ATLAS measurements of collective flow of heavy-flavor hadrons in small and large collision systems

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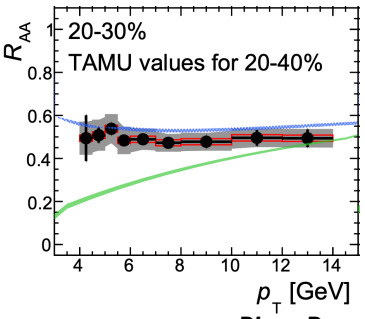
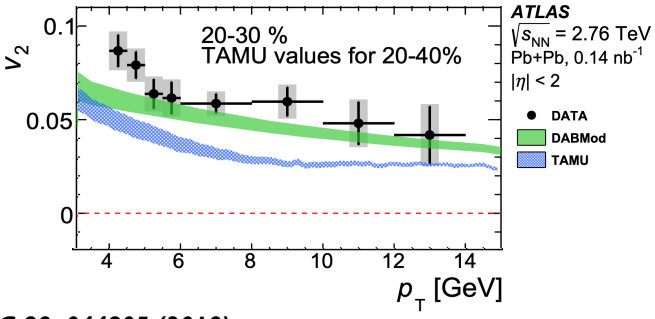
University of Colorado Boulder

Heavy quarks in heavy-ion collisions

Nuclear modification factor



Elliptic flow



Phys. Rev. C 98, 044905 (2018)

- Significant p_T distribution modification and elliptic flow in heavy-ion collisions
- Models qualitatively describe the data

Heavy quarks in heavy-ion collisions

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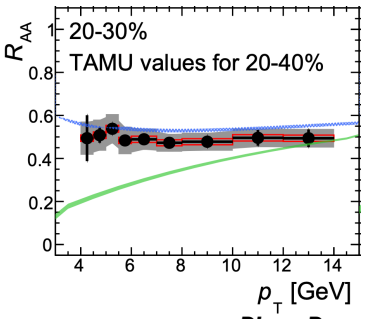

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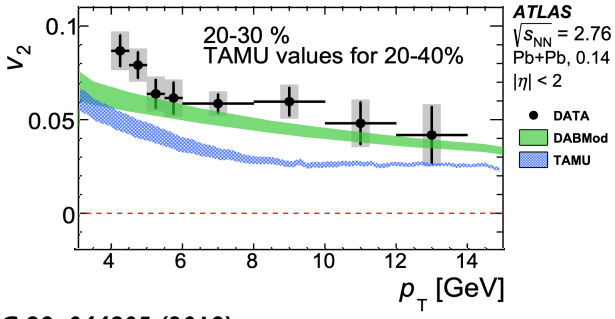

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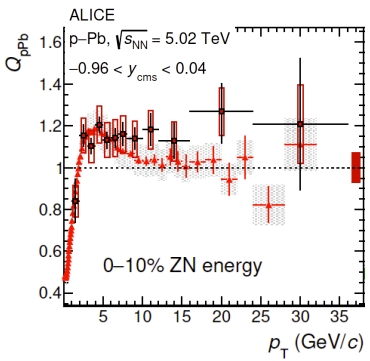
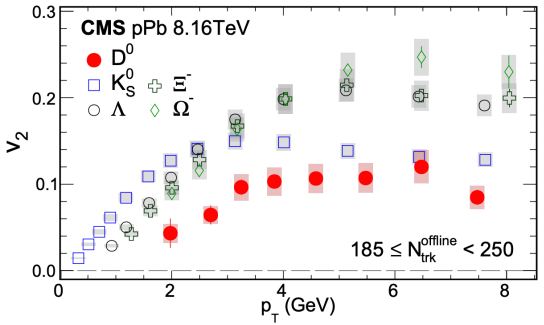


arXiv:1906.03425



Phys. Rev. Lett. 121, 082301 (2018)

- Significant v_2 for D mesons but modest modification (enhancement) of p_T distribution

Heavy quarks in heavy-ion collisions

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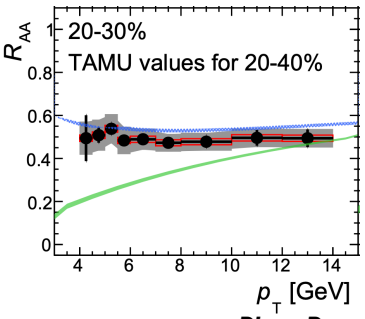

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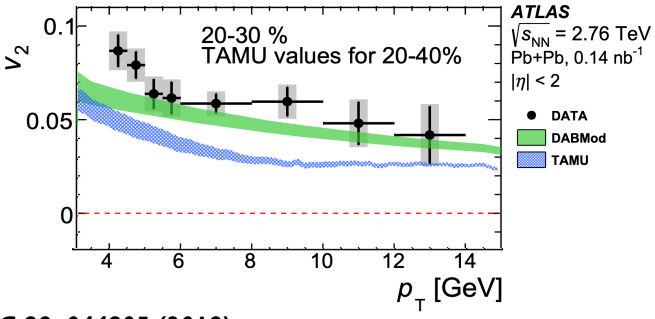

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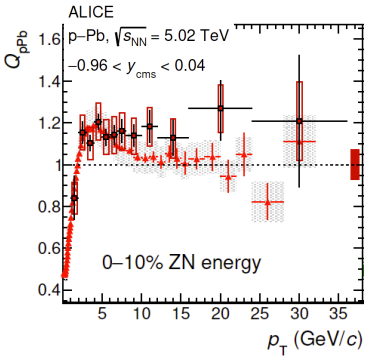

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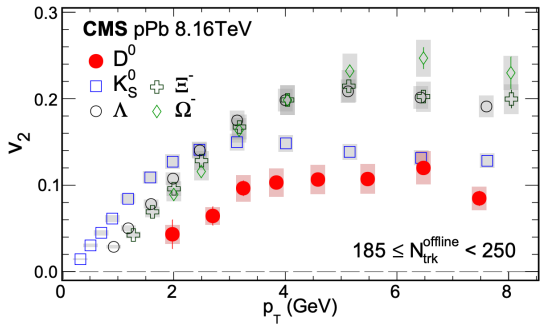


Phys. Rev. Lett. 121, 082301 (2018)

- Significant p_T distribution modification and elliptic flow in heavy-ion collisions
- Models qualitatively describe the data

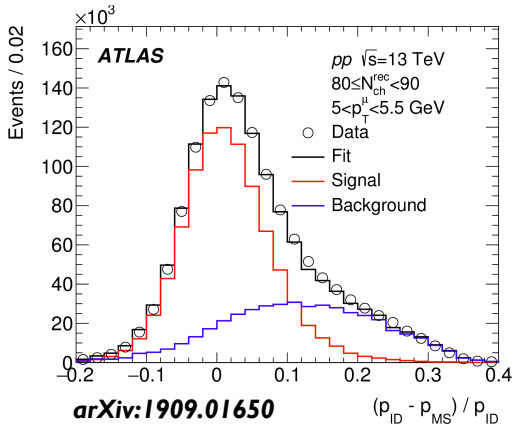
- Significant v_2 for D mesons but modest modification (enhancement) of p_T distribution

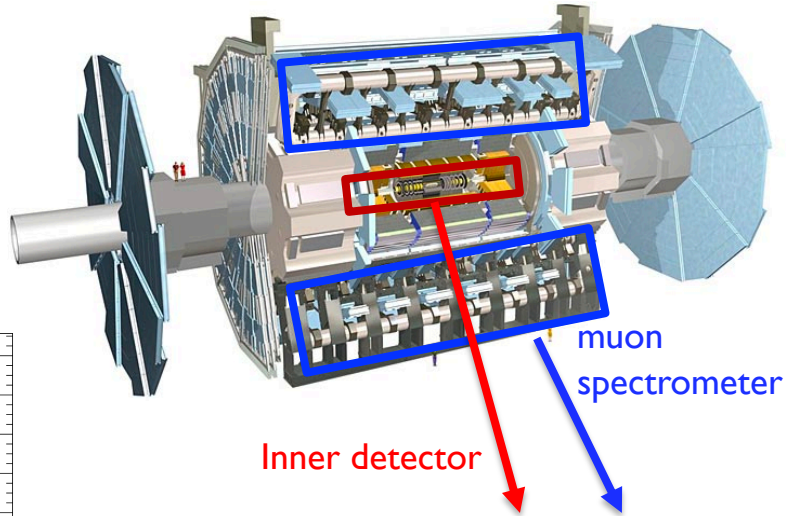
- How about smaller collisions system, *pp*?
- Is bottom flow similar with charm?

Heavy-flavor muon flow analysis in pp collisions

- Data set:
  - 150 pb^{-1} *pp* collisions at 13 TeV collected in 2017 (μ~2)

- Analysis procedure:
  - Two particle correlation
  - Template fit method to subtract non-flow
  - Identify signal muons with momentum imbalance





Momentum imbalance: $(p_{ID} - p_{MS}) / p_{ID}$

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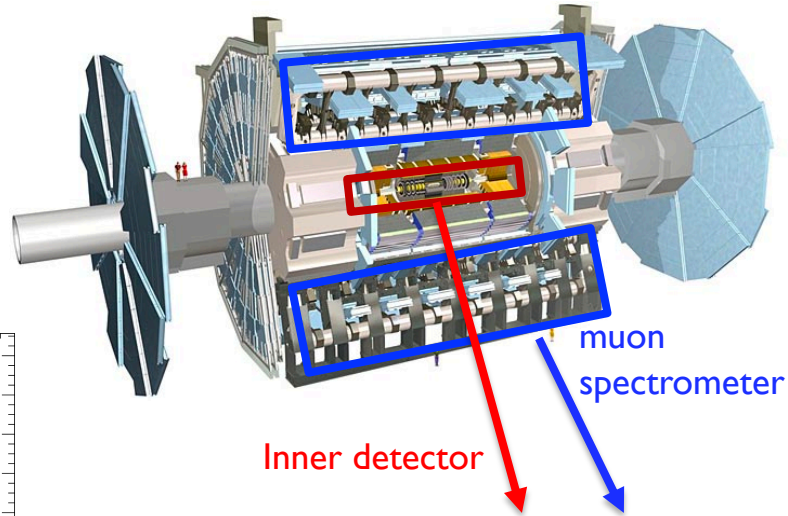

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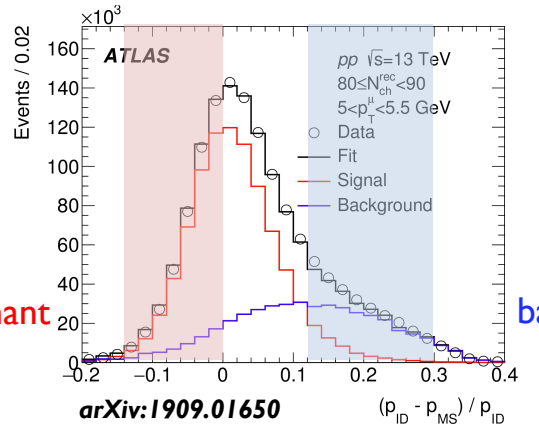
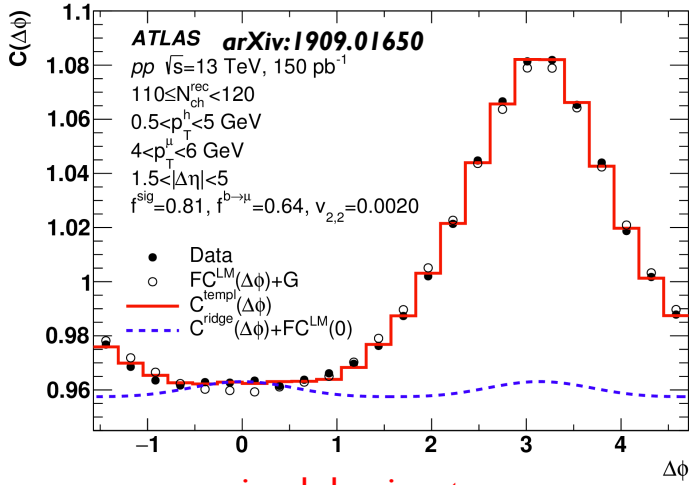


signal dominant

background dominant

arXiv:1909.01650

Muon-hadron correlation



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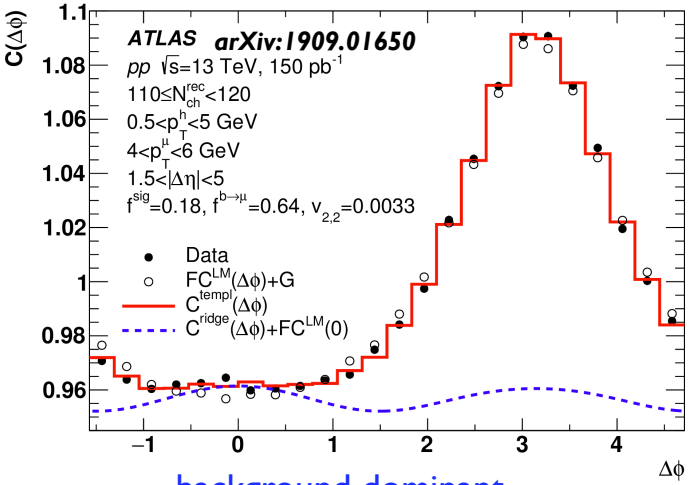

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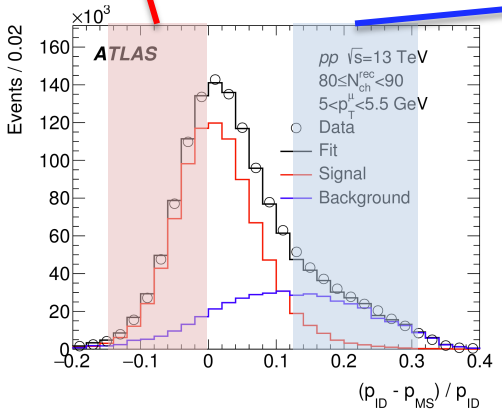
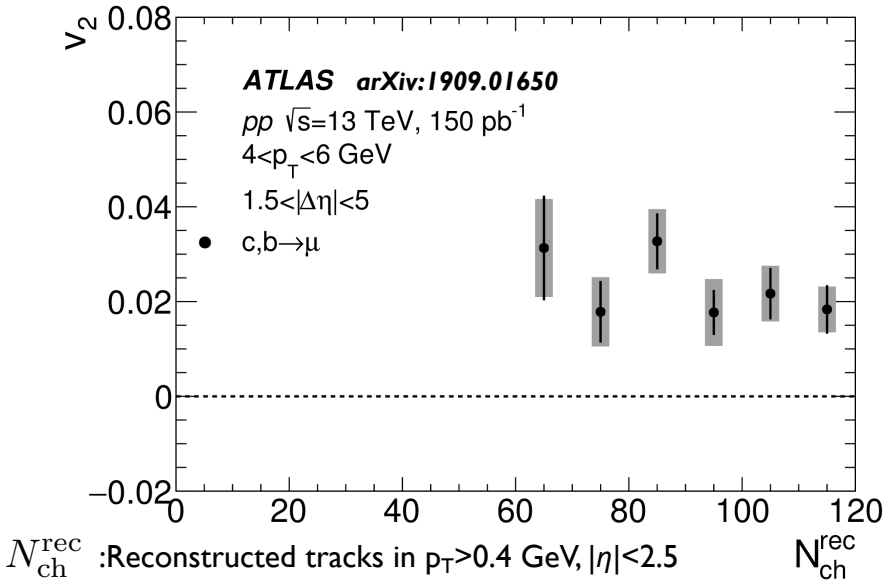
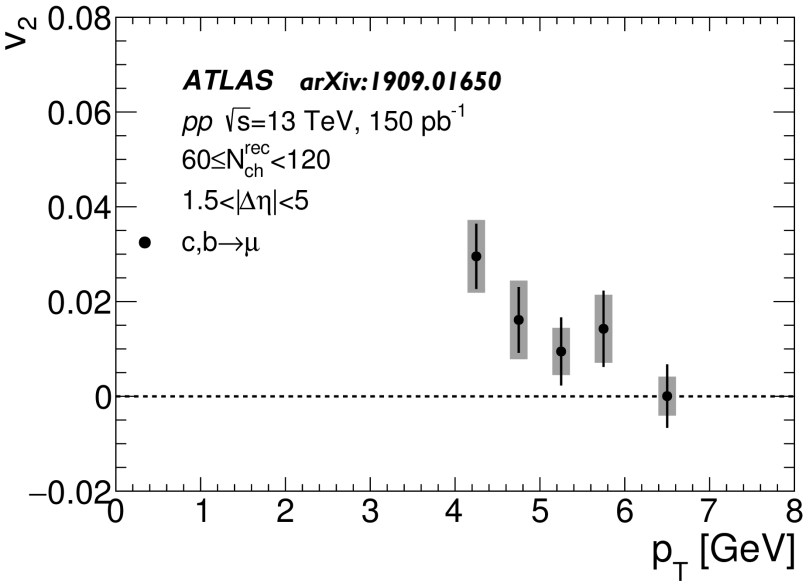


- One dimensional long-range ($1.5<|\Delta\eta|<5$) muon-hadron correlation function in three different momentum imbalance ranges

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

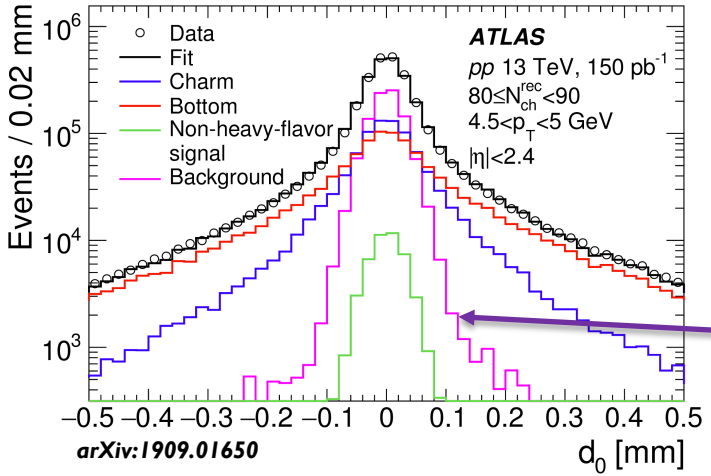
Inclusive heavy-flavor muon v_2 in pp



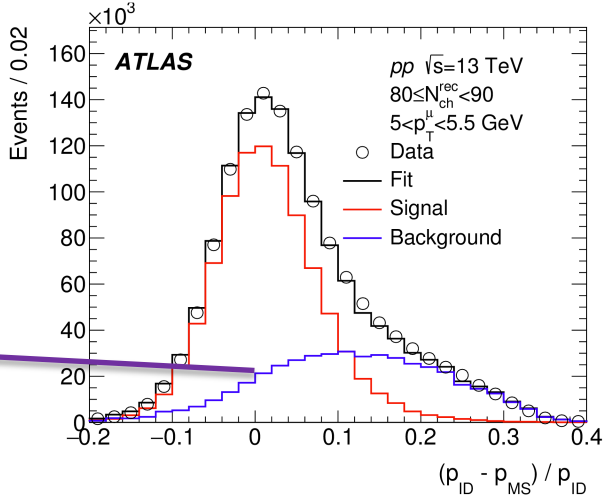


- First results of heavy-flavor elliptic flow in *pp* collisions
- Non-zero v_2 almost independent of multiplicity in $N_{\mathrm{ch}}^{\mathrm{rec}} \geq 60$
  ~1.5% highest multiplicity *pp* events
- Decreasing v_2 as a function of p_T

Separation of charm and bottom muon

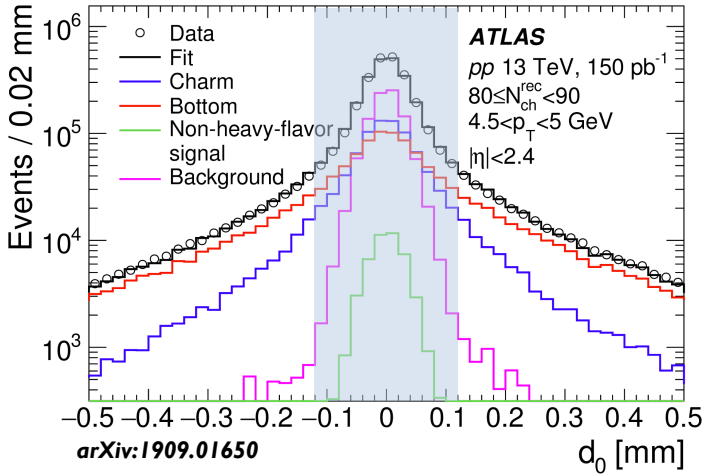


Fixed background



d_0 = *transverse impact parameter relative to the collision vertex*

Separation of charm and bottom muon



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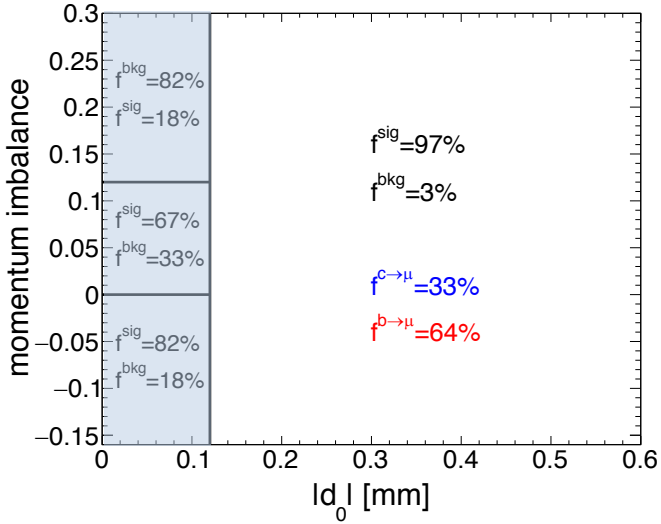
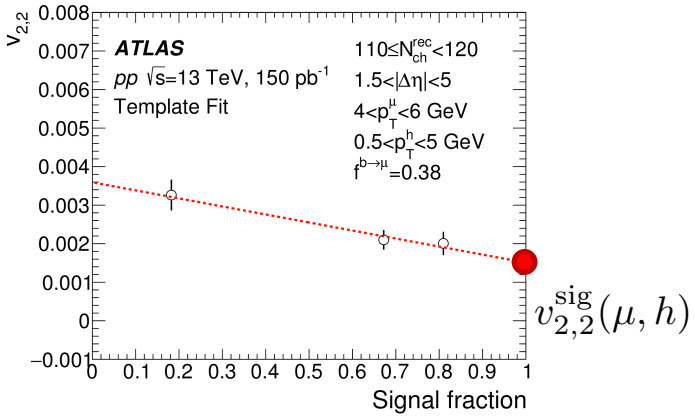


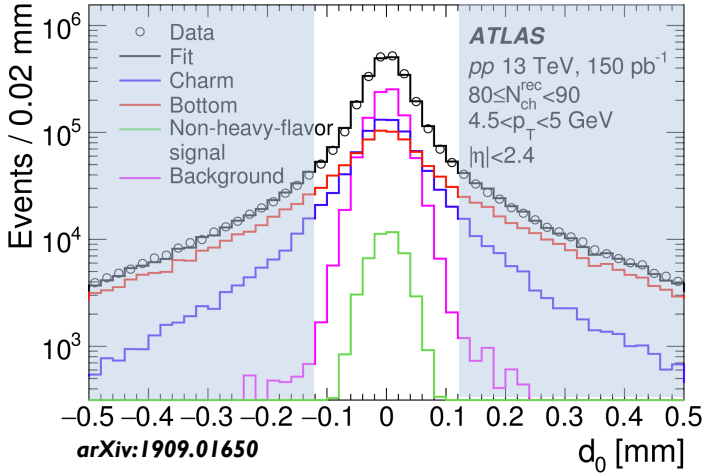


$v_{2,2}^{\mathrm{sig}}(\mu, h)$

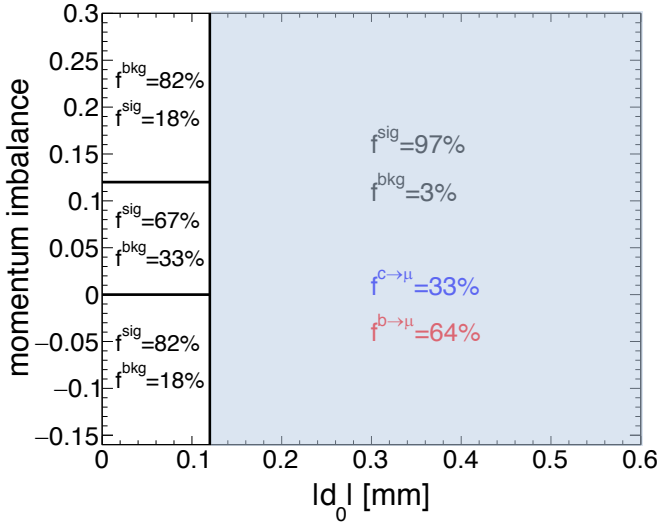
- Calculate inclusive heavy-flavor muon v_2 in charm dominant region ($|d_0|$<0.12 mm)

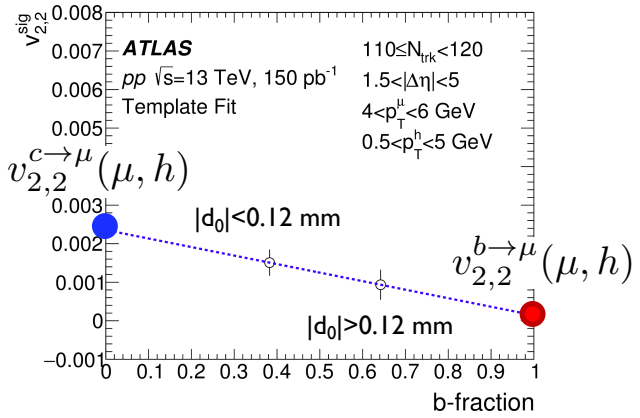
$$v_{2,2}(\mu, h) = f^{\mathrm{sig}} v_{2,2}^{\mathrm{sig}}(\mu, h) + (1 - f^{\mathrm{sig}}) v_{2,2}^{\mathrm{bkg}}(\mu, h)$$

Separation of charm and bottom muon



d_0 = transverse impact parameter relative to the collision vertex



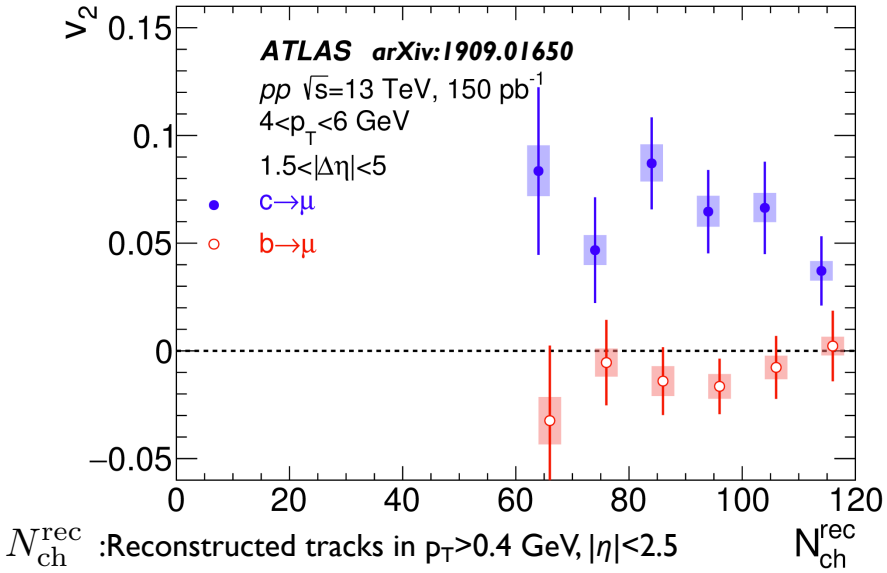


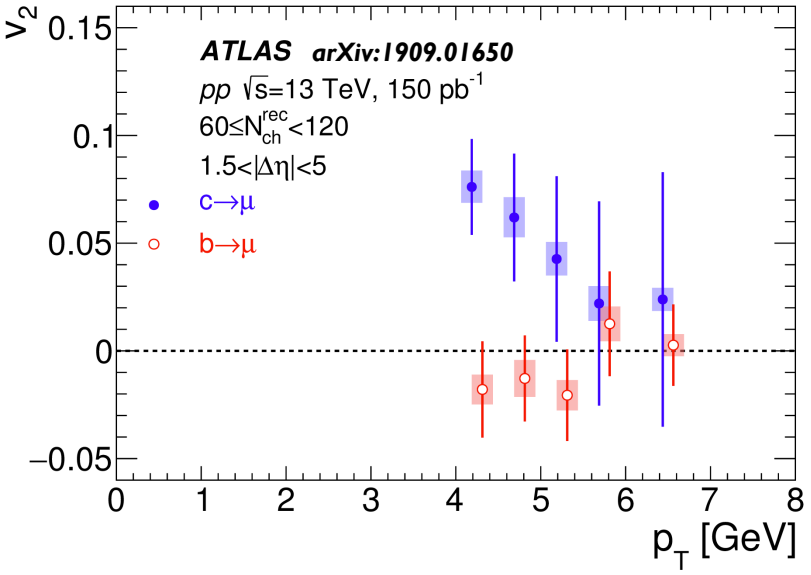
- Calculate inclusive heavy-flavor muon v_2 in bottom dominant region ($|d_0|>0.12$ mm)

- Calculate charm and bottom muon v_2

$$v_{2,2}^{\mathrm{sig}}(\mu,h) = f^{b\to\mu} v_{2,2}^{b\to\mu}(\mu,h) + (1-f^{b\to\mu}) v_{2,2}^{c\to\mu}(\mu,h)$$

Charm and bottom muon v_2 in pp



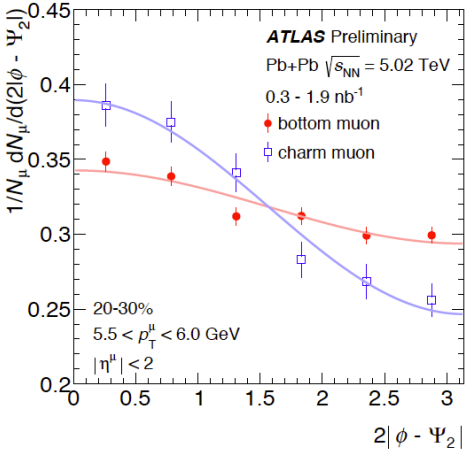


- Significant non-zero v_2 for charm muons
  Consistent with independent of multiplicity and decreasing with p_T
- Bottom muon v_2 is consistent with zero in multiplicity and p_T
- Clear difference between charm and bottom in *pp* collisions
  ➔No theory/model for comparison

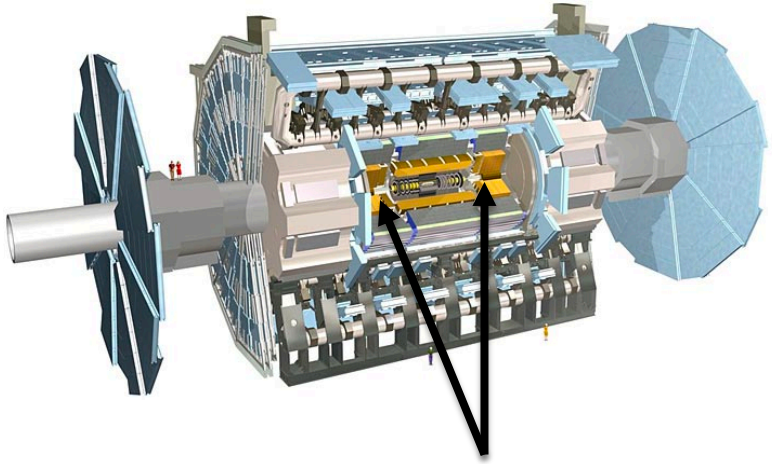
Heavy-flavor muon flow analysis in Pb+Pb collisions

- Data set:
  - 1.9 nb^{-1} Pb+Pb collisions at 5.02 TeV collected in 2015 and 2018

- Analysis procedure:
  - Event plane method
  - Heavy-flavor muon yields as a function of ϕ w.r.t. the EP angle



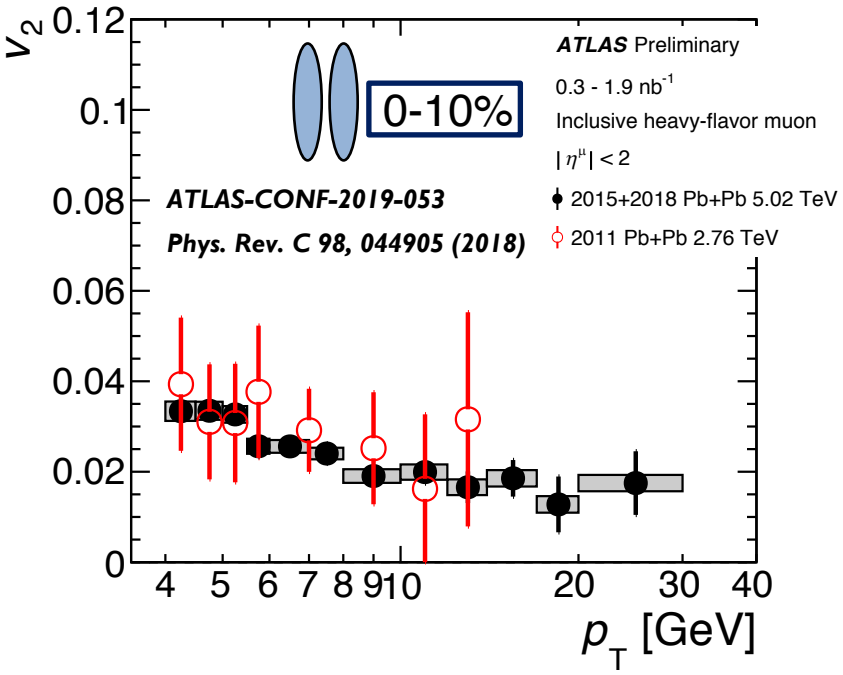
$$\frac{1}{N^\mu}\frac{dN^\mu}{d(n(\phi^\mu - \Psi_n))} \propto 1 + 2v_n^{\mathrm{raw}}\cos(n(\phi^\mu - \Psi_n))$$

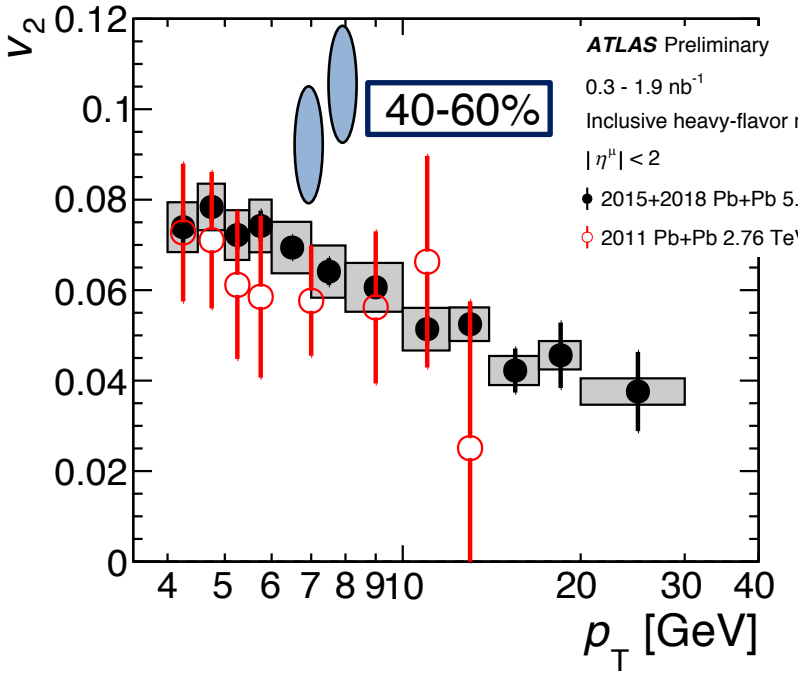


Forward calorimeter for EP

3.1<|η|<4.9

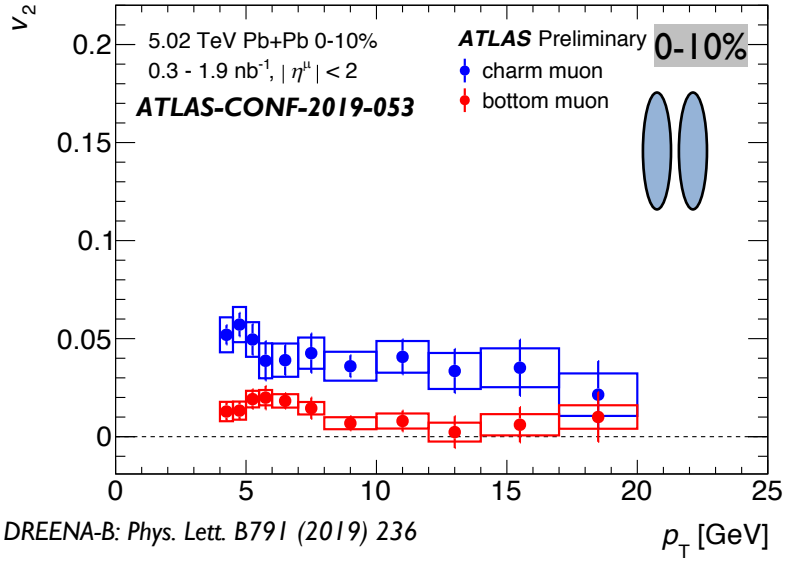
Inclusive heavy-flavor muon flow in Pb+Pb





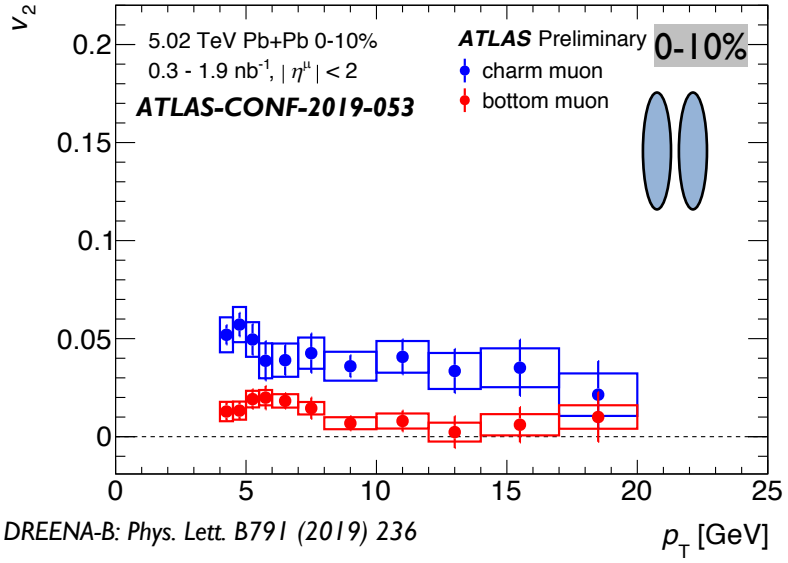
- Significant heavy-flavor muon v_2 in all centrality intervals up to p_T 30 GeV
- Consistent inclusive heavy-flavor muon v_2 between 2.76 TeV and 5.02 TeV

Charm and bottom muon v_2 in Pb+Pb

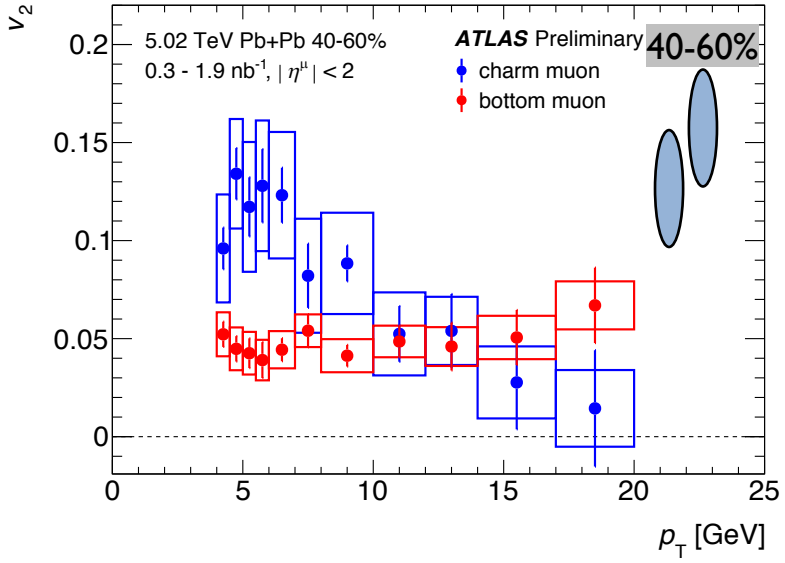


- Non-zero bottom muon v_2

Charm and bottom muon v_2 in Pb+Pb

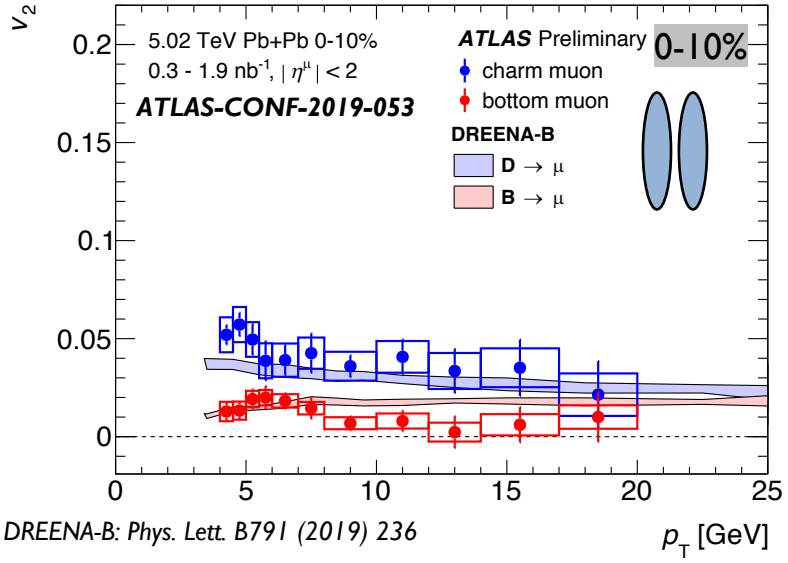


DREENA-B: Phys. Lett. B791 (2019) 236



- Non-zero bottom muon v_2
- Charm muon v_2 is higher than bottom muon v_2 in lower p_T region and becomes similar in higher p_T of 40-60% centrality interval

Charm and bottom muon v_2 in Pb+Pb



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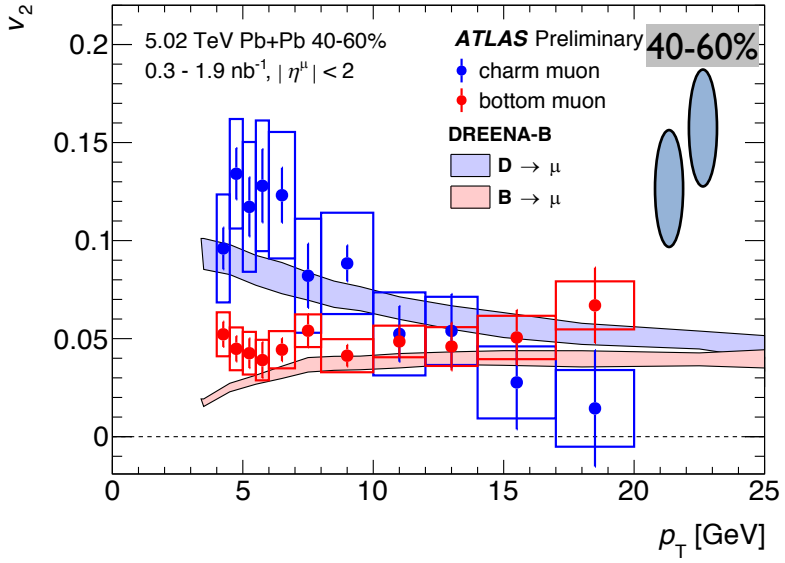
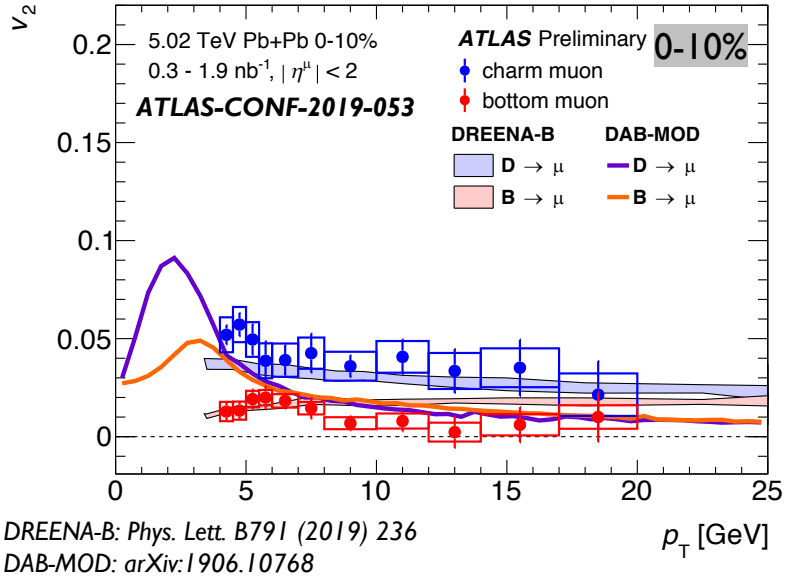
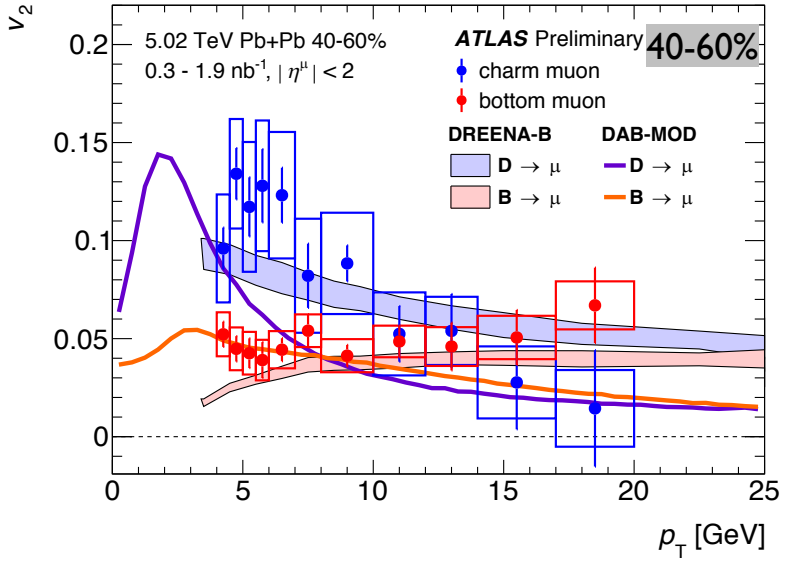


- DREENA-B considering energy loss inside medium can reproduce the magnitude of v_2 both for charm and bottom muon

Charm and bottom muon v_2 in Pb+Pb

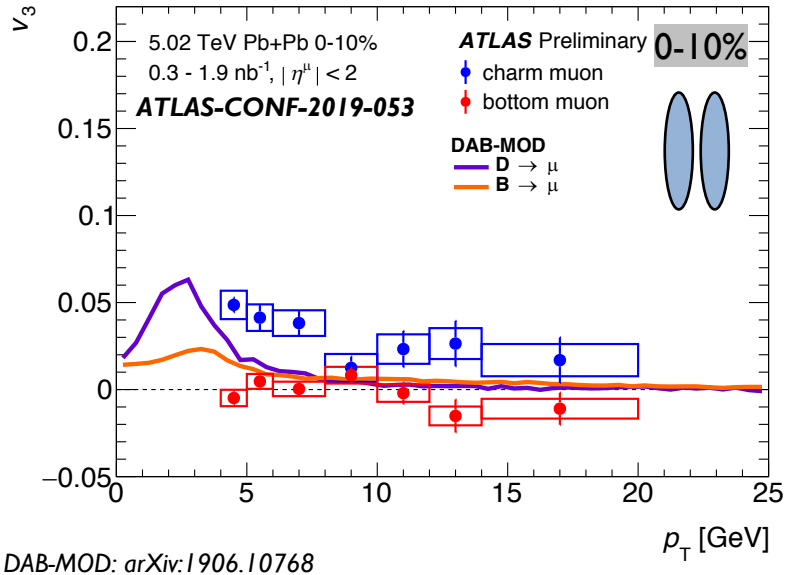


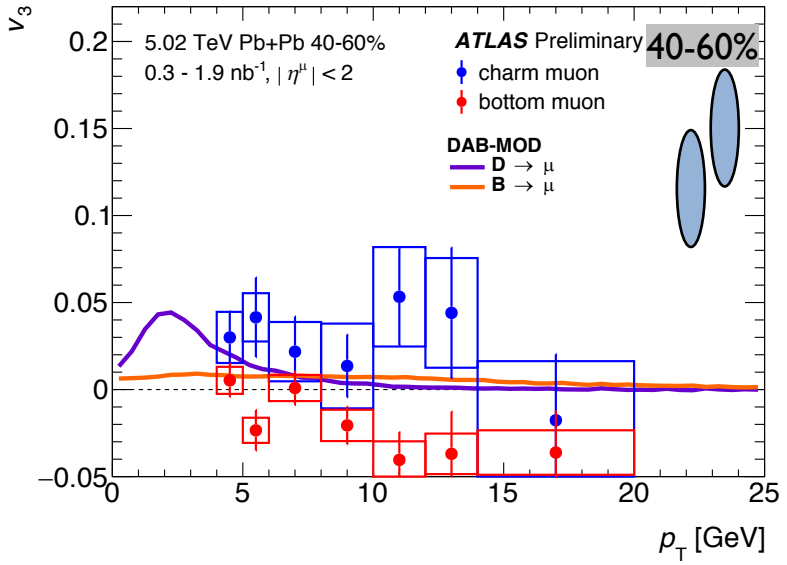
DREENA-B: Phys. Lett. B791 (2019) 236
DAB-MOD: arXiv:1906.10768



- DREENA-B considering energy loss inside medium can reproduce the magnitude of v_2 both for charm and bottom muon
- DAB-MOD model including Langevin drag and diffusion underestimates charm muon v_2
  - a consistent v_2 between charm and bottom muons in higher p_T region

Charm and bottom muon v_3 in Pb+Pb



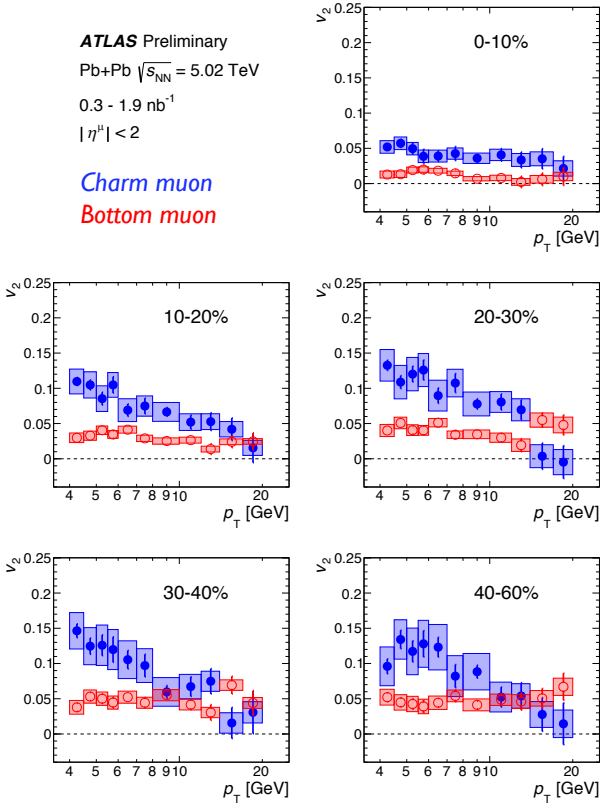


DAB-MOD: arXiv:1906.10768

- Non-zero v_3 for charm muon but consistent with zero for bottom muon

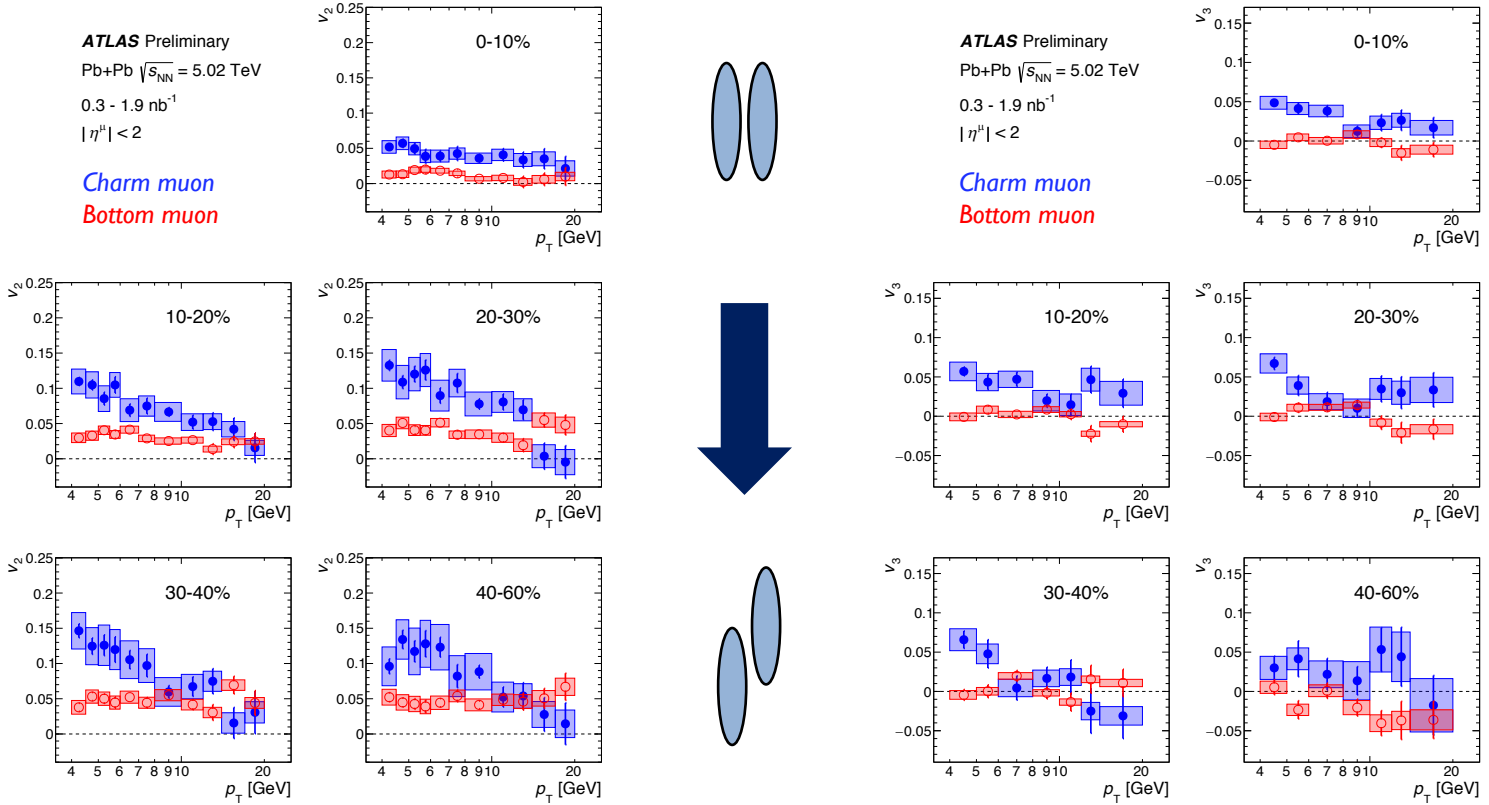
- DAB-MOD model underestimates charm muon v_3 in 0-10% central Pb+Pb collisions like the v_2 case

Charm and bottom muon flow in various centrality



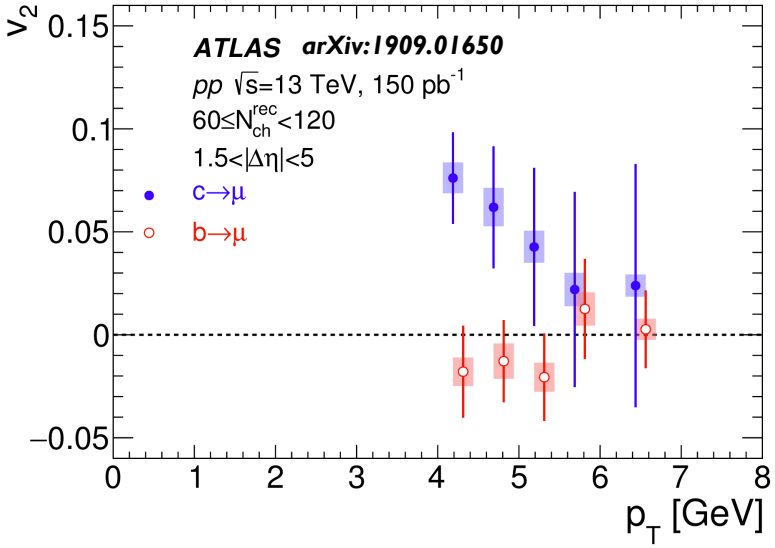
- Non-zero bottom muon v_2 in all centrality intervals but smaller than charm muon

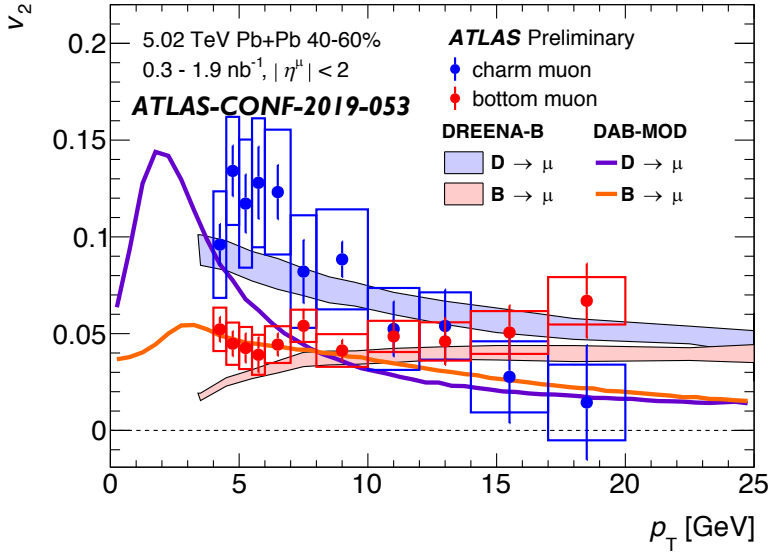
Charm and bottom muon flow in various centrality



- Non-zero bottom muon v_2 in all centrality intervals but smaller than charm muon
- Similar trend in v_3 (little bottom muon v_3)

Summary

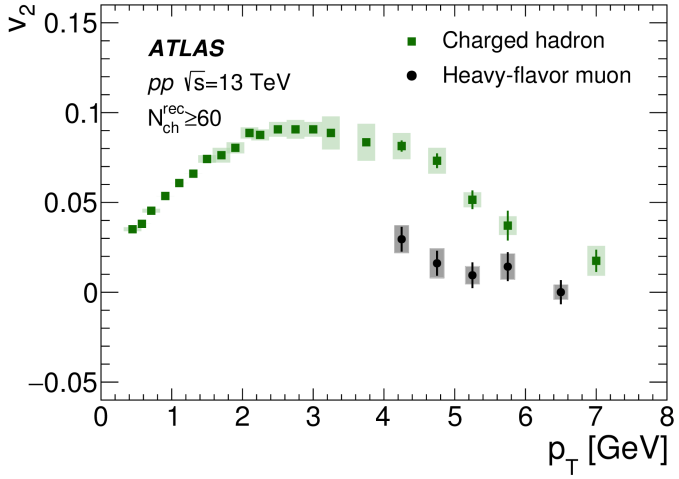


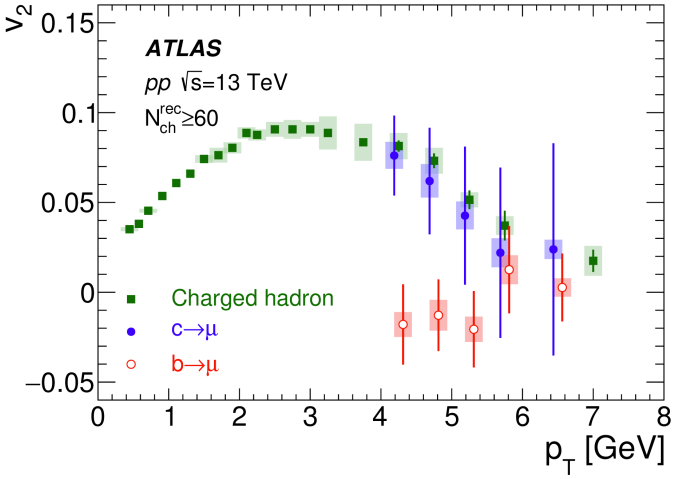


- ATLAS measured inclusive heavy-flavor, charm, and bottom muon flow in 13 TeV p+p and 5.02 TeV Pb+Pb collisions
  - Clear difference between charm and bottom muons
  - Bottom muon v_2 is consistent with zero in *pp* collisions but non-zero in Pb+Pb collisions
- Interesting to see models for *pp* and p+Pb!

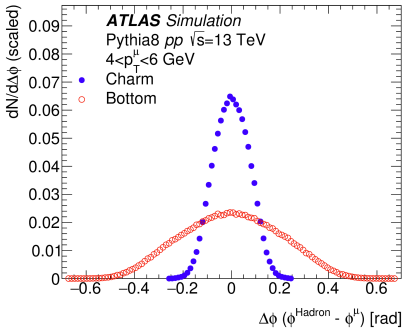
BACKUP

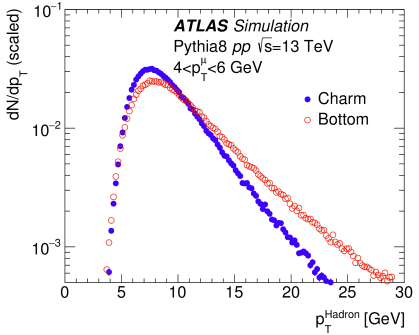
Comparison with charged hadrons in pp 13 TeV





- Similar v_2 between charged hadrons and charm muons
- Due to decay kinematics,
  charm muons in $4<p_T<6$ GeV from
  charm hadrons at $p_T \sim 7$ GeV
- There is also a small ϕ broadening effect





Inclusive heavy-flavor muon flow in Pb+Pb

ATLAS Preliminary

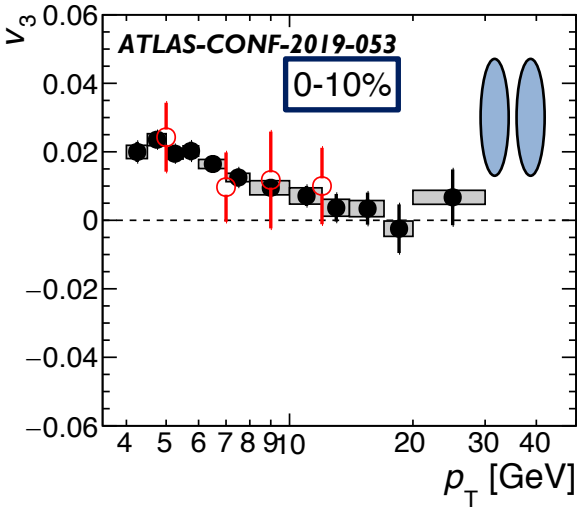
0.3 - 1.9 nb^{-1}

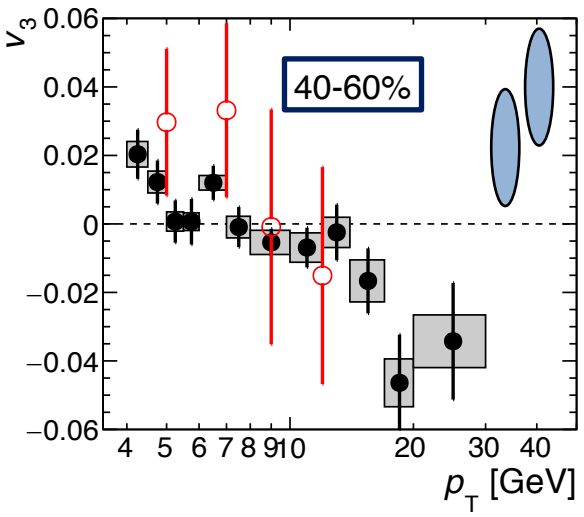
Inclusive heavy-flavor muon

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

2015+2018 Pb+Pb 5.02 TeV

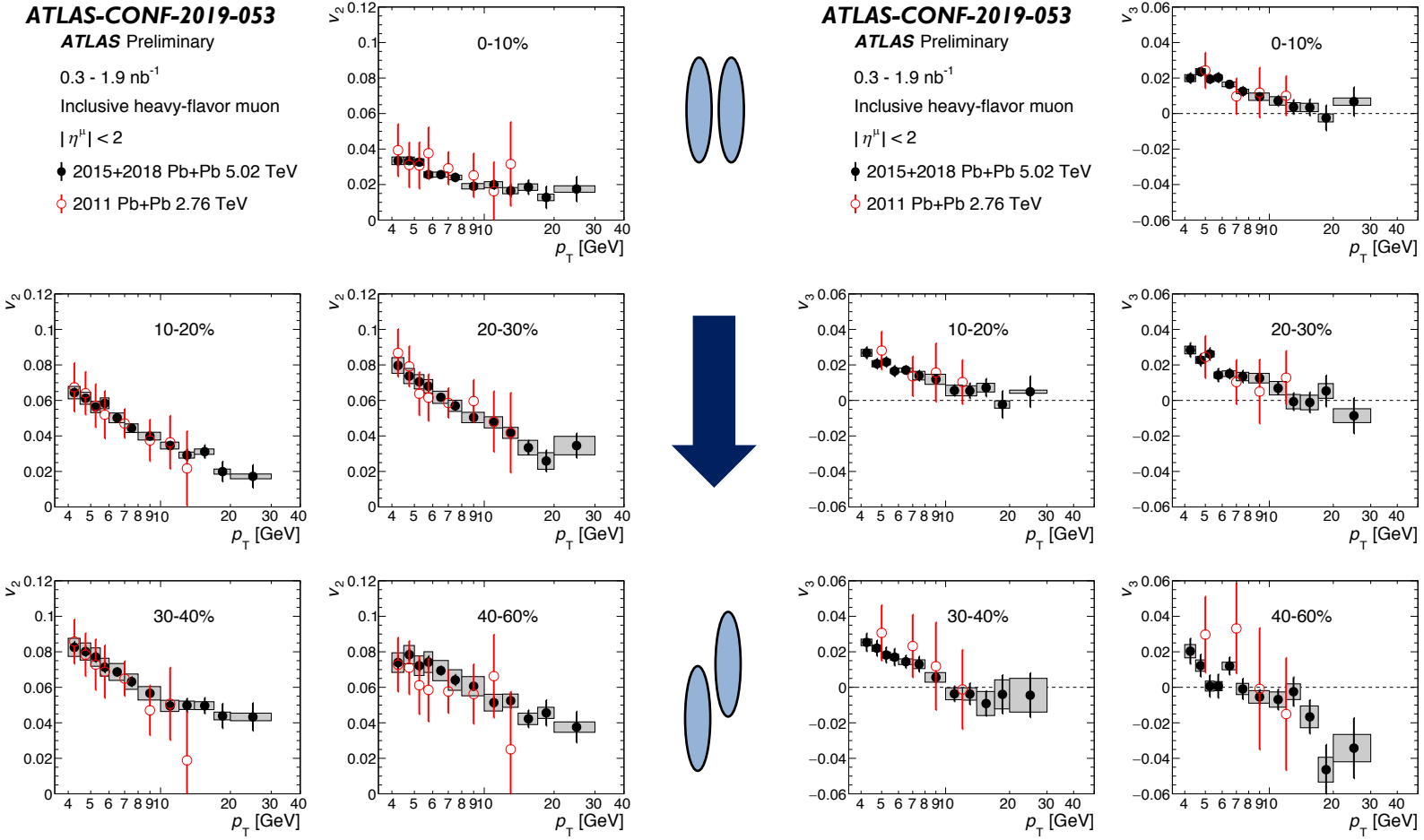
2011 Pb+Pb 2.76 TeV





- Little centrality dependence in inclusive heavy-flavor muon v_3
- Consistent inclusive heavy-flavor muon v_3 between 2.76 TeV and 5.02 TeV

Inclusive heavy-flavor muon flow in Pb+Pb



Comparison with charged hadrons in Pb+Pb 5.02 TeV