

online

Production and azimuthal anisotropy of muons from heavy flavor decays in small and large systems with ATLAS

Qipeng Hu

for the ATLAS Collaboration

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University of Colorado
Boulder



Motivation

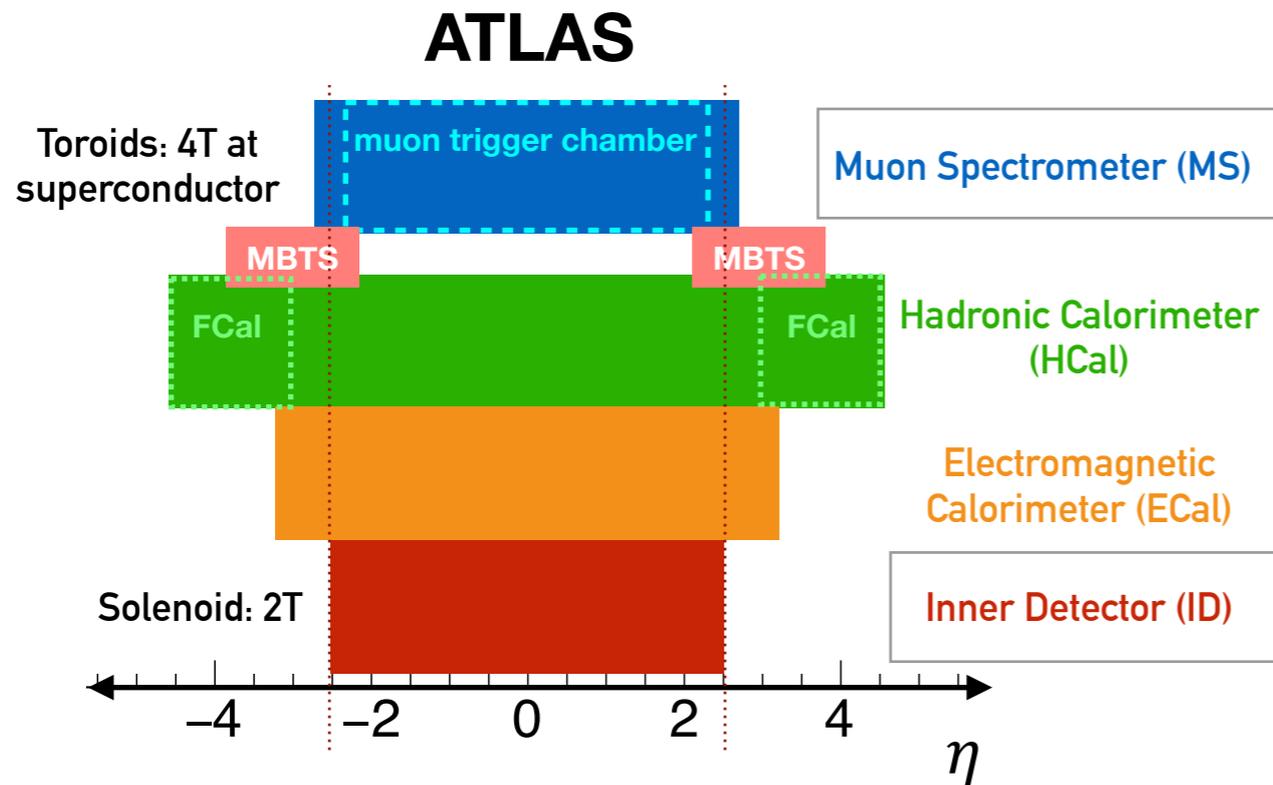
Heavy-flavor (HF) quarks, charm and bottom, are expected to be produced isotropically prior to QGP medium formation in A+A collisions

HF interacts with QGP → suppression and azimuthal anisotropy wrt. its vacuum production. Provide constraint on transport / medium properties

HF azimuthal anisotropy in small system helps to understand origin of small system flow

Muon from HF hadron decays is used as a proxy to study HF in ATLAS

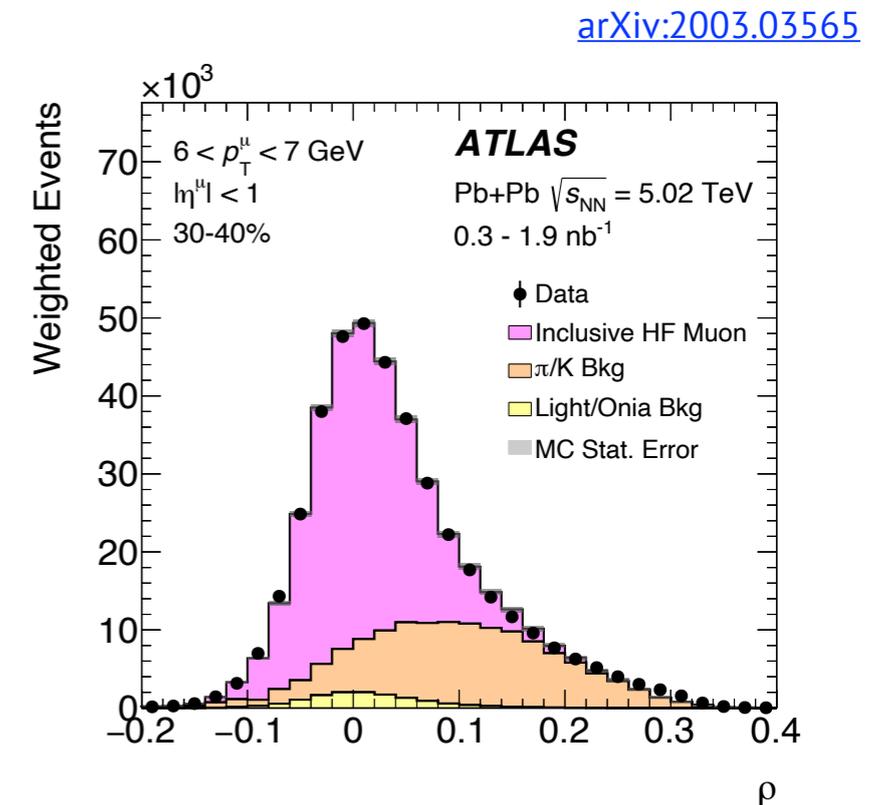
HF muon identification



Muon identified as combination of **ID** and **MS** tracks

Background:

- muon background: light resonances, EW bosons and quarkonia
- hadron background: punch-through and π/K decay-in-flight



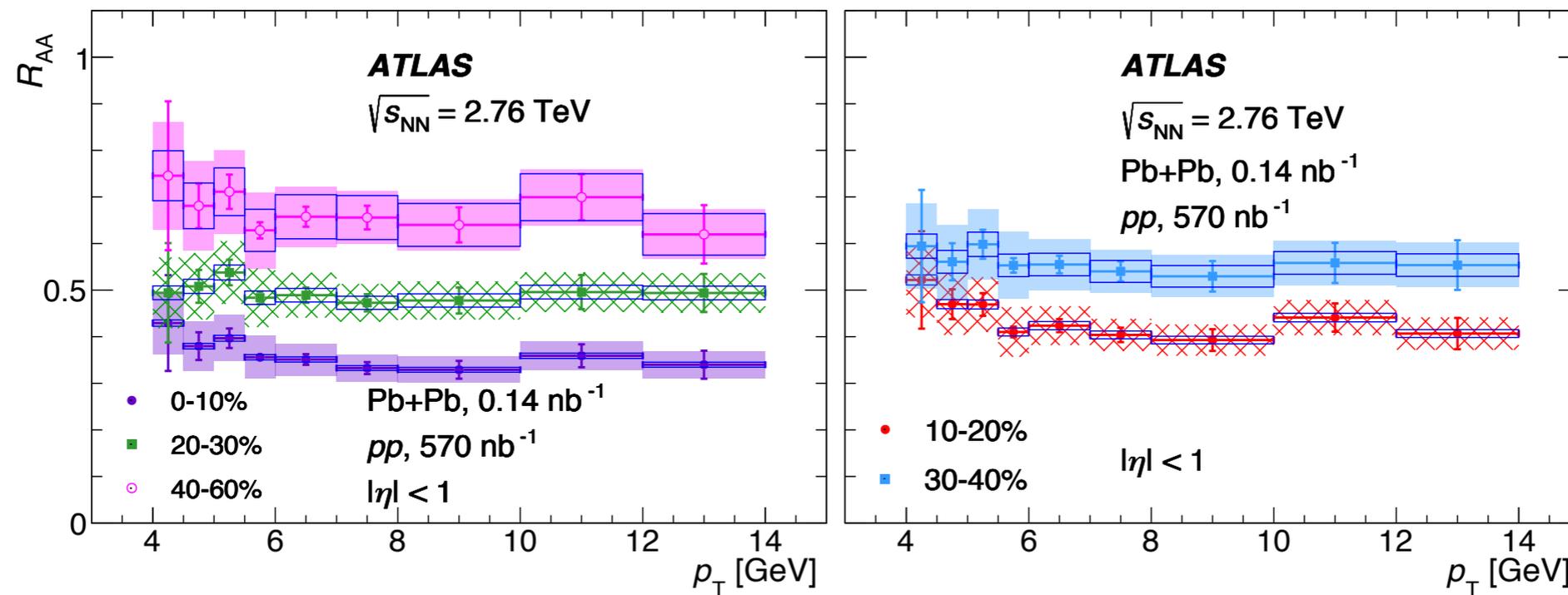
Momentum imbalance:

$$\rho = (p^{\text{ID}} - p^{\text{MS}}) / p^{\text{ID}}$$

- MC simulation
- Momentum imbalance fit

Inclusive HF muon R_{AA}

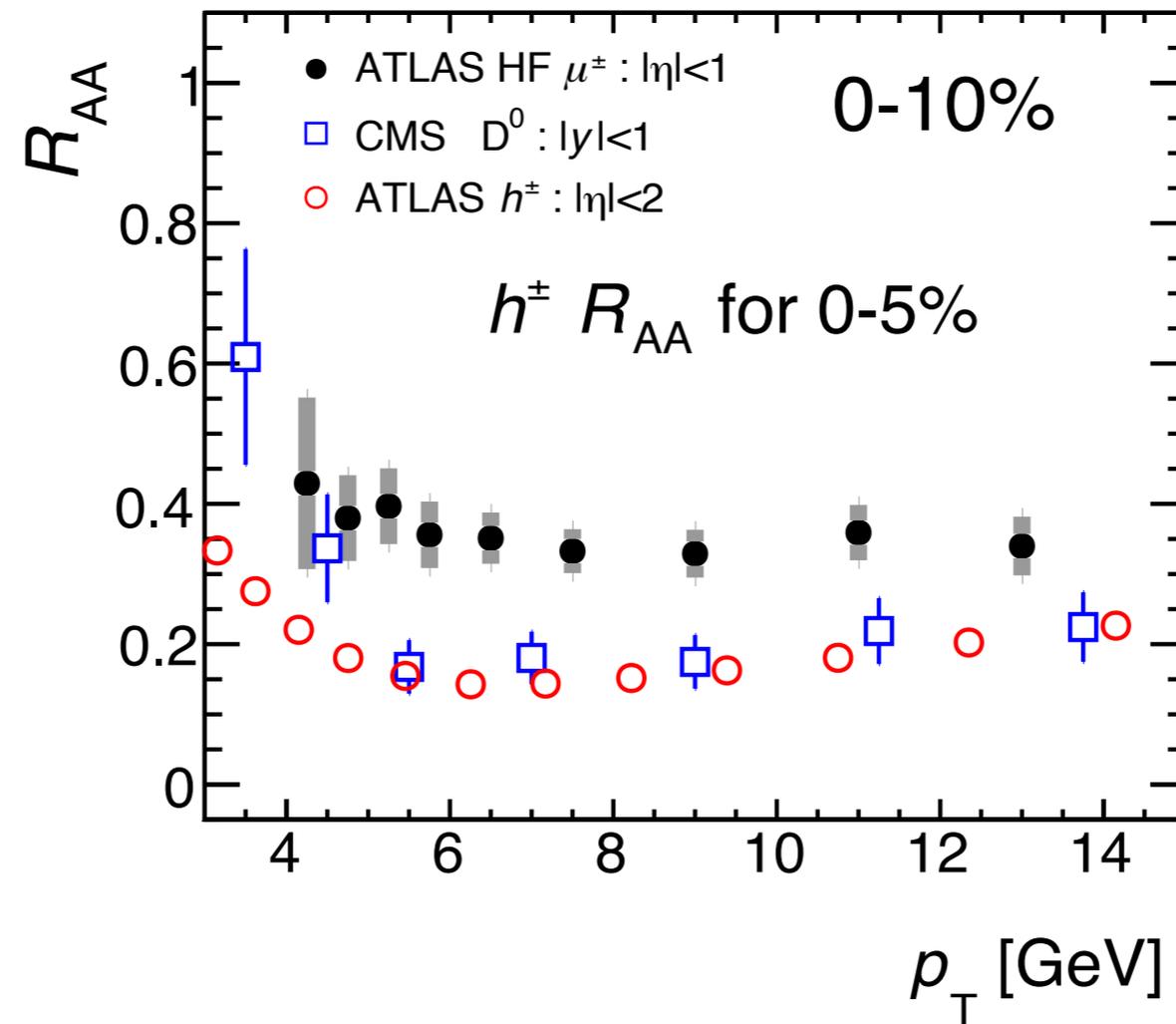
[arXiv: 1805.05220](https://arxiv.org/abs/1805.05220)



- HF muon R_{AA} measurement based on Run1 data at 2.76 TeV
- Significant suppression with clear centrality ordering
- No significant dependence on p_T

Inclusive HF muon R_{AA}

[arXiv: 1805.05220](https://arxiv.org/abs/1805.05220)

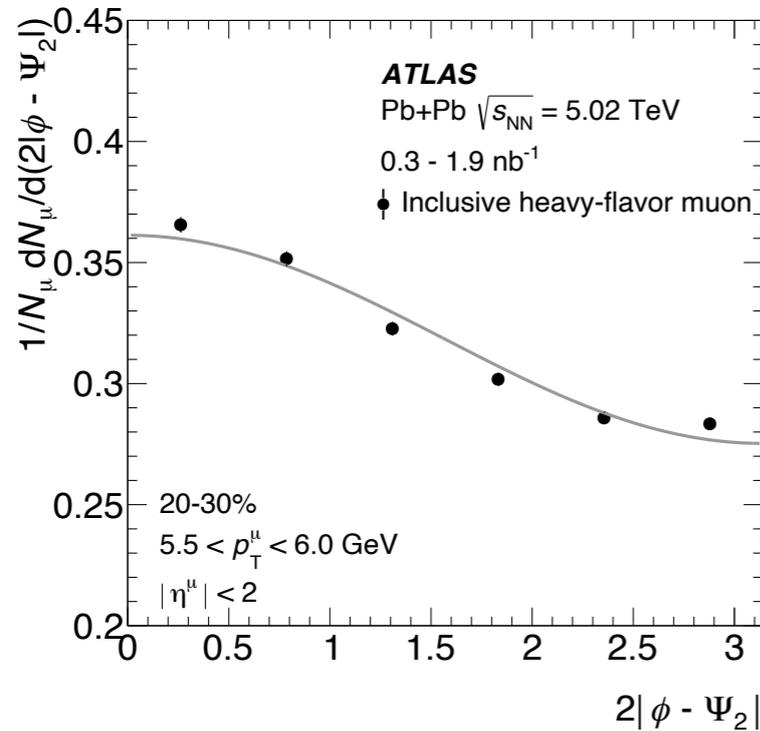


Inclusive HF muon vs. prompt D^0

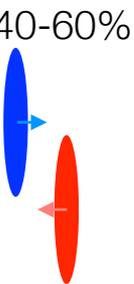
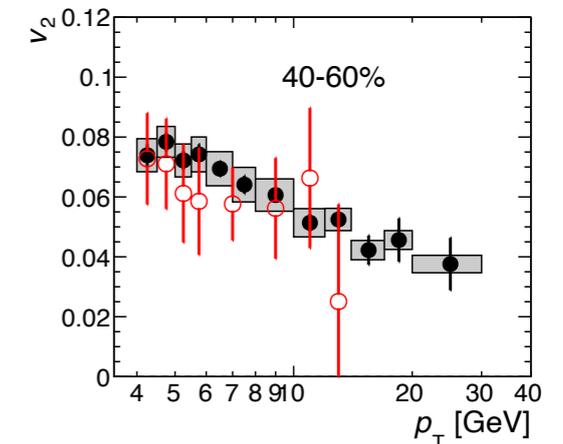
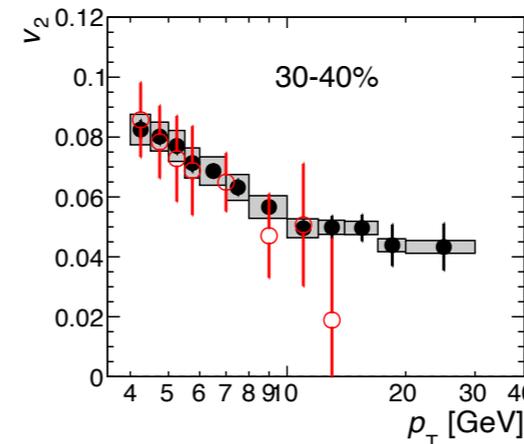
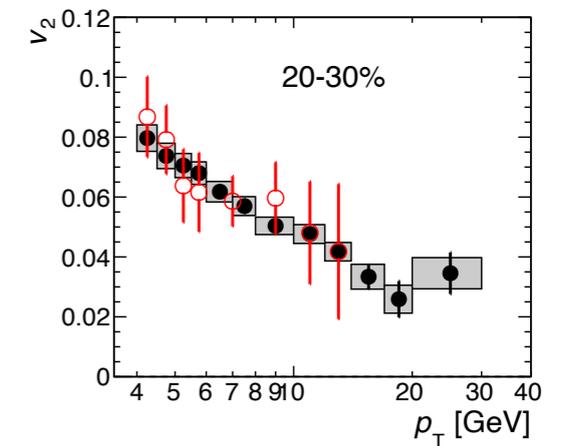
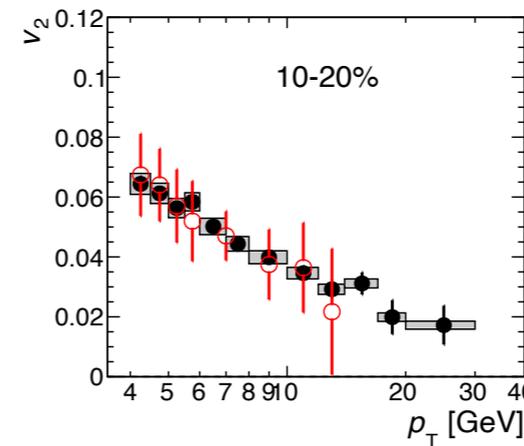
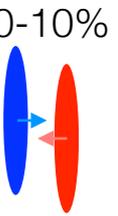
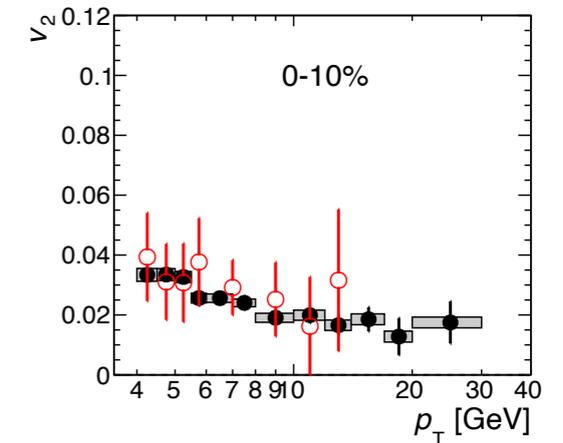
- Similar suppression at $p_T \sim 4$ GeV
- Less suppression of HF muon at higher $p_T \rightarrow$ indication of bottom less suppressed than charm

HF muon azimuthal anisotropy in Pb+Pb

[arXiv:2003.03565](https://arxiv.org/abs/2003.03565)



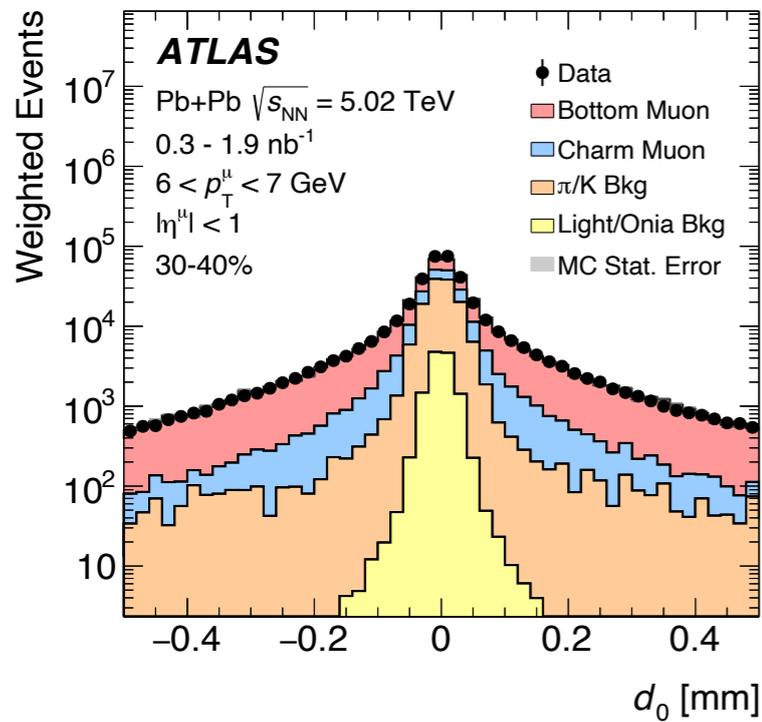
ATLAS
0.3 - 1.9 nb⁻¹
Inclusive heavy-flavor muon
 $|\eta^\mu| < 2$
◆ 2015+2018 Pb+Pb 5.02 TeV
◇ 2011 Pb+Pb 2.76 TeV



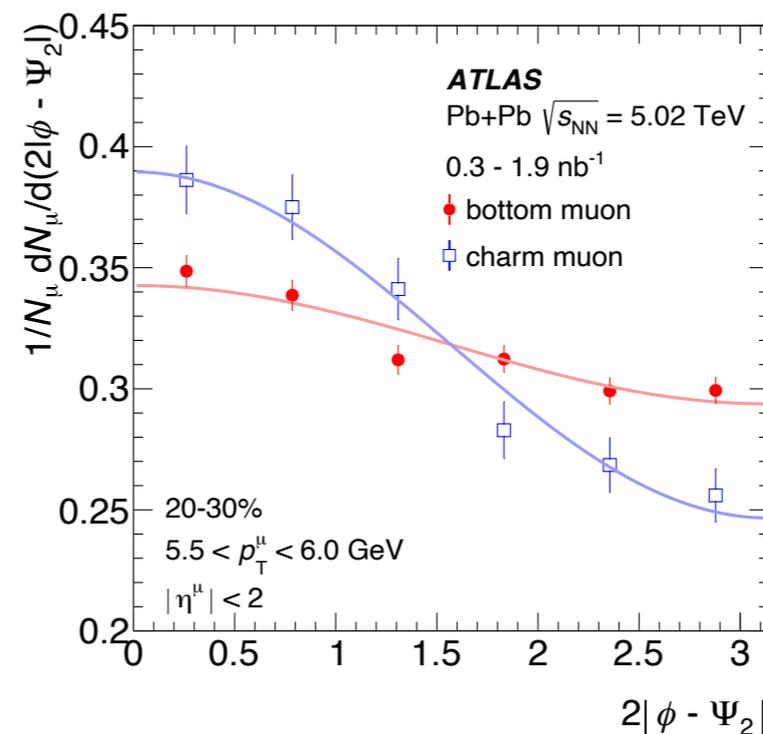
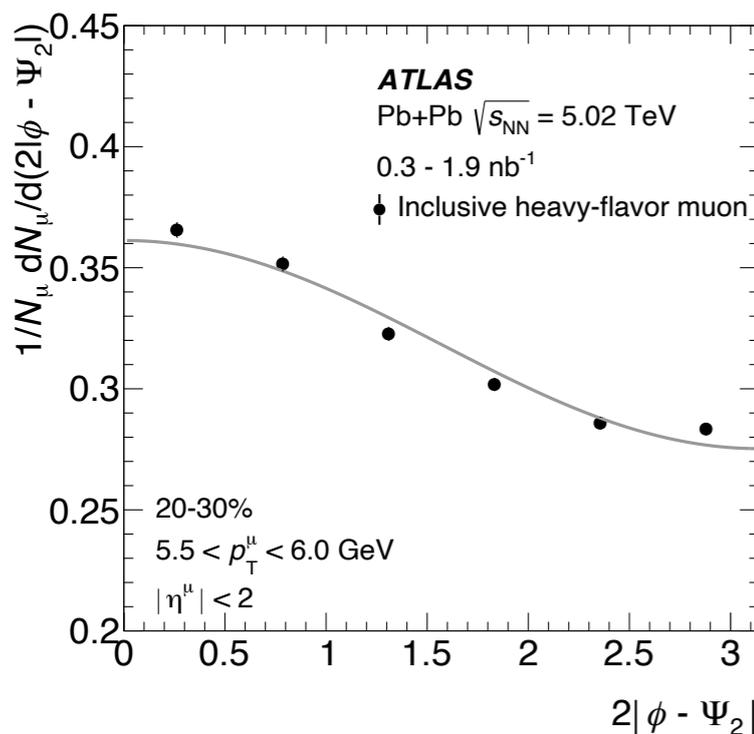
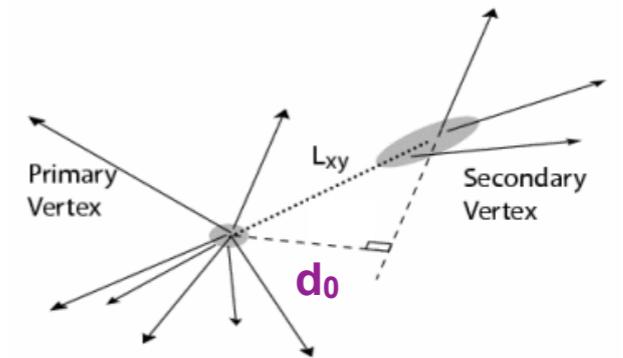
- Event-plane method
- **Run1 2.76 TeV** and **Run2 5.02 TeV** results in good consistency
- Significant v_2 up to $p_T \sim 20$ GeV

Charm and bottom muon separation

[arXiv:2003.03565](https://arxiv.org/abs/2003.03565)



- Charm/bottom separation via transverse impact parameter: d₀
- Bkg contribution fixed at simulated values or momentum imbalance fit results



Charm and bottom muon v_2 in Pb+Pb

[arXiv:2003.03565](https://arxiv.org/abs/2003.03565)

ATLAS

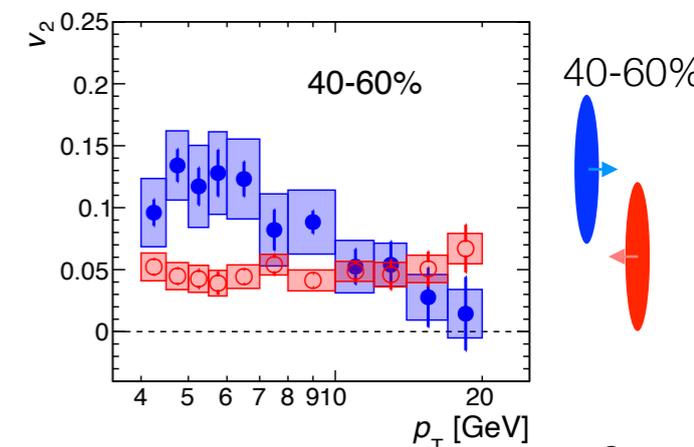
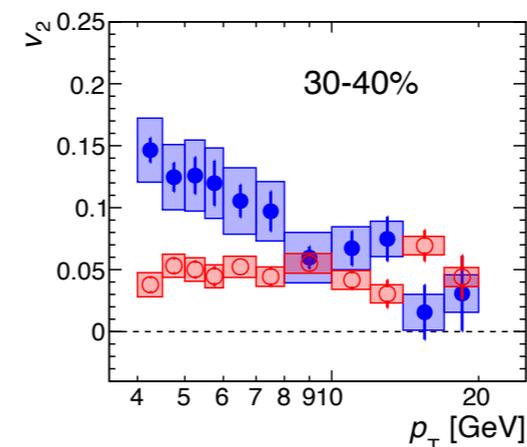
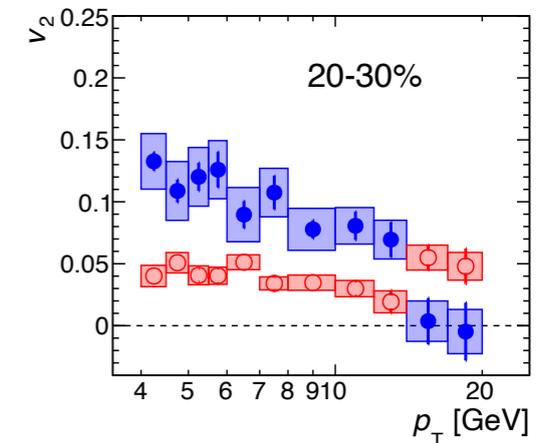
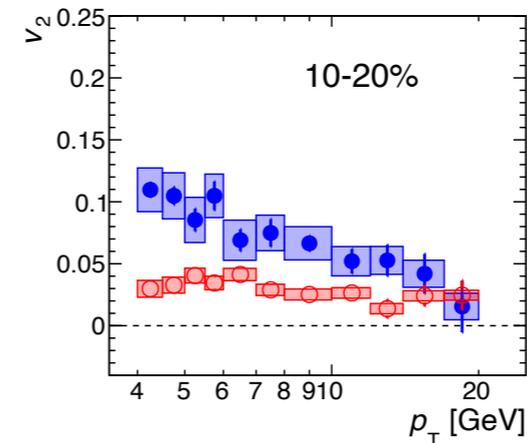
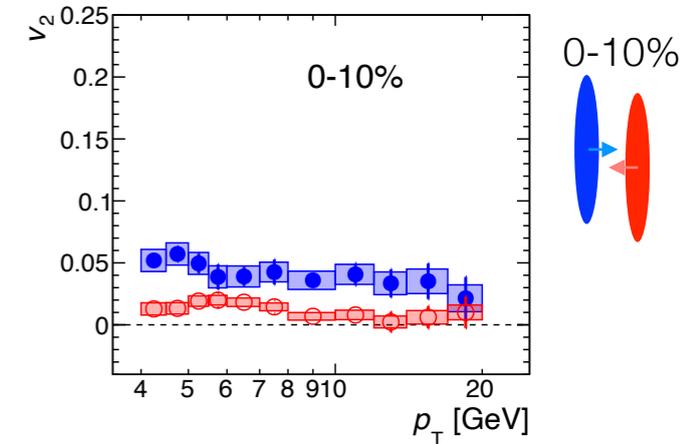
Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

0.3 - 1.9 nb⁻¹

$|\eta^{\mu}| < 2$

• charm muon

• bottom muon



Significant non-zero v_2 for c and b muon

- $v_2(\mathbf{c}) > v_2(\mathbf{b})$ at low p_T
- $v_2(\mathbf{c}) \sim v_2(\mathbf{b})$ at high p_T
- Anti-correlated stat. uncertainty ($\rho = -0.9$)

Charm and bottom muon v_3 in Pb+Pb

[arXiv:2003.03565](https://arxiv.org/abs/2003.03565)

ATLAS

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

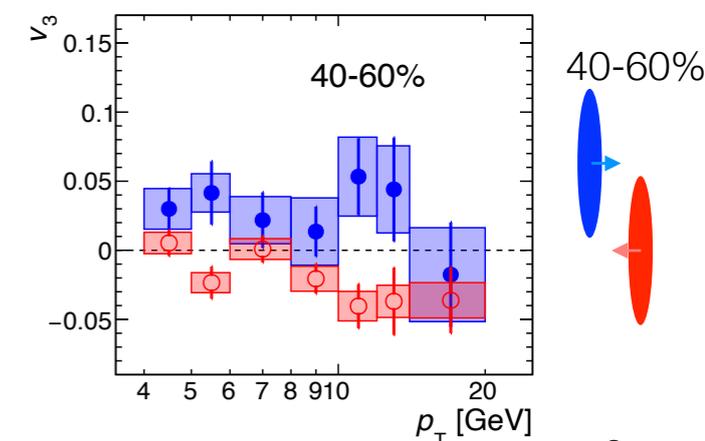
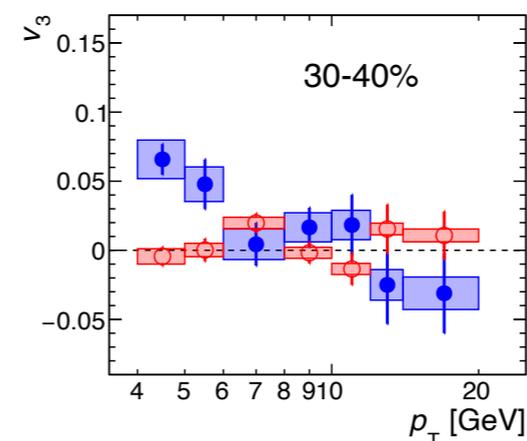
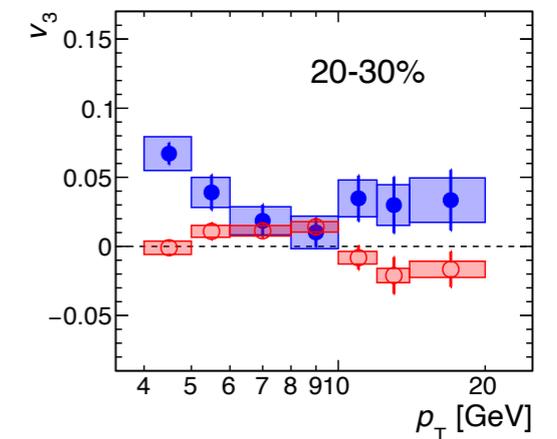
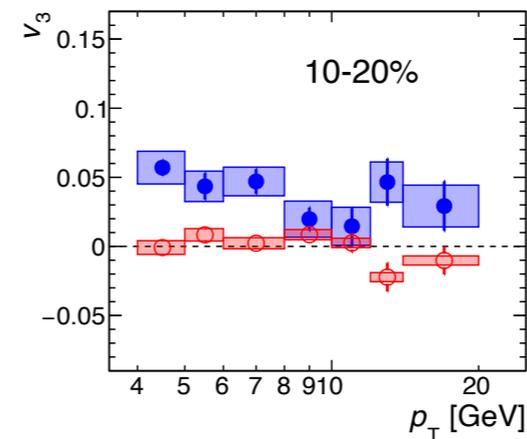
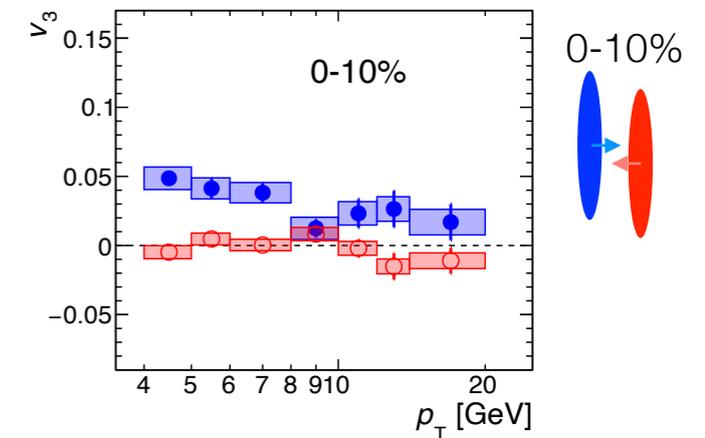
0.3 - 1.9 nb^{-1}

$|\eta^{\mu}| < 2$

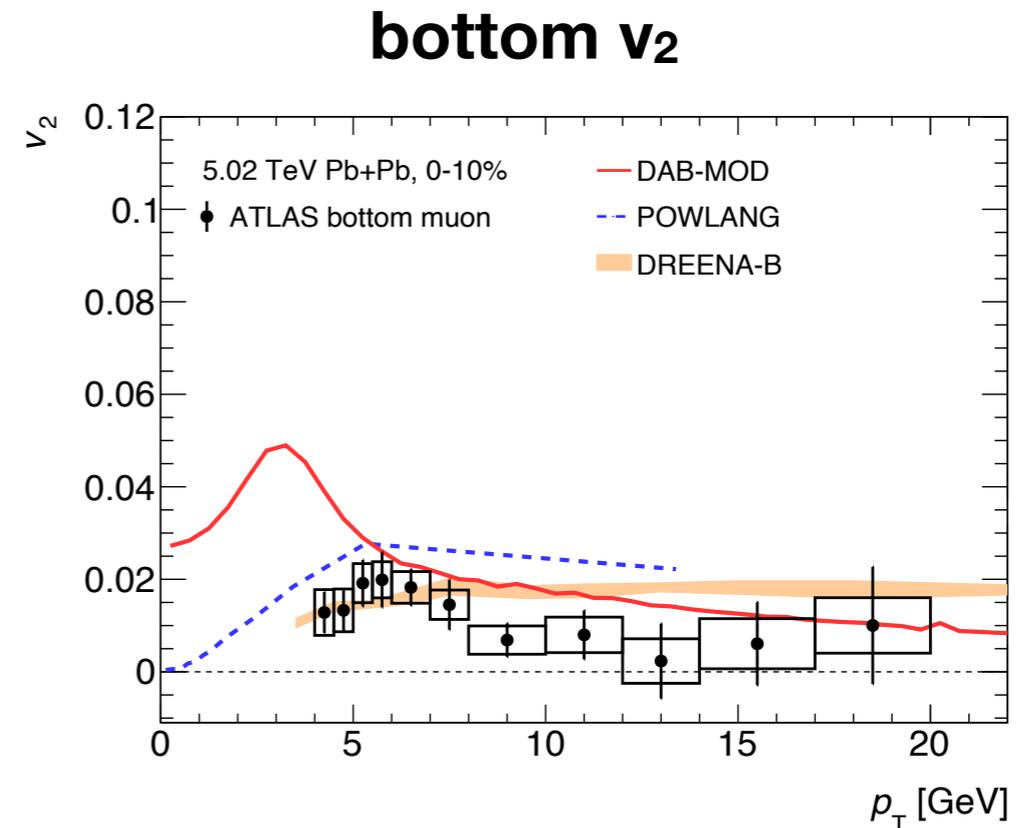
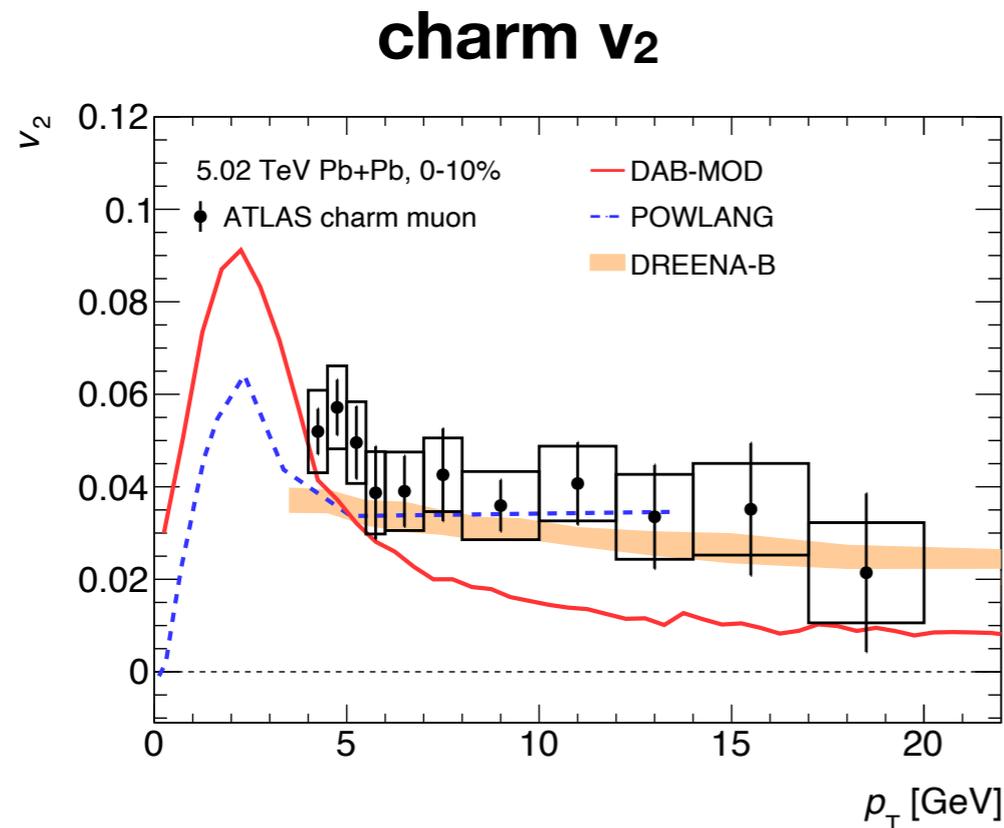
• charm muon

◊ bottom muon

- $v_3(\text{c}) \sim 2\text{-}5\%$
- $v_3(\text{b}) \sim 0$
- No obvious centrality dependence at high p_T



v_2 vs. selected calculations



- **DAB-MOD** Langevin
- **POWLANG** Langevin (collisional E_{loss})
- **DREENA-B** 1+1D ideal medium, dynamical radiative and collisional E_{loss}

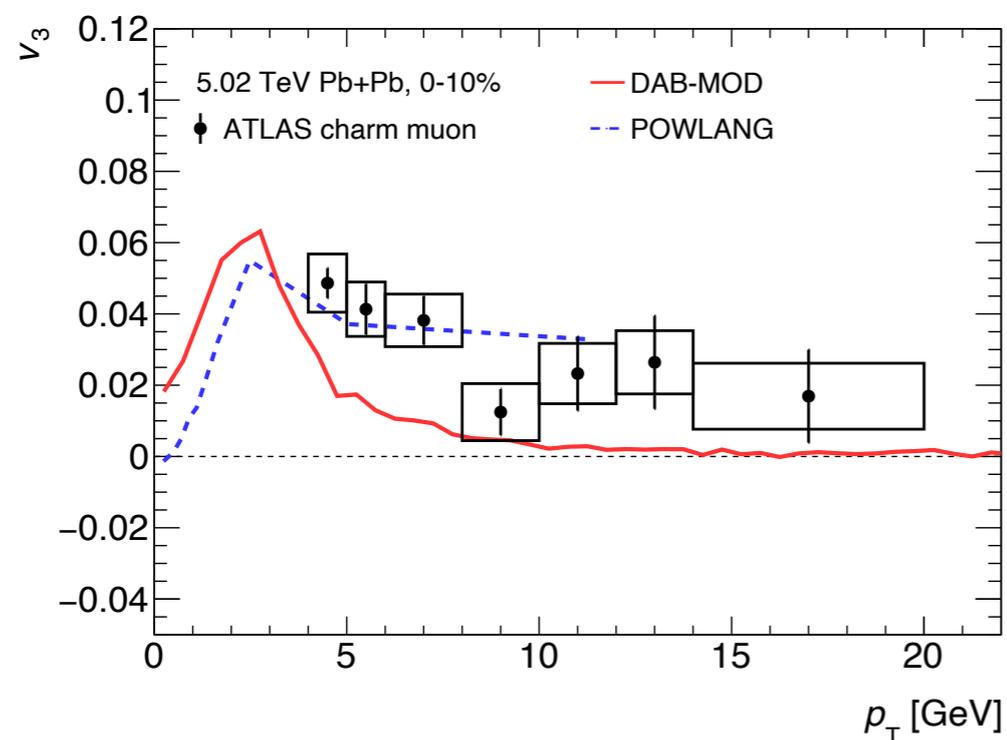
DAB-MOD [arXiv:1906.10768](https://arxiv.org/abs/1906.10768)
 POWLANG [arXiv:1712.00588](https://arxiv.org/abs/1712.00588)
 DREENA-B [arXiv:1805.04786](https://arxiv.org/abs/1805.04786)
 Data points [arXiv:2003.03565](https://arxiv.org/abs/2003.03565)

For HF muon $4 < p_T < 20$ GeV

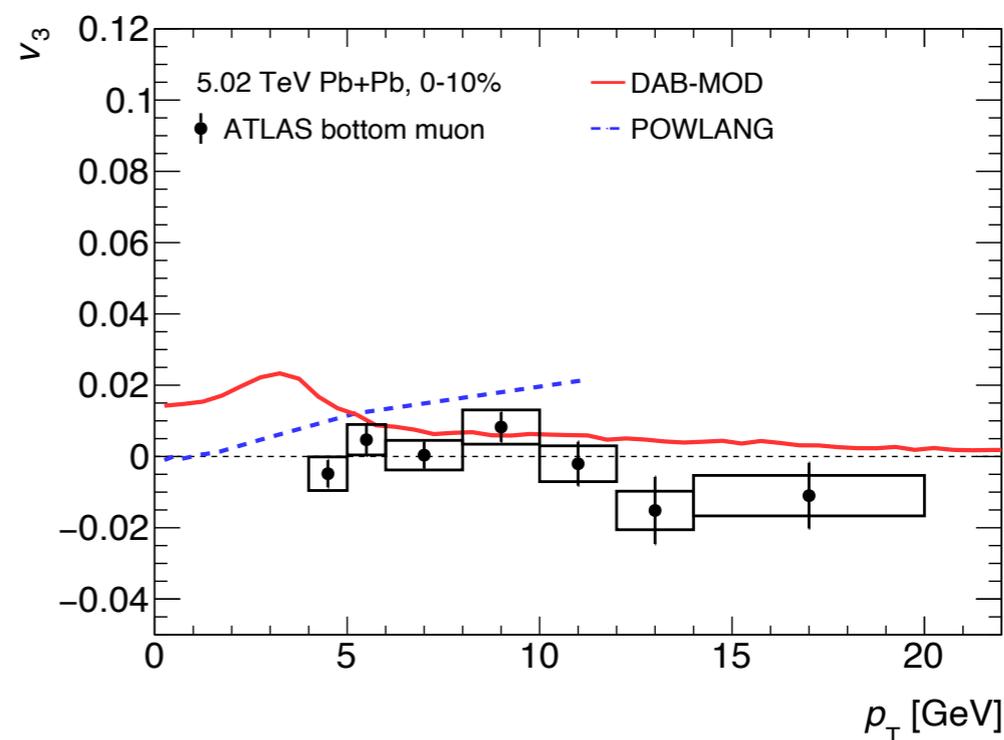
- Path-length dependence of E_{loss} are driven the azimuthal anisotropy
- Radiative E_{loss} is needed for simultaneous description of charm and bottom

v_3 vs. selected calculations

charm v_3



bottom v_3



- **DAB-MOD** Langevin
- **POWLANG** Langevin (collisional E_{loss})

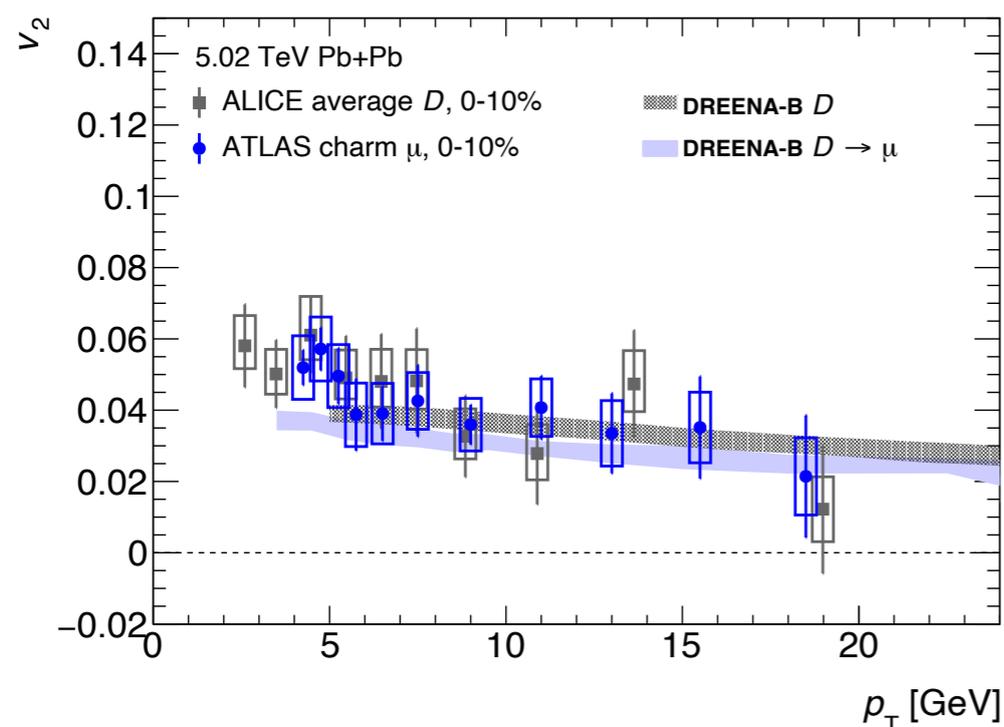
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For HF muon $4 < p_T < 20$ GeV

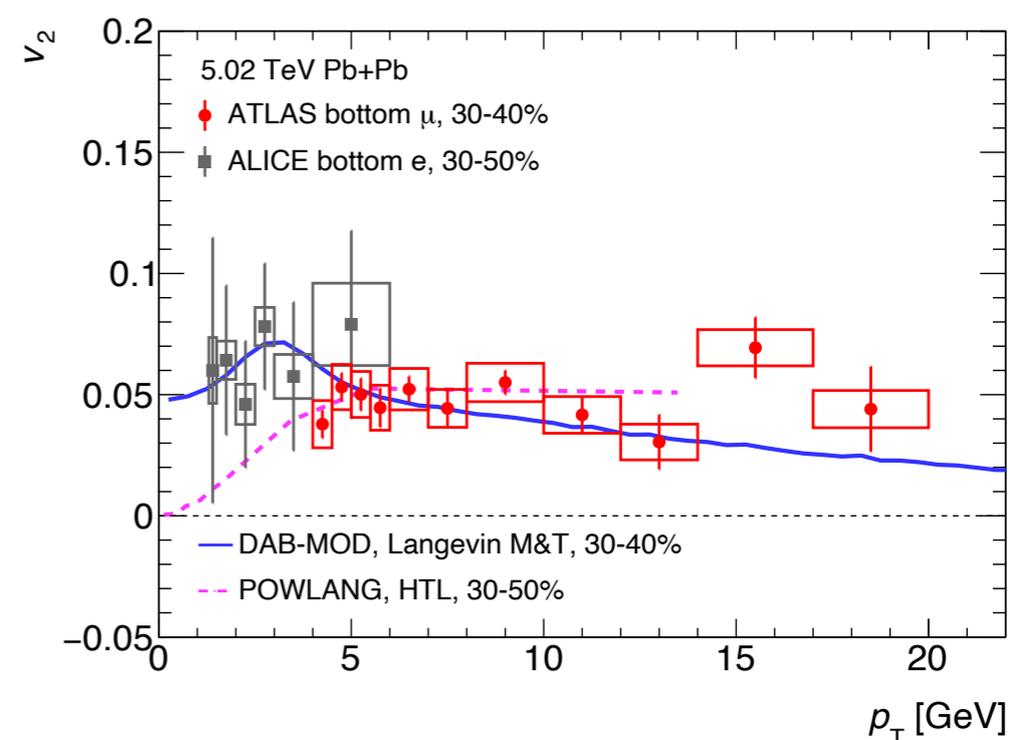
- No simultaneous description yet

Comparison to other experiments

charm muon v_2 vs. D v_2
0-10%



bottom muon v_2 vs bottom e v_2
30-40(50)%

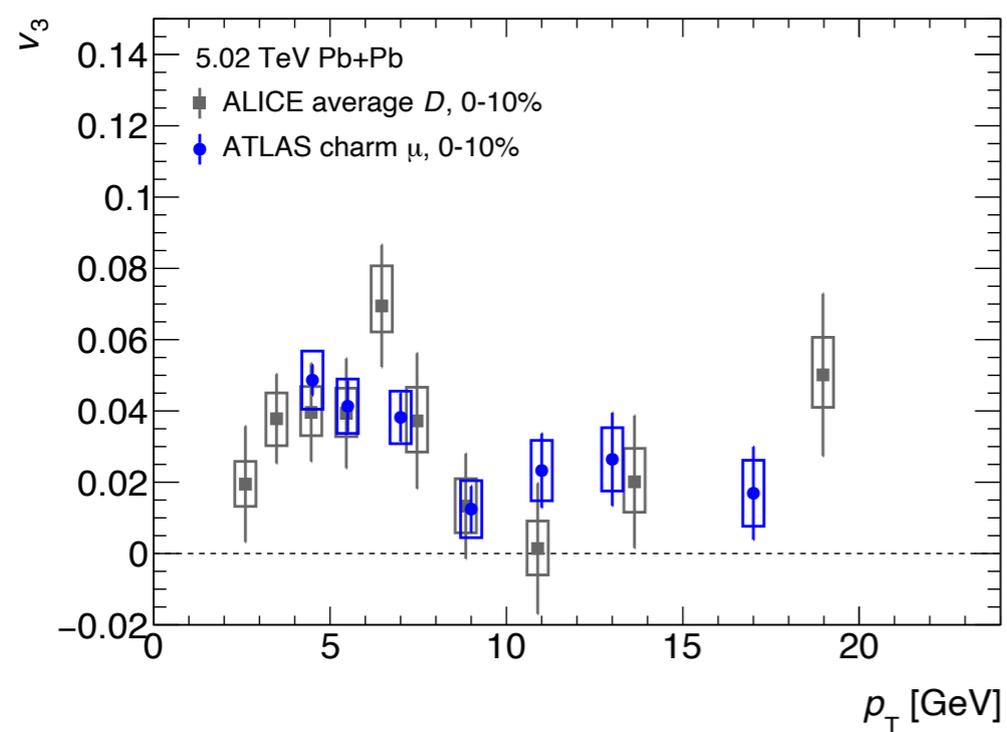


ATLAS [arXiv:2003.03565](https://arxiv.org/abs/2003.03565)
ALICE D [arXiv:2005.11131](https://arxiv.org/abs/2005.11131)
ALICE e [arXiv:2005.11130](https://arxiv.org/abs/2005.11130)

- $v_2(\text{charm } \mu) \approx v_2(D)$, small kinematic smearing due to $D \rightarrow \mu$ decay
- $v_2(\text{bottom } \mu) \sim v_2(\text{bottom } e)$, no clear peak \rightarrow not fully thermalized ?

Comparison to other experiments

charm muon v_3 vs. D v_3 0-10%

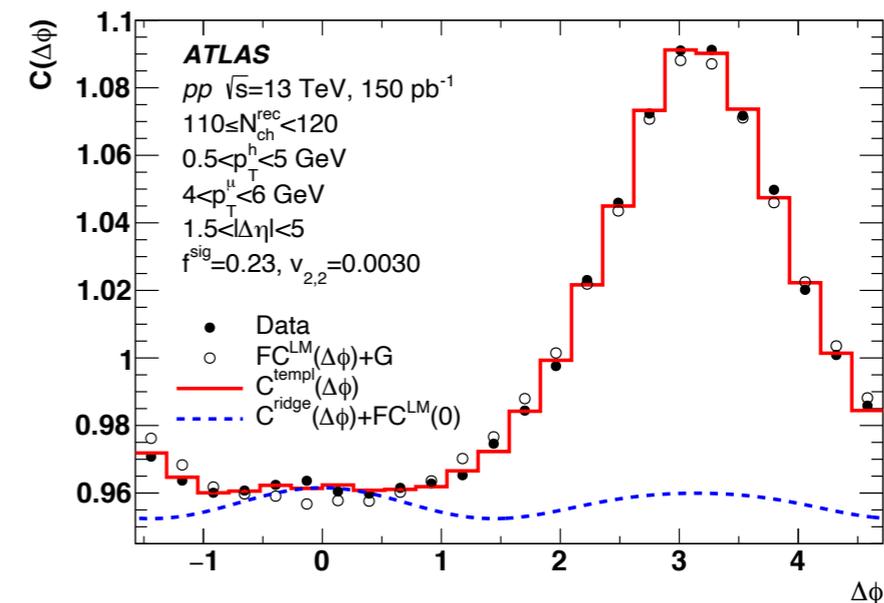
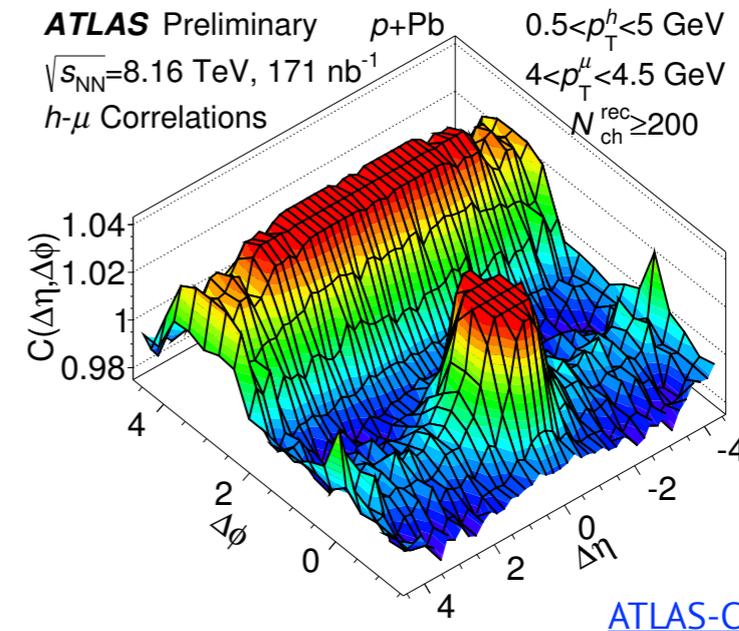


ATLAS [arXiv:2003.03565](https://arxiv.org/abs/2003.03565)
ALICE D [arXiv:2005.11131](https://arxiv.org/abs/2005.11131)

- Excellent agreement despite small kinematic smearing due to decay

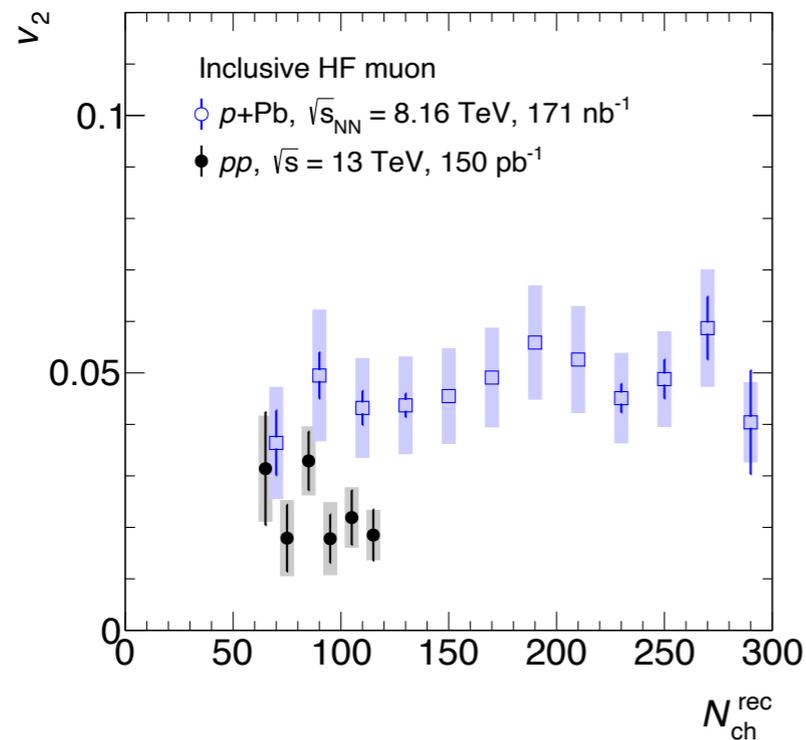
HF muon-hadron 2PC in small systems

- Small system flow extracted from muon-hadron two-particle correlation
- Non-flow contribution subtracted using non-flow subtraction template fit
- Background contribution removed statistically based on momentum imbalance

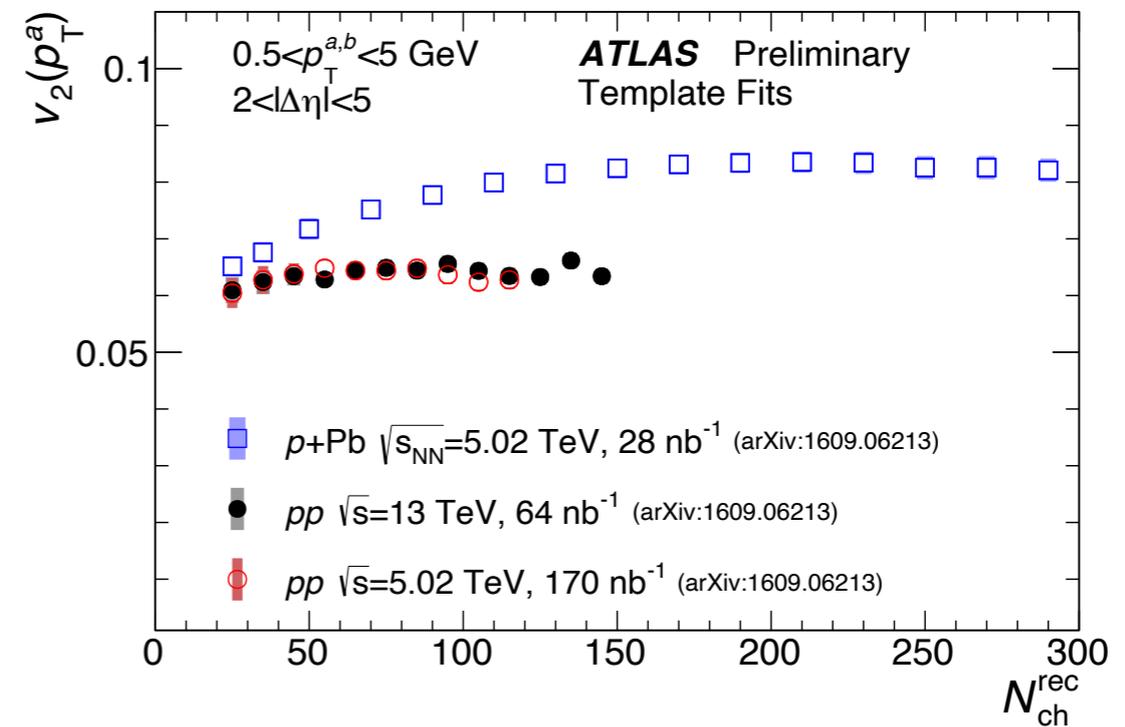


HF muon flow in small systems

HF muon



charged hadron

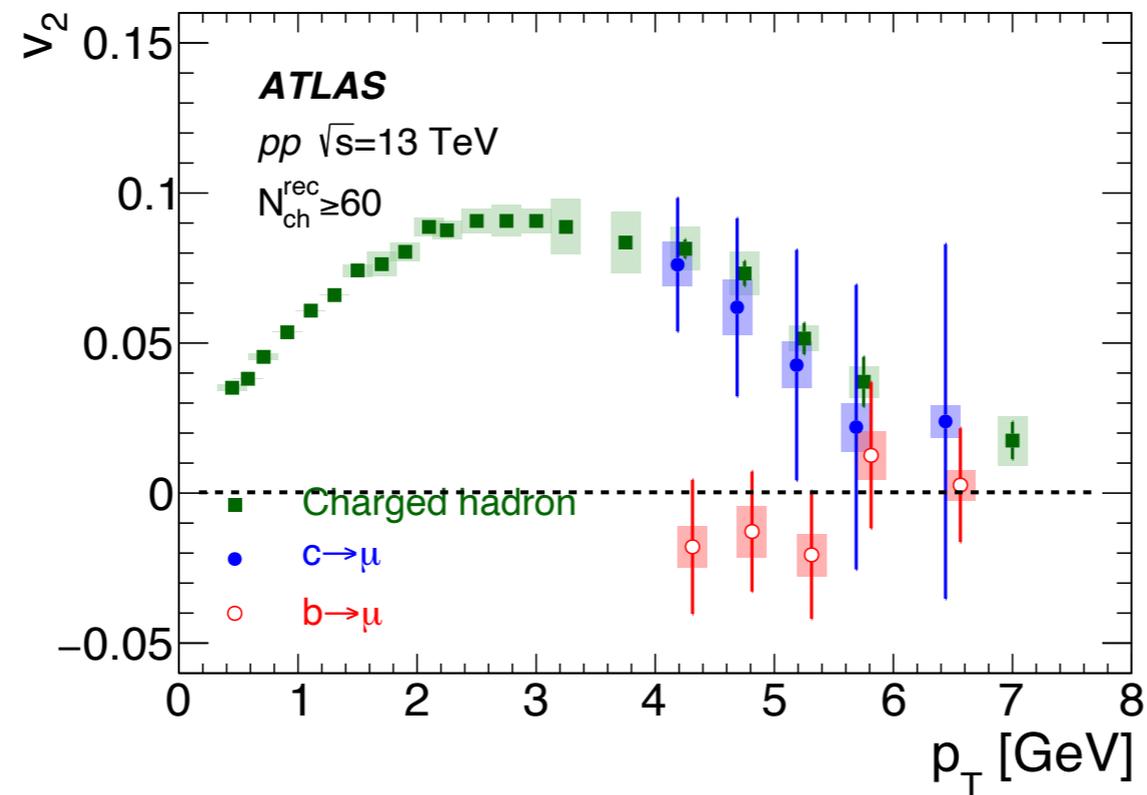


[ATLAS-CONF-2017-006](#)

[Phys. Rev. Lett. 124 \(2020\) 082301](#)

- Smaller but non-zero v_2 for muons than charged hadron in both pp and p +Pb
- Similar difference between pp and p +Pb
- Same origin of flow for light- and heavy-flavor particle?

Charm/bottom muon v_2 in pp



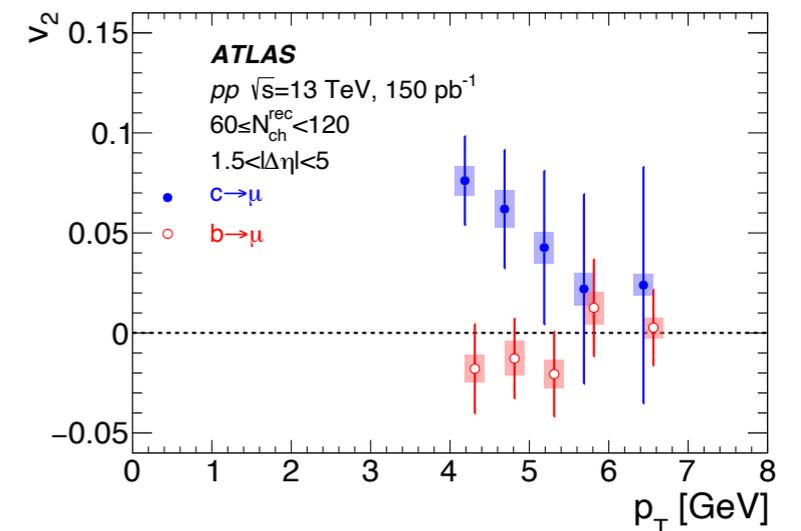
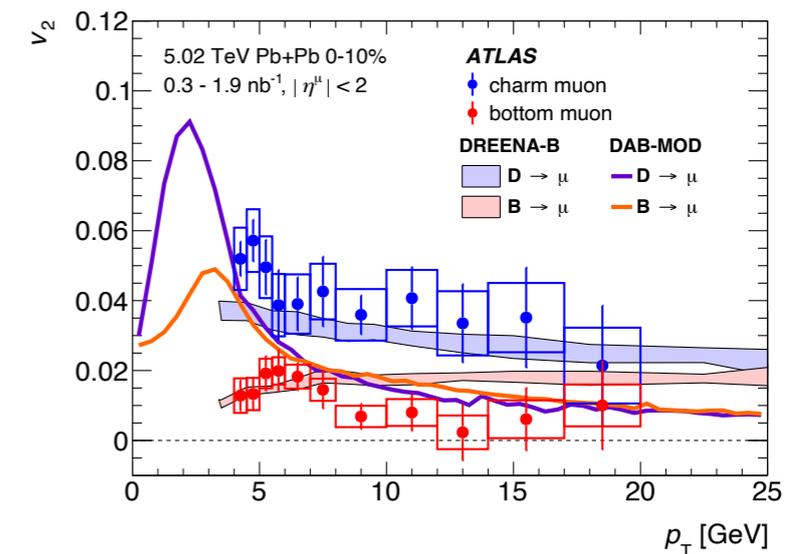
[Phys. Rev. Lett. 124 \(2020\) 082301](#)
 charged hadron [arXiv:1609.06213](#)

After separating charm / bottom in pp :

- Charm muon $v_2 \sim$ charged hadron v_2
- Bottom muon $v_2 \sim 0$
- Clear quark dependence of muon v_2 , challenge to both initial and final state interactions
- More data would help

Summary

- HF muon R_{AA} : indications of less bottom suppression than charm; charm/bottom separated muon R_{AA} is coming soon
- HF muon flow in Pb+Pb: v_2 consistent with path-length dependence of E_{loss}
- HF muon flow in pp : charm is like light hadron while bottom has zero v_2

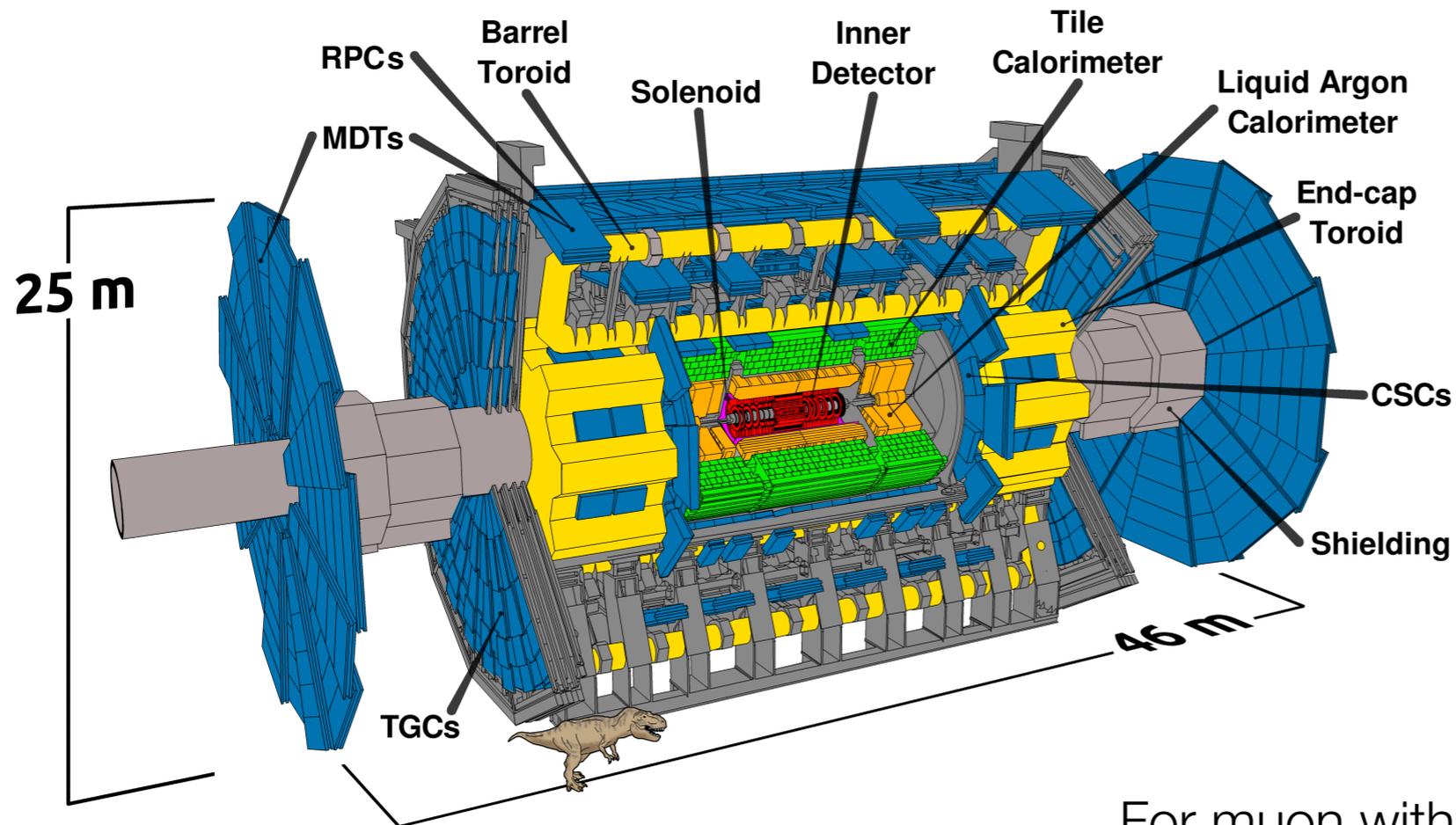


Related publications

- Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at 5.02 TeV with the ATLAS detector, [arXiv:2003.03565](#)
- Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at 13 TeV with the ATLAS detector, [arXiv:1909.01650](#), *Phys. Rev. Lett.* [124 \(2020\) 082301](#)
- Measurement of the suppression and azimuthal anisotropy of muons from heavy-flavor decays in Pb+Pb collisions at 2.76 TeV with the ATLAS detector, [arXiv:1805.05220](#), *Phys. Rev. C* [98 \(2018\) 044905](#)

Backup

ATLAS detector

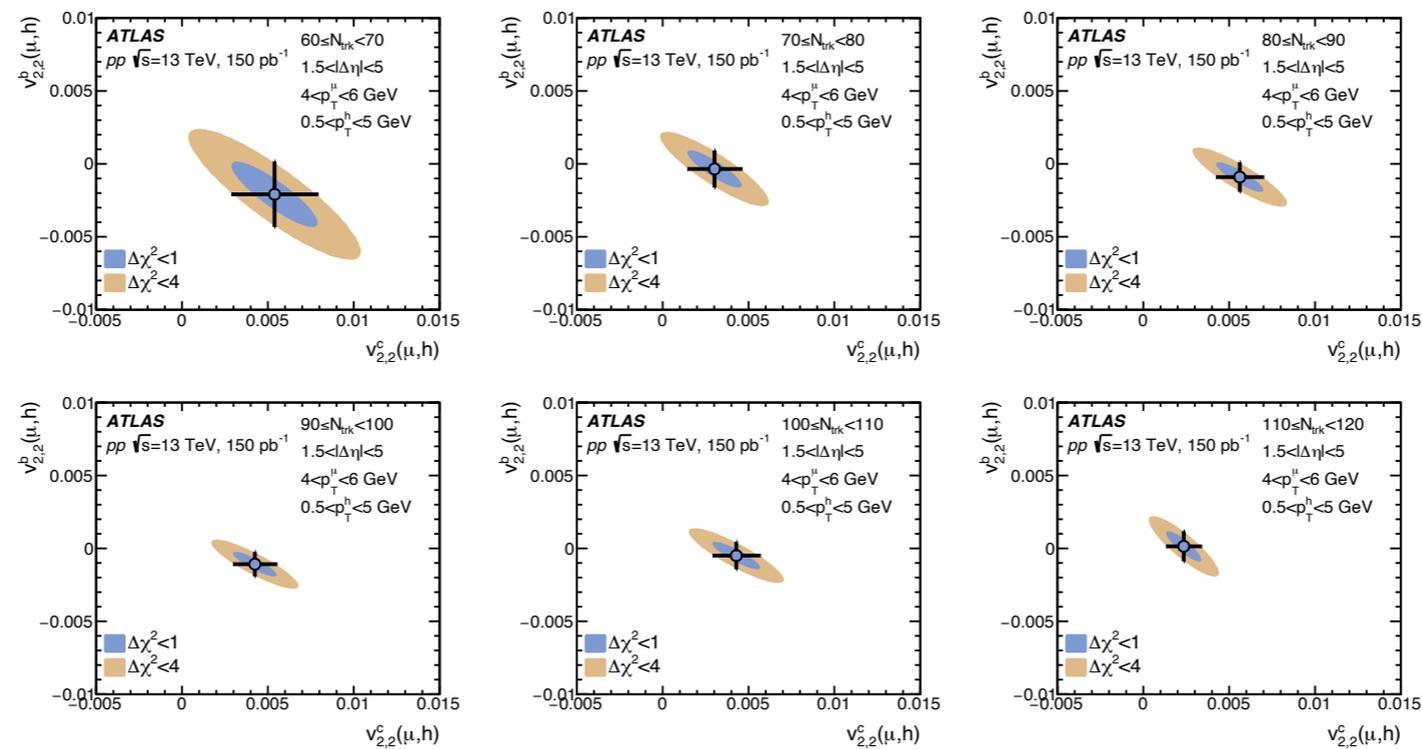


For muon with $p_T = 5$ GeV, $\eta = 0$:

- d_0 resolution ~ 0.020 mm
- ID p_T resolution $\sim 2\%$
- MS p_T resolution $\sim 6\%$

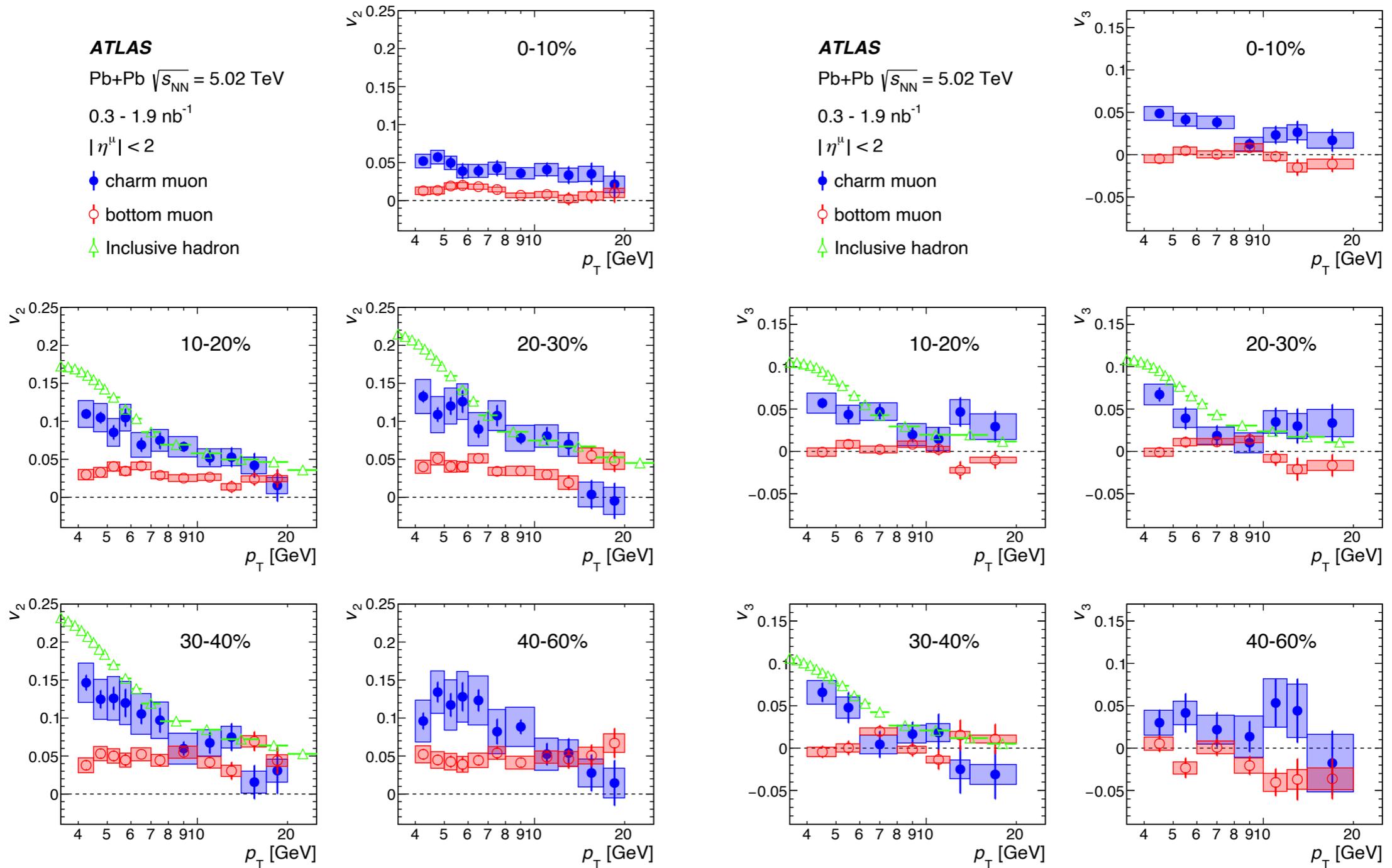
Correlations between c and b results

[Phys. Rev. Lett. 124 \(2020\) 082301](#)



Due to the methodology of the b/c separation, the results are anti-correlated. Statistical correlation of the results are also provided by ATLAS for theorists to perform a simultaneous comparison to charm and bottom results

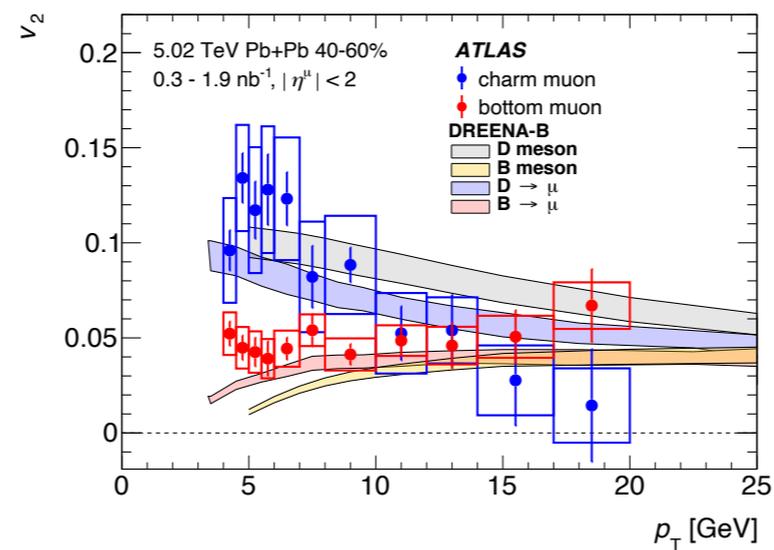
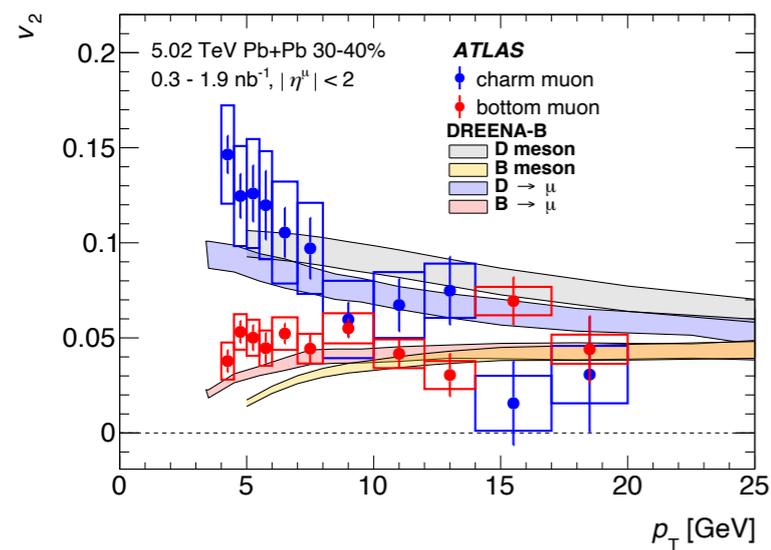
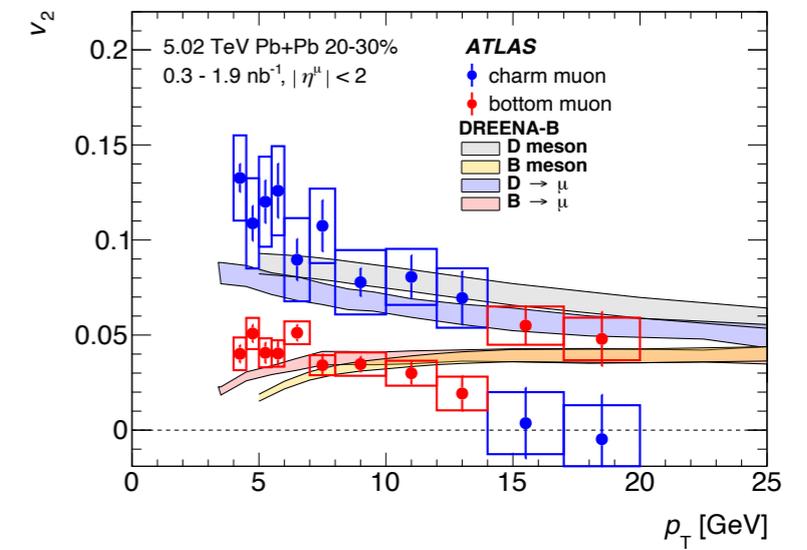
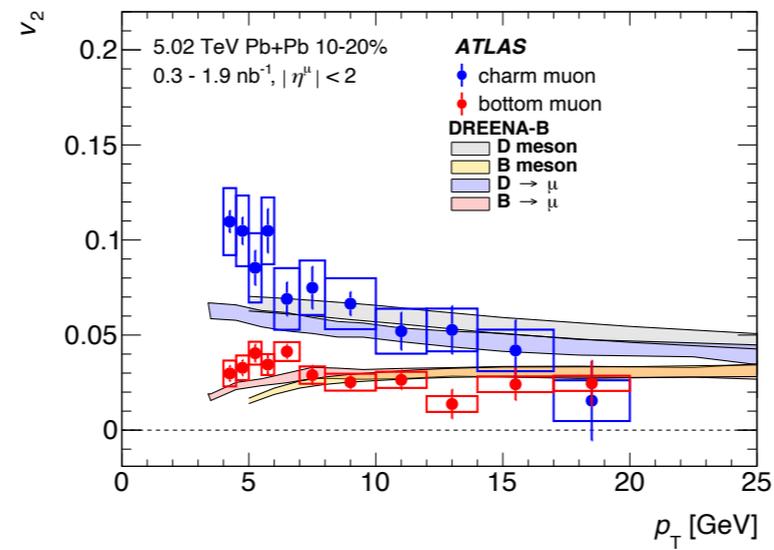
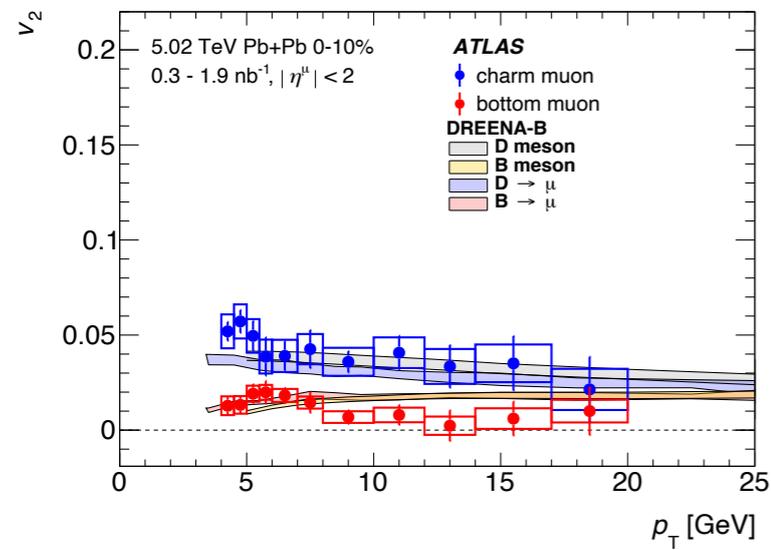
HF muon vs. hadron in Pb+Pb



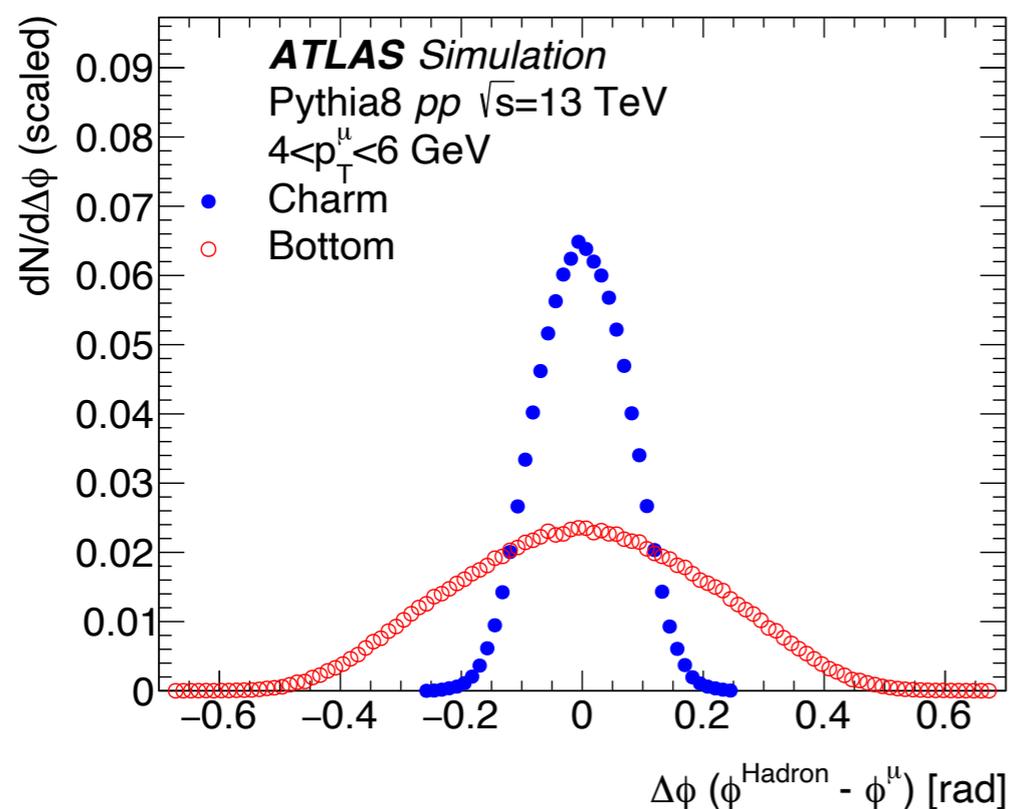
Calculations for HF flow in Pb+Pb

- **DREENA-B** ([1805.04786](#)): 1+1D static medium, dynamical radiative + collisional energy loss; uncertainty from varying magnetic to electric mass ratio
- **DAB-MOD** ([1906.10768](#)): 2+1D medium, TRENTO initial geometry, Langevin M&T with $2\pi TD_s = 2.23$ (2.79) for charm (bottom)
- **POWLANG** ([1712.00588](#)): 2+1D medium, Glauber-MC initial geometry, Langevin with HTL transport coefficients ($2\pi TD_s \sim 3$)

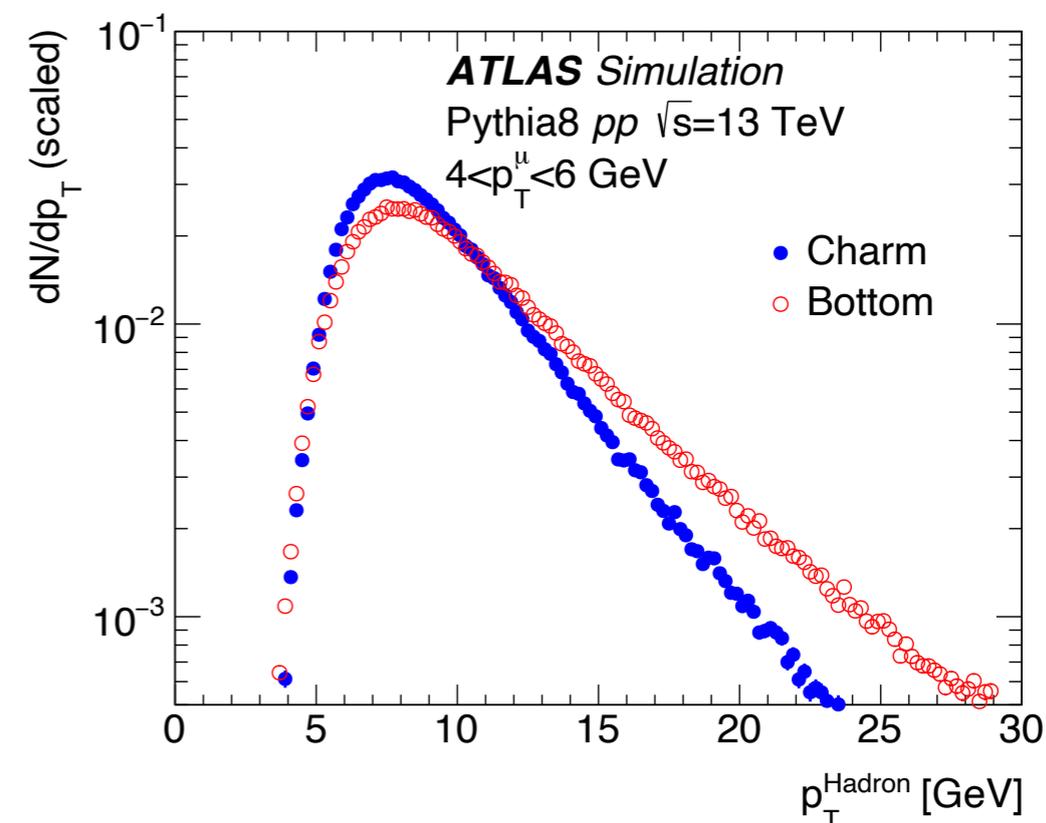
DREENA-B



Hadron to muon smearing in Pythia

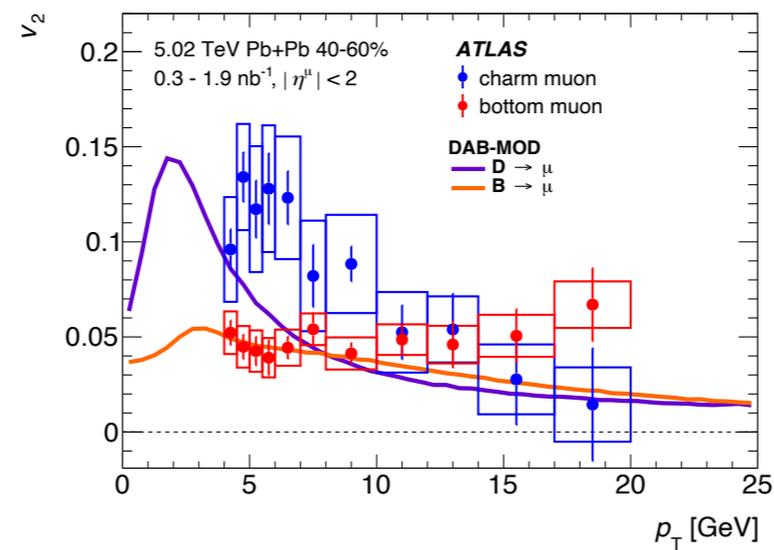
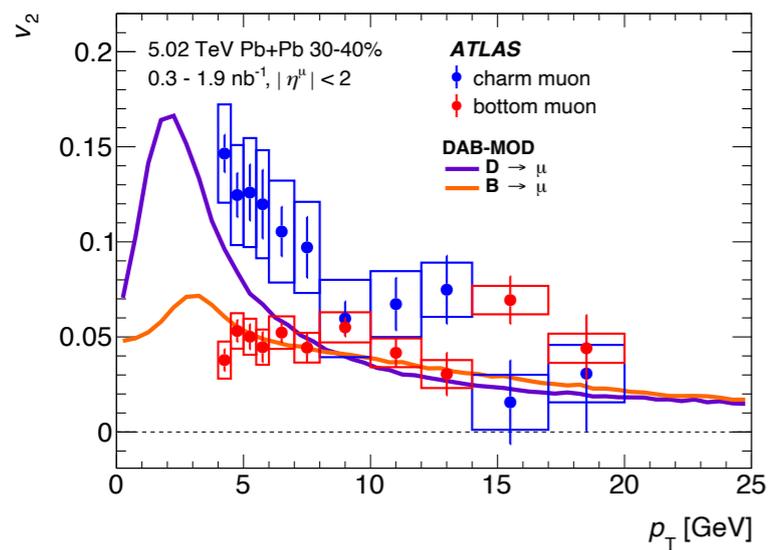
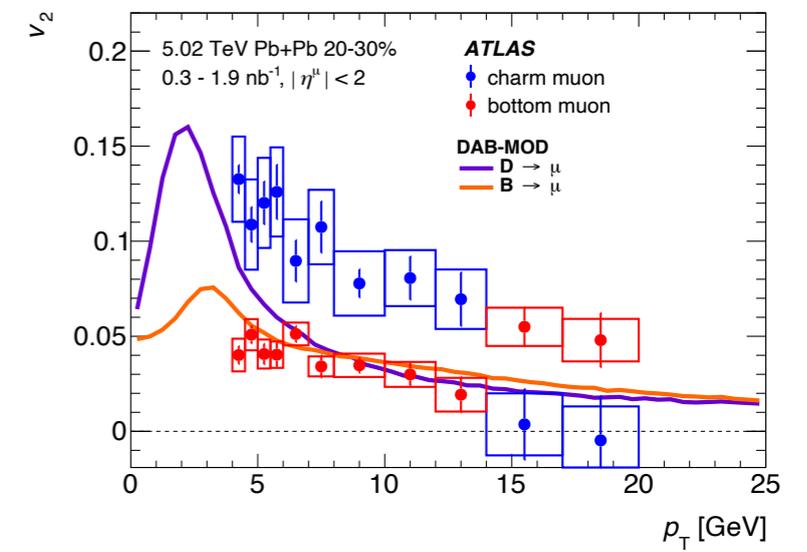
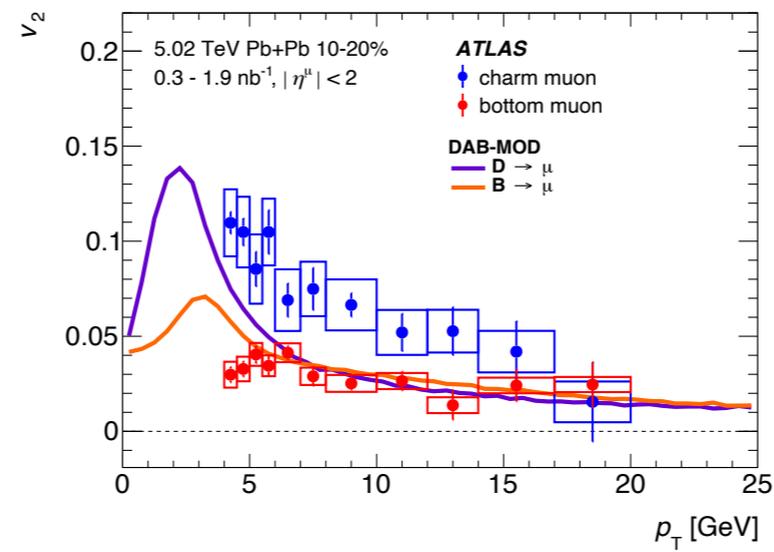
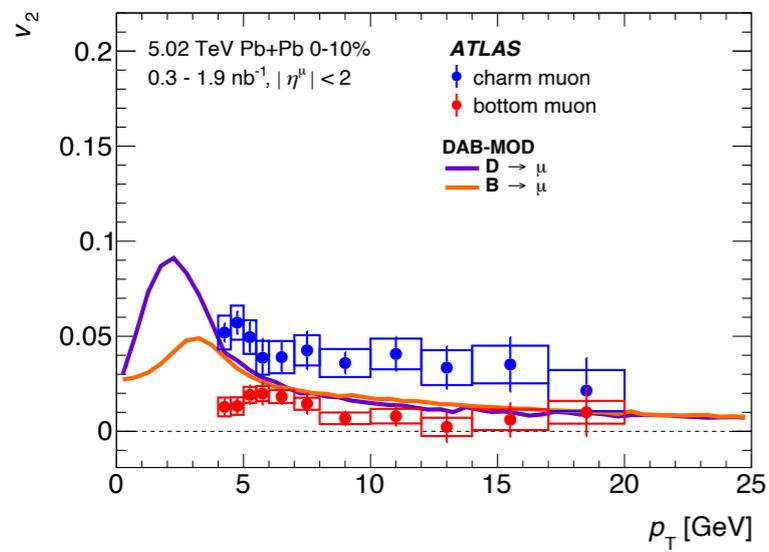


azimuthal angle smearing

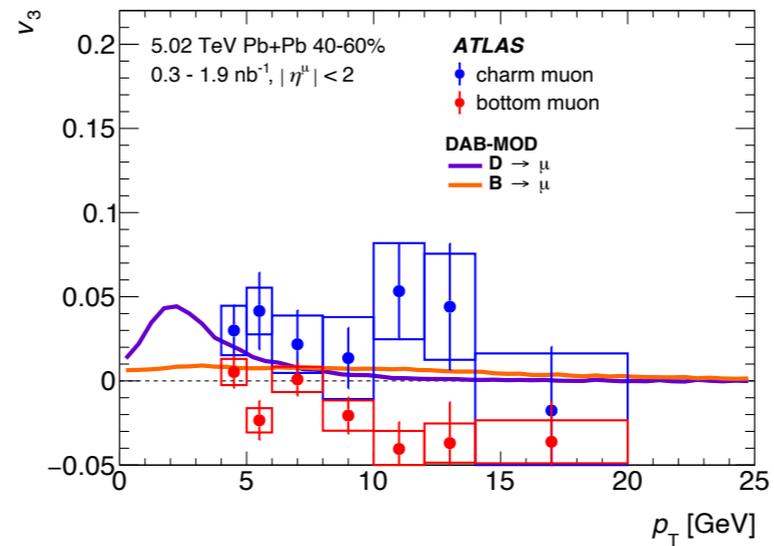
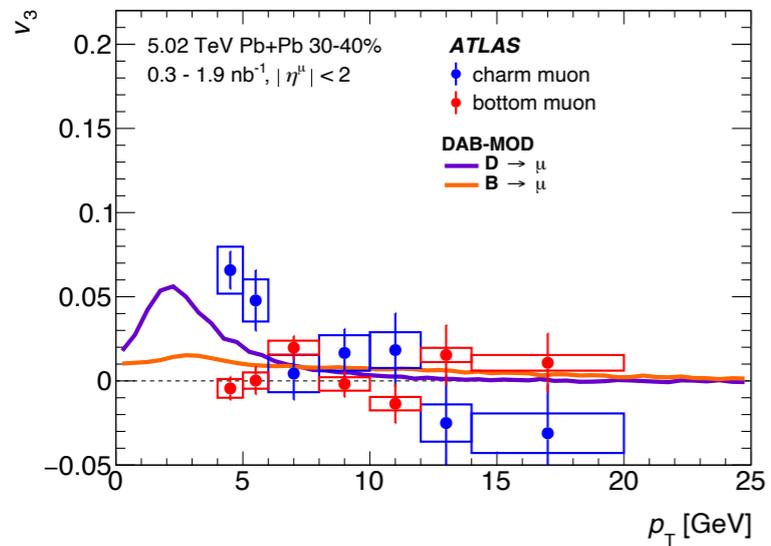
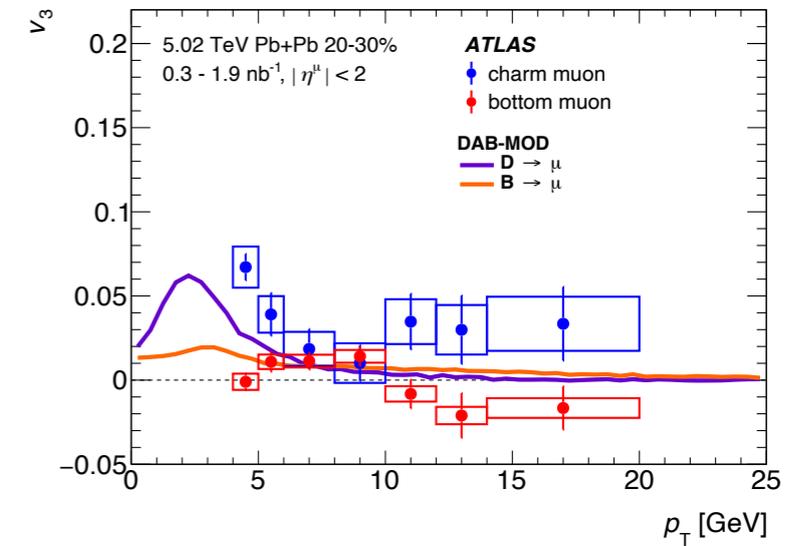
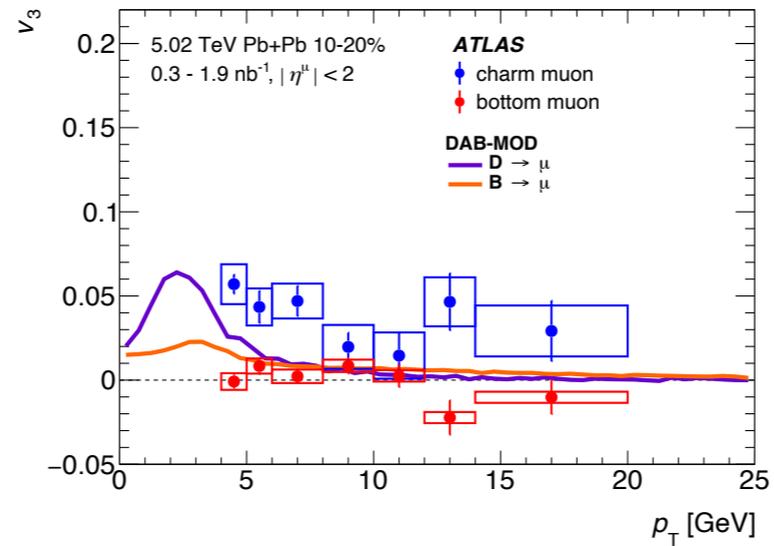
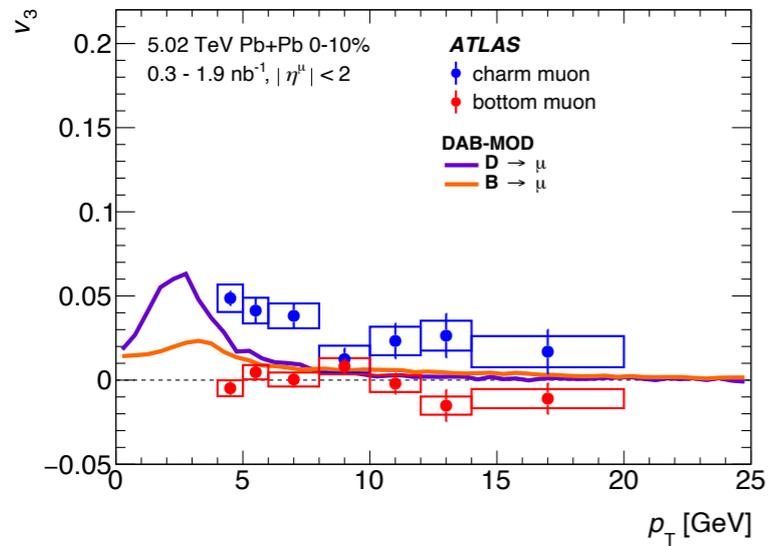


p_T shift and smearing

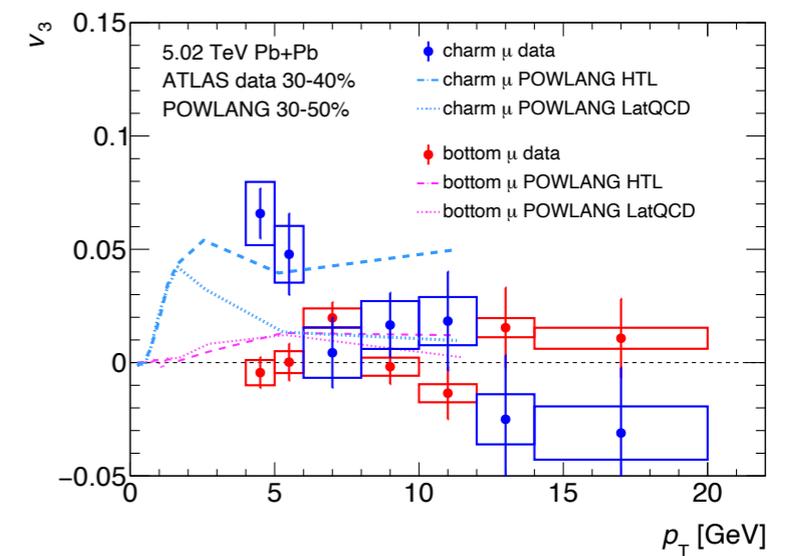
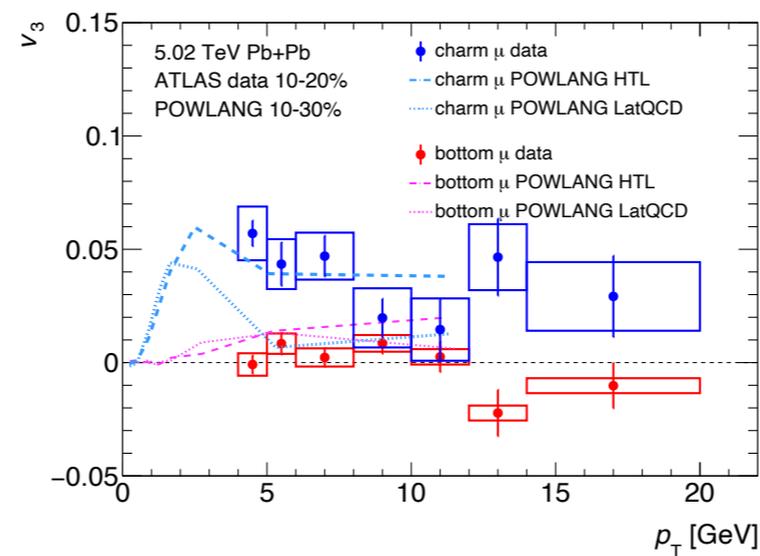
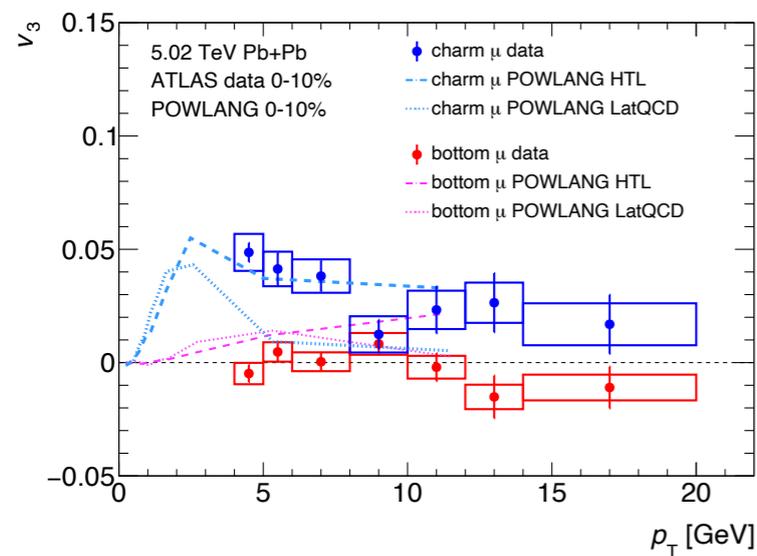
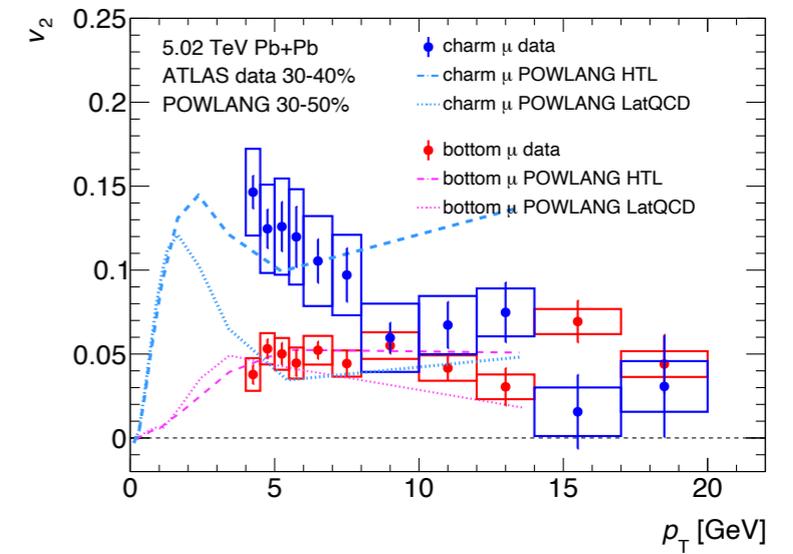
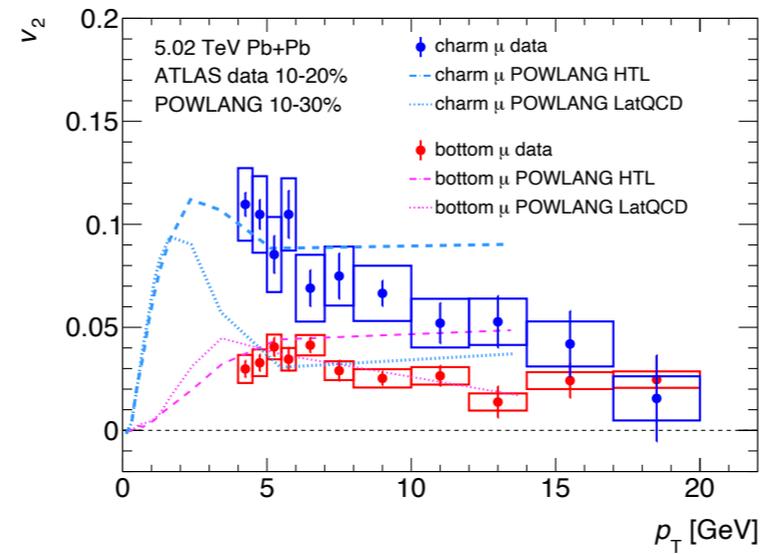
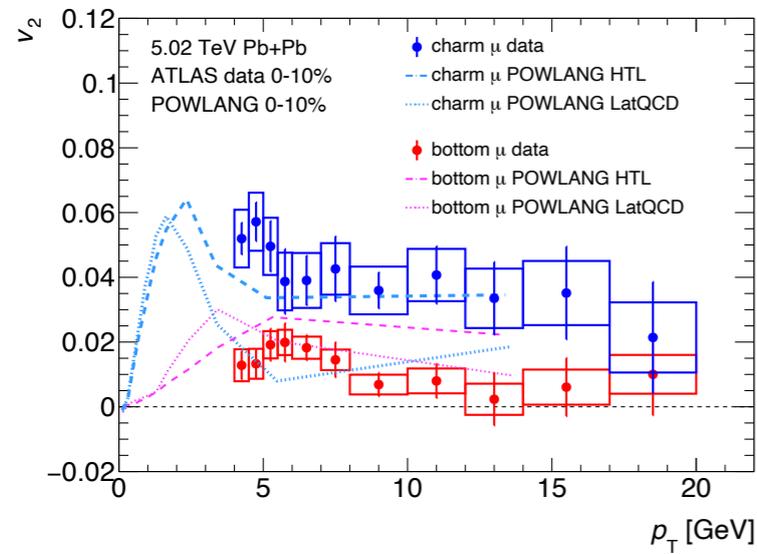
DAB-MOD — V_2



DAB-MOD — V_3

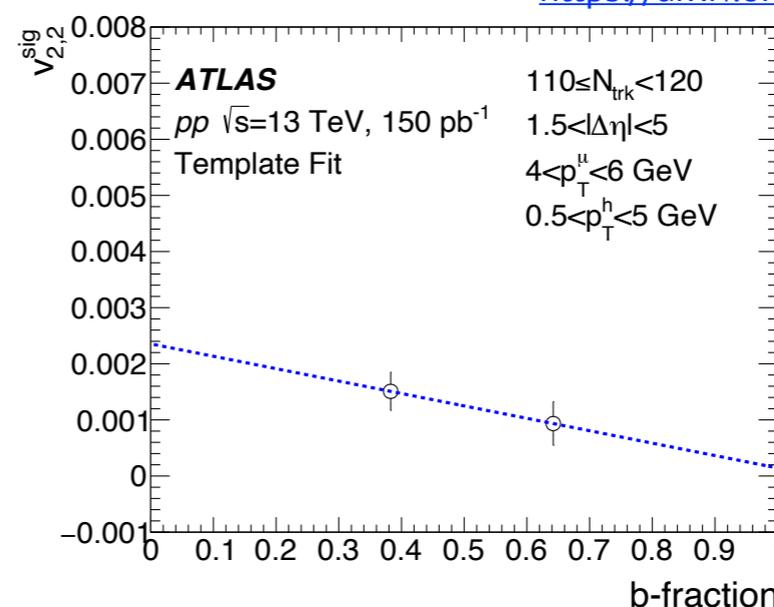
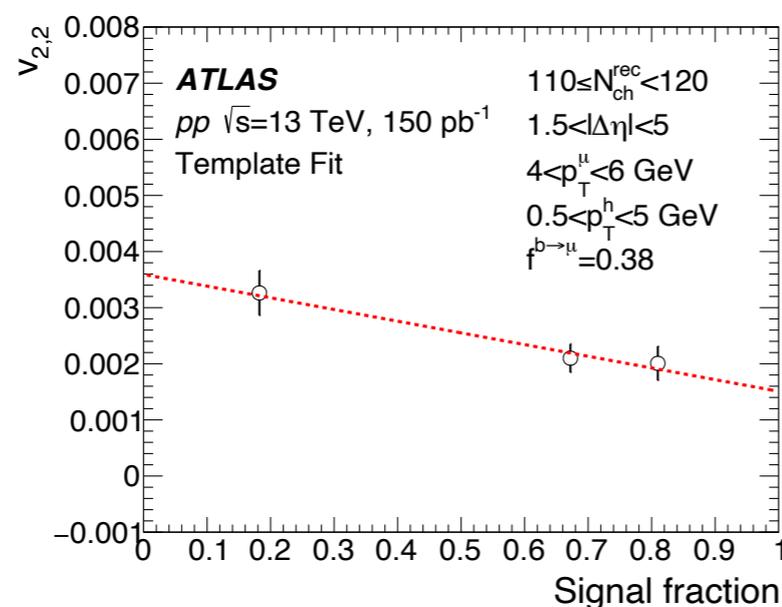


POWLANG flow comparison



HF muon flow extraction in pp

<https://arxiv.org/abs/1909.01650>



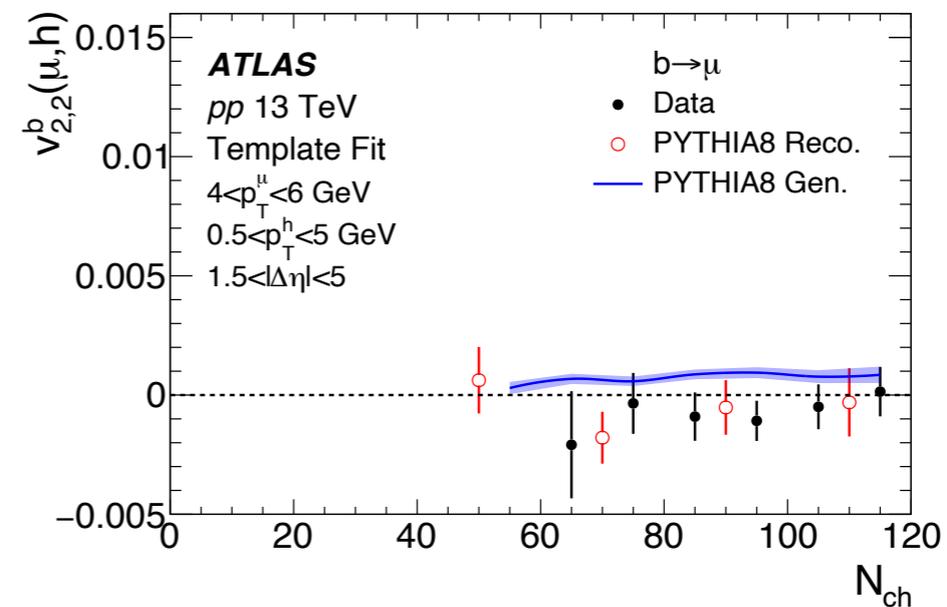
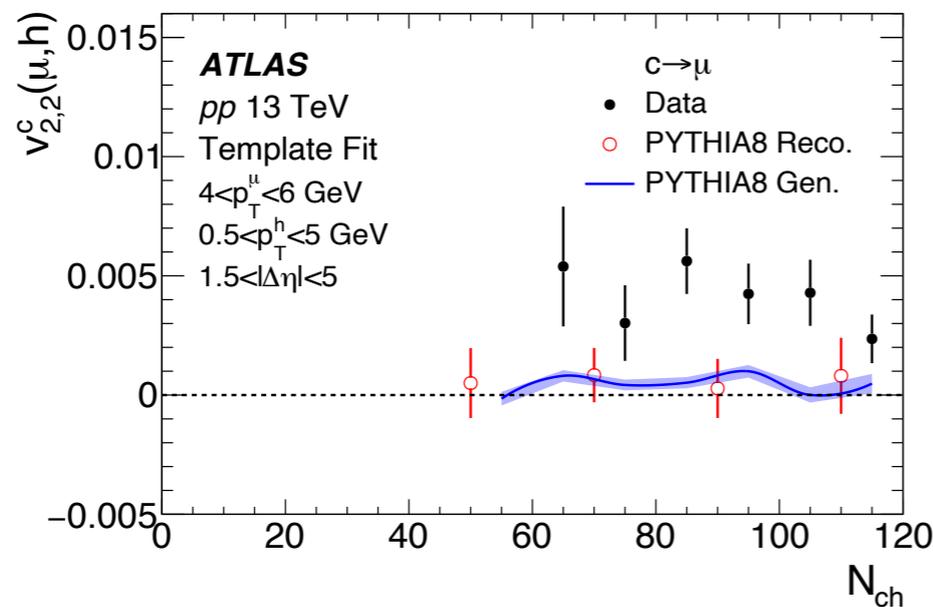
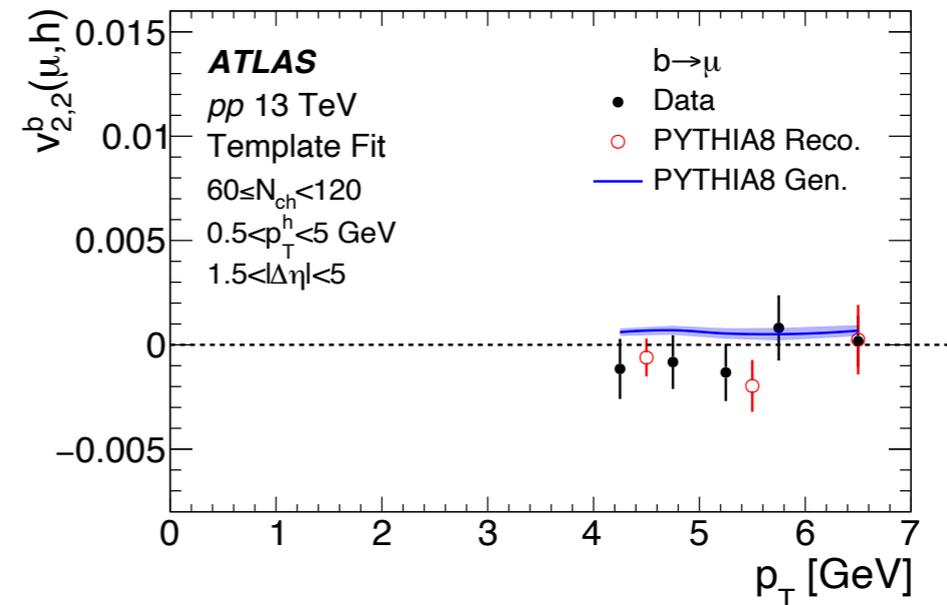
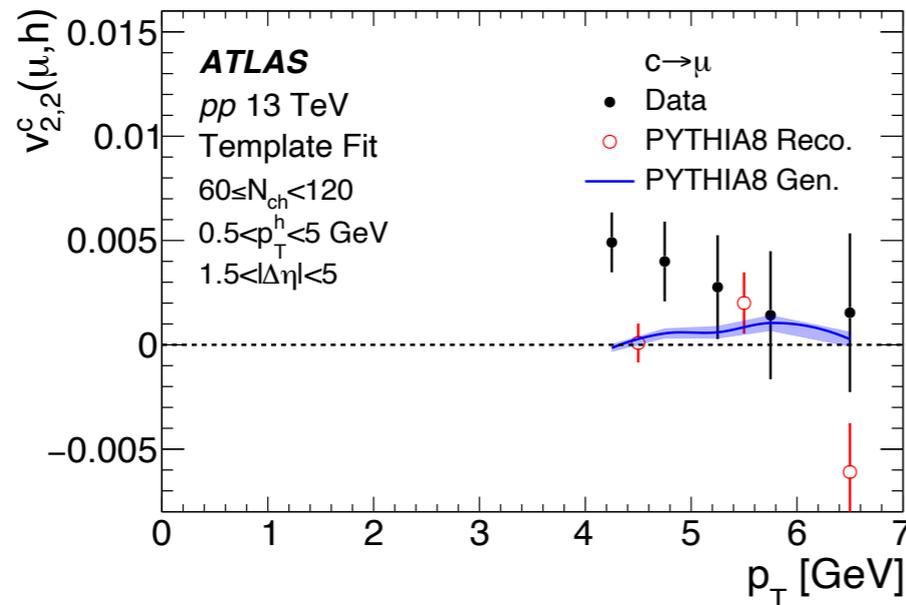
- Low pile-up pp collision data at 13 TeV collected in 2017
- Correlation coefficients $v_{n,n}$ is additive, so a linear combination of different contributions:

$$v_{2,2} = f^{\text{sig}} v_{2,2}^{\text{sig}} + (1 - f^{\text{sig}}) v_{2,2}^{\text{bkg}}$$

$$v_{2,2}^{\text{sig}} = f^b v_{2,2}^b + (1 - f^b) v_{2,2}^c$$

- Intervals in momentum imbalance to allow variation on signal fraction
- Intervals in impact parameter to allow variations on b-fraction

Closure test in Pythia8



- Closure test in Generator-level and reconstruction-level Pythia events
- No azimuthal anisotropy in Pythia as expected \rightarrow no bias from selection/non-flow subtraction