Jet and heavy flavour measurements in heavy ion collisions with ATLAS

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Motivation

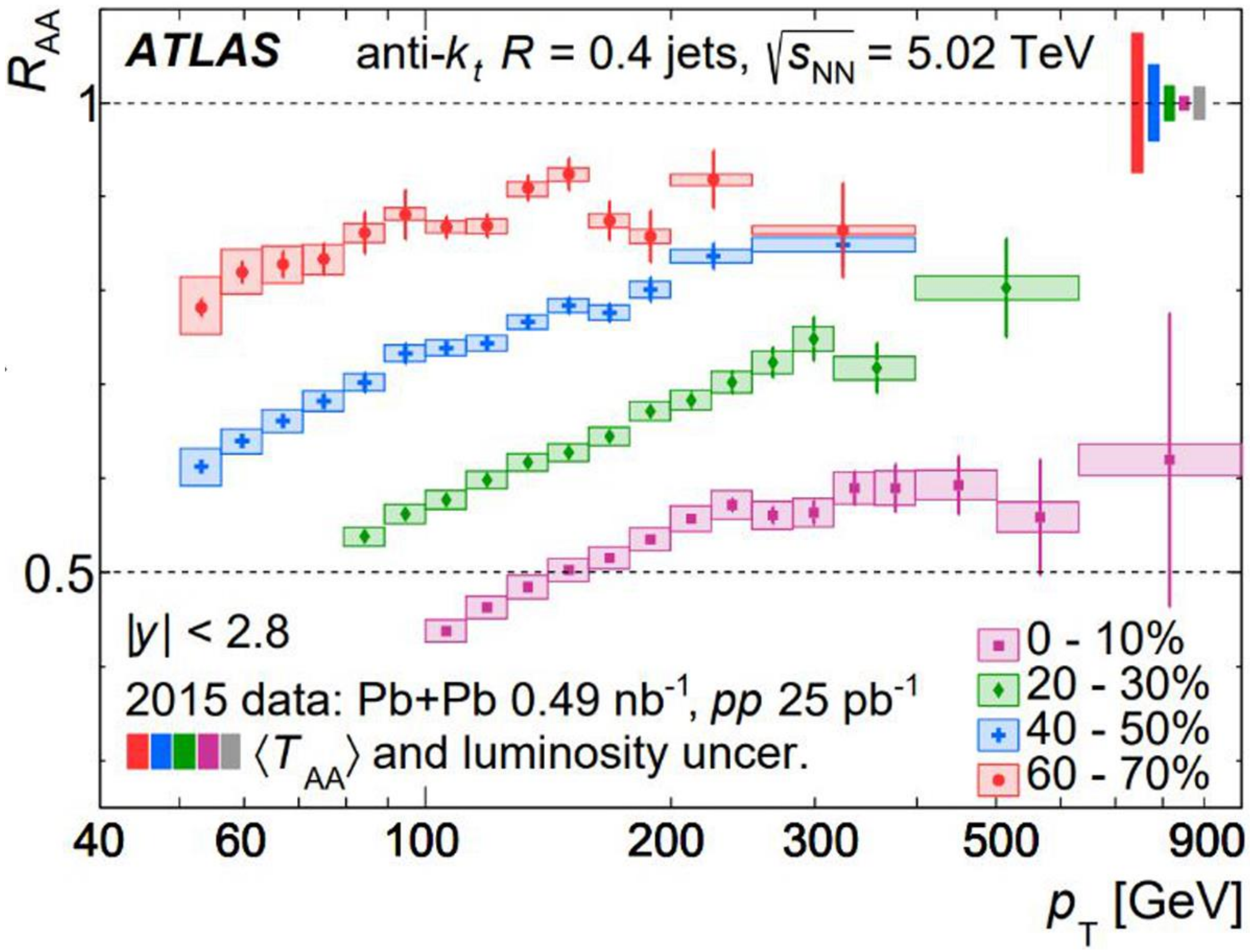
Jets and heavy flavour are produced at the early stages of HI collisions and propagate through the hot and dense matter created in those collisions.

Both jets and heavy flavour are excellent tools to study QGP properties.

- How does the color charge interact and lose energy in the medium?
- How does the hadronization process work?
- Is there a flavour or mass dependence of the energy loss?
- and many more...

Inclusive jet production in *pp* and Pb+Pb

Phys. Lett. B 790 (2019) 108-128



Nuclear modification factor:

$$R_{AA} = \frac{Yield\ (Pb+Pb)}{N_{COLL}\ Yield\ (p+p)}$$

$R_{AA} < 1$ → suppression

Suppression increases with centrality

More detailed studies are necessary

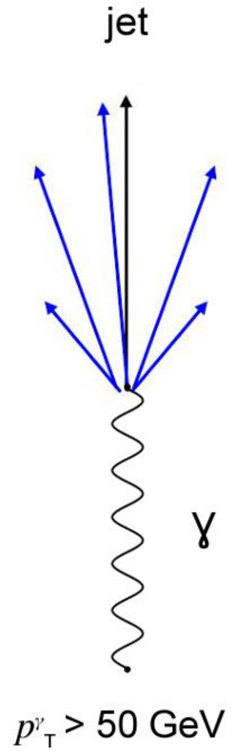
γ-tagged jets

Do quark/gluon-initiated jets have the same energy loss?

- γ-tagged jets are dominated by quark-initiated jets

- remove survival bias

- go to lower p_T



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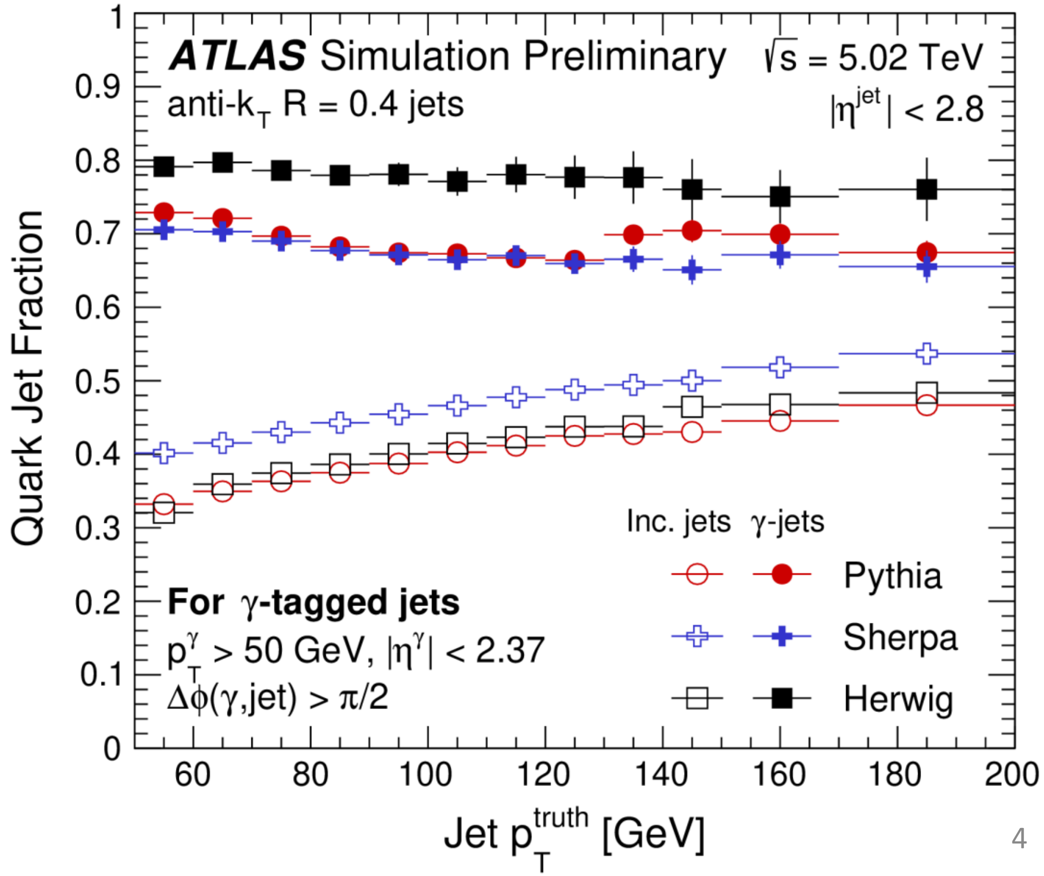

γ-tagged jets (continued)

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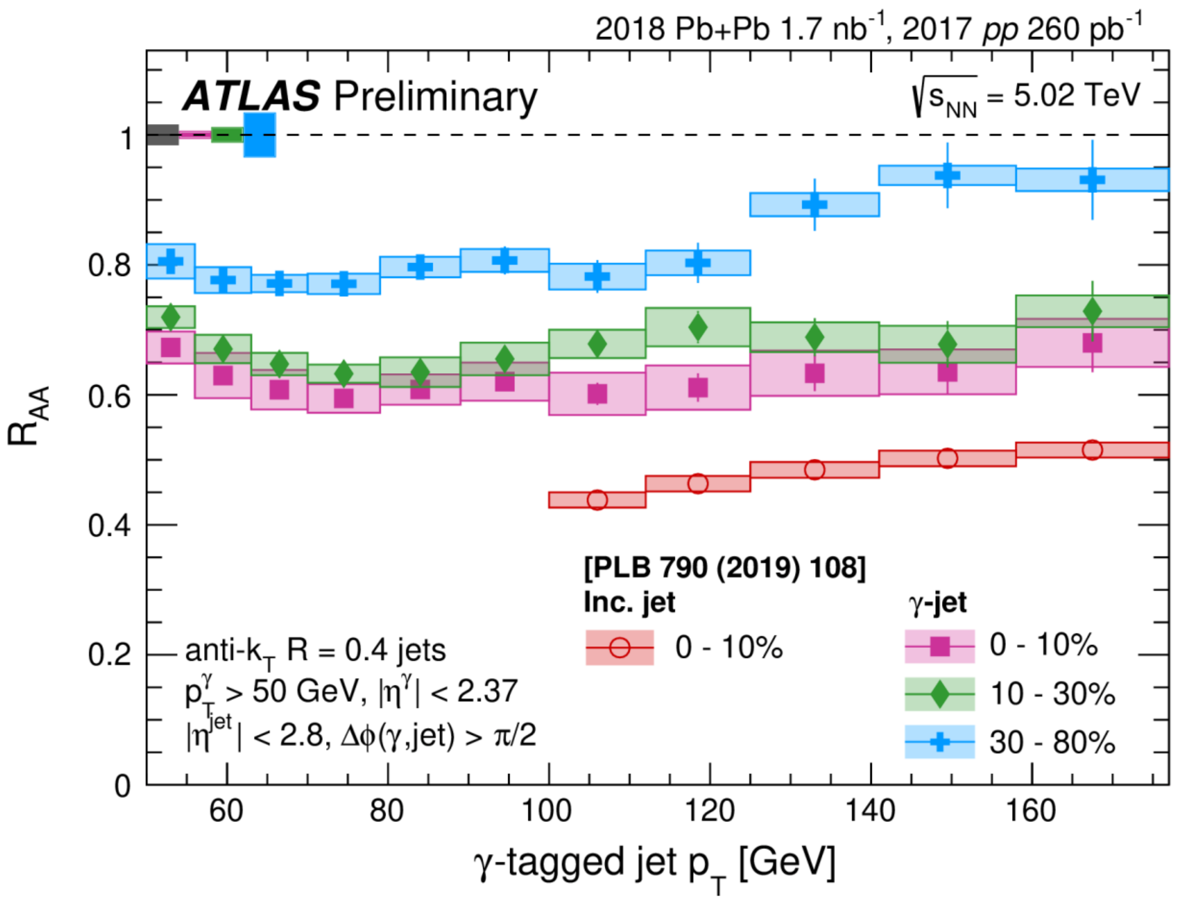
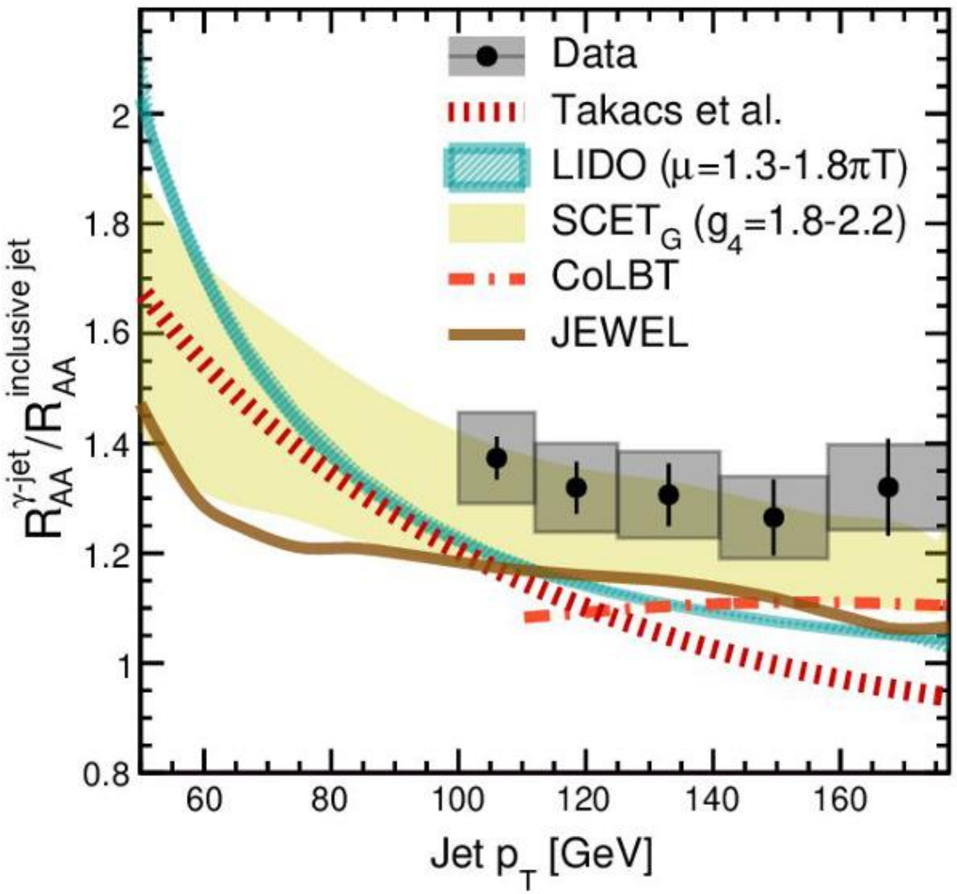




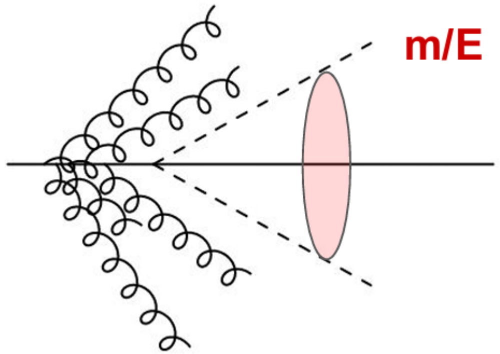
Less suppression for γ-tagged jets, consistent with gluon jets losing more energy

Models overestimate γ-tagged jet suppression

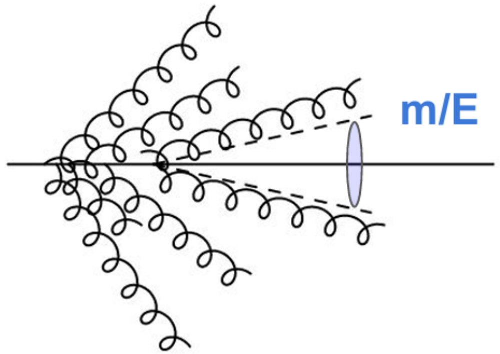
b-tagged jets

Is there mass dependence of energy loss?

Dead cone effect:



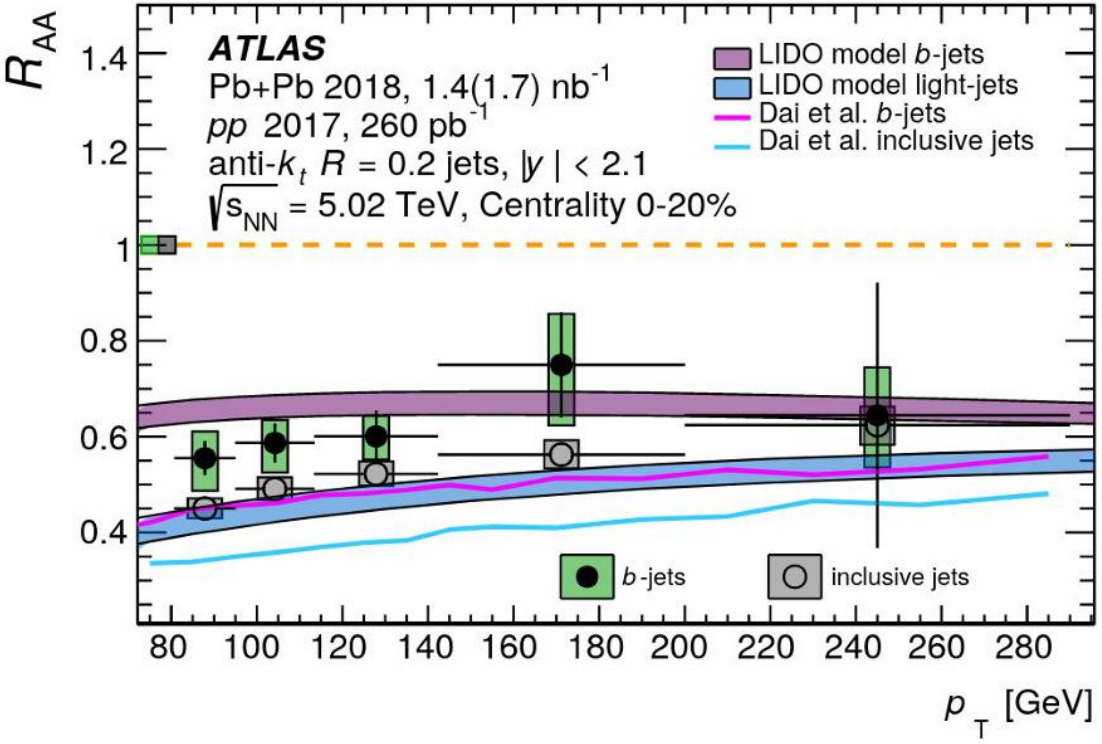
heavy-quark jets

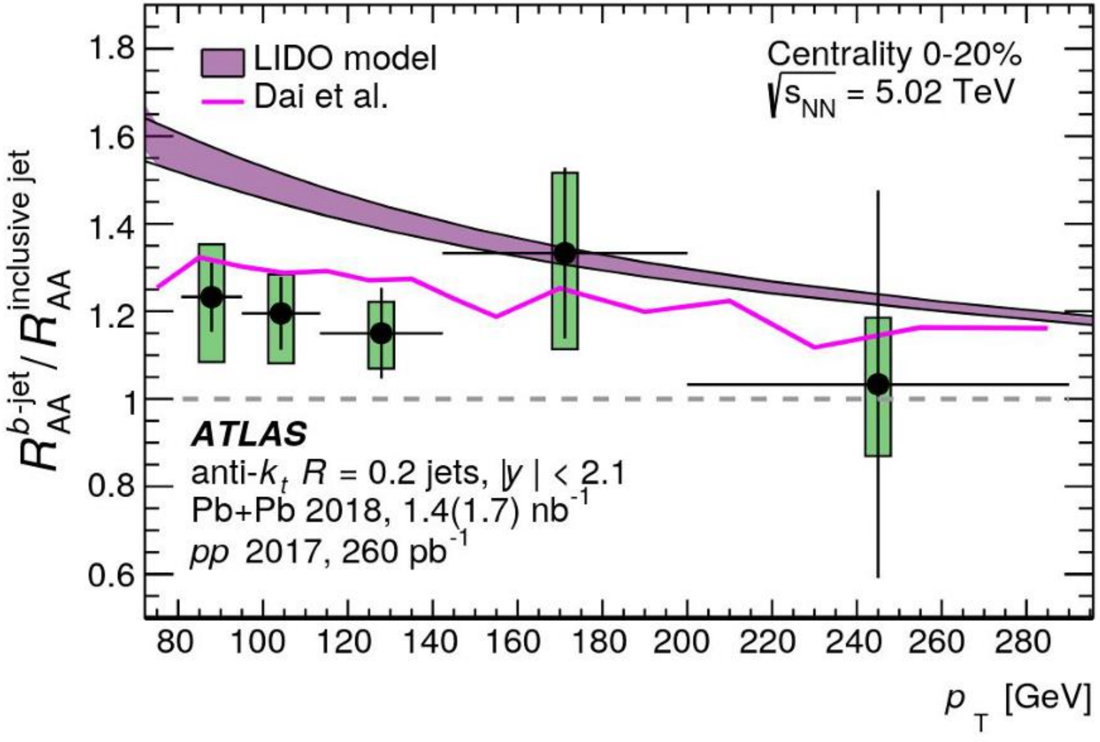


inclusive jets

b-tagged jets (continued)

arXiv:2204.13530



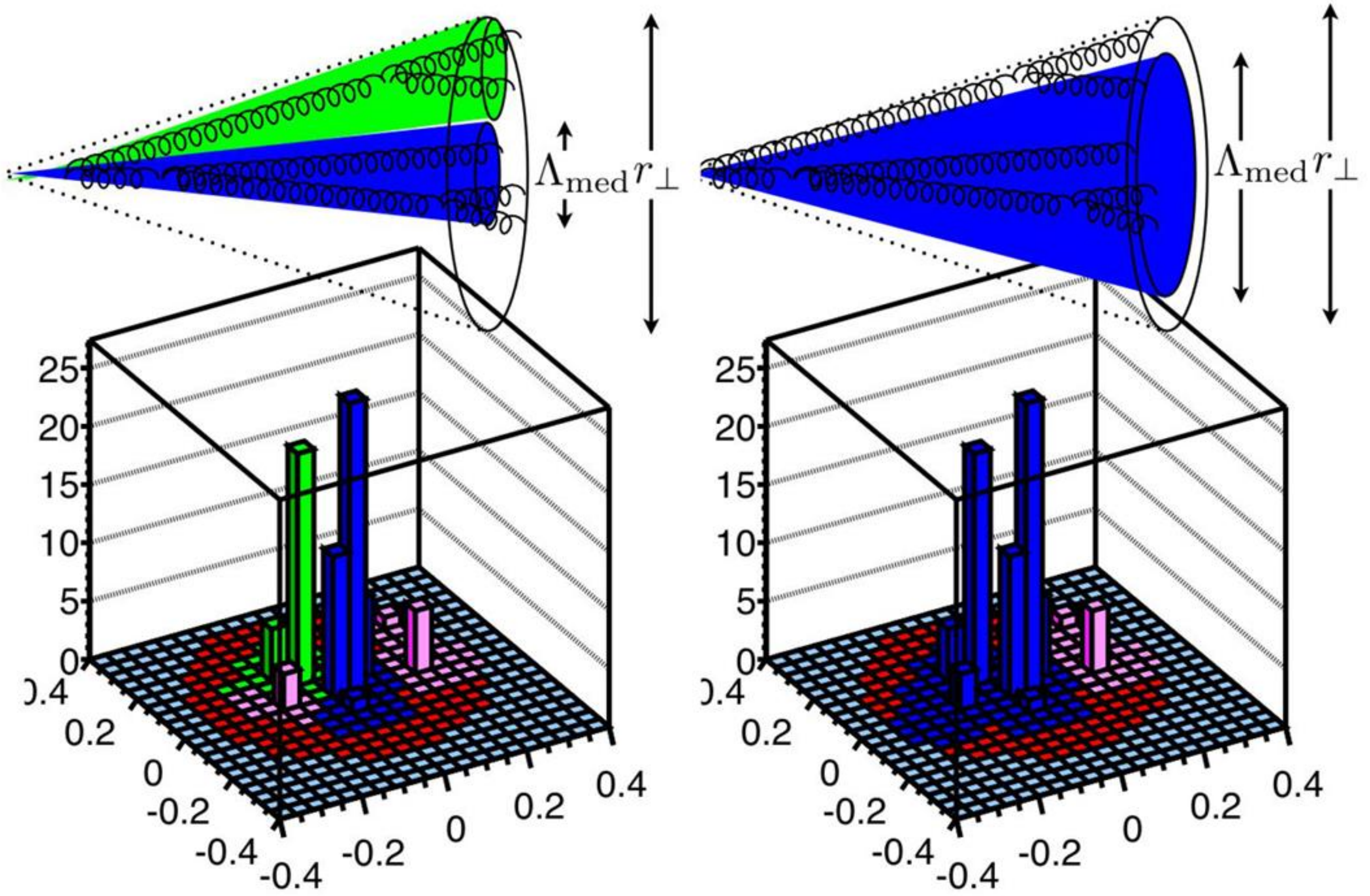


- b-jets are less suppressed than inclusive by about 20%
- No p_T dependence is observed

Suppression vs jet structure

What is the resolution scale of the medium?

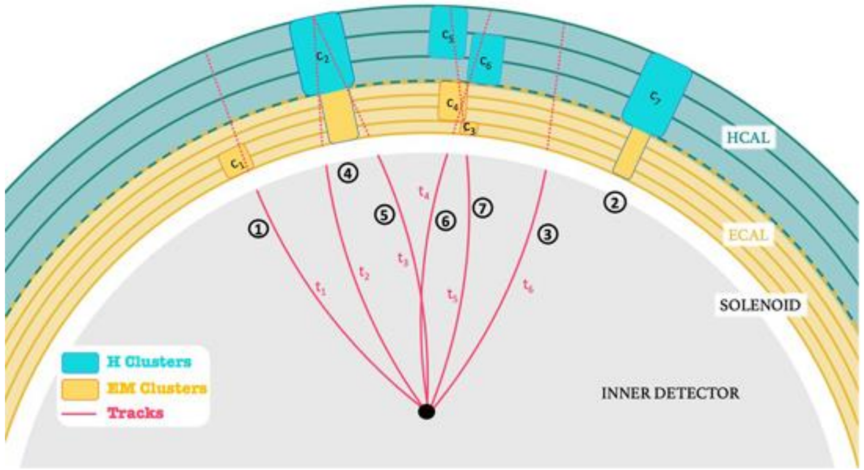
Identify the first hard splitting in a jet's parton shower.



Jet structure analysis

Measure R_{AA} vs “splitting”

Track-Calo-Cluster constituents (p_T>4GeV) ⇨ Anti-k_t R = 0.4 ⇨ Cambridge-Aachen re-cluster with soft grooming (z=0.2, β = 0) ⇨ unfold p_T, r_g



soft-drop condition:

$$\frac{\min(p_T^{sj_1}, p_T^{sj_2})}{p_T^{sj_1} + p_T^{sj_2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

$$r_g = \Delta R_{12} = \sqrt{\Delta\eta_{12}^2 + \Delta\phi_{12}^2}$$

→ $r_g > 0$ → jet has substructure

→ $r_g = 0$ → jet does not have substructure

Energy loss vs jet substructure

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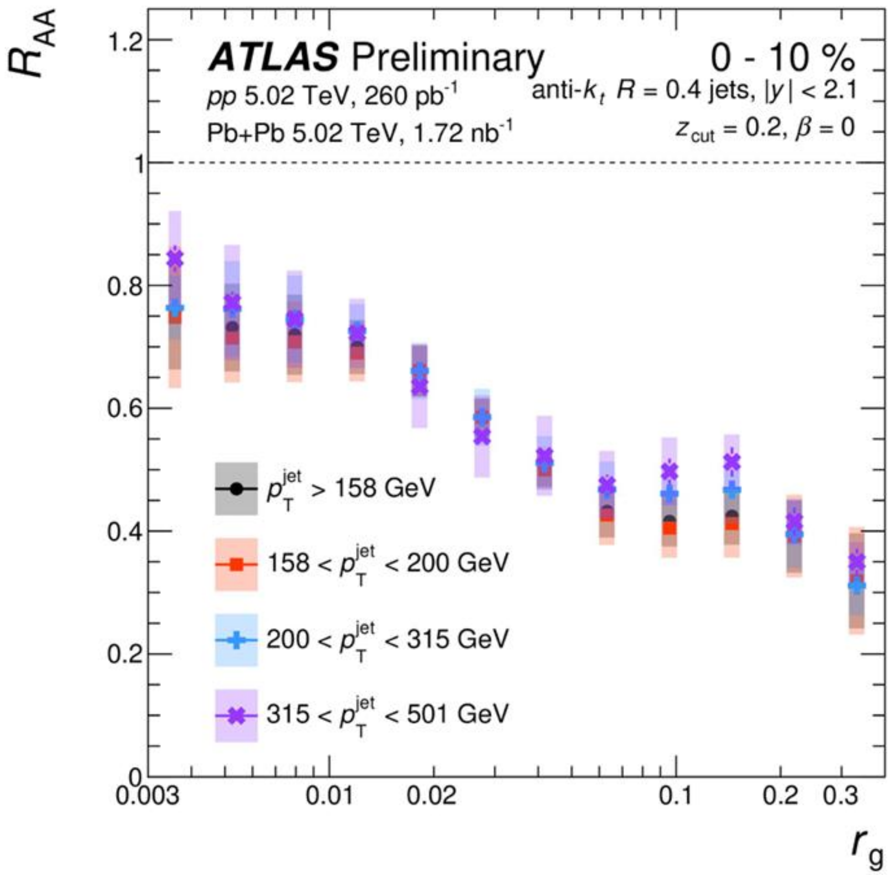
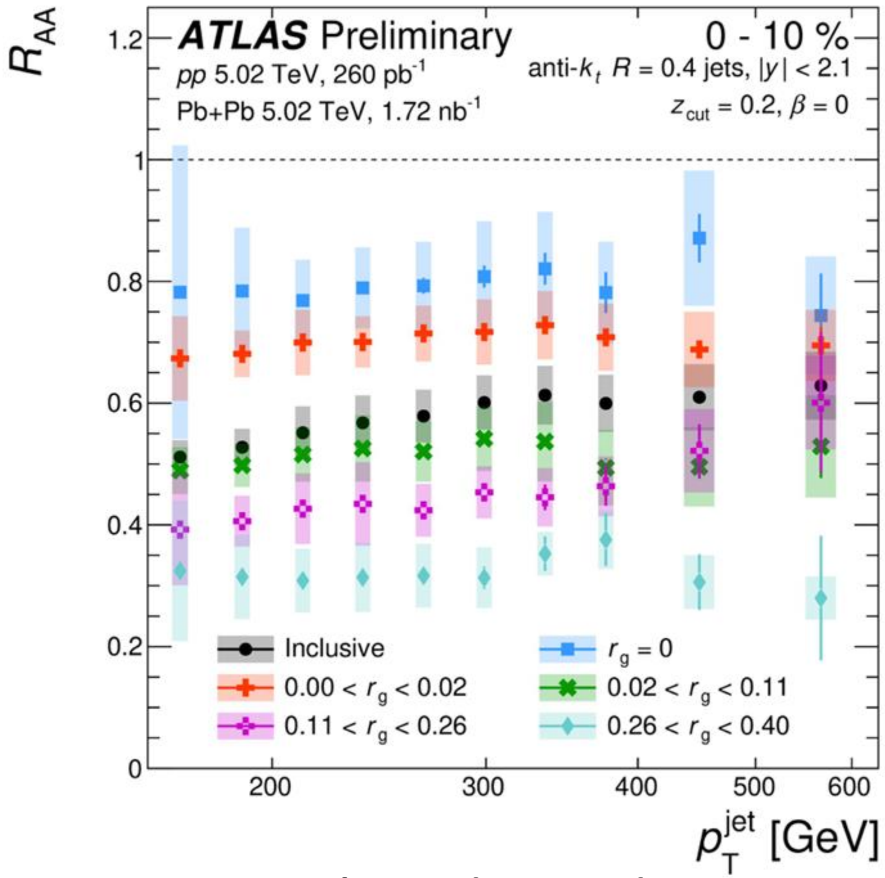


Strong r_g dependence



Weak p_T dependence

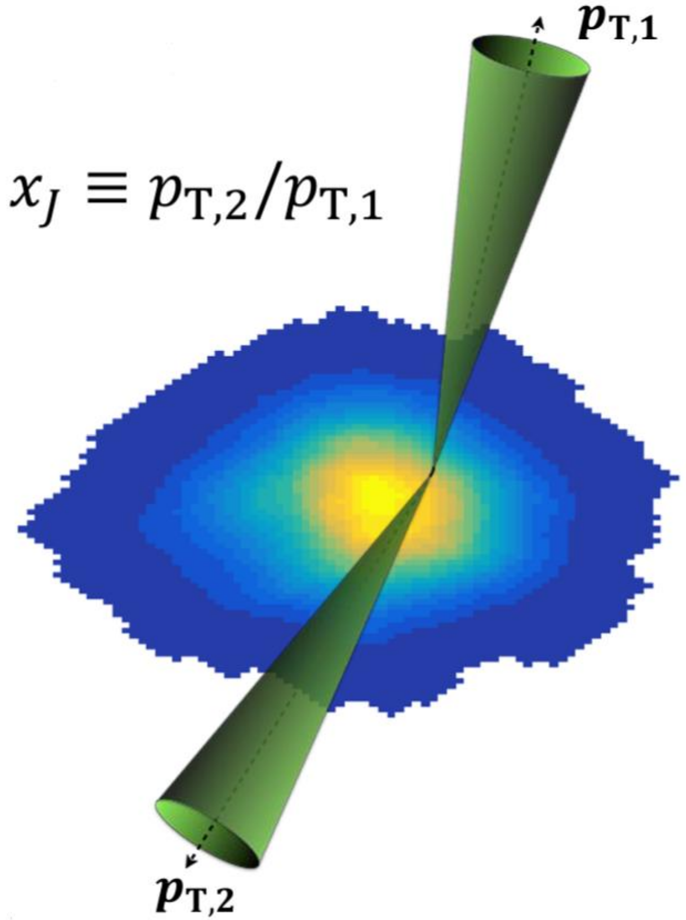
- Jets with larger opening angle loose more energy
- Internal jet substructure more important than p_T

Di-jet balance

Study energy loss vs path length

Constrains contributions from:
- path length dependent energy loss
- energy loss fluctuations

Provides enhanced sensitivity to small amount of jet quenching



Per jet pair normalized x_J distributions: $1/N_{pair}\, dN_{pair} / dx_J$
- Enables direct comparison of the x_J shape across centrality in Pb+Pb and in *pp*

Absolutely normalized x_J distributions: $1/ (N_{evt}\langle T_{AA}\rangle)\, dN_{pair}/ dx_J$
- Enables evaluation of the di-jet per event yields as a function of x_J
- Provides insight into the dynamics of di-jet energy loss

Di-jet analysis overview

Two-dimensional ($p_{T,1}$,$p_{T,2}$) distributions are measured for the leading jet

Corrected for combinatoric di-jets, then unfolded for detector effects using 2D Bayesian unfolding

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

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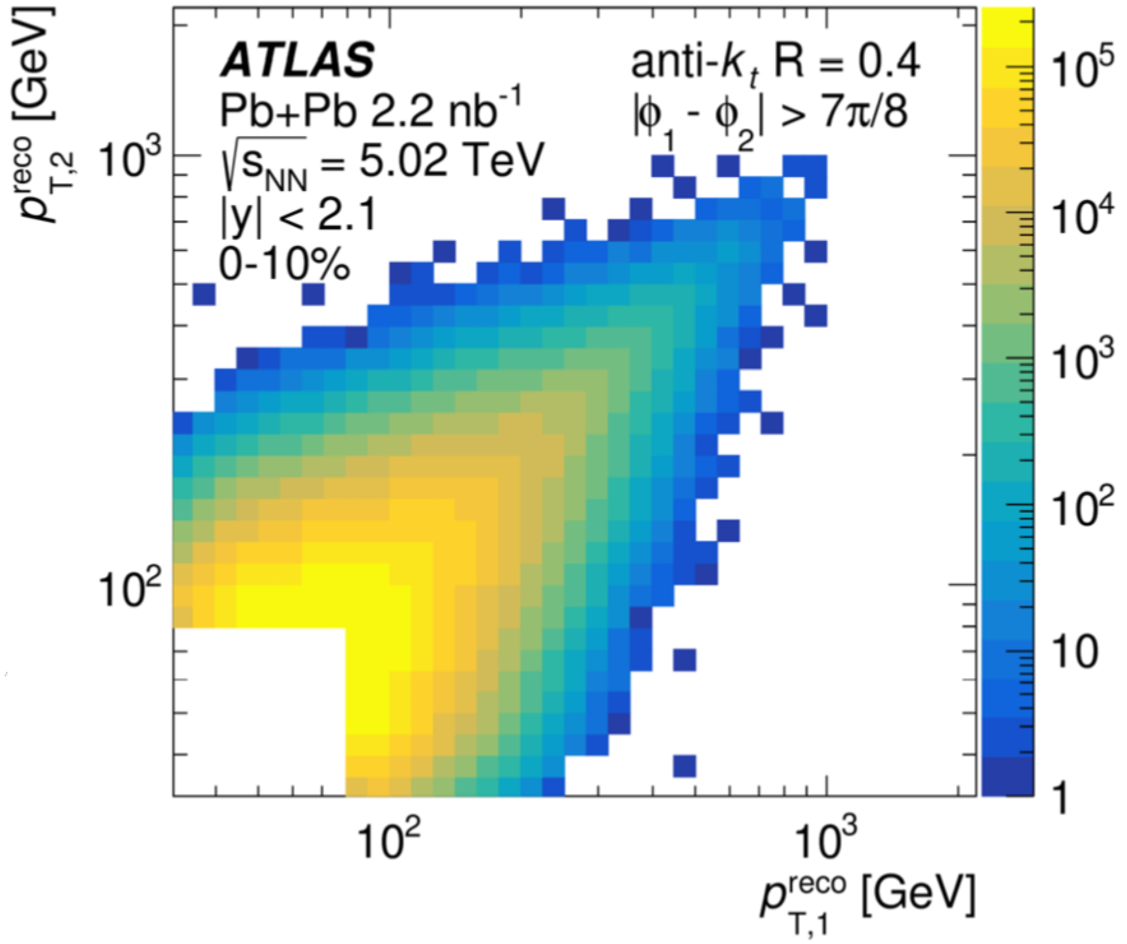

Di-jet balance

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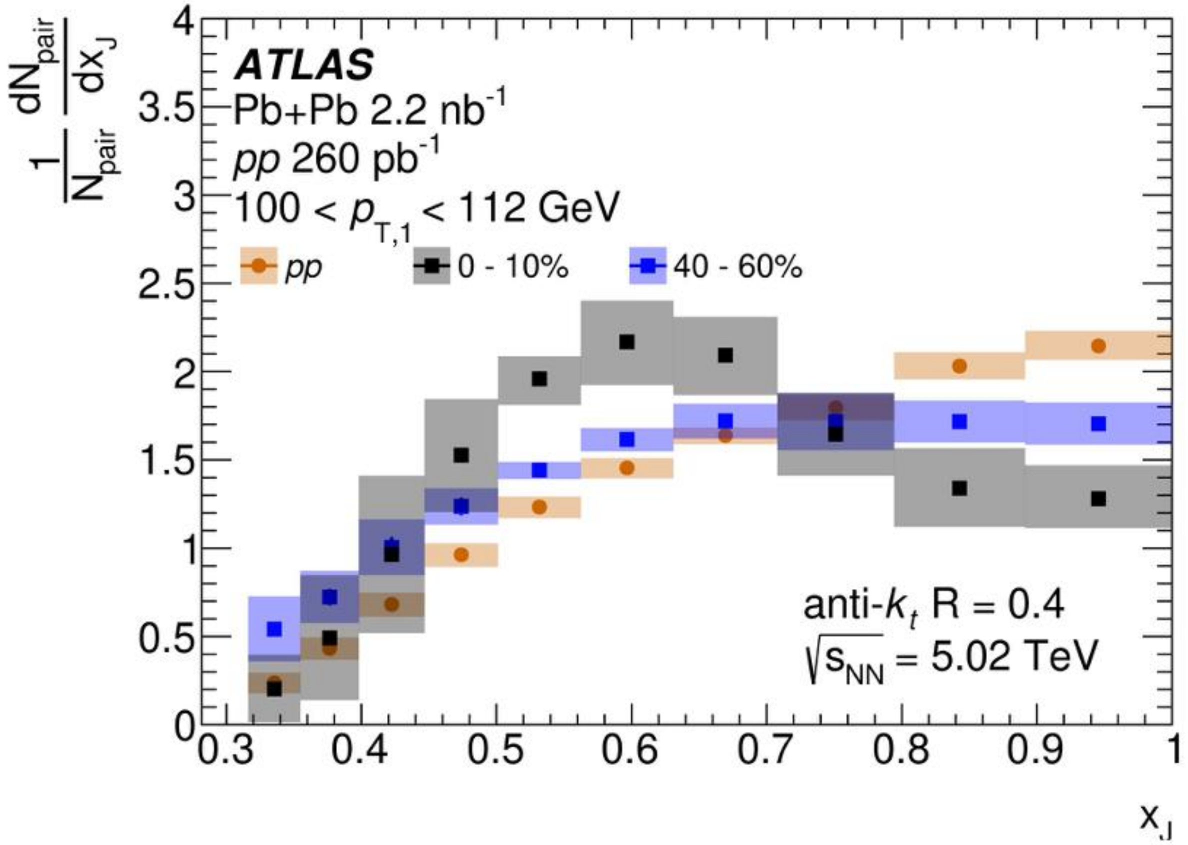

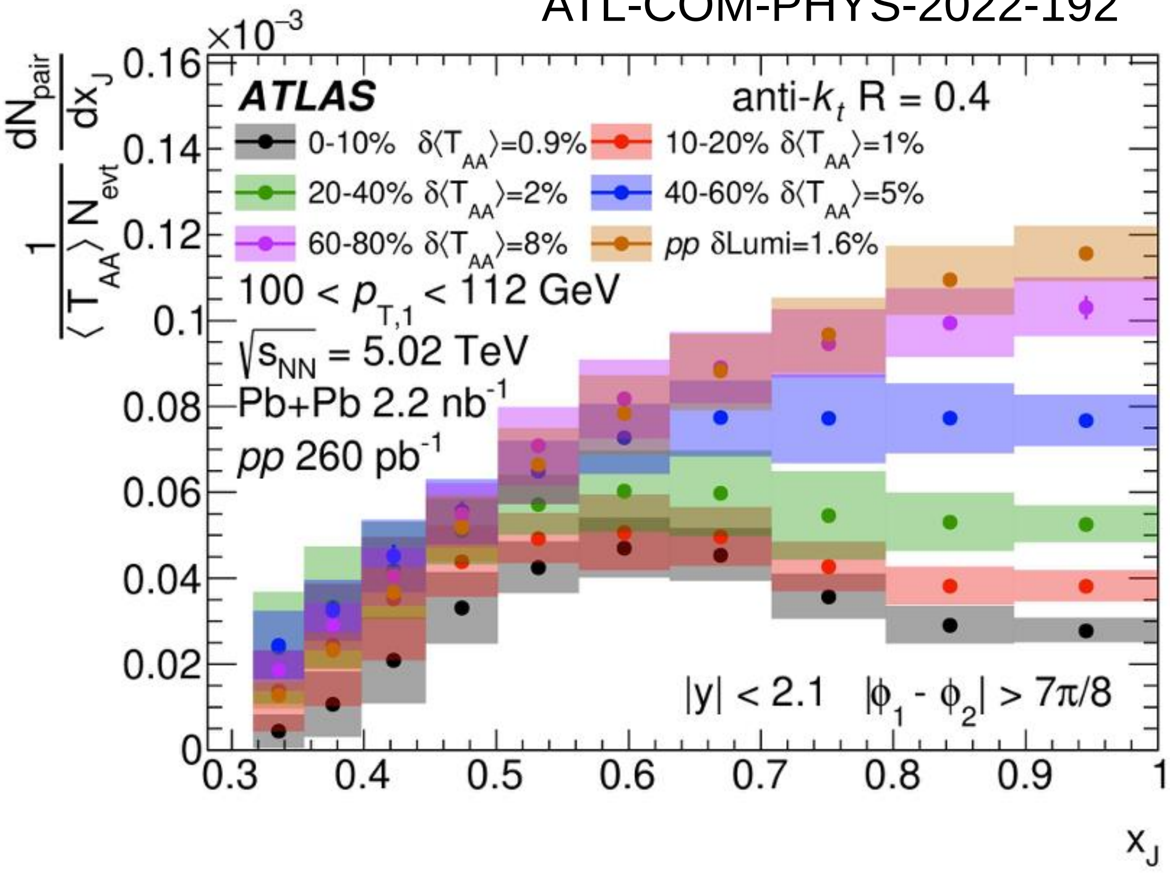

- Significant di-jet imbalance seen in central collisions.
- The effect goes away for less central collisions or higher p_T.

This imbalance is due to a suppression of balanced di-jet topologies rather than enhancement in imbalanced topologies.

Di-jet nuclear modification factor R_{AA}^{pair}

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

$R_{AA}^{pair}(p_{T,2})$ quantifies the suppression of the sub-leading jet in a di-jet

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

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

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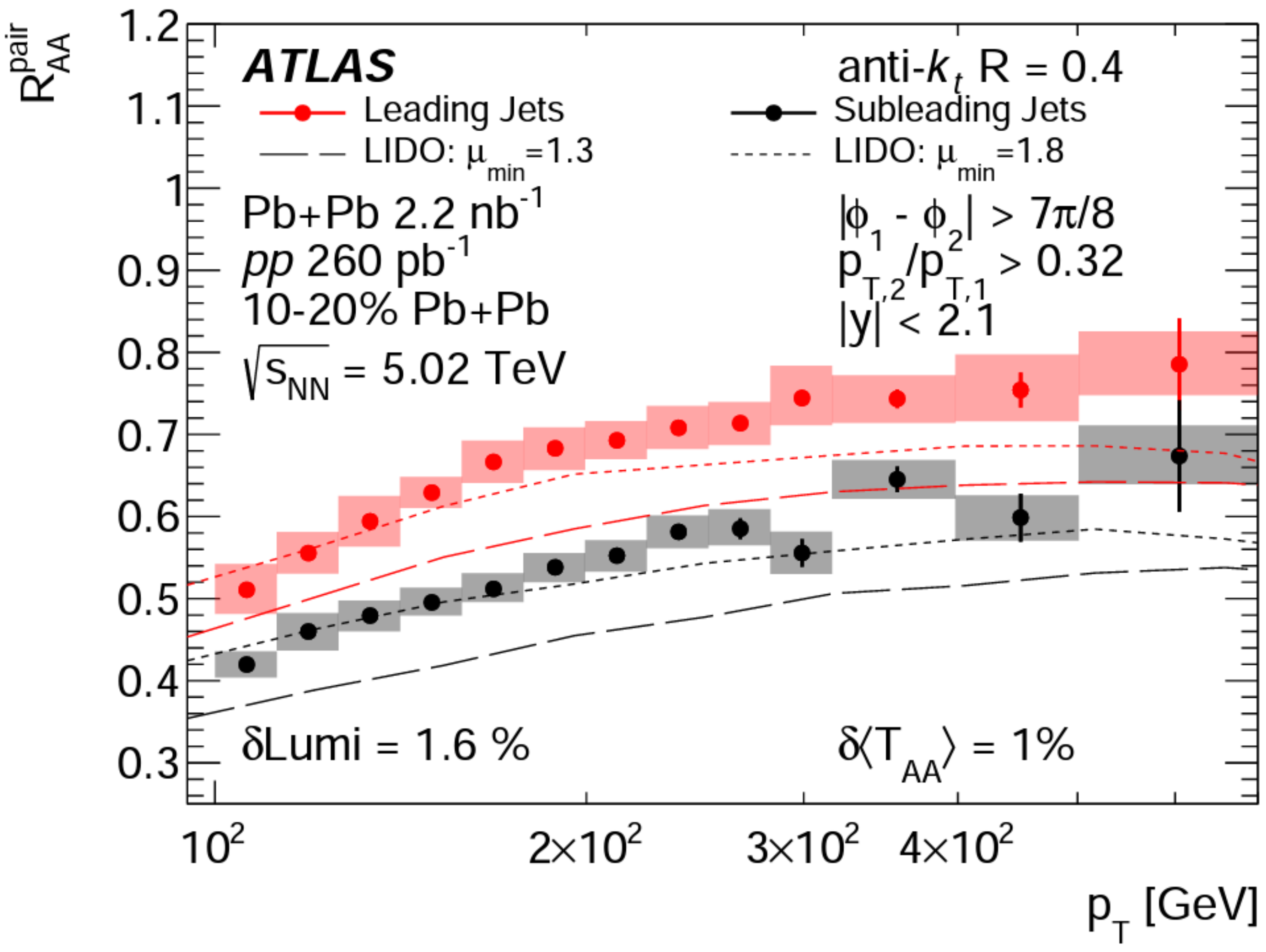

$R_{AA}^{pair}(p_{\mathrm{T},2})\ /\ R_{AA}^{pair}(p_{\mathrm{T},1})$

- Evidence for suppression of sub-leading jets relative to leading jets is observed even in peripheral collisions

- LIDO calculations with a μ_{min} = 1 reproduces the measurement well

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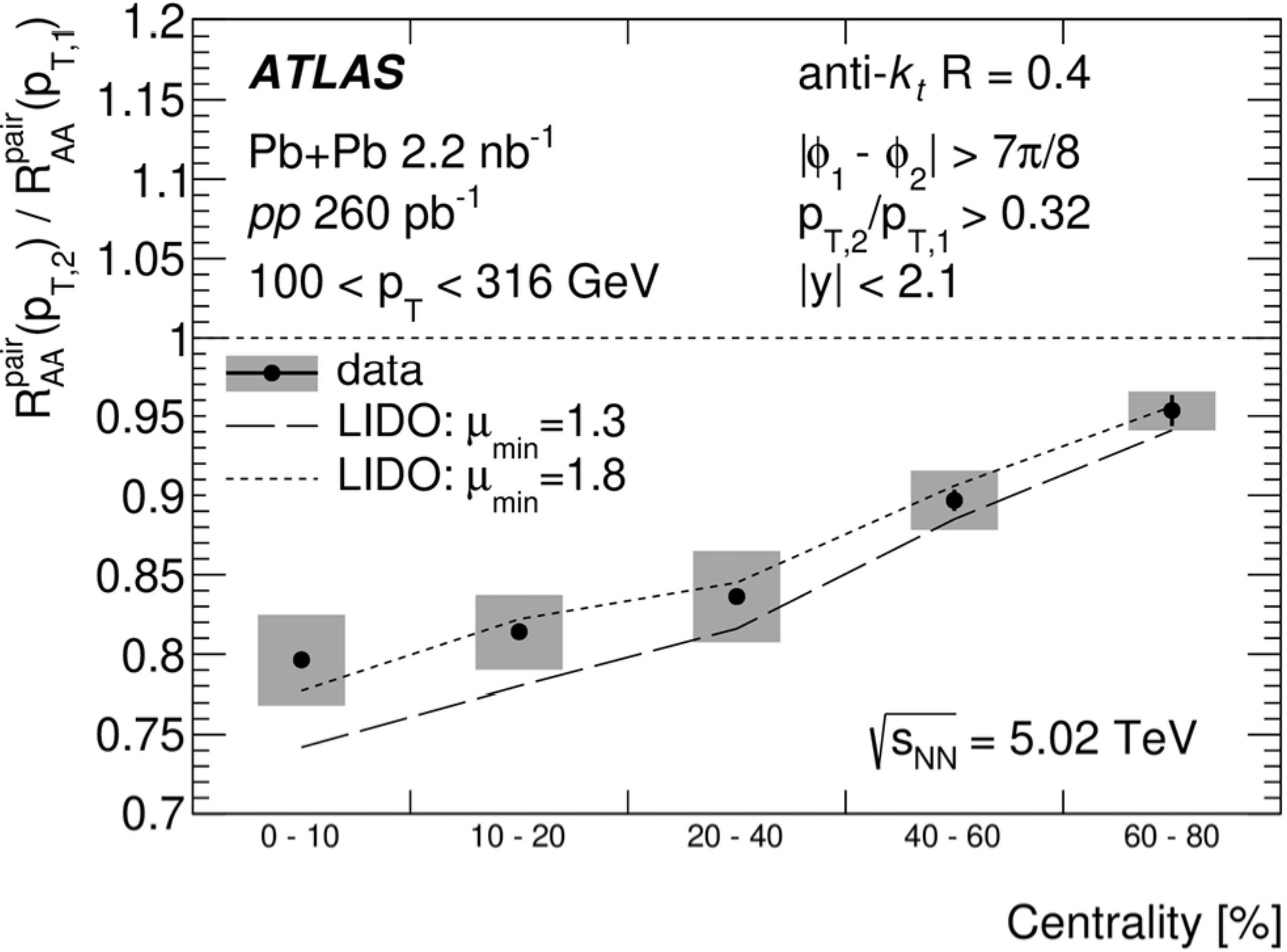


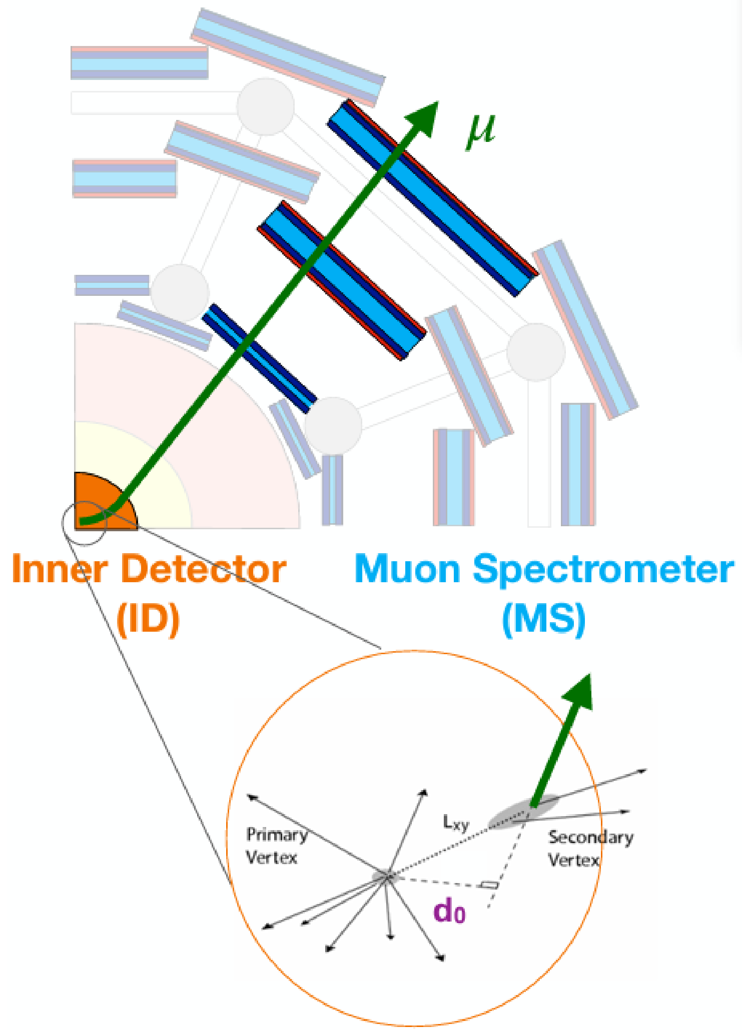
ATLAS heavy flavor measurements

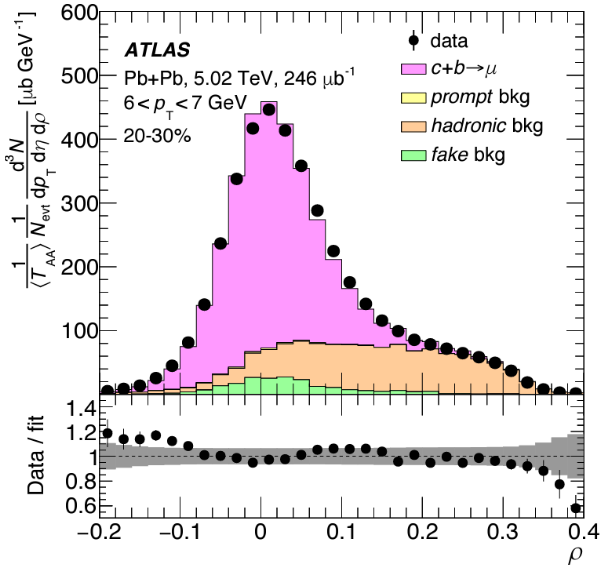
Heavy flavor (b/c) measurements provide information complementary to jets.

- Heavy quarks are produced in initial hard scatterings
  - carry information about all stages of the collision
  - production can be calculated with pQCD ($m_b > m_c > \Lambda_{QCD}$)
- Probe QGP through energy loss mechanisms
  - collisional + radiative
  - mass hierarchy, flavor dependence.
- Keep identity after hadronization
- Quarkonia can serve as a “QGP thermometer” (sequential melting)

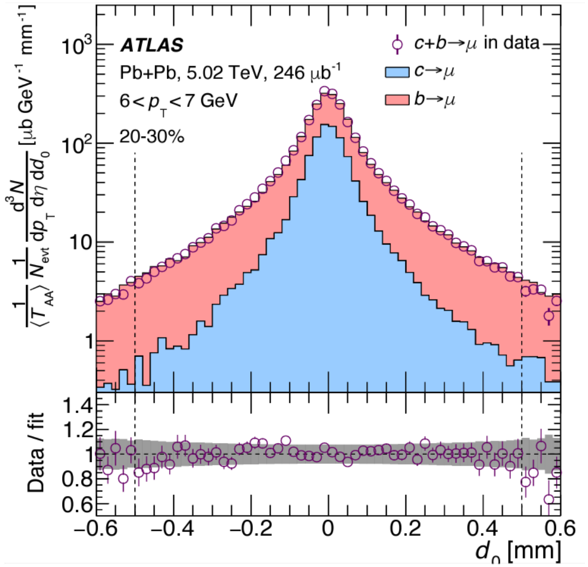
Open HF measurement with ATLAS

displaced vertex measurement





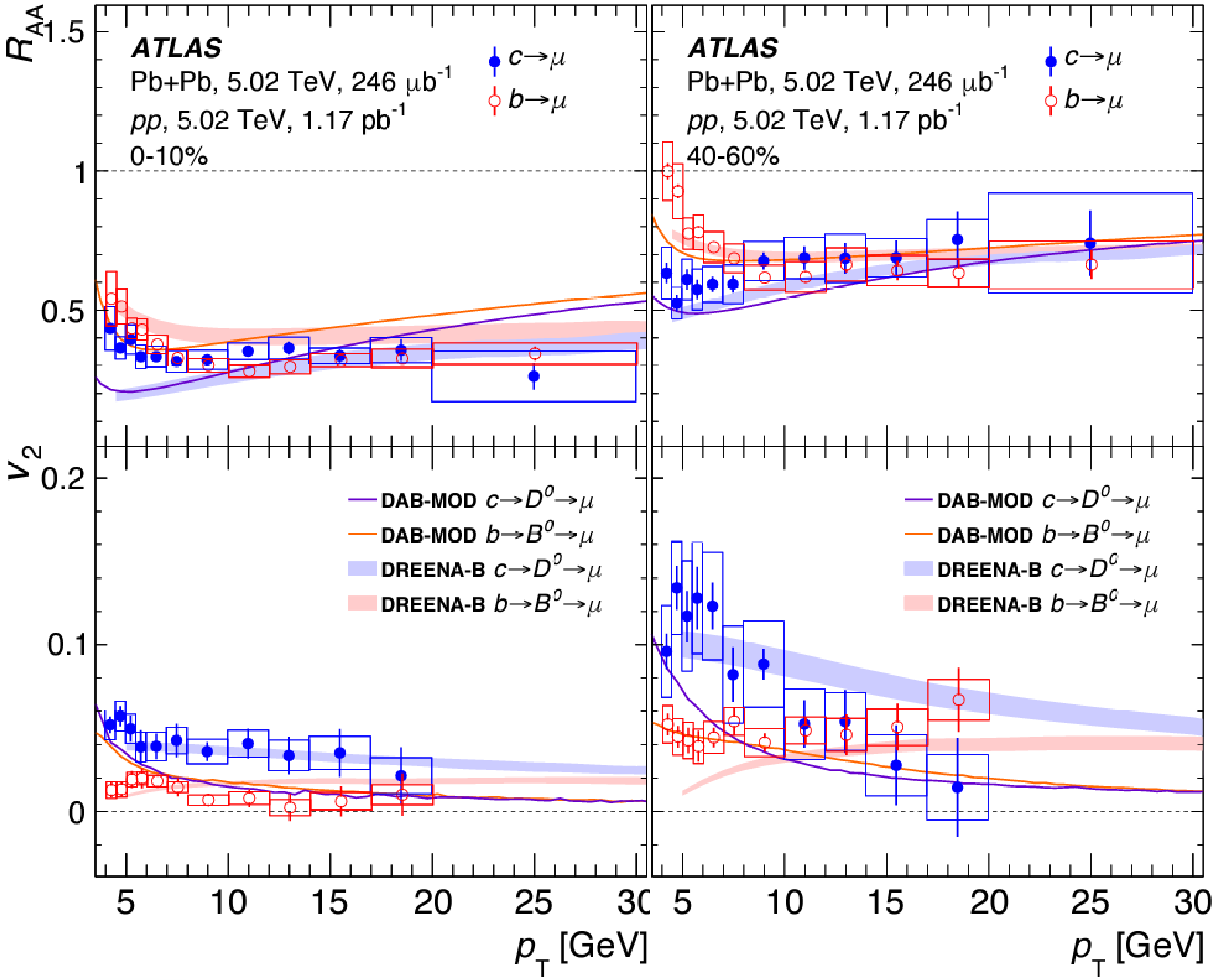
Background is removed using momentum imbalance between inner tracks and muon spectrometer.



Distance of Closest Approach (DCA) distribution unfolding with templates obtained from MC (based on difference of lifetimes for charm and beauty mesons).

HF suppression (R_{AA}) vs anisotropy (v_2)

Phys. Lett. B 829 (2022) 137077



Charm is more suppressed than bottom at low p_T, consistent above 10 GeV

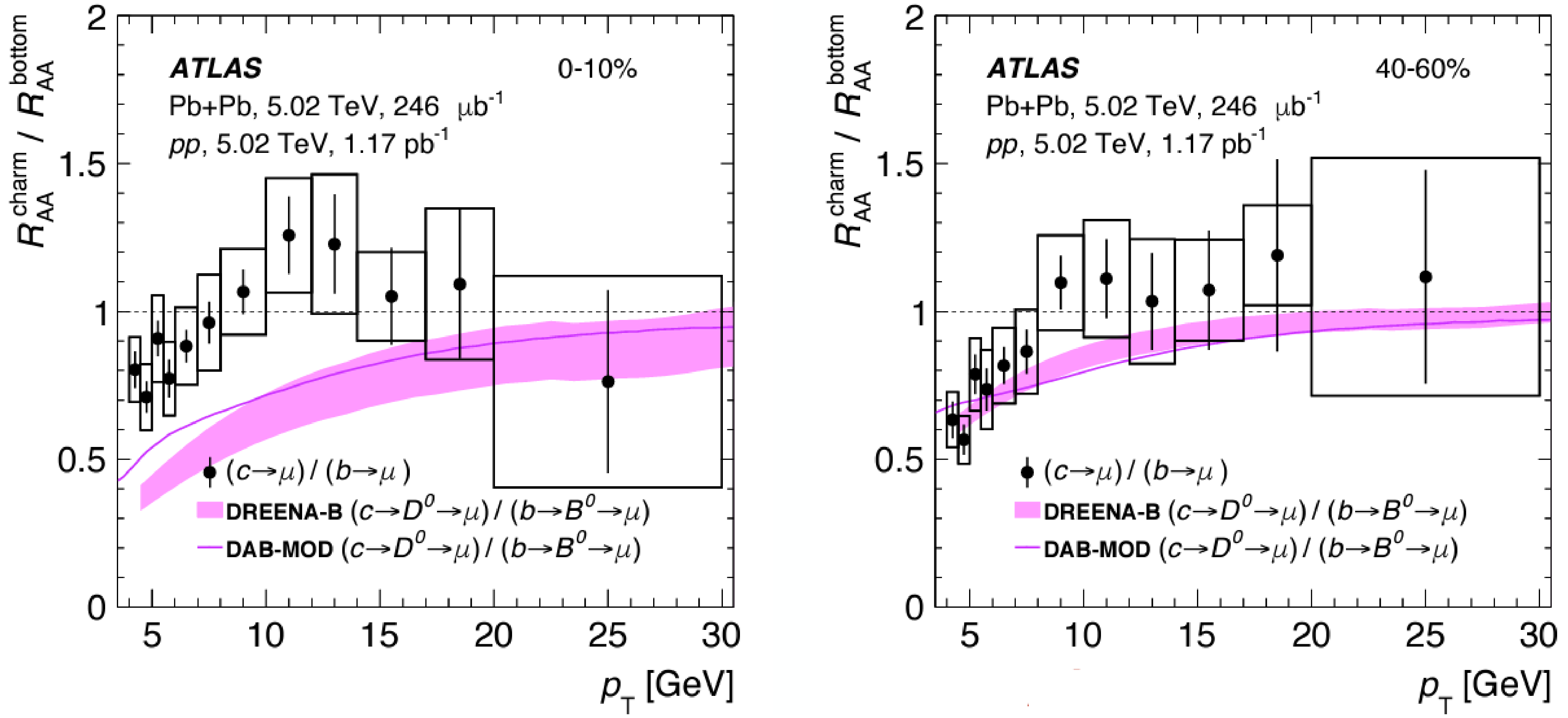
Charm flows more than bottom

Significant centrality dependence for both R_{AA} and v_2

No model describes b/c R_{AA}/v_2 simultaneously

Charm/bottom double ratio

Phys. Lett. B 829 (2022) 137077



- Large uncertainty due to c/b anti-correlation
- Charm is more suppressed at low p_T, compatible at high p_T
  - models underestimate charm R_{AA} (and double ratio) at low p_T in central collisions
- Mass ordering consistent with dead cone effect

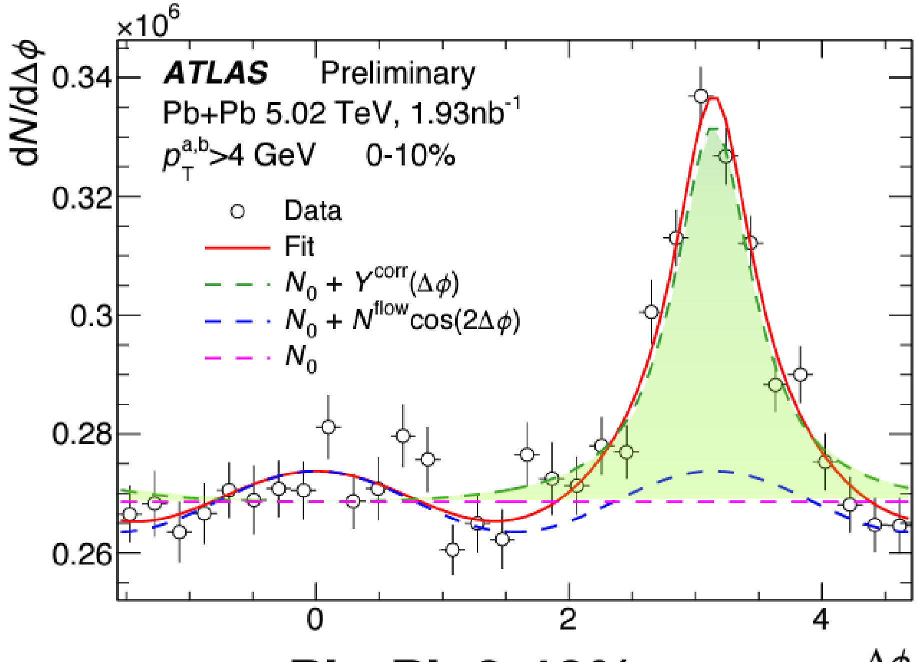
Back-to-back muon pairs

Back-to-back muon pairs from semi-leptonic decays of HF quarks:

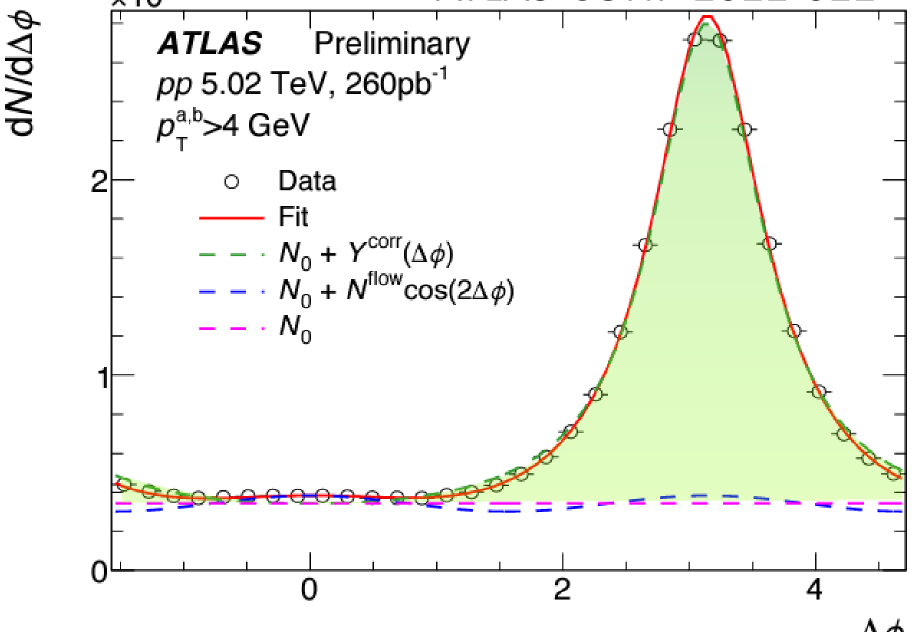
|Δη| > 0.8 → remove the near-side jet peak. Invariant mass cuts to remove J/ψ, Υ etc.

$b\bar{b}$ dominate the same-sign pairs (neutral B mixing)

ATLAS-CONF-2022-022



Pb+Pb 0-10%



pp

$$dN/d\Delta\phi = N_0 + N^{\text{flow}}\cos(2\Delta\phi) + Y^{\text{corr}}(\Delta\phi)$$

Yields with no azimuthal correlation

Collective flow modulation

Back-to-back correlation yields

Di-muon correlation: yields

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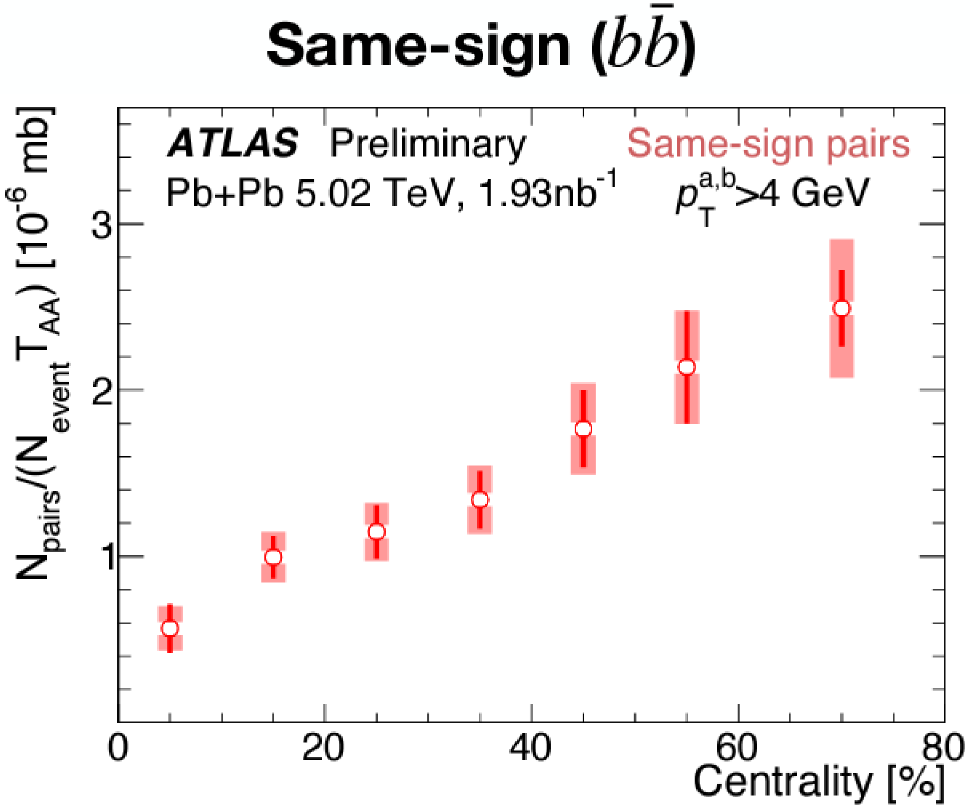

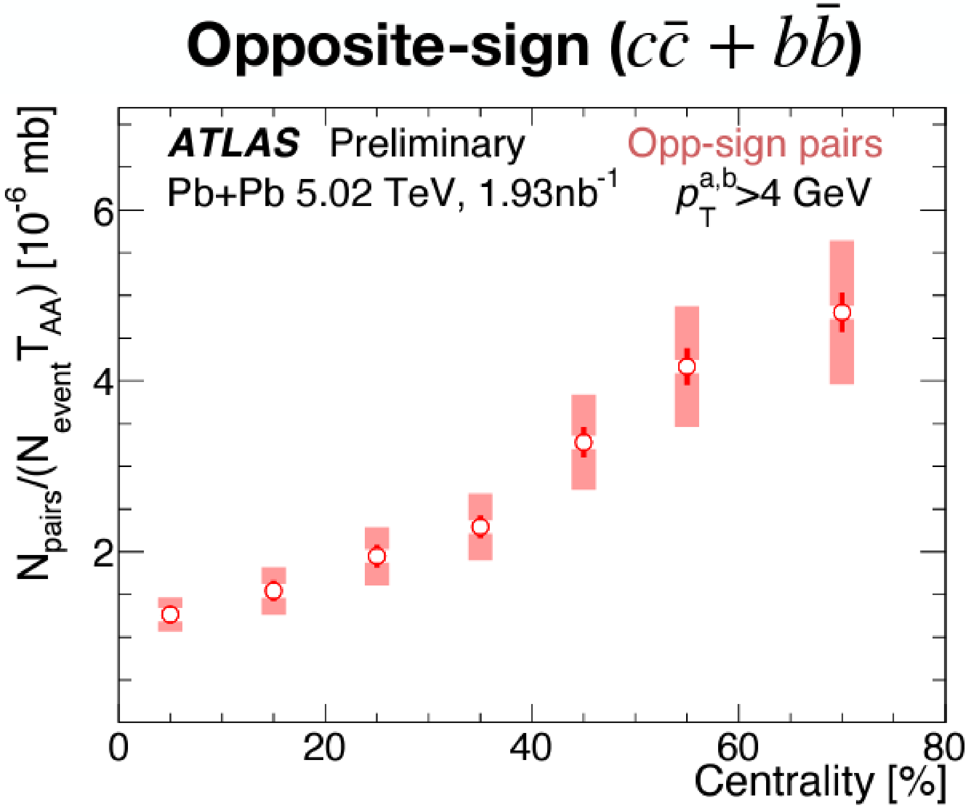

- Stronger suppression in more central collisions
- Similar trend for both same sign and opposite sign pairs

Di-muon correlation: width

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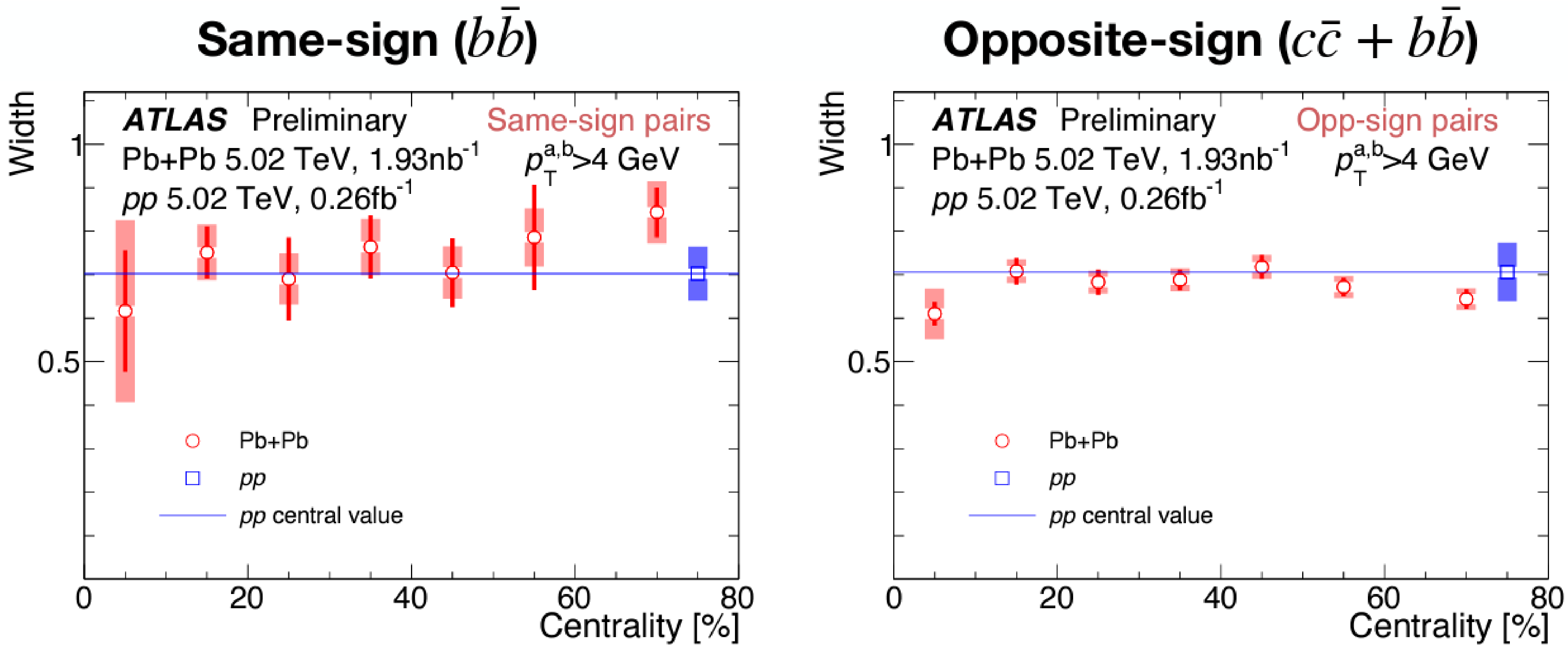
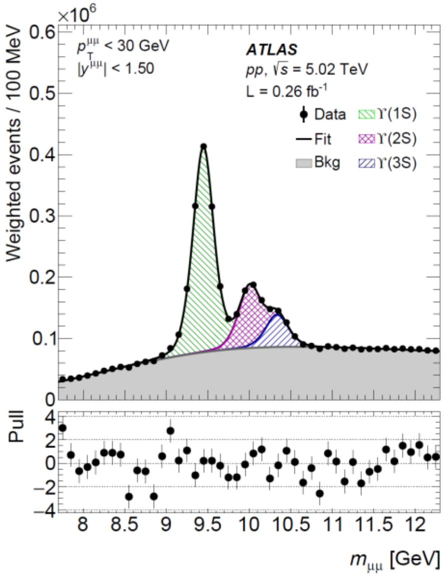
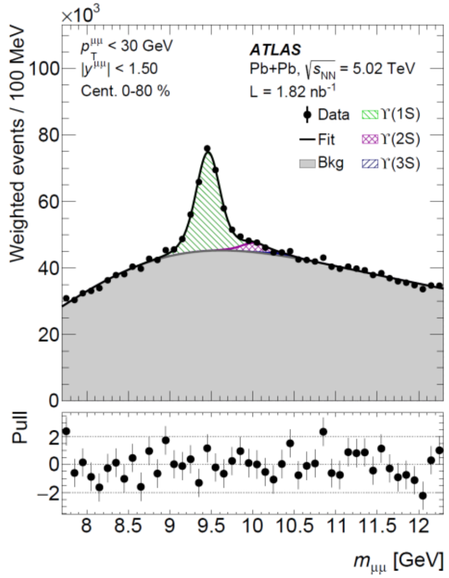


- No centrality dependence (both collisional and radiative loss should lead to broadening).
- Comparable width between *pp* and Pb+Pb

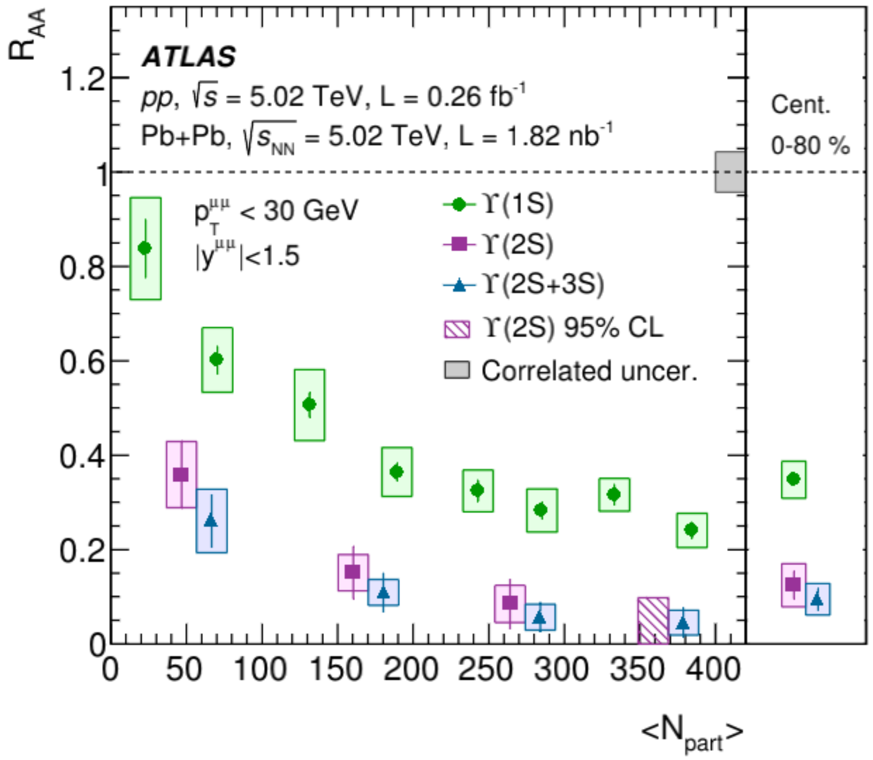
Upsilons in *pp* and Pb+Pb

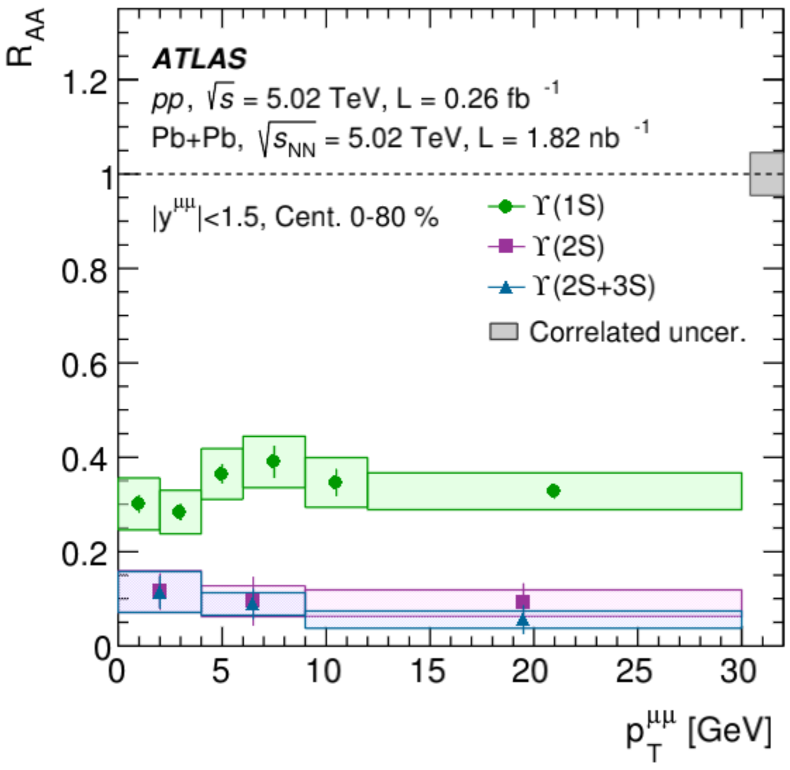




Y are measured via inv. mass distributions of opposite sign muon pairs

arXiv:2205.03042





- Ordering in R_{AA}: Y(1S) > Y(2S) > Y(2S+3S)
- More suppression in more central collisions
- No strong p_T dependence.

Comparison with models (Upsilon R_{AA})

arXiv:2205.03042

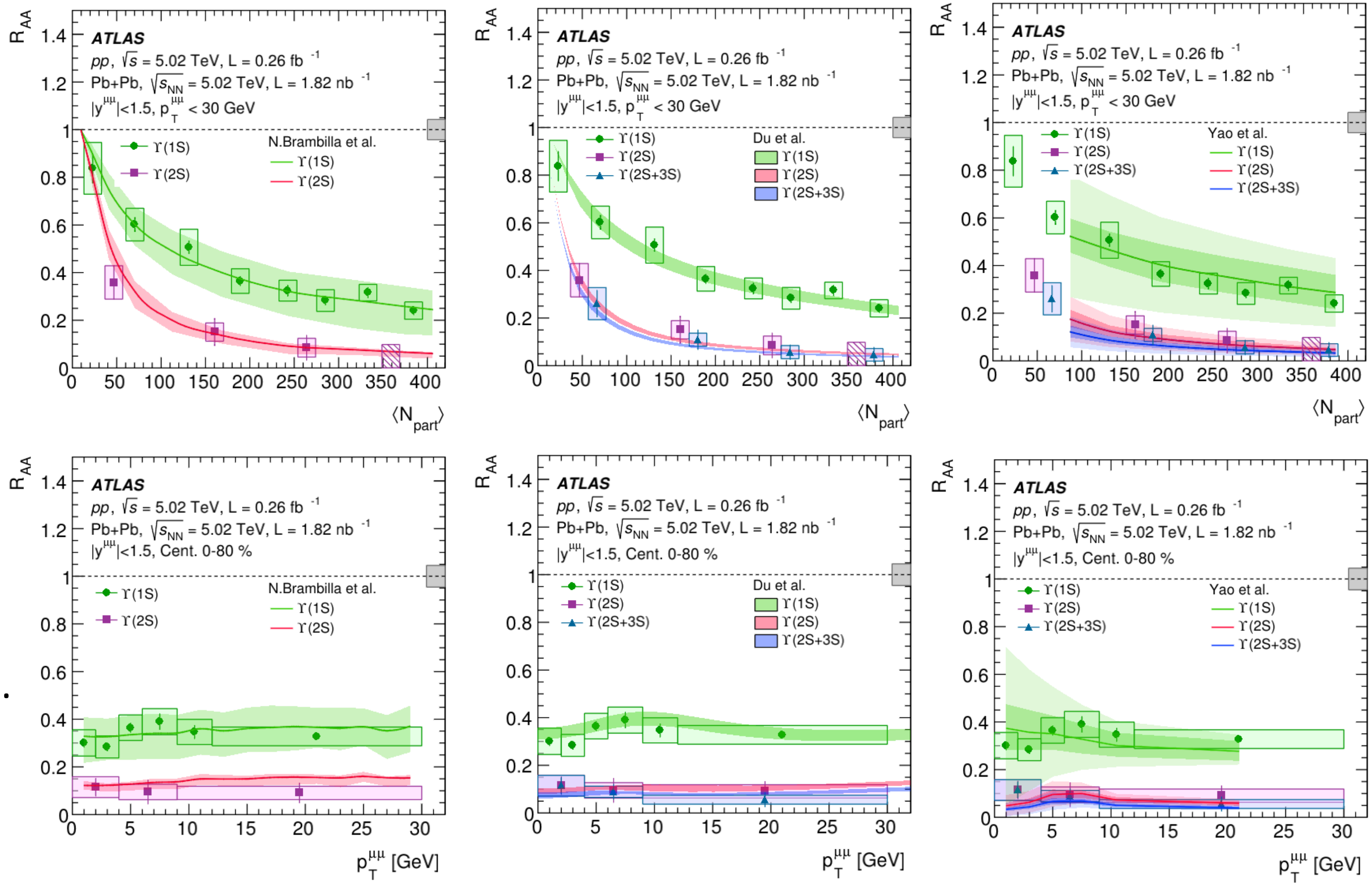
[1] N.Brambilla et al.,
Phys. Rev. D 104 (2021) 094049

[2] M. H. X.Du and R. Rapp,
Phys. Rev. C 96 (2017) 054901

[3] X. Yao et al.,
JHEP 2021 (2021) 46

- Models use different approach to Υ suppression, but include deconfinement as key ingredient.
- Good agreement with the data. Previous Υ suppression data available to authors.

[1] [2] [3]



Conclusions

Jet suppression in Pb+Pb vs pp:

- γ-tagged jets (quark-initiated) are less suppressed than inclusive.
- b-tagged jets are less suppressed than inclusive.
- Split jets lose more energy, jet substructure is more important than p_T.

  - *Energy loss depends on parton flavour and mass, and jet substructure.*
- Significant di-jet imbalance observed at low p_T in central collisions.

  - *Sub-leading jets are more suppressed than leading jets.*

Heavy flavor and quarkonia:

- Muon from c-quarks are more suppressed than muons from b-quarks at low p_T.
- HF back-to-back muon pairs: no significant open angle broadening is observed.
- Sequential suppression for the three Υ states observed.

Backup Slides

Comparison with models (Upsilon double ratios)

arXiv:2205.03042

- Many model uncertainties cancel in double ratio.
- Good agreement with the data.
- Y(2S+3S) suppression relative to Y(2S) in models consistent with data.

[1] [2] [3]