Open heavy-flavour measurements at forward rapidity via semi-muonic decays with ALICE at the LHC

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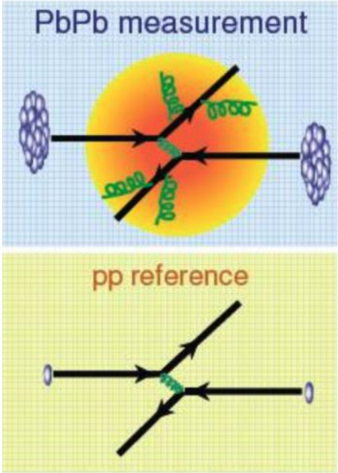
Nov. 17, 2023
Shanghai
The 9th China LHC Physics Workshop

Physics Motivation

Heavy (charm and beauty) quarks: sensitive probes of the Quark-Gluon Plasma (QGP)

- Open heavy-flavours in nucleus-nucleus (AA) collisions
  - In-medium parton energy loss: induced gluon radiations vs. elastic collisions
  - Heavy-quark participation in the collective expansion, thermal degree of freedom

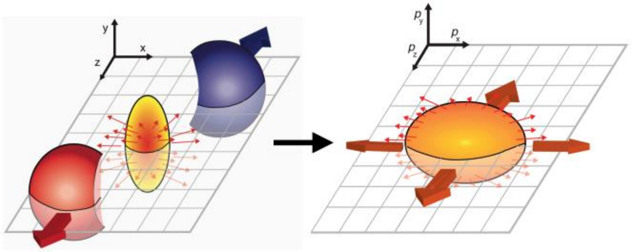


- Observables
  - Nuclear modification factor, R_{AA}
    - No nuclear effects: $R_{\mathrm{AA}} = 1$

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y) = \frac{1}{< T_{\mathrm{AA}} >} \times \frac{d^2N_{\mathrm{AA}}/dp_{\mathrm{T}}dy}{d^2\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}dy} = \frac{\text{QCD Medium}}{\text{QCD Vacuum}}$$

  - Elliptic flow
    - Second-order coefficient of the Fourier expansion of the azimuthal (φ) distribution w.r.t. to the reaction plane (Ψ_{RP})

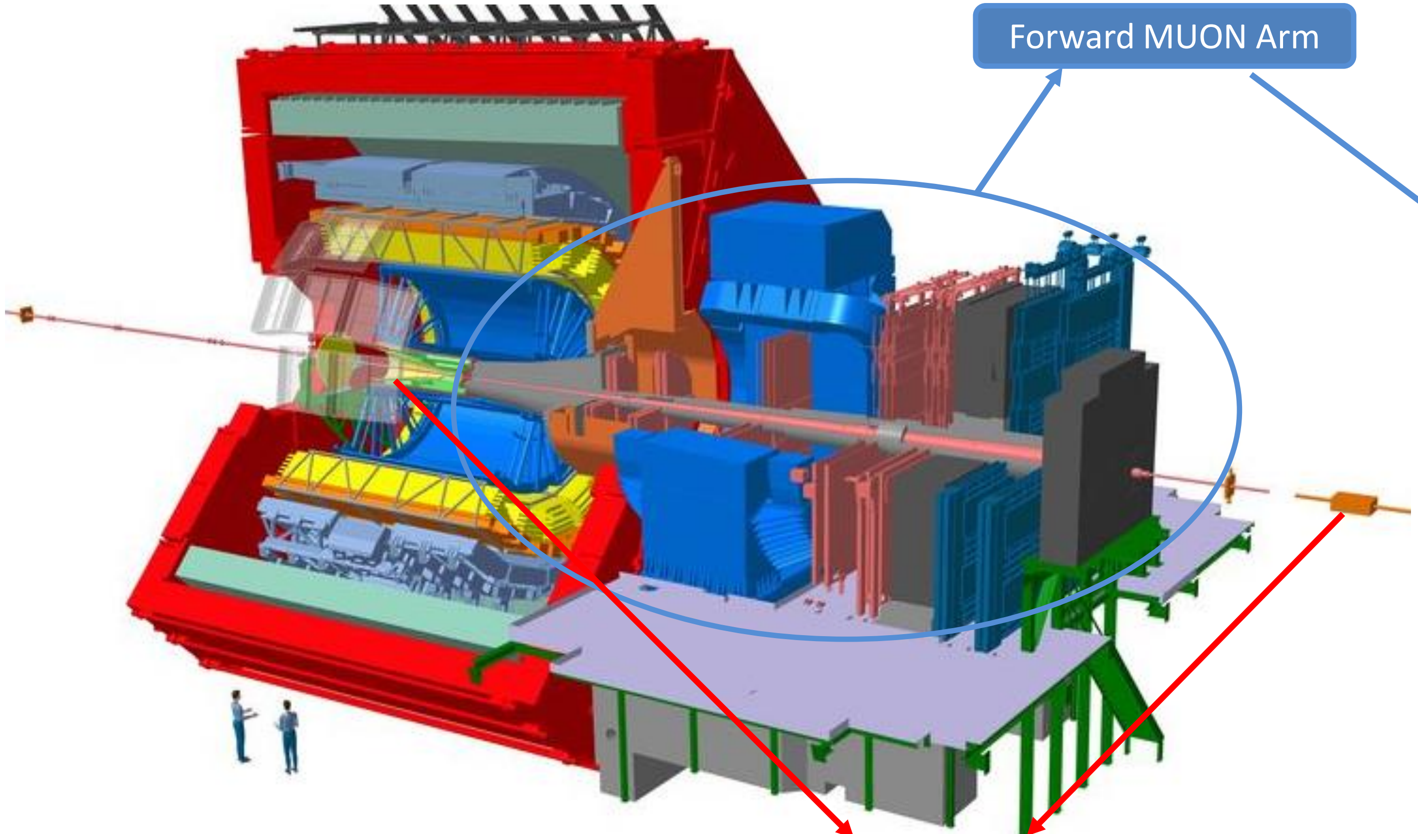
$$v_2 = < \cos[2(\varphi - \Psi_{RP})] >$$



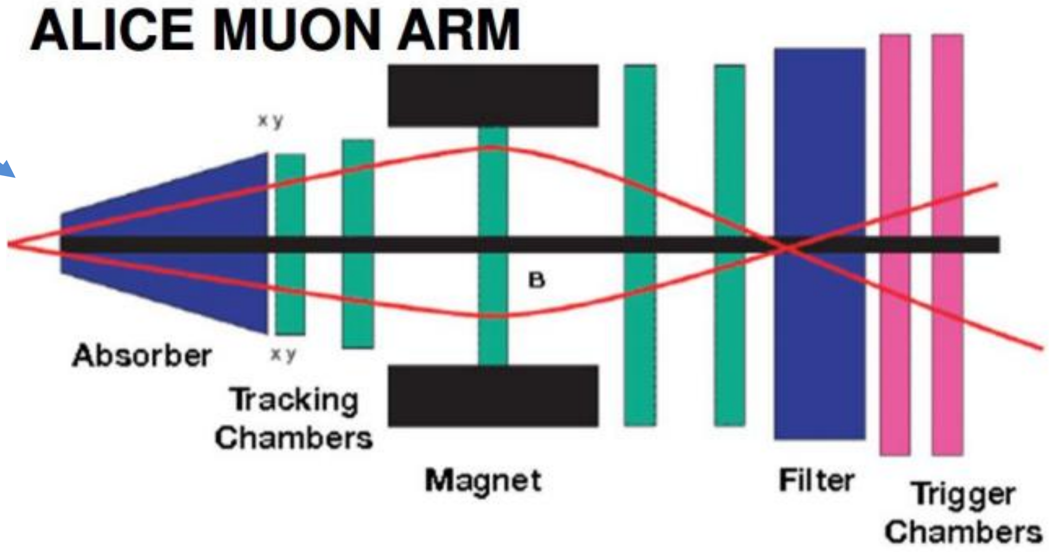
- Small collision systems (pp and p-Pb collisions)
  - Baseline for heavy-ion collisions
  - Cold nuclear matter effects (p-Pb)
  - Reveal the origin of flow-like phenomena at high multiplicity in small collision systems

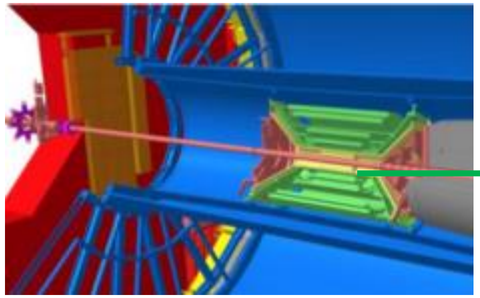
Open heavy-flavour muon measurement with ALICE detector

- Heavy-flavour muons: c, b → $\mu^{\pm}$ (2.5 < y <4)



Forward MUON Arm





V0, T0

Silicon Pixel Detector

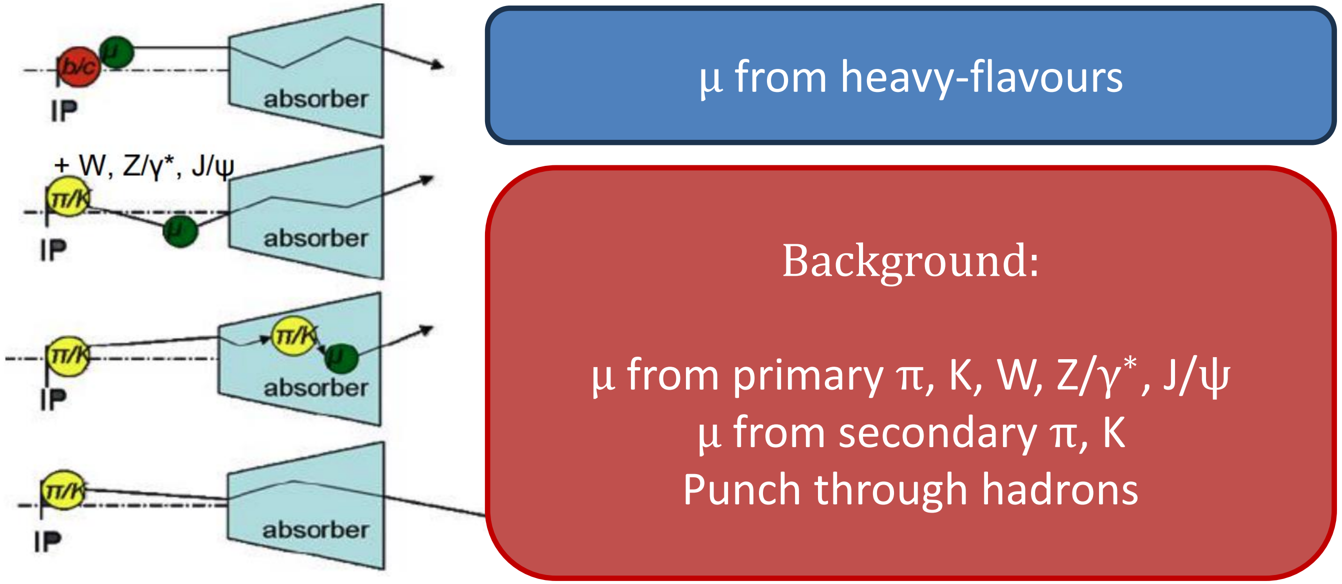
Forward Muon spectrometer ($-4 < \eta < -2.5$)
- Muon trigger, tracking

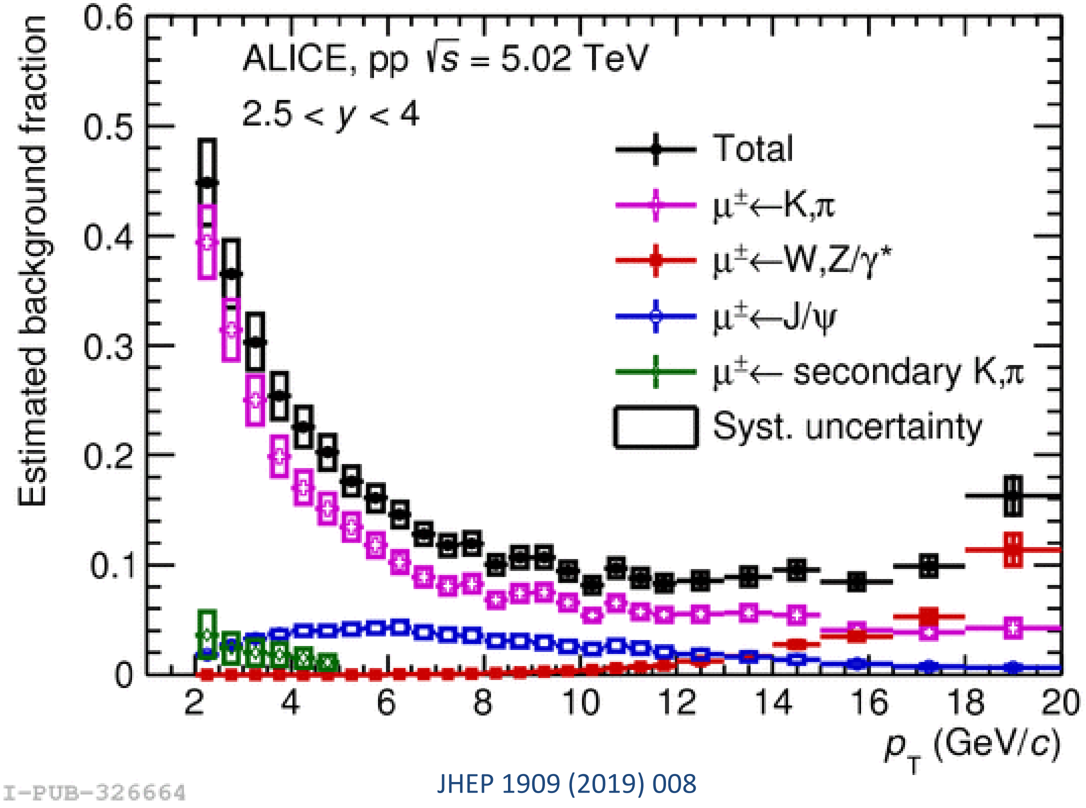
Forward/backward detectors: V0, T0
- Event trigger, multiplicity, timing

SPD (Silicon Pixel Detector) ($|\eta| < 1.4$)
- Vertexing

Muons analysis methodology

- Muon track selection
  - **Acceptance & geometrical cuts**
    - $-4.0 < \eta < -2.5$: acceptance of the ALICE muon spectrometer
    - $170^\circ < \theta_{abs} < 178^\circ$: geometry of the spectrometer
  - **Muon tracking tracks matched with muon trigger tracks**
    - Reject hadrons crossing the front absorber
  - ***p*×DCA (Dist. Of Closest Approach) in 6*σ***
    - Reject beam-gas interactions and particles produced in the absorber
  - **Low p_T cut**
    - Reject μ from secondary π, K

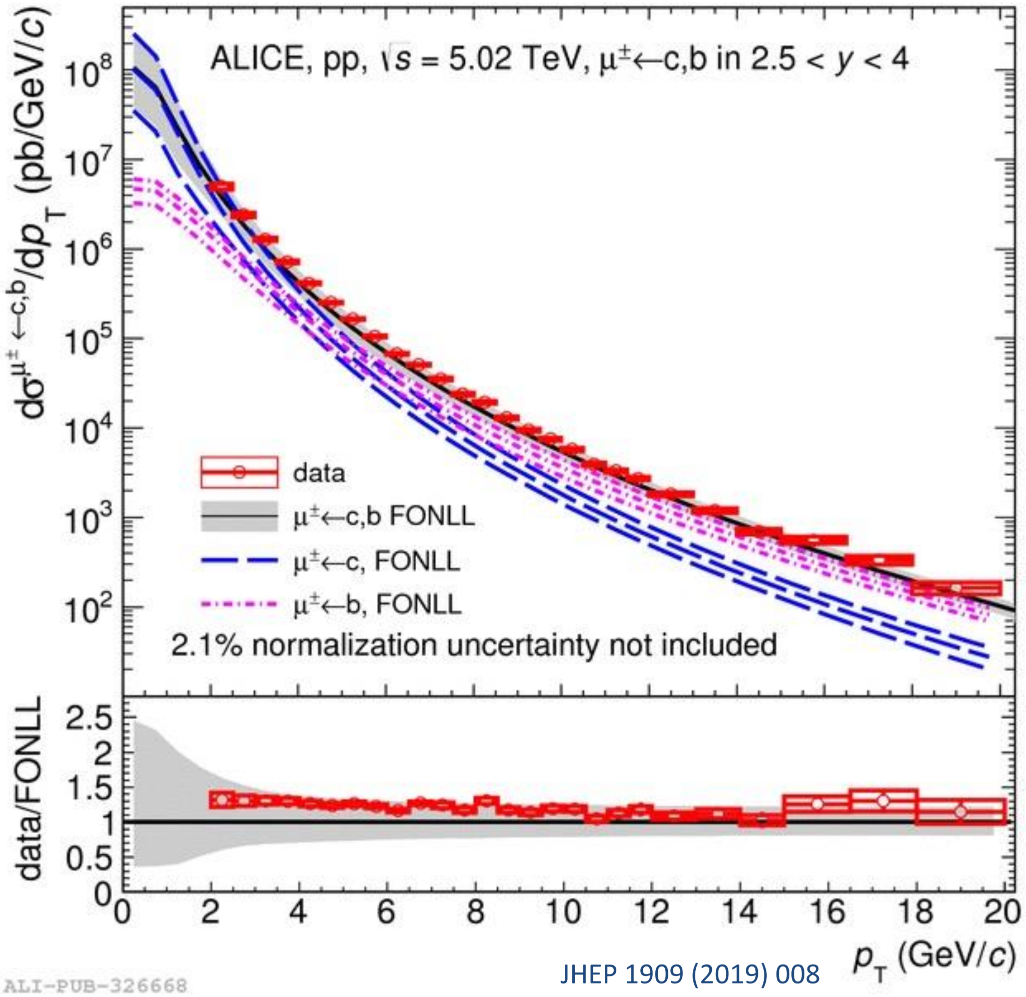




JHEP 1909 (2019) 008

$p_{\rm T}(y)$-differential production cross section in pp collisions

- Measurement over a wide $p_{\rm T}$ range: 2-20 GeV/*c* in pp collisions at 5.02 TeV
  - In 2-7 GeV/*c*, muons from charm hadron decays dominate
  - In 7-20 GeV/*c*, muons from beauty hadron decays take over



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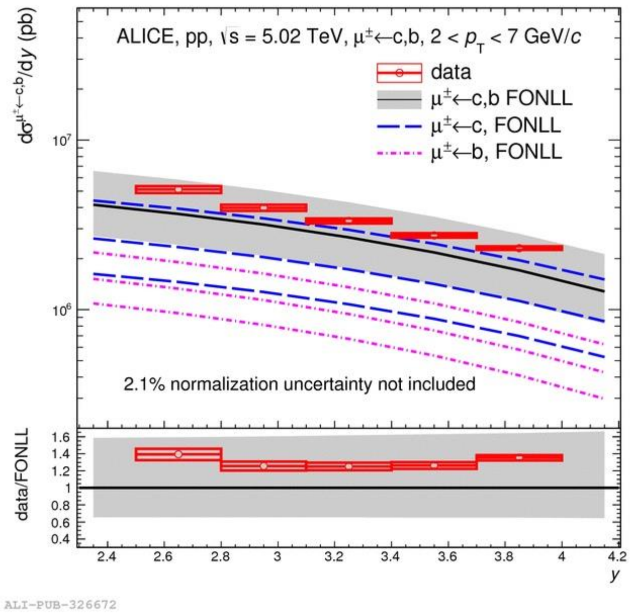
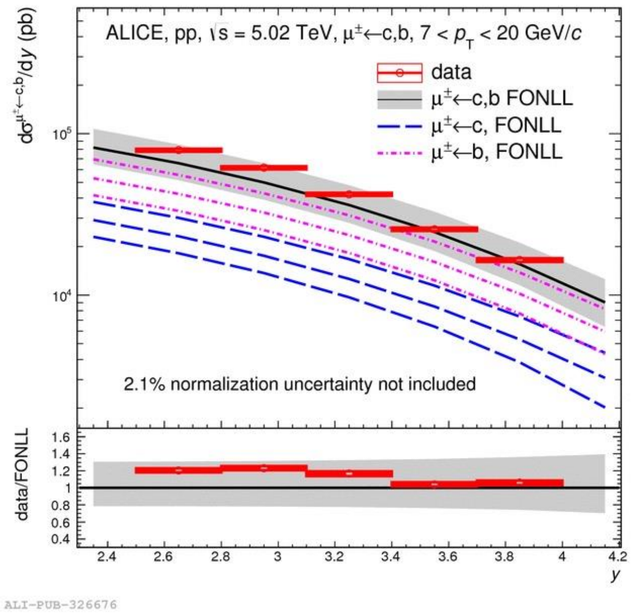
- Data in agreement with FONLL predictions within uncertainties
- Precise measurement, strong constraints on pQCD-based calculations
- The reference for Pb-Pb measurements at $\sqrt{s_{\rm NN}}$ = 5.02 TeV



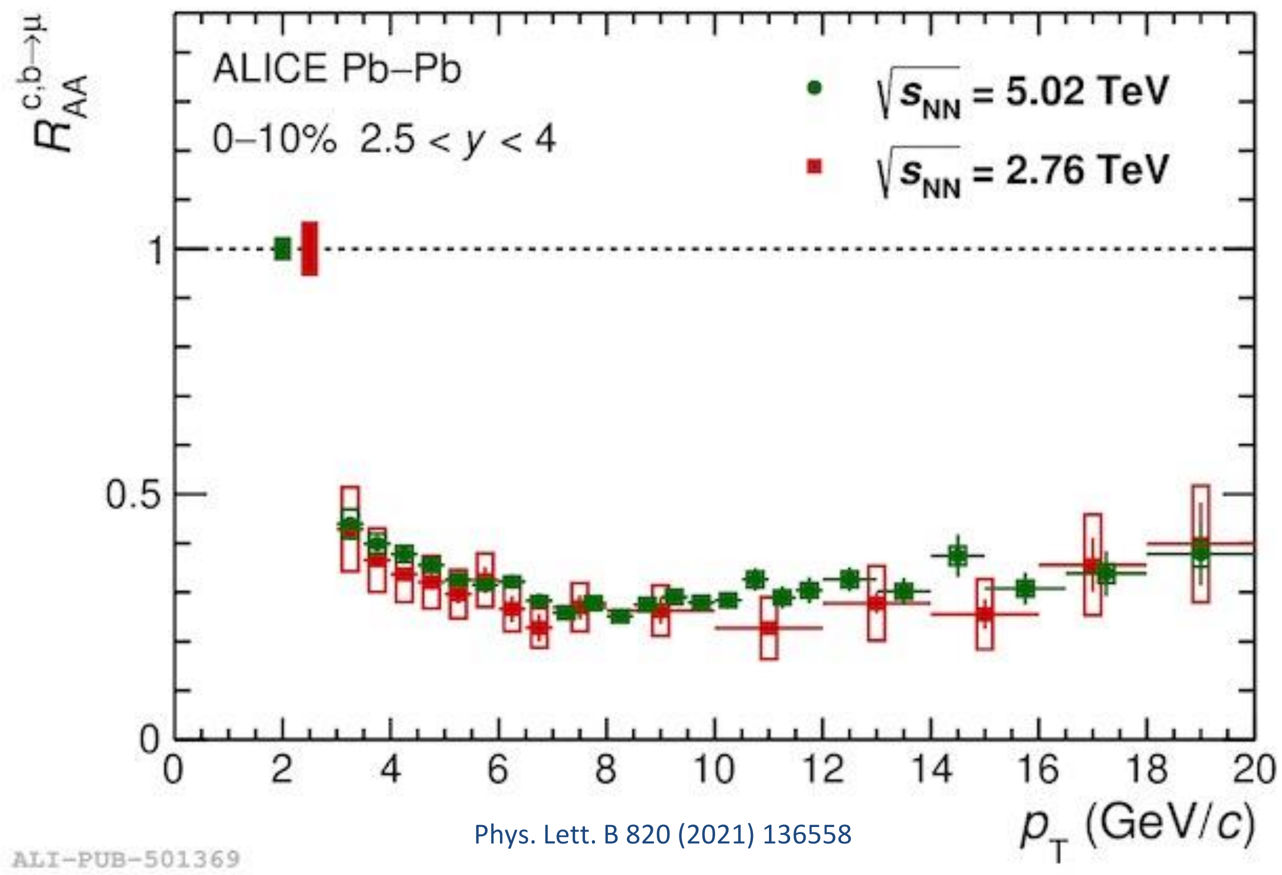


R_{AA} of muons ← c, b in Pb-Pb collisions

- Similar strong suppression observed at 5.02 TeV and at 2.76 TeV for most 10% central collisions
  - Improved precision at 5.02 TeV
  - Harder spectra and denser medium counterbalance

- ✓ Flattening of the p_T spectra of initial charm and beauty quarks with increasing collision energy: decrease the heavy-quark suppression (increase R_{AA}) by about 5% (if medium temperature remains unchanged)

- ✓ Medium temperature estimated to be higher by about 7% at 5.02 TeV than 2.76 TeV: increase the suppression 10% (5%) for charm (beauty)[1]



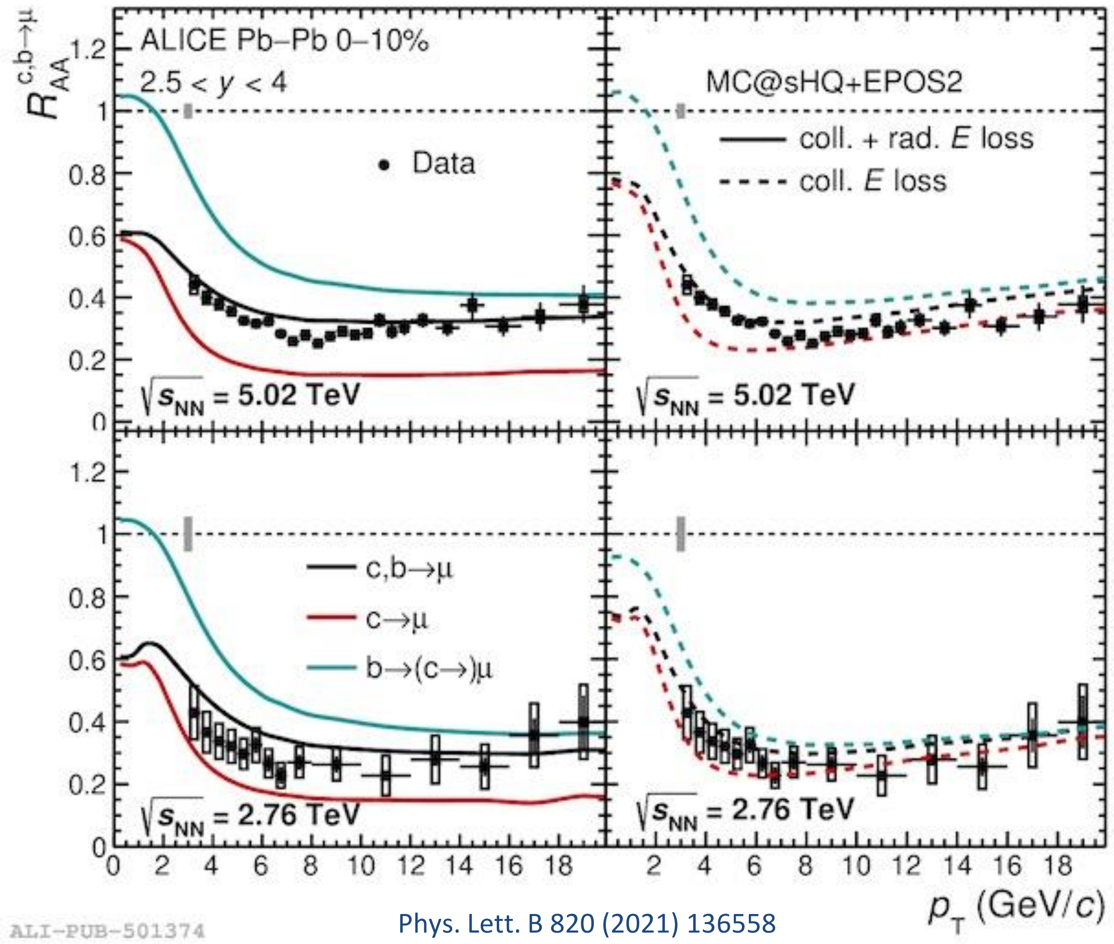
Phys. Lett. B 820 (2021) 136558

[1] M. Djordjevic: Phys. Rev. C 92, 024918 (2015)

R_{AA} of muons ← c, b in Pb-Pb collisions

- MC@sHQ+EPOS2 calculations:
  - Different in-medium energy loss expected for charm and beauty
  - Predictions with different energy loss scenarios in fair agreement with the measured R_{AA} of muons from both charm- and beauty-hadron decays
  - μ ← b : dominant source at high p_T region

- Elastic collisional energy loss processes dominate at low and intermediate p_T region
- Radiative energy loss processes are more pronounced at high p_T region



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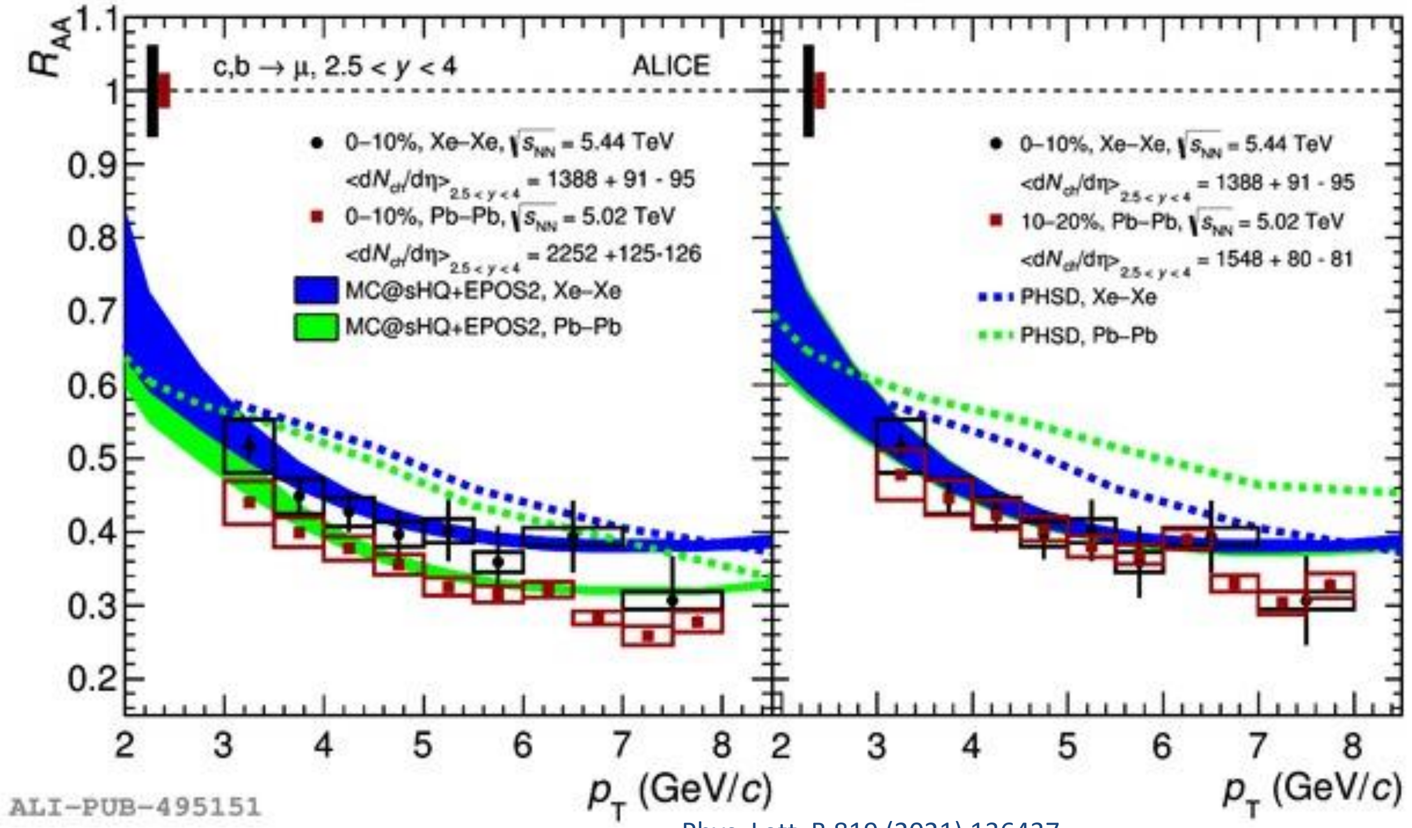
R_{AA} of muons ← c, b: Xe-Xe vs Pb-Pb collisions

- Smaller suppression in Xe-Xe than Pb-Pb collisions for same centrality classes
- Similar R_{AA} observed in 0-10% Xe-Xe and 10-20% Pb-Pb collisions with similar charged-particle multiplicity
  - Possible interplay of geometry and path-length dependence of energy loss[1]
- MC@sHQ+EPOS2: in agreement with the measured R_{AA} for both collision systems
- PHSD: overestimated R_{AA} for both collisions (only collisional energy loss processes implemented)
  - Additional constraints to model calculations



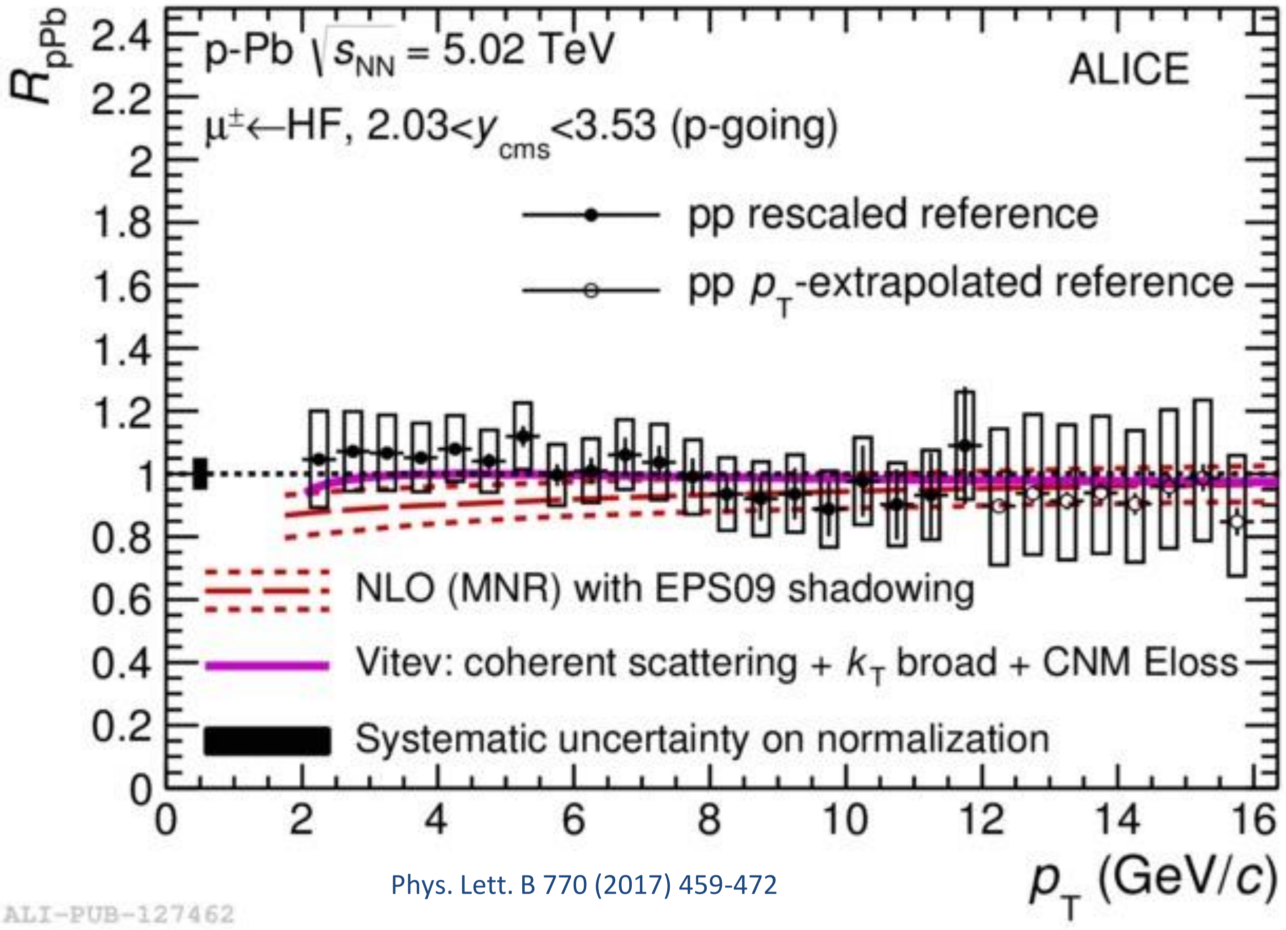
Phys. Lett. B 819 (2021) 136437

PHSD: PRC 93 (2016) 034906
MC@sHQ: PRC 89 (2014) 014905

[1]M. Djordjevic et al, arXiv: 1805.04030

Results from small systems: R_{pPb} measurement

- ❑ Forward rapidity: compatible with unity over whole p_{T} range (R_{pPb}~1)
- ❑ Data measured at forward rapidity can be well described by the models within uncertainties
  - ➢ Cold Nuclear Matter effects are small
  - ➢ The suppression of R_{AA} observed in A-A collisions should result from final-state effects



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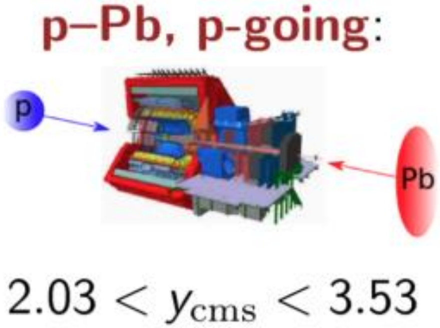
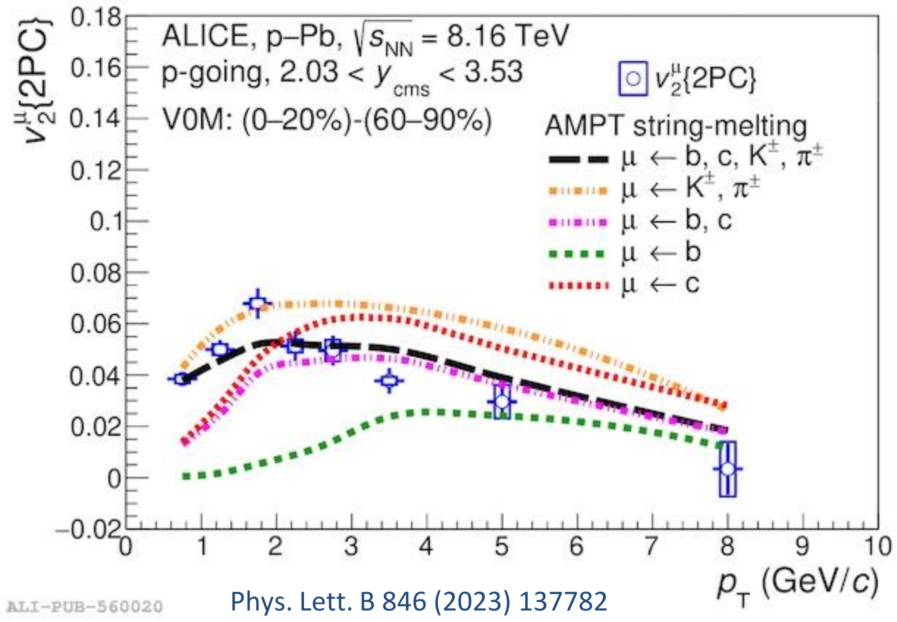


Results from small systems: Inclusive muon v_2 in p-Pb collisions

- Collective flow usually considered as the evidence of QGP
  - Not expected in small collision systems

- In p-Pb collisions at 8.16 TeV
  - Significant positive v_2 ($2 < p_T < 6$ GeV/c) observed: collectivity in small systems
  - Smaller v_2 at high p_T ($6 < p_T < 10$ GeV/c): beauty-dominated region
  - v_2 in AMPT: flow explained by the anisotropic parton escape mechanism
  - v_2 in CGC: qualitative agreement with data suggest possible contributions from initial-state effects



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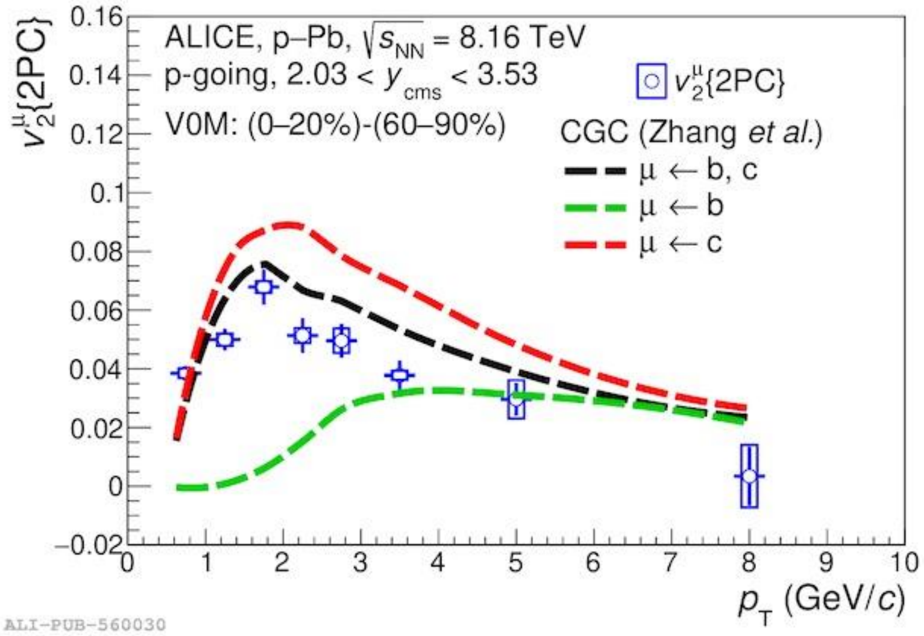
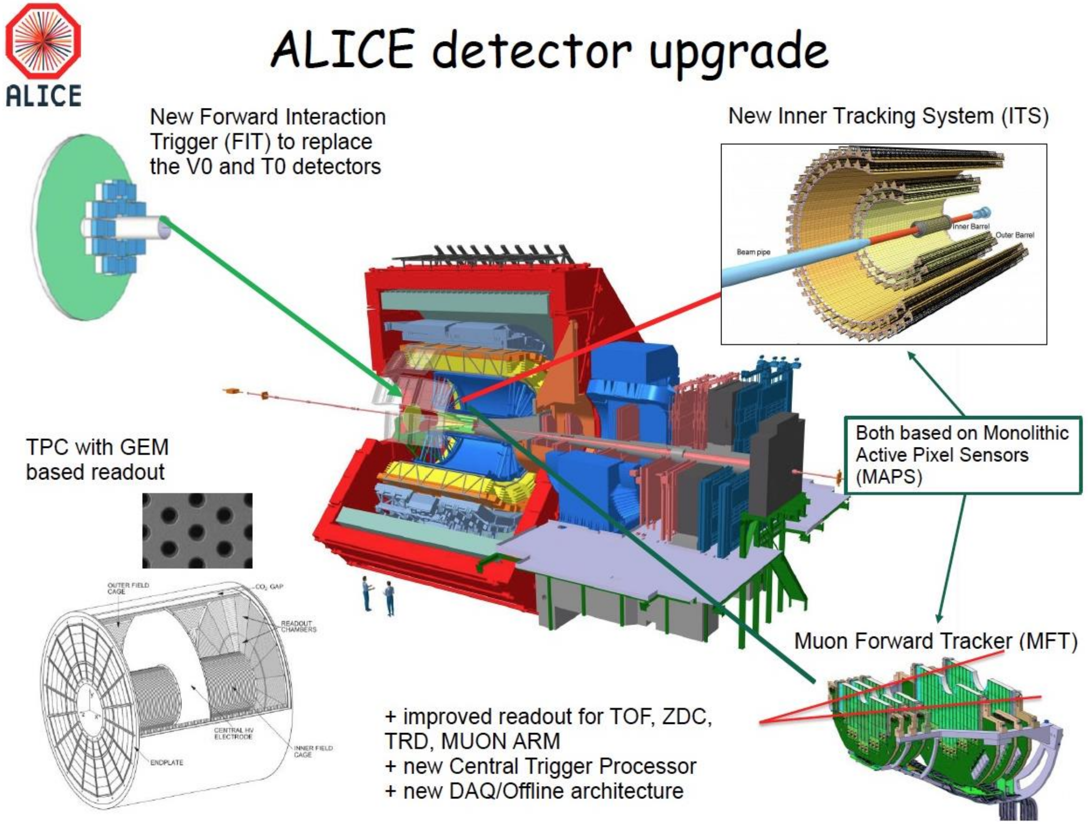
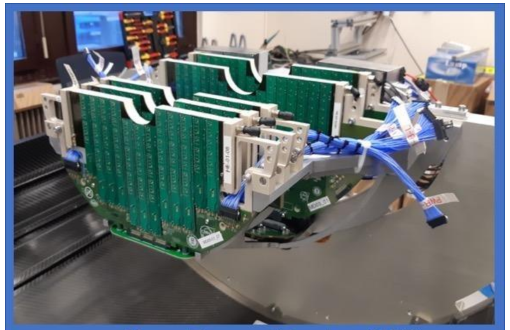


- Significant azimuthal anisotropy for heavy-flavour decay muons, while the R_{pPb} is unity
- More studies on models which combine initial- and final-state effects needed

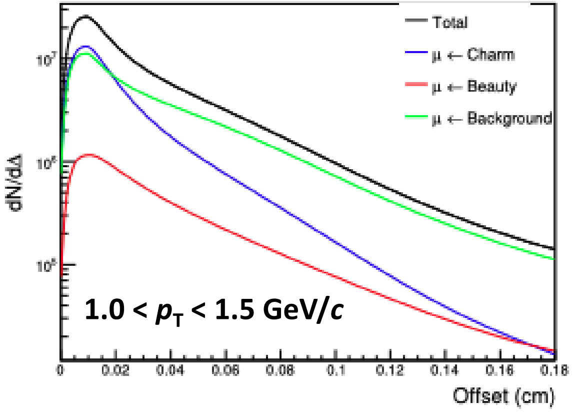
Run 3: c, b separation at forward rapidity

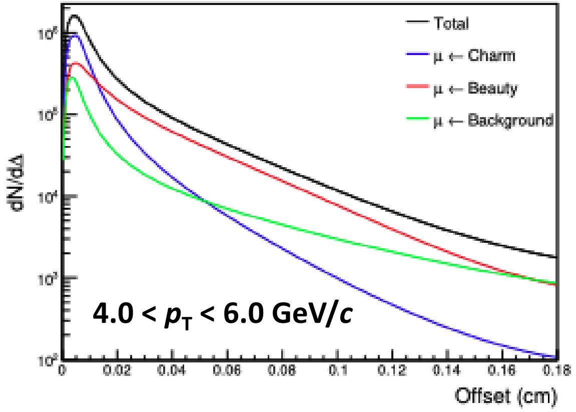




Muon Forward Tracker (MFT)

- Vertexing capabilities at forward rapidity complemented with the new Muon Forward Tracker (MFT) in the Run 3
- New upgraded Inner Tracking System
- New readout system for all detectors
- Increased luminosity
  - Possible to distinguish charm and beauty contributions in the single muon channel in a wide kinematics region, down to lower and higher p_T, for the first time
- Extend the precision measurements of the QGP properties towards the forward rapidity region

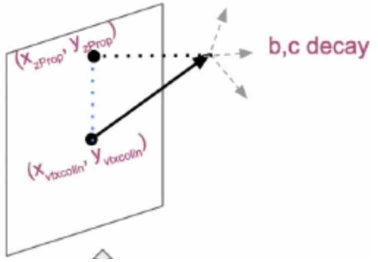




MFT TDR: ALICE-TDR-018

Run 3: c, b separation at forward rapidity

- Separation based on the different decay length of charm- and beauty-hadrons
- Key observable: DCA$_{xy}$ (DCA in the transverse plane)



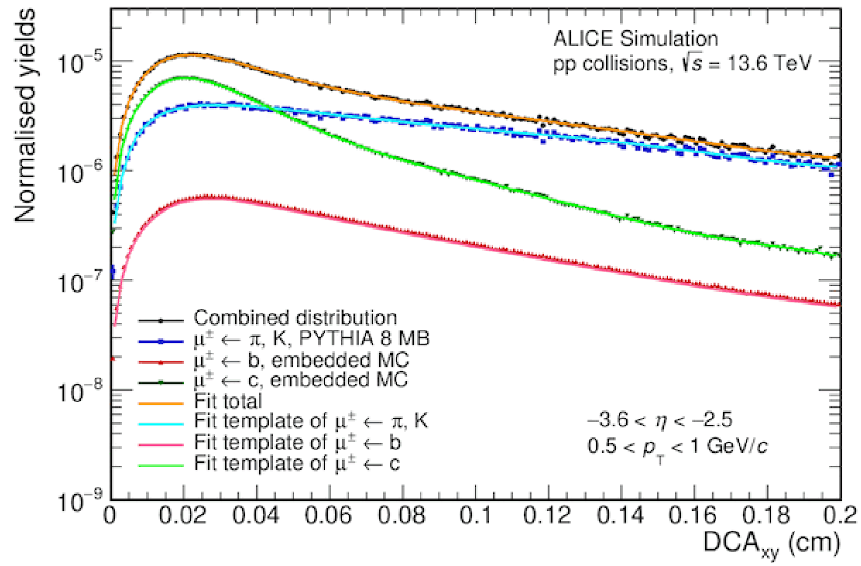
$$\mathbf{DCA_{xy}} = \sqrt{(x_v - x_{extrap})^2 + (y_v - y_{extrap})^2}$$

- Templates: DCA$_{xy}$ of $\mu \leftarrow$ c, $\mu \leftarrow$ b (direct b and b chain) and $\mu \leftarrow \pi$, K from MC
- Fit with the variable-width Gaussian function:

$$f(x) = Ae^{-(x-\mu)^2/2\sigma(x)^2}$$
$$\sigma(x) = \sigma_0^L + \sigma_1^L(\mu - x) + \ldots + \sigma_3^L(\mu - x)^3 \text{ for } x \leq \mu$$
$$\sigma(x) = \sigma_0^R + \sigma_1^R(x - \mu) + \ldots + \sigma_6^R(x - \mu)^6 \text{ for } x > \mu$$

Current status：

- Three template fit method tested and validated with realistic MC simulations in pp collisions
- Charm and beauty components at forward *y* can be measured separately, down to p_T ~ 0.5 GeV/*c* for charm and down to p_T ~1-2 GeV/*c* for the beauty component in pp collisions



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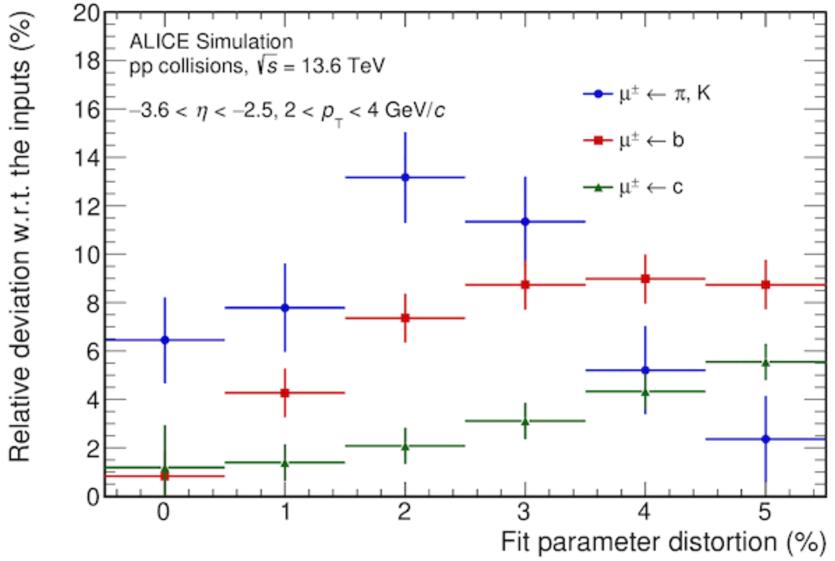


ALI-SIMUL-547377

Conclusion and outlooks

- R_{AA} of open heavy-flavour decay muons in heavy-ion collisions
  - Strong suppression, a factor ~3 in most-central collisions observed
  - The measured suppression is due to hot nuclear matter effects (R_{pPb}~1)
  - Results compatible within uncertainties with those obtained at Pb-Pb (Xe-Xe) collisions with the similar charged-particle multiplicity
  - R_{AA} measurements have the potential to constrain energy loss models

- Positive v_2 of open heavy-flavour decay muons observed at high multiplicity in p-Pb collisions at 8.16 TeV
  - New constraints to understand the origin of collectivity in small collision systems

- The Run 3 analysis ongoing
  - Fit method for c, b separation validated with MC and will be applied on pp and Pb-Pb data

- More study on high-precision multi-differential measurements of both muons from charm and beauty decays at forward rapidity will be performed in Run 3 for the first time

Stay tuned, more to come soon

Thank you for your listening!

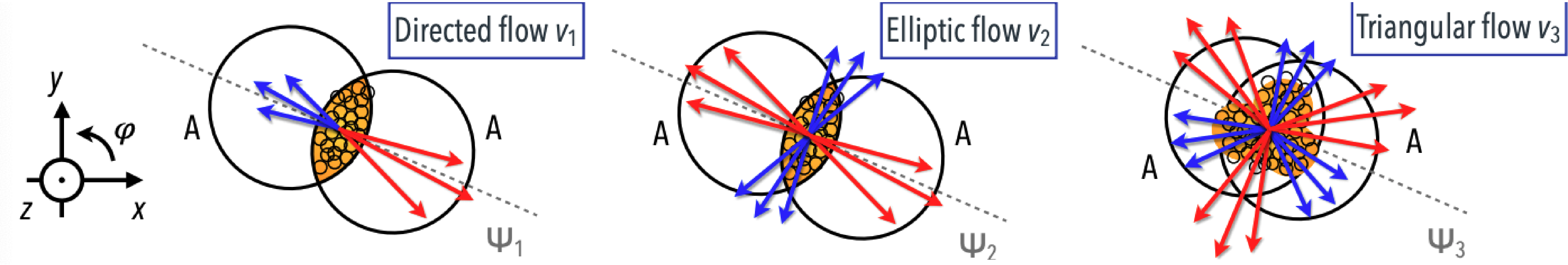
Backup

Physics motivation

- Azimuthal anisotropy in the QGP
- Participation of heavy quarks in the collective motions and the possible thermalization
  - Study path-length dependence of in-medium parton energy loss
  - Sensitivity to initial-state event-by-event fluctuations
  - Probe strong initial electromagnetic fields in the QGP

$$\frac{d^2N}{dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{dp_T}(1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi - \Psi_n)])$$

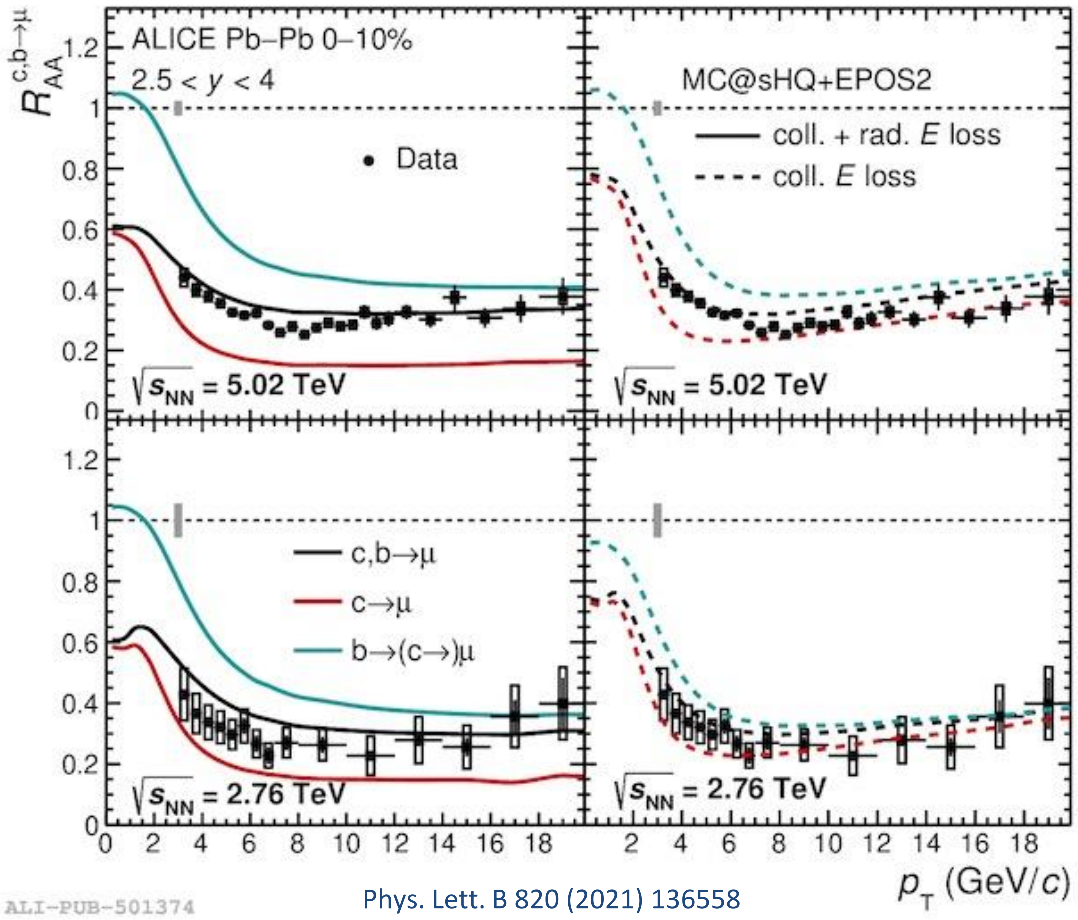
$$v_n = < \cos[n(\varphi - \Psi_{RP})] >$$



R_{AA} of muons ← c, b in Pb-Pb collisions

- MC@sHQ+EPOS2 calculations:
  - Different in-medium energy loss expected for charm and beauty
  - Predictions with different energy loss scenarios in fair agreement with the measured R_{AA} of muons from both charm- and beauty-hadron decays
  - μ ← b : dominant source at high p_T region

- Radiative energy loss neglects finite path-length effects due to the gluon formation outside the QGP and is overestimated at high p_T
  - More pronounced for charm quarks than beauty quarks



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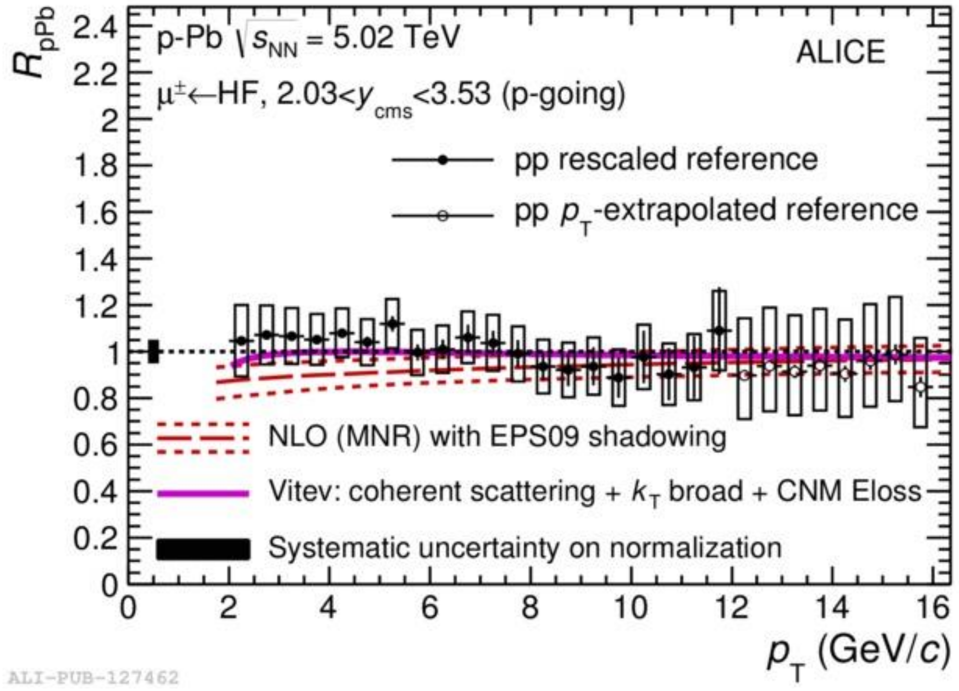
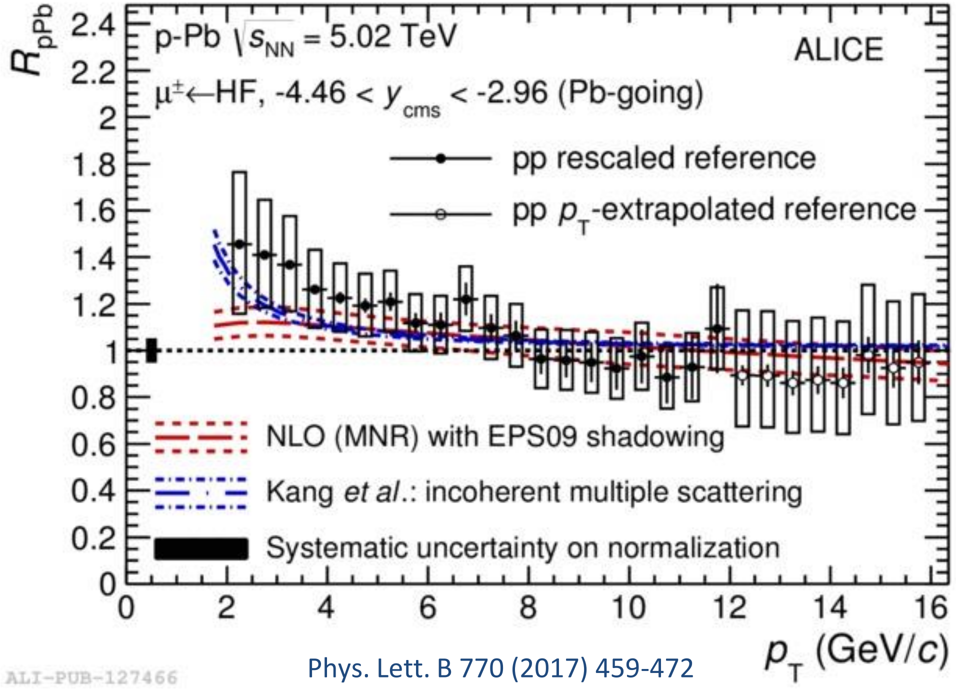
Results from small systems: R_{pPb}

- Forward rapidity: compatible with unity over the whole p_{T} range
- Backward rapidity: larger than unity with a maximum significance of 2.2σ for the interval $2.5 < p_{\mathrm{T}} < 3.5$ GeV/c; Compatible with unity at higher p_{T}
  - Cold Nuclear Matter effects are small
  - The suppression of R_{AA} observed Pb–Pb collisions should result from final-state effects

- Next-to-Leading Order (NLO) pQCD calculations with EPS09 do not include any final-state effect
- Vitev's model: including energy loss in cold nuclear matter, nuclear showing and k_T-broadening
- Kang's model: including both initial state-and final-state interactions





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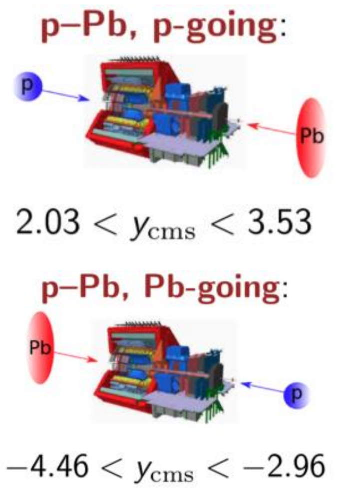
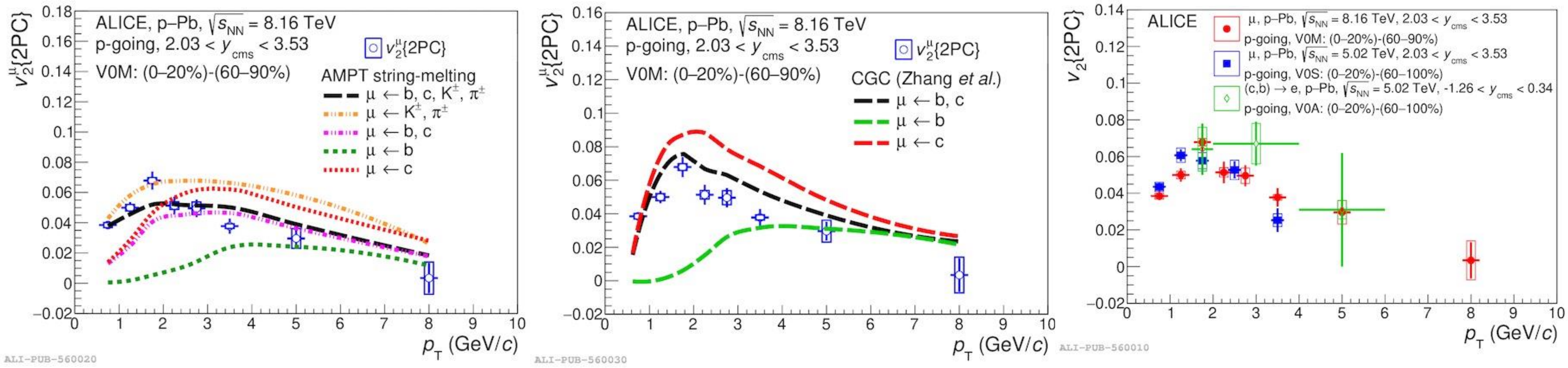


Results from small systems: Inclusive muon v_2 in p-Pb collisions

- Positive v_2 with a significance of up to ~12σ (2 < p_T < 6 GeV/c): collectivity in small systems
- Smaller v_2 at high p_T (6 < p_T < 10 GeV/c): beauty-dominated region
- v_2 in AMPT: flow explained by the anisotropic parton escape mechanism
- v_2 in CGC: qualitative agreement with data suggest possible contributions from initial-state effects



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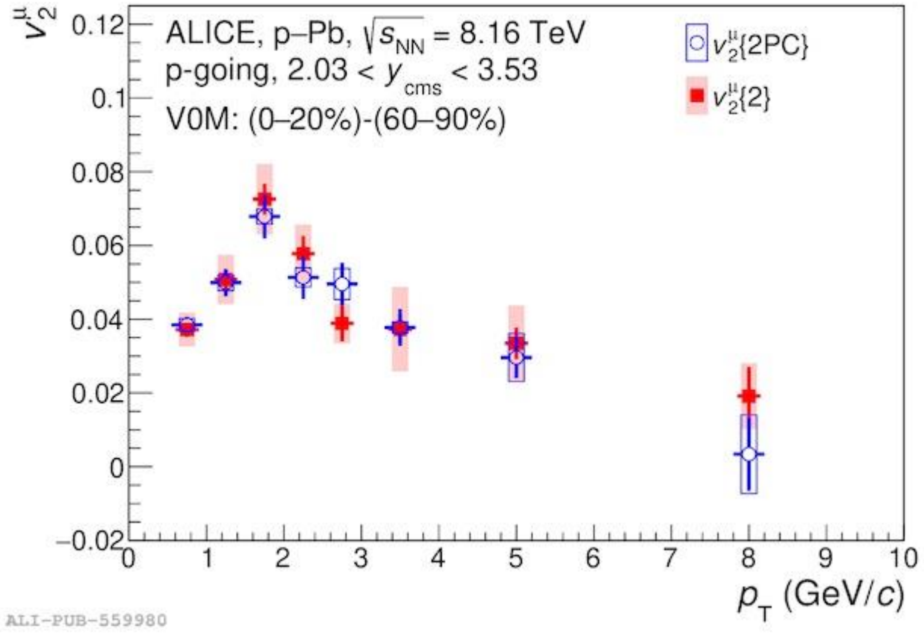
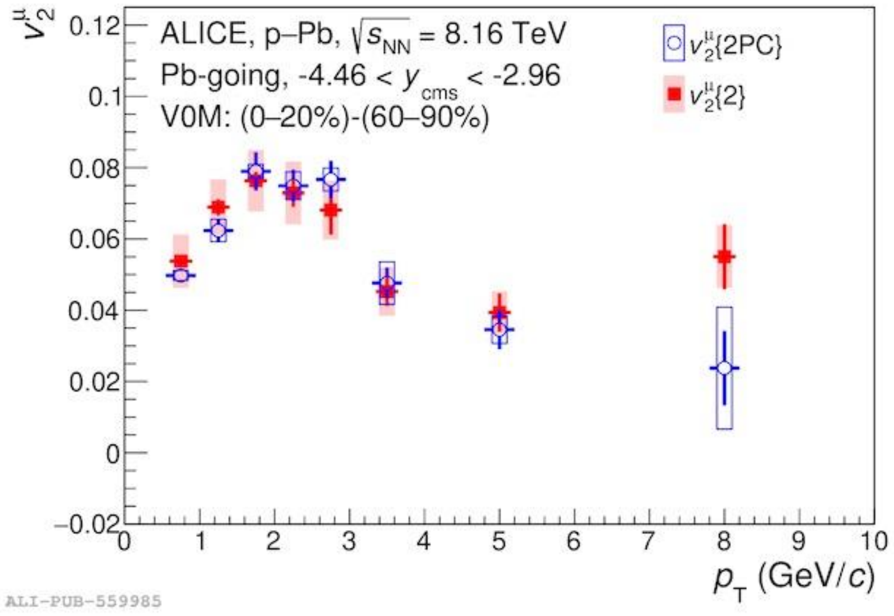
- Significant azimuthal anisotropy for heavy-flavour decay muons, while the R_{pPb} is unity
- More studies on models which combine initial and final state effects needed

- The muon v_2 measured is compatible with published inclusive muons v_2 at forward rapidity and HF-e v_2 at mid rapidity in p-Pb collisions 5.02 TeV

Results from small systems: Inclusive muon v_2 in p-Pb collisions

- The two methods(2-particle correlation and 2-particle cumulants) give compatible results after respective nonflow subtraction
- A tendency for a slight increase of v_2 in the highest p_T region is visible at backward rapidity with the two-particle cumulant method





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