Measurements of heavy-flavor azimuthal correlations and *b*-jet suppression in Pb+Pb collisions with ATLAS

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(Columbia University)

For the ATLAS Collaboration

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HF probes of the QGP

- Heavy-Flavor (HF) quarks are produced at early times in *AA* collisions
  - Masses much larger than temperature of QGP
  - $T_{\mathrm{QGP}} \sim 200 - 500$ MeV
  - Charm Mass : 1.275 GeV
  - Bottom Mass : 4.18 GeV

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  - But with mass dependent modifications
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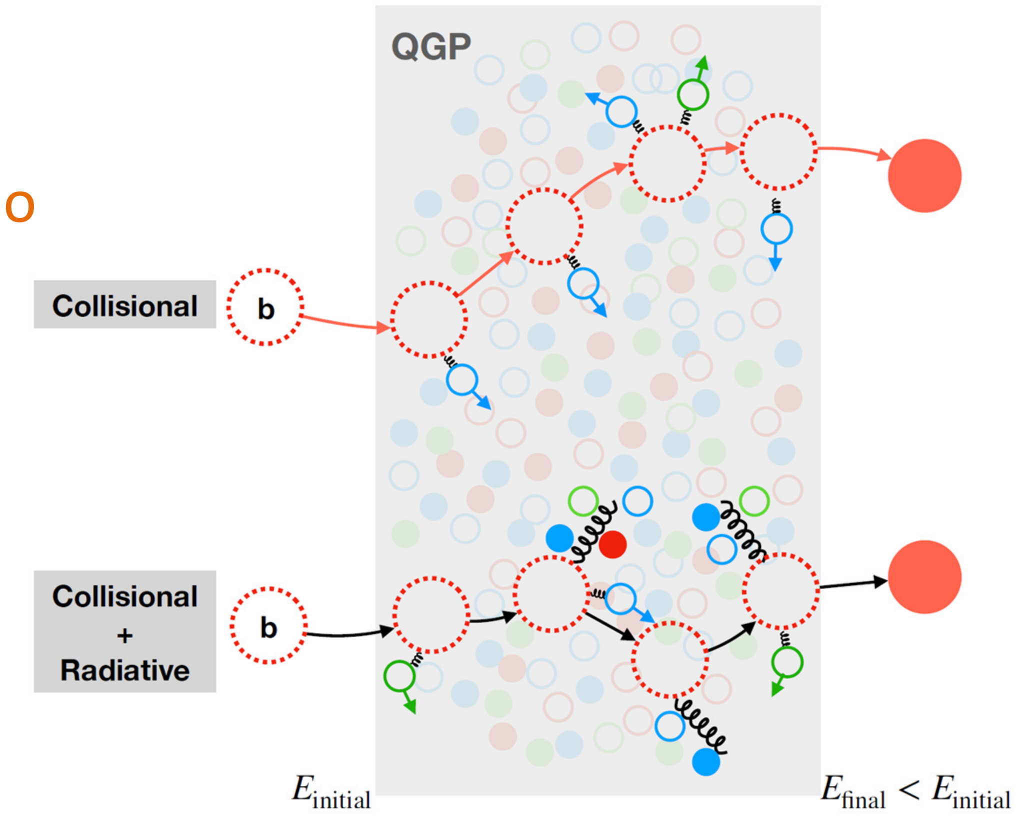
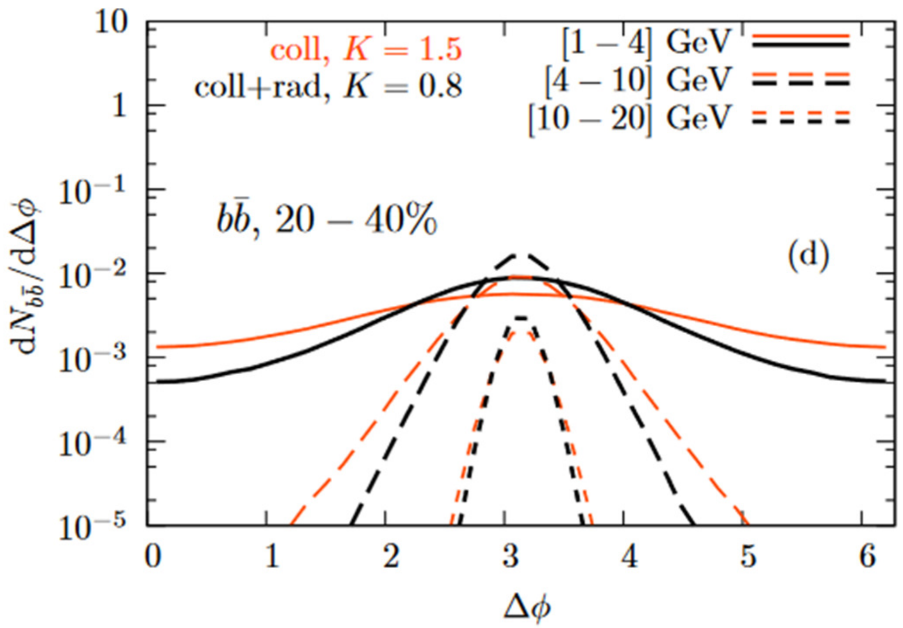
- Two ATLAS HF measurements discussed today:
  - Azimuthal correlation between muon-pairs from HF decays (PRL 132 (2024) 202301)
  - Suppression of *b*-jets (EPJC 83 (2023) 438)

Disentangling radiative vs collisional energy loss

- HF-quark pairs provide a possible method to disentangle collisional and radiative energy loss (*PRC 90 (2014) 024907*)
  - Azimuthal correlations more broadened in “collision only” scenario
  - Less broadened when including radiative energy loss





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  - But measuring lepton-pairs from decays of HF-hadron pairs possible
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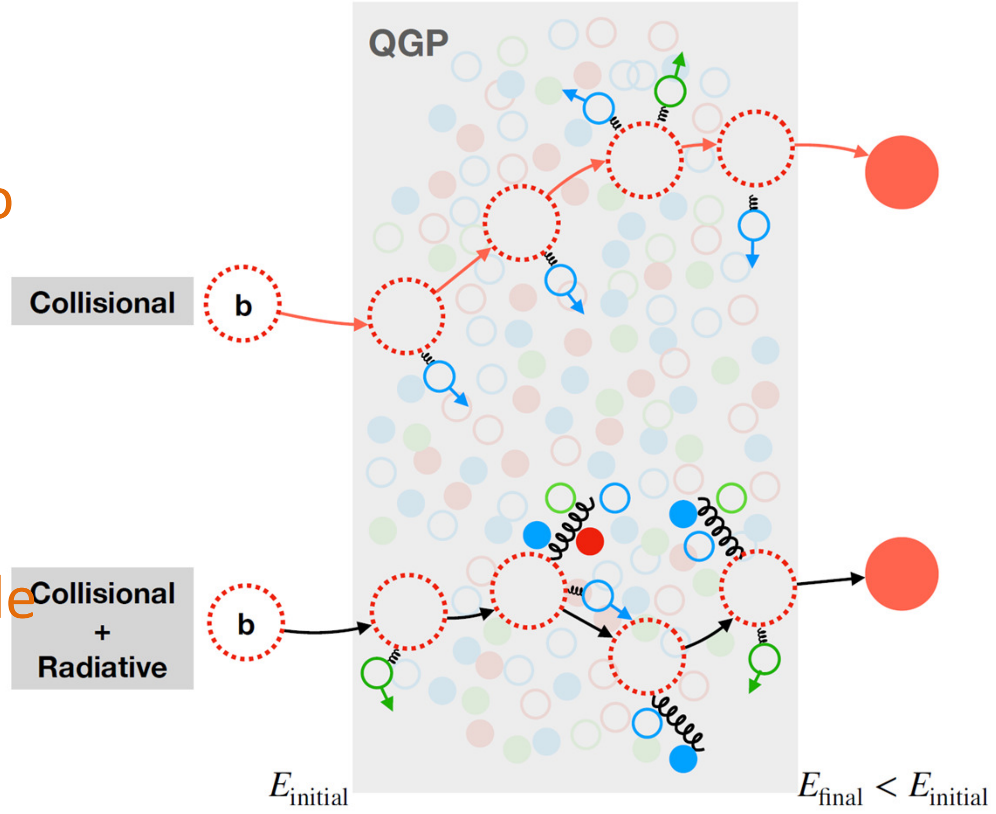
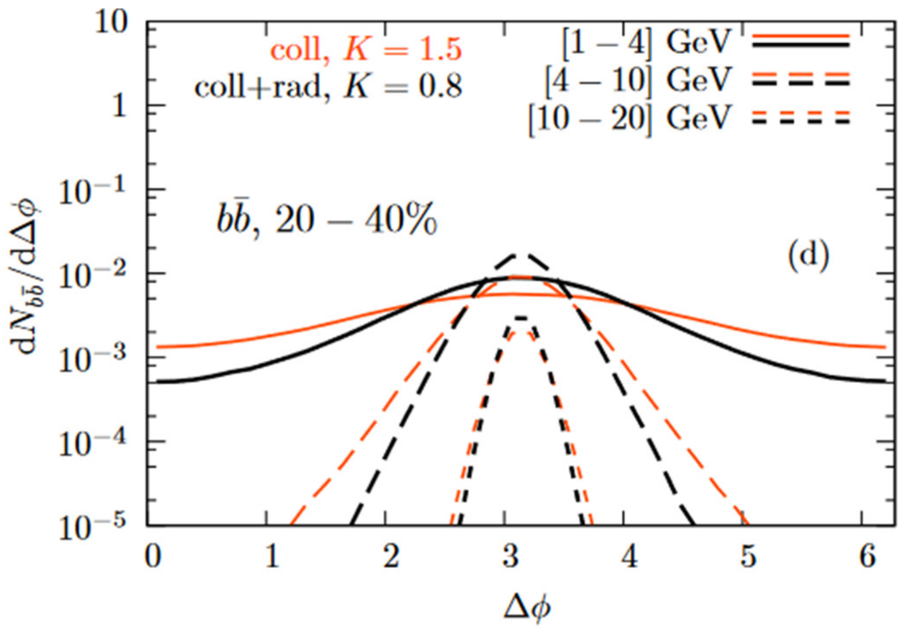
  - Used extensively by ATLAS to study v_2 and R_{AA} of bottom & charm





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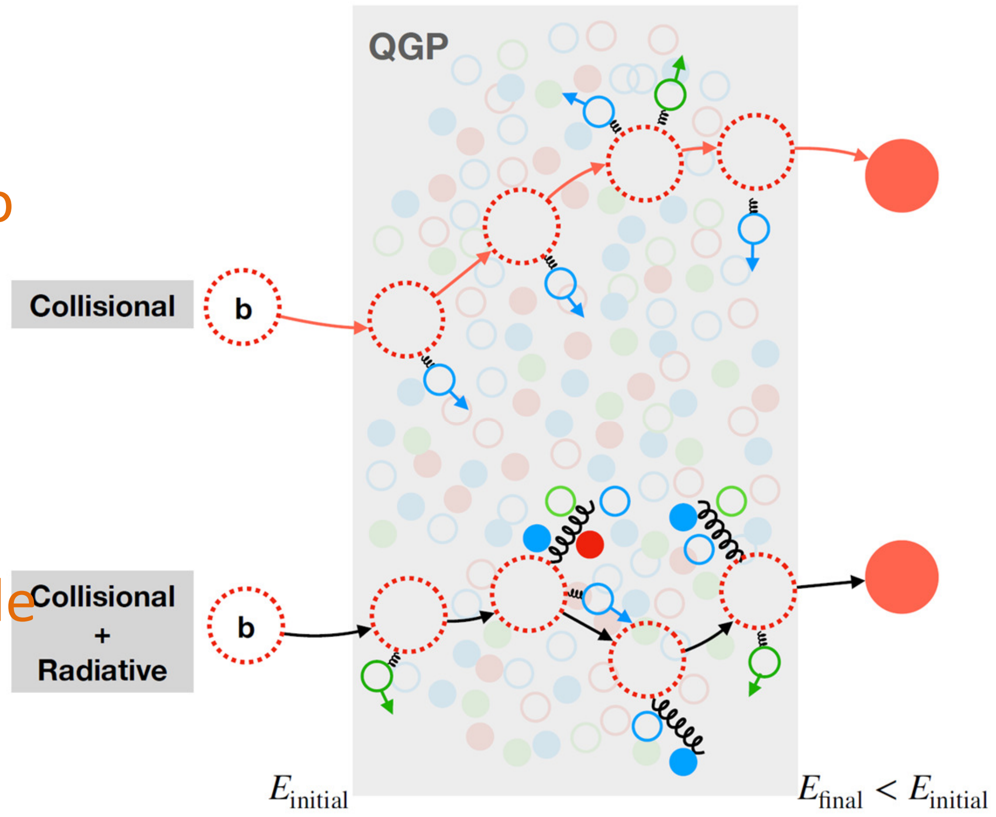
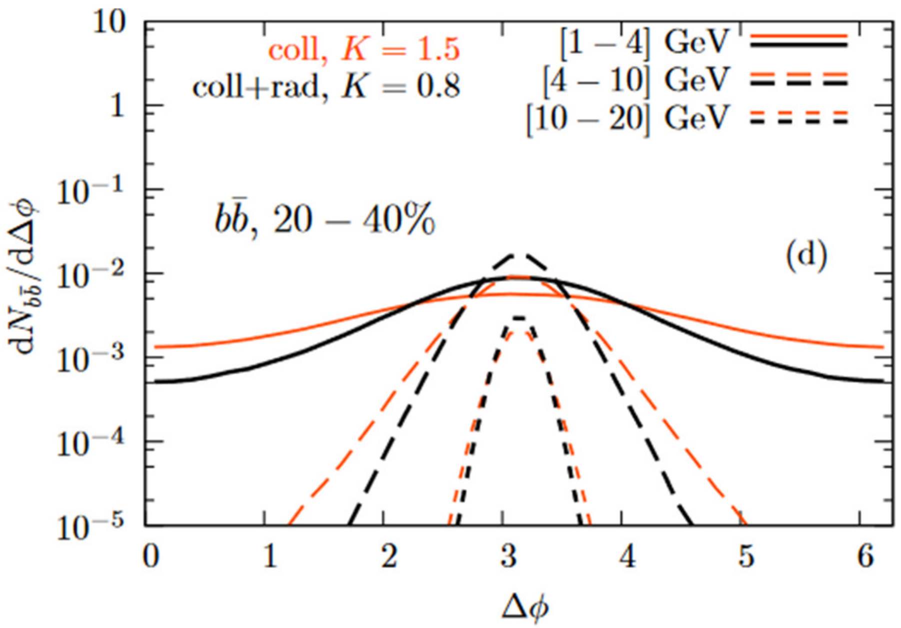
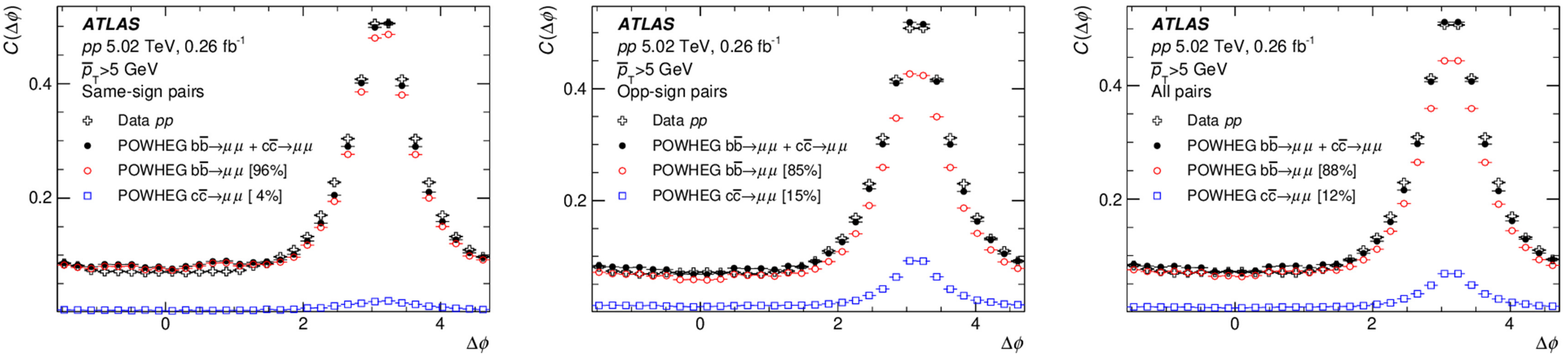
- Muon-pairs with p_{T} of each muon more than 4 GeV
  - Opp-sign pairs : originating from $b\bar{b}$ ~5x more likely than $c\bar{c}$
  - Same-sign pairs : almost exclusively from $b\bar{b}$ pairs





Data-MC comparisons for *pp* measurements



- $\Delta\phi = \phi_1 - \phi_2$ distribution for muon pairs in *pp* collisions
  - Same-sign (left), opposite-sign (center), combined (right)

- *pp* Δϕ correlations well reproduced by POWHEG
  - HF Production well understood

- POWHEG calculations show:
  - Nearly all (96%) same-sign muon pairs result from $b\bar{b}$ decays
  - Most (85%) opp-sign muon pairs result from $b\bar{b}$ decays

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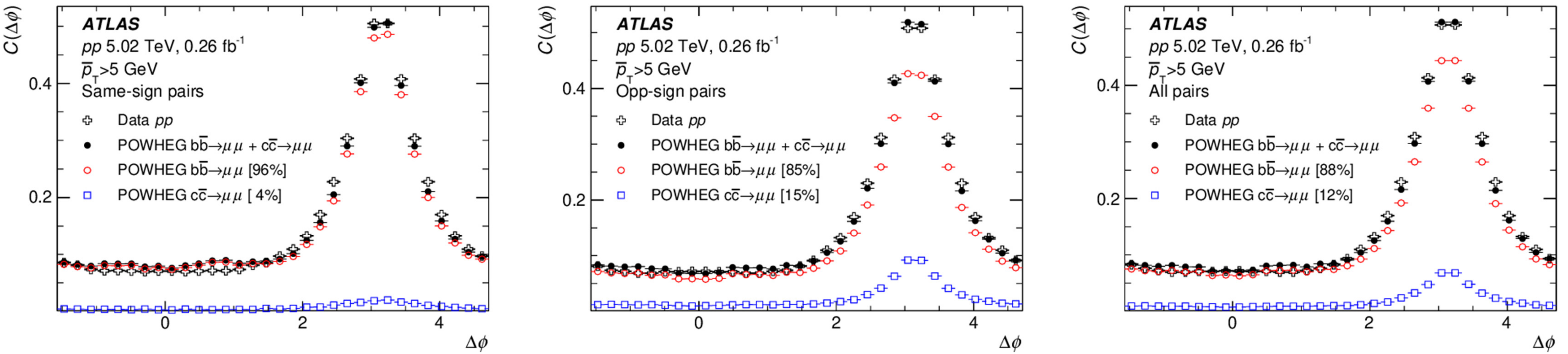

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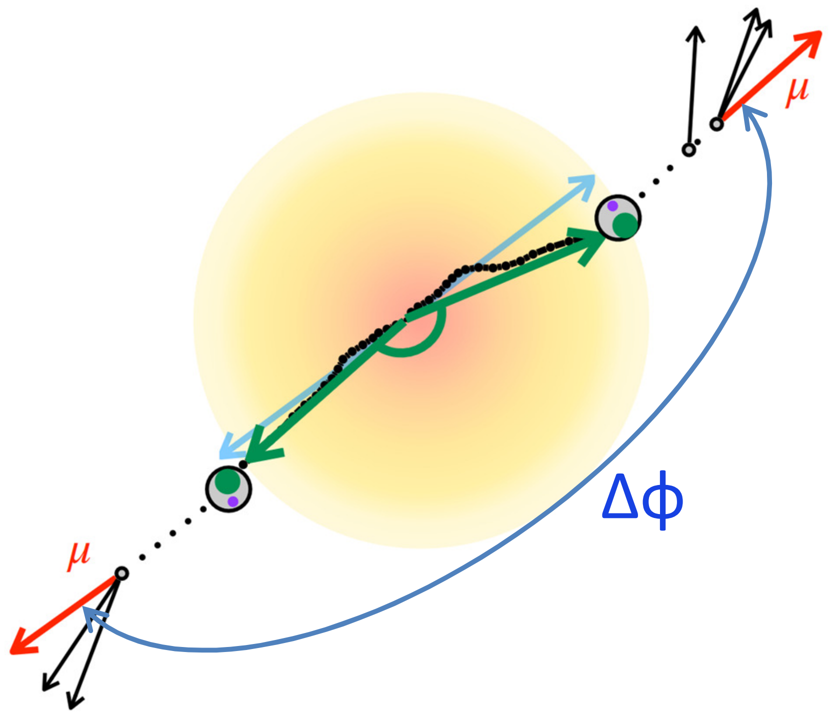


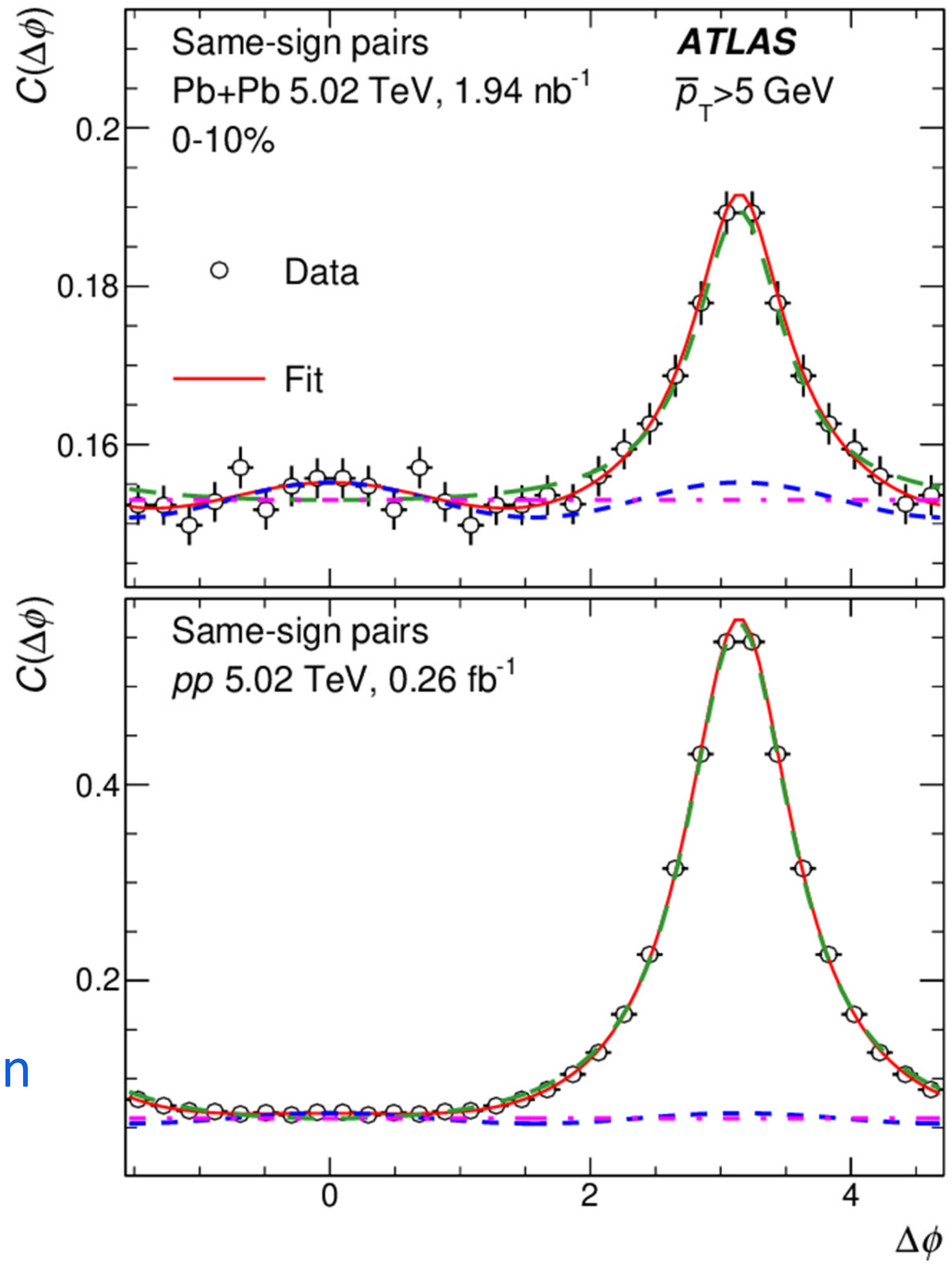
Measuring Δϕ correlations between muon-pairs

- Compare (self-normalized) Δϕ correlations between Pb+Pb and *pp*.
- For Pb+Pb:
  - Huge pedestal from combinatoric pairs
  - Flow modulation present in pedestal!
- For *pp:*
  - Much smaller pedestal, most pairs are back-to-back
- Fit correlation functions with the form:

$$C^{\mathrm{Fit}}(\Delta\phi) = C_{\mathrm{comb}}\left[1 + 2v_{2,2}^{\mathrm{eff}}\cos(2\Delta\phi)\right] + C_{\mathrm{corr}}(\Delta\phi)$$

With:

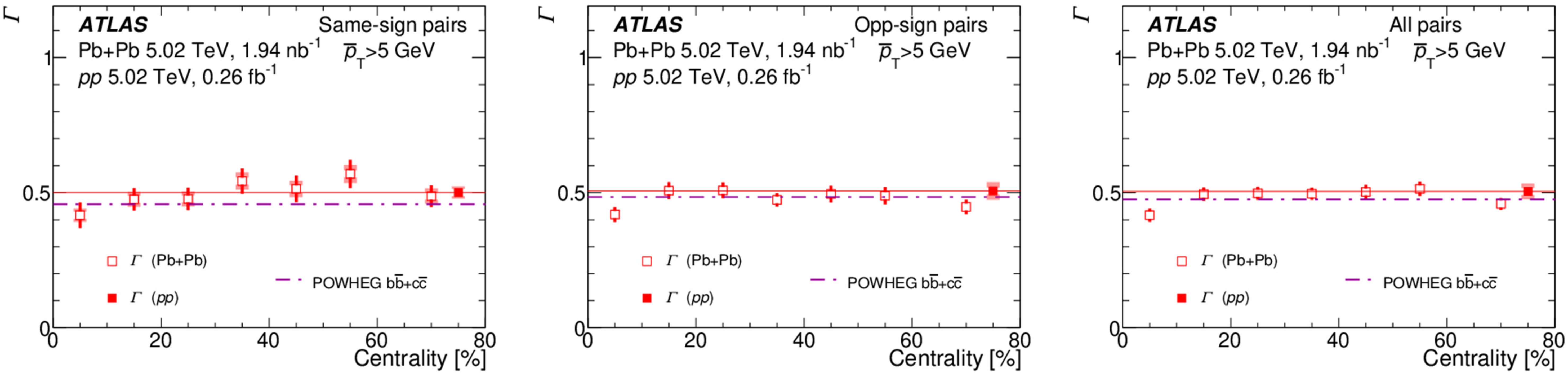
$$C_{\mathrm{corr}}(\Delta\phi) = \frac{C_{\mathrm{corr}}^{\max}\,\Gamma^2}{(\Delta\phi-\pi)^2+\Gamma^2}$$



- The half-width at half-maximum (Γ) quantifies the shape of the correlation
- Alternate parameterization:

$$\sigma \equiv \sqrt{\int (\Delta\phi-\pi)^2\left(C_{\mathrm{corr}}(\Delta\phi) - C_{\mathrm{corr}}(0)\right)\mathrm{d}\Delta\phi}$$

Quantifying correlation shape vs centrality



- Compare Γ as a function of centrality
  - Measurements consistent with “no centrality dependence”
  - Pb+Pb and *pp* values consistent.
  - Widths identical for “same-sign” and “opp-sign” pairs

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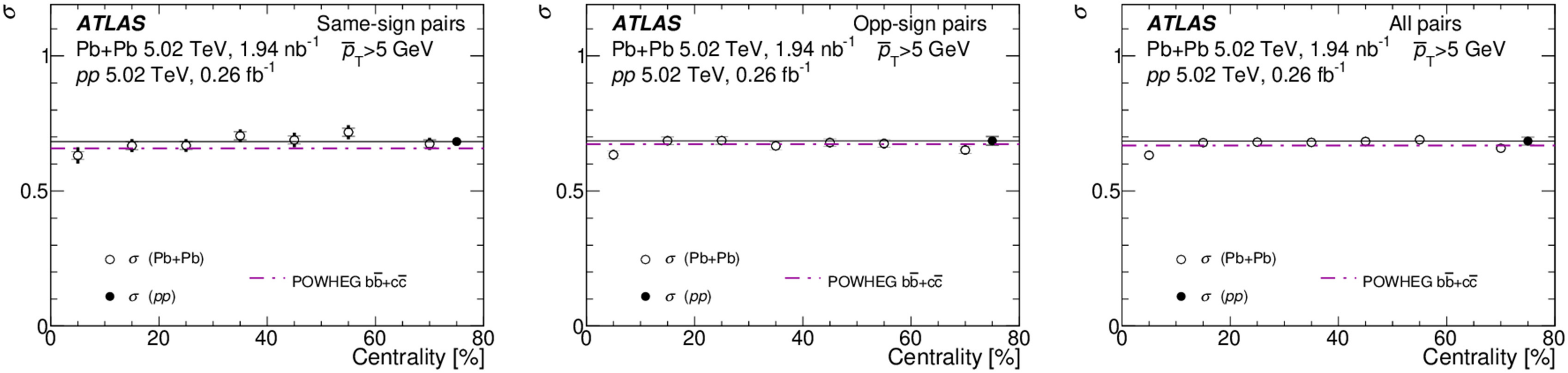

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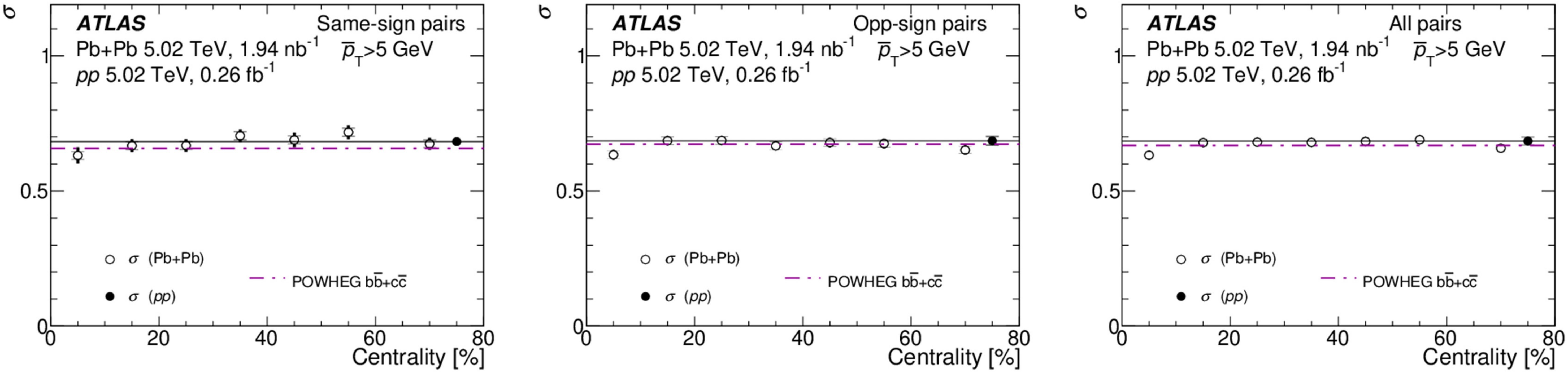

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- See strong $b \rightarrow \mu$ suppression (single b and for pairs)
- But not much angular deflection

b-jets in heavy-ion collisions

- *b*-jets vs inclusive jets in heavy ion collisions
  - Dead-cone effect : medium-induced gluon radiation expected to be suppressed
  - Sensitive to the mixture of radiative and collisional energy loss in the QGP
  - Color charge known; inclusive jets are mixture light quarks and gluons

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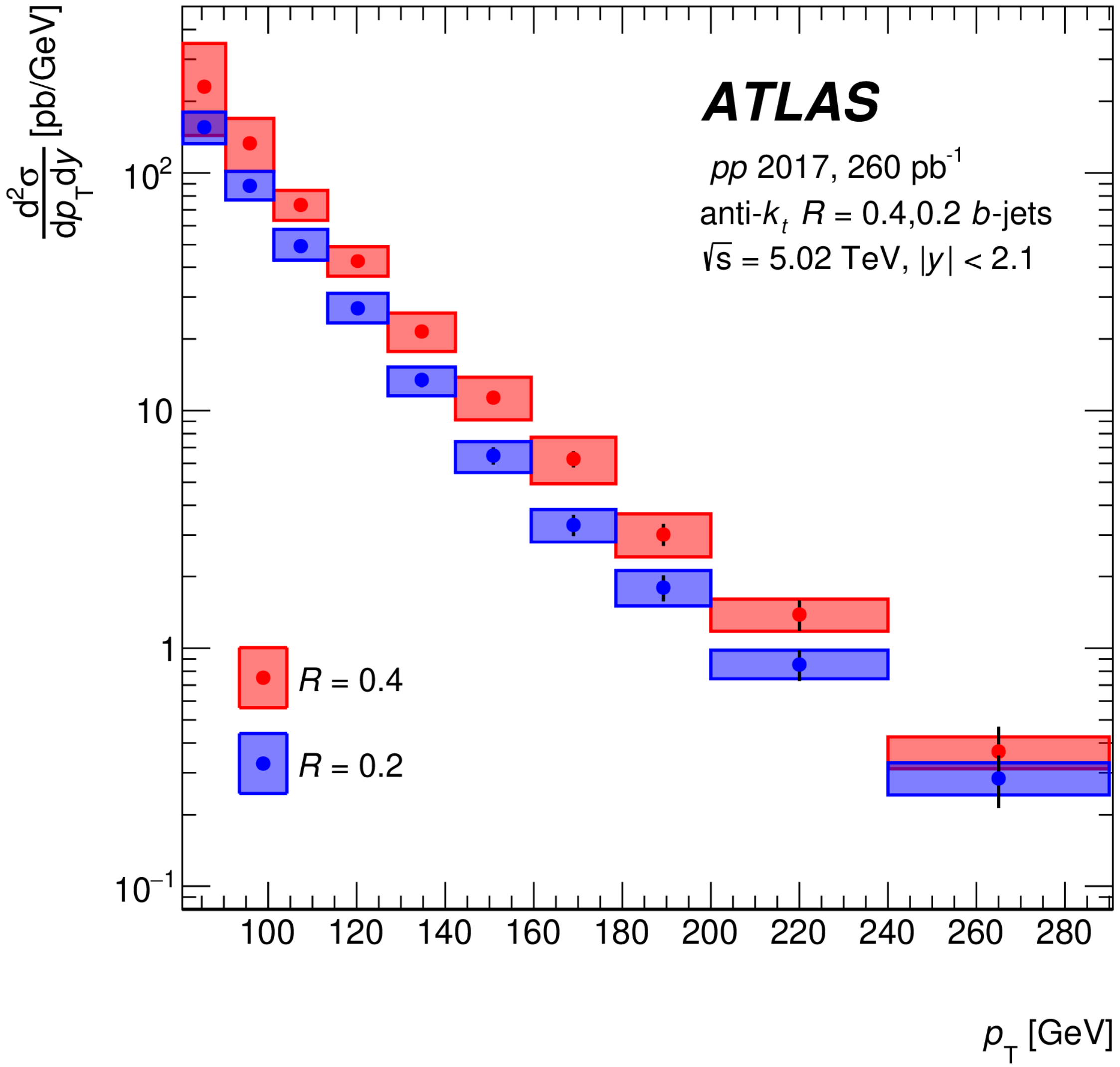
- Suppression quantified by R_{AA}
  - Per-event yield of b-jets vs expectation from pp scaled by nuclear thickness function T_{AA}

$$R_{\mathrm{AA}}^{b\text{-jet}} \equiv \left. \frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N_{\mathrm{AA}}^{b\text{-jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \right|_{\mathrm{cent}} \Big/ \langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma_{pp}^{b\text{-jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

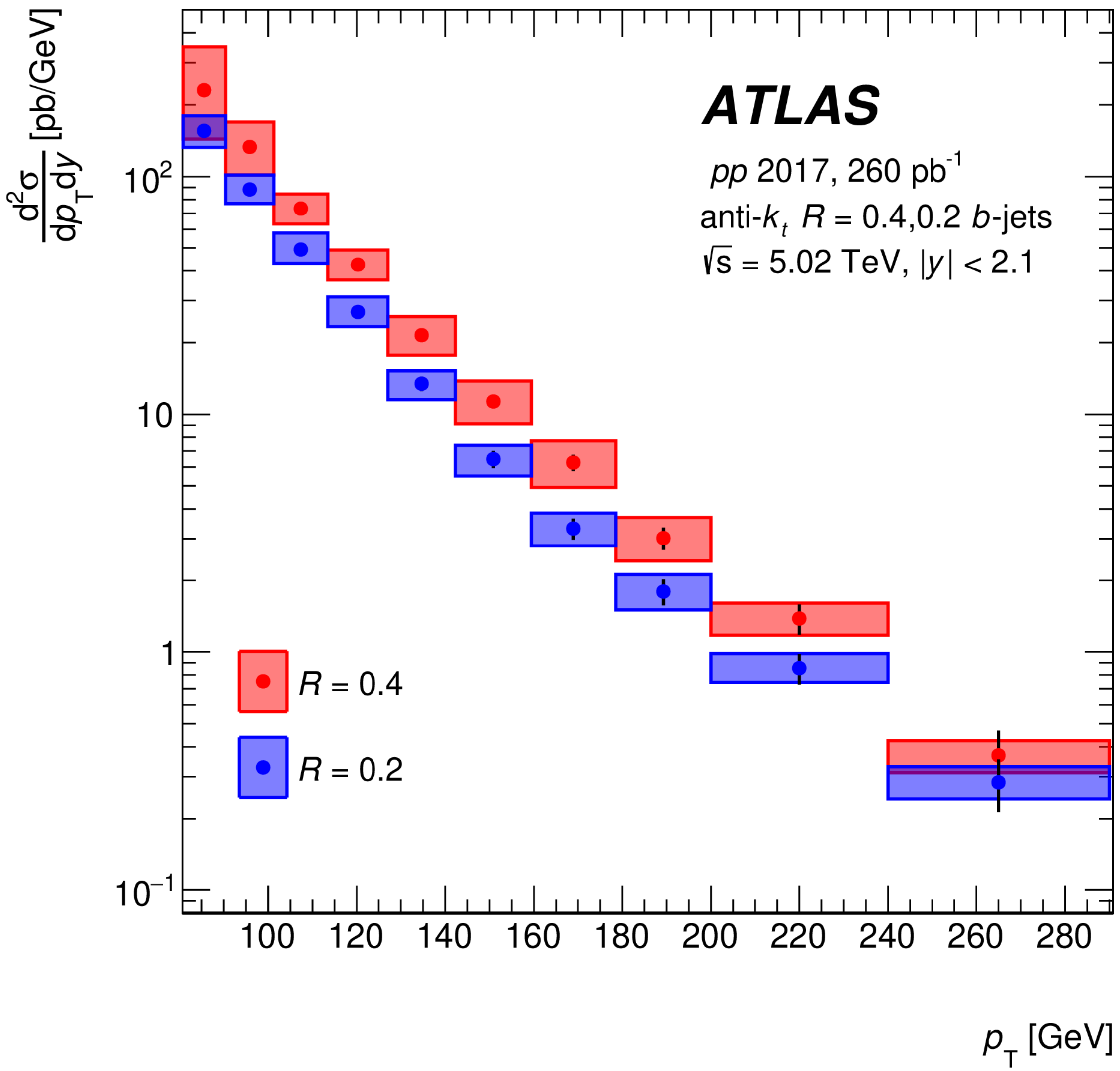
- *b*-Jets are tagged by requiring a muon within the Jet cone
- Statistically corrected for contributions from
  - Light-jets
  - *c*-jets
  - Combinatorics

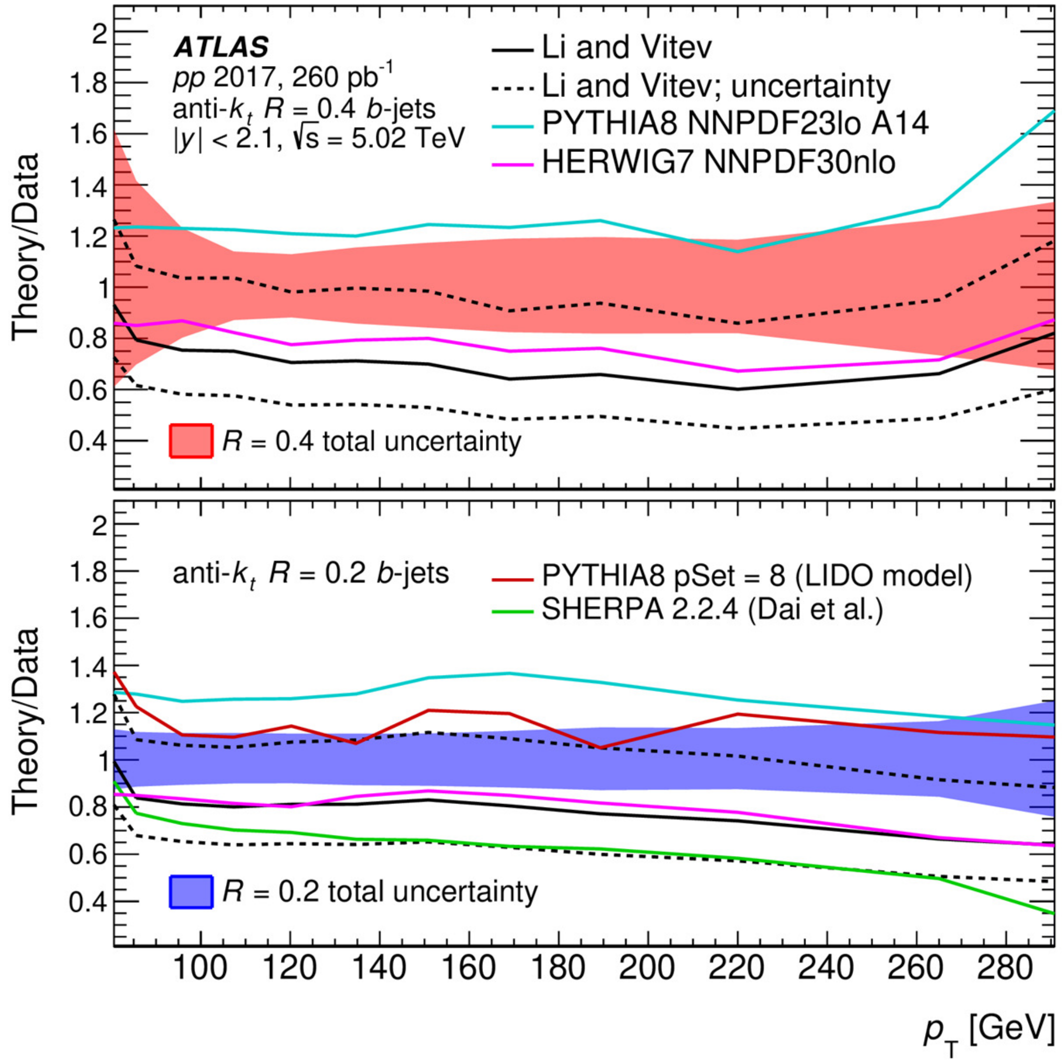
Cross-sections for *b*-jets in *pp* collisions



- Left: cross-sections for R=0.4 and 0.2 *b*-jets in 5.02 TeV *pp* collisions

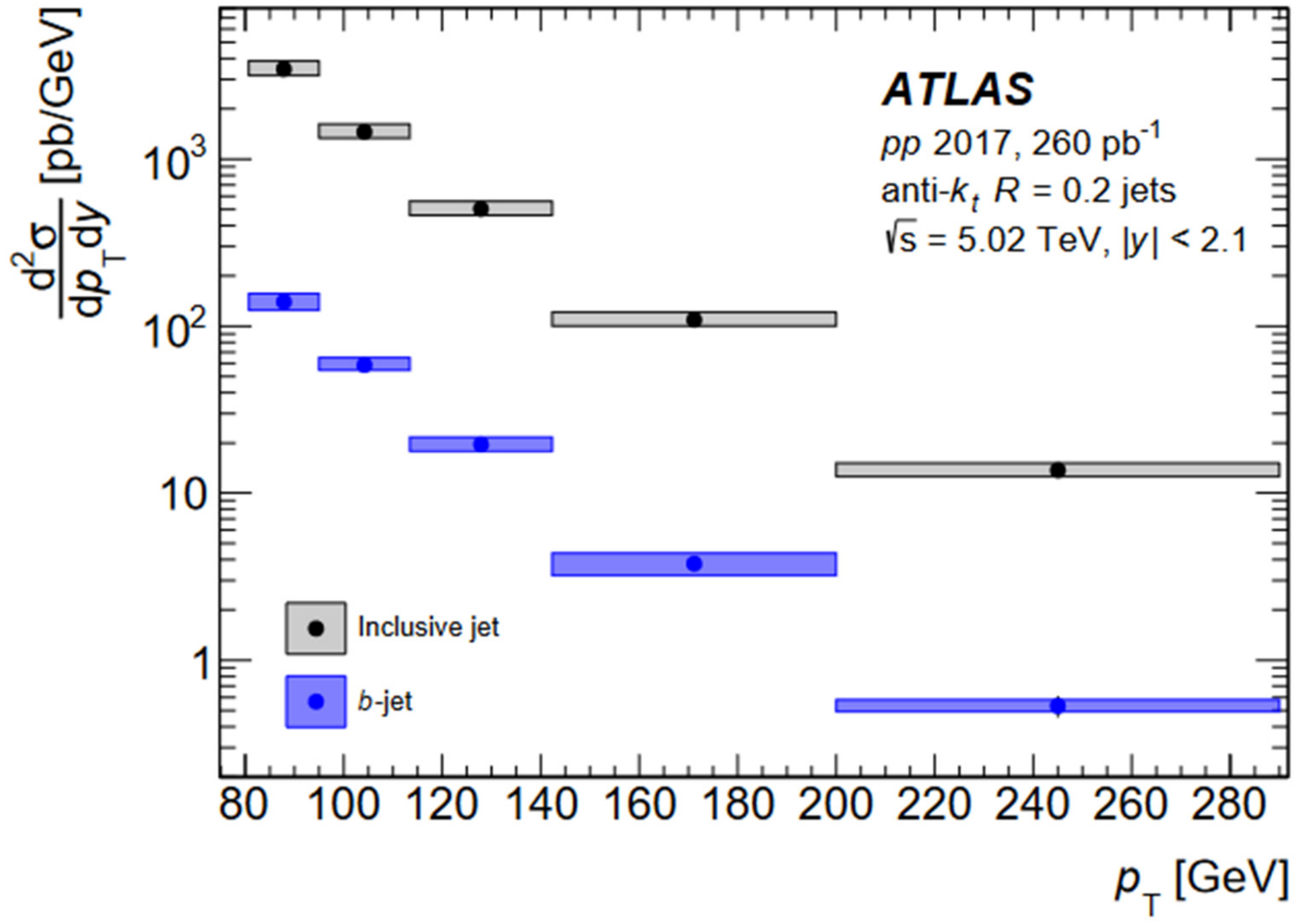
Cross-sections for *b*-jets in *pp* collisions





- Left: cross-sections for R=0.4 and 0.2 *b*-jets in 5.02 TeV *pp* collisions
- Right: ratio to Theory/Generators
- Model/Generator calculations consistent with data within 20% or better

Cross-sections : *b*-jets vs inclusive (*pp*)



- Comparison of *b*-jet and inclusive jet cross-sections for R= 0.2 jets.

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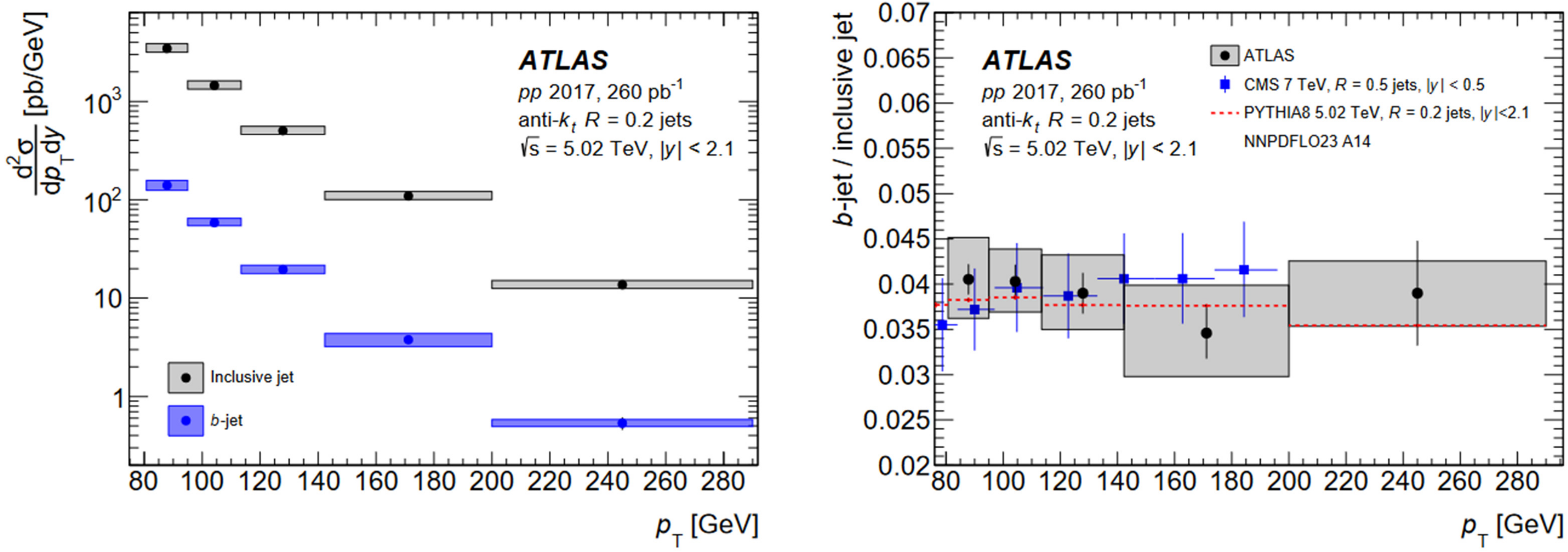
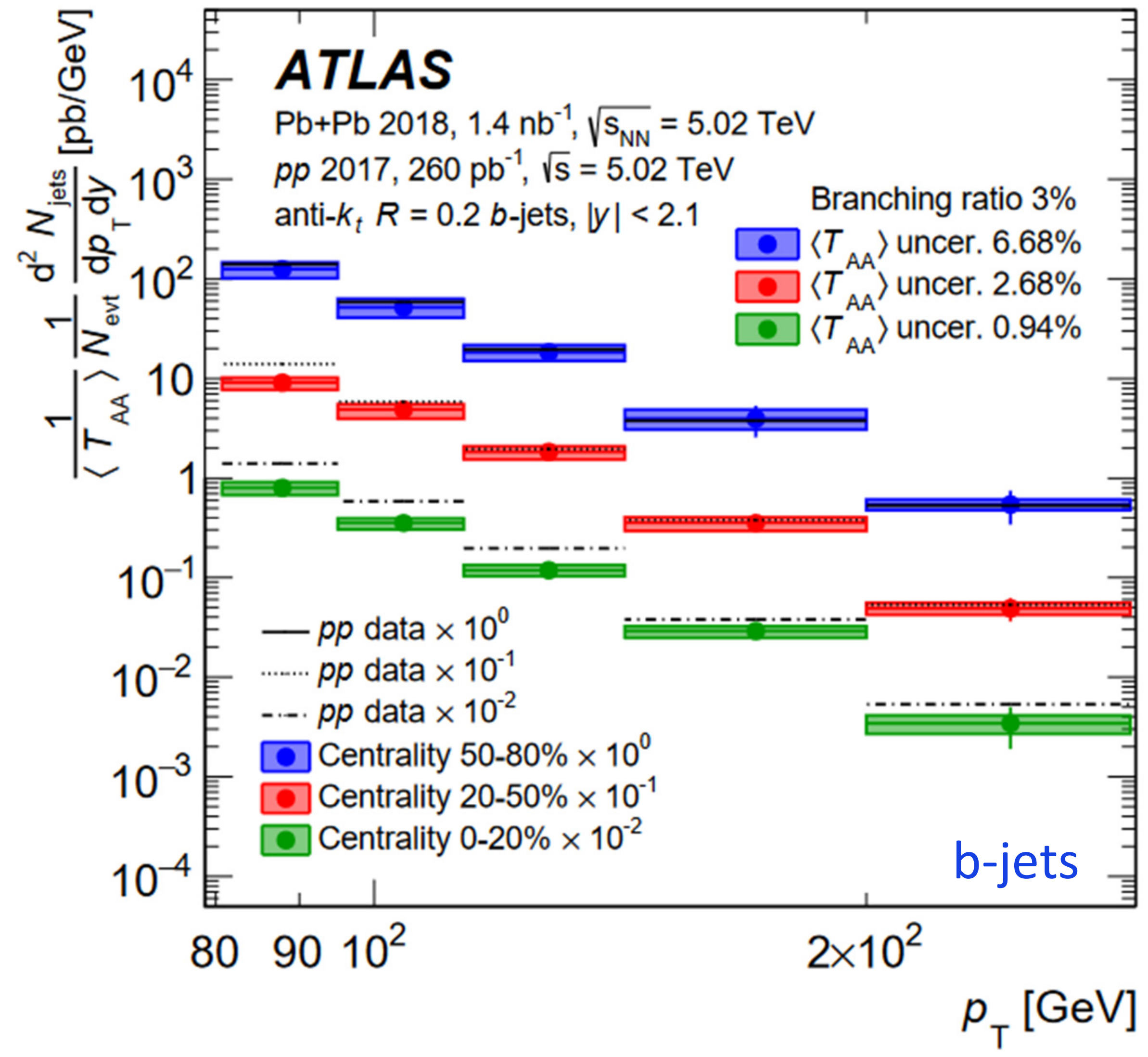
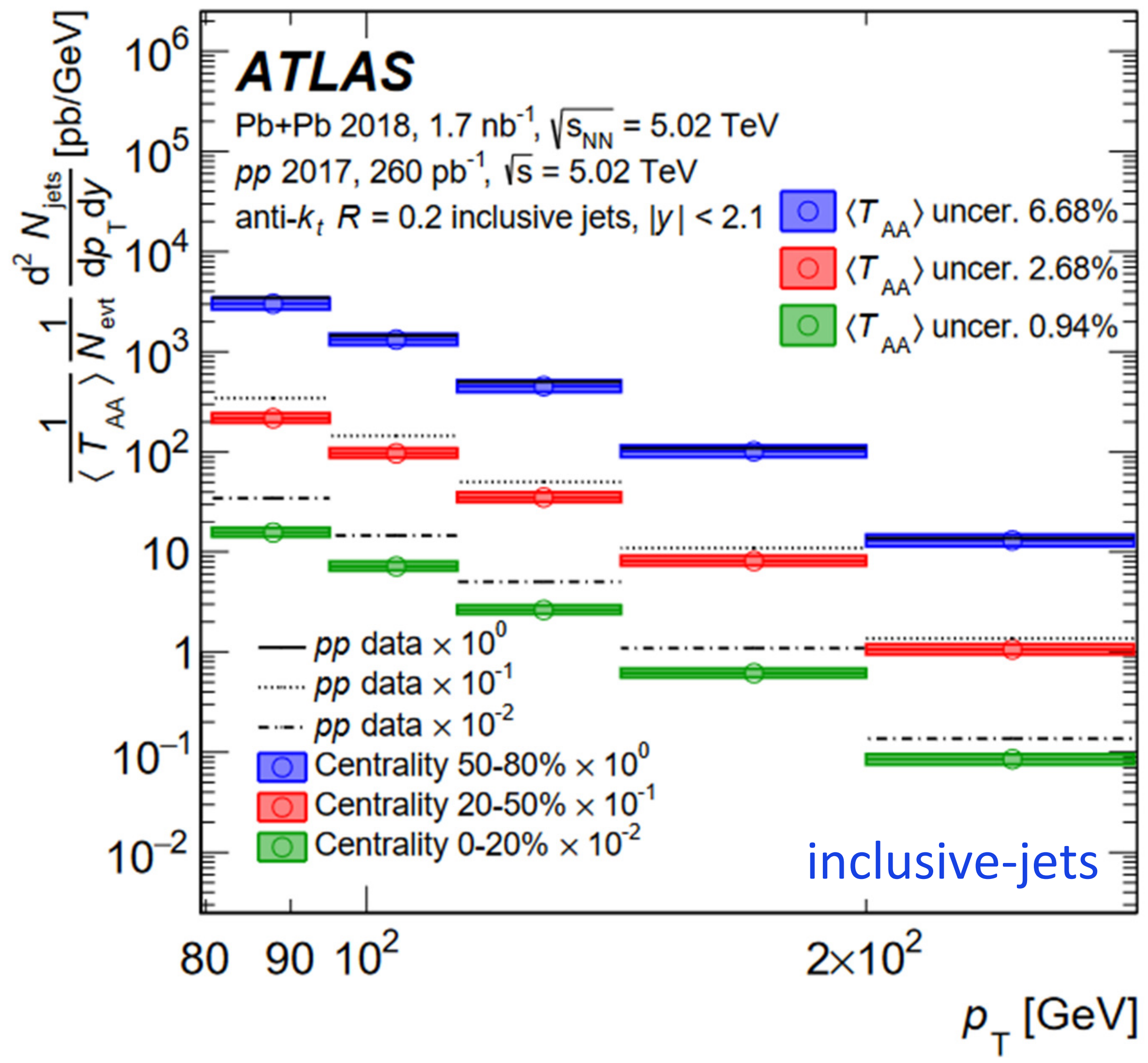


- Comparison of *b*-jet and inclusive jet cross-sections for R= 0.2 jets (left) and their ratio (right).
  - Ratio comparison to PYTHIA8 MC : consistent with data
  - Comparisons to CMS 7 TeV data

- Ratio independent of p_{T} (within uncertainties)
  - Important for R_{AA} interpretation

T_{AA} scaled per-event yields in Pb+Pb

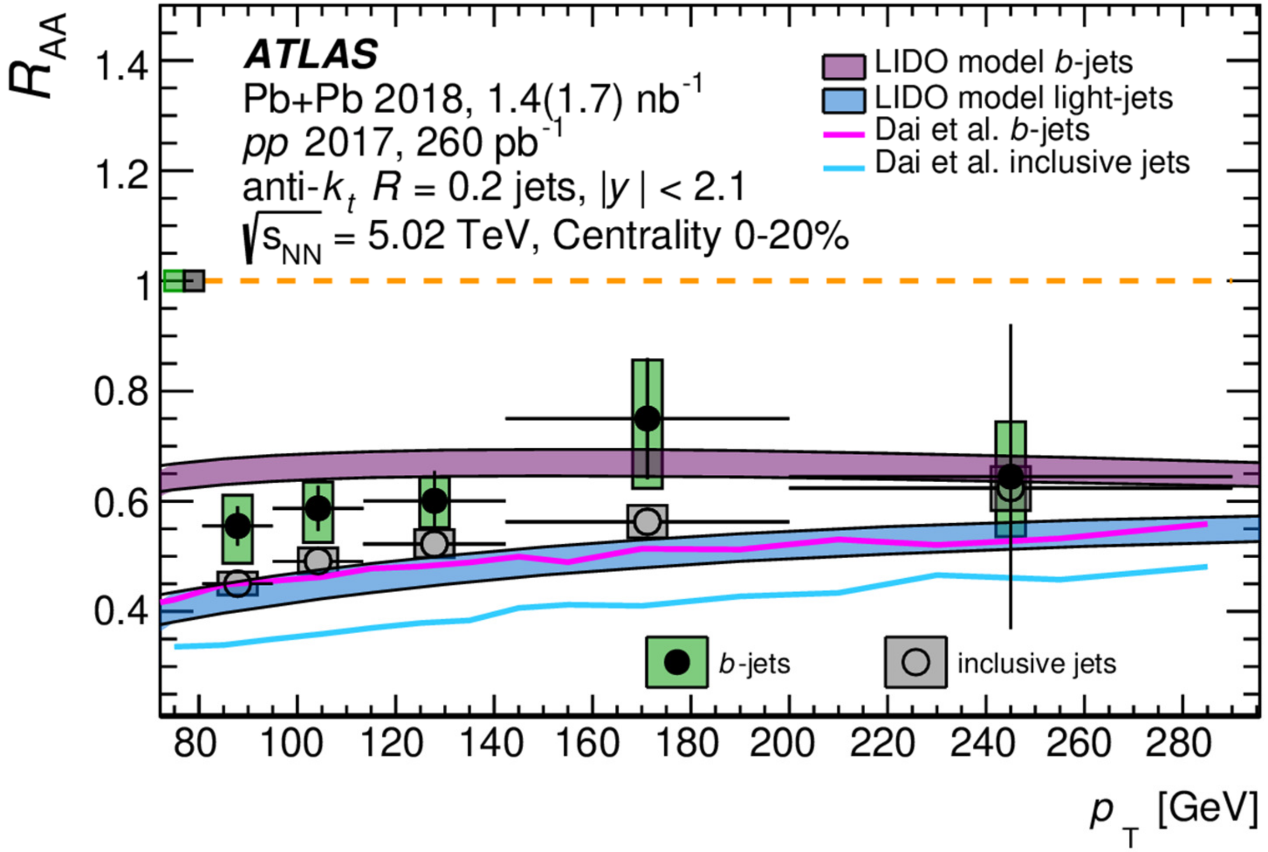


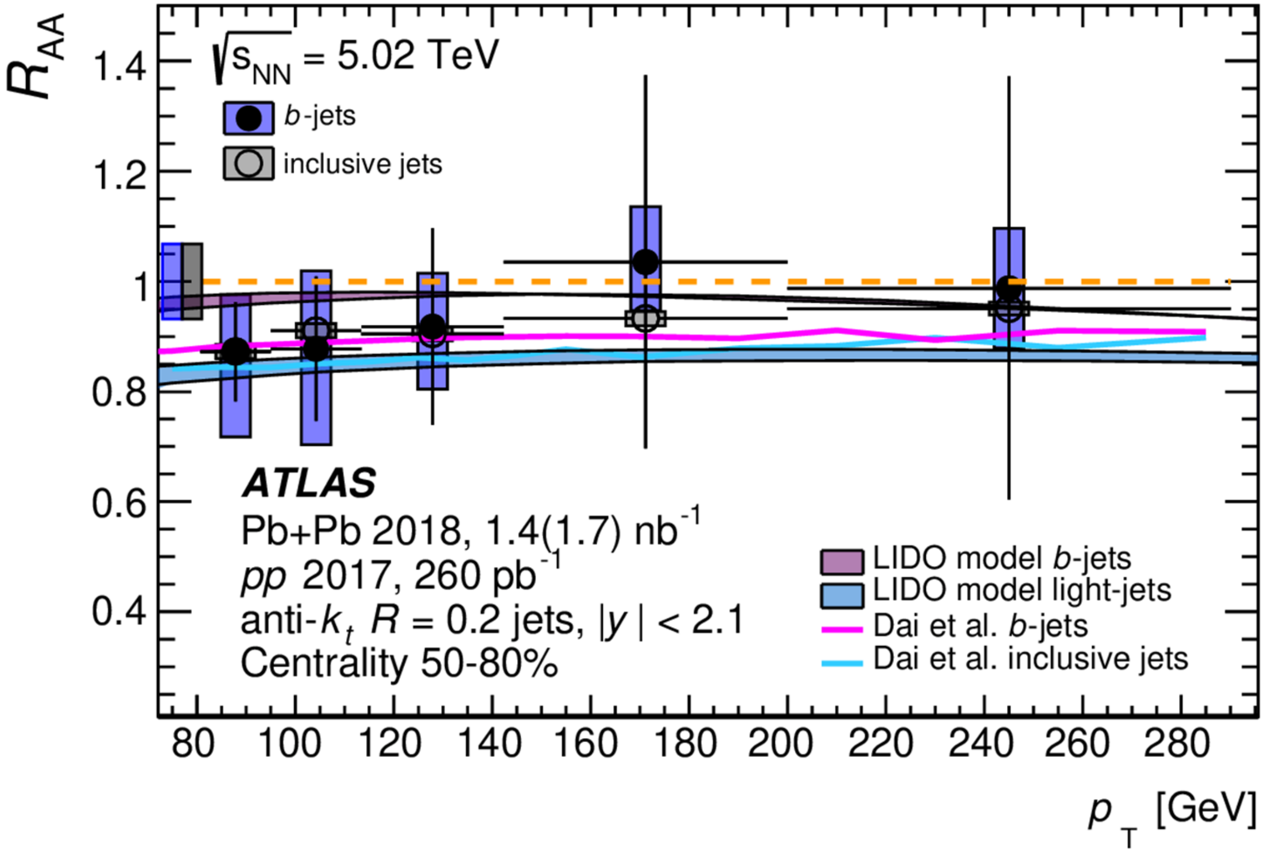


- b-jets (left) and inclusive–jets (right)
  - Shown for 0-20%, 20-50% and 50-80% centralities

- Also shown for comparison are the *pp* cross-sections

R_{AA} for *b*-jets

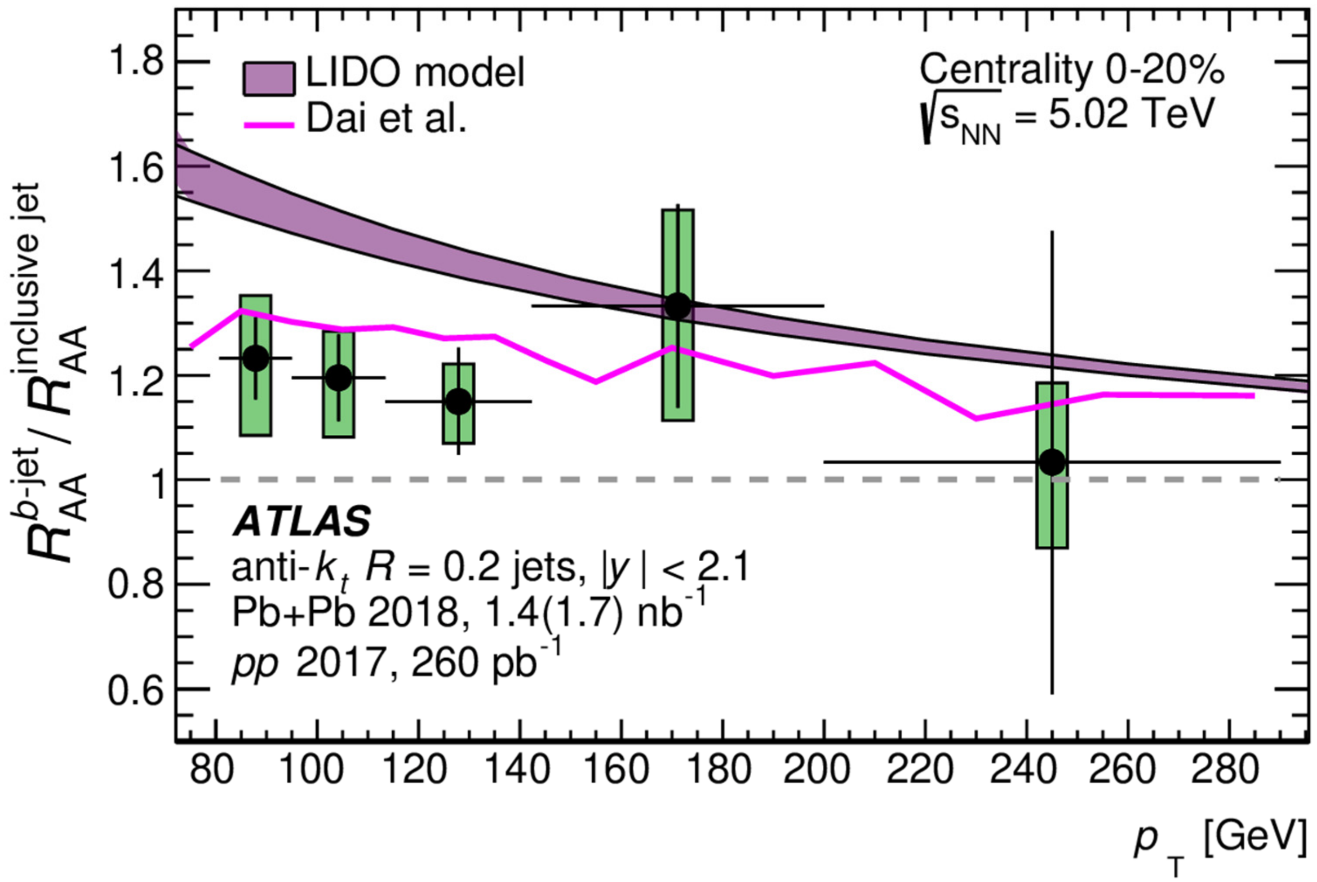


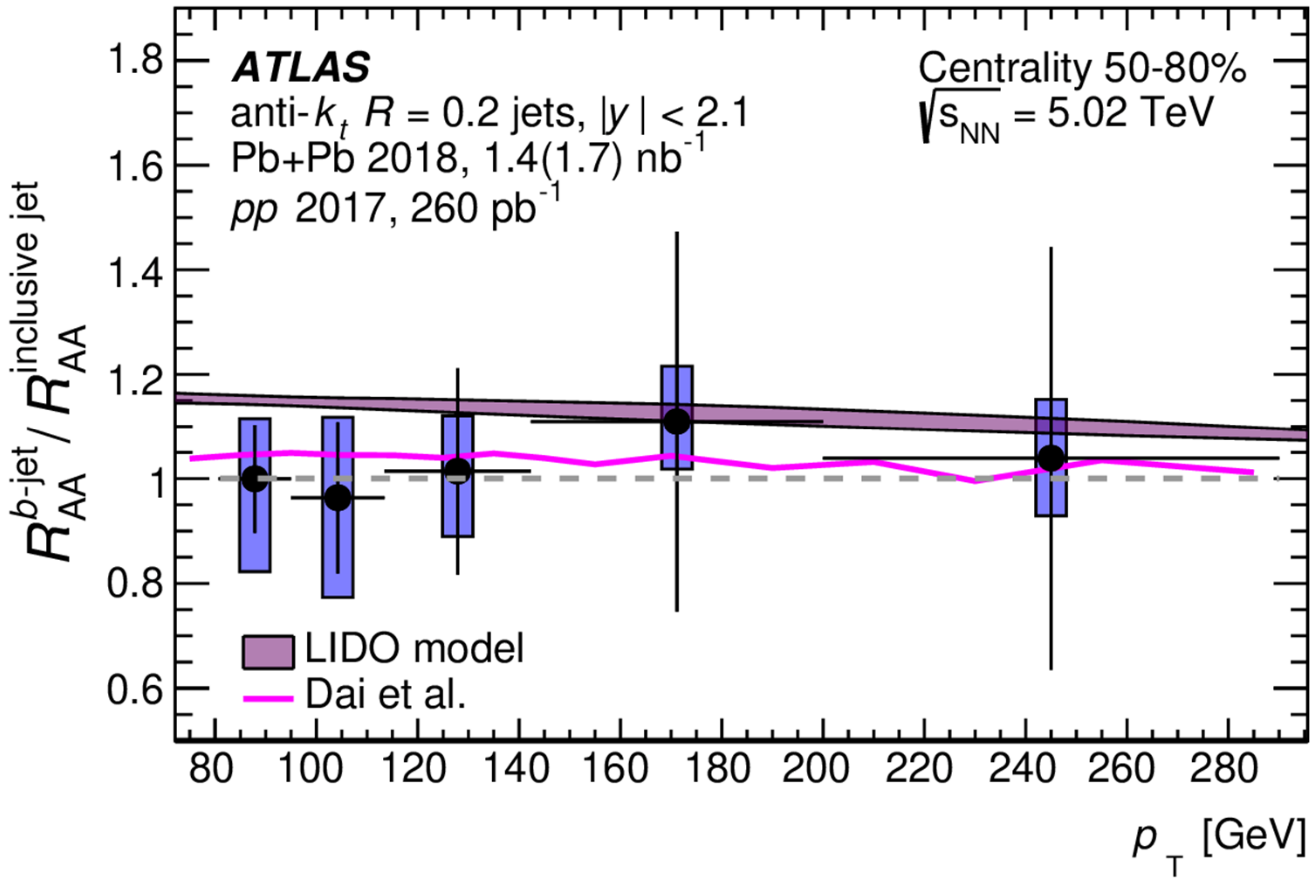


- R_{AA} for b-jets and inclusive jets: 0-20% centrality (left), 50-80% centrality (left)
  - Consistent with unity in peripheral collisions
  - R_{AA} decreases from peripheral to central events
  - R_{AA} larger for *b*-jets: smaller suppression as compared to light jets

- Theory Comparisons
  - LIDO model calculations consistent with data
  - Calculations from Dai et. al. predict smaller R_{AA} (i.e. overpredict suppression)

R_{AA} double-ratios : *b*-jets/inclusive-jets





- Double ratios show that b-jets about 20% less suppressed in central collisions
  - Weak p_T dependence in relative suppression
- LIDO model calculations overpredict double ratios
- Calculations from Dai et. al. more consistent with double ratio
  - Though less consistent with R_{AA}

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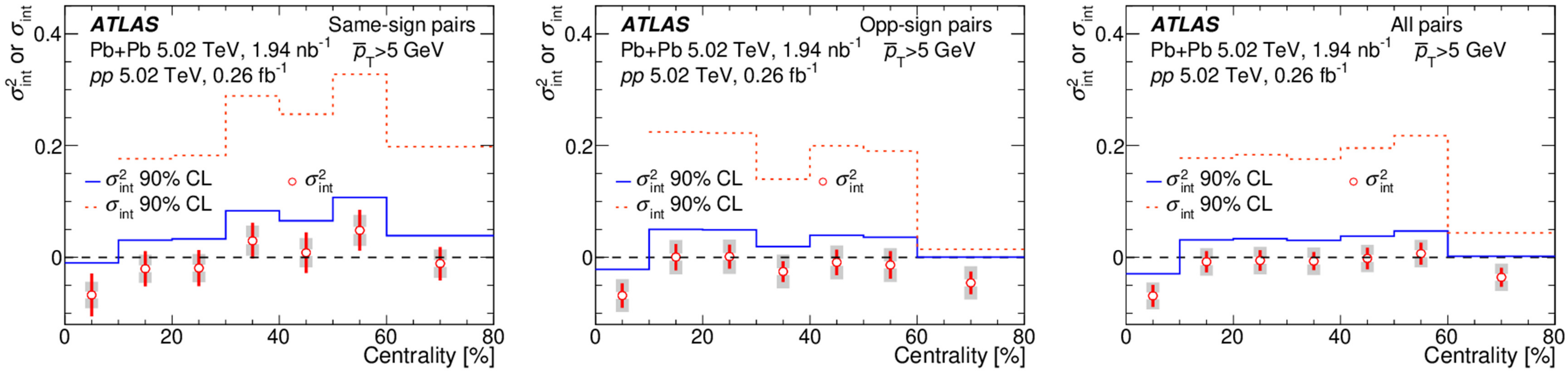
  - Theory comparisons indicate a role for mass and color-charge effects in partonic energy loss
  - More measurements needed to fully disentangle effects

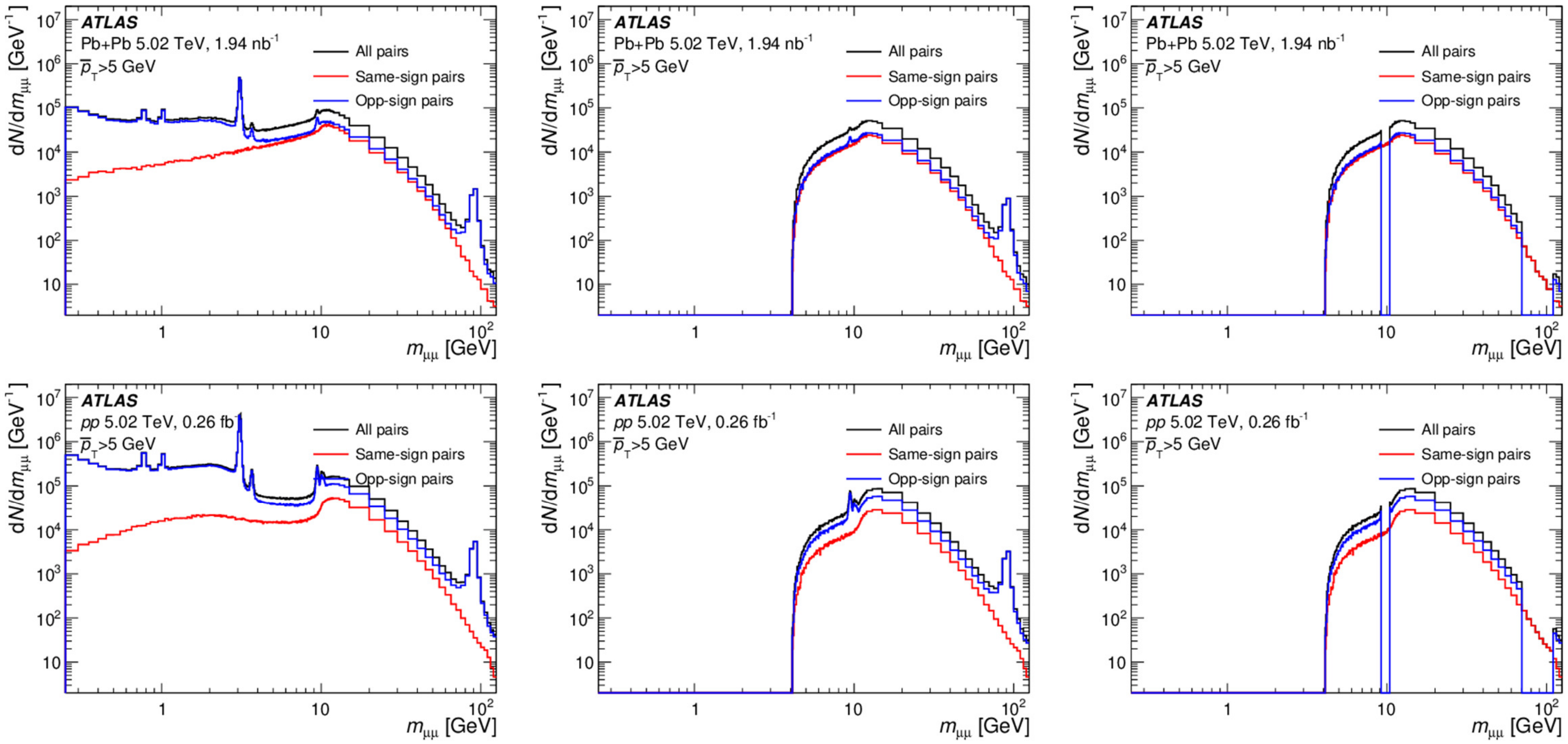
Backup

Quantifying the Pb+Pb vs *pp* width difference



$$\sigma^2_{\mathrm{int}} = \sigma^2_{\mathrm{Pb+Pb}} - \sigma^2_{pp}$$

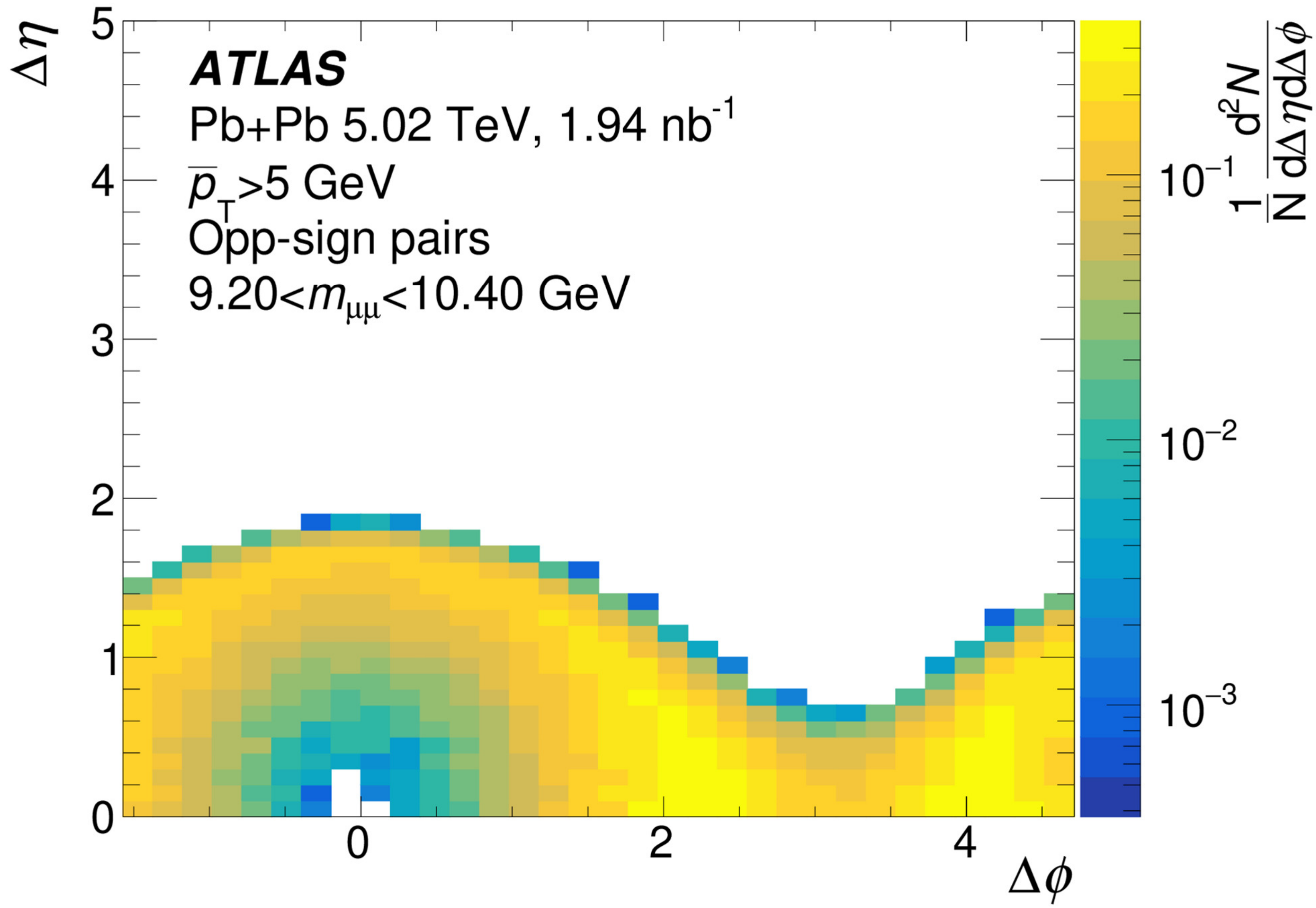
Mass distributions



- Left : Invariant mass ($m_{\mu\mu}$) distributions for muon pairs before applying any selections on Δη or $m_{\mu\mu}$.
- Middle : $m_{\mu\mu}$ distributions after requiring |Δη|>0.8.
- Right : The distributions after further applying cuts on $m_{\mu\mu}$ to the opposite-charge pairs.
- Top and bottom : Pb+Pb and pp, respectively.

Δφ acceptance effects form $m_{\mu\mu}$ requirements

The Δη-Δφ distribution for opposite-sign muon pairs with $9.20<m_{\mu\mu}<10.40$ GeV.



p_T^{rel} Template-Fits

$$\vec{u}_T^{\,\mathrm{jet}+\mu} = \frac{\vec{p}_T^{\,\mu} + \vec{p}_T^{\,\mathrm{jet}}}{\left|\vec{p}_T^{\,\mu} + \vec{p}_T^{\,\mathrm{jet}}\right|}$$

$$p_T^{\mathrm{rel}} = \left|\vec{p}_T^{\,\mu} \times \vec{u}_T^{\,\mathrm{jet}+\mu}\right|$$