Heavy Quarks across Scales:
QGP, Hadronization & CNM effects

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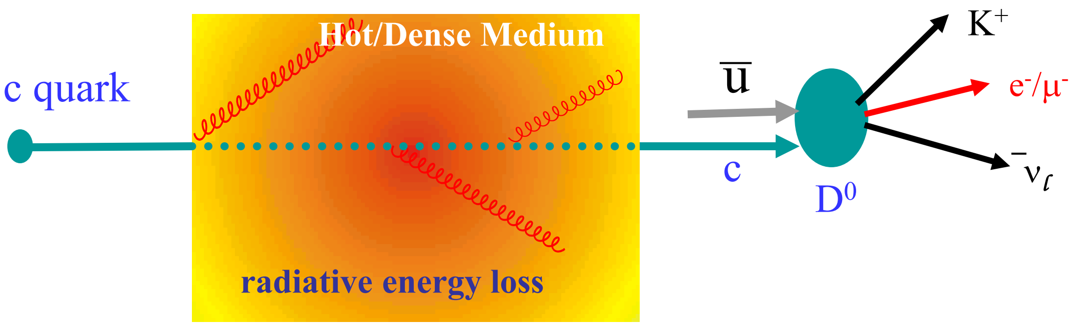
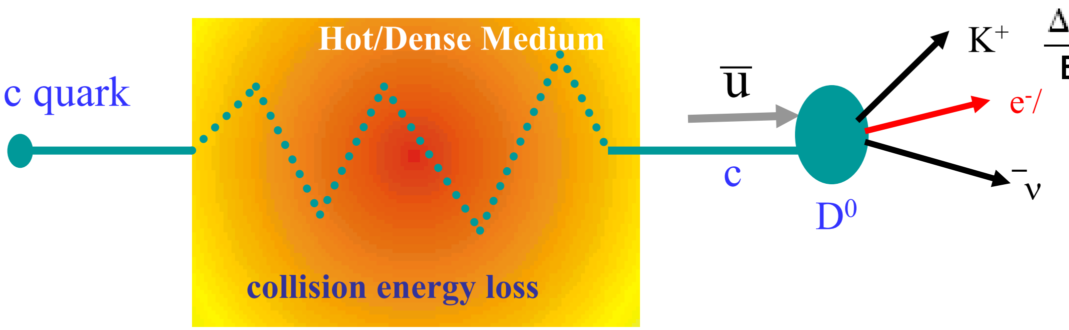
Essential to understand Open Heavy Flavor Production

- One of the most important probes for sQGP
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc

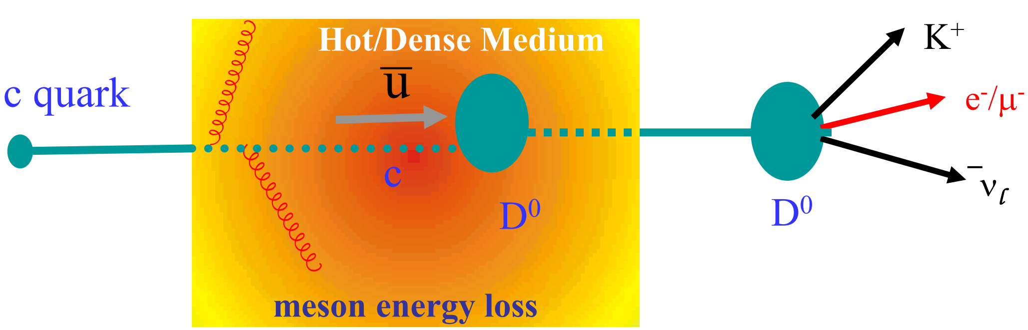
The Large Suppression of Non-photonic Electron Production was a Surprise



(Baier *et al*, Kharzeev *et al*, Djordjevic *et al*, Wiedemann *et al* .)

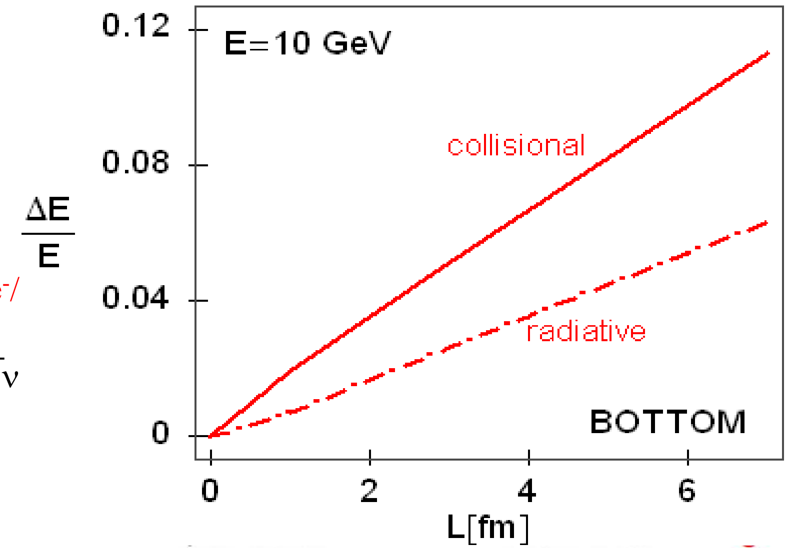


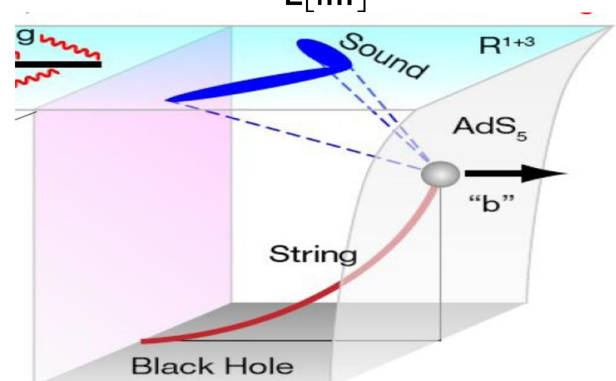
(Teaney *et al*, Rapp *et al*, Molnar *et al*, Gossiaux *et al*.)



Vitev, et al

"dead cone effect":
gluon radiation
suppressed at $\theta < m_Q/E_Q$





(Gubser *et al.*, Herzog *et al.*, Horowitz, Gyulassy *et al.*)

Essential to understand Open Heavy Flavor Production

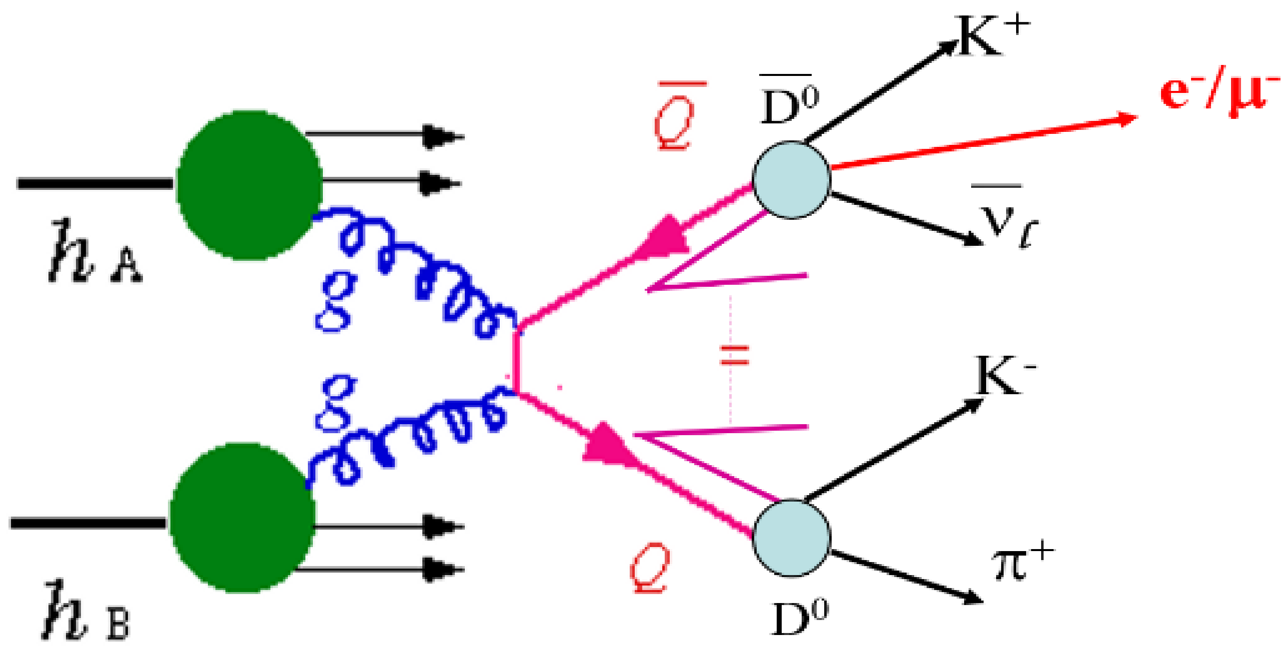
- One of the most important probes for sQGP
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc
  - allow further understanding of the medium properties.
  - A "**Gold Mine**" being fully explored.

- A good reference to quarkonia production
  - Similar initial state effects
    - CGC, Shadowing, initial state energy loss, etc.
  - Large cross section (compared to J/ψ).
    - Accurate reference measurements.

Key Ingredients to study HQ in QGP

- ❑ Baseline
  - p_T spectra, total cross section in pp & PbPb, ……..
- ❑ Cold nuclear matter effects
  - Gluon shadowing , Color glass condensate, initial state E-loss, Cronin effect, …..
  - Num(HQ)@pPb&PbPb/N-N $\neq$ Num(HQ)@pp
- ❑ Bulk Evolution
  - v_n and radial flow, ……
- ❑ Interactions with the Partonic and Hadronic medium
  - gluon radiation, collisional energy loss, …….
- ❑ Hadronization
  - Vacuum fragmentation
  - Coalescence
  - Color reconnection
  - SHM+RQM
  - ....

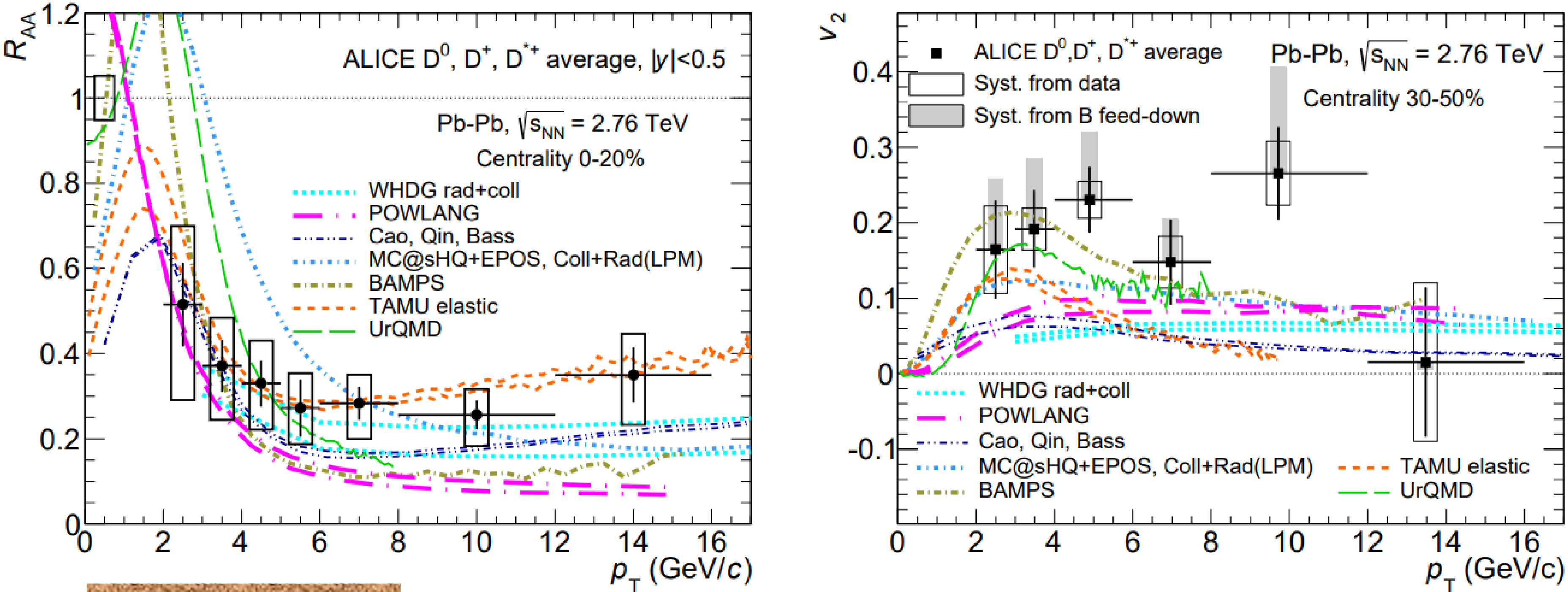
How to study Heavy Quarks



- Heavy quark proxies:
  - Jet associated with the heavy quark
  - HF hadron via direct reconstruction
  - HF-decay, i.e. electrons, muons

- Production of each individual proxies, e.g. R_{AA} and V_2
- Correlation among proxies

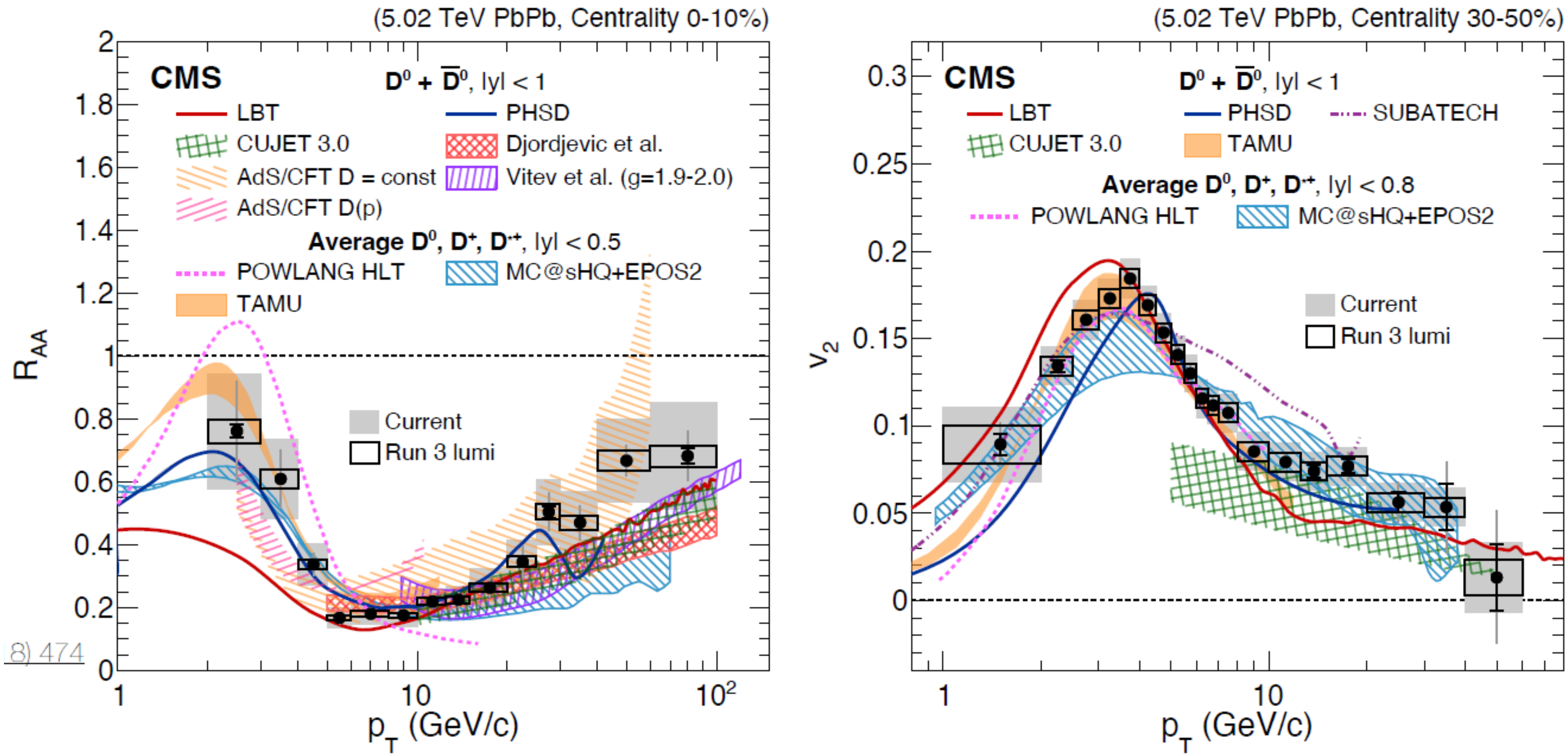
Modeling of HQ-Medium interaction in the past



A. Beraudo@QM2014

- The R_{AA} vs. v_2 Puzzle
  - R_{AA} match data→ Large medium Opacity→ too small v_2
  - v_2 match data→smaller Opacity→too small suppression.

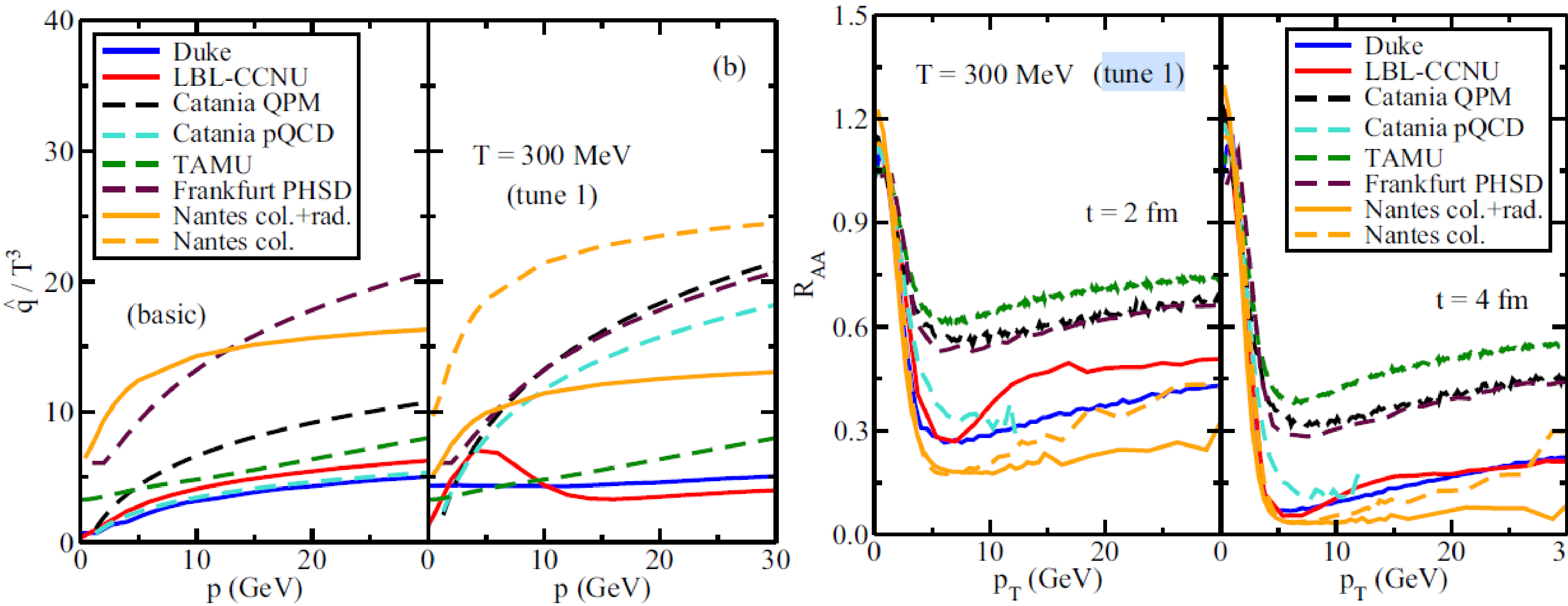
Modeling of HQ-Medium interaction not converged yet



- ❑ Various models qualitatively described the R_{AA} and v_2
  - Through tuning the different ingredients

PLB 782 (2018) 474
PLB 816 (2021) 136253

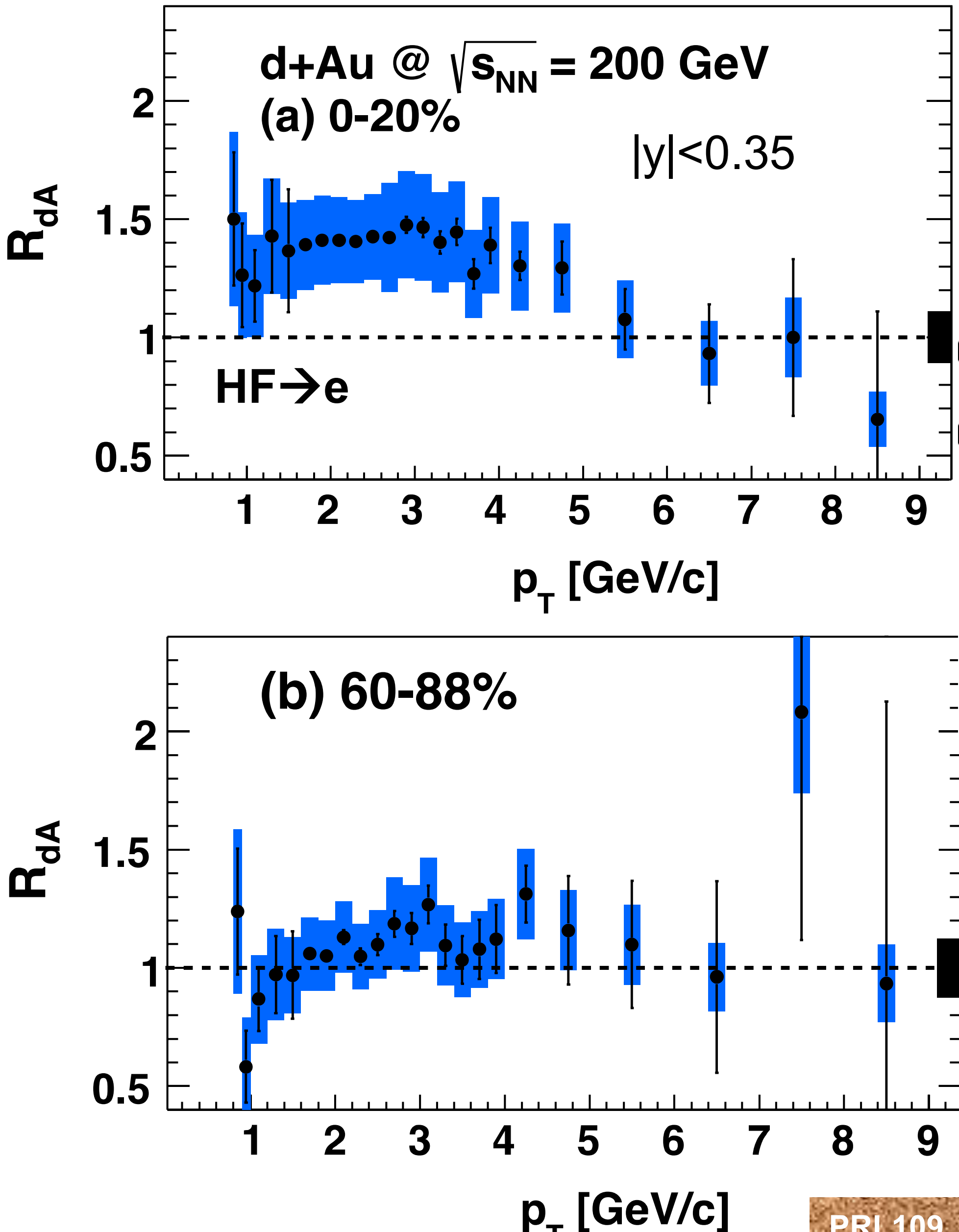
Modeling of HQ-Medium interaction not converged yet



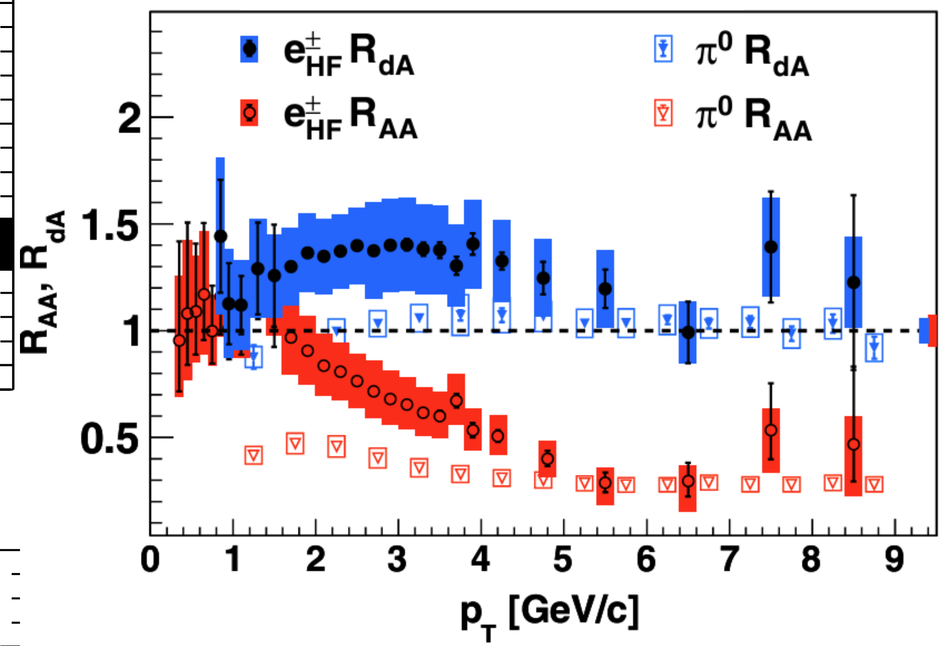
PRC (2019) 054907

- Various models qualitatively described the R_{AA} and v_2
- Large differences in modeling
  - Transport coefficients
  - hadronization
  - medium evolution
  - ……..

Suppression & enhancement in small systems



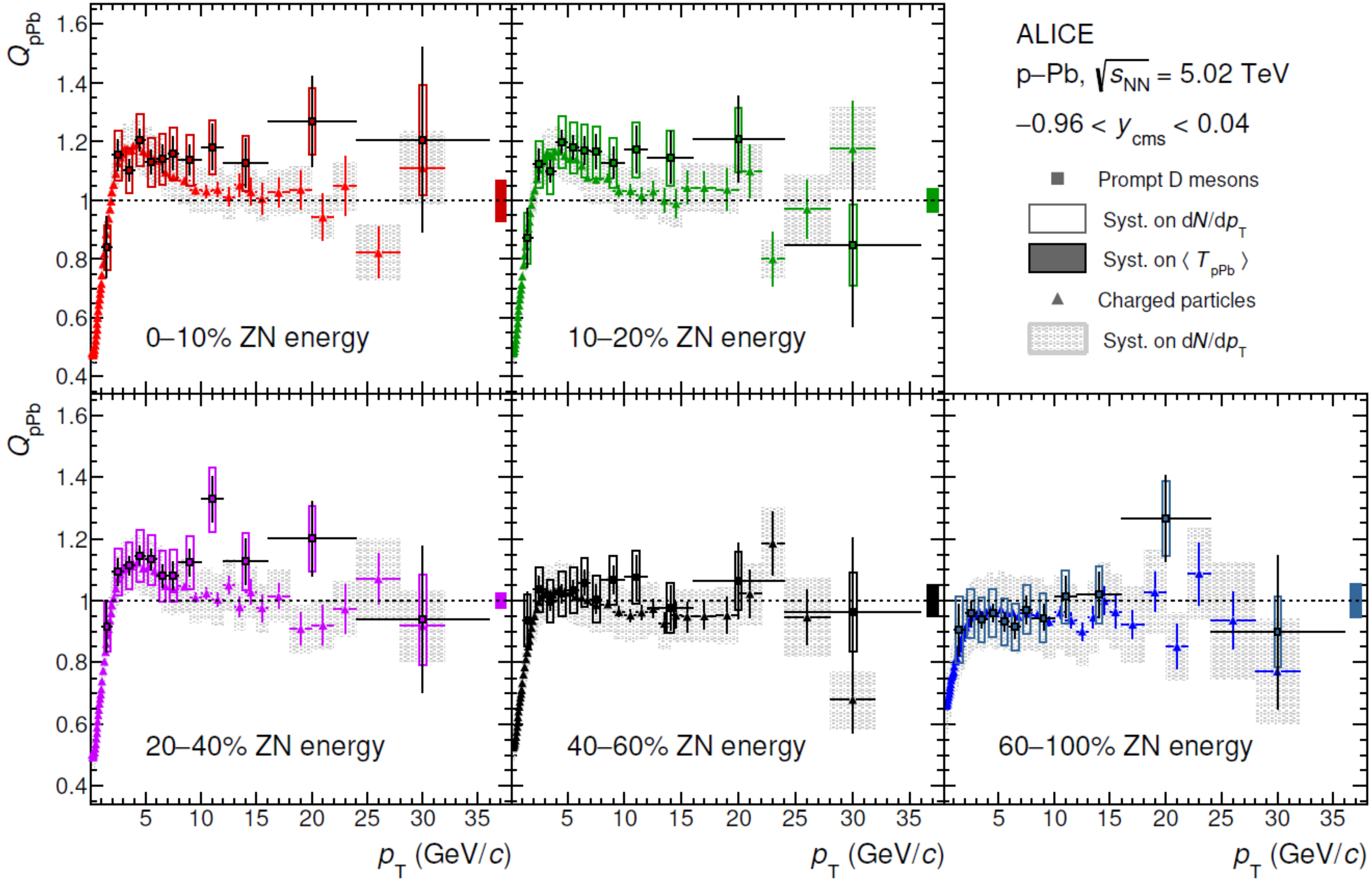
$$R_{dA} = \frac{dN^{e}_{dA}/dp_T}{\langle N_{\rm coll}\rangle \times dN^{e}_{pp}/dp_T}$$



- d-Au@200GeV (|y|<0.35)
  - $R_{dA} \approx 1.0$ in 60-88%
  - Large enhancement in 0-20%
  - Different from Au-Au
    - CNM effects, selection bias ….

PRL109, 242301 (2012)

Suppression & enhancement in small systems

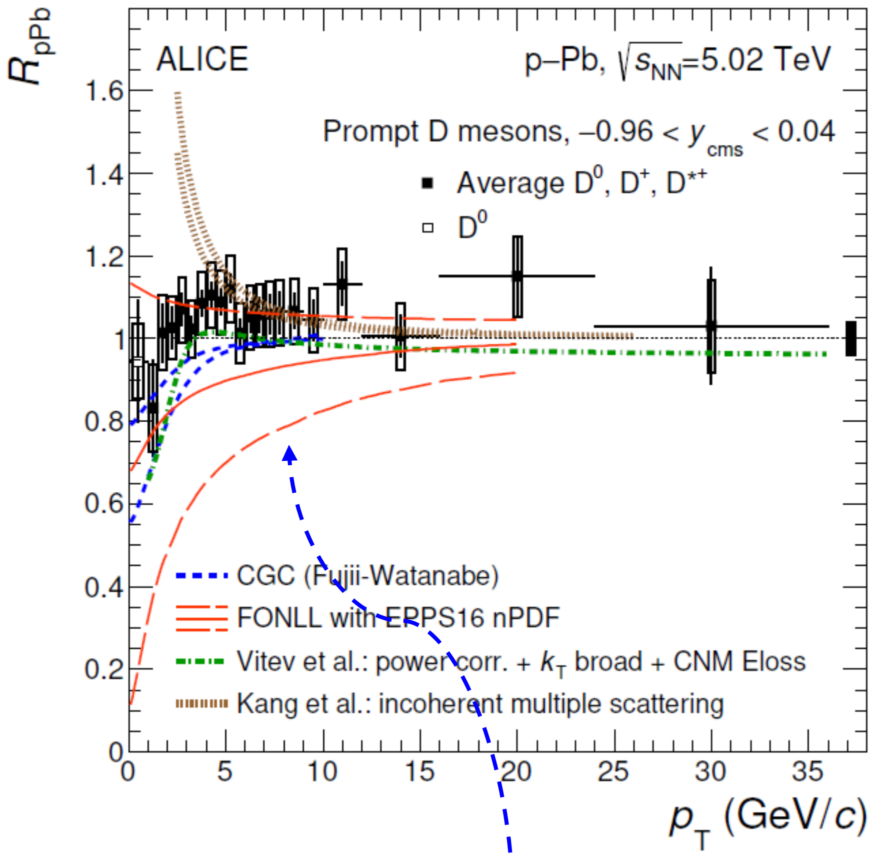


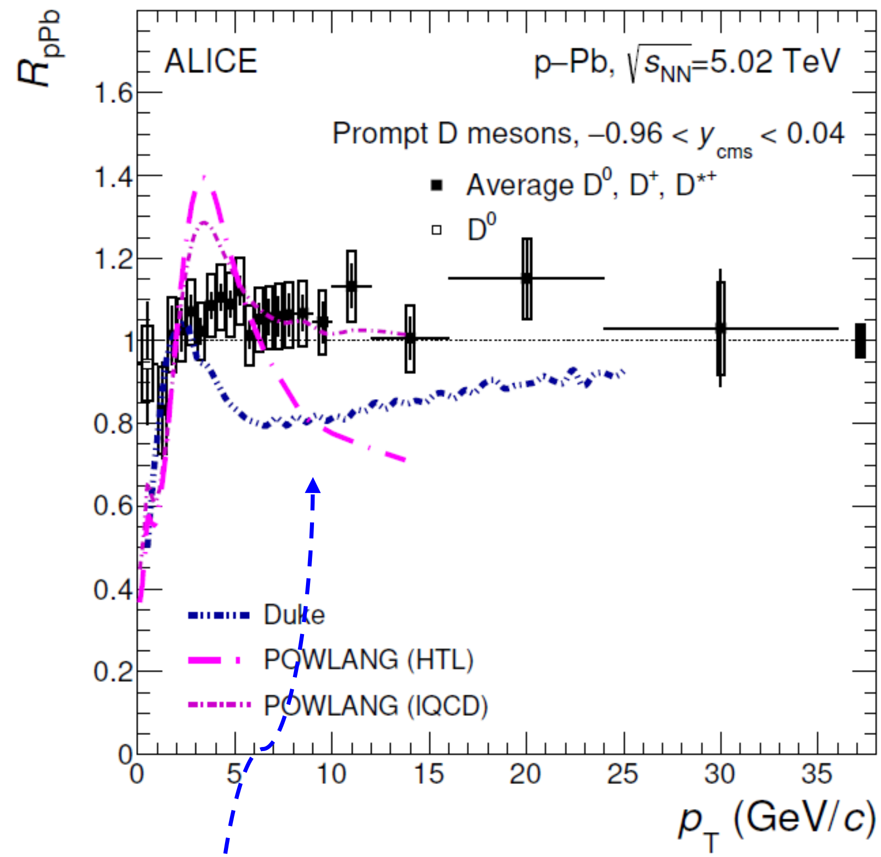
- Similar trend as RHIC

$$Q_{\rm pPb} = \frac{({\rm d}^2 N^{\rm prompt\,D}/{\rm d}p_{\rm T}{\rm d}y)^{\rm i}_{\rm p-Pb}}{\langle T_{\rm pPb}\rangle_{\rm i} \times ({\rm d}^2\sigma^{\rm prompt\,D}_{\rm pp}/{\rm d}p_{\rm T}{\rm d}y)}$$

JHEP 12 (2019) 092

Suppression & enhancement in small systems



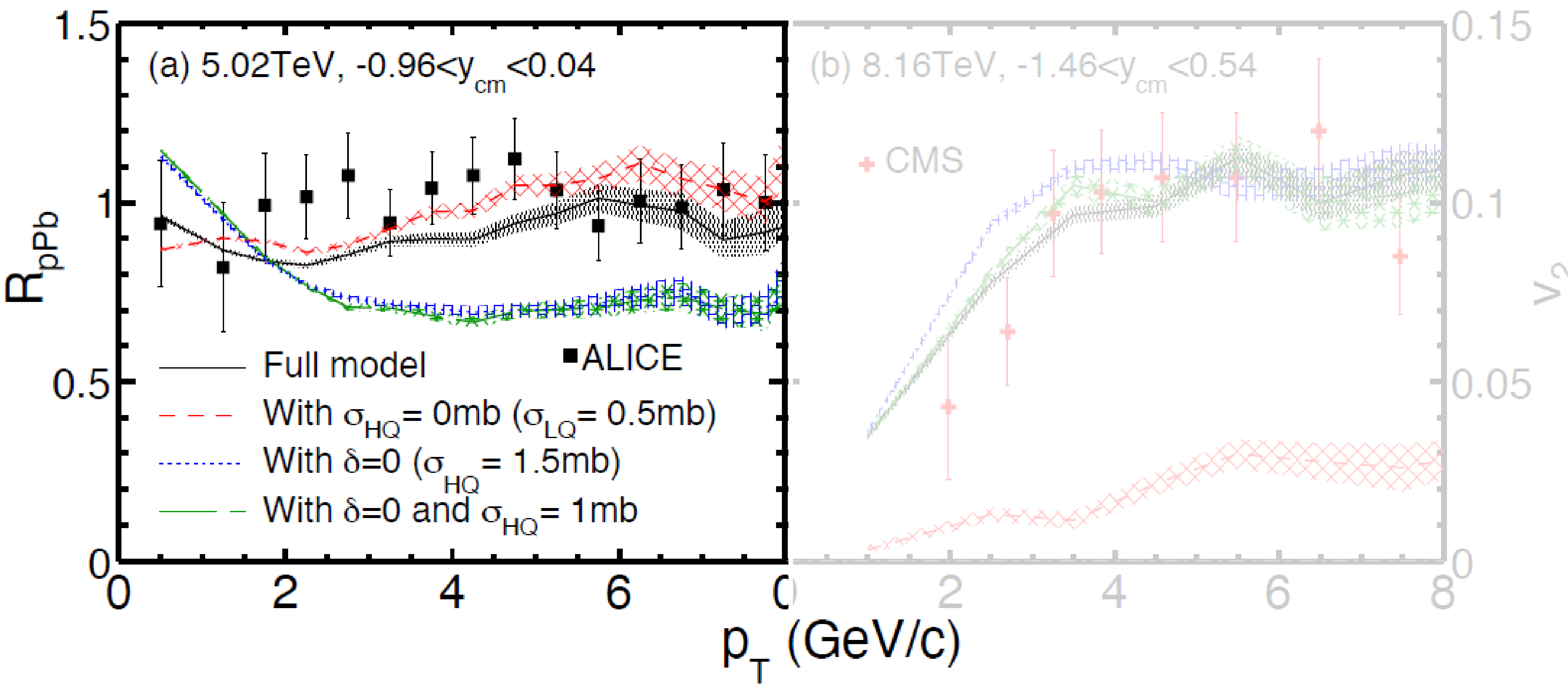


- ❑ Models with CNM only describe the data
- ❑ Models with QGP formation can't described the data
  - Duke: radiative + collisional E-loss
  - POWLANG: collisional E-loss

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{p-Pb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y},$$

JHEP 12 (2019) 092

Suppression & enhancement in small systems

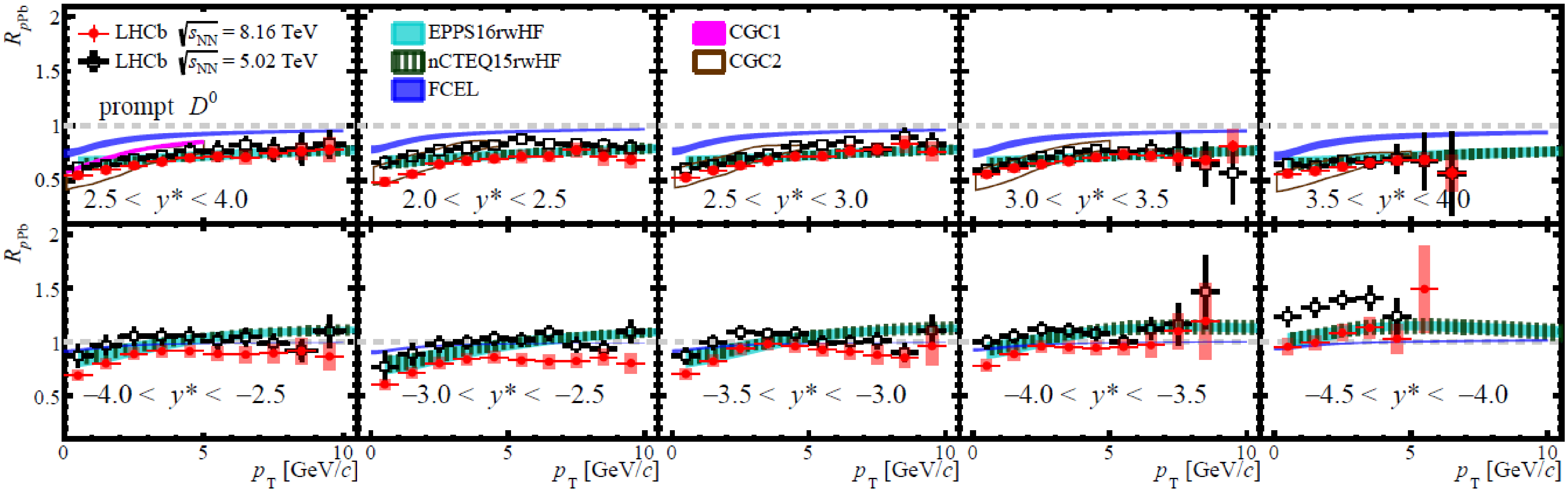


- ❑ Models with CNM only describe the data
- ❑ Models with QGP formation can't described the data
  - Duke: radiative + collisional E-loss
  - POWLANG: collisional E-loss
- ❑ AMPT describes the R_{pPb} with Cronin effect

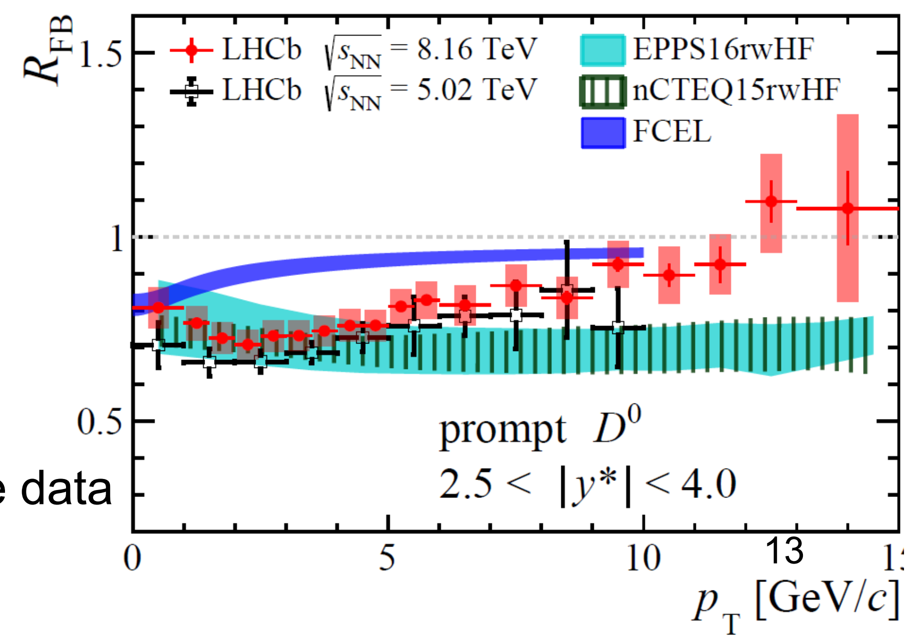
$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{p-Pb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y},$$

Suppression & enhancement in small system

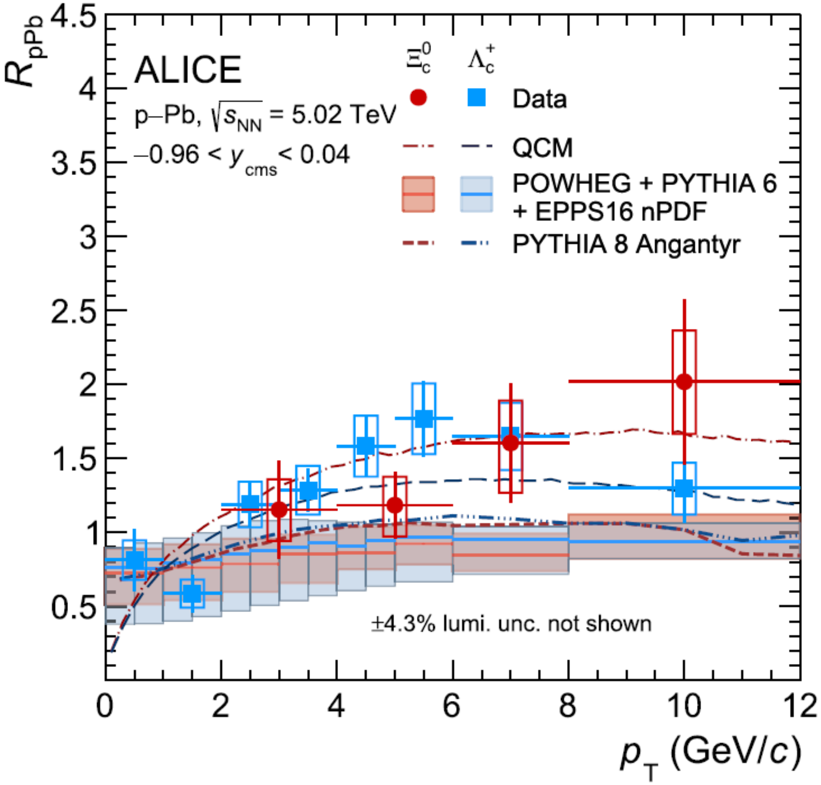
PRL 131 (2023) 102301

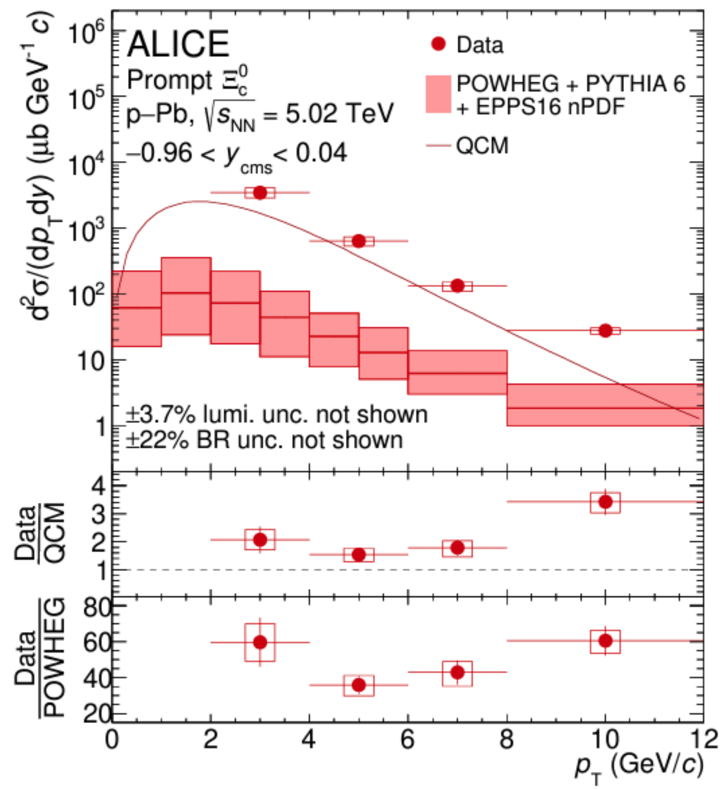


- ❑ enhancement: -4.0<y*<-2.5 (Pb-going)
- ❑ Suppression: 2.5 < y*< 4.0 (p-going)
- ❑ Model w/nPDF only differ from Pb-going
  - Describe the p-going results nicely.
- ❑ CGC describe the data
  - No applicable in Pb going, i.e. large x
- ❑ CNM E-loss (FCEL) alone can't describe the data
- ❑ Sqrt(s) dependence ← difference in x distribution.



Suppression & enhancement in small system





- ❑ nPDF underestimated the charm baryon R_{pb}.
- ❑ QCM model agrees with the data
  - ▪ Charm hadronization w/coalescence when close in phase space.
- ❑ More on charm baryons later when discussing hadronizations.

JHEP 12 (2023) 086
EPJC 85 (2025) 86

Can QGP E-loss be Quantified from the suppression & enhancement of HF production in small systems?

- QGP E-loss in small system should be relatively small
  - trend from central to peripheral AA collisions.

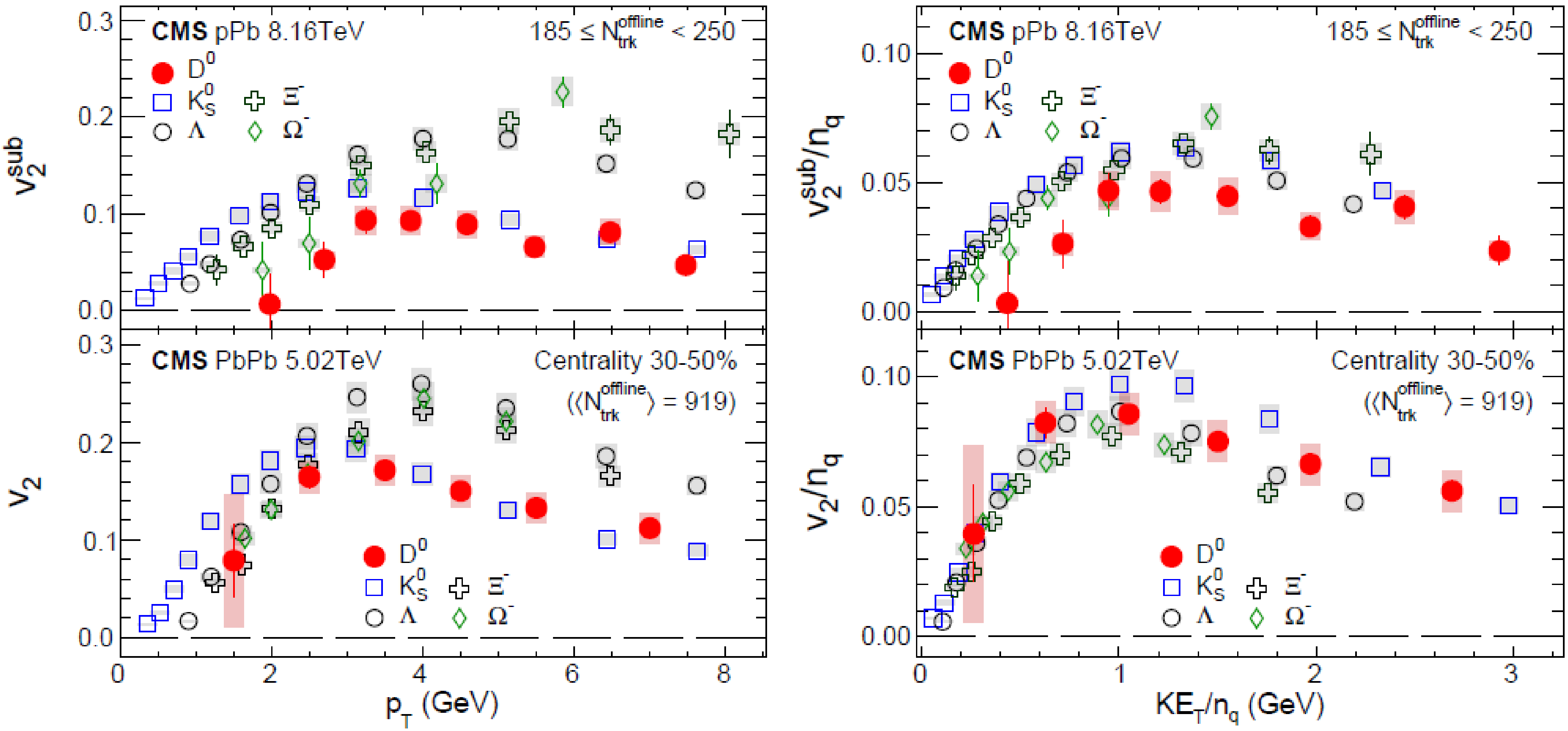
- Impacts from CNM effects are large:
  - nPDF, CNM E-loss, Cronin effect, shadowing, CGC….

- **CNM** can qualitatively describe the D^0 results.
  - Models w/QGP transport **rejected**.

- CNM can't describe charm baryon results.
  - QCM involves a coalescence, a hint of QGP in small system
    - *Failed to describe bayron/meson ratio (discussed later)*

- It's a "**big challenge**" to extract QGP E-loss, **if any,** from the suppression/enhancement of HF production.
  - Need to quantify all CNM effects in high precision first.
  - but all effects are entangled,
  - maybe fitting high precision data with templates of different contributors to reproduce subtle p_T dependence of the measurements.

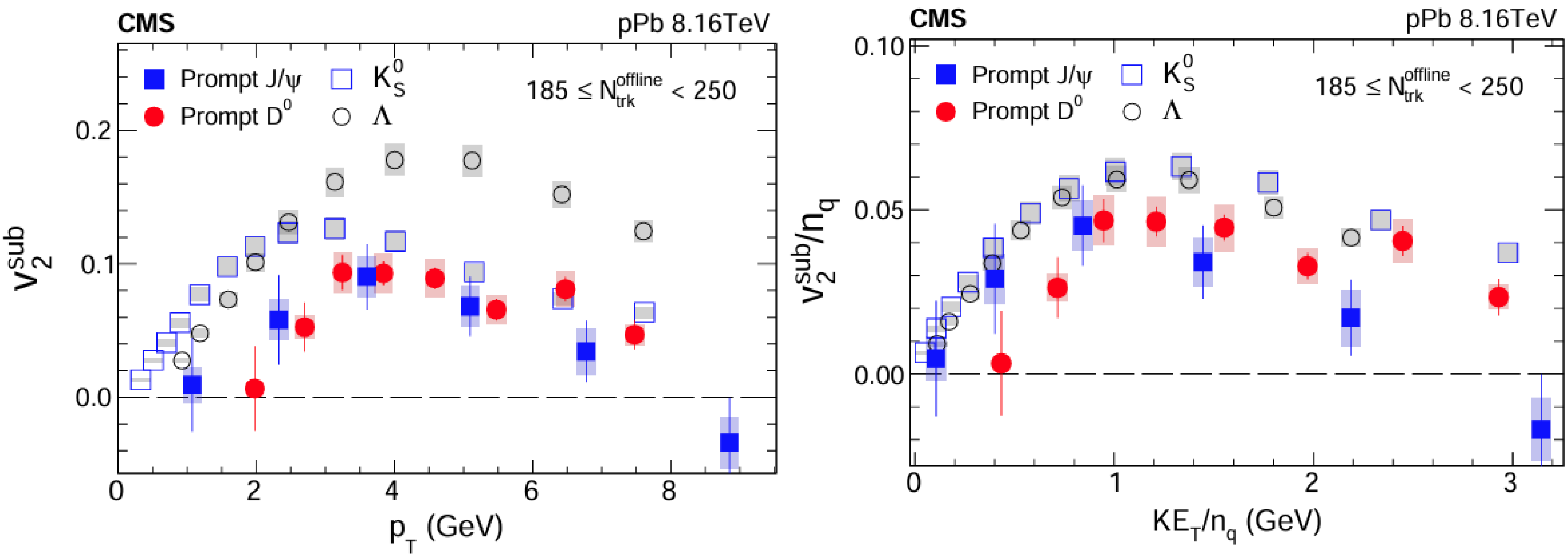
Significant D^0 v_2 in p-Pb at 8.16 TeV



- ❑ Similar mass ordering in pPb and PbPb.
- ❑ NCQ scaling doesn't quite work for D^0 in pPb.

PRL 121 (2018) 082301

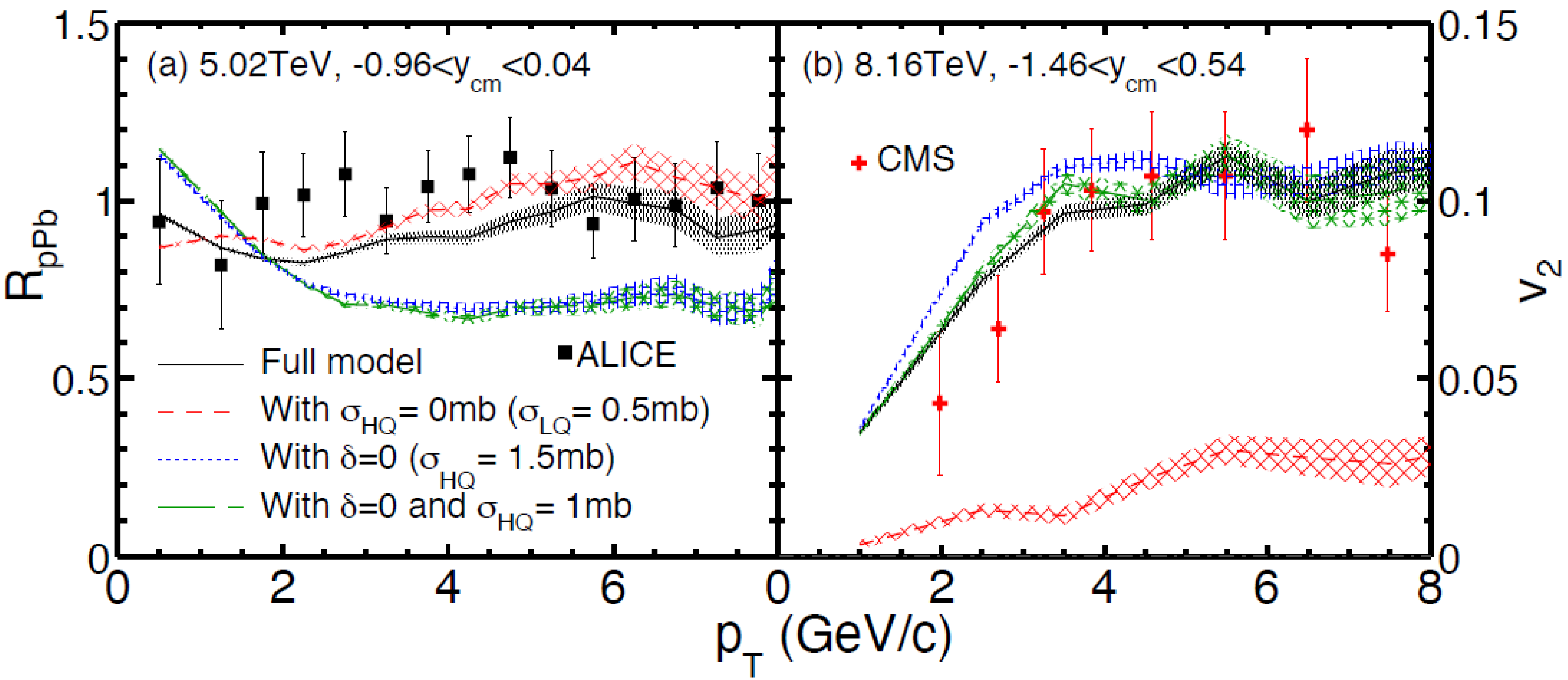
Significant J/ψ v_2 in p-Pb at 8.16 TeV



- $v_2(J/\psi) \approx v_2(D^0) < v_2(K_S^0)$
- Coalescence require consistent with similar velocity.
  - J/ψ: scaling $p_T(J/\psi)/2$
  - For D^0:
    - $v_2[D^0@p_T(D^0)] \sim v_2[c@p_T(c)] + v_2[u@p_T(u)]$
      - ✓ $p_T(c) \sim p_T(D^0) \cdot m_c/(m_c + m_u) \sim p_T(D^0)/1.3$
      - ✓ $p_T(u) \sim p_T(D^0) \cdot m_u/(m_c + m_u) \sim p_T(D^0)/5.2$

PLB 791 (2019) 172
PRC 68 (2003) 044901

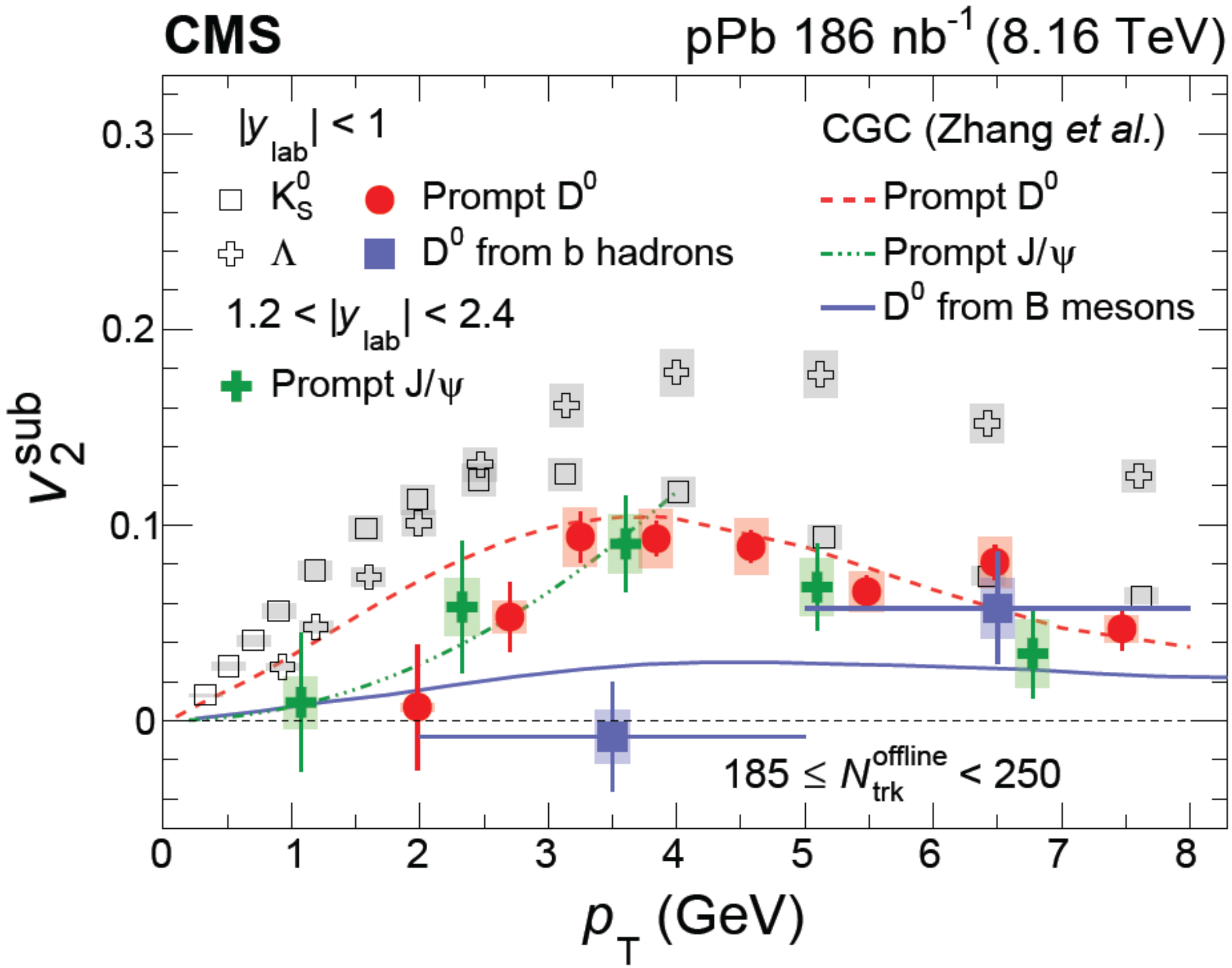
Significant D^0 v_2 in p-Pb at 8.16 TeV



- AMPT described both R_{AA} and v_2
  - Cronin is the key for R_{pPb}
  - Charm scattering with the partons created from the collision is the key for significant v_2.

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{p-Pb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y},$$

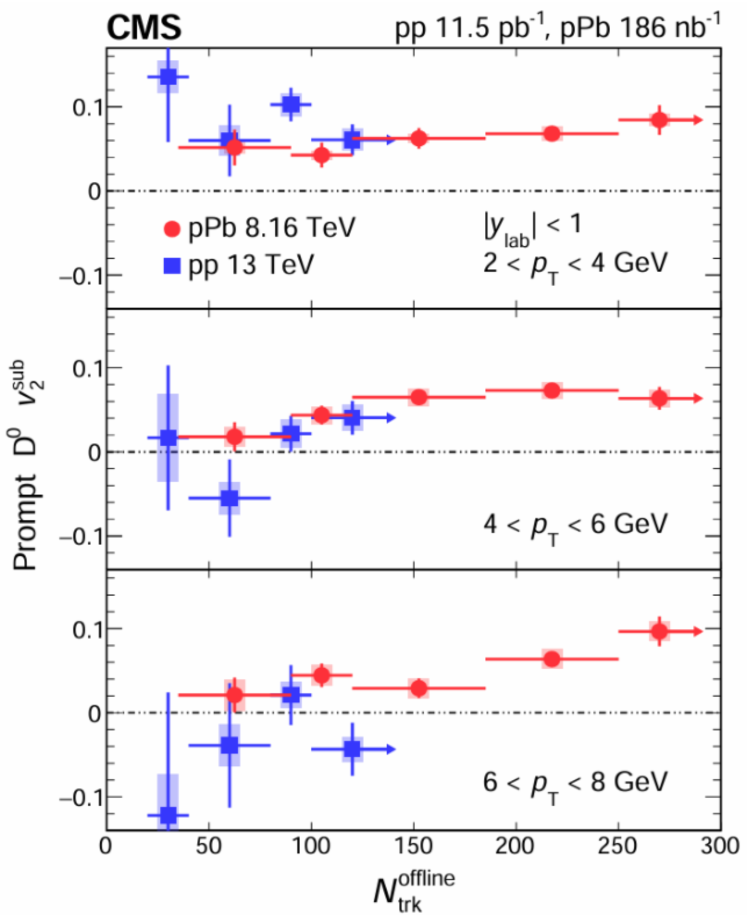
$B \rightarrow D^0$ v_2 in p-Pb at 8.16 TeV

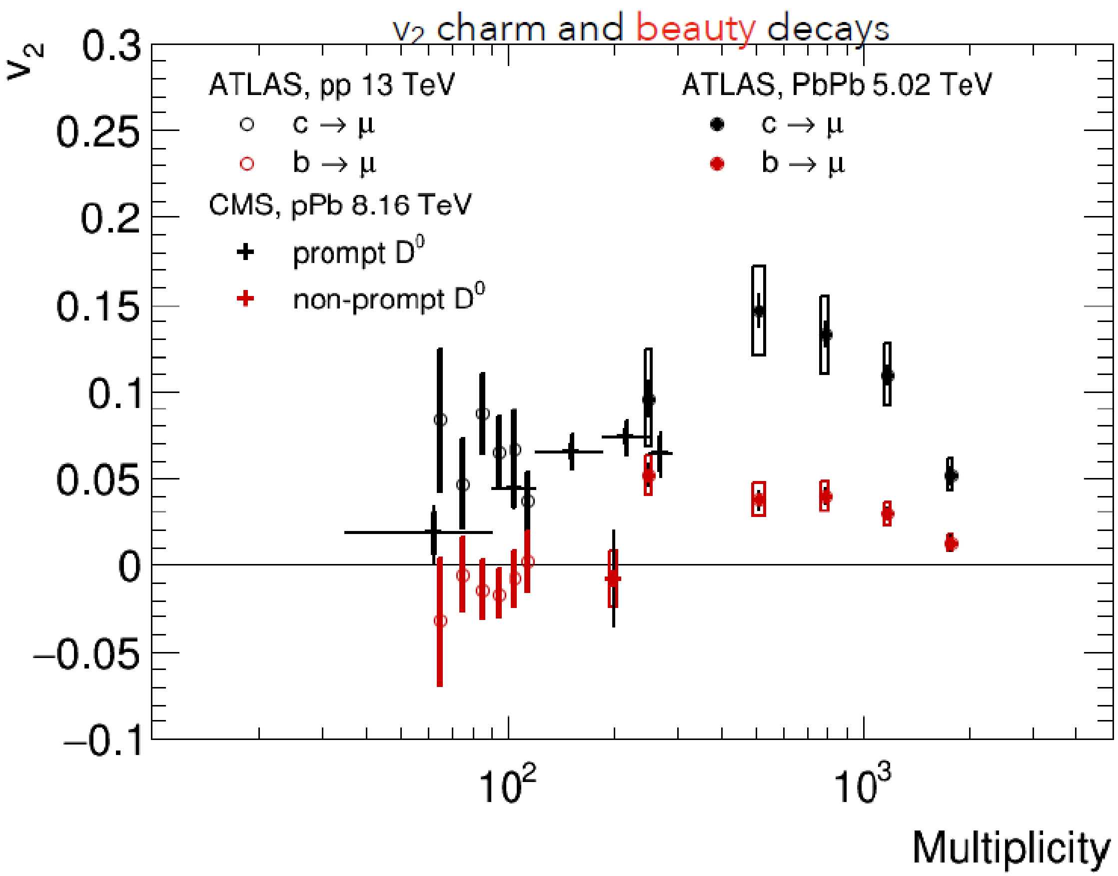


- ❑ $v_2(B - D^0) < v_2(D^0)$
- ❑ CGC qualitatively describe the data

PLB 813 (2021) 136036
PLB 850 (2024) 138389

System size dependence of charm and bottom v_2





- ❑ v_2 increase with multiplicity (<~500)
- ❑ Decrease towards higher multiplicity
  - ❖ Less eccentricity@more central PbPb

PLB 813 (2021) 136036;
PRL 124 (2020) 082301;
PLB 807 (2020)135595

Can we quantify QGP effects from flow measurements of heavy flavor?

JHEP03(2019)015

ABSTRACT: We study charmonium production in proton-nucleus (p-A) collisions focusing on final-state effects caused by the formation of an expanding medium. Toward this end we utilize a rate equation approach within a fireball model as previously employed for a wide range of heavy-ion collisions, adapted to the small systems in p-A collisions. The initial geometry of the fireball is taken from a Monte-Carlo event generator where initial anisotropies are caused by fluctuations. We calculate the centrality and transverse-momentum dependent nuclear modification factor (R_{pA}) as well as elliptic flow (v_2) for both J/ψ and $\psi(2S)$ and compare them to experimental data from RHIC and the LHC. While the R_{pA}s show an overall fair agreement with most of the data, the large v_2 values observed in p-Pb collisions at the LHC cannot be accounted for in our approach. While the former finding generally supports the formation of a near thermalized QCD medium in small systems, the discrepancy in the v_2 suggests that its large observed values are unlikely to be due to the final-state collectivity of the fireball alone.

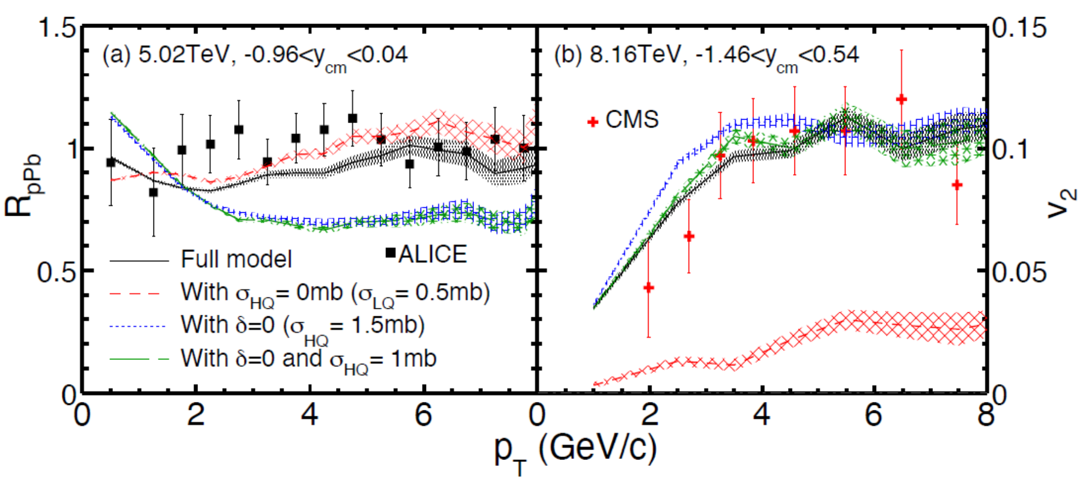
From the limited selection of models:

- ❑ final state collectivity in QGP droplet can't describe data
- ❑ Correlation from projectile parton interaction with the dense gluon field before onset of QGP.
- ❑ Parton cascade@AMPT: **Escape**

➔ **thermalized QGP droplet:**

- **can't or not needed to describe the data.**

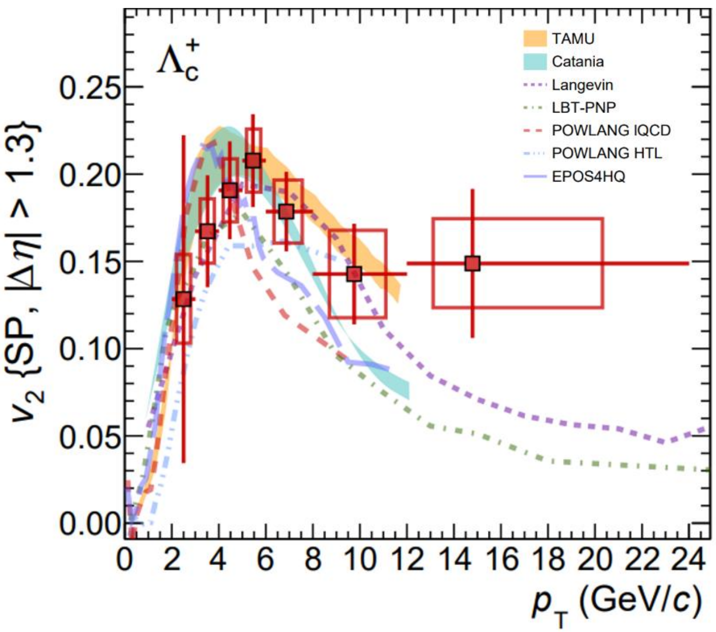
AMPT

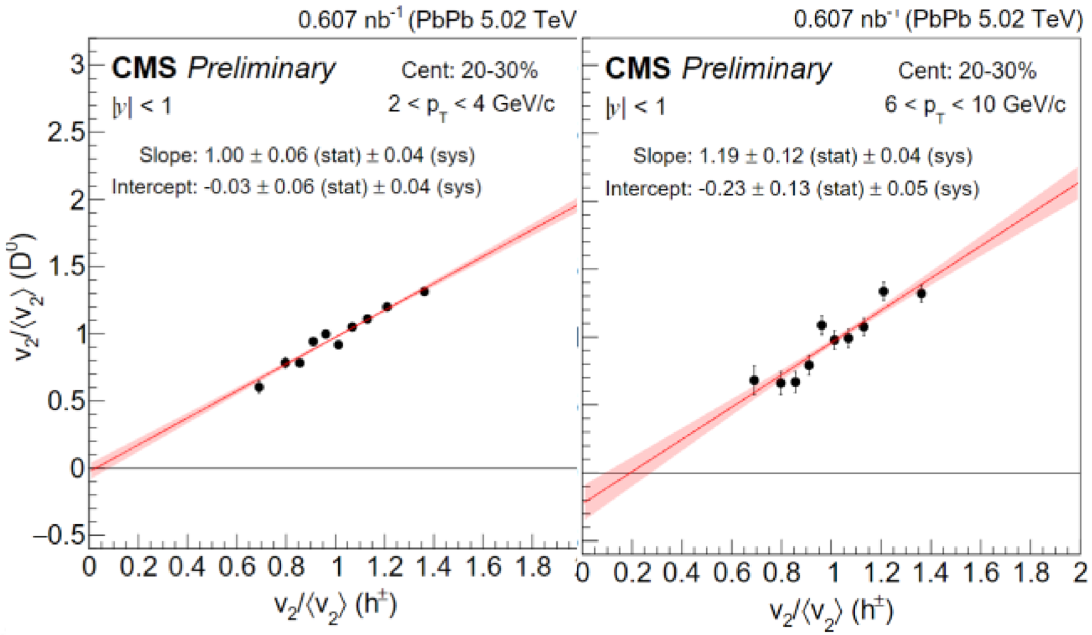


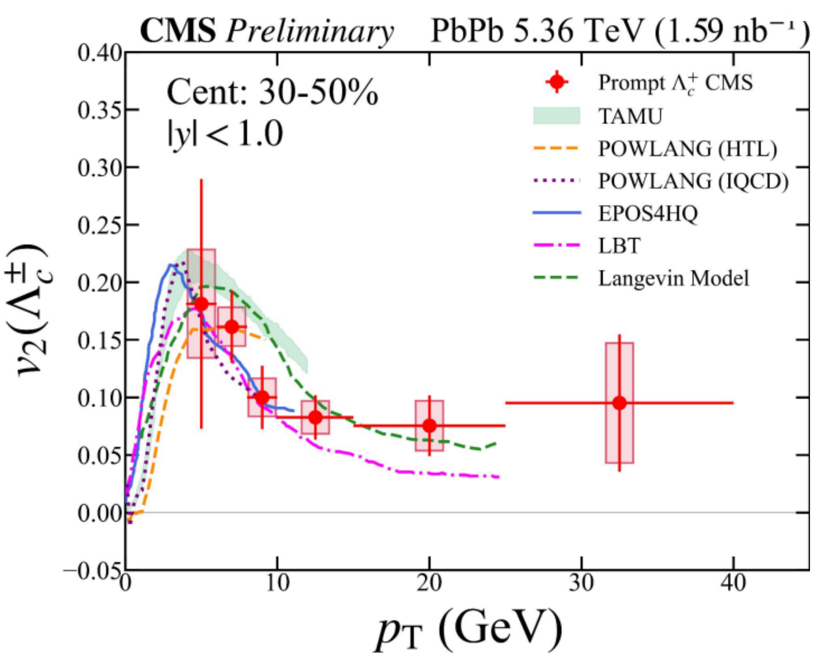
PRD 102 (2020) 034010

ground gluon fields in high-energy pPb collisions, the produced particles usually also have small correlations, which can also be interpreted as collective behavior. During the initial-state production process prior to the onset of hydrodynamical evolutions, uncorrelated active partons from the projectile proton strongly interact with the dense gluonic background fields inside the target heavy nucleus and can pick up nontrivial quantum correlations described by the so-called quadrupole correlators [61,62] in the CGC framework. In the language of Mueller's dipole model, the

New Measurements May Shed New Light



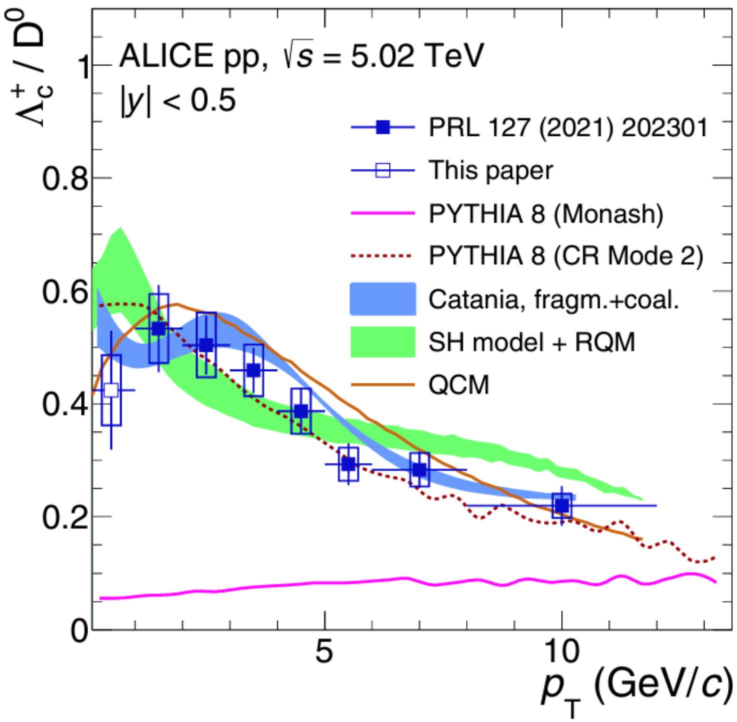


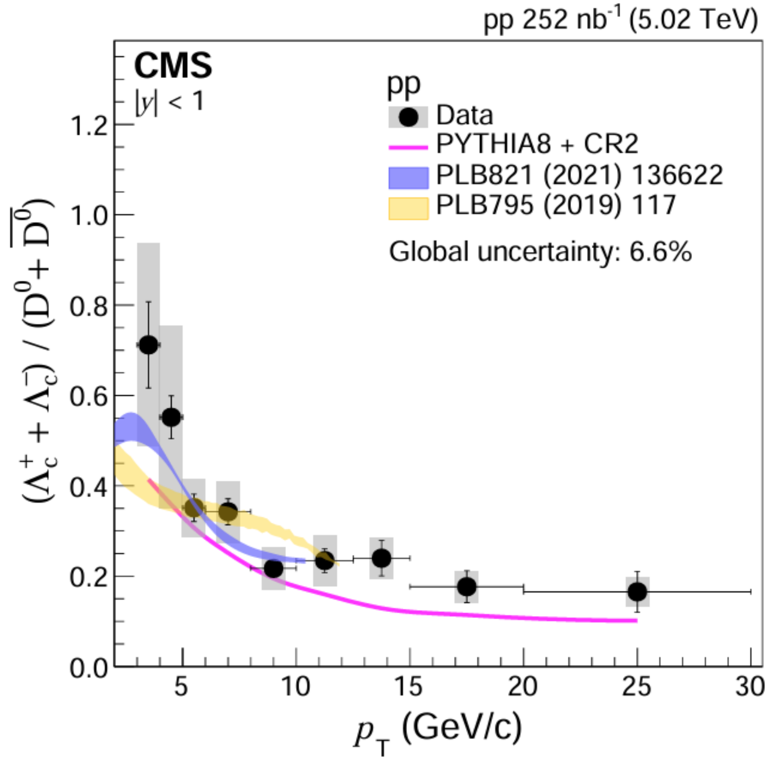


- How much role does coalescence play in various systems, incl. small systems.
- How does v_n scale with event-shape in small system?
  - Soft-hard correlation via ESE place tighter constraints on modeling.
  - e.g. what would happen if heavy quark not thermalized but light quark is.

arXiv:2603.18966
CMS PAS HIN-25-022
CMS PAS HIN-24-015

Enhanced Λ_c(udc)/D^0 ratio in small systems

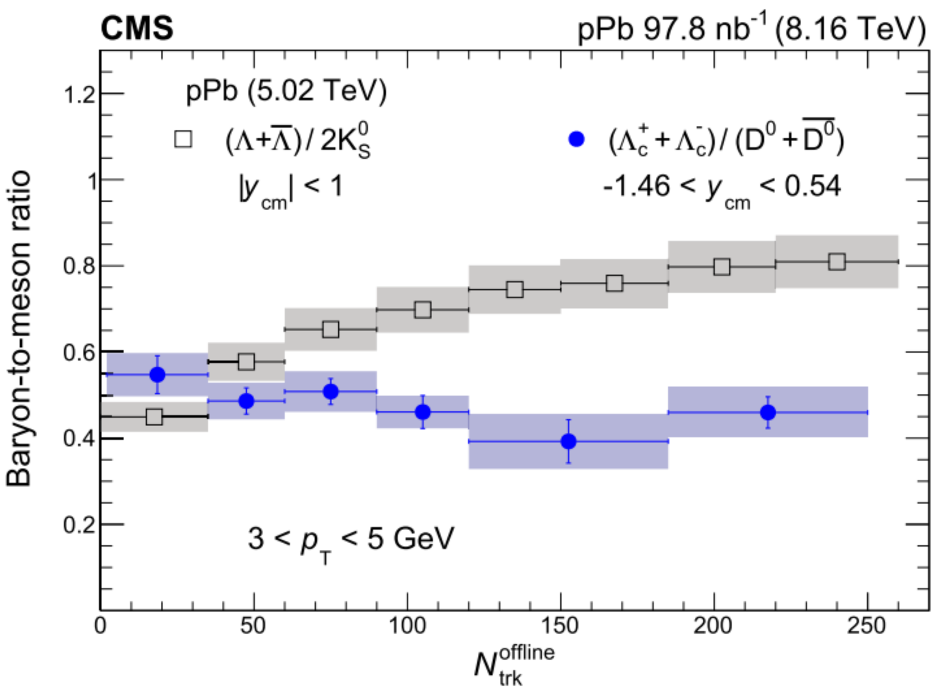


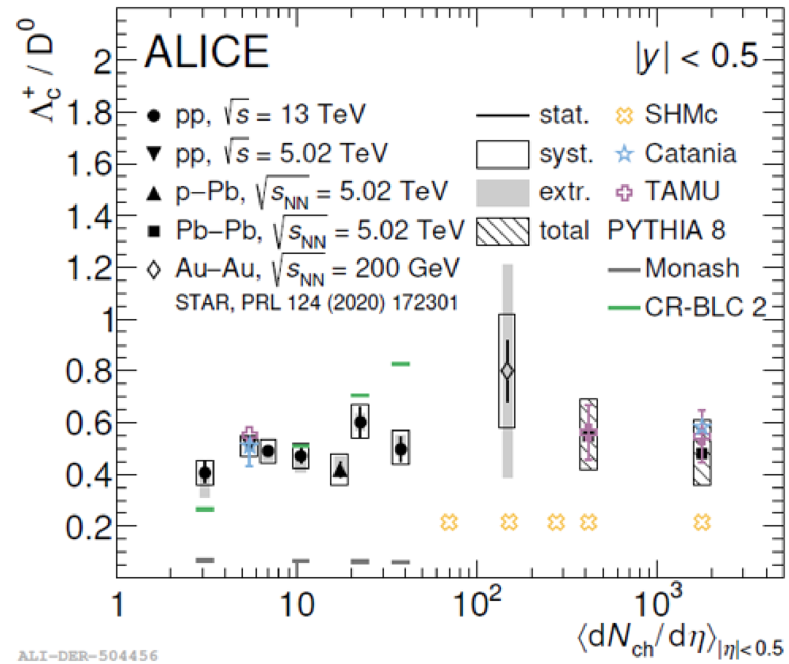


- ❑ Large enhancement at low p_T w.r.t. ee (PYTHIA Monash tune)
- ❑ PYTHIA + CR ≈ data for p_T < 10 GeV/c
  - ❖ Lower than data in higher p_T
- ❑ SHM+RQM described data incl. unlisted charm baryons in PDG.
- ❑ Catania describe the data after involving coalescence.
  - ❖ Fragmentation function chosen to reproduce the tail at p_T > 10GeV/c

JHEP 01 (2024) 128
PRC 107 (2023) 064901

System size dependence of the enhanced Λ_c(udc)/D^0 ratio

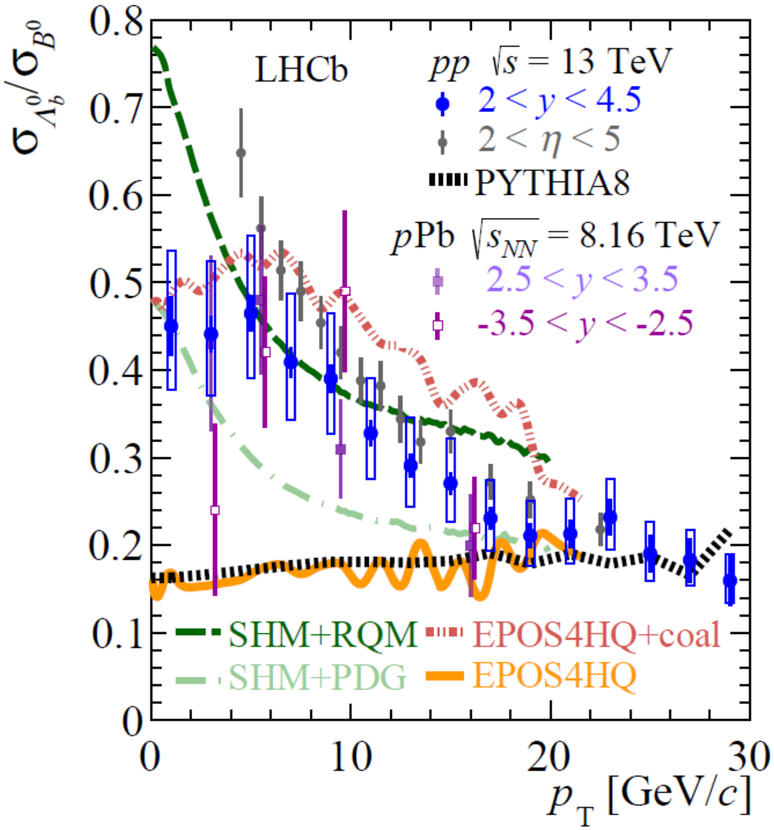


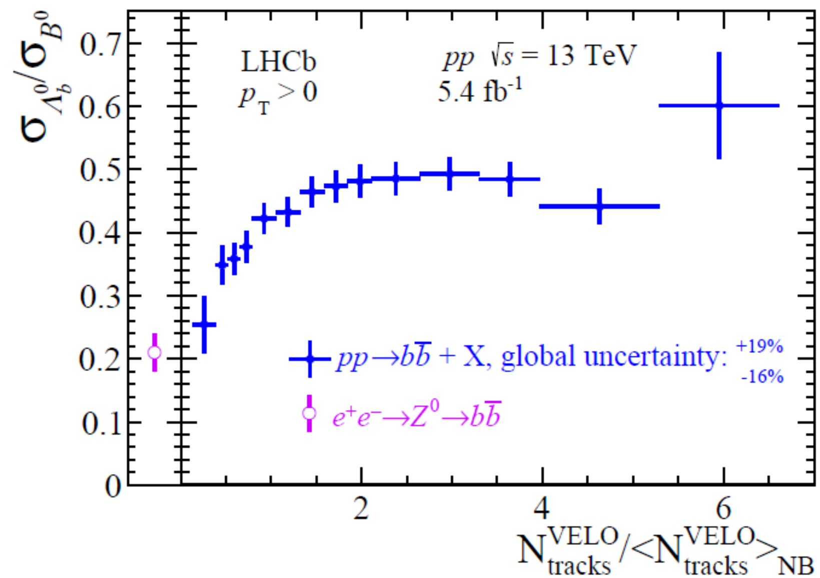


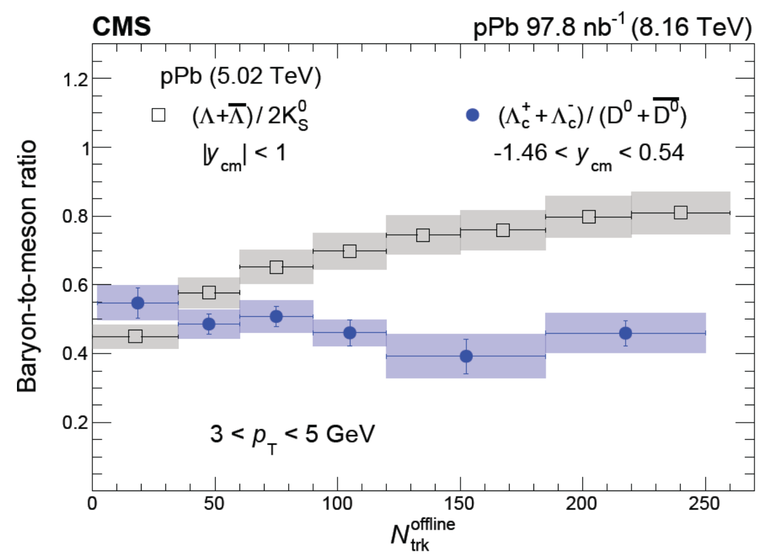
- ❑ No significant dependence on multiplicity
  - ▪ different from the strange hadrons.
- ❑ Trend differs from PYTHIA+CR

PLB 868 (2025) 139672
PLB 829 (2022) 137065
PLB 839 (2023) 137796

Enhanced Λ_B(udb)/B^0 ratio in small systems



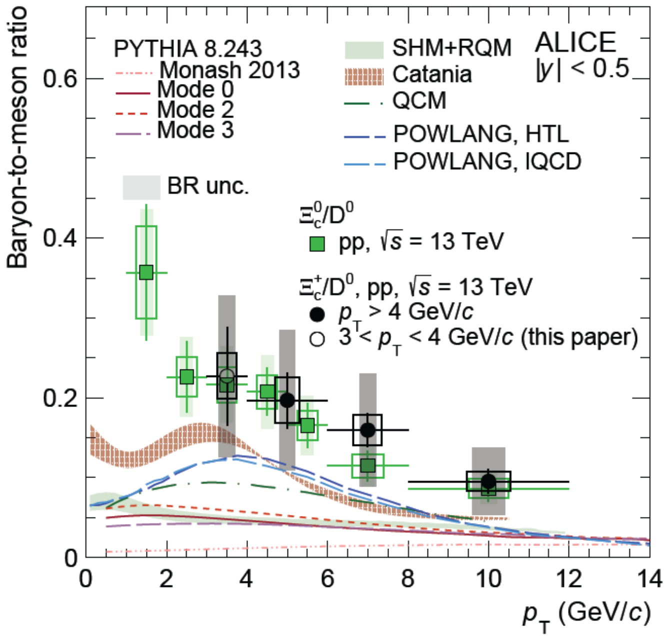


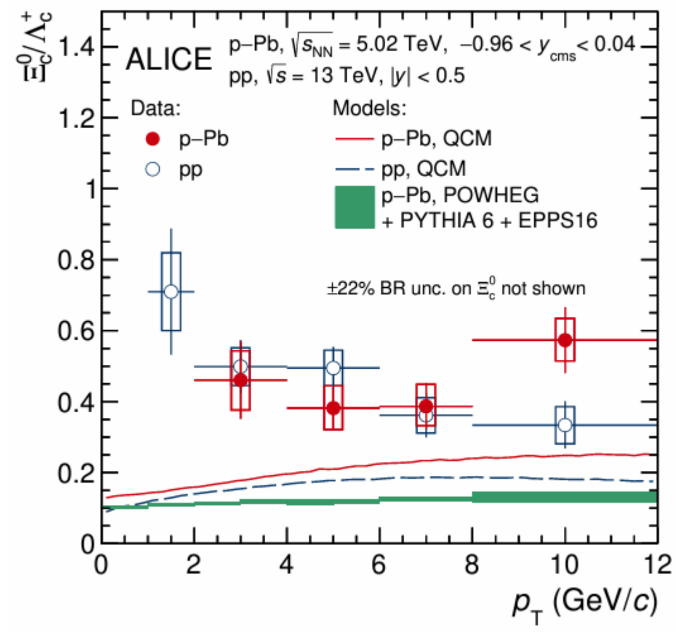


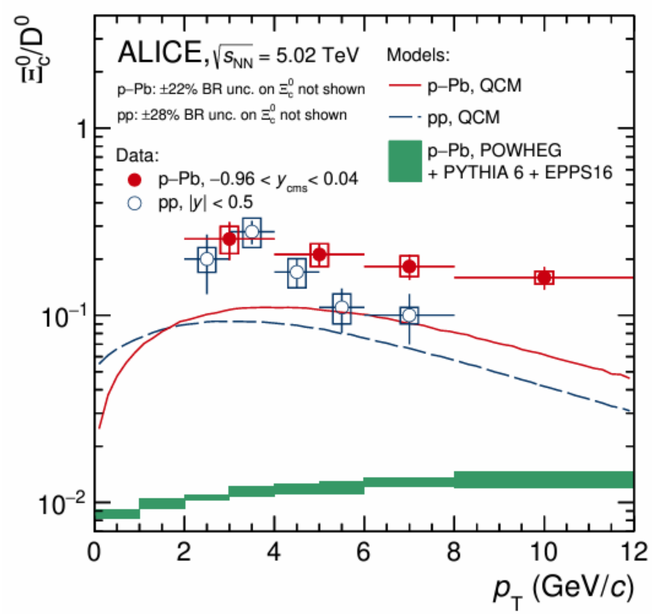
- ❑ Large enhancement in pp & pPb w.r.t. ee
- ❑ p-going ≈ Pb-doing
- ❑ SHM(RQM/PDG) ≈ data in different p_T
- ❑ EPOS4HQ+coal > data
- ❑ Λ_B/B^0 increase towards higher multiplicity
  - Differ from multiplicity dependence of Λ_c/D^0

PRL 132 (2024) 081901
PLB 868 (2025) 139672

Enhanced Ξc(u/dsc) production in small systems



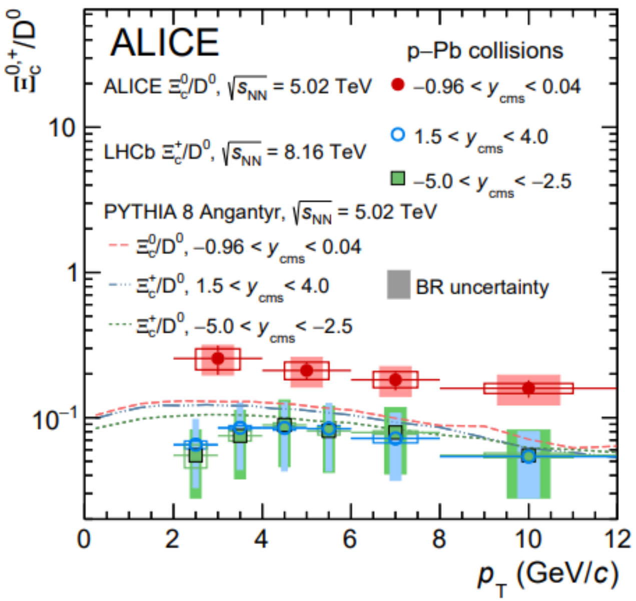


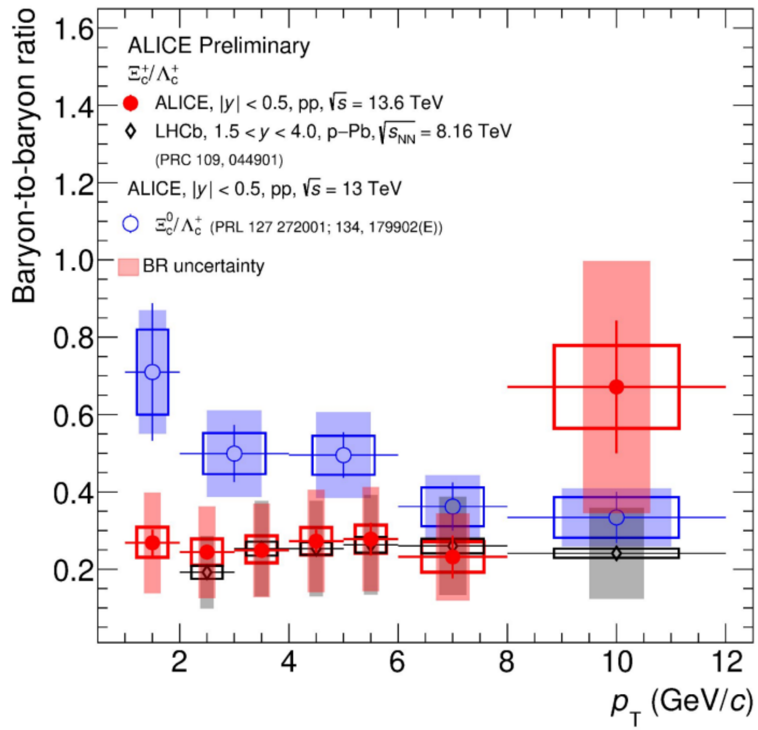


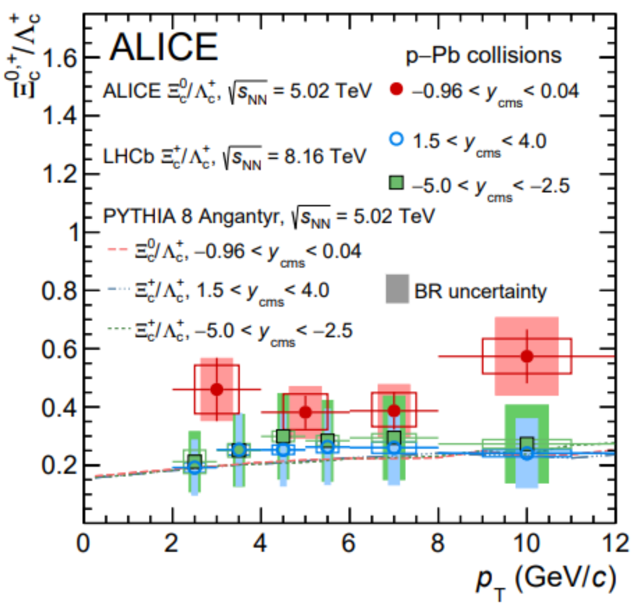
- ❑ All models underestimate the Ξc/D^0 and Ξc/Λc in pp
- ❑ QCM described Ξc R_{pPb} but underestimate the Ξc/D^0 ratio

JHEP 12 (2023) 086
EPJC 85 (2025) 86

Enhanced Ξc(u/dsc) production in small systems







- ❑ All models underestimate the Ξc/D^0 and Ξc/Λc in pp
- ❑ QCM described Ξc R_{pPb} but underestimate the Ξc/D^0 ratio
- ❑ Large rapidity dependence in data
  - Model predict little rapidity dependence
- ❑ New Run3 measurements tell a different story

JHEP 12 (2023) 086
EPJC 85 (2025) 86
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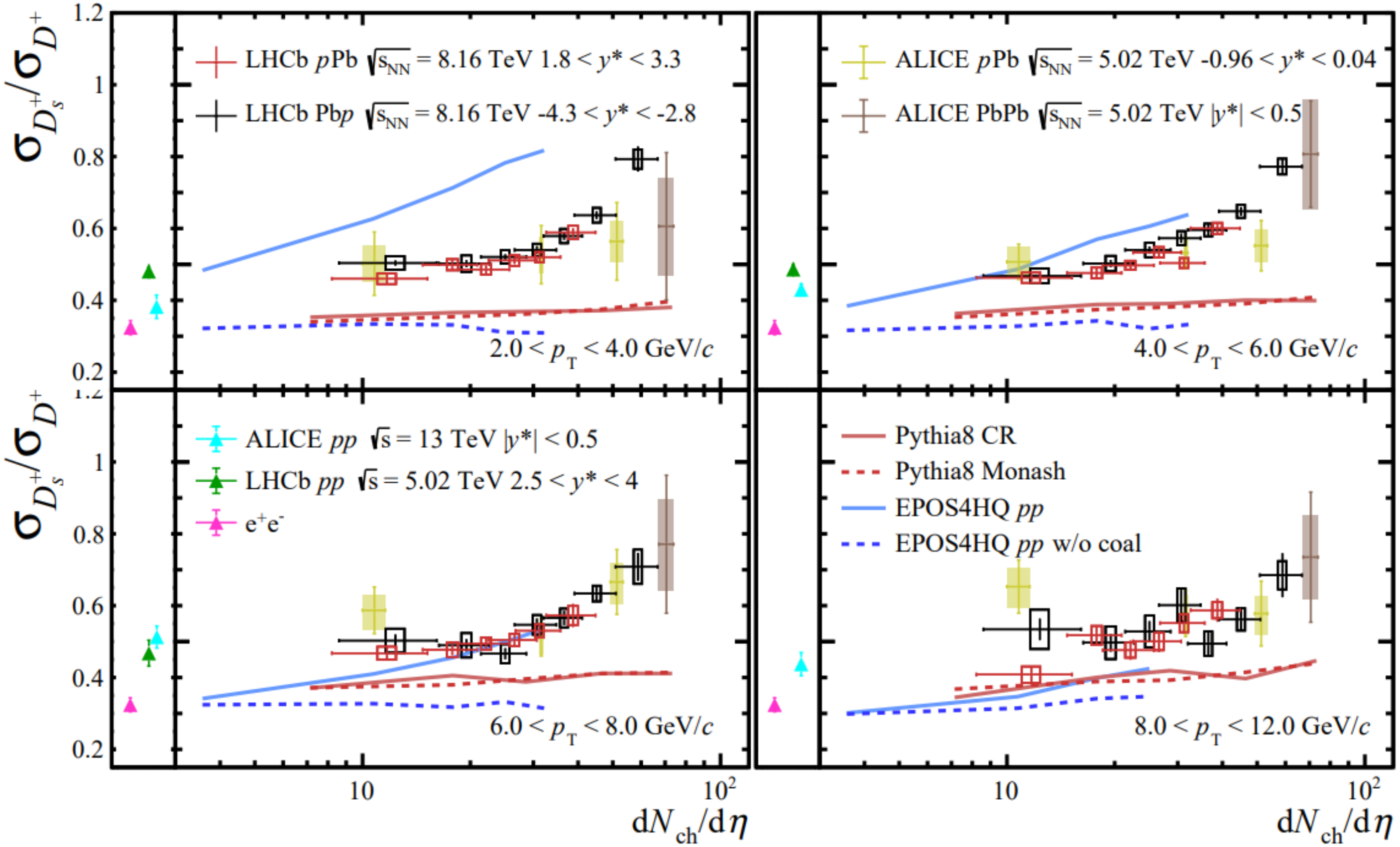
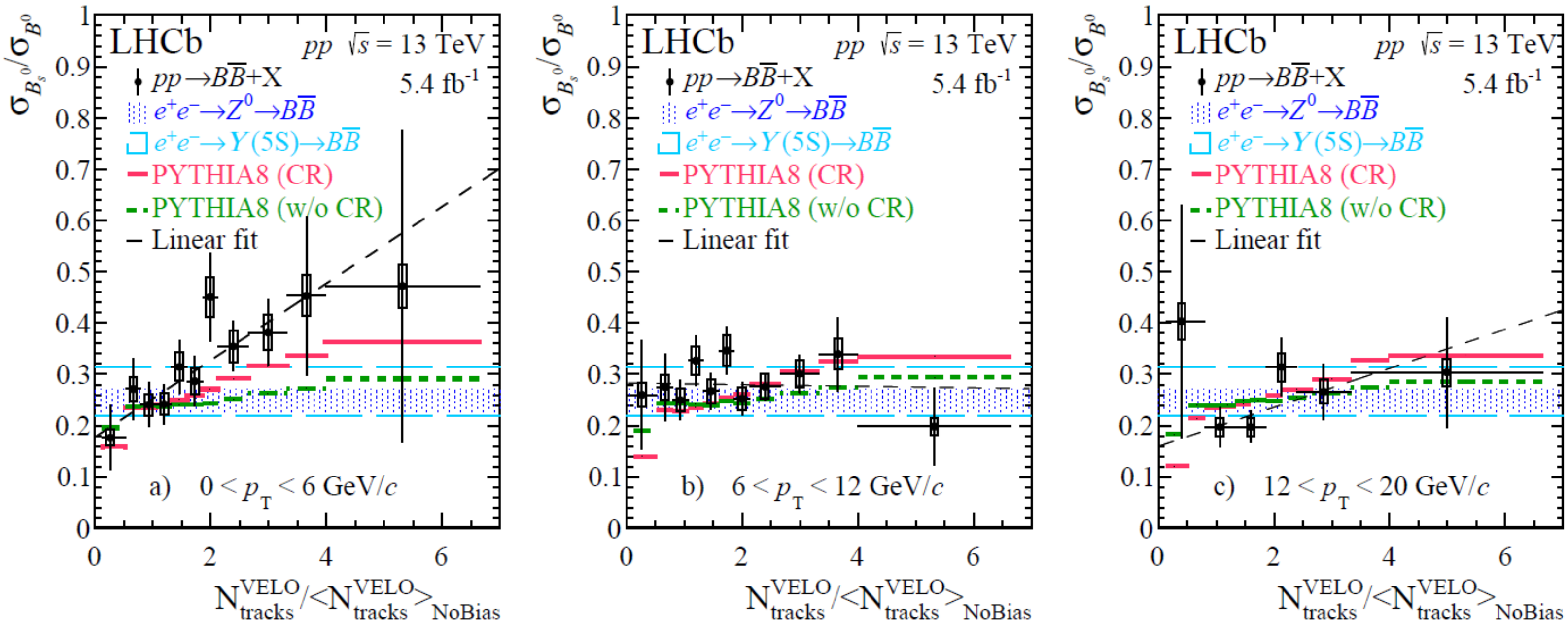
Strangeness enhancement with charm meson in small systems



- ❑ D_s/D^+ enhanced towards high multiplicity
  - In both p-going and Pb-going direction
  - Similar dependence on multiplicity for all p_T
- ❑ EPOS4HQ & PYTHIA8 w/ or w/o CR < data
- ❑ EPOS4HQ +coal: Ds/D+ vs. multiplicity differ in different p_T
  - Different trend from data

PRD 110 (2024) L031105

Strangeness enhancement with bottom meson in small systems



- ❑ B_s/B^0 increase vs. multiplicity at low p_T & systematically above PYTHIA w/ or w/o CR (large uncertainty though)
- ❑ No significant dependence on multiplicity in higher p_T & consistent with PYTHIA.
- ❑ B_s/B^0 in pp consistent with ee (large uncertainty).

PRL 131 (2023) 061901

Can we quantify QGP effects from heavy flavor hadronization?

The Baryon enhancement is still a hotspot

- ❑ PYTHIA: Color Reconnection
- ❑ SHM+RQM: feed down from charm baryon states unlisted in PDG.
- ❑ Catana: include coalescence to describe the data
- ❑ POWLANG: include coalescence and diquark excitations.
- ❑ EPOS4HQ: w/ and w/o coalescence
- ❑ ……

All require interactions beyond the baseline string fragmentations, but no model can describe all data

Summary & comments

- For both charm and bottom hadron in small systems, data shows:
  - Significant enhancement or suppression in production
  - Significant elliptic flow
  - Significant enhancement of baryons production w.r.t. ee
  - Significant enhancement of charm, bottom mesons with strangeness
- All models requires physics processes beyond baseline string fragmentation.
  - Some don’t involve thermalized QGP droplet but qualitatively describe the data.
- More precise and more differential measurements needed to gain further insight
  - For both small and large systems