Inclusive jet and dijet suppression in Pb+Pb and Xe+Xe collisions with ATLAS

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On behalf of the ATLAS collaboration

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Introduction

We study the properties of quark gluon plasma (QGP), the most extreme case of matter (in terms of density & temperature) which is created in heavy ion collisions.

- How? E.g. by using jets as probes which should tell us about:
  - Properties of de-confined matter created in heavy-ion collisions.
  - Radiation of energetic color charges in this de-confined medium.

- In this talk three measurements will be presented:
  - Inclusive jet measurement @ 5.02 TeV in Pb+Pb collisions. arXiv:1805.05635
  - Jet mass @ 5.02 TeV in Pb+Pb collisions. ATLAS-CONF-2018-014
  - Dijet asymmetry @ 5.44 TeV in Xe+Xe collisions. ATLAS-CONF-2018-007

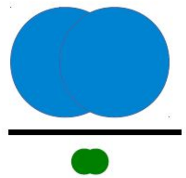
- For the first time Xe+Xe recorded in Oct 2017 ~ 6 hours.

Nuclear modification factor R_{AA}

Partons lose energy through interactions with the medium $\rightarrow$ **jet quenching**

QCD in medium

Yields in A+A

$$R_{AA} = \frac{1}{N_{\mathrm{coll}}}$$


$$= \frac{1}{N_{\mathrm{coll}}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}} = \frac{1}{T_{AA}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}}$$

QCD in vacuum

pp reference

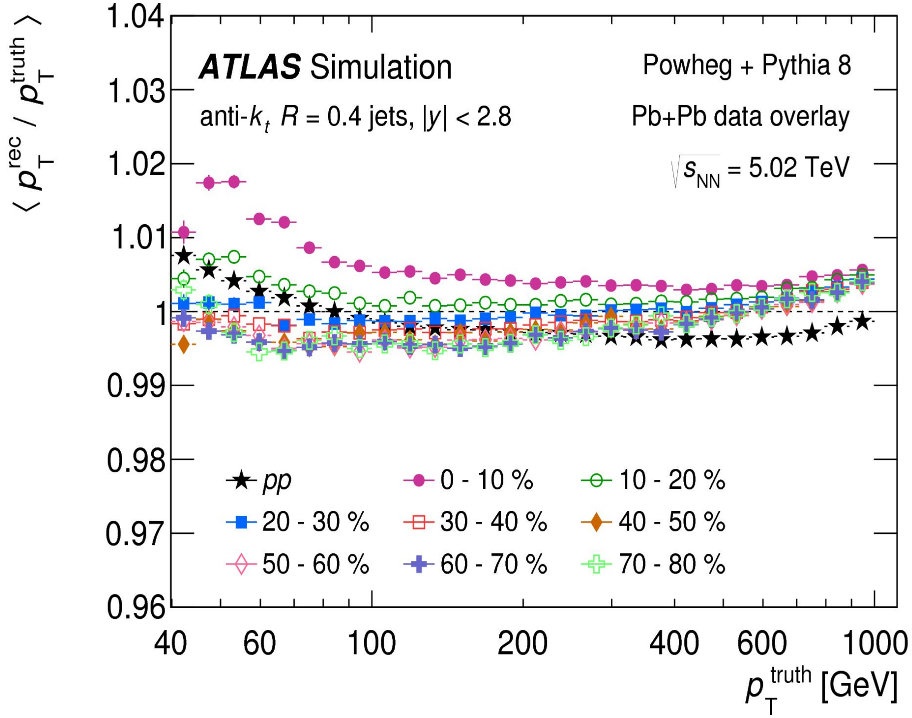
- Compares HI and *pp* collisions and removes the geometrical scaling.
- Jet nuclear modification factor quantifies the magnitude of jet suppression, which arise mainly from final-state interactions with constituents of the medium.

Performance of jet reconstruction

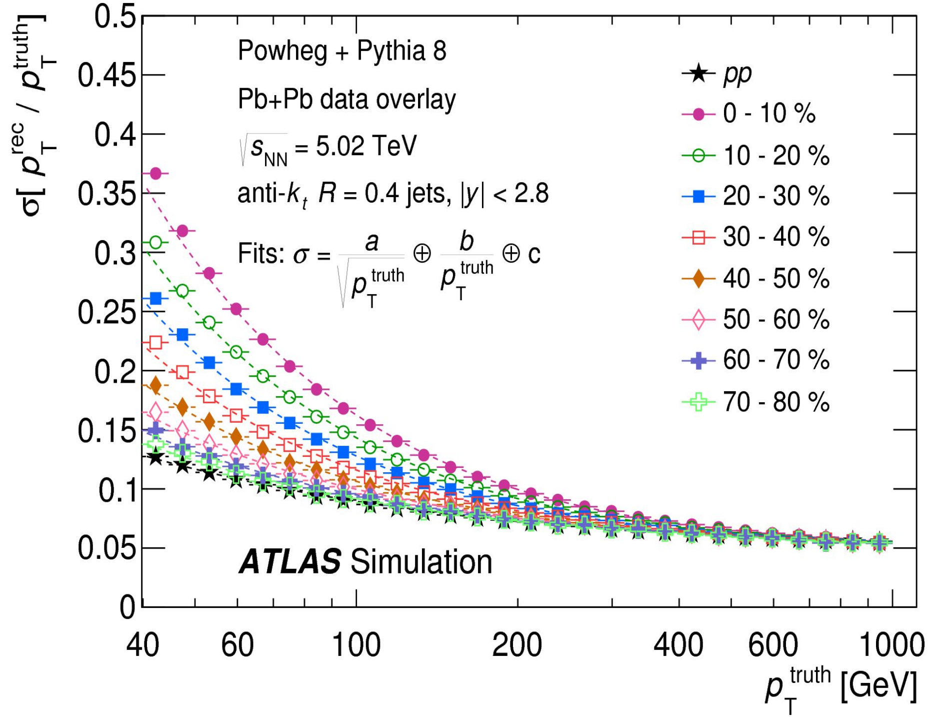
- Realistic jet MC: NLO POWHEG+PYTHIA8 + minimum bias Pb+Pb data overlay with full simulation by Geant4.

arXiv:1805.05635

Jet energy scale



Jet energy resolution

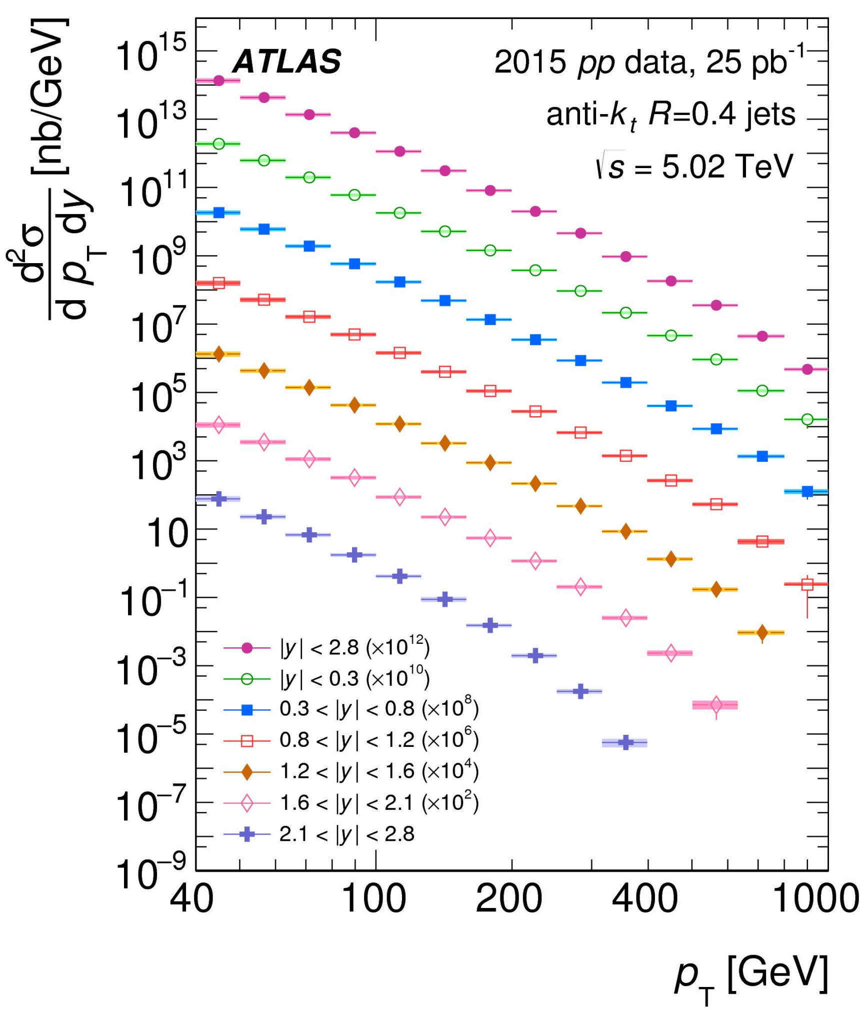


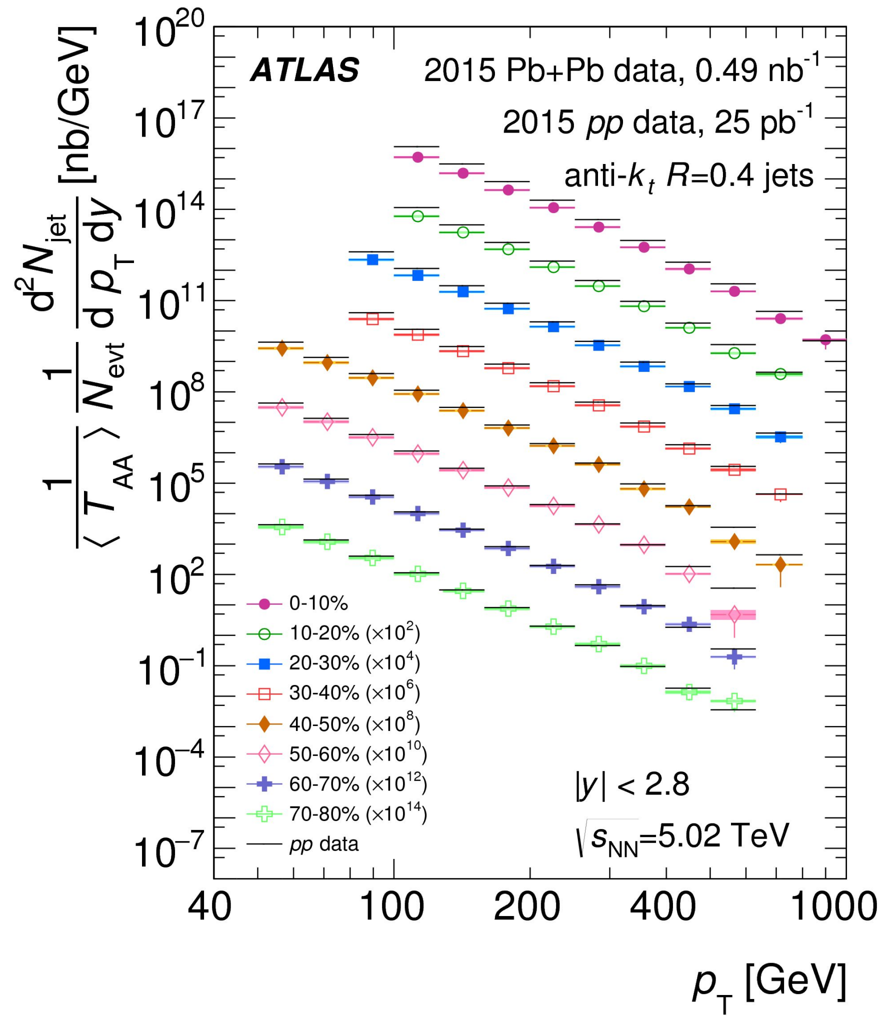
- JES: Good understanding, ~1% centrality dependence above 100 GeV.
- JER: expected behavior, degraded in central collisions due to UE fluctuations.

Jet cross-section and yields @ 5.02 TeV

- Left: Jet cross-section measured differentially in rapidity for *pp* collisions.
- Right: Jet yields measured differentially in centrality for Pb+Pb collisions.

arXiv:1805.05635

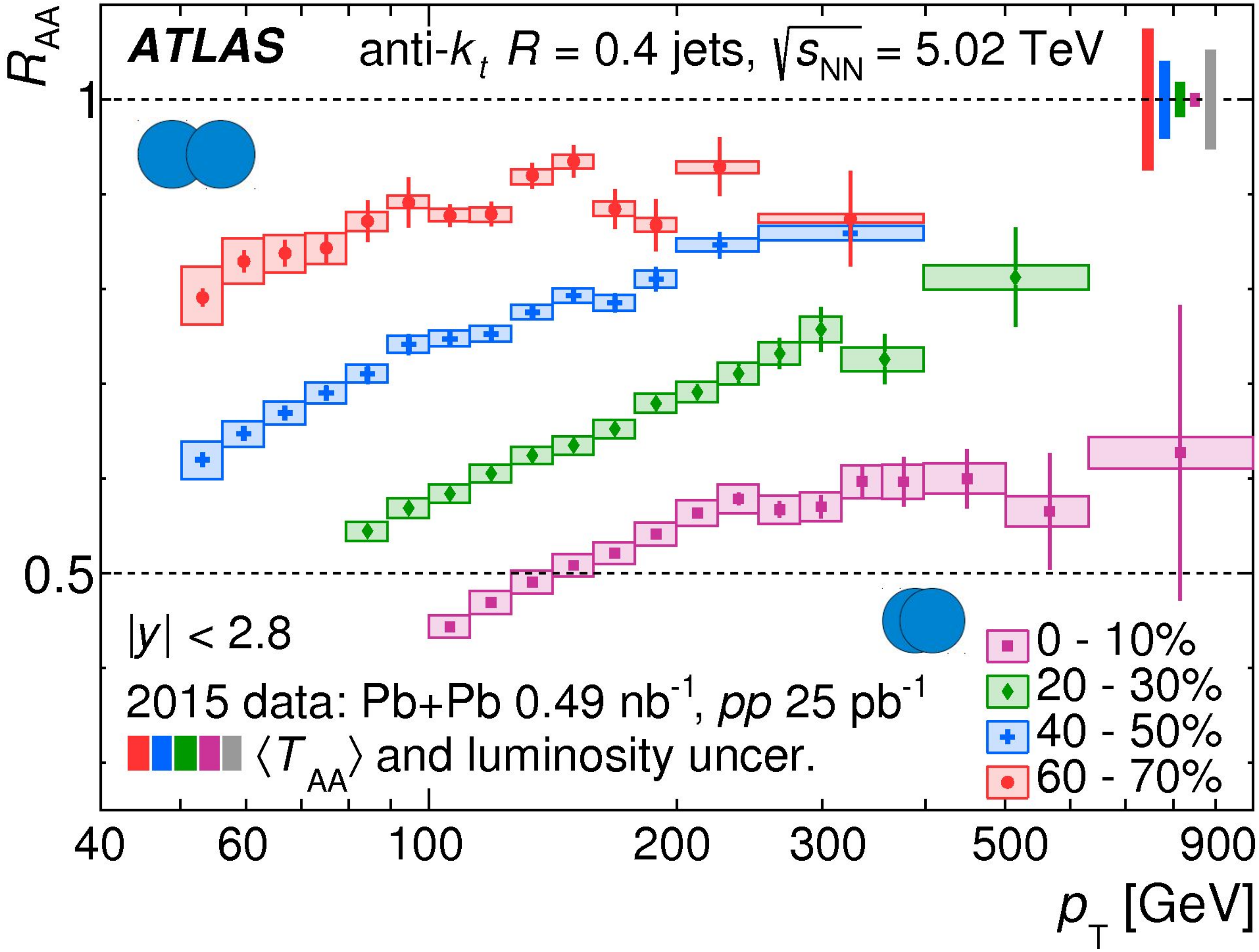




Jet R_{AA} vs p_T @ 5.02 TeV

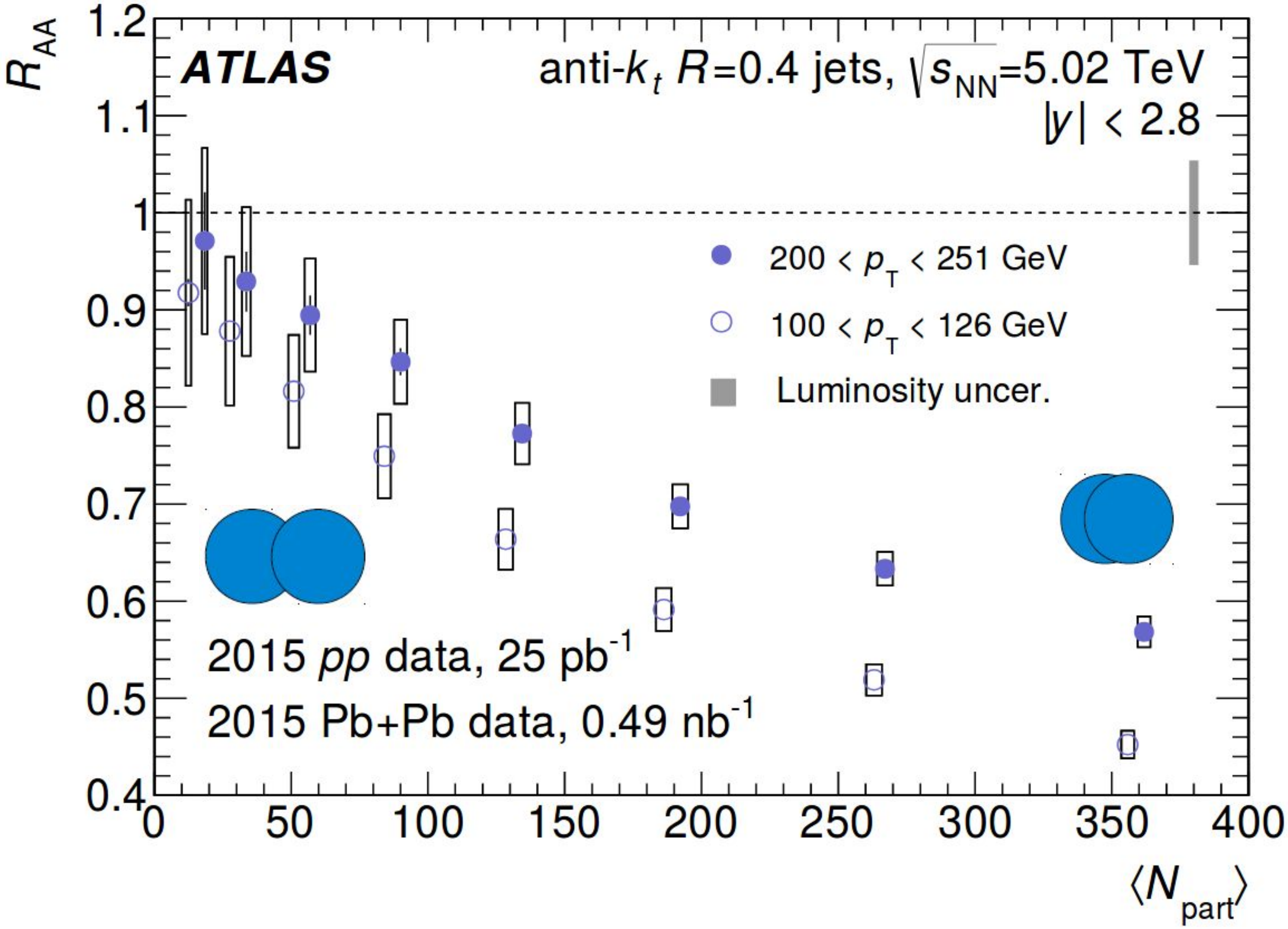
- Most central events: only modest grow with p_T, flattening for p_T > 200 GeV.
- Peripheral events: Still significant suppression even in 60-70%.

arXiv:1805.05635



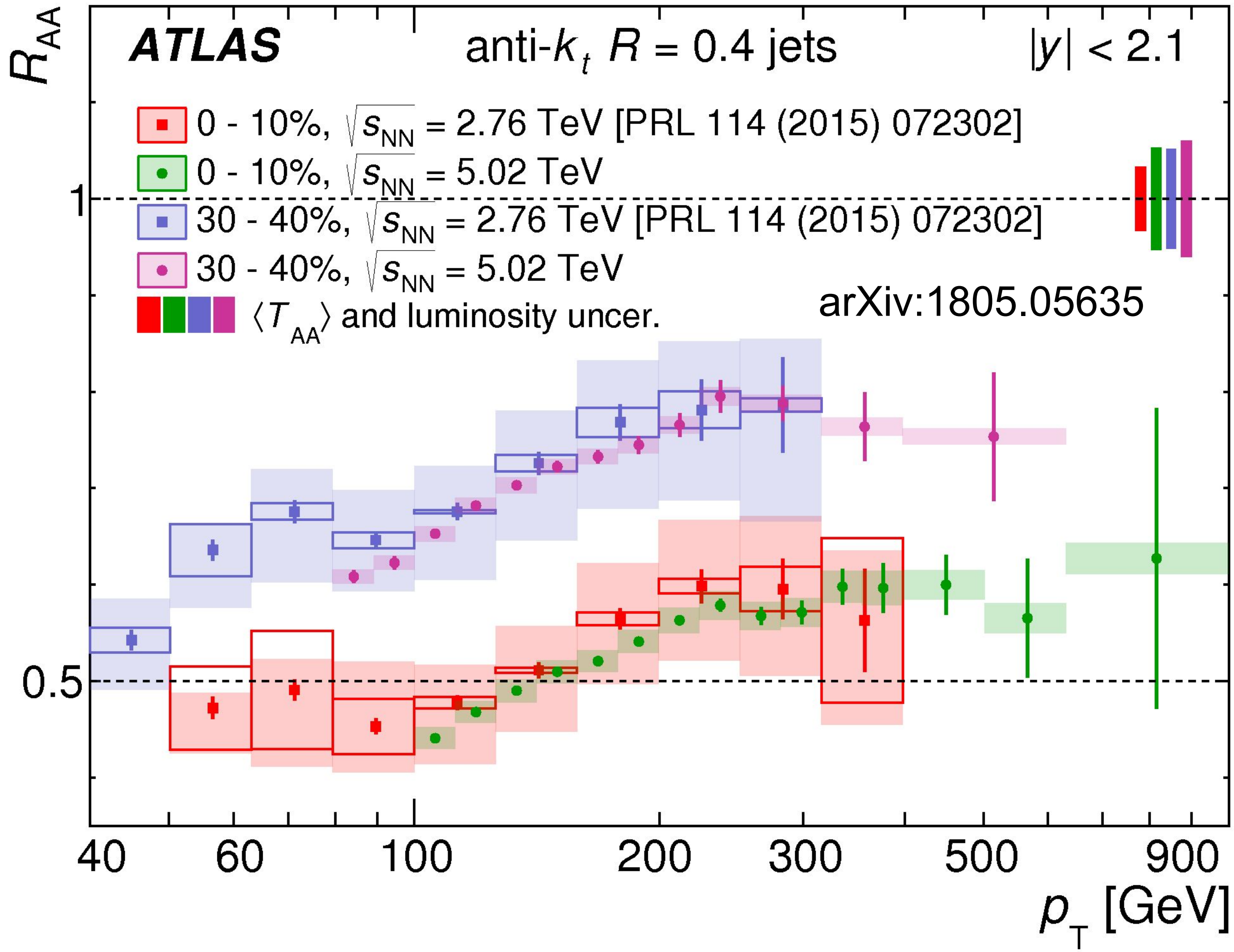
Jet R_{AA} vs N_{part} @ 5.02 TeV

- Centrality dependence for jets in $100 < p_T < 126$ GeV and $200 < p_T < 251$ GeV.
- Smooth decrease of R_{AA} with increasing centrality.



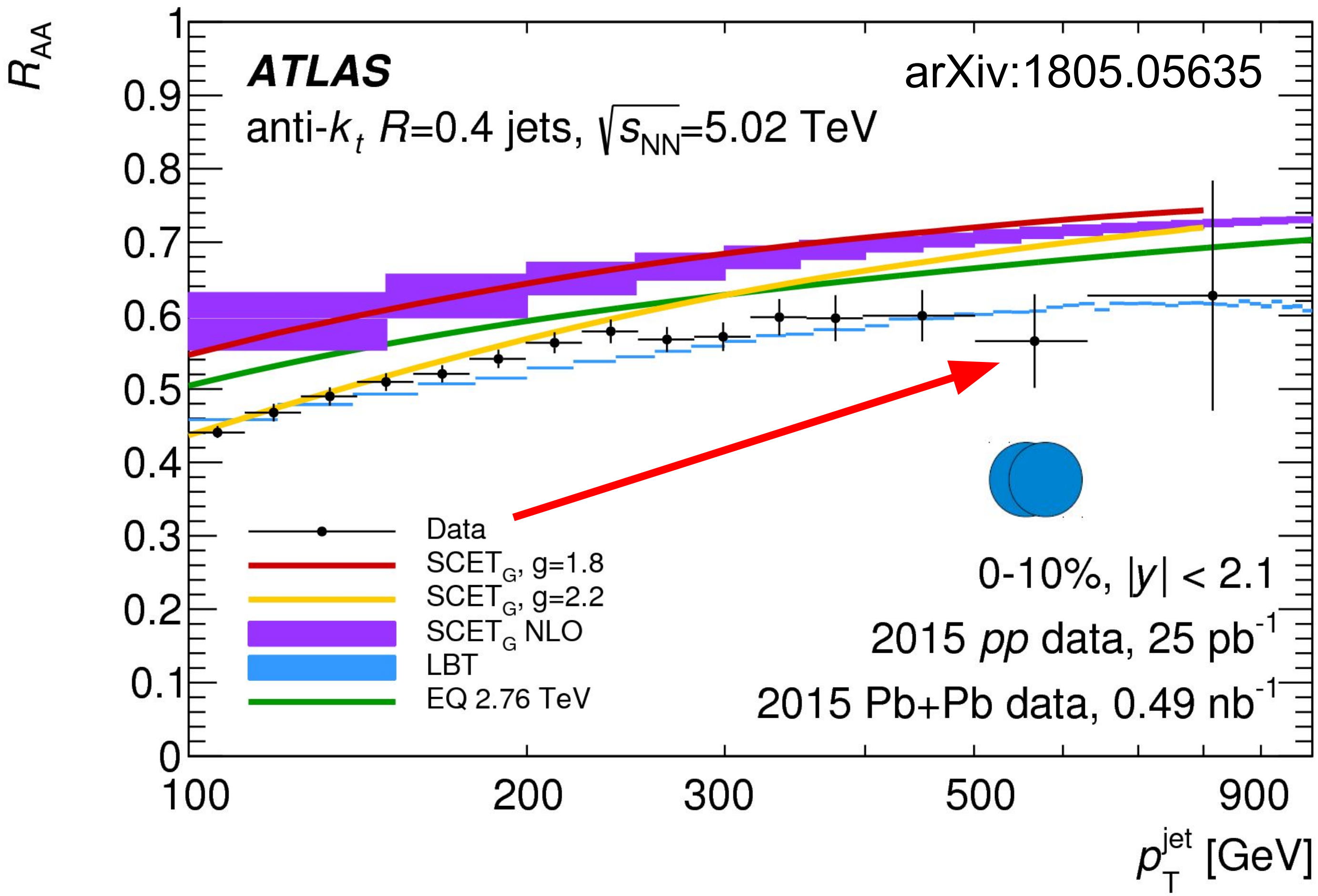
arXiv:1805.05635

Jet R_{AA} vs p_T @ 2.76 TeV and 5.02 TeV



- No centre-of-mass energy dependence observed between 2.76 and 5.02 TeV.

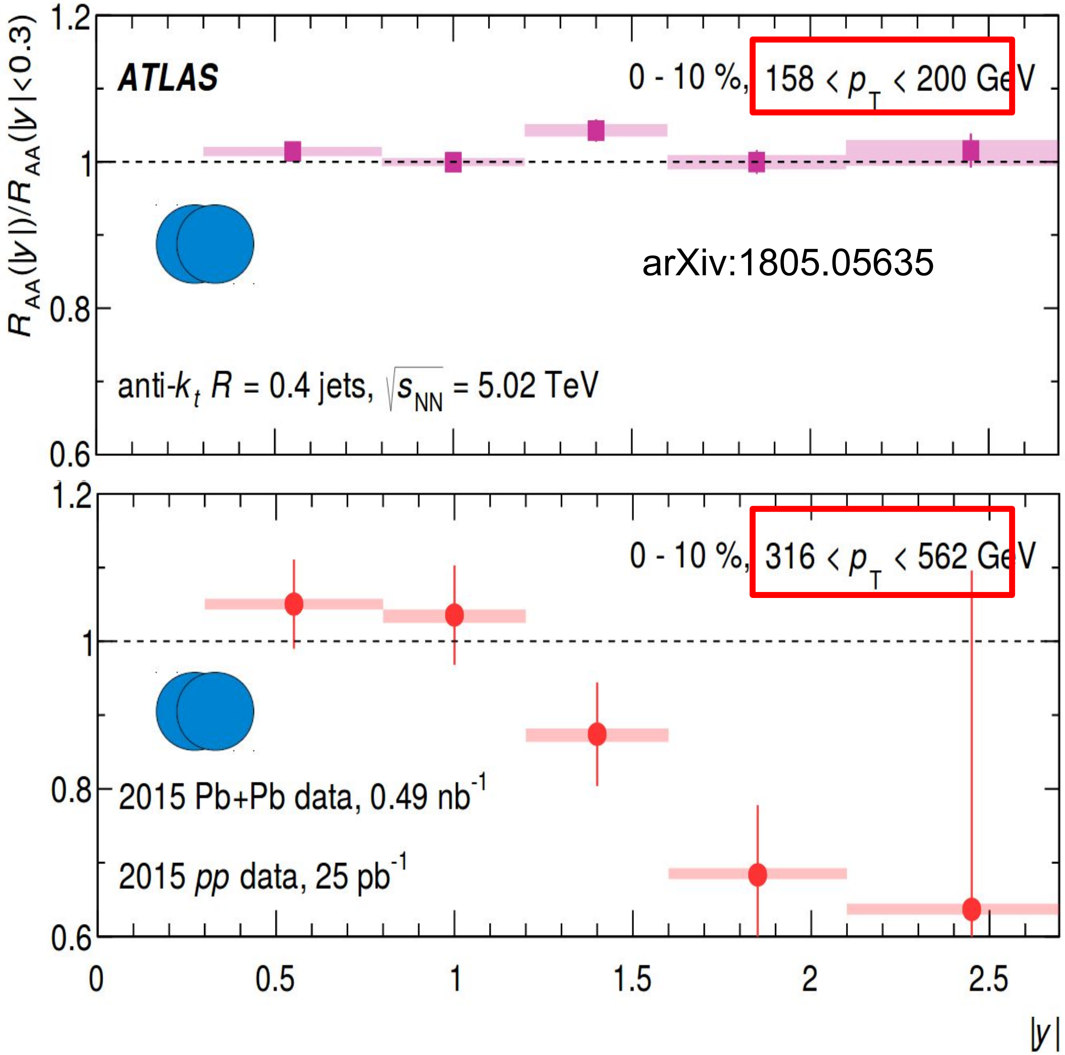
Jet R_{AA} vs theory comparisons



- Jet R_{AA} measurements are (now) providing stringent tests of jet quenching calculations.
- All models can reproduce the trend seen in data.

Jet R_{AA} vs rapidity

$$\frac{R_{\mathrm{AA}}(|y|)}{R_{\mathrm{AA}}(|y|<0.3)}$$



- Fraction of quark jets increases with $|y|$ at fixed jet p_T.
- Quark jets should lose less energy than gluon jets:
  - Increase R_{AA} with $|y|$
- Spectra become steeper with increasing |y|:
  - Decrease R_{AA} with $|y|$.

- For p_T > 316 GeV: The effects of the steeper spectra seems to dominate the measurement.

arXiv:1805.05635

Jet mass measurement @ 5.02 TeV

- Do jets of different widths lose energy differently? How does R_{AA} depend on m/p_T?
- m/p_T is related to the angular width of the jet. Information about transverse structure of jet, connection to virtuality of initial parton.
- Distribution of m/p_T is measured, where m is the norm of jet four-momentum from calo towers ($\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$):

$$m = \sqrt{\Big(\sum_{i\in J} E_i\Big)^2 - \Big(\sum_{i\in J} \vec{p}_i\Big)^2}$$

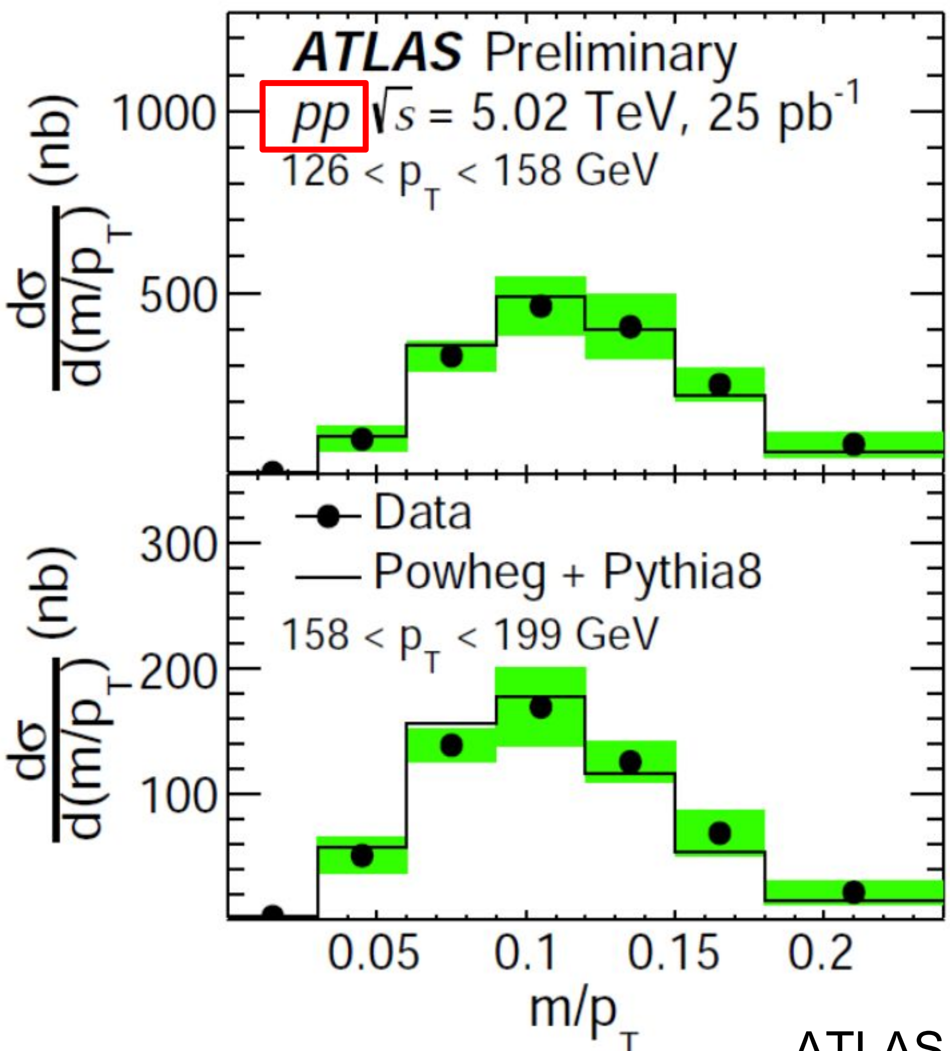
- First fully-unfolded measurement of jet mass in Pb+Pb and *pp* collisions at 5.02 TeV by ATLAS.

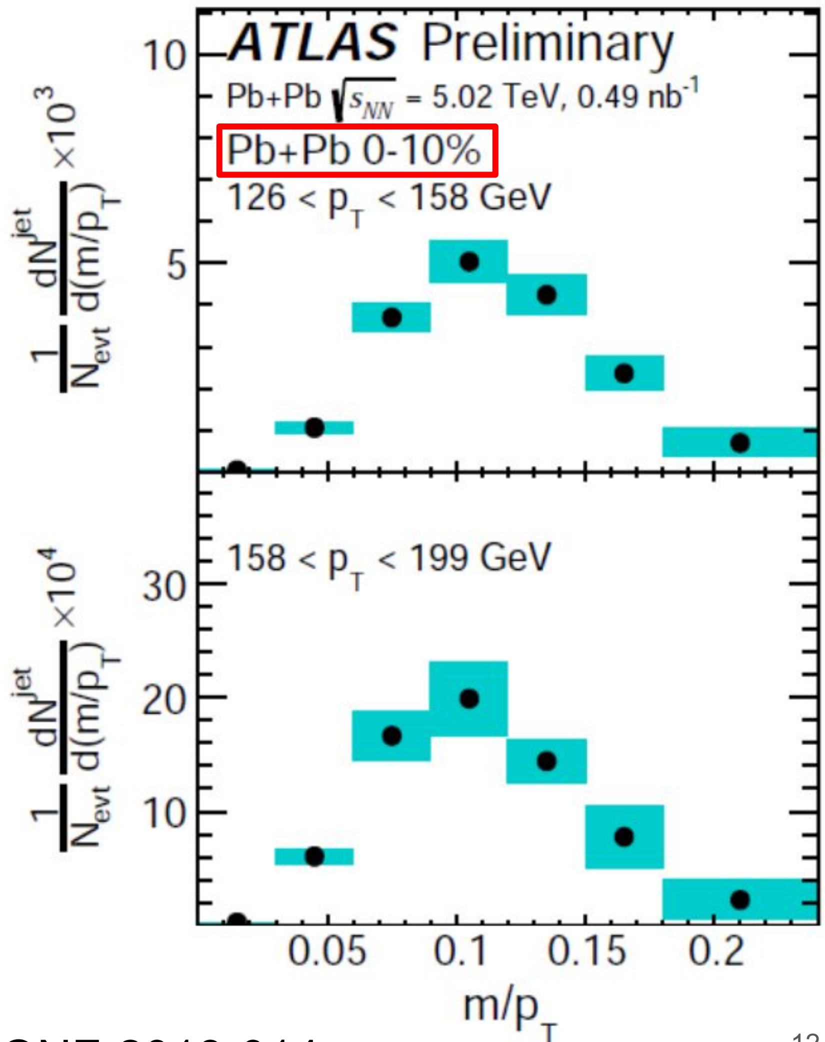
$$R_{\mathrm{AA}}(m/p_{\mathrm{T}}, p_{\mathrm{T}}) = \frac{\boxed{\left.\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{Pb+Pb}}}{\mathrm{d}(m/p_{\mathrm{T}})}(p_{\mathrm{T}})\right|_{\mathrm{cent}}}}{\boxed{\langle T_{\mathrm{AA}}\rangle}\boxed{\frac{\mathrm{d}\sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}(m/p_{\mathrm{T}})}(p_{\mathrm{T}})}}$$

Measured in Pb+Pb

Measured in *pp*

Jet mass distributions @ 5.02 TeV

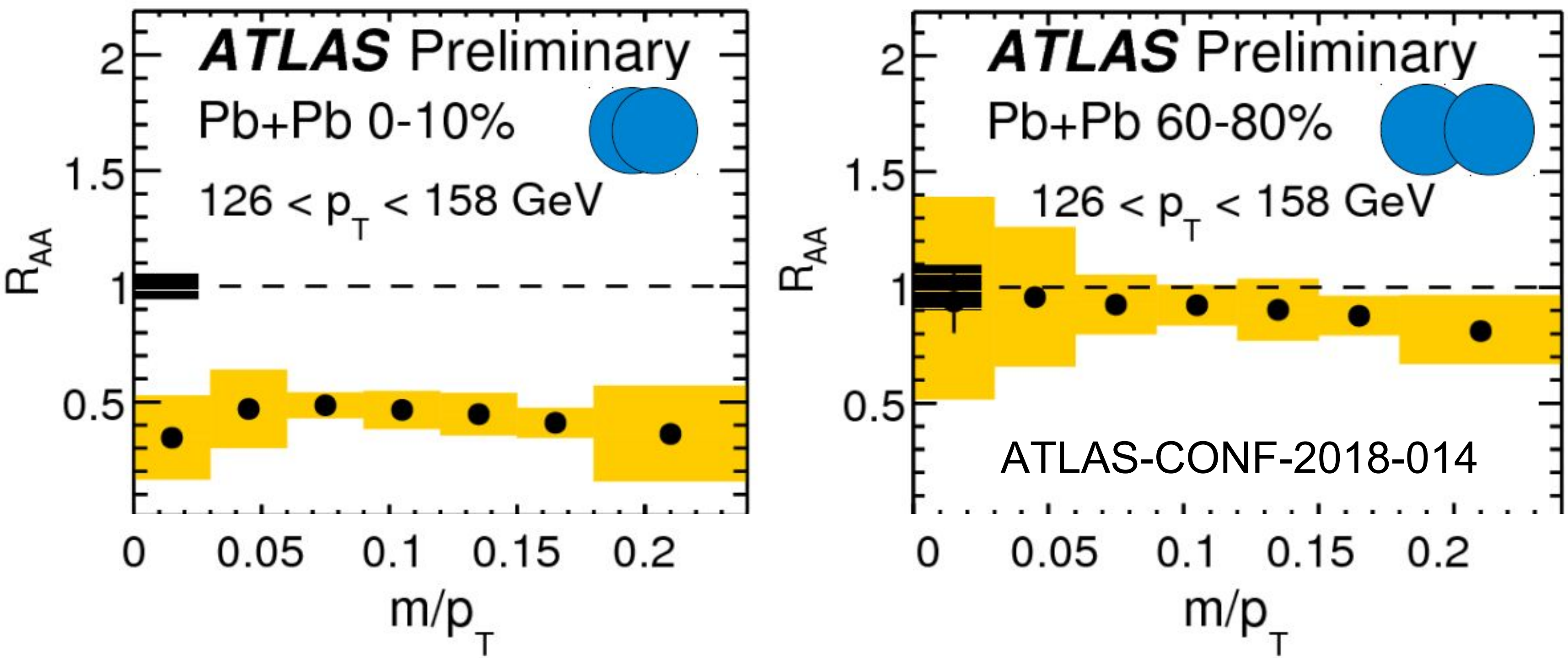




ATLAS-CONF-2018-014

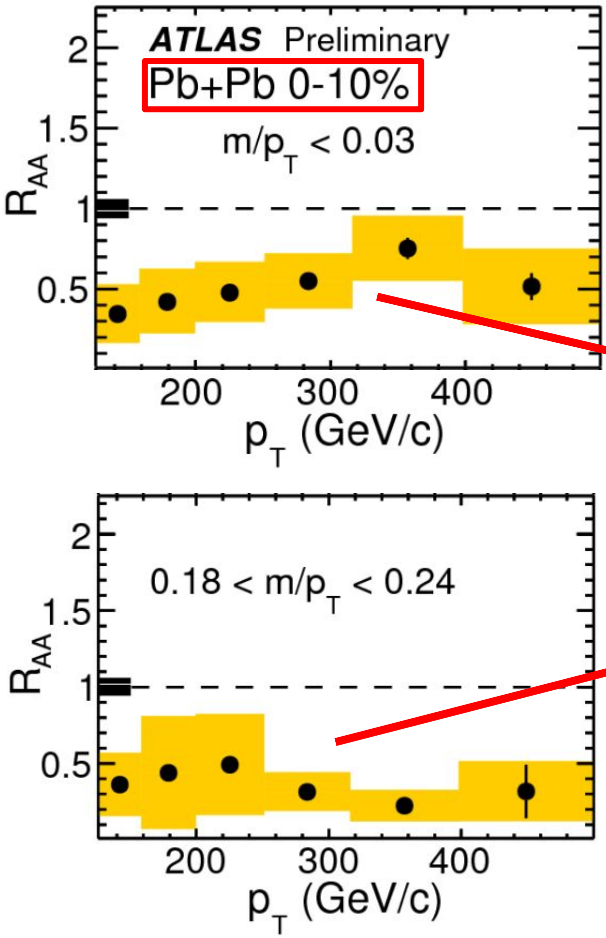
Jet mass R_{AA} vs m/p_T @ 5.02 TeV

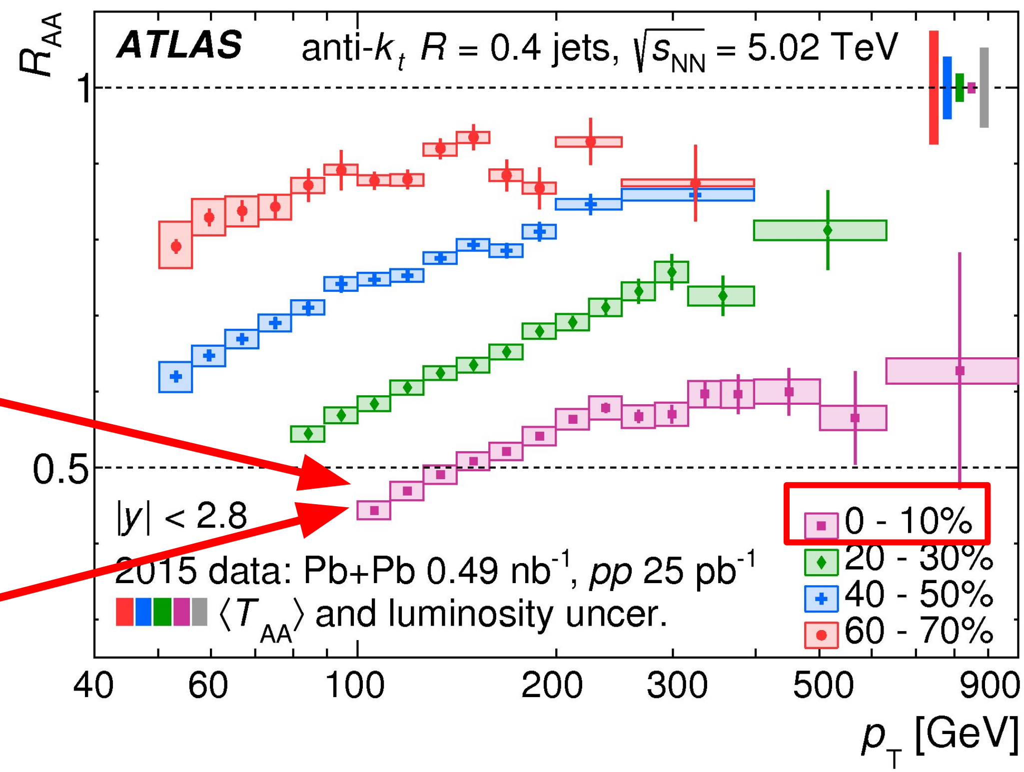
- Jet mass R_{AA} measured differentially in centrality and over a wide kinematic range of $100 < p_T < 500$ GeV.
- No significant modification of $R_{AA}(m/p_T)$ observed.
- Next step: reducing the systematic uncertainties and measure rapidity dependence to observe the quark/gluon fractions.



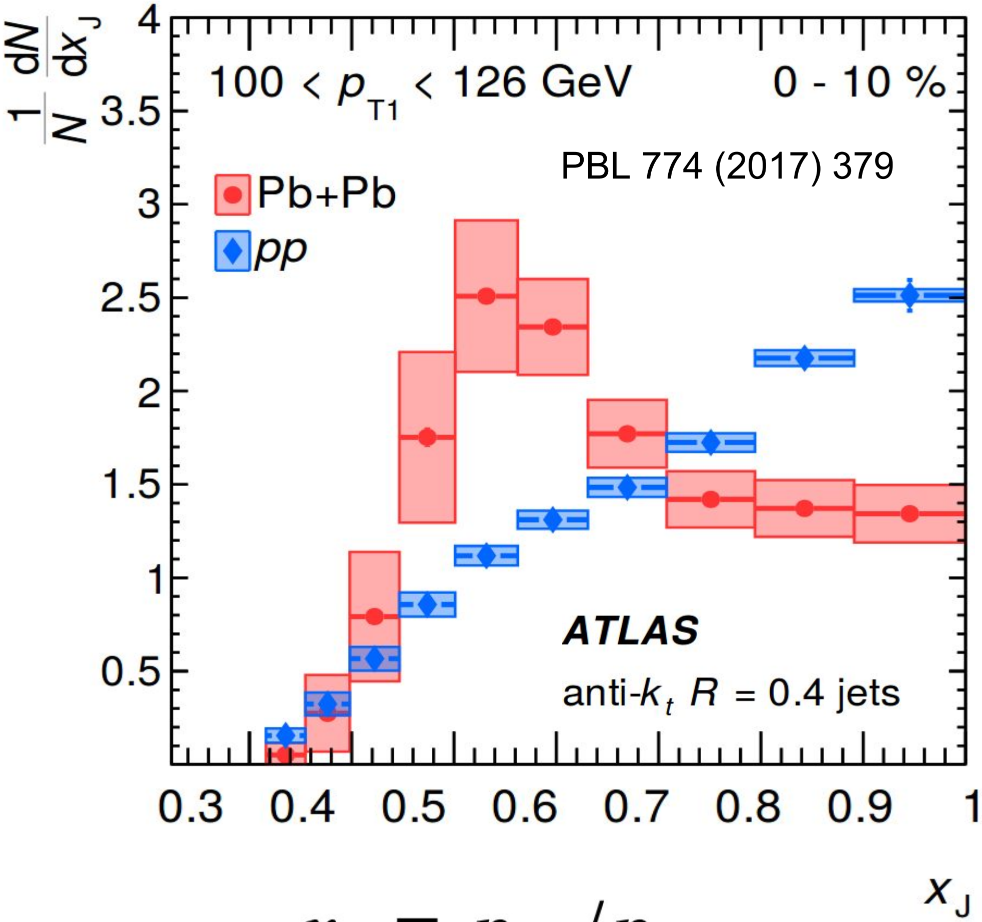
Jet mass R_{AA} vs p_T @ 5.02 TeV

- Jet mass R_{AA} measured differentially in centrality and over a wide kinematic range of $100 < p_T < 500$ GeV.
- All m/p_T bins consistent with inclusive jet $R_{AA}(p_T)$.





Reminder: Dijet asymmetry in Pb+Pb @ 2.76 TeV



$$x_J \equiv p_{T_2}/p_{T_1}$$

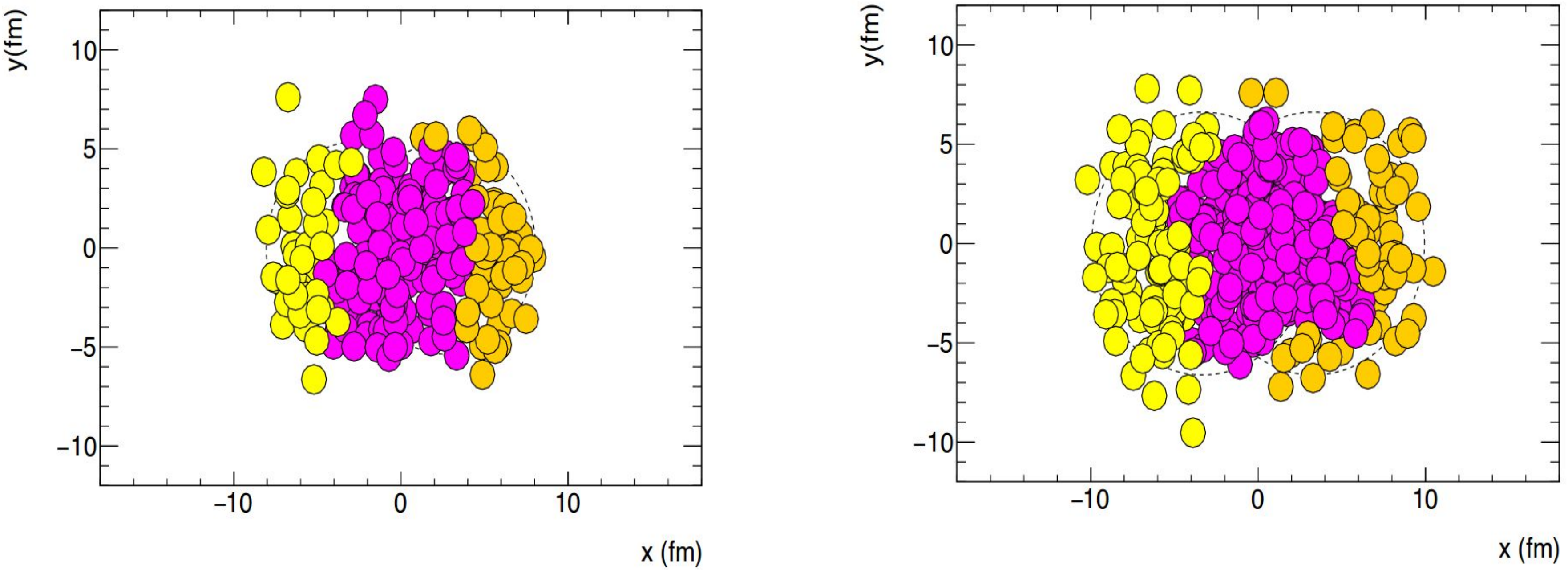
- **Measured for:**
  - $p_{T,subleadning}$ >25 GeV,
  - $p_{T,leadning}$ >100 GeV (various bins),
  - $|\Delta\varphi| > 7\pi/8$
  - $|\eta| < 2.1$
  - R=0.4, R=0.3 jets

- Corrected to particle-level by 2D bayesian unfolding (in p_{T1} and p_{T2} simultaneously).
- Energy loss very different for the second jet.

Xe+Xe vs. Pb+Pb

Xe+Xe (A = 129)

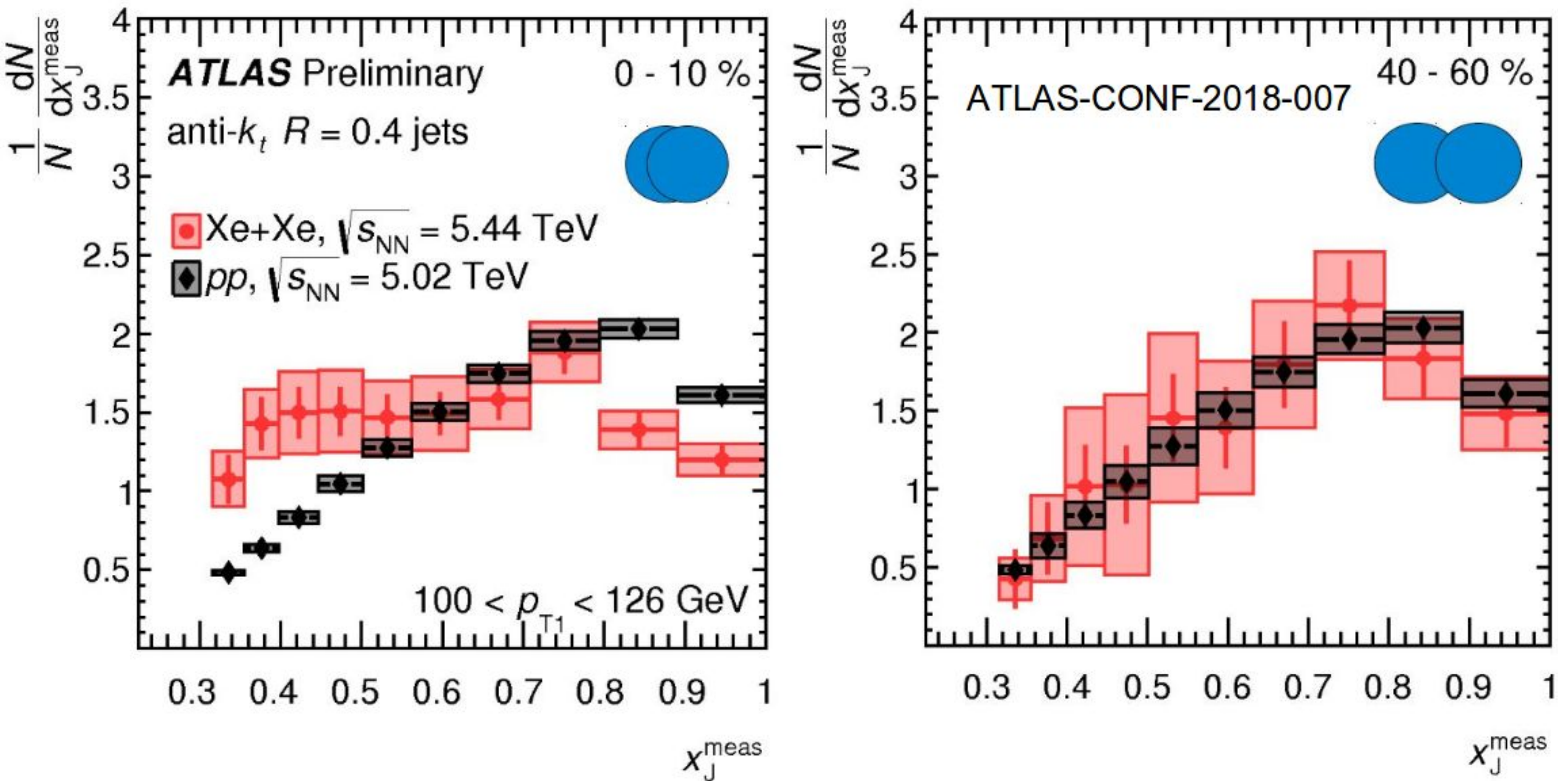
Pb+Pb (A = 208)



- Xe+Xe collisions have typically a shorter path length through medium (formed in overlap region). Smaller jet suppression expected.
- Xe+Xe and Pb+Pb collisions have also different density and geometry.

Dijet asymmetry in Xe+Xe and *pp* collisions

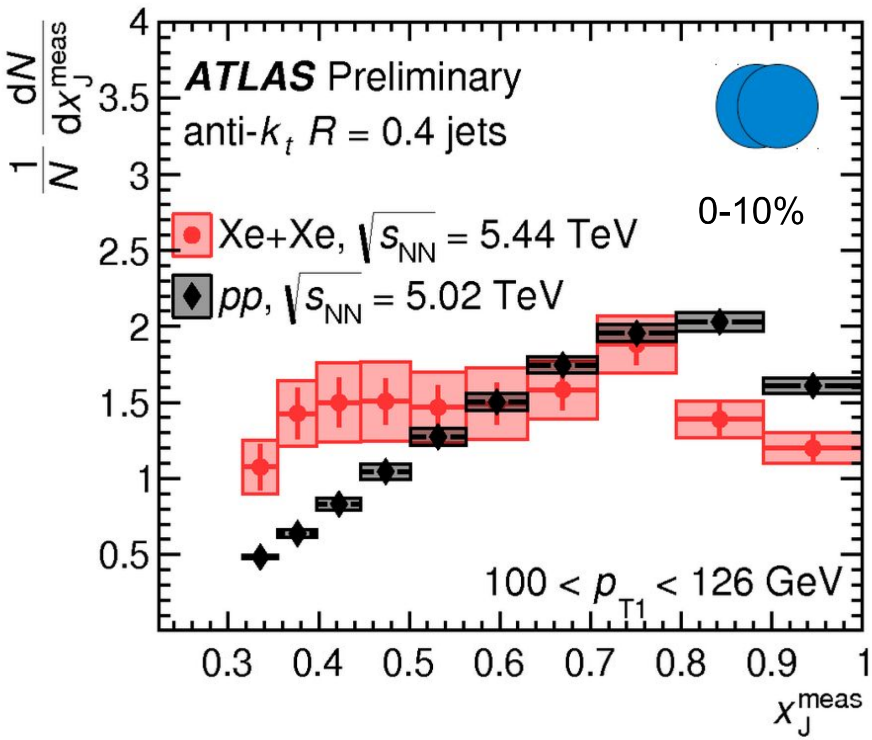
- Xe+Xe data sufficient for low-statistics measurements,
- Both Xe+Xe and *pp* data not unfolded for detector effects.
- See shift of x_J distribution similar to first ATLAS result in Pb+Pb.
- Centrality dependence for $100 < p_{T1} < 126$ GeV:

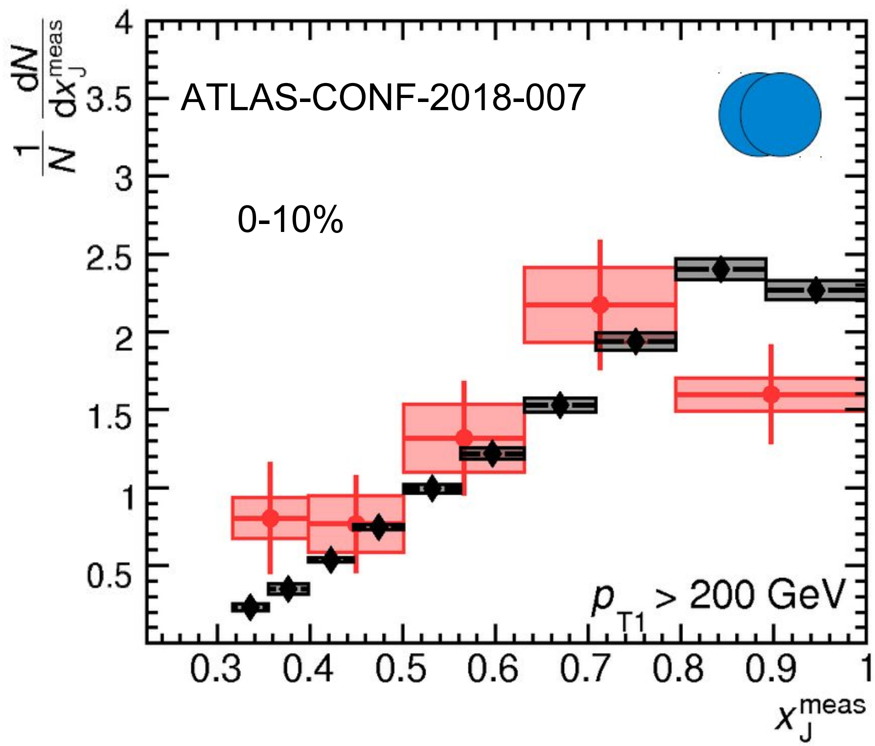


- Xe+Xe collisions: x_J decreases with decreasing centrality.

Dijet asymmetry in Xe+Xe and *pp* collisions

- Xe+Xe data sufficient for low-statistics measurements,
- Both Xe+Xe and *pp* data not unfolded for detector effects.
- See shift of x_J distributions similar to first ATLAS result in Pb+Pb.
- Leading jet momentum dependence for centrality 0-10%:



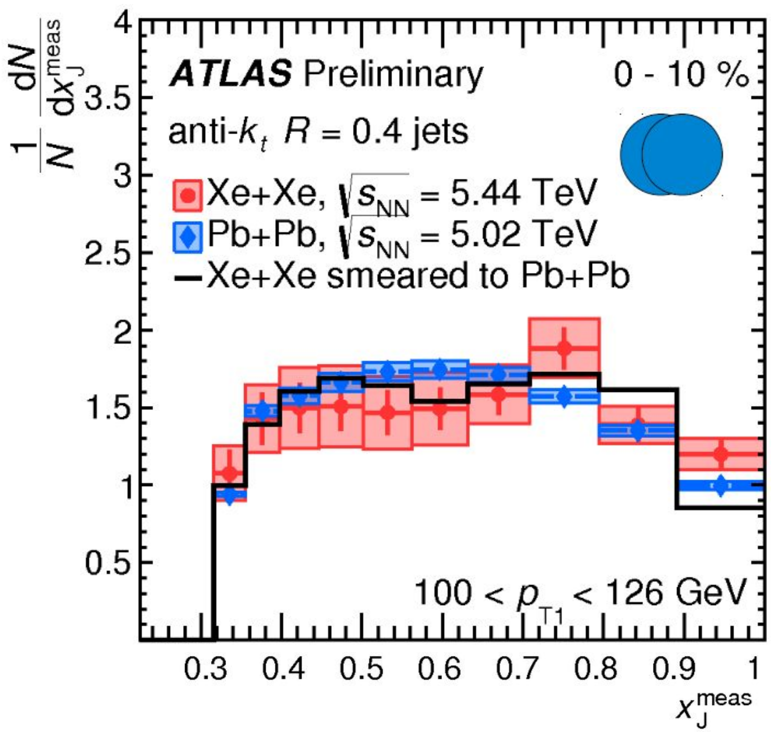


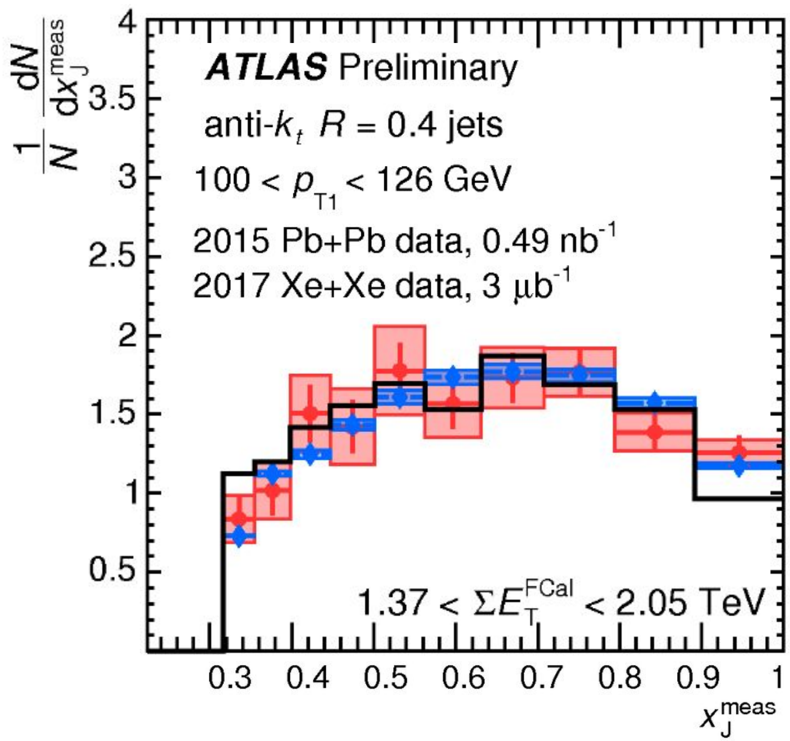
- In Xe+Xe collisions: Larger dijet asymmetry decreases with increasing jet p_T.

Dijet asymmetry in Xe+Xe and Pb+Pb collisions

- Xe+Xe data sufficient for low-statistics measurements,
- Both Xe+Xe and Pb+Pb data not unfolded for detector effects.
- Left: Consistent in same centrality percentiles 0-10%.
- Right: Consistent in same FCal E_T bins.

ATLAS-CONF-2018-007





- Black line: Xe+Xe smeared to Pb+Pb because of missing unfolding and presence of calorimeter fluctuations.

Dijet asymmetry in Xe+Xe and Pb+Pb collisions

- Xe+Xe data sufficient for low-statistics measurements,
- Both Xe+Xe and Pb+Pb data not unfolded for detector effects.
- Left: Consistent in same centrality percentiles 0-10%.
- Right: Consistent in same FCal E_T bins.

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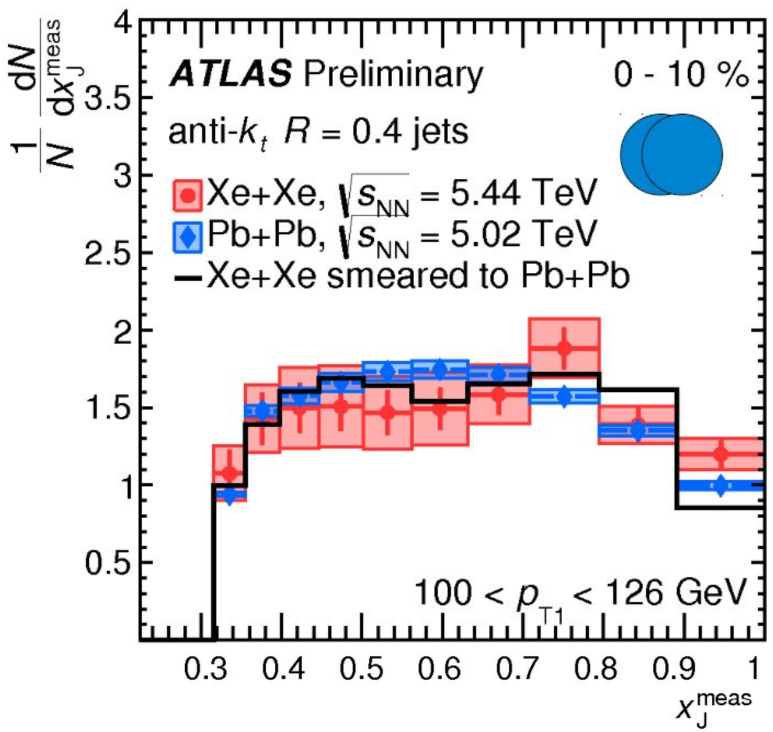
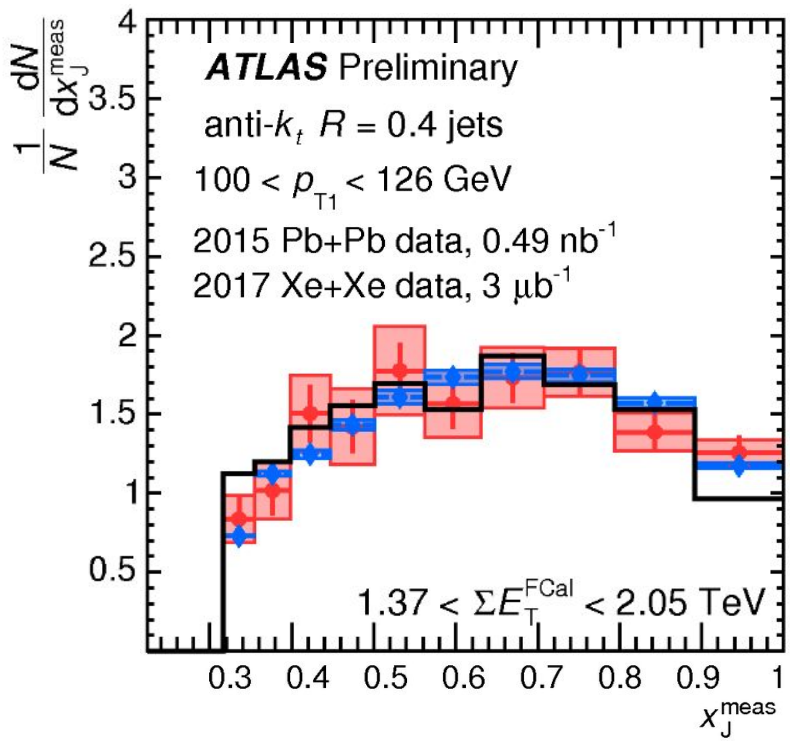




- The difference in calorimeter fluctuations has minimal impact on the result.
- No clear preference for geometry vs. density.

Conclusions

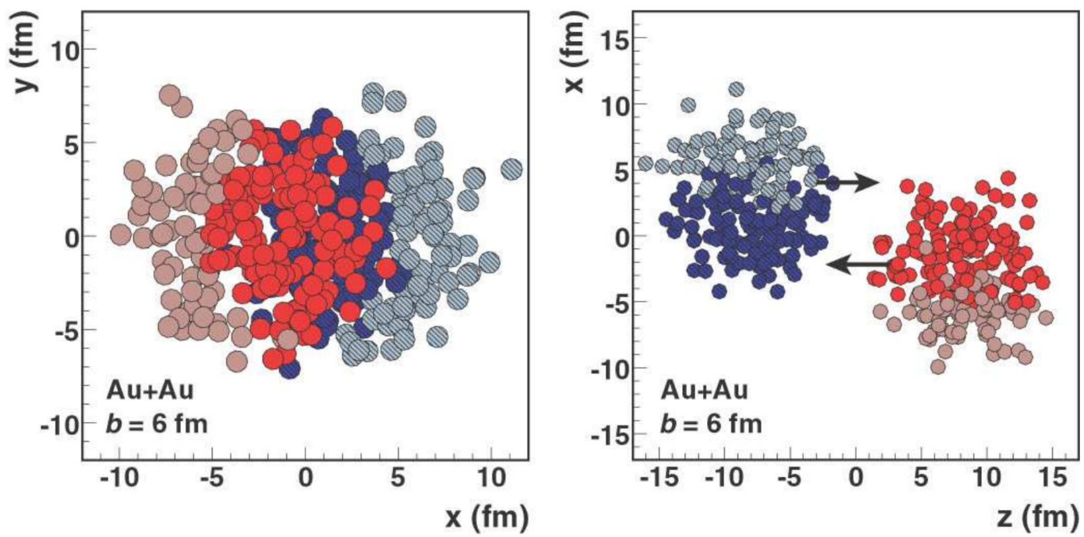
- Inclusive jet suppression in 5.02 TeV Pb+Pb collisions:
  - Significant suppression seen up to ~1 TeV with weak p_T dependence.
  - Sign of rapidity dependence of R_{AA} observed for high-p_T jets.
  - No differences in R_{AA} between 2.76 TeV and 5.02 TeV.
- Mass of jets measured in Pb+Pb & *pp* collisions at 5.02 TeV:
  - No dependence of R_{AA} on m/p_T of jets observed.
- Dijet asymmetry in 5.44 TeV Xe+Xe collisions:
  - No differences in comparison to Pb+Pb collisions observed.

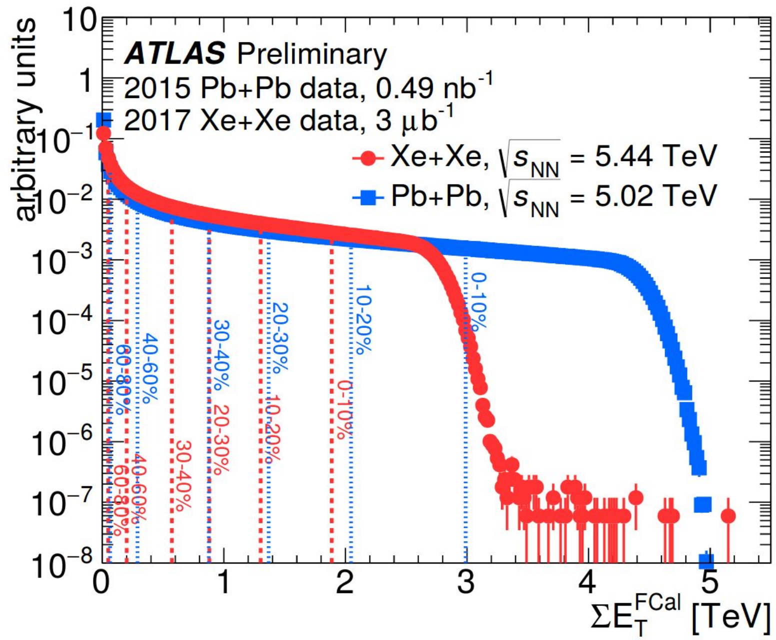
ATLAS public results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Back up

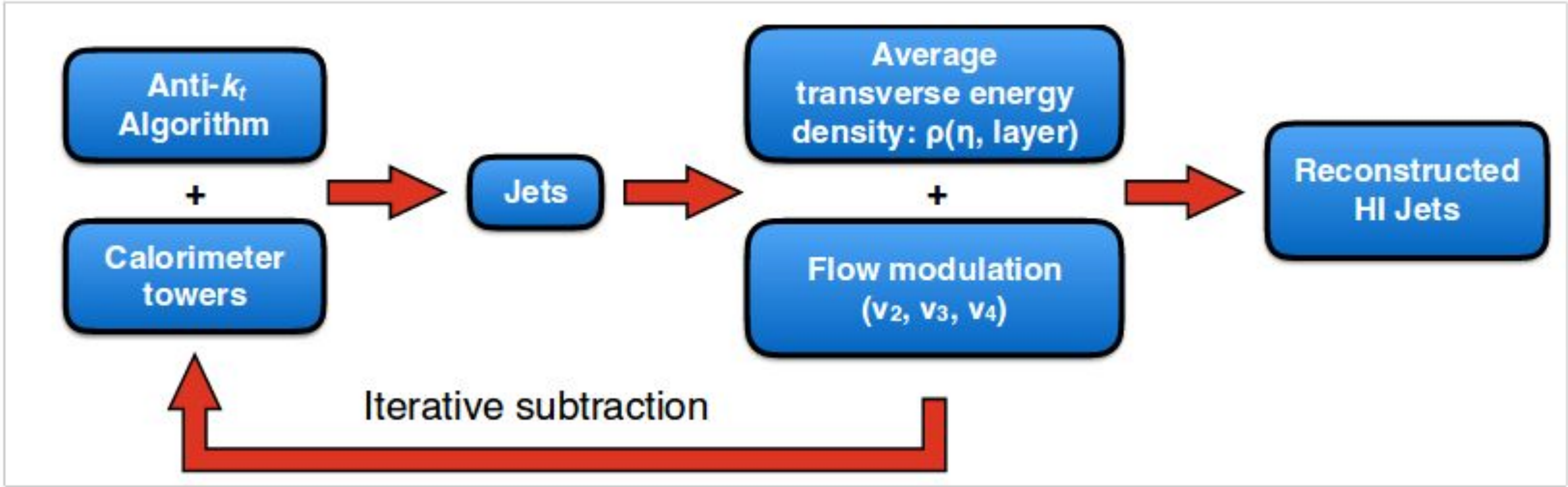
Centrality in HI collisions



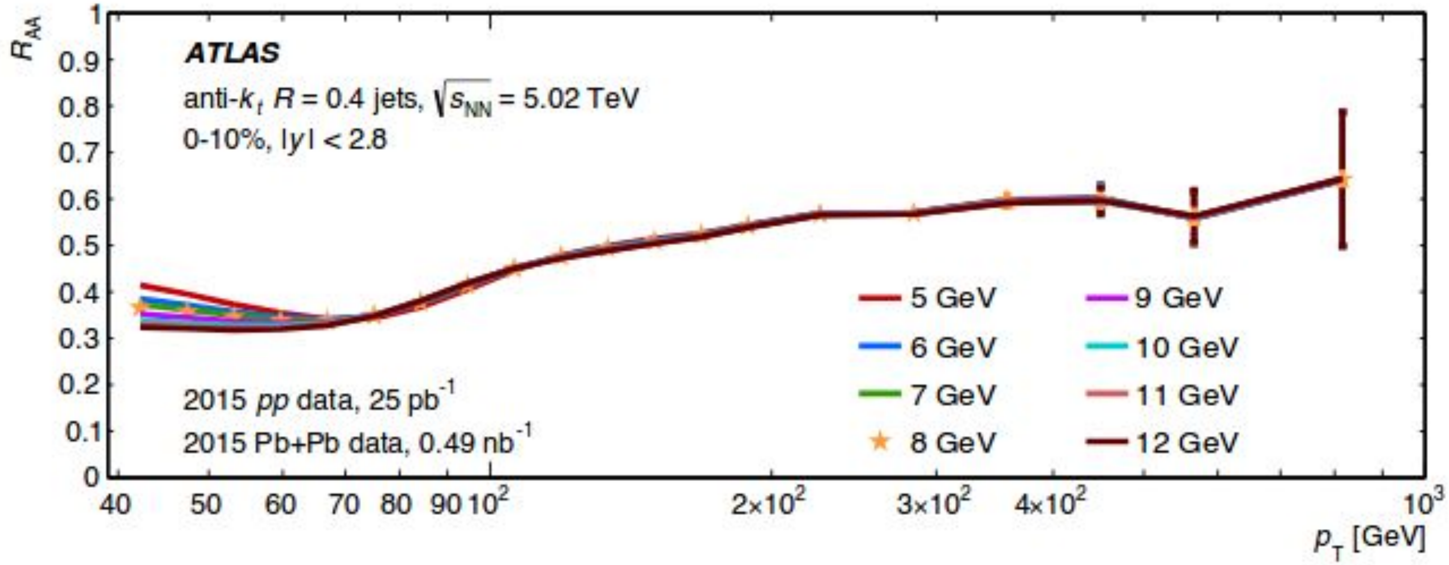


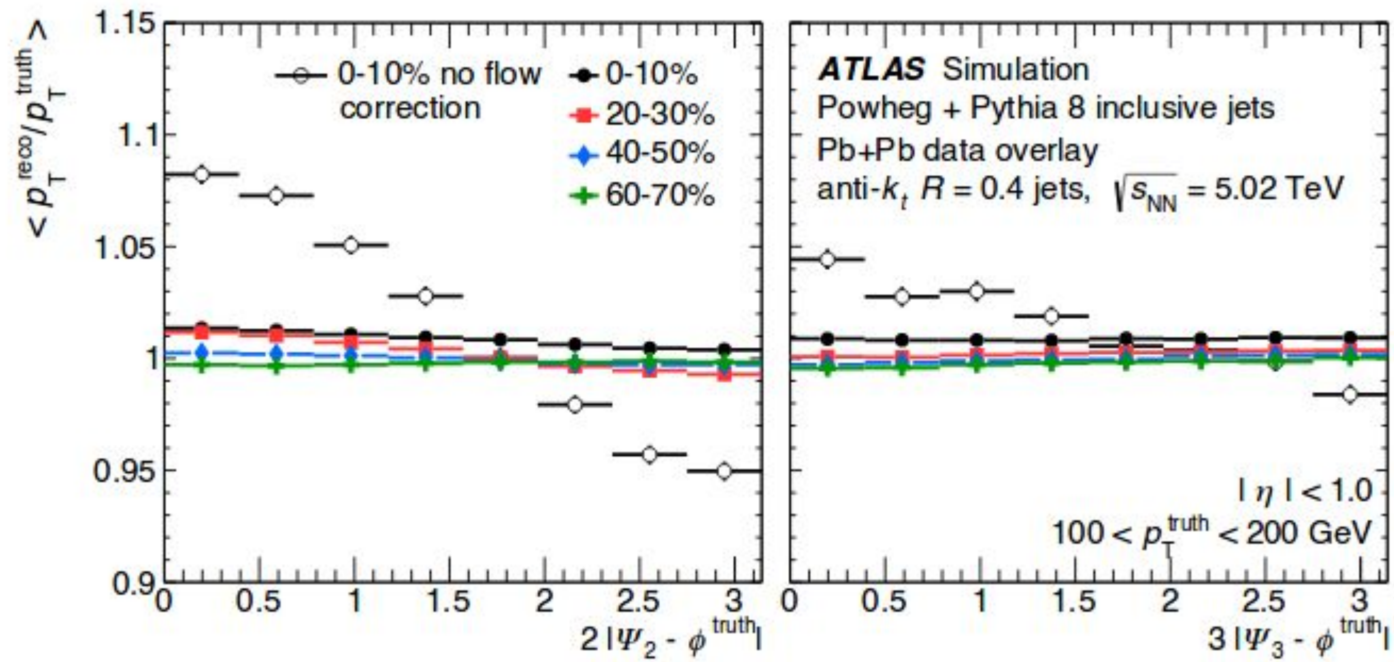
- Centrality is a measure of overlap of two colliding nuclei.
- Determined by the sum of the transverse energy deposited in the Forward calorimeters.
- It is closely related to the average number of participant nucleons N_{part} and number of binary inelastic collisions N_{coll}
- Events divided into successive percentiles of the $\sum E_{\mathrm{T}}^{\mathrm{FCal}}$
- Central collisions: Large overlap, high number of participating nucleons N_{part}
- Peripheral collisions: Small overlap, low number of participating nucleons N_{part}

Jet reconstruction



Fake jet rejection and flow effects on JES

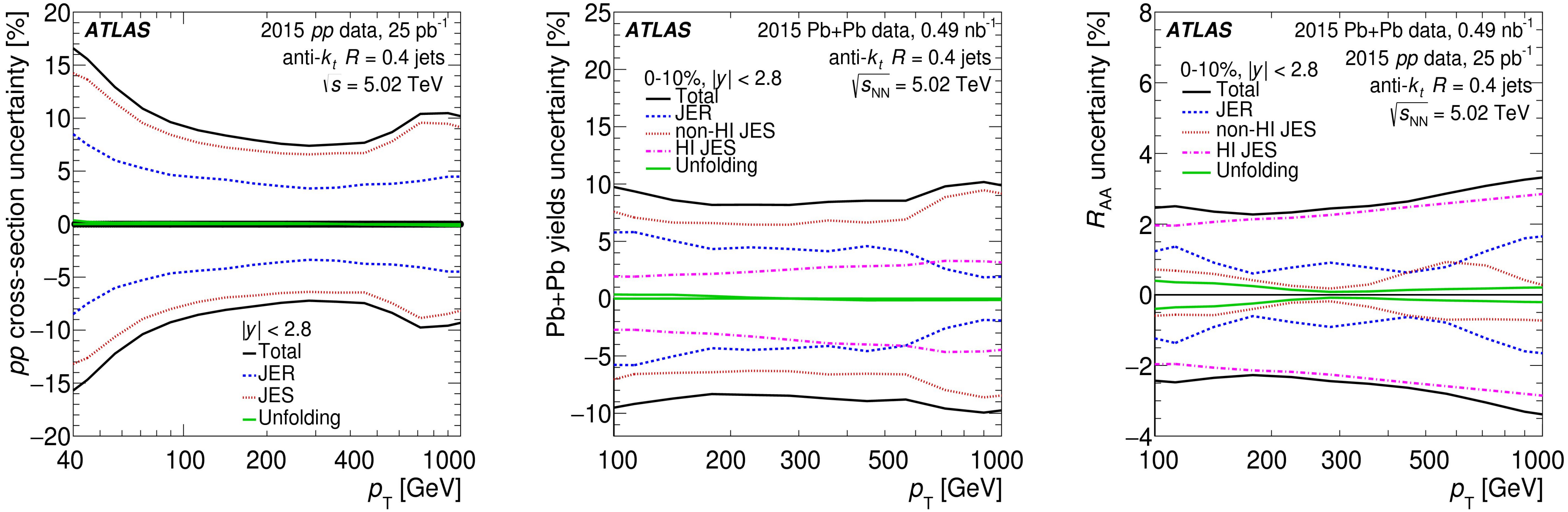




Systematic uncertainties @ 5.02 TeV

Left: Jet cross-section measured differentially in rapidity for *pp* collisions.
Right: Jet yields measured differentially in centrality for Pb+Pb collisions.

arXiv:1805.05635



- Jet energy scale (JES) uncertainties: 11 sources for pp baseline + 3 heavy-ion specific.
- JES further involves in situ studies using-jet and Z-jets in pp, “insitu” comparison using track jets and various MC checks.

Jet R_{AA} vs p_T @ 5.02 TeV

- Central events: only modest grow with p_T, flattening for $p_T > 200$ GeV.
- Peripheral events: Still significant suppression even in 70-80%.

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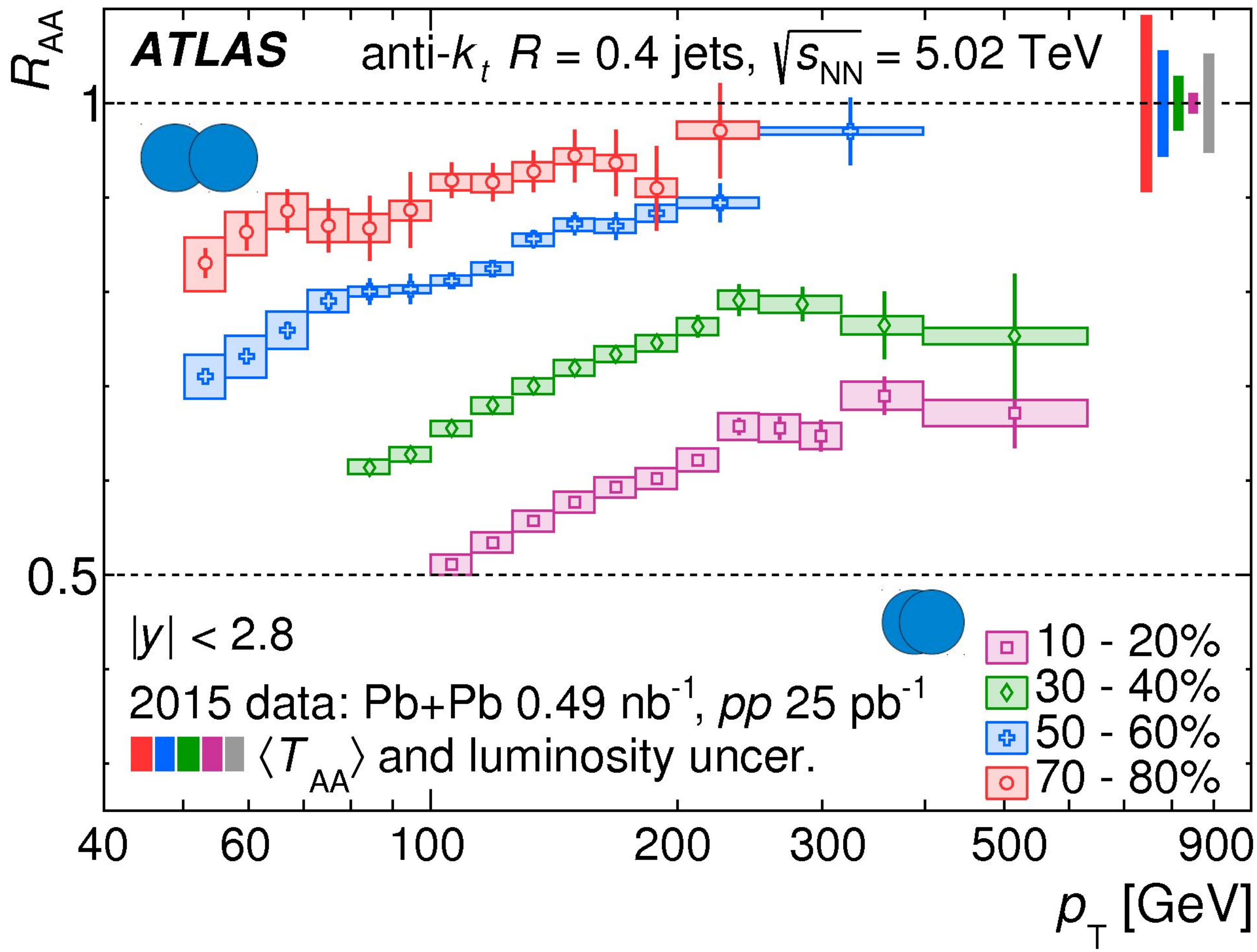
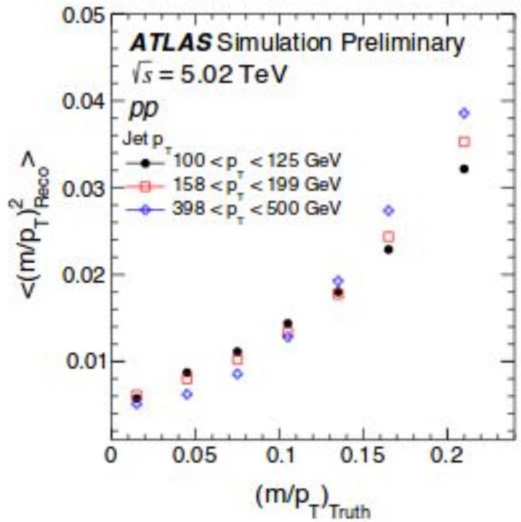
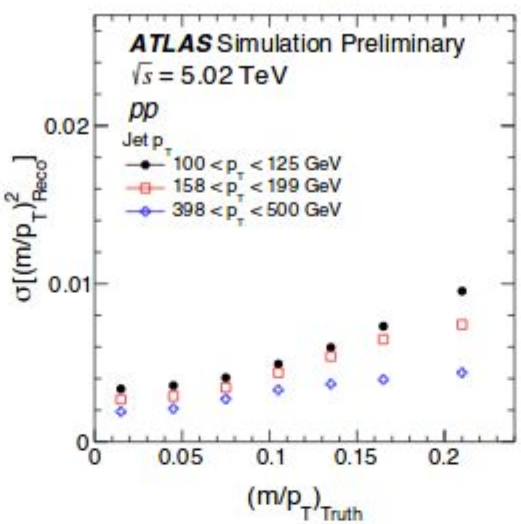


Jet mass performance

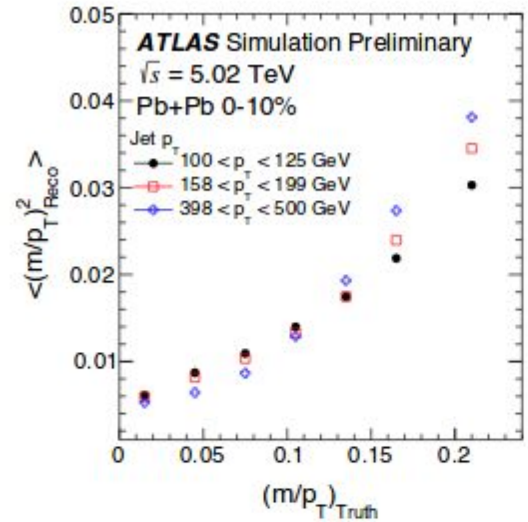
- jet mass scale (JMS): approximately independent of centrality
- jet mass resolution (JMR): increases in central collisions and at low jet p_T
  - expected from worse JER/ UE in this region

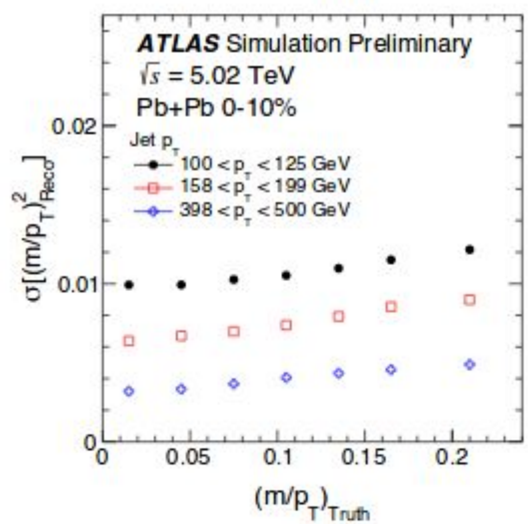
pp collisions



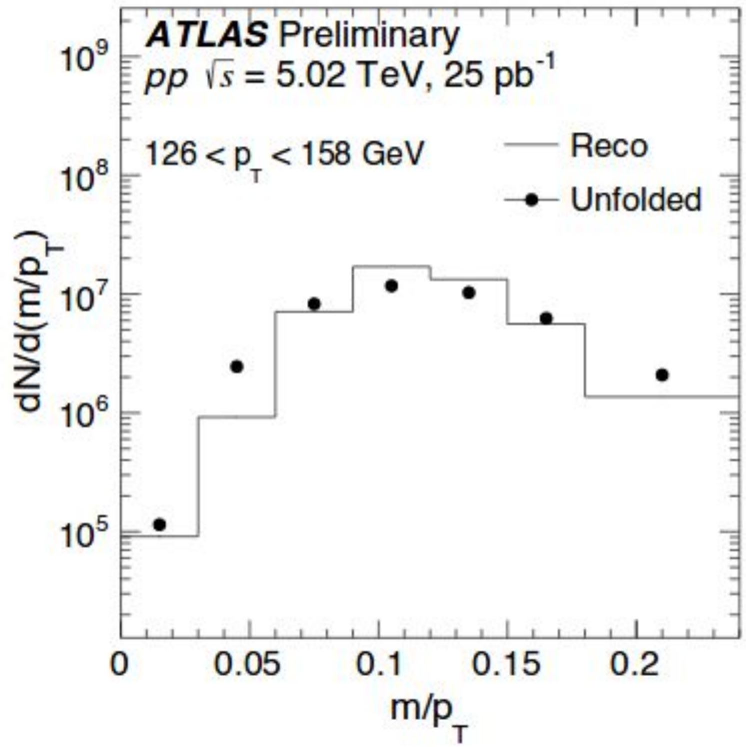


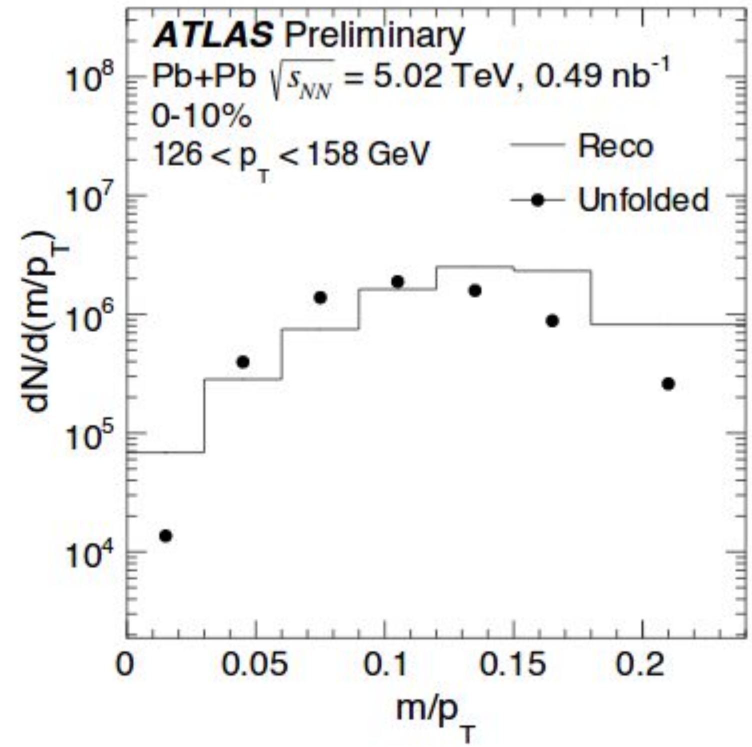
PbPb collisions





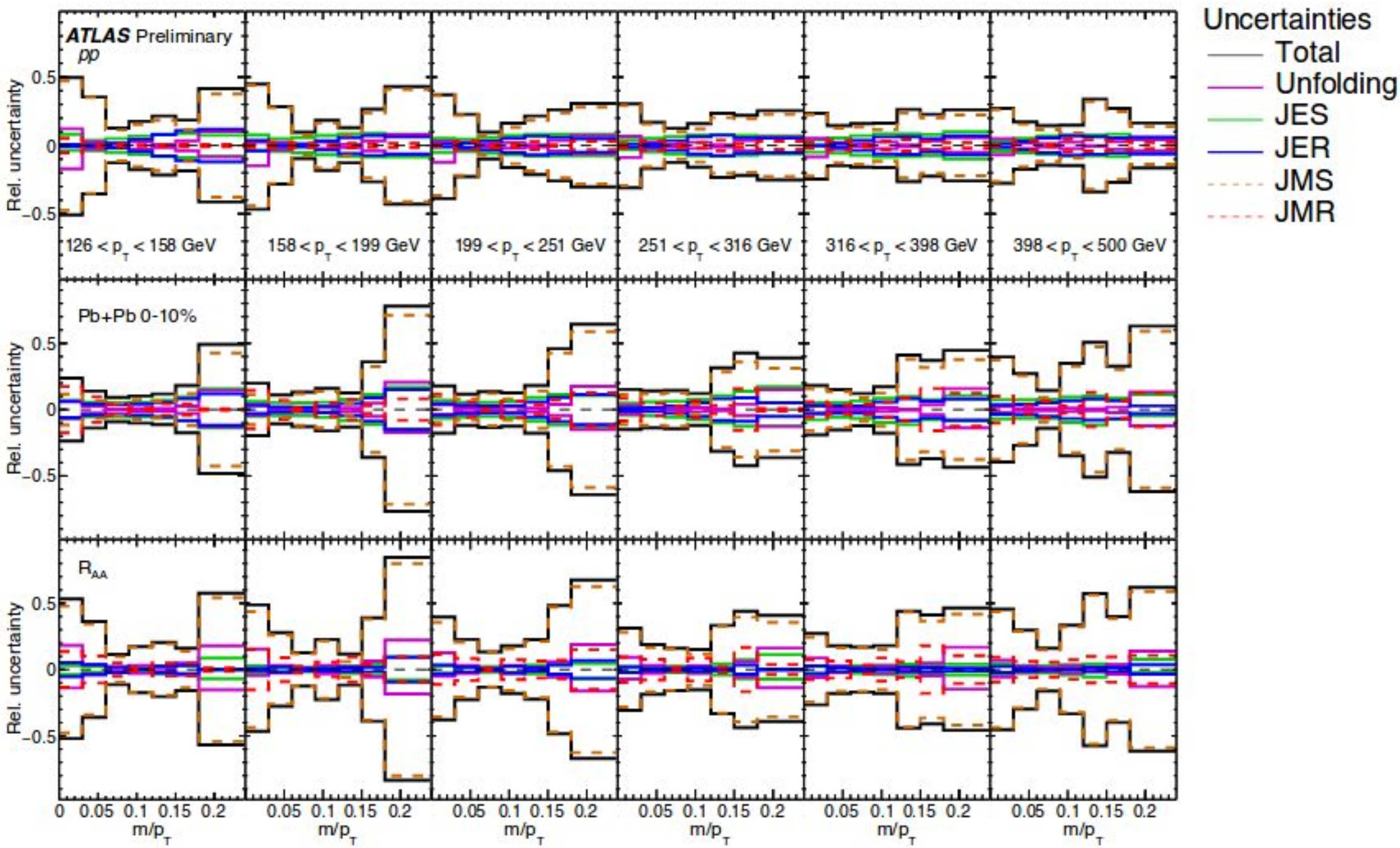
Jet mass unfolding





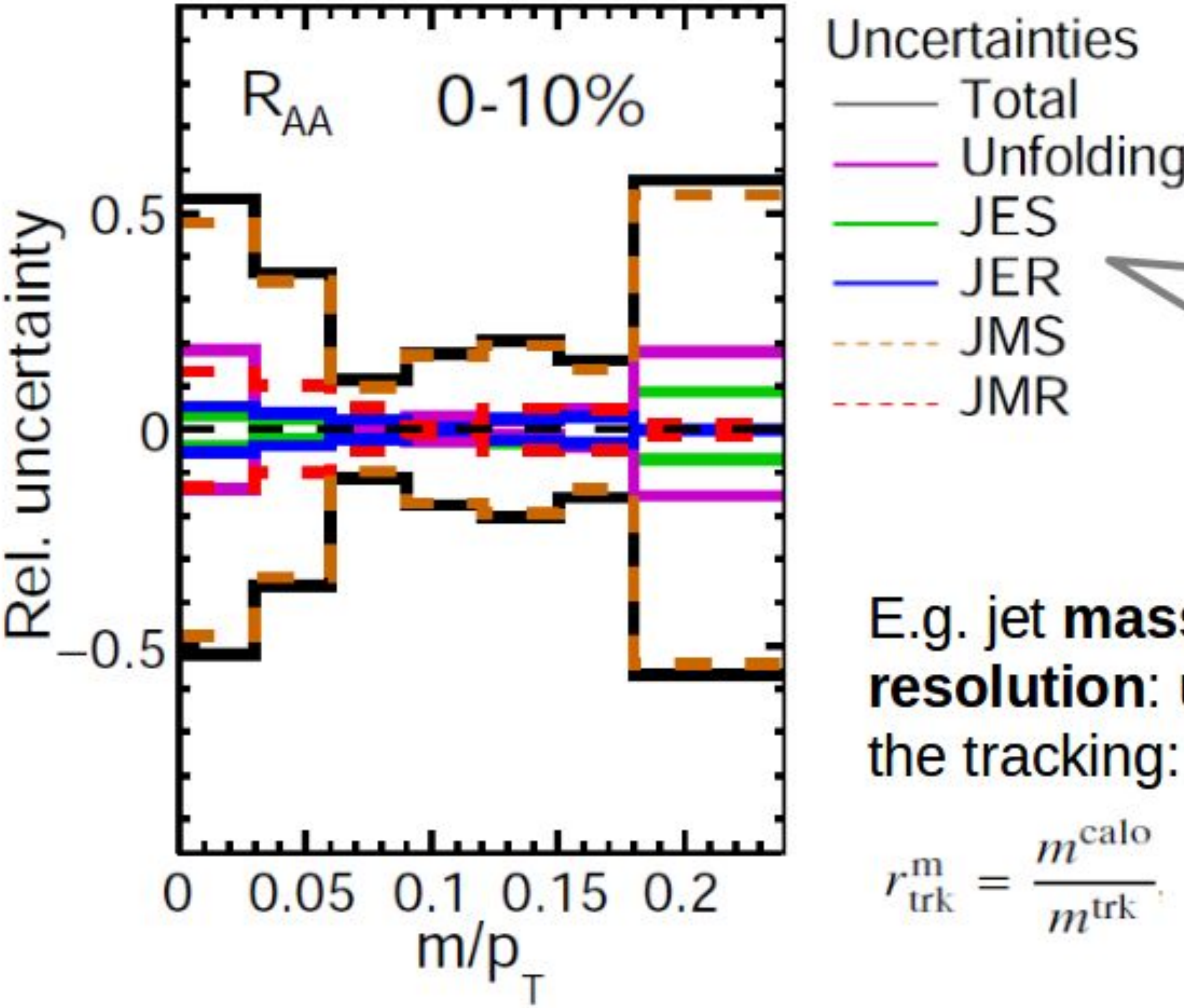
- Two dimensional Bayesian unfolding was used in m/p_T and p_T to correct for jet energy mass (JMS) and resolution effects.

Jet mass uncertainties



- Dominated by the JMS uncertainty in the entire measurement range.

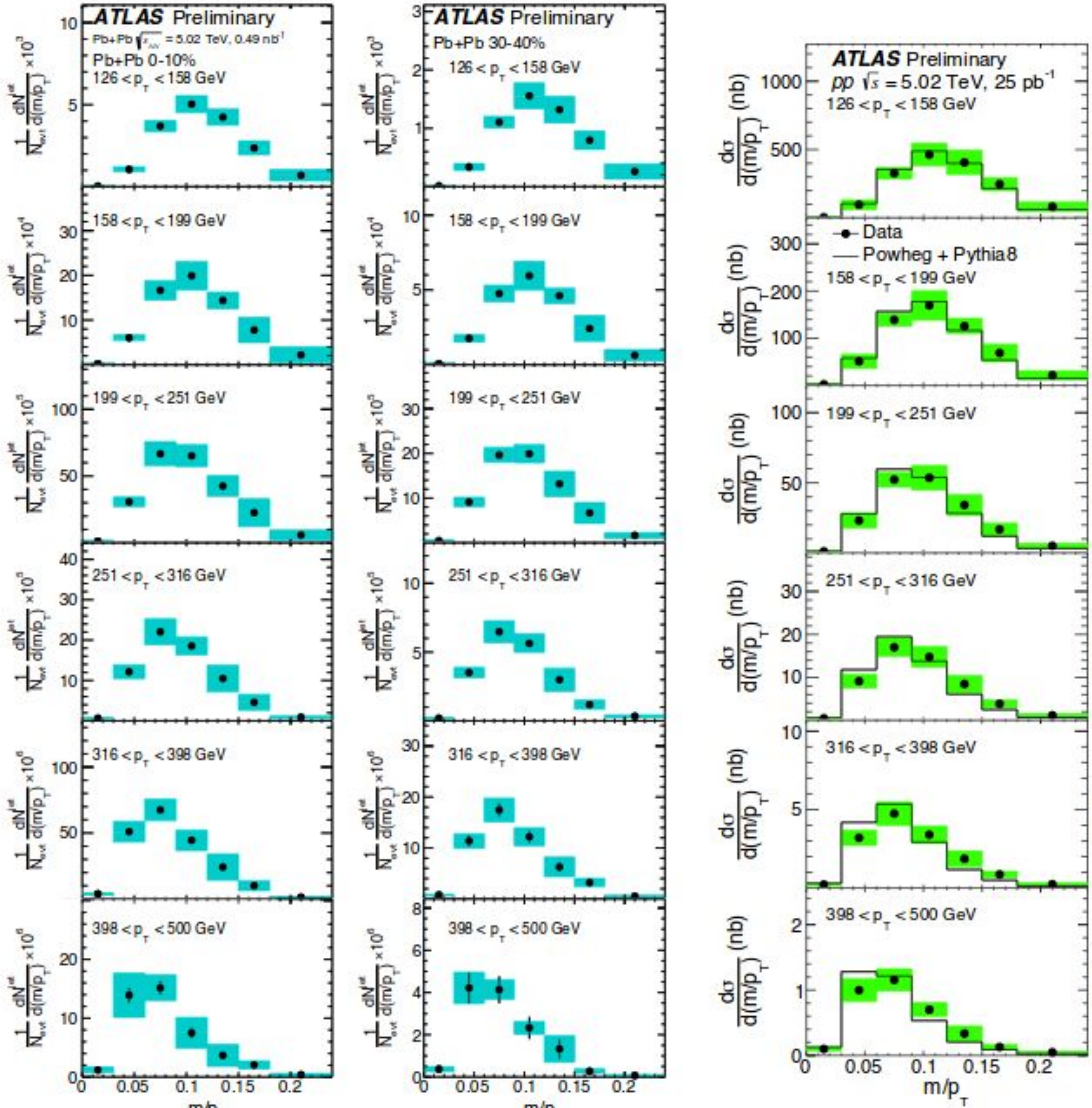
Jet mass uncertainties

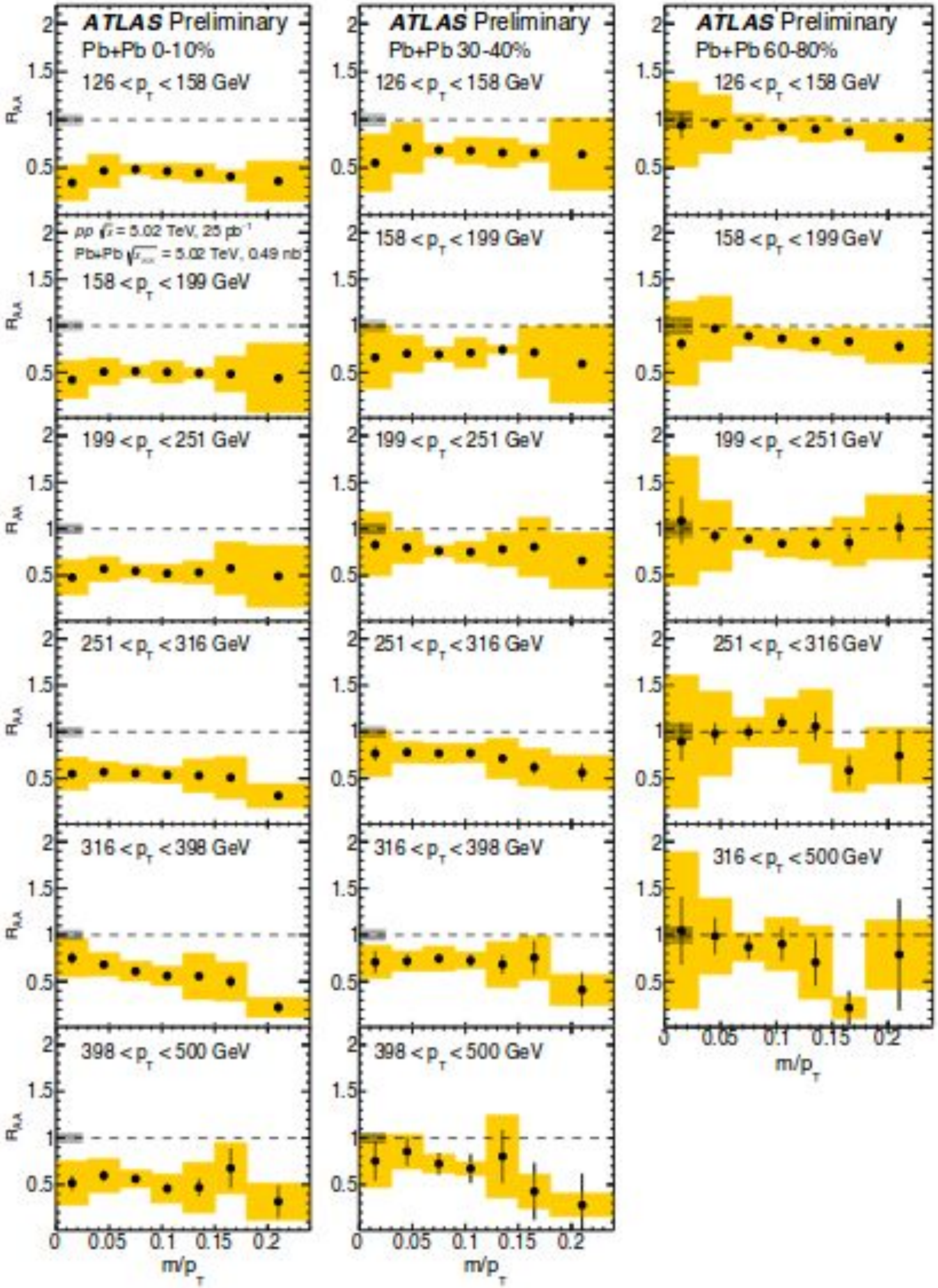


Jet energy scale and resolution … the same as for the inclusive R_{AA}

E.g. jet **mass scale**, jet **mass resolution**: using information from the tracking:

$$r^{\mathrm{m}}_{\mathrm{trk}} = \frac{m^{\mathrm{calo}}}{m^{\mathrm{trk}}} \longrightarrow R^{\mathrm{m}} = \frac{\langle r^{\mathrm{m}}_{\mathrm{trk}} \rangle|_{\mathrm{data}}}{\langle r^{\mathrm{m}}_{\mathrm{trk}} \rangle|_{\mathrm{MC}}}$$


ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 0.49 nb^{-1}
Pb+Pb 0-10%
Pb+Pb 30-40%
pp $\sqrt{s}$ = 5.02 TeV, 25 pb^{-1}
Data
Powheg + Pythia8
126 < p_T < 158 GeV
158 < p_T < 199 GeV
199 < p_T < 251 GeV
251 < p_T < 316 GeV
316 < p_T < 398 GeV
398 < p_T < 500 GeV
$\frac{1}{N_{evt}} \frac{dN^{jet}}{d(m/p_T)}$
$\frac{d\sigma}{d(m/p_T)}$ (nb)
m/p_T



ATLAS Preliminary
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pp $\sqrt{s}$ = 5.02 TeV, 25 pb^{-1}
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 0.49 nb^{-1}
R_{AA}
m/p_T

Dijet asymmetry uncertainties