Correlations and heavy flavour in small systems

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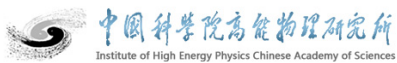


Probing small systems with heavy flavour

Why study heavy flavour production in small systems (pA, pp)?

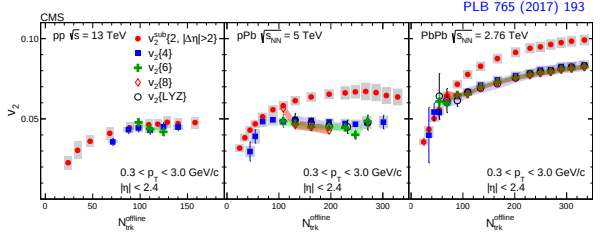
- Modifications of the initial state
  - Gluon saturation: nuclear PDFs, Color Glass Condensate (CGC)...
- Interpretation of PbPb results: intermediate size system
  - Different interplay of initial state and other cold nuclear matter (CNM) effects, QGP?
- Insights on collectivity
  - Heavier quark mass: do HF hadrons flow? + comparison with light flavours
- **Help understanding collectivity in small systems**

Collectivity in small systems: light flavour

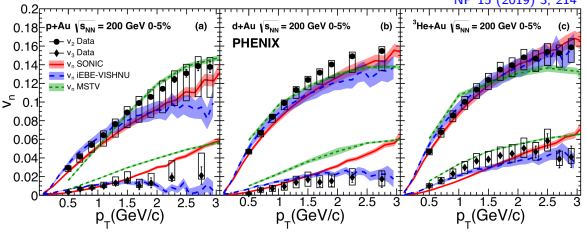
see e.g. R. Belmont's talk (Tue)

- Collectivity (long-range multi-particle correlations) also in small systems (pA, pp)
- What is the relative importance of:
  - initial state: initial *momentum* correlations, e.g. CGC
  - final state: initial *spatial* anisotropy + interactions in the final state (hydro, transport)
- Light flavours: mostly final-state + geometry?
- Heavy flavours (this talk): ...

PLB 765 (2017) 193



NP 15 (2019) 3, 214

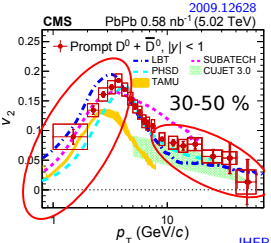


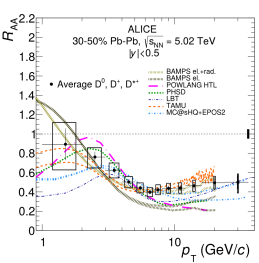
Heavy flavour in large systems

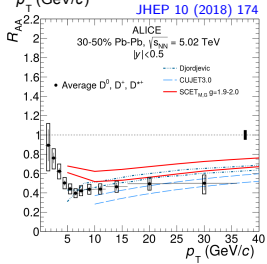
Heavy flavour production in PbPb: a 1-minute overview

Can roughly separate two regimes:

- Low p_T :
  - Study the **thermalisation** of heavy quarks
  - Constrain the color potential of HQ-medium interaction
- High p_T :
  - Study the **energy loss** of heavy quarks
  - Constrain the flavour hierarchy of parton energy loss







Outline

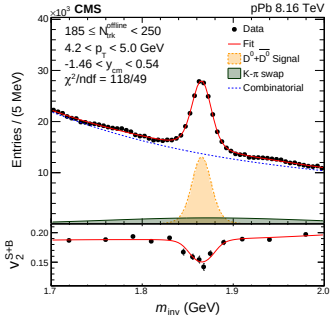
Flow and correlations: experimental methods

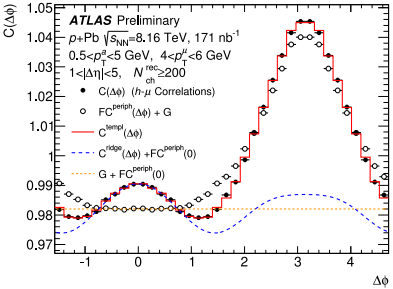
see e.g. Q. Hu's talk (Tue)

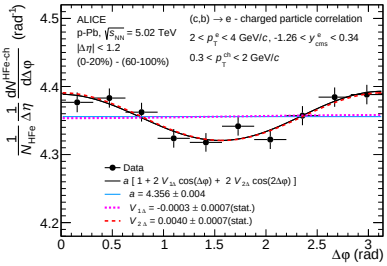
Heavy flavour hadron flow in small systems: **challenges**

- Account for nonflow contribution (estimated using low multiplicity events)
- Extract signal v_2 from signal + background

- ALICE, CMS: 2-particle correlation (Fourier fit) with nonflow subtraction
- ATLAS: template fit of $\Delta\phi$, accounting for nonflow from peripheral



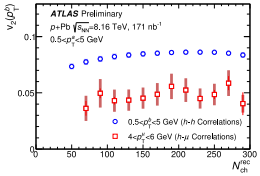


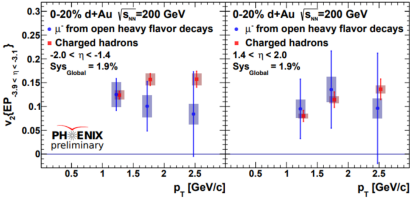


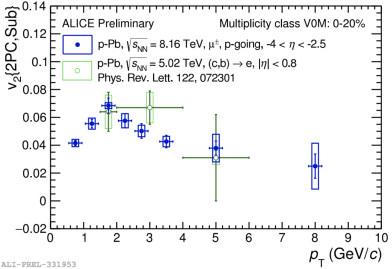
Heavy flavour decay leptons in pPb

- Large v_2 (up to $\approx 7\%$)
  - Over a wide rapidity range: forward and backward muons, mid-rapidity electrons
  - Smaller than charged hadrons

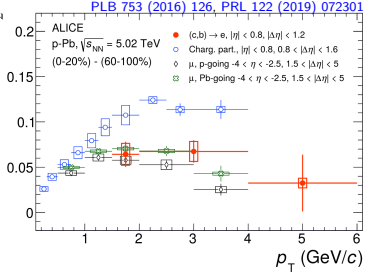
ATLAS-CONF-2017-006







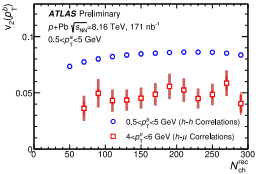
PLB 753 (2016) 126, PRL 122 (2019) 072301

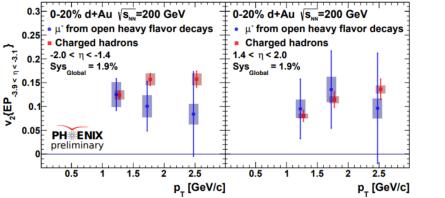


Heavy flavour decay leptons in pPb

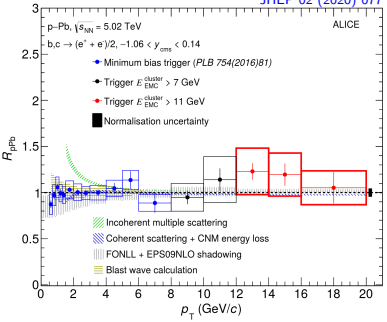
- Large v_2 (up to $\approx 7\%$)
  - Over a wide rapidity range: forward and backward muons, mid-rapidity electrons
  - Smaller than charged hadrons
- R_{pPb} consistent with 1

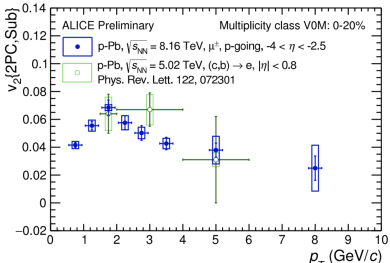
ATLAS-CONF-2017-006



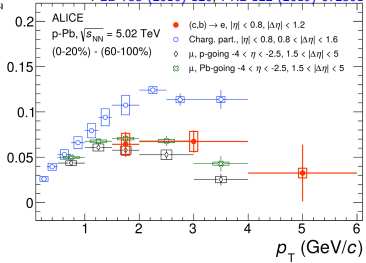


JHEP 02 (2020) 077





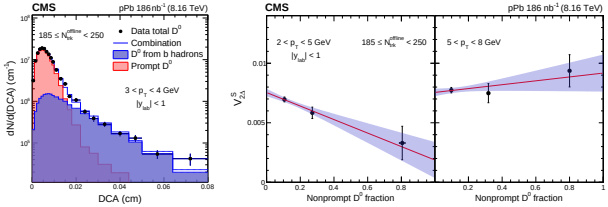
PLB 753 (2016) 126, PRL 122 (2019) 072301

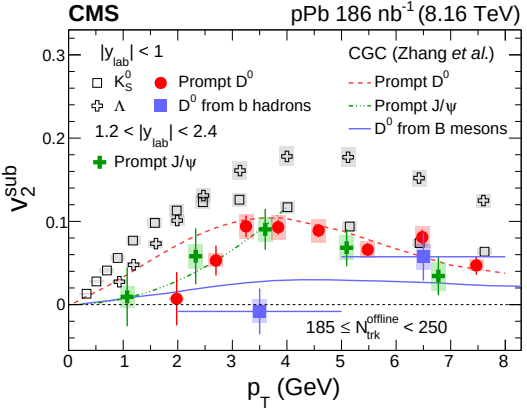


ALI-PREL-331953

Prompt D mesons in pPb

PLB 813 (2020) 136036



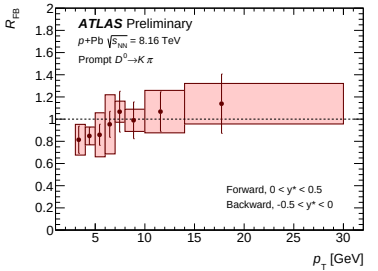


- Prompt and nonprompt D^0 mesons in pPb
  - First time measurements for $B \rightarrow D$!
- Prompt and nonprompt separated using templates in DCA
- v_2(nonprompt D) < v_2(prompt D) at medium p_T (2.7σ)

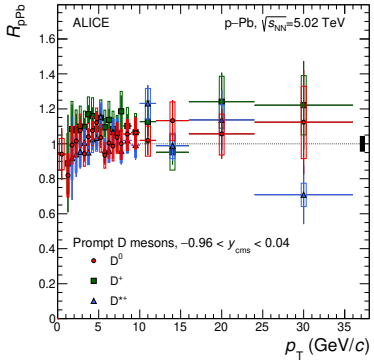
Prompt D meson R_{pA}: midrapidity

Similar results for D^+ ($\rightarrow K^-\pi^+\pi^+$), D^0 ($\rightarrow K^-\pi^+$), D^{*+} ($\rightarrow D^0\pi^+$)... even D_s^+ ($\rightarrow \phi\pi^+$)!

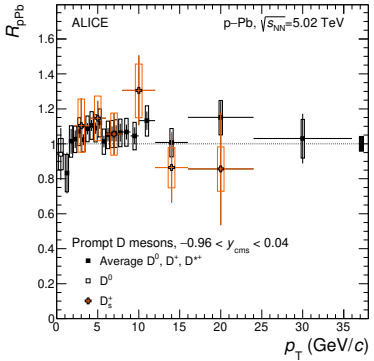
ATLAS-CONF-2017-073



JHEP 12 (2019) 092



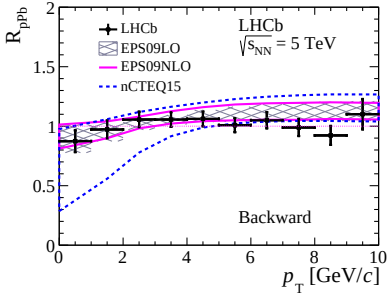
JHEP 12 (2019) 092

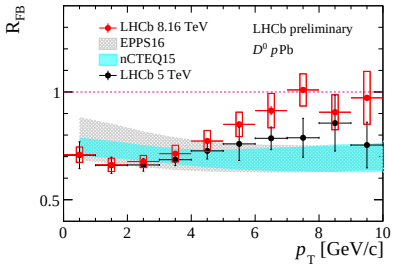


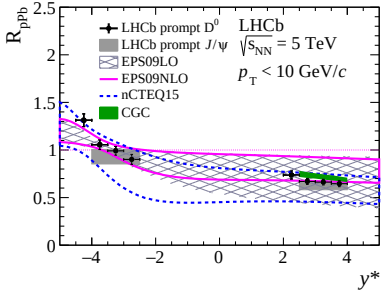
Prompt D meson R_{pA}: forward rapidity

JHEP 10 (2017) 090, LHCb-CONF-2019-004

- Modification consistent with nPDF expectations (also CGC at forward)
- Precise data: can it be used to constrain nPDF? (gluon shadowing at forward, antishadowing at backward)
  - See e.g. PRL 121 (2018) 052004, JHEP 05 (2020) 037





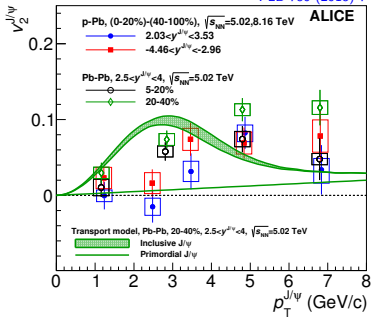


Prompt J/ψ in pPb

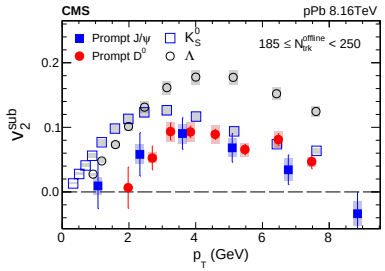
Large J/ψ flow in pPb!

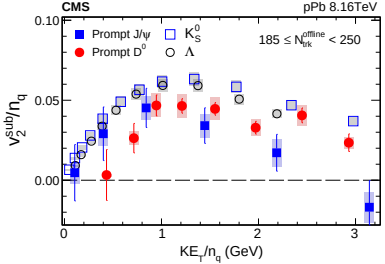
- Comparable to PbPb values
- Similar values at forward and backward
- Lower v_2 than light (strange)
  - But similar at low KE_T/n_q?
- Similar v_2 as D^0 mesons

PLB 780 (2018) 7



PLB 791 (2019) 172

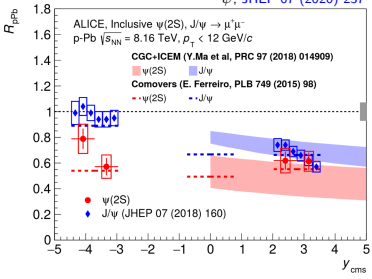




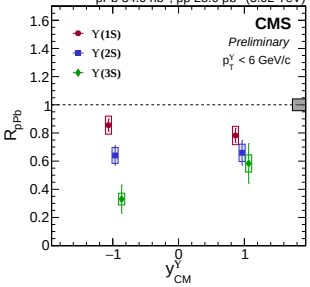
Quarkonia and final state interactions

- Different modification of excited vs ground state in pA
  - Both for charmonia and bottomonia
- Hint for the importance of final state interactions
  - At least for the fragile excited states

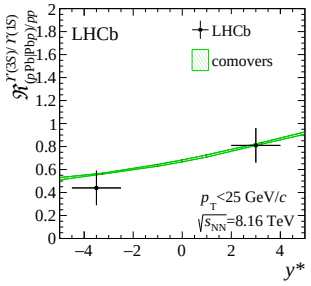
ψ, JHEP 07 (2020) 237



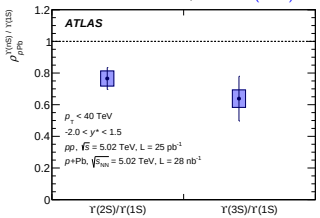
Υ, CMS-PAS-HIN-18-005



Υ, JHEP 11 (2018) 194



Υ, EPJC 78 (2018) 171

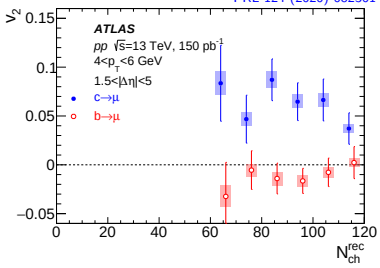


What about pp?

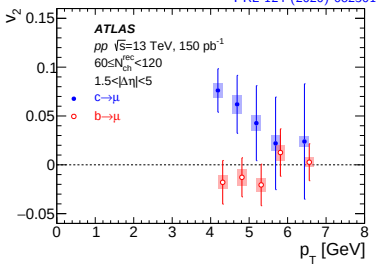
Also non-zero v_2 for charm in pp! But not for beauty?

- ATLAS: HF decay muons
- CMS: prompt D^0 mesons

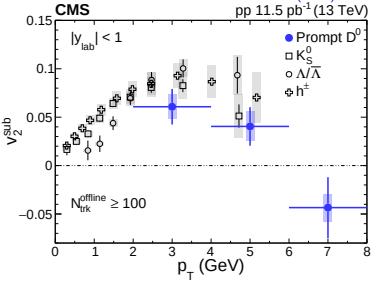
PRL 124 (2020) 082301



PRL 124 (2020) 082301



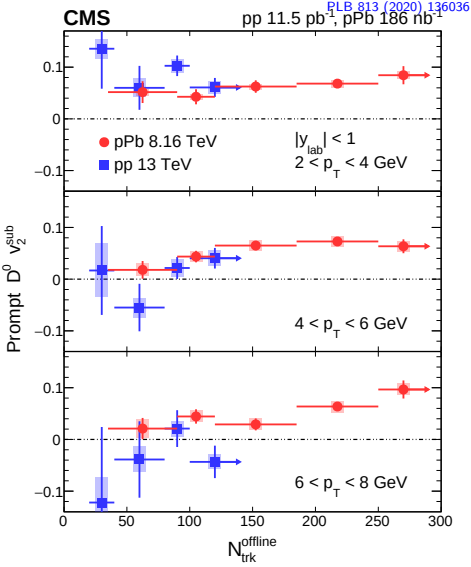
PLB 813 (2020) 136036



No clear understanding yet of the origin of HF flow in pp...

Multiplicity dependence of collecitivity

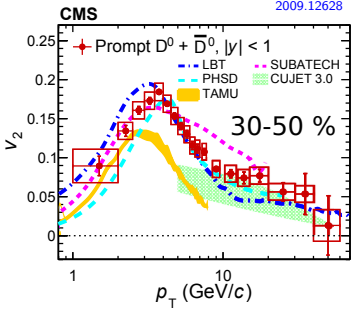
- Similar prompt D v_2 in pp and pPb for similar multiplicities
- Significant v_2 in pPb down to low multiplicities
- Hint for a larger v_2 at high multiplicities for $p_T > 4$ GeV

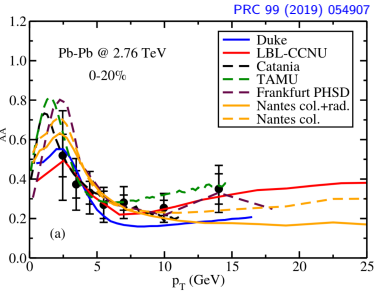


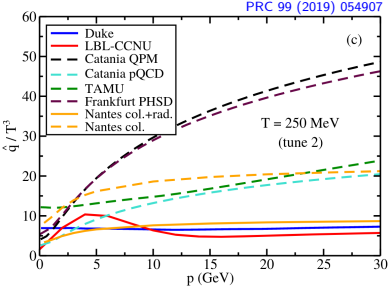
Outline

Transport models: PbPb

- Many models on the market
- Good description of R_{AA} and v_2 data
- Differences remain in model ingredients (e.g. HQ transport)





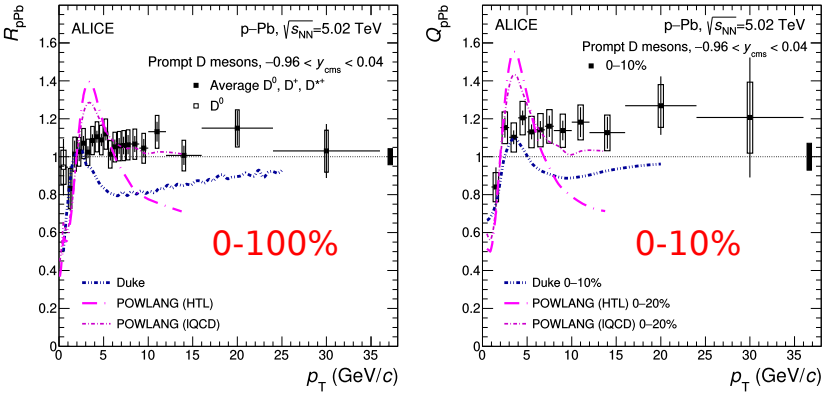


Transport models for D mesons: Duke, Powlang

Transport models assuming QGP: Duke (1510.07520), POWLANG (JHEP 03 (2016) 123)

ALICE: JHEP 12 (2019) 092

- No hint for peak or high p_T suppression in data, even in central data
- Large uncertainties, e.g. hadronisation
- Duke: v_2 requires a very different spatial diffusion coefficient D in pPb and PbPb



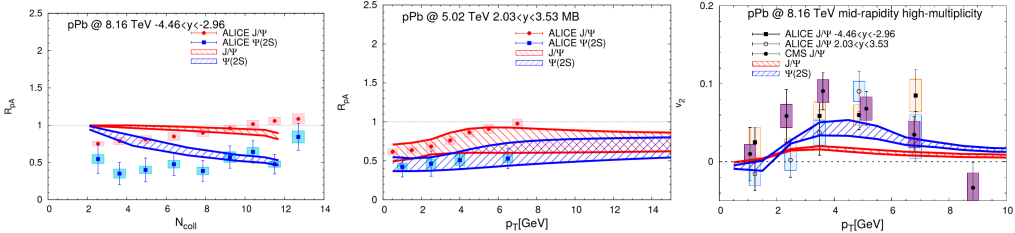
Transport model for J/ψ: TAMU

JHEP 03 (2019) 015

- Includes nPDF, final state from expanding fireball (QGP + hadronic phase)
- Good description of R_{pPb}
- Under-prediction of v_2

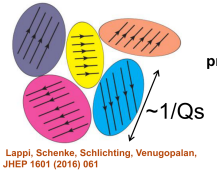
Conclusions:

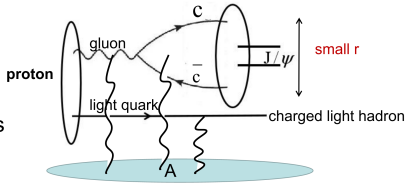
- v_2 cannot originate from final-state interactions alone
  - see also similar v_2 at forward and backward in data
- Elastic interactions? (not in model)

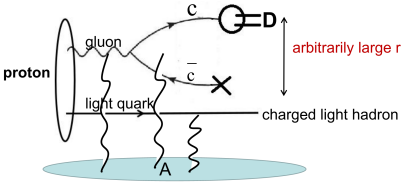


CGC

PRL 122 (2019) 172302







Recent CGC calculation:

- Angular correlation between HF and LF hadrons
- Difference between closed and open HF: separation of the Q and $\bar{Q}$

Caveats:

- HQ momentum anisotropy is not correlated with the spatial anisotropy of the IS
  - contrasts with experimental results for light flavours
- Only applicable to forward rapidities

CGC

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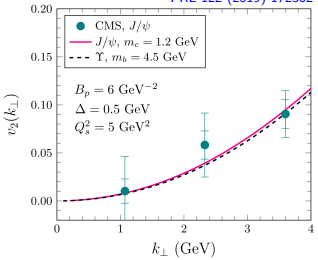
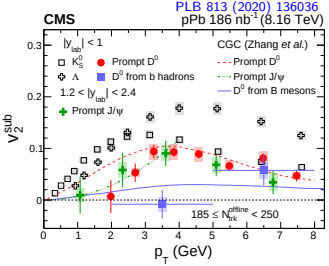


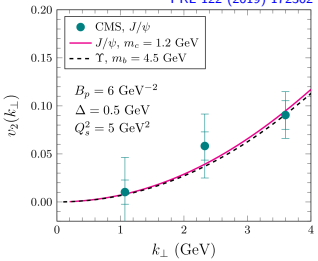
PLB 813 (2020) 136036



- Good description of the data
- Predicts a smaller v_2 for open beauty as compared to open charm (as observed in data)
- J/ψ and Υ are predicted to be the same

CGC

PRL 122 (2019) 172302



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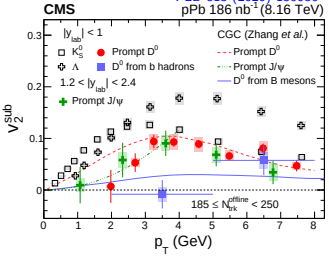
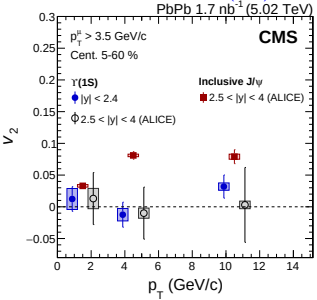


2006.07707, PRL 123 (2019) 192301



- Good description of the data
- Predicts a smaller v_2 for open beauty as compared to open charm (as observed in data)
- J/ψ and Υ are predicted to be the same
  - Strong claim: not the case in PbPb...
  - Need a measurement in pPb

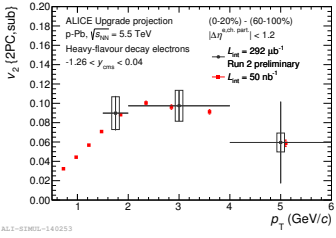
Experimental outlook

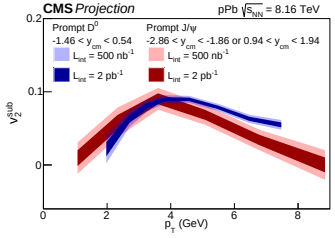
Experimental prospects:

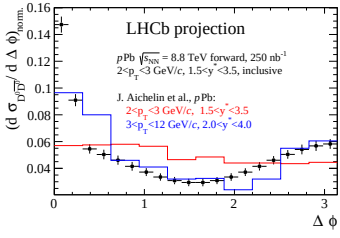
- Run 3 of the LHC starting in 2022: more data!
- Major upgrades of the ALICE (and LHCb) detectors

Experimental wishlist:

- More precise v_2 measurements for charm and bottom in pPb and pp
- Bottomonium (and $\psi(2S)$?) v_2 in pPb
- More differential measurements (e.g. event activity or light v_2 classes)







Summary

- "Puzzle": significant HF v_2 in pPb, but $R_{pA} \approx 1$ (midrapidity D)
- Transport models fail to provide a good description of both
- Good modelling from CGC, within current uncertainties
- For a better understanding of HF colelctivity in small systems:
  - More experimental results: Υ, more precise J/ψ, D, B
  - Improved transport models for pA?
  - Theory for pp

Thanks to Pol-Bernard Gossiaux, Wei Li, and Cyrille Marquet for inputs and discussion.