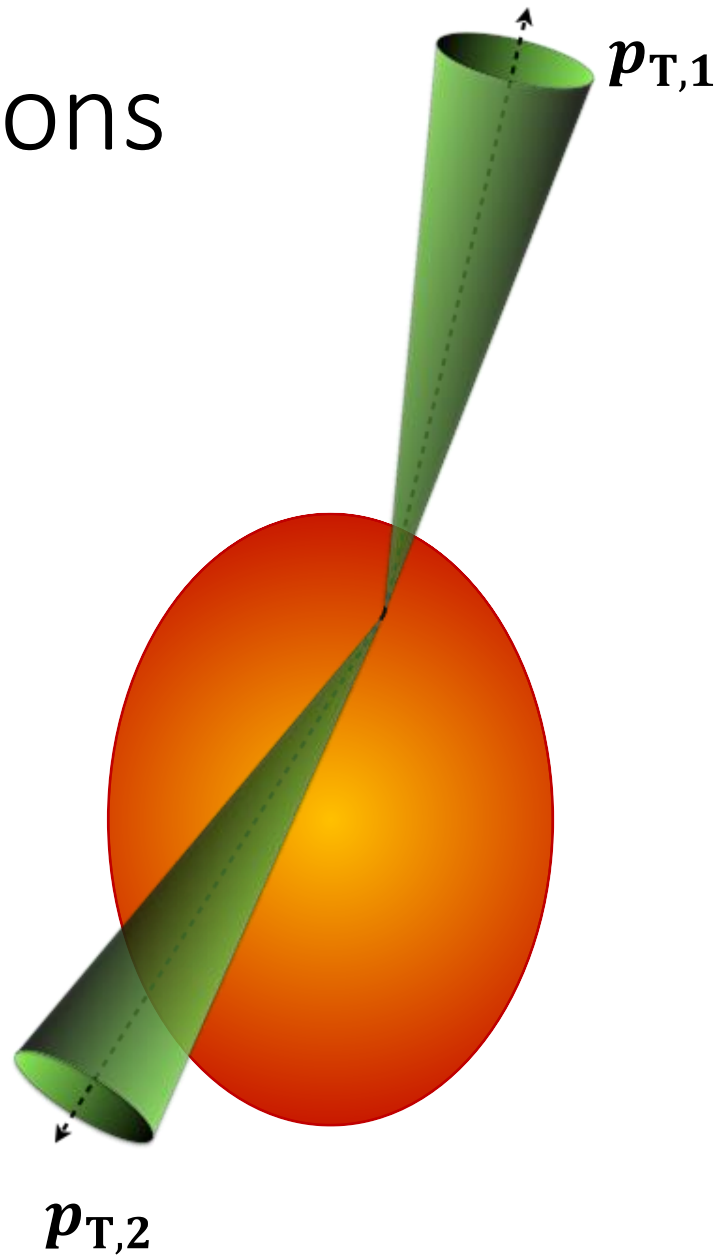
$E_{T1} > 100$ GeV
$E_{T2} > 25$ GeV

Early Dijet measurements in Pb+Pb collisions observed significant modifications of E_T balance of back-to-back jets

A picture of dijets in HI collisions

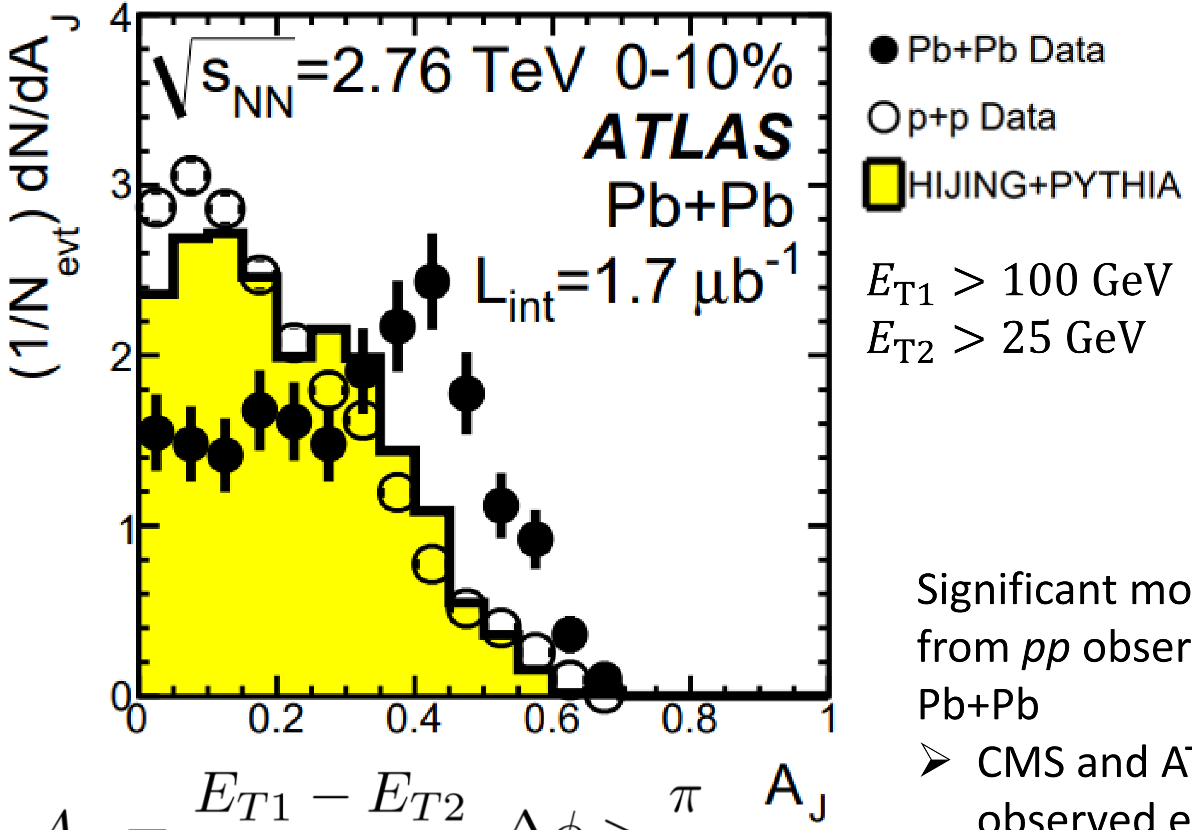
- Leading jets are produced near the surface and rapidly exit the medium
  - Short trajectory through QGP
  - Largely unmodified

- Subleading jets traverse a large path length in the QGP
  - Significant QGP interaction and large energy loss



Early dijet results:

Phys.Rev.Lett.105:252303,2010



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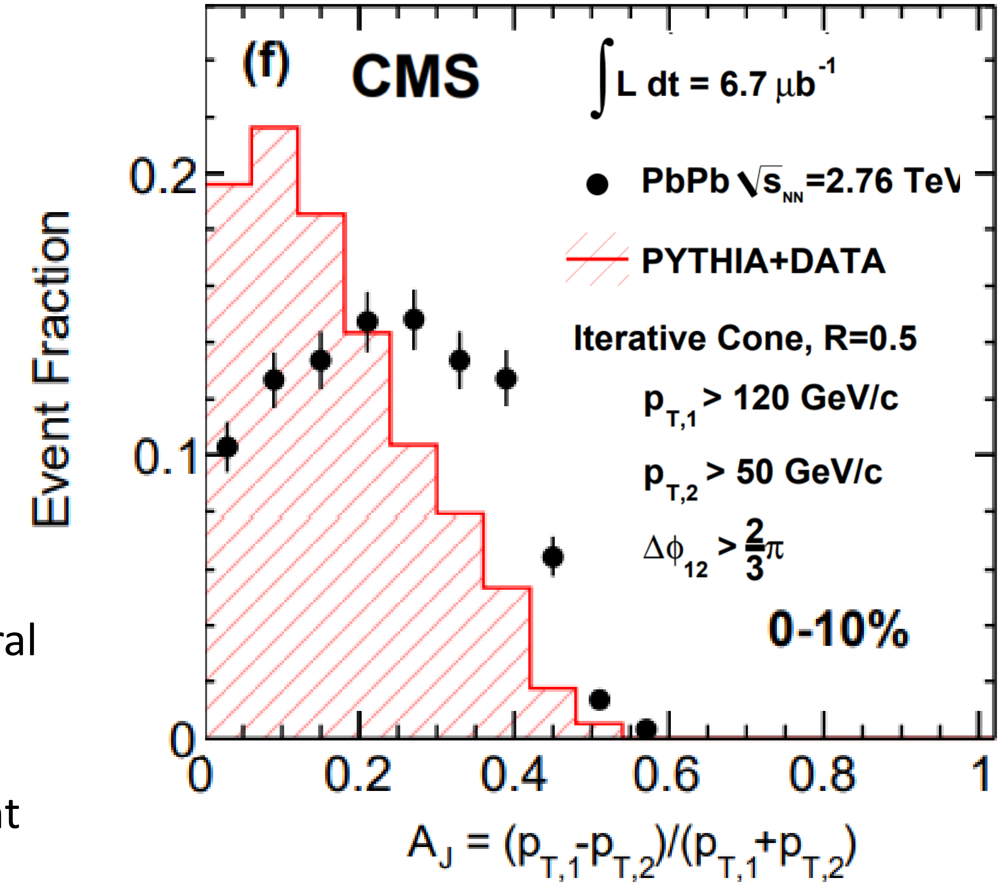
Phys.Rev.C84:024906,2011



Significant modification from *pp* observed in central Pb+Pb

- CMS and ATLAS observed enhancement of intermediate A_J

Unfolded dijet analysis overview:

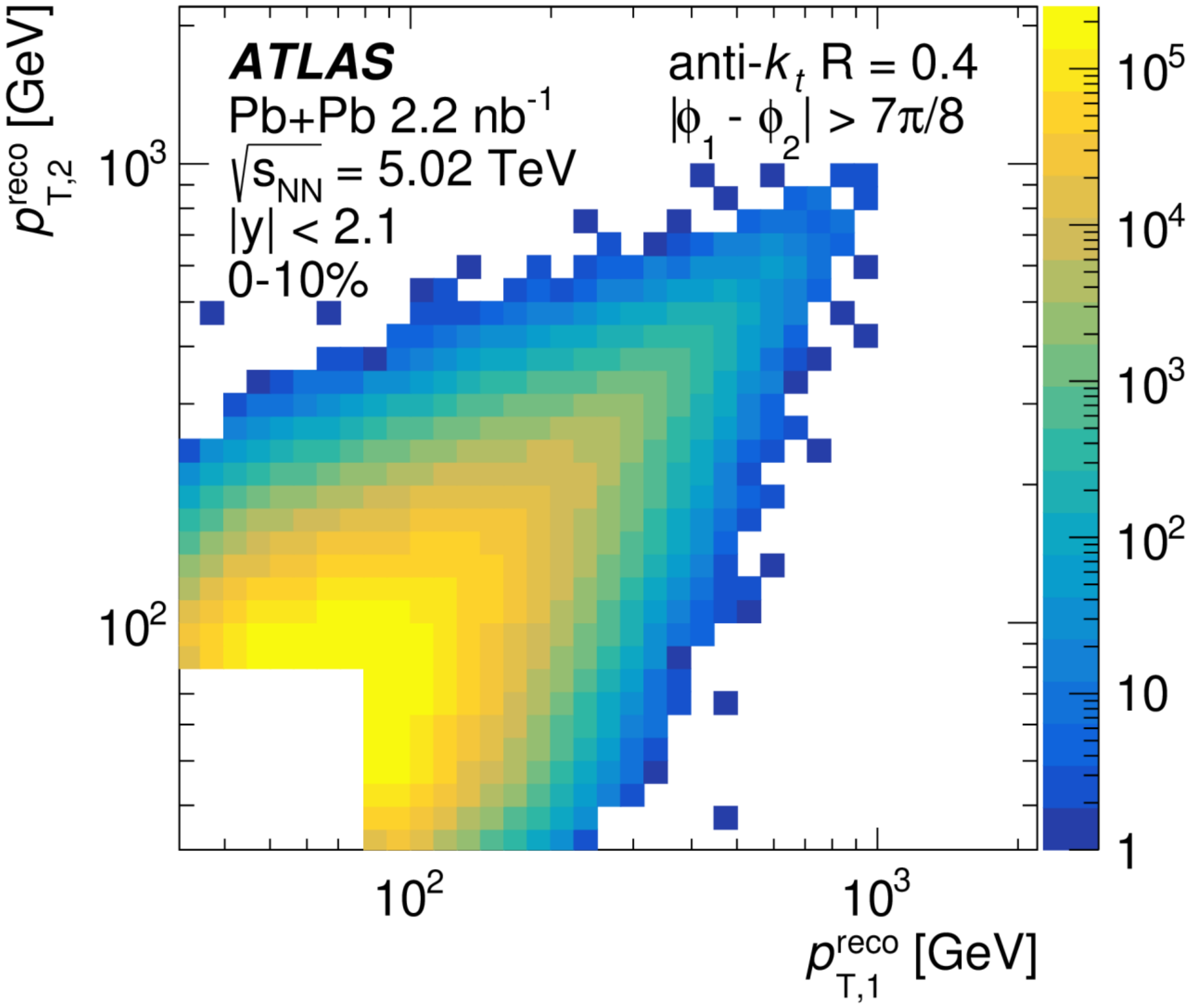
Two-dimensional $(p_{\mathrm{T},1}, p_{\mathrm{T},2})$ distributions are measured for the leading dijet pair per event

Unfolded for detector effects using 2D Bayesian unfolding

- Simultaneously correct for migrations of leading and subleading jet p_T

Unfolded 2D distributions can be projected/integrated to extract dijet observables

https://arxiv.org/pdf/2205.00682.pdf



$$x_J \equiv p_{T,2}/p_{T,1}$$

Dijet balance observables

Per dijet pair normalized x_J distributions: $\frac{1}{N_{pair}}\frac{dN_{pair}}{dx_J}$

- Enables direct comparison of the x_J shape across centrality in Pb+Pb and in *pp*

Absolutely normalized x_J distributions: $\frac{1}{N_{evt}\langle T_{AA}\rangle}\frac{dN_{pair}}{dx_J}$

- Enables evaluation of the dijet per event yields as a function of x_J
- Provides insight into the dynamics of dijet energy loss

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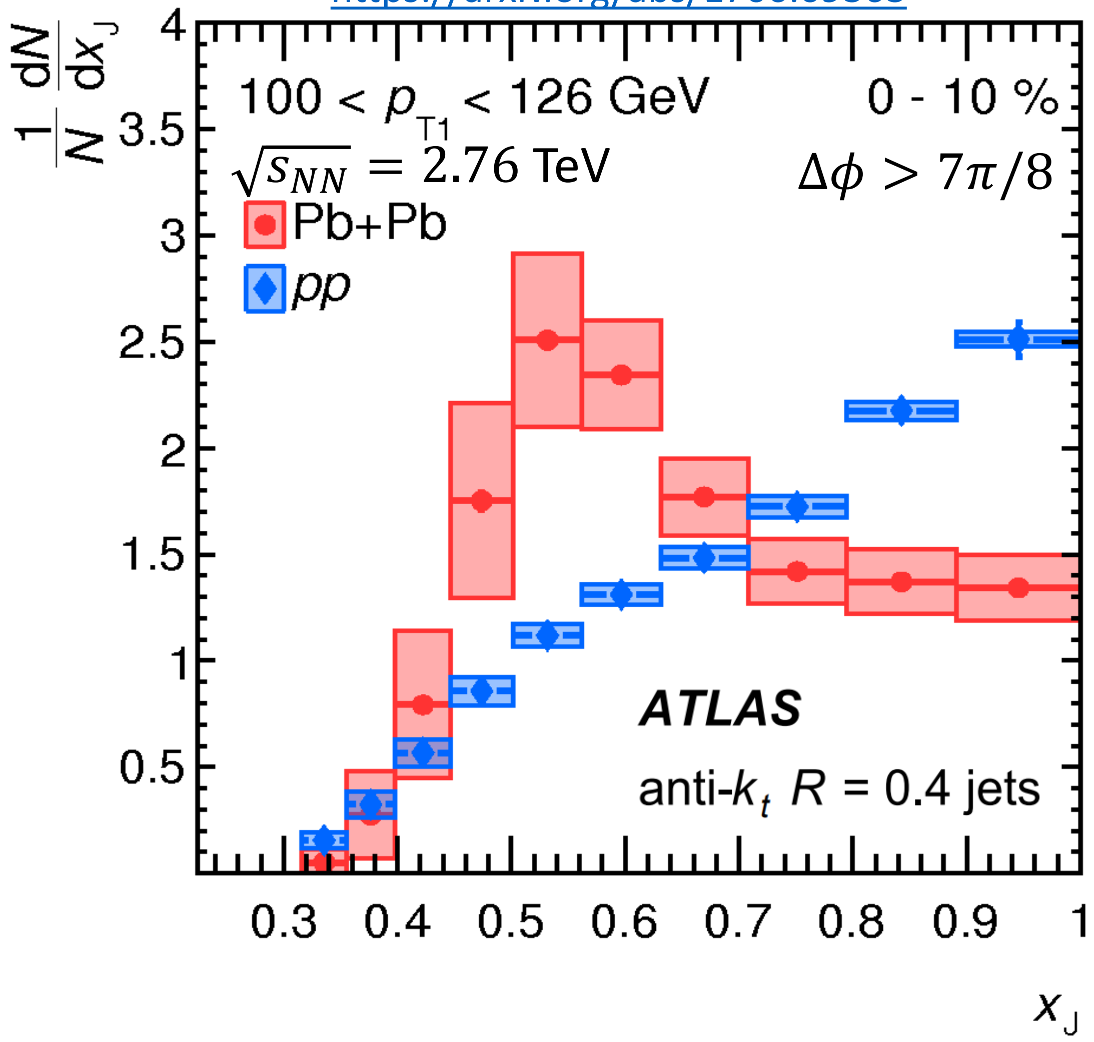
Pair normalized x_J distributions

- Fully unfolded measurements of the x_J *shape* enables direct comparisons between Pb+Pb and *pp* collisions
- Significant modification from *pp* collisions are observed
- A peak was observed in 0-10% Central Pb+Pb at $x_J \approx 0.5$
  - Explaining this behavior has been a challenge in the community

https://arxiv.org/abs/1706.09363

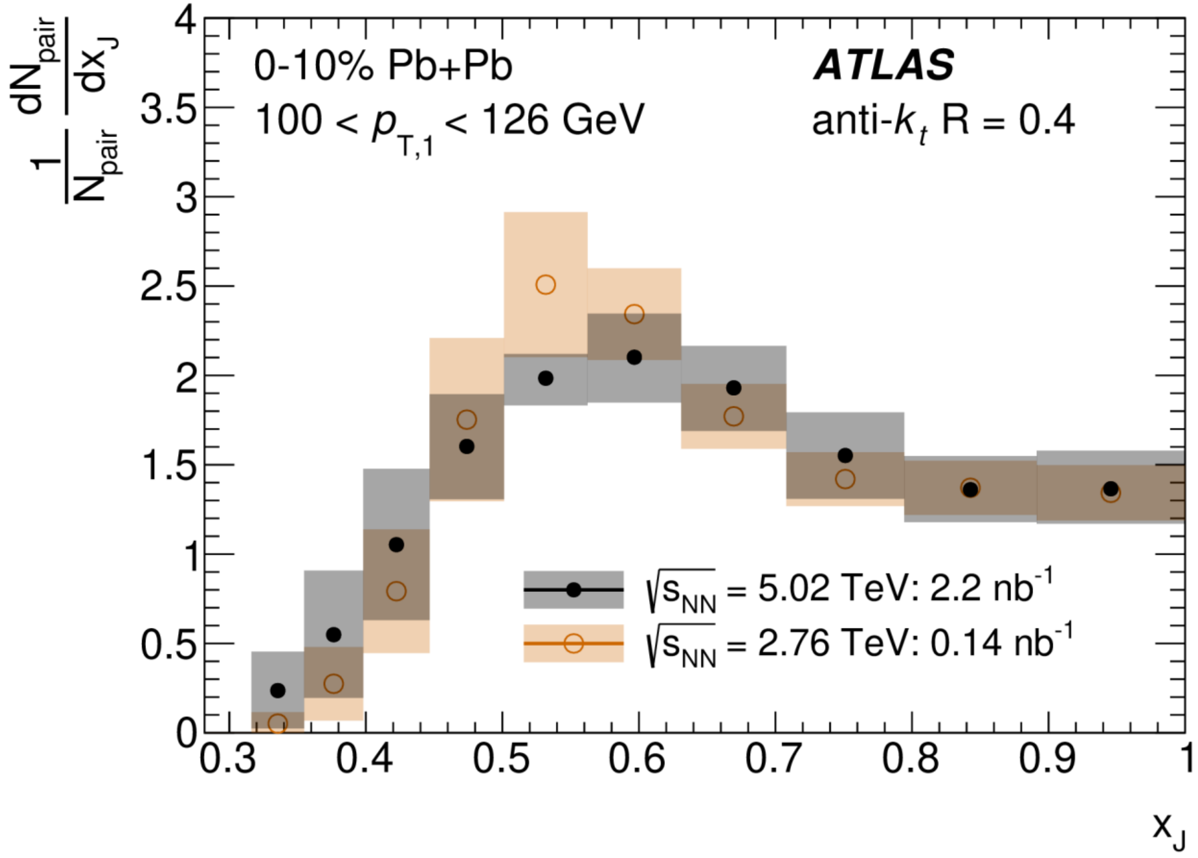


Pair normalized x_J distributions

- Utilizing the large LHC Run 2 sample the measurement of the dijet momentum balance was repeated

- 5.02 TeV analysis reproduces the peak observed in earlier measurements

https://arxiv.org/pdf/2205.00682.pdf



Pair normalized x_J: comparison with theory

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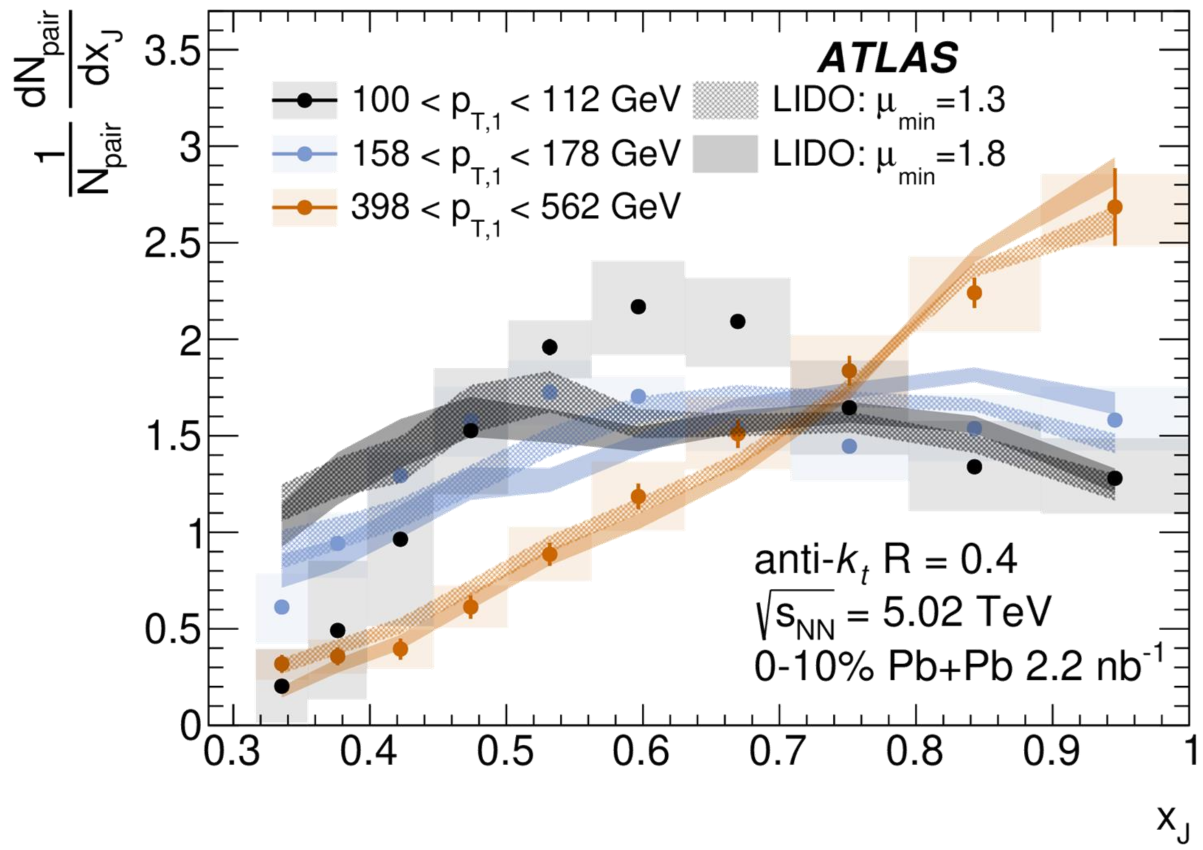

LIDO is a transport model containing both radiative and collisional energy loss sources and tuned to world R_{AA} data

LIDO well predicts the x_J shape for intermediate and high $p_{\mathrm{T},1}$ in central events

- Does not reproduce the peak observed at intermediate x_J at low $p_{\mathrm{T},1}$

Dijet x_J observables

Per dijet pair normalized x_J distributions: $\frac{1}{N_{pair}}\frac{dN_{pair}}{dx_J}$

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Absolutely normalized x_J

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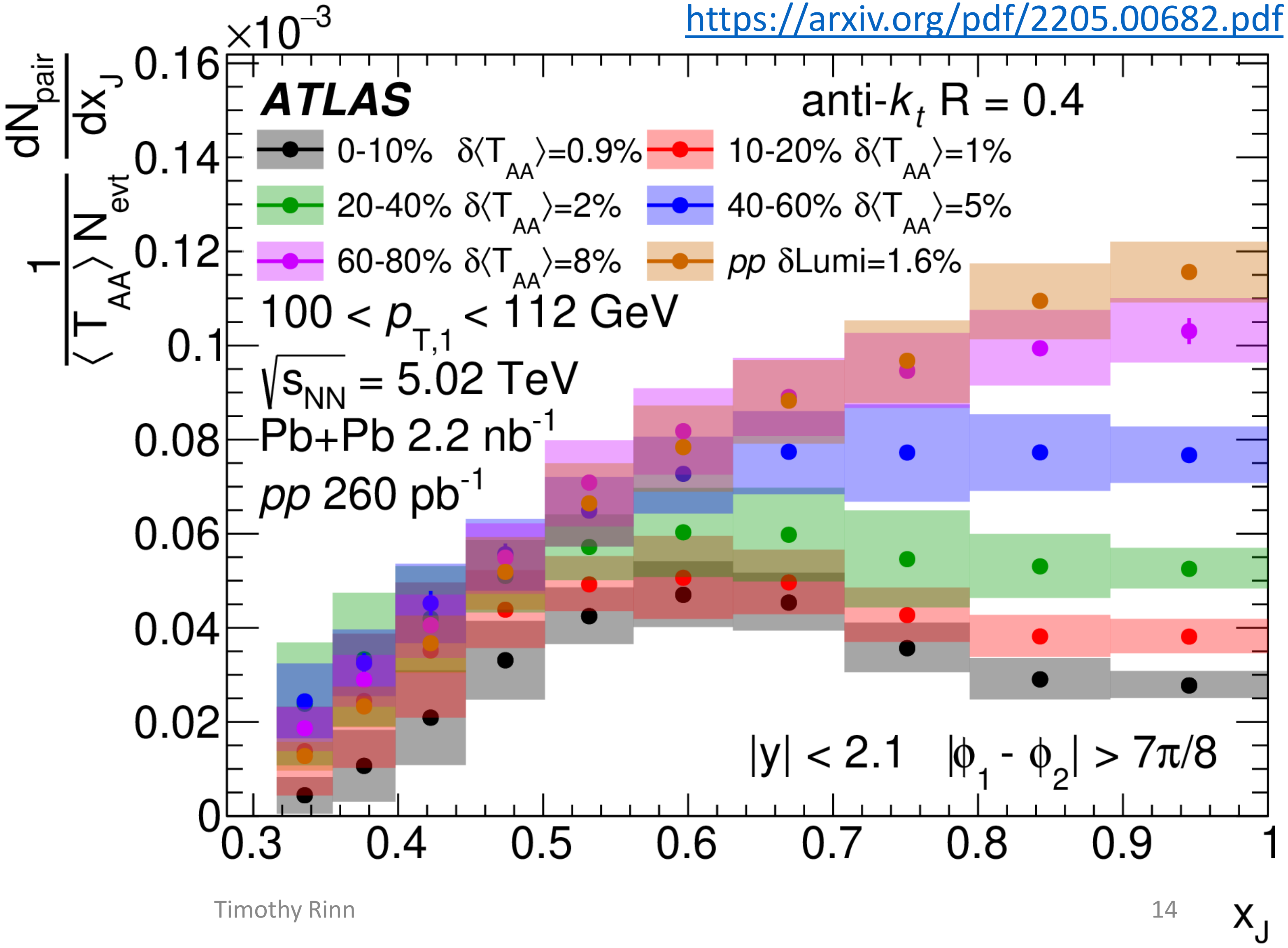
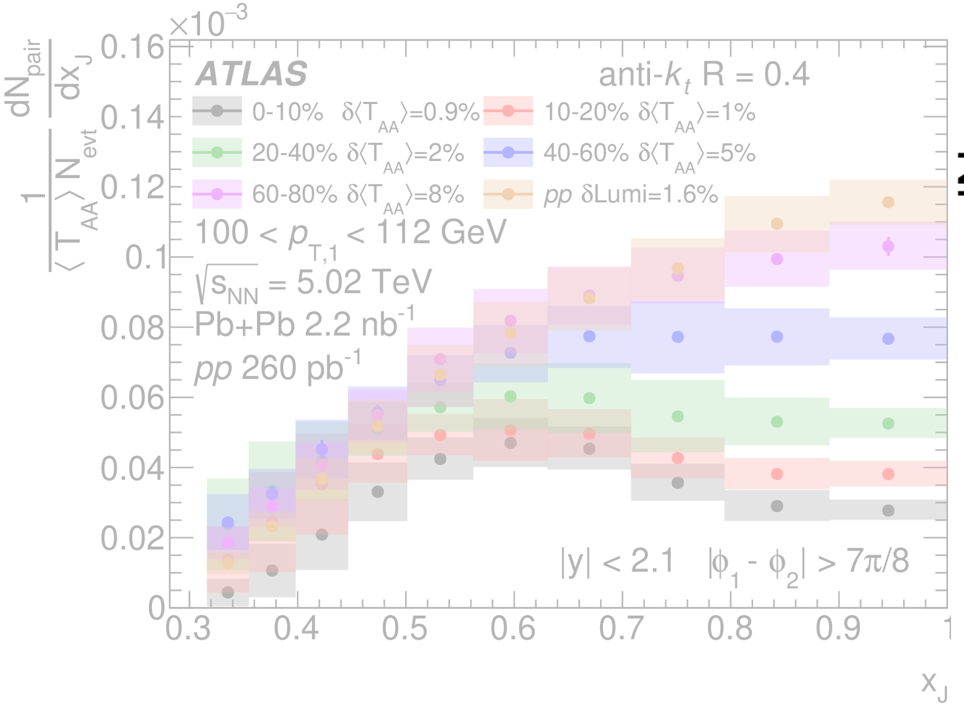
Using a $\frac{1}{\langle T_{AA}\rangle N_{evt}}$ normalization enables the study of dijet yields as a function of x_J

The peak shape observed at intermediate x_J stems from the **favorable suppression of symmetric dijets**

- No evidence for enhancement over *pp* of intermediate x_J



Absolutely normalized x_J



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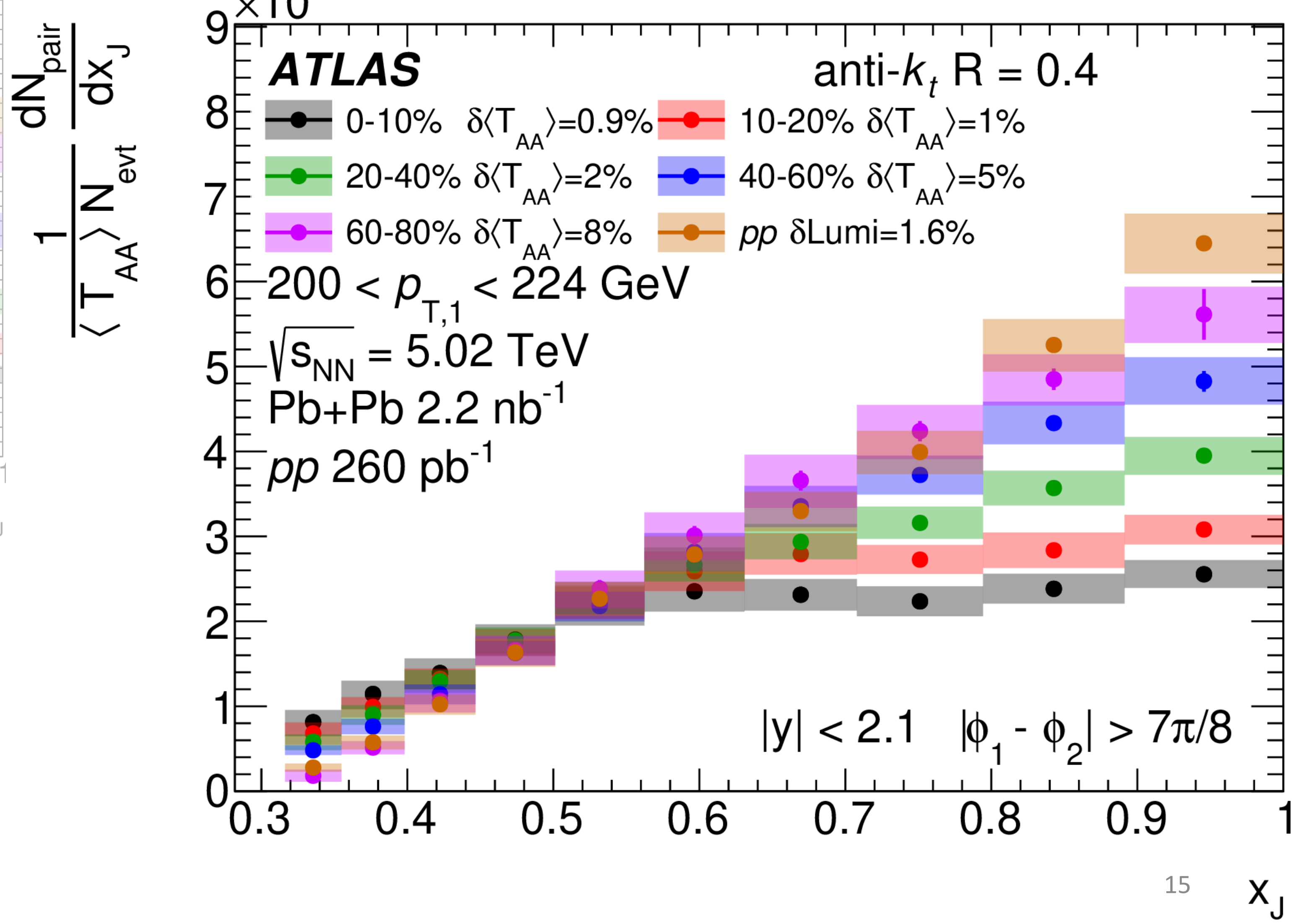
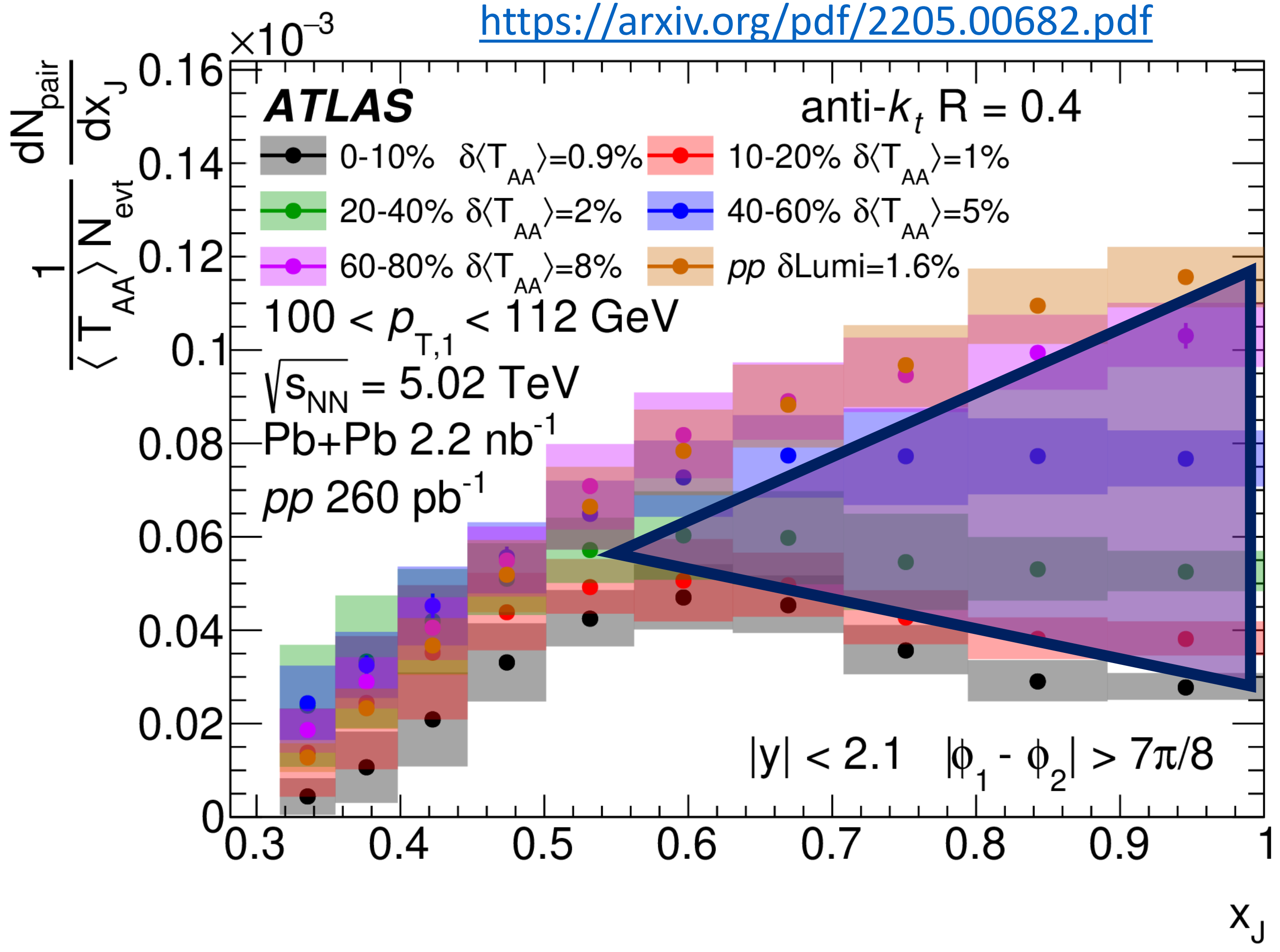


The systematic suppression of symmetric dijets persists with increasing $p_{T,1}$

Dijet quenching: Some thoughts

https://arxiv.org/pdf/2205.00682.pdf



Why is there no enhancement over *pp* at low x_J?

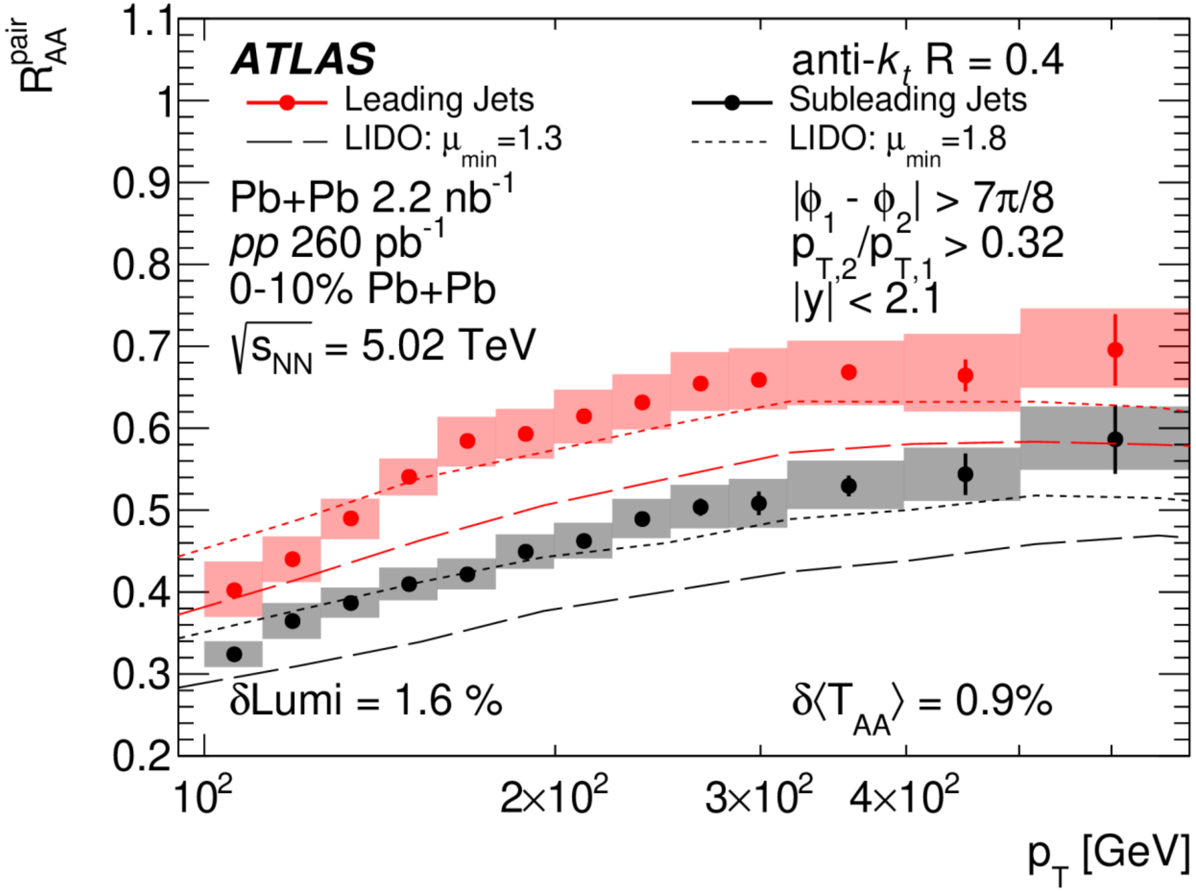
- **Suppression of both jets is key!**
  - Both leading and subleading jets lose significant energy

How does this compare to expectations from surface bias effects?

- Surface Bias expected to create a significant enhancement asymmetric jets

Dijet nuclear modification factors (R_{AA}^{pair})

https://arxiv.org/pdf/2205.00682.pdf



Significant suppression of both leading and subleading jets are observed across jet p_T

Subleading jets are systematically more suppressed than leading jets

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

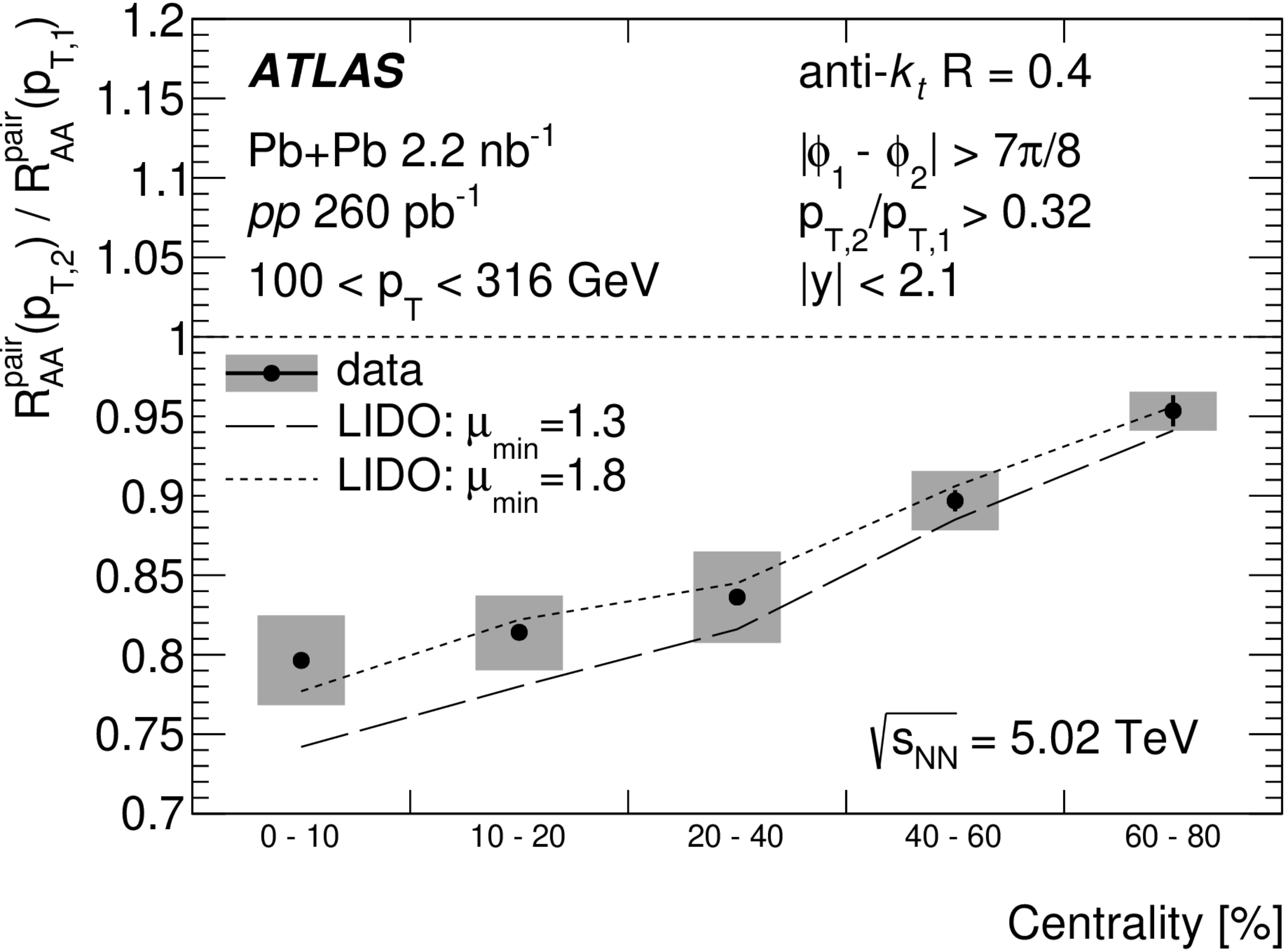
$$R_{AA}^{pair}(p_{T,2}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2N_{pair}^{AA}}{dp_{T,1}dp_{T,2}} dp_{T,1}}{\frac{1}{L_{pp}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2N_{pair}^{pp}}{dp_{T,1}dp_{T,2}} dp_{T,1}}$$

Dijet threshold condition of $\frac{p_{T,2}}{p_{T,1}} > 0.32$

$R_{AA}^{pair}(p_{\mathrm{T},2})\ /\ R_{AA}^{pair}(p_{\mathrm{T},1})$

Evidence for suppression of subleading relative to leading jets in dijets is observed

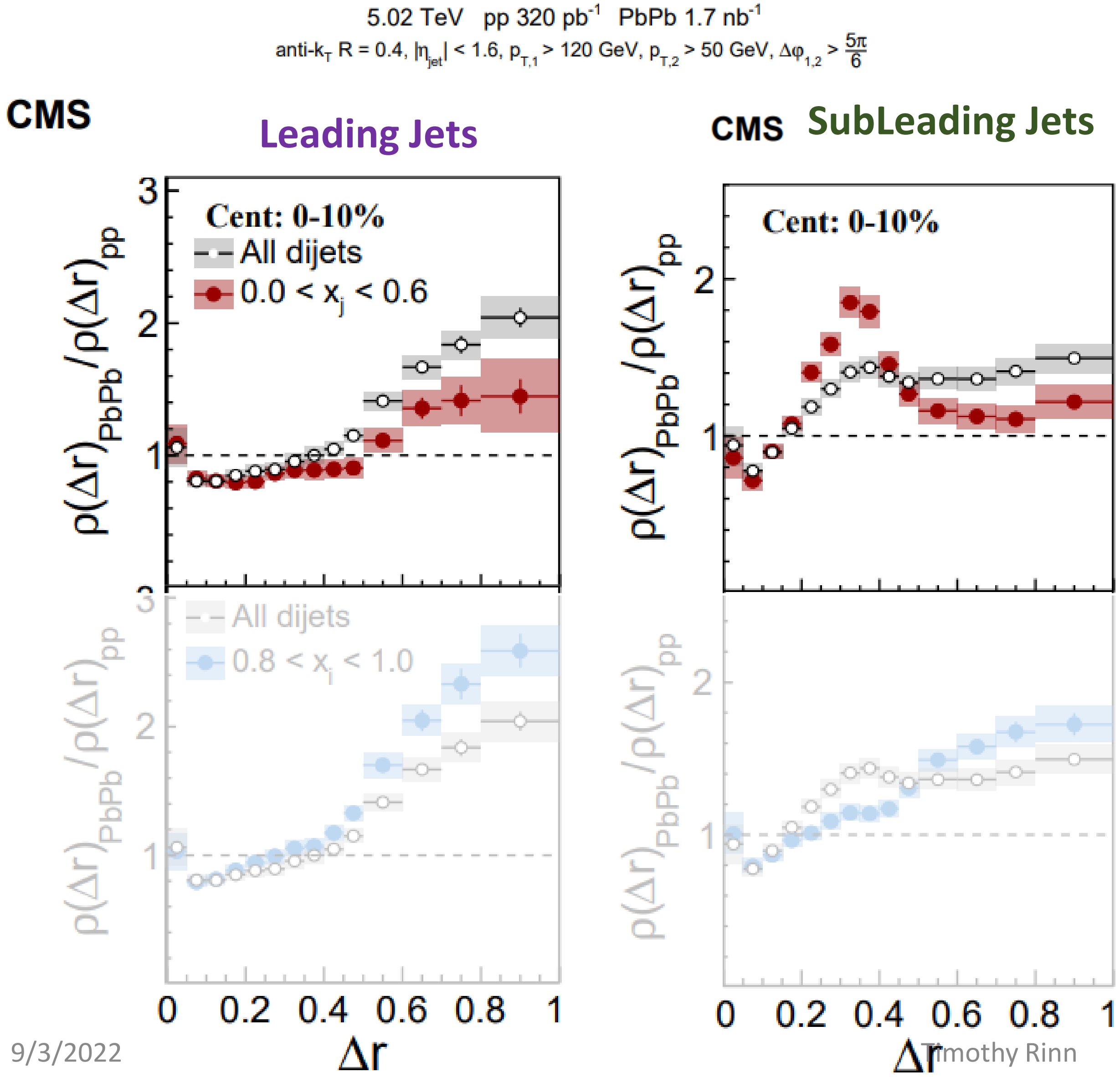
- 3σ significant relative suppression observed in peripheral Pb+Pb



arXiv:2101.04720

Leading dijet fragmentation

ρ is proportional to track momentum density in a radius window



Subleading jets for $x_J < 0.6$ observe significant enhancement of fragment momentum between $0.2 < \Delta R < 0.4$

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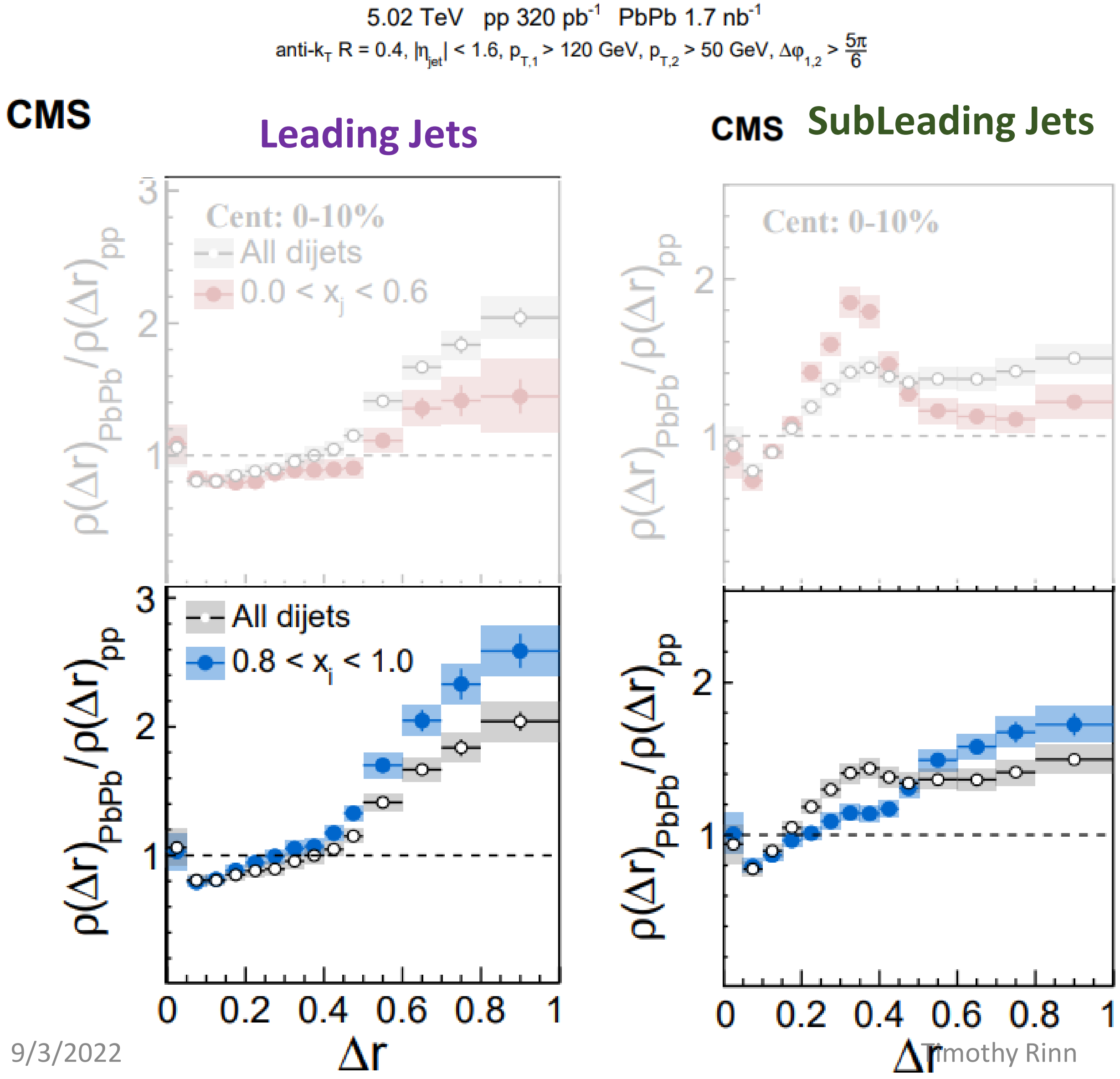


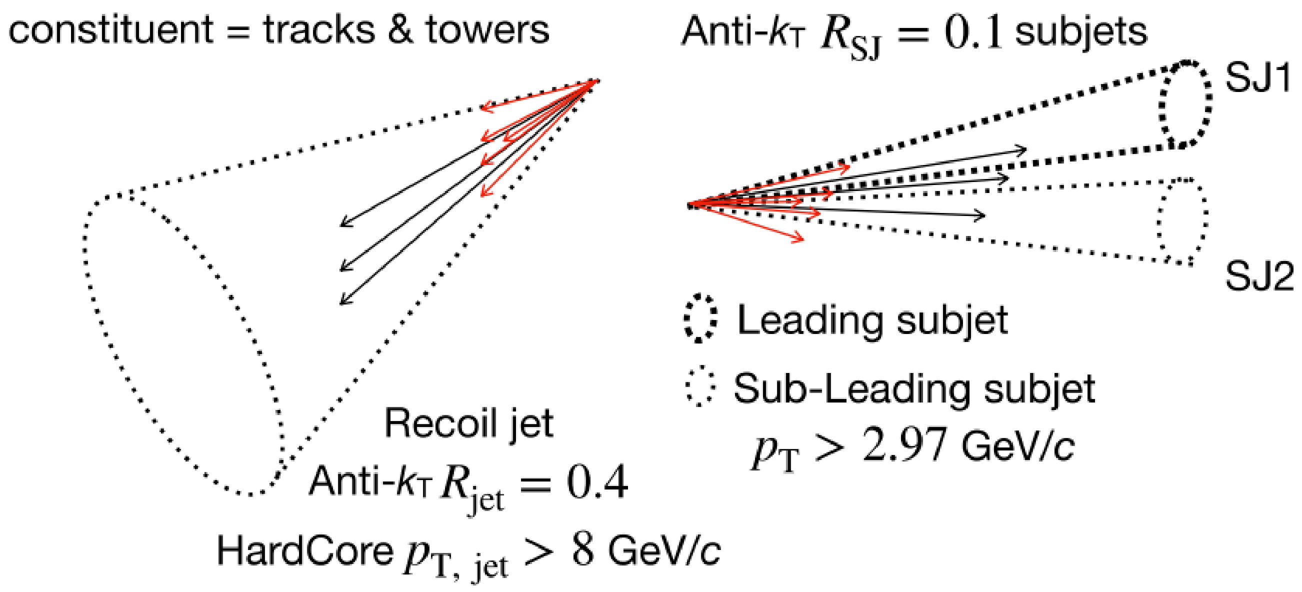
Subleading jets for $x_J < 0.6$ observe significant enhancement of fragment momentum between $0.2 < \Delta R < 0.4$

For **symmetric jets** similar modification is seen for the **leading** and **subleading** jet

Jet substructure in dijets

Substructure of subleading jets enables probing of jet size dependence to dijet asymmetry

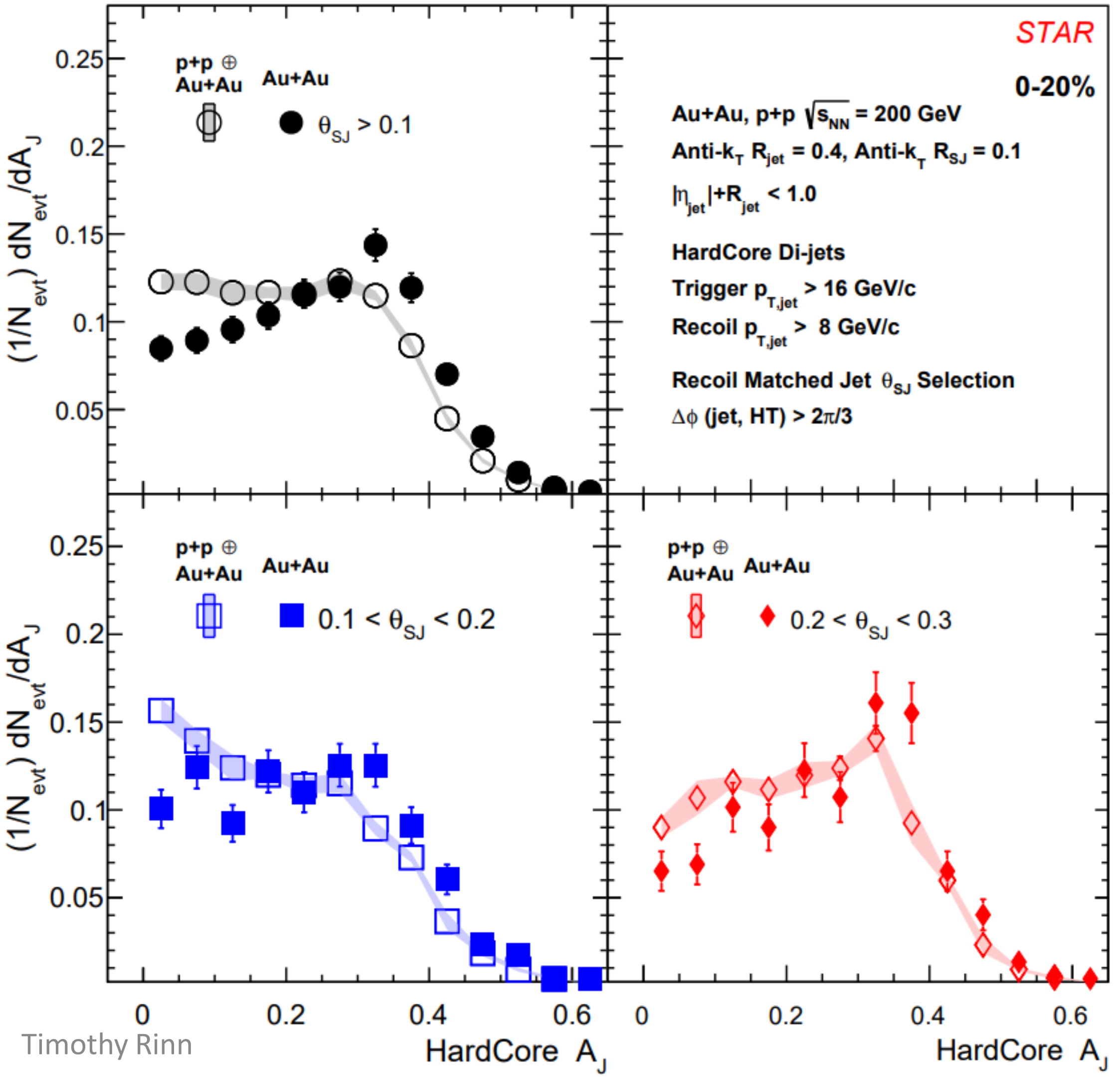
- Do dijets with wider subleading jets experience enhanced asymmetry?



$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

Opening angle dependence to A_J

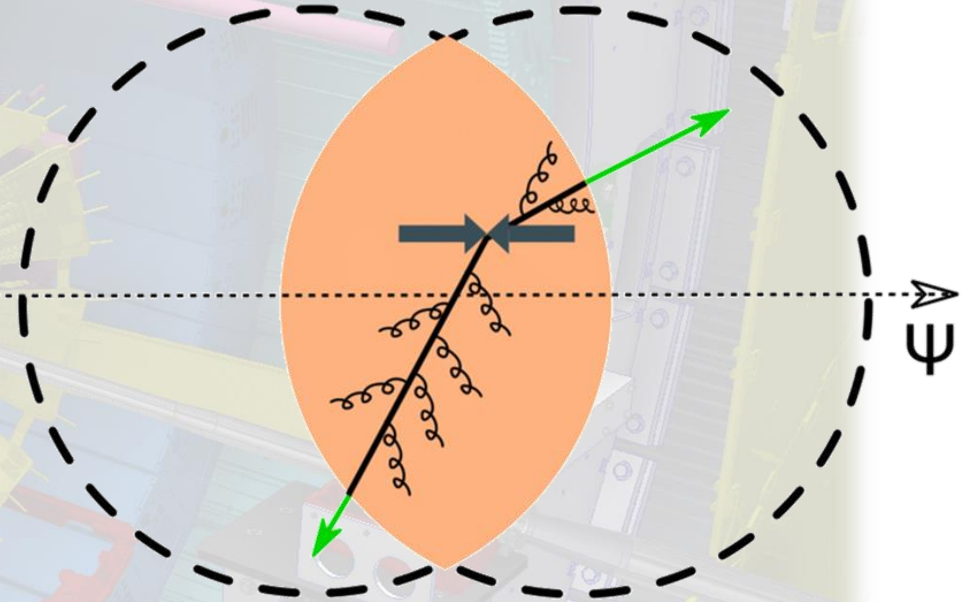
PhysRevC.105.044906



- STAR observes significant modification of the A_J shape in central Au+Au
- Within uncertainties no significant θ_{SJ} dependence for $0.1 < \theta_{SJ}$
  - p_T asymmetry of narrow and wide jets are similar

Thoughts for future dijet measurements:

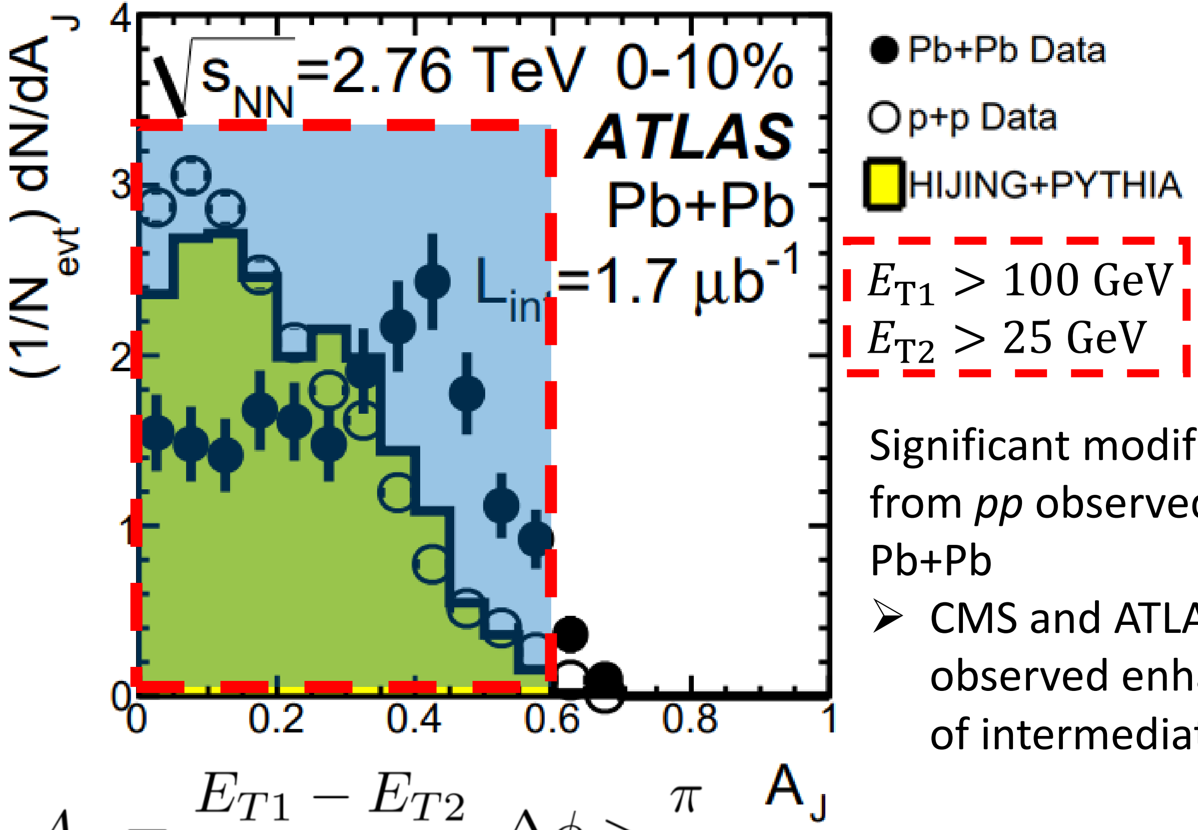
- Event plane angle dependence to dijet momentum balance
  - Directly explore the role of path length dependent energy loss effects
- Jet Structure/Radius Scan
  - Gain insight to the role of the jet structure to the dijet suppression
- Measure jet quenching in small systems
  - Subleading jets provide enhanced sensitivity to energy loss effects
- Precision unfolded measurements of dijets at RHIC:
  - Stay tuned for results from sPHENIX and STAR using high statistics 2023-2025 runs!



Backups

Early dijet results:

Phys.Rev.Lett.105:252303,2010



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Significant modification from *pp* observed in central Pb+Pb

- CMS and ATLAS observed enhancement of intermediate A_J

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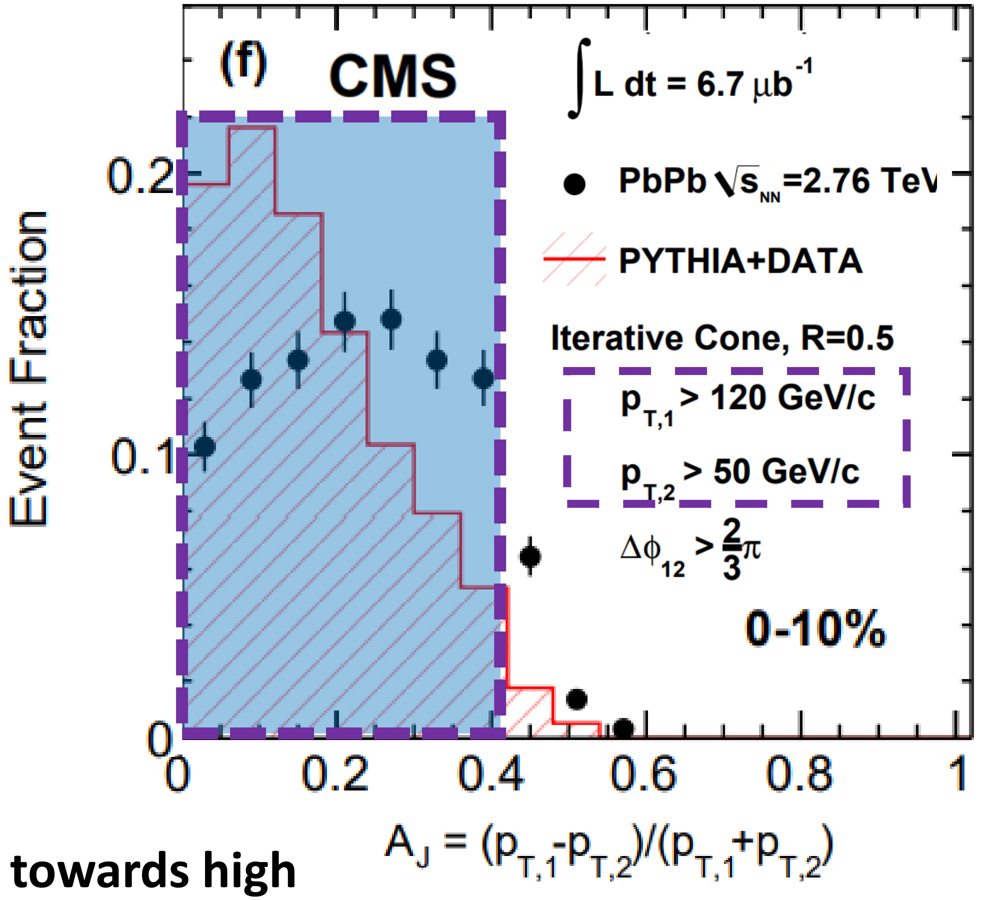


Large values of A_J are biased towards high $p_{T,1}$ (E_{T1}) due to minimum $p_{T,2}$ (E_{T2})

Dijet nuclear modification factor: R_{AA}^{pair}

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

$R_{AA}^{pair}(p_{T,1})$ quantifies the suppression of the leading jet **in a dijet**

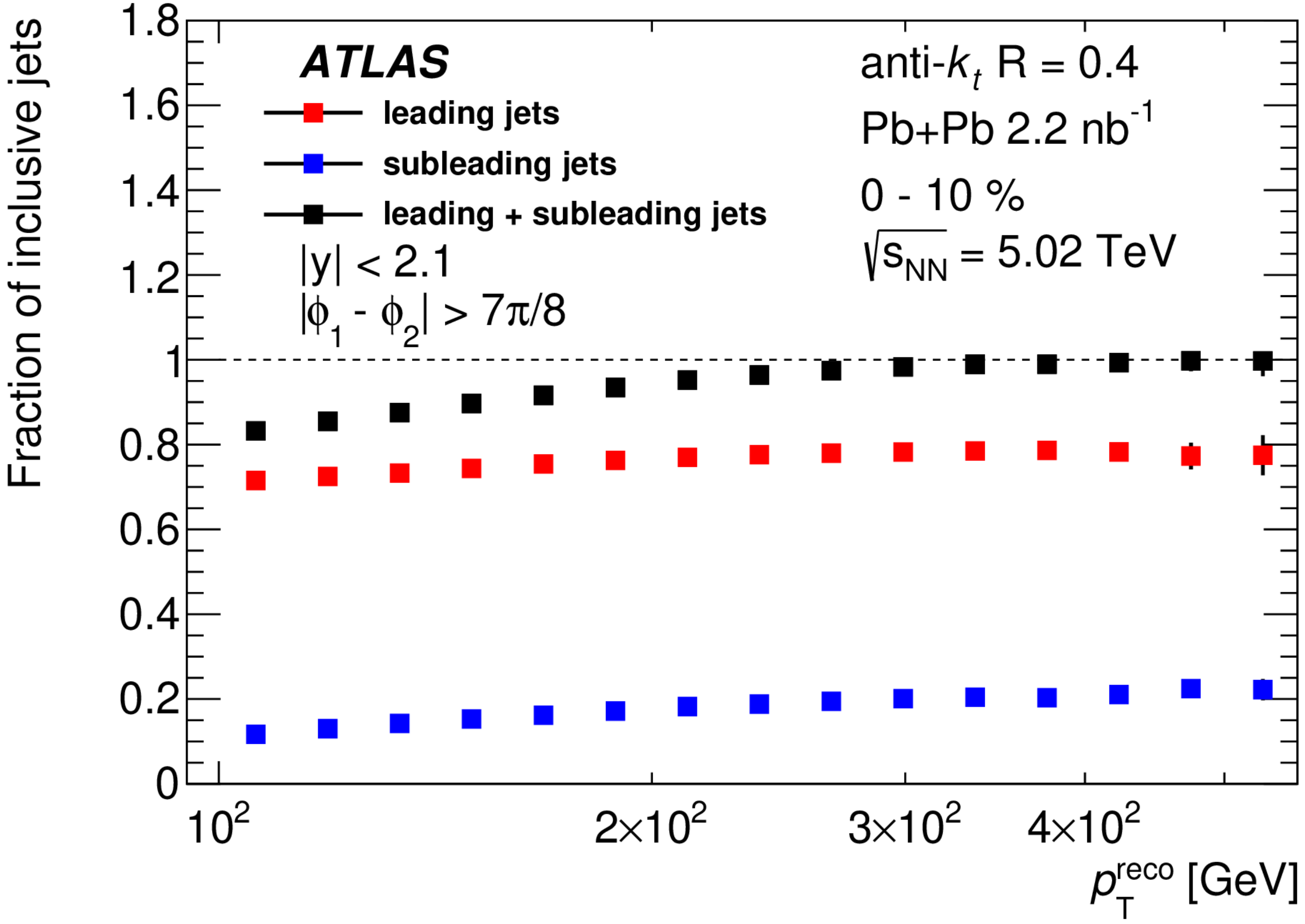
$$R_{\mathrm{AA}}^{\mathrm{pair}}(p_{T,2}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2 N_{pair}^{AA}}{dp_{T,1}dp_{T,2}} dp_{T,1}}{\frac{1}{L_{pp}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2 N_{pair}^{pp}}{dp_{T,1}dp_{T,2}} dp_{T,1}}$$

$R_{AA}^{pair}(p_{T,2})$ quantifies the suppression of the subleading jet **in a dijet**

$$\frac{p_{T,2}}{p_{T,1}} > 0.32$$

Dijet threshold condition of $\frac{p_{T,2}}{p_{T,1}} > 0.32$

Dijet fraction of inclusive jets

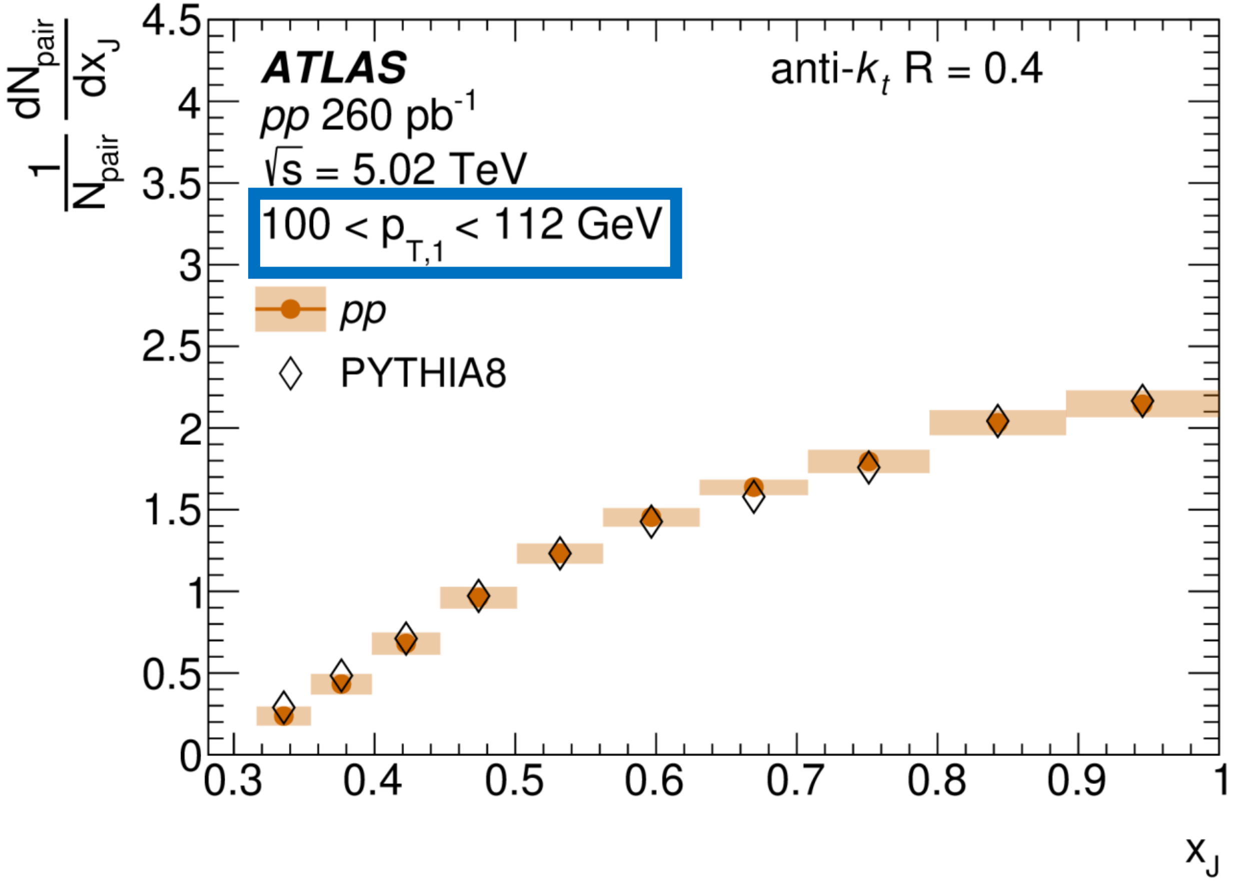


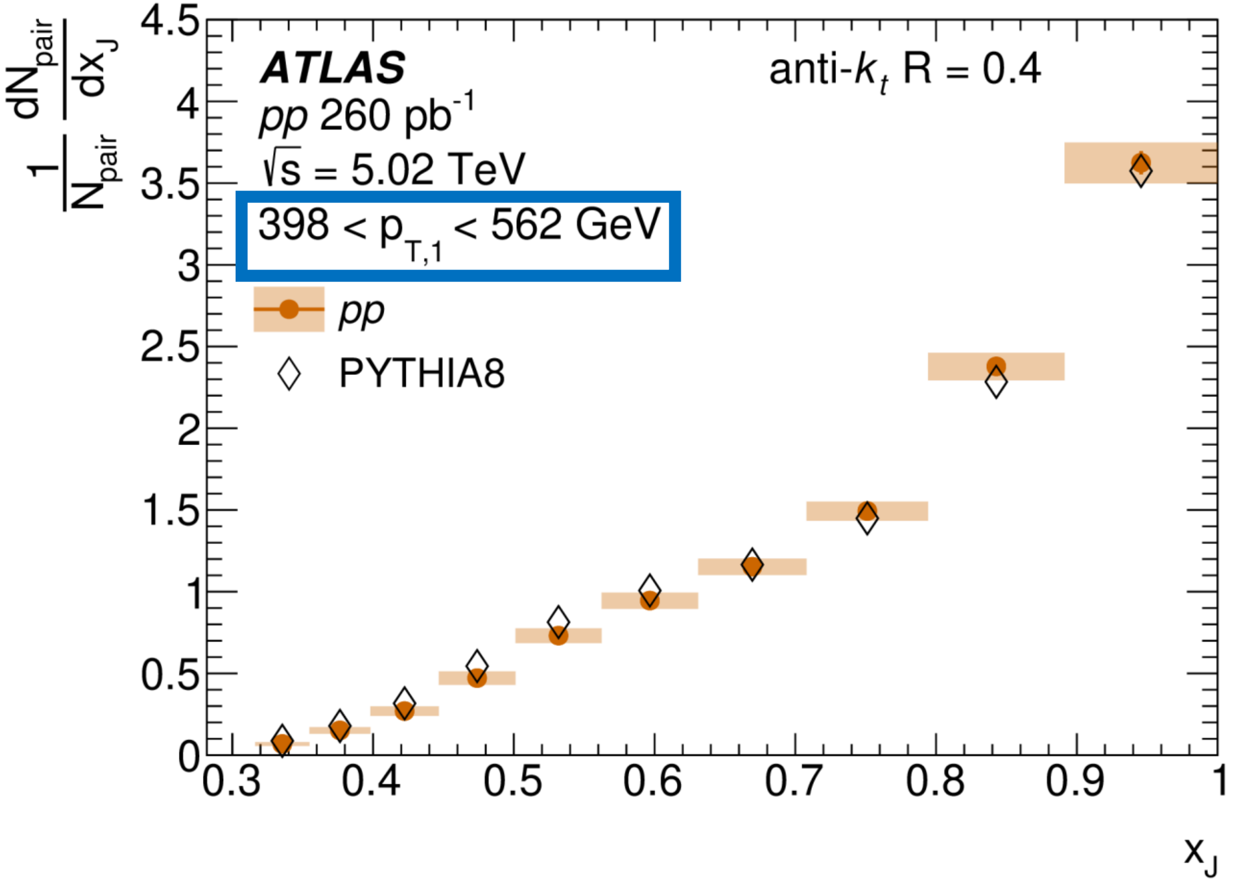
Measured fractions of inclusive jets which are part of the leading **dijet**, the **leading jet** of the dijet, or the **subleading** jet of the dijet

At 100 GeV: 83% of inclusive jets are part of the leading dijet

- Over 95% for $p_T^{reco} > 200$ GeV

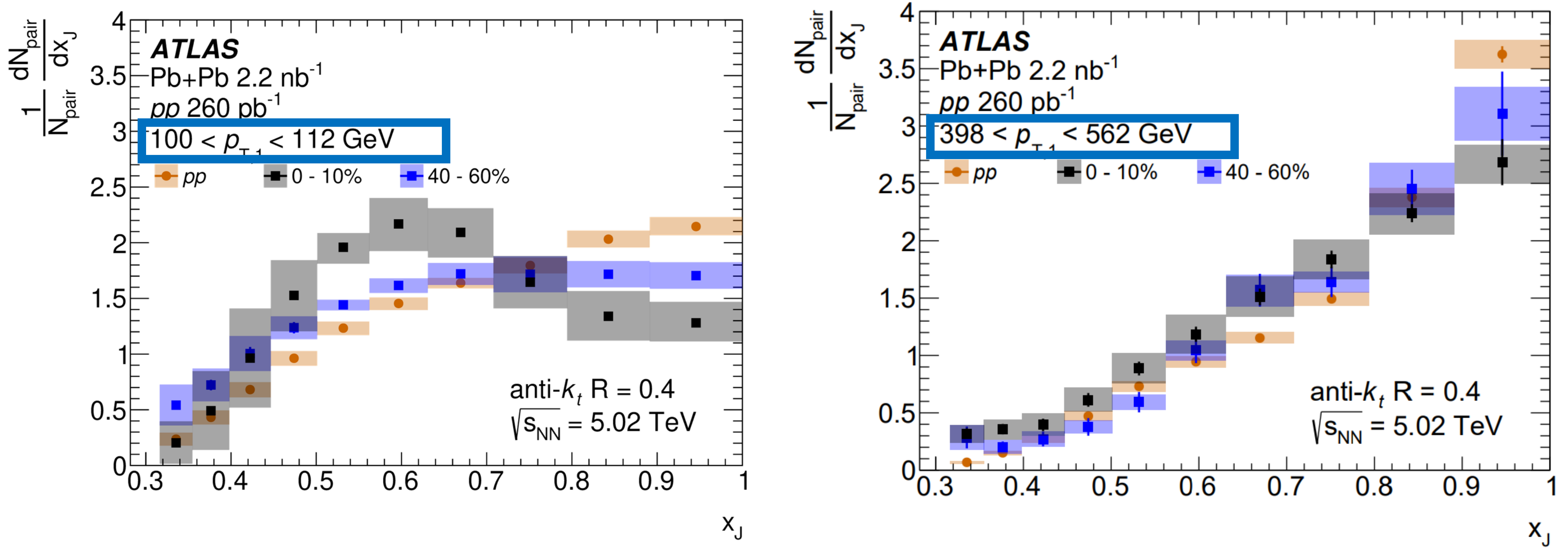
$^{1}/_{N_{pair}}\ ^{dN_{pair}}/_{dx_J}$ pp results





Higher p_T jets → more collimated → more balanced

${}^{1}/_{N_{pair}} \, {}^{dN_{pair}}/_{dx_J}$ distributions

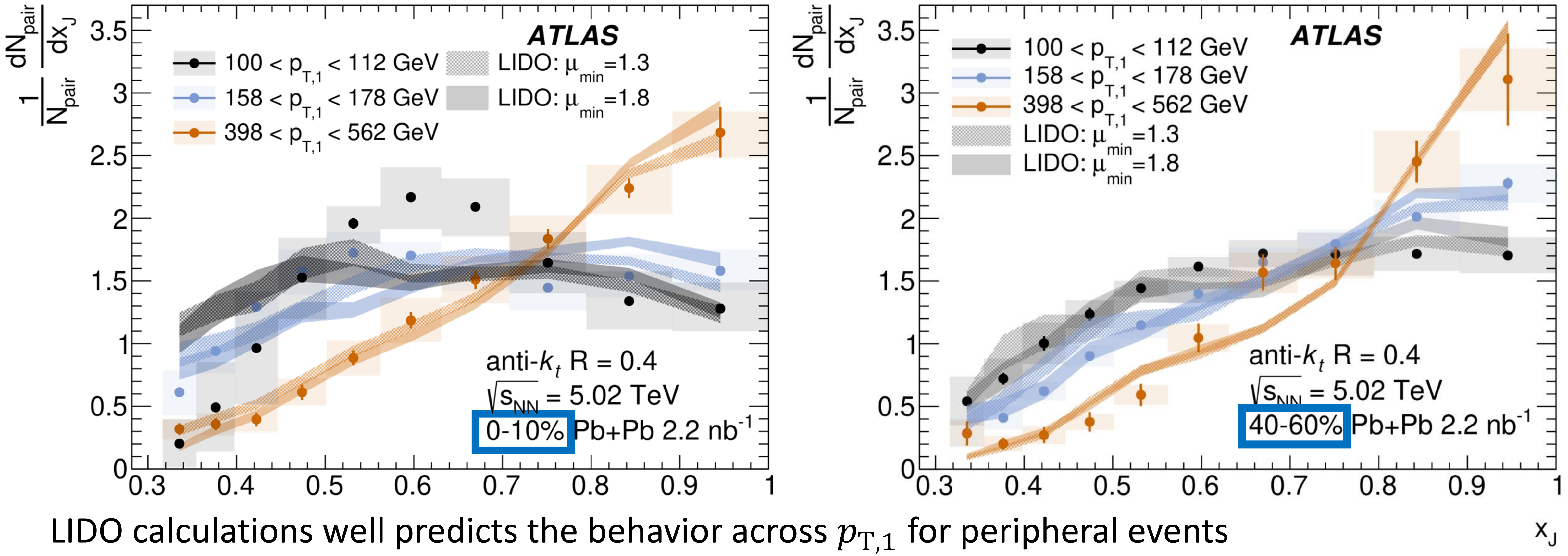


Smooth evolution from central Pb+Pb events towards *pp*

Significant modifications from *pp* collisions observed even at the highest $p_{\mathrm{T},1}$

Pair normalized x_J: comparison with theory

https://arxiv.org/pdf/2205.00682.pdf



LIDO calculations well predicts the behavior across $p_{\mathrm{T},1}$ for peripheral events

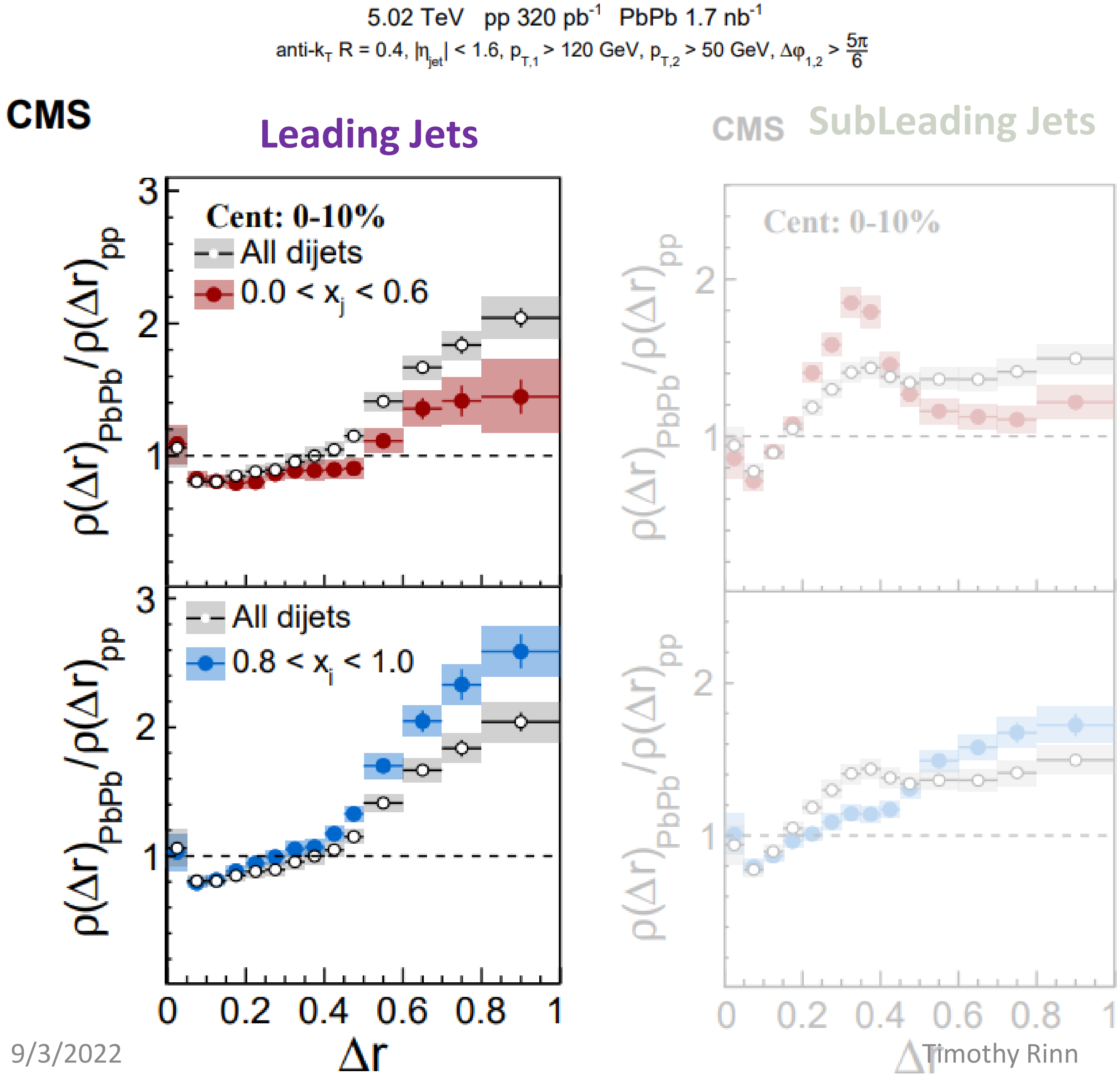
- Reproduces the x_J shape for intermediate and high $p_{\mathrm{T},1}$ in central events

LIDO does not reproduce the peak observed at intermediate x_J at low $p_{\mathrm{T},1}$

arXiv:2101.04720

ρ is proportional to track momentum density in a radius window

Leading dijet fragmentation



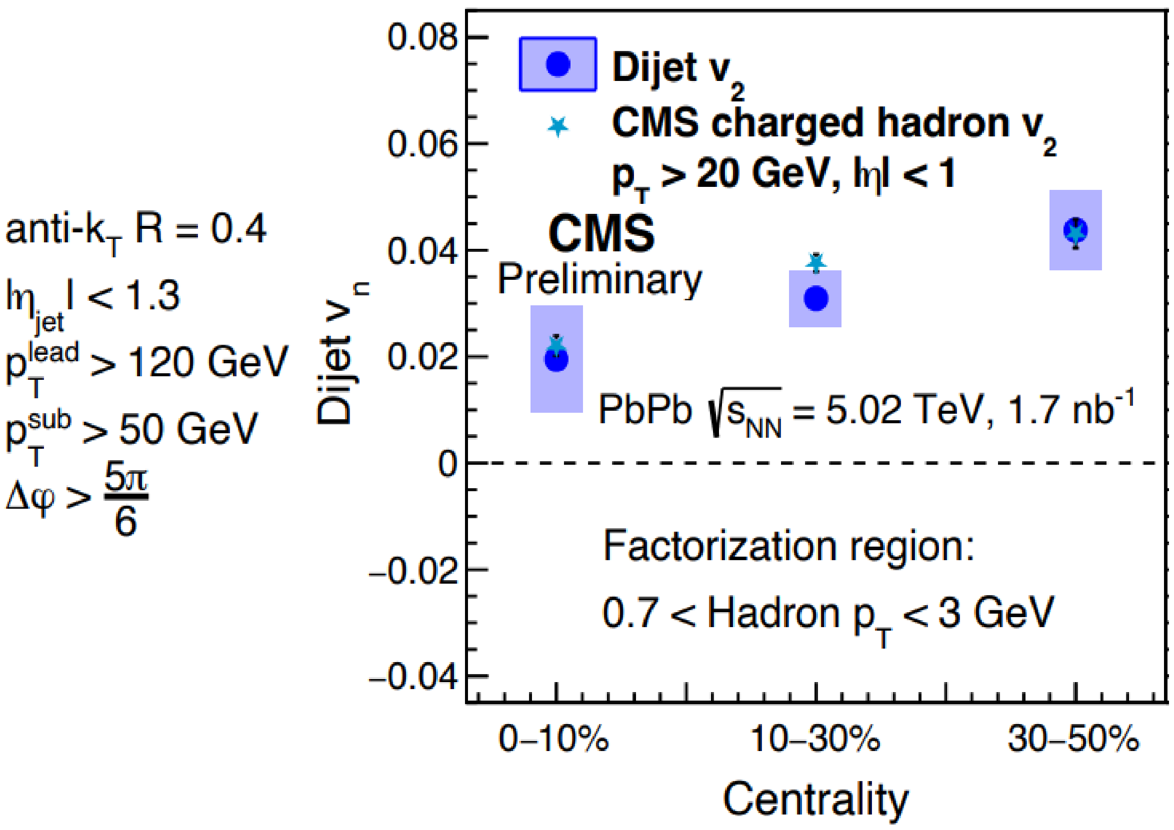
Leading jets observe enhancement of momentum caried at large radii for **Symmetric dijets** relative to **inclusive** and x_J **< 0.6**

$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\Sigma_{\text{tracks}\in(\Delta r_a,\Delta r_b)}\, p_{\text{T}}^{\text{ch}},$$

$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{\text{jets}}\Sigma_{\text{tracks}\in\Delta r<1}\, p_{\text{T}}^{\text{ch}}}.$$

Dijet azimuthal correlations

HIN-21-002



- Dijet v_2 was measured by the CMS collaboration
- Significant non-zero dijet v_2 is observed
  - Increases with increasing event ellipticity
- Consistent v_2 as measured for high p_T hadrons

sPHENIX: Jets

- State of the art Jet detector at RHIC

- Full Hadronic and Electromagnetic calorimetery
  - Full azimuthal coverage
  - $|\eta| < 1.1$ acceptance

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| < 10$ cm	Samp. Lum. $|z| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}