Measurements of heavy-flavor Quark probes of the QGP with the ATLAS detector

Qipeng Hu (LLNL) for the ATLAS Collaboration

Quark Matter 2022

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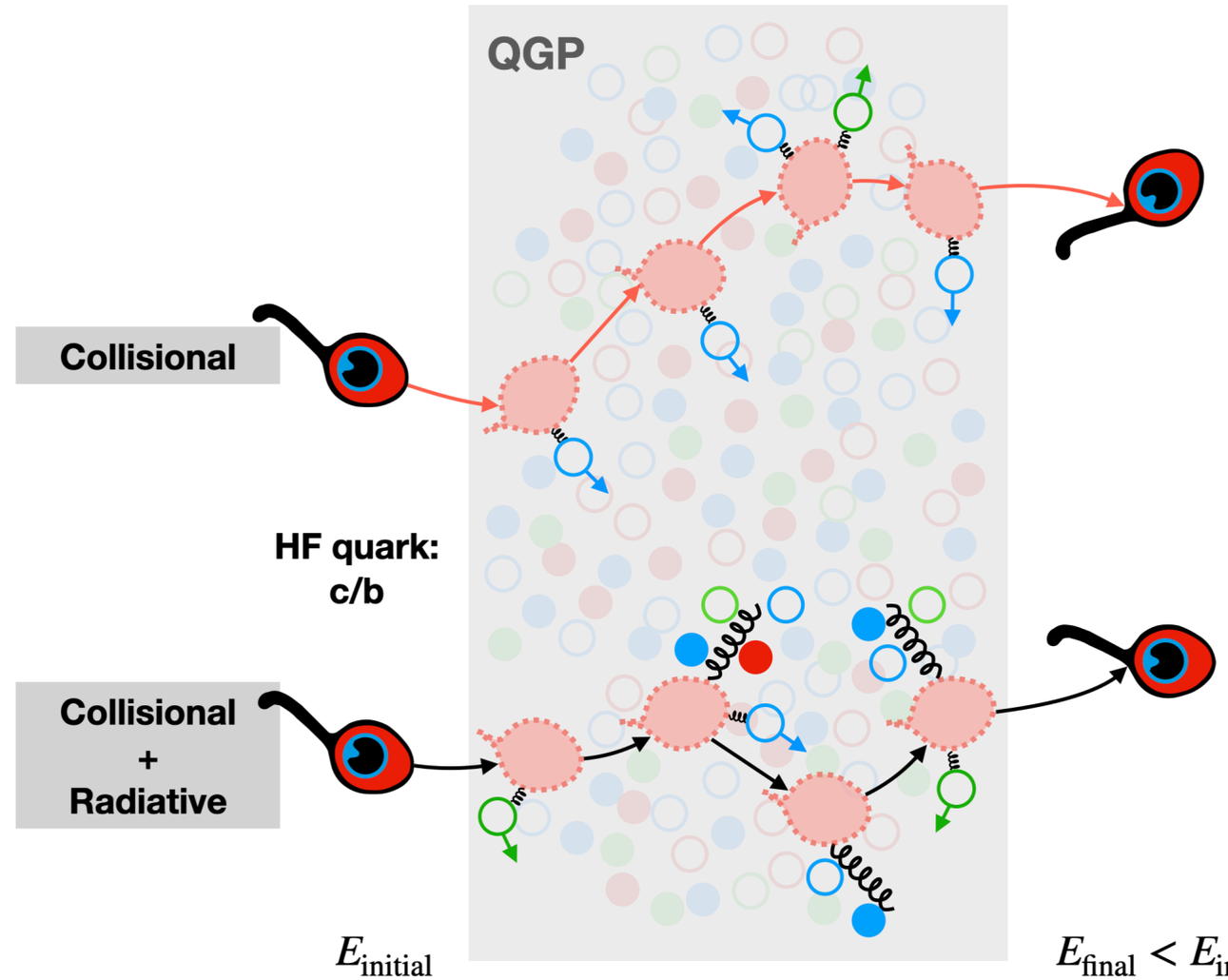
Heavy flavors in heavy ion collisions

- Open heavy flavors (HF) quarks — ***c, b*** — are *produced early* in the collision; *masses above QGP temperature*
- HF in heavy ion collisions are sensitive probe to **energy loss mechanisms** and QGP transport property
- HF pair angular correlation have additional sensitivity to QGP-induced angular deflection

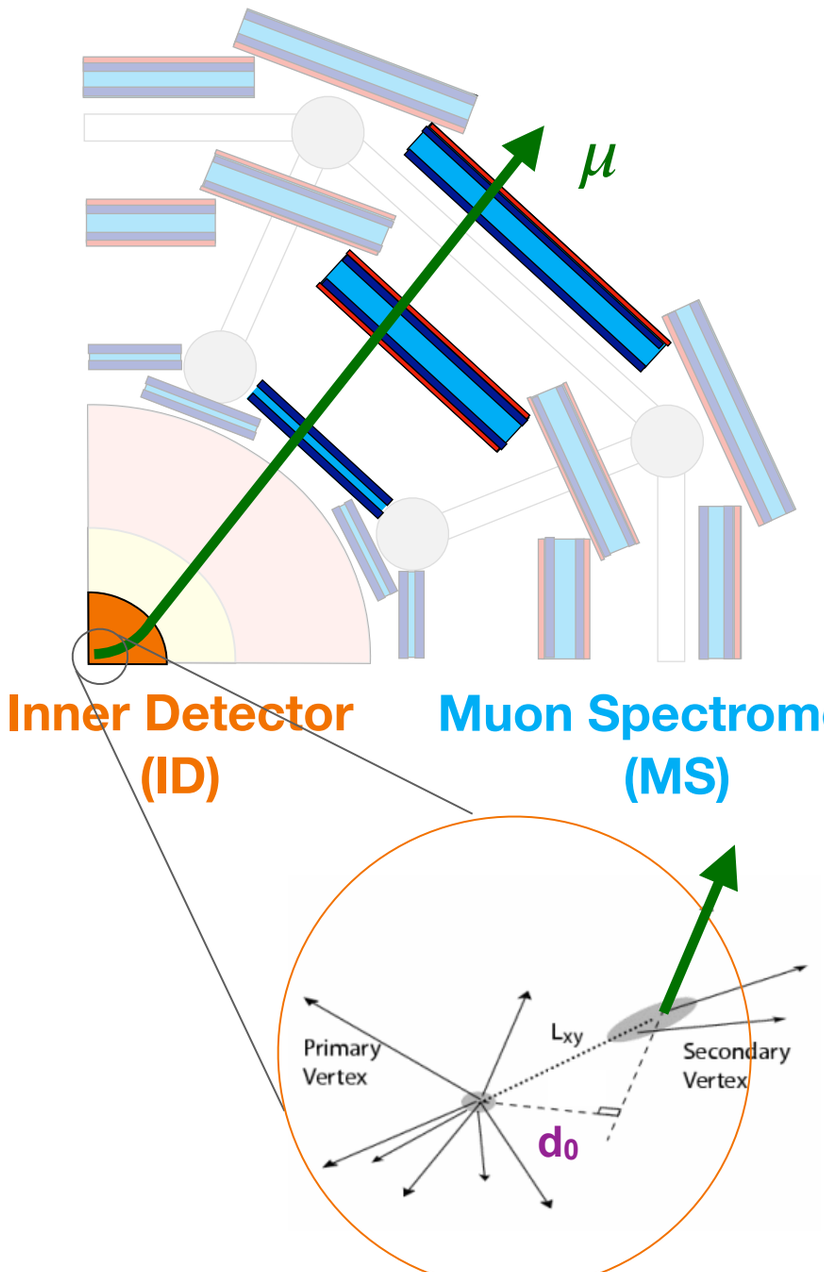


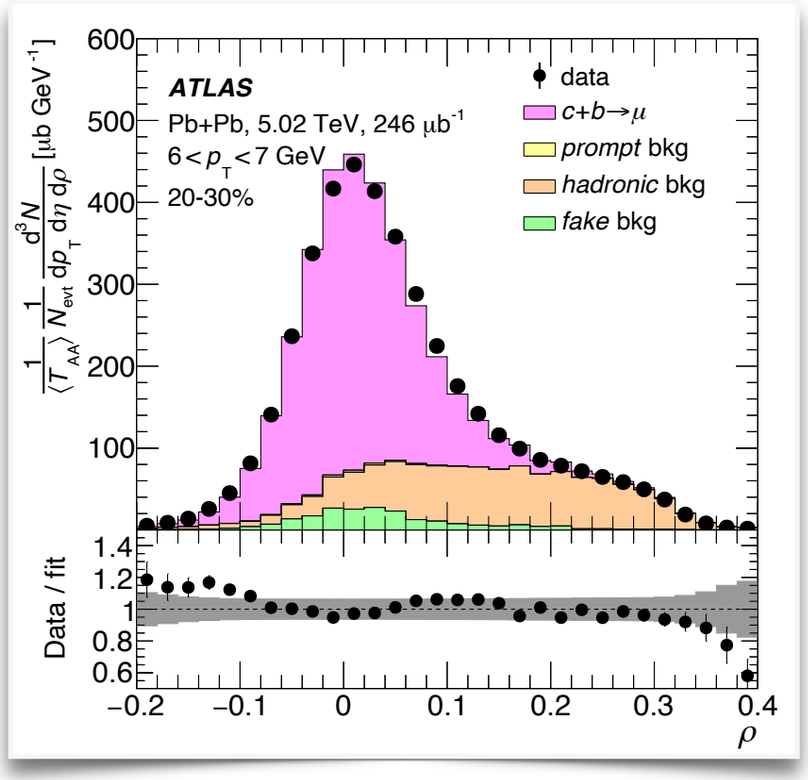
Weakly interaction picture

ATLAS HF muon programs

arXiv:2109.00411

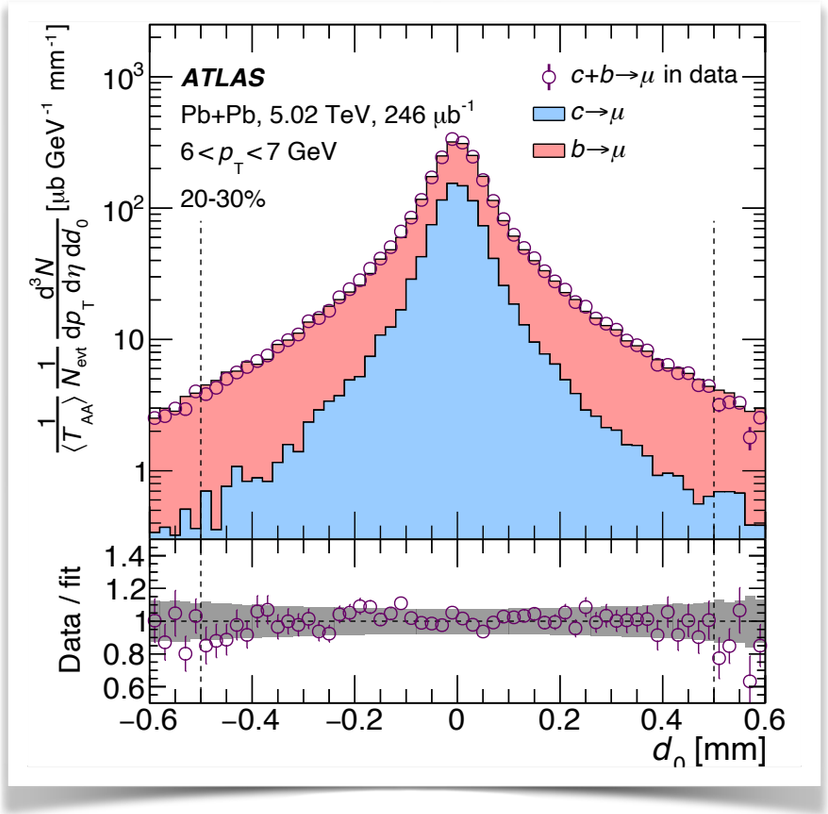
ATLAS HF program focuses on semi-leptonic decay to **muons**





Background removed using **ID-MS** momentum difference:

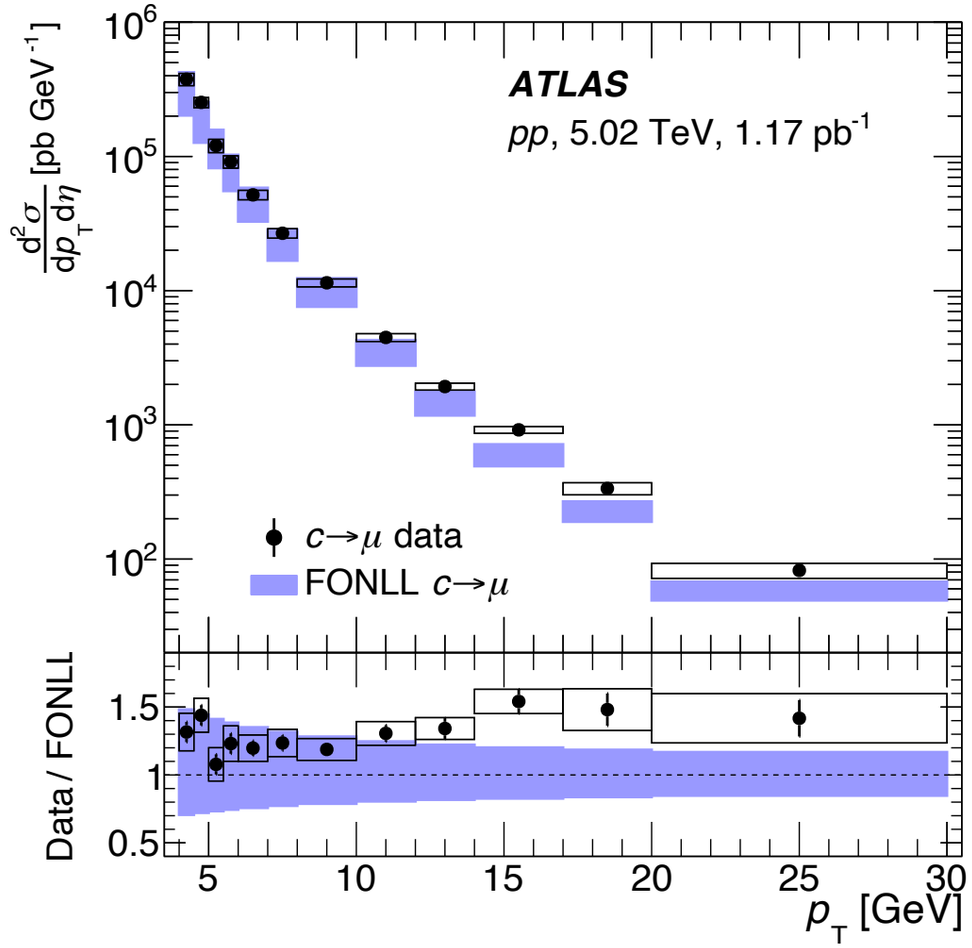
$$\rho = (p_{\mathrm{T}}^{\mathrm{ID}} - p_{\mathrm{T}}^{\mathrm{MS}})/p_{\mathrm{T}}^{\mathrm{ID}}$$



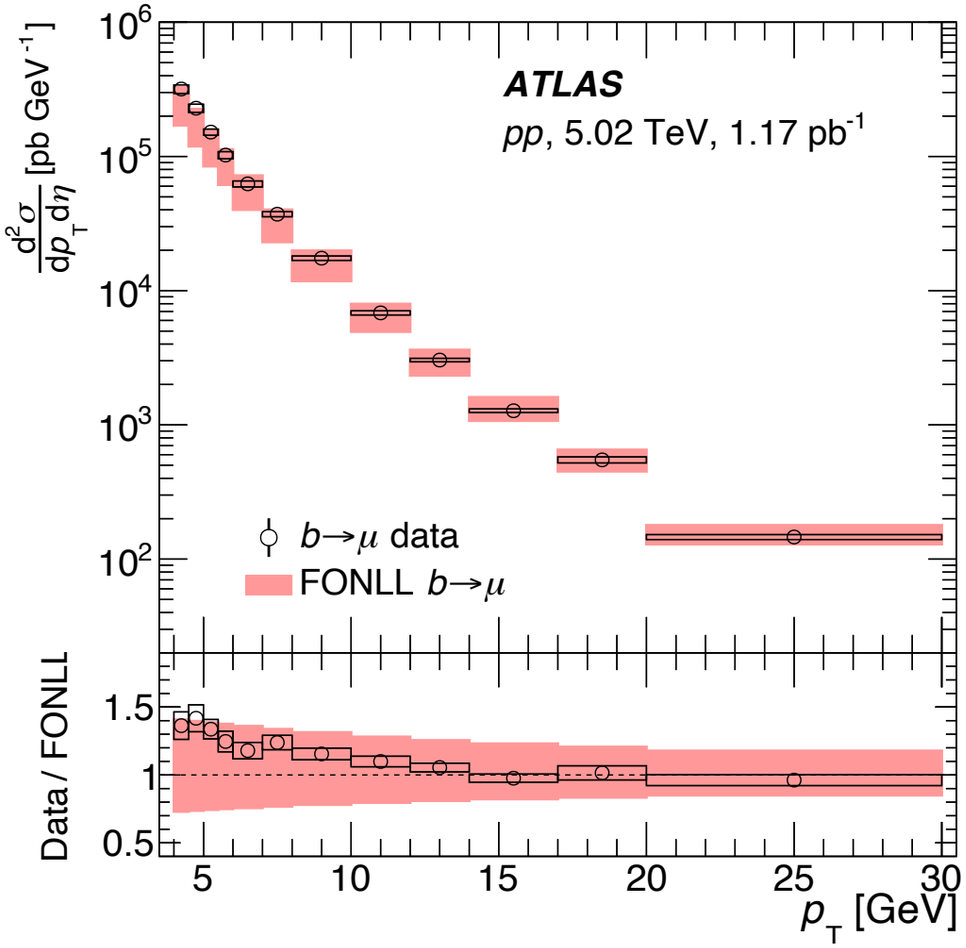
Charm / **bottom** separated via ID impact parameter (DCA): d_0

HF production in *pp* collisions

arXiv:2109.00411



Charm muon

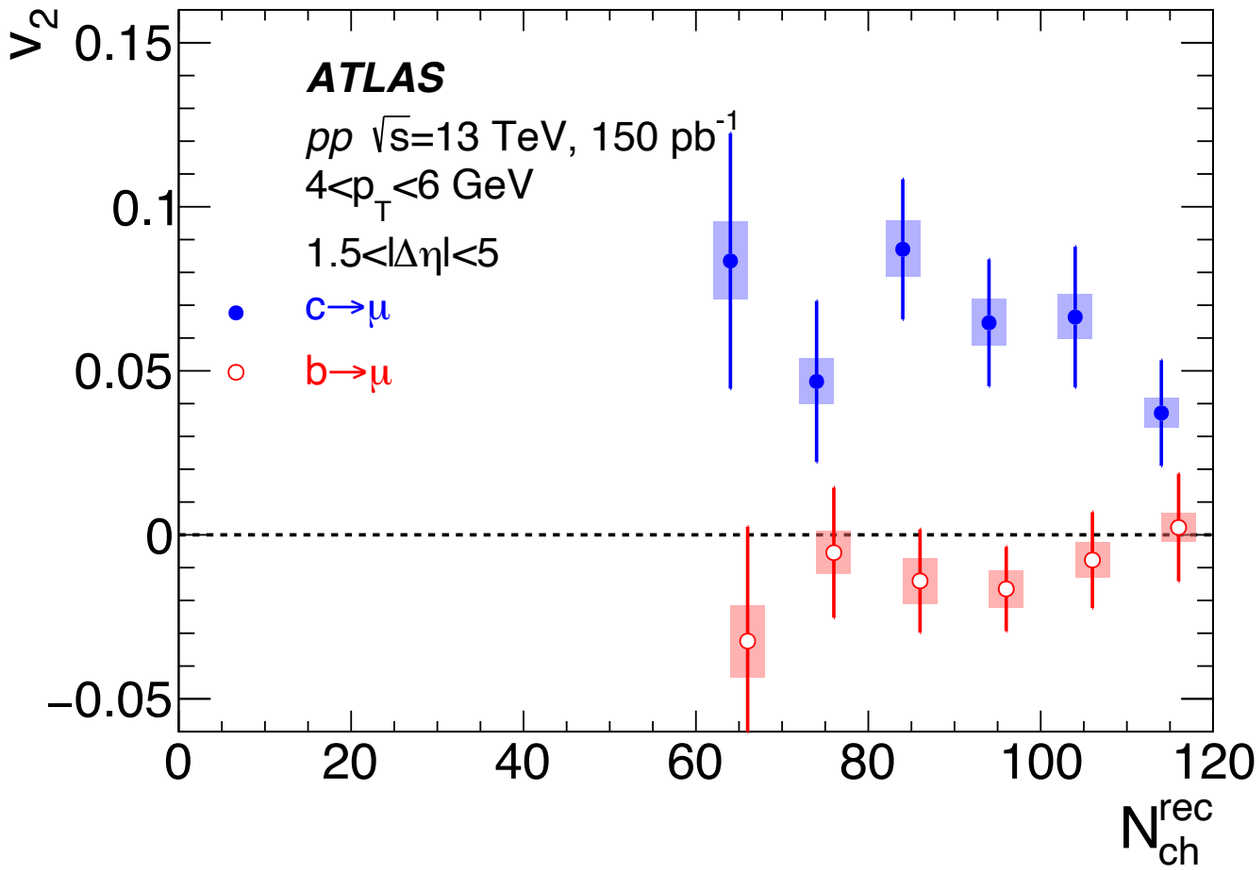


Bottom muon

- **Charm muon** data lay at the upper boundary of **FONLL** uncertainty
- **Bottom muon** data agree with **FONLL**
- Consistent picture with other HF measurements (e.g. ALICE *D*'s: arXiv:2102.13601)

HF azimuthal anisotropy in *pp* collisions

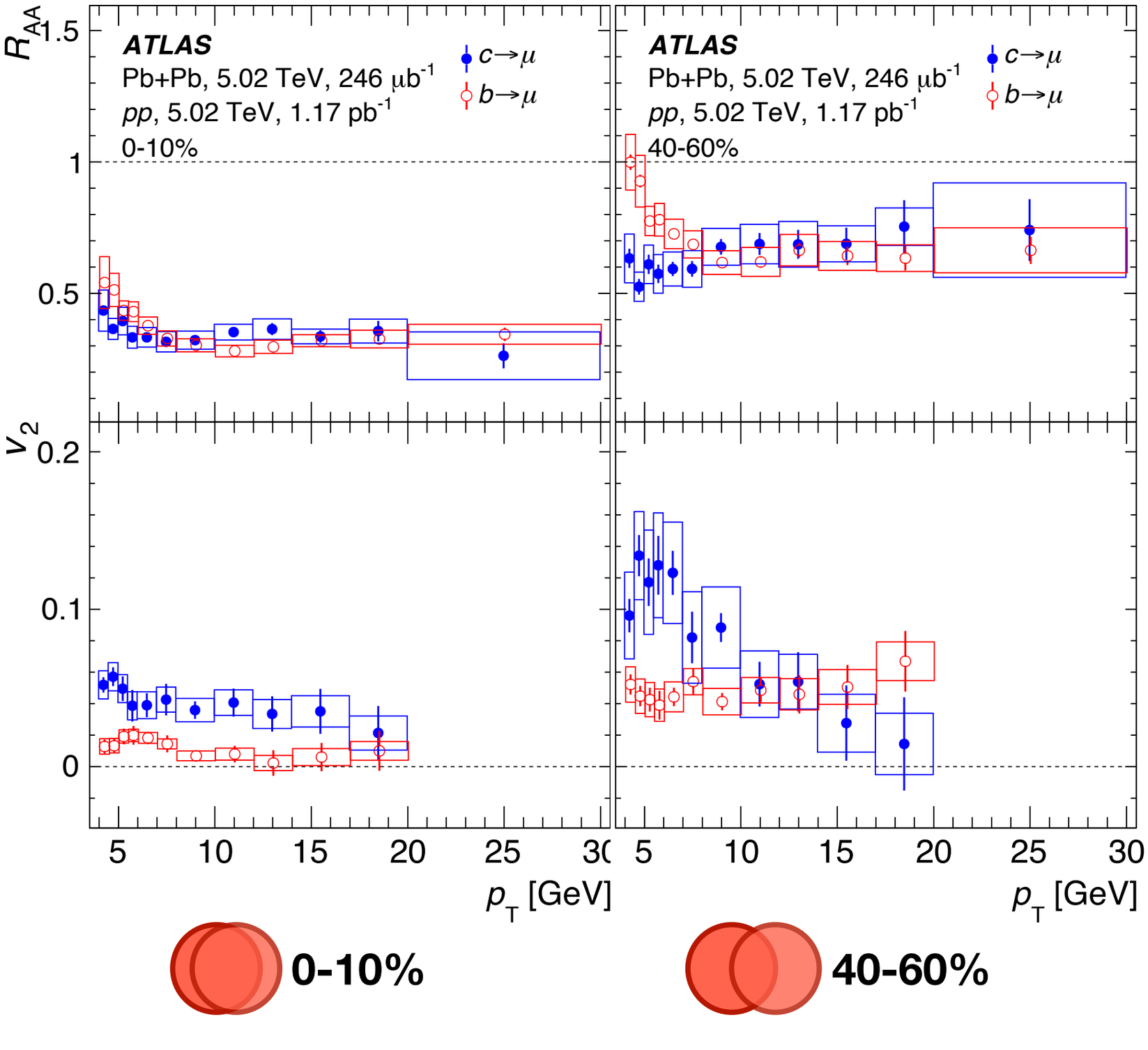
PRL 124 (2020) 082301



- Significant azimuthal anisotropy for charm muon in high multiplicity *pp* events
- v_2(b) ~0. Charm and bottom difference is significant

Charm and bottom muon R_{AA} vs. v_2

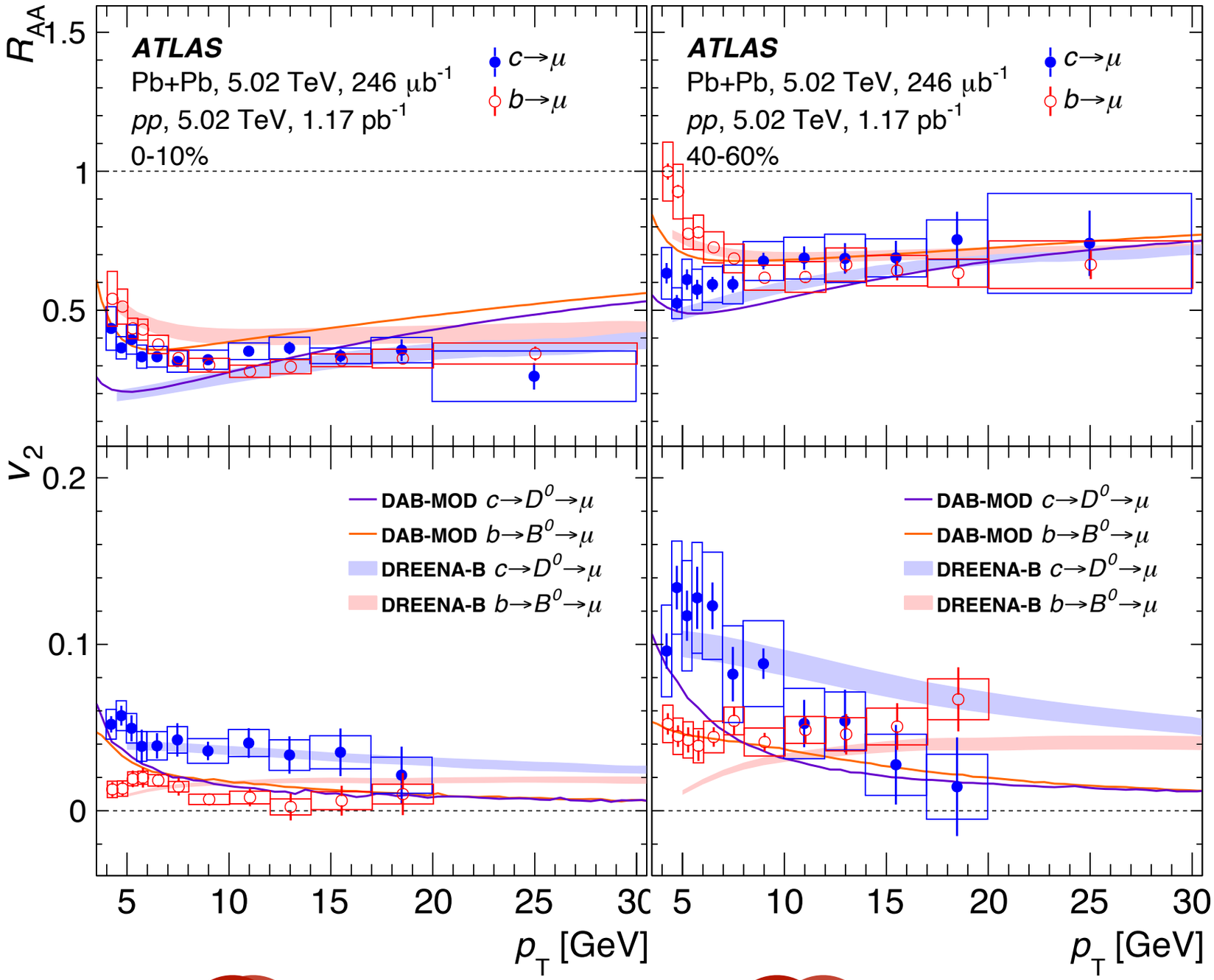
R_{AA}: arXiv:2109.00411
v_2: PLB 807 (2020) 135595



- $R_{\mathrm{AA}}(c) < R_{\mathrm{AA}}(b)$ at low p_{T}, insignificant difference above 10 GeV
- $v_2(c) > v_2(b)$
- Strong centrality dependence for R_{AA} and v_2

R_{AA} vs. v_2 — model comparison

R_{AA}: arXiv:2109.00411
v_2: PLB 807 (2020) 135595
DAB-MOD: R. Katz et al. PRC 102 (2020) 024906
DREENA-B: D. Zigic et al. PLB 791 (2019) 236

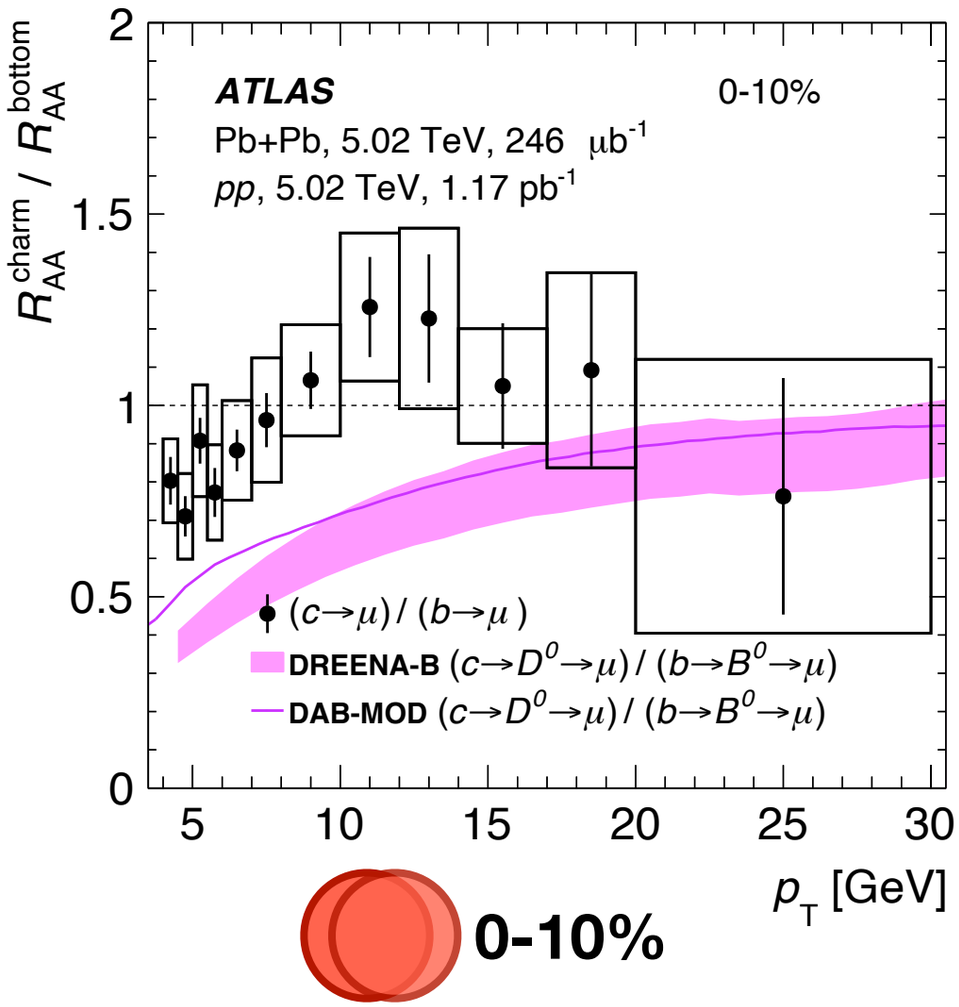


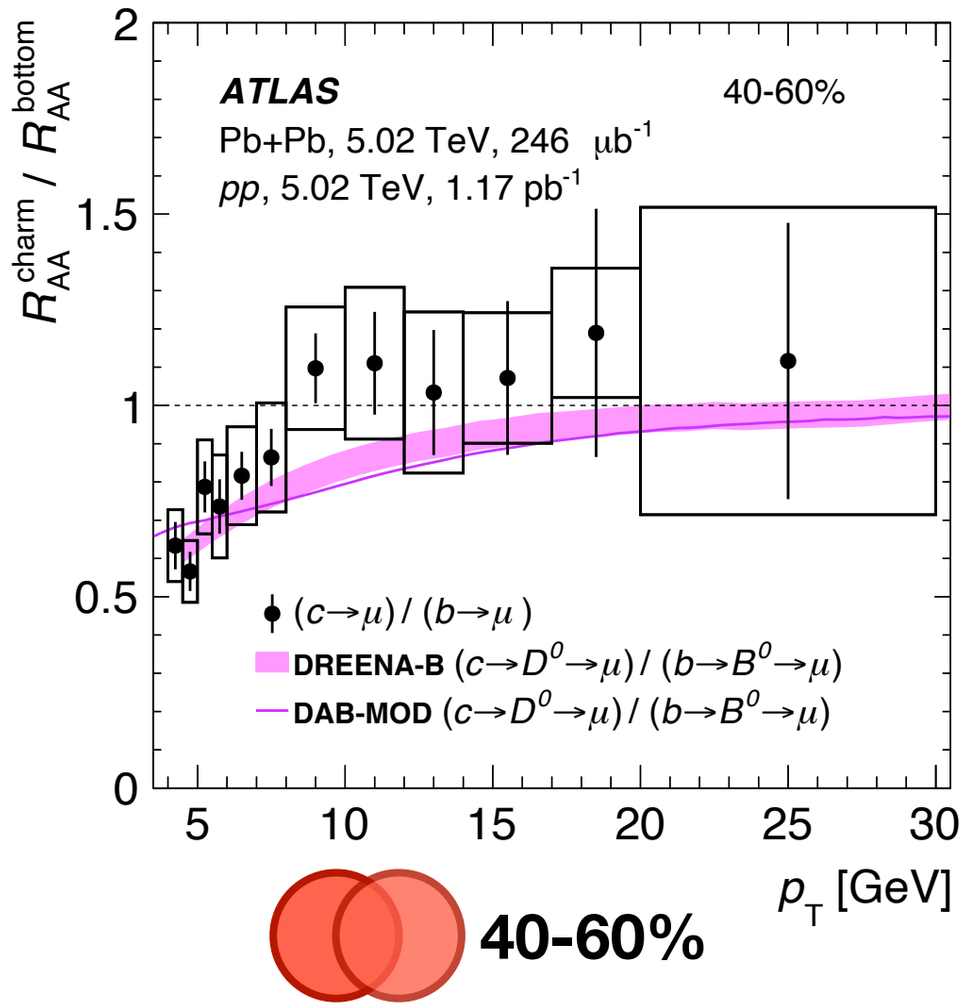
- **DAB-MOD** Langevin
- **DREENA-B** dynamical radiative + collisional E_{loss}

Other centrality bins can be found at web

Charm to bottom double ratio

arXiv:2109.00411





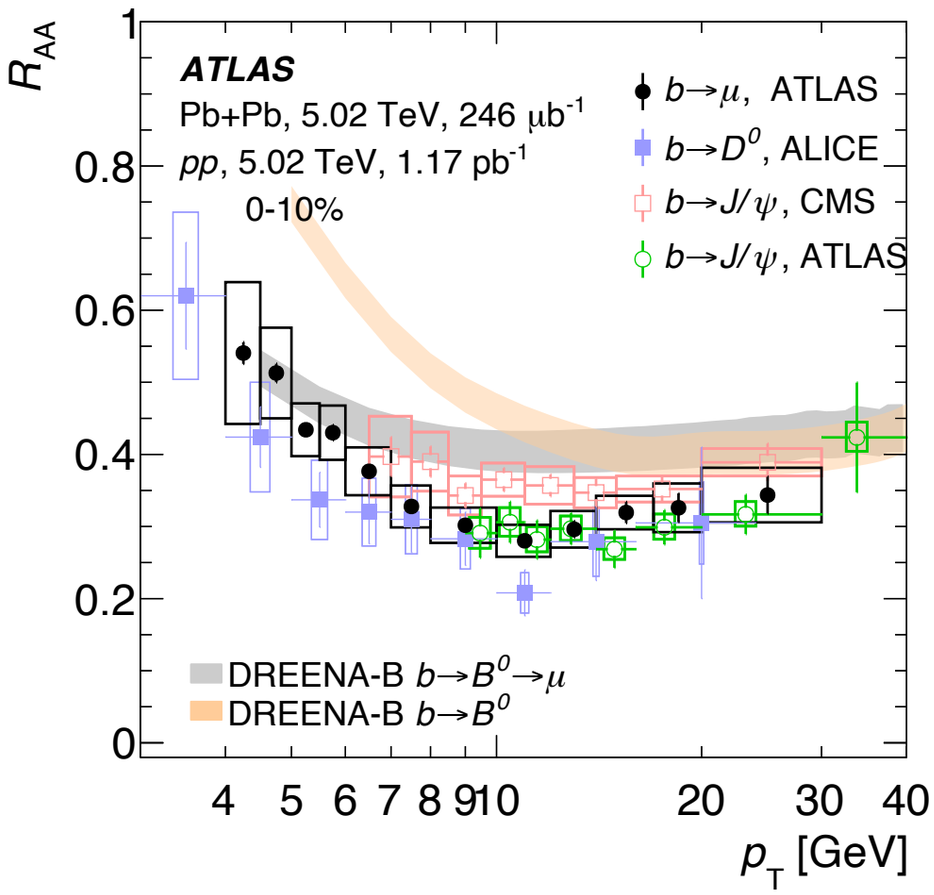
- Large uncertainties due to strong anti-correlation between charm and bottom
- **Charm is more suppressed than bottom** at low p_T; comparable at high p_T
- In radiation picture: mass hierarchy inline with “dead-cone” effect

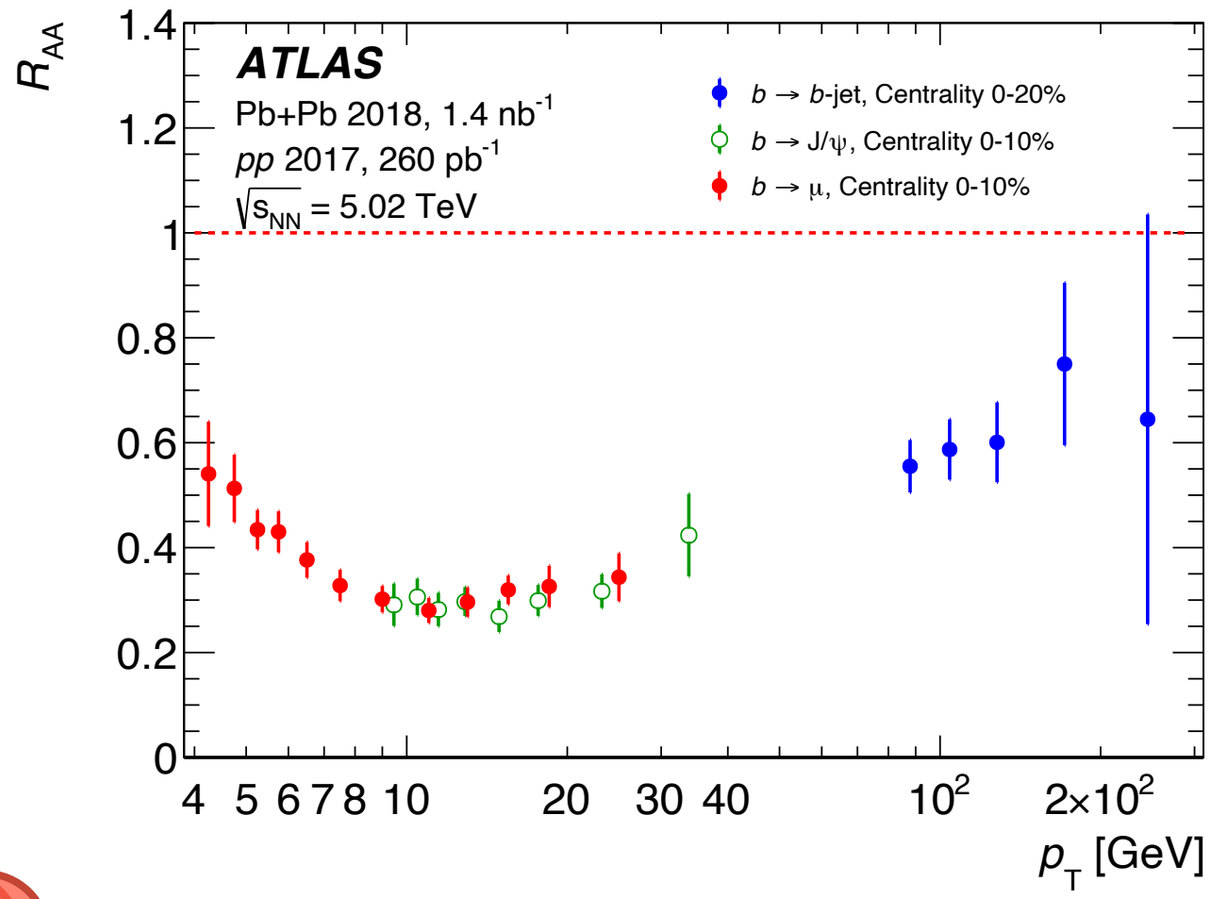
$$\mathrm{d}P_{\mathrm{Rad;Q}}(\theta) \propto \left(1 + \left(\frac{M_{\mathrm{Q}}}{E_{\mathrm{Q}}}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

Other centrality bins can be found at web

ATLAS muon: arXiv:2109.00411
ATLAS J/ψ: EPJC 78 (2018) 762
ATLAS b-jet: HION-2018-24
ALICE D^0: arXiv:2202.00815
CMS J/ψ: EPJC 78 (2018) 509

Comparison — bottom R_{AA}



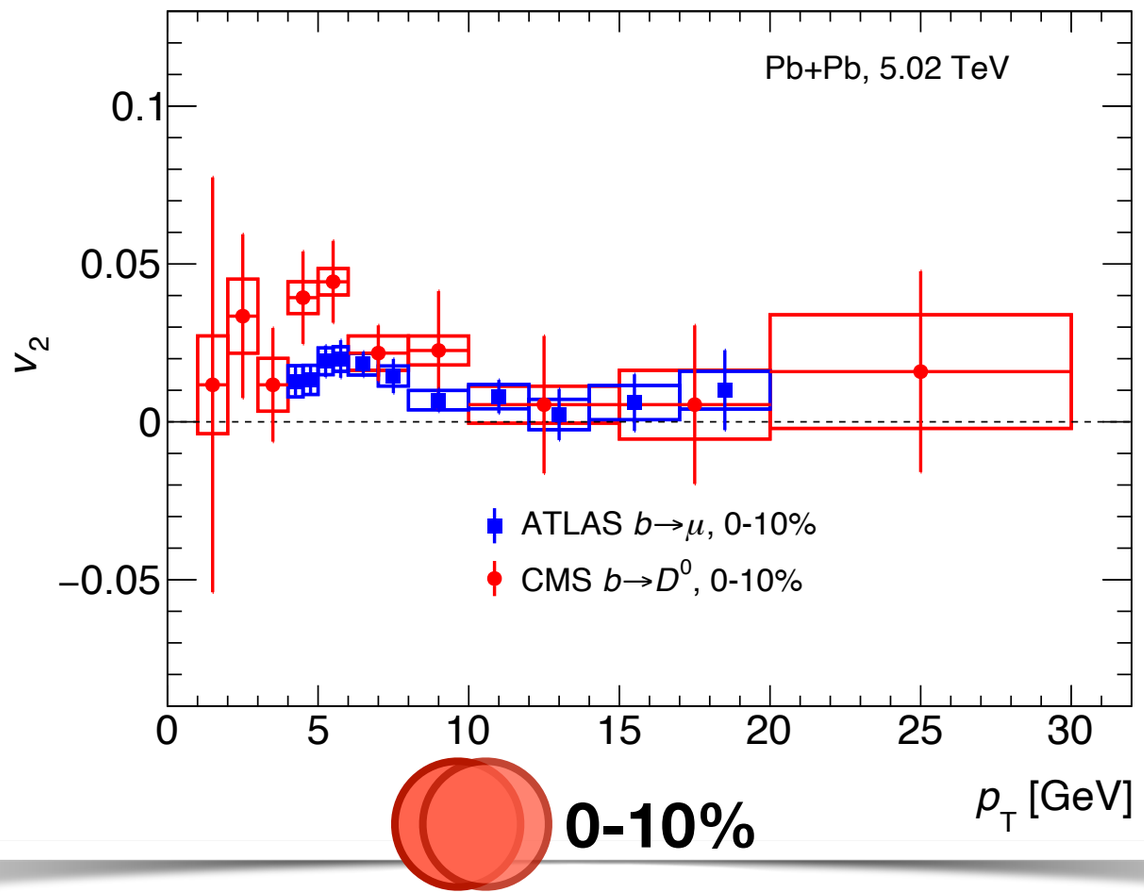


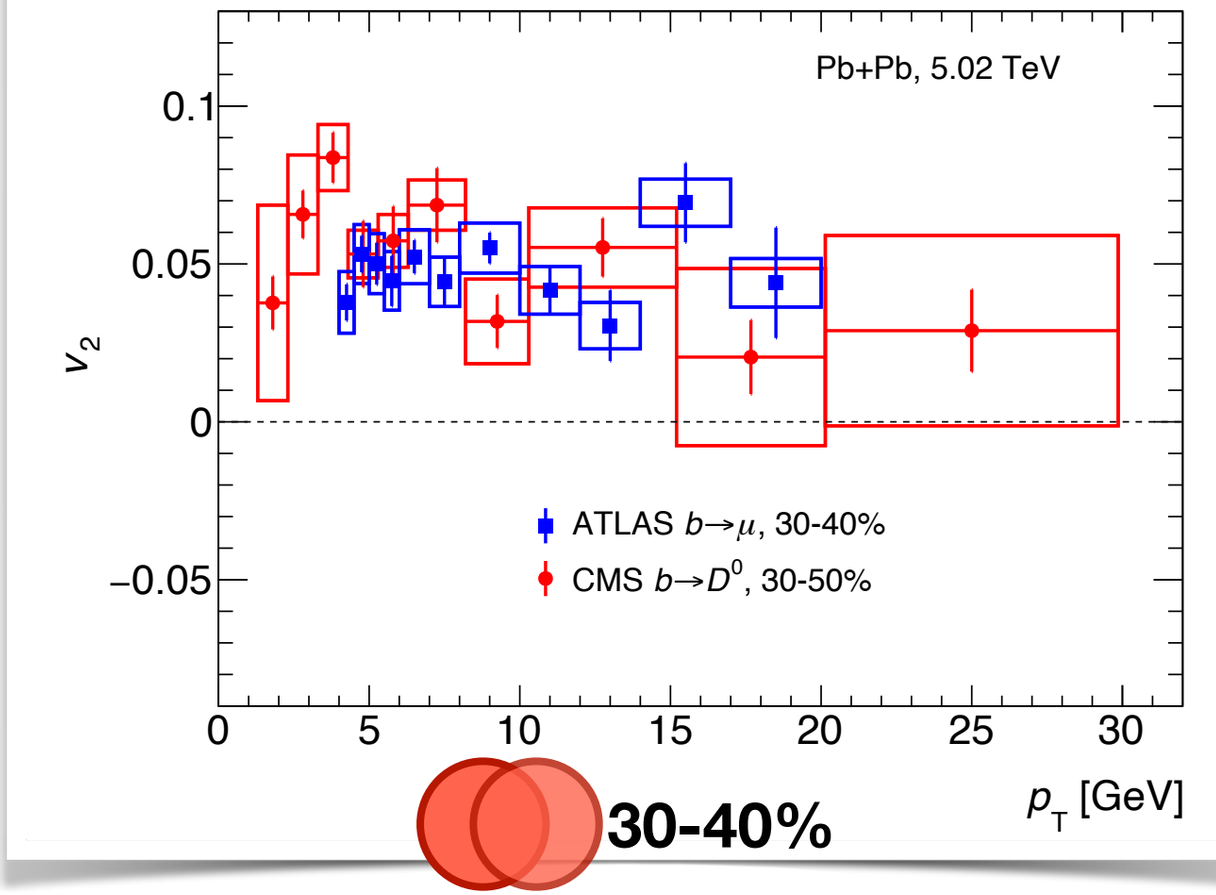
0-10%

- B-decay (muon, D^0, J/ψ) in 0-10% in comparison to **DREENA-B**
- B-decay and (muon-tagged) b-jet show smooth trend in wide p_T range

Comparison — bottom v_2

ATLAS muon: PLB 807 (2020) 135595
CMS D^0: HIN-21-003

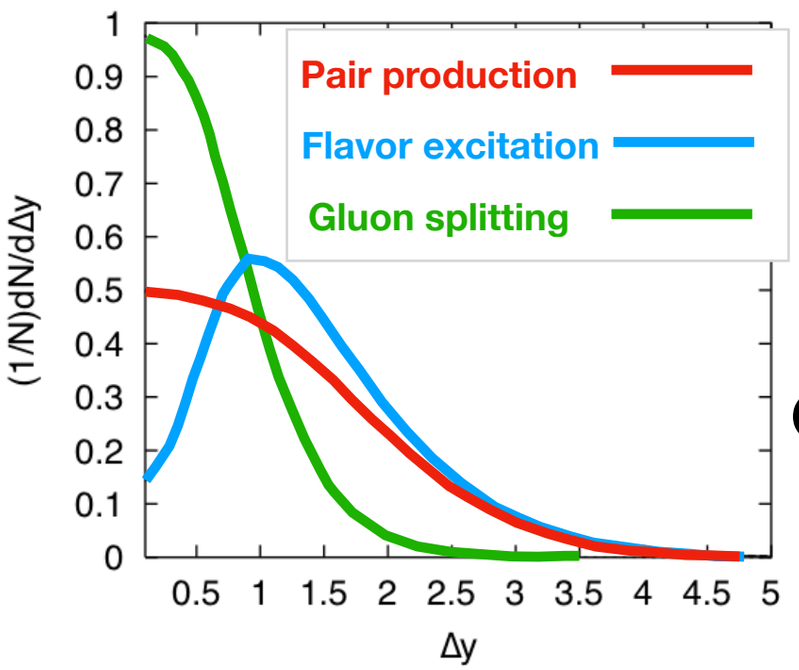




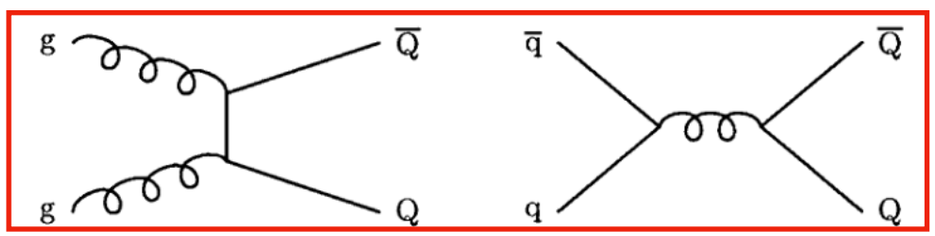
- Similar v_2 for muon and D^0 from b
- Different channels have different advantages

HF muon pair selection

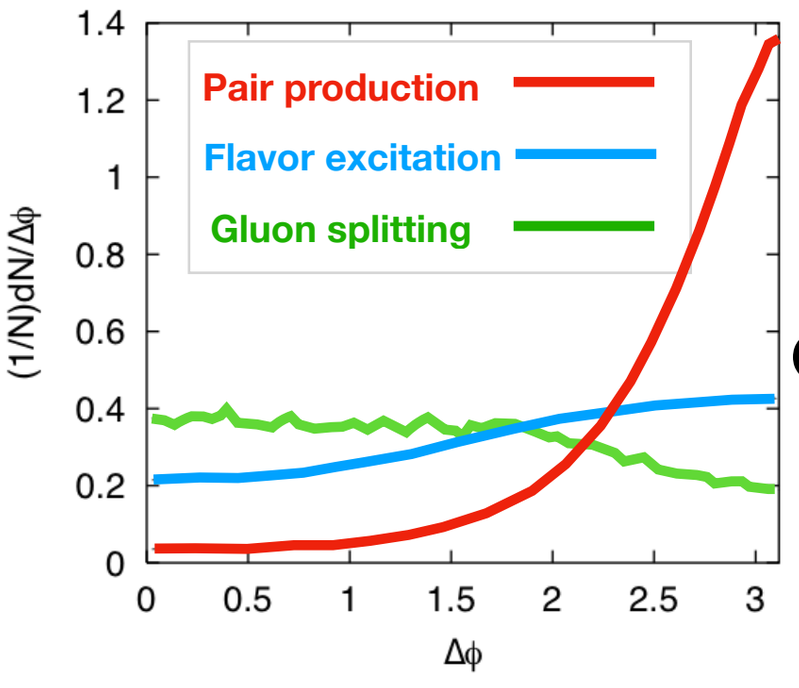
E. Norrbin & T. Sjöstrand: EPJC 17 (2000) 137



Rapidity Correlation



Ideal probe for QGP induced angular broadening: **back-to-back** muon pairs from LO pair production processes



Azimuthal Correlation

$b - \bar{b}$ correlation at 2 TeV from **pQCD**

Rapidity gap between two muons: $|\Delta\eta| > 0.8$

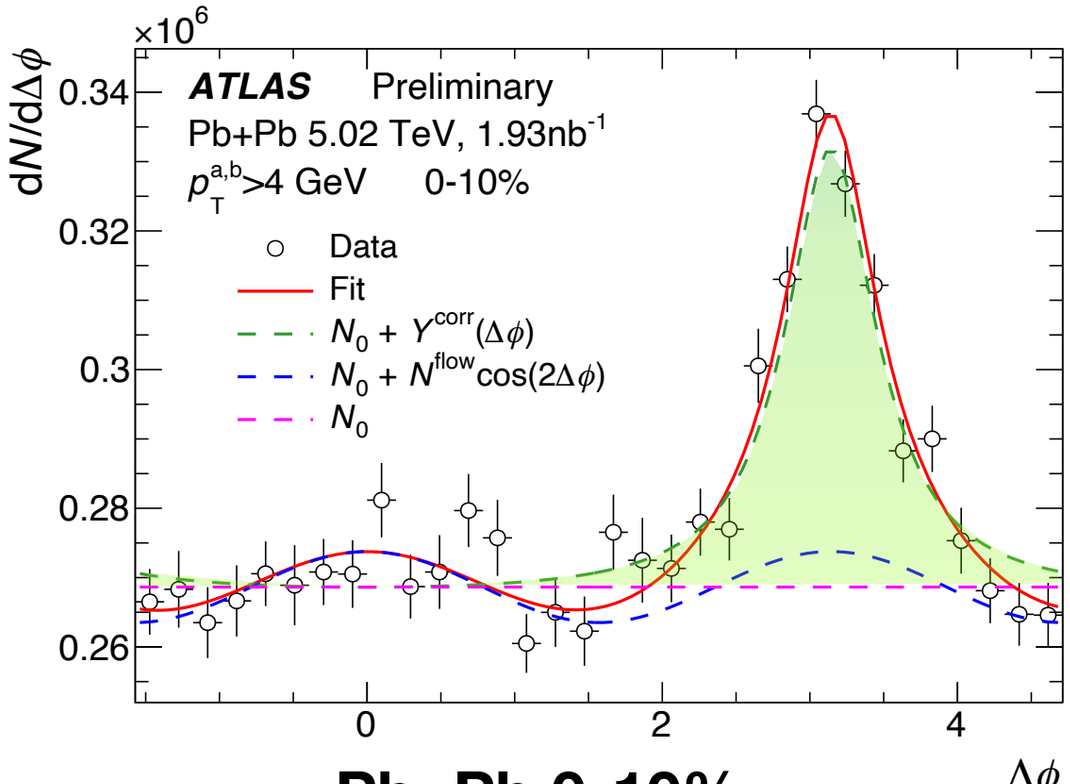
- Suppress HF-bkg contribution from jets
- Suppress gluon splitting contribution

Azimuthal correlation at $\Delta\phi \sim \pi$:

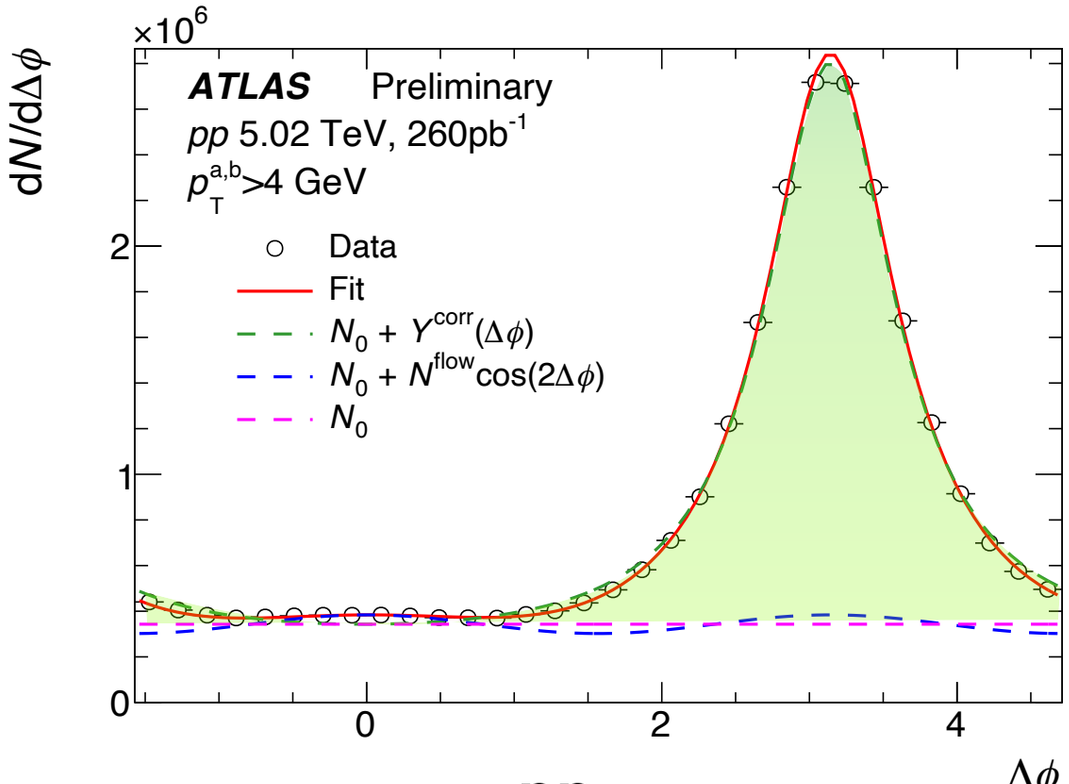
- Back-to-back pair production
  - Contribution of flavor excitation
  - Small non-HF bkg contamination

Back-to-back yield extraction

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

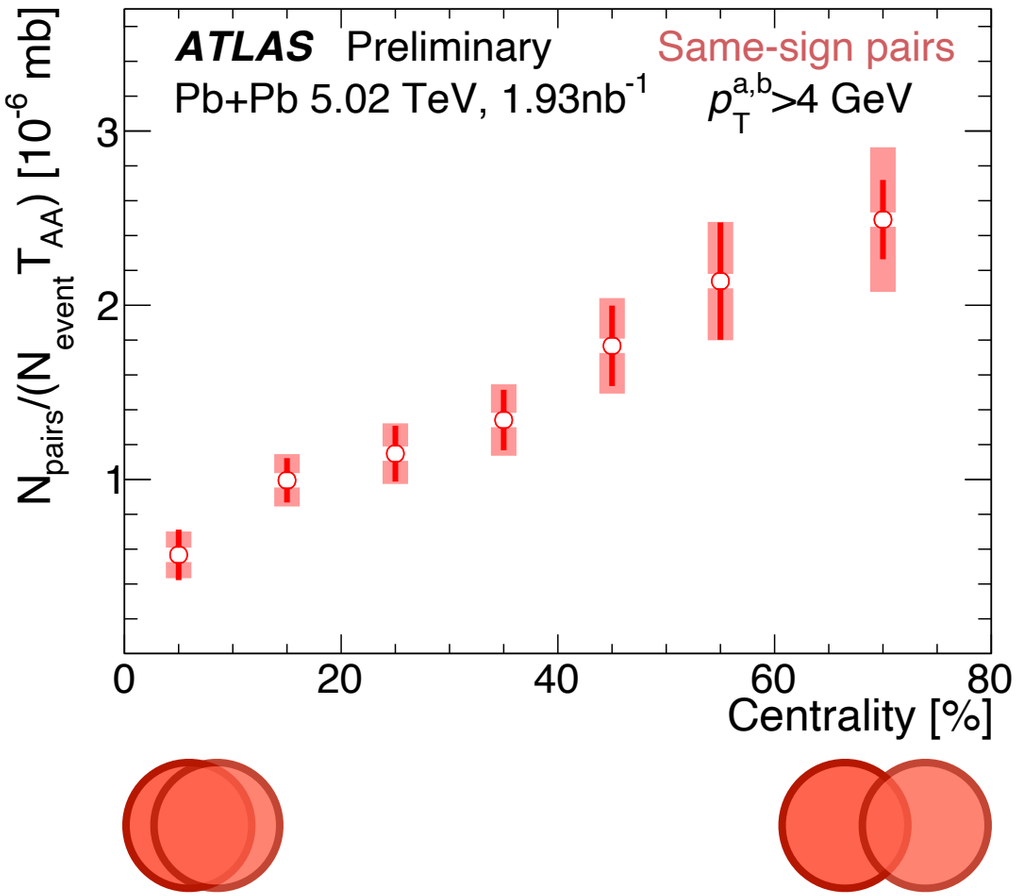
Back-to-back correlation yields Lorentzian

- Correlated yields and its width (std deviation) are extracted
- Separately for same-sign ($b\bar{b}$) and opposite-sign ($c\bar{c} + b\bar{b}$) HF pairs

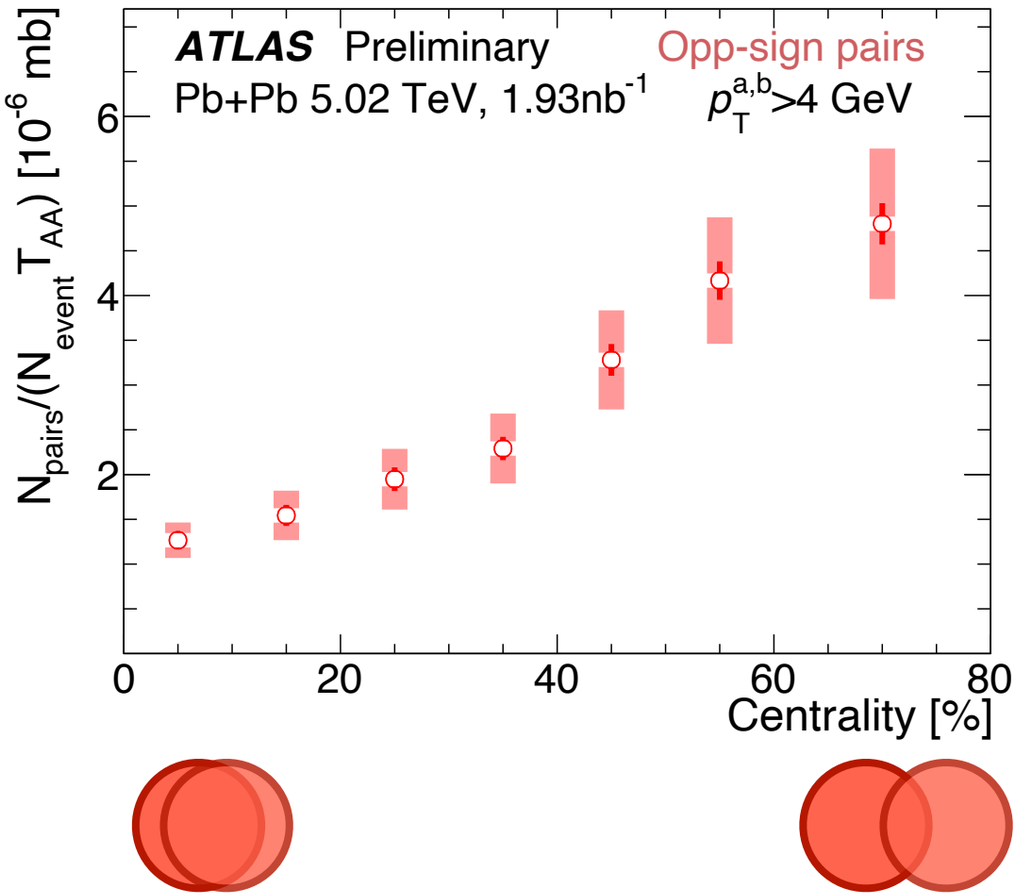
HF pair azimuthal correlation — yields

ATLAS-CONF-2022-022

Same-sign ($b\bar{b}$)



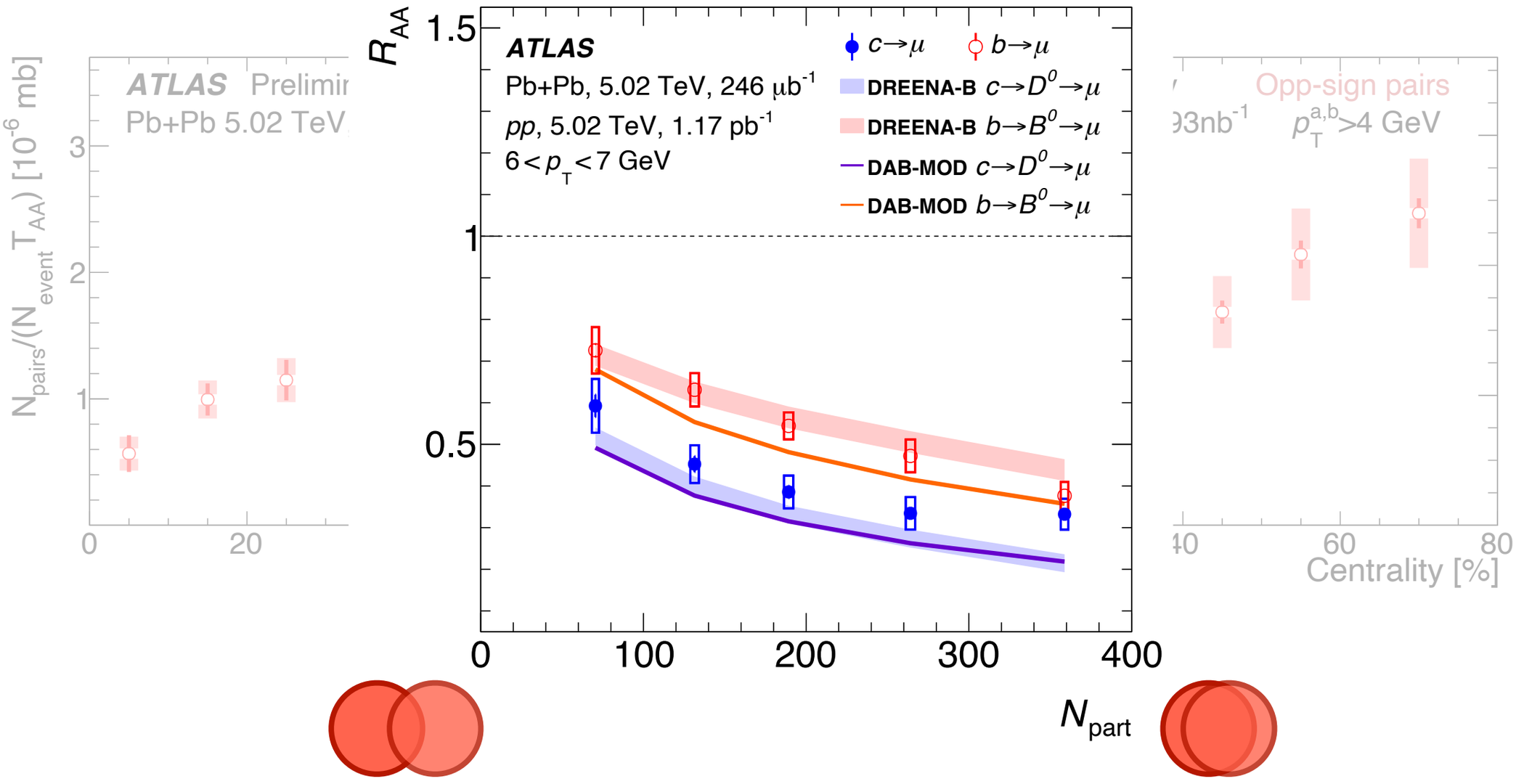
Opposite-sign ($c\bar{c} + b\bar{b}$)



- Stronger suppression on back-to-back HF pair production in central wrt. peripheral
- Same-sign and Opposite-sign pairs have similar trend

HF pair azimuthal correlation — yields

PLB 807 (2020) 135595

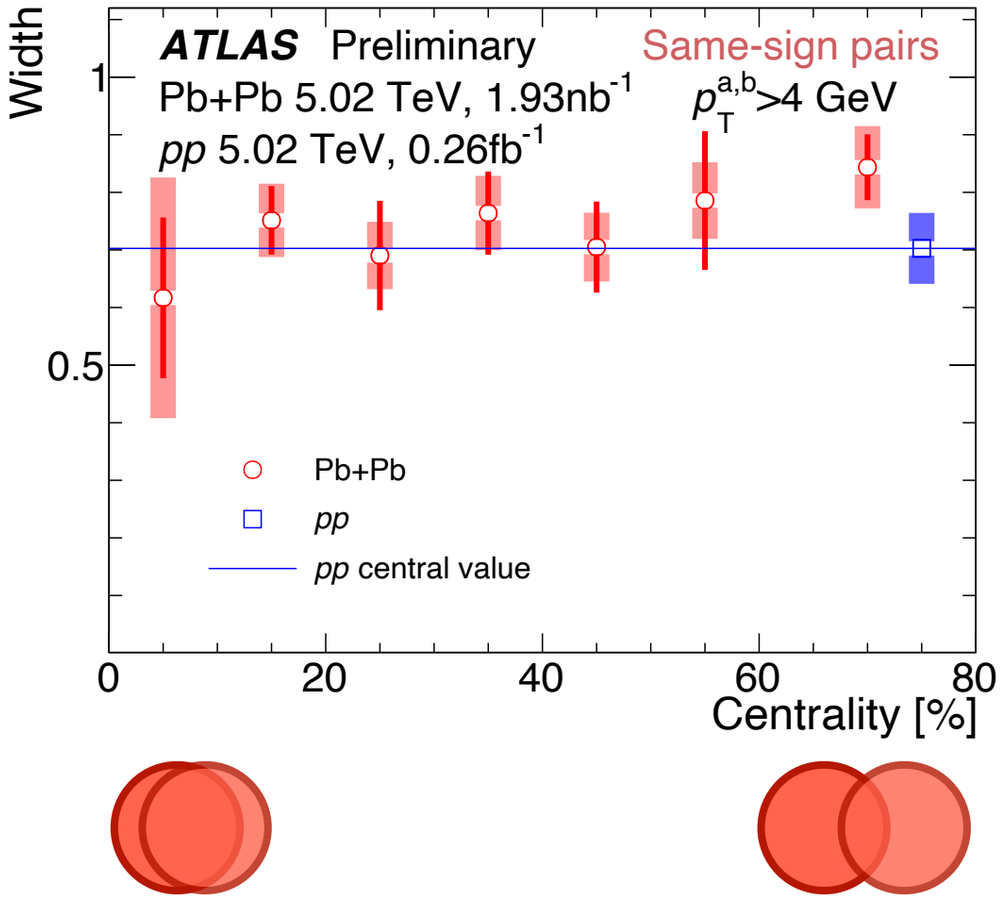


- Stronger suppression on back-to-back HF pair production in central wrt. peripheral
- Same-sign and Opposite-sign pairs have similar trend, consistent with single HF

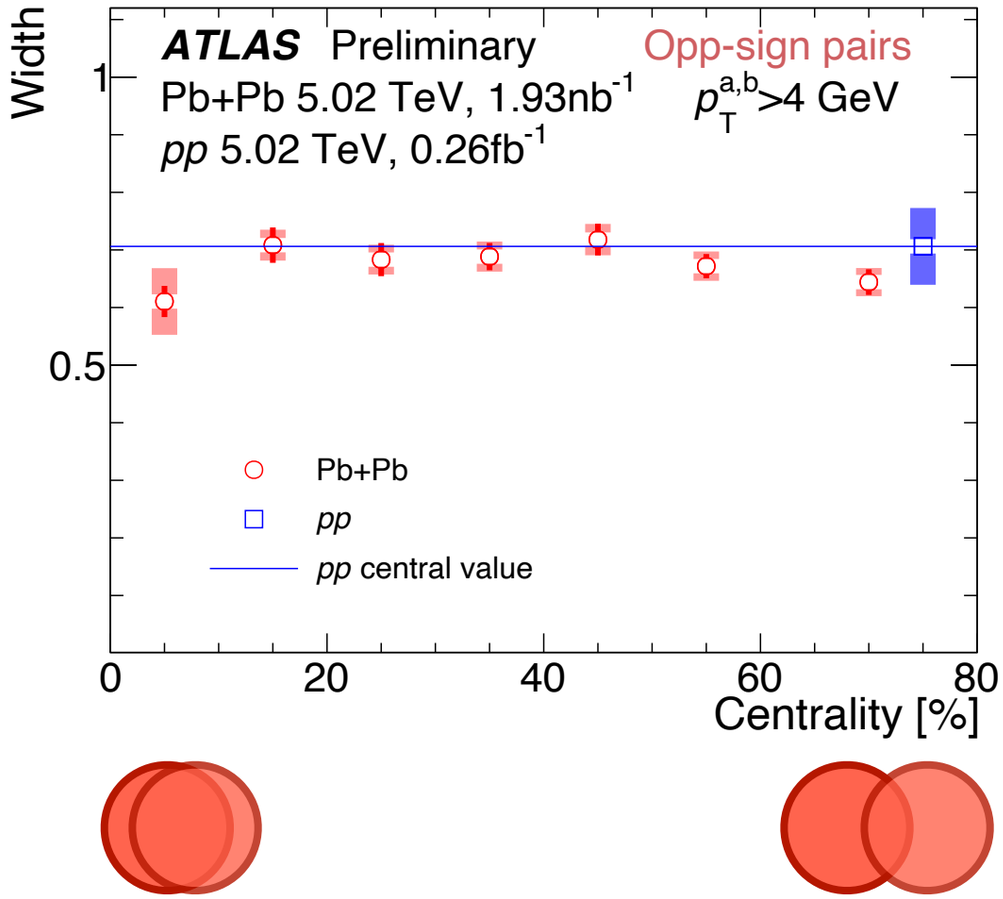
HF pair azimuthal correlation — width

ATLAS-CONF-2022-022

Same-sign ($b\bar{b}$)



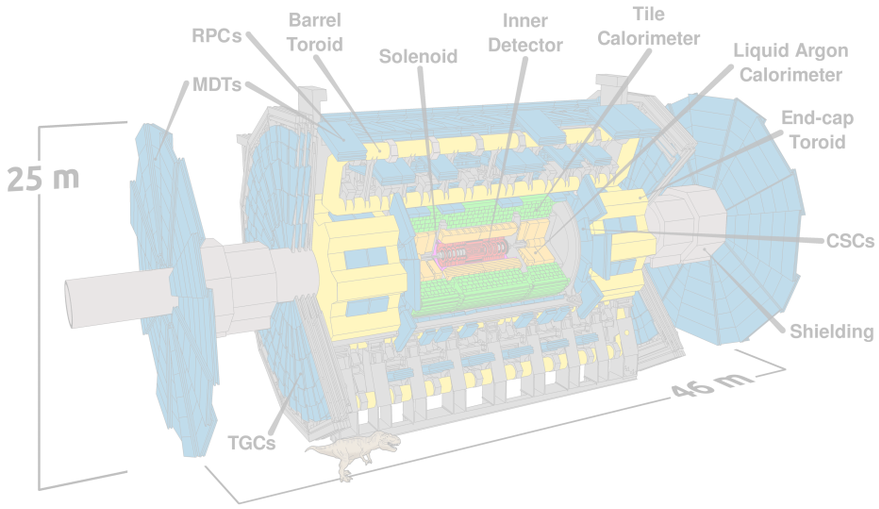
Opposite-sign ($c\bar{c} + b\bar{b}$)



- Comparable width between different centralities and between Pb+Pb and *pp*
- Centrality-independent width indicates small angular deflection. In weakly interaction picture: important role of radiative energy loss

Summary

- Decay muons serve as powerful HF probes in HIC, especially for probing bottom quarks
- Detailed yield and azimuthal anisotropy measurements of HF muon in *pp* and Pb+Pb collisions are available in recent ATLAS publications
- HF pair azimuthal correlation measured with muon pairs. No significant azimuthal correlation broadening observed



Latest ATLAS HF results:

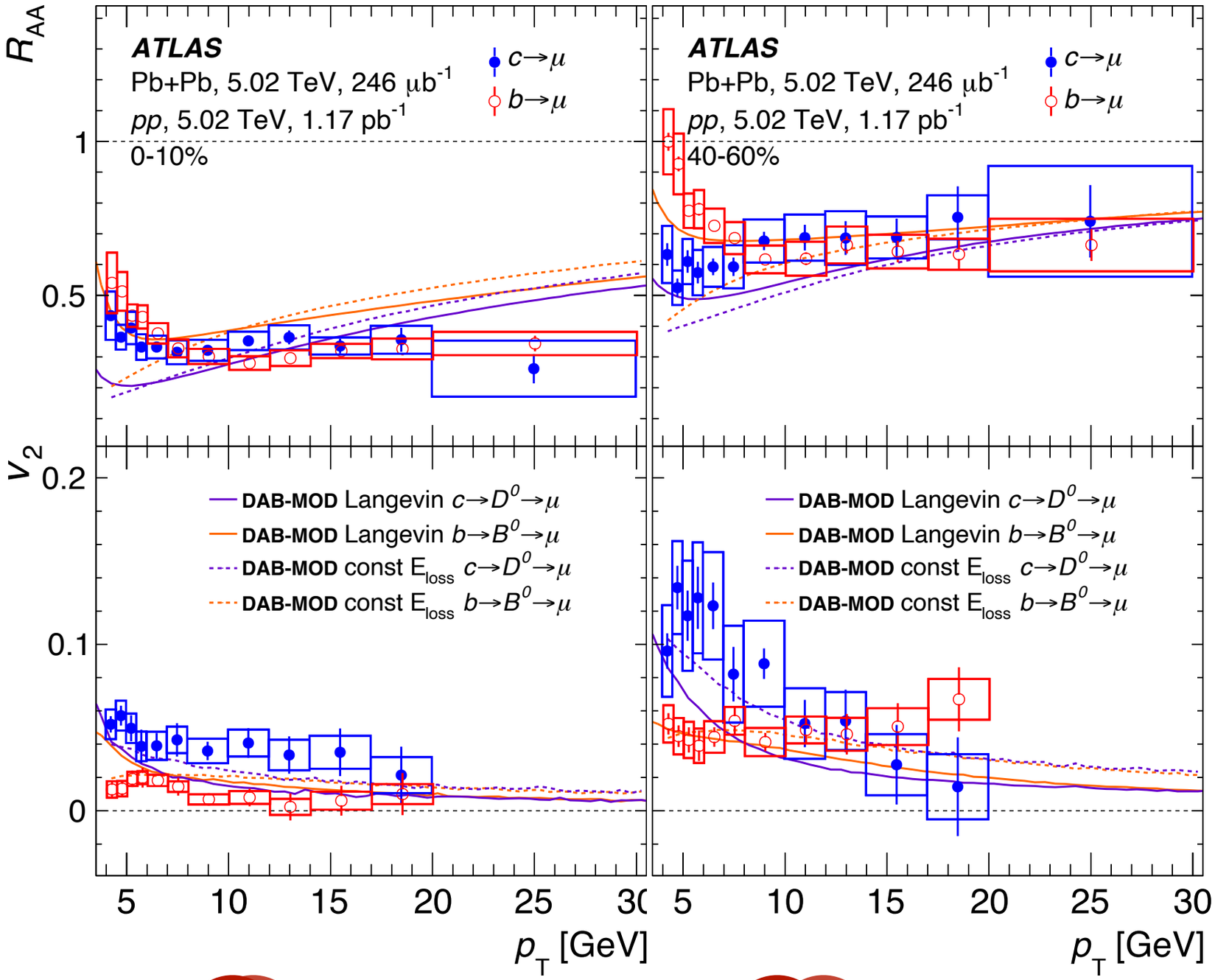
- HF muon (b/c) v_2 in *pp* (link)
- HF muon (b/c) v_n in Pb+Pb (link)
- HF muon (b/c) R_{AA} at 5.02 TeV (link)
- Muon tagged b-jet R_{AA} at 5.02 TeV (link)
- HF muon (b+c) pair azimuthal correlations (link)

- Visit https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults for more ATLAS heavy ion results and auxiliary materials

Backup Slides

R_{AA} vs. v_2 — DAB-MOD configurations

R_{AA}: arXiv:2109.00411
v_2: PLB 807 (2020) 135595



0-10% **40-60%**

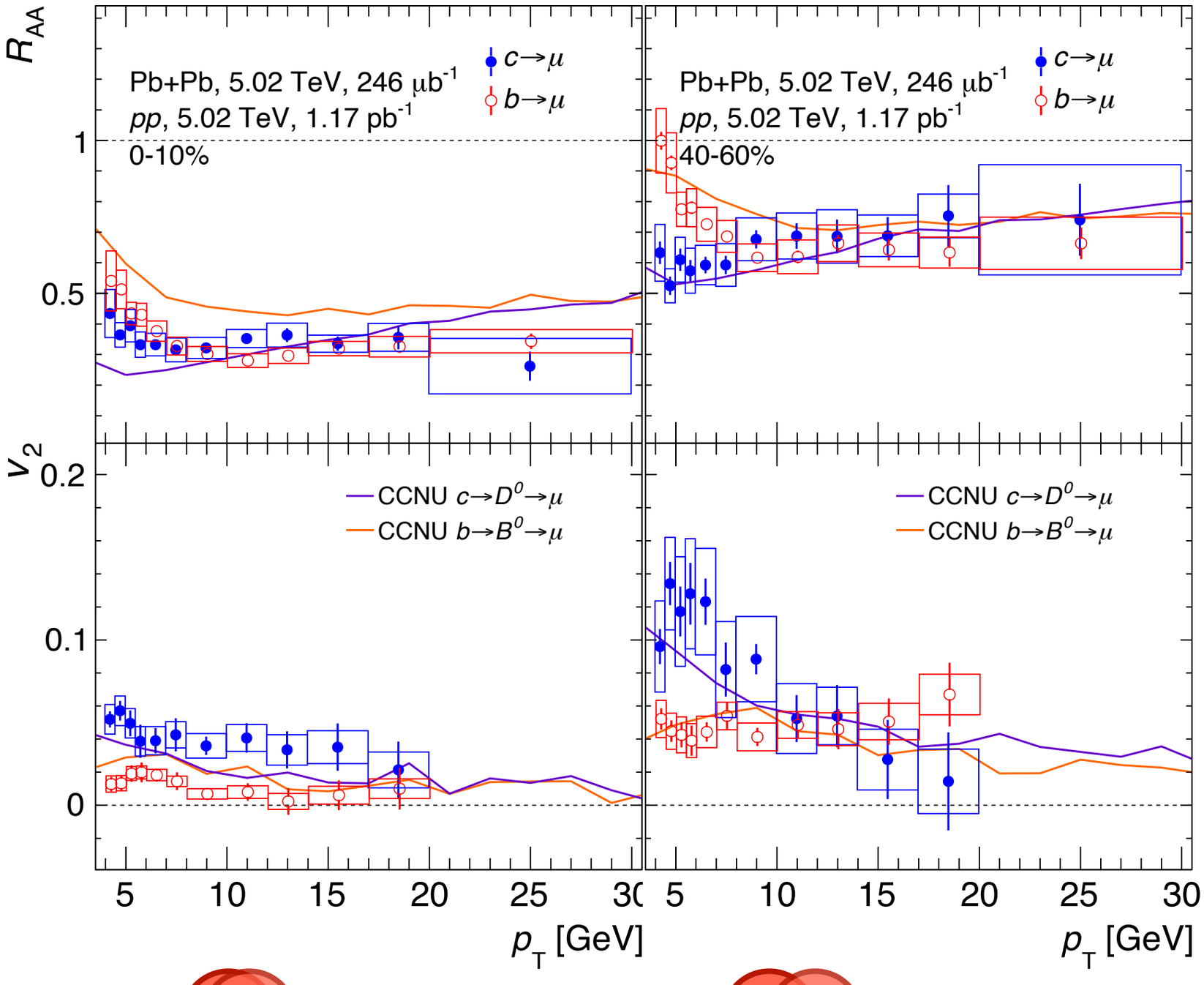
DAB-MOD

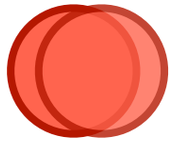
- **Langevin** vs. **constant E_{loss}** (dashed lines)

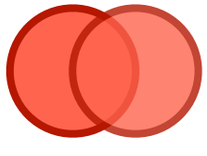
Other centrality bins can be found at web

R_{AA} vs. v_2 — CCNU model

arXiv:2109.00411
PLB 807 (2020) 135595



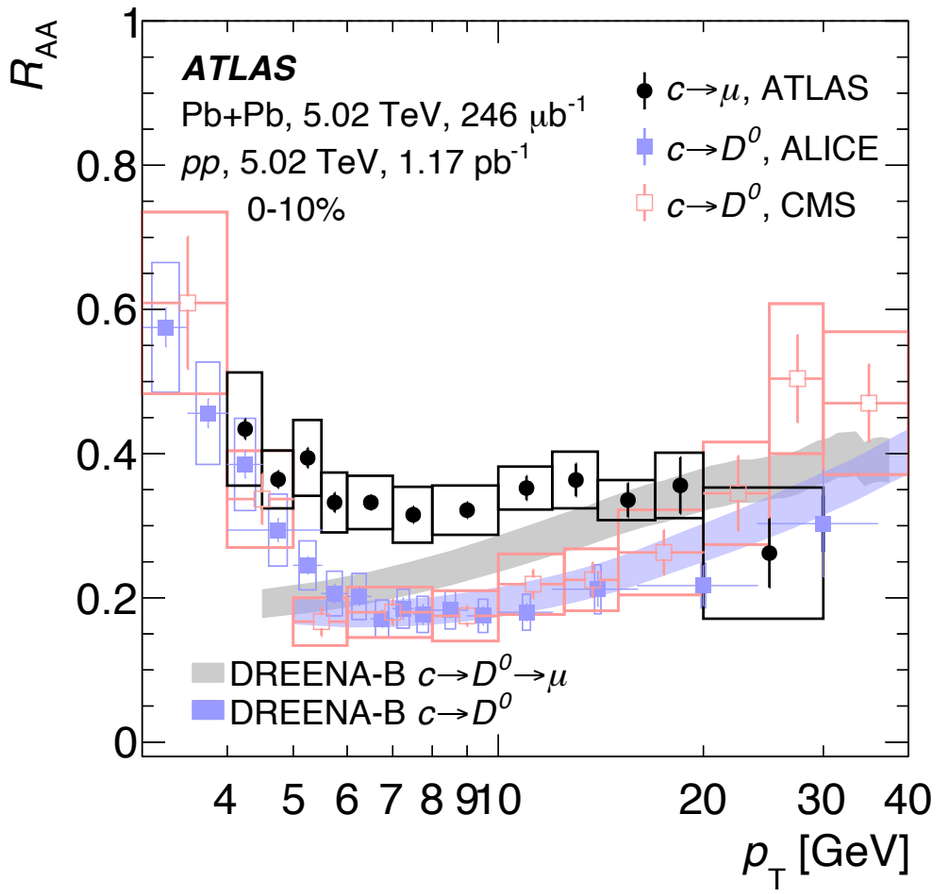




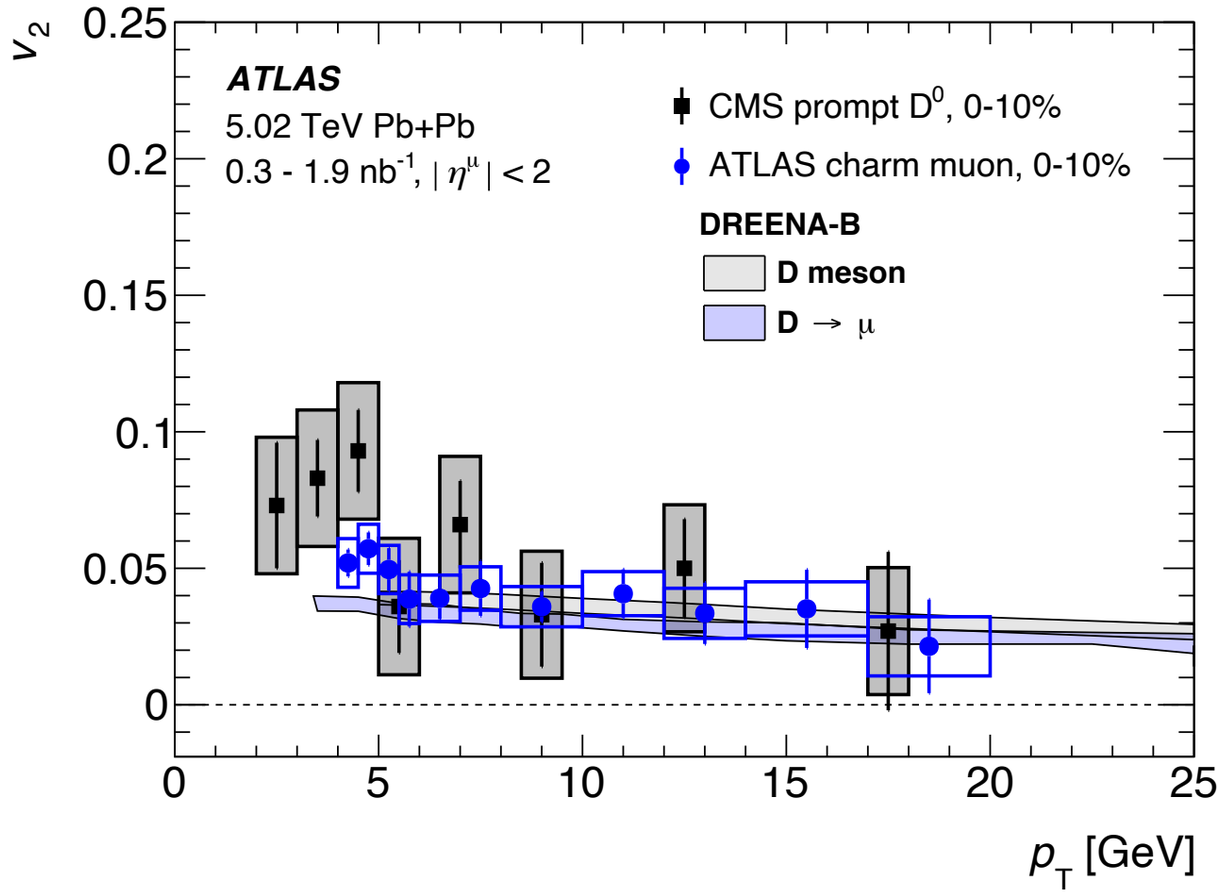
- **CCNU model** (2005.03330): Langevin-hydrodynamics framework + hybrid fragmentation-coalescence hadronization
- Modified Langevin with radiative E_{loss}

Compare to other experiments — charm

arXiv:2109.00411
PLB 807 (2020) 135595



R_{AA}

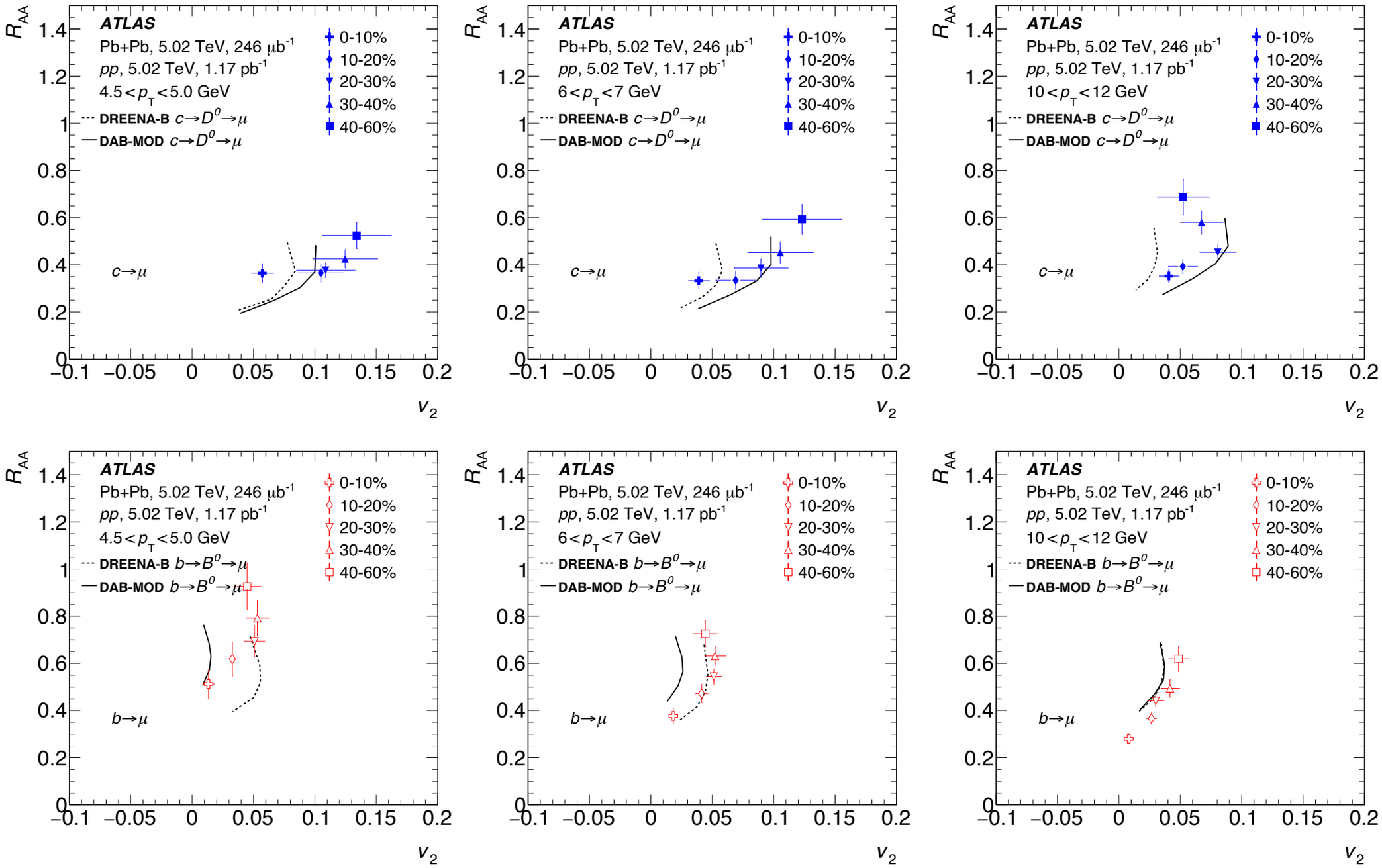


v_2

- Charm muon vs. prompt D^0 in 0-10% in comparison to **DREENA-B** predictions
- Difference between charm muon and prompt D^0 R_{AA} (CMS: arXiv:1708.04962, ALICE: arXiv:1804.09083) is larger than DREENA-B predicts

R_{AA} vs. v_2 in centralities

arXiv:2109.00411
PLB 807 (2020) 135595



Charm muon

Bottom muon

4.5 < p_T < 5 GeV

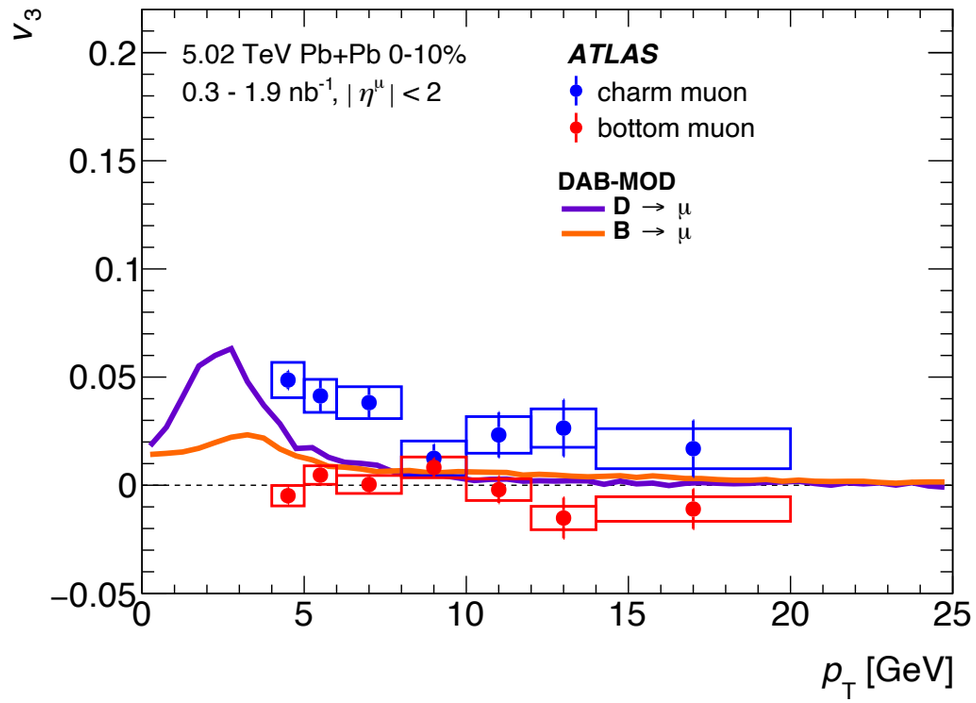
6 < p_T < 7 GeV

10 < p_T < 12 GeV

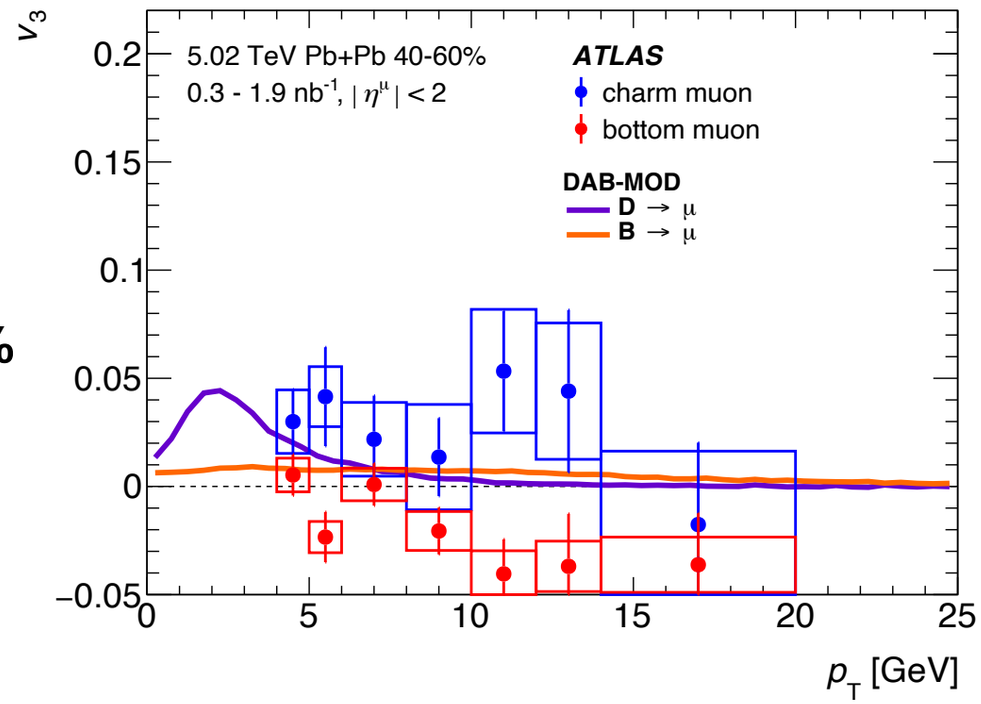
v_3 — DAB-MOD comparisons

PLB 807 (2020) 135595

0-10%



40-60%

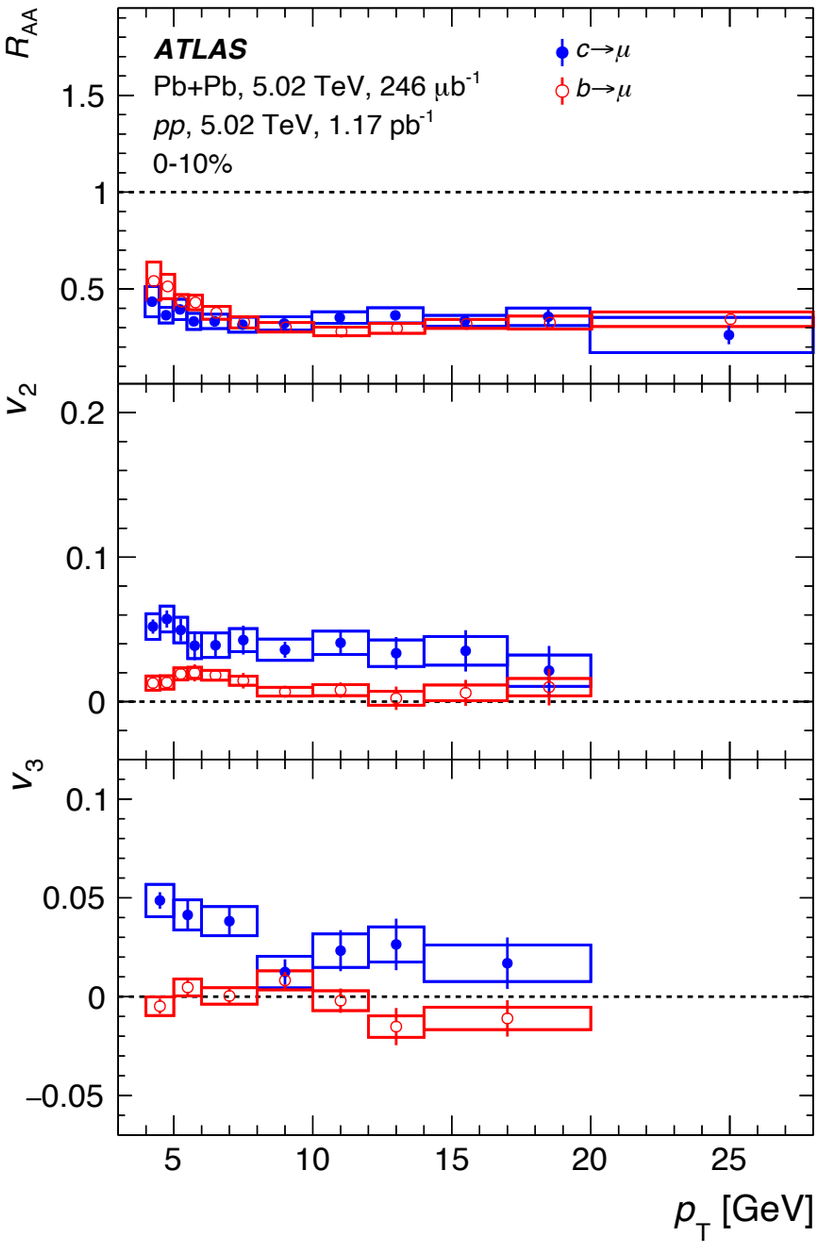


- $v_3(c \to \mu) > 0$
- $v_3(b \to \mu) \sim 0$
- **DAB-MOD Langevin** with fluctuating medium under predicts charm muon v_3 in the measured p_T range in central events

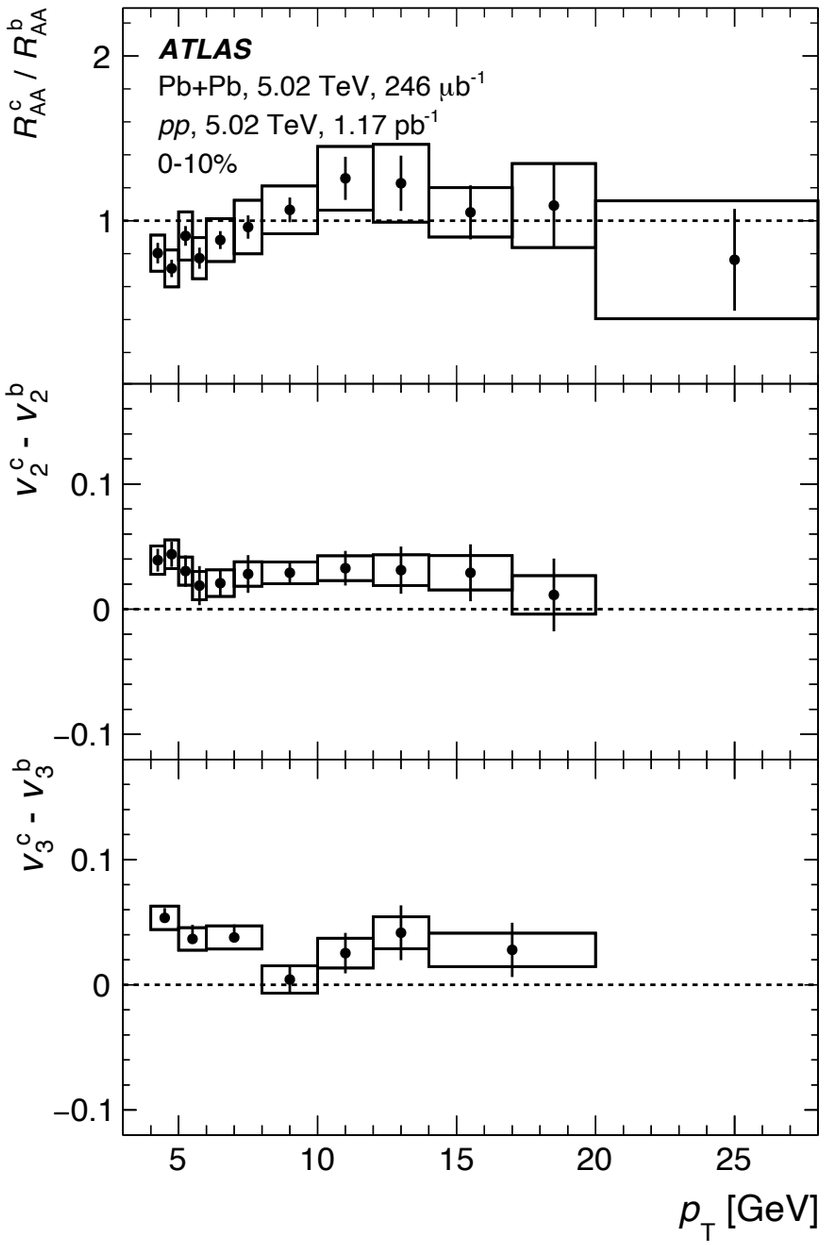
Other centrality bins can be found at web

Charm-bottom difference

arXiv:2109.00411
PLB 807 (2020) 135595



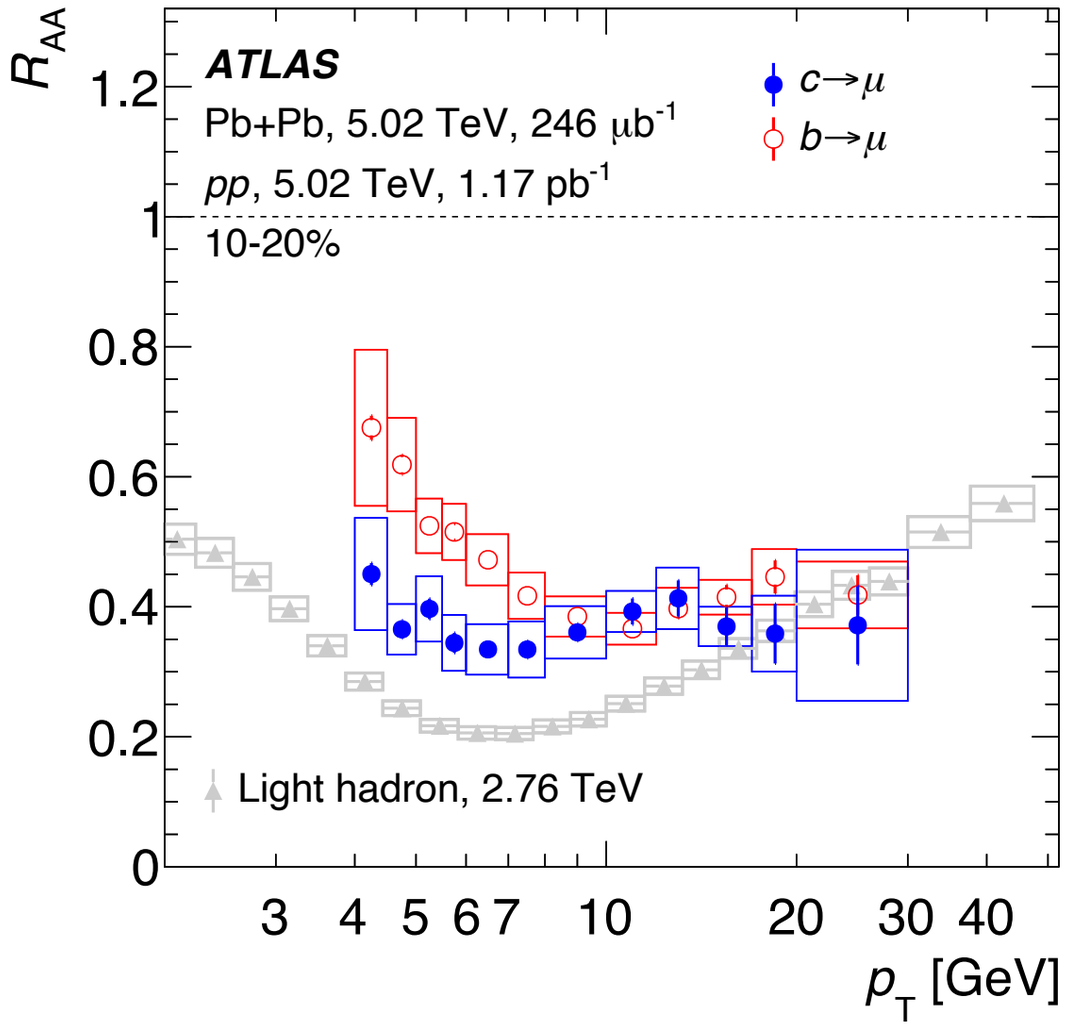
Charm/bottom muon measurements

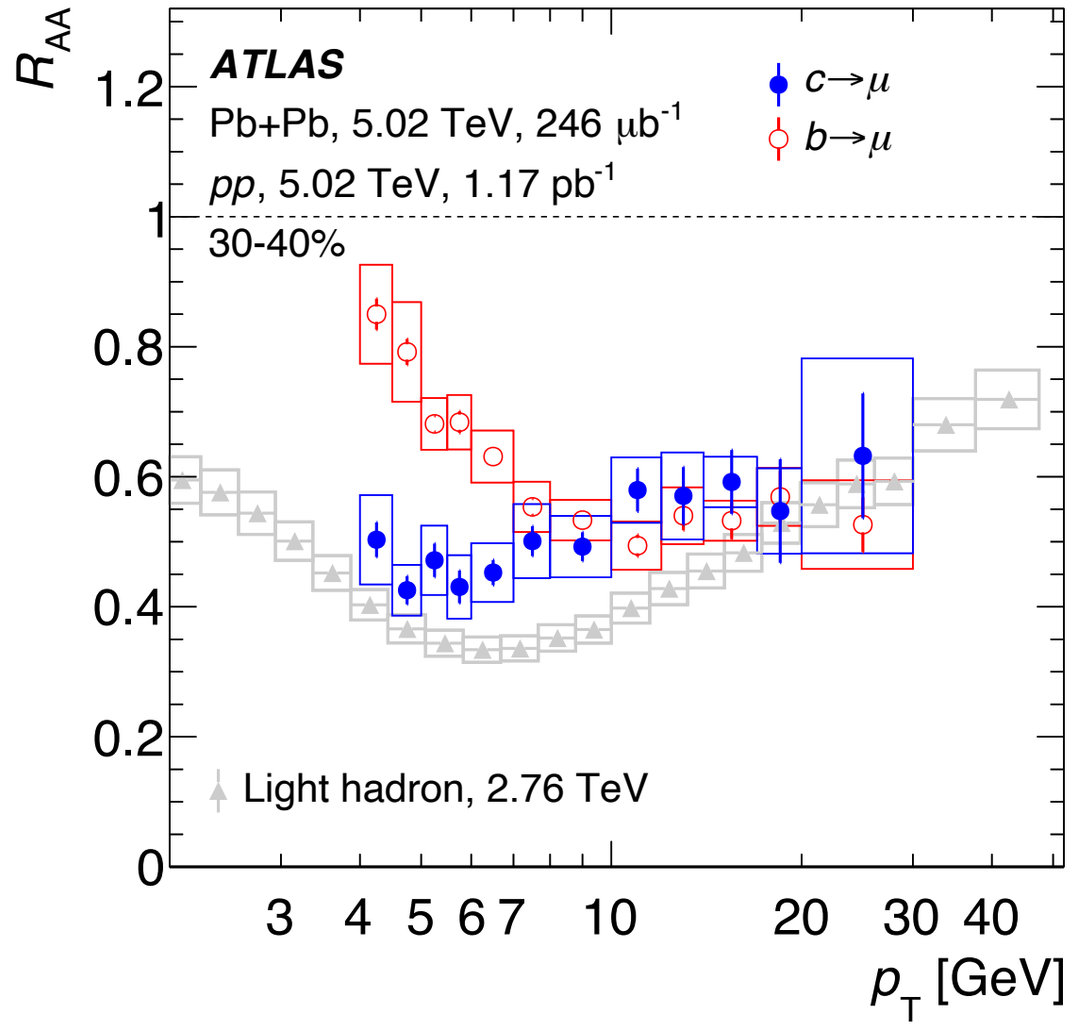


Charm/bottom muon difference

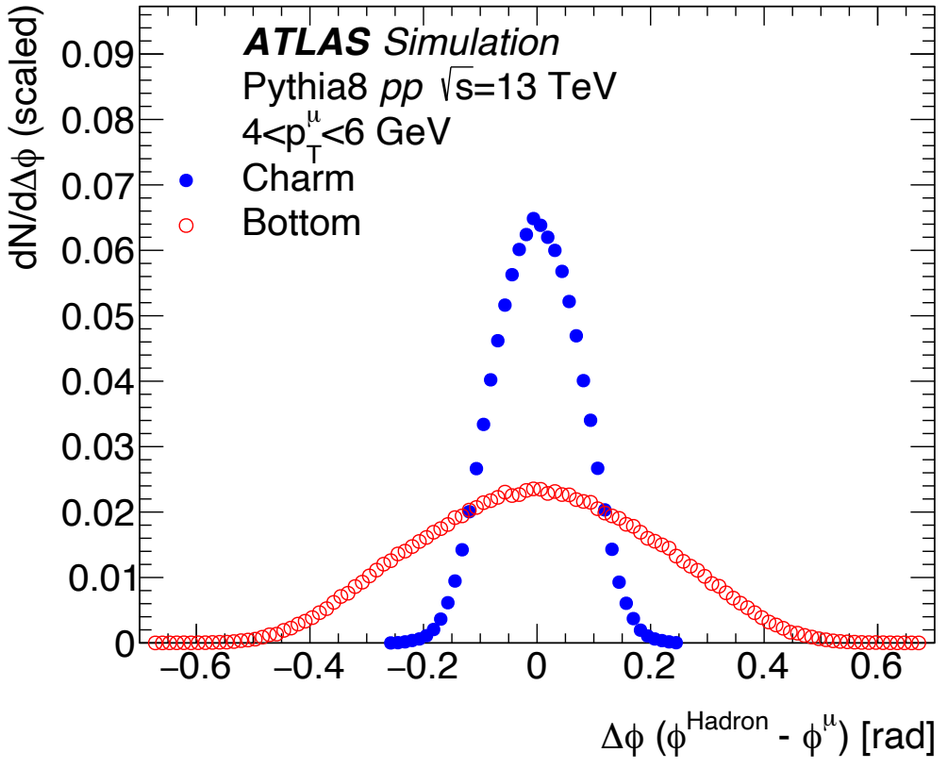
Other centrality bins can be found at web

Compare to light hadrons

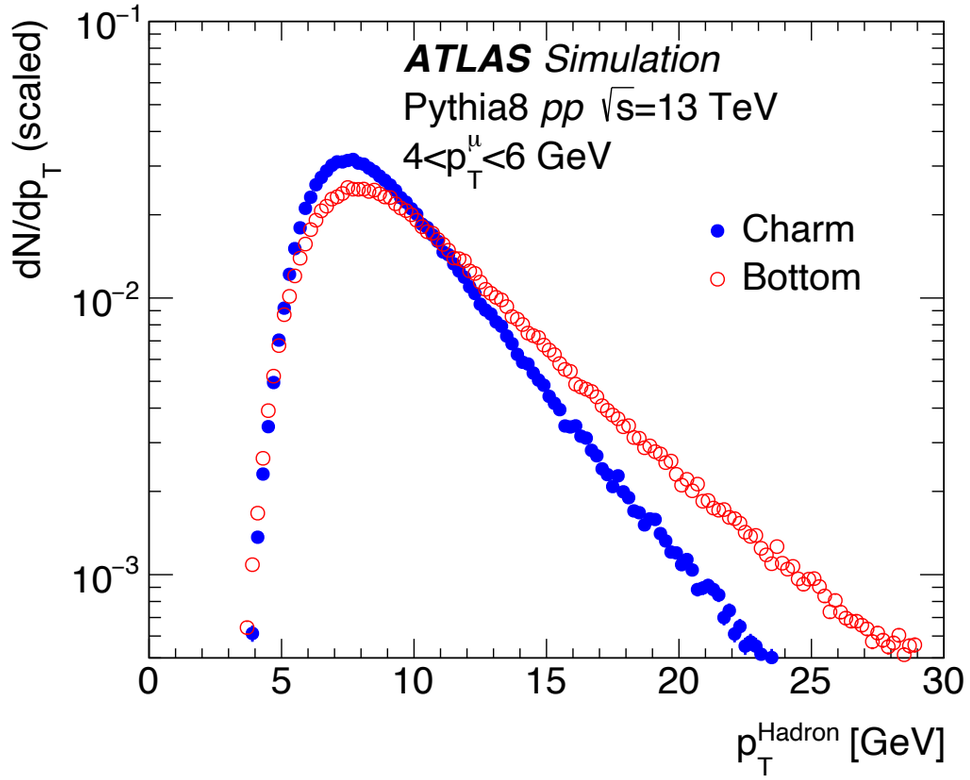




Hadron to muon smearing in Pythia



azimuthal angle smearing



p_T shift and smearing