XXXIII International (ONLINE) Workshop on High Energy Physics
"Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests"

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Logunov Institute for High Energy Physics (Protvino, Moscow region, Russia) of National Research Centre "Kurchatov Institute"

Measurements of leptons from HF decays and understanding small systems

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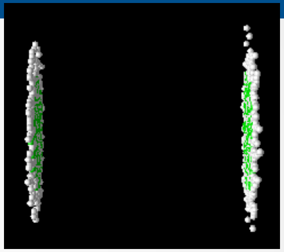
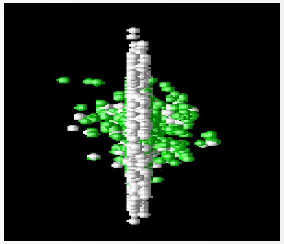
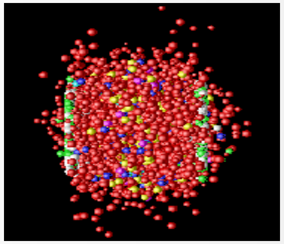
Heavy Quarks

Heavy quarks carry information about early stage of collisions:

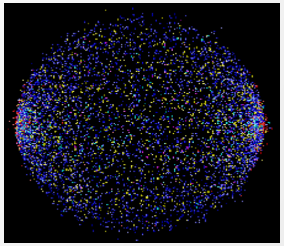




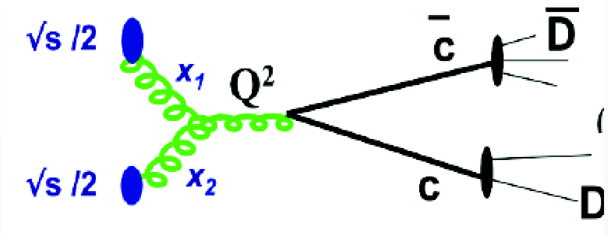
- **Charm(c) and bottom(b) quarks are massive**



- **Formation takes place only early in the collision.**



- **Sensitivity to initial gluon density and gluon distribution**



Selected results on HF and Quarkonia

D.Das , Nucl.Phys.A 1007 (2021) 122132,

D.Das, IJMPA Vol. 36, No. 24, 2130014 (2021)

Why good probes?

Heavy Quarks : Why good probes?

Large Mass : $m_{c,b} >> \Lambda_{QCD}$

Are hard probes, even at low p_T

Do not change flavor while interacting with the QCD medium, although the phase-space distribution does change

$\tau_{prod} \sim 1/2m \sim 0.1$ fm $<< \tau_{QGP} \sim 5\text{-}10$ fm

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{Yield\,(A+A)}{Yield\,(p+p) \times \langle N_{coll} \rangle}$$

- Knowing system properties in a simple way
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile of the medium
- Heavy-ion (AA) collisions
  - hard processes : calibrated probe
  - transported through the whole evolution of the system
  - suppression provides density measurements

Heavy quarks in pp and pA collisions

pp : test understanding of heavy-quark production

- parton level production processes

– LO contributions:

gluon fusion, quark-antiquark annihilation

– NLO contributions: gluon splitting, flavor excitation

– also complex mechanisms, like,

Multi Parton Interactions (MPI)

- understand perturbative QCD calculations where theoretical uncertainties are due to

– renormalization and factorization scales

– quark masses

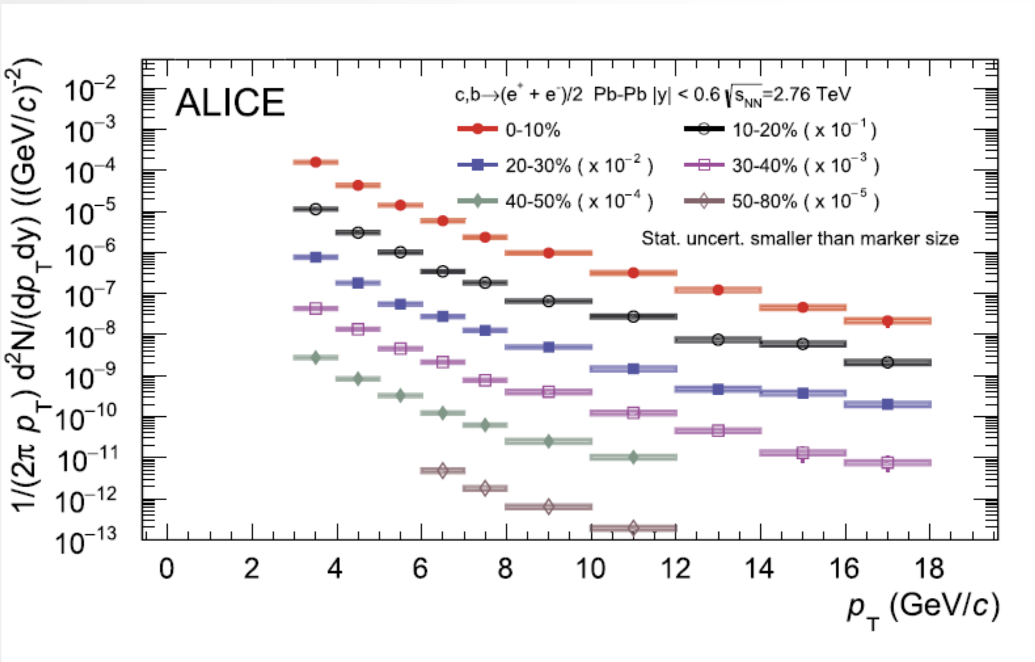
- production mechanisms via differential measurements
  - multiplicity dependence of heavy-flavor production cross sections
  - angular correlation measurements
- pp collisions act as a reference for pA and AA collisions

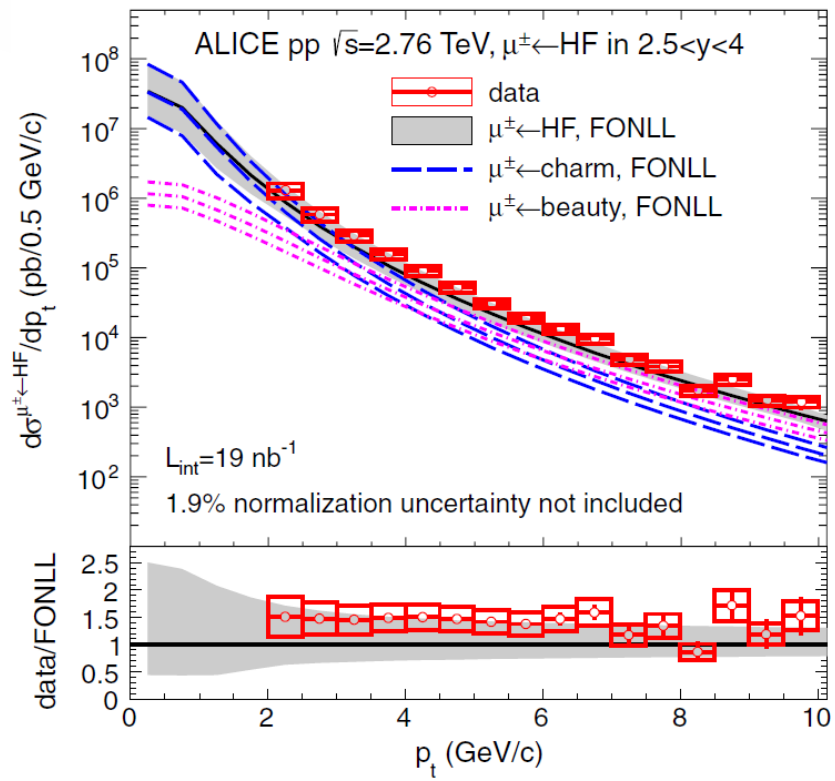
pA collisions : Useful as there is no QGP expected while there are some high density effects

- Nuclear modification of Parton Density Functions
- Saturation and shadowing effects
- Energy loss in Cold Nuclear Matter (CNM)
- Multiple binary collisions and k_T broadening
- Help to compare AA collisions

Electron and Muon spectra at LHC

Pb+Pb Physics Letters B771(2017) 467–481 ALICE PRL 109, 112301 (2012) pp





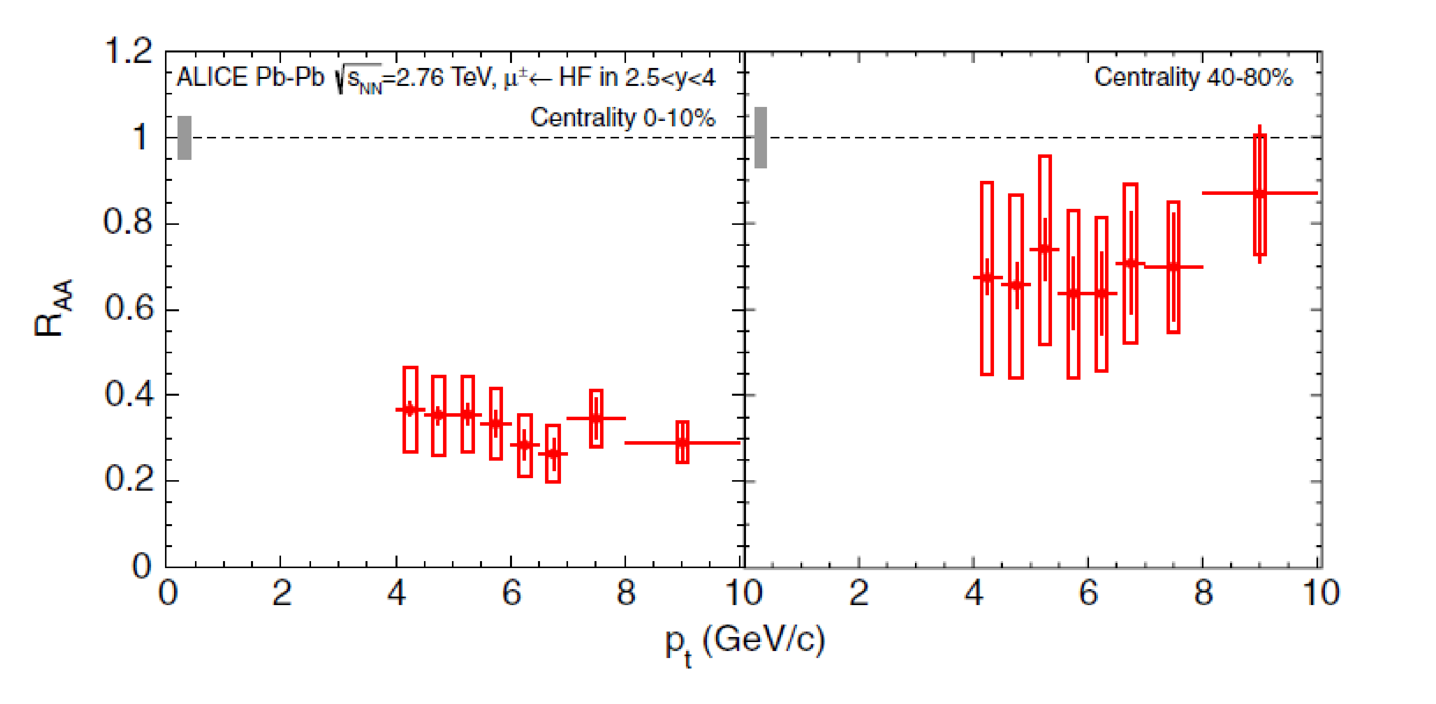
- Left plot : the electrons from semi-leptonic decays of HF hadrons at mid-rapidity in Pb-Pb collisions
- Right plot shows the pQCD calculations in agreement with data at forward rapidity in pp collisions

HF decay lepton R_{AA} : LHC

PRL 109, 112301 (2012)

Pb+Pb 2.76 TeV

ALICE

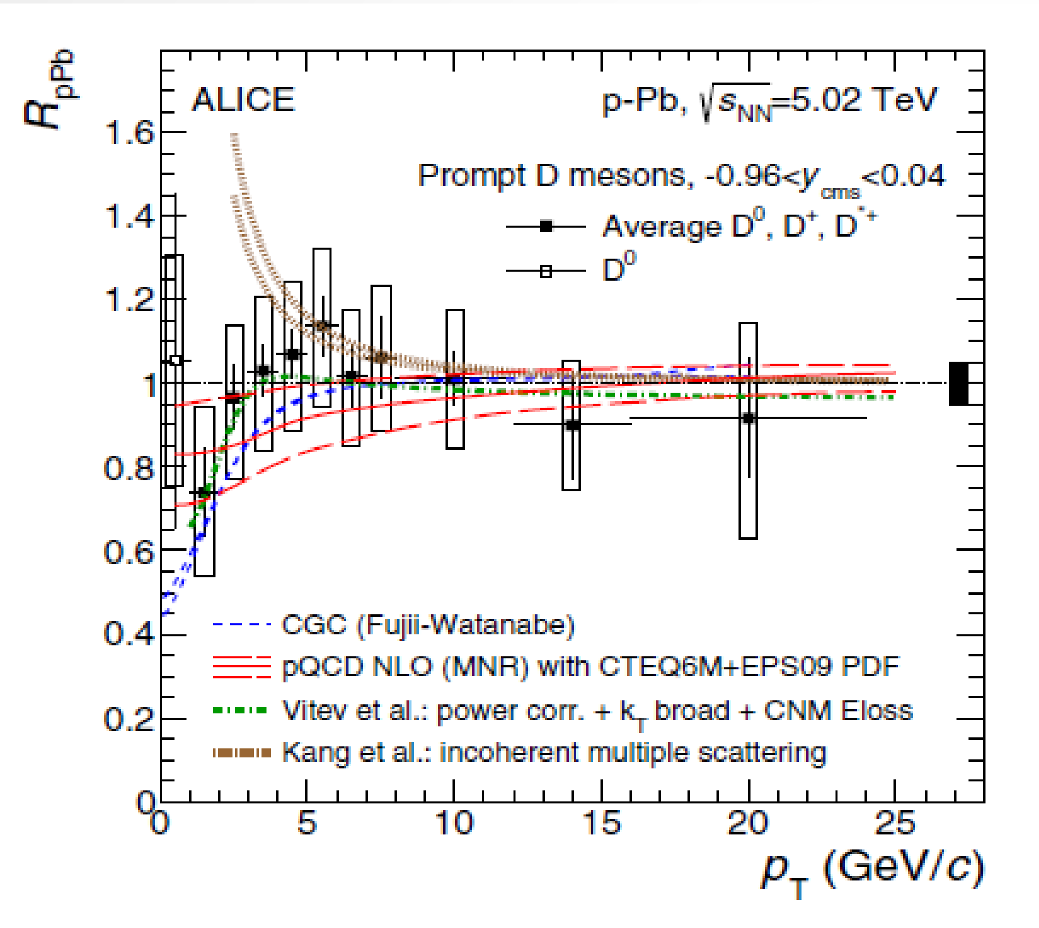


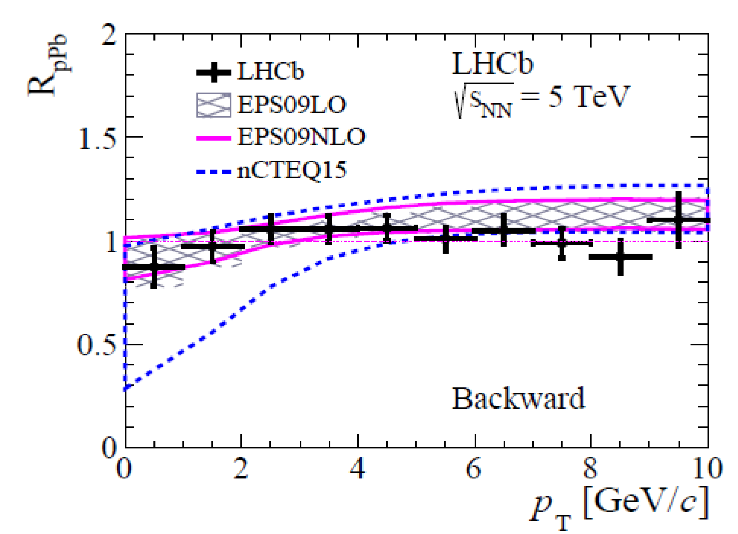
- yields of leptons from heavy-flavor decays show suppression at high-pT in central Pb-Pb collisions, compared with binary scaled pp collisions
- less suppression in more peripheral collisions

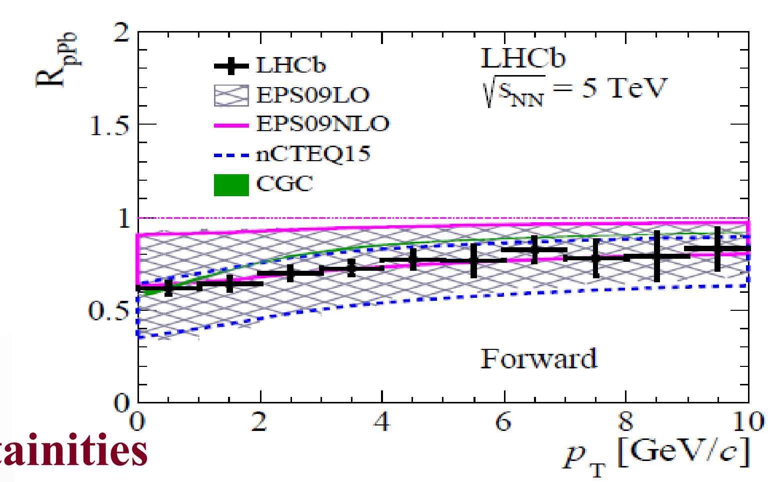
D^0 mesons in pA collisions : LHC

ALICE, PHYSICAL REVIEW C 94, 054908 (2016)

LHCb , JHEP 1710 (2017) 090







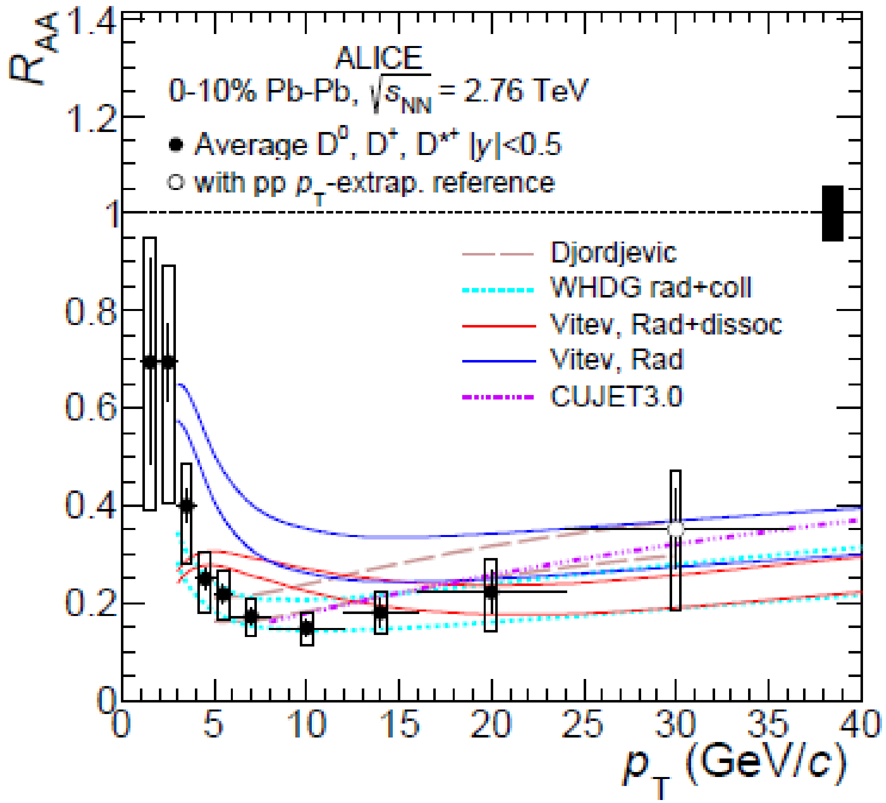
- **ALICE R_{pA} data are consistent with 1 within uncertainities**

  - **We see no major modification in pPb and also similar with LHCb**

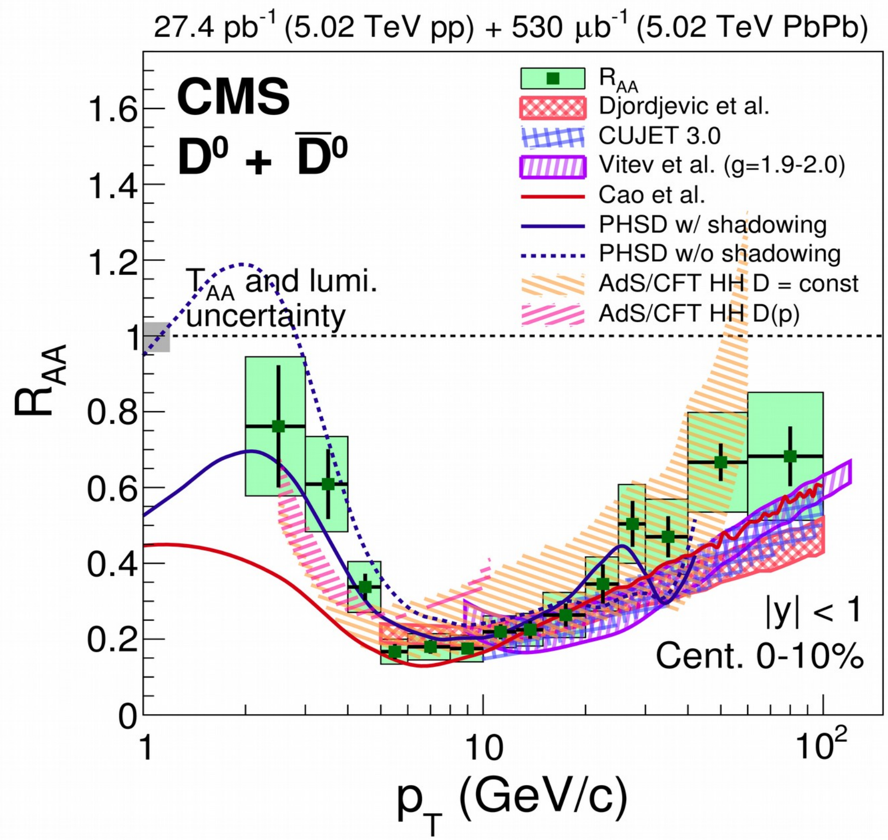
- **We need more precise data to be able to separate between the models**

D mesons in AA collisions : LHC

ALICE , Pb+Pb 2.76 TeV ,JHEP 03 (2016) 081



CMS , Pb+Pb 5.02 TeV , CMS-PAS-HIN-16-001
Phys. Lett. B 782 (2018) 474

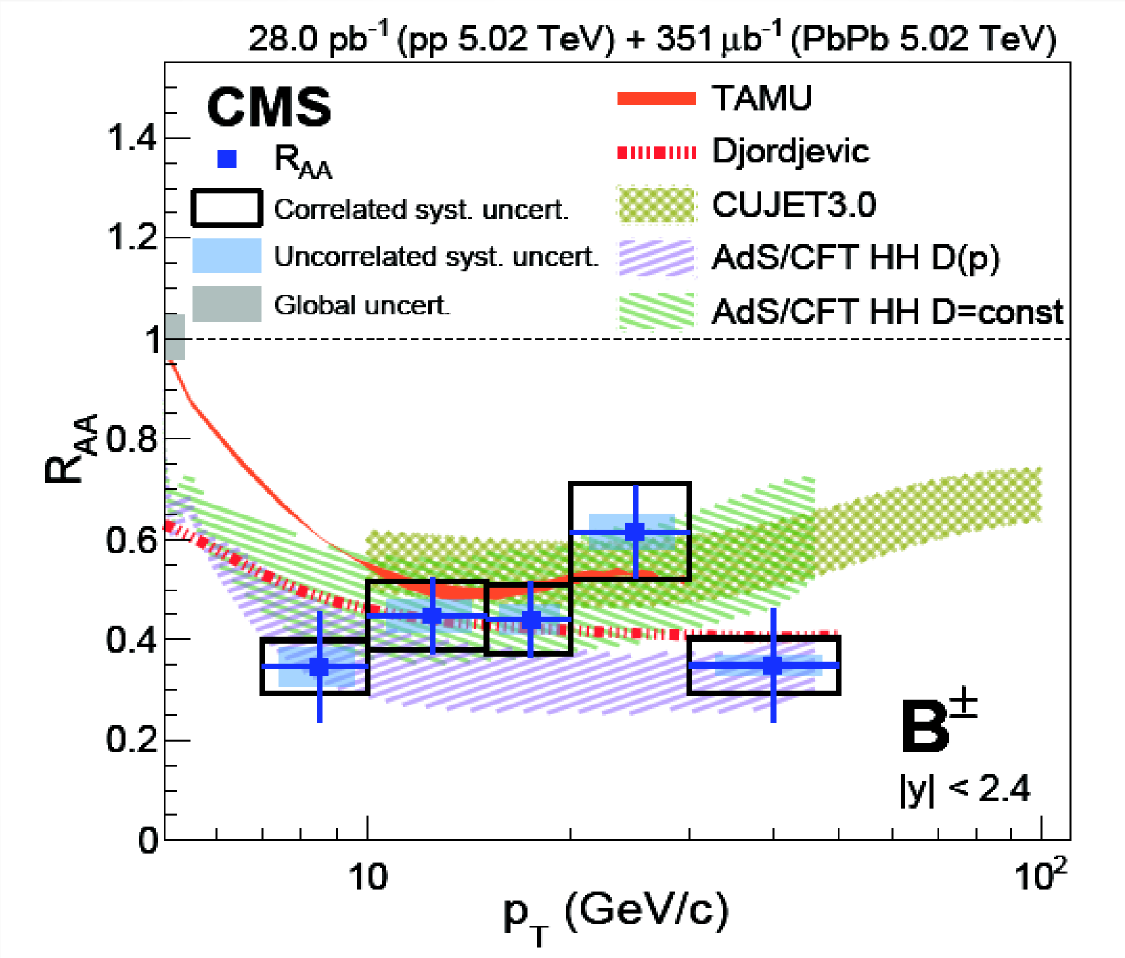


- **Similar suppression in Pb+Pb at 2.76 TeV and 5.02 TeV**

Beauty Suppression : LHC

CMS

Pb+Pb 5.02 TeV, Phys. Rev. Lett. 119, 152301 (2017)



- Consistent with various models
- But we need more precise data to extract detailed underlying mechanism from the various models

Phenix, d-Au

Cu+Cu, Au+Au

System size dependence

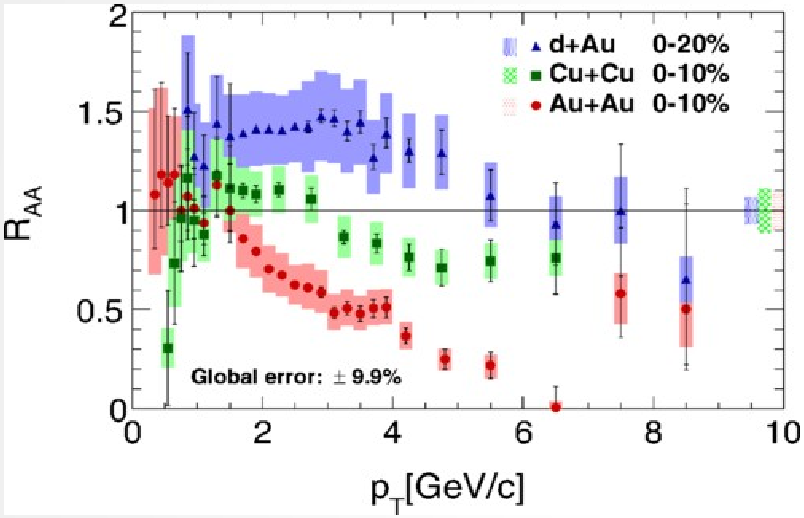
PRC 90, 034903 (2014)

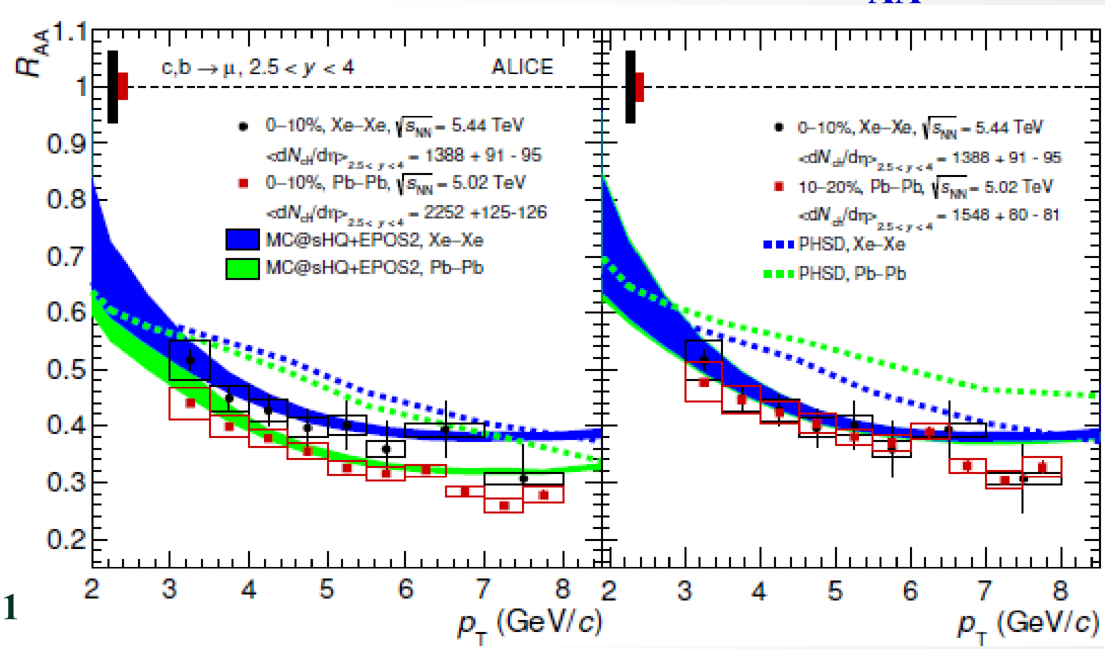
ALICE, Pb-Pb,Xe-Xe

Phys. Lett. B 819, 136437 (2021)

200 GeV, R_{AA}

5.44 & 5.02 TeV, R_{AA}





- The dAu collisions R_{AA} consistent or larger than 1
- High-pT suppression observed in central Au+Au collisions
- Final-state effect due to the formation of a hot and dense medium.
- Cu+Cu show smaller suppression than central Au+Au collisions due to the smaller size of the system created in the collisions of the lighter Cu nuclei.

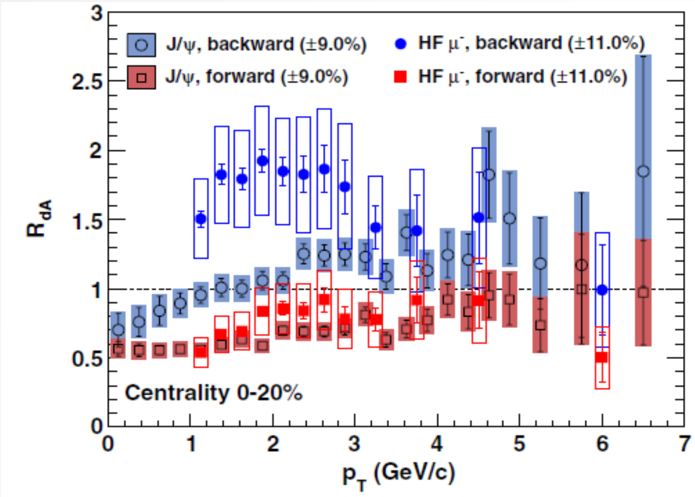
- We see clear systematic difference between the two sets of R_{AA} results
- Hence showing that the suppression is stronger in Pb-Pb collisions for the same centrality class

Different particle species

Medium studies

Phenix, d+Au

PRL 112, 252301 (2014)



HF & J/ψ

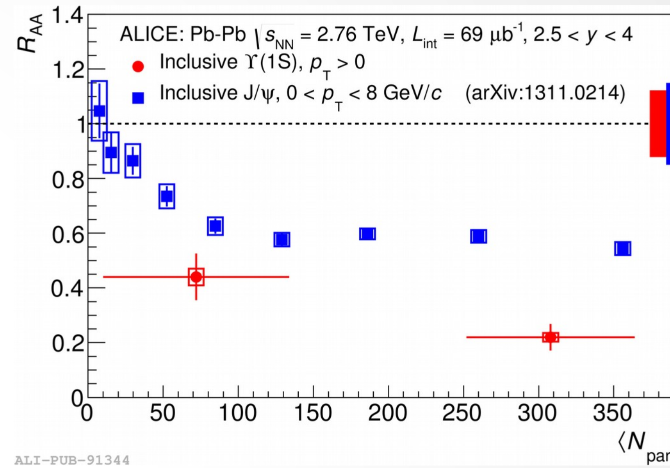
Backward rapidity (−2.0 < y < −1.4, Au-going direction)

Forward rapidity (1.4 < y < 2.0, d-going direction)

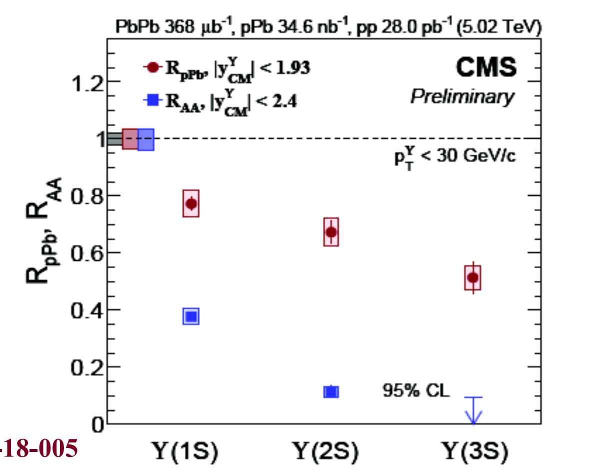
- J/ψ and open charm at backward rapidity have larger difference compared to forward rapidity
- Maybe related to the longer time this $c\bar{c}$ state requires to traverse the nuclear matter or the larger density of co-moving particles after the initial collision at backward rapidity
- This comparison motivates that additional CNM effect, nuclear breakup, significantly affects J/ψ production at mid and backward rapidity

ALICE, CMS

Phys. Lett. B 738 (2014) 361



More suppression for bottomonia



CMS PAS HIN-18-005

- Sequential suppression, consistent with predictions from hadronic comover effects, is observed in pPb, indicating the presence of final-state effects in pPb collisions

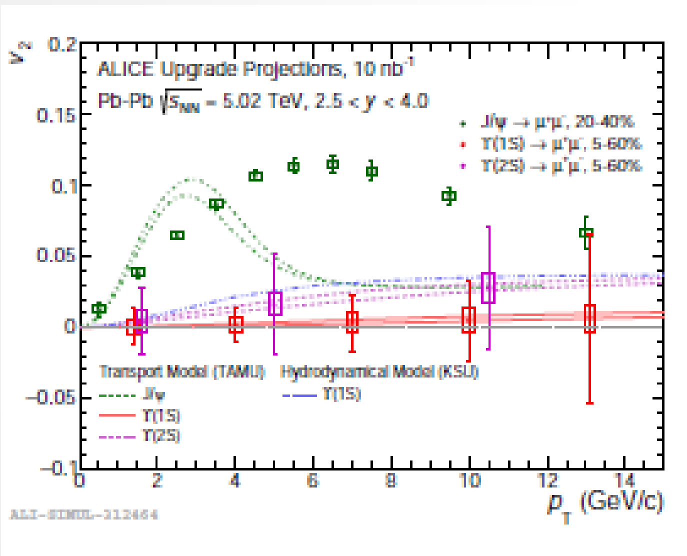
Bottomonia flow?

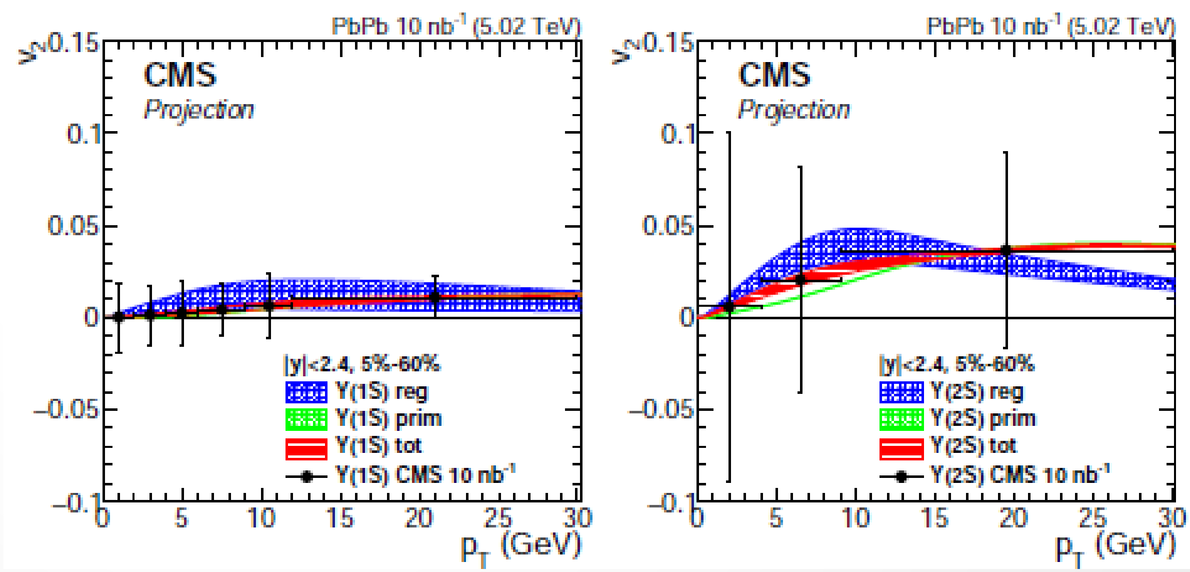
DD and N.Dutta, Int.J.Mod.Phys. A33 **(June 2018)** no.16, 1850092

> Studies of J/ψ v_2 at RHIC and LHC energies have provided important elements toward the understanding on the production mechanisms and thermalization of charm quarks. Bottomonia has an advantage since it is a cleaner probe. A brief discussion has been provided for $\Upsilon(1S)$ v_2, which can become the new probe for QGP, including the necessity of studies for small systems.

ALICE and CMS

ArXiv: 1812.06772 **(December 2018)** YELLOW REPORT





(CERN) Yellow Report on Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

What's new : **ALICE** : PRL, 123, 192301 (2019) & **CMS** : PLB 819, 136385 (2021) comparable at 5.02 TeV Pb+Pb

Bottomonia flow at LHC

DD and N.Dutta, Int.J.Mod.Phys. A33 **(June 2018)** no.16, 1850092

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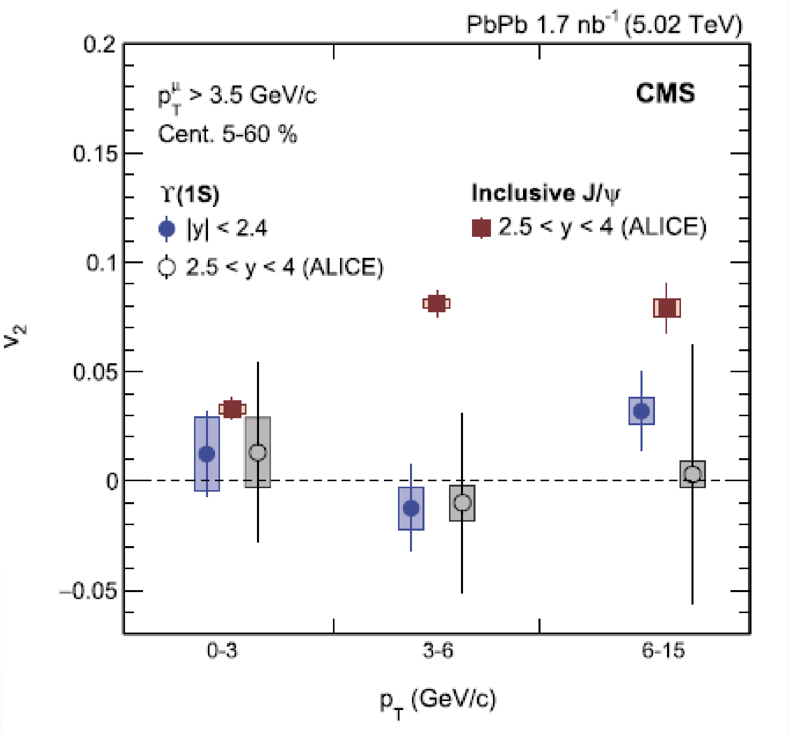
ALICE and CMS

- **Both CMS and ALICE results show that the geometry of the medium has little influence on the Upsilon (1S) yields and that recombination is not a dominant process in the production**
- **Path-length dependence of Upsilon (1S) suppression is small**

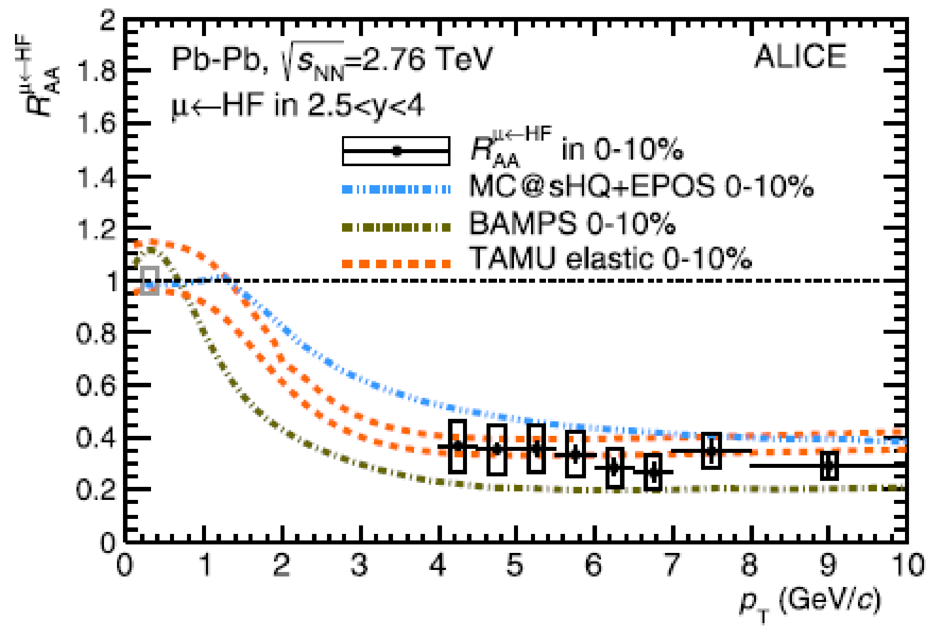


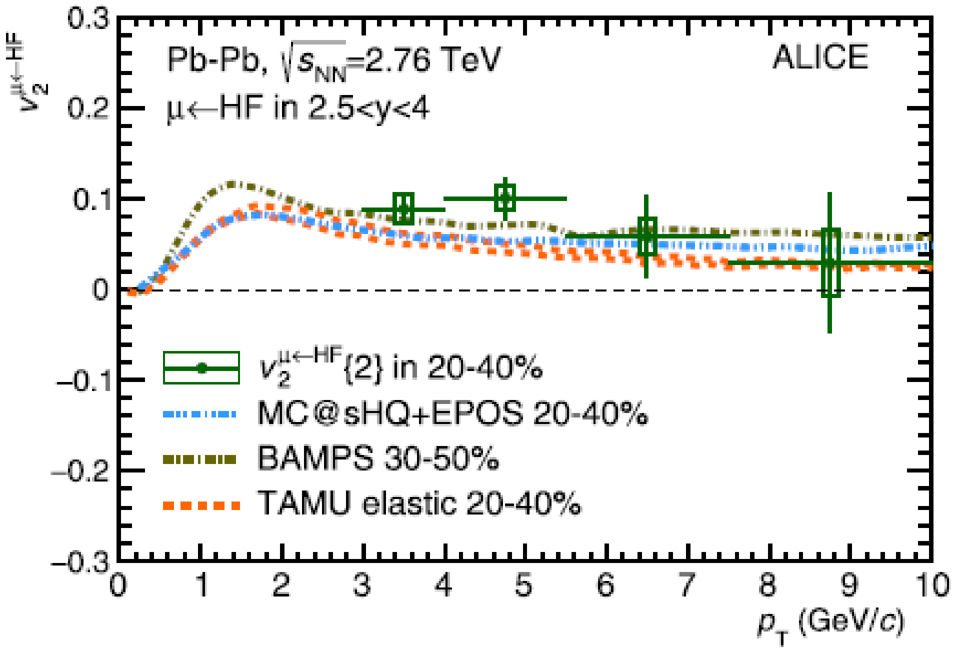
ALICE : PRL, 123, 192301 (2019) & **CMS** : PLB 819, 136385 (2021) comparable at 5.02 TeV Pb+Pb

The challenge and where?

Forward rapidity

ALICE, PLB 753 (2016) 41





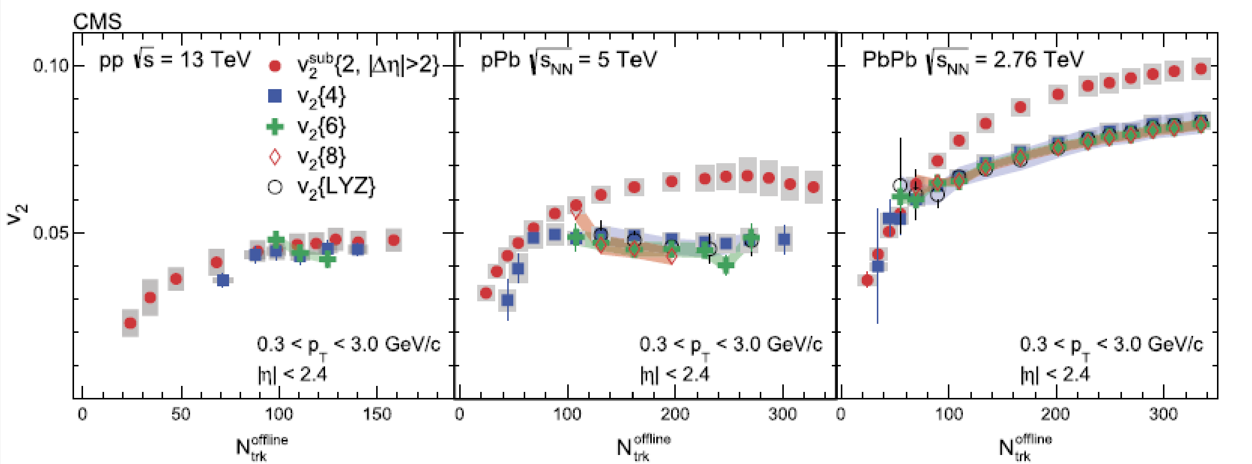
simultaneous description of HF decay R_{AA} and v_2 is a challenge

-- can constrain energy loss models

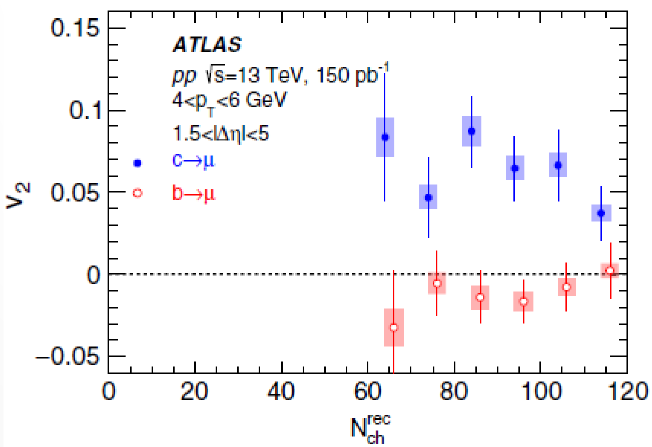
Small Systems and further challenges?

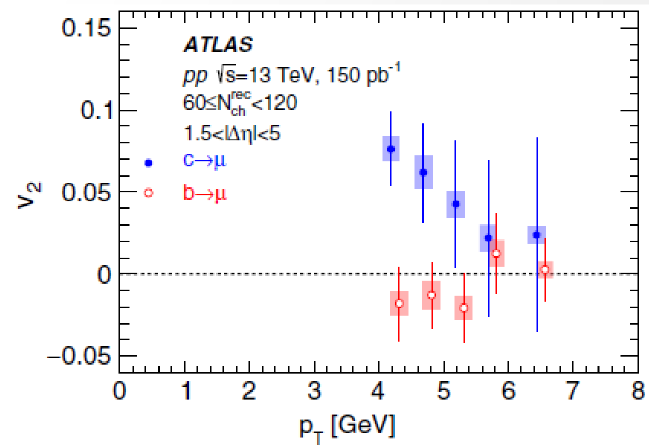
Mid rapidity

CMS PLB 765 (2017) 193 ATLAS PRL 124, 082301 (2020)



strong evidence for the collective nature of the long-range correlations observed in pp collisions at LHC





Bottom quarks have less elliptic flow in high multiplicity p+p collisions unlike light and charm quarks

Unanswered Questions and next steps

- Heavy quarks are particularly good probes to study the properties of hot QCD matter

- pp data are important baseline measurements
  - examine interplay of soft and hard processes
- pA which is more than just a control
  - needed to study the CNM effects in various x ranges
- AA collisions : for understanding dense/hot QCD matter
  - strong interaction of heavy quarks with the QCD medium
- But do we understand Pb+Pb at 2.76 TeV and 5.02 TeV ?
- The role of shadowing effect ?
- Flow in pp collisions ?
- Next steps :

DD and N.Dutta, Int.J.Mod.Phys. A33 (June 2018) no.16, 1850092
D.Das , Nucl.Phys.A 1007 (2021) 122132
D.Das, IJMPA Vol. 36, No. 24, 2130014 (2021)

-New differential measurements to constrain models and address open questions

-Need more statistics,better precision & extended coverage (in terms of p_T),Run3/HL-LHC

- Bottomonia production studies in pA collisions helps in understanding CNM effects

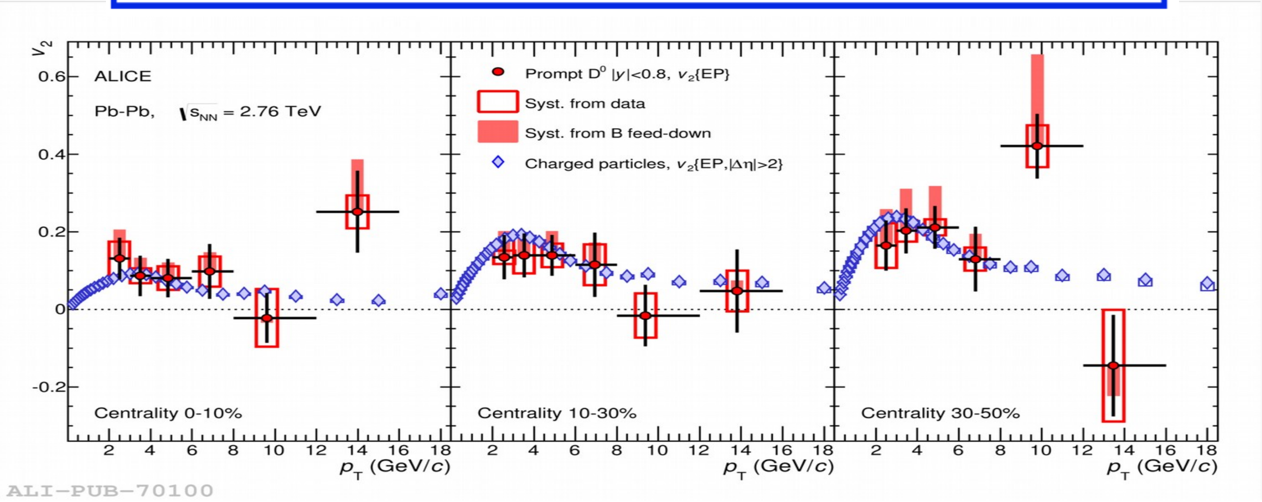
-for "small systems" less deeply bound bottomonia states and large chance to escape

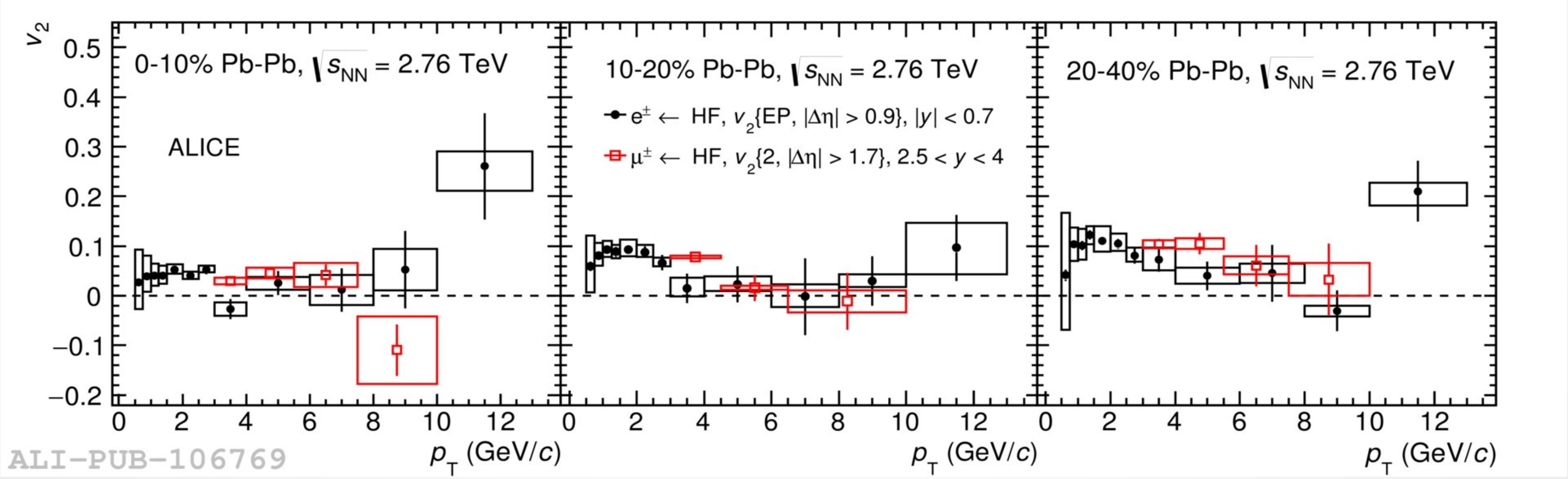
-such measurements in pA will help us to understand the initial state correlations

MORE

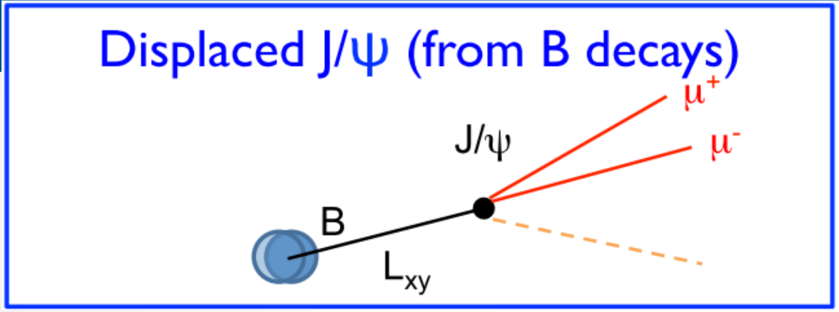
Comparisons at LHC

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos(\varphi - \Psi_2) + \ \ldots\right)$$





Measuring heavy-flavor particles



Heavy-Flavor(HF) hadrons

decay via weak interaction:

- **decay length cτ ~ few 100 μm**
- **measure decay products**
- **signal on invariant mass distribution**
- **difficulty is in understanding the background**
- **need good event mixing and vertex information**

Measurements of electrons and muons from heavy flavor decays

D --> e/μ+X, BR ~ 10%

B --> e/μ+X, BR ~ 11%