Path-length dependence of jet quenching

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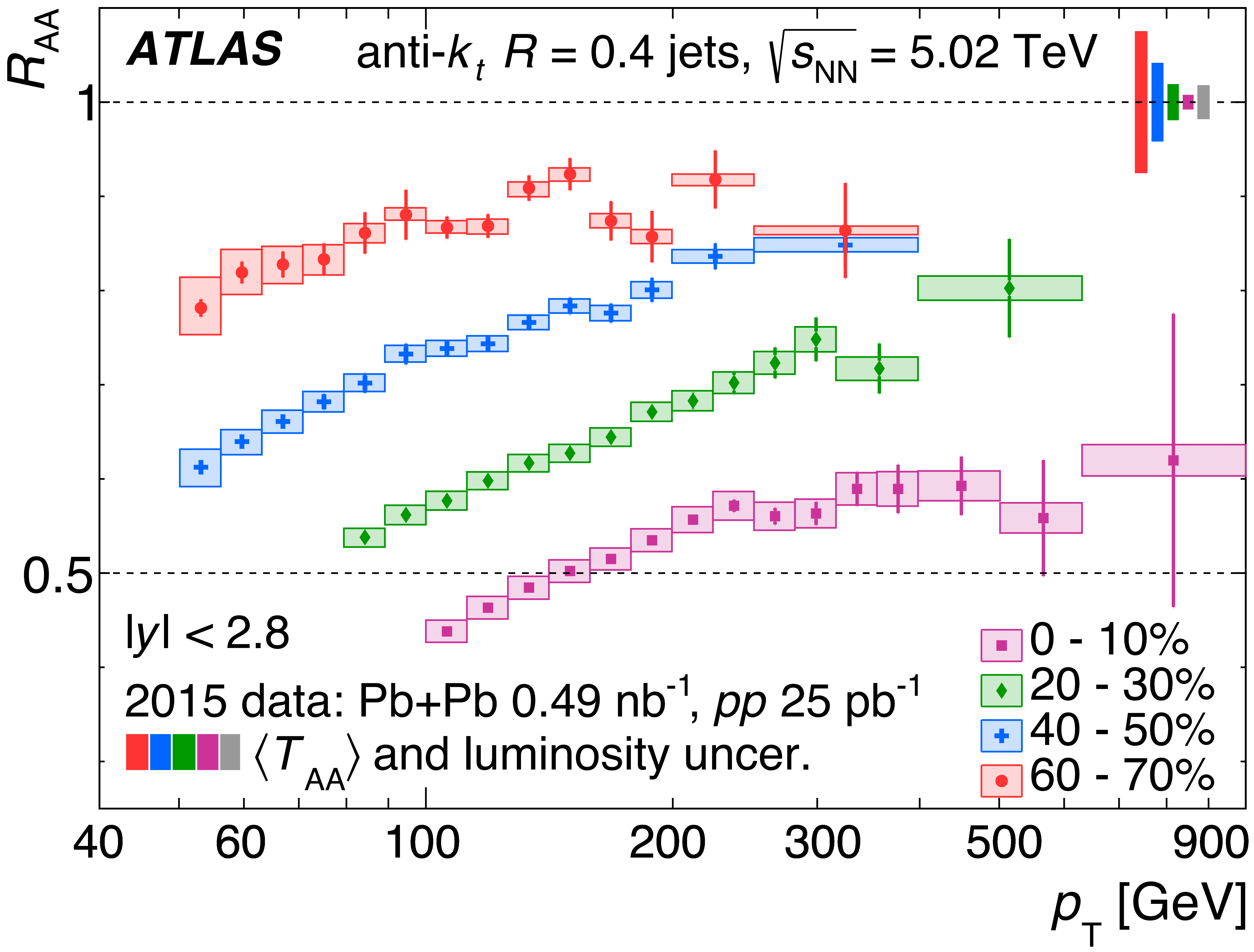
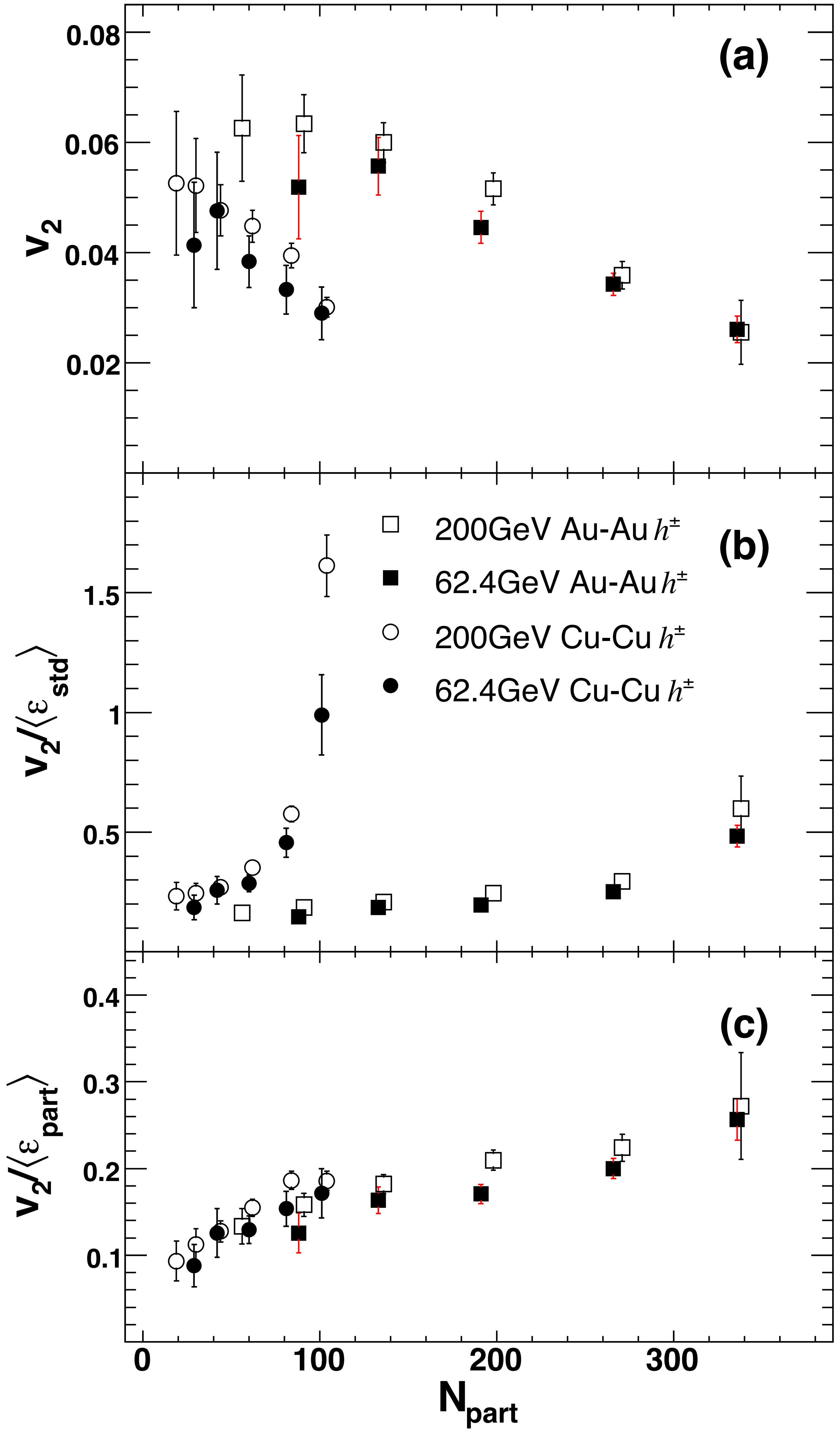
jet *quenching*

- 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



geometry & fluctuations is key in the soft sector



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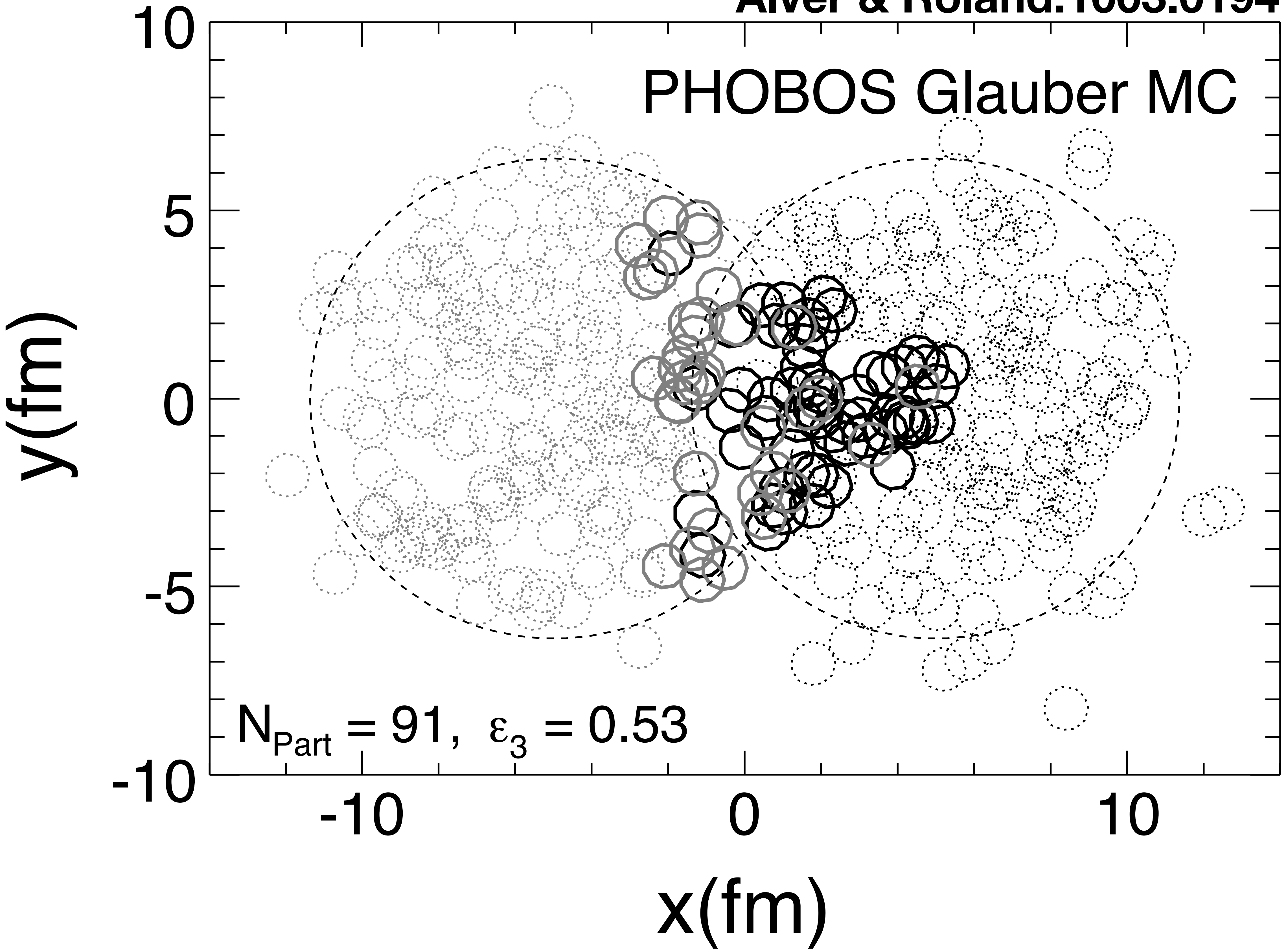

geometry & fluctuations in the soft sector are key to the extractions of η/s

geometry is different in jets

- the jets traverse the entire QGP lifetime as it expands and cools
- both the geometry of the QGP and the sensitivity to it (via the overall strength of quenching) change as a function of time.
- we measure the jets only after quenching

measurements sensitive to path length

- 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 ~balanced partons—we measure imbalanced jets in PbPb collisions
- pA: how small of a QGP can cause energy loss?

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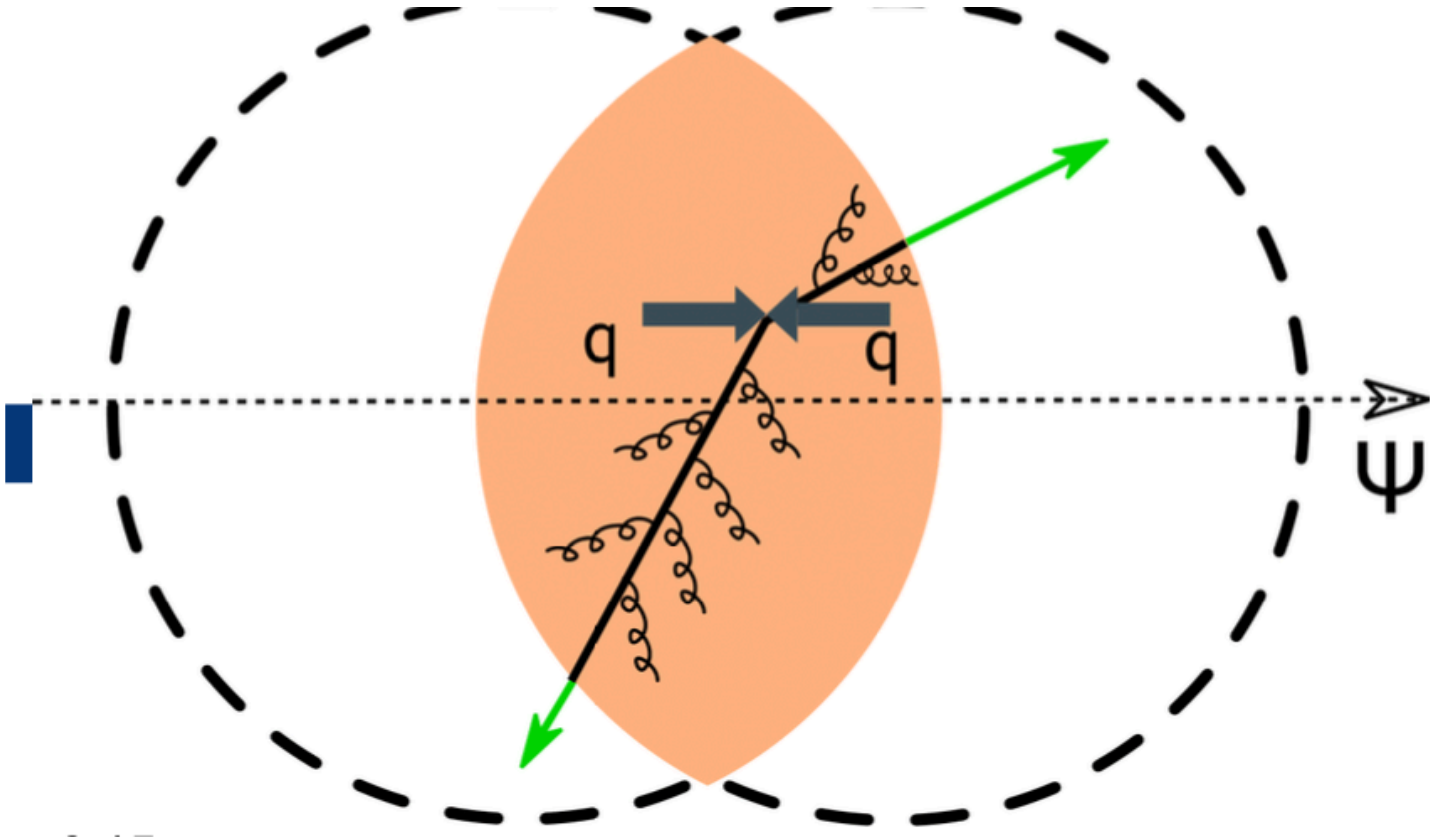
this is a biased selection of results and is in no way comprehensive

high p_T v_n



measurements of the jet rates as a function of 2, 3 & 4th order event planes

sensitive to the path length dependence of jet energy loss

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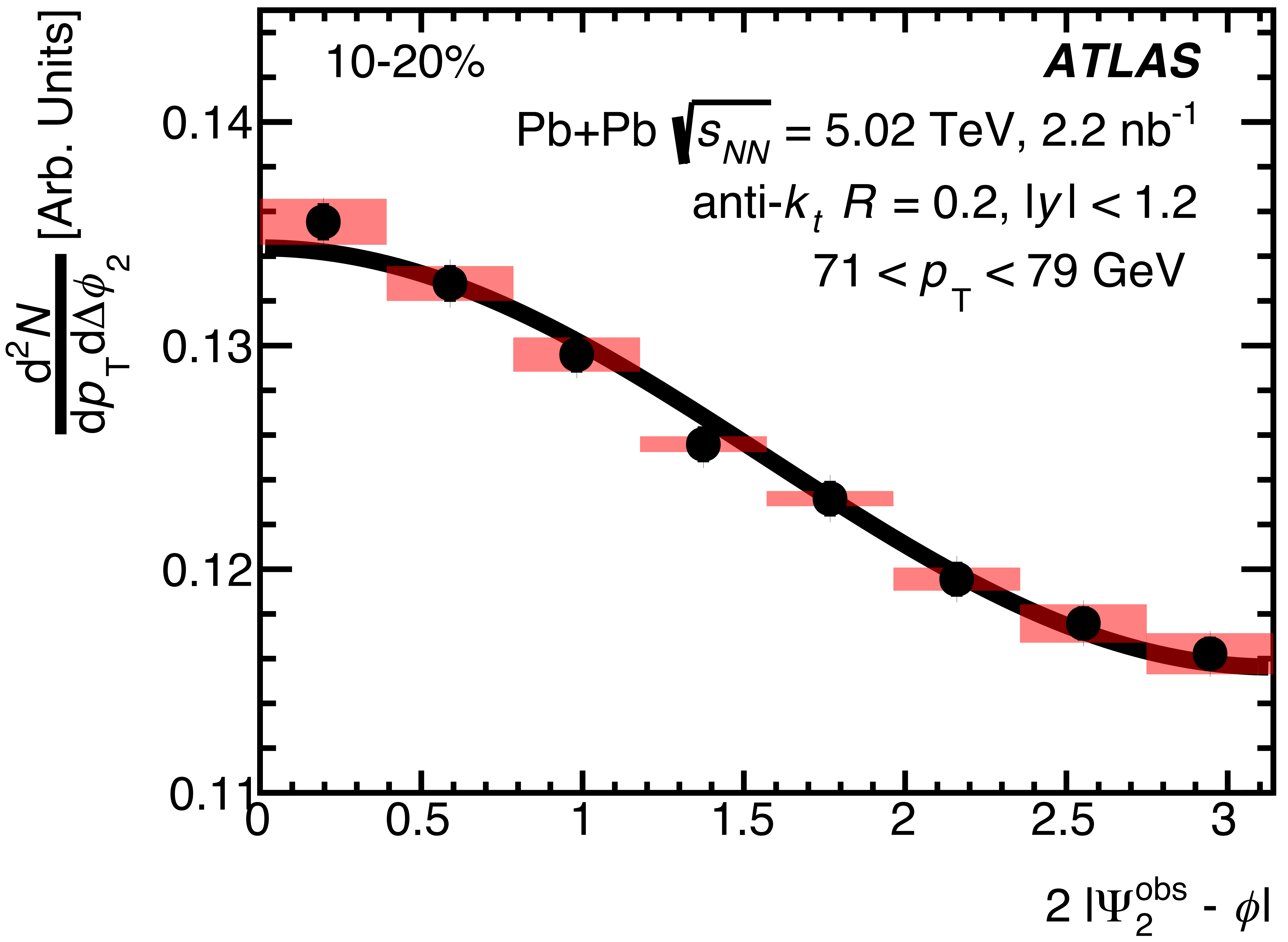
jet v_N: analysis procedure

- rapidity separation between jet & event plane > 2.8
  - justified based on PYTHIA studies of η of away side jet & data driven checks
  - only use outer half of the ATLAS FCal for event plane (in other measurements full detector is used)
- jet momentum is unfolded
- jet position resolution is greatly improved by using small R = 0.2 jets



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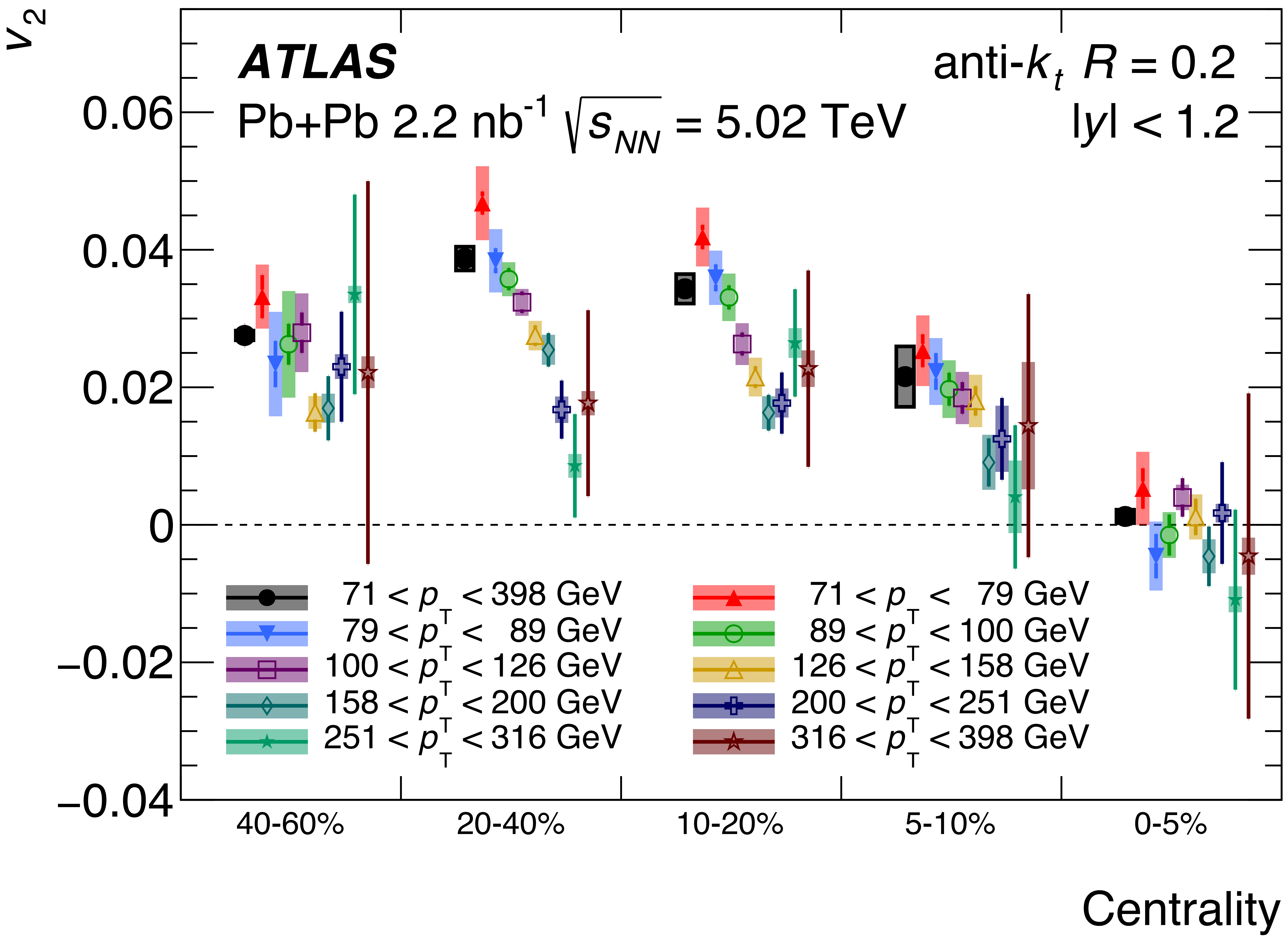
jet v_2



- $v_2 > 0$ 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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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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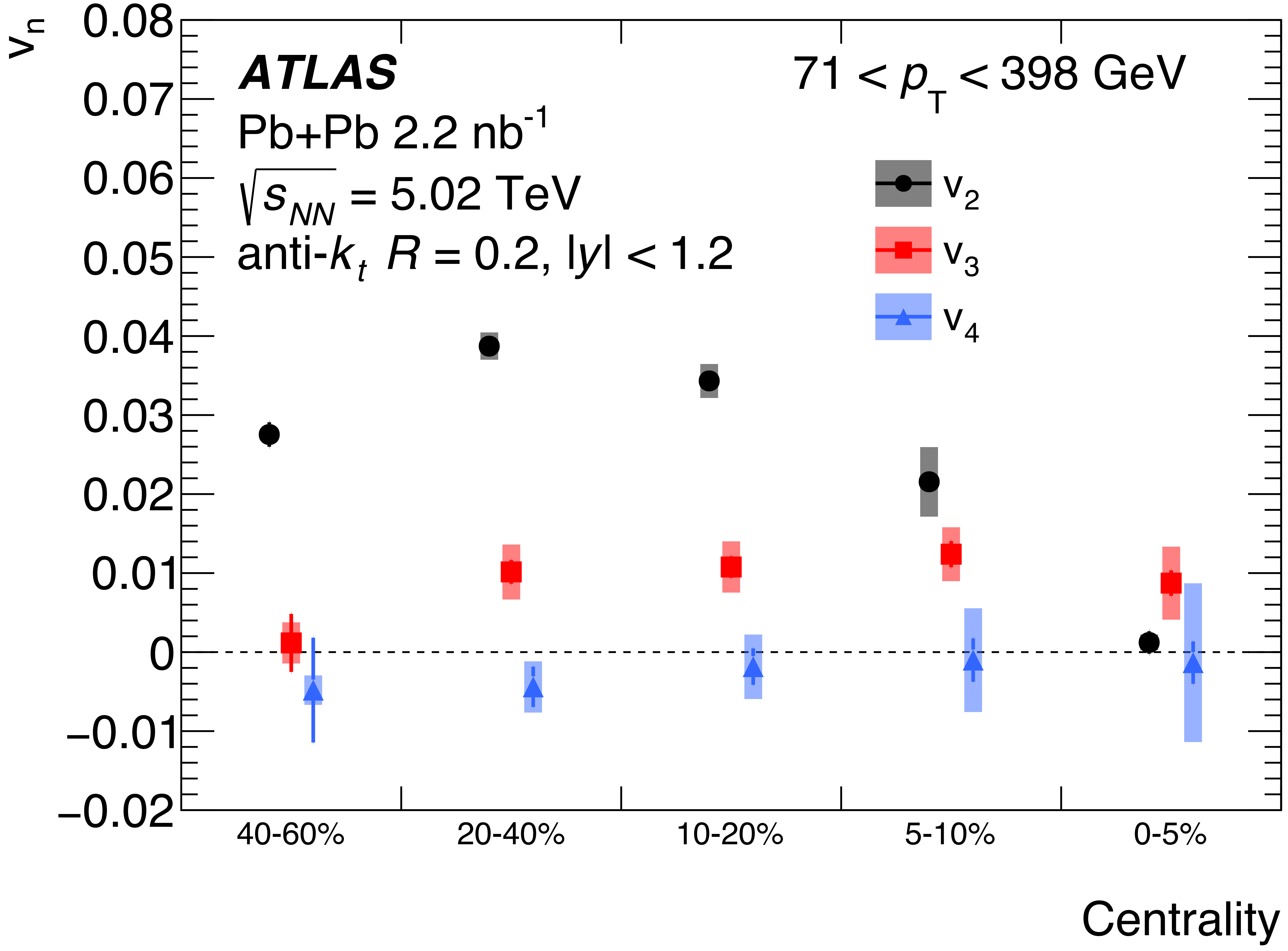
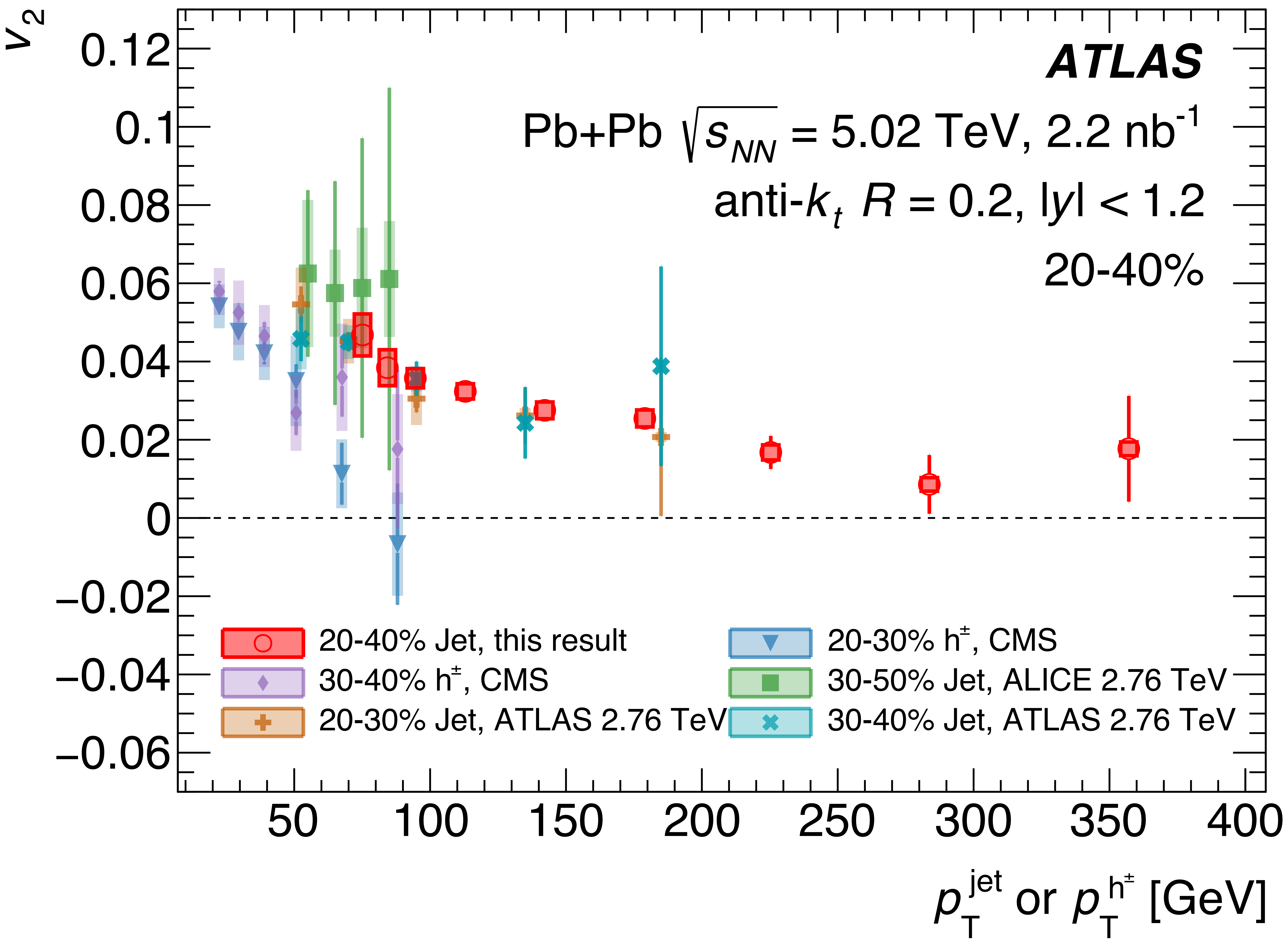


comparison to previous measurements

- 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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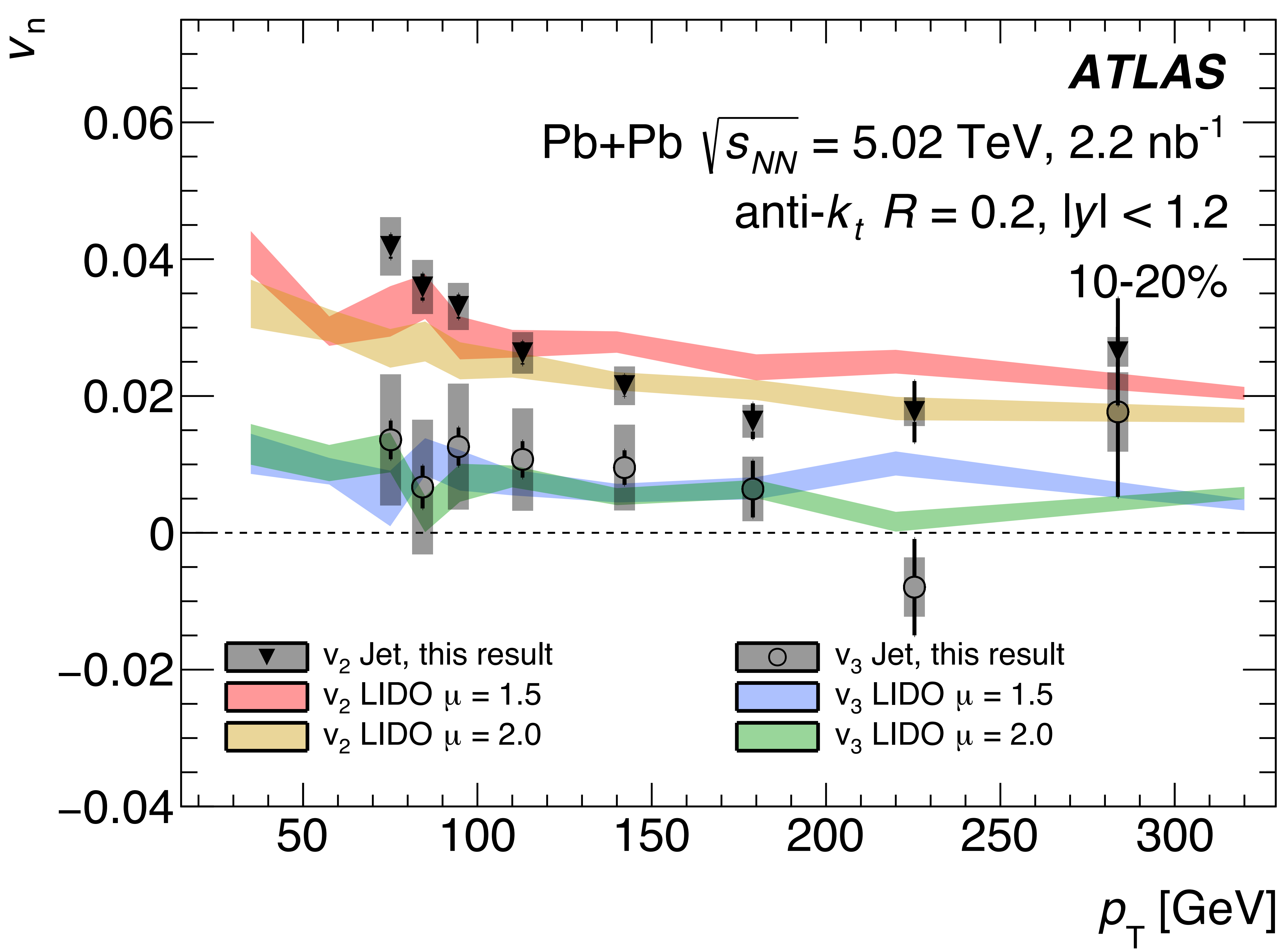
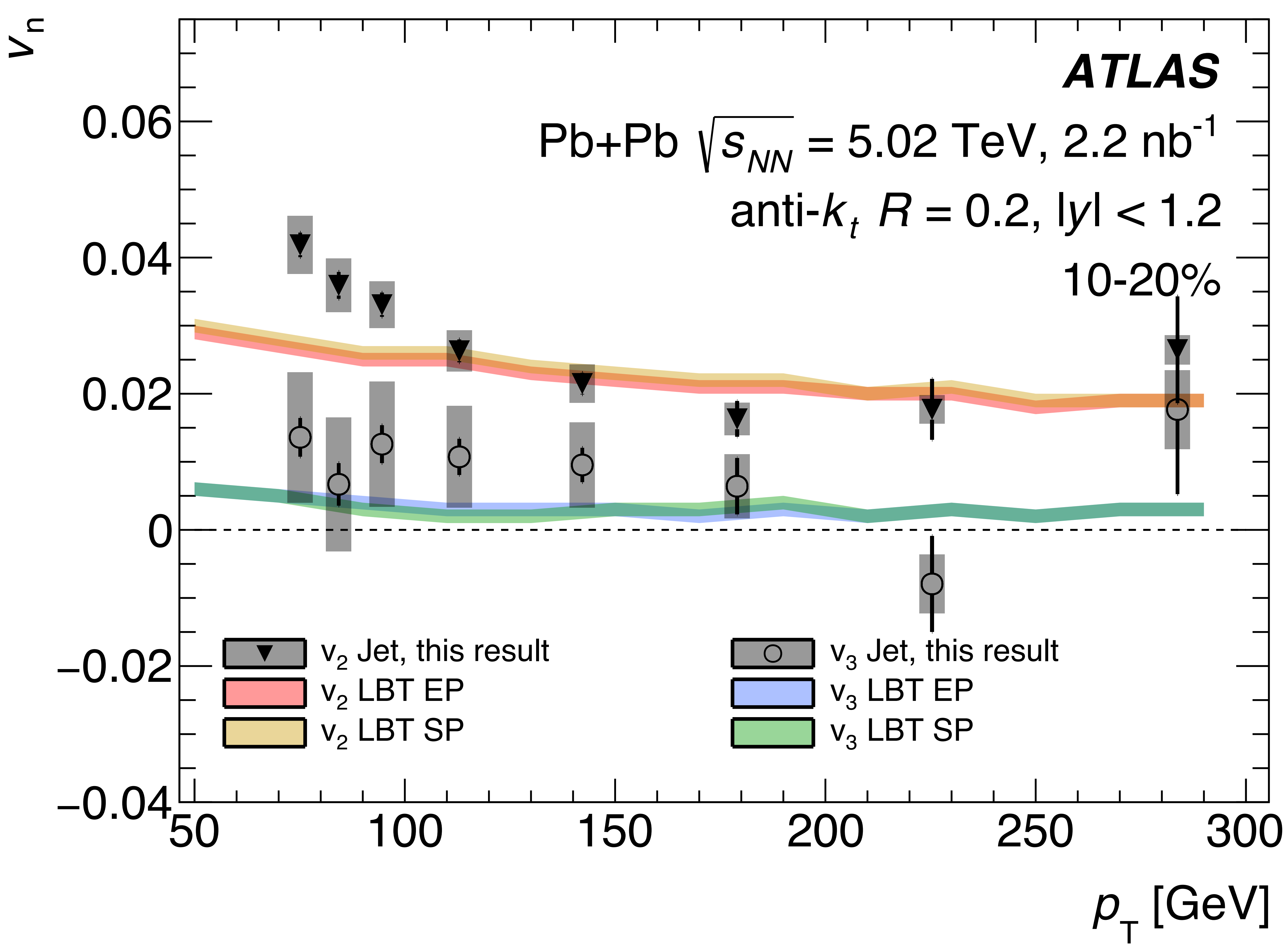
comparison to theory





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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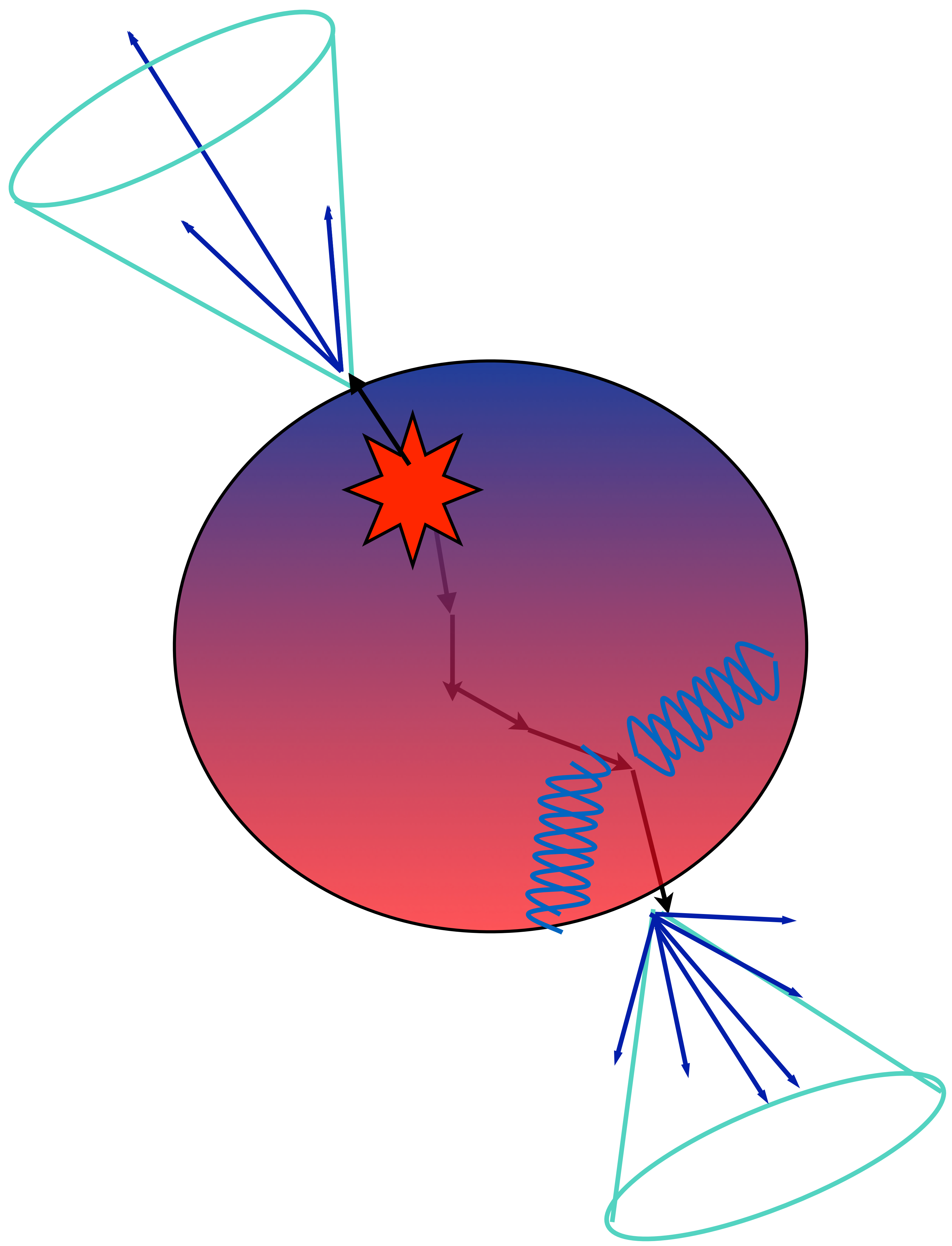
ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET
Calorimeter Towers
Tracks
E_T [GeV]
P_T [GeV]
ϕ
η

a picture of dijets

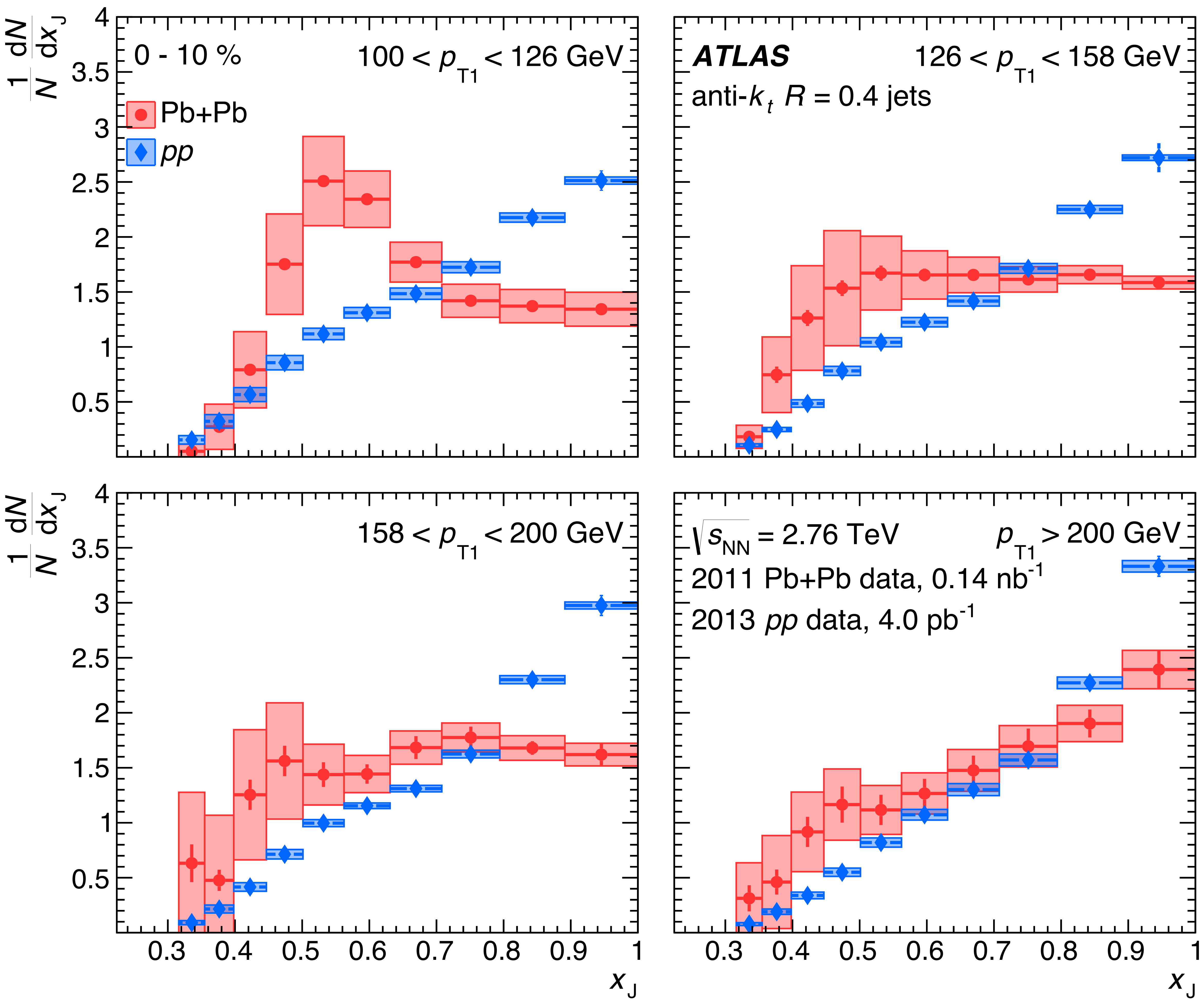
leading jet: very short path length thourgh the QGP, nearly no energy loss

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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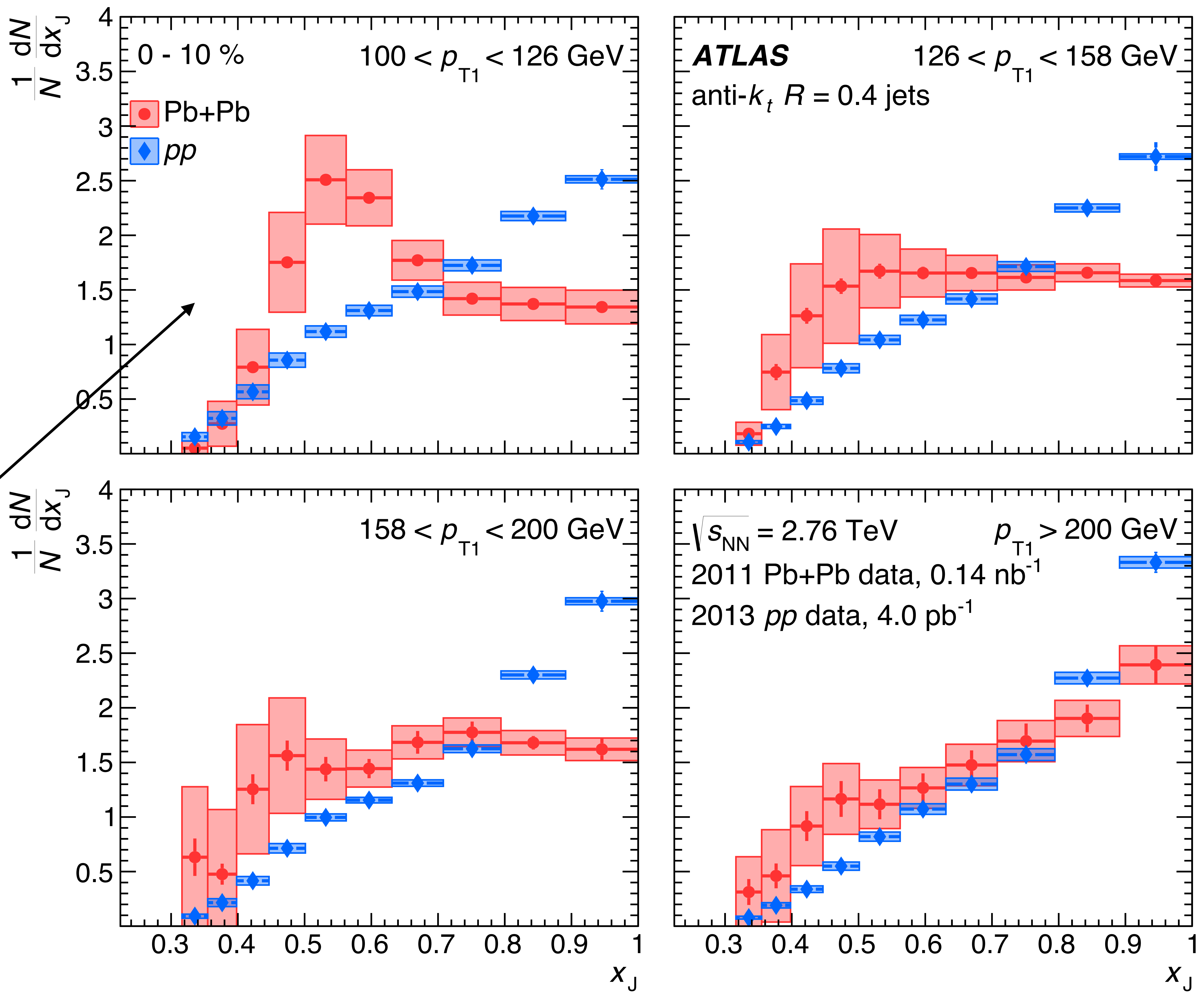

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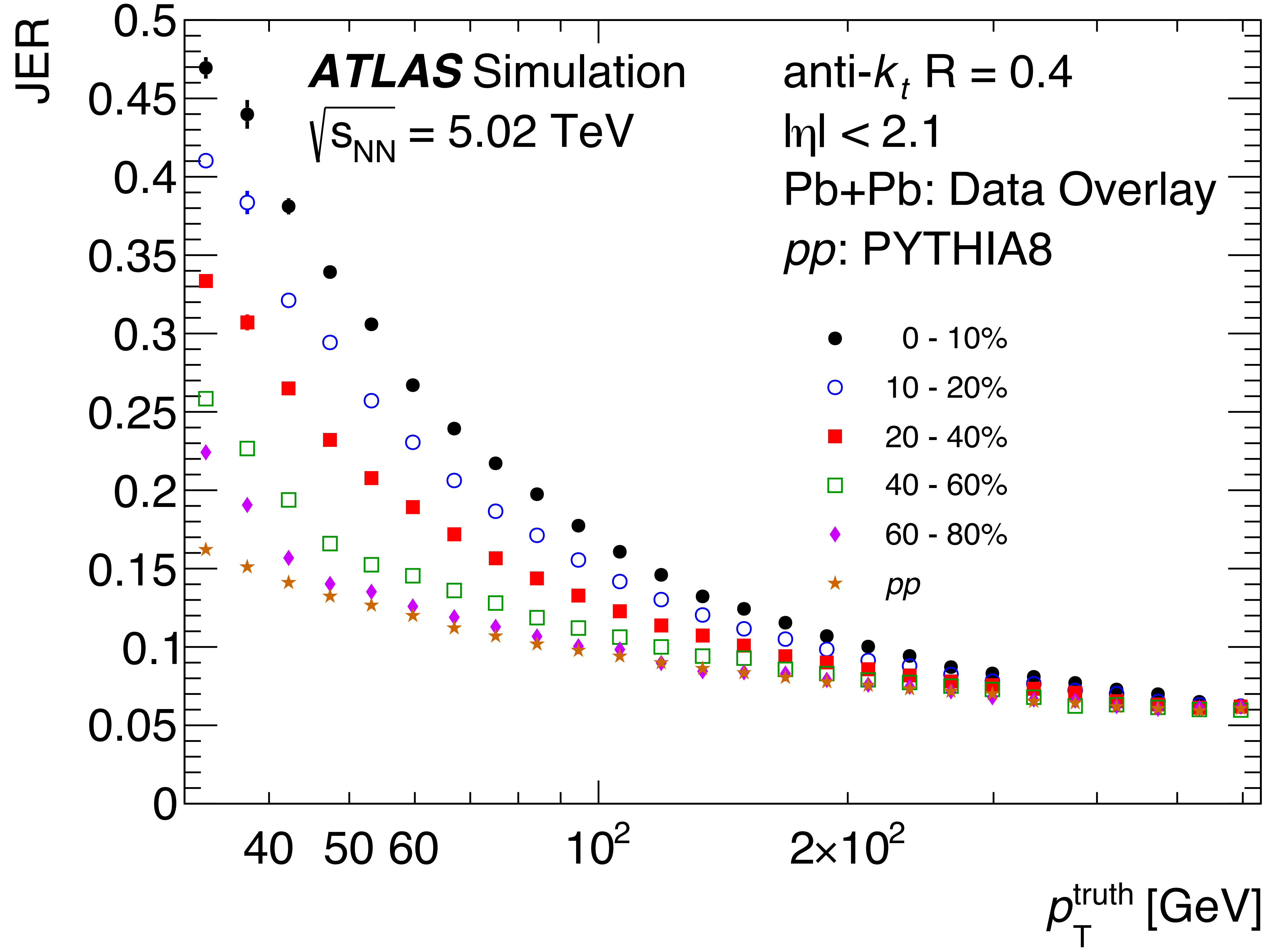
effect of UE fluctuations



jet energy resolution up to 50% in central collisions at ~30 GeV

due to fluctuations of the underlying event

JER dominates the x_J distributions without unfolding

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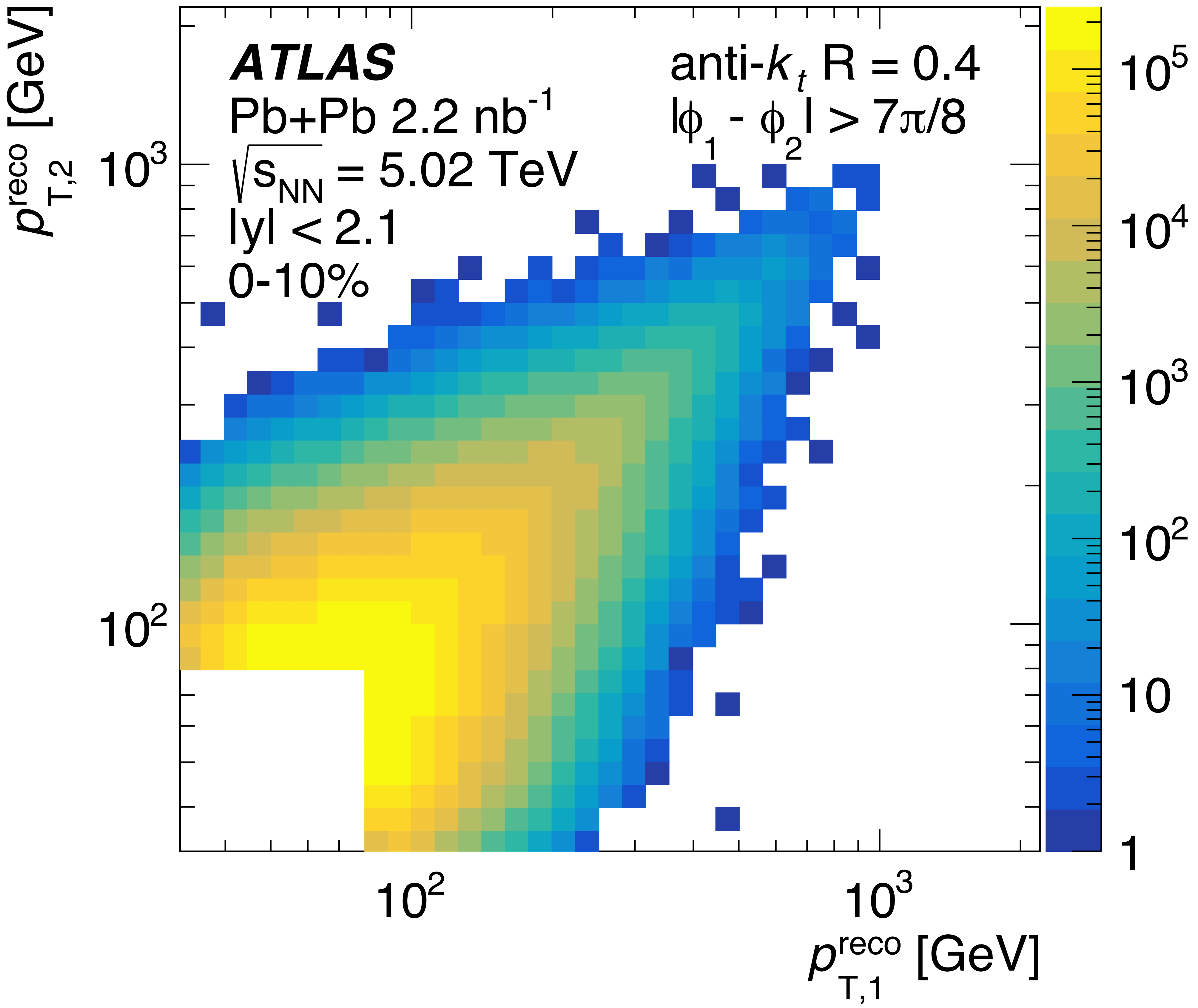
Run 2 dijet measurement

- 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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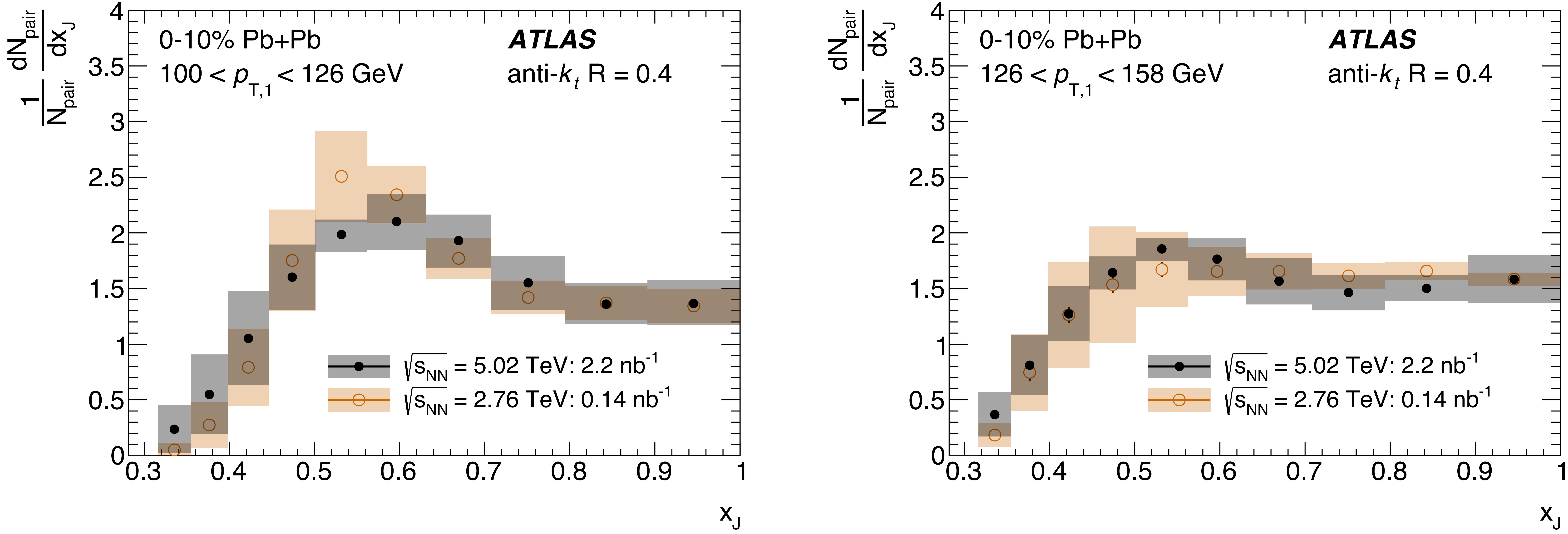
comparison of 5.02 TeV & 2.76 TeV



x_J distributions have consistent shapes at the two collision energies

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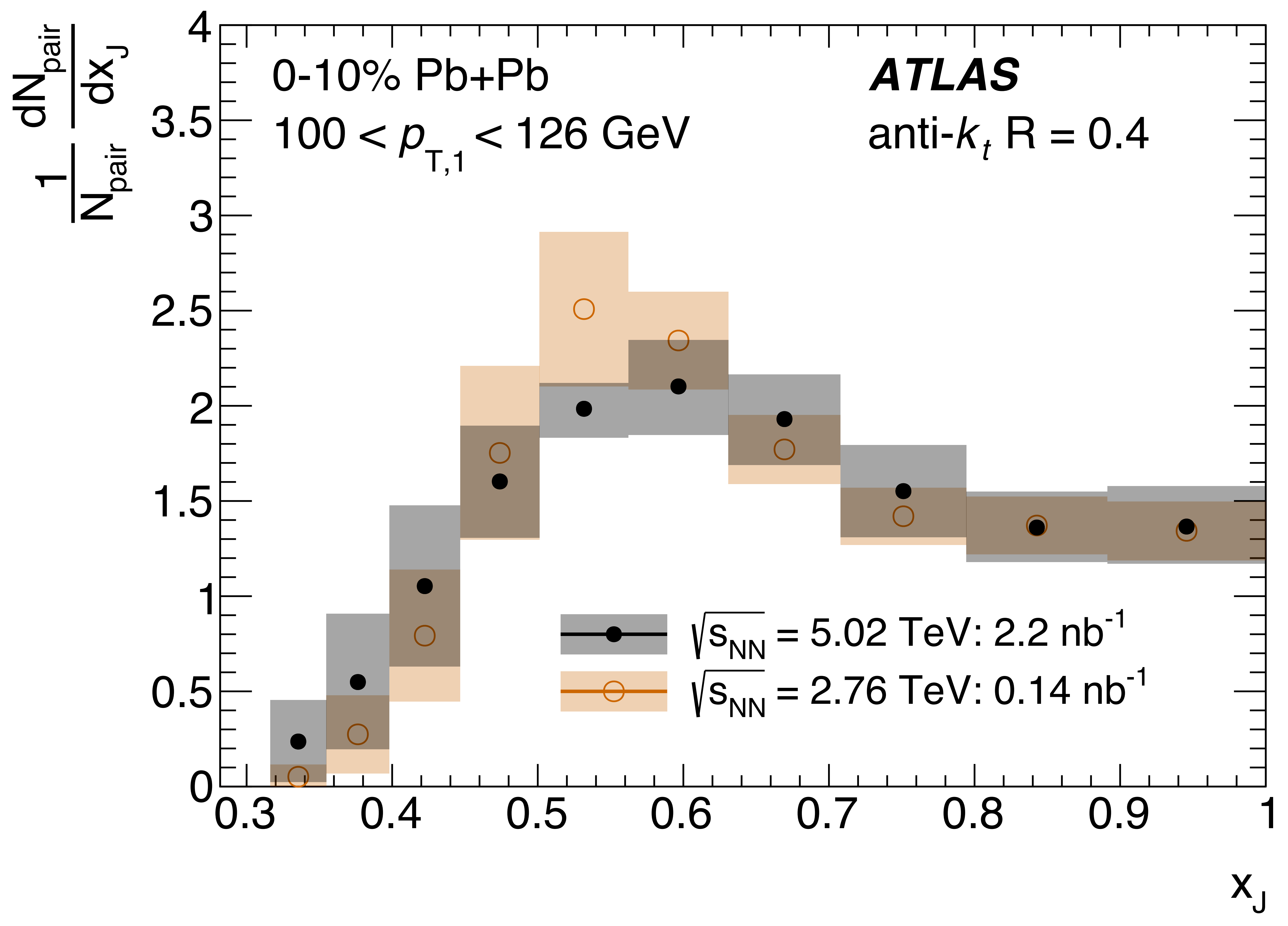

is there an enhancement of imbalanced dijets or a suppression of balanced dijets?

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

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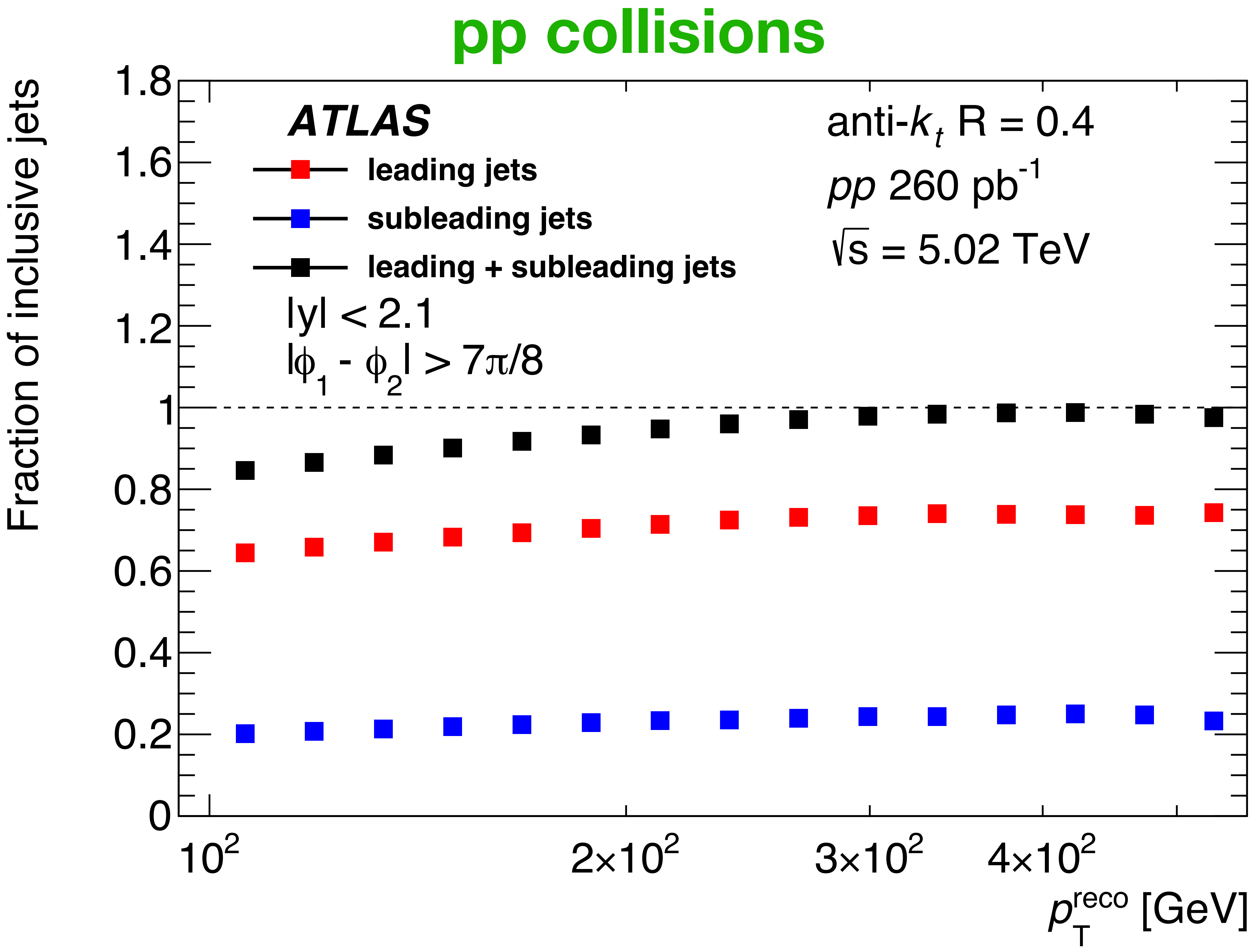
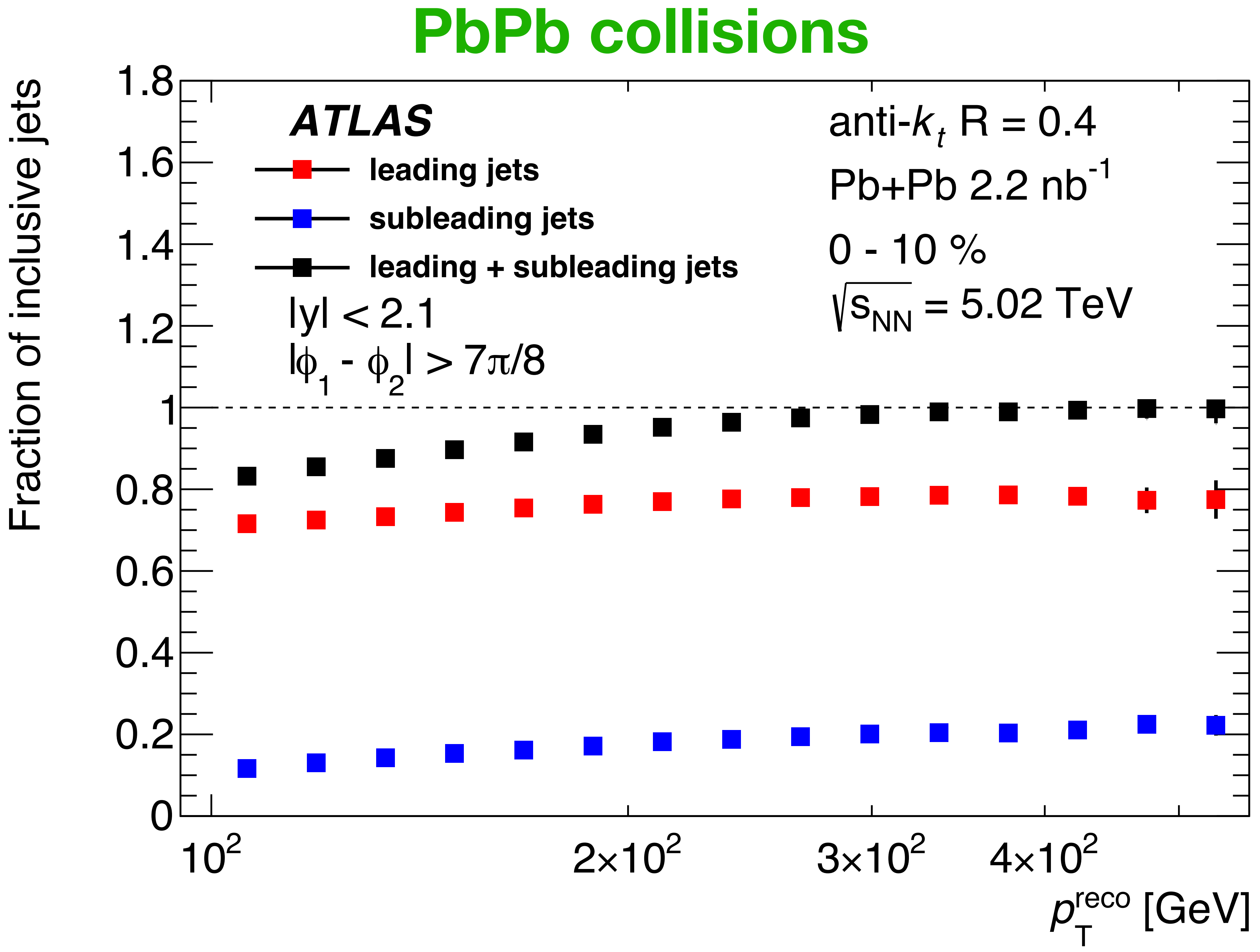
most jets > 100 GeV are in dijet pairs





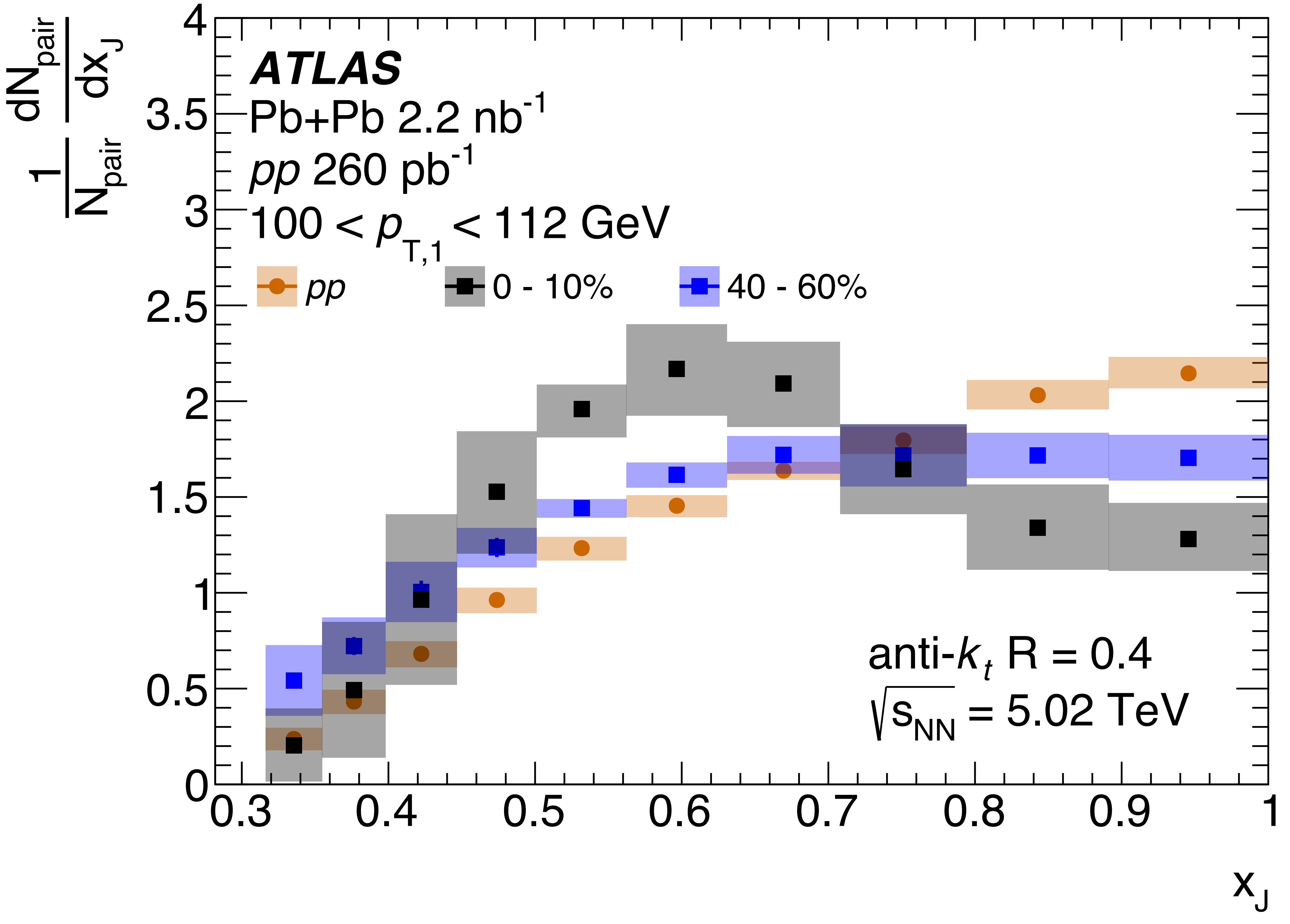
at 100 GeV over 80% of all jets are included in a leading dijet pair; at 200 GeV it is over 95%

at a given p_T most jets are leading jets, rather than subleading jets

since the bulk of the jets above 100 GeV are in dijet pairs, the overall rate of dijets must be suppressed at a level similar to that of inclusive jets

new method for studying x_J

$$\frac{1}{N_{\text{pair}}}\frac{dN_{\text{pair}}}{dx_{\text{J}}}.$$ **area normalization**



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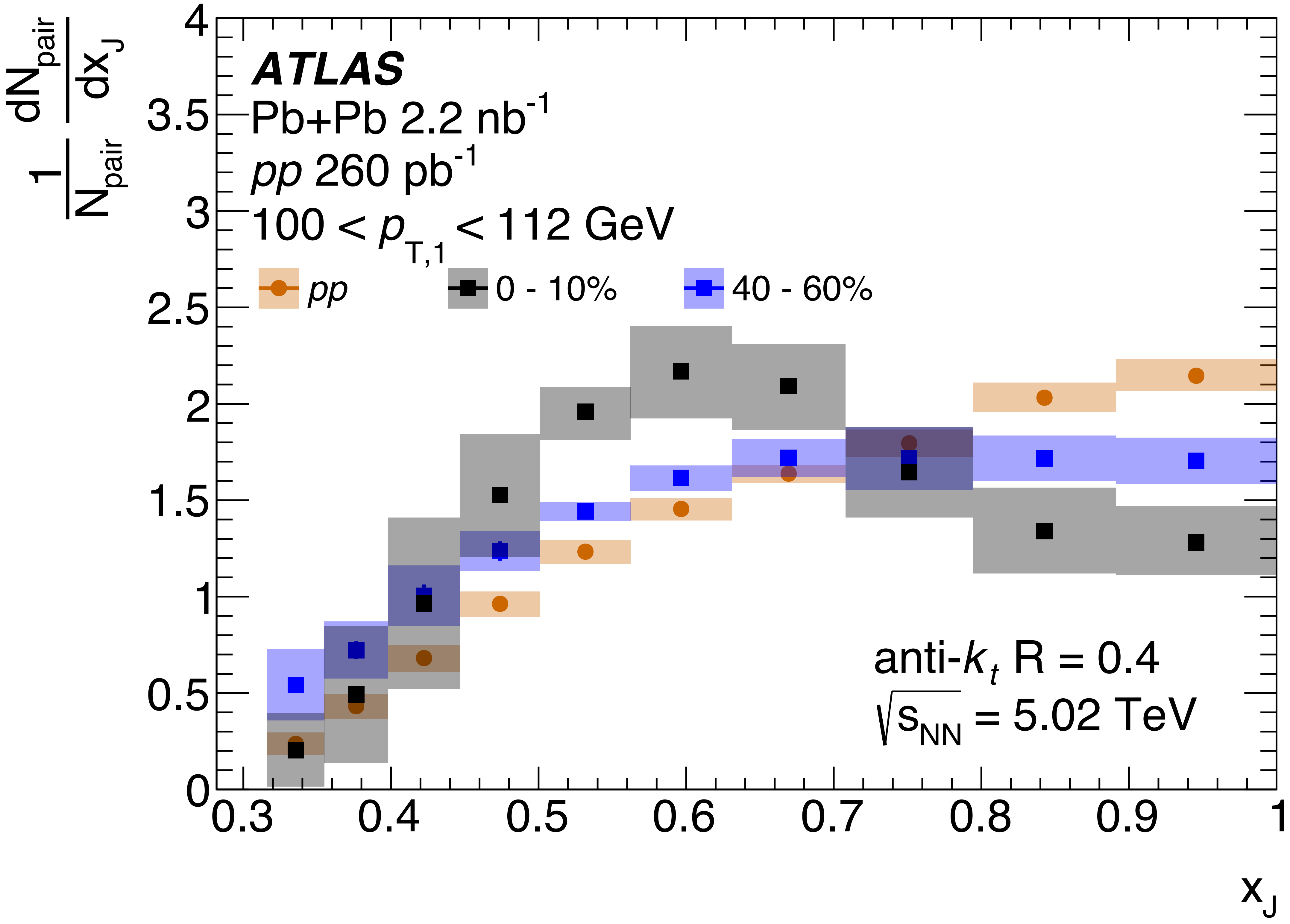
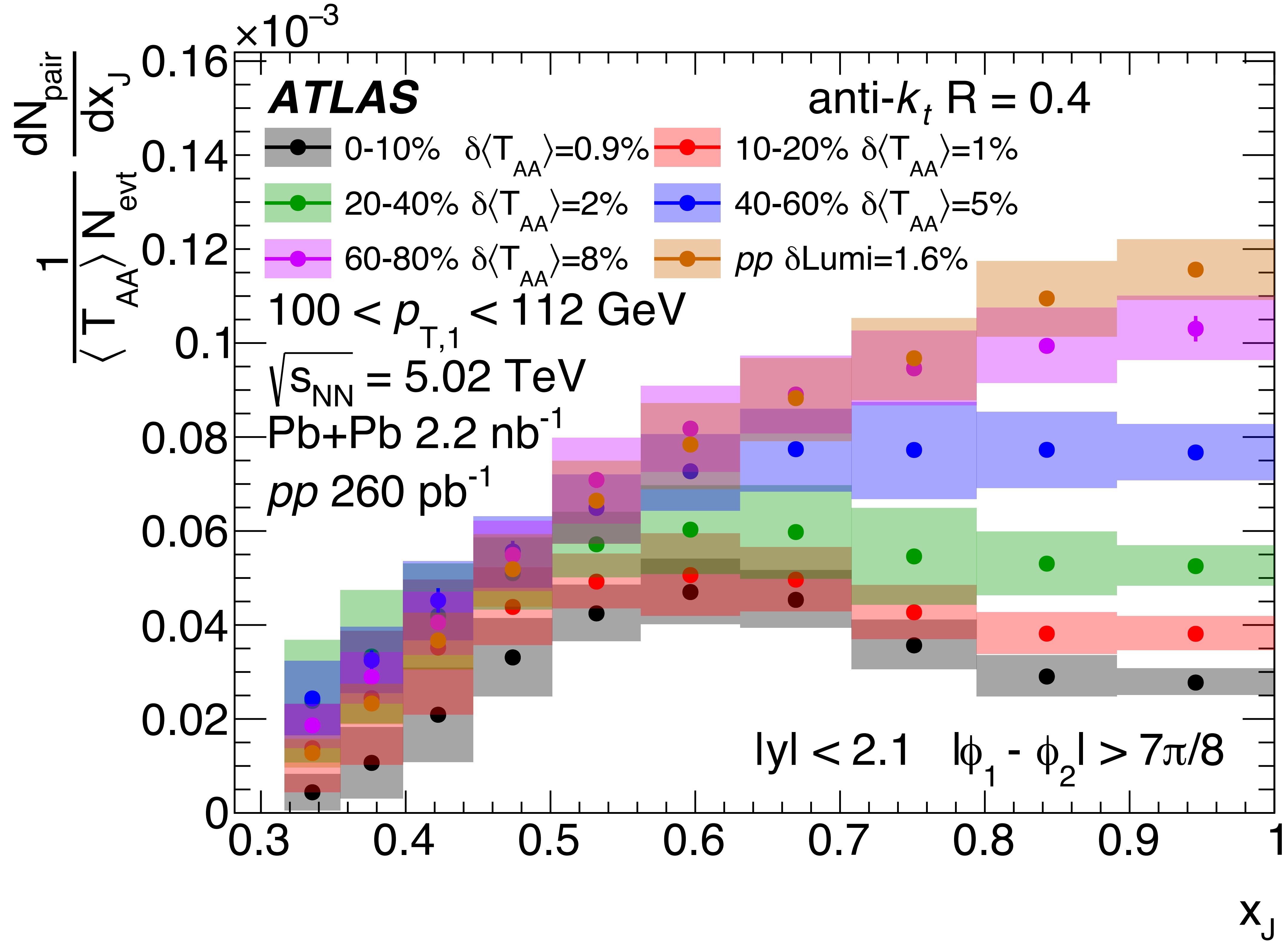
$$\frac{1}{\langle T_{\rm AA}\rangle N_{\rm evt}^{\rm AA}}\frac{dN_{\rm pair}^{\rm AA}}{dx_{\rm J}}$$ **absolute normalization**





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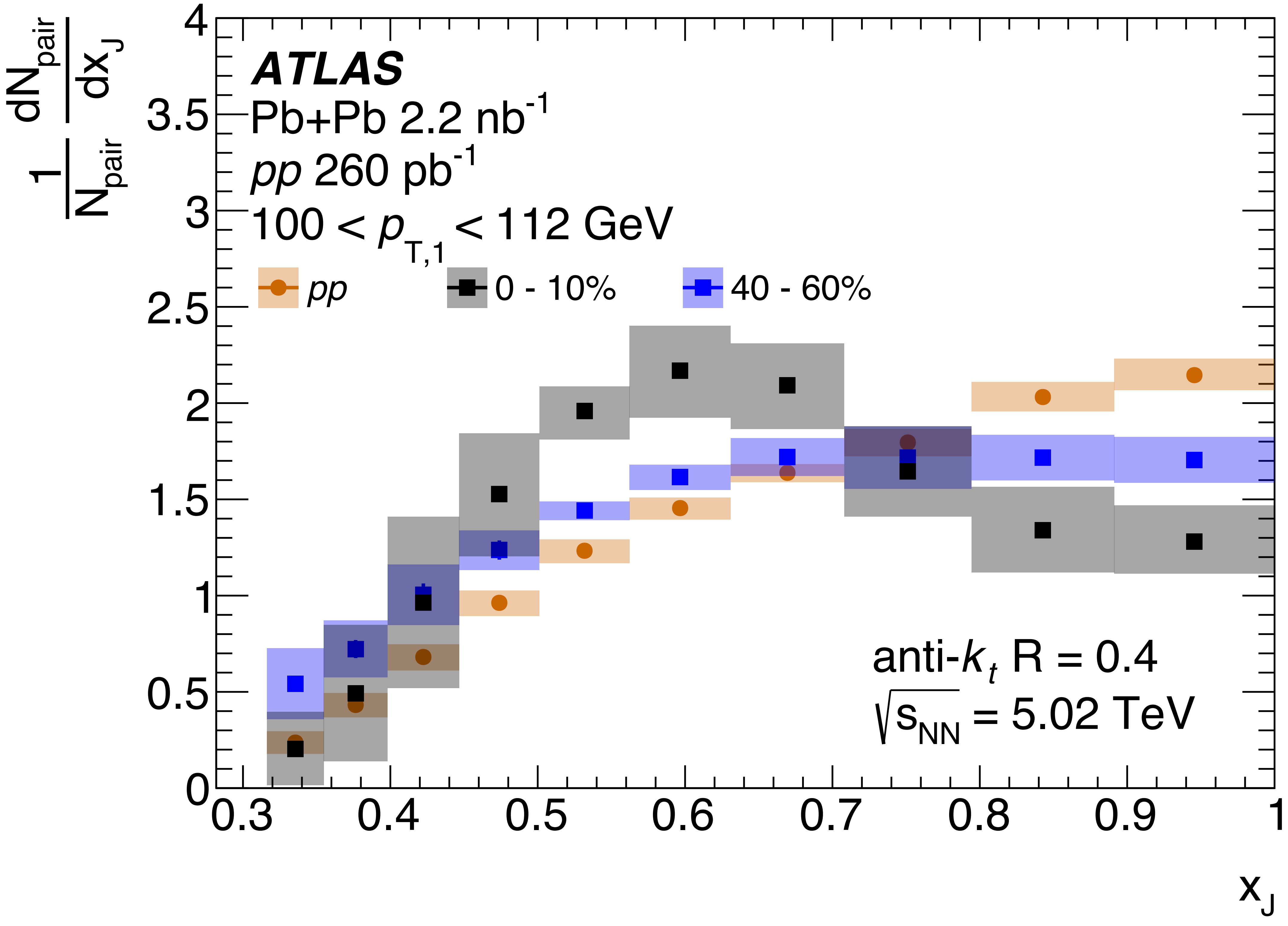
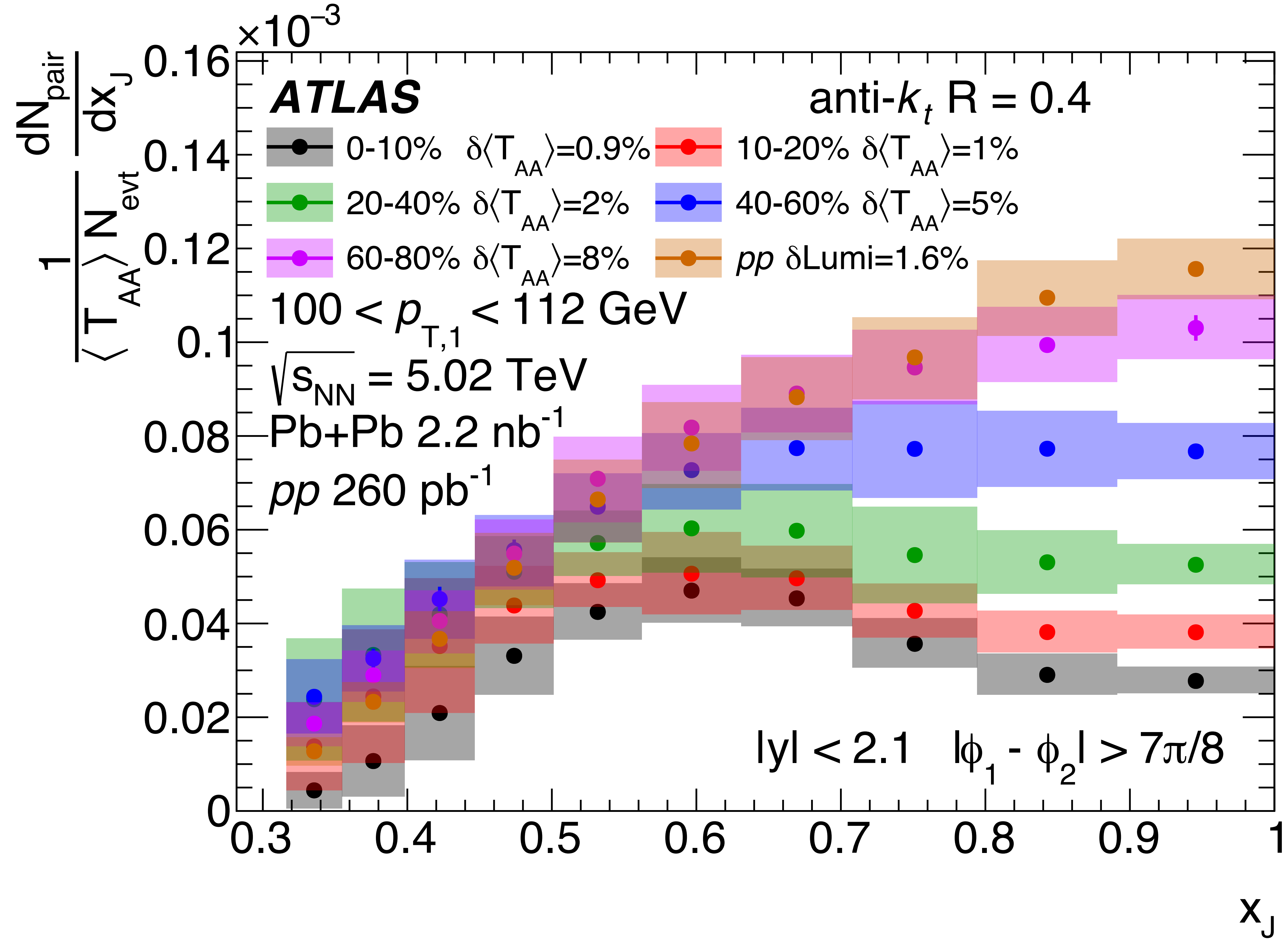
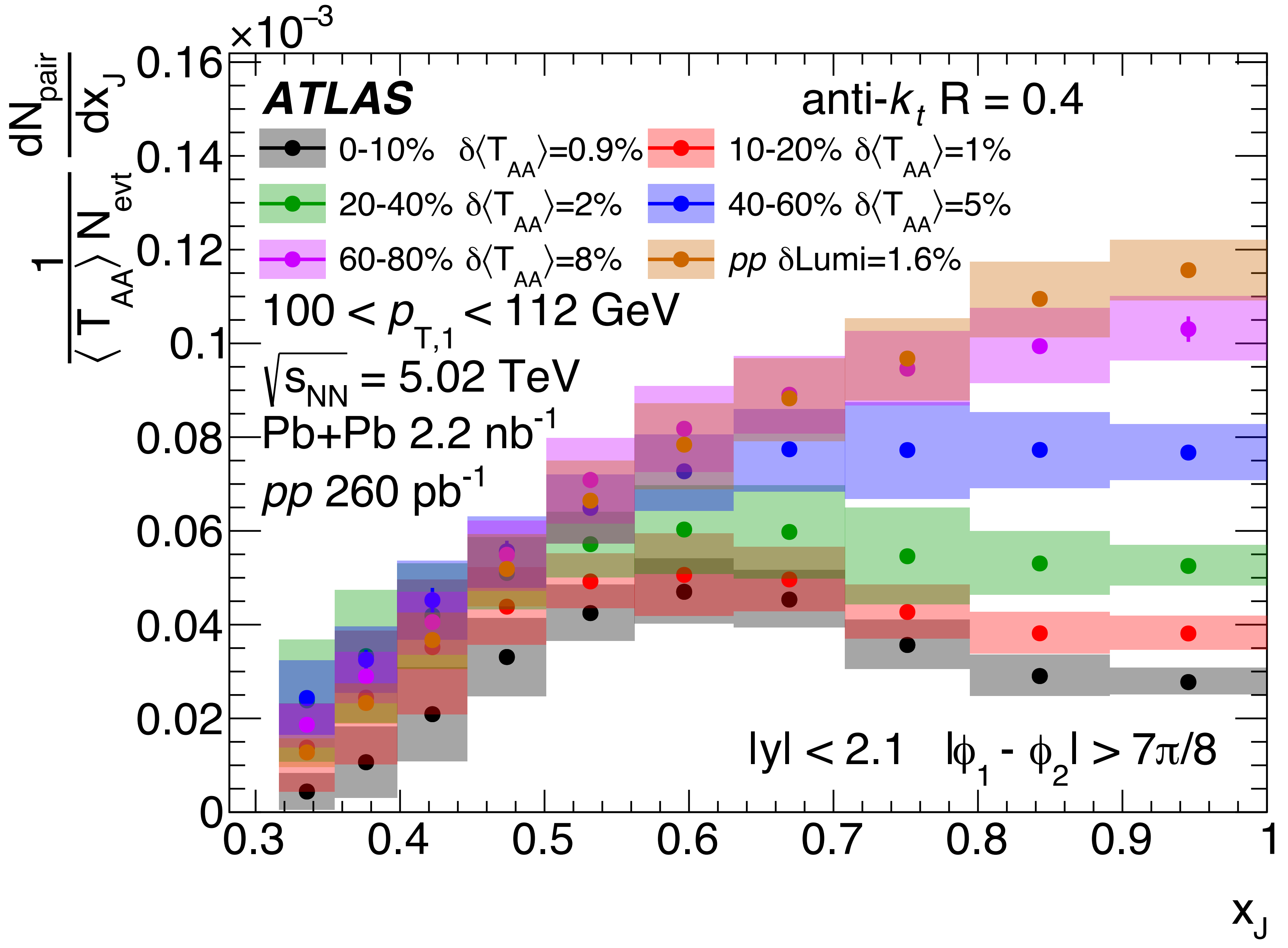




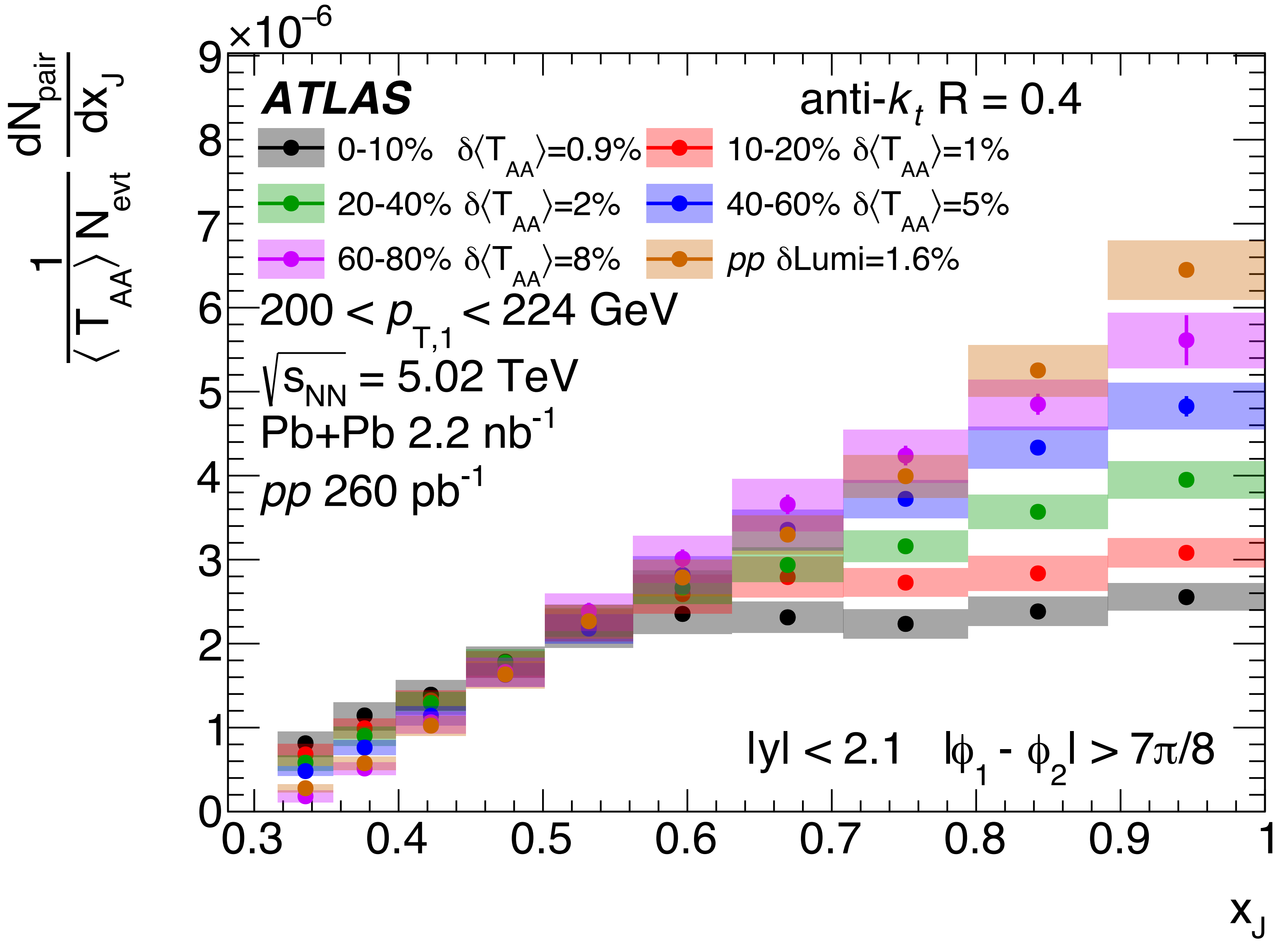
absolutely normalized distributions show that *balanced* jets are preferentially suppressed

suppression of balanced dijets

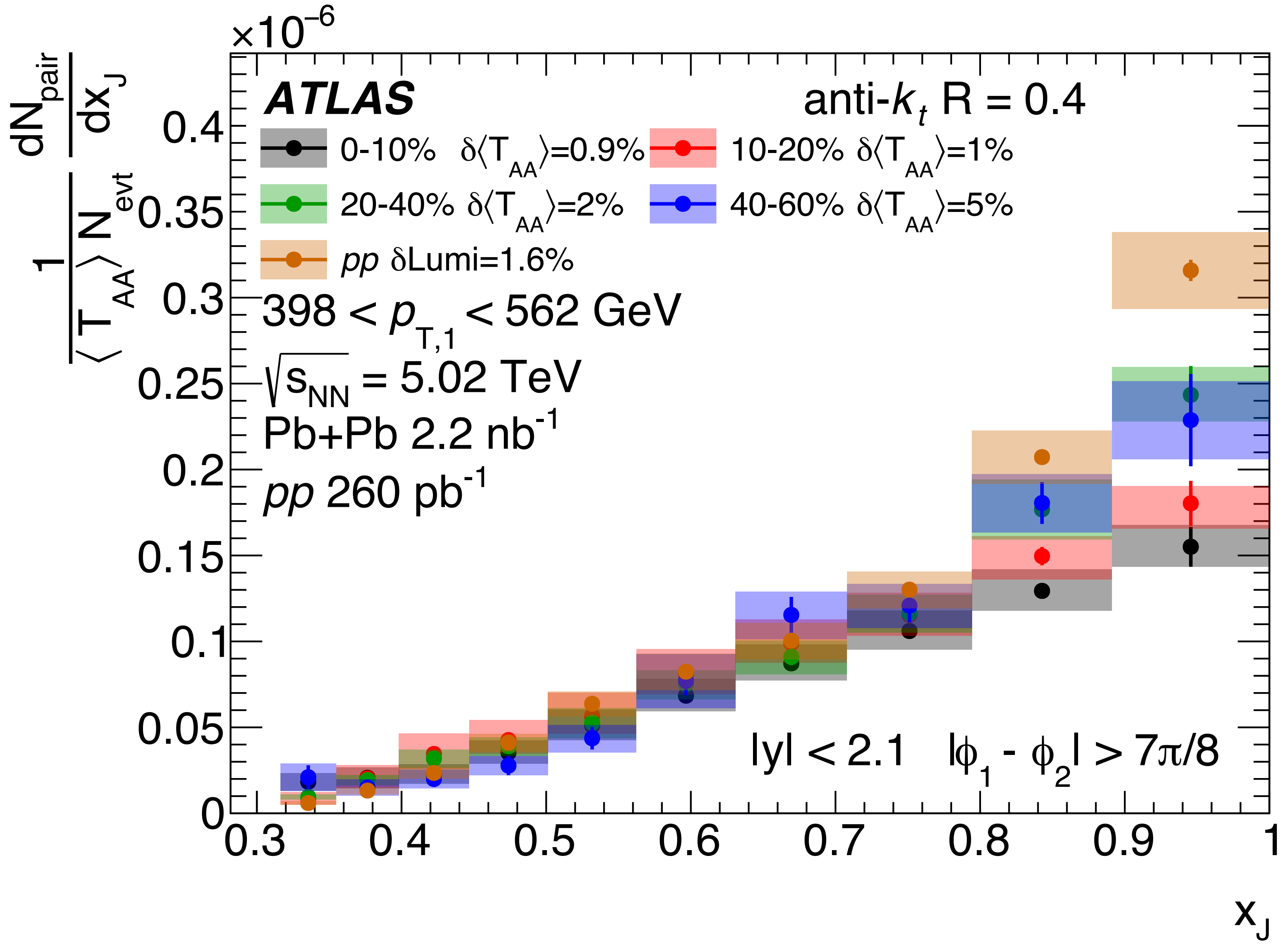
100 < p_{T1} < 112 GeV



200 < p_{T1} < 224 GeV



398 < p_{T1} < 562 GeV



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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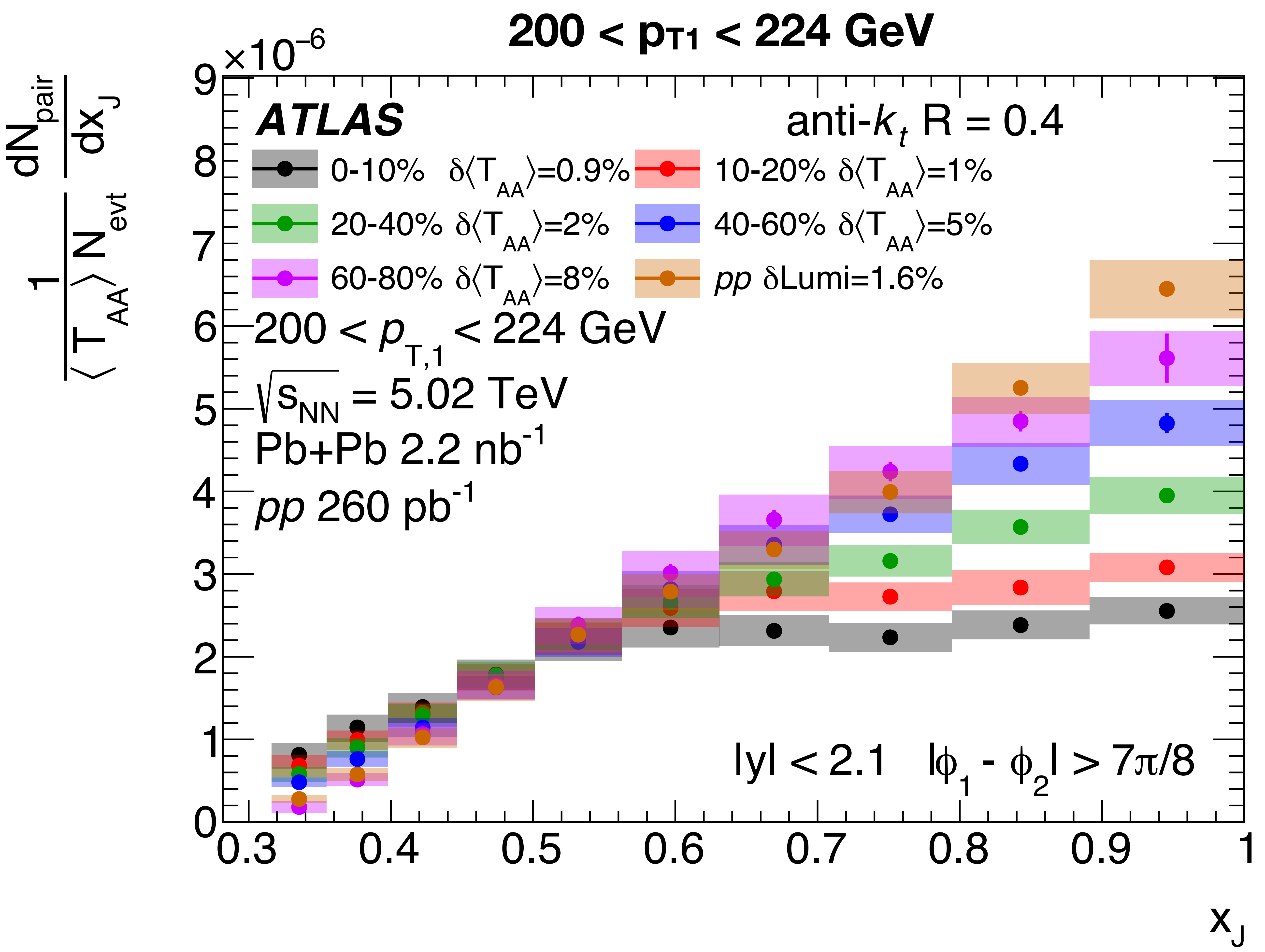
dijet suppression picture



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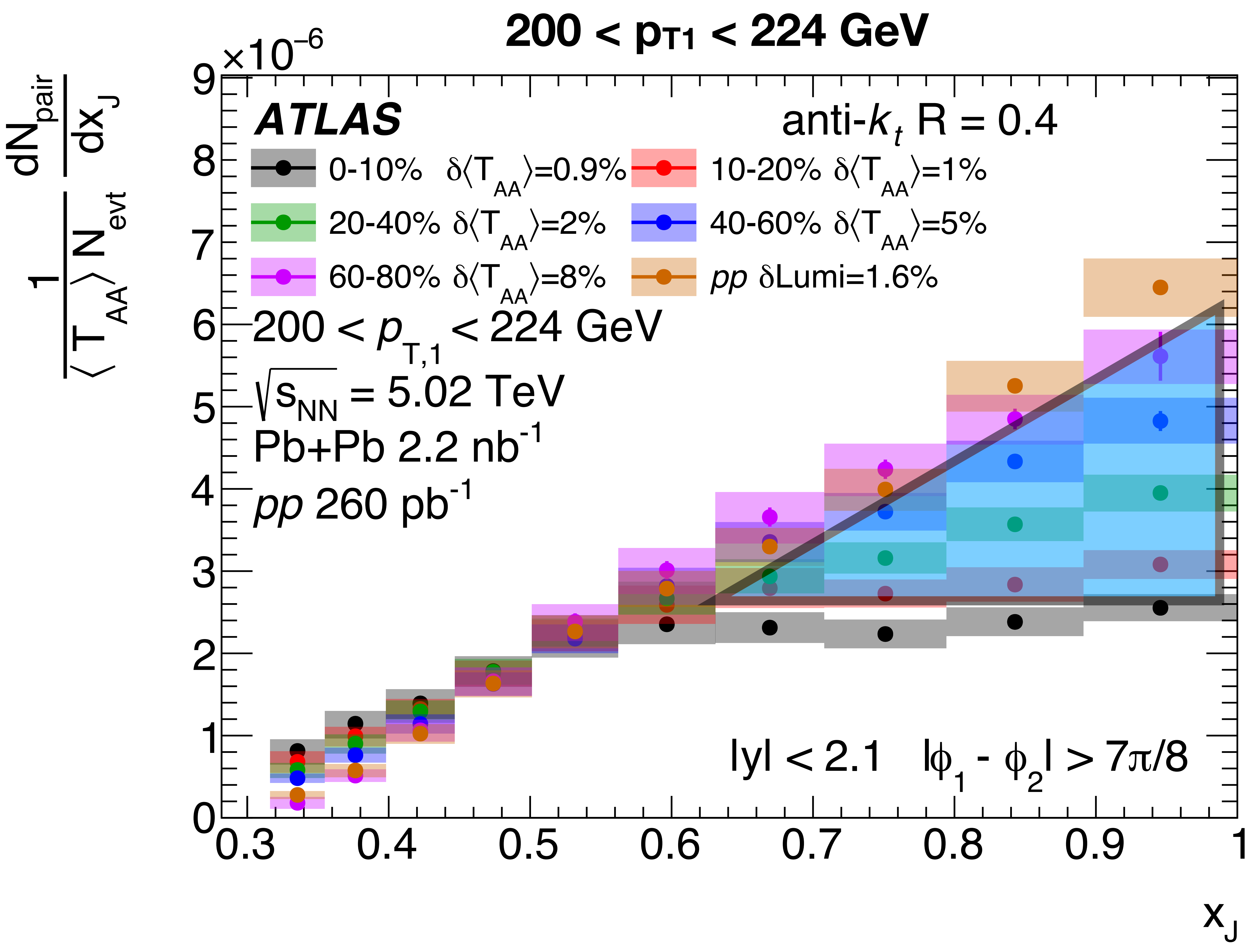

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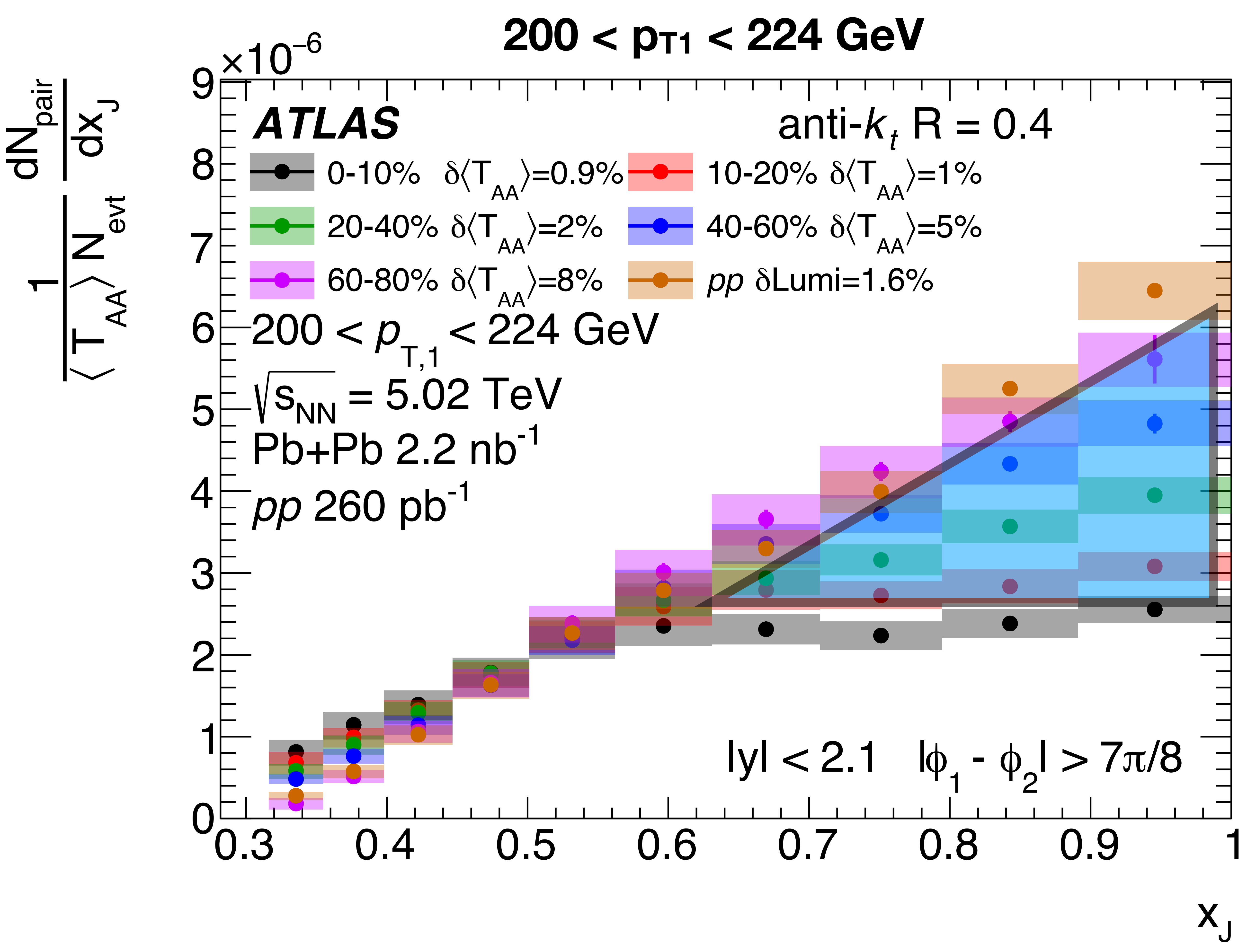

most of the quenched dijets must be moved to a lower p_{T1} bin

since the overall jet rate falls quickly with p_T, they make a small impact on the lower p_{T1} selection

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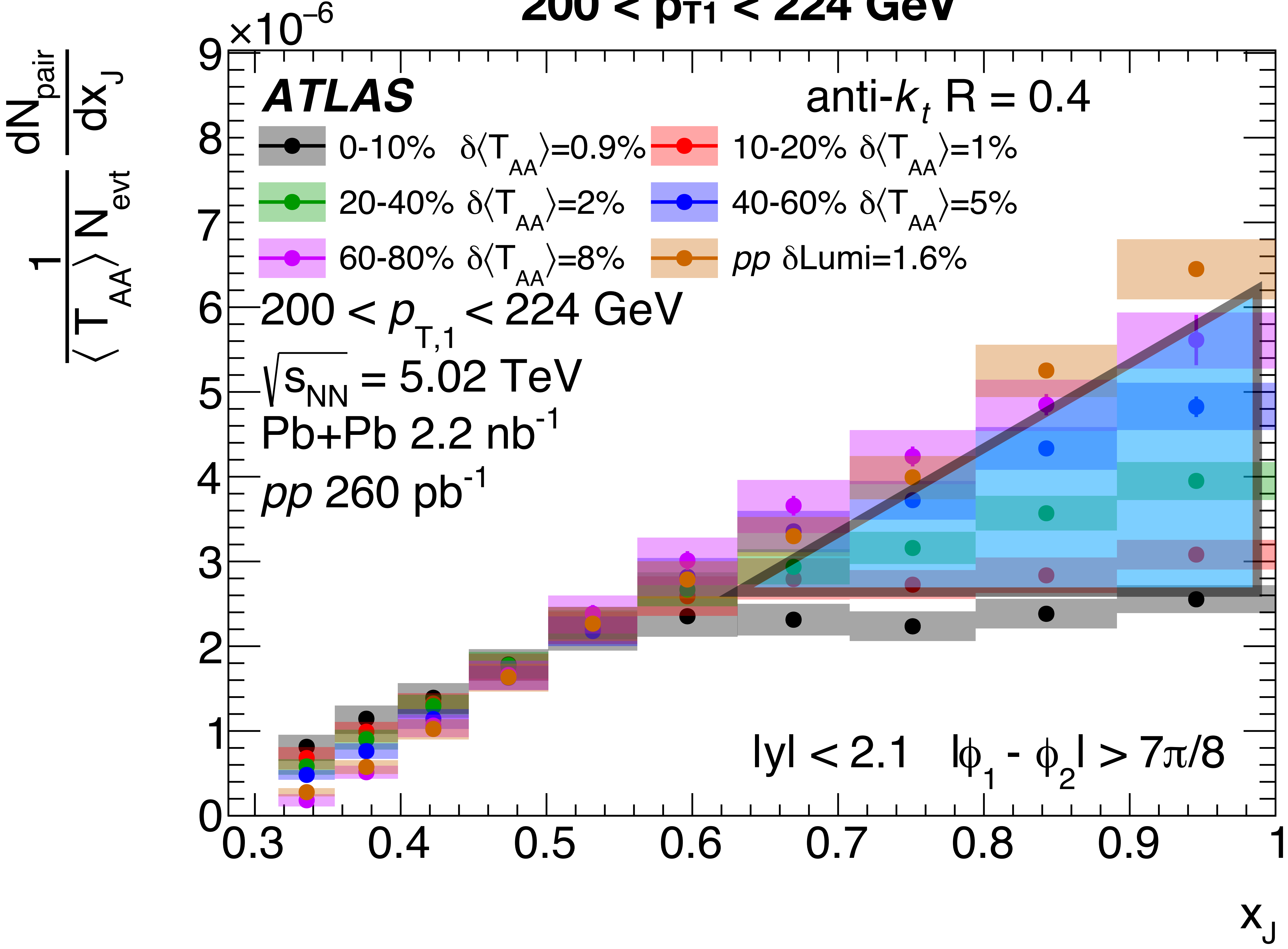
dijet suppression picture

200 < p_{T1} < 224 GeV



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which balanced dijets are suppressed?

—is it due to the path length dependence?

measure x_J as a function of ψ_2

—is it due to the jet structure?

measure x_J as a function of substructure (very hard—4D unfolding) and/or jet radius

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overall suppression of leading/subleading jets

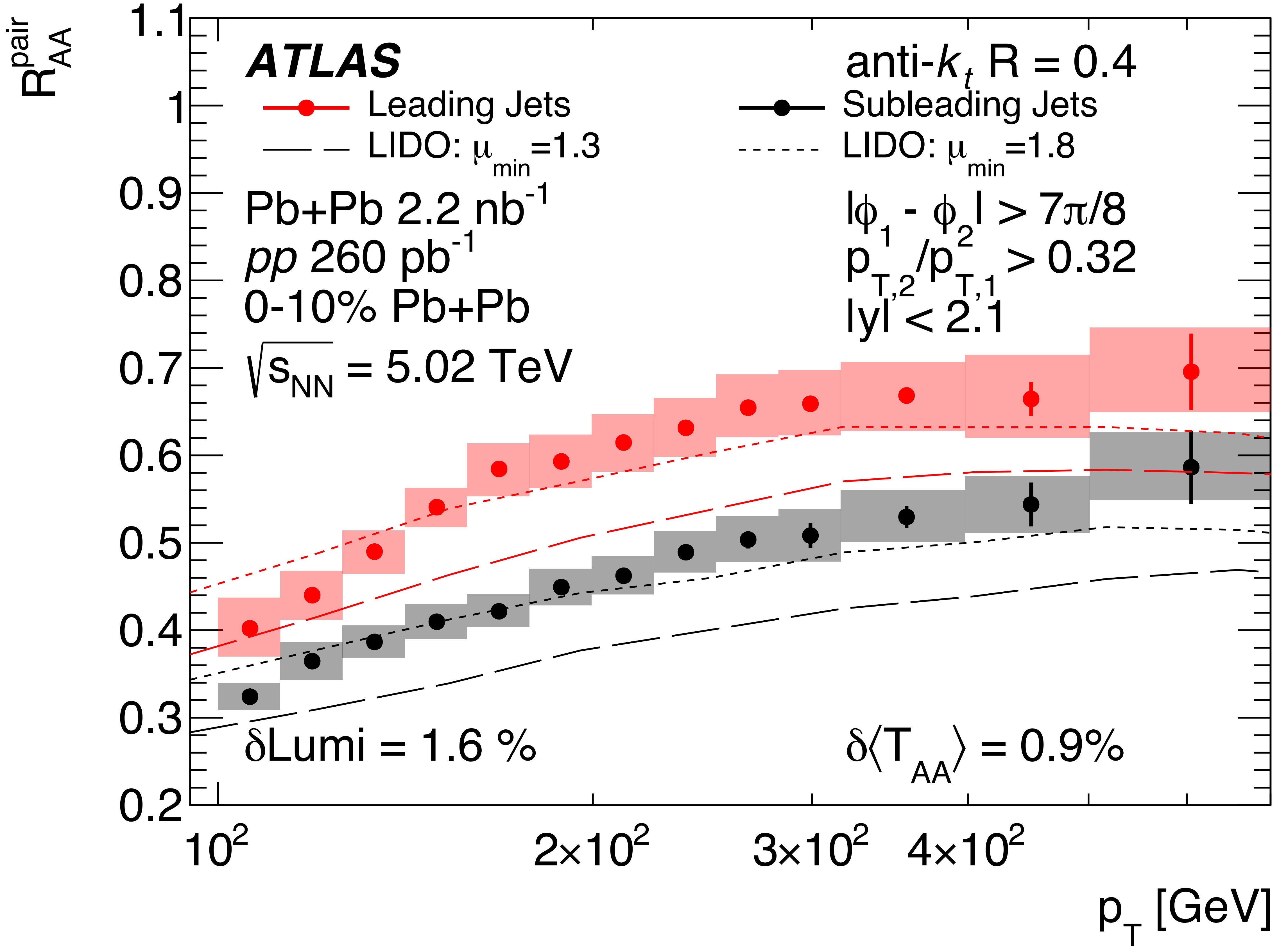
R_{AA} of leading jets after integrating over all subleading jet x_J

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

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

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

0-10% central events



leading jets are significantly suppressed in central collisions

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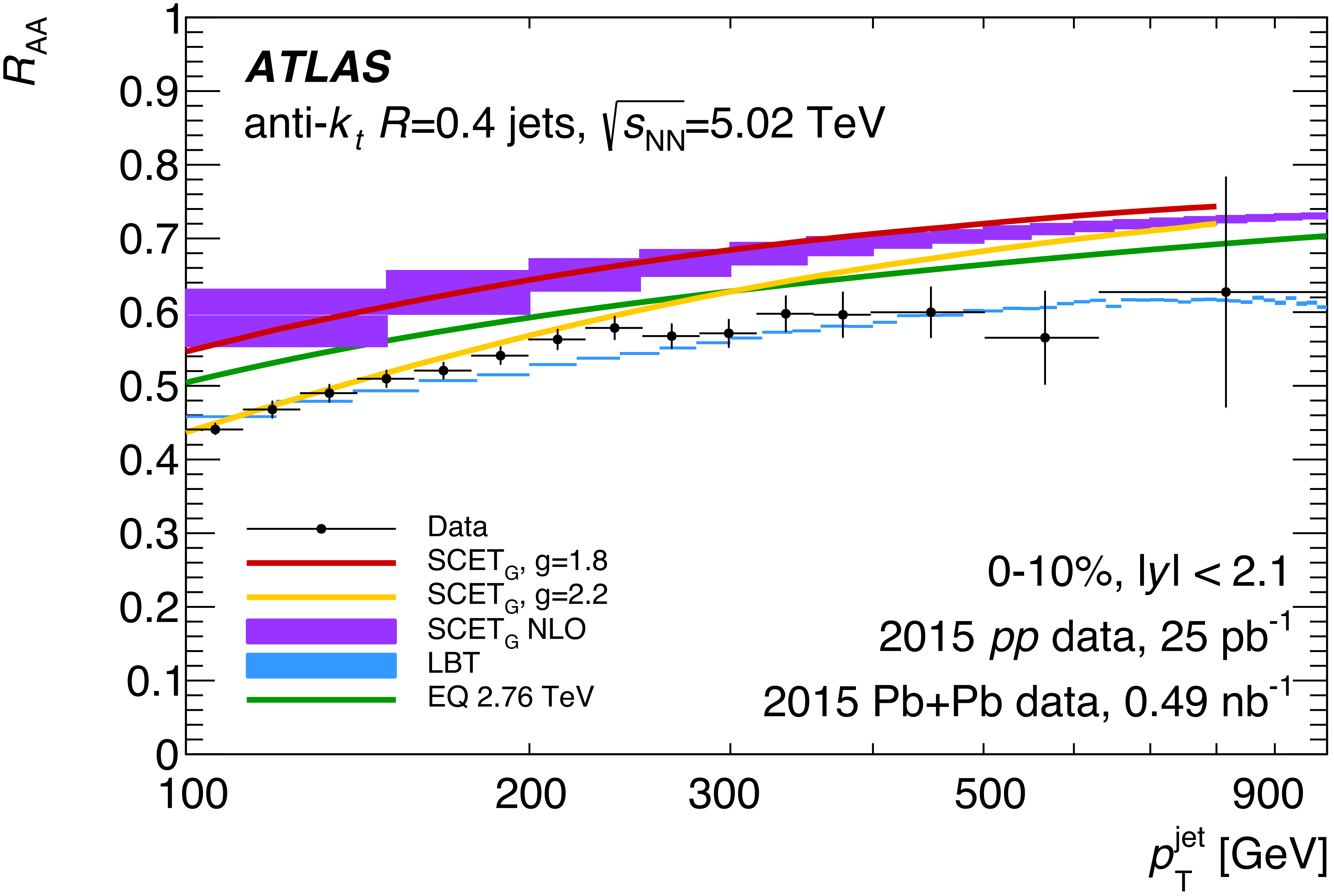
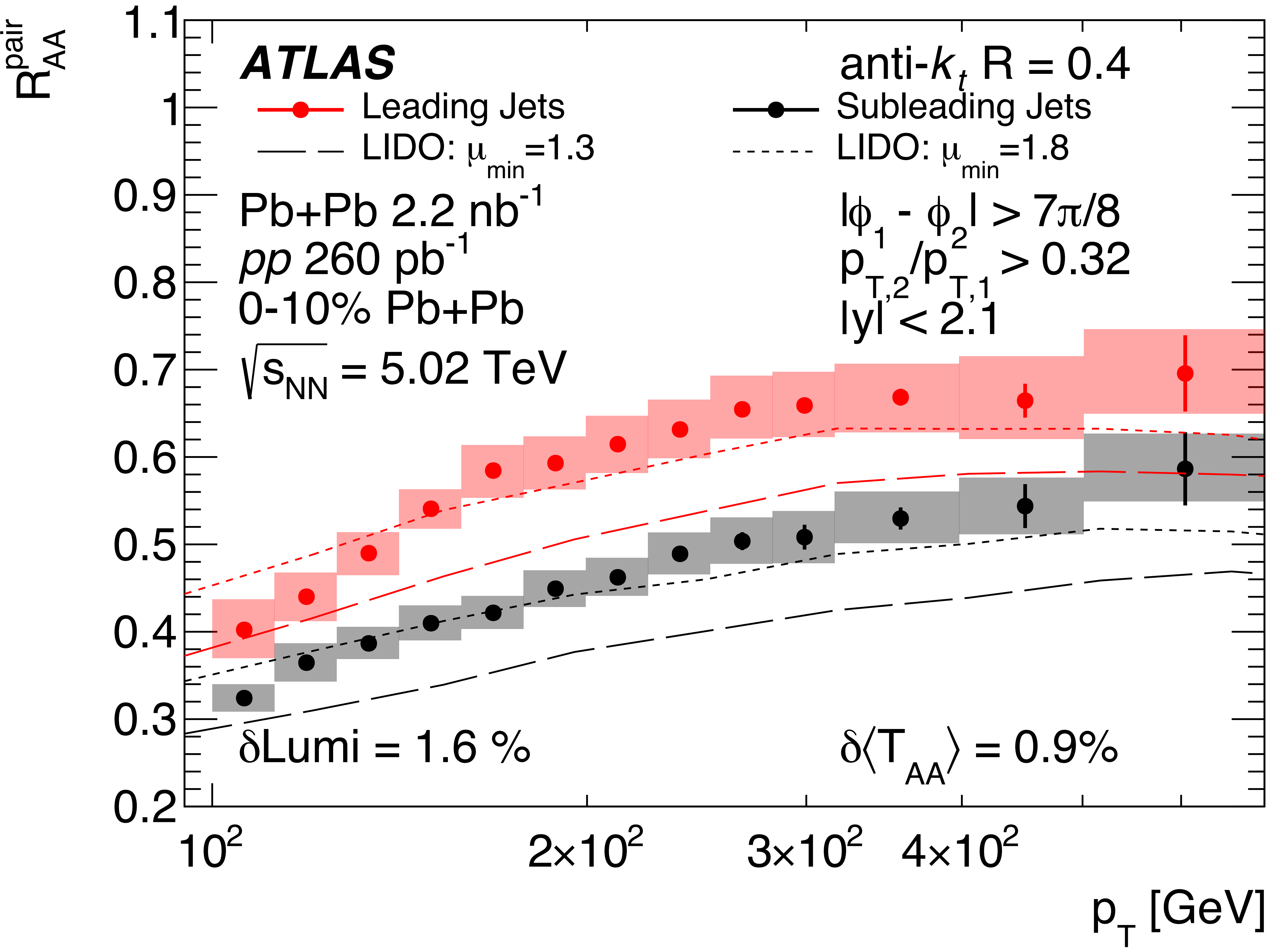
comparison of leading/subleading jets to inclusive jets

inclusive jets





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

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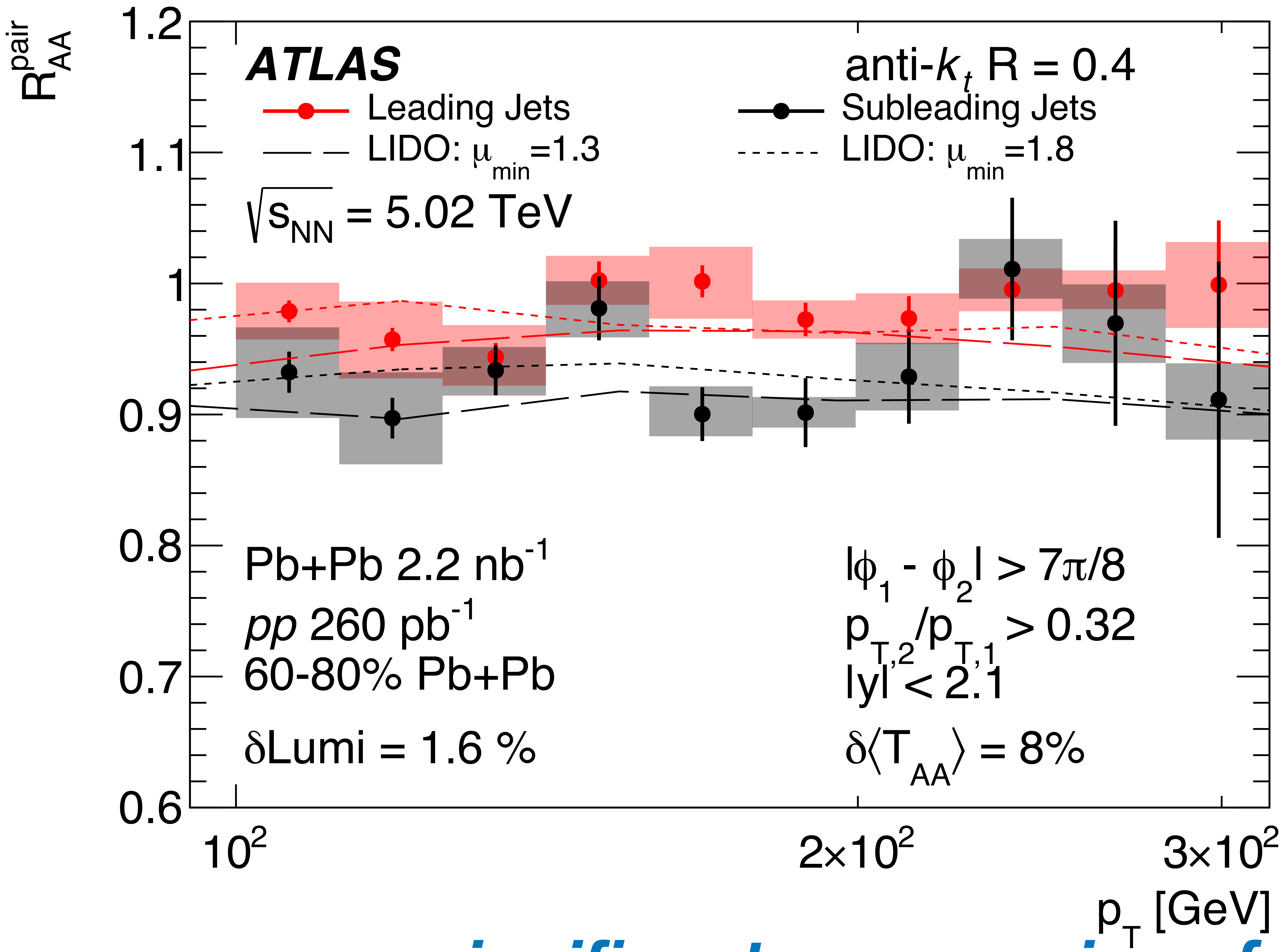
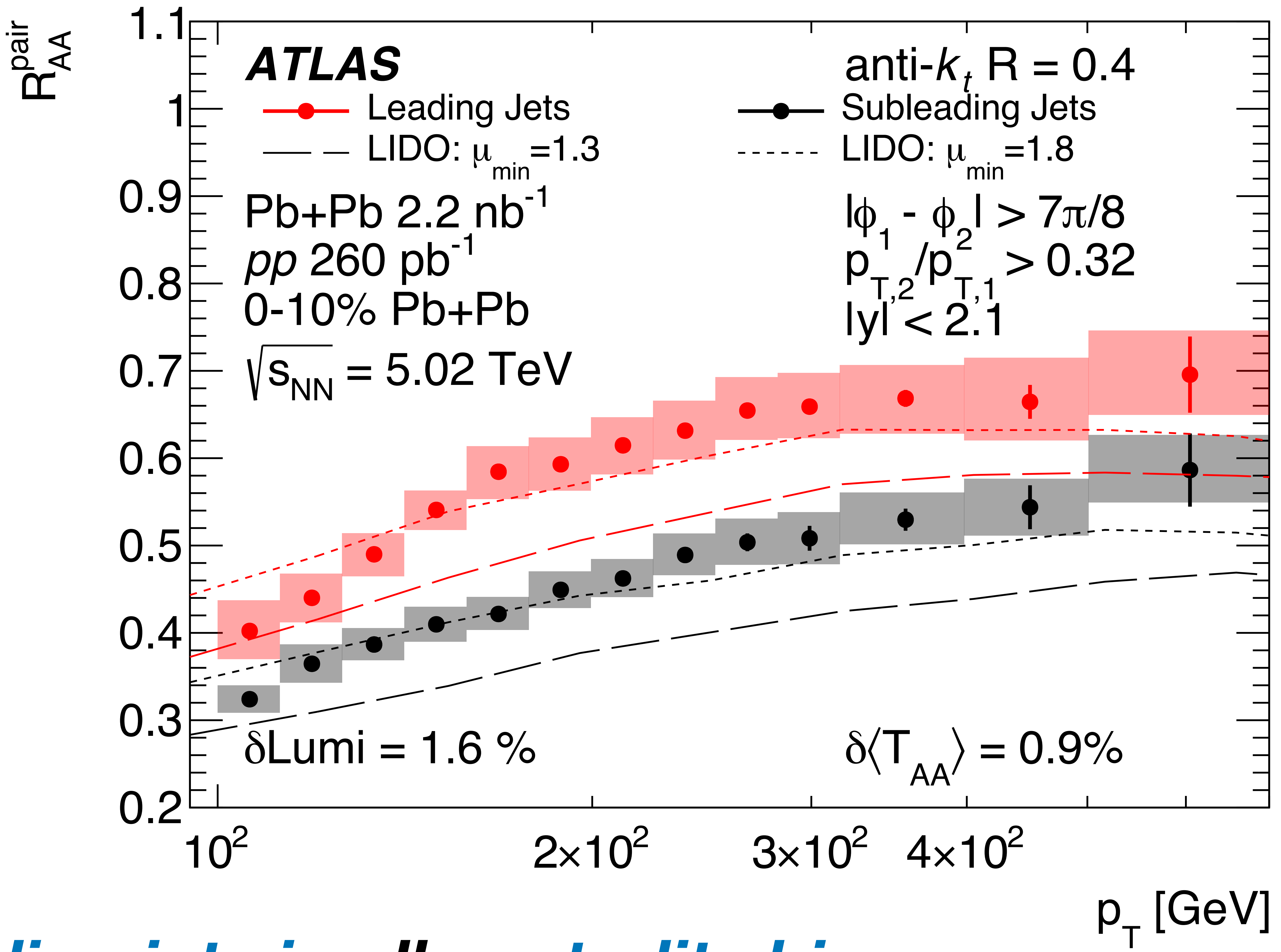
overall suppression of leading/subleading jets

60-80% central events



0-10% central events



significant suppression of subleading jets in all centrality bins

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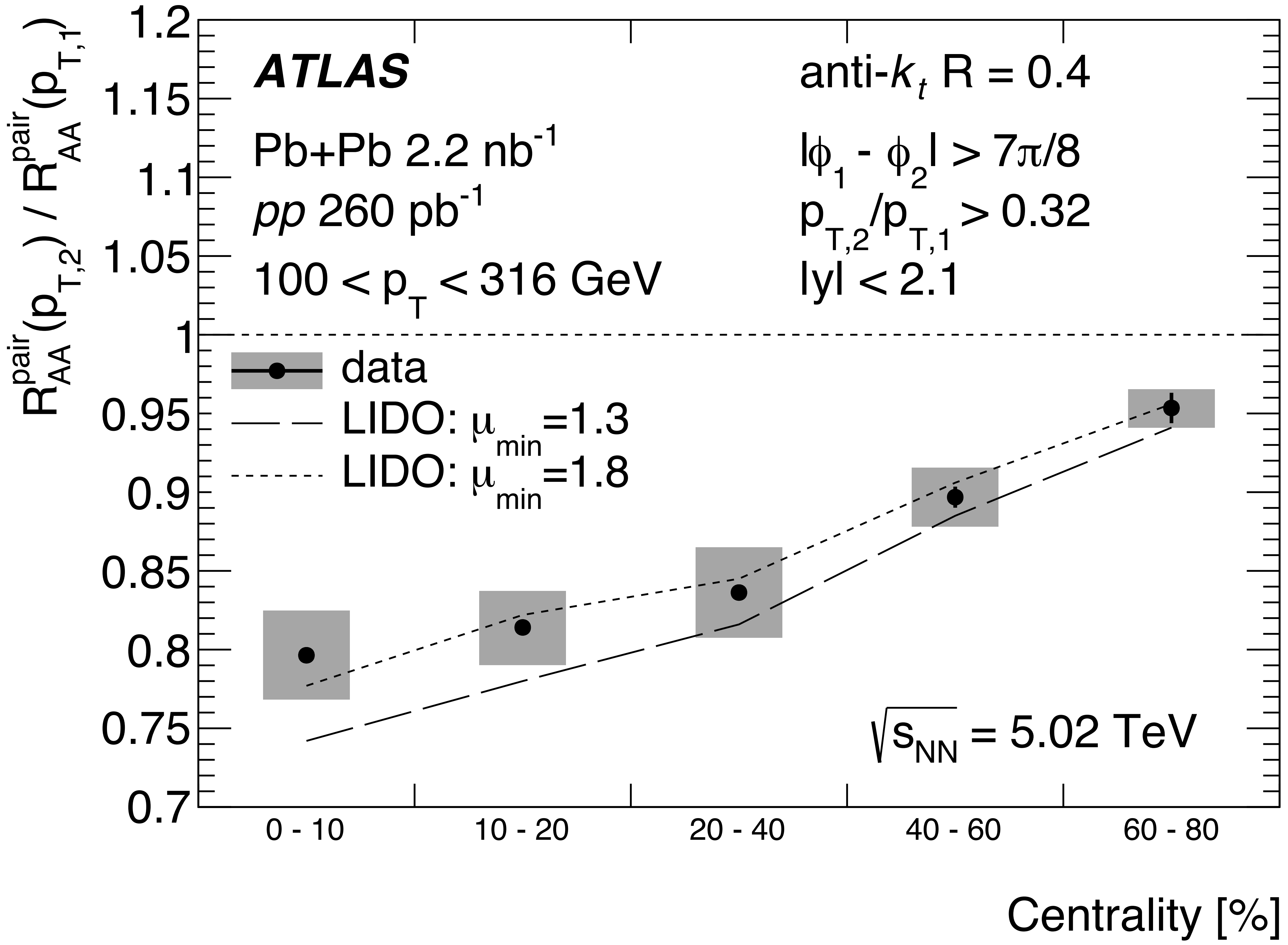
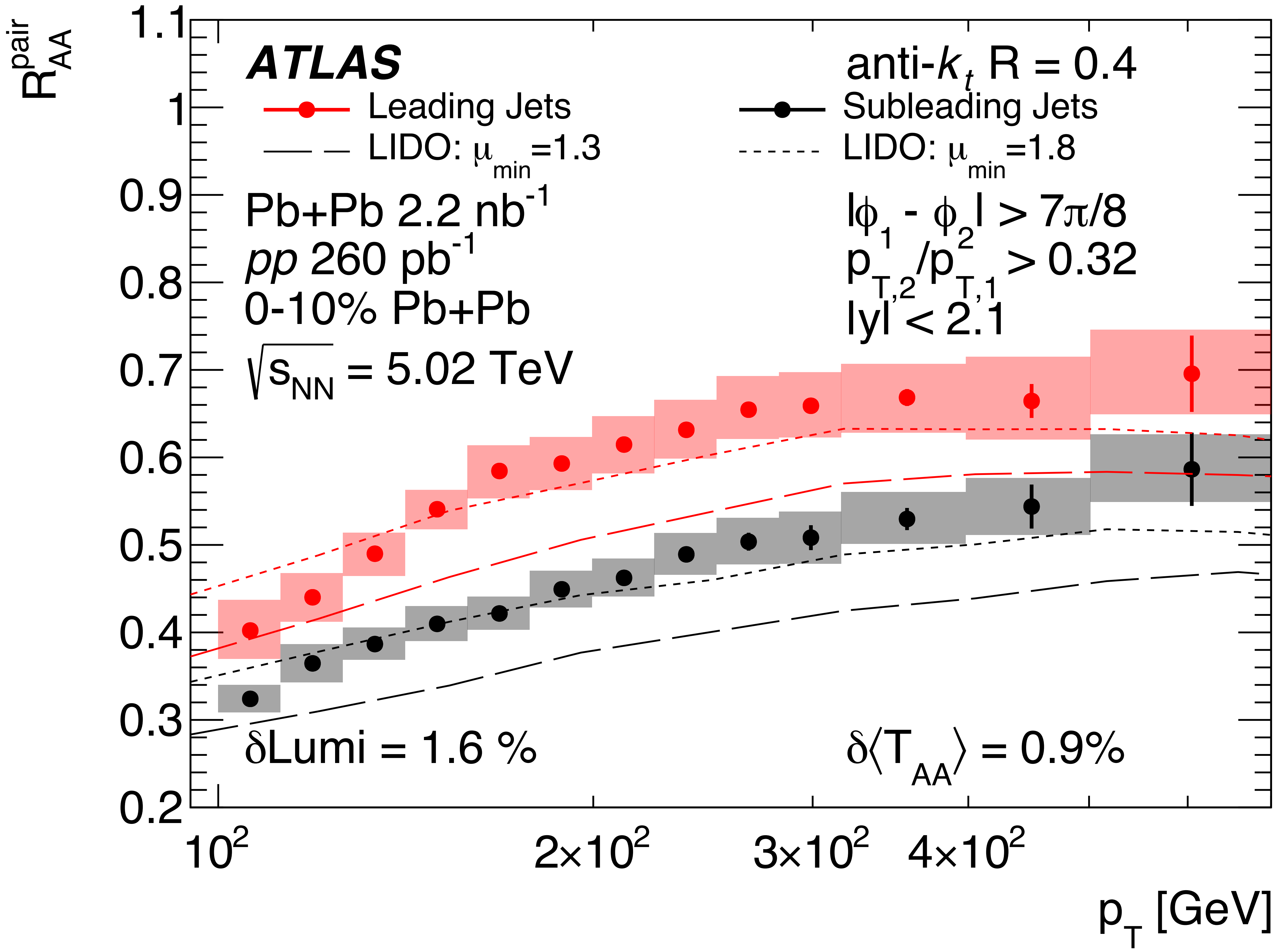
overall suppression of leading/subleading jets

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





subleading jets suppressed more than leading jets in all centralities

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what is the small size limit of jet quenching?

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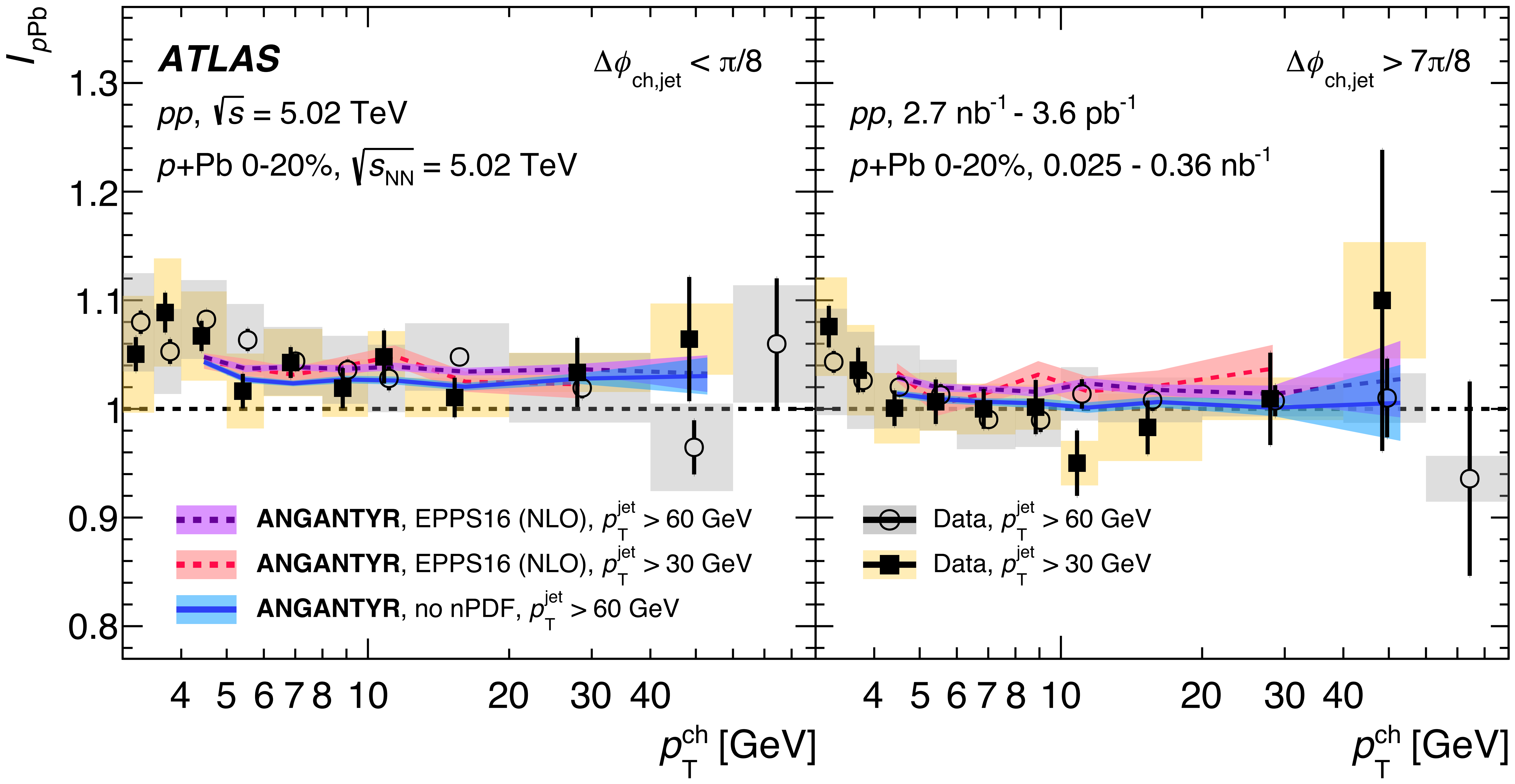
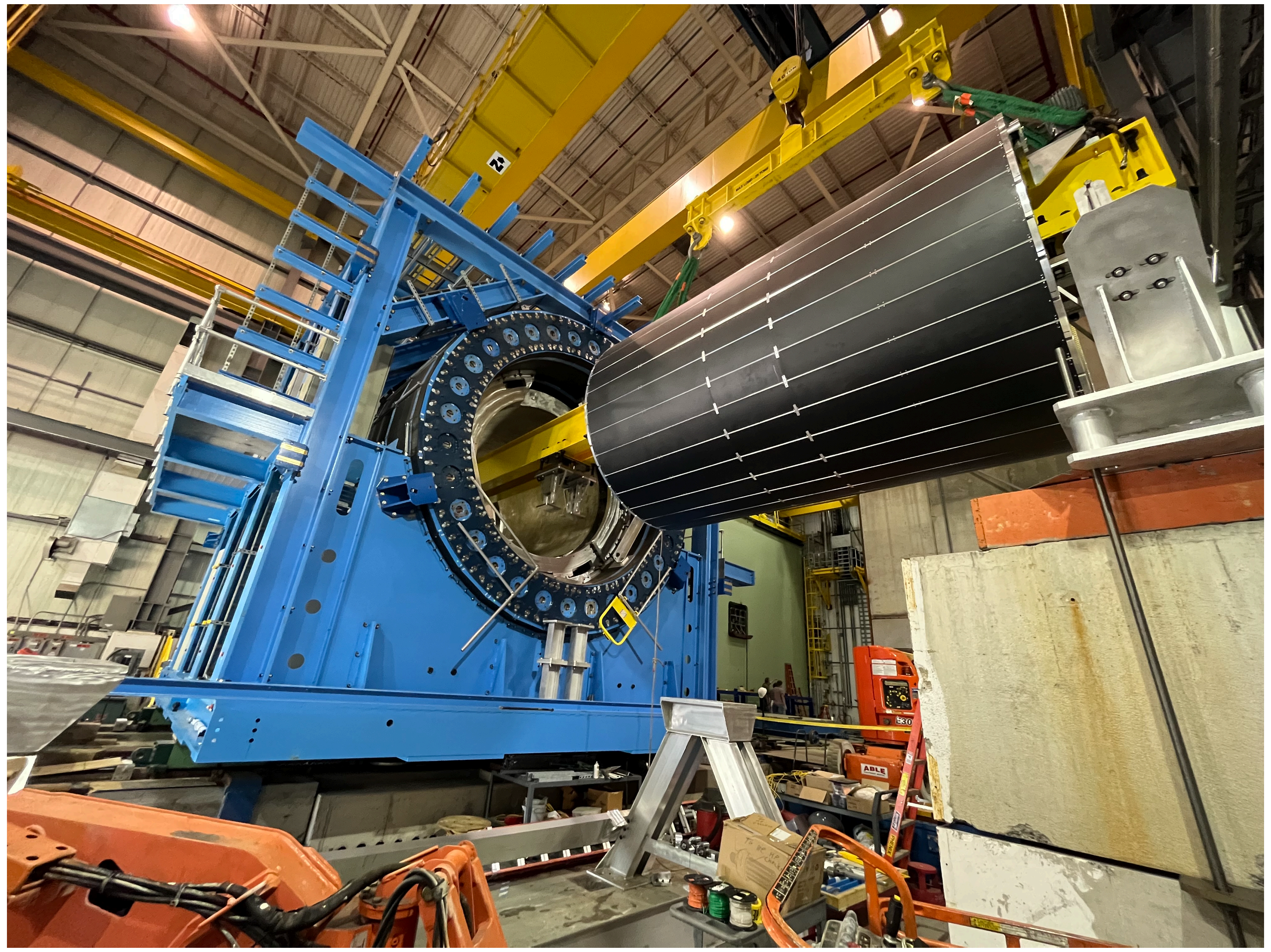


new ATLAS paper looking at jet-hadron correlations in pPb collisions; still no evidence of jet quenching in pPb collisions

this lack of suppression highlights the importance of the OO data at STAR & upcoming LHC data in understanding the small path length limit of jet quenching

sPHENIX

inner HCal insertion June 2022



- the kinematic reach of the LHC measurements has been key to extracting the physics

- with sPHENIX we will be able to fully exploit the RHIC luminosity and have large samples of jets in pp & AuAu collisions over most the available kinematic range

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <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}

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

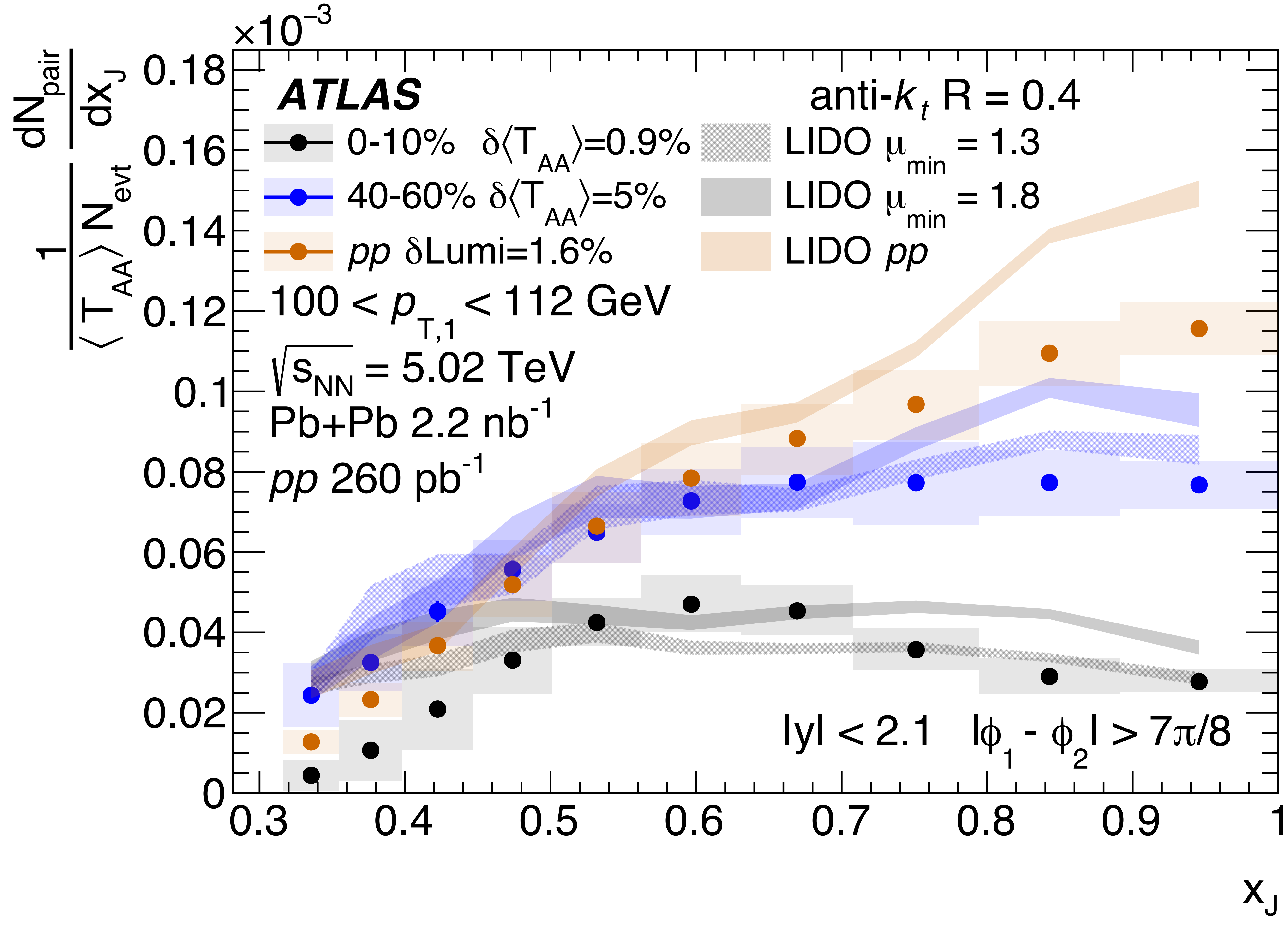
https://www.bnl.gov/sphenix2022/

summary

- precision measurements of jet v_2 & non-zero jet v_3 shows quenching is sensitive to path length differences of the size generated by ε_3
- balanced dijet rated reduced in PbPb collisions
- new strong limits on the effects of quenching in pPb collisions
- challenge: all the measurements shown here integrate over all the jet structures; would be extremely powerful to disentangle these effects
- new opportunities with LHC Run 3, OO (STAR & LHC), & sPHENIX, along with increasingly sophisticated theory make the next several years an excellent time to study jets

backups

LIDO compared to data



significant differences between LIDO and data in at high xJ in pp collisions

key to bench-mark models and data in the reference system in addition to heavy-ions

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jet v_n systematic uncertainties