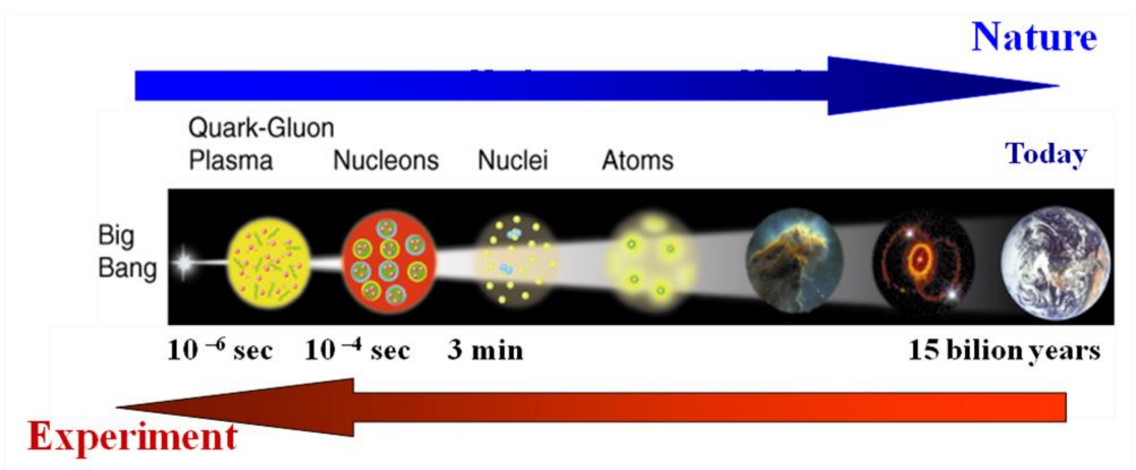
Probing Jet Suppression with Pairs of Jets in ATLAS

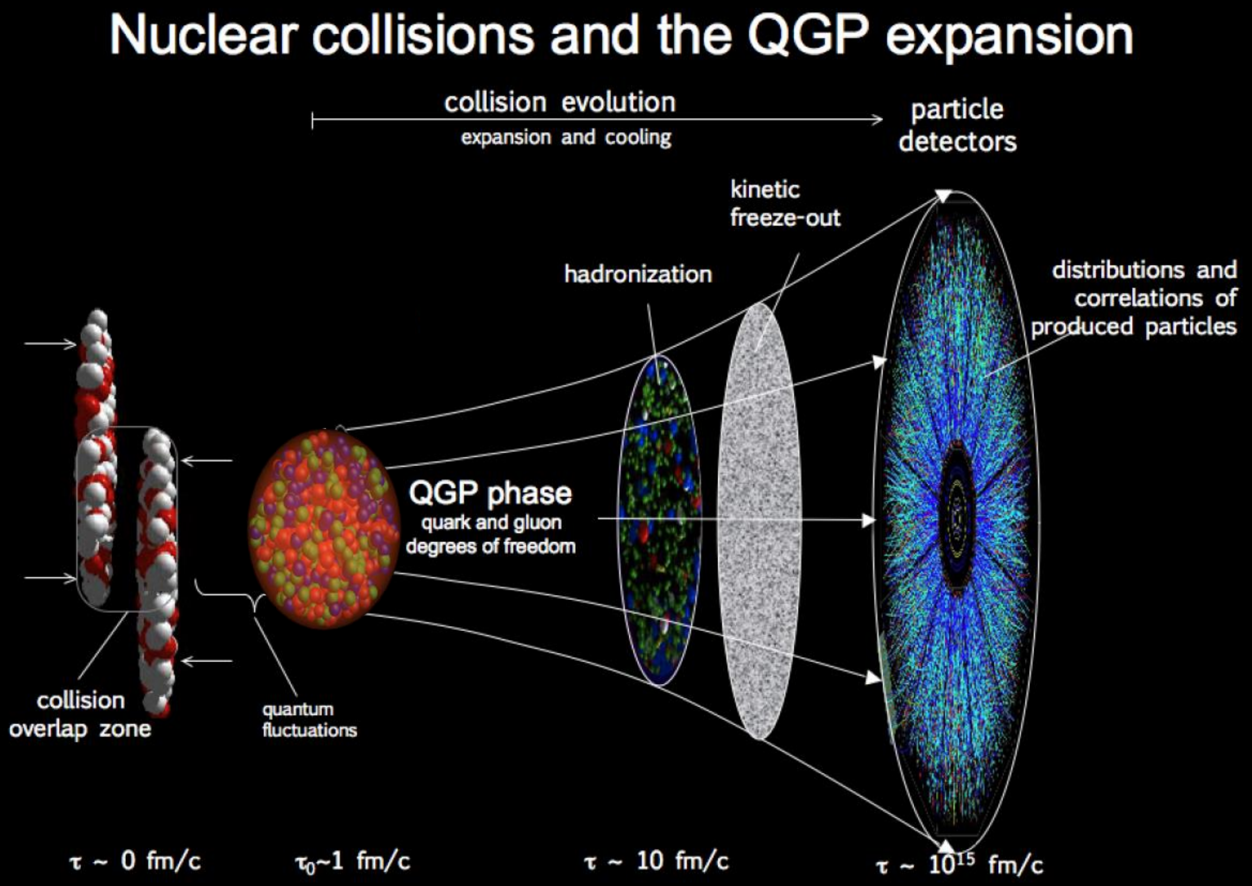
Timothy Rinn

Discussing new ATLAS results documented at: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2019-02/

QGP in Heavy Ion Collisions

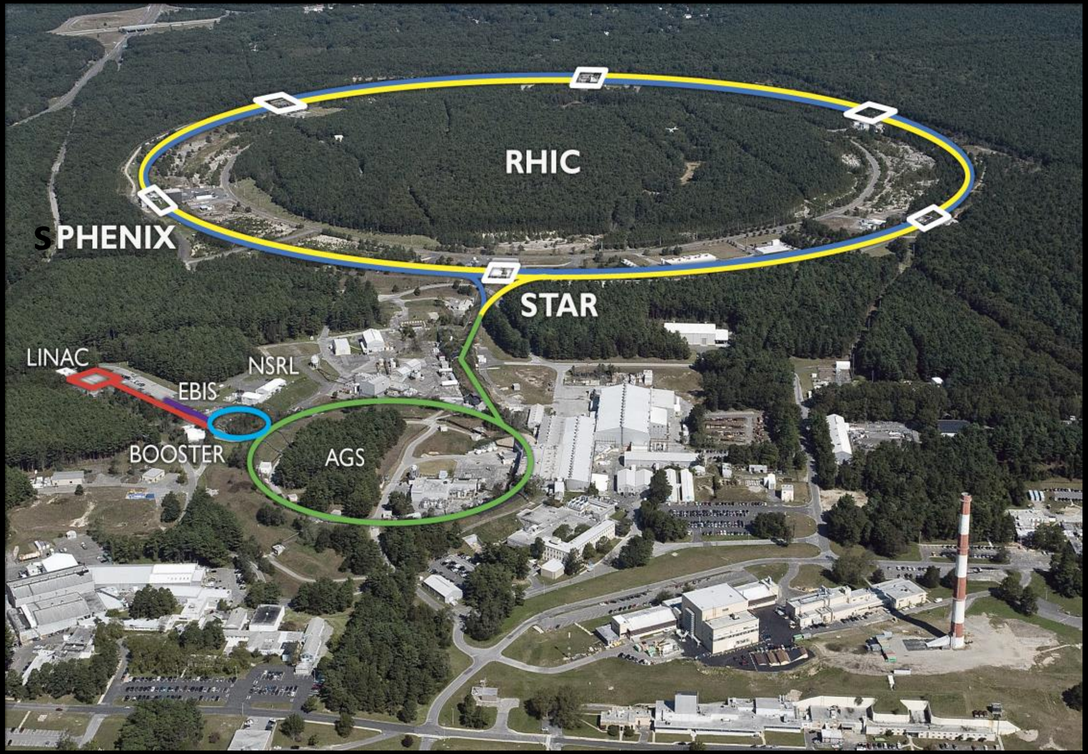
Heavy ion collisions enable the creation of a high density and temperature medium to study strong force interactions in conditions similar to those of the early universe

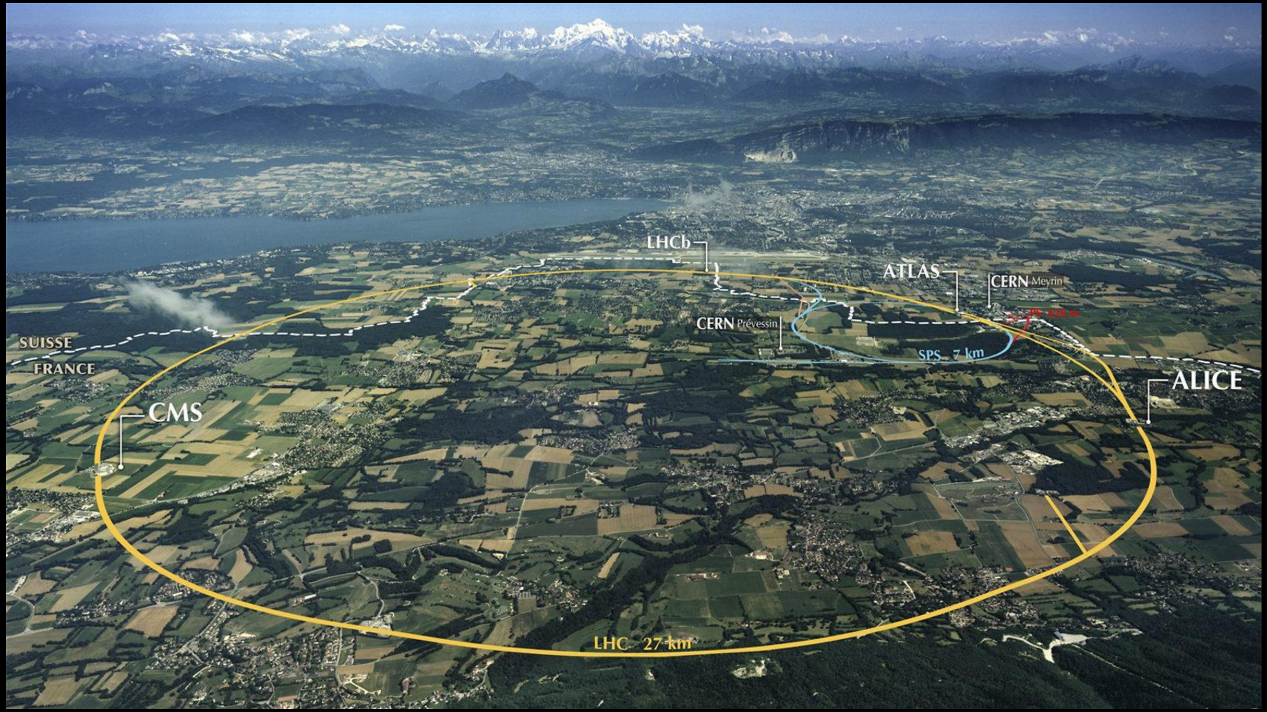




Producing the QGP in laboratories:

- Two collider facilities
  - Relativistic Heavy Ion Collider on Long Island New York
  - The Large Hadron Collider at CERN in Switzerland/France





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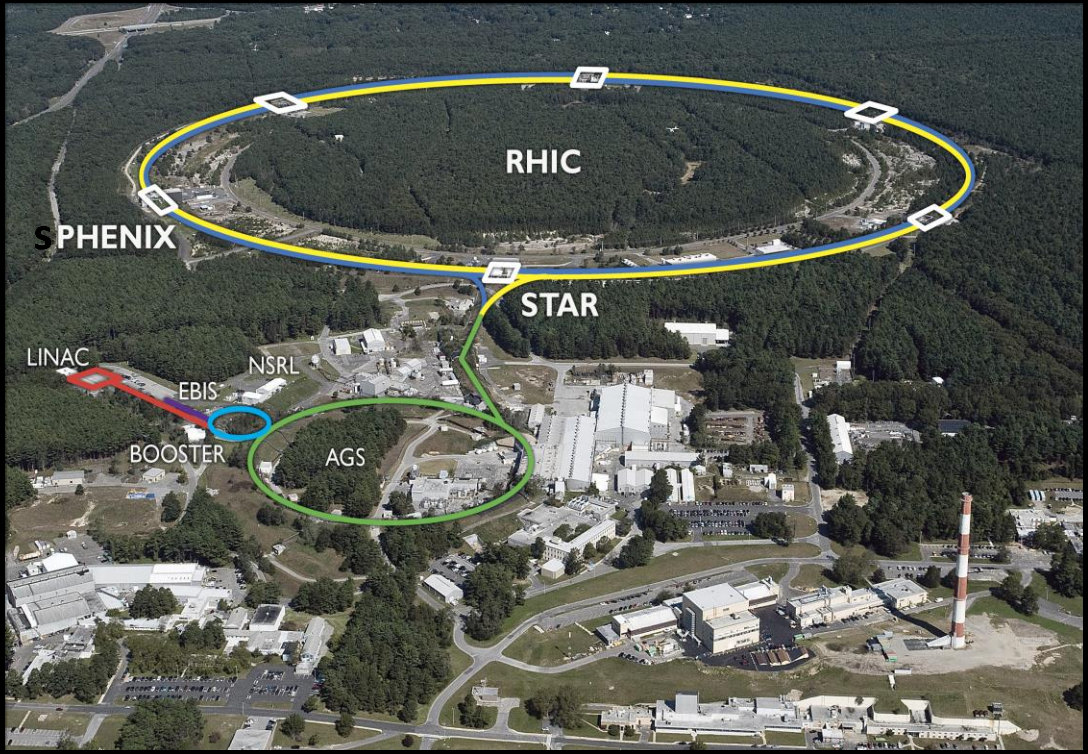


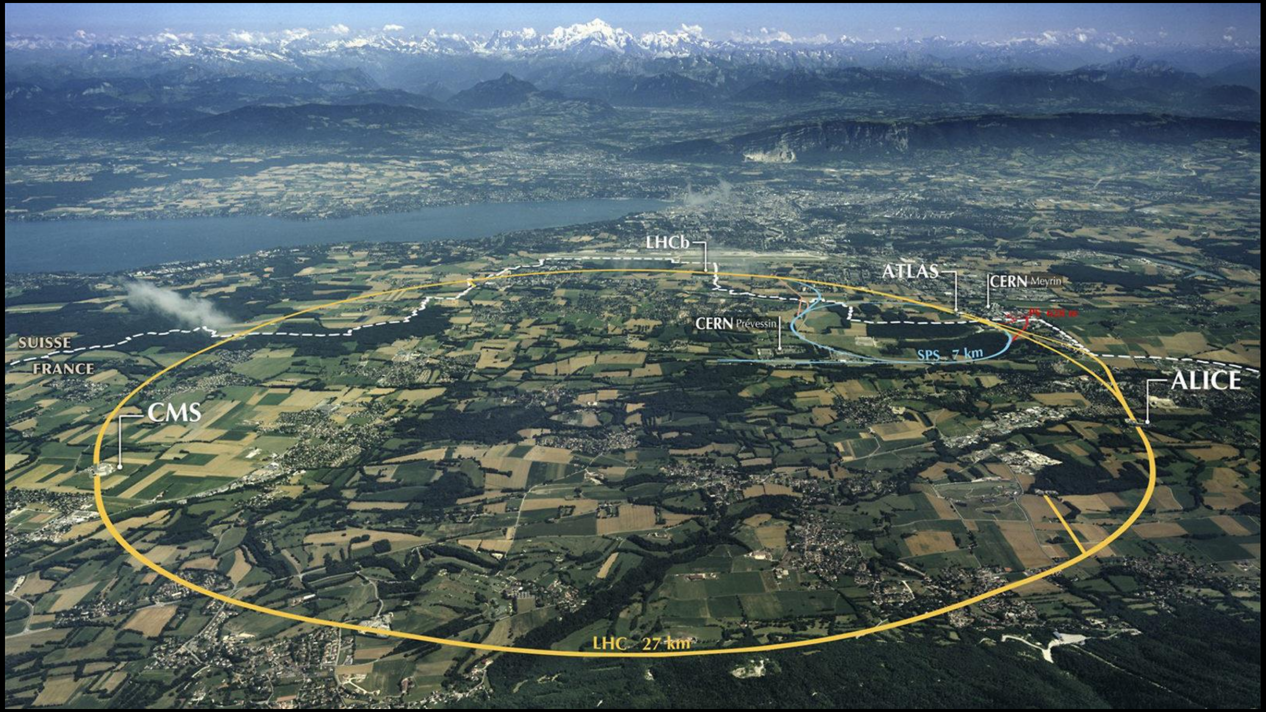
- ➢ Specifically designed for the study of heavy ion collisions
- ➢ Versatile Colliding facility!
  - ➢ Collides a vast range of nuclei:
    - ▪ Au+Au, Cu+Cu, d+Au, U+U, p+Au, He^3+Au
  - ➢ Capable of producing transversely polarized proton beams
- ➢ Tunable "low" collision energy of ≤200 GeV
  - ➢ Produces a Quark Gluon Plasma with T ~ 220 MeV

https://arxiv.org/pdf/1308.2440.pdf

Producing the QGP in laboratories:

- Two collider facilities
  - Relativistic heavy Ion Collider on Long Island New York
  - The Large Hadron Collider at CERN in Switzerland/France

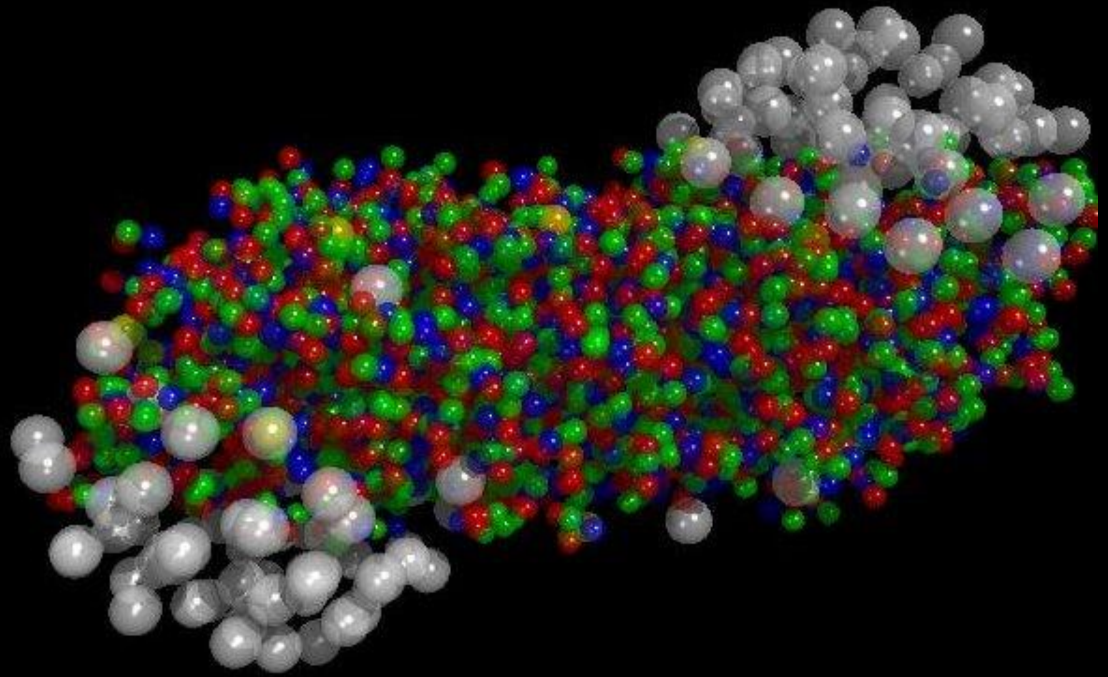
- ➢ Joint facility for high energy particle and heavy ion physics
  - ➢ Share running time between Particle and Nuclear physics efforts
- ➢ High luminosity collider facility
  - ➢ ~30 kHz event rate in Pb+Pb
    - ➢ Run3 will enable 50 kHz running
- ➢ High collision energy of 5.02 TeV
  - ➢ Produces a QGP with T ~ 300 MeV



https://arxiv.org/pdf/1308.2440.pdf

Probing the properties of the QGP

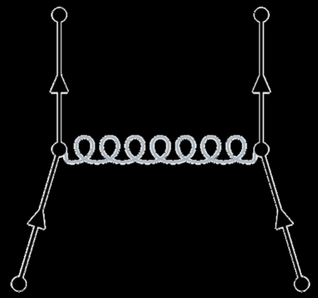
- In order to understand the properties of interactions within the QGP we utilize a variety of probes:
  - High p_T probes, such as jets of high p_T particles
  - Probes with a variety of masses:
    - heavy flavor quarks
  - Correlations of particles



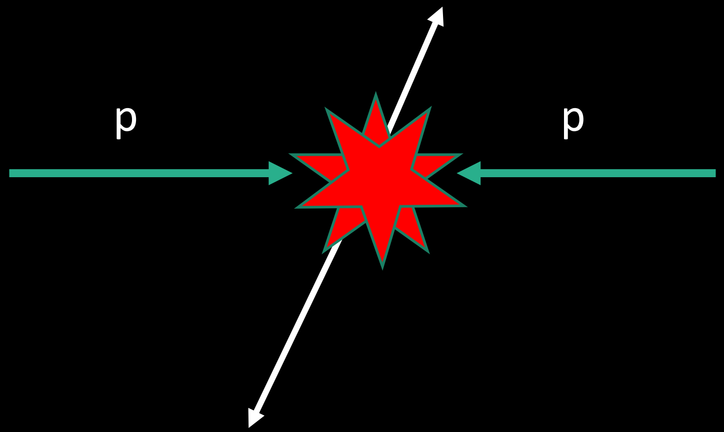
QCD jets

Produced in large momentum transfer QCD interactions:

- Such as:
  q + q -> q + q



- Calculable using perturbative techniques



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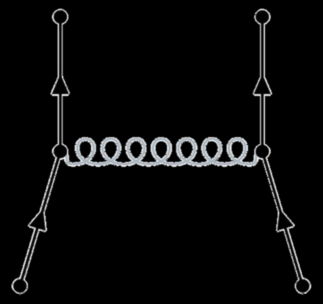
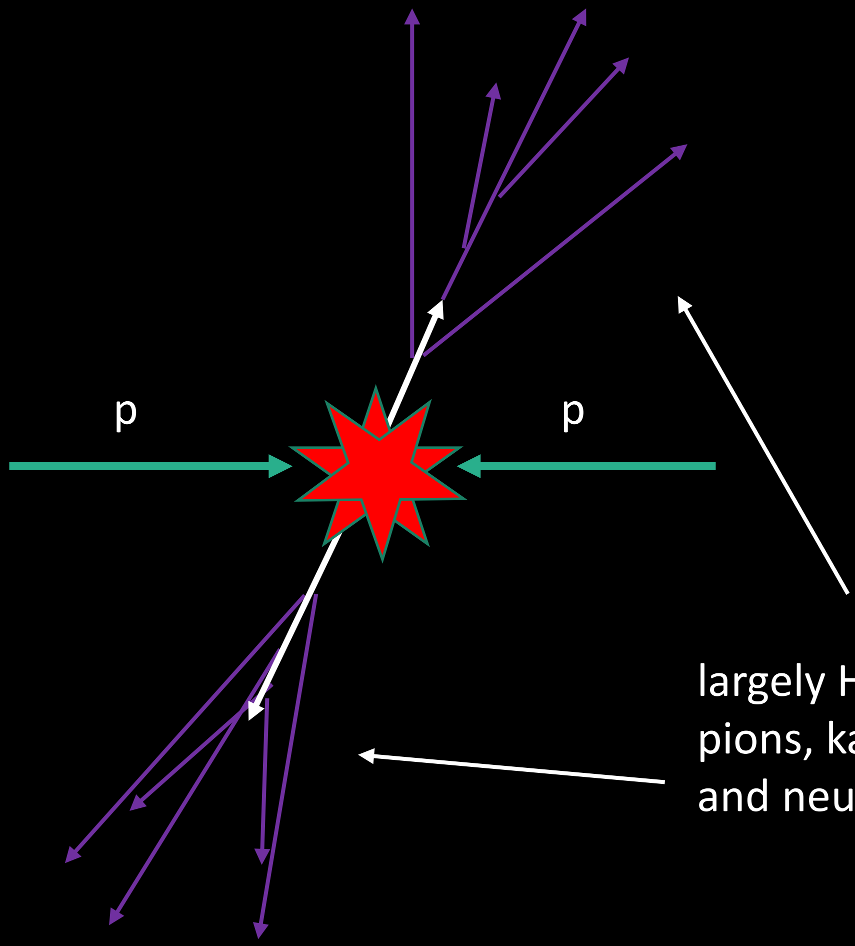


- Calculable using perturbative techniques

- Initial produced quarks/gluons evolve into a particle shower through fragmentation and hadronization

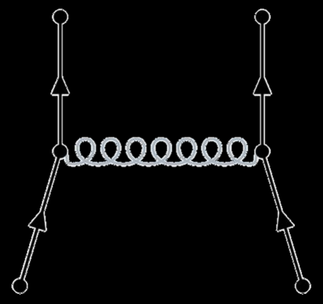


largely Hadrons:
pions, kaons, protons, and neutrons

QCD jets

Produced in large momentum transfer QCD interactions:

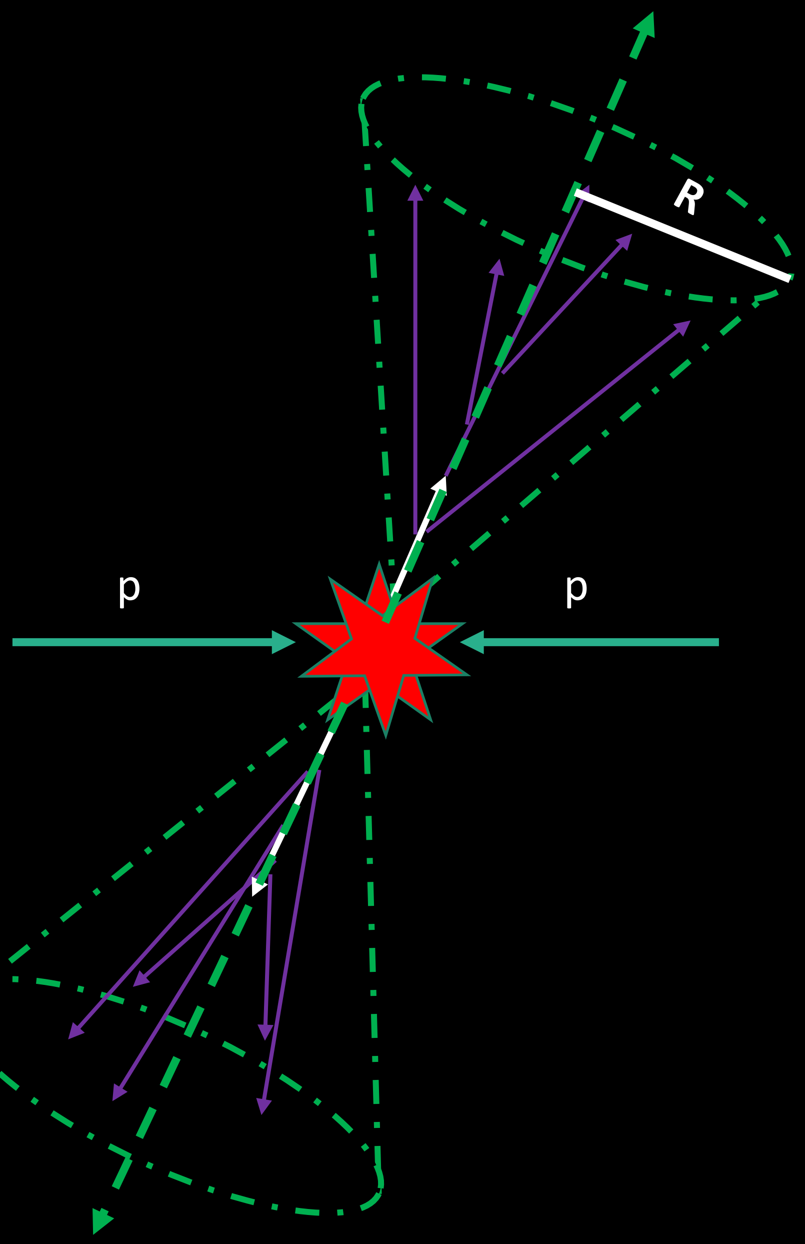
- Such as:
  q + q -> q + q

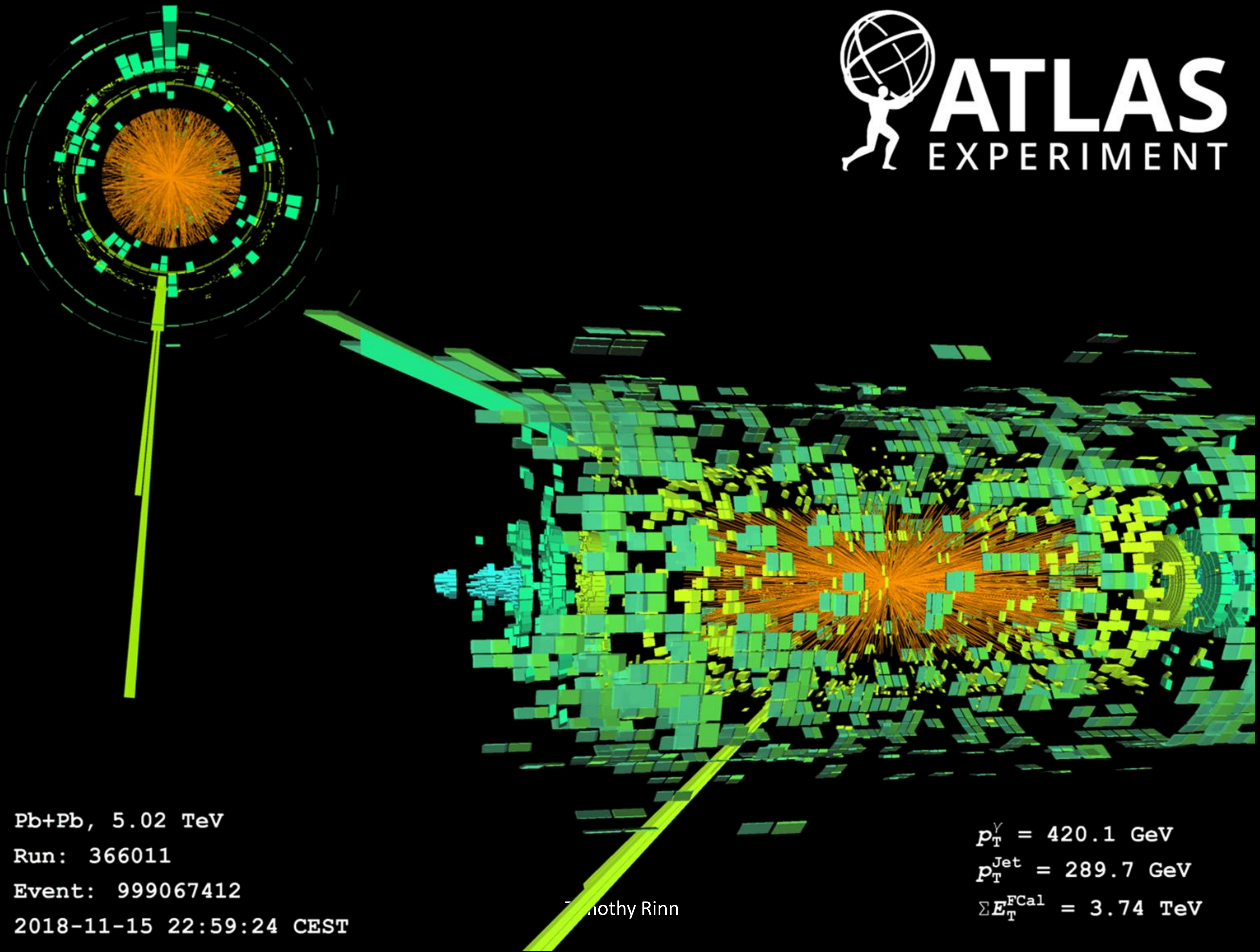


- Calculable using perturbative techniques

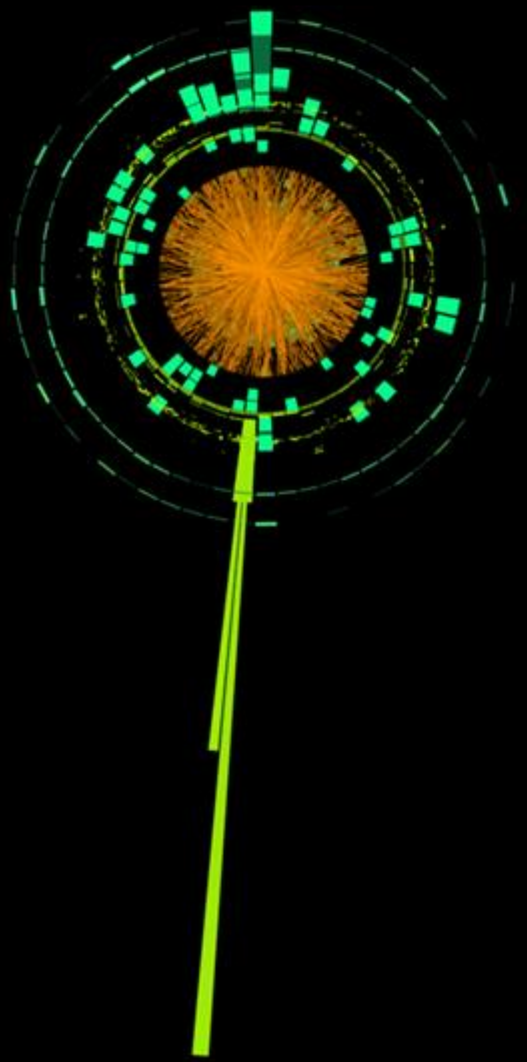
- Initial produced quarks/gluons evolve into a particle shower through fragmentation and hadronization

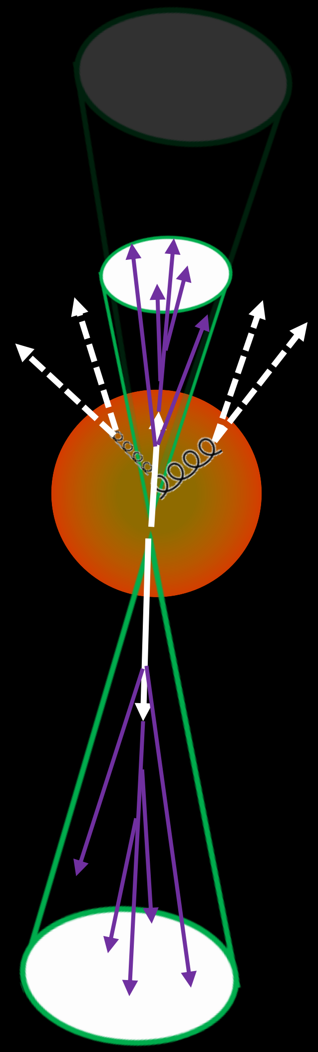
- Final state particles grouped into jets using “jet finding algorithms”




ATLAS
EXPERIMENT
Pb+Pb, 5.02 TeV
Run: 366011
Event: 999067412
2018-11-15 22:59:24 CEST
p_T^{γ} = 420.1 GeV
p_T^{Jet} = 289.7 GeV
ΣE_T^{FCal} = 3.74 TeV

Jets as probe of QGP:





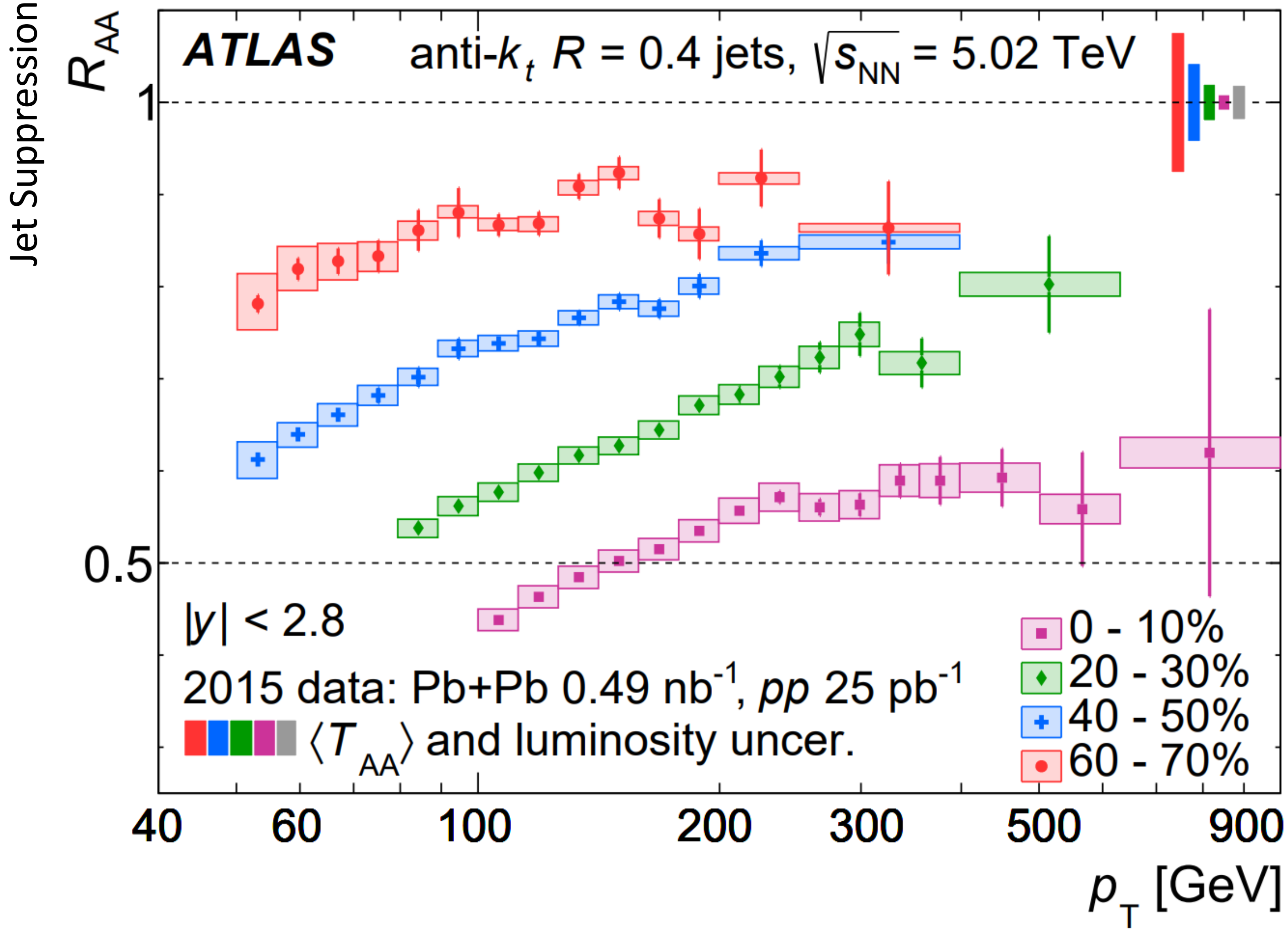
Quarks and Gluons interact with the QGP as they traverse the nuclear medium

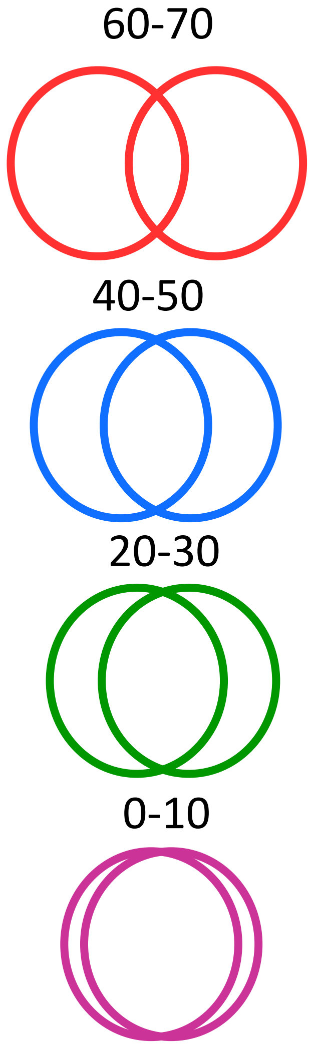
- Multiple scatterings with quarks and gluons
- Experience medium induced gluon radiation

Results in energy moved outside of the jet cone

Jets Quenching

$$R_{AA} \equiv \frac{\frac{1}{N_{evnt}\langle T_{AA}\rangle}\frac{dN^{AA}}{dp_T}}{\frac{1}{L_{pp}}\frac{dN^{pp}}{dp_T}}$$





Dijets as probes of energy loss

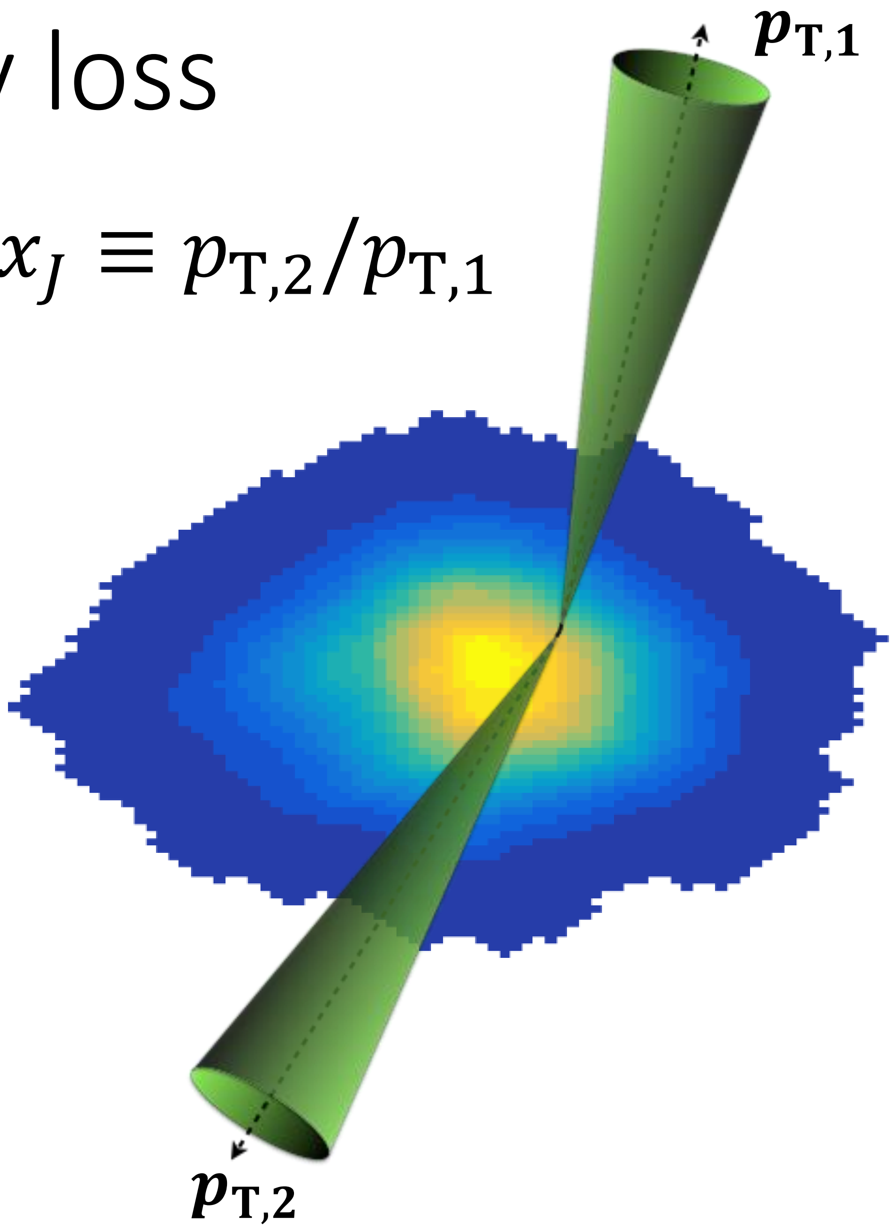
Back-to-back jet pairs provide access to asymmetric energy loss

Can provide constraint on the contributions from:

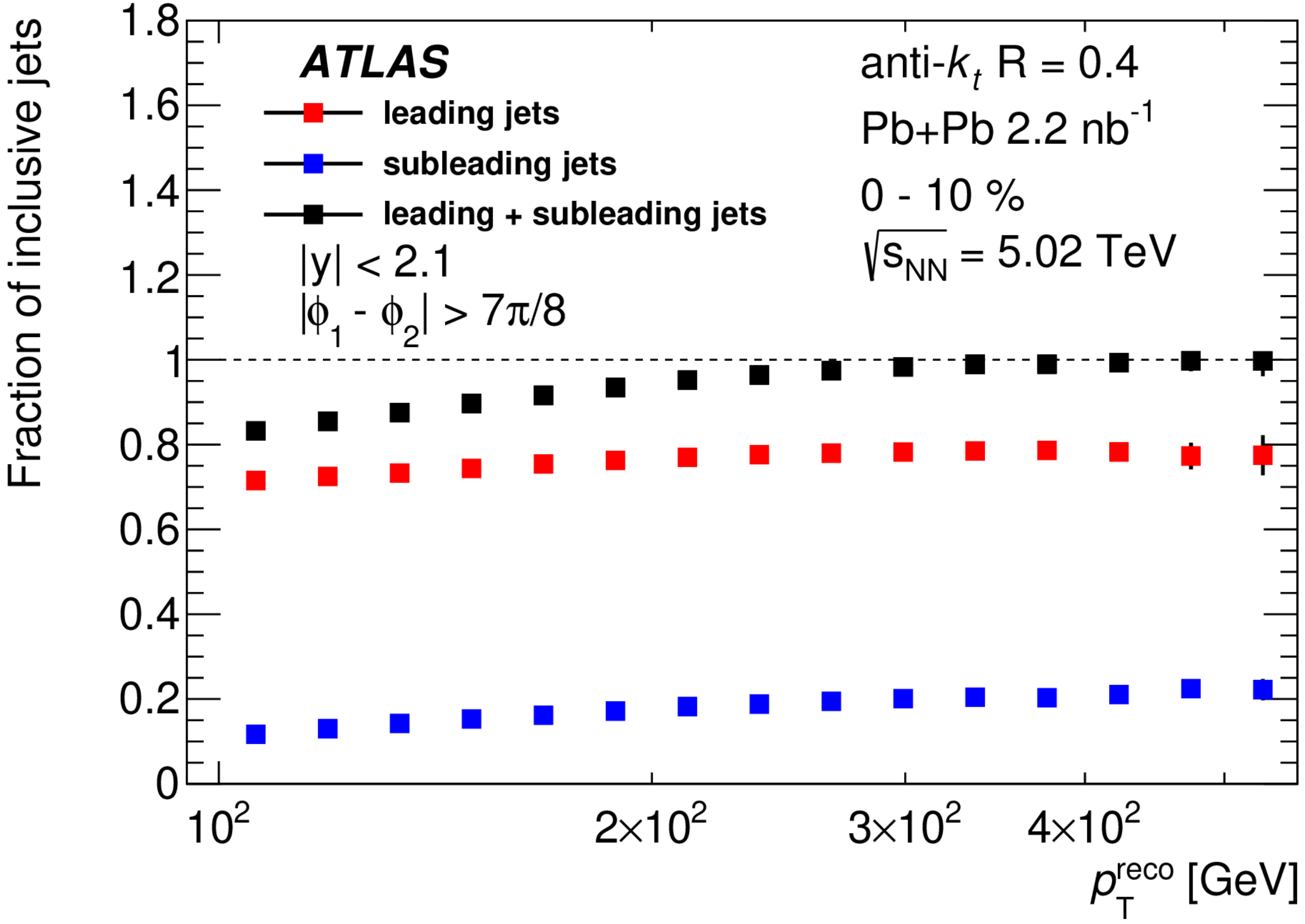
- Path length dependent energy loss
- Energy loss fluctuations

Provide enhanced sensitivity to small amounts of jet quenching

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



Dijet fraction of inclusive jets

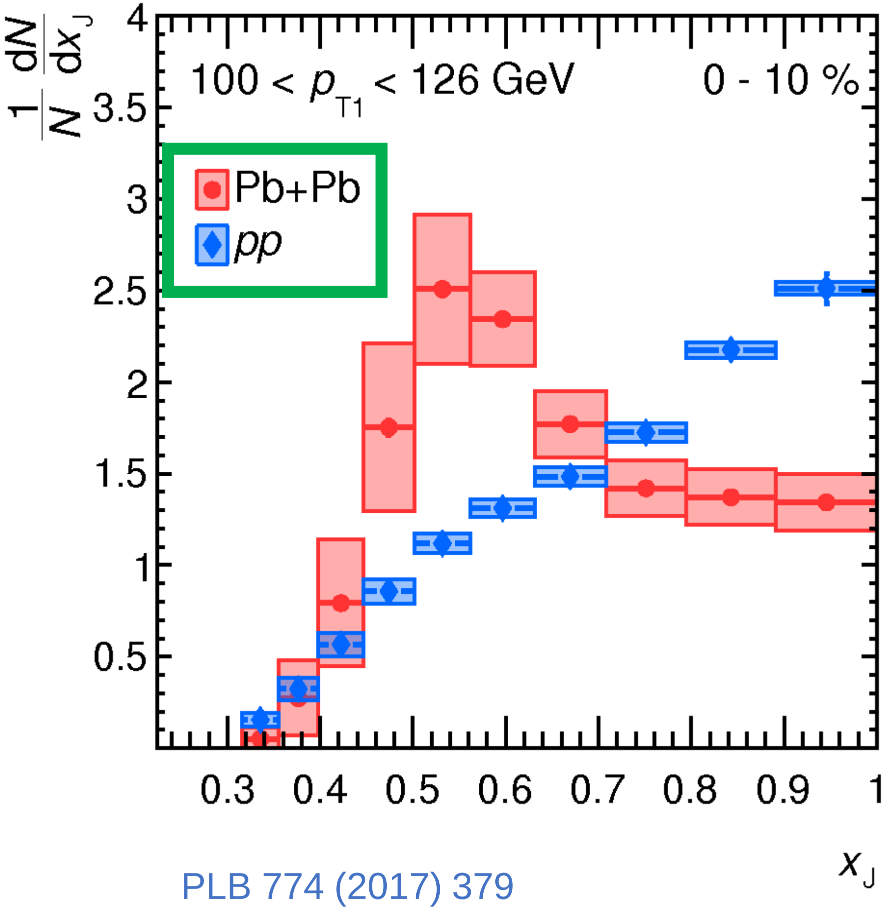


Measured fractions of inclusive jets which are part of the leading **dijet**, the **leading jet** of the dijet, or the **subleading** jet of the dijet

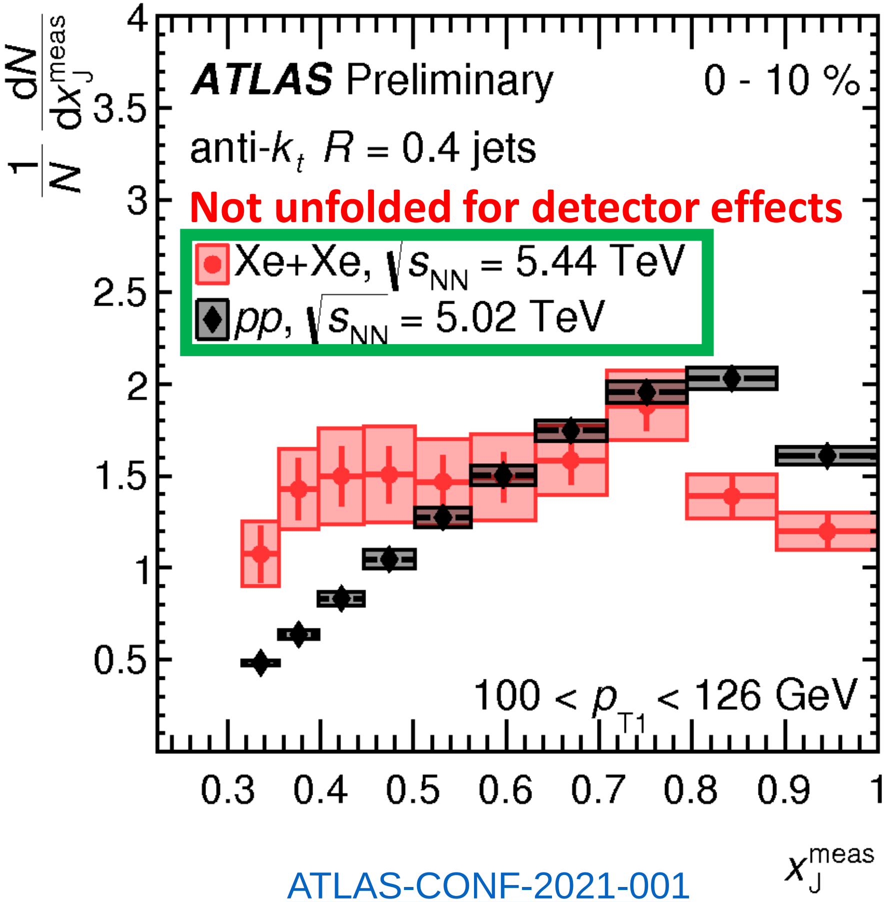
At 100 GeV: 83% of inclusive jets are part of the leading dijet

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

Previous ATLAS results of dijet balance



PLB 774 (2017) 379
(see also: PRL 105(2010) 252303)



ATLAS-CONF-2021-001

Modifications of the x_J **shape** are measured in both Pb+Pb and Xe+Xe

In central Pb+Pb a peak structure is observed at intermediate x_J

- ➢ A persistent challenge for the theory community

Dijet analysis overview:

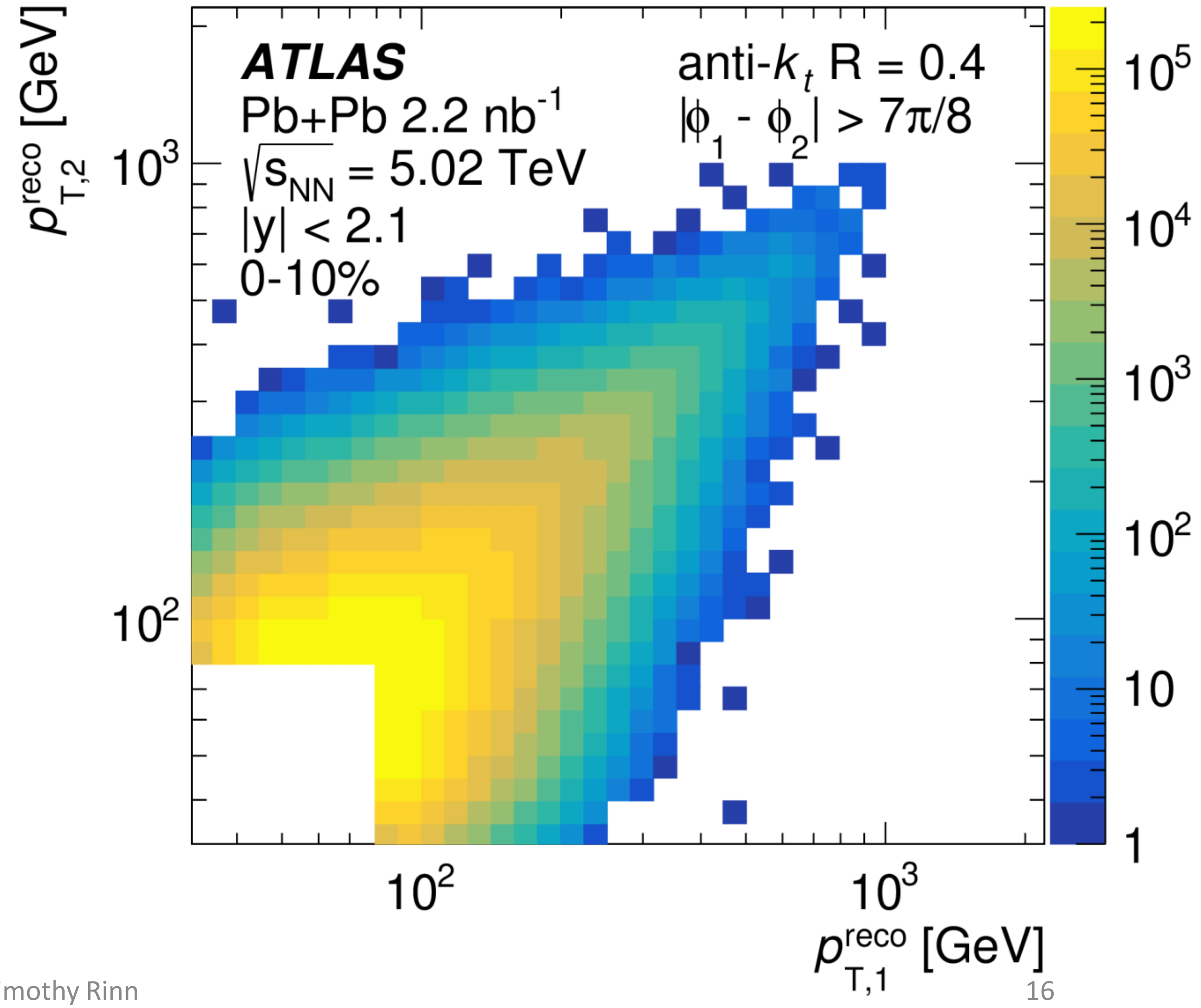
Two-dimensional $(p_{\mathrm{T},1}, p_{\mathrm{T},2})$ distributions are measured for the leading dijet pair

- $\Delta\phi_{1,2} > \frac{7\pi}{8}$
- $|\eta| < 2.1$

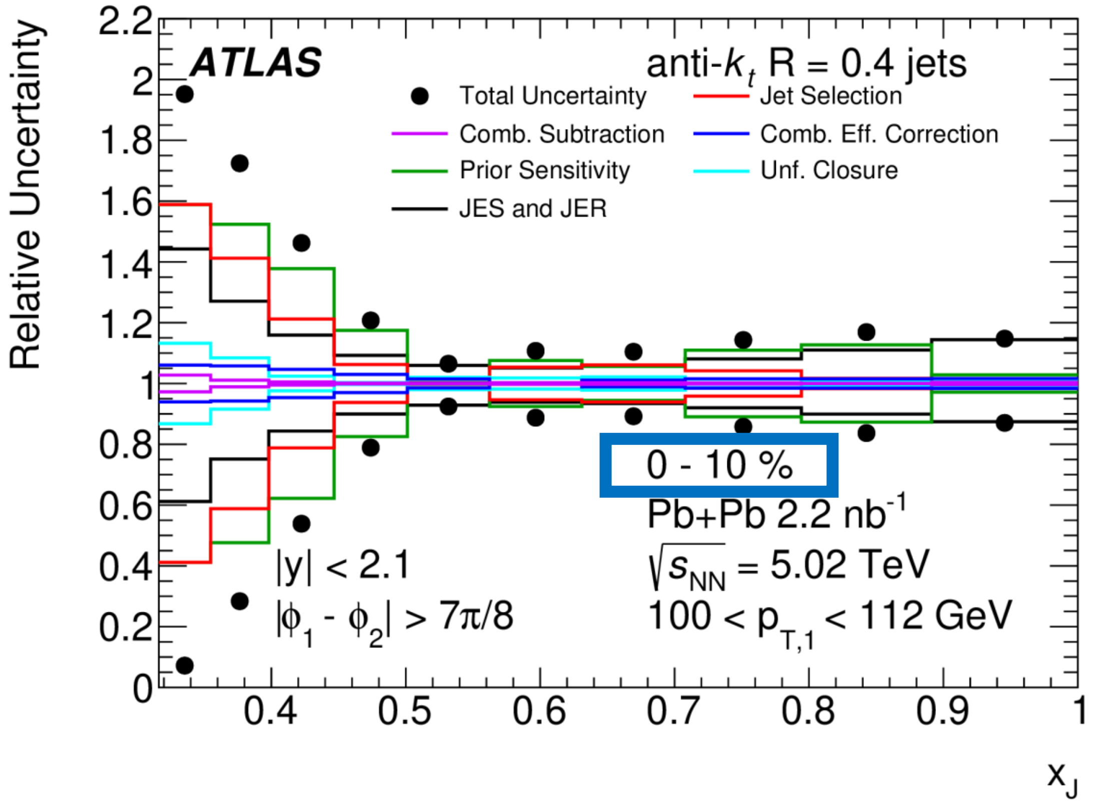
Corrected for combinatoric dijets using a $\Delta\phi_{1,2}$ sideband

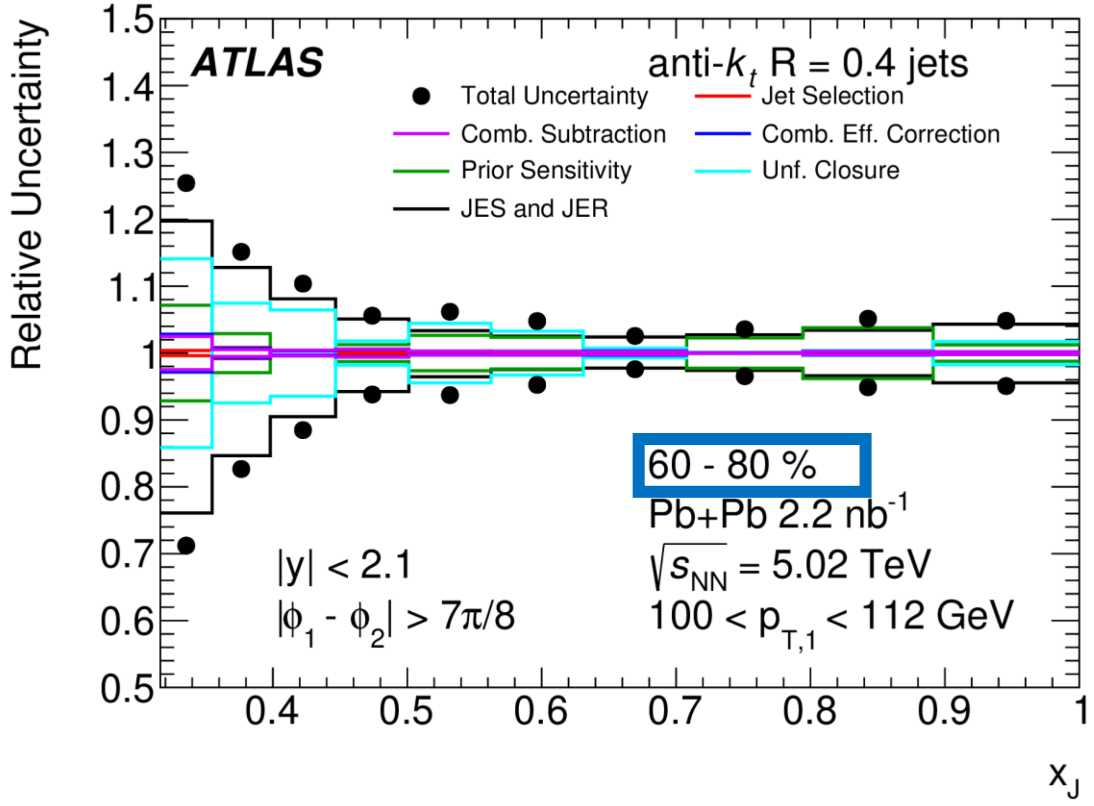
Unfolded for detector effects using 2D Bayesian unfolding

Unfolded $\frac{dN_{pair}}{dp_{T,1}dp_{T,2}}$ distribution projected across selections of $p_{\mathrm{T},1}$ to extract $\frac{dN}{dx_J}$ distributions



Uncertainties on per dijet pair x_J distributions





In central events the uncertainties are driven by unfolding

In peripheral events the uncertainty from the jet energy scale and resolution are dominant

Dijet x_J 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*

Never Before Measured

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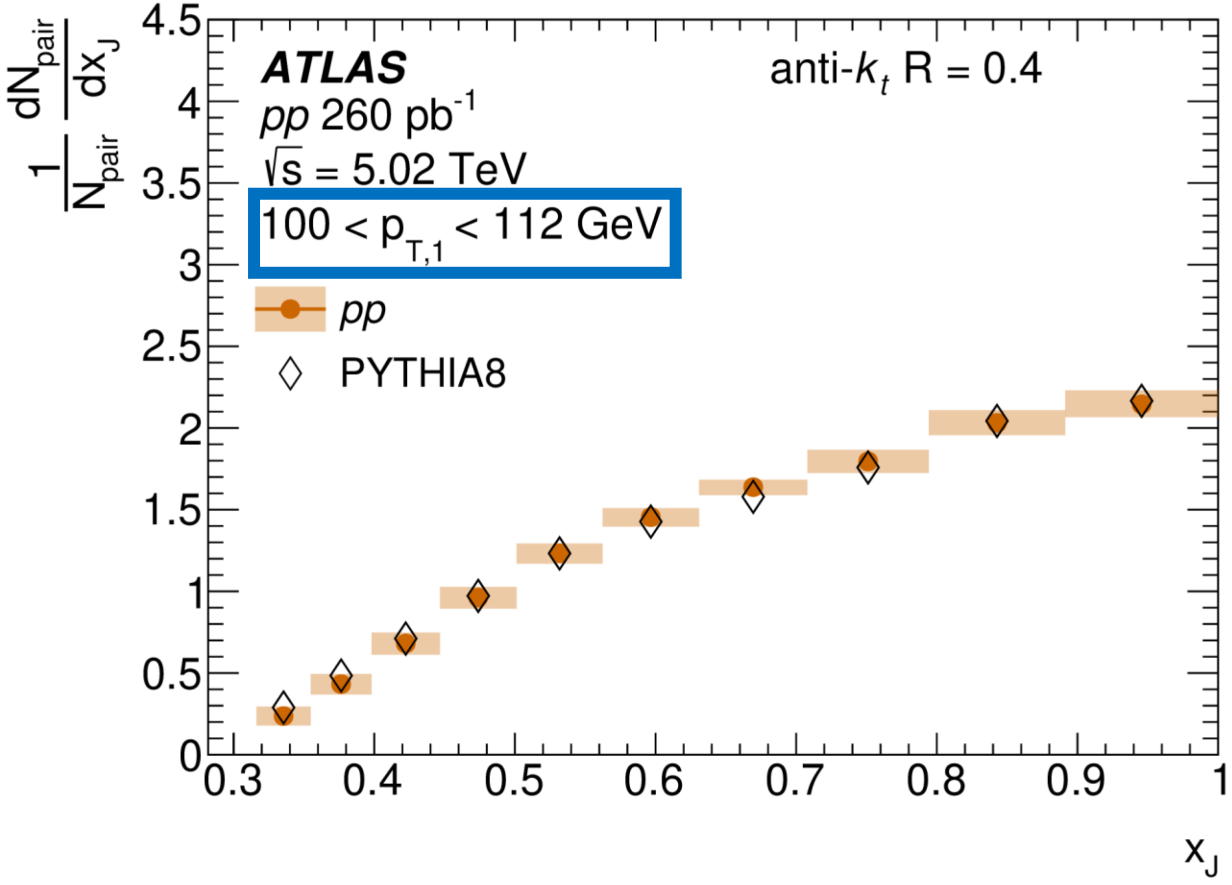
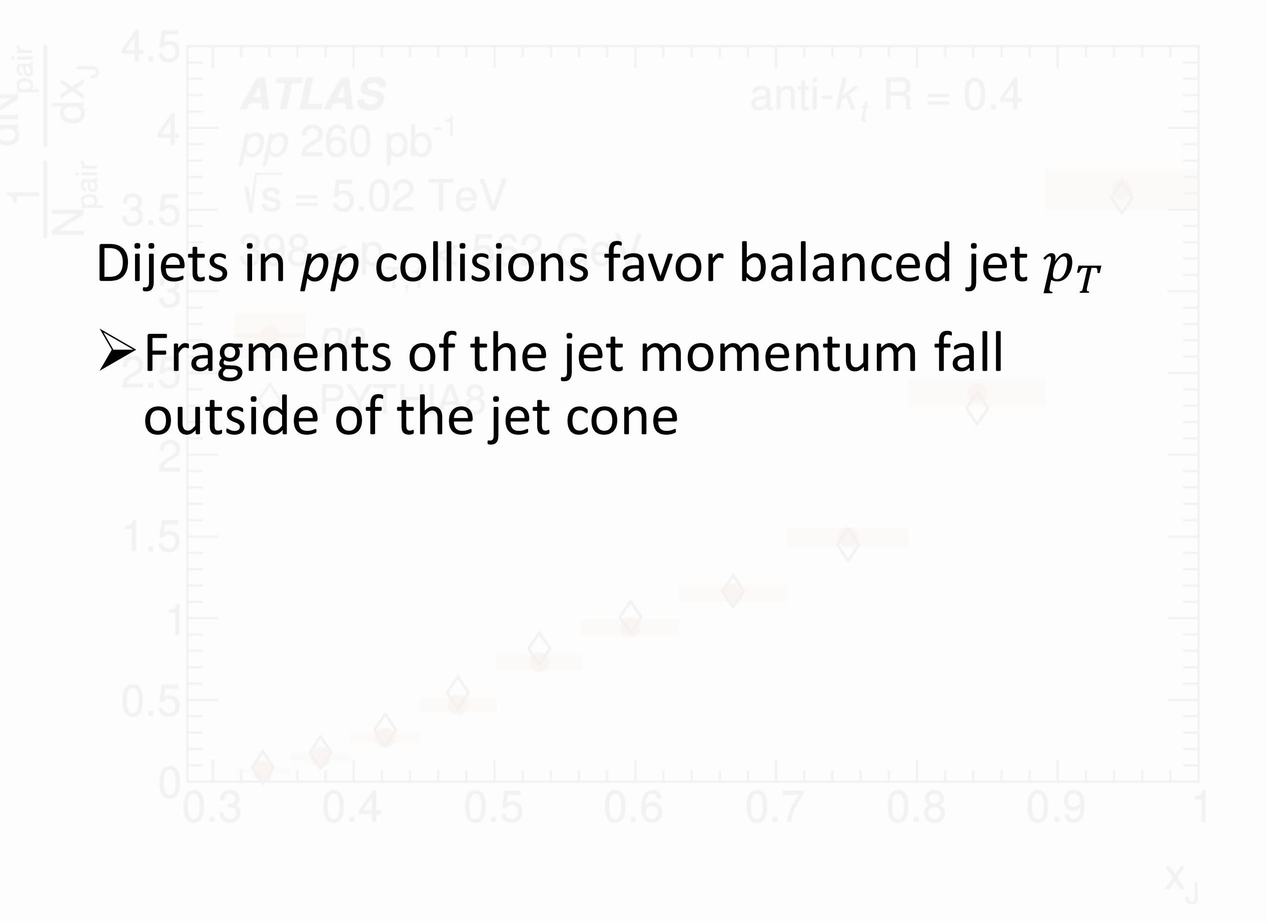
$^{1}/_{N_{pair}}\ ^{dN_{pair}}/_{dx_J}$ *pp* results

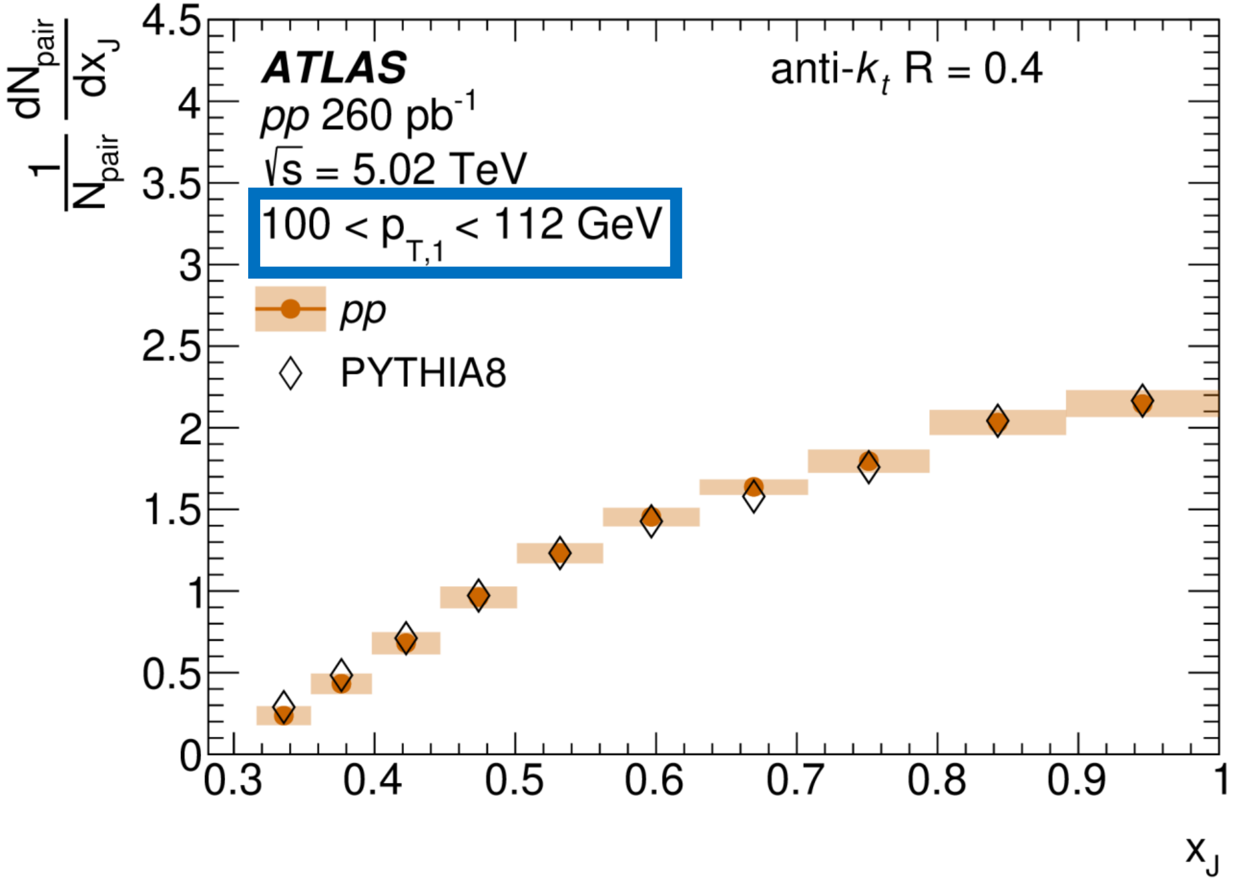


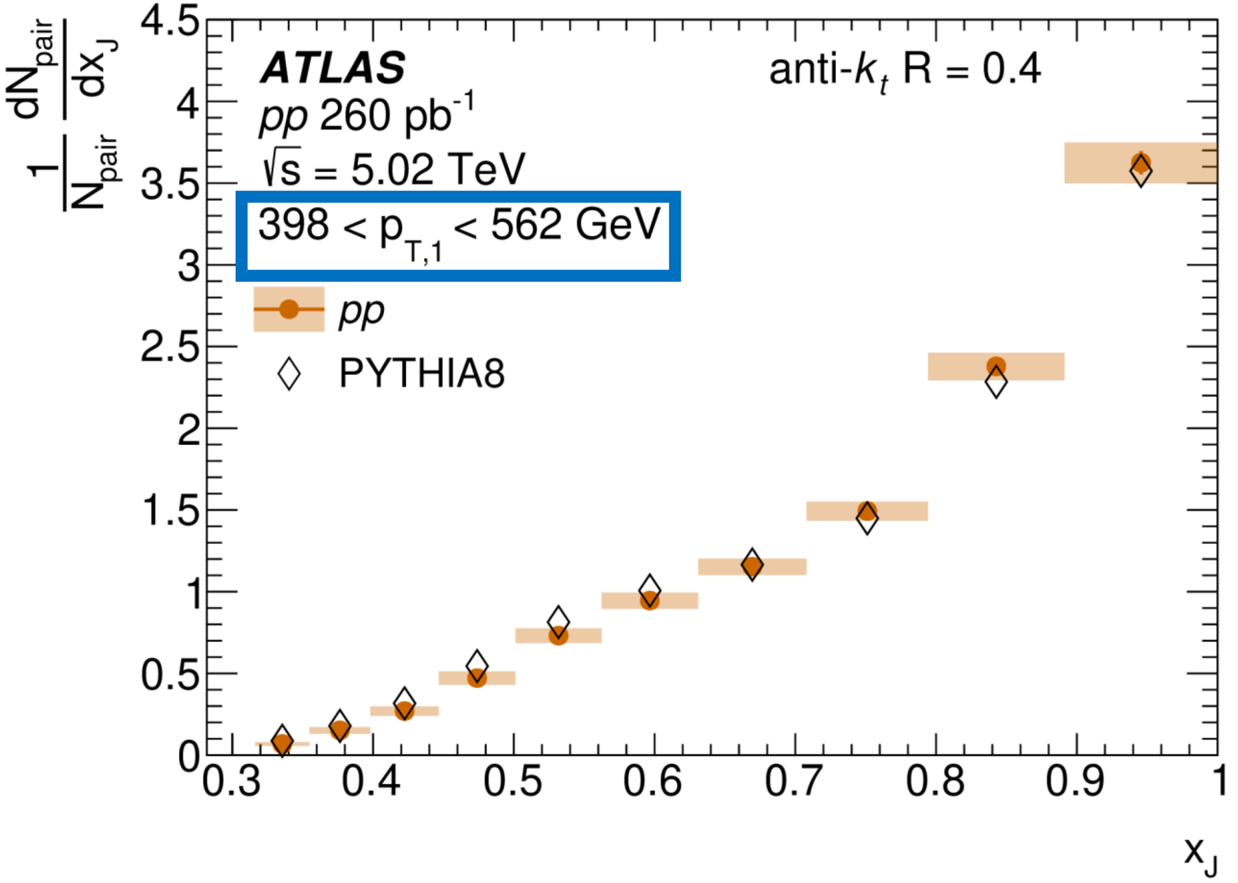


Dijets in *pp* collisions favor balanced jet p_T

- ➢Fragments of the jet momentum fall outside of the jet cone

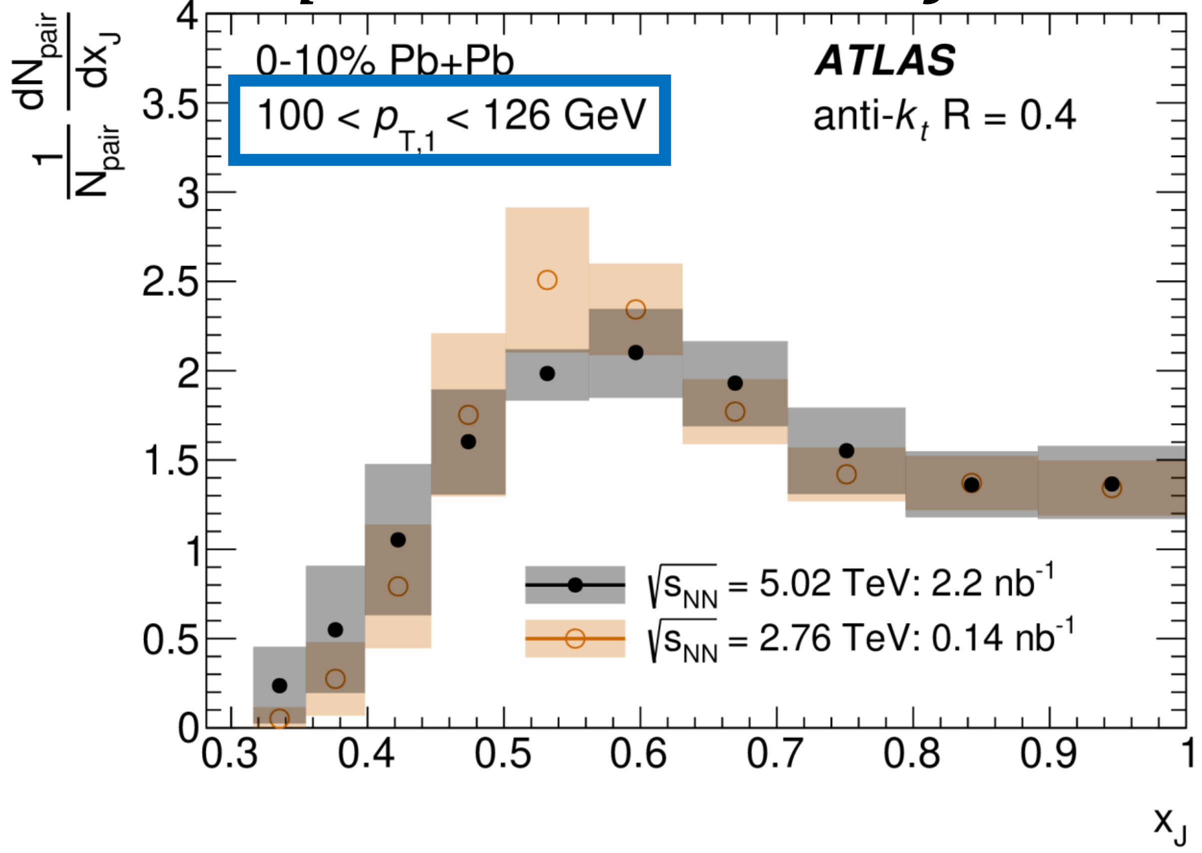
$^1/_{N_{pair}} \, {}^{dN_{pair}}/_{dx_J}$ *pp* results

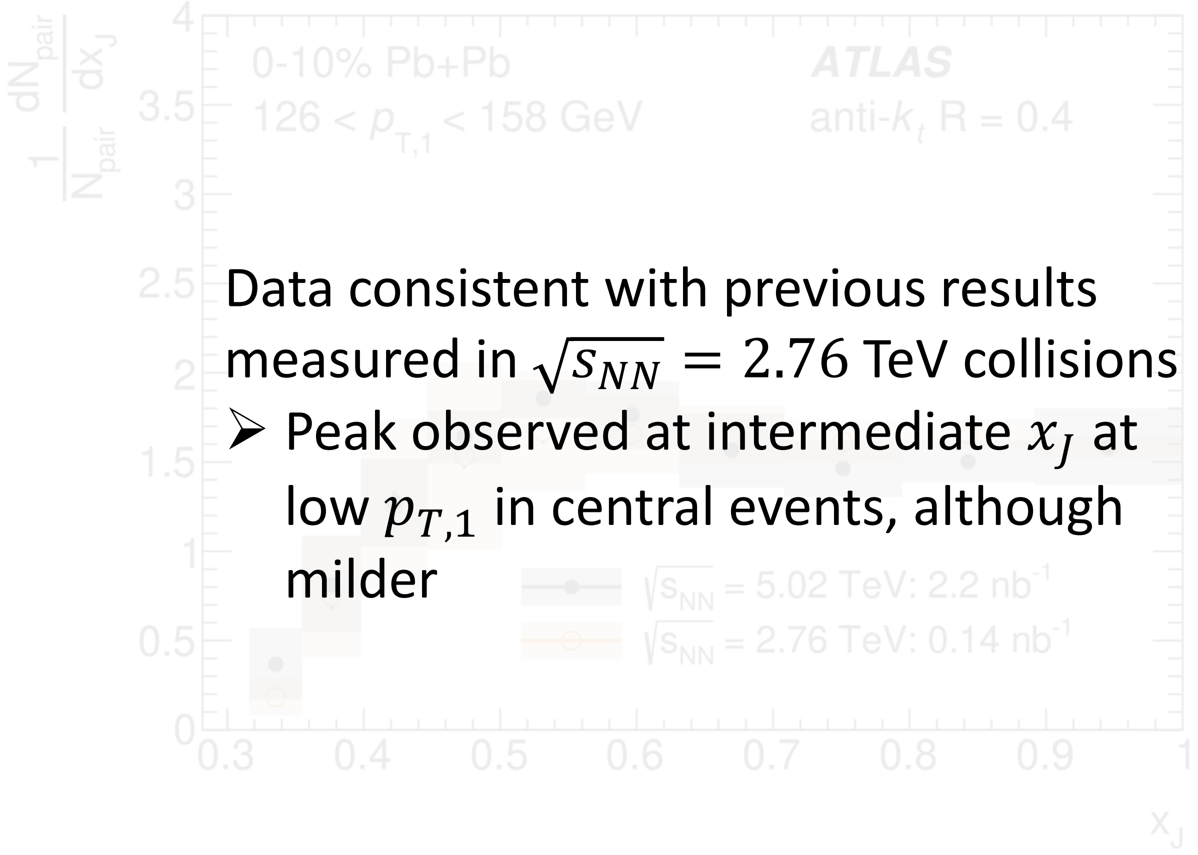




Higher p_T jets → more collimated → more balanced

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

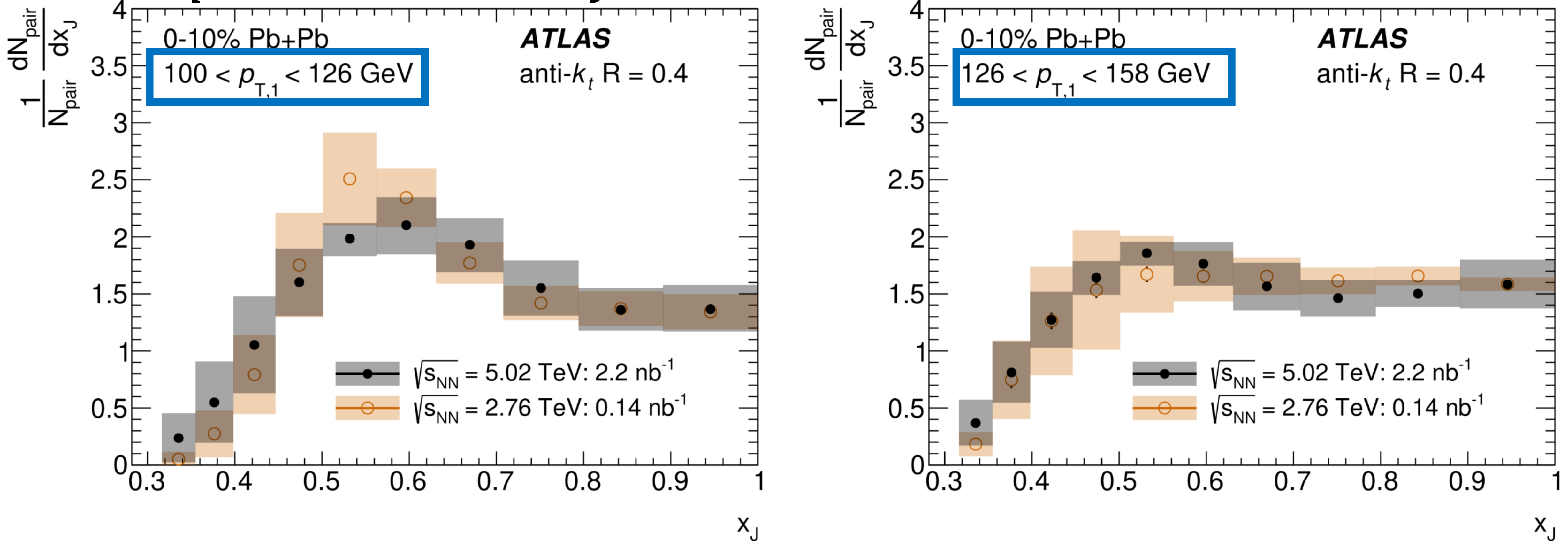




Data consistent with previous results measured in $\sqrt{s_{NN}} = 2.76$ TeV collisions

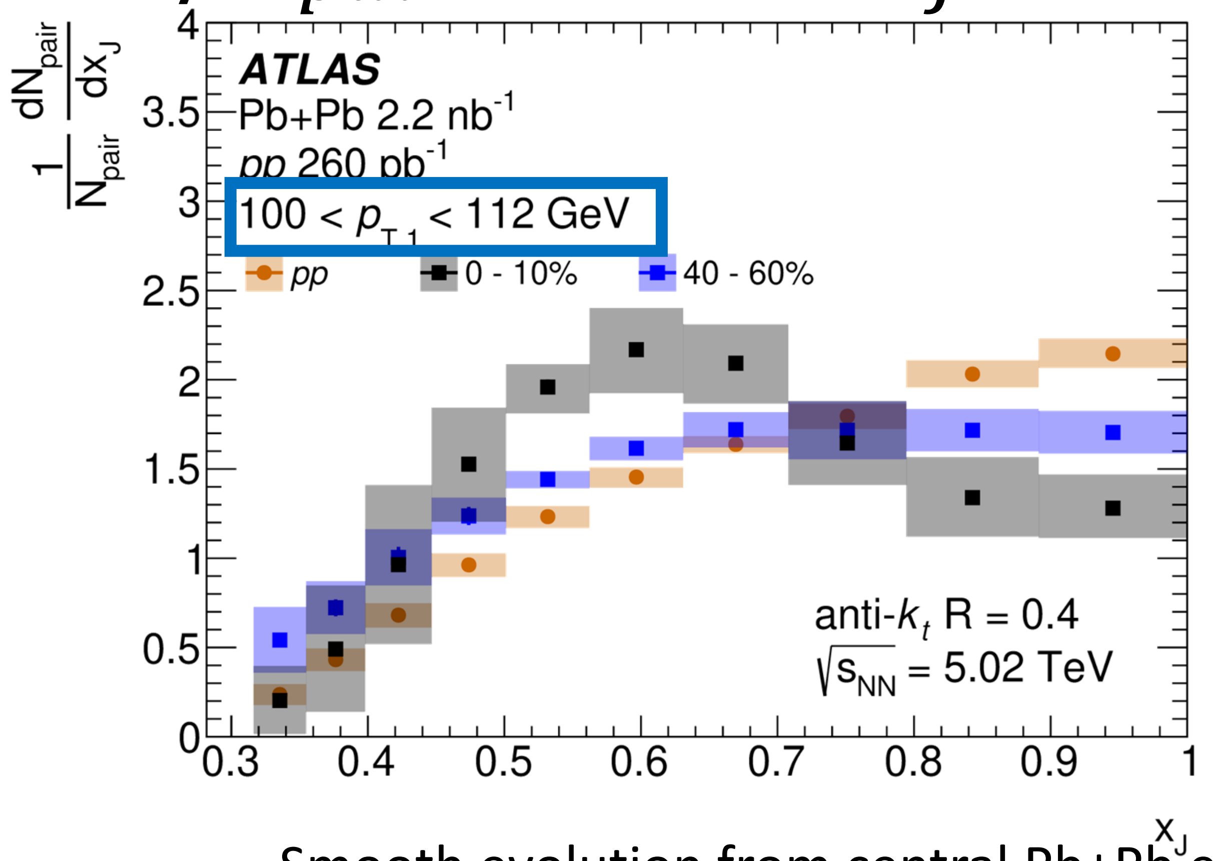
- ➢ Peak observed at intermediate x_J at low $p_{T,1}$ in central events, although milder

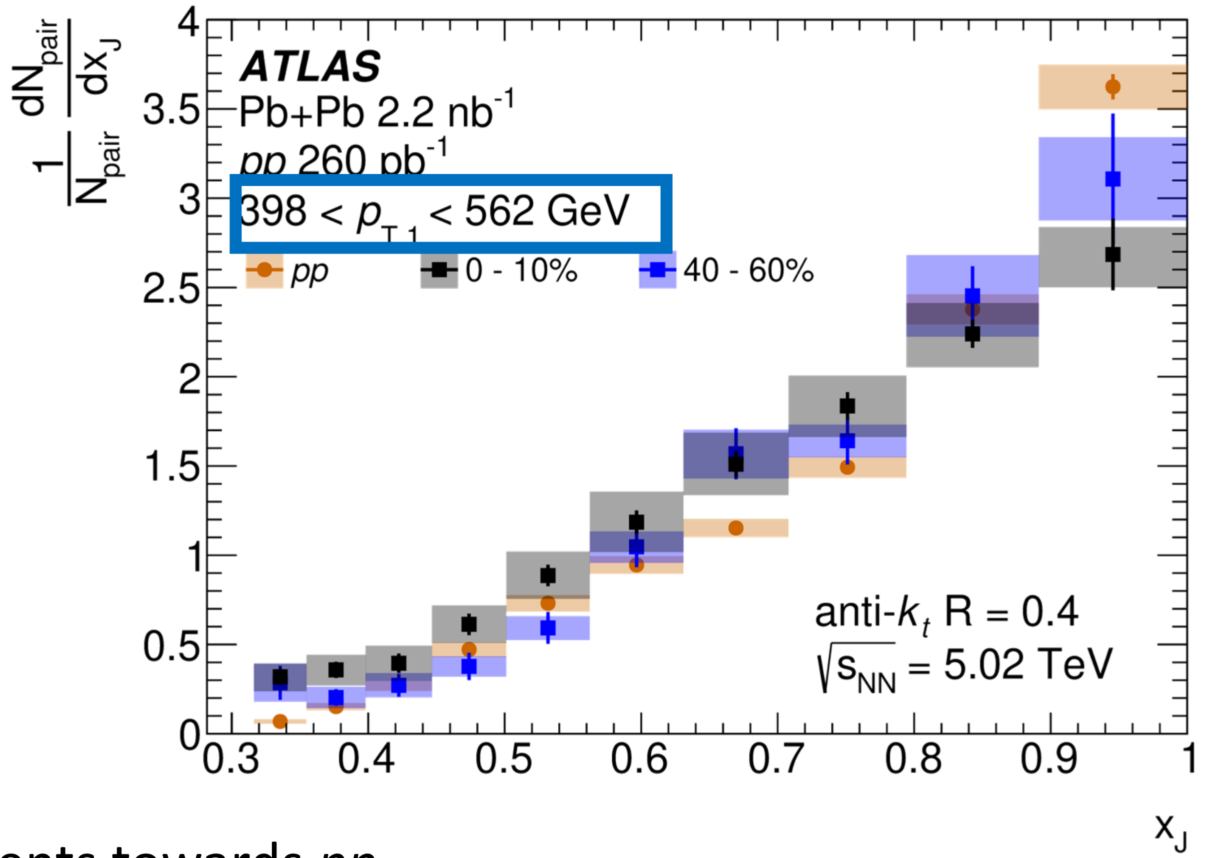
$^1/_{N_{pair}}\ ^{dN_{pair}}/_{dx_J}$ distributions



Both results observe significant flattening of the peak structure with increasing leading jet p_T

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

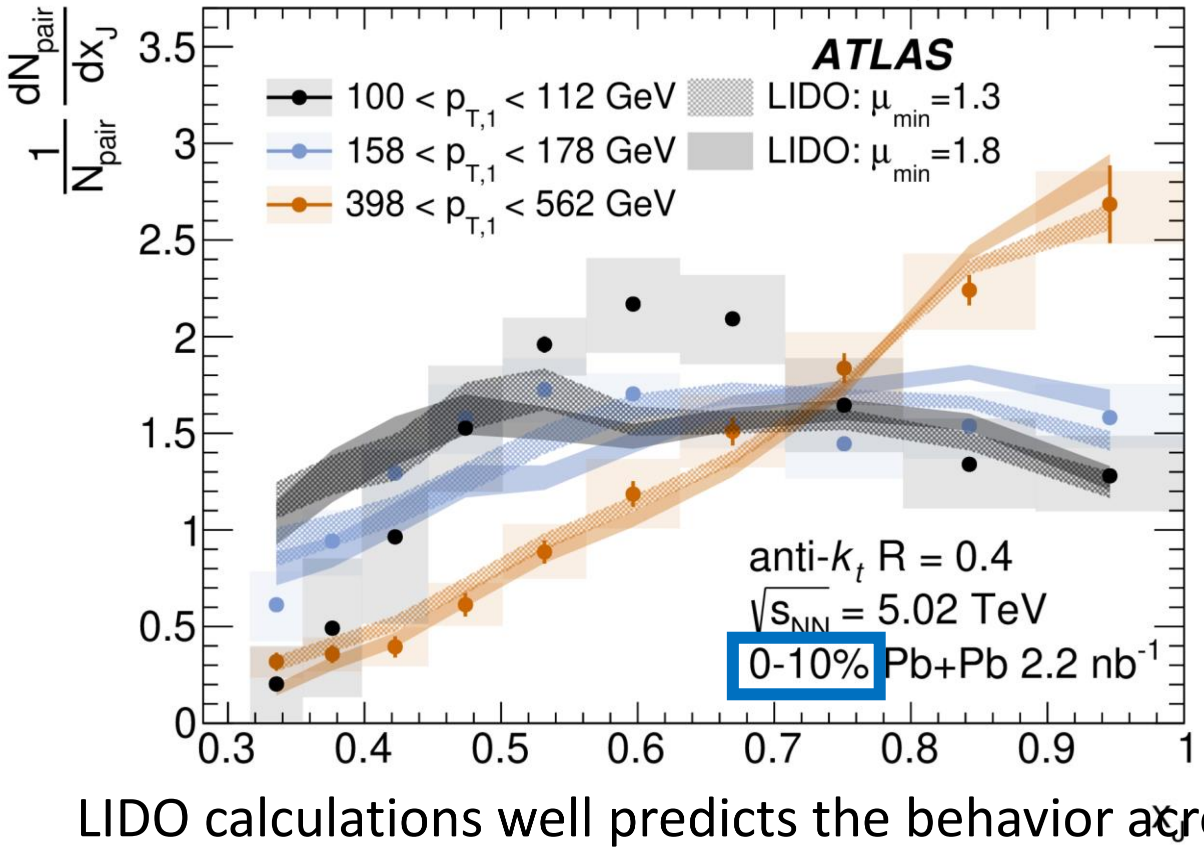


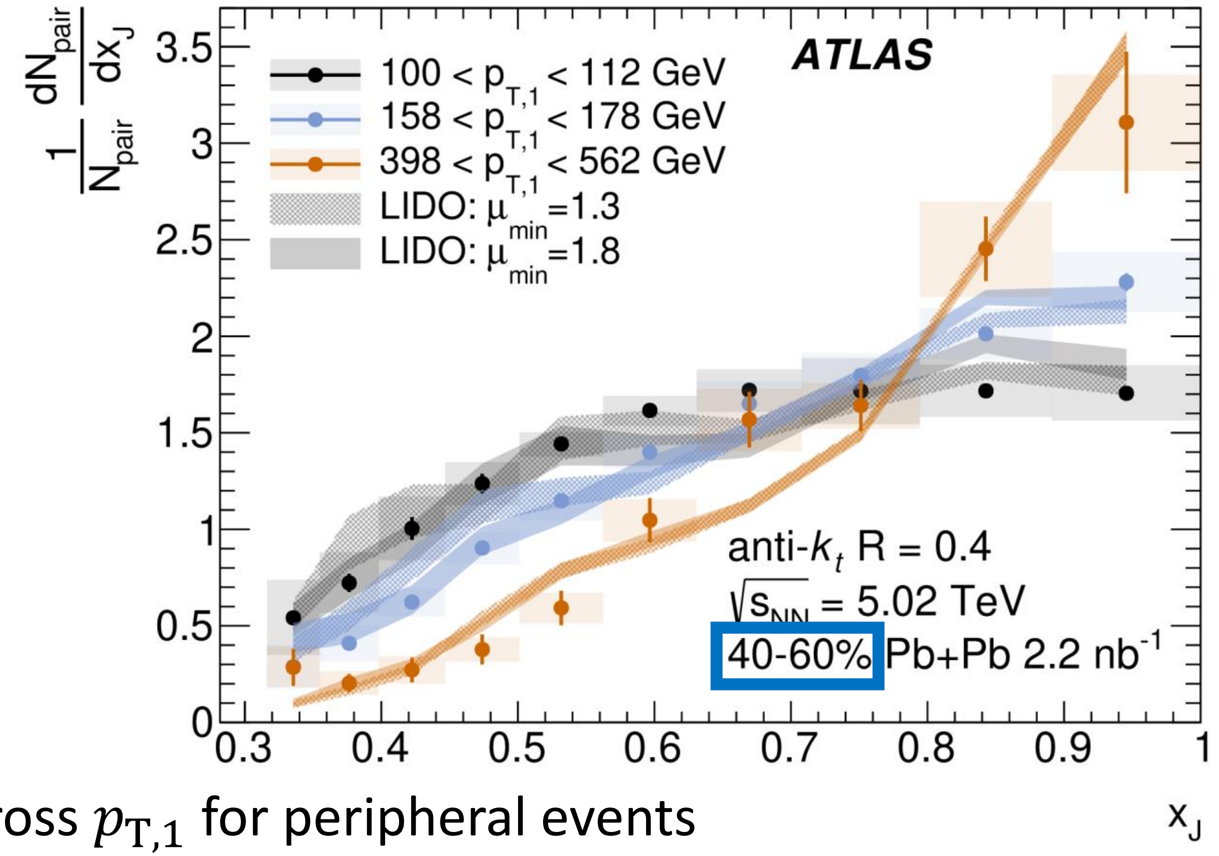


Smooth evolution from central Pb+Pb events towards *pp*

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

$^{1}/_{N_{pair}}\ ^{dN_{pair}}/_{dx_J}$: Comparison with theory





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 $p_{\mathrm{T},1}$

Dijet x_J 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*

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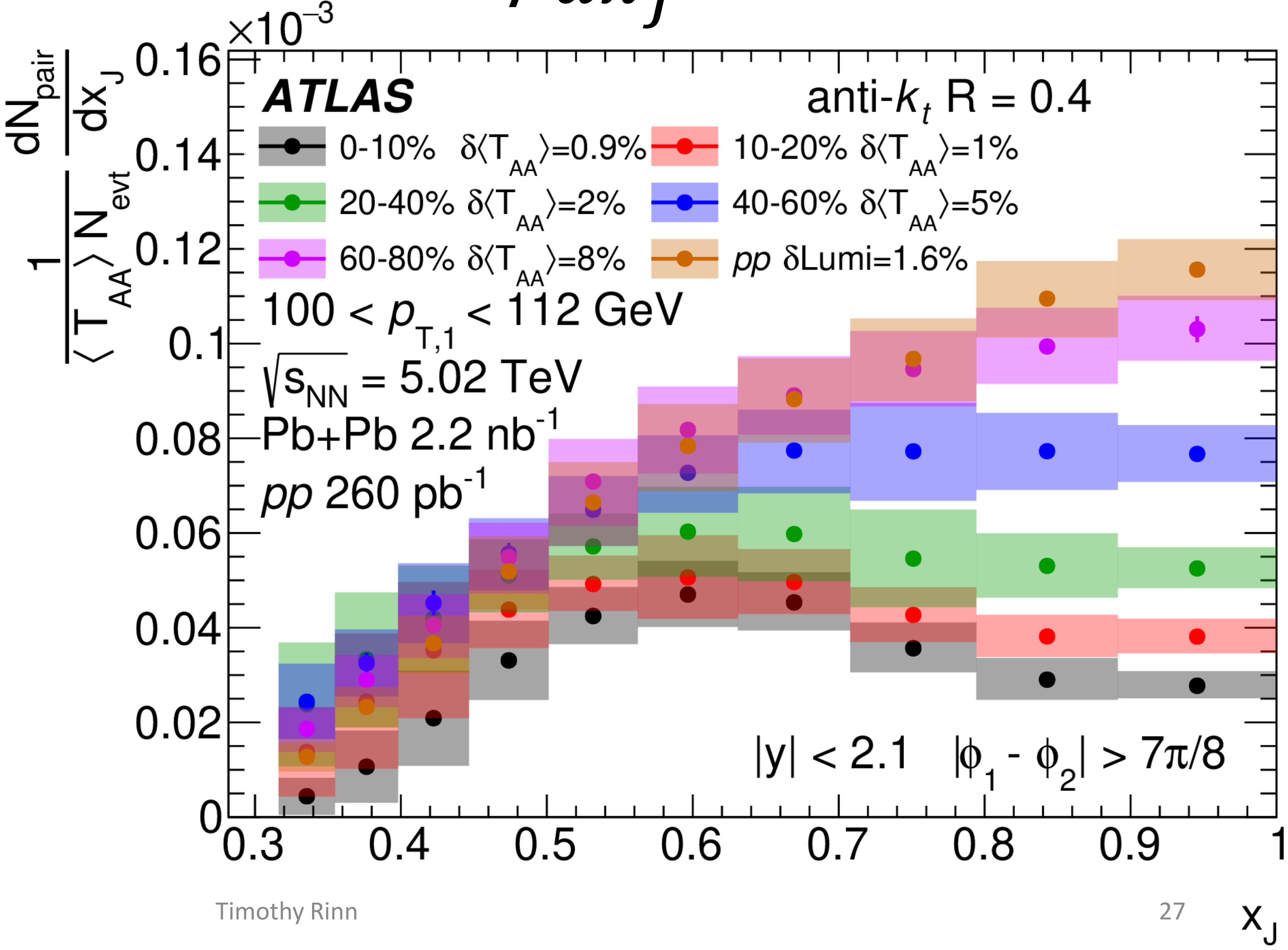
- Enables evaluation of the dijet per event yields as a function of x_J
- Provides insight into the dynamics of dijet energy loss

Absolutely normalized $^{dN_{pair}}/_{dx_J}$

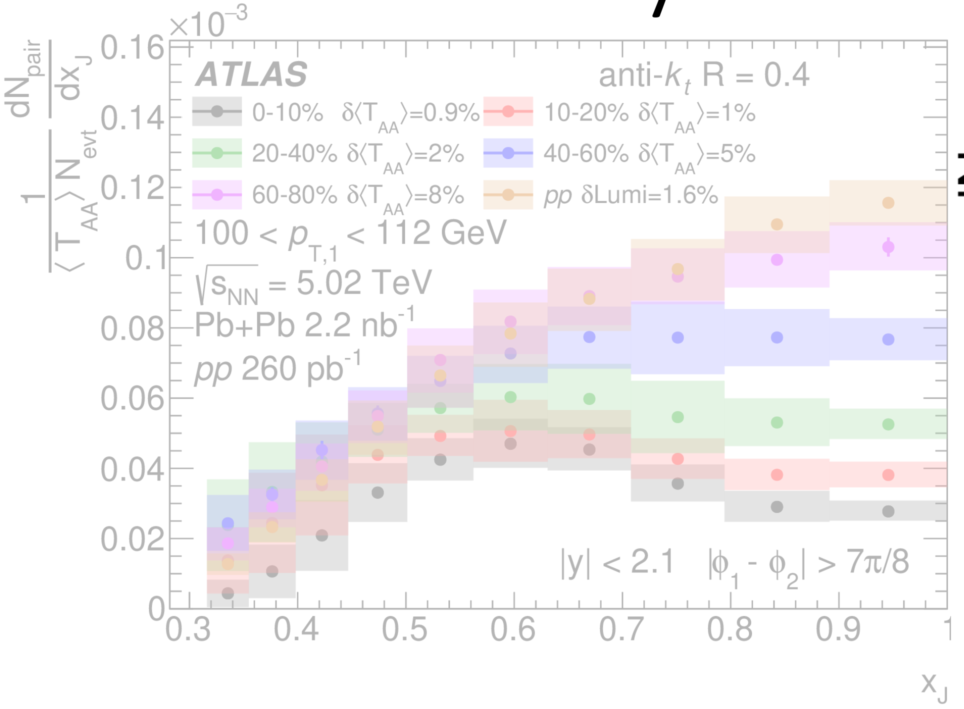
Using a $\frac{1}{\langle T_{AA}\rangle N_{evt}}$ normalization enables the study of dijet yields as a function of x_J

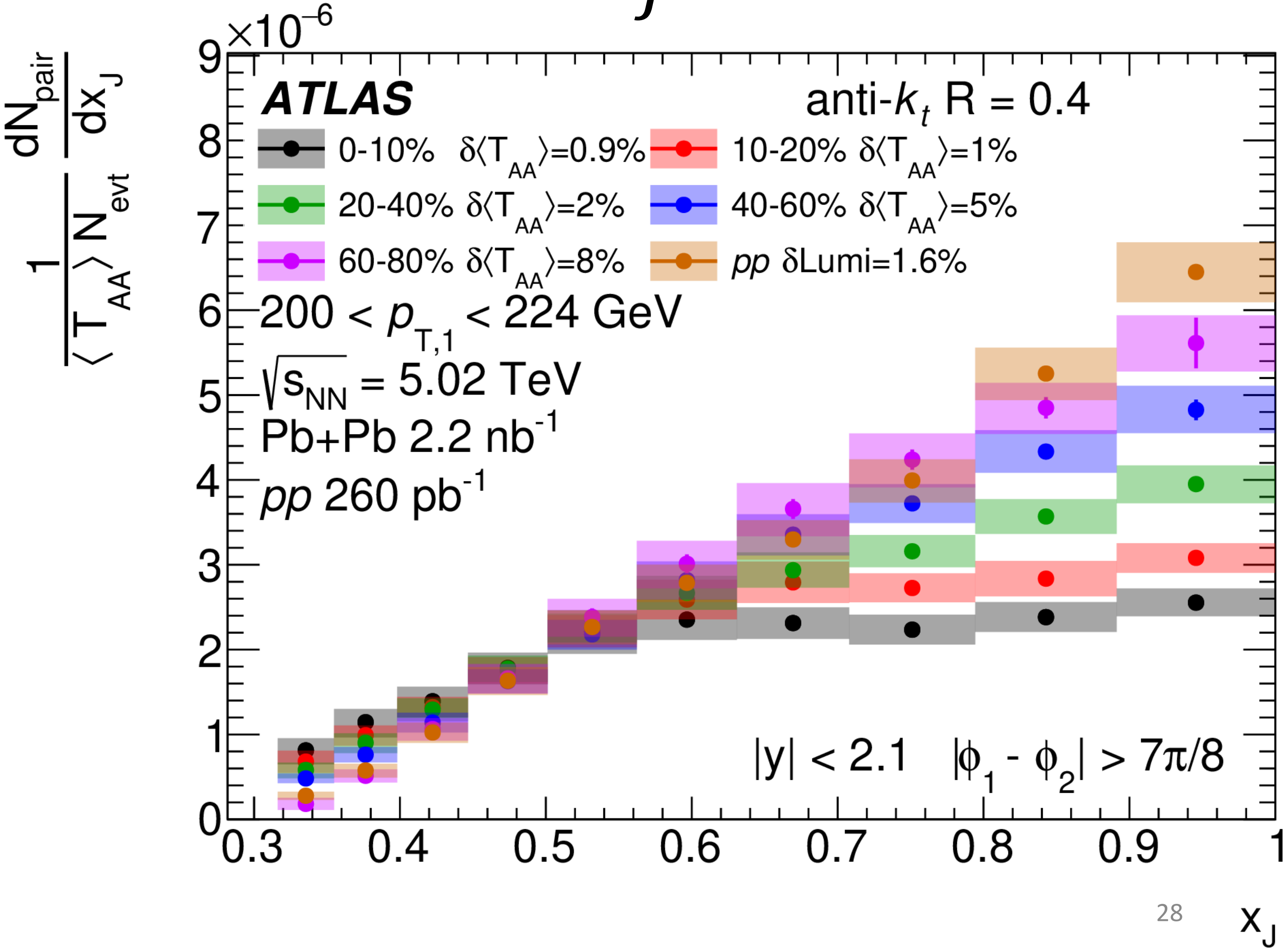
The peak structure observed at intermediate x_J stems from the favorable suppression of symmetric dijets

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



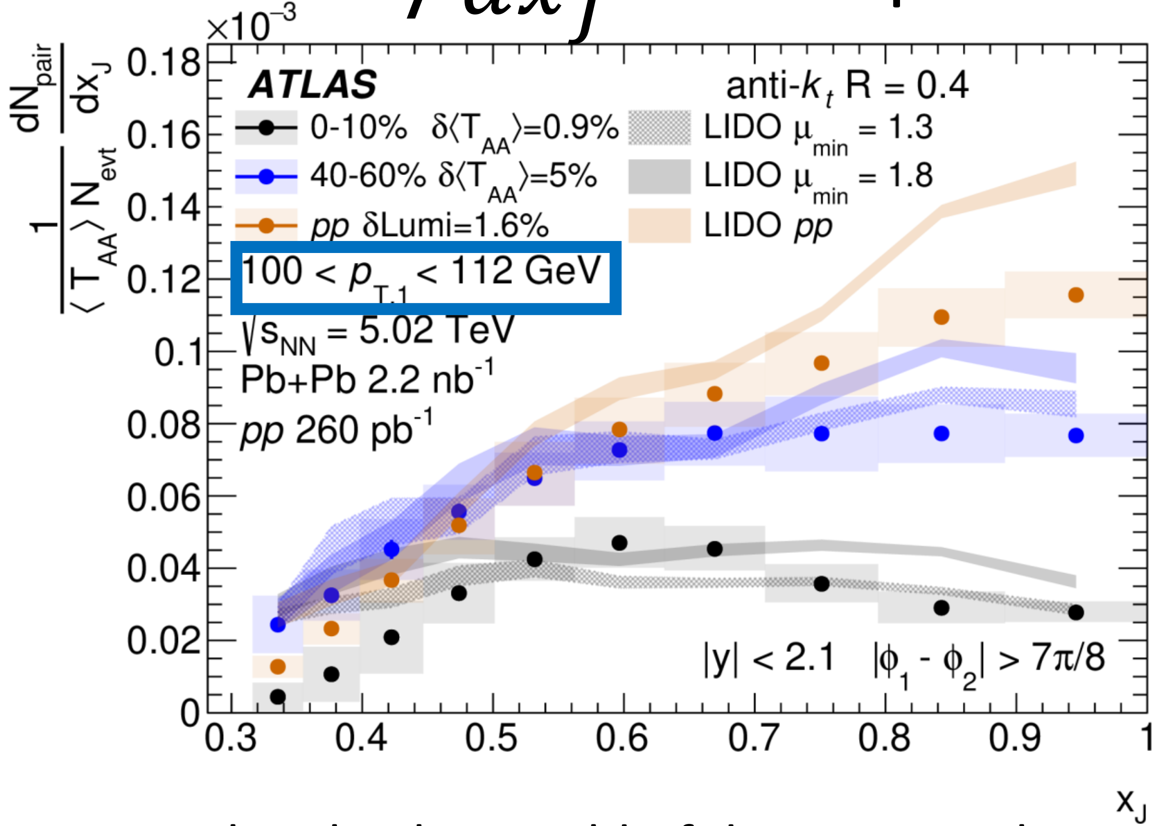
Absolutely normalized dN_{pair}/dx_J

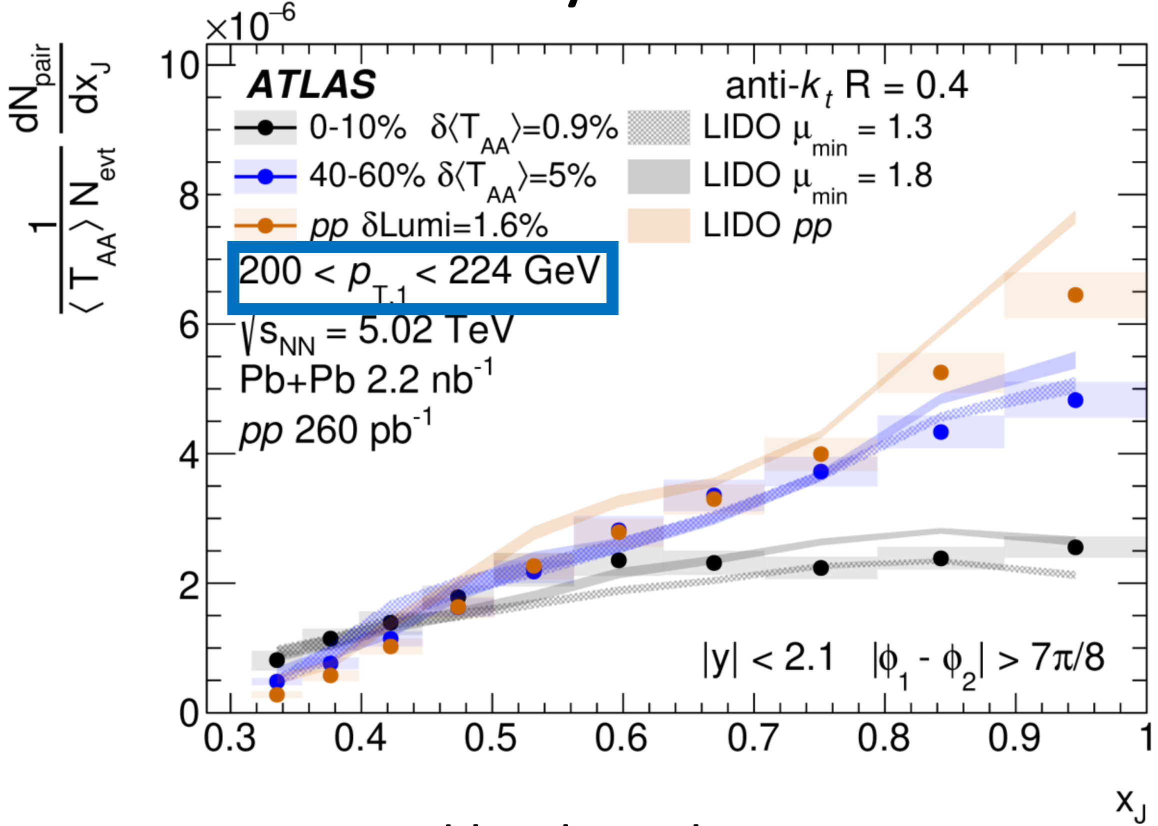




The systematic suppression of symmetric dijets persists with increasing $p_{T,1}$

${}^{dN_{pair}}/_{dx_J}$: Comparison with theory

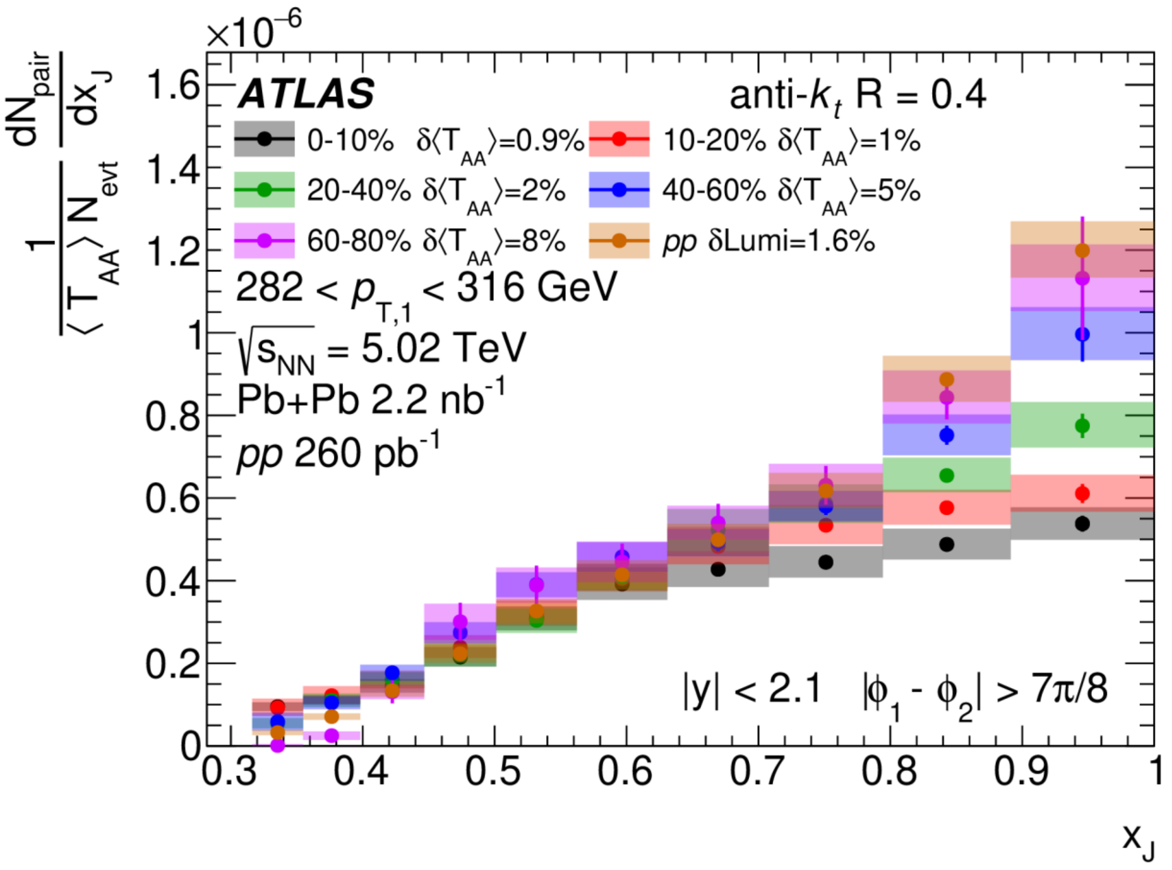


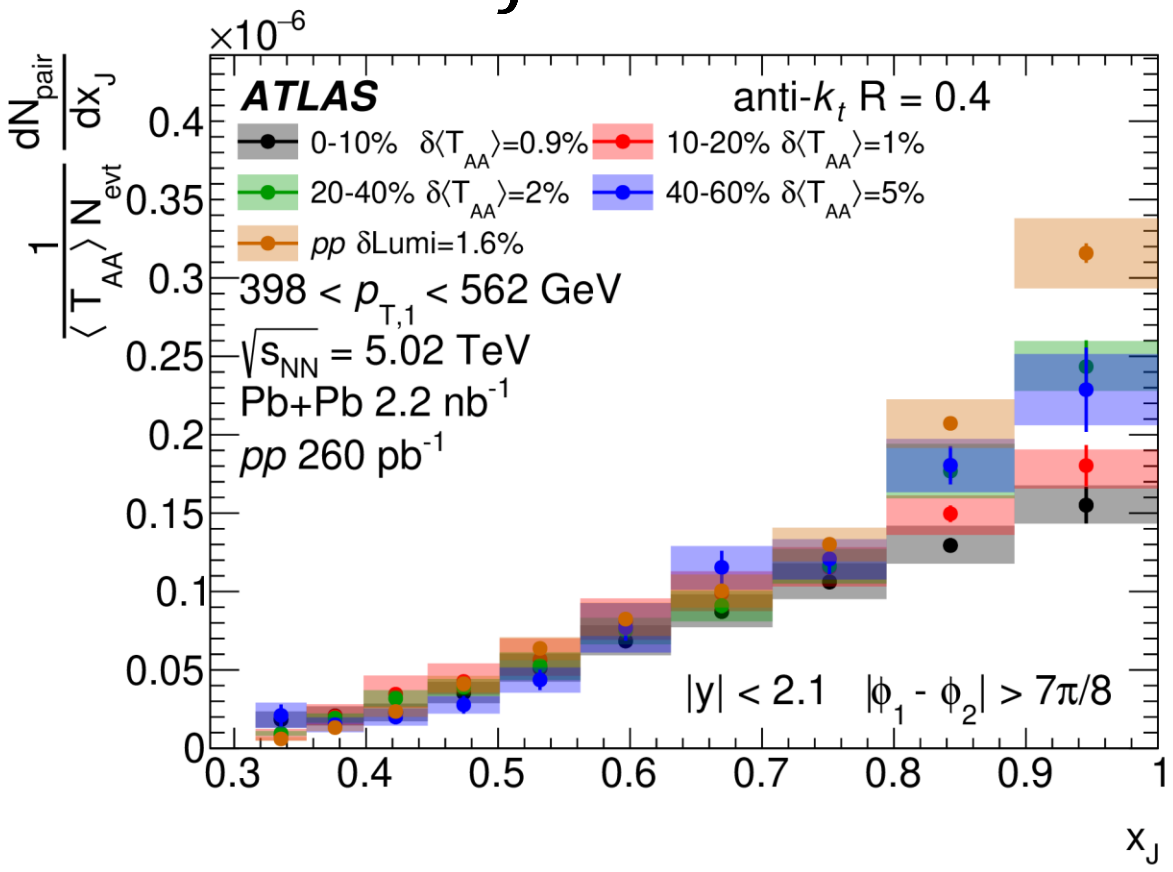


The absolute yield of dijet pairs at low $p_{T,1}$ are overestimated by the Pyhtia8 A14 tune with CTEQL1 PDF used in LIDO

LIDO qualitatively predicts the depletion of symmetric dijets observed across $p_{\mathrm{T},1}$

Absolutely normalized $^{dN_{pair}}/_{dx_J}$





Significant suppression of symmetric dijets measured at the highest $p_{T,1}$

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

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

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

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

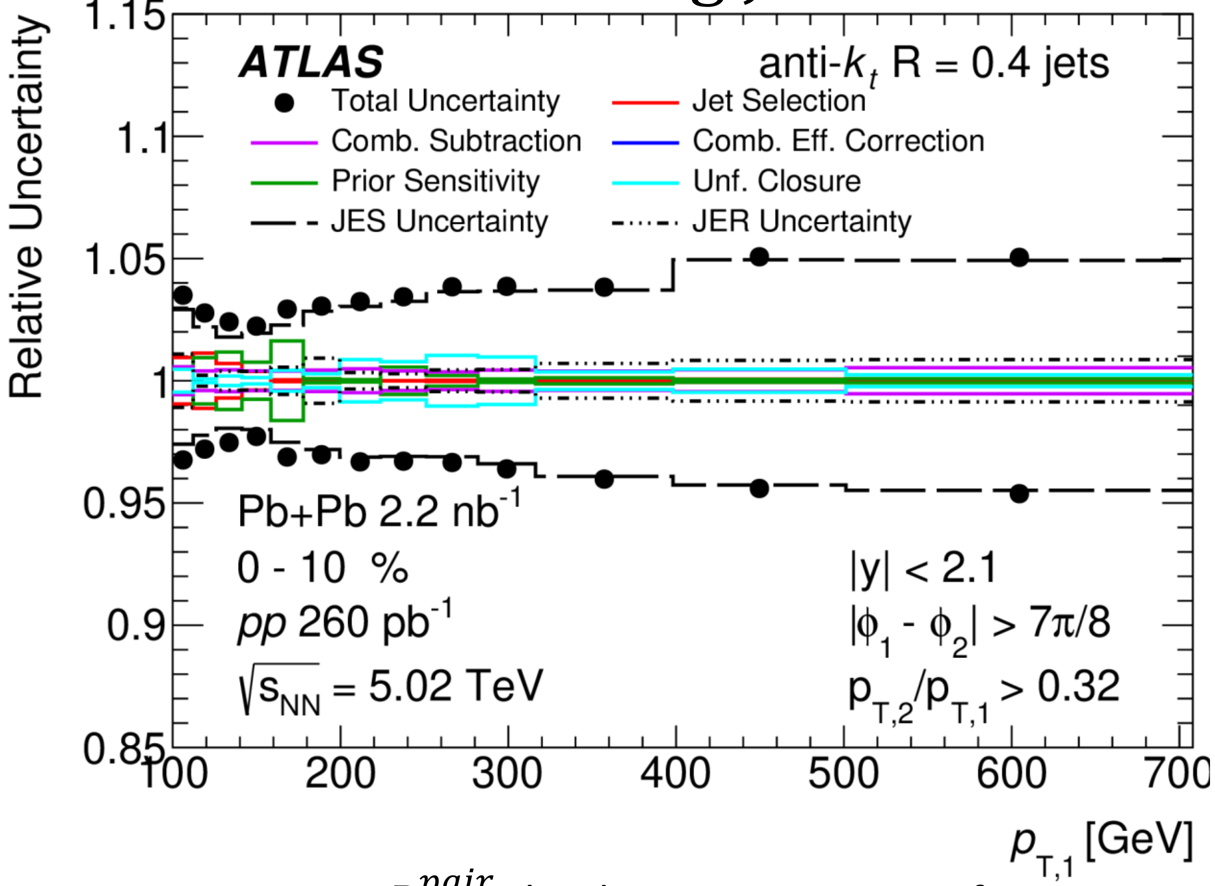
$R_{AA}^{pair}(\boldsymbol{p_{T,2}})$ quantifies the suppression of the **subleading jet** in a dijet

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

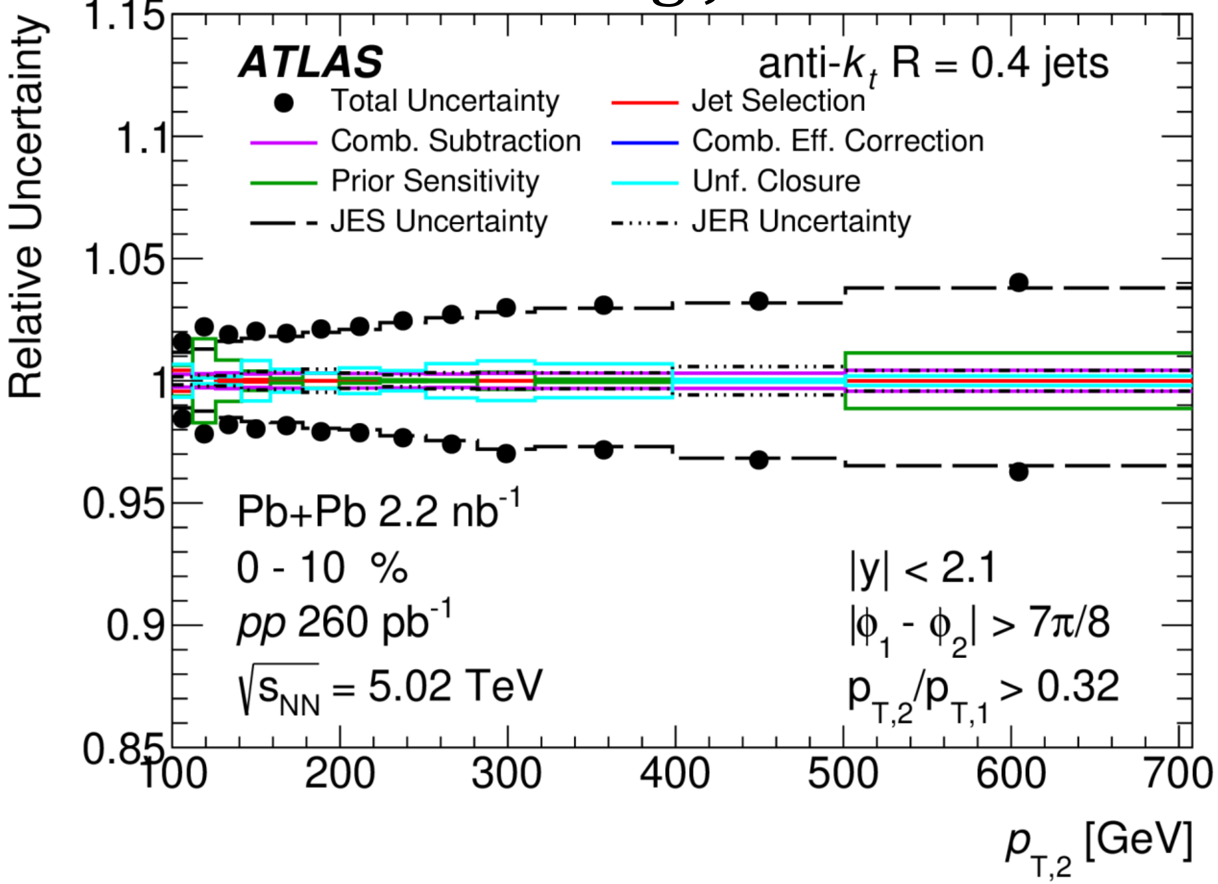
Dijet threshold condition of $\frac{\boldsymbol{p_{T,2}}}{\boldsymbol{p_{T,1}}} > 0.32$

Systematic uncertainties for R_{AA}^{pair}

Leading Jets

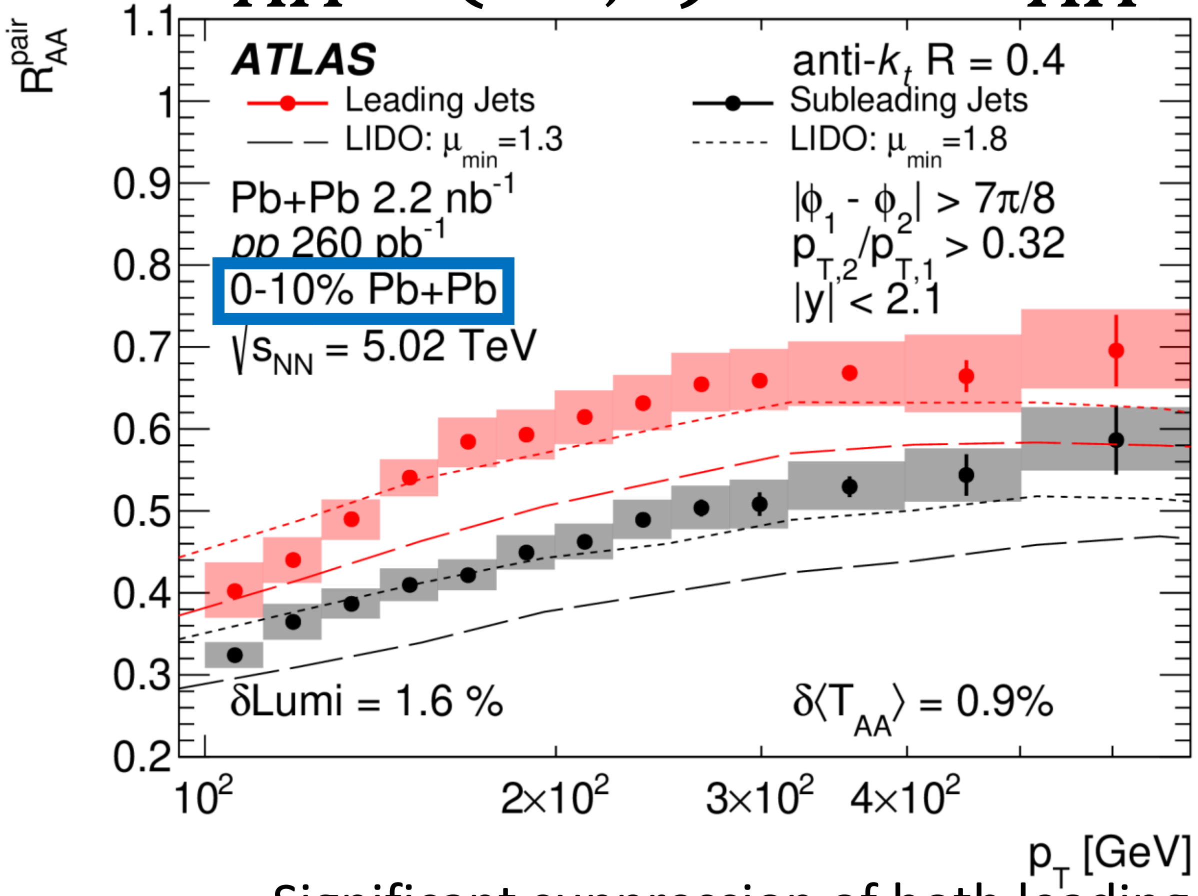


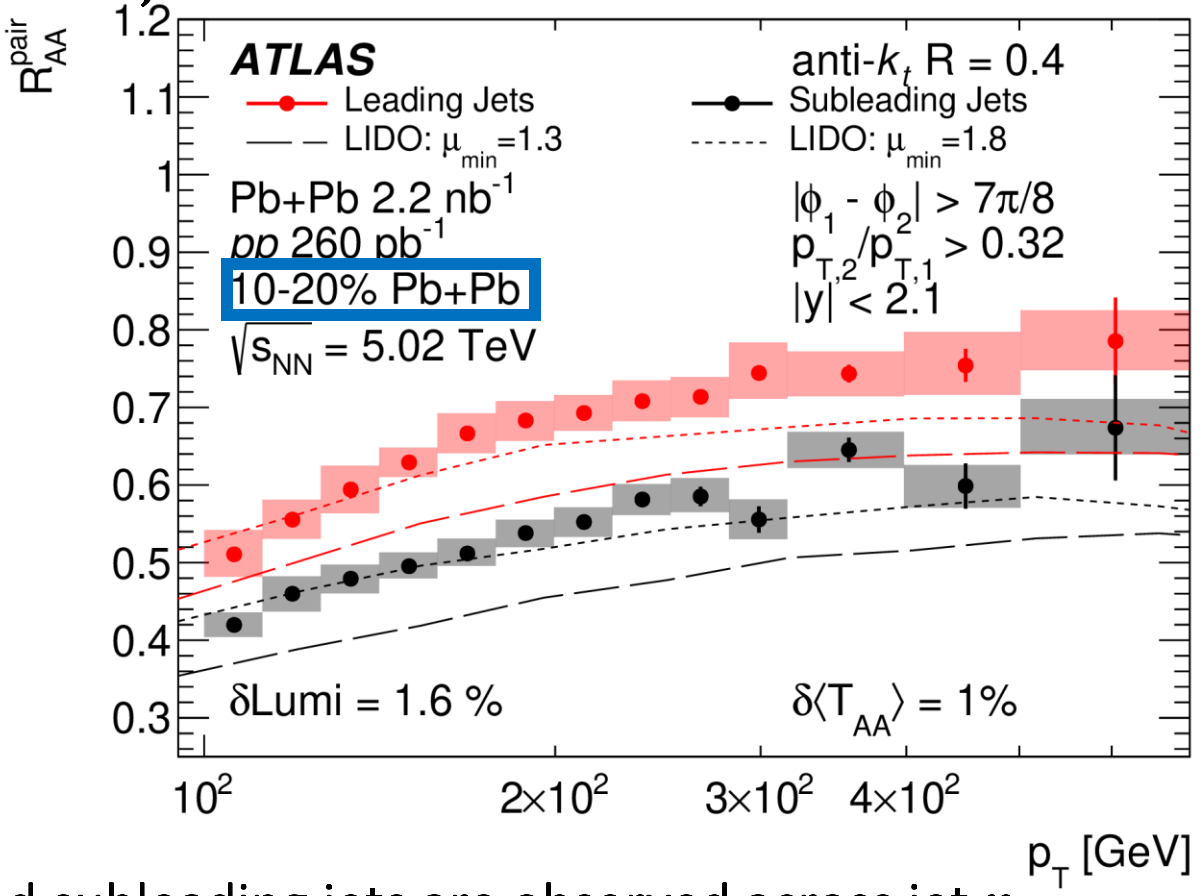
Subleading Jets



For R_{AA}^{pair} the dominant sources of systematic uncertainty stem from uncertainty on the JES

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





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

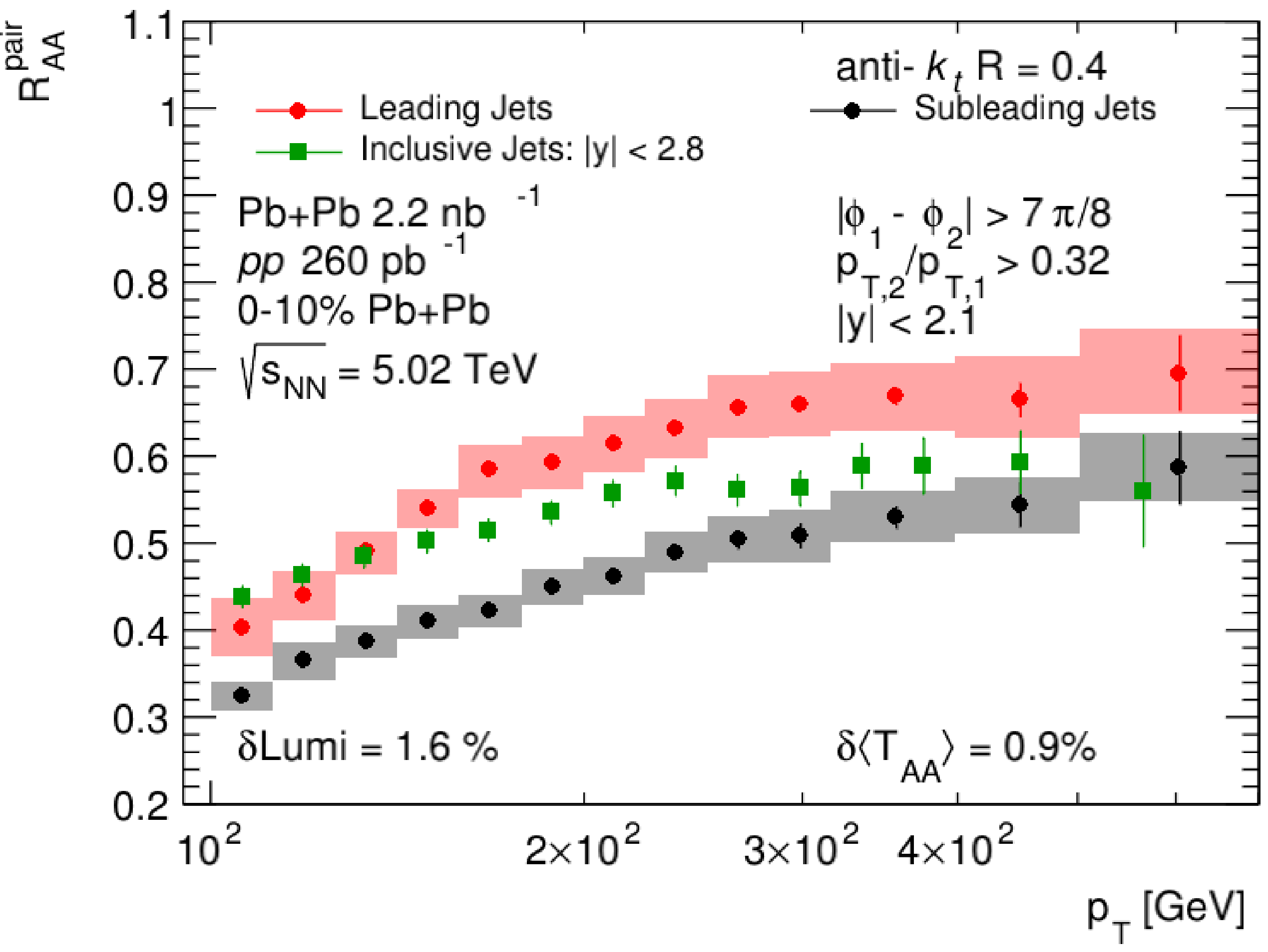
Subleading jets are systematically more suppressed than leading jets

$R_{AA}^{pair}(p_{T,1})$ and $R_{AA}^{pair}(p_{T,2})$

Inclusive jet R_{AA} is sandwiched between leading and sub leading jets above 158 GeV

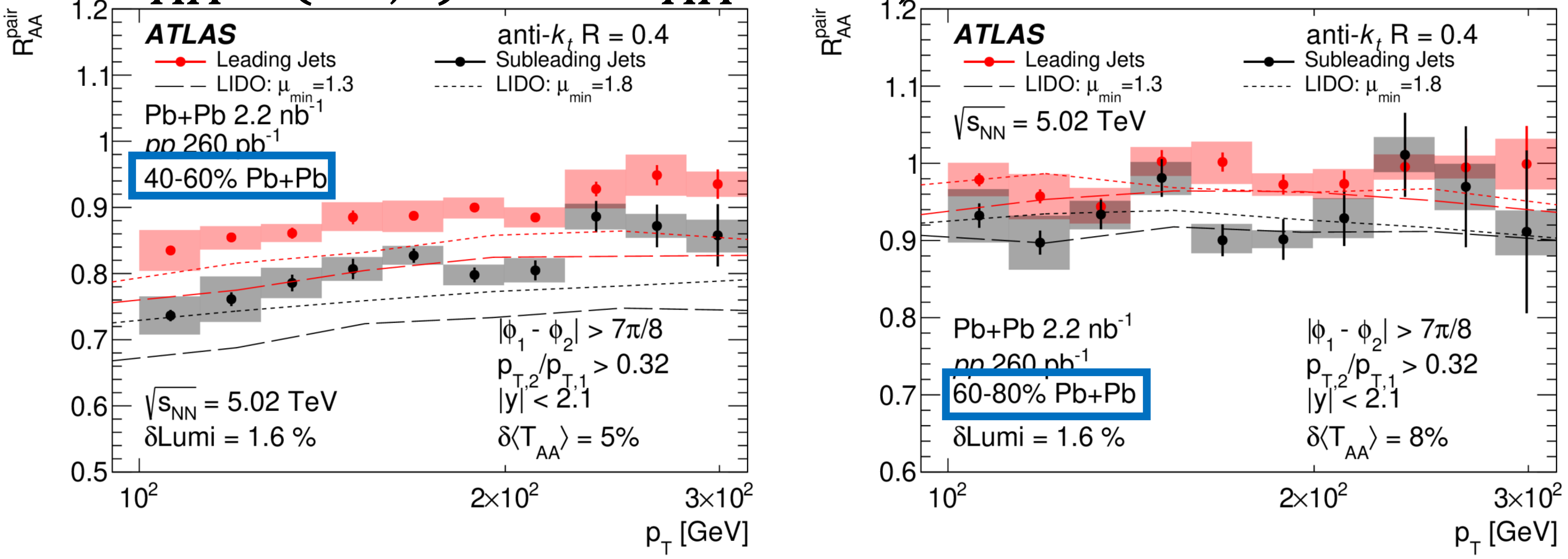
- ➢Consistent with dijets dominating the inclusive jet spectrum

At low p_T the inclusive jet R_{AA} is above that of leading jets



Inclusive jets: https://arxiv.org/abs/1805.05635

$R_{AA}^{pair}(p_{T,1})$ and $R_{AA}^{pair}(p_{T,2})$



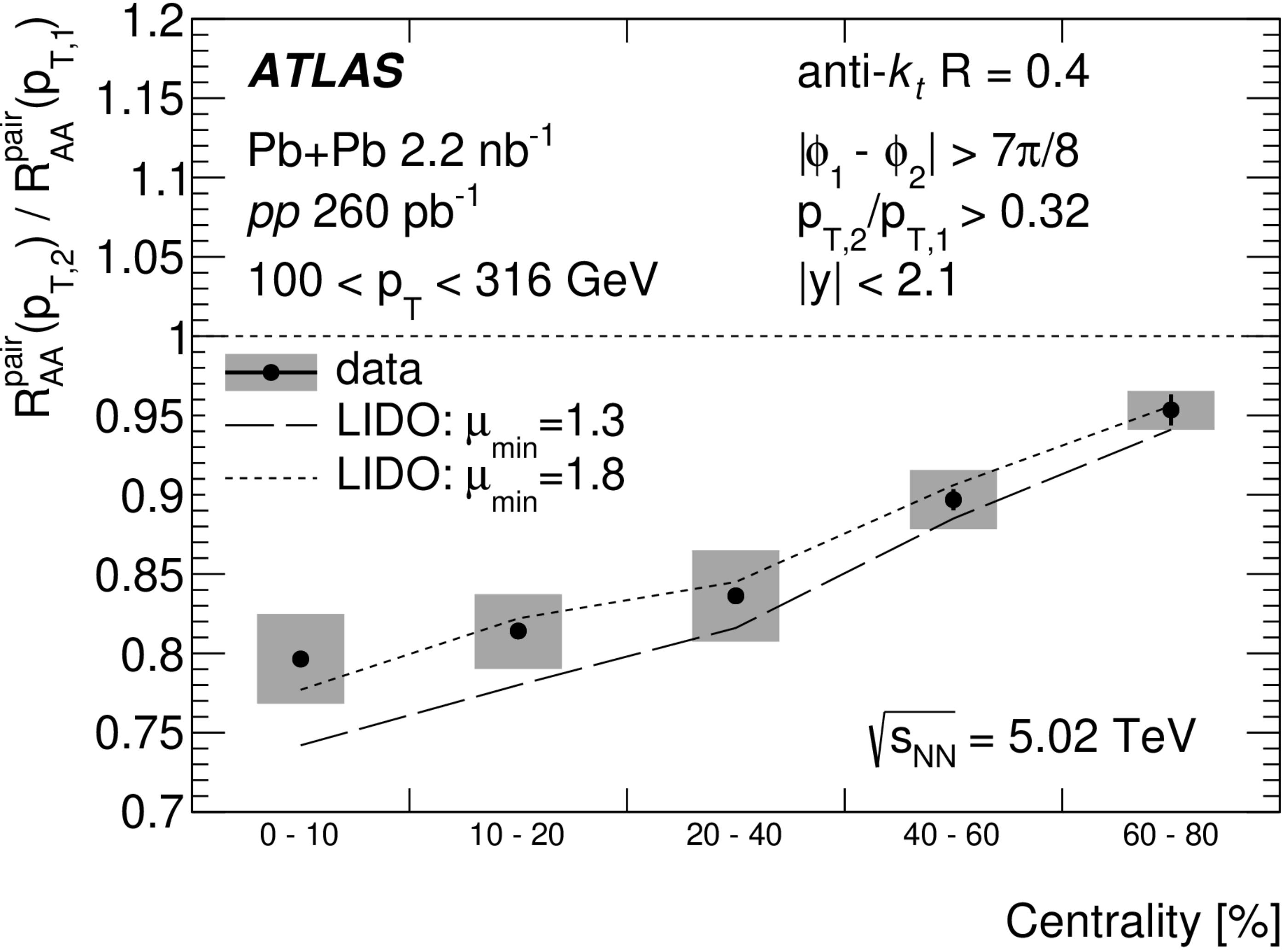
Systematic suppression of subleading jets relative to leading jetshas been measured across event centrality

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

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

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

LIDO calculations with a $\mu_{min} = 1.8$ well reproduces the measurement



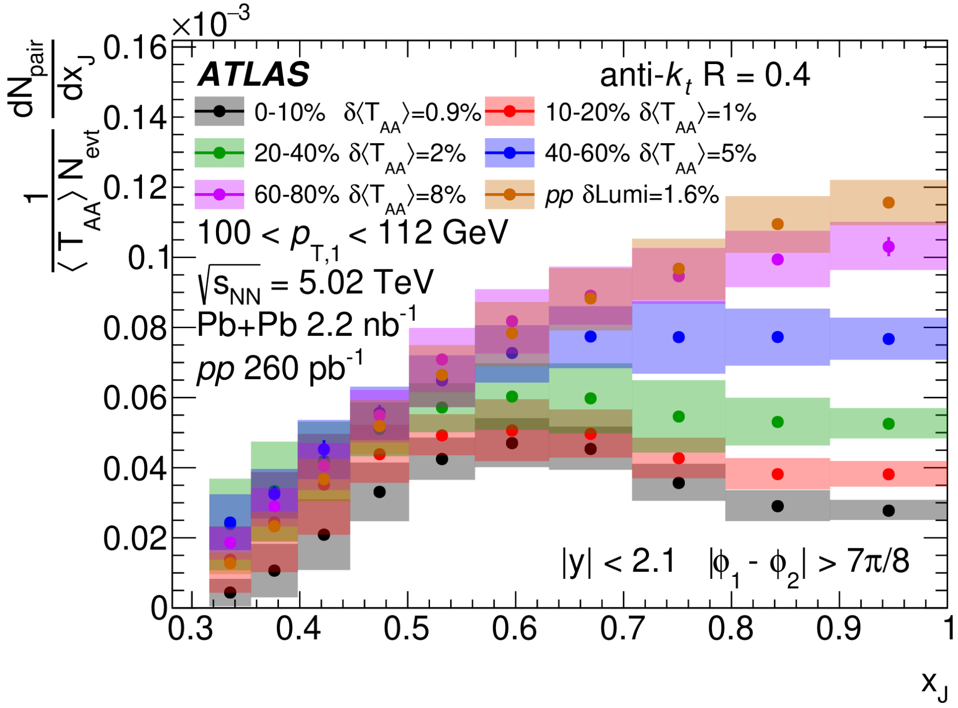
Summary

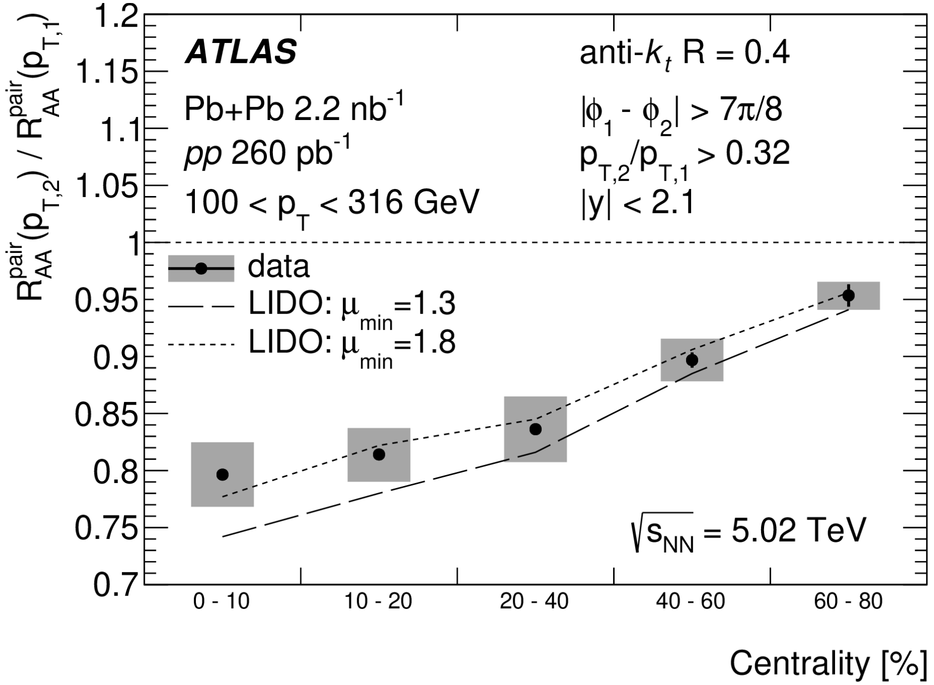
Novel measurements of dijets in Pb+Pb collisions have been presented

- Measurements of the absolutely normalized x_J distributions provide evidence of preferable depletion of balanced dijets

- Measurements of $R_{AA}^{pair}(p_{\mathrm{T},1})$ and $R_{AA}^{pair}(p_{\mathrm{T},2})$ quantify the suppression of leading and subleading jets

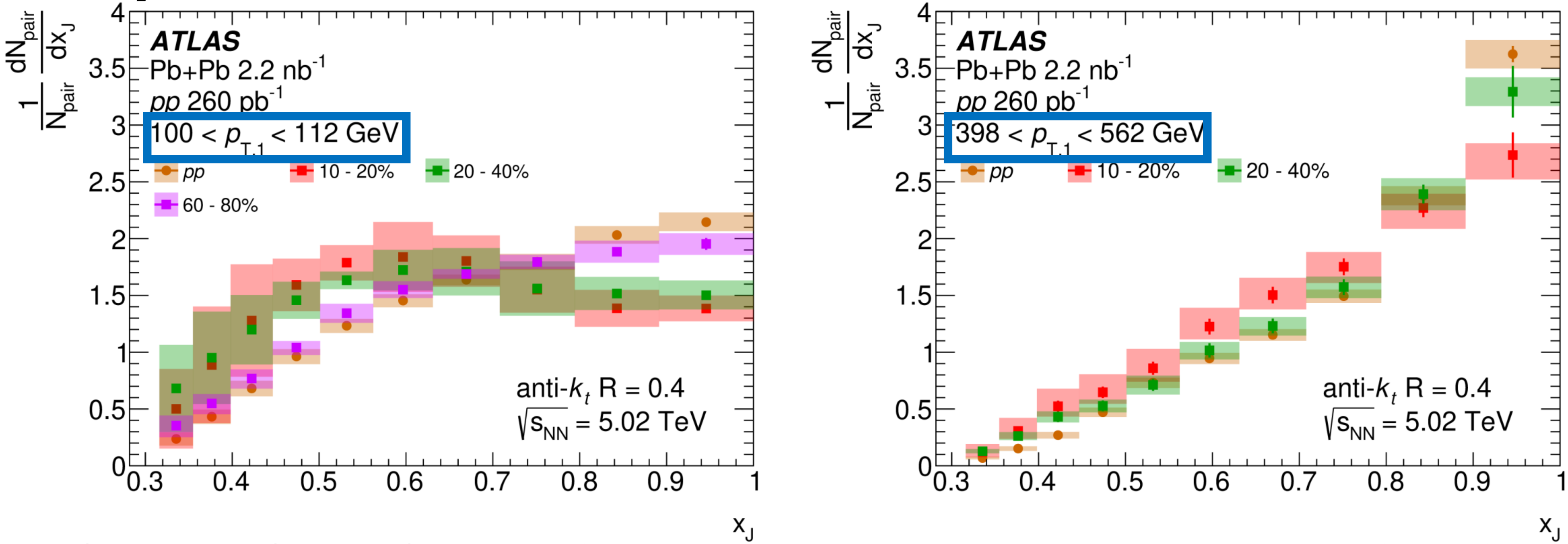
- A 3σ suppression of subleading jets to leading jets is observed in peripheral Pb+Pb





backups

$\frac{1}{N_{pair}} \frac{dN_{pair}}{dx_J}$ additional centrality intervals

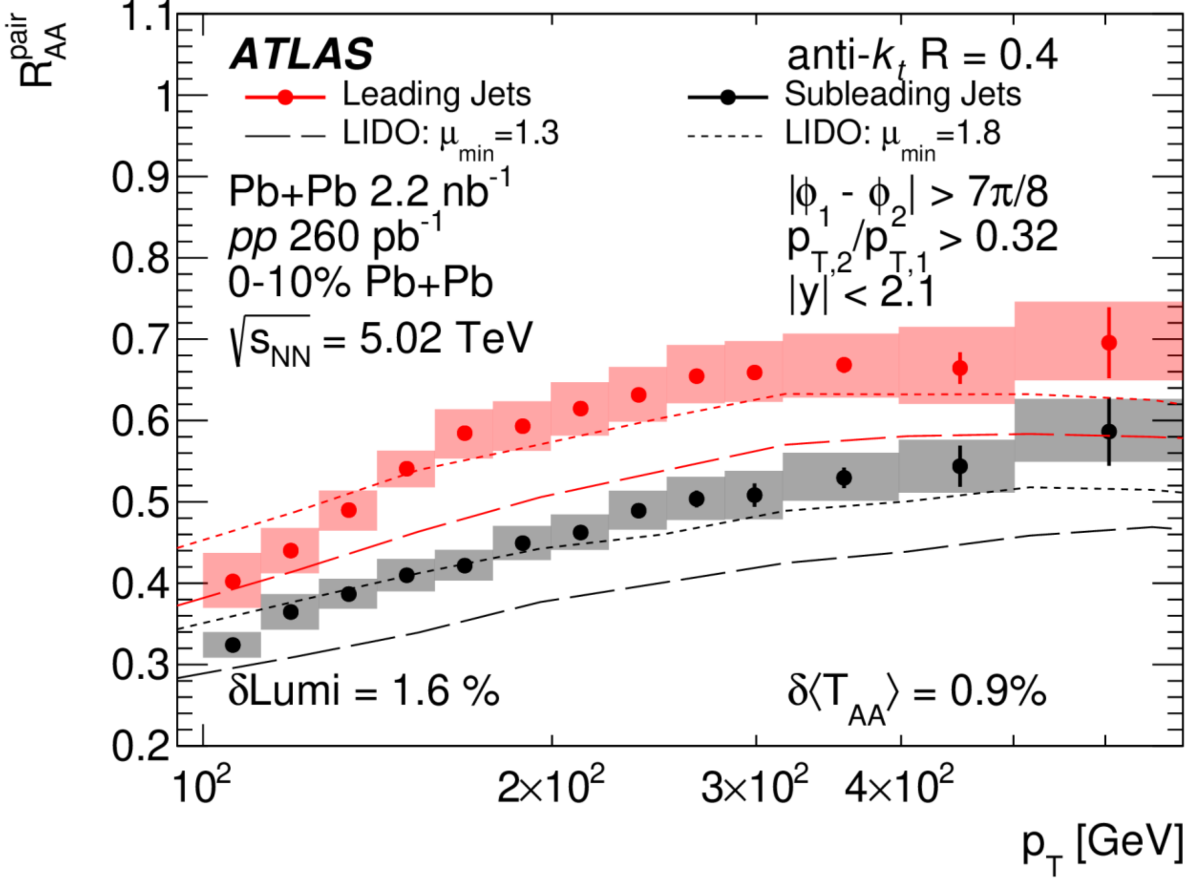


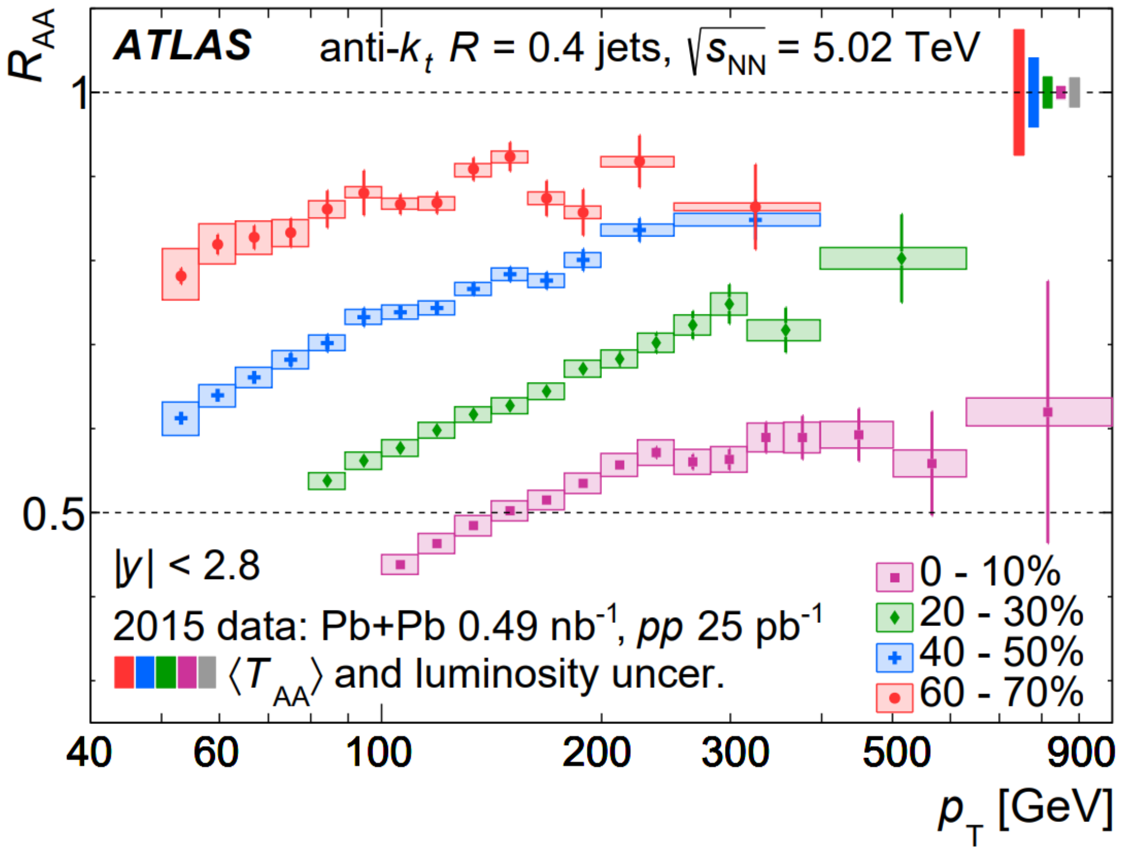
Significant modification from *pp* collisions in the x_J shape is observed across centrality at low $p_{\mathrm{T},1}$

Notable deviations from *pp* is observed up through 60% central Pb+Pb events for 398 < $p_{\mathrm{T},1}$ < 562 GeV

R_{AA}^{pair} and inclusive jets R_{AA}

https://arxiv.org/pdf/1805.05635.pdf





The inclusive jet R_{AA} above 150 GeV is bracketed by the $R_{AA}^{pair}(p_{T,1})$ and $R_{AA}^{pair}(p_{T,2})$

- Below 150 GeV the inclusive jet R_{AA} is consistent with the $R_{AA}^{pair}(p_{T,1})$