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Physics and Astronomy

Probing QCD medium effects in small systems at the LHC via heavy flavor particles

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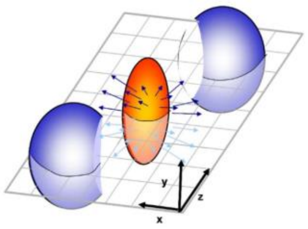
Ninth Workshop of the APS Topical Group on Hadronic Physics

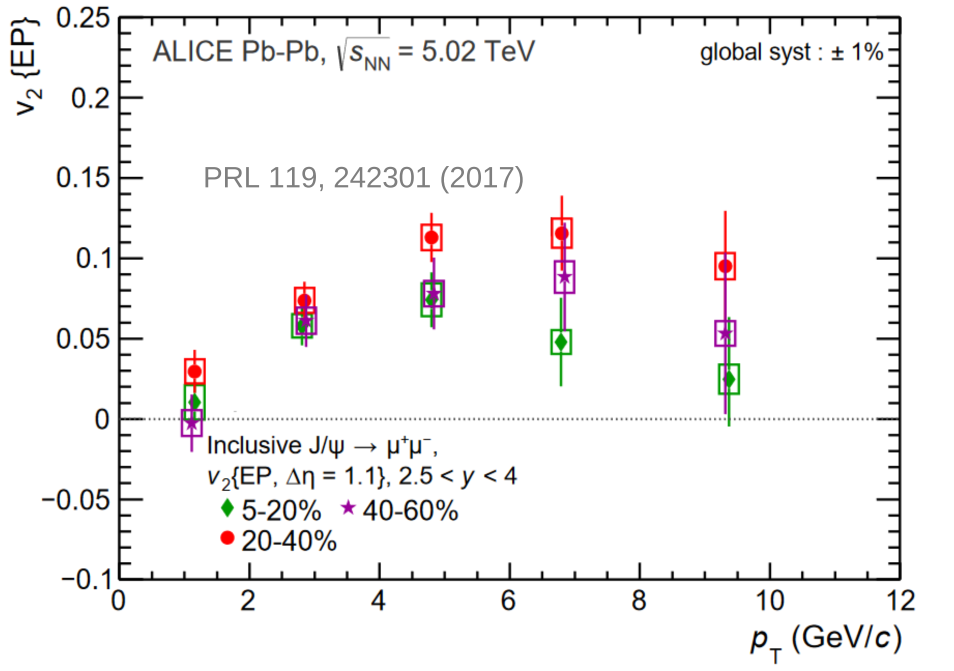
Hot medium in large systems

- QGP droplet in heavy ion collisions
  - Hot dense medium, partons interacts strongly
  - Perfect fluid — initial geometric eccentricity hydrodynamically propagate to final states

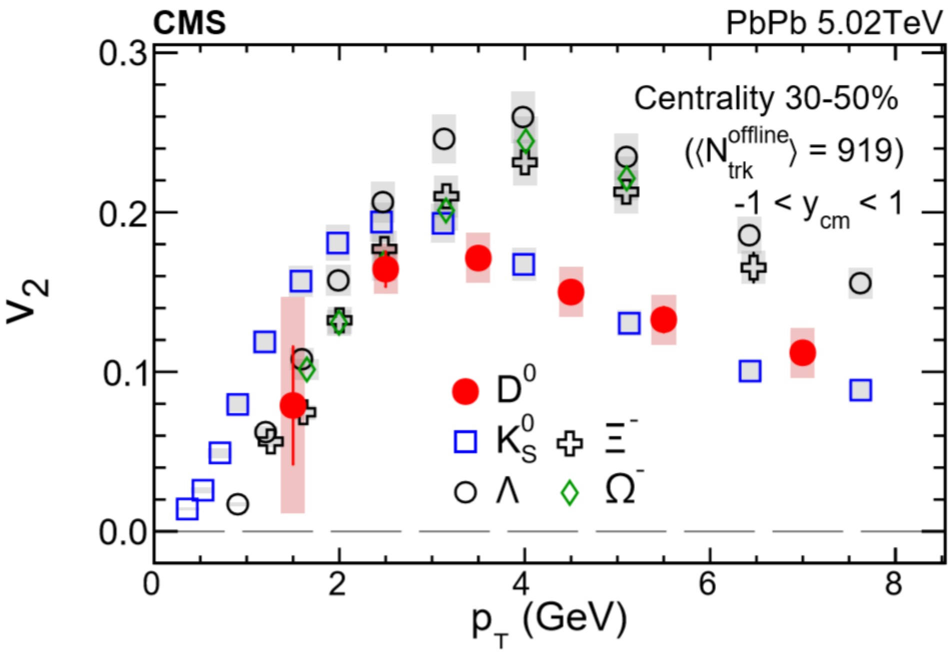


$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

- Heavy flavor quarks – strongly coupled with medium
  - can only be created at initial stage
  - Experience the entire evolution
  - Large v_2 for open charm mesons and charmonia

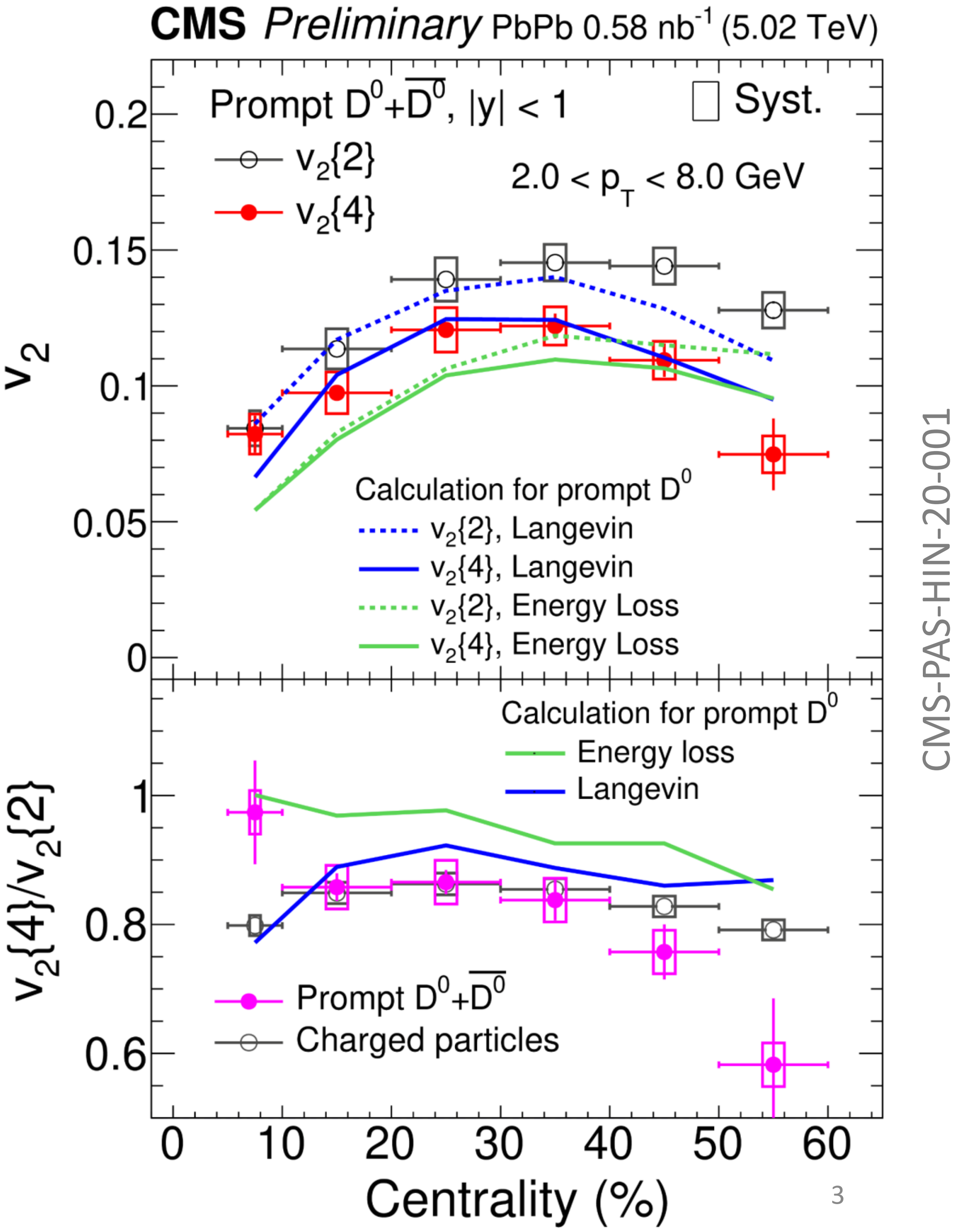


PRL 120, 202301 (2018), PRL 121, 082301 (2018)

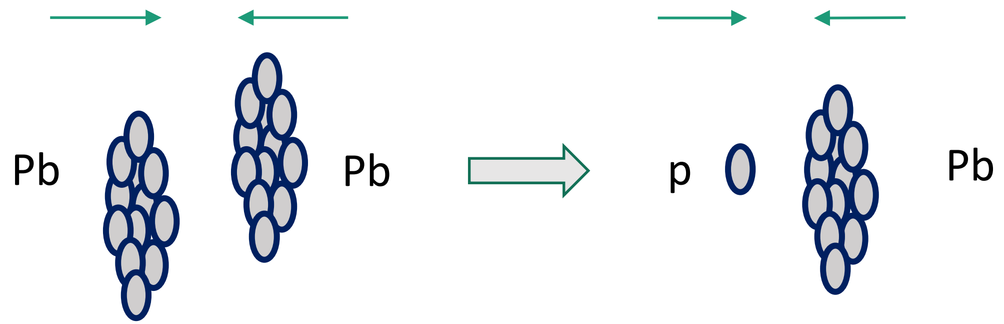


Hot medium in large systems

- Charm v_2 fluctuates more and becomes smaller as event activity reduces
  - Hot medium effects diminish towards peripheral events
  - Charm productions decrease with lower multiplicity
- What will happen if event activity is as low as **small colliding systems**?



Collectivity in small systems

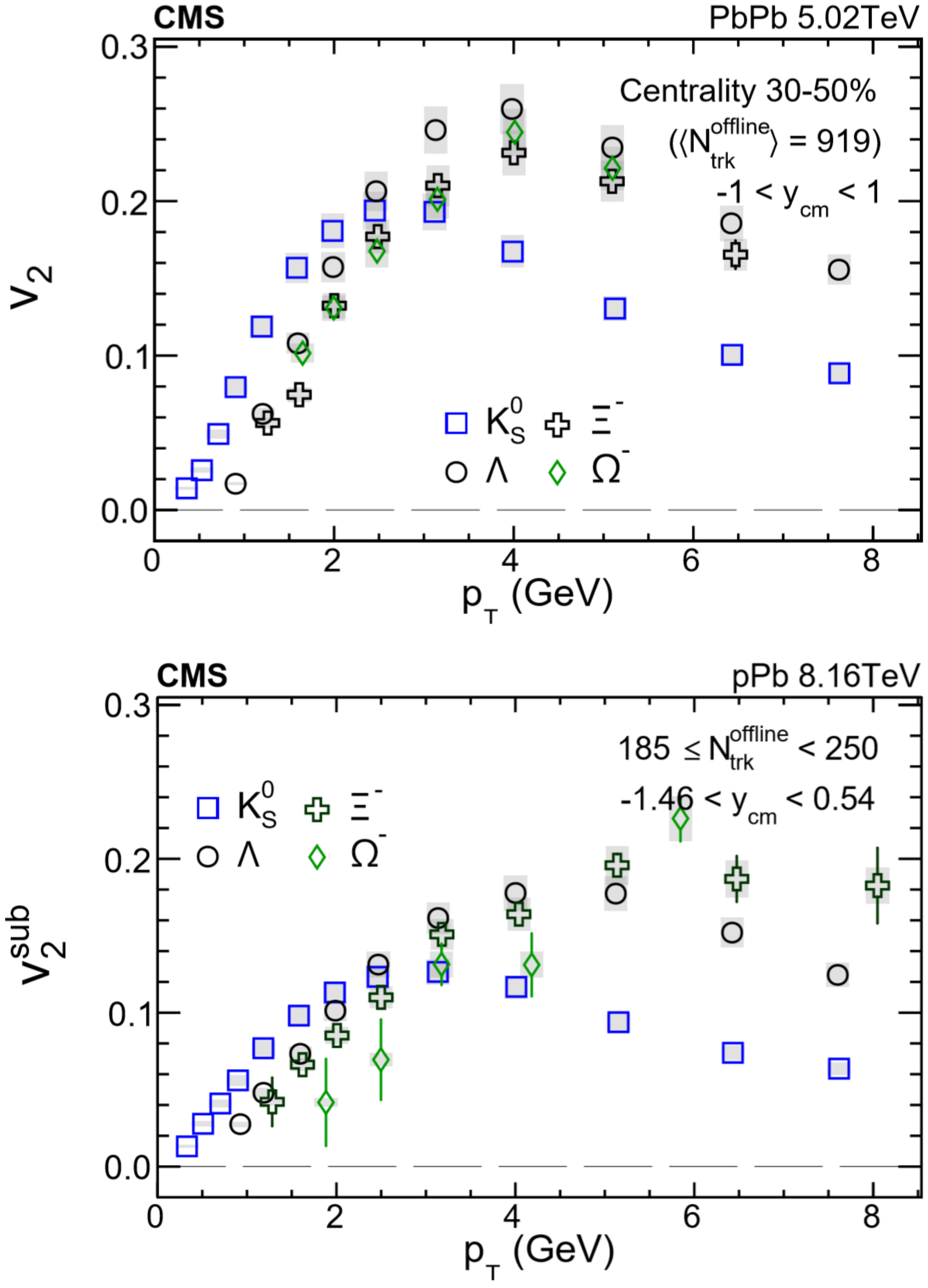


A smaller system

- Positive v_2 of light flavor hadrons
- Mass order shows common velocity
- Similar observations to large systems

Is the origin of collectivity in pPb collisions the same as that in PbPb? – from the hot medium effects?

- Light flavor sector cannot tell us since they can be created anytime during system evolution
- We need **heavy flavor** particles



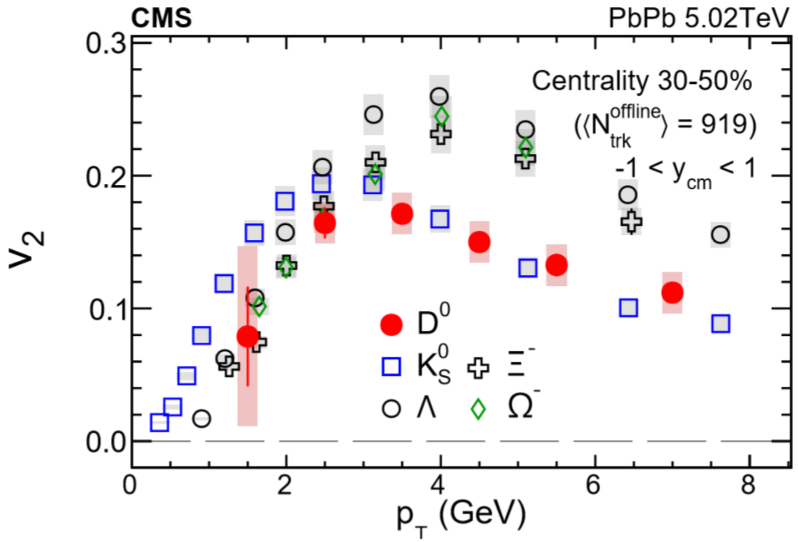
PRL 121, 082301 (2018)

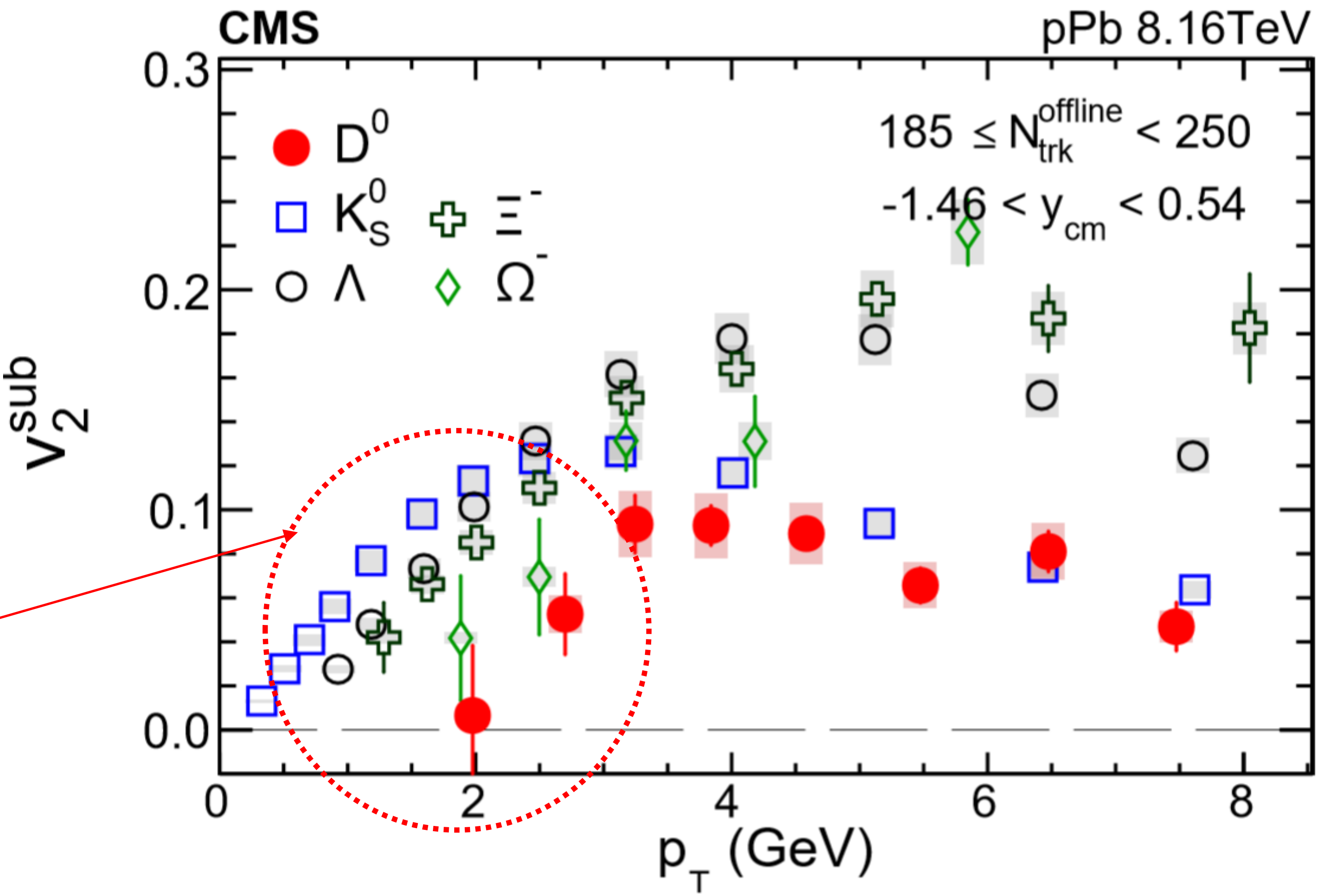
Hot medium effects in small systems?

- Possibly find similar observations in small systems if there is any hot medium effect
  - Collective motion
  - Yield modifications
  - Yields ratios
  - …
- Study the heavy flavor quarks via:
  - Open heavy flavor particles
    - Prompt D^0, D_s^+, Λ_c^+ …
  - Quarkonia
    - Prompt J/ψ, $\psi(nS)$, $\Upsilon(nS)$ …
  - Decay products
    - Nonprompt D^0 ($b \to D^0$), $b \to \mu$, $c \to \mu$ …
- System size
  - Large to small: PbPb -> pPb -> pp

Open charm flow in pPb collisions

PRL 120, 202301 (2018)





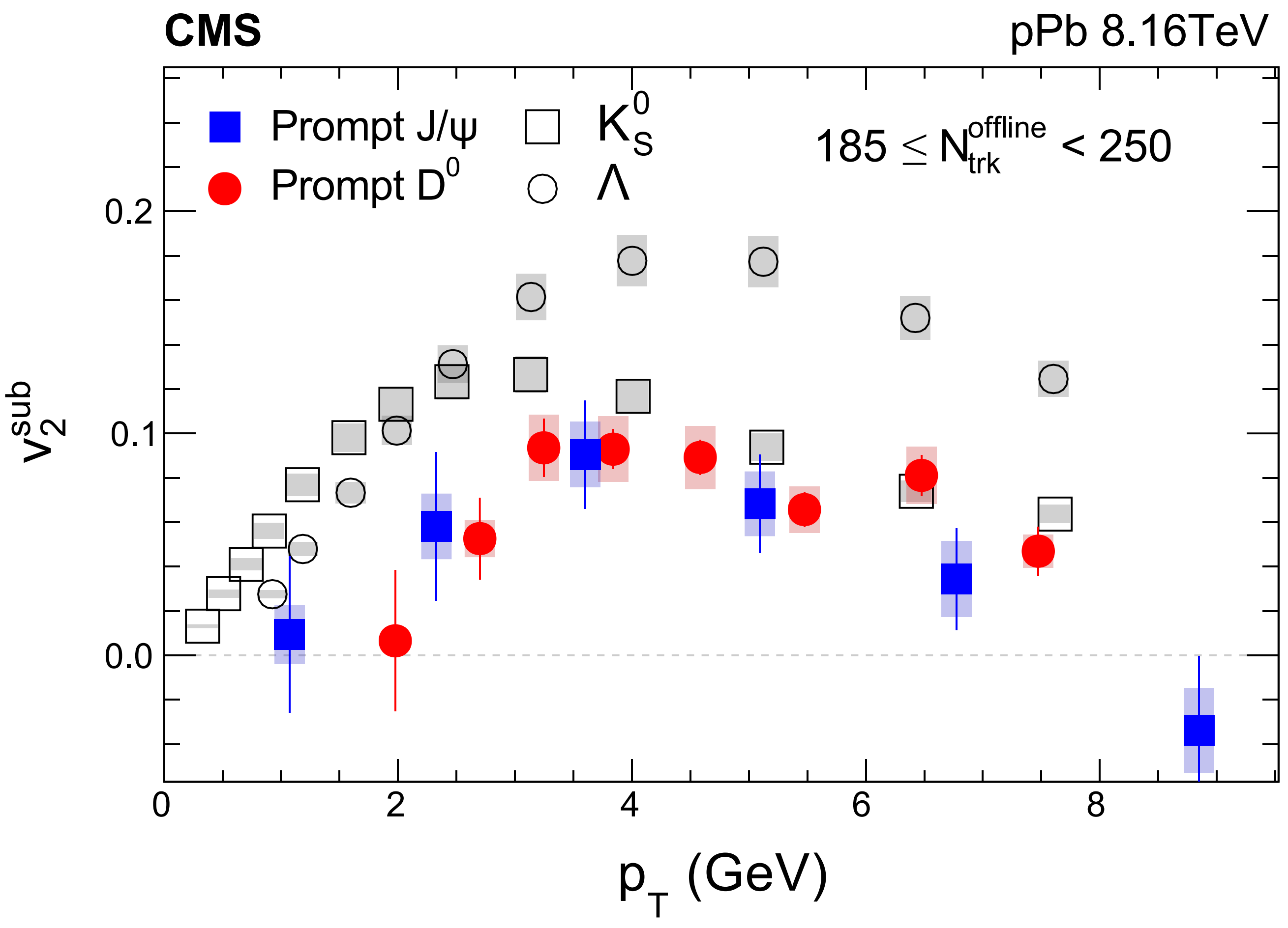
PRL 121, 082301 (2018)

- Mass order at low p_T -- common flow velocity
- Similar to PbPb

Prompt $J/\psi(c\bar{c})$ in pPb Collisions

- Can also observe positive v_2 signal for **prompt J/ψ**
- Calculations based on medium effects inconsistent with data
- Caveat: medium effects may not strong enough in MB samples

v_2 for
Prompt J/ψ
Prompt D^0



PRL 121, 082301 (2018)
PLB 791 (2019) 172

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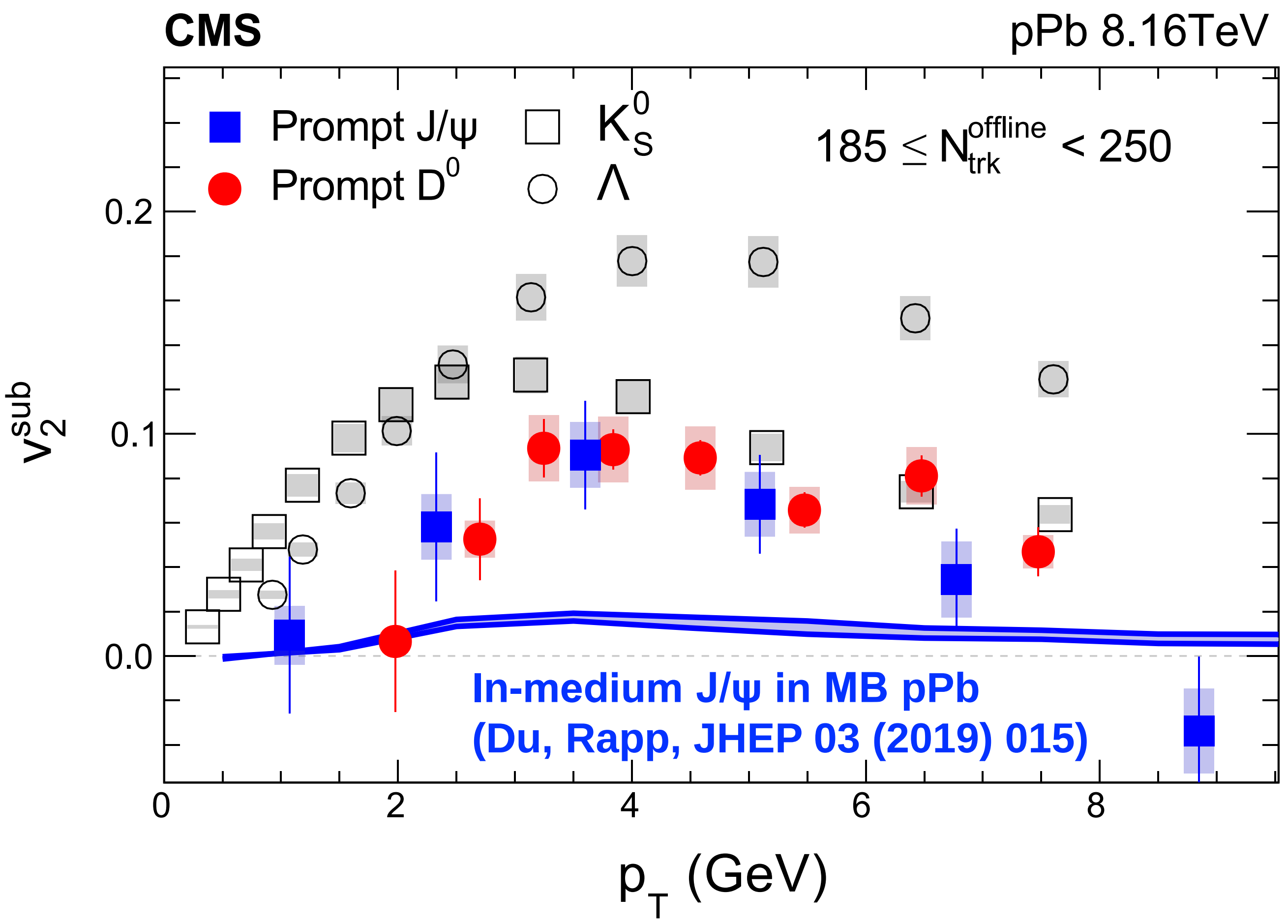

PRL 121, 082301 (2018)
PLB 791 (2019) 172

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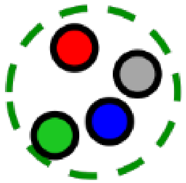
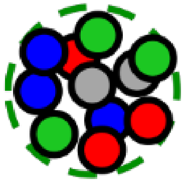
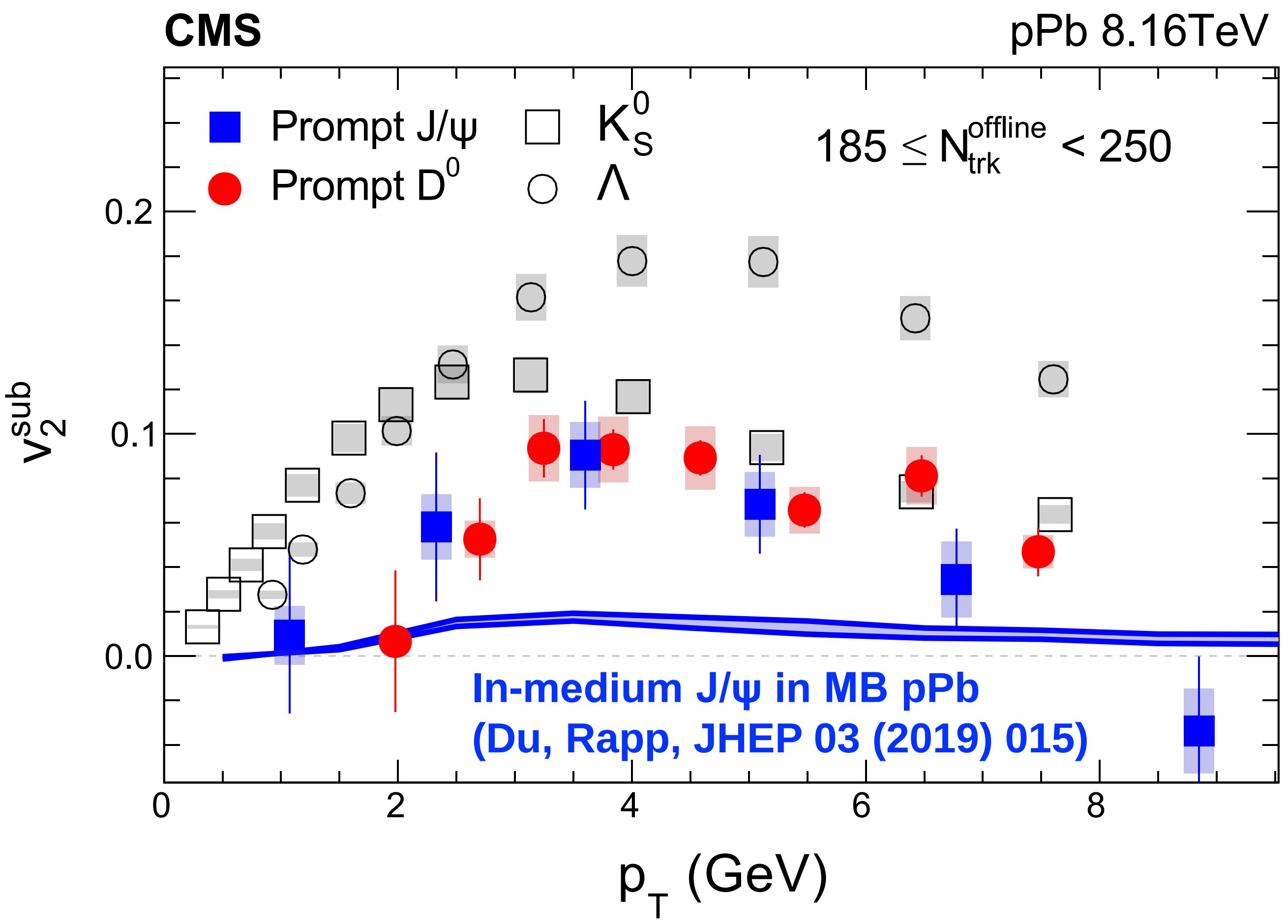


low temperature (energy density), weak hot medium effect



high temperature, strong hot medium effects



PRL 121, 082301 (2018)
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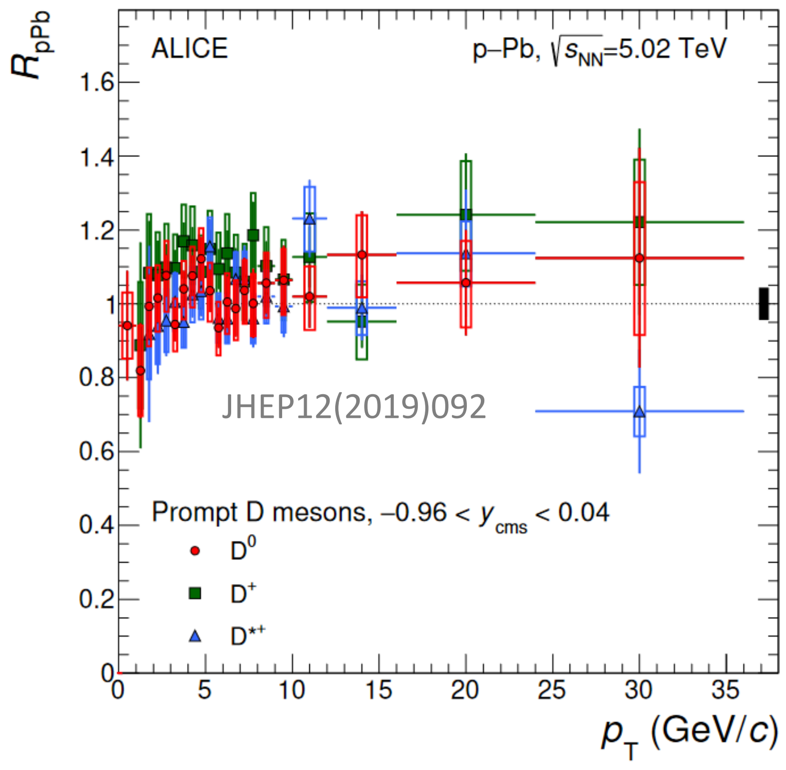
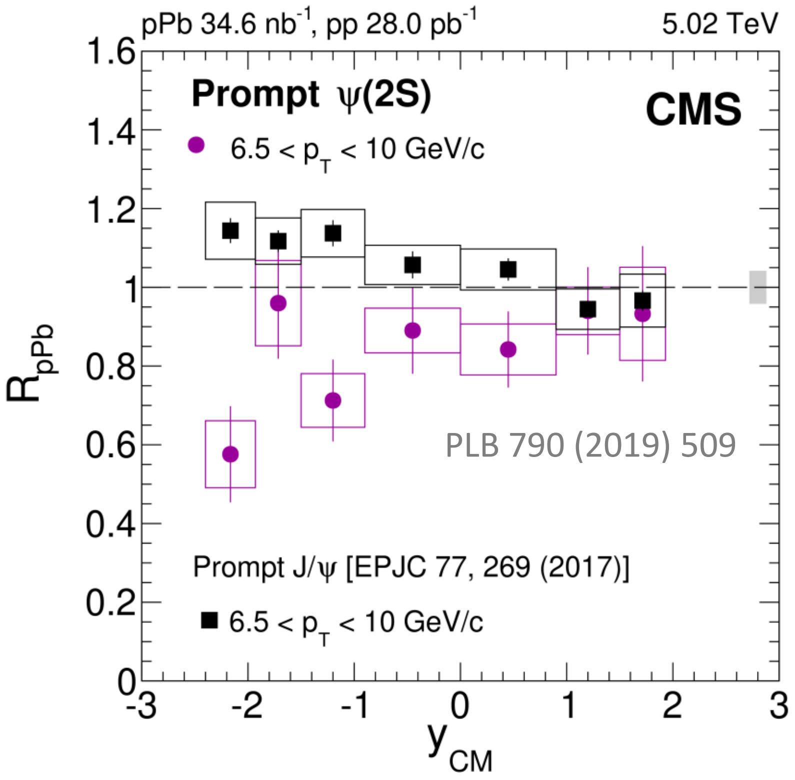
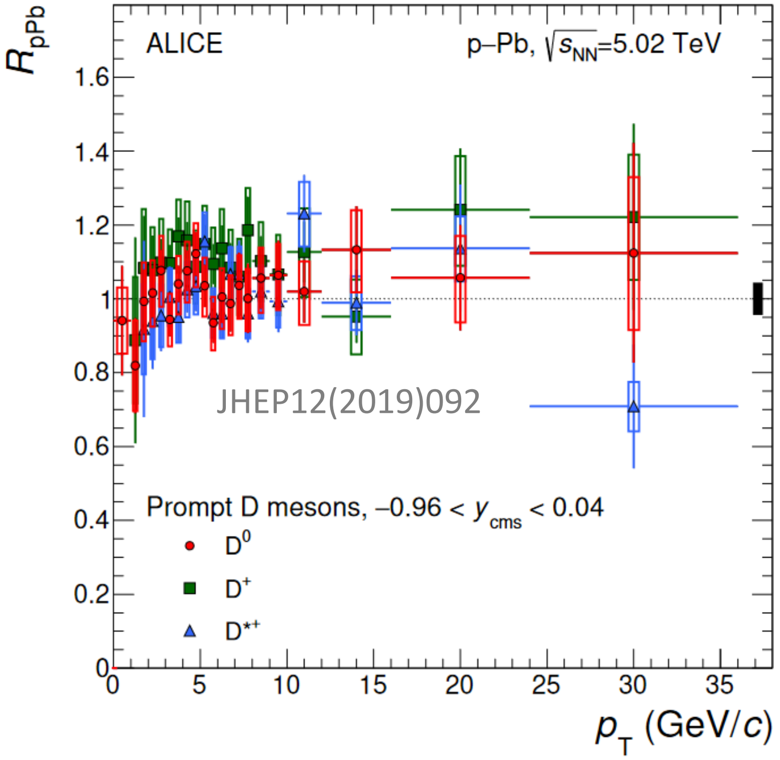
Modifications for charm mesons in pPb collisions

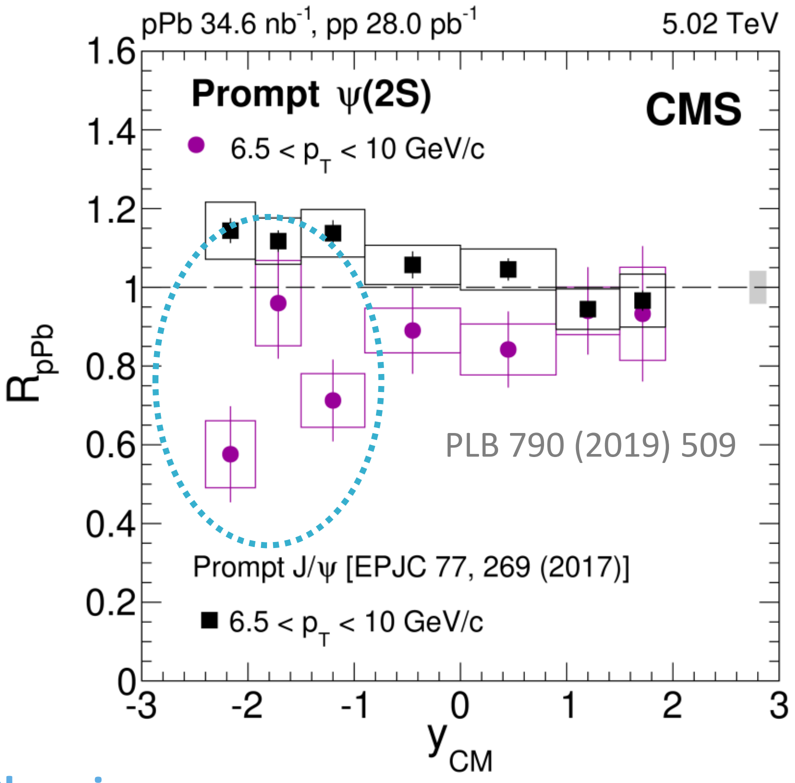




- Little modifications for **prompt D-meson**, **prompt J/ψ** and **prompt ψ(2S)** in **MB** events
- ψ(2S) slightly suppressed in backward (Pb-going) compared to J/ψ
- A hint for final state effects

Modifications for charm mesons in pPb collisions



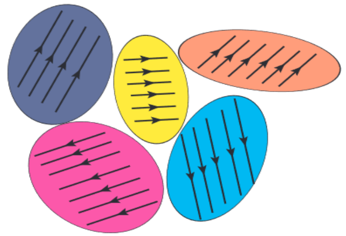


Pb-going ← → p-going

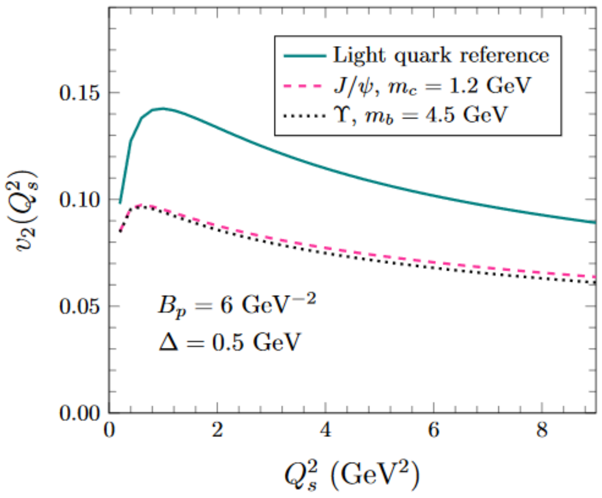
- Little modifications for prompt D-meson, prompt J/ψ and prompt ψ(2S) in MB events
- **Prompt ψ(2S)** slightly suppressed in **backward (Pb-going)** compared to prompt J/ψ
- A hint for final-state effects?

An alternative scenario

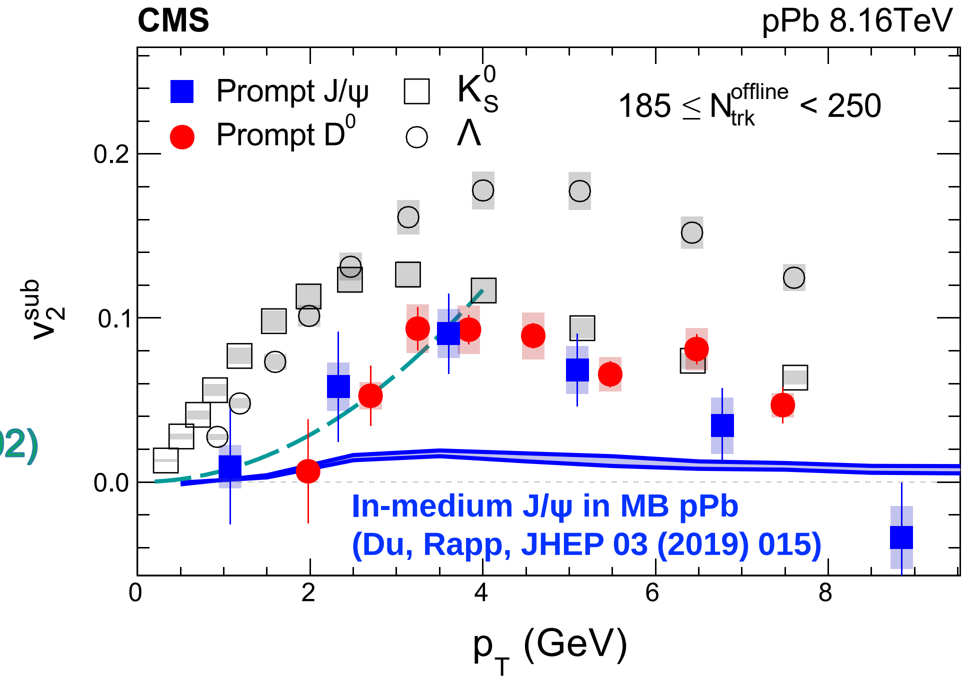
- An alternative scenario based on initial state interactions – Color Glass Condensate
  - Before collisions, non-zero color electric fields exist
  - Non-geometry-related and non-hydrodynamical evolution
  - Predict large v_2 for prompt J/ψ



Lappi, Schenke, Schlichting, Venugopalan
JHEP 01 (2016) 061



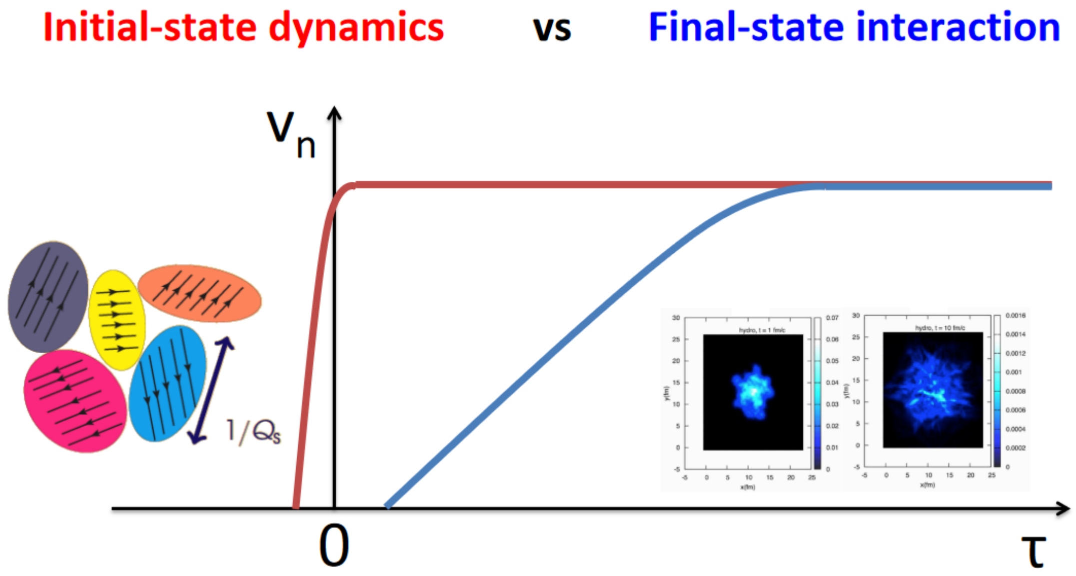
CGC (Zhang et. al.
PRL 122 (2019), 172302)

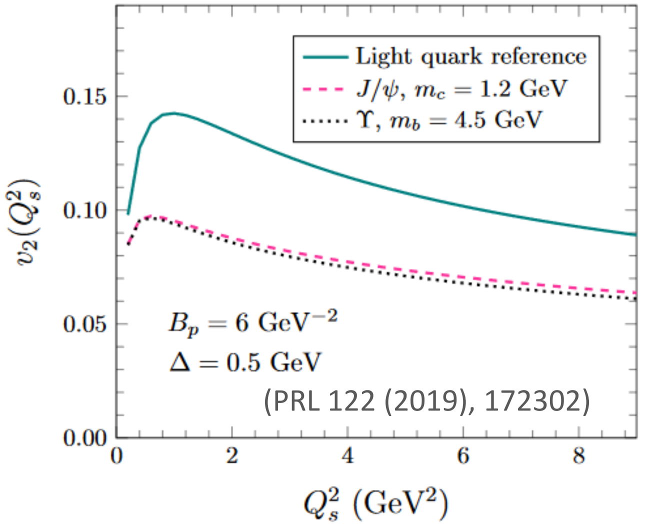


PRL 121, 082301 (2018)
PLB 791 (2019) 172

Beauty quarks in pPb Collisions

- Can we observe collectivity of b quarks?
  - **Heavier** and **harder** to evolve in collectivity from medium effects compared to charm quarks
  - CGC calculations predict **large v_2 for ϒ** comparable to prompt J/ψ
  - b quarks provide new opportunities to study the origin of collective flow in small systems

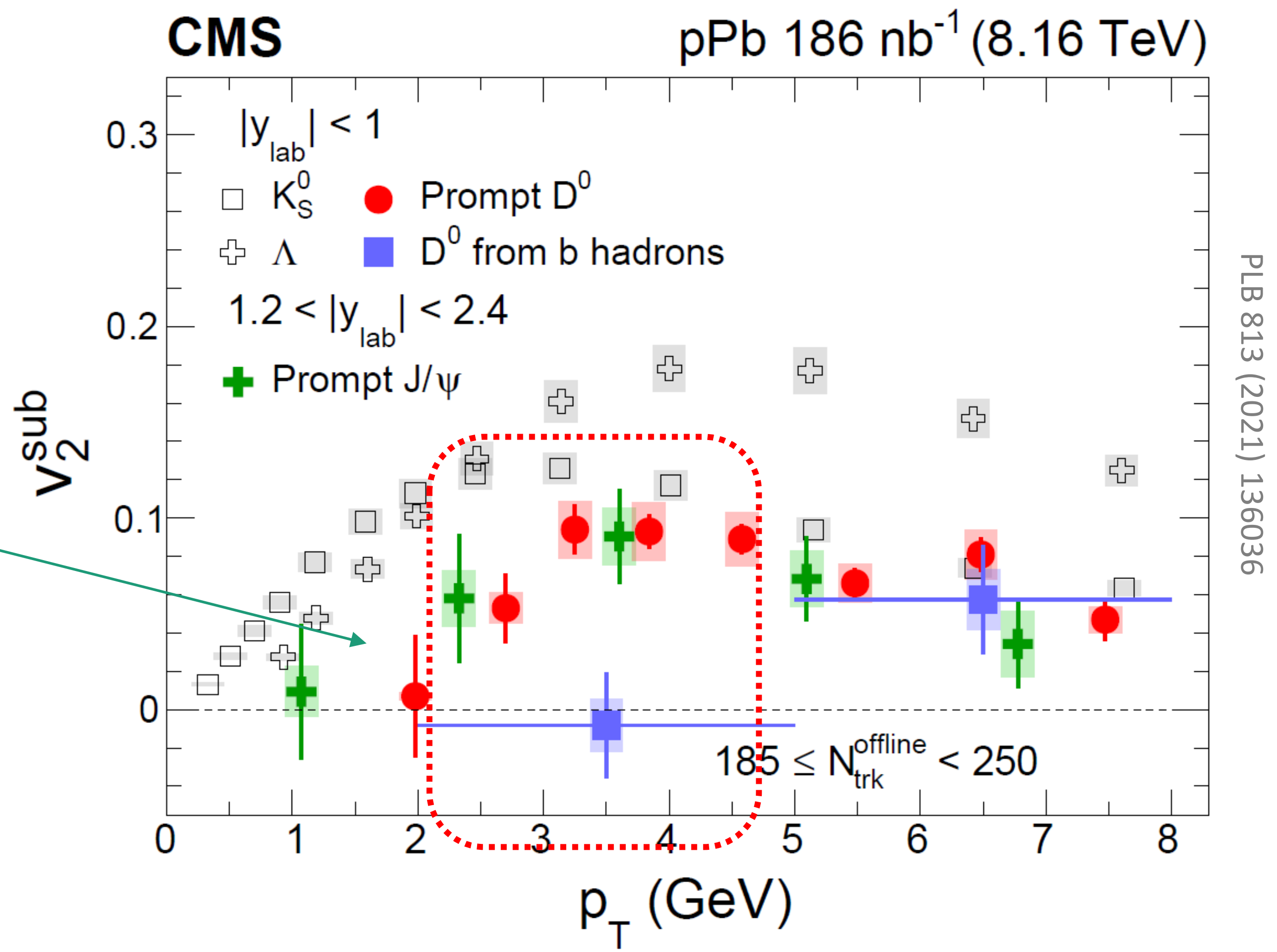




(PRL 122 (2019), 172302)

b -> D^0 in pPb Collisions

- b flow consistent with zero
- Indication of flavor hierarchy between **charm** and **beauty** at low p_T
- Comparison between CGC calculations and data



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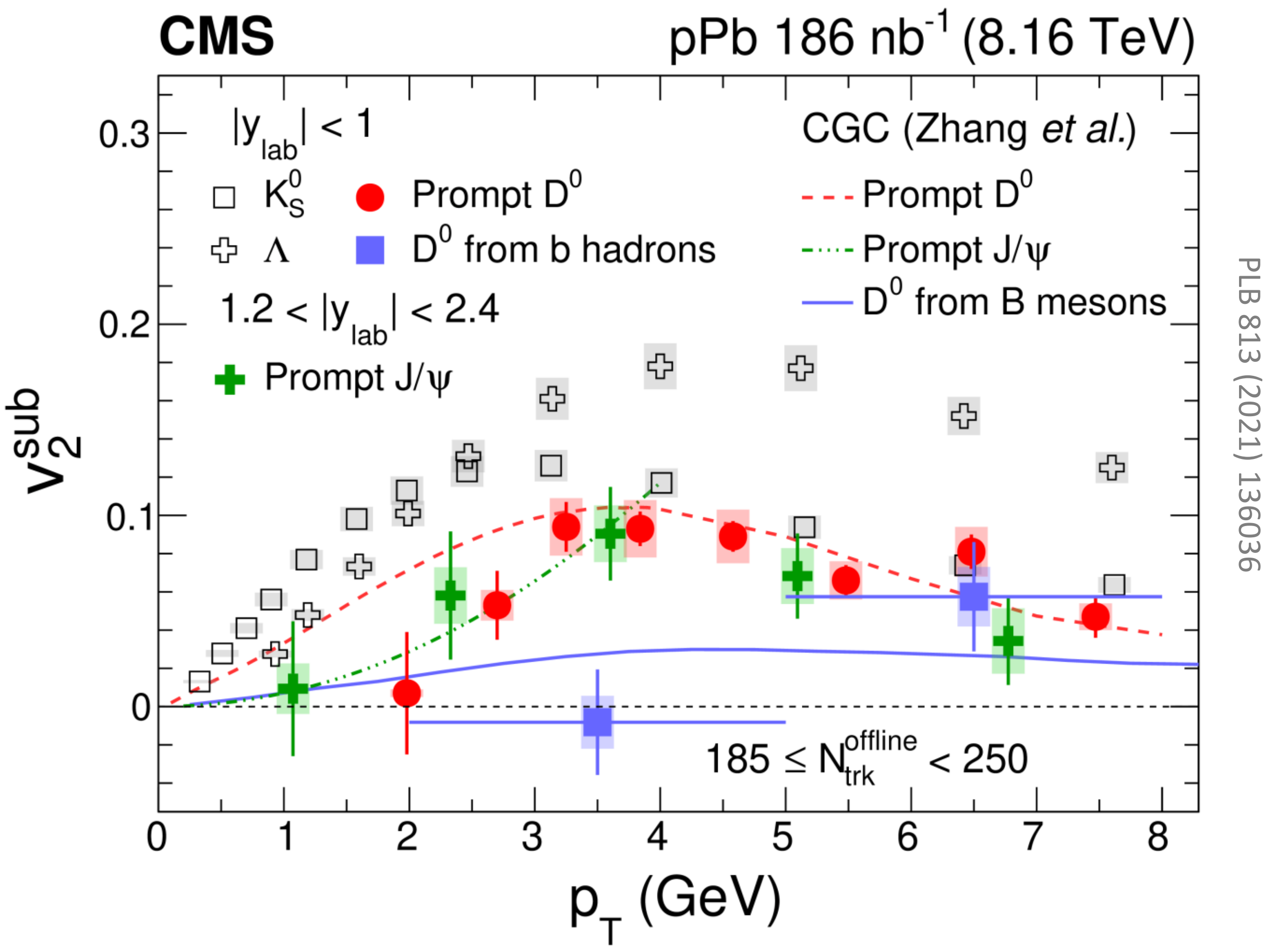
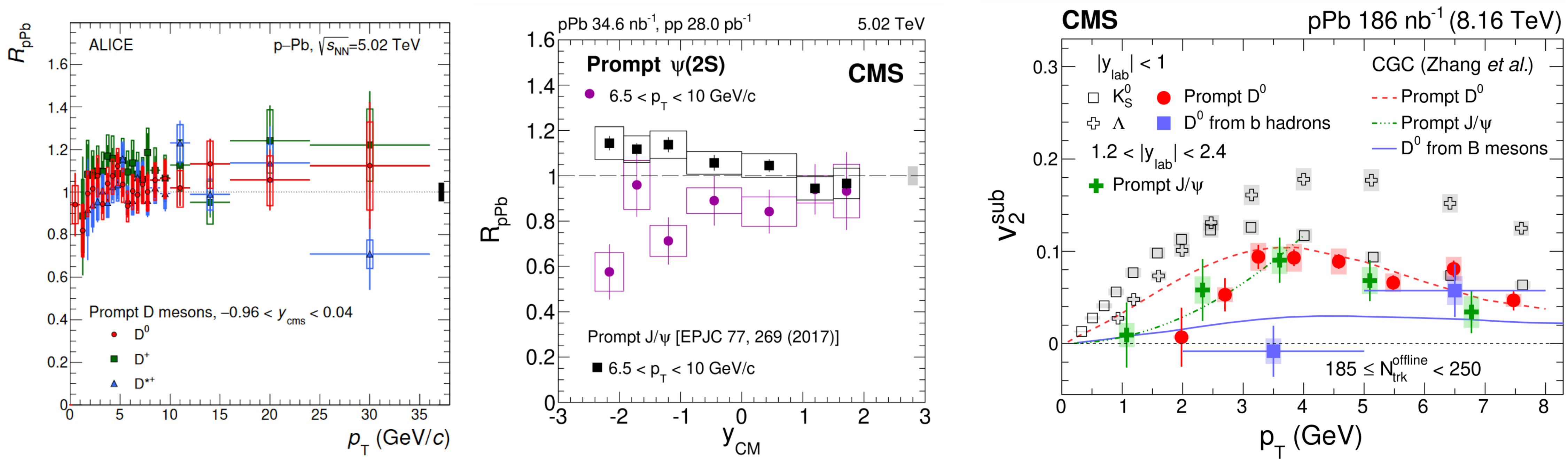


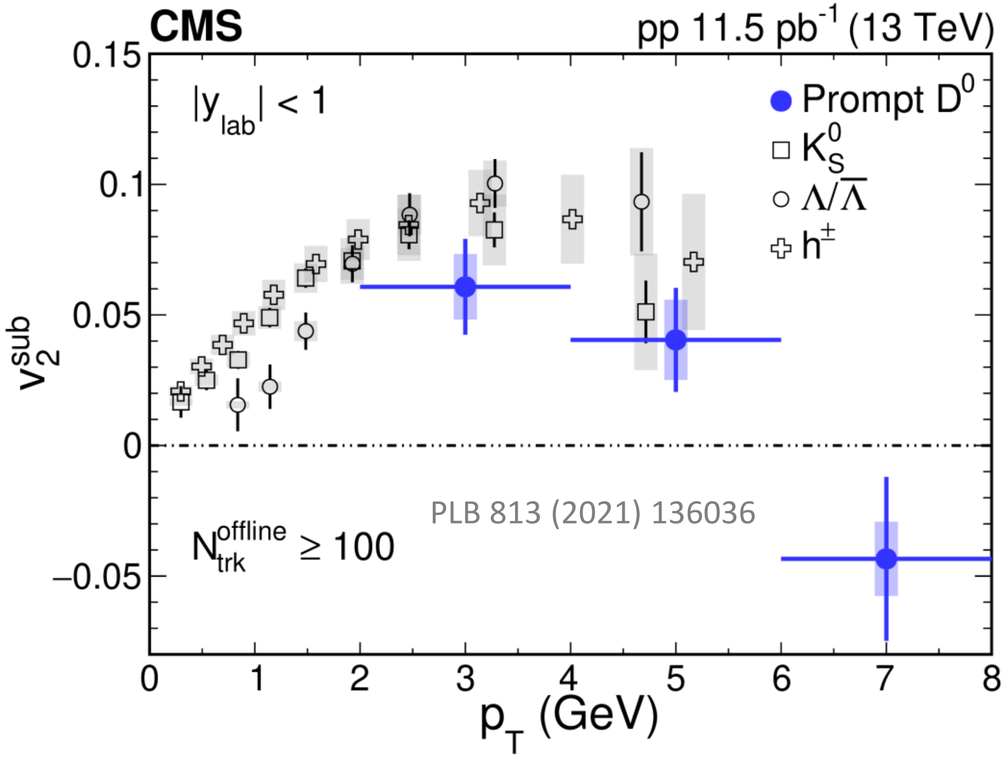
Studies in pPb collisions

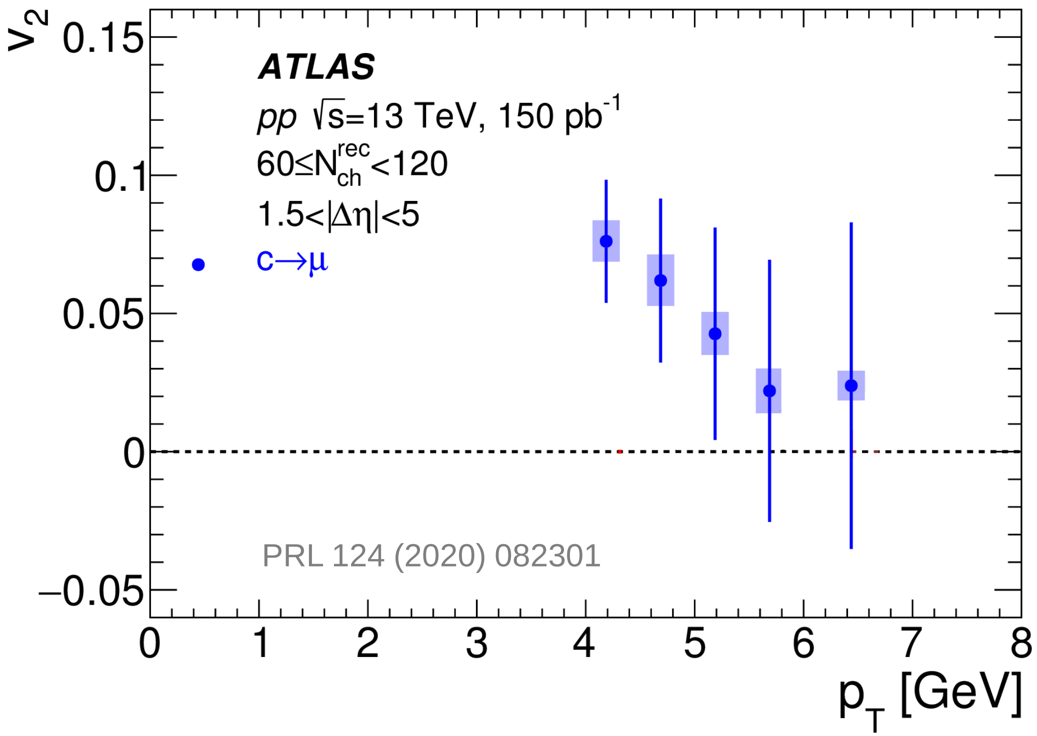
- **Large charm flow** signal in high multiplicity but little modifications of yields in MB events
- **Ordering** between charm and beauty quarks is suggested.
- More precise measurements are needed in the future to uncover the origin of collective flow
- Can we observe collectivity in even **smaller** systems, pp collisions?



Charm flow in even smaller system — pp collisions

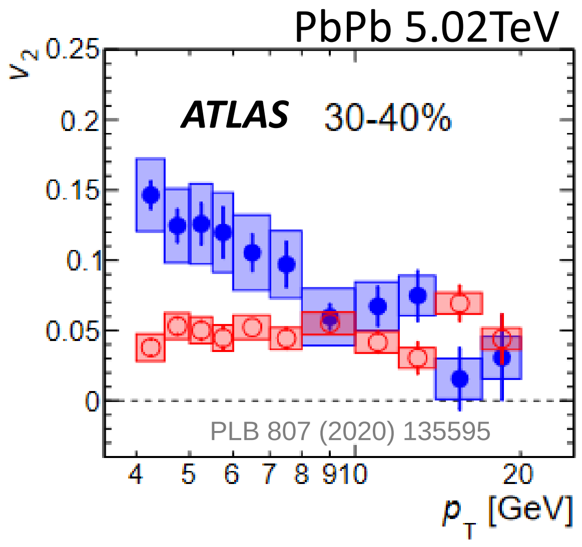
- Indication of positive v_2 at low p_T and flow are comparable to light flavor particles
- Decreasing trend towards high p_T regime



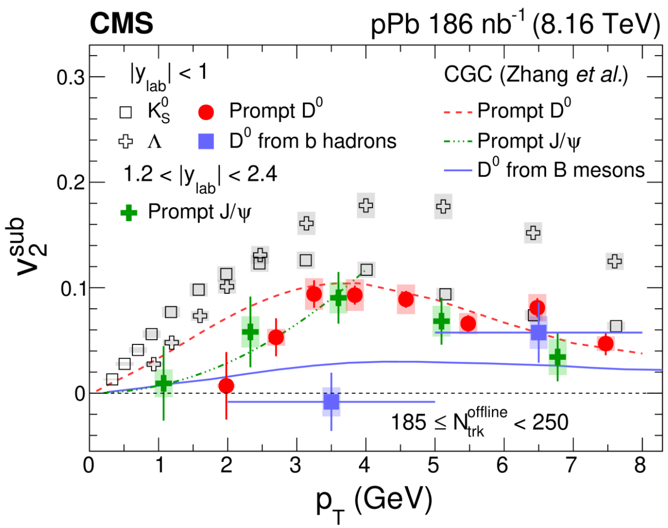


Beauty flow in pp collisions

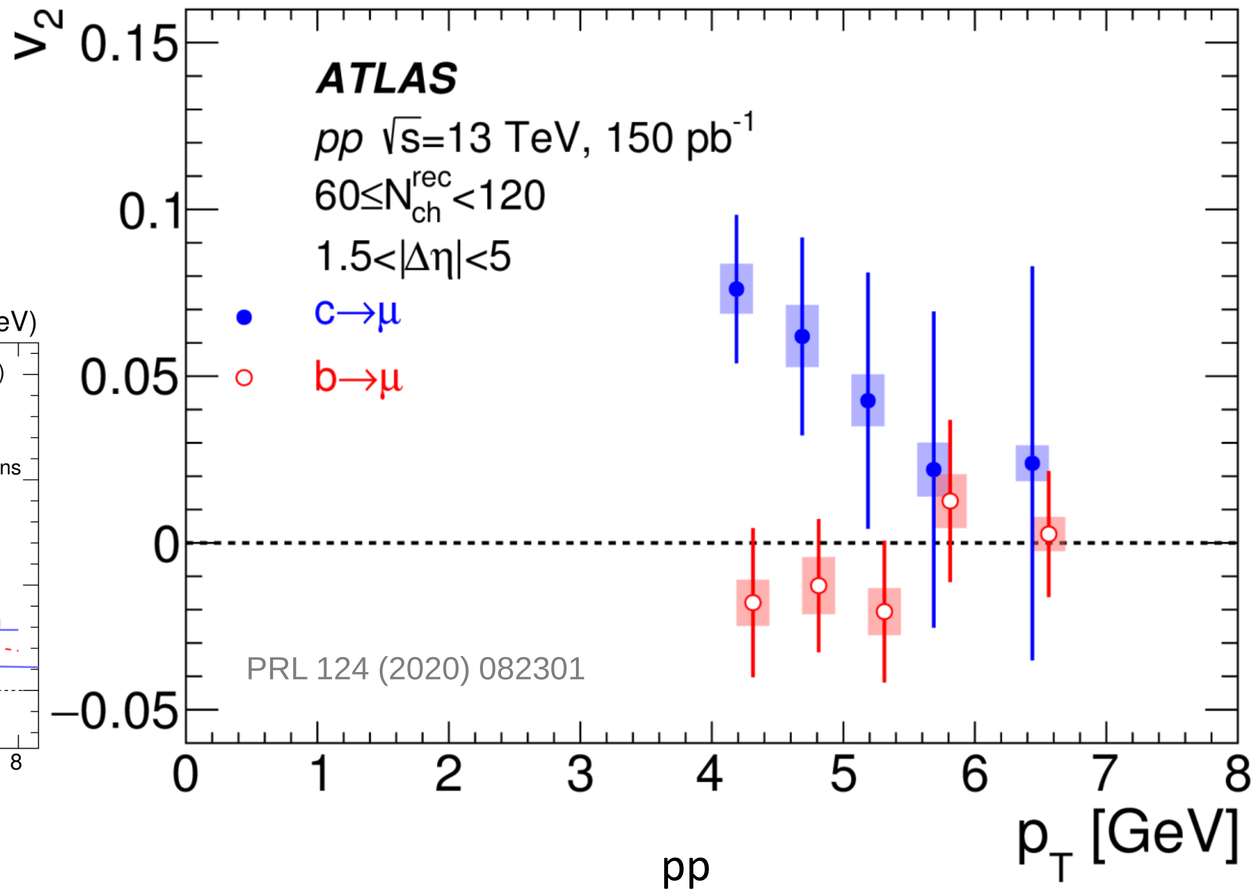
- Flow of muons from b quark decay is consistent with zero.
- v_2 ordering between charm and bottom quarks (in pp, pPb, PbPb).



PbPb



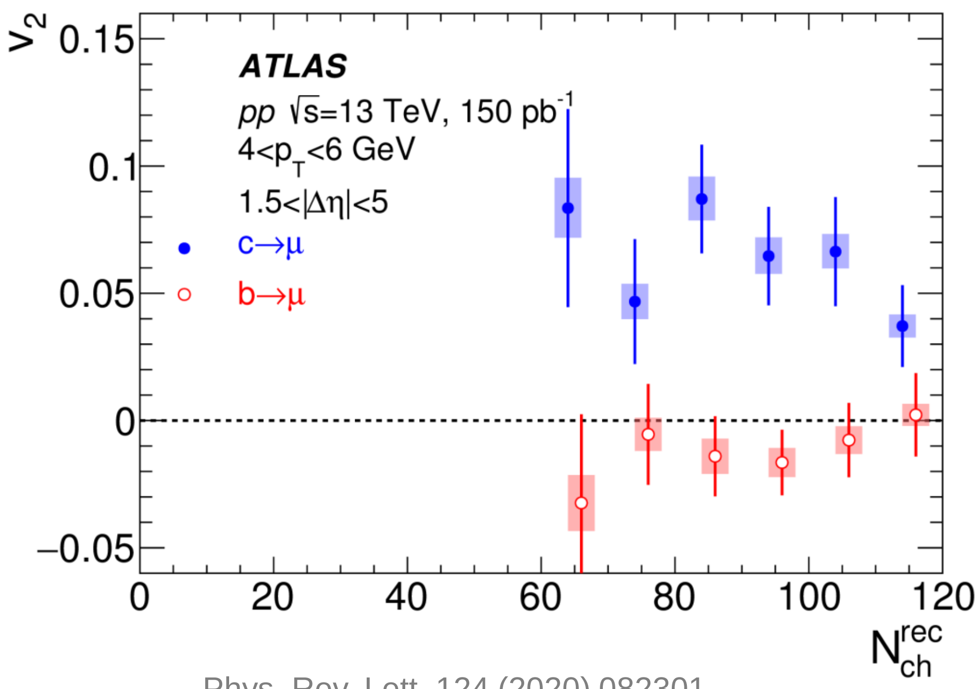
pPb



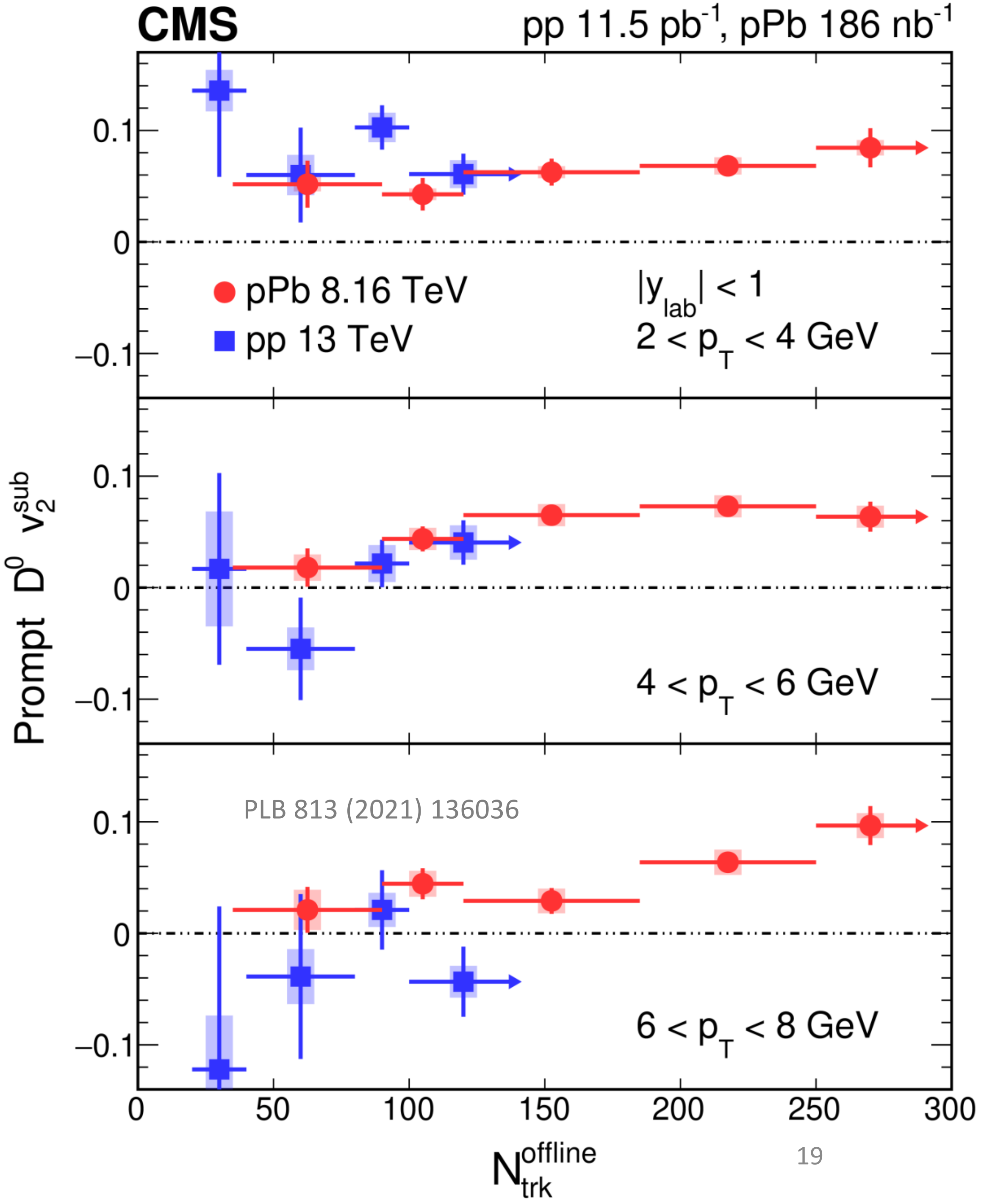
pp

System size dependence

- Charm v_2 increase with multiplicity ($L/\lambda_{m.f.p} \sim N_{trk}^{1/3}$)
- Medium effects becomes larger in high multiplicity events?

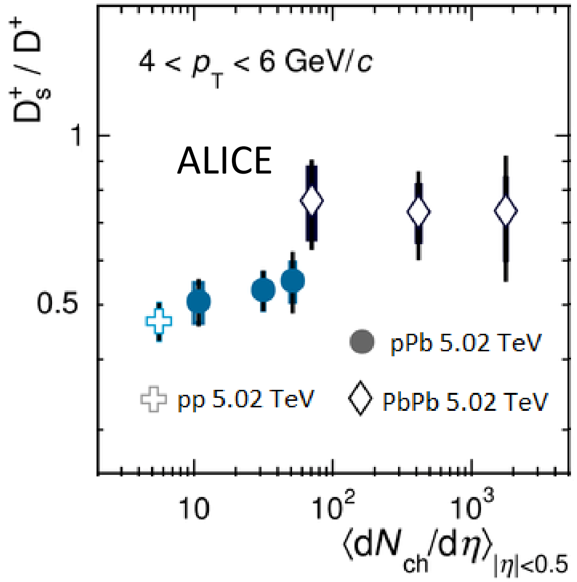


Phys. Rev. Lett. 124 (2020) 082301

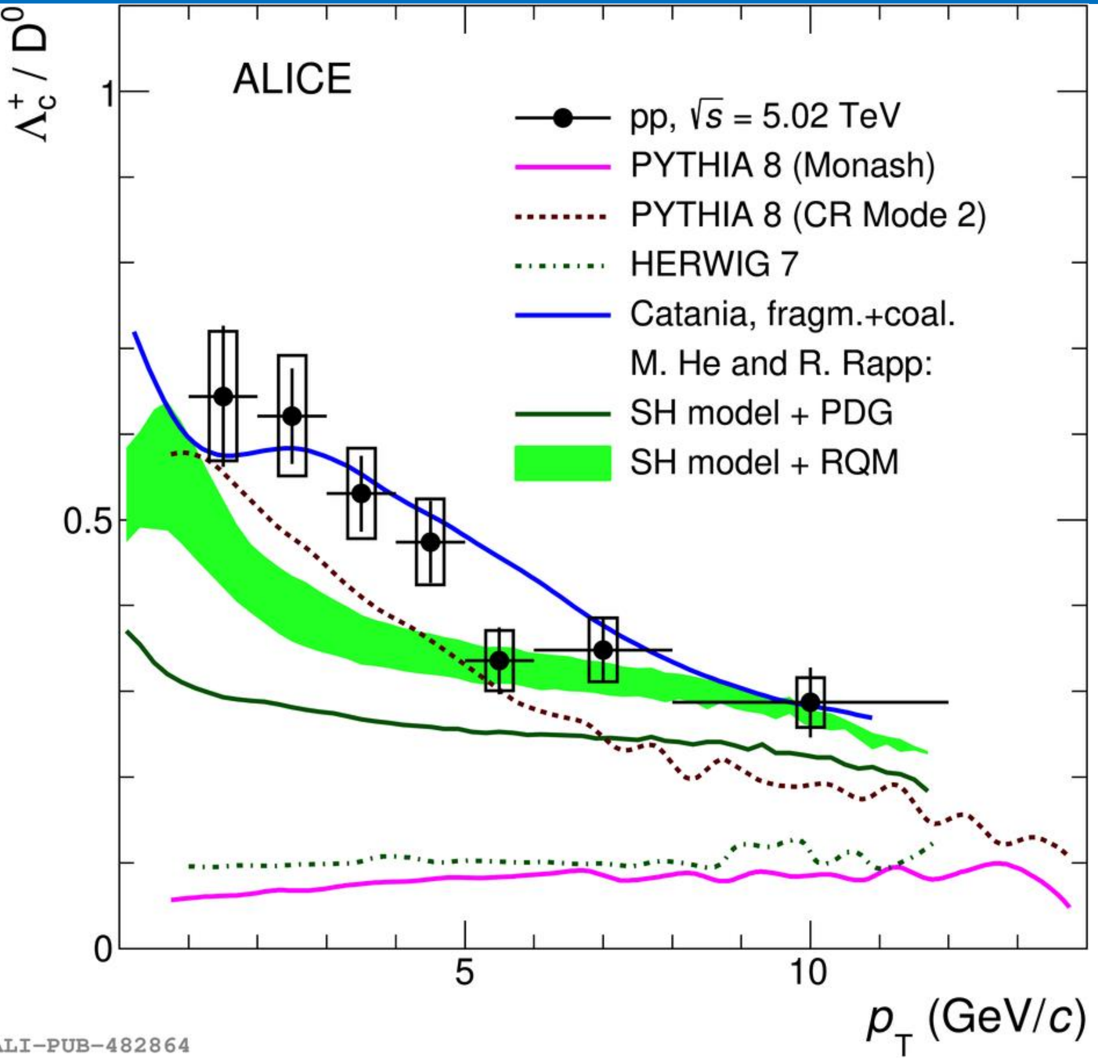


Coalescence in small systems

- Fragmentation + coalescence can describe charm baryon to meson ratio.
- Hint of strangeness enhancement with multiplicity increasing
- Coalescence plays an important role in the hadronization process. An indication for final state effects?

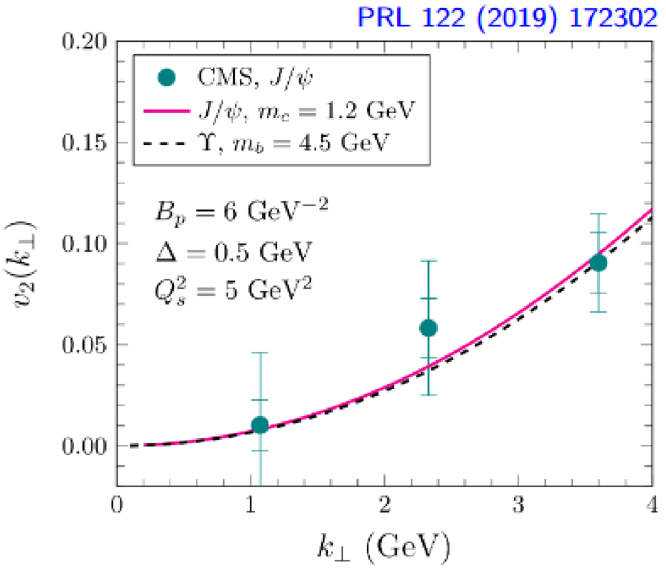


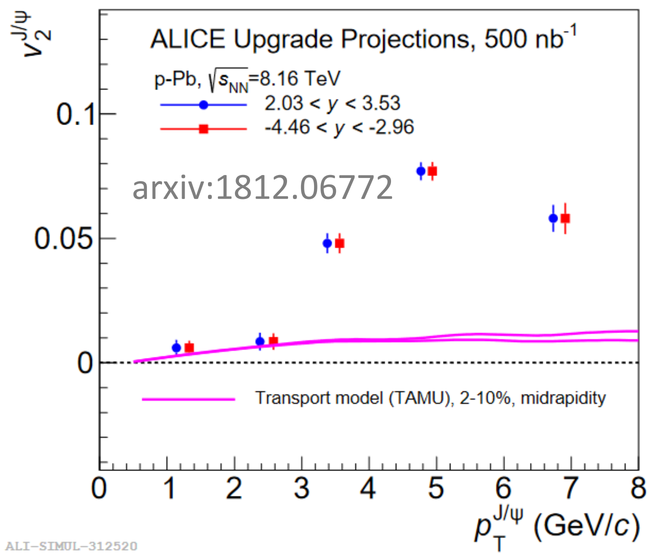
JHEP12(2019)092

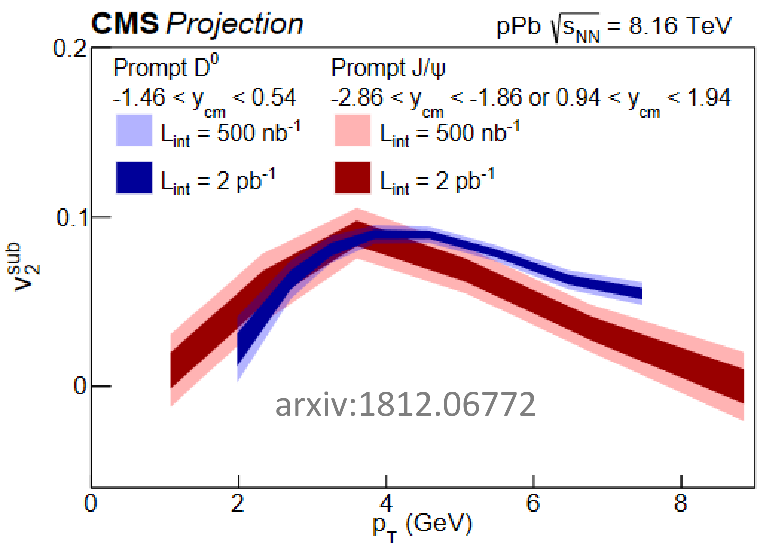


Summary

- Collective motions of charm quarks become visible in **high multiplicity** where relative system size is large.
- **Ordering between charm and beauty** quarks is suggested in small systems, similar to observations in large systems.
- Data precision need to be improved with more events and detector upgrades. More exciting physics can be explored in LHC-Run3 and HL-LHC era.







Acknowledgement

U.S. DEPARTMENT OF ENERGY

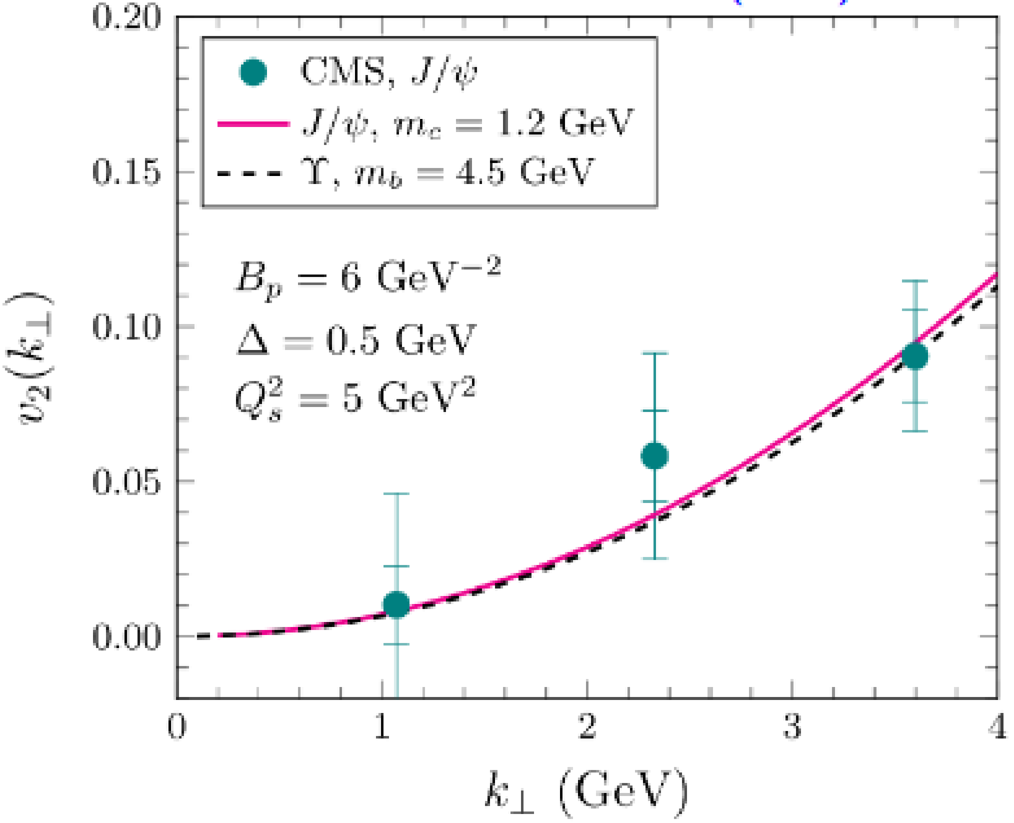
Office of Science

Alfred P. Sloan FOUNDATION

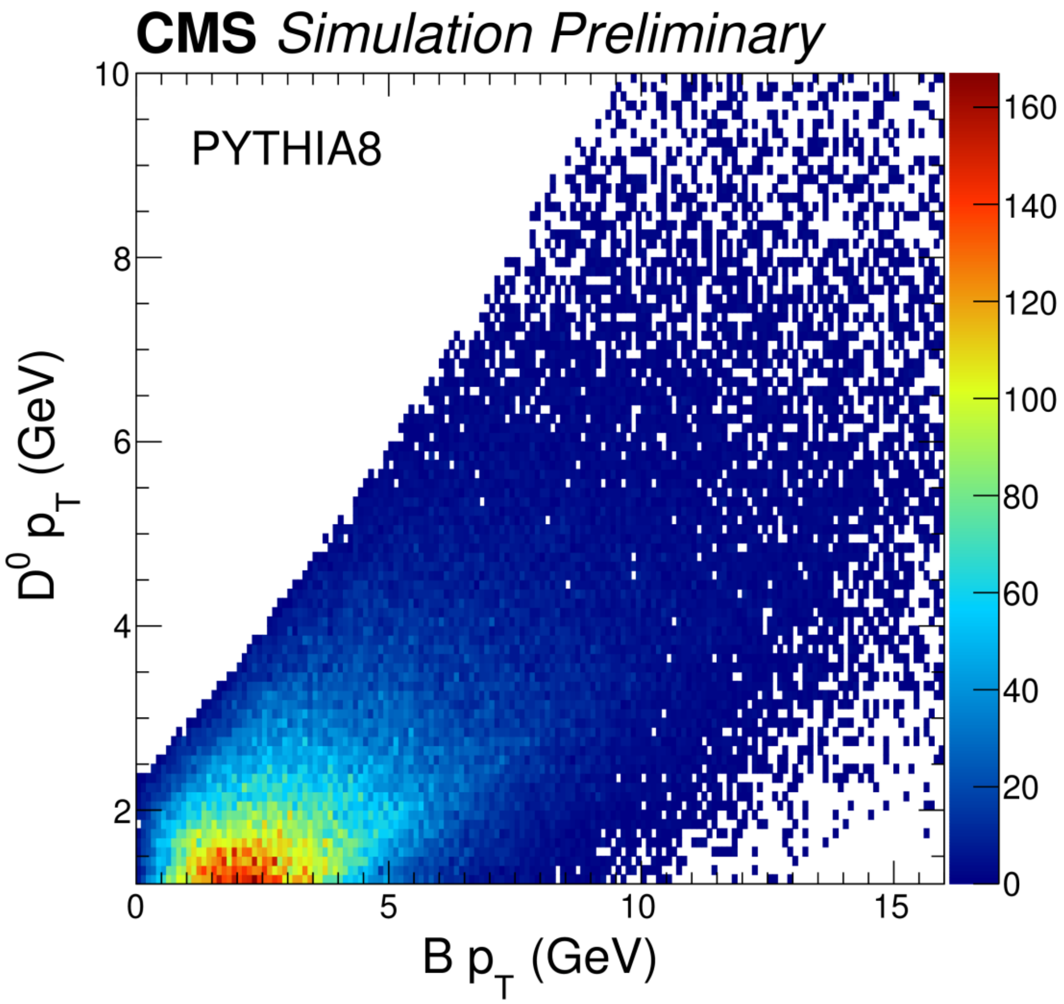
THE Welch FOUNDATION

Backup, CGC predictions for upsilon and Jpsi

PRL 122 (2019) 172302



Backup

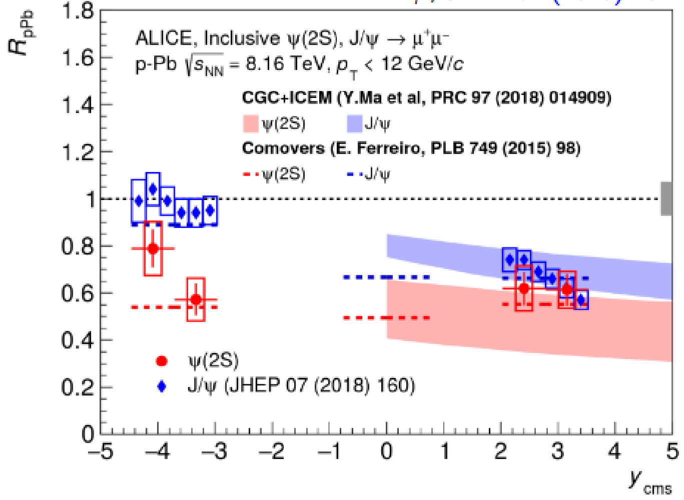


CMS Simulation Preliminary
PYTHIA8
D^0 p_T (GeV)
B p_T (GeV)
0
5
10
15
2
4
6
8
10
0
20
40
60
80
100
120
140
160

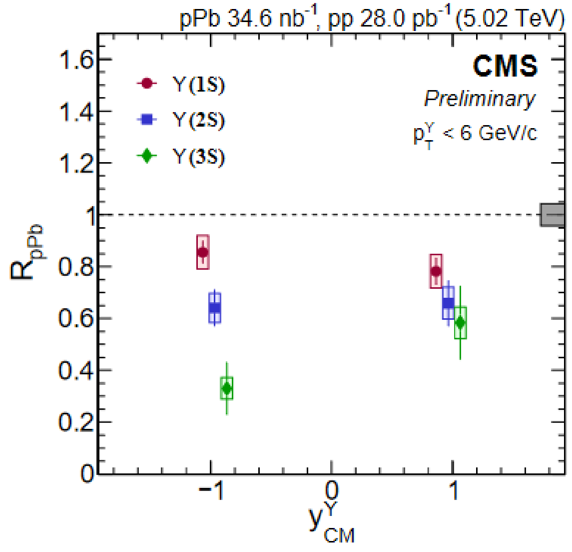
Backup, quarkonia from Emilien, Initial Stage 2021

- 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

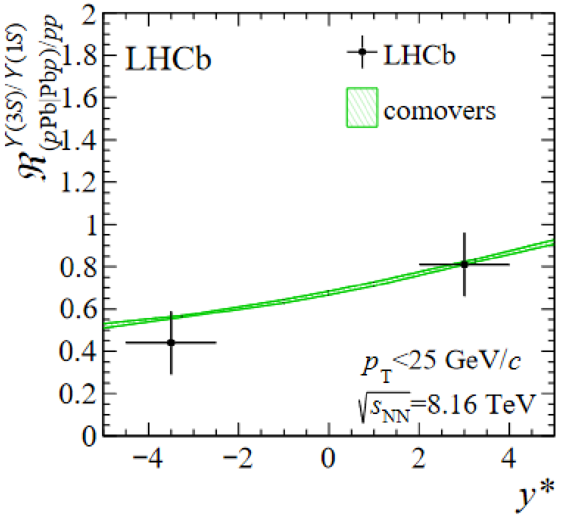
ψ, JHEP 07 (2020) 237



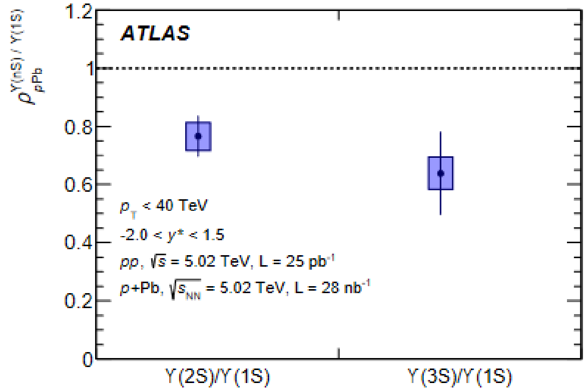
Υ, CMS-PAS-HIN-18-005



Υ, JHEP 11 (2018) 194



Υ, EPJC 78 (2018) 171



Backup, In-medium, Du, Rapp, JHEP 03 (2019) 015

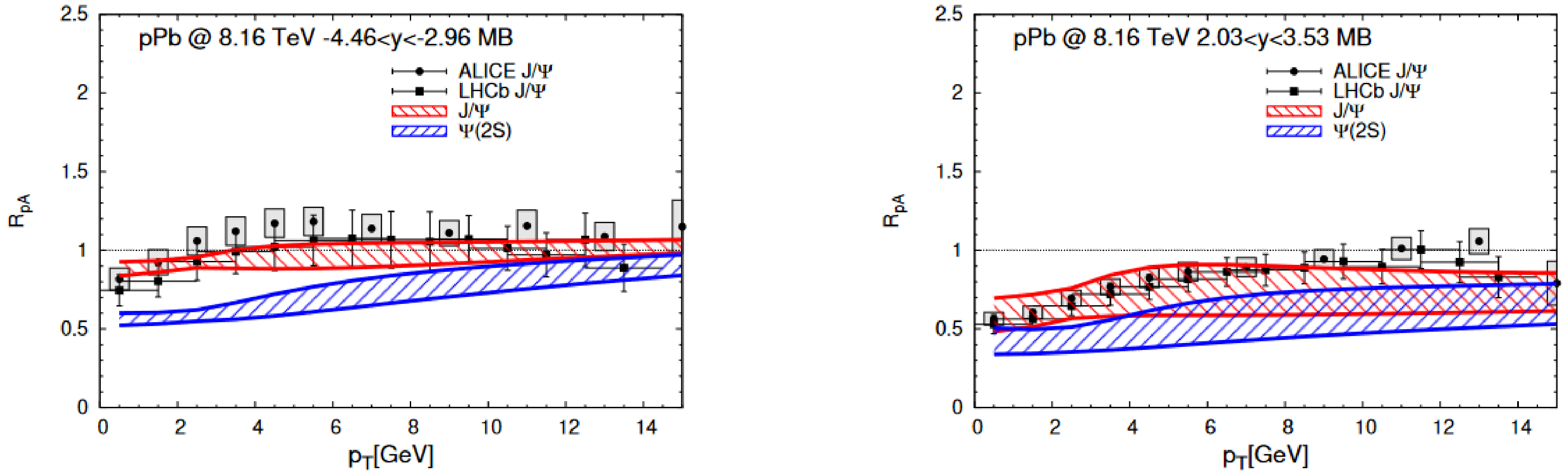
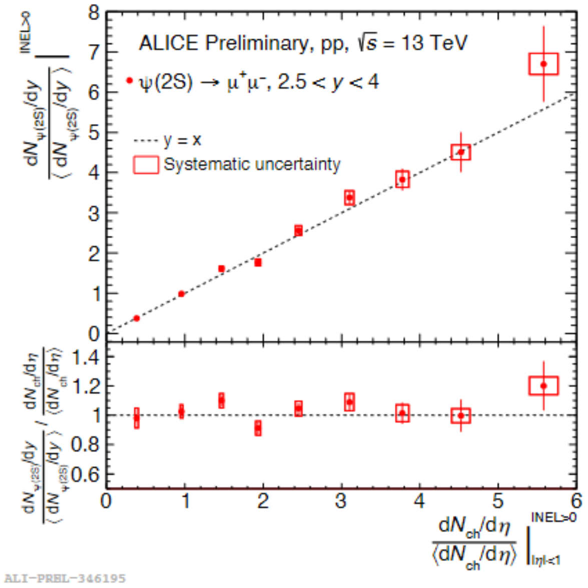


Figure 7. Same as figure 6 but for 8.16 TeV p-Pb collisions with ALICE and LHCb data [20, 21] at 8.16 TeV.

Backup, from Ophélie Bugnon, Initial Stage 2021

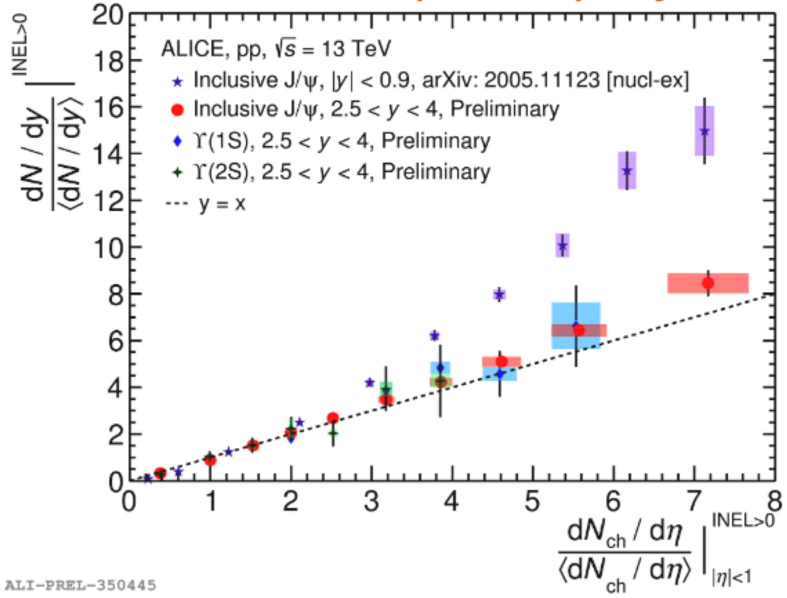
Multiplicity-dependent quarkonium measurements at forward rapidity

ψ(2S) vs multiplicity



Full LHC Run 2 data sample

ϒ(nS) and J/ψ vs multiplicity

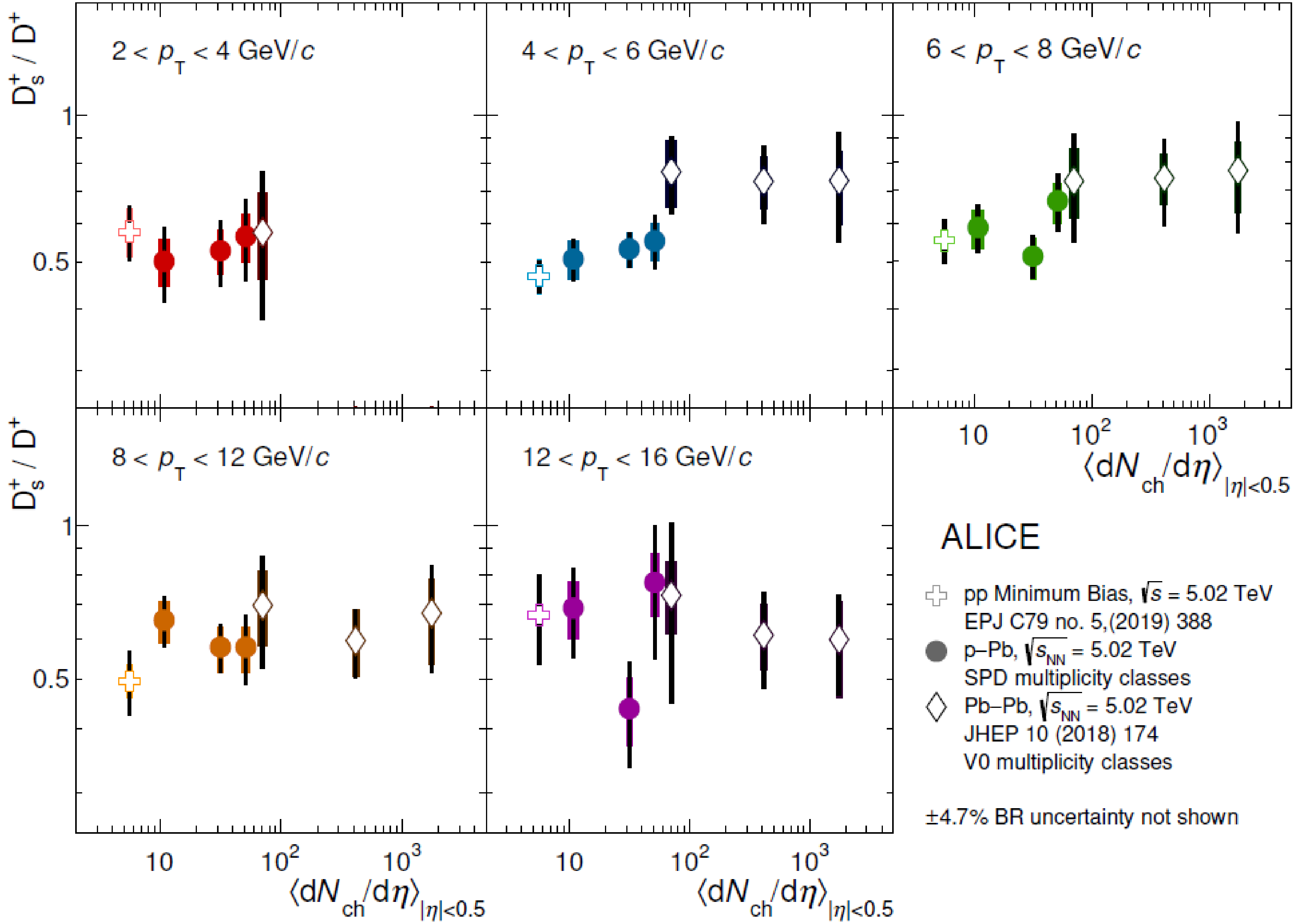


2016 data sample

- J/ψ, ψ(2S), ϒ(1S) and ϒ(2S) measurements at **forward rapidity compatible with linear** dependence on multiplicity
- J/ψ self normalized yield increases **stronger than linear at midrapidity**
- Full LHC Run 2 ϒ(nS) results coming soon

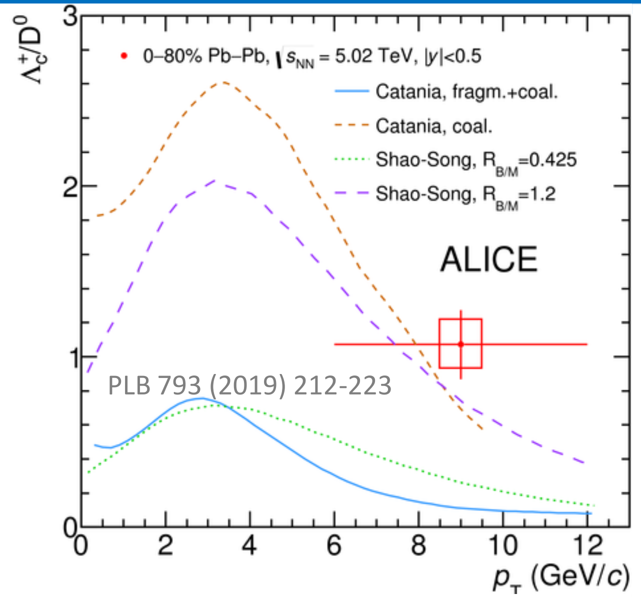
Backup, Ds

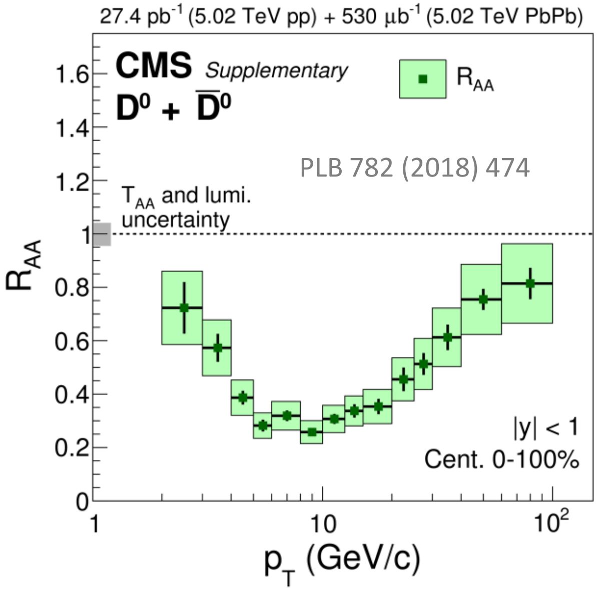
- Strangeness enhancement

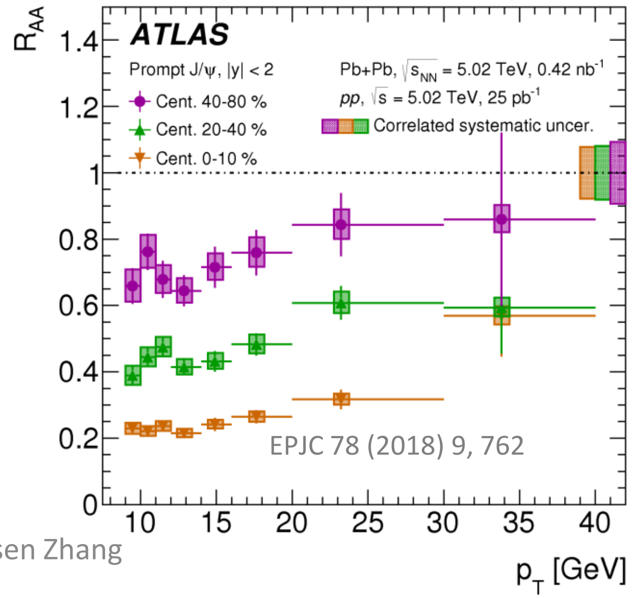


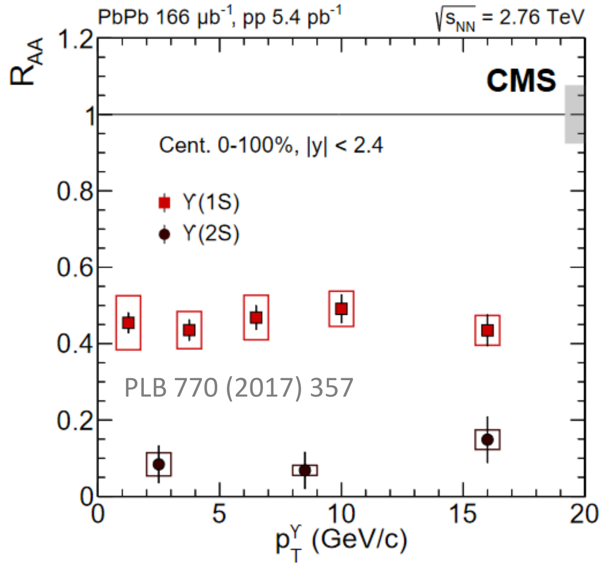
Backup, Hot medium in large systems

- QGP droplet in heavy ion collisions
  - Coalescence: existing quarks recombine together
    - Baryon to meson ratio enlarged compared to fragmentation
    - …
  - Particle productions are suppressed
    - Energy loss
    - …
  - Screening effects
    - Quarkonia suppression, Debye screening radius < binding radius









Backup, Collectivity in small systems

- In large system, $L/\lambda_{m.f.p.} >> 1$
- How to explore it?
  - Decrease system size, $L/\lambda_{m.f.p} \sim N_{trk}^{1/3}$

Phys. Rev. Lett. 116, 172301 (2016)