Latest measurements of heavy flavor production in heavy-ion collisions with the ATLAS detector

Xinyan Liu 刘新宴
On behalf of the ATLAS Collaborations
Shandong University(Qingdao)

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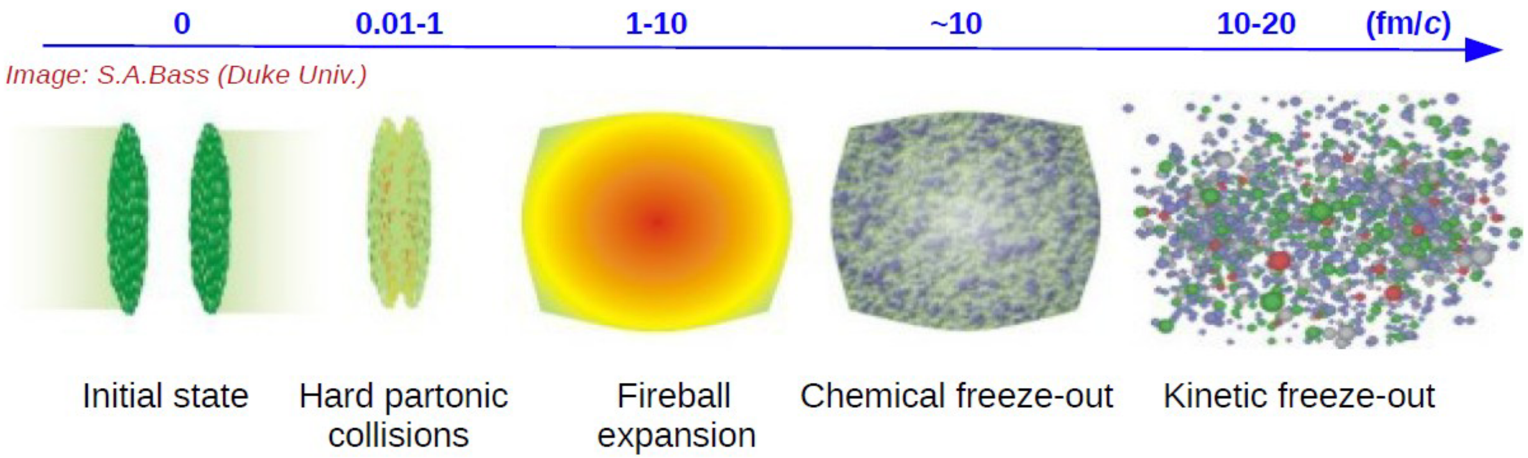
ATLAS EXPERIMENT

山东大学 SHANDONG UNIVERSITY

The Importance of Heavy Flavor

- **Early Production:**
  Heavy quarks are produced in the early stages of high-energy collisions
- **Sensitive to QGP:** Masses much larger than temperature of QGP
  - T_{QGP} ~ 200 – 500 MeV
  - Charm Mass : 1.275 GeV
  - Bottom Mass : 4.18 GeV
- **Hadronization mechanisms in medium :**
  Interaction with medium – coalescence

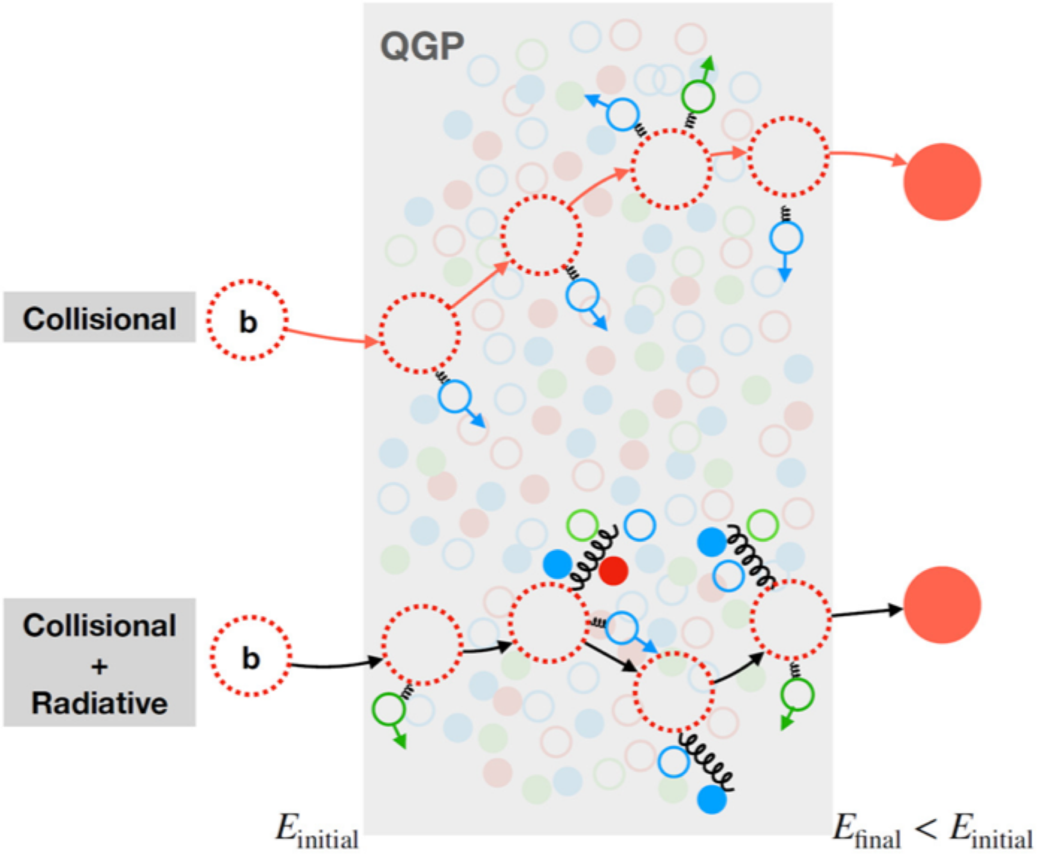


Heavy flavors in heavy ion collisions

- **Energy Loss Mechanisms**:
  Dead-Cone Effect (suppression of radiation emitted at small angles). HF in heavy ion collisions are sensitive probe to the QGP's **density** and **transport properties**.

- HF pair angular correlation have additional sensitivity to **QGP-induced angular deflection**

- Direct observation of bottom/charm hadron-pairs is experimentally difficult. But **measuring lepton-pairs from decays of HF-hadron pairs** is possible



The different energy loss mechanisms of heavy quarks in the QGP.

Ref. Phys. Rev. D **44**, R2625(R)

b-jets in heavy-ion collisions

- **Motivation of b-jet measurement** (compared to inclusive jets):
  - b-jet have different quark/gluon mixture: Color charge known; inclusive jets are mixture of light quarks and gluons
  - Sensitive to the mixture of radiative and collisional energy loss in the QGP
  - Medium-induced gluon radiation expected to be suppressed due to dead-cone effect

- Suppression quantified by the nuclear modification factor R_{AA}
  - Per-event yield of b-jets vs expectation from pp scaled by nuclear thickness function(T_{AA}):

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

- Two latest results of HF measurements with ATLAS will discuss today:
  - Azimuthal correlation between muon-pairs from HF decays (PRL 132 (2024) 202301)
  - Suppression of b-jets (EPJC 83 (2023) 438)

Ref. arXiv: 1903.07709

ATLAS Heavy Ion Data

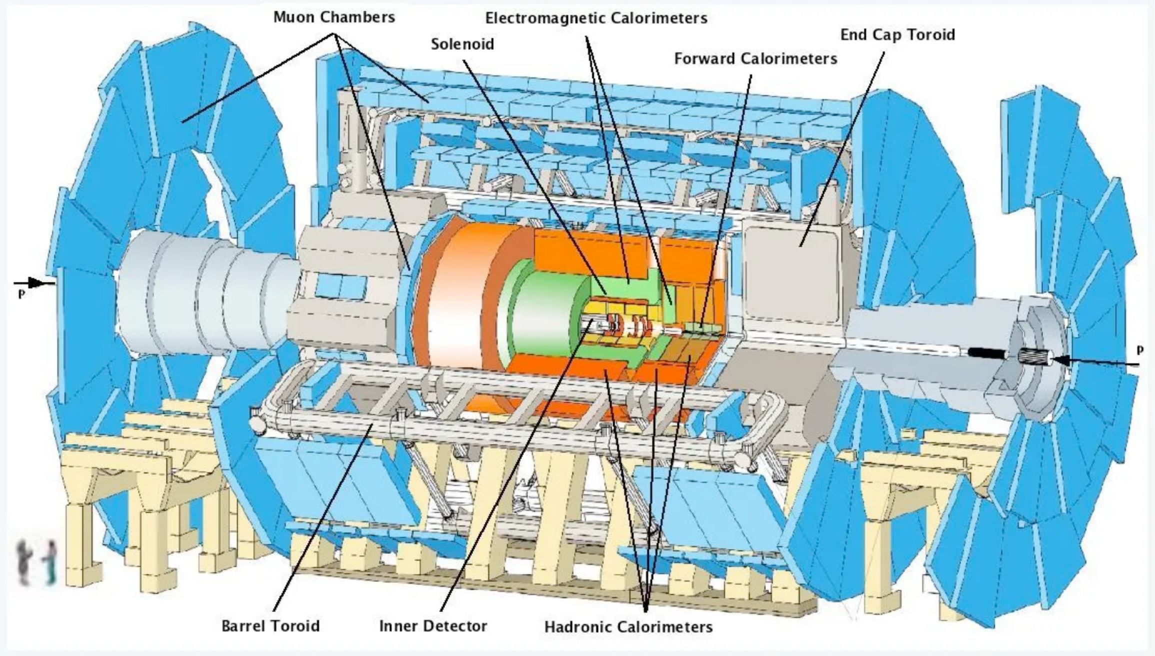
- Summary of heavy-ion collision data collected by ATLAS:

System	Year	$\sqrt{s_{NN}}$ [TeV]	$\mathcal{L}_{int}$
Pb+Pb	2010	2.76	7 μb^{-1}
Pb+Pb	2011	2.76	0.14 nb^{-1}
pp	2013	2.76	4 pb^{-1}
p+Pb	2013	5.02	29 nb^{-1}
pp	2015	5.02	28 pb^{-1}
Pb+Pb	2015	5.02	0.49 nb^{-1}
p+Pb	2016	5.02	0.5 nb^{-1}
p+Pb	2016	8.16	0.16 pb^{-1}
Xe+Xe	2017	5.44	3 μb^{-1}
pp	2017	5.02	270 pb^{-1}
Pb+Pb	2018	5.02	1.76 nb^{-1}
Pb+Pb	2023	5.36	1.71 nb^{-1}
pp	2024	5.36	425 pb^{-1}
Pb+Pb	2024	5.36	1.67 nb^{-1}

Run1

Run2

Run3



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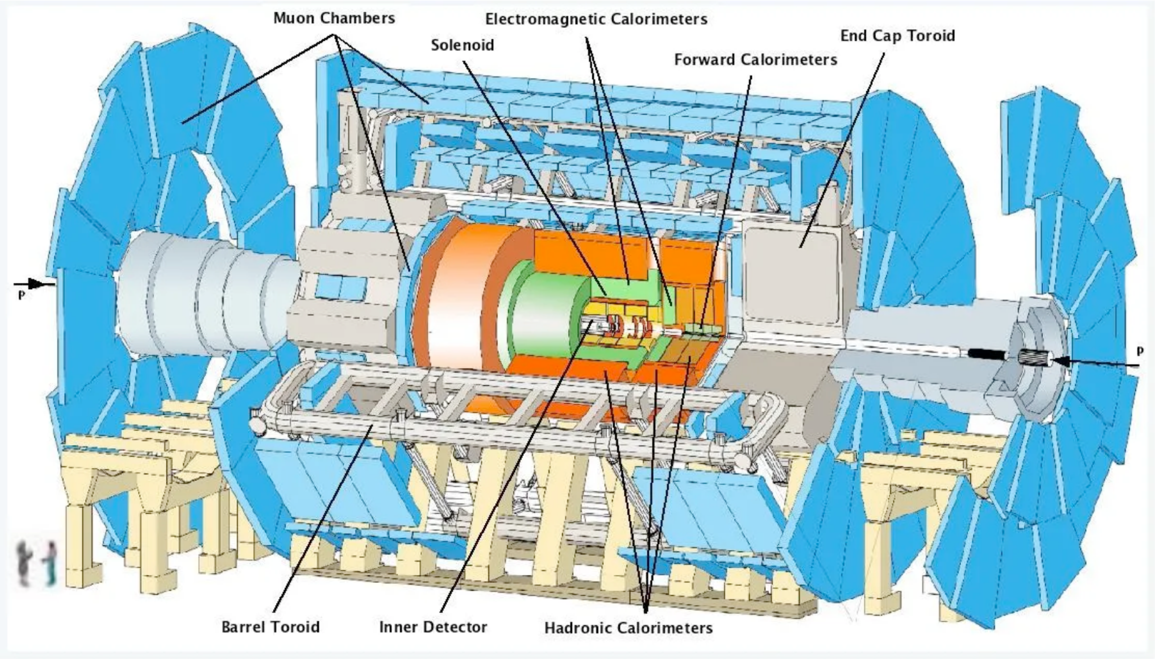


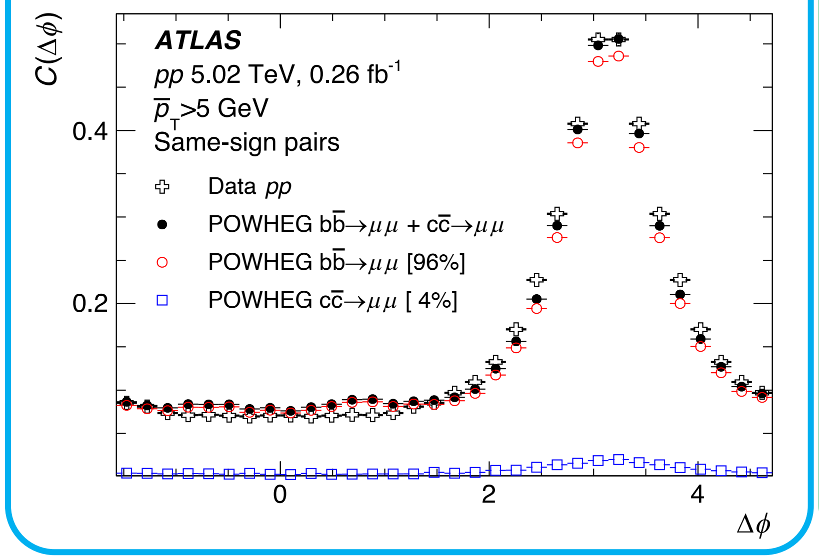
The results presenting today are based on 2017 pp run, 2015 and 2018 Pb+Pb runs

Data-MC comparisons for pp measurements

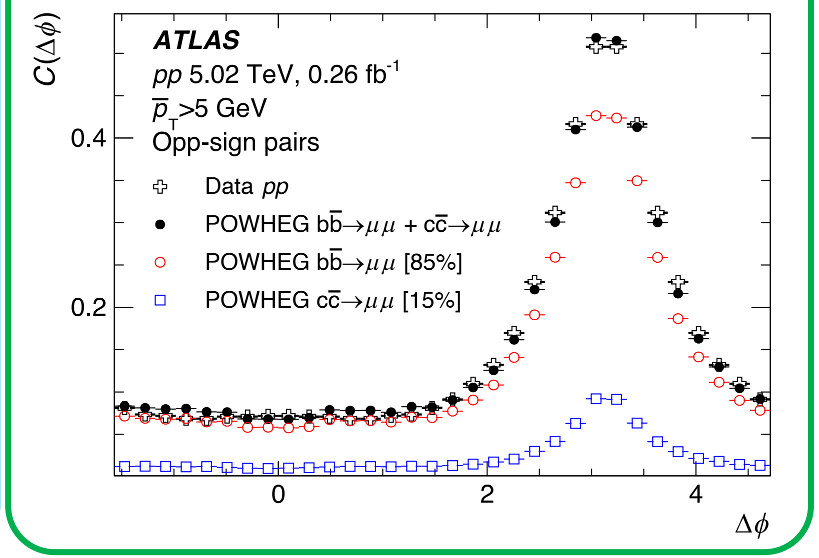
PRL 132 (2024) 202301

- $\Delta\phi = \phi_1 - \phi_2$ distribution for muon pairs in pp collisions:

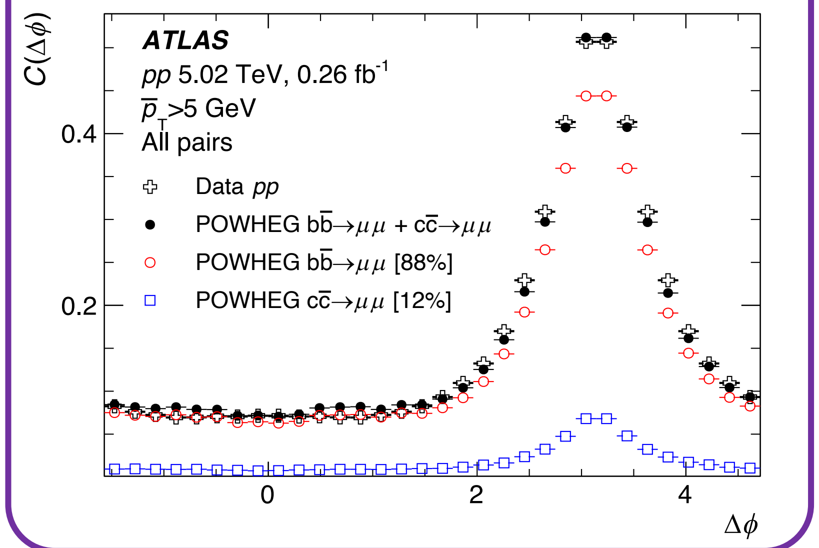
Same-sign



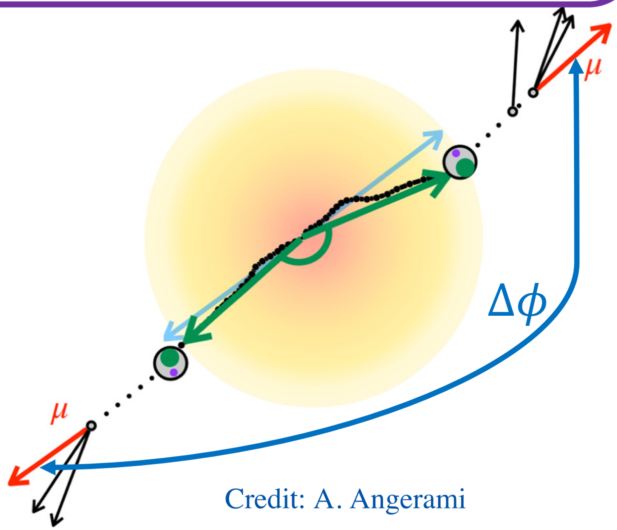
opposite-sign



combination



- pp $\Delta\phi$ correlations of HF production well reproduced by POWHEG
- POWHEG calculations show relative contribution of $b\bar{b}$ and $c\bar{c}$:
  - 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 (15% from $c\bar{c}$ decays)

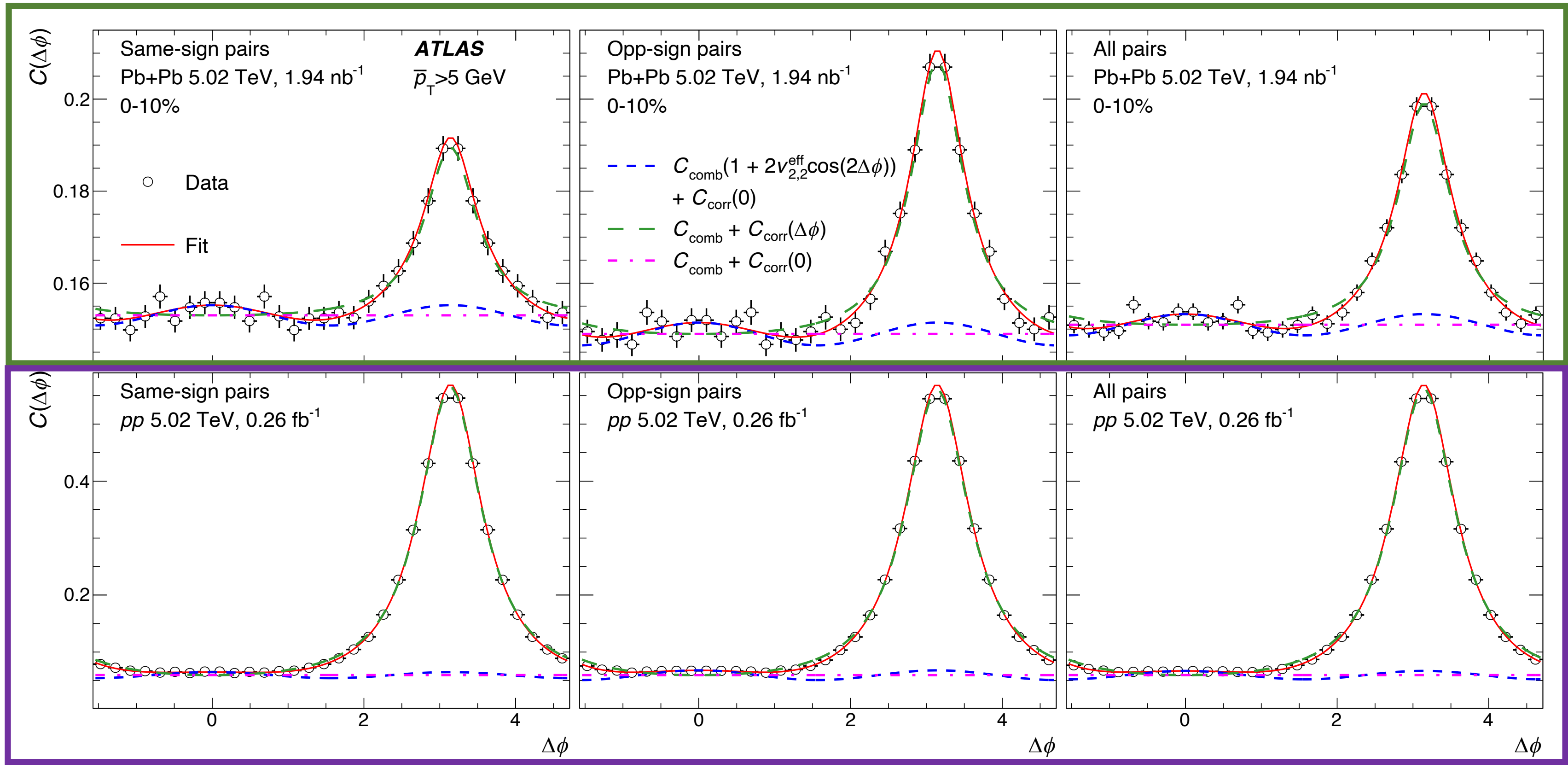


Credit: A. Angerami

Extraction of correlated pairs

PRL 132 (2024) 202301

- Compare (self-normalized) $\Delta\phi$ 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: $C^{Fit}(\Delta\phi) = C_{comb}\left[1 + 2v_{2,2}^{eff}\cos(2\Delta\phi)\right] + C_{coor}(\Delta\phi)$

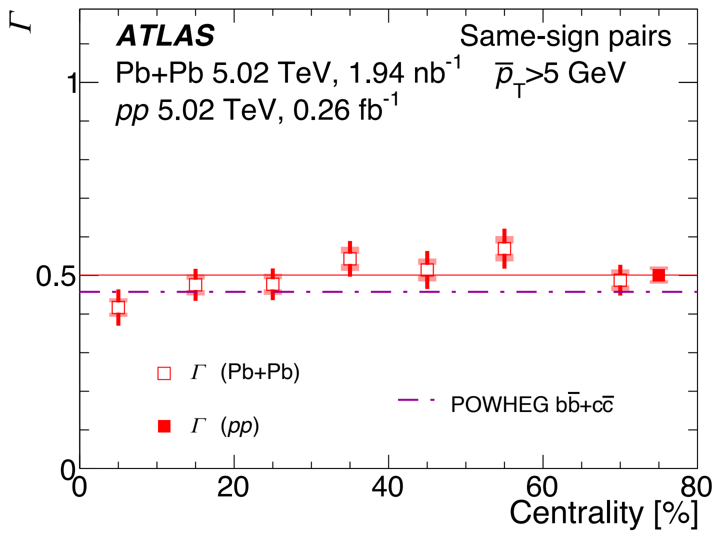
With $C_{coor}(\Delta\phi) = C_{corr}^{max}\Gamma^2/((\Delta\phi-\pi)^2+\Gamma^2)$. The half-width at half-maximum (Γ) quantifies the shape of the correlation. Alternate parameterization: $\sigma \equiv \sqrt{\int(\Delta\phi-\pi)^2\left(C_{coor}(\Delta\phi) - C_{coor}(0)\right)d\Delta\phi}$

Quantifying correlation shape vs centrality

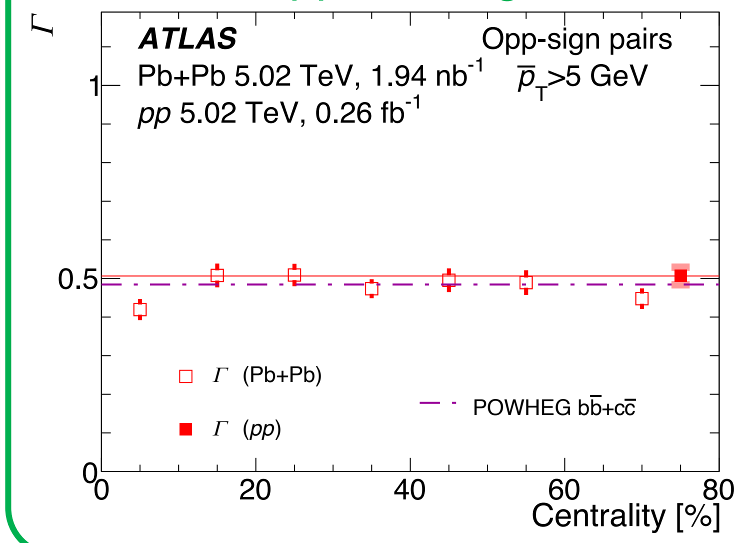
PRL 132 (2024) 202301

- Compare half-width at half-maximum (Γ) as a function of centrality:

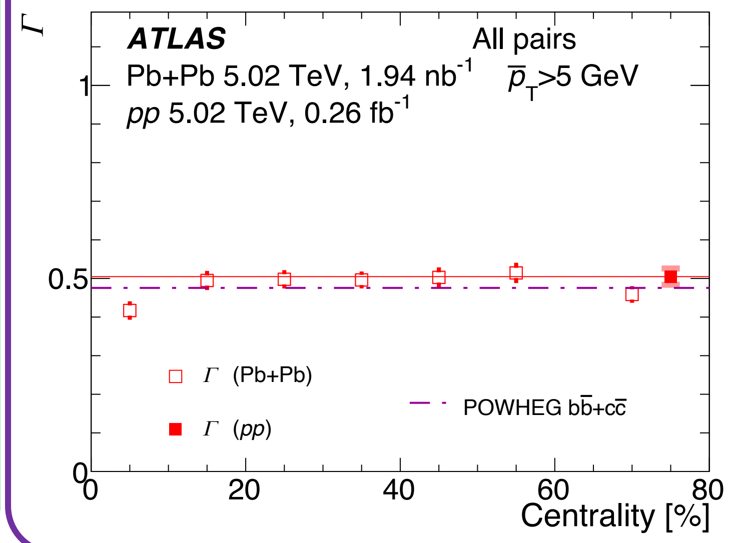
Same-sign



opposite-sign



combination



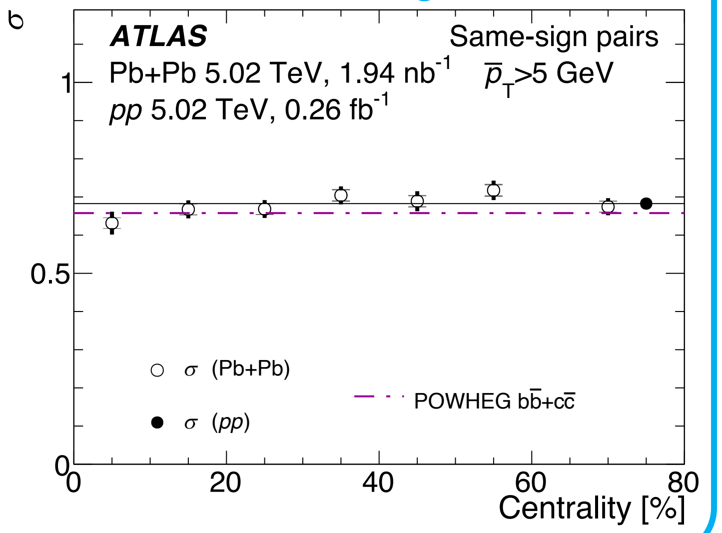
- Measurements consistent with “no centrality dependence”
- Pb+Pb and pp values consistent.
- Widths identical for “same-sign” and “opp-sign” pairs
- No indication of any centrality dependent broadening for $\bar{p}_T > 5GeV$!

Quantifying correlation shape vs centrality

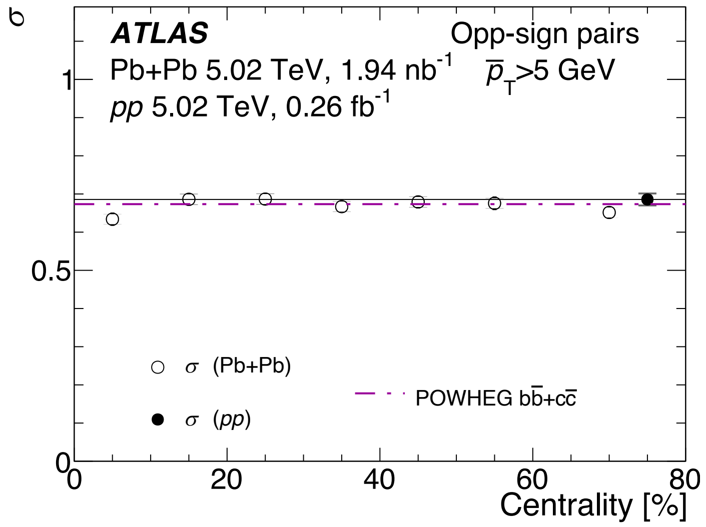
PRL 132 (2024) 202301

- Compare widths (σ) as a function of centrality:

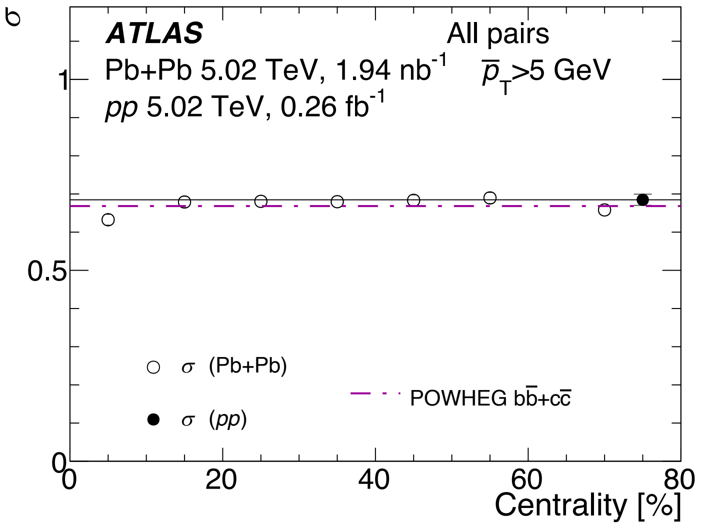
Same-sign



opposite-sign



combination



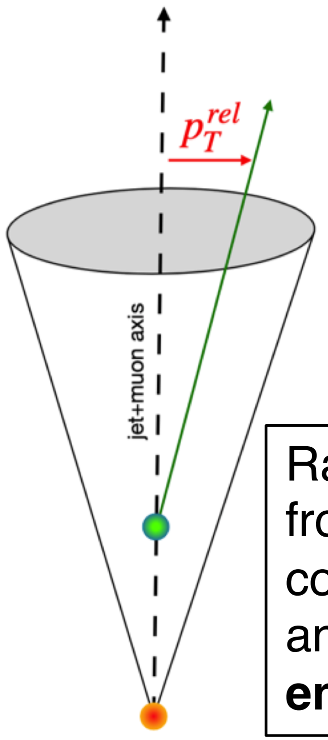
- Same features observed for standard-deviation σ
- See strong $b \rightarrow \mu$ suppression (single b and for pairs)
- No significant angular deflection in $\Delta\phi$ correlation, indicating that the scattering effect of heavy-flavor particles in the QGP is minimal.

b-jets via muons in heavy-ion collisions

EPJC 83 (2023) 438

***b*-fraction estimated using template fit method on muon p_T-rel distribution**

$$p_T^{rel} = ||\vec{p}_\mu \times \vec{u}||, \textit{ where } \vec{u} = \frac{\vec{p}_{jet+\mu}}{||\vec{p}_{jet+\mu}||} \textit{ is the jet} + \mu \textit{ axis}$$

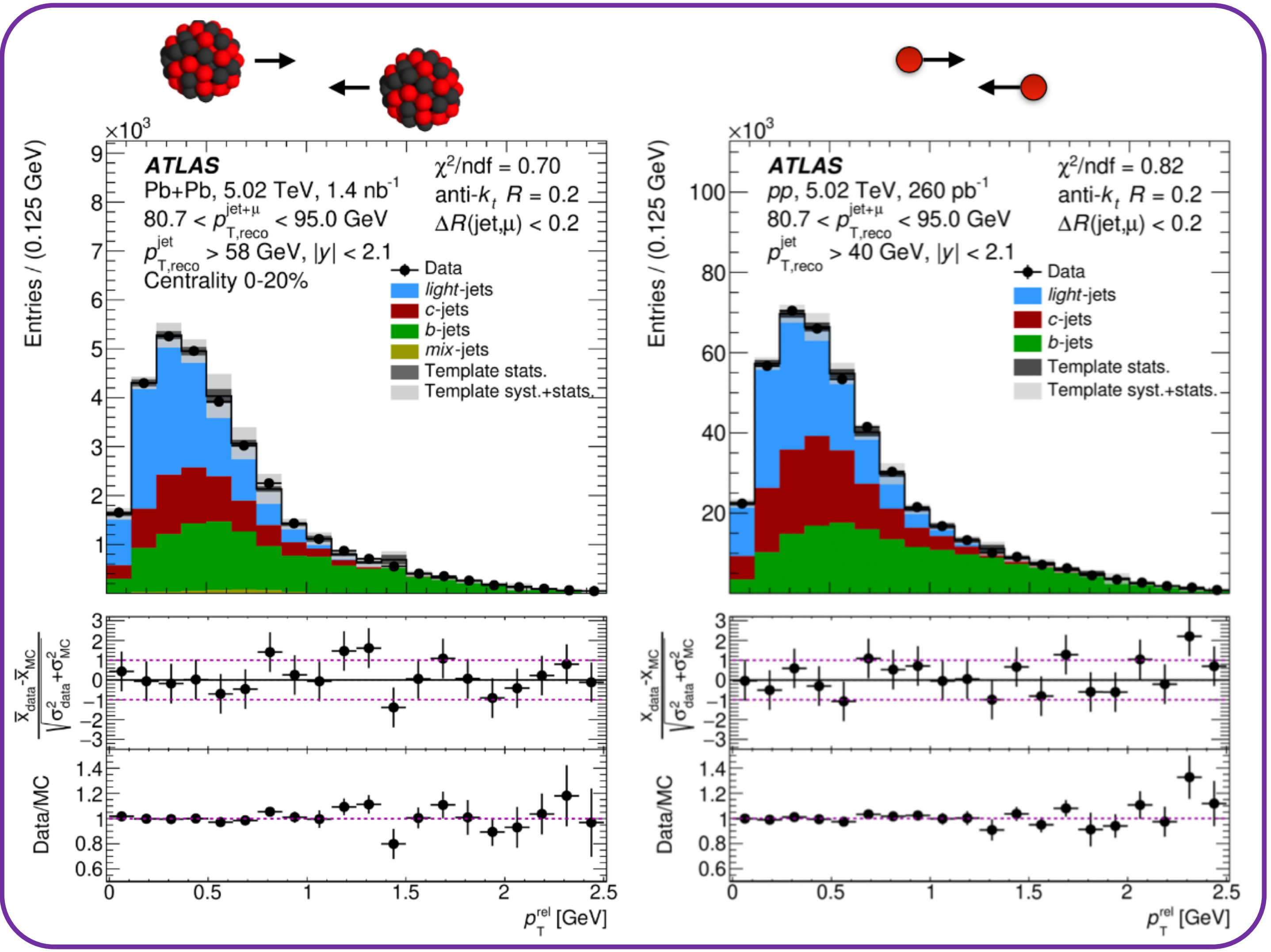


Muon selection:

- Muon p_T > 4 GeV
- ΔR(jet,muon) < R

Raw b-jet spectra obtained from fit is **unfolded** to correct for detector effects and **missing neutrino energy**

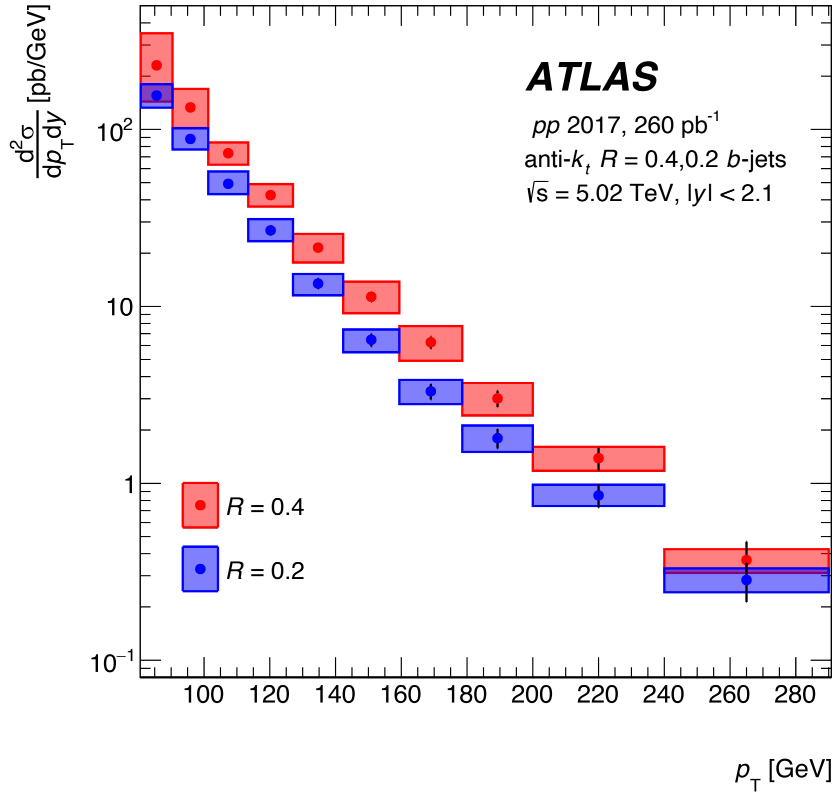
Raw spectrum (before unfolding)



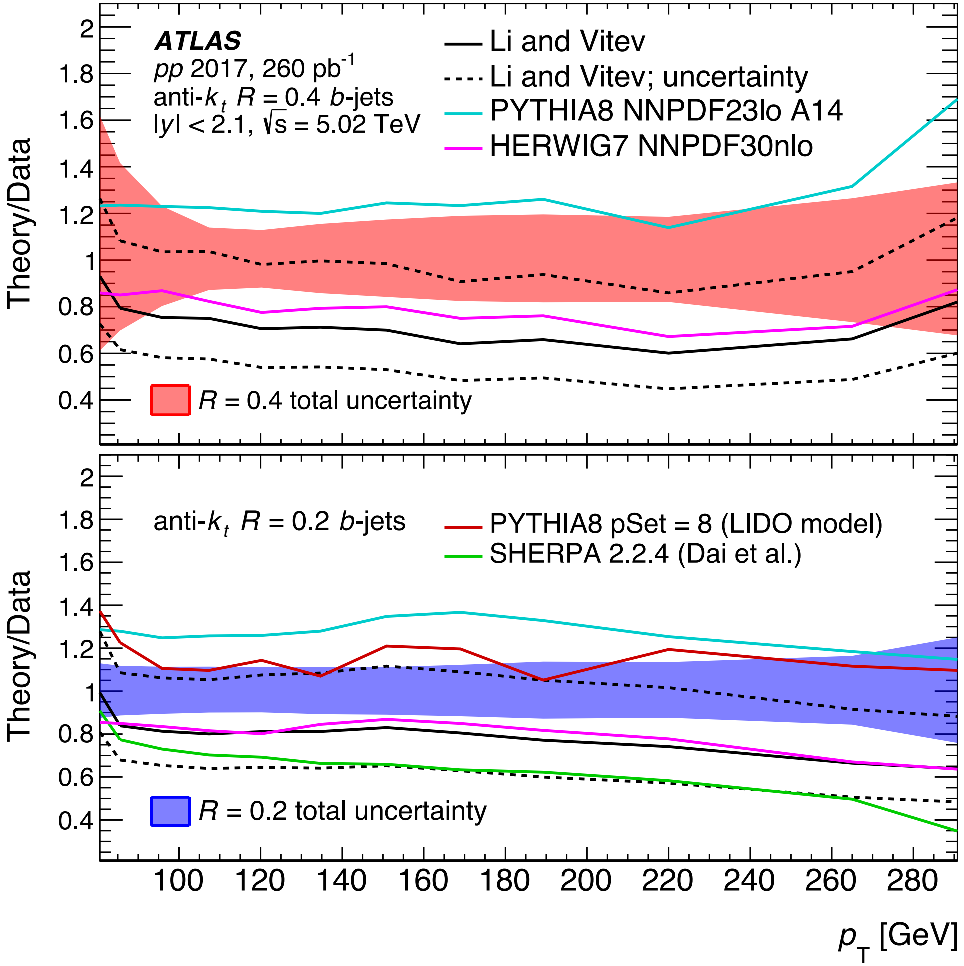
Differential cross-section for b-jet production

EPJC 83 (2023) 438

- Cross-sections for R=0.2 and R=0.4 b-jets with |y|<2.1 in 5.02 TeV pp data:



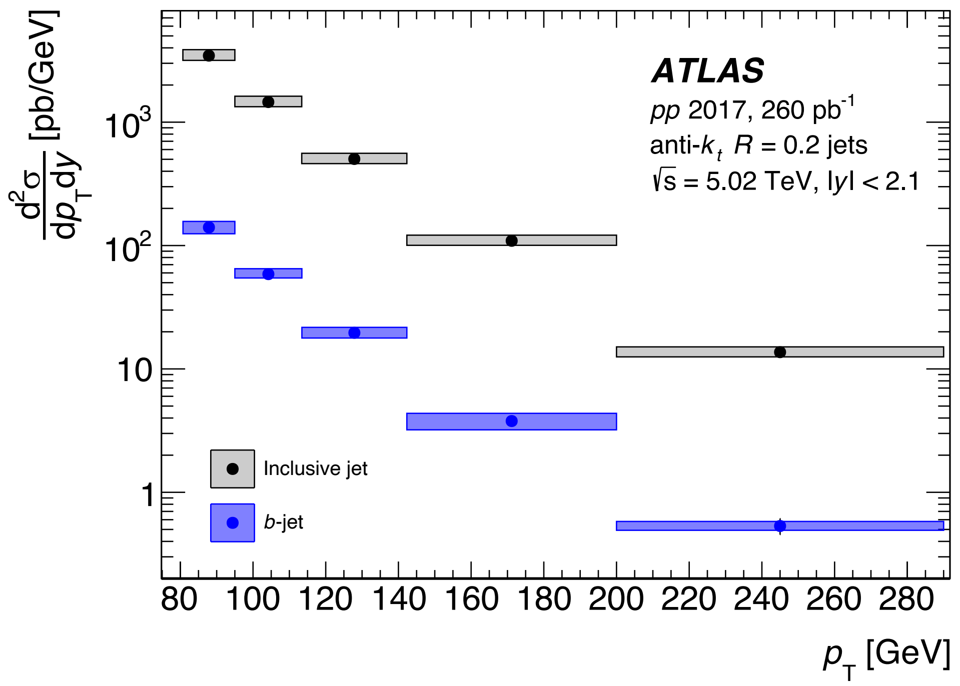
- Ratio of the predictions to the measured b-jet cross-section:



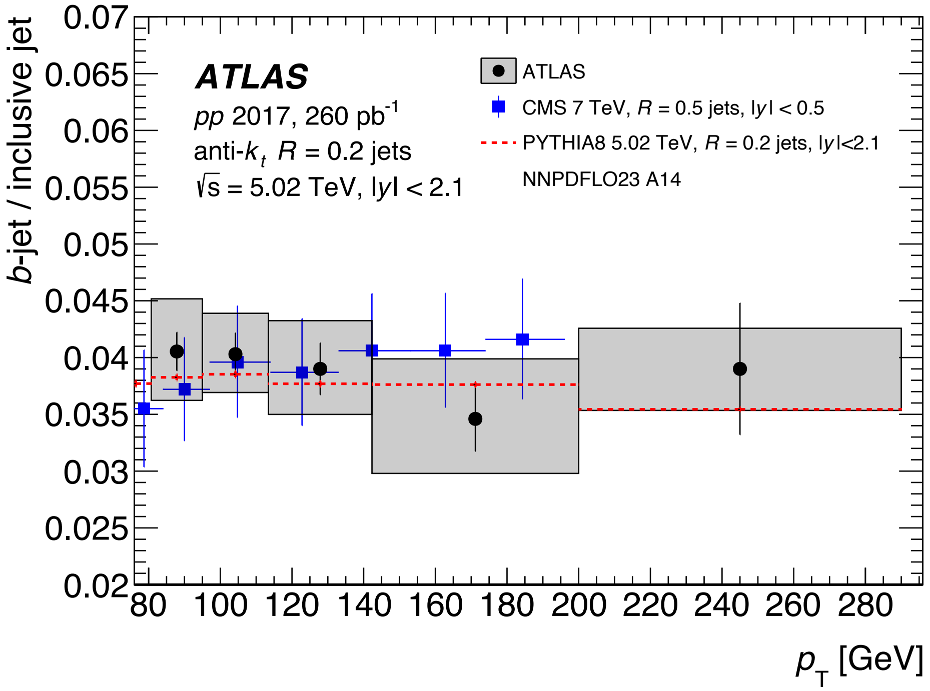
- Both cross-sections are compared with Pythia8 and Herwig calculations (consistent with data within 20% or better)
- The bands around unity represent the total uncertainty of the data

Comparison of b-jet and inclusive jet cross-sections EPJC 83 (2023) 438

- Cross-section of R=0.2 b-jet and inclusive jet production in pp collisions at 5.02 TeV:



- The b-jet to inclusive jet cross-section ratio:

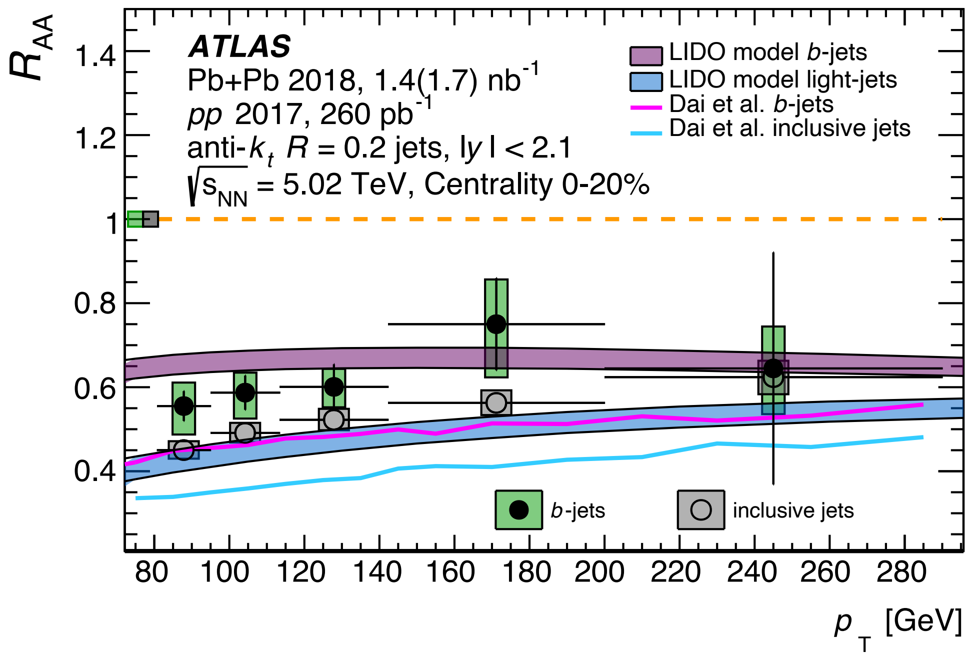


- b-jets around 4% of the inclusive jet yield, independent of p_T from 80-280 GeV → Important for R_{AA} interpretation
- Measurement consistent with previous measurements from CMS @ 7 TeV and PYTHIA8

b-jet vs inclusive-jet R_{AA} difference

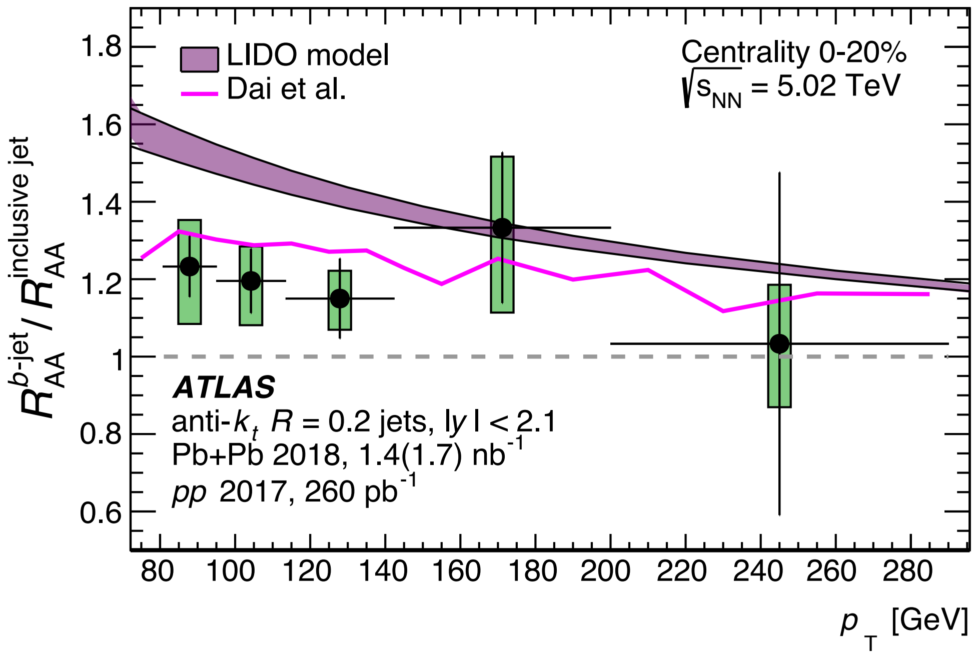
EPJC 83 (2023) 438

- b-jet R_{AA} for 0-20% centrality class compared with the inclusive jet R_{AA} :



- R_{AA} larger for b-jets ⟹ smaller suppression as compared to light jets
- LIDO model calculations consistent with data

- Ratio of b-jet R_{AA} to the inclusive jet R_{AA} for 0-20% centrality class:

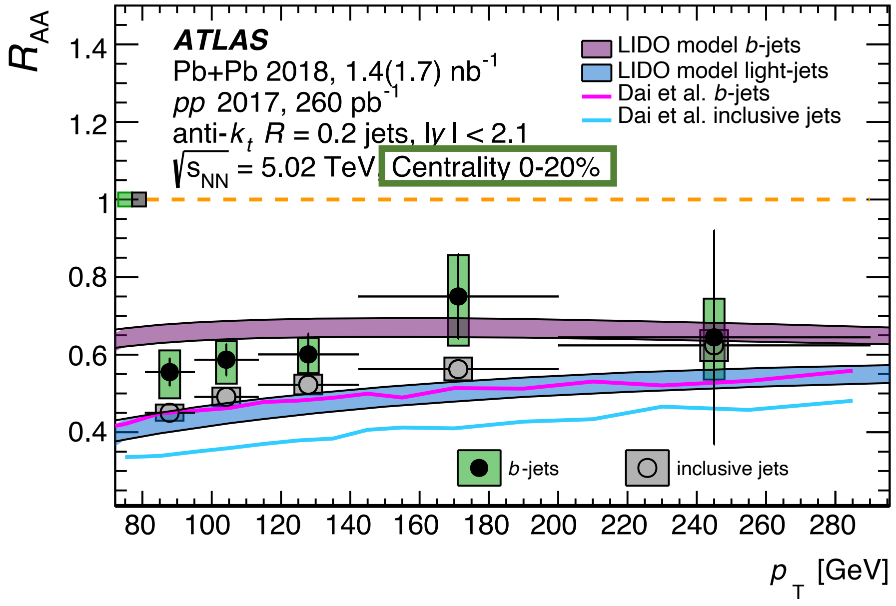


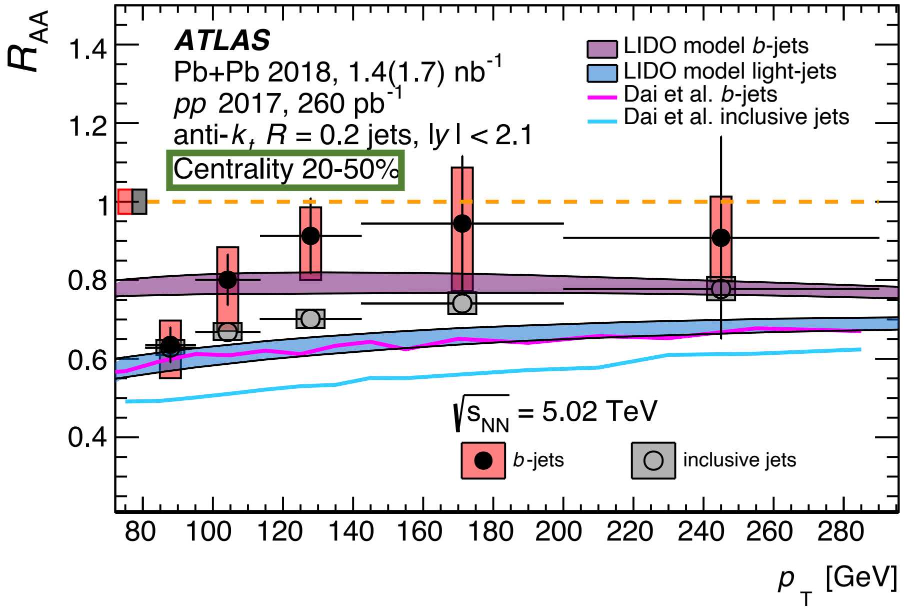
- b-jets about 20% less suppressed (Weak p_T dependence in relative suppression)
- LIDO model calculations overpredict double ratios
- Calculations from Dai et. al. more consistent with double ratio (Though less consistent with R_{AA})

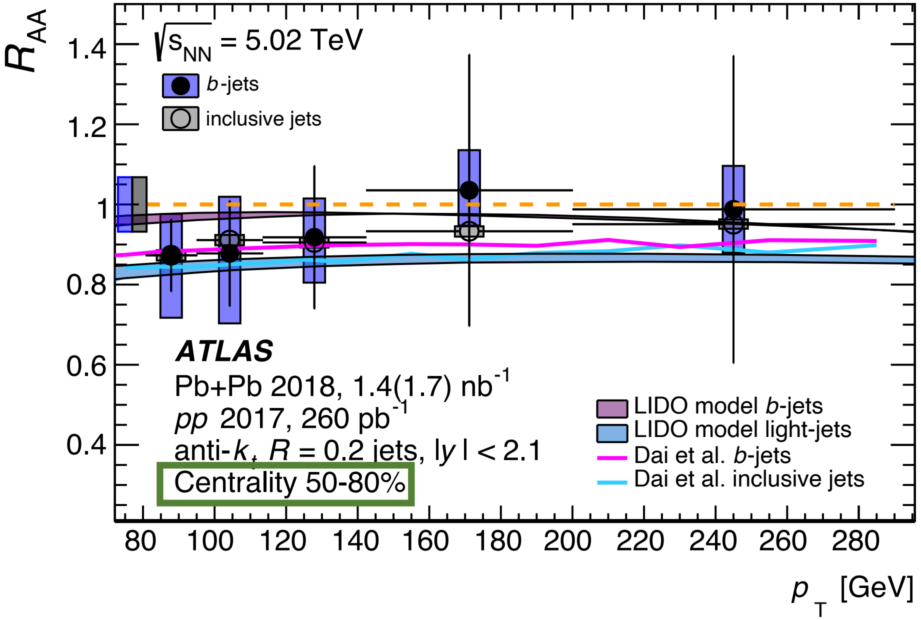
b-jet vs inclusive-jet R_{AA} difference

EPJC 83 (2023) 438

- Comparison of R_{AA} at 0-20%, 20-50% and 50-80% centrality:







- Consistent with unity in peripheral collisions
- R_{AA} decreases from peripheral to central events

Summary

- Azimuthal correlation between muon-pairs from HF decays (PRL 132 (2024) 202301)
  - Probe of heavy flavor interaction with the QGP
  - Dimuons provide access to back-to-back heavy quark pairs
  - No indication of any centrality dependent broadening for $\bar{p}_T > 5GeV$!
  - Provide constraints on stochastic deflection of bottom quarks in the QGP

- Suppression of b-jets (EPJC 83 (2023) 438)
  - Provide a direct way to compare b-jets to inclusive jets
  - R_{AA} for b-jets larger than for inclusive-jets in central Pb+Pb collisions $\Longrightarrow$ b-jets less suppressed
  - Significant improvements are expected with the ongoing Run 3 luminosity increase!

- For more ATLAS heavy ion results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

THANKS FOR YOUR ATTENTION

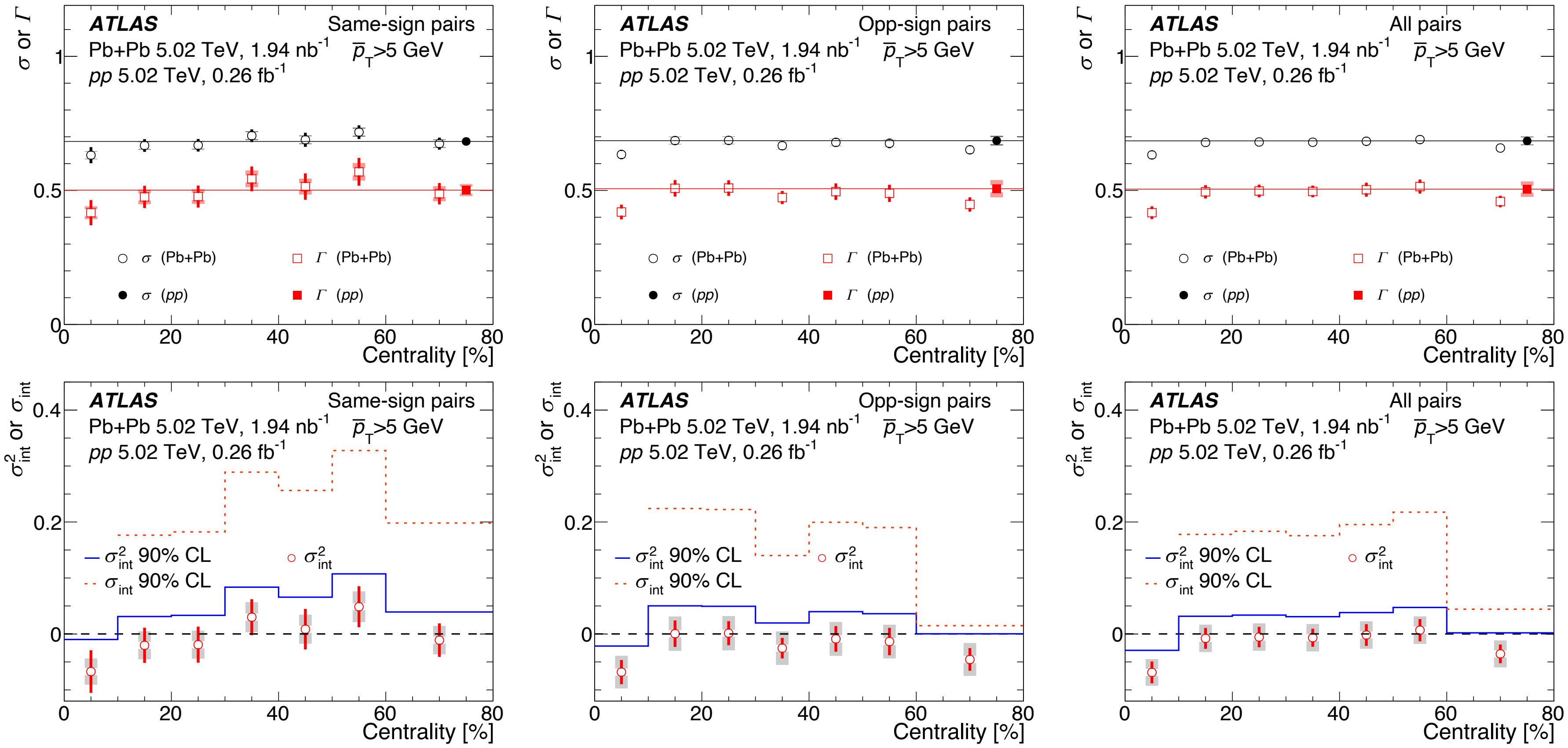
Backup

Final Results

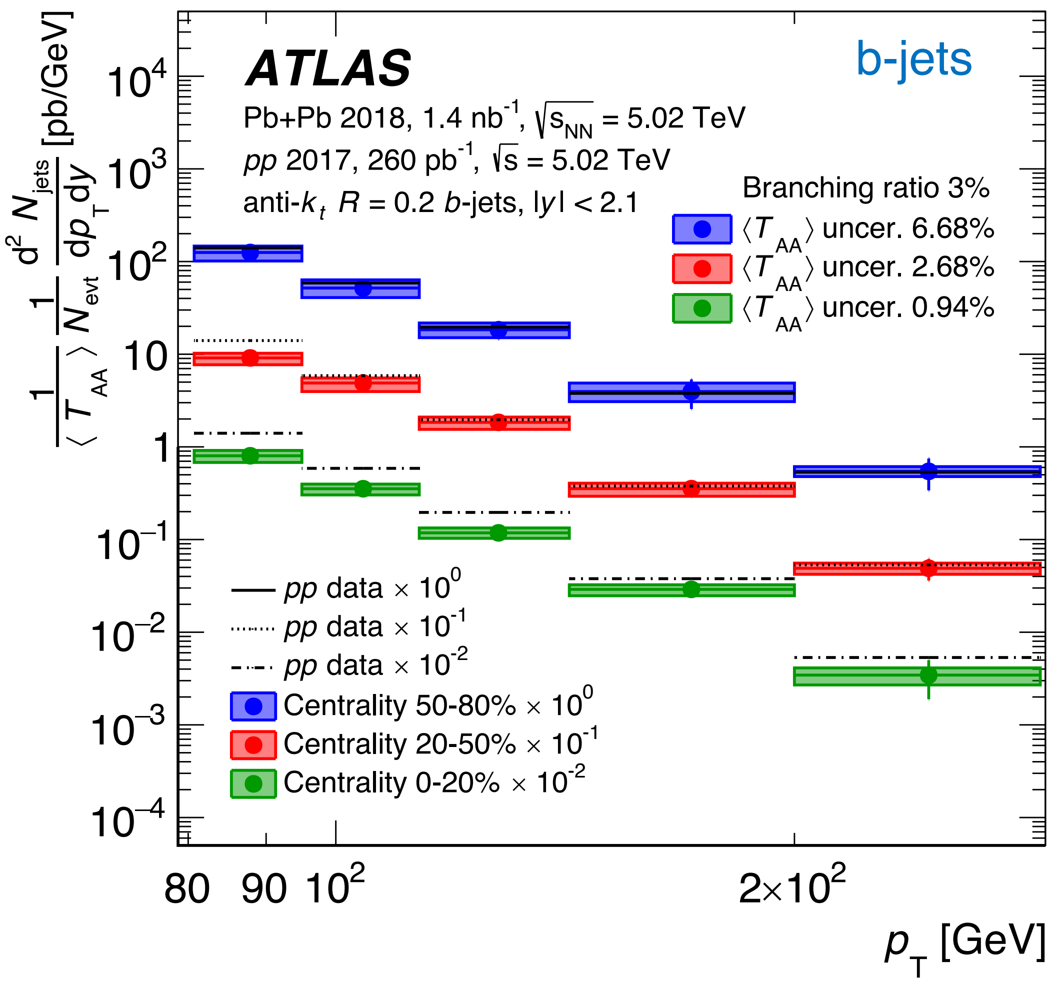
PRL 132 (2024) 202301

- Difference of Widths between Pb+Pb and pp
- Measure of smearing from QGP interactions

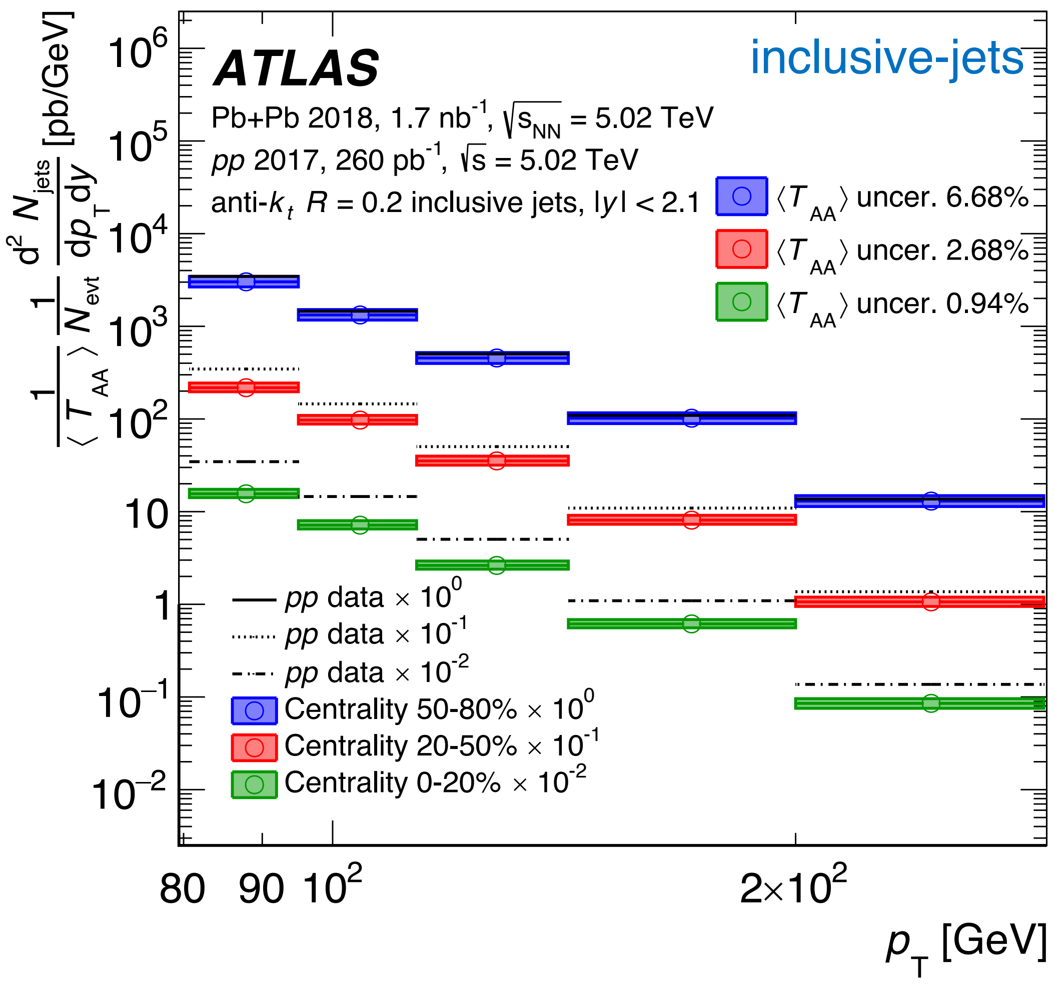
$$\sigma^2_{int} = \sigma^2_{Pb+Pb} - \sigma^2_{pp}$$



- both sign combinations dominated by b-bbar pairs according to PYTHIA but c-cbar only contributes to opposite sign pairs



ATLAS
b-jets
Pb+Pb 2018, 1.4 nb^{-1}, $\sqrt{s_{NN}}$ = 5.02 TeV
pp 2017, 260 pb^{-1}, $\sqrt{s}$ = 5.02 TeV
anti-k_t R = 0.2 b-jets, |y| < 2.1
Branching ratio 3%
⟨T_{AA}⟩ uncer. 6.68%
⟨T_{AA}⟩ uncer. 2.68%
⟨T_{AA}⟩ uncer. 0.94%
pp data × 10^0
pp data × 10^{-1}
pp data × 10^{-2}
Centrality 50-80% × 10^0
Centrality 20-50% × 10^{-1}
Centrality 0-20% × 10^{-2}
$\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{d^2N_{jets}}{dp_T dy}$ [pb/GeV]
p_T [GeV]



ATLAS
inclusive-jets
Pb+Pb 2018, 1.7 nb^{-1}, $\sqrt{s_{NN}}$ = 5.02 TeV
pp 2017, 260 pb^{-1}, $\sqrt{s}$ = 5.02 TeV
anti-k_t R = 0.2 inclusive jets, |y| < 2.1
⟨T_{AA}⟩ uncer. 6.68%
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pp data × 10^0
pp data × 10^{-1}
pp data × 10^{-2}
Centrality 50-80% × 10^0
Centrality 20-50% × 10^{-1}
Centrality 0-20% × 10^{-2}
$\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{d^2N_{jets}}{dp_T dy}$ [pb/GeV]
p_T [GeV]

b-jet vs inclusive-jet R_{AA} difference

EPJC 83 (2023) 438

- Ratio of b-jet R_{AA} to the inclusive jet R_{AA} for 0-20%, 20-50% and 50-80% centrality :