Path-length dependence of jet quenching at the LHC & RHIC

Anne M. Sickles
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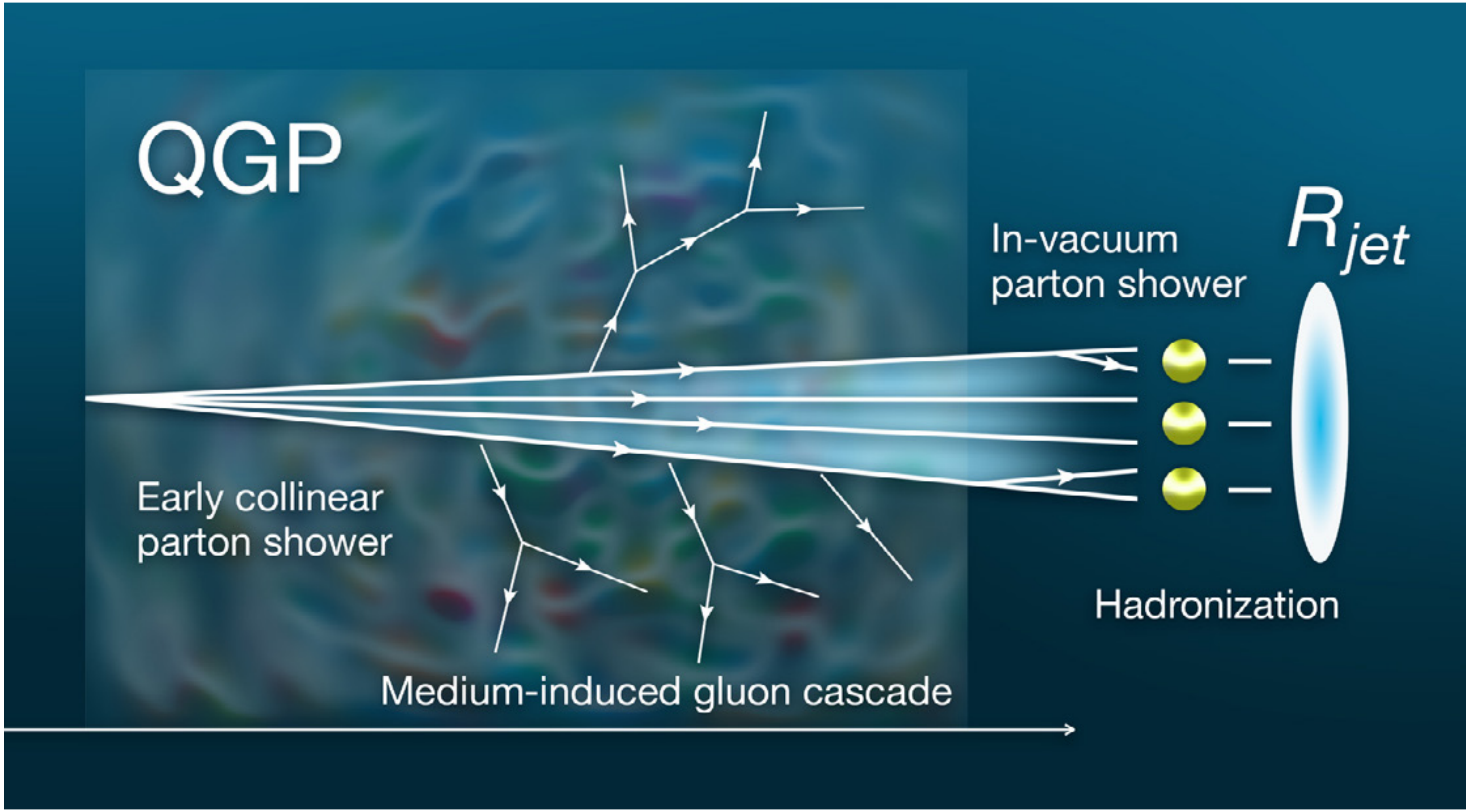
UNIVERSITY OF
ILLINOIS
URBANA-CHAMPAIGN

goal of jet physics



understand the interaction of the evolving parton shower with the QGP
length/timescale of that interaction is an essential component of this quest

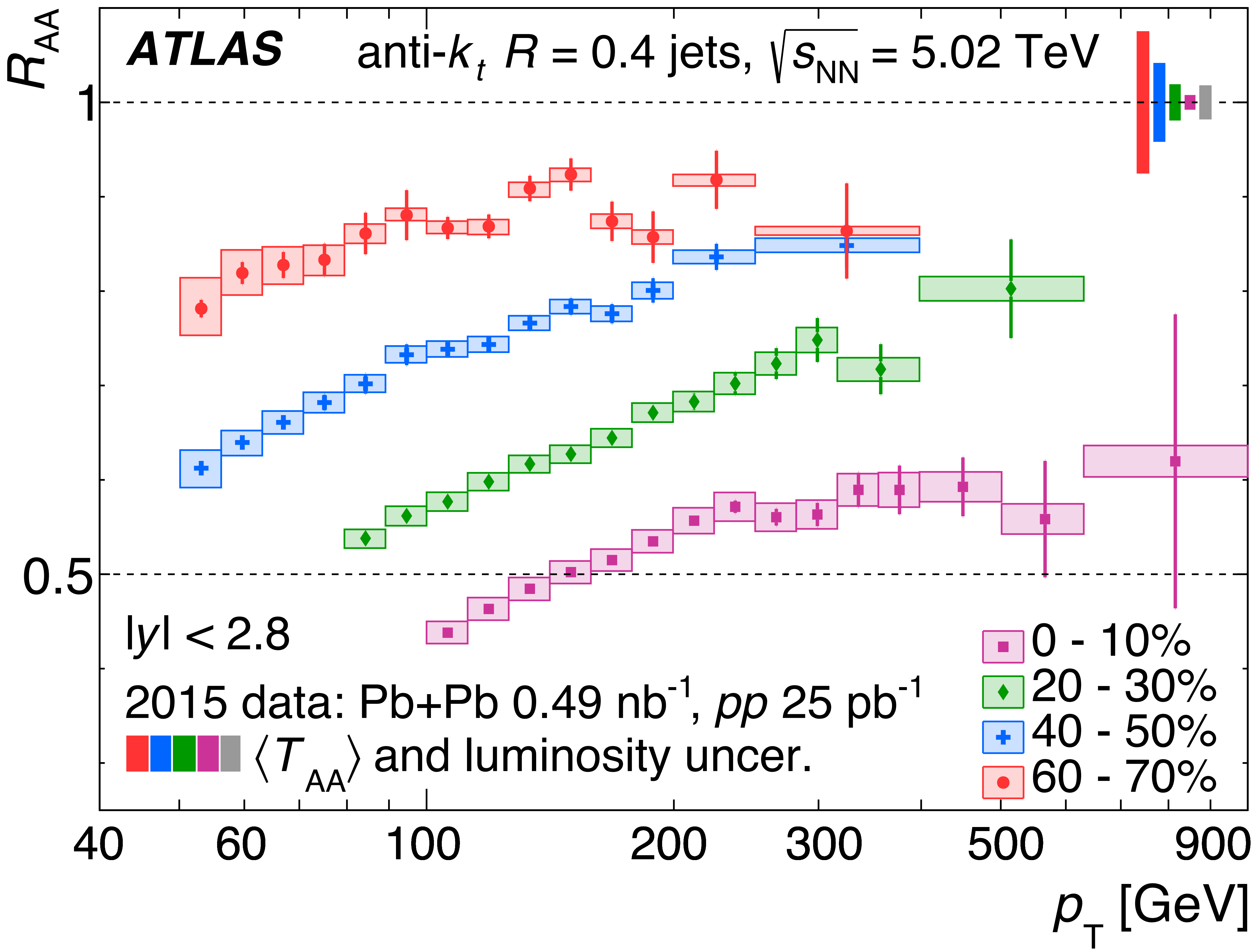
2023 LRP

jet *quenching*

$$R_{AA} = \equiv \frac{dN^{PbPb}/dp_T}{T_{AA} d\sigma^{pp}/dp_T}$$

- inclusive R_{AA} tells us jet quenching is important but it integrates over everything except the jet momentum
- the focus of current measurements is to understand how quenching depends on the:
  - structure of the jet
  - amount of QGP the jet sees

inclusive jet R_{AA}



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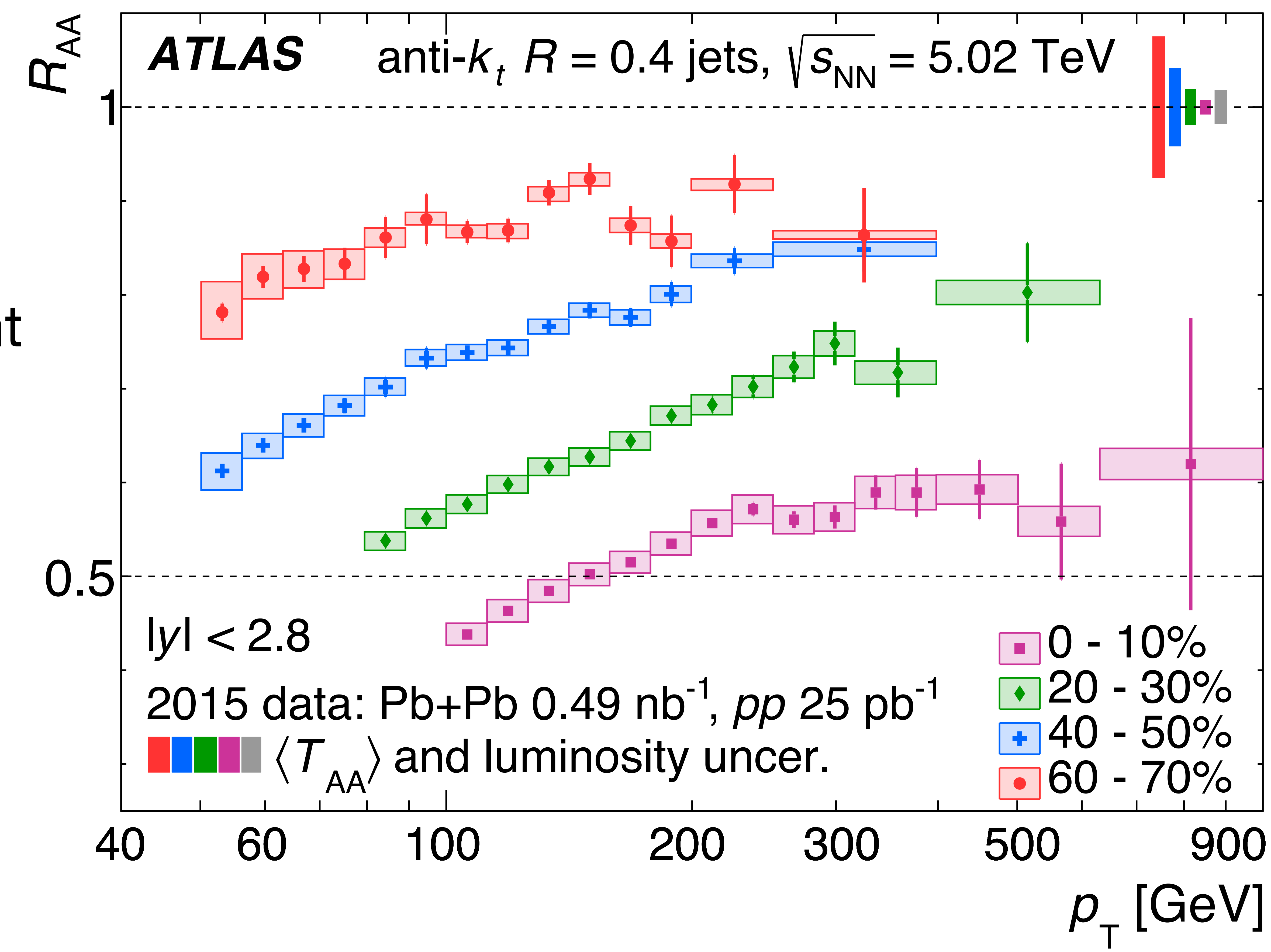

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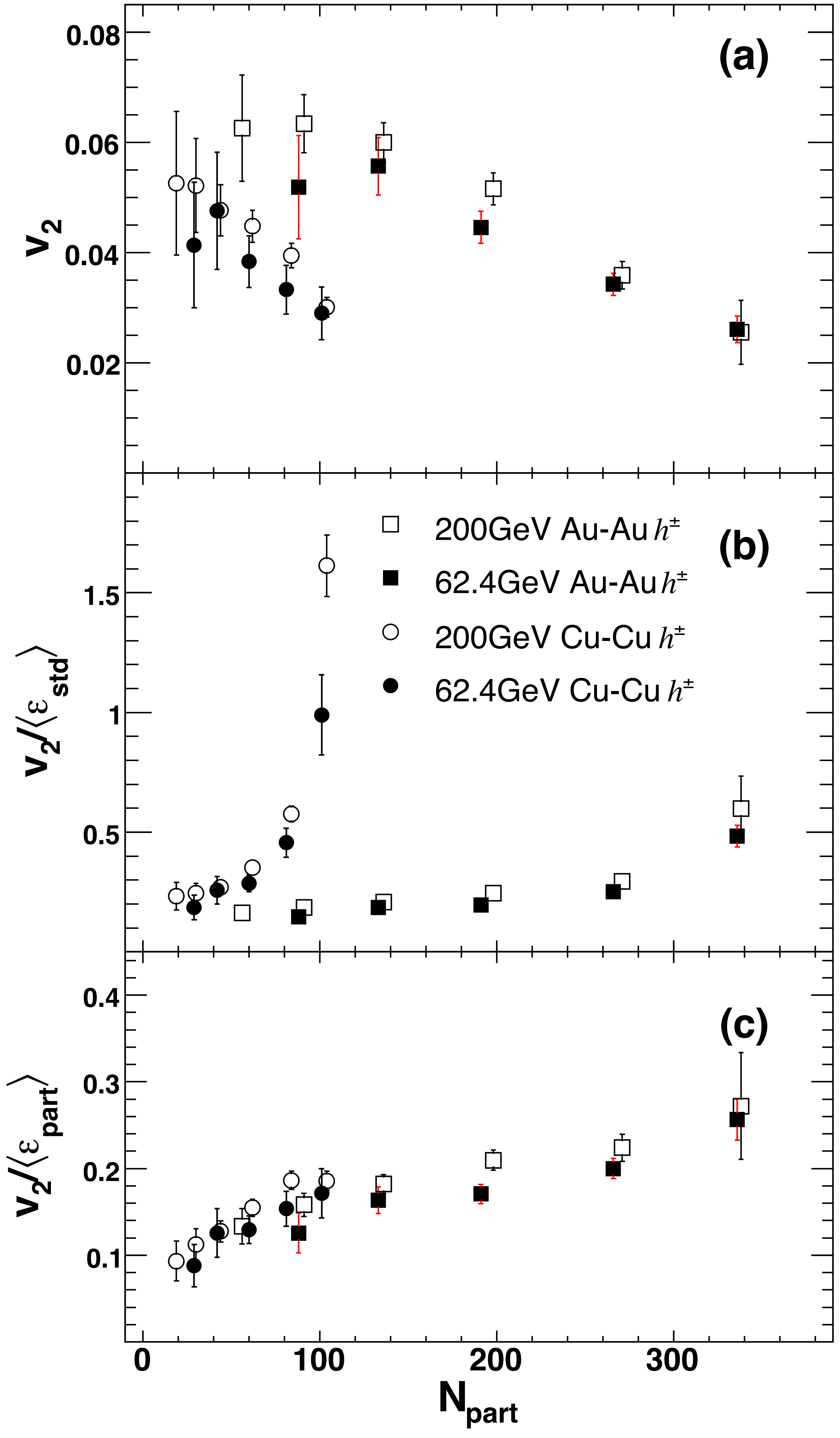
geometry & fluctuations is key in the soft sector



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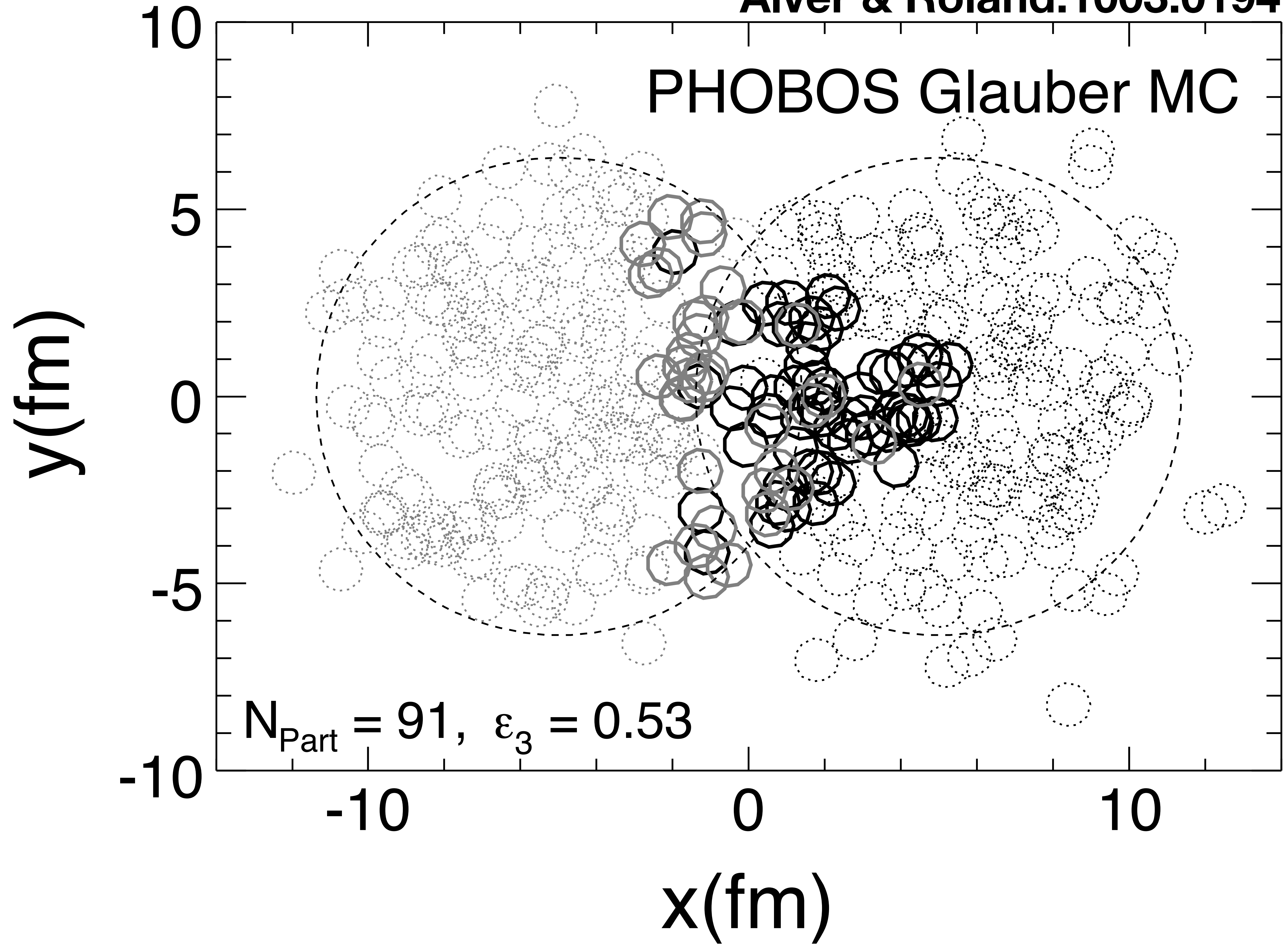
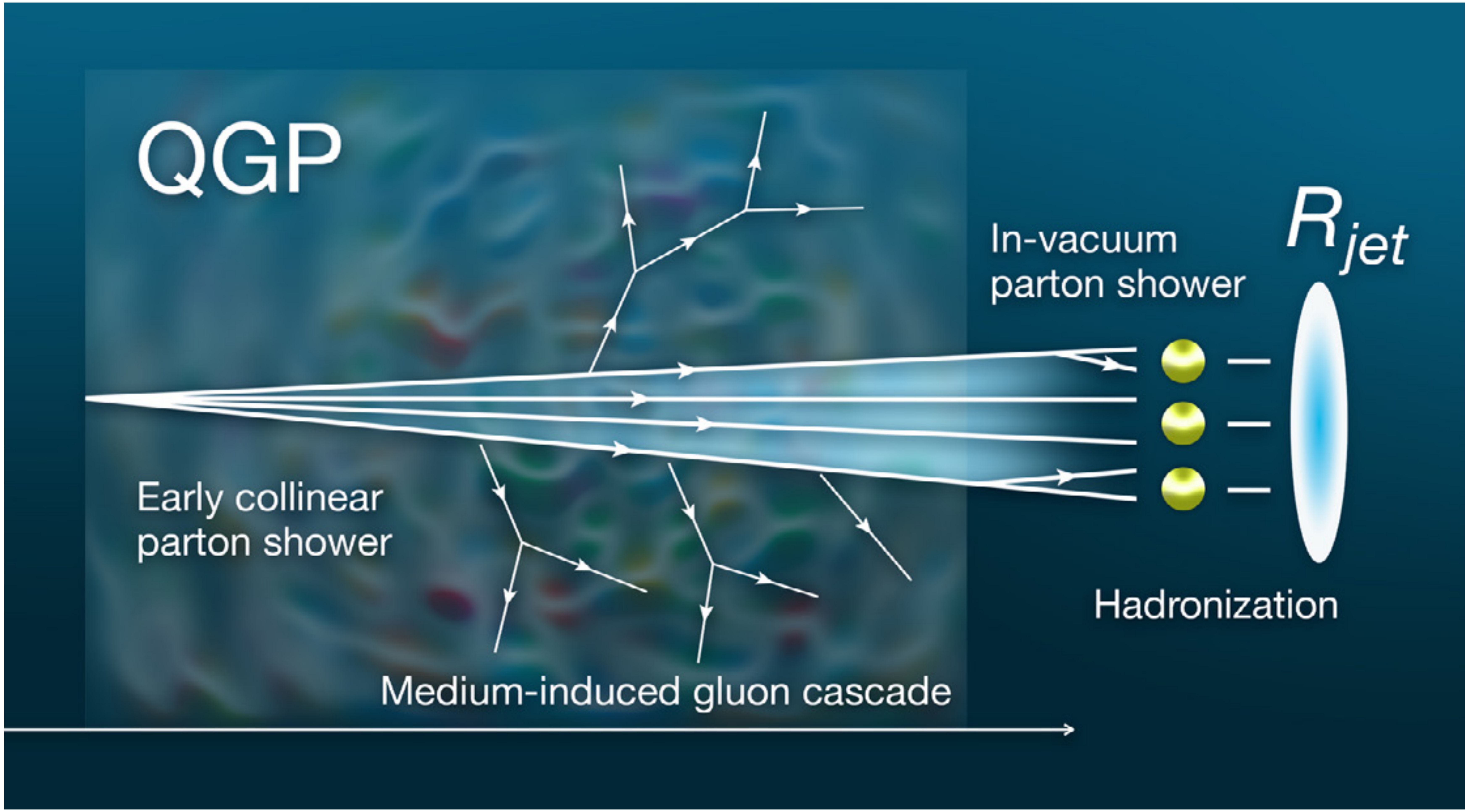


geometry & fluctuations in the soft sector are key to the extractions of η/s

jets in the QGP

evolving parton shower traverses the time evolution of the QGP

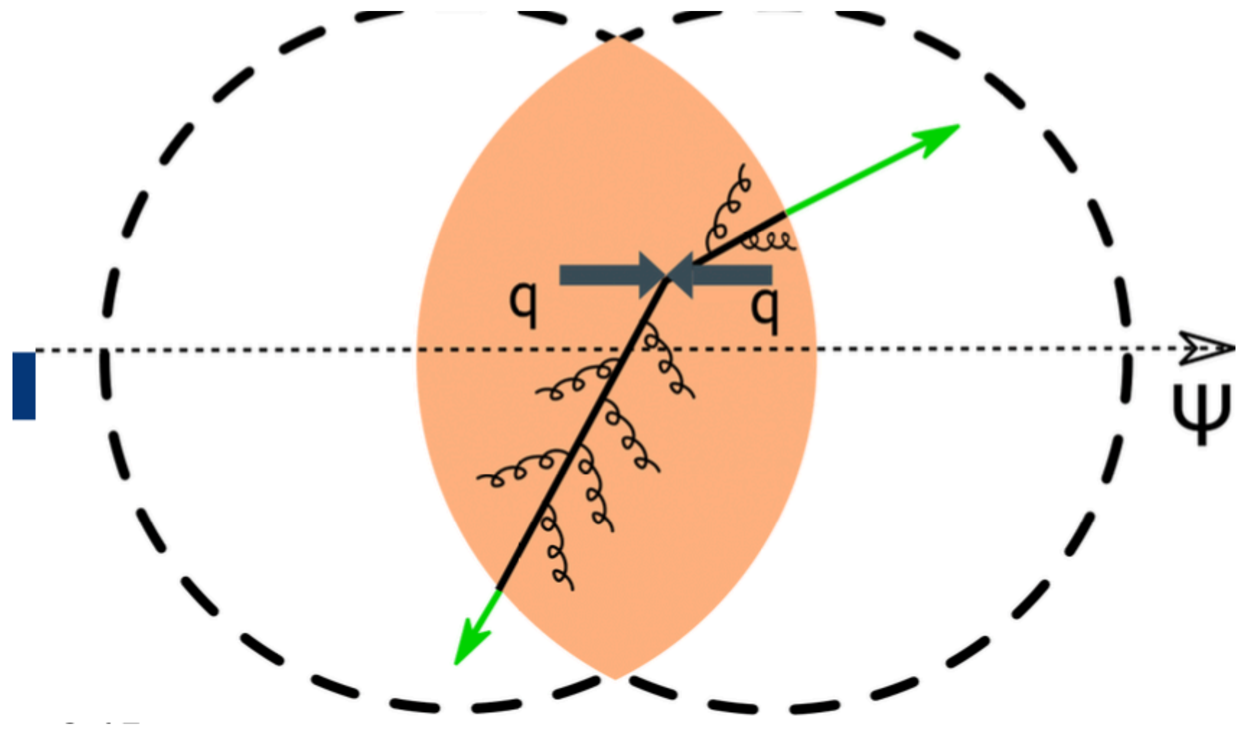


jets in the QGP

evolving parton shower traverses the time evolution of the QGP

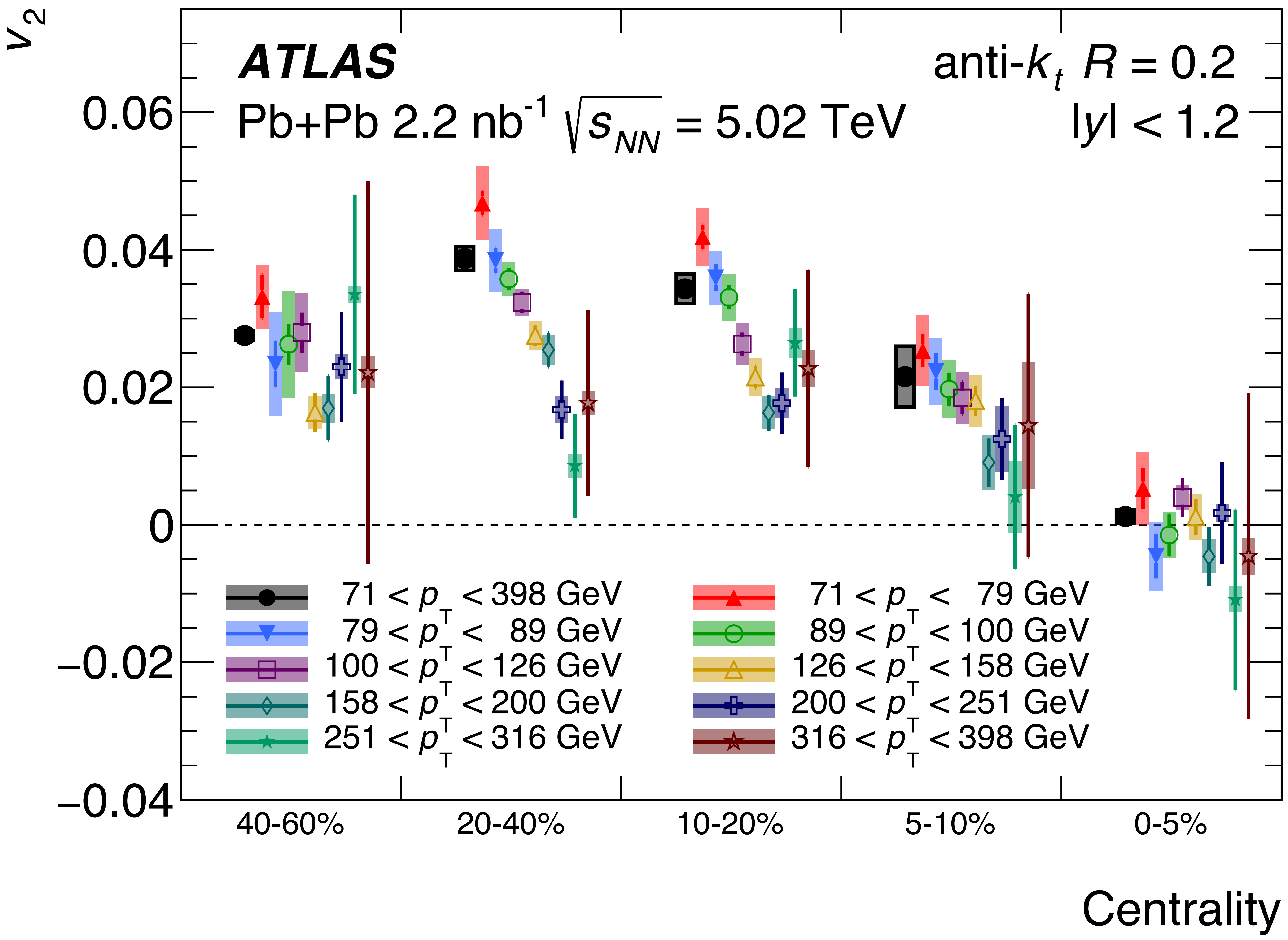
measurements sensitive to path length

- **(di)jet v_n, etc**: correlation of jets with the event planes
    - sensitive to overall event geometry & path length differences on the scale of geometry of the initial state.



- **dijets**: hard scattering produces approximately balanced partons—we measure imbalanced jets in PbPb collisions
- **smaller collisions**: how small of a QGP can cause energy loss?

jet v_2



- $v_2 > 0$ observed for all but the most central collisions
- v_2 decreases with increasing p_T but remains > 0 in mid-central collisions up to at least 250 GeV

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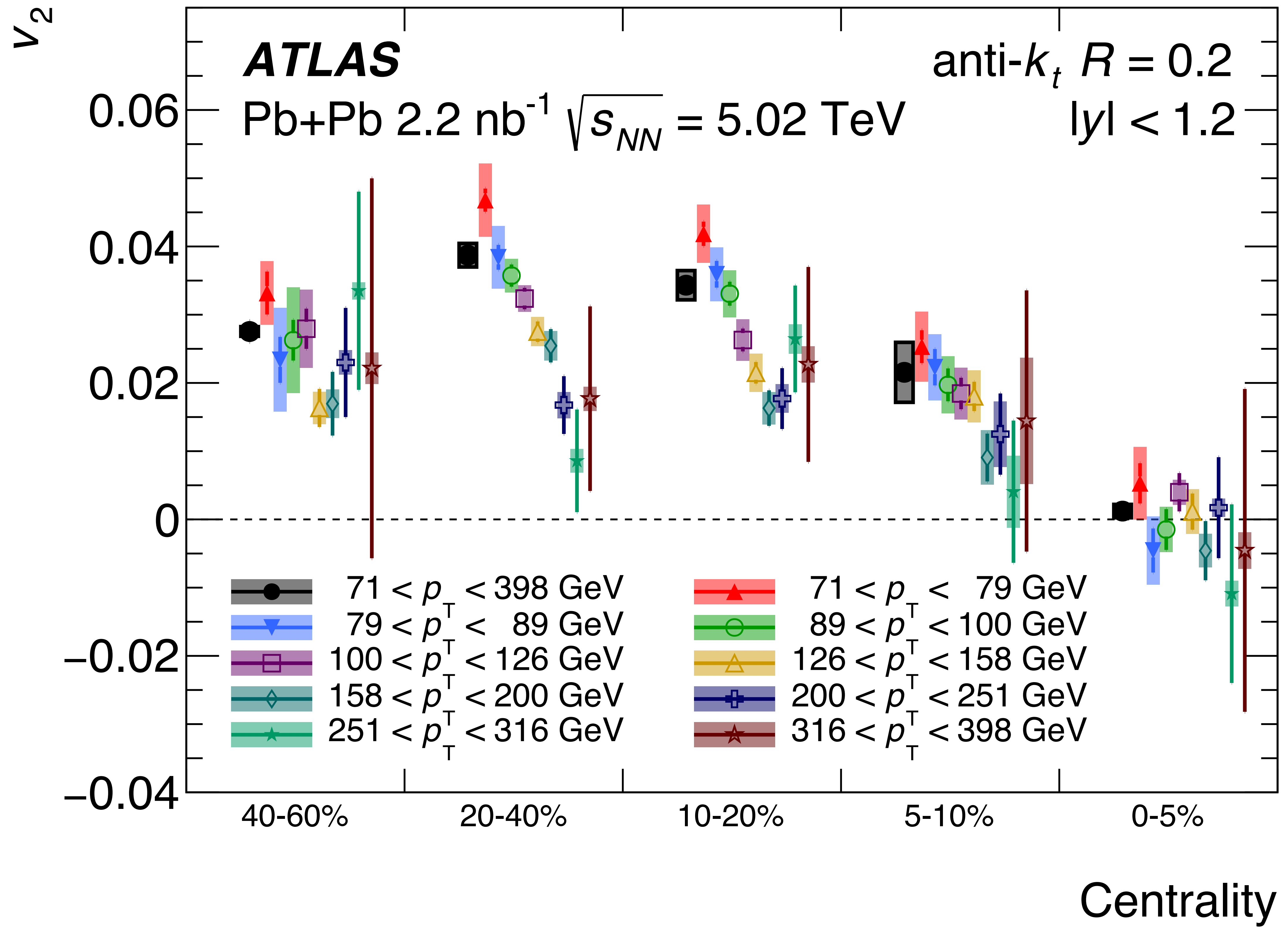
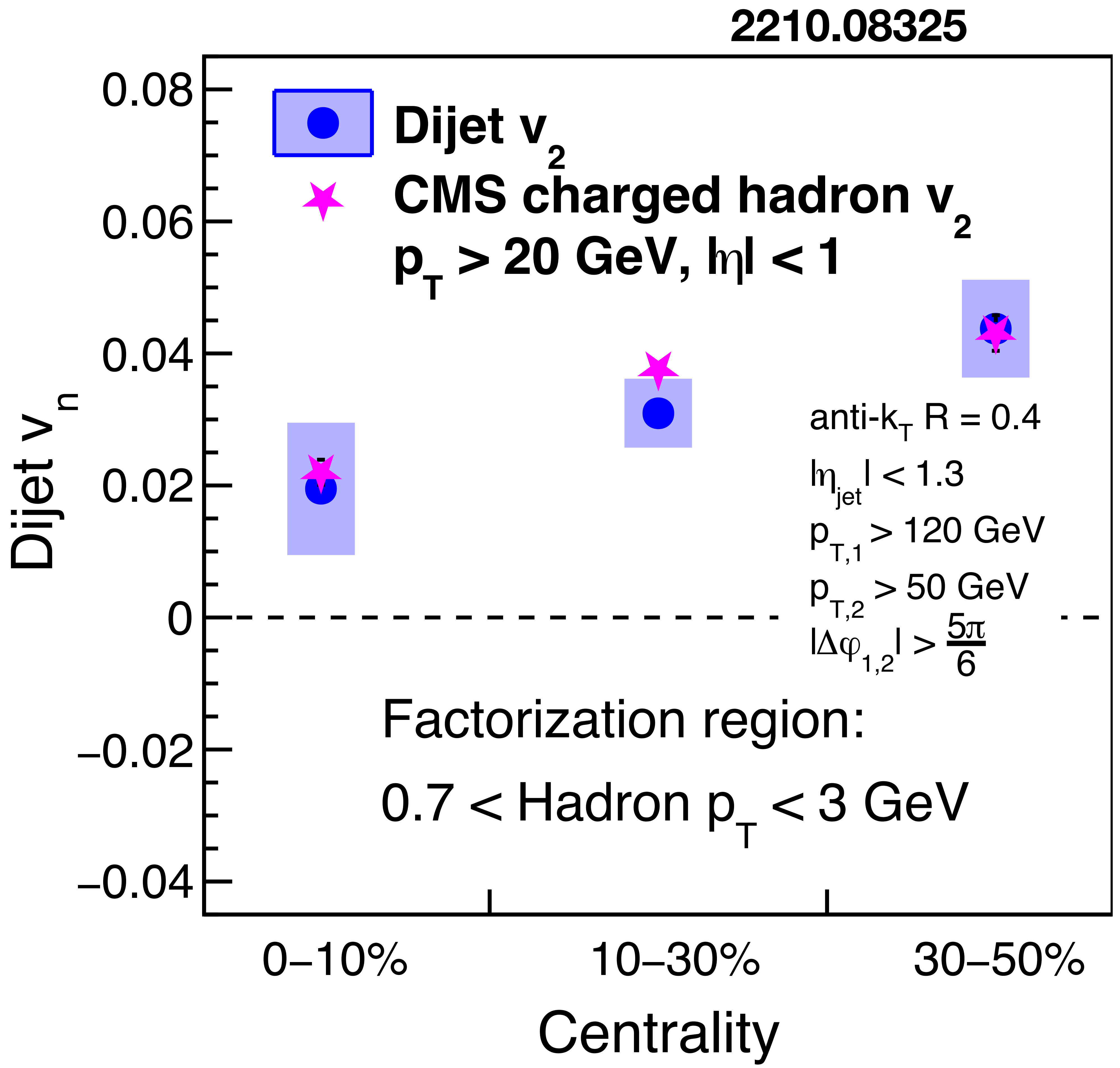
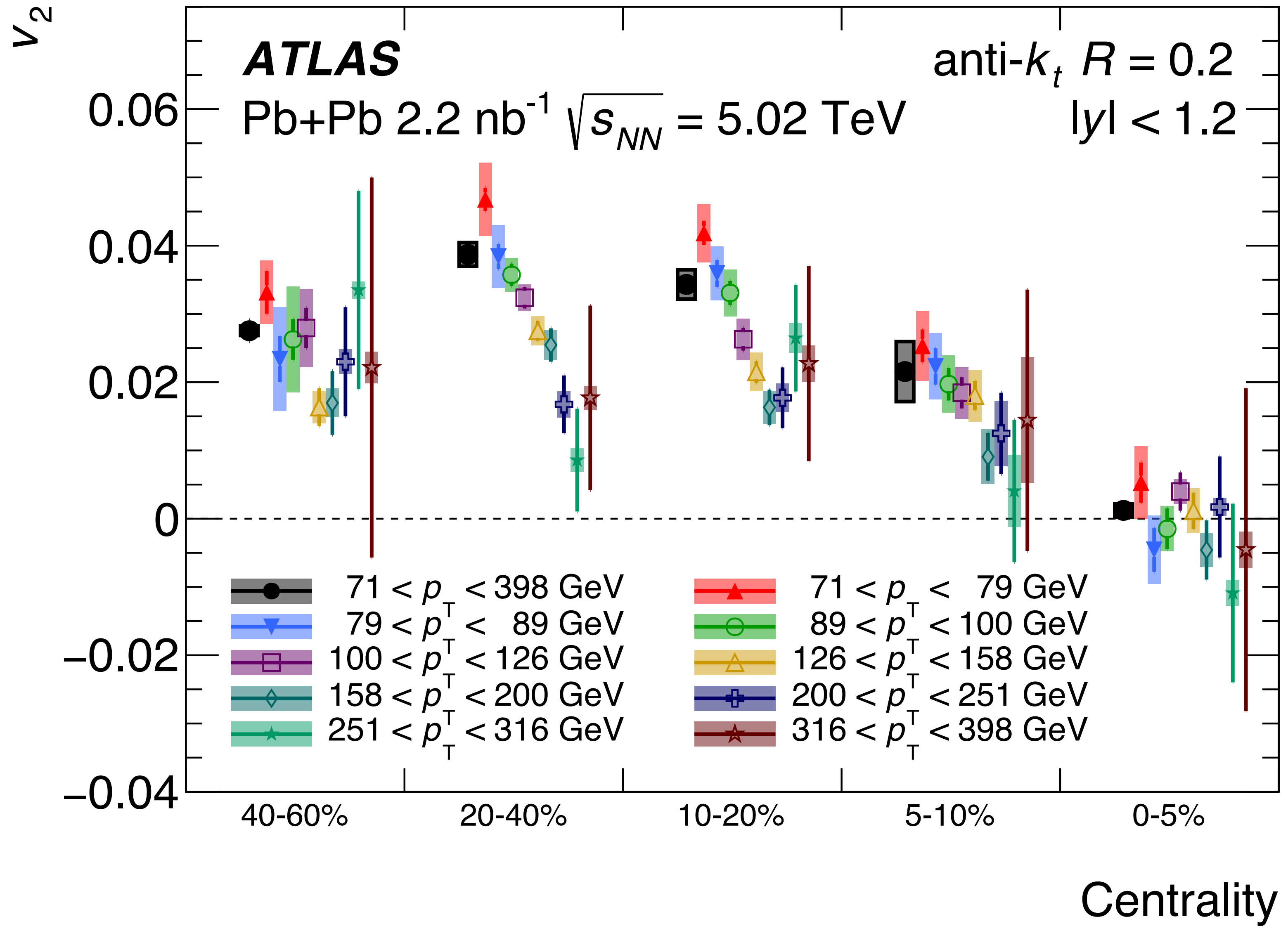
dijet v_2



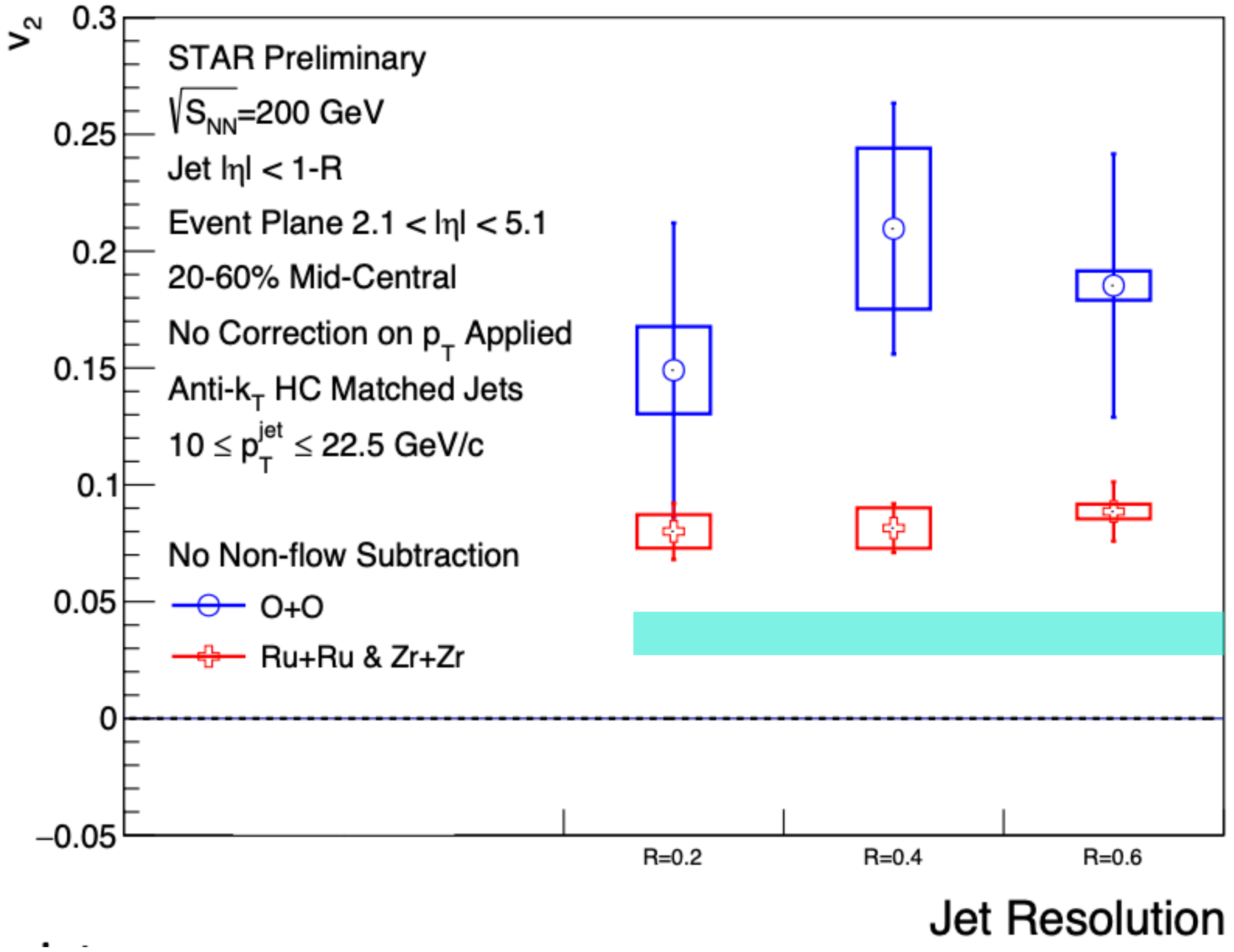


- dijet v_2 similar to that of charged particles and single jet v_2 from ATLAS
- given the different pt and centrality selections it is difficult to quantify any radial dependence

smaller systems & RHIC

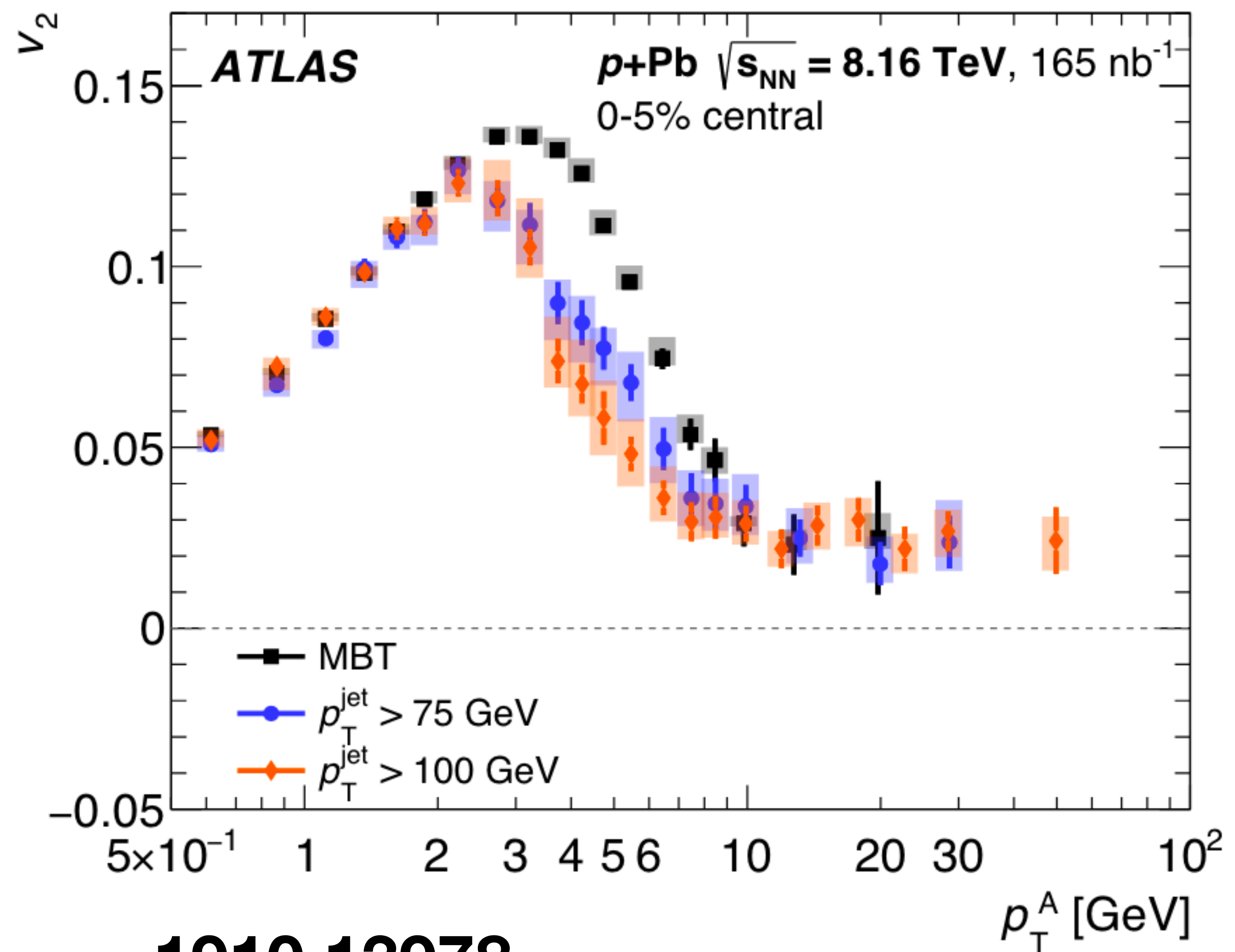


T. Protzman QM23



OO & **RuRu/ZrZr** **v_2 much larger than that seen at the LHC in smaller & larger collision systems**

PbPb collisions @ the LHC



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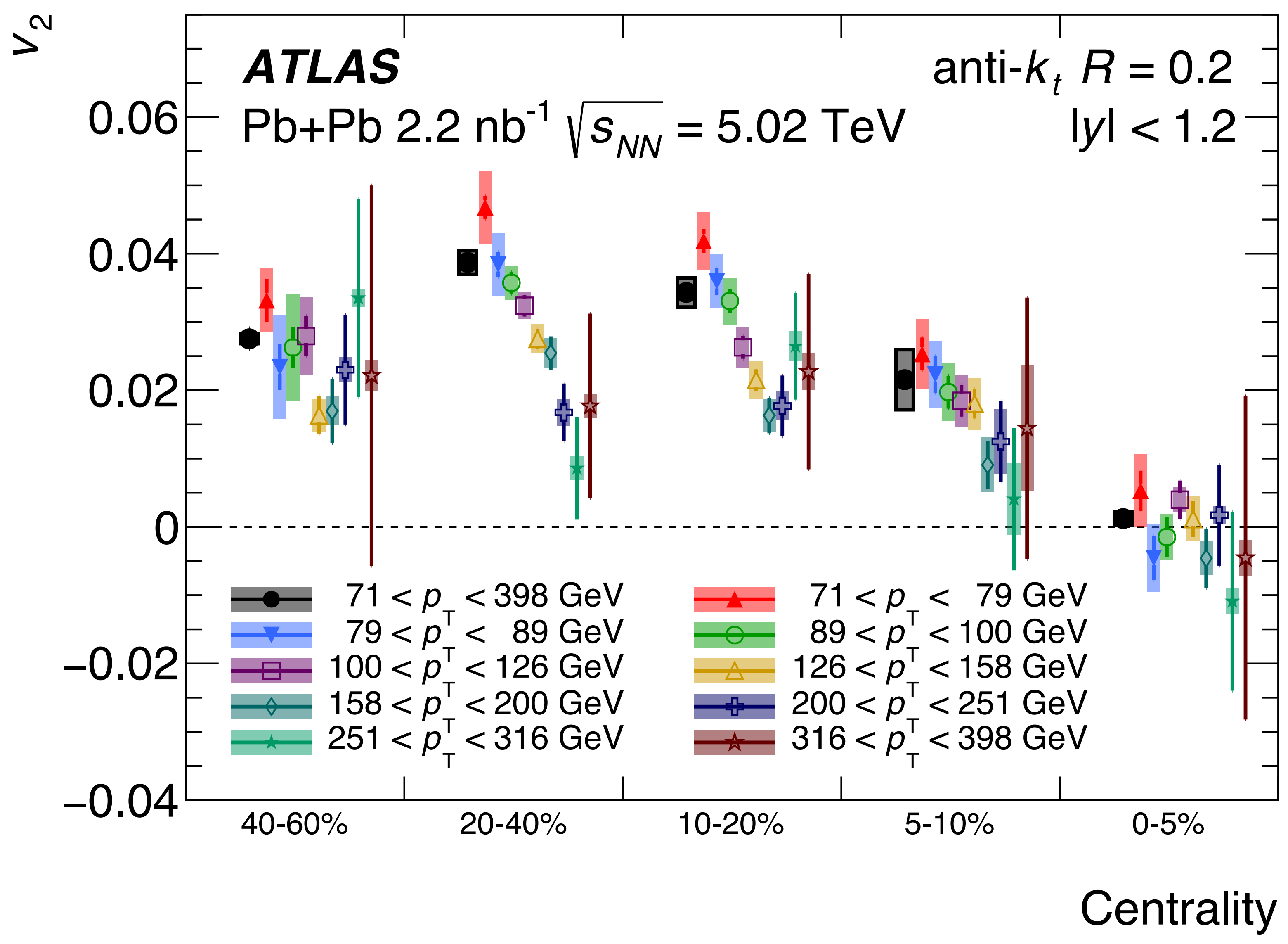
pPb @ LHC evidence for ~1-2% v2 for ~30 GeV particles

smaller systems & RHIC



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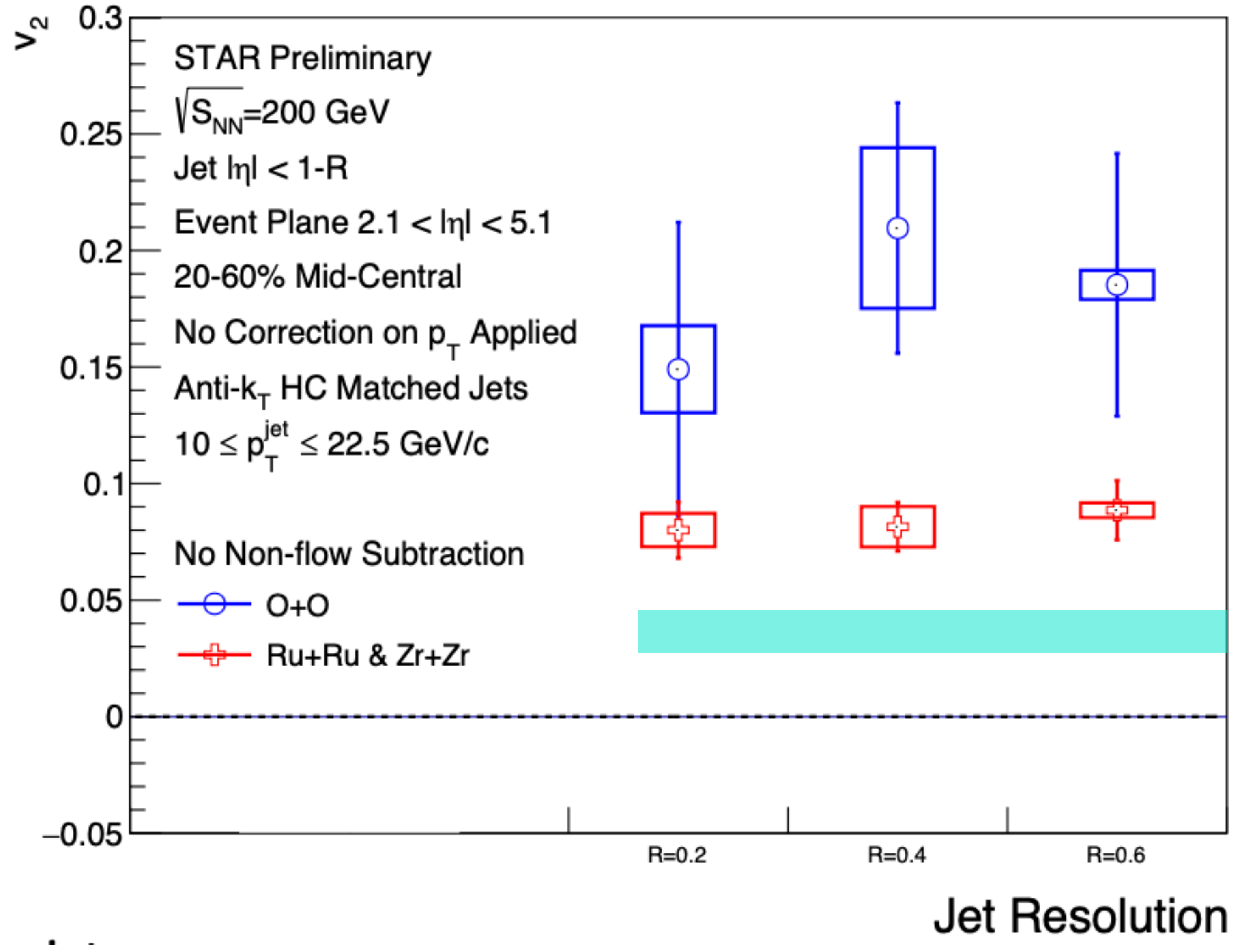

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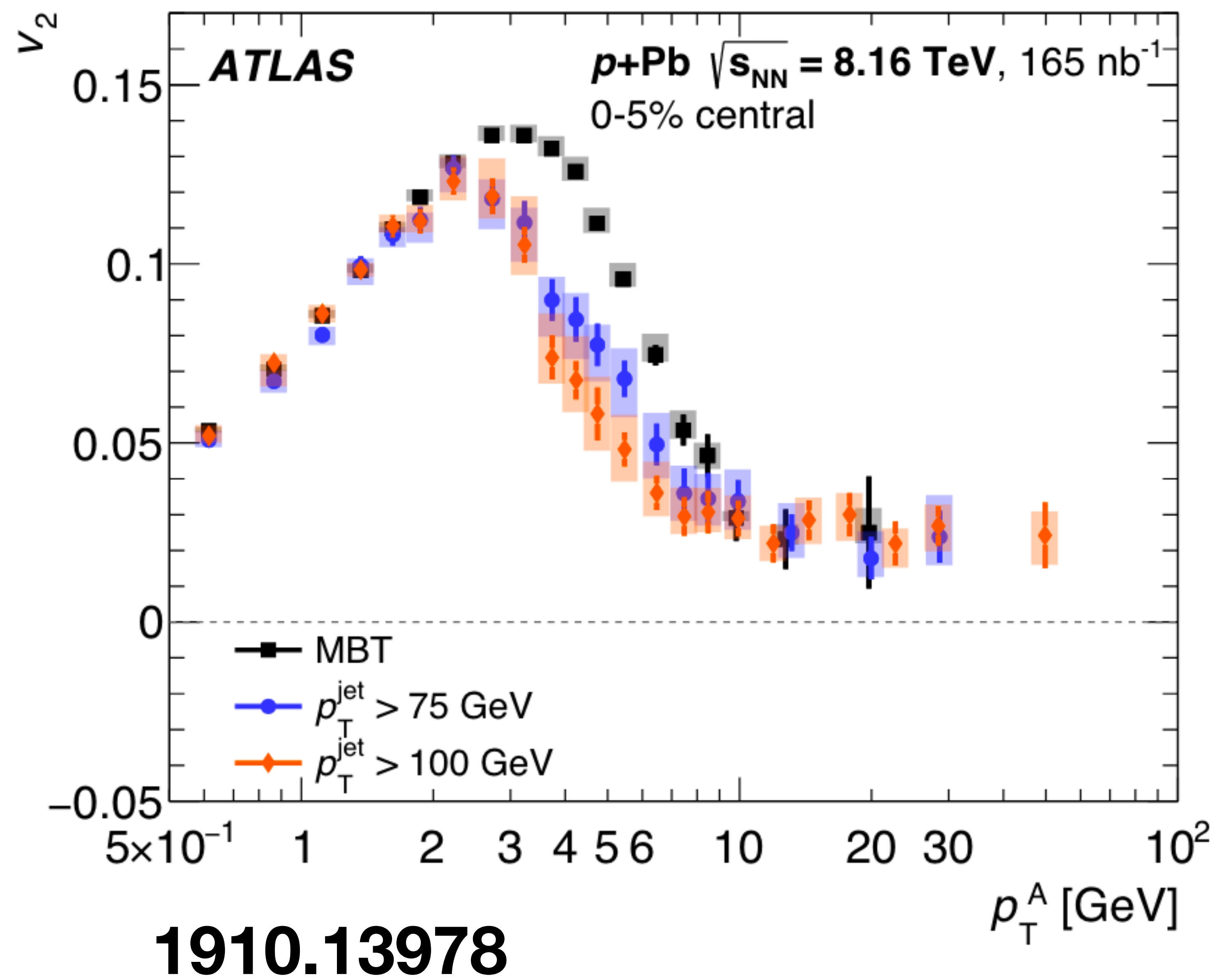

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pPb @ LHC evidence for ~1-2% v2 for ~30 GeV particles

critical to have measurements from OO collisions at the LHC (anticipated in 2024/25) and AuAu measurements from sPHENIX to disentangle the system size/ collision energy dependence

centrality dependence of jet v_n

- v_2 largest in mid-central collisions; consistent with 0 in the most central collisions
- v_3 ~1% for mid-central/central collisions
  - for both v_2 & v_3 the centrality dependence is similar to that of hydrodynamic vn which is driven by the initial collision geometry
  - suggests the same geometry plays a significant role in jet quenching
- v_4 consistent with 0
  - larger uncertainties from poor 4th-order event plane resolution

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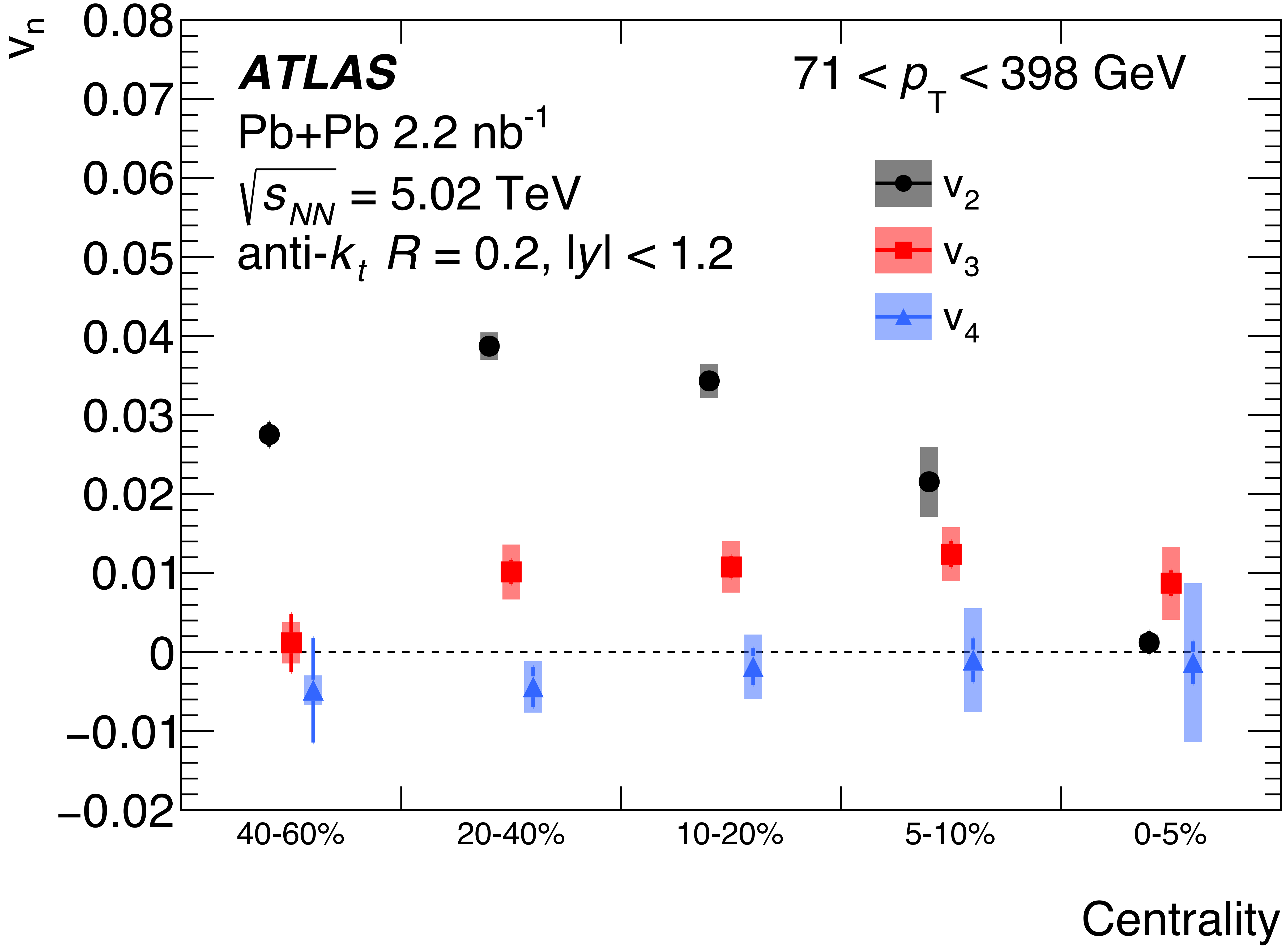
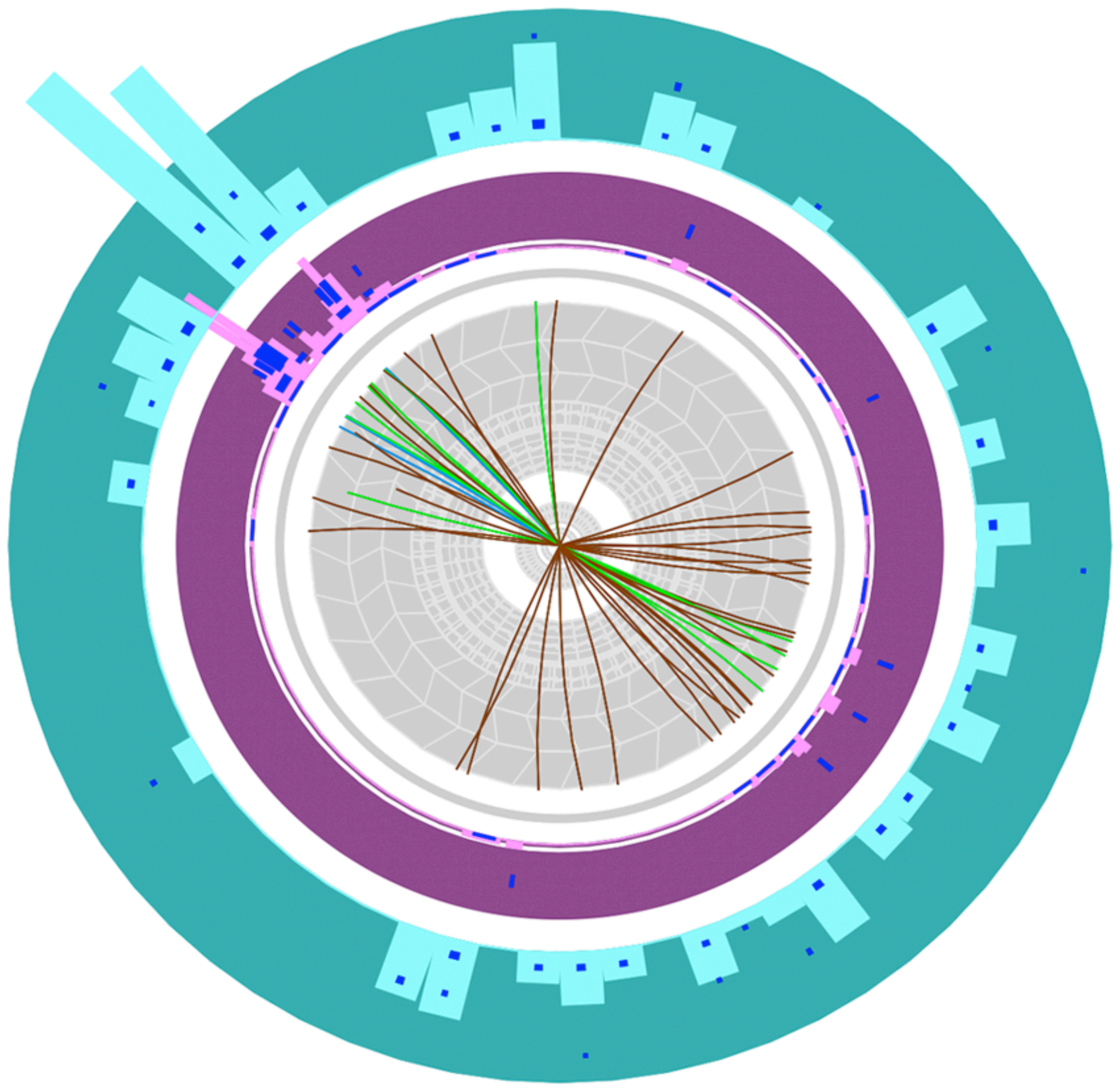
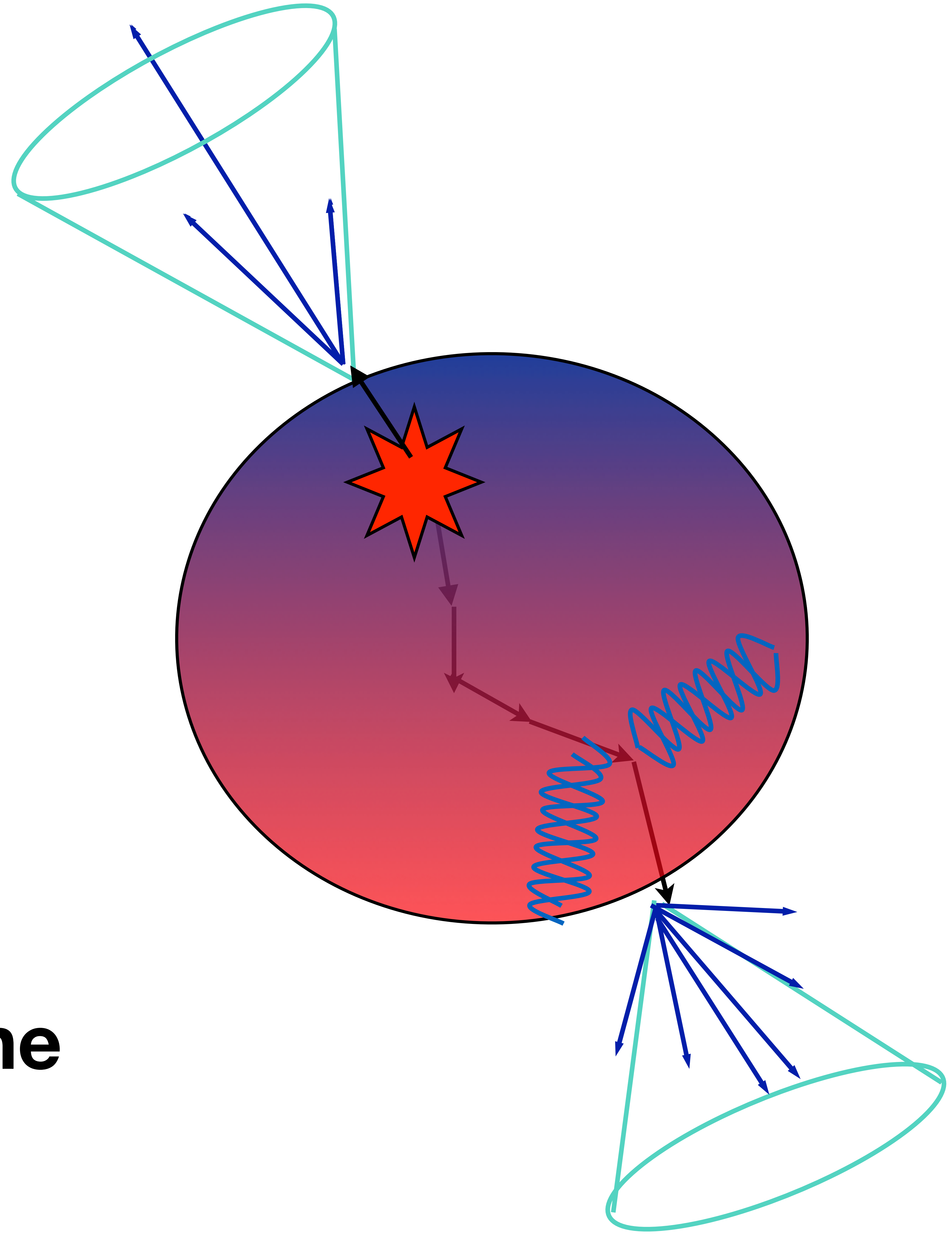


a picture of dijets

leading jet: very short path length thourgh the QGP, nearly no energy loss

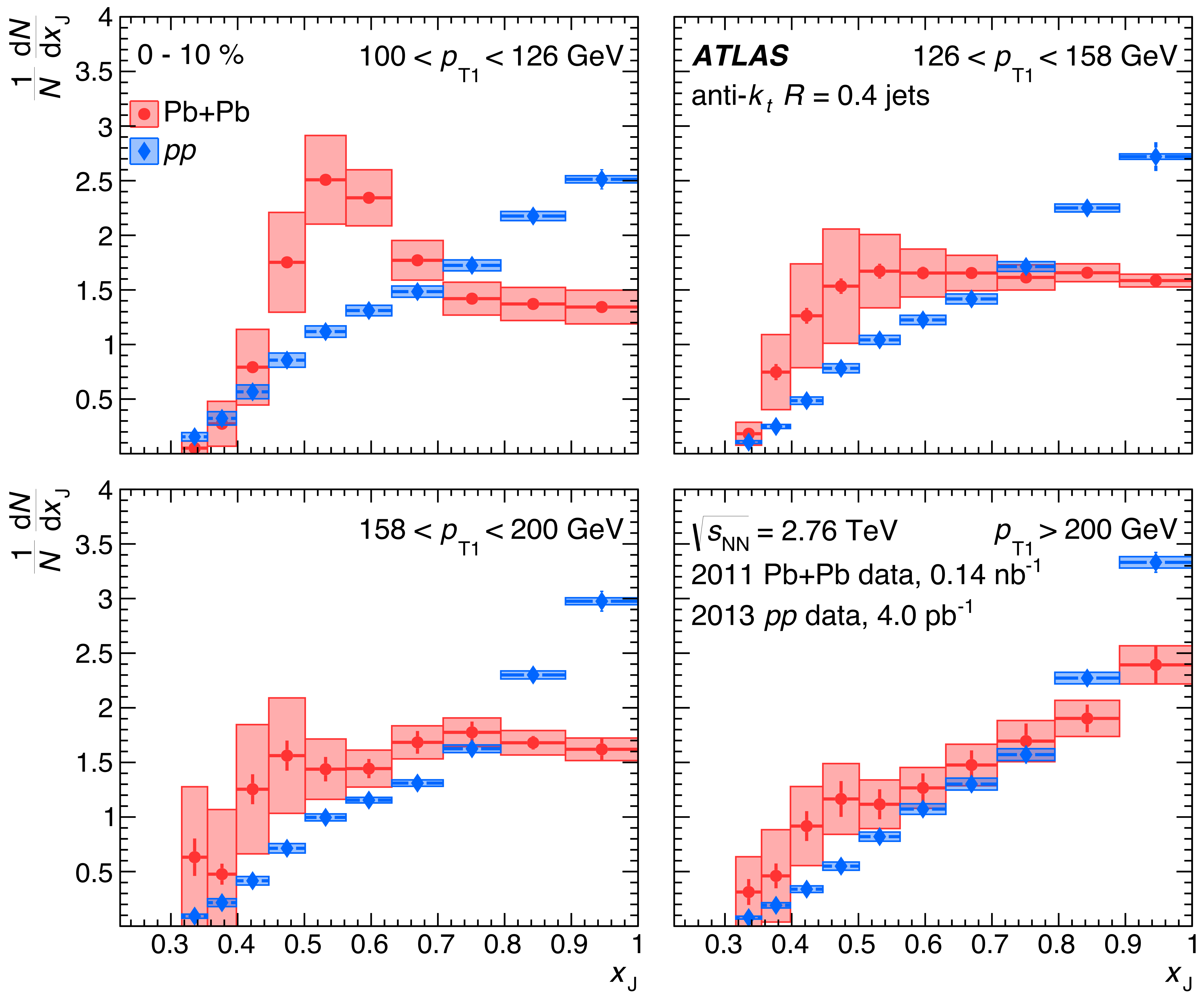




subleading jet: lots of interactions through the QGP, stronger quenching of the jet

dijets at 2.76 TeV

- shift from balanced jets to imbalanced jets makes sense in a surface bias picture
- however, these distributions are sensitive only to the shape (area normalization)
- which jets are actually being suppressed?
- also, what's that peak?



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x_J = momentum of jet 2 / momentum of jet 1

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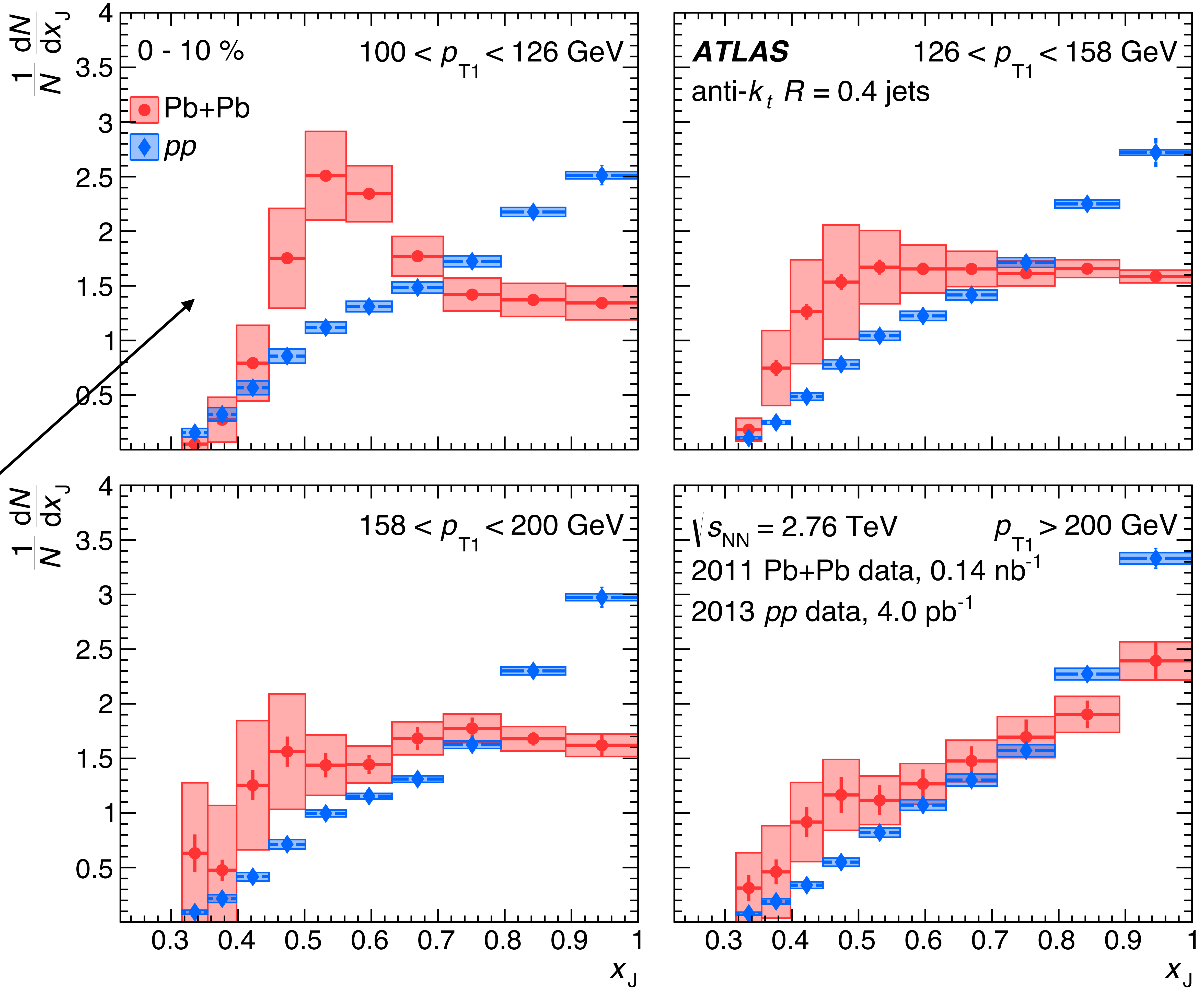

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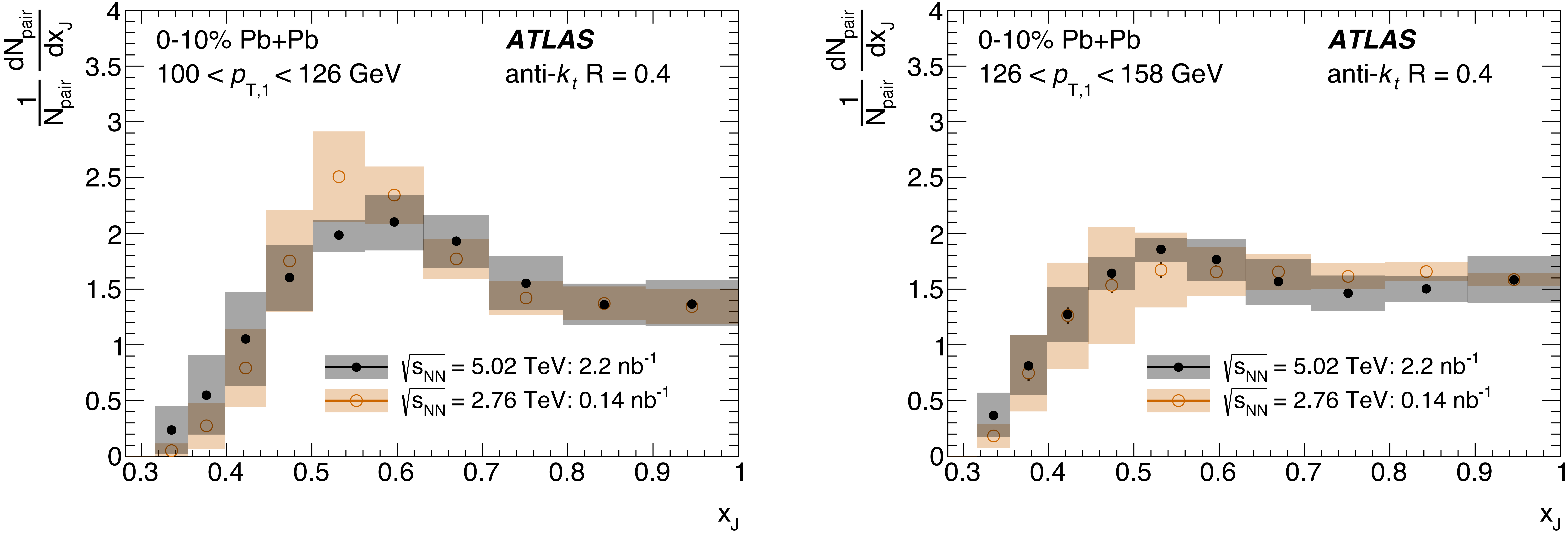
x_J = momentum of jet 2 / momentum of jet 1

comparison of 5.02 TeV & 2.76 TeV



x_J distributions have consistent shapes at the two collision energies

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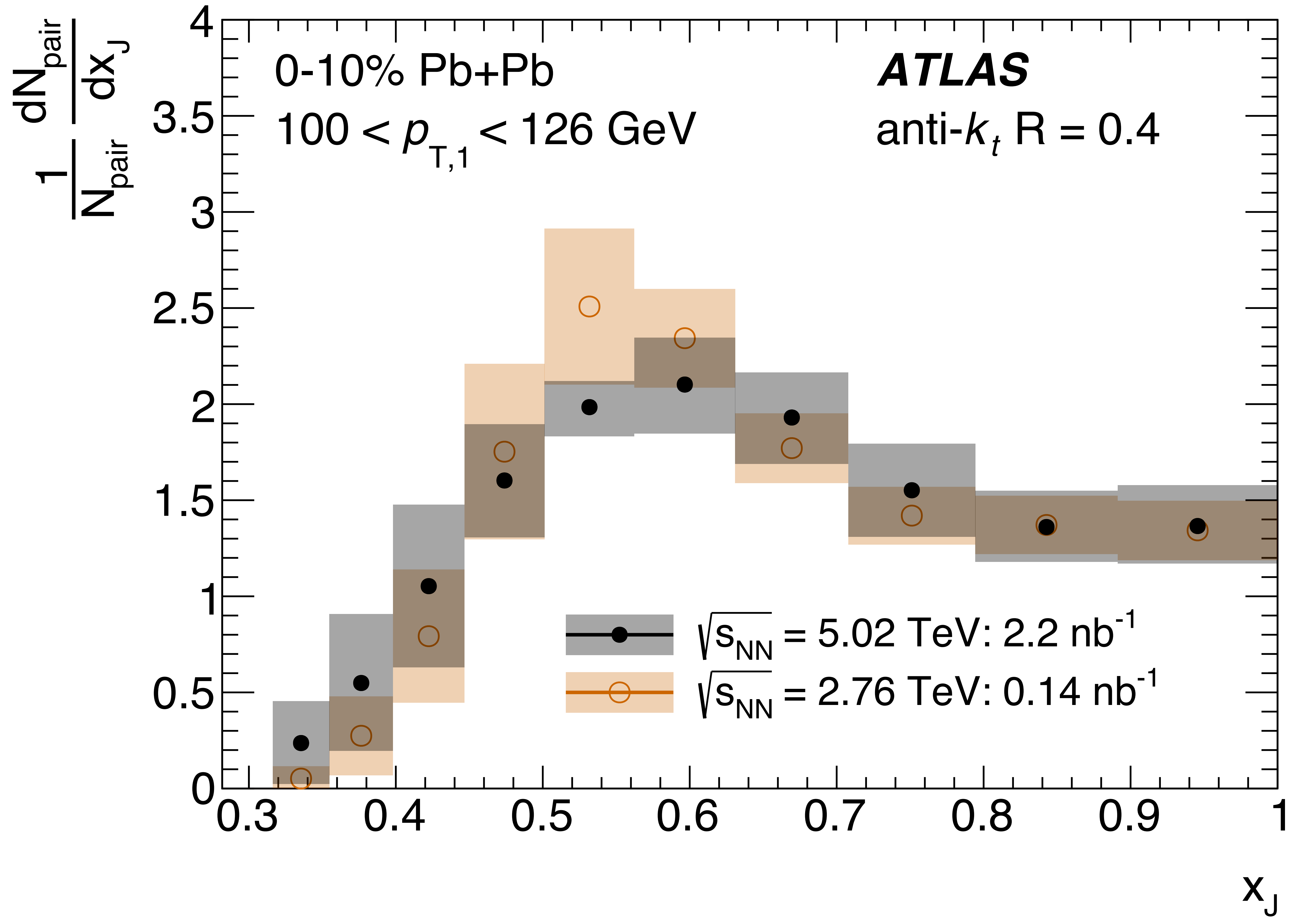
comparison of 5.02 TeV & 2.76 TeV



is there an enhancement of imbalanced dijets or a suppression of balanced dijets?

to answer that, look at the absolute rate of dijets, not the relative rate

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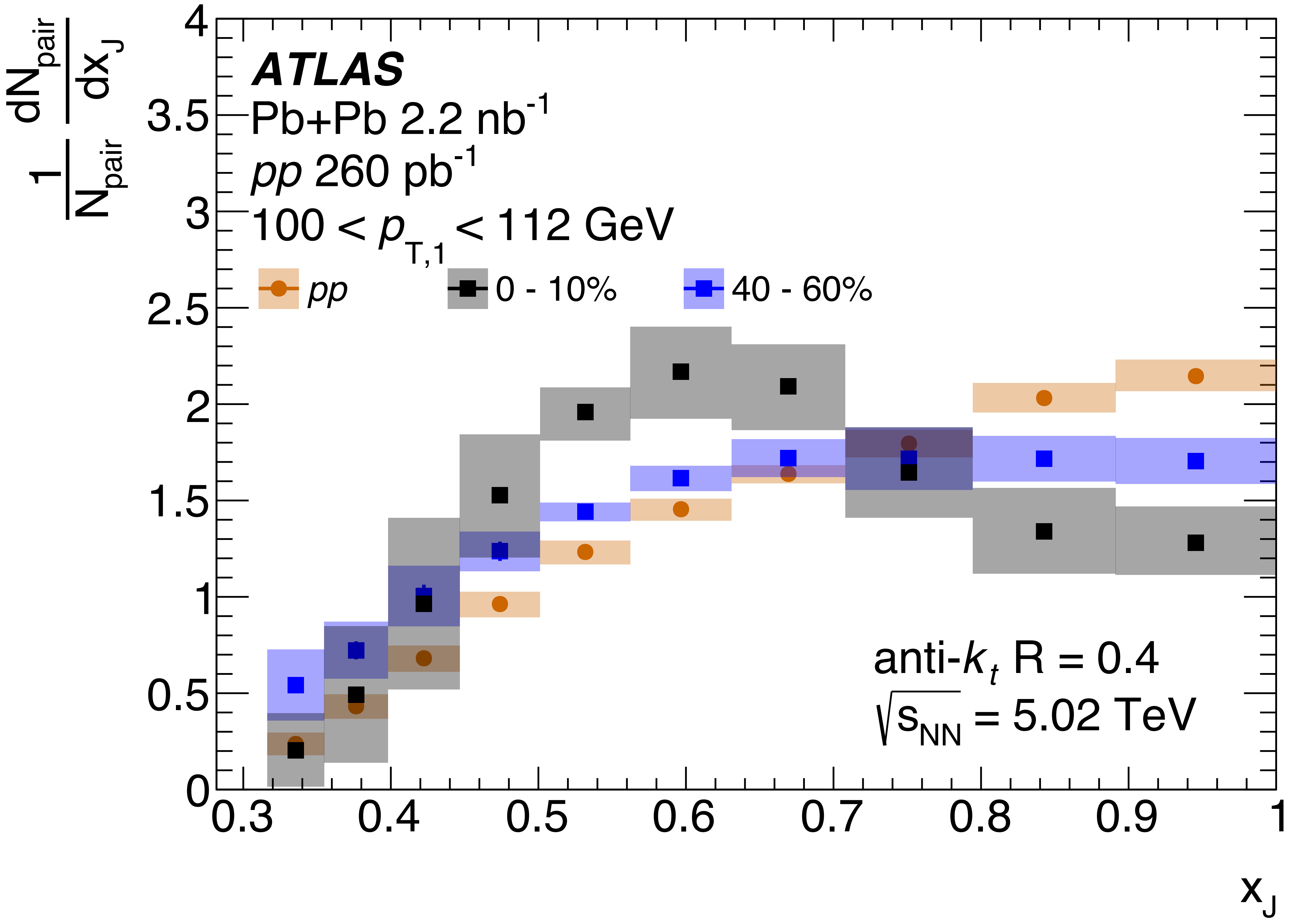
new method for studying x_J

$$\frac{1}{N_{\text{pair}}}\frac{dN_{\text{pair}}}{dx_{\text{J}}}$$

area normalization



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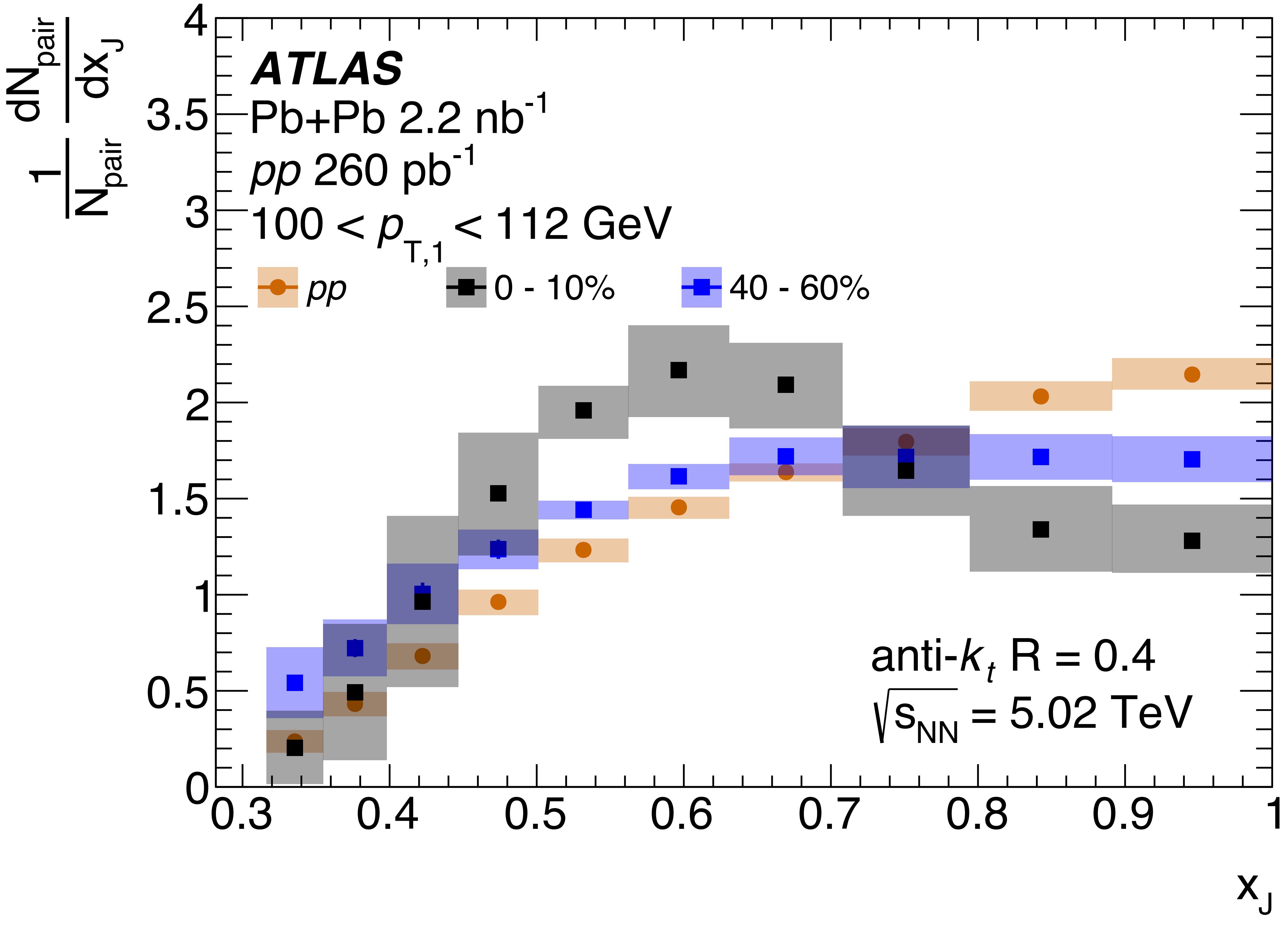
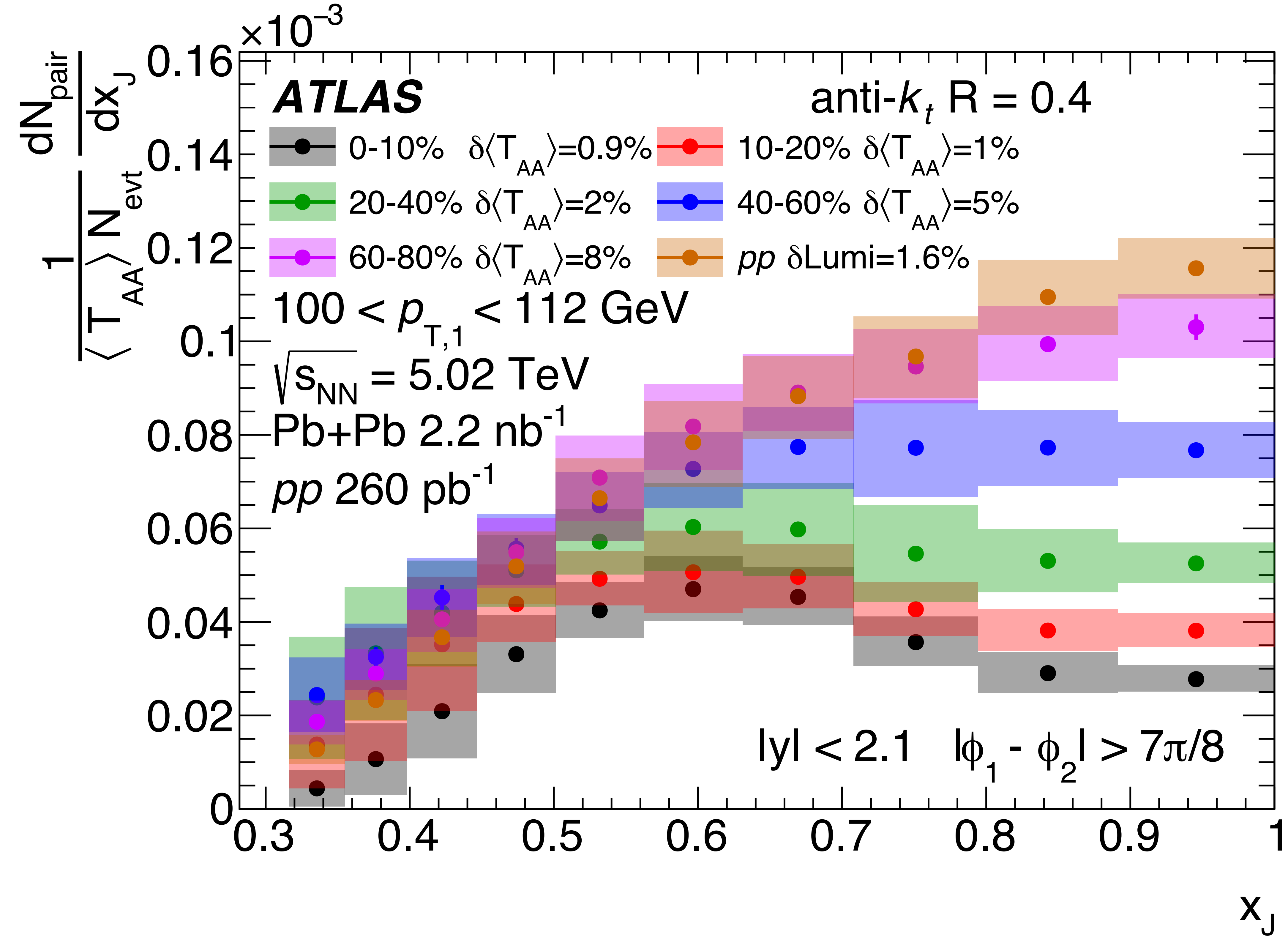
$$\frac{1}{N_{\mathrm{pair}}}\frac{dN_{\mathrm{pair}}}{dx_{\mathrm{J}}}$$

area normalization

$$\frac{1}{\langle T_{\mathrm{AA}}\rangle N_{\mathrm{evt}}^{\mathrm{AA}}}\frac{dN_{\mathrm{pair}}^{\mathrm{AA}}}{dx_{\mathrm{J}}}$$

absolute normalization





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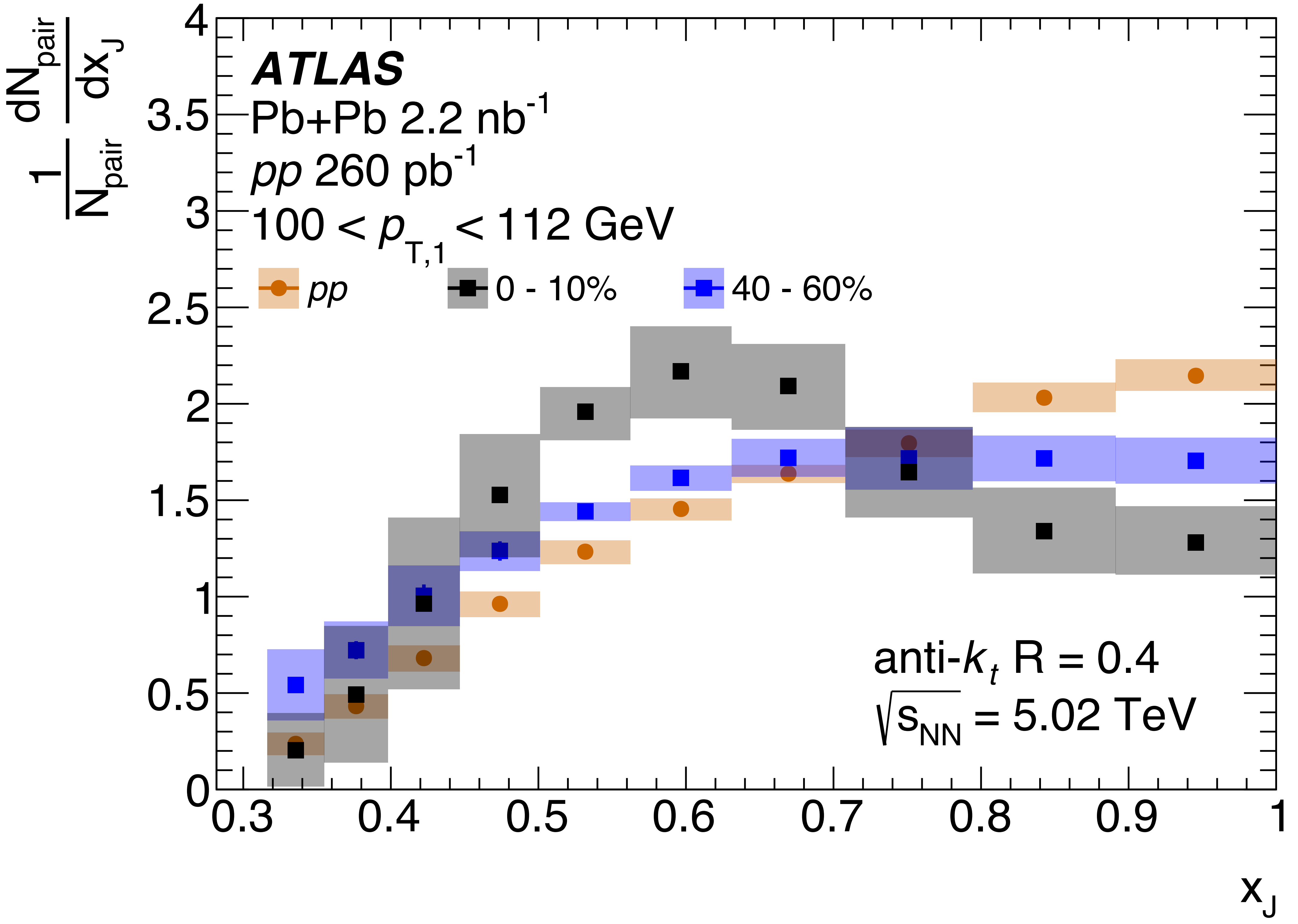

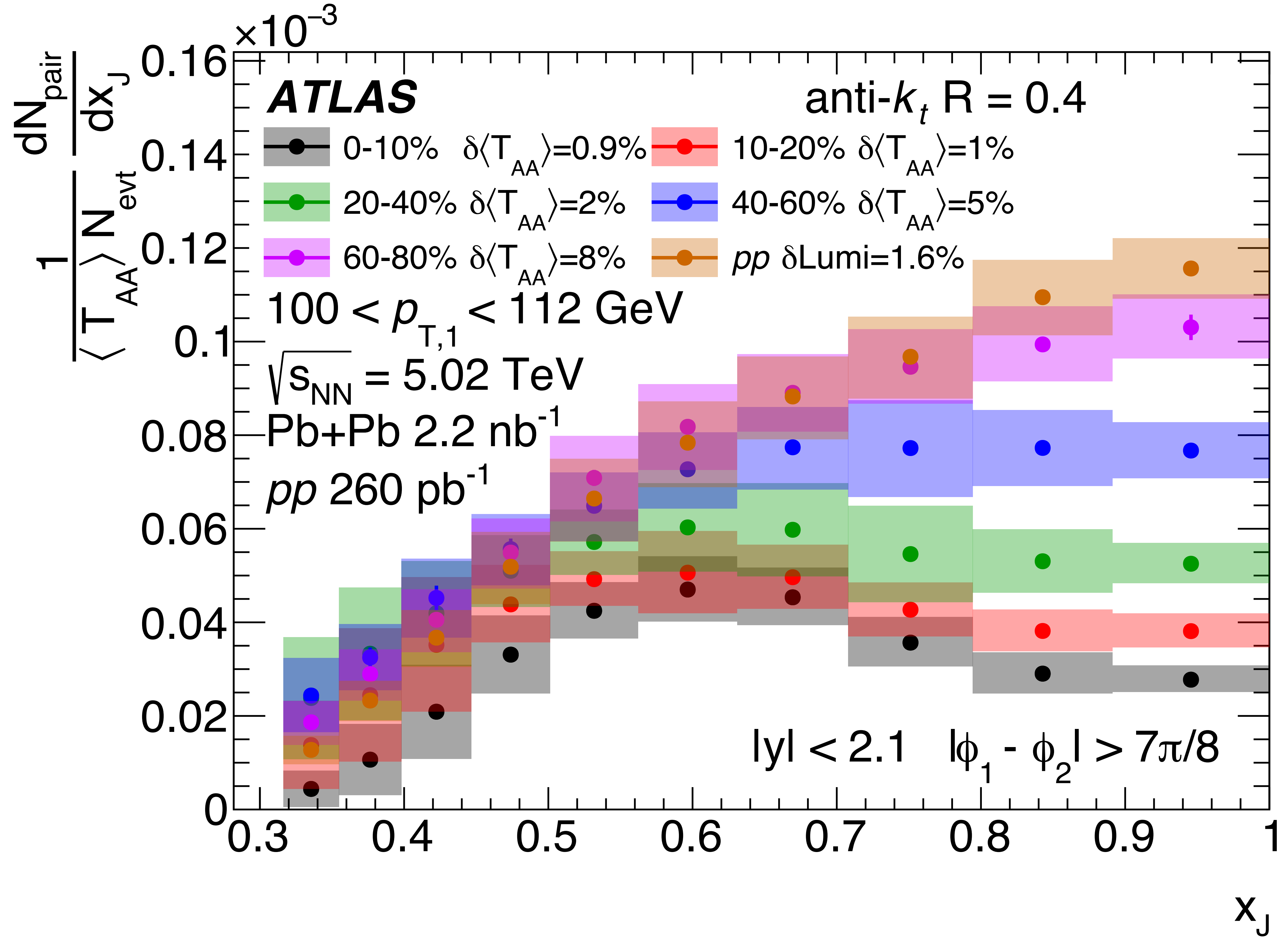

absolutely normalized distributions show that *balanced* jets are preferentially suppressed

suppression of balanced dijets

viewed in this way the "peak" is an artifact of the suppression of balanced jets which persists over all leading jet p_T

suppression of both jets important!

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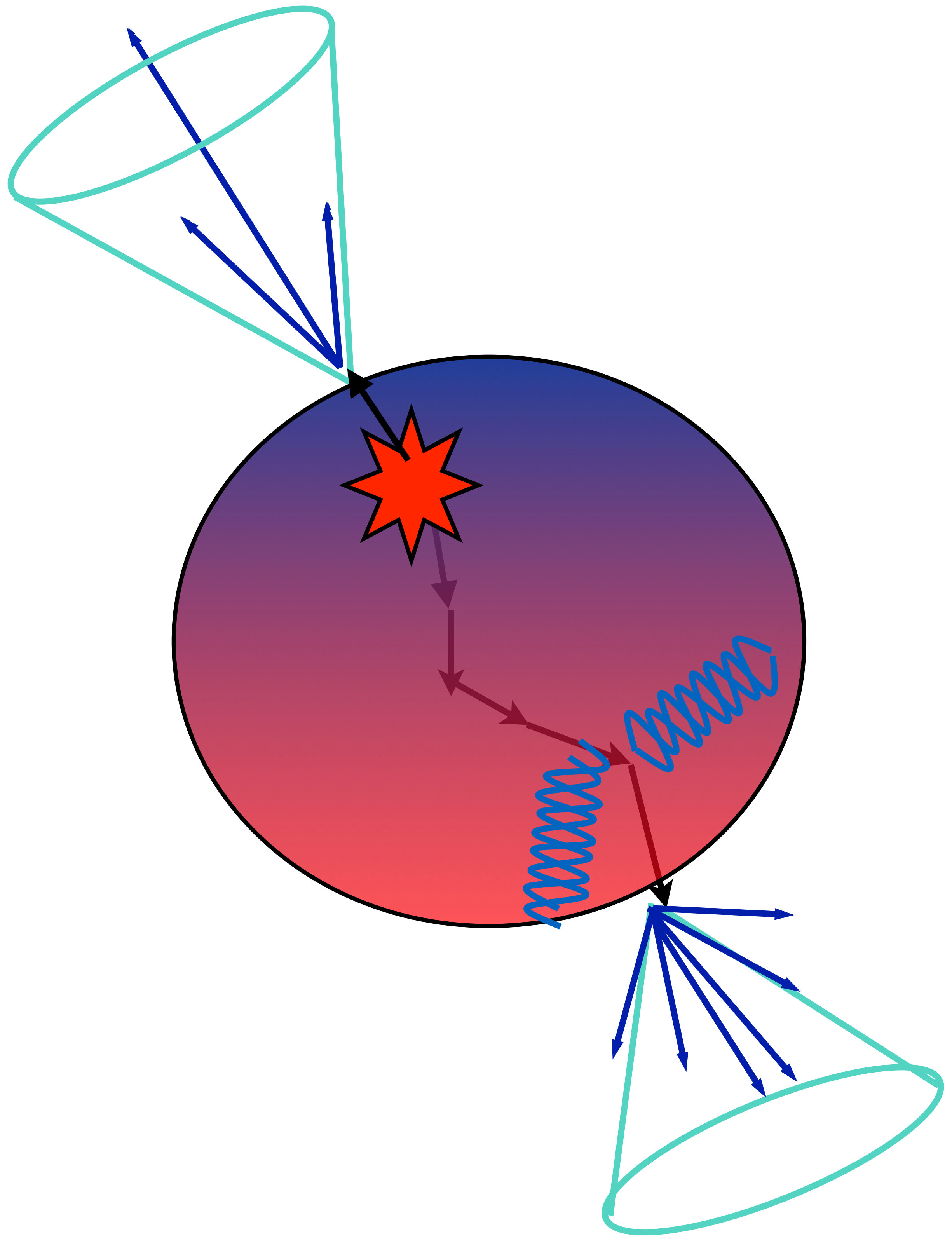
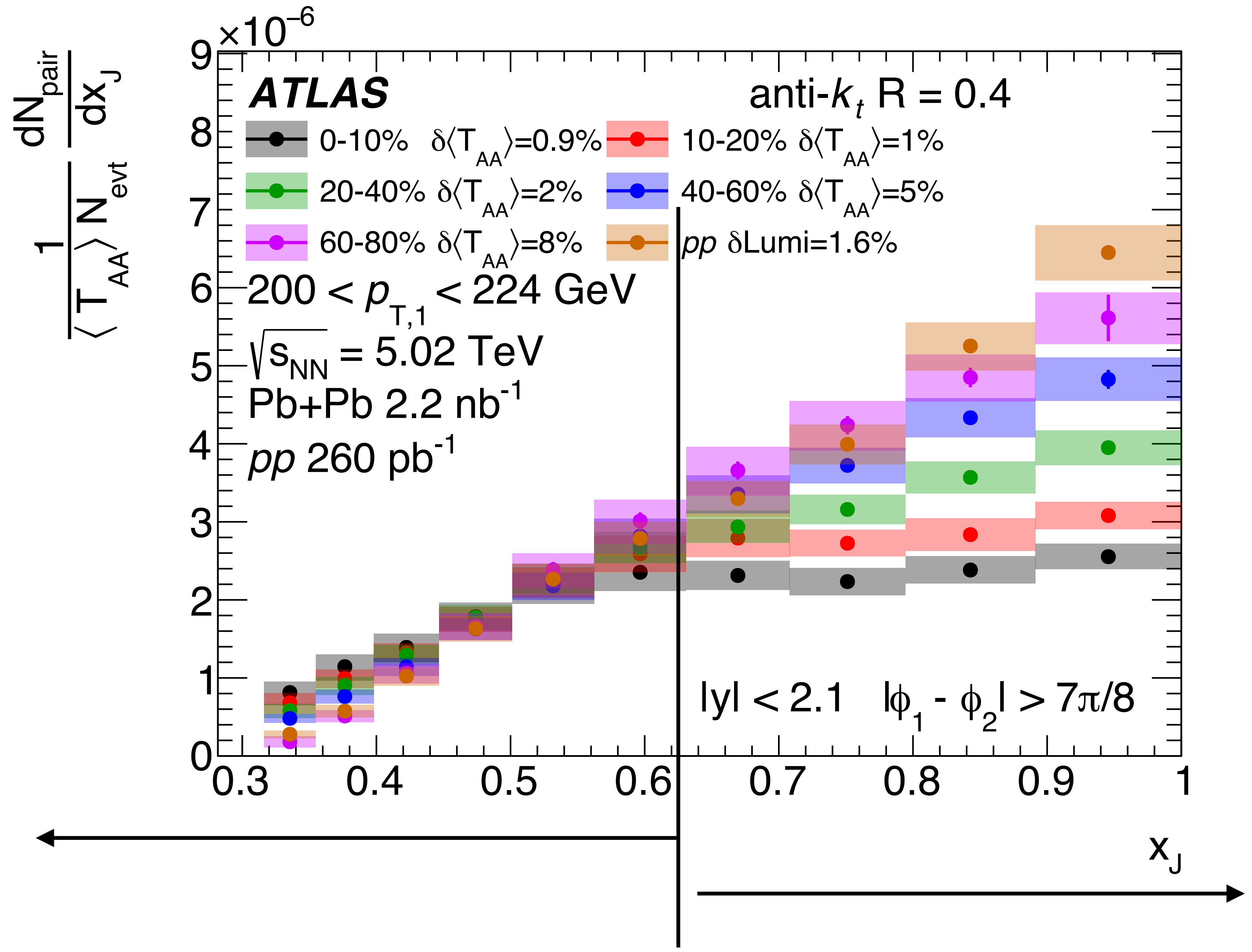
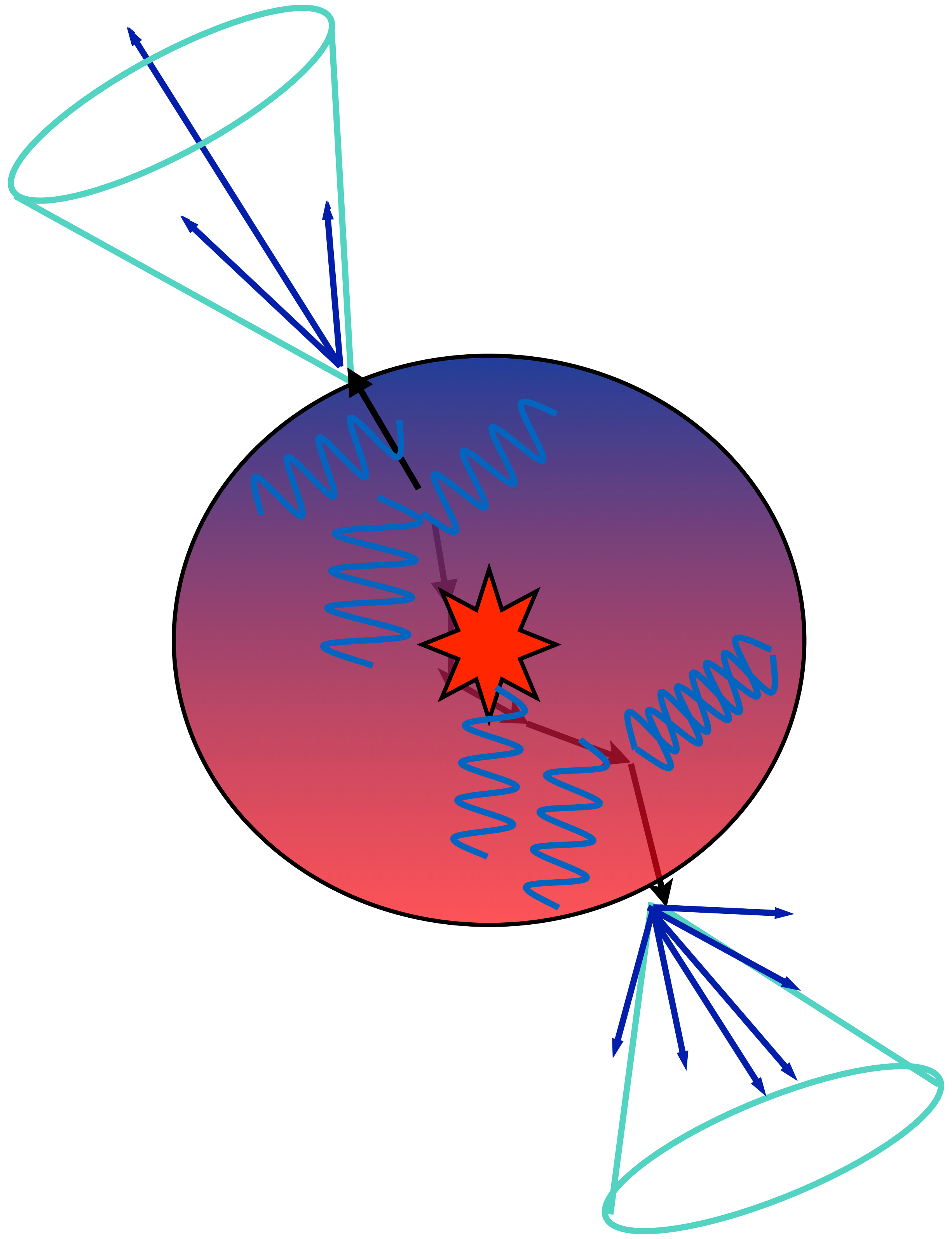
different geometry probed as a function of x_J?

200 < p_{T1} < 224 GeV







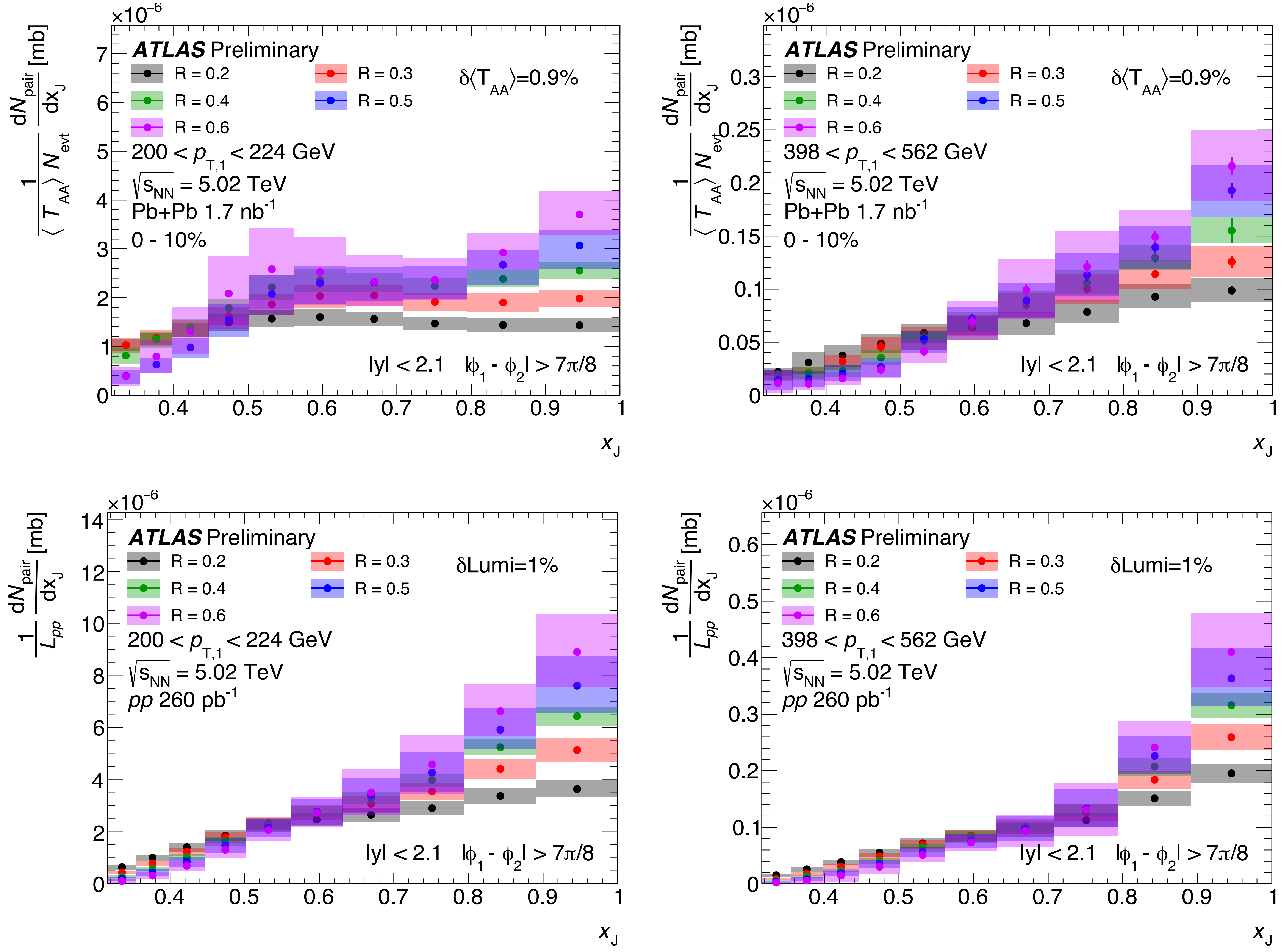
surface biased jets
leading jet loses little energy

more balanced dijets
both jets have lost significant energy

jet R dep. to dijet suppression

p_{T1}: 200-224 GeV

p_{T1}: 398-562 GeV



Pb+Pb, 0-10%

p+p

- **R = 0.6** jets are more balanced than **R = 0.2** jets in both pp & PbPb collisions

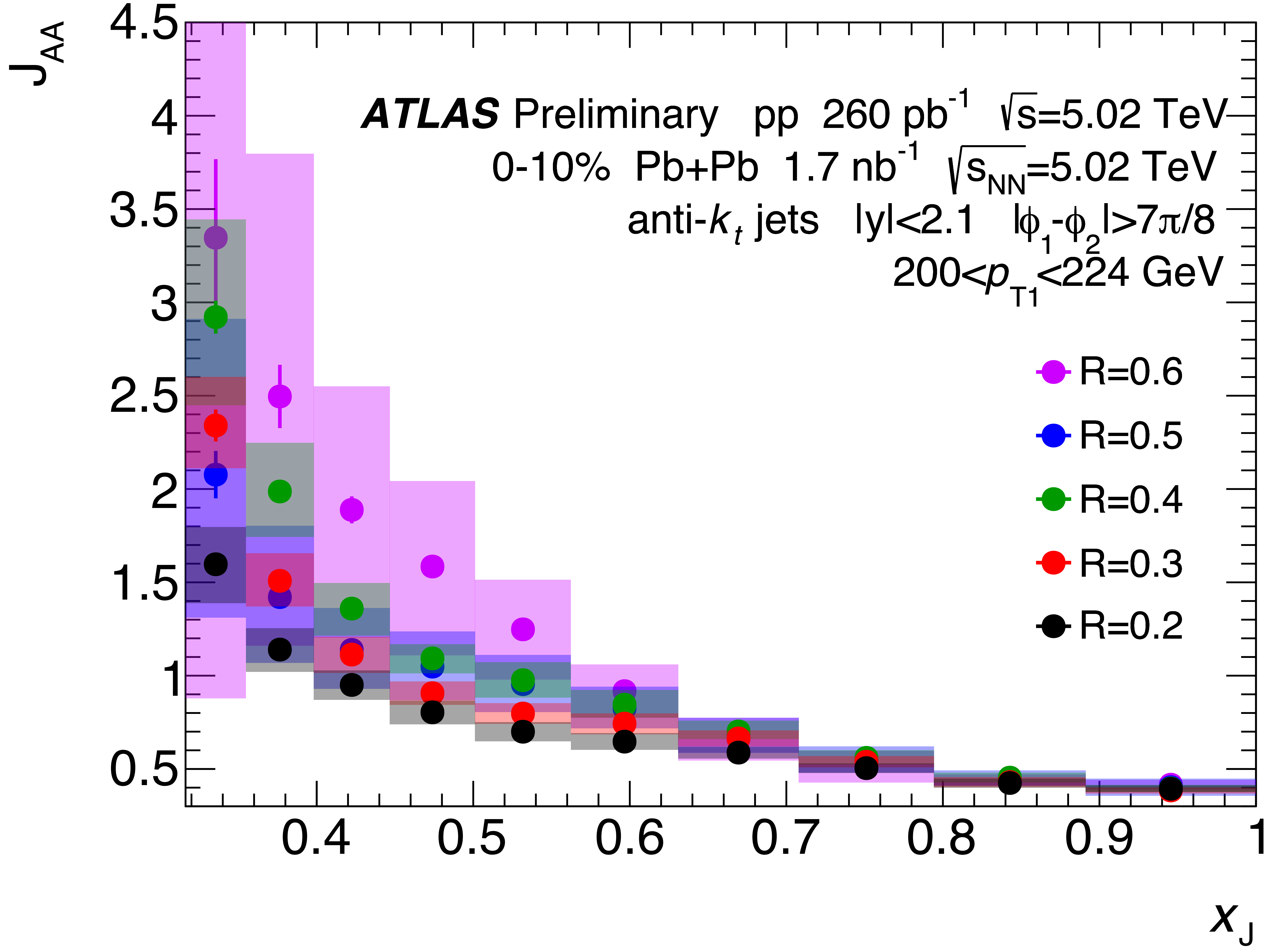
ATLAS-CONF-2023-060

J_{AA}

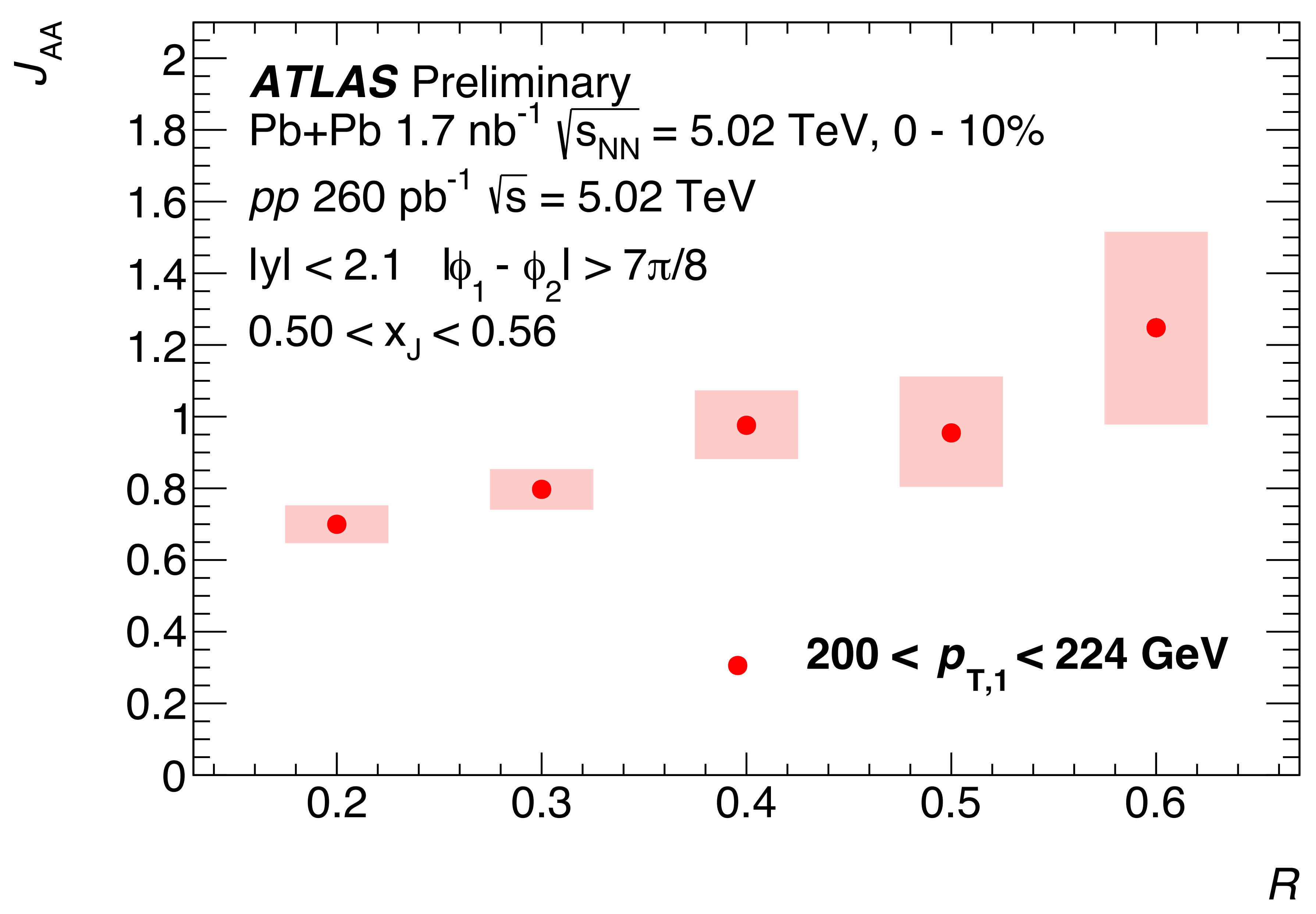
$$J_{AA} \equiv \frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \frac{dN_{pair}^{AA}}{dx_J} \Bigg/ \left(\frac{1}{L_{pp}} \frac{dN_{pair}^{pp}}{dx_J}\right)$$

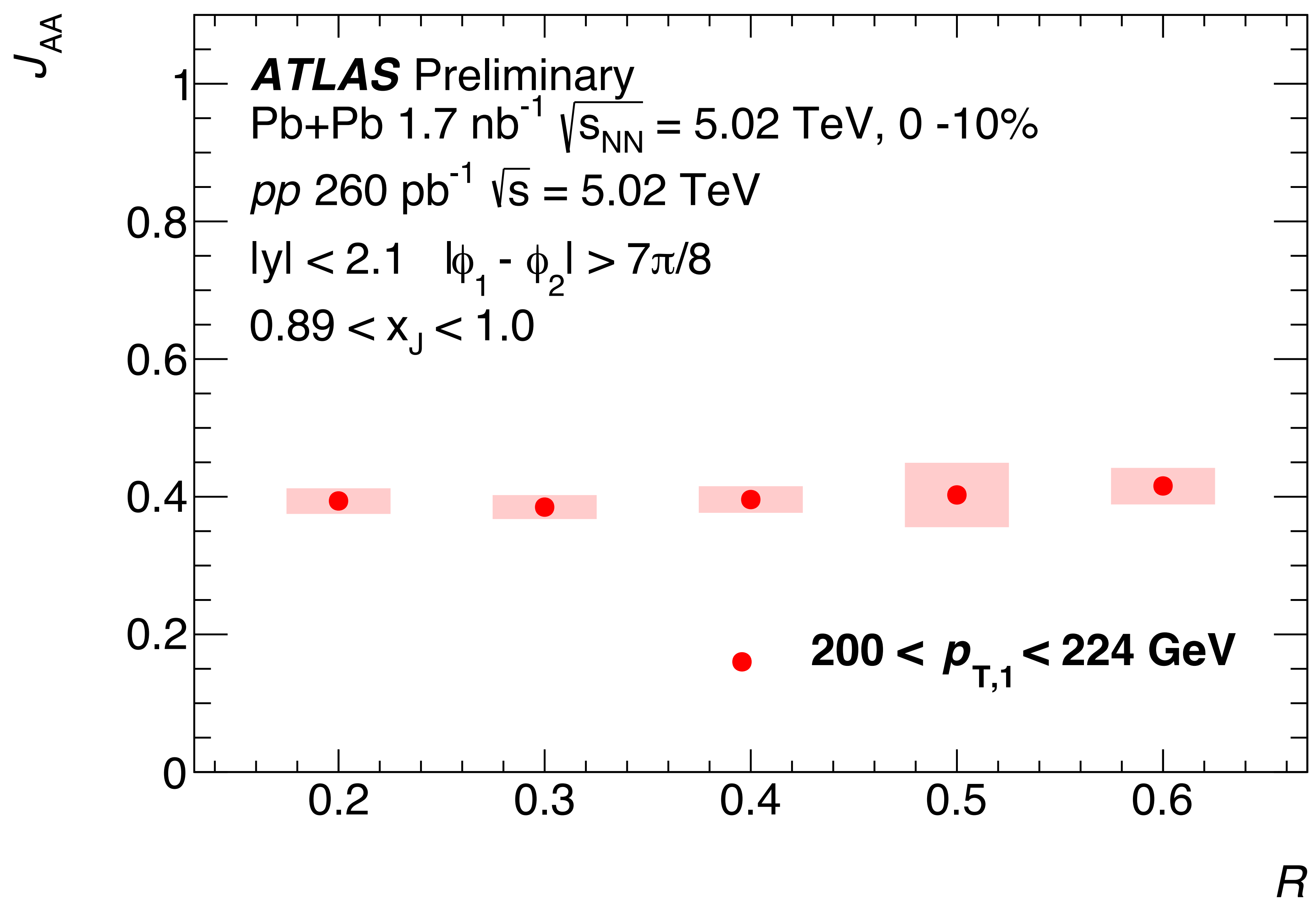
- J_{AA} provides a way to compare the modification of the absolutely normalized xJ distributions in PbPb collisions
- think of it like an R_{AA} for dijets

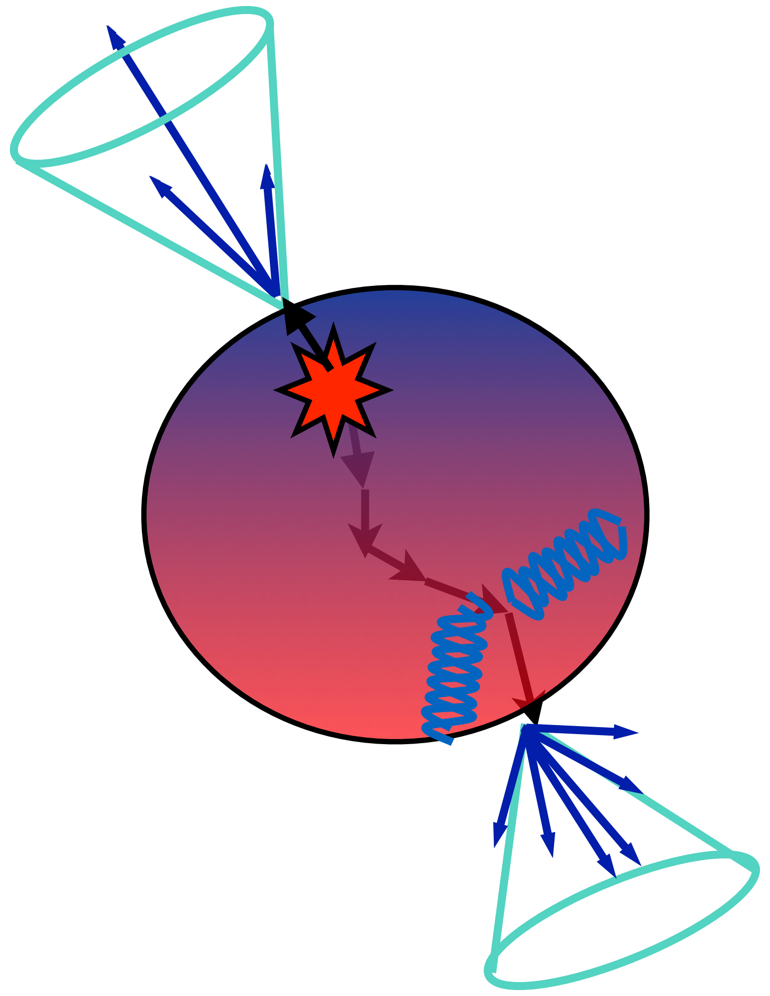
ATLAS-CONF-2023-060



different geometry probed as a function of x_J?

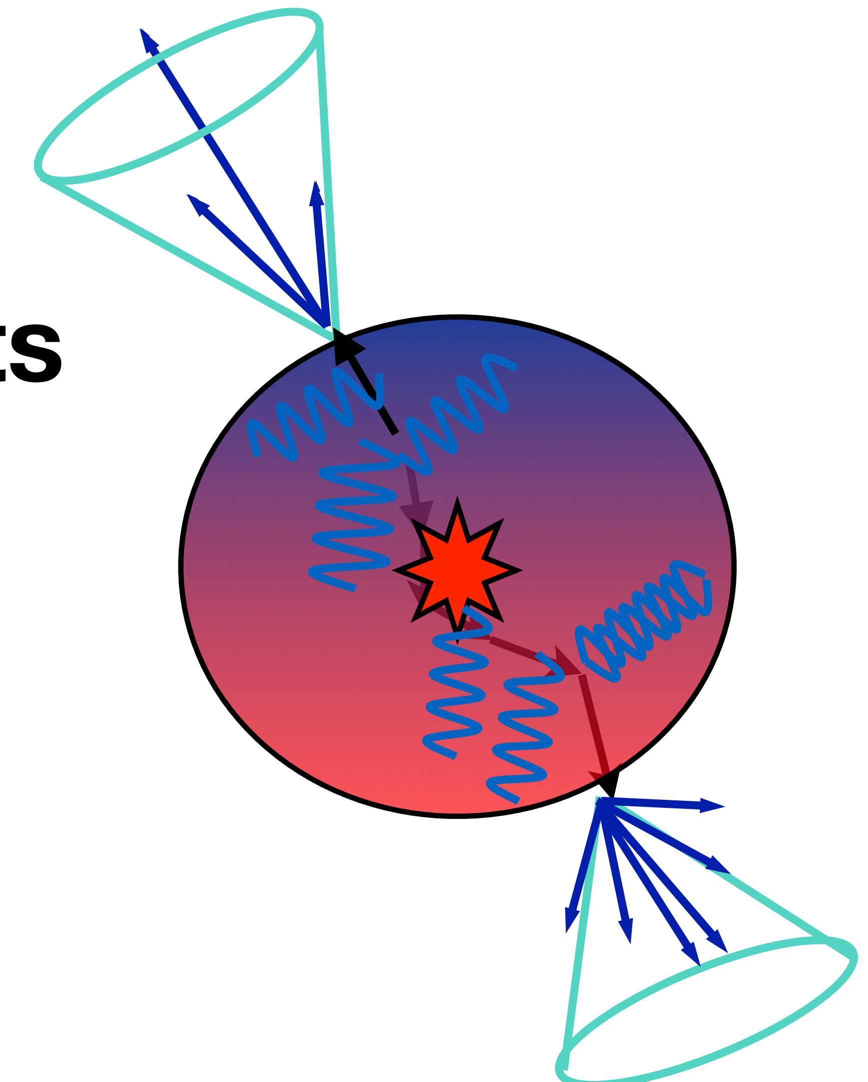






surface biased jets leading jet loses little energy; increase in J_{AA} with R as energy is recovered in the cone

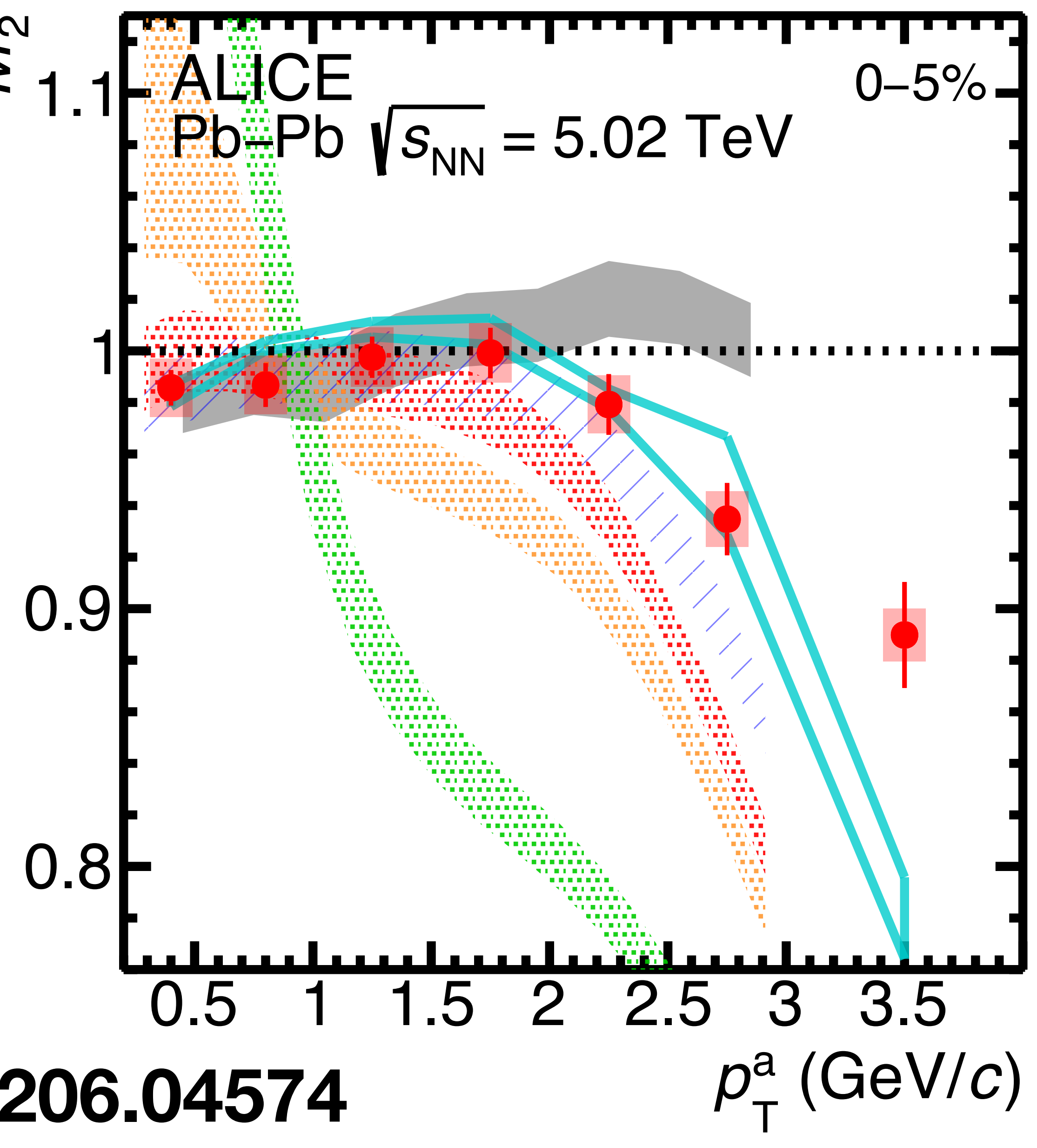
more balanced dijets *both* jets have lost significant energy



fluctuations in energy loss

- given the importance of fluctuations in soft physics, what role do they play in hard physics?

M^f_2 is a 2-hard/2-soft 4 part. correlator where a deviation from unity means a p_T-dep v_2 fluctuation



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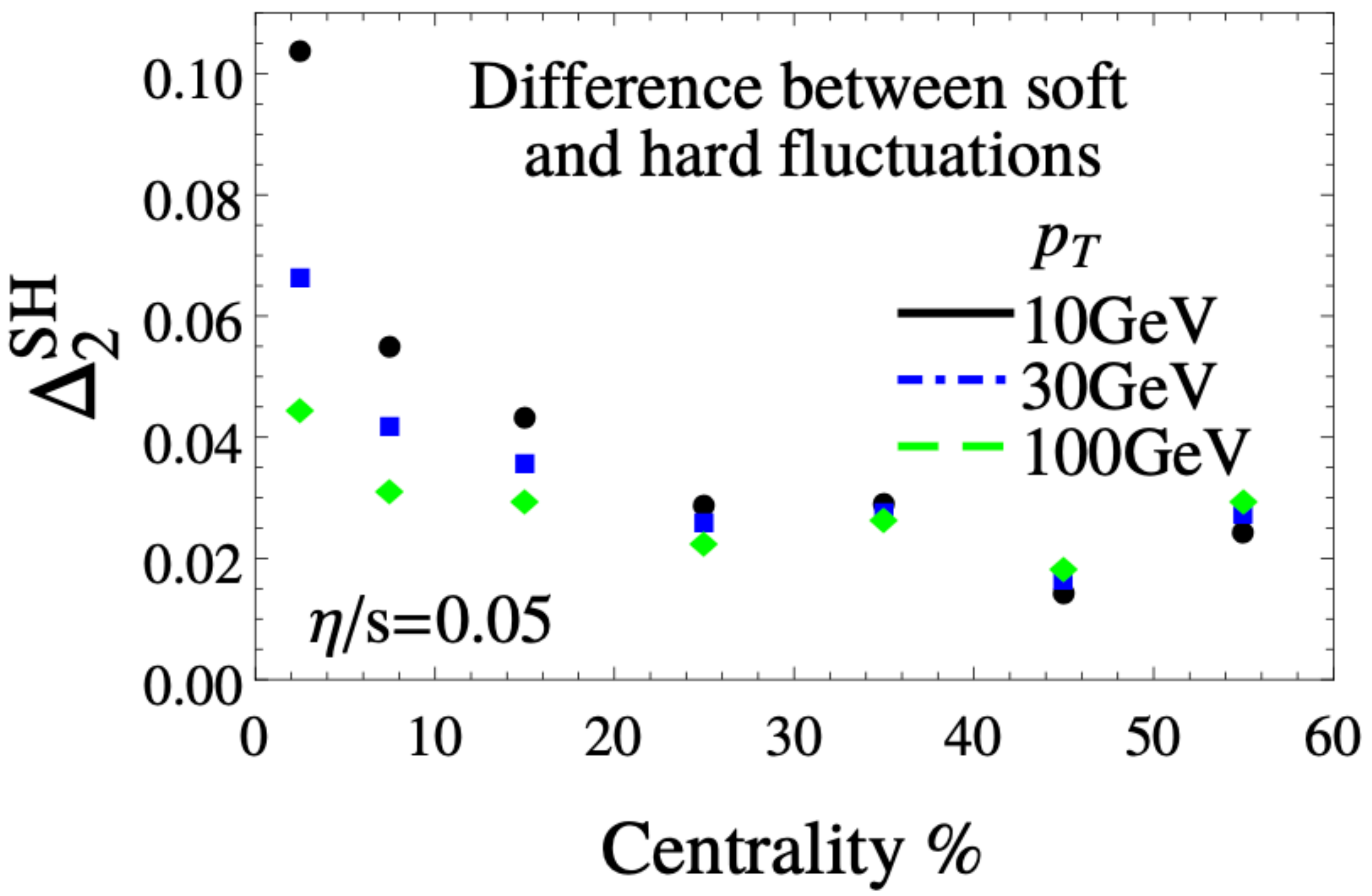
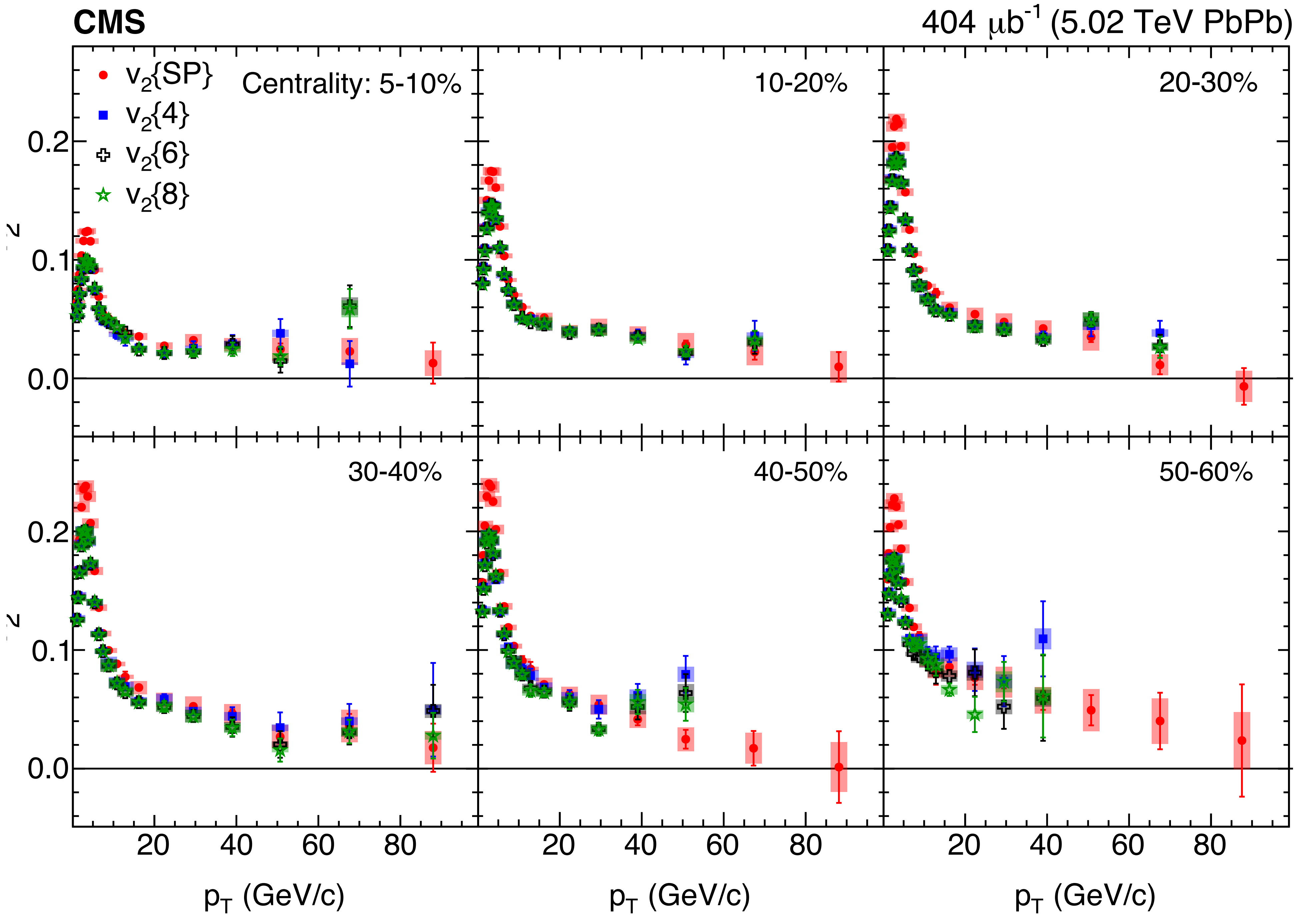
Noronha-Hostler et al: 1609.05171





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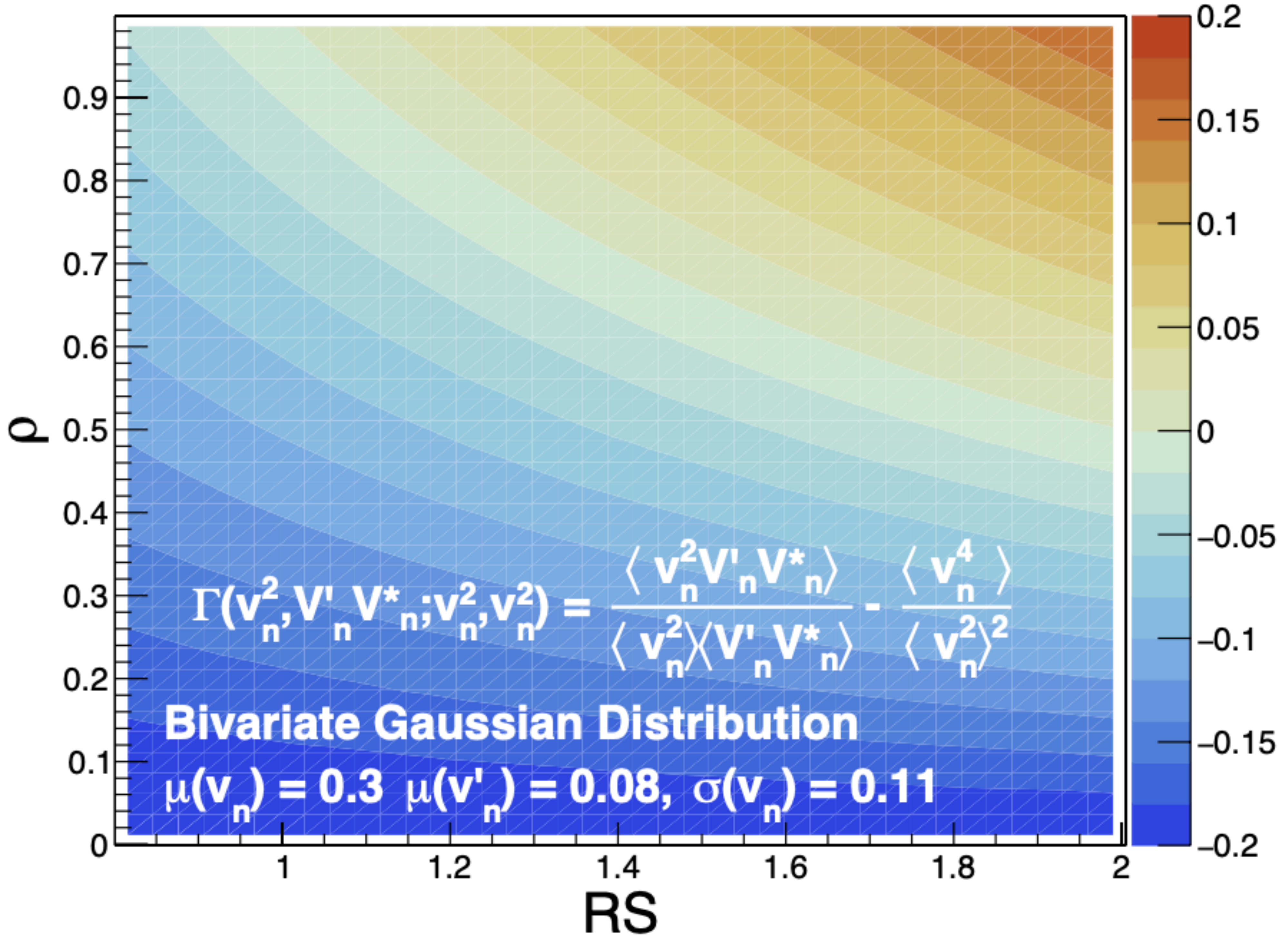
fluctuations in energy loss

- a systematic look can come from new observables which compare the fluctuations in hard v_n to those at low p_T: Holtermann, Noronha-Hostler, AS & Wang: 2307.16796 & 2402.03512

	Reference Flow Analysis	Differential (v'_n) Flow Analysis
Expected value of v_n	$v_n\{SP\}, v_n\{2k\}$	$v'_n\{SP\}, v'_n\{2k\}$
Fluctuations and Correlations in v_n	$v_n\{2k\}, SC(v_n^2, v_m^2)$, $ASC(v_n^2, v_m^2)$	$ASC(v_n^2, v'^2_n), CM(v_n^2, v'^2_n)$ $\Gamma, \zeta, h_n\{2k\}$

correlation in hard v_n wrt soft v_n

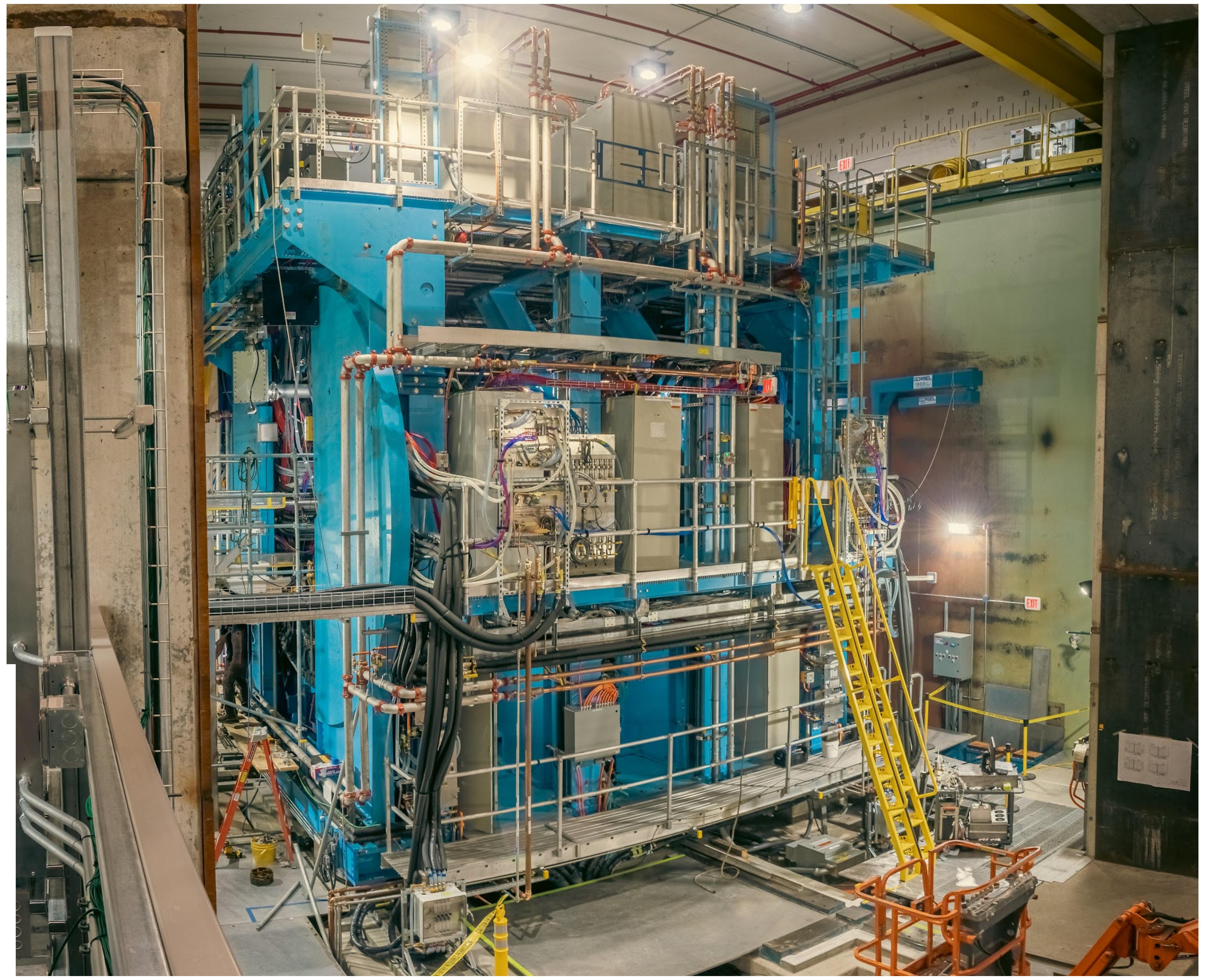


fluctuations in hard v_n / soft v_n

these measurements are possible at the LHC & RHIC with the huge data samples we have

sPHENIX

- completion of full planned sPHENIX program in both pp & AuAu collisions is key to understanding this physics



2023 LRP

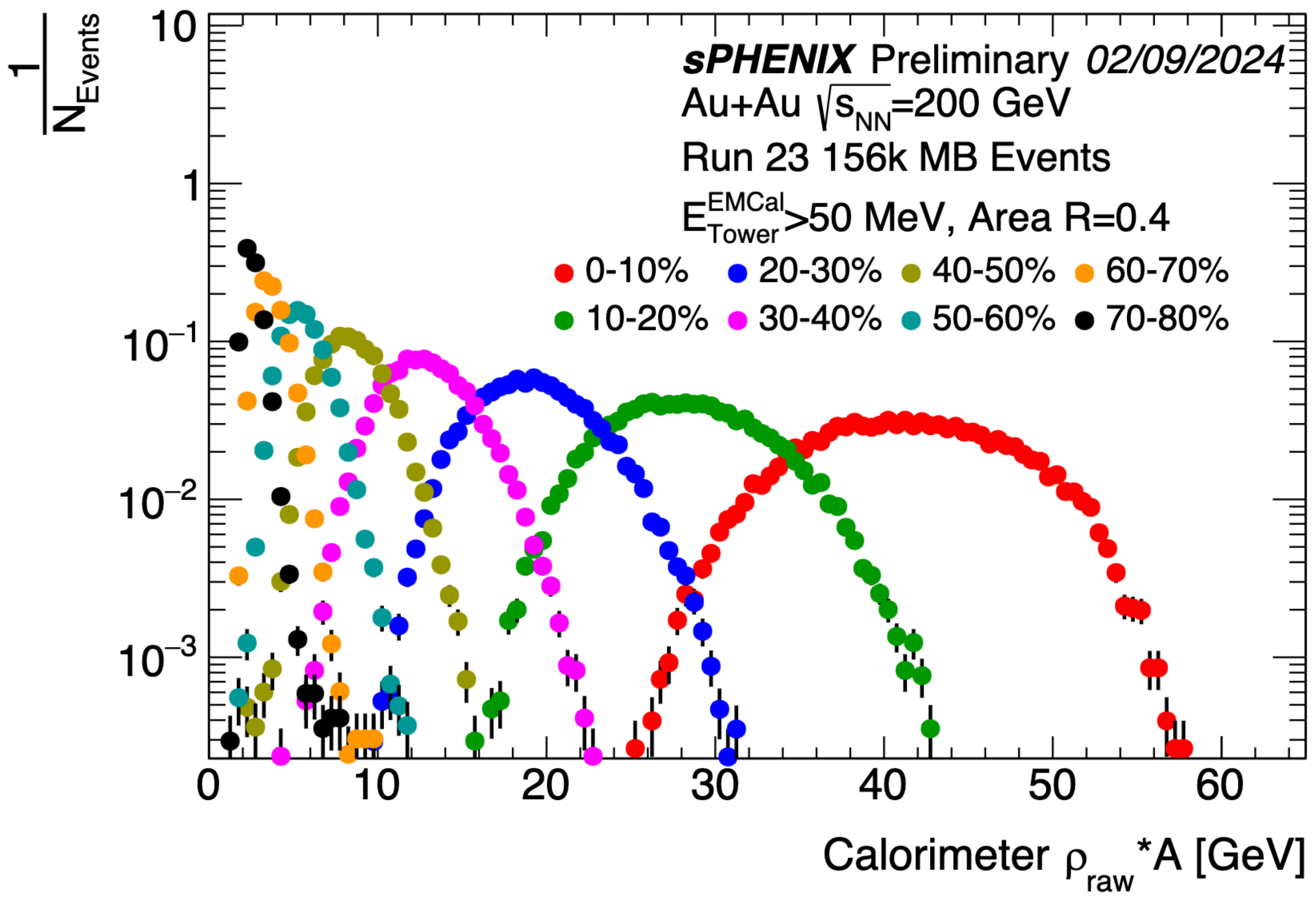
To successfully conclude the RHIC science mission, it is essential to (1) complete the sPHENIX science program as highlighted in the 2015 Long Range Plan, (2) complete the concurrent STAR data collection with the forward upgrade, and (3) analyze the data from all RHIC experiments. Crucially, sPHENIX, with its large acceptance, is beginning its physics program. The sPHENIX detector combination of electromagnetic calorimetry, hadronic calorimetry, precision tracking, and very high data rate will enable measurements of jets, jet substructure, and jet correlations at RHIC with a kinematic reach that is complementary to similar measurements at the LHC. The sPHENIX detector will have the first mid-rapidity hadronic calorimeter at RHIC, allowing both calorimetric and particle track-based measurements of jets and their structure.

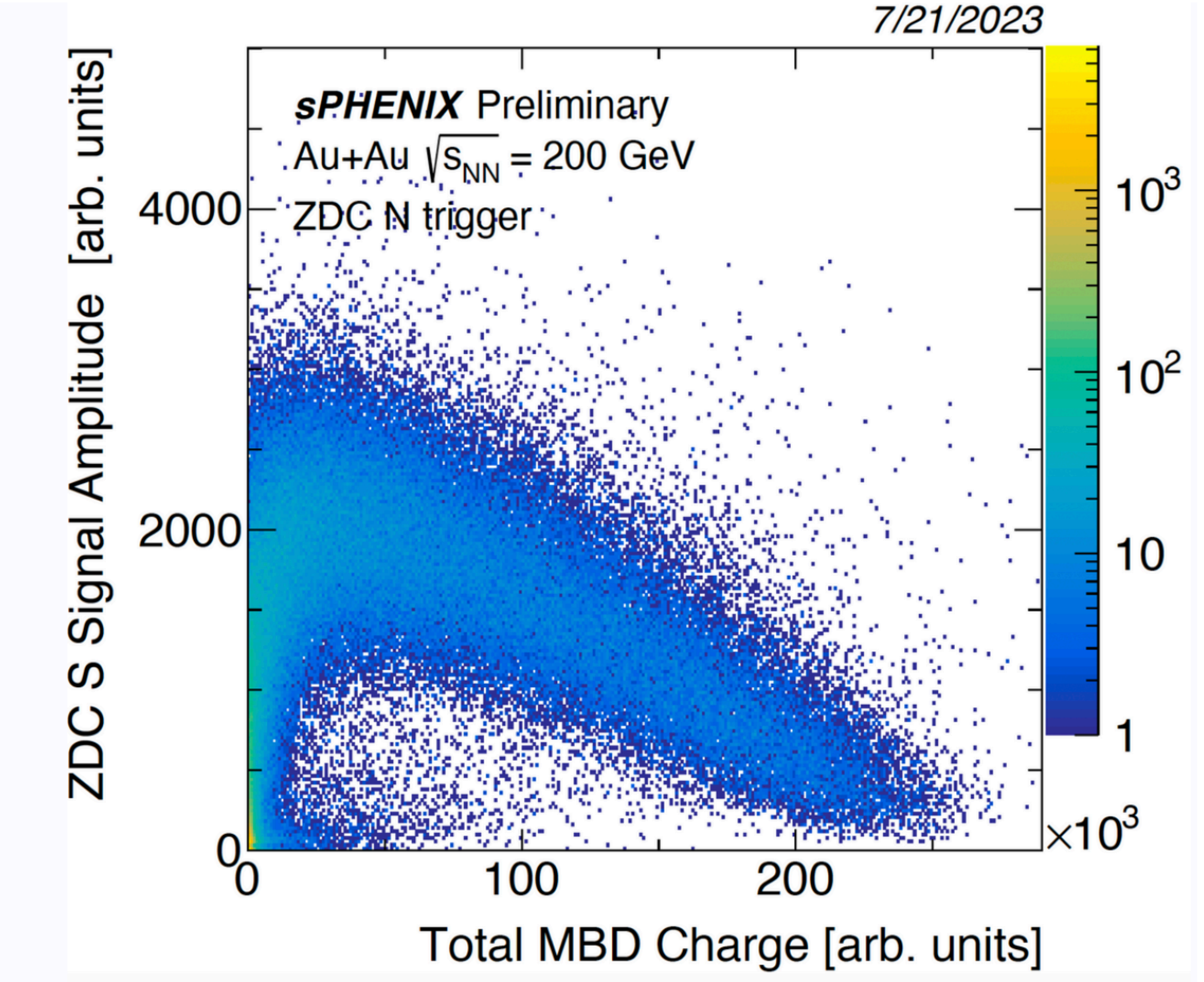
https://www.bnl.gov/sphenix2022/

both sPHENIX & the LHC jet measurements are necessary to constrain the physics of jet quenching

sPHENIX status

- **lots** of ongoing work analyzing the 2023 dataset & preparing for 2024 run
  - see some details in the talks from Ben, Ejiro & Tristan
- Run Plan
  - 2024: essential pp baseline measurements and some AuAu running
  - 2025: high luminosity AuAu running
  - for more details see BUP: https://indico.bnl.gov/event/20331/





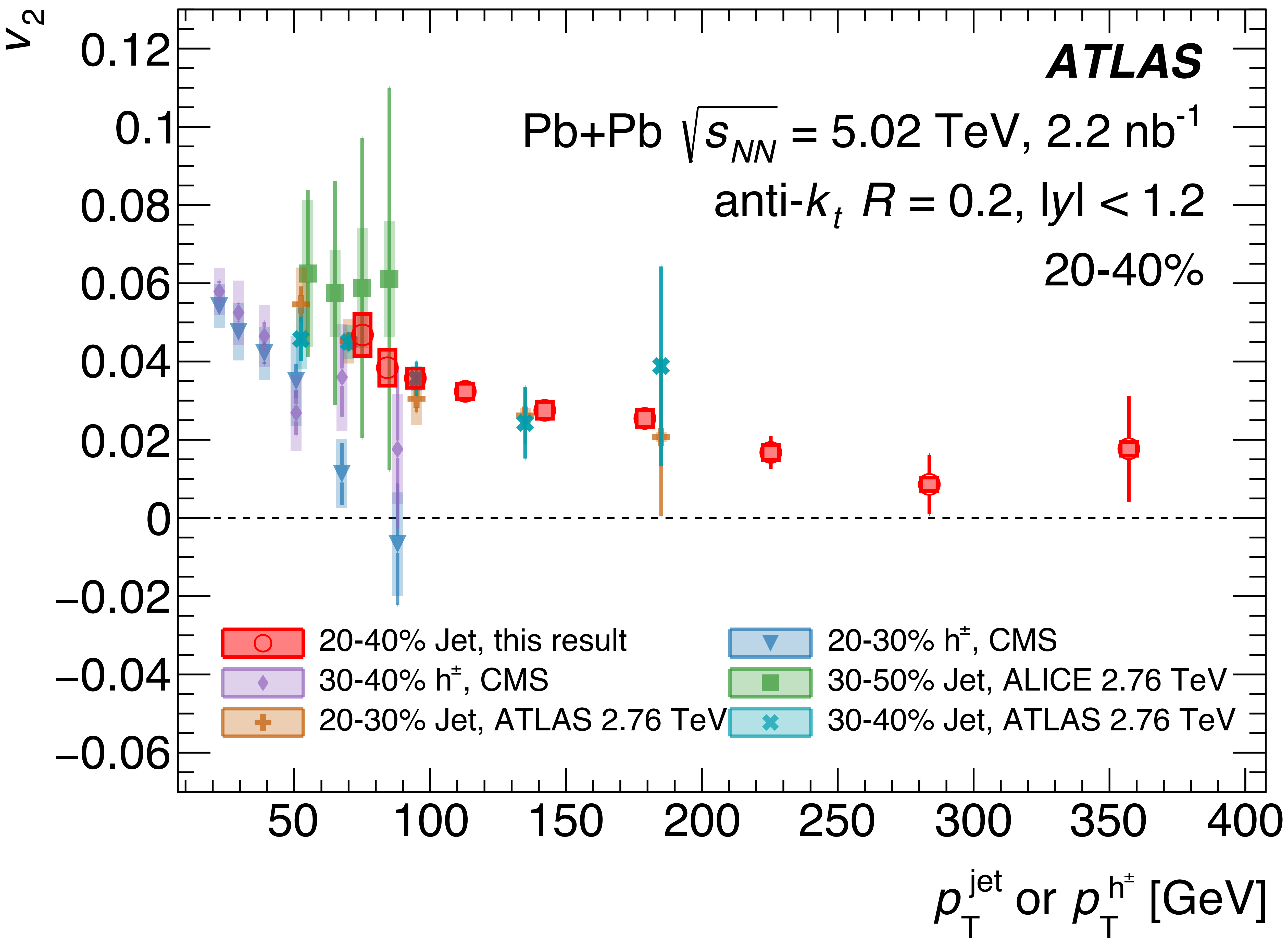
the path ahead

- **understanding how jet quenching depends on path length is key for understanding jet quenching**
- **new techniques will allow us to get more from the data we have**
- **the large data samples from sPHENIX & the LHC Run 3 allow us to do the differential measurements necessary to constrain this physics**
- **this talk was just a subset of the exciting results; great advancement from both experiment and theory**

backups

comparison to previous measurements

- full Run 2 data & jets provide large increase in precision and kinematic range over 2.76 TeV results & charged hadron measurements
- what causes the p_T dependence to v_n? related to quark/gluon mixture or jet structure?



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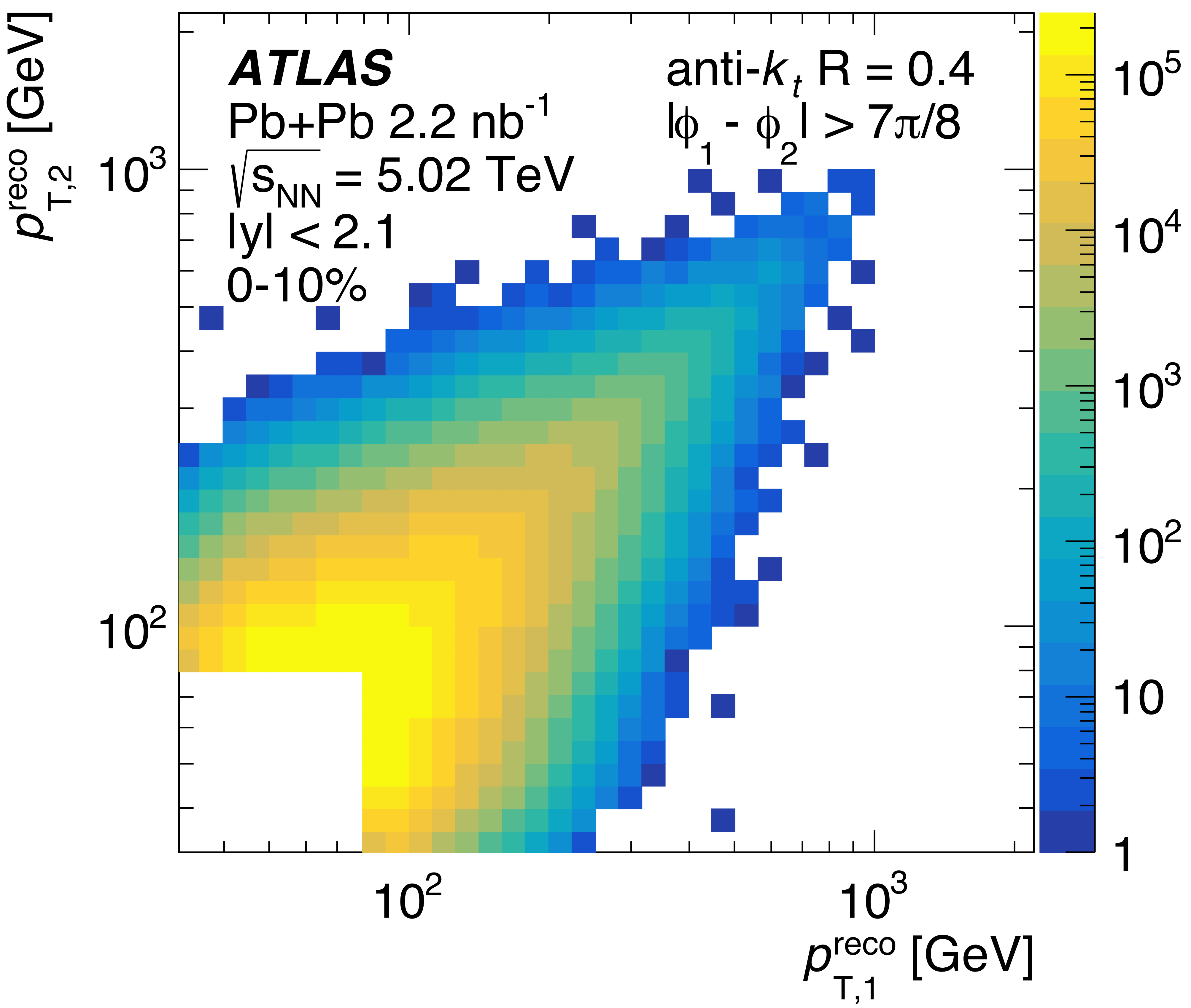
Run 2 dijet measurement

- use the same jet cuts as the 2.76 TeV measurement & compatible binning to facilitate direct comparisons
  - the leading p_T jets in the event have $|\Phi_1 - \Phi_2| > 7\pi/8$, $|y_{jet}| < 2.1$, other events are rejected from the measurement
- fully unfold in p_{T1} & p_{T2}, $x_J = p_{T2}/p_{T1}$ constructed from unfolded p_{T1} & p_{T2} distribution



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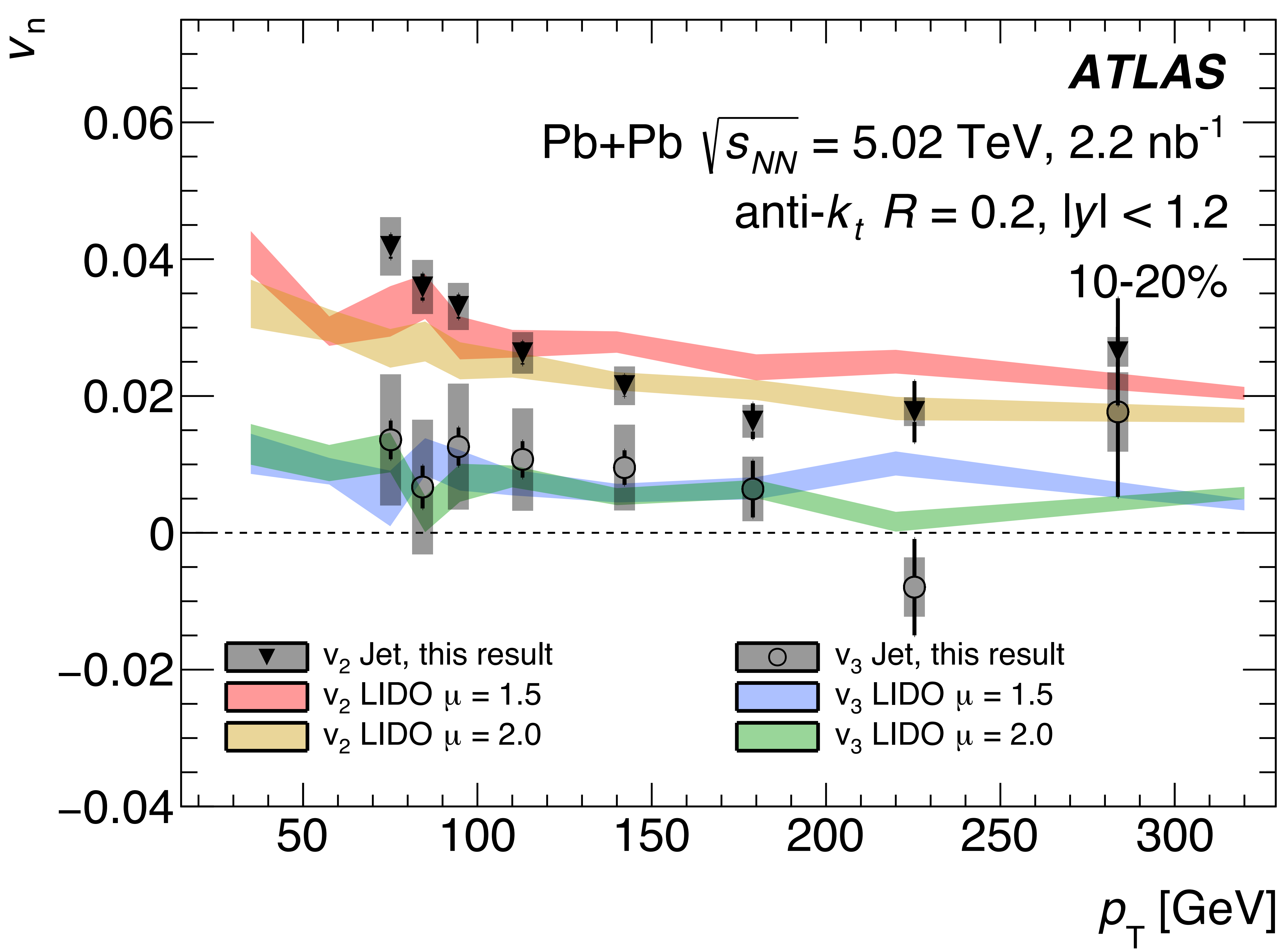
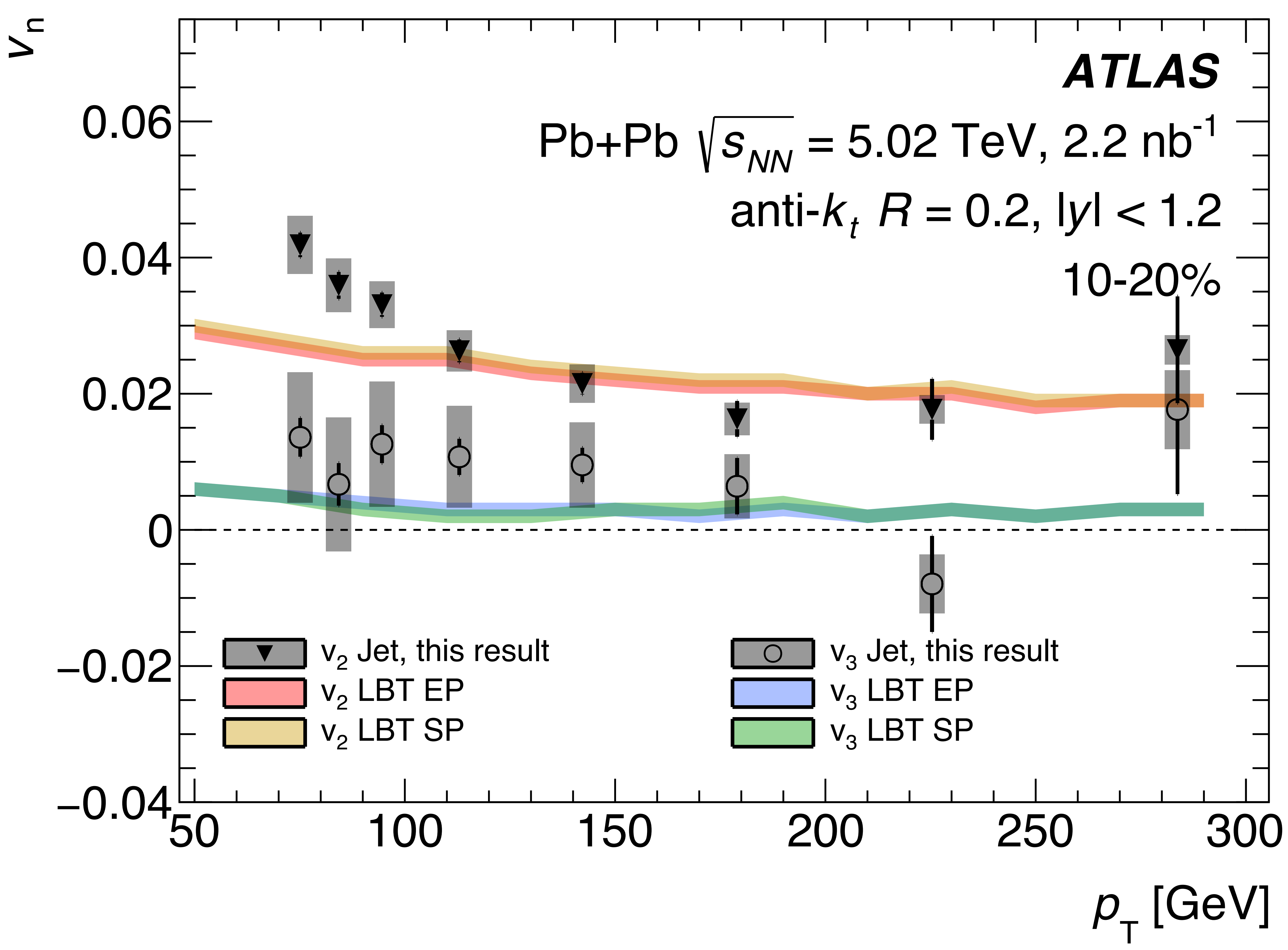
comparison to theory





p_T dependence of the v_2 stronger than expected in LBT & LIDO, LBT v_3 calculations on the low edge of the data

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overall suppression of leading/subleading jets

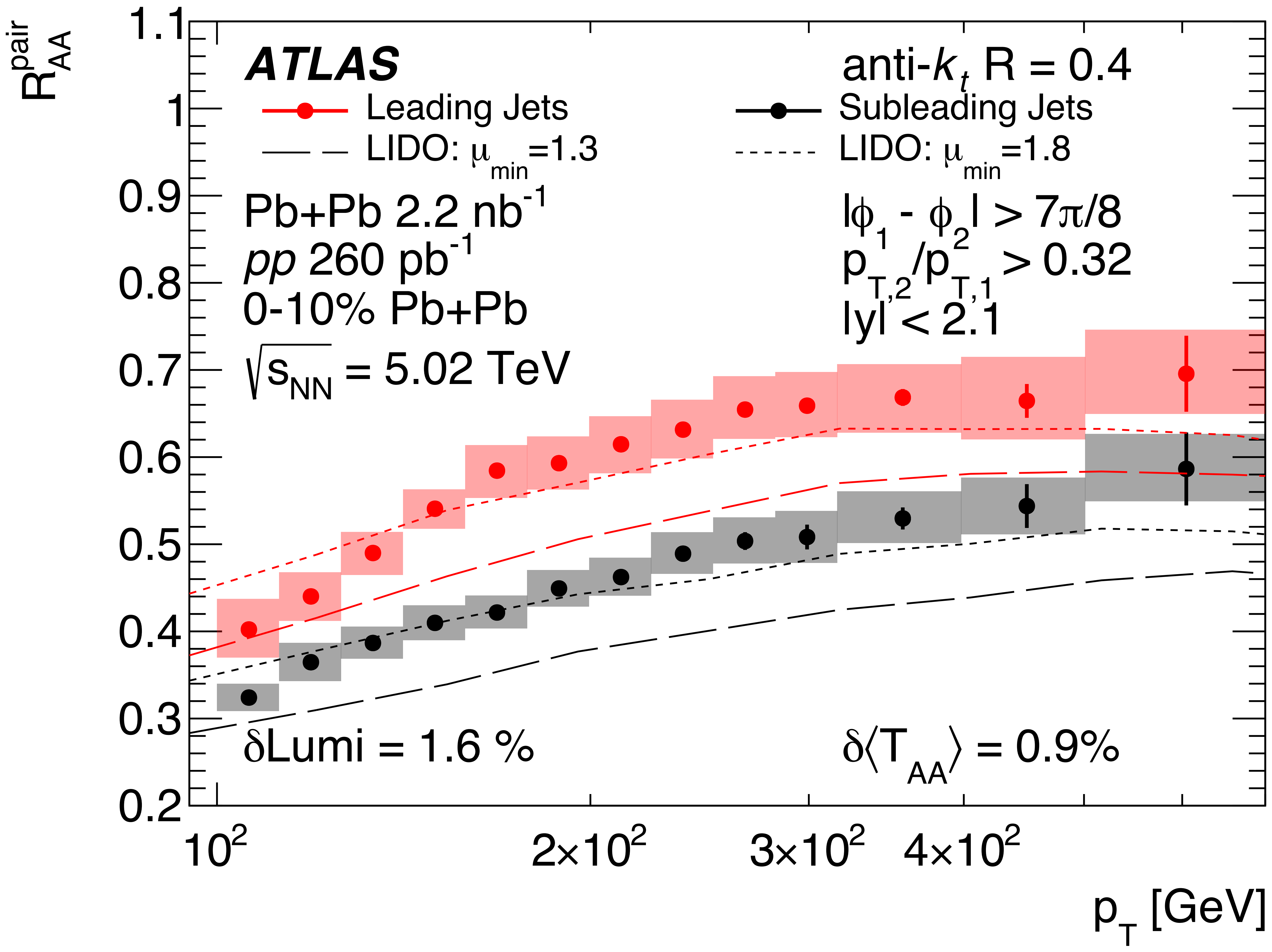
R_{AA} of leading jets after integrating over all subleading jet x_J

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

R_{AA} of subleading jets after integrating over all leading jet x_J

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

0-10% central events

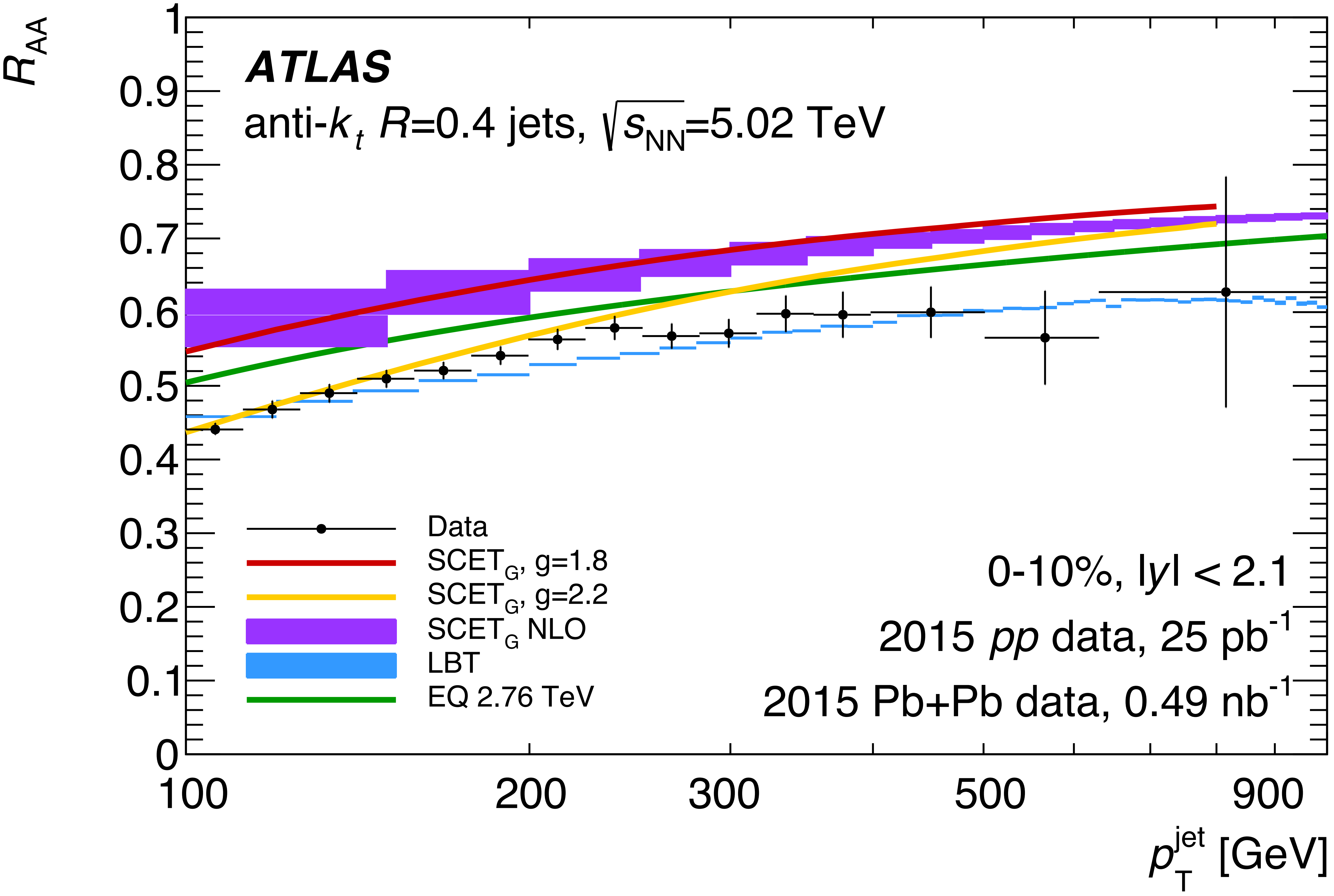


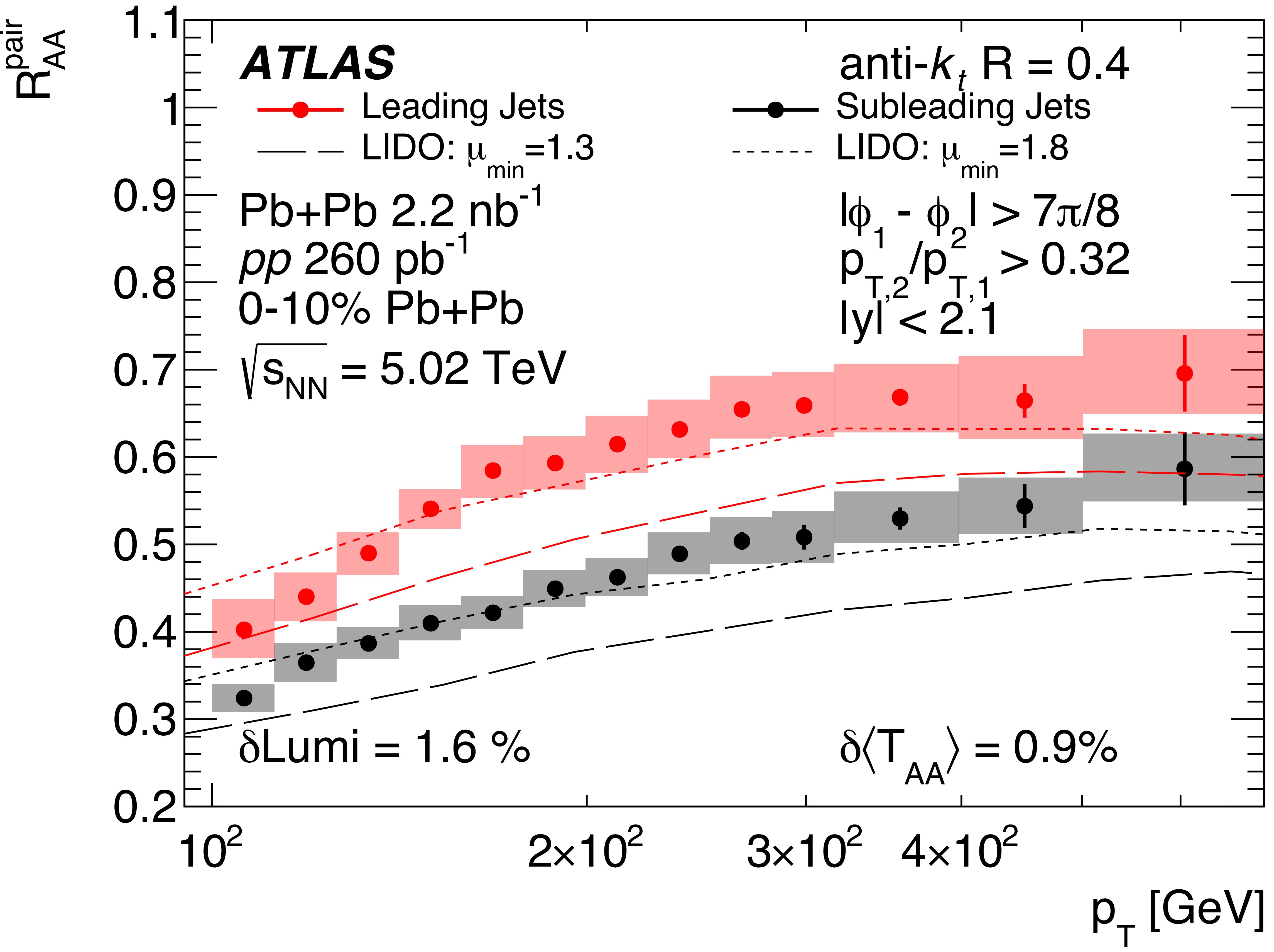
leading jets are significantly suppressed in central collisions

2205.00682

comparison of leading/subleading jets to inclusive jets

inclusive jets

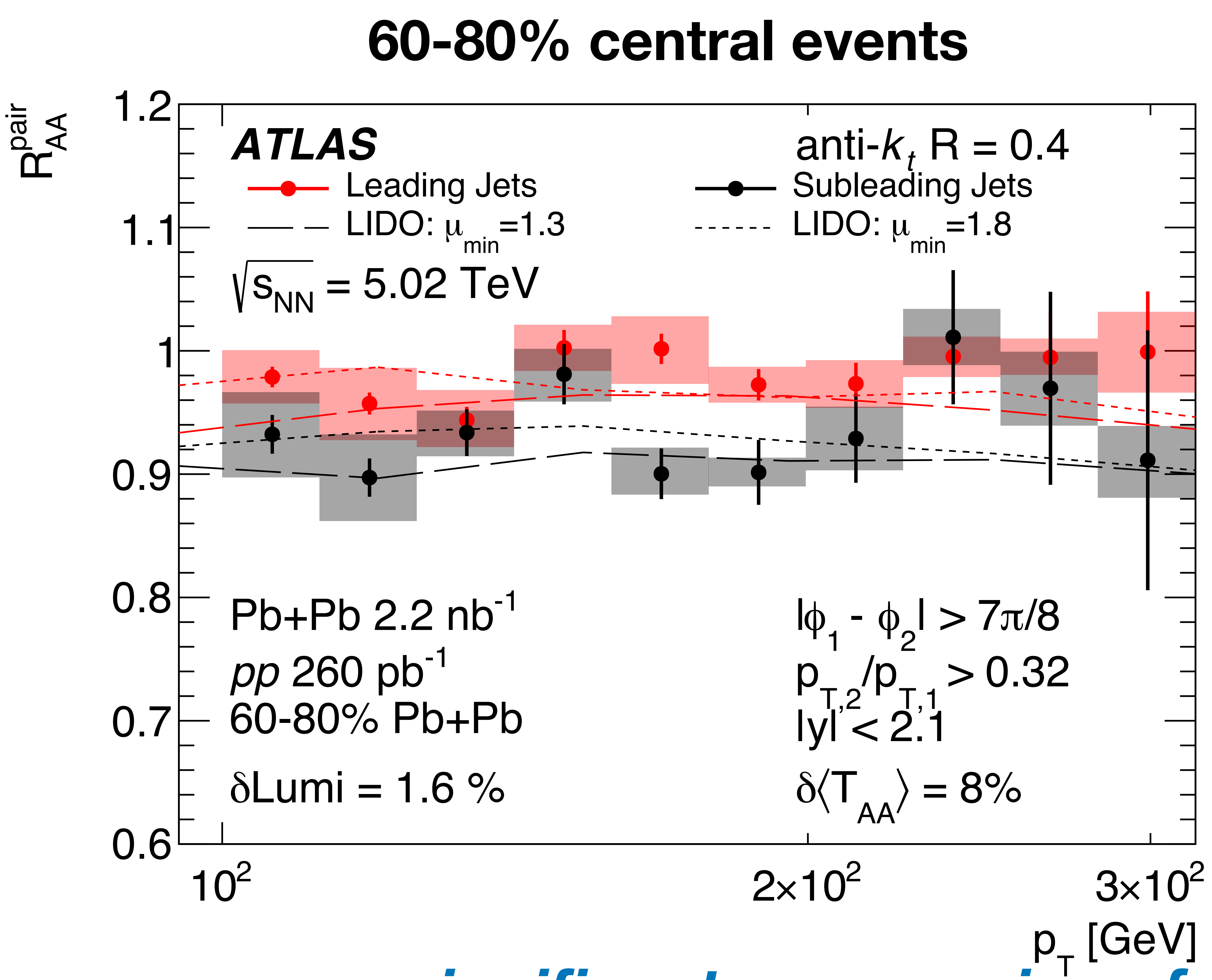


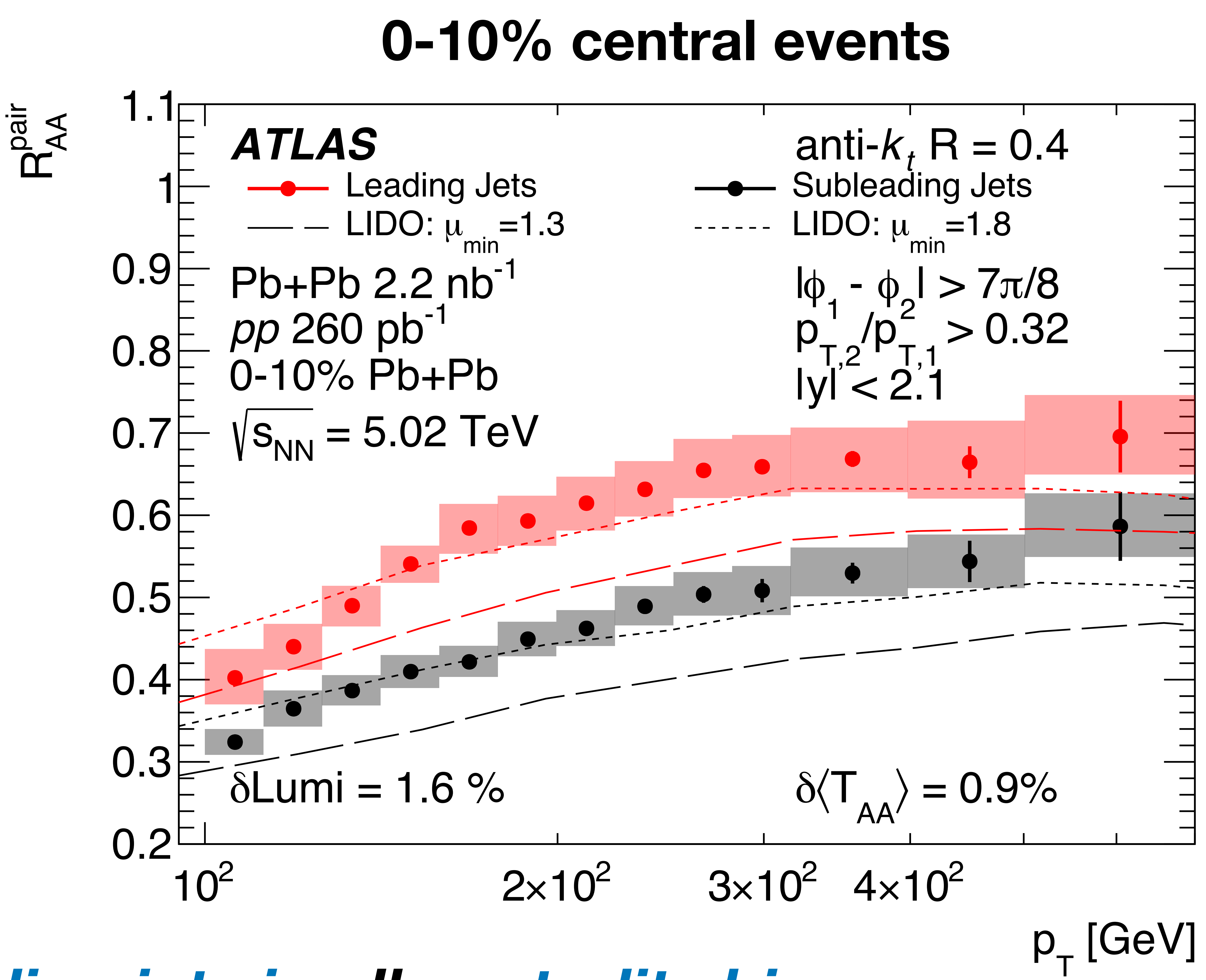


$$R_{AA}^{pair}{}_{subleading} < R_{AA,inc} < R_{AA}^{pair}{}_{leading}$$

2205.00682

overall suppression of leading/subleading jets



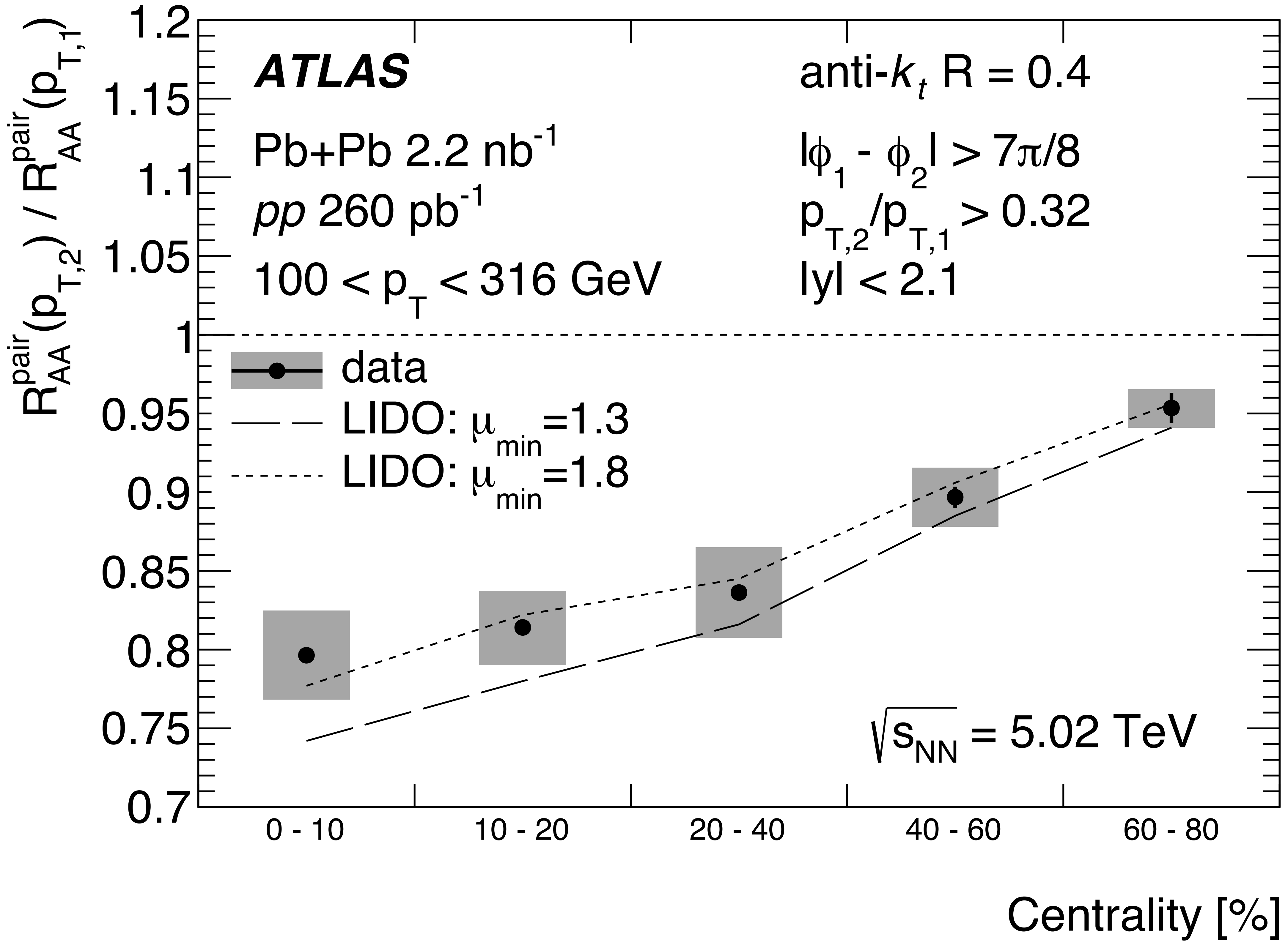


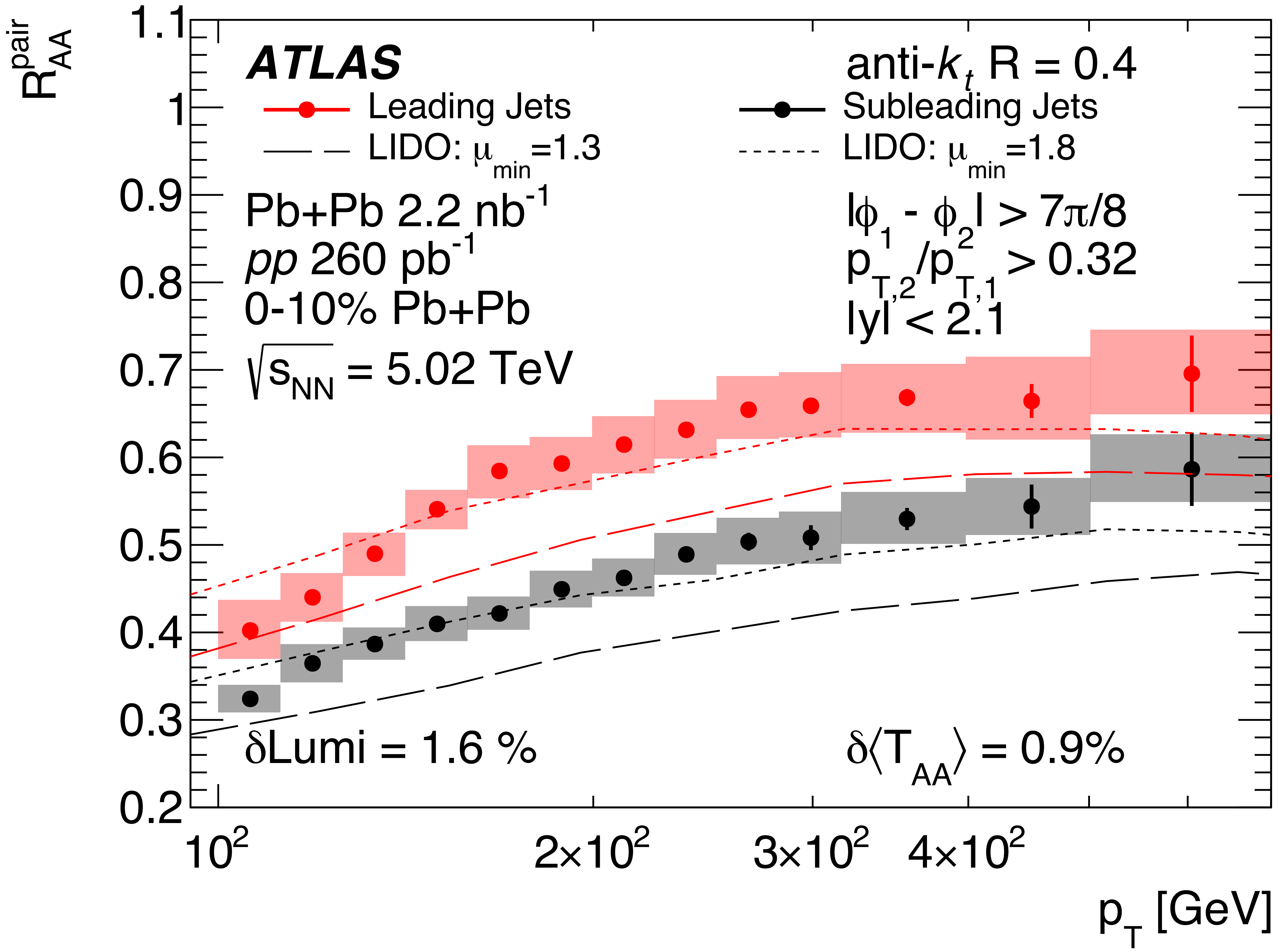
significant suppression of subleading jets in all centrality bins

2205.00682

overall suppression of leading/subleading jets

R_{AA}(subleading jet) / R_{AA}(leading jet)





subleading jets suppressed more than leading jets in all centralities

2205.00682