

Heavy Flavor Measurements at LHC

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Motivation

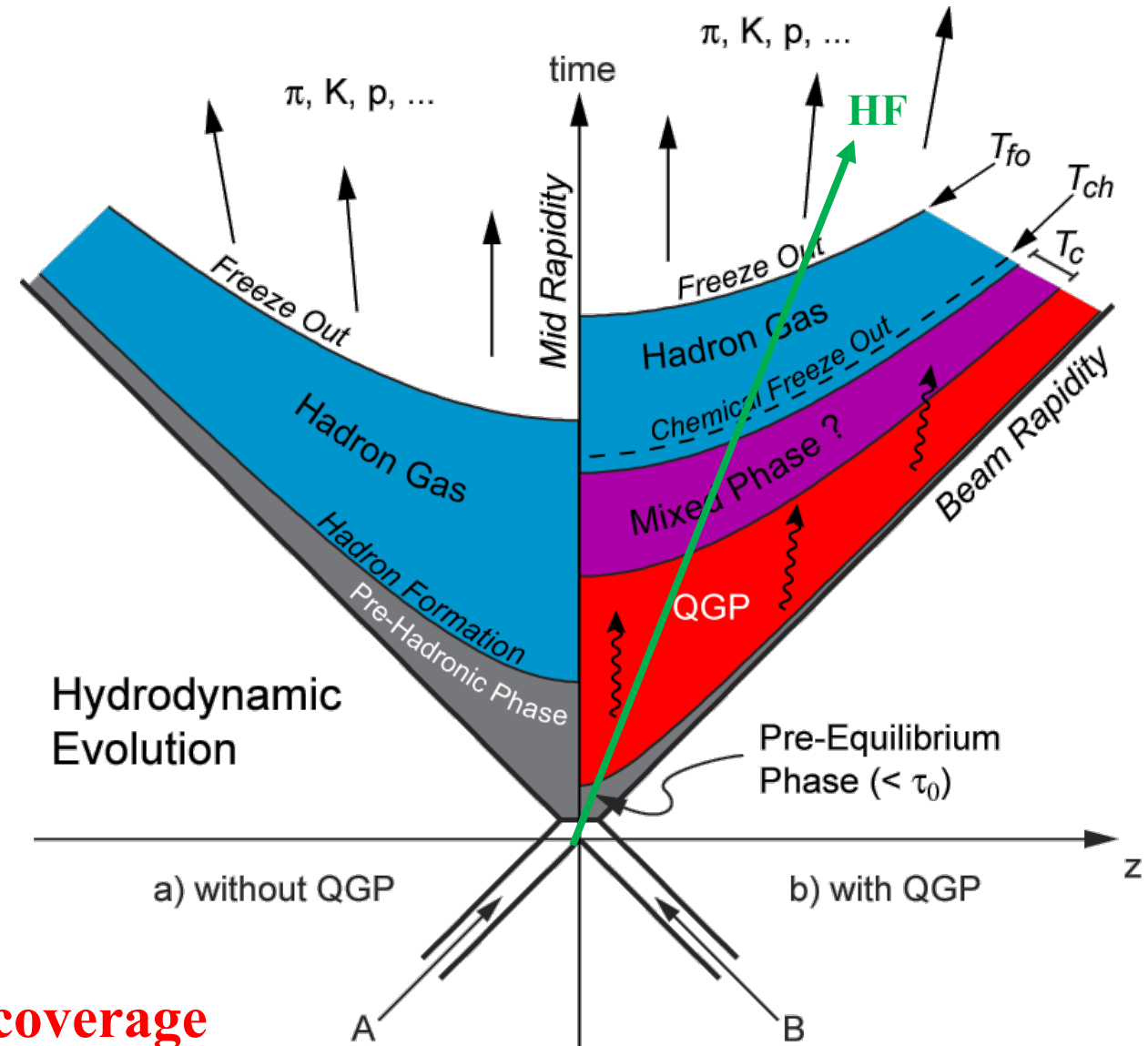
Open HF

Quarkonia

Other New Studies

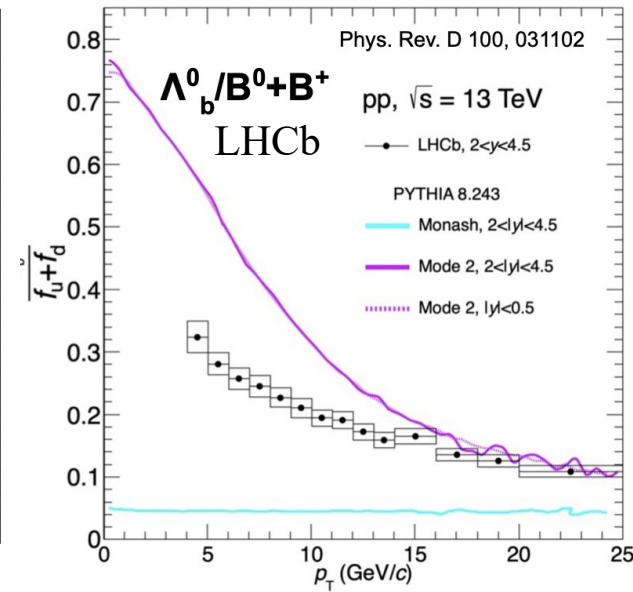
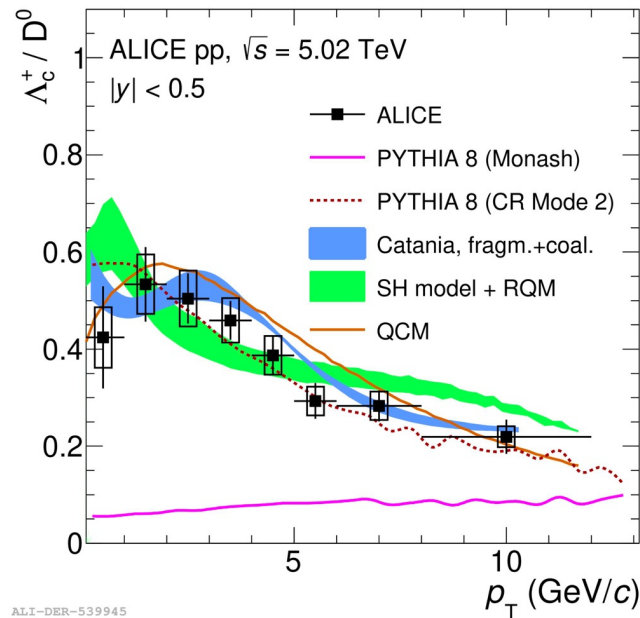
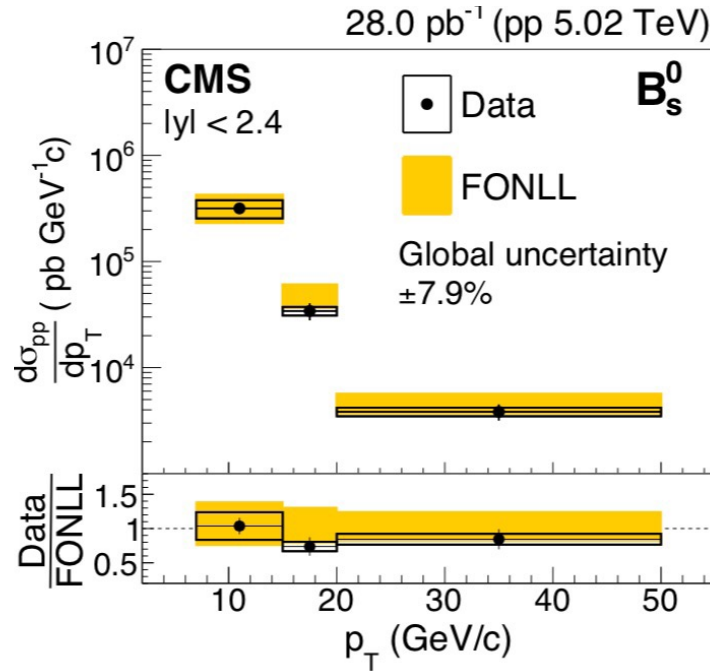
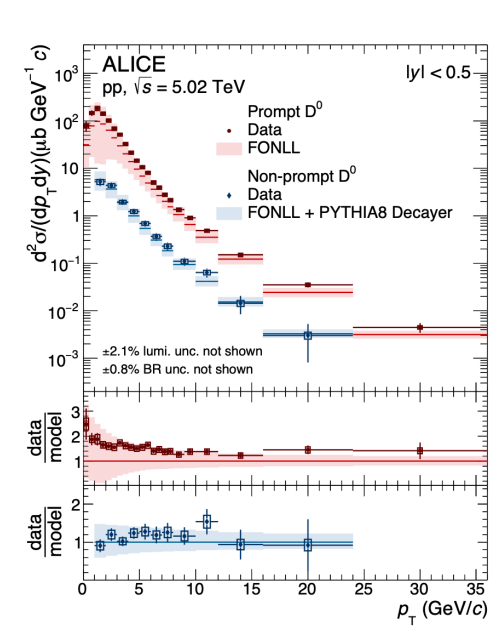
Motivation

- **Strong interaction**
 - HQ production in hard scatterings
 - Parton energy loss in the medium
 - HQ hadronization
- **Properties of QCD matter**
 - **Initial state**
 - CGC at low-x
 - Nuclear PDFs
 - **Final state**
 - Quark Gluon Plasma
 - Small systems
 - Exotic particles



Experimental measurement precision and coverage

Open HF Production in pp Collisions

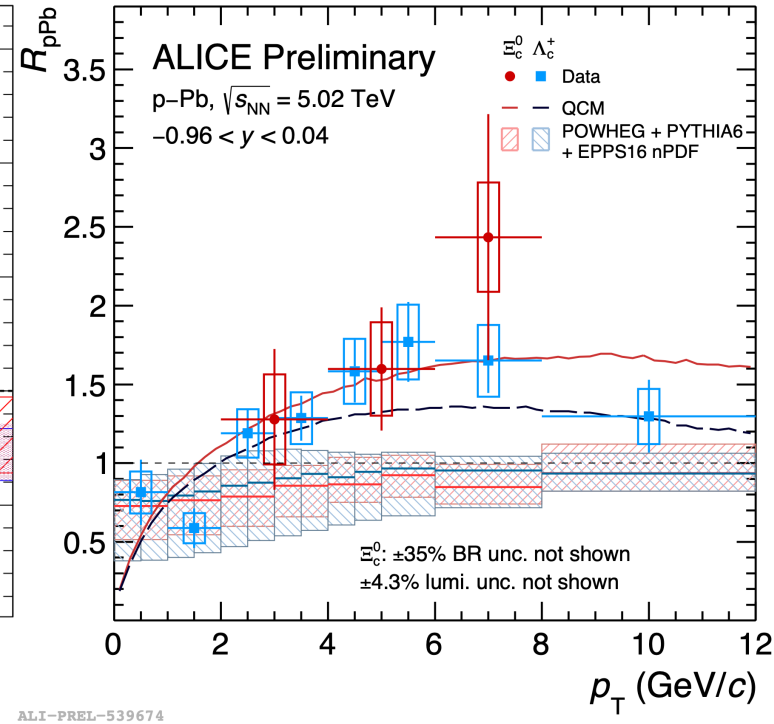
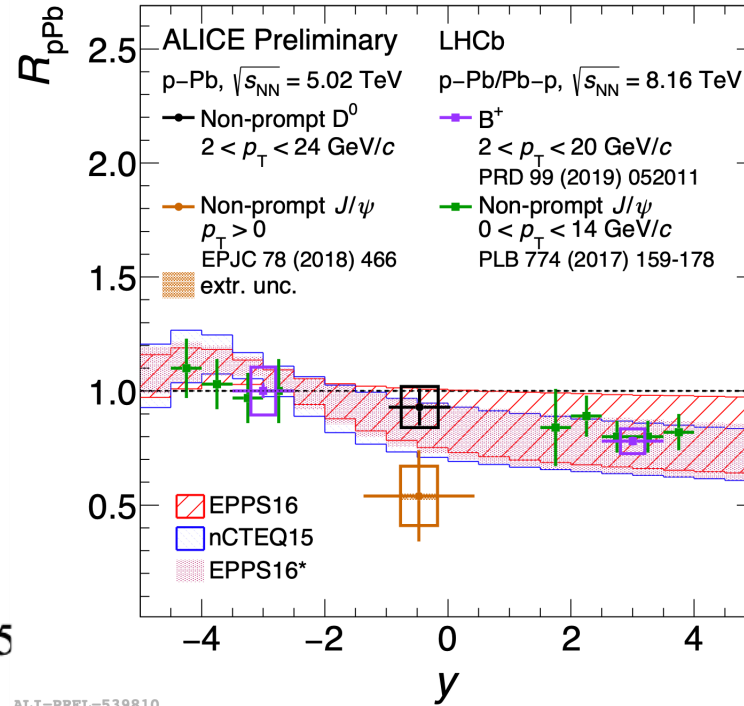
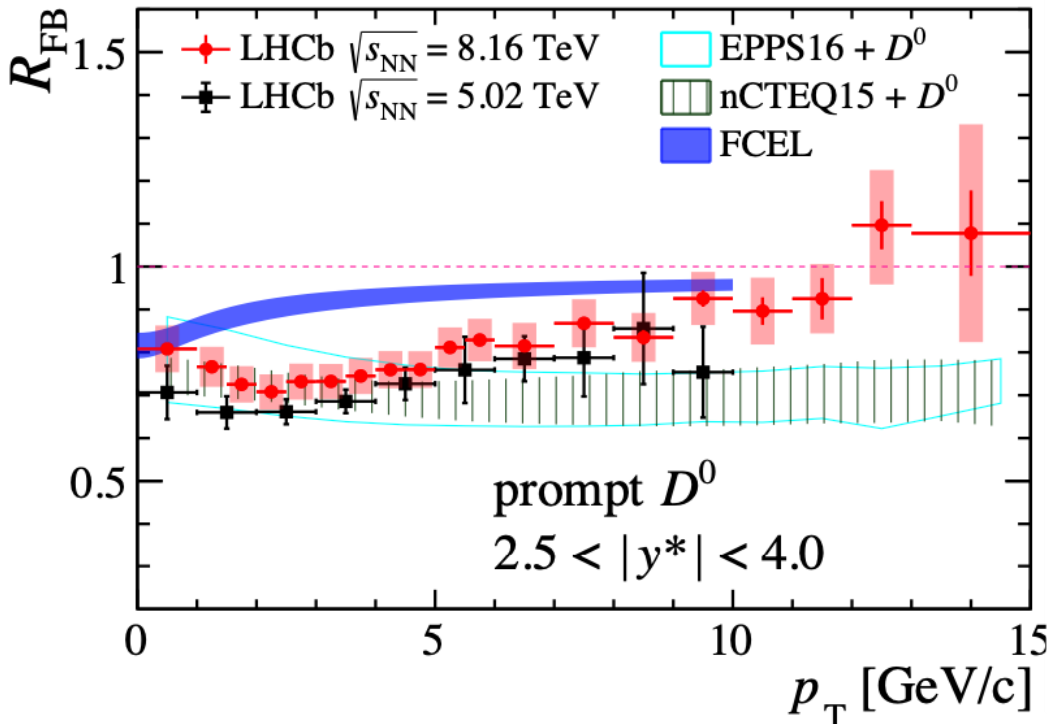


$$d\sigma^{H+X} \simeq \sum_{i,j,k} \int_0^1 dx_i \int_0^1 dx_j \int_0^1 dz f_i^A(x_i, \mu_F) f_j^B(x_j, \mu_F) d\hat{\sigma}_{ij \rightarrow k+X}[p_T, m_Q] D_k^H(z, \mu'_F)$$

• Do we understand the pp “reference”?

- pQCD based on factorization theorem with **PDFs** and **FFs** from ee/ep collisions describe HQ meson but not baryon production in pp collisions: **fragmentation is not universal**. The latter is better described by PYTHIA with **color reconnection (beyond leading color approximation)** or **coalescence hadronization models**.
- Improvement to measurement precision and extension to low p_T for bottom hadrons are needed.

Modification to Open HF Production in pA Collisions

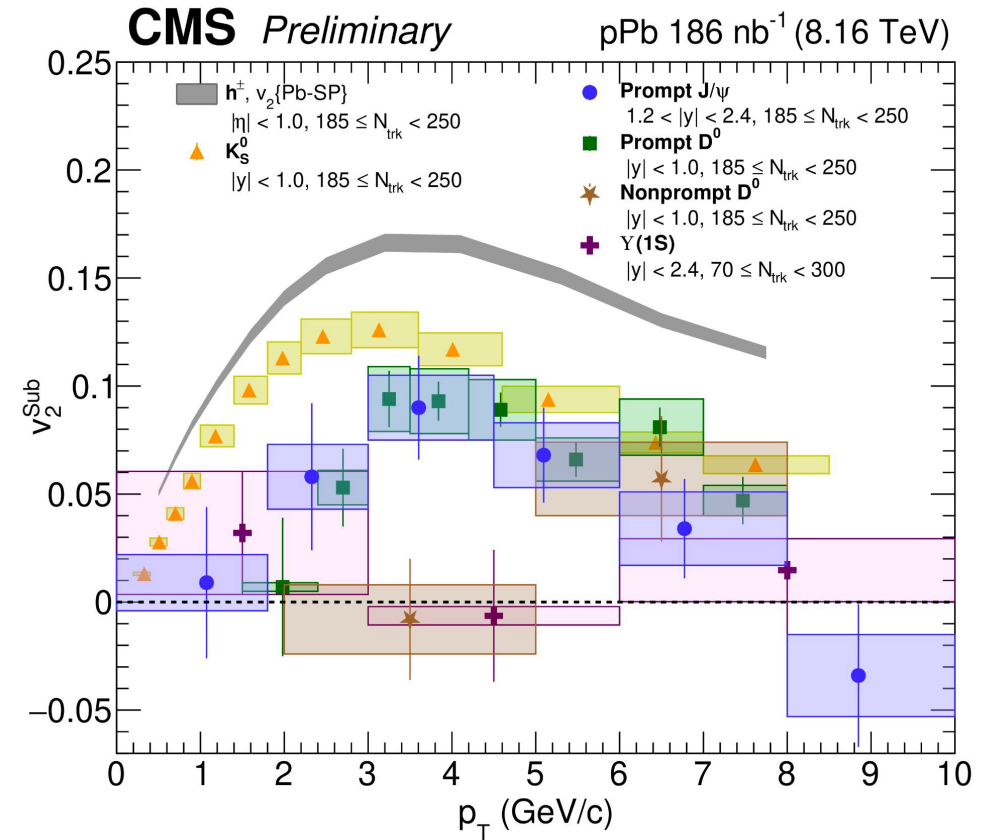
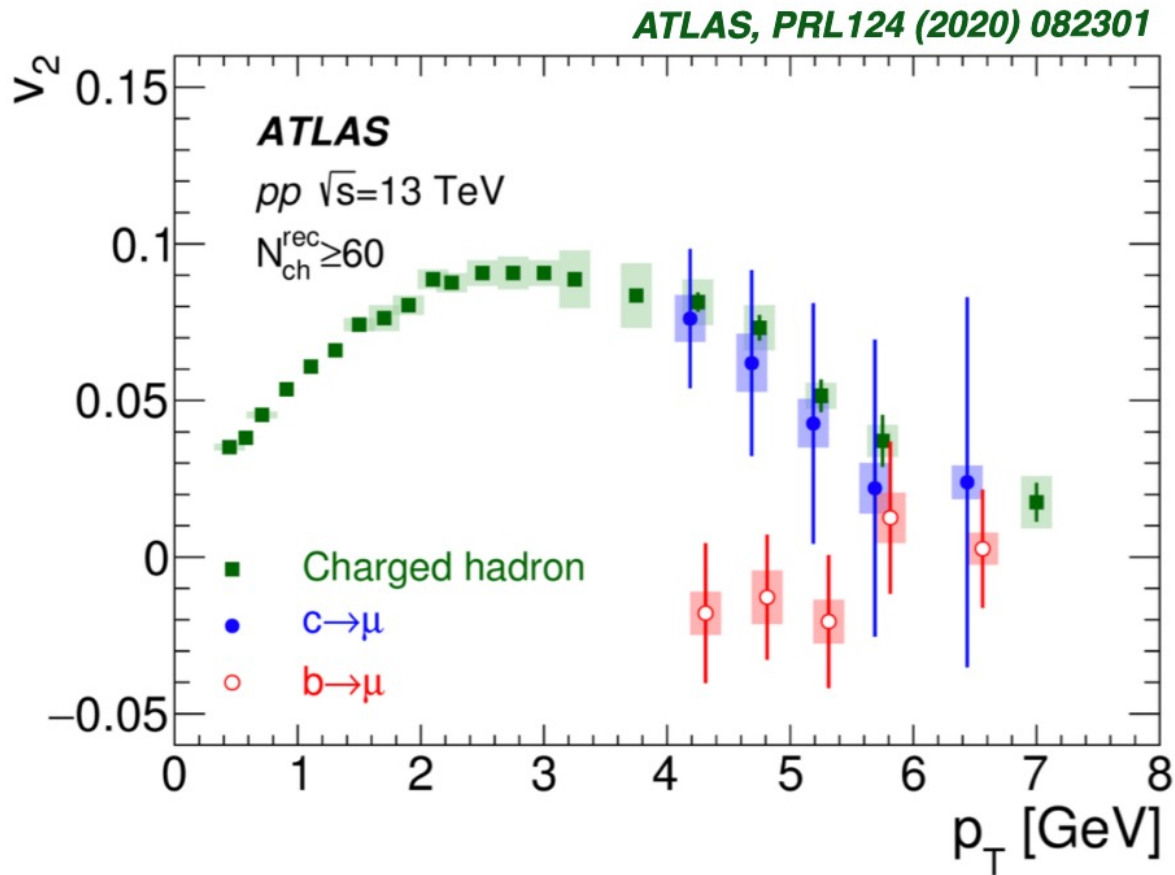


$$d\sigma^{H+X} \simeq \sum_{i,j,k} \int_0^1 dx_i \int_0^1 dx_j \int_0^1 dz \left[f_i^A(x_i, \mu_F) f_j^B(x_j, \mu_F) \right] d\hat{\sigma}_{ij \rightarrow k+X}[p_T, m_Q] \left[D_k^H(z, \mu'_F) \right]$$

- **“Cold nuclear matter effects” are important for interpreting data in HI collisions**

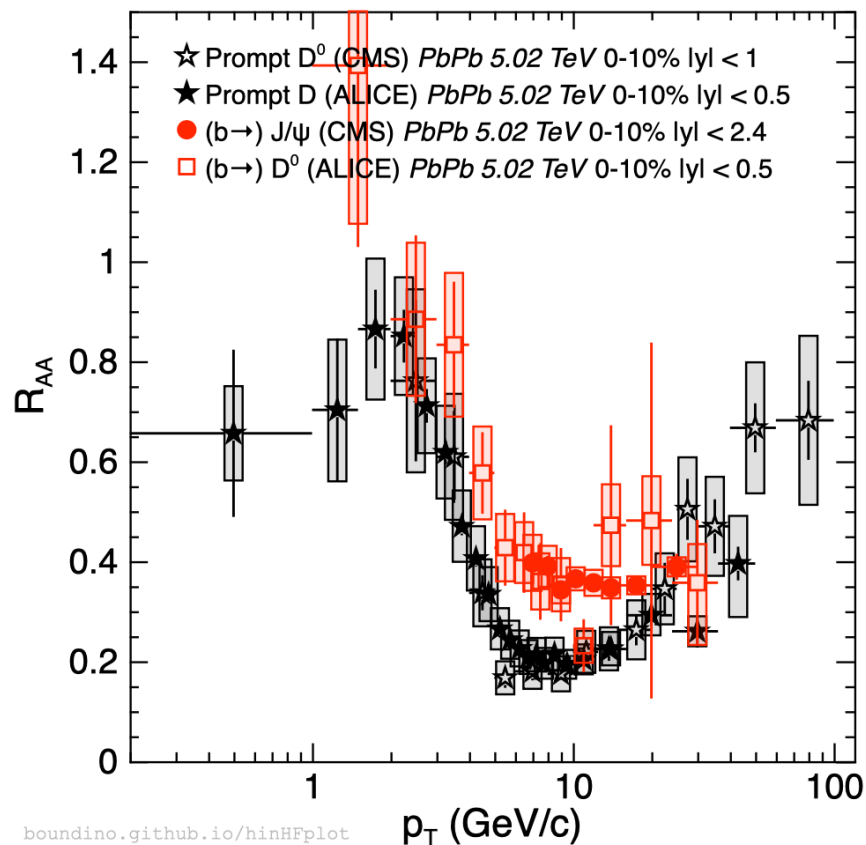
- pQCD calculations with nPDFs and FFs can describe modification to HQ mesons but not baryons in pA collisions. The latter can be described by **coalescence hadronization models**.
- Improvement to measurement precision of charm baryons and extension to bottom baryons are needed.

Collectivity in High-multiplicity pp and pA Collisions

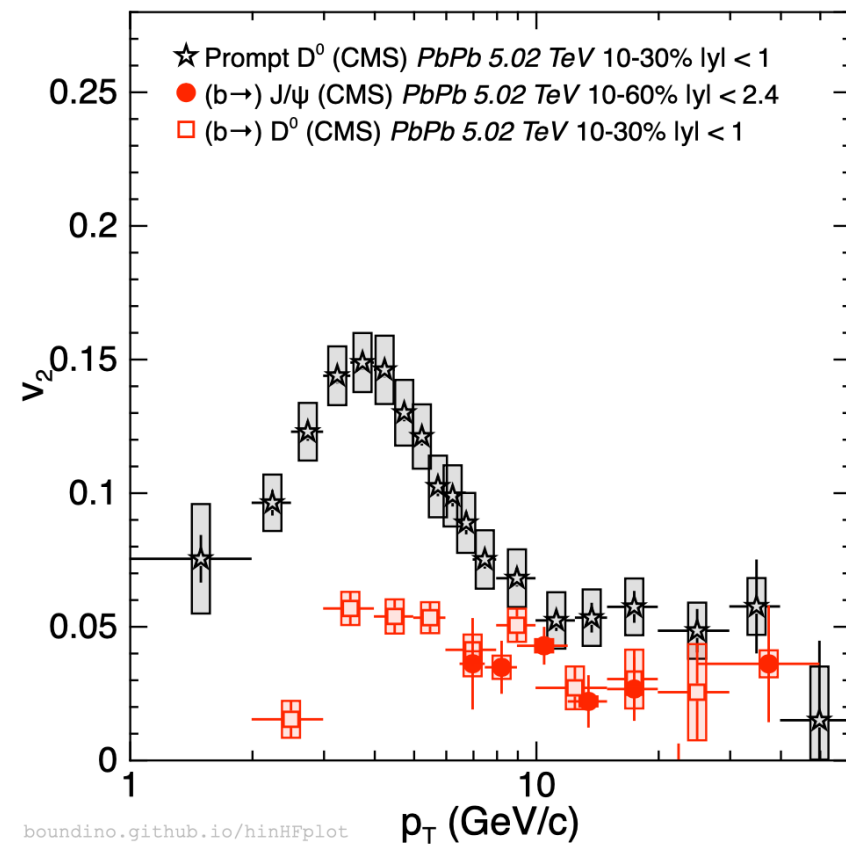


- **Is non-zero v_2 observed for charged hadrons in small systems due to initial or final state effects?**
 - Non-zero v_2 observed for charm but not bottom in high mult. pp and pA. So more likely **final state effect?**
 - Improvement to measurement precision for bottom hadrons and extension to baryons are needed.

Open HF in AA Collisions



ALICE, JHEP 01 (2022) 174
 CMS, PLB 782 (2018) 474
 ALICE, JHEP 12 (2022) 126
 CMS, EPJC 78 (2018) 509

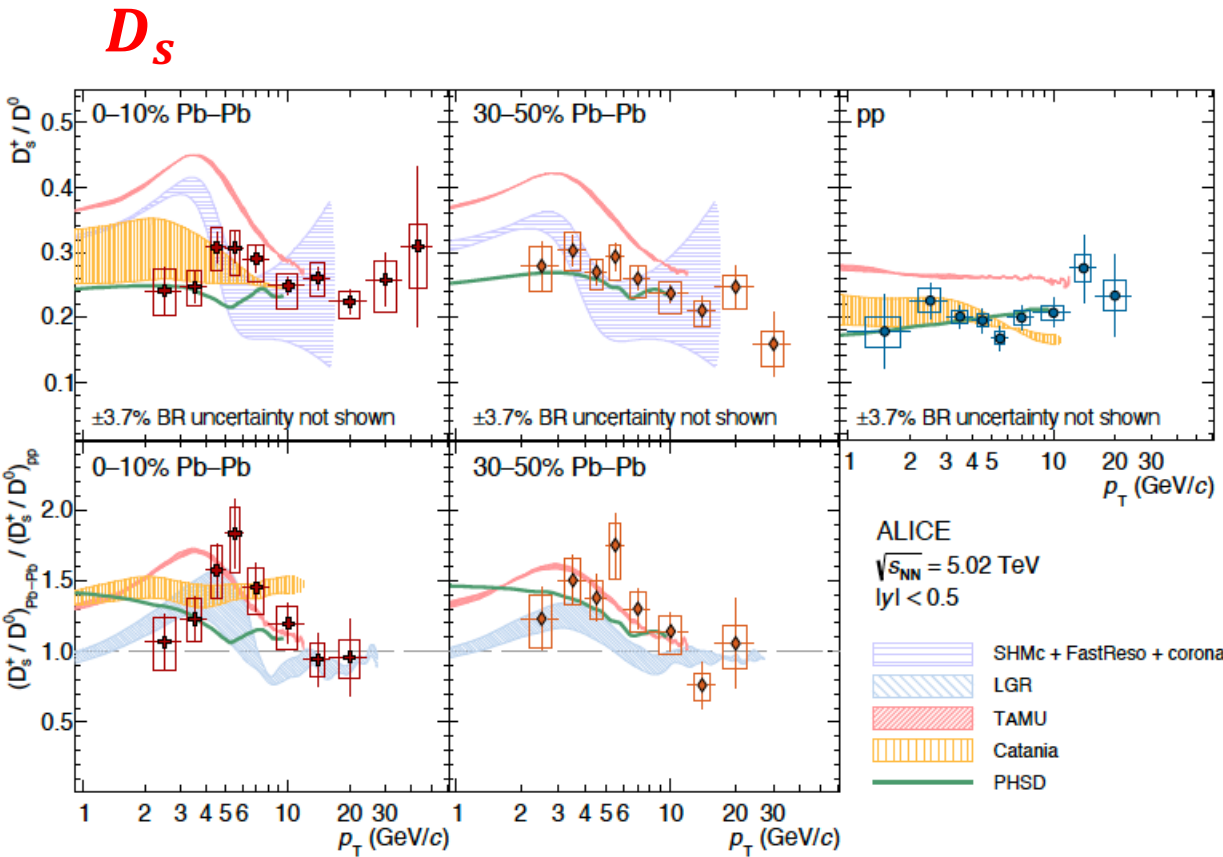


CMS, PLB 816 (2021) 136253
 CMS, CMS-PAS-HIN-21-008
 CMS, arXiv:2212.01636

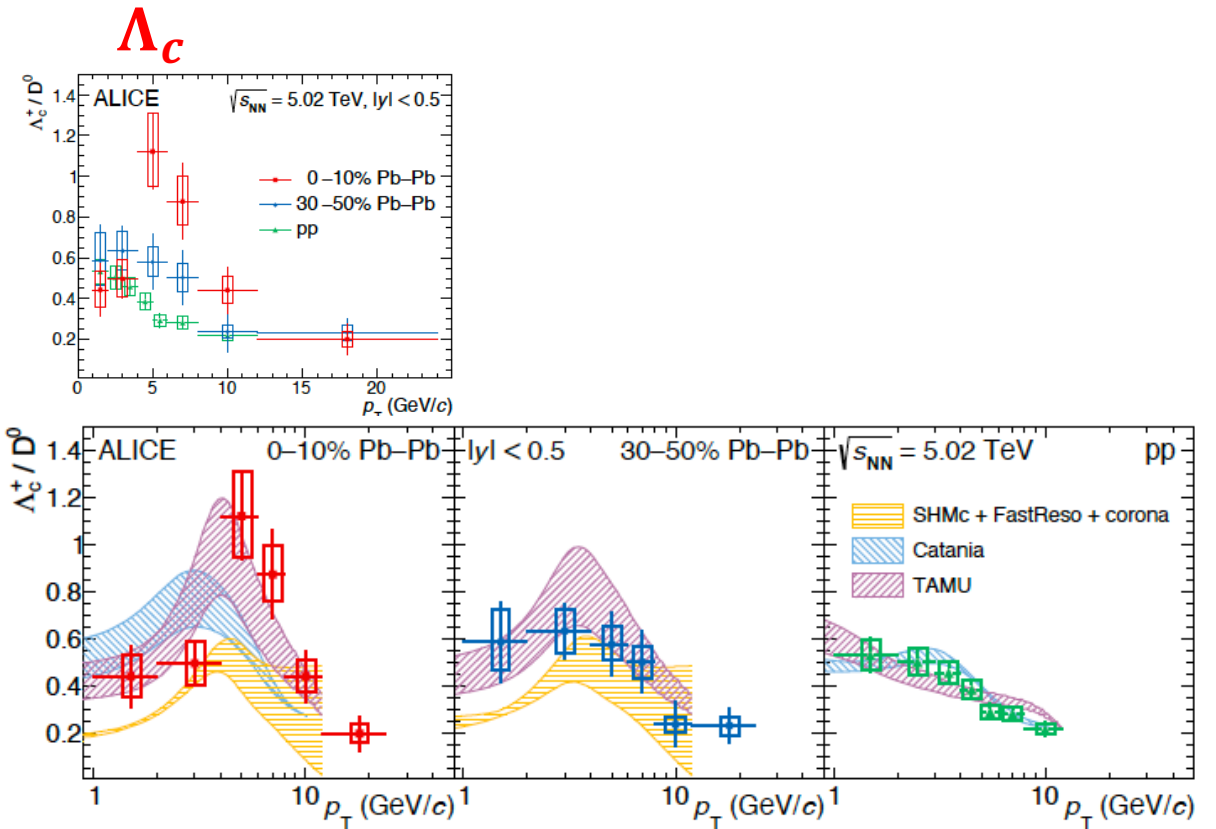
• How partons interact with QGP (elastic versus radiative)? What are the properties of QGP?

- Less suppression for non-prompt J/psi and D than prompt D, consistent with **mass hierarchy $\Delta E_b < \Delta E_c$**
- Less flow for non-prompt J/ψ & D than prompt D suggesting **not thermalized b-quark in contrary to charm**
- Improvement to low p_T measurement and extension to baryons and fully reconstructed B hadrons are needed

HQ Hadronization in AA Collisions



ALICE, Phys. Lett. B 827 (2022) 136986



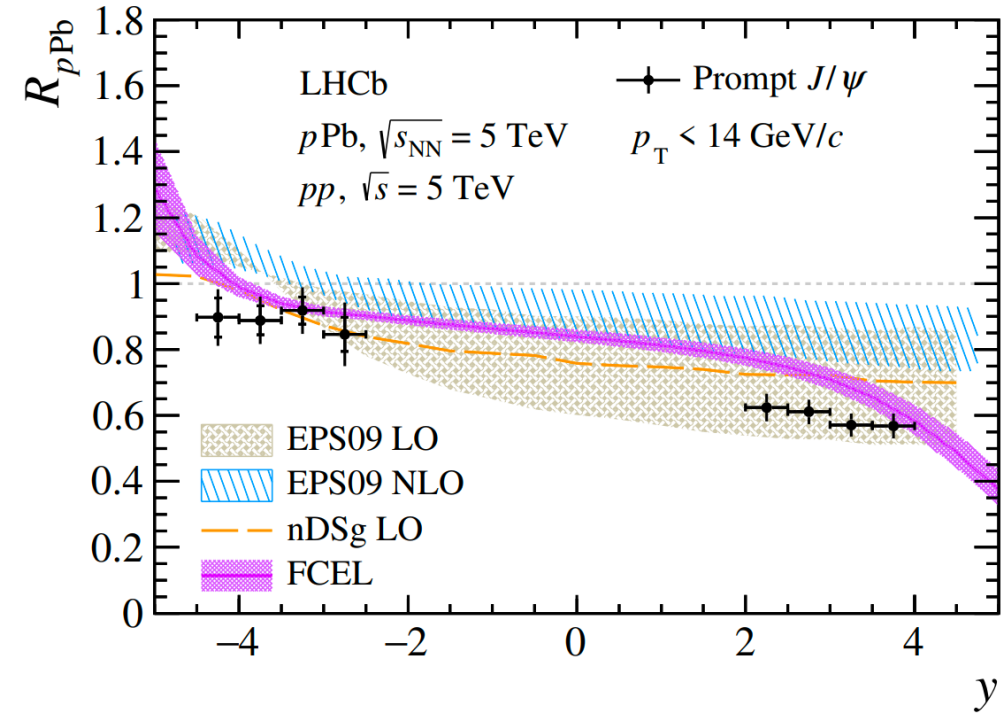
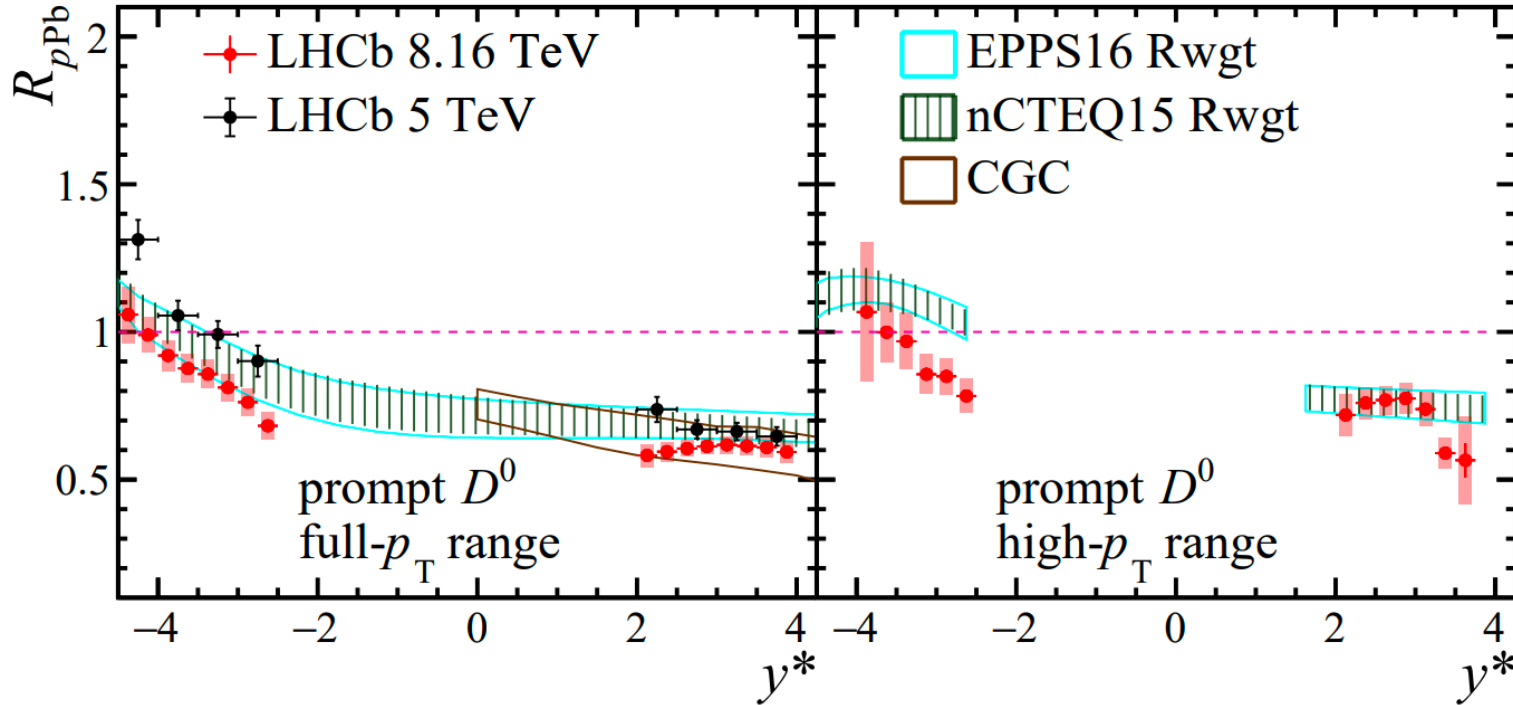
ALICE, PLB (2023) arXiv:2112.08156

• How hadronization gets affected by QGP medium?

- Indication of strangeness enhancement in the charm (and bottom) sector
- Enhancement of baryon-to-meson ratio observed
- Improvement to measurement precision and extension to B baryons is needed

} coalescence hadronization

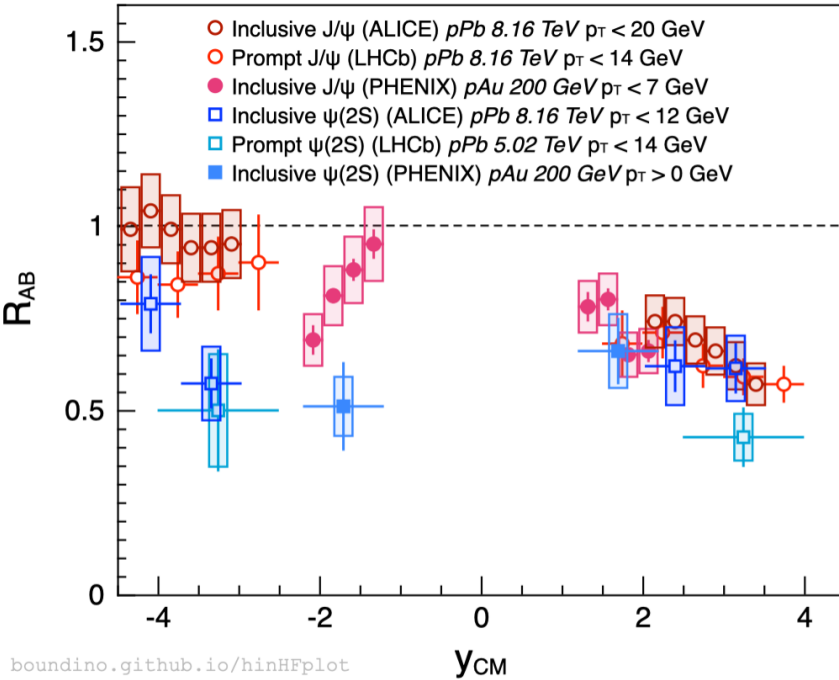
Quarkonium Production in pp and pA Collisions



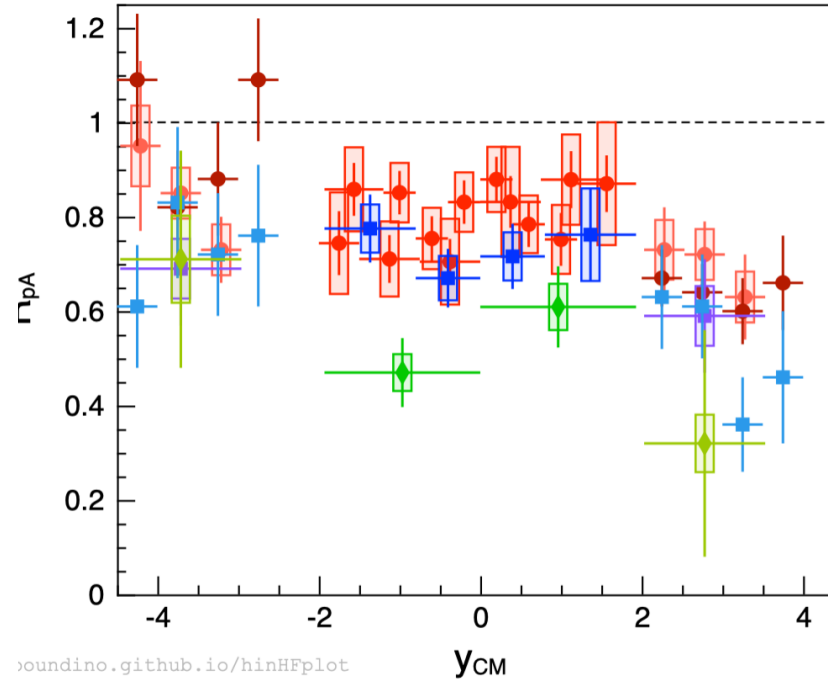
- **Do we understand our reference? How about “CNM” effects?**
 - (NOT SHOWN) pQCD based on factorization theorem with **PDFs** and **phenomelological hadronization models (CEM/NRQCD etc)** can not simultaneously describe spectra and polarization in pp collisions
 - R_{pA} similar between prompt D^0 and J/ψ , little room for additional final state effect on J/ψ

Quarkonium Production in pp and pA Collisions

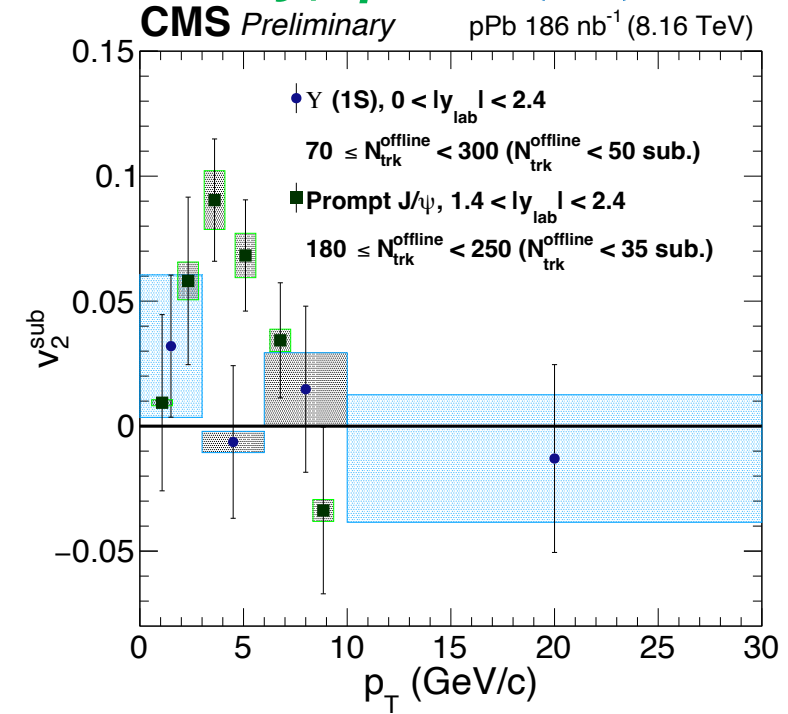
J/ψ vs $\psi(2S)$



$\Upsilon(1S)$ vs $\Upsilon(2S)$ vs $\Upsilon(3S)$



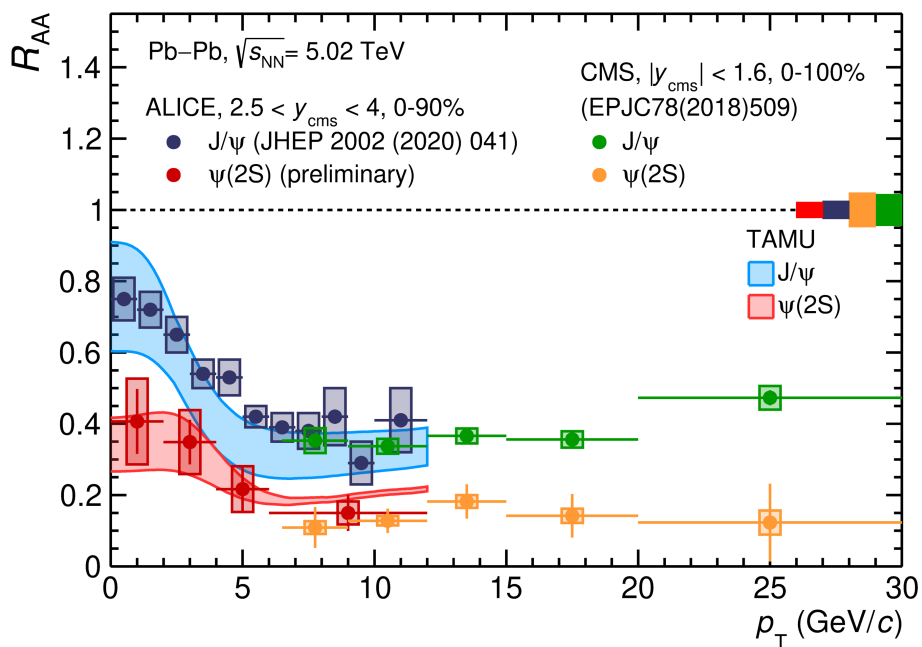
J/ψ vs $\Upsilon(1S)$



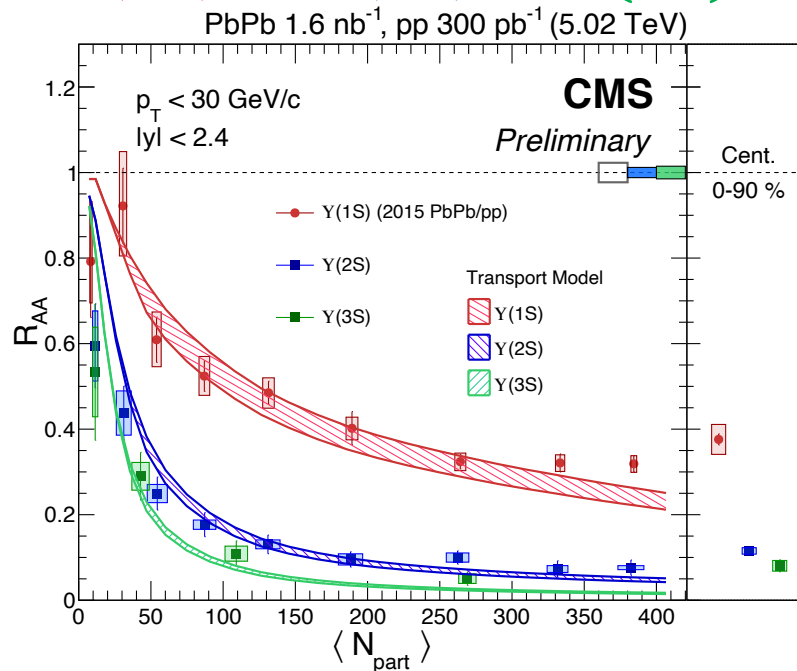
- **Do we understand our reference? How about “CNM” effects?**
 - (NOT SHOWN) pQCD based on factorization theorem with **PDFs** and **phenomenological hadronization models (CEM/NRQCD etc)** can not simultaneously describe spectra and polarization in pp collisions
 - **Indication of final state effects coming into play for excited states**
 - Significant v_2 for charmonia but v_2 consistent with zero for bottomonia -> **similar to open HF (p5)**
 - Improvement to R_{pA} measurement for excited states and v_2 in pA (and high mult. pp) collisions is needed.

Quarkonium Production in AA Collisions

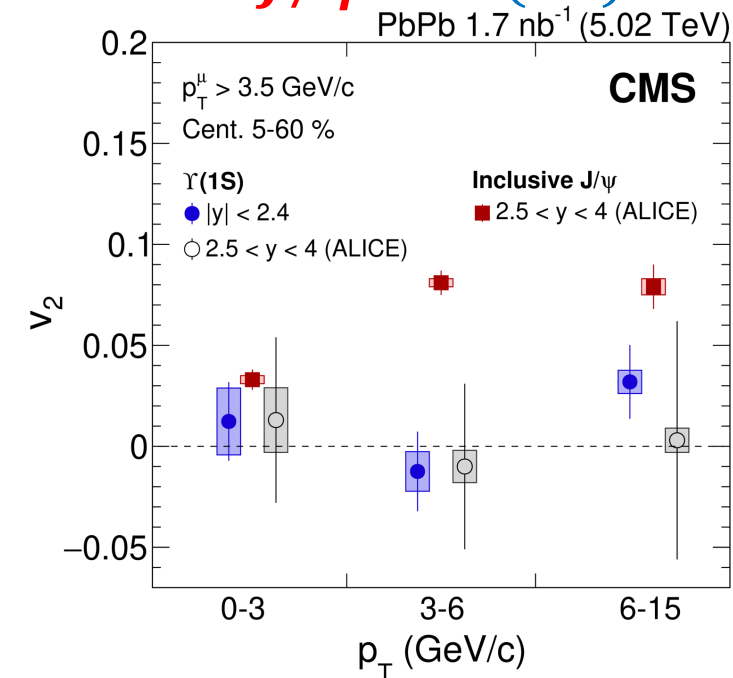
J/ψ vs $\psi(2S)$



$\Upsilon(1S)$ vs $\Upsilon(2S)$ vs $\Upsilon(3S)$



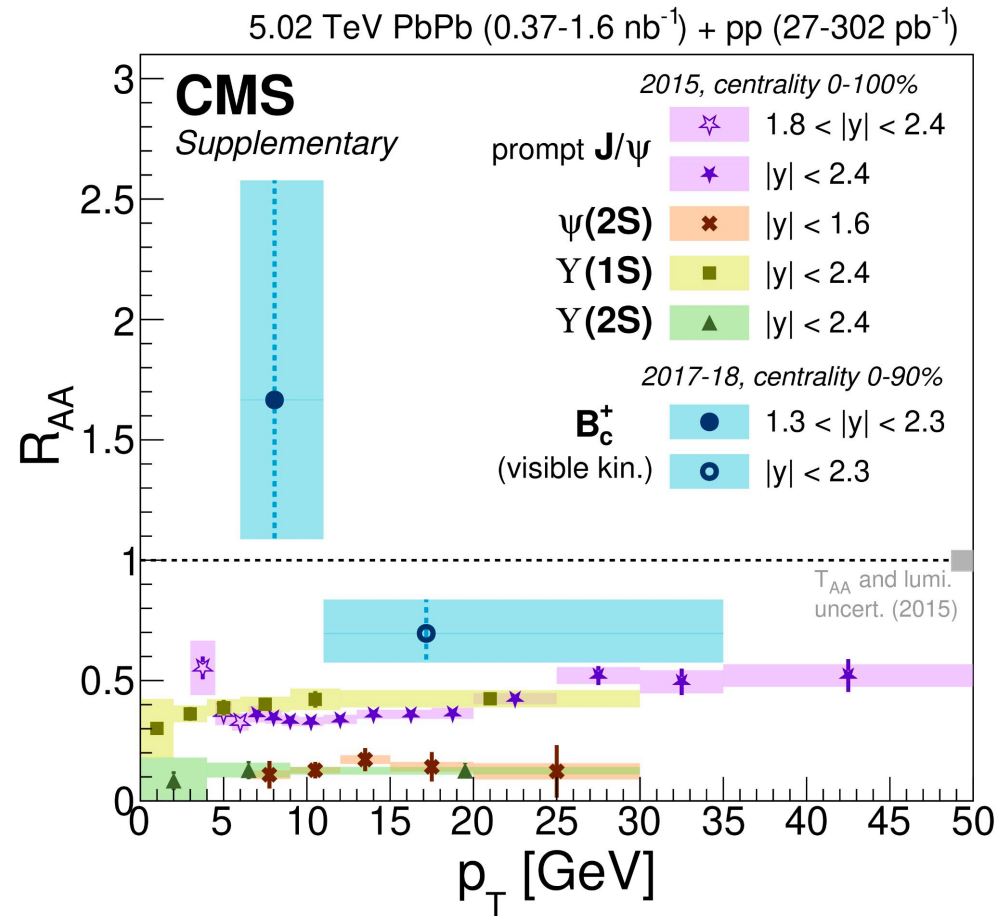
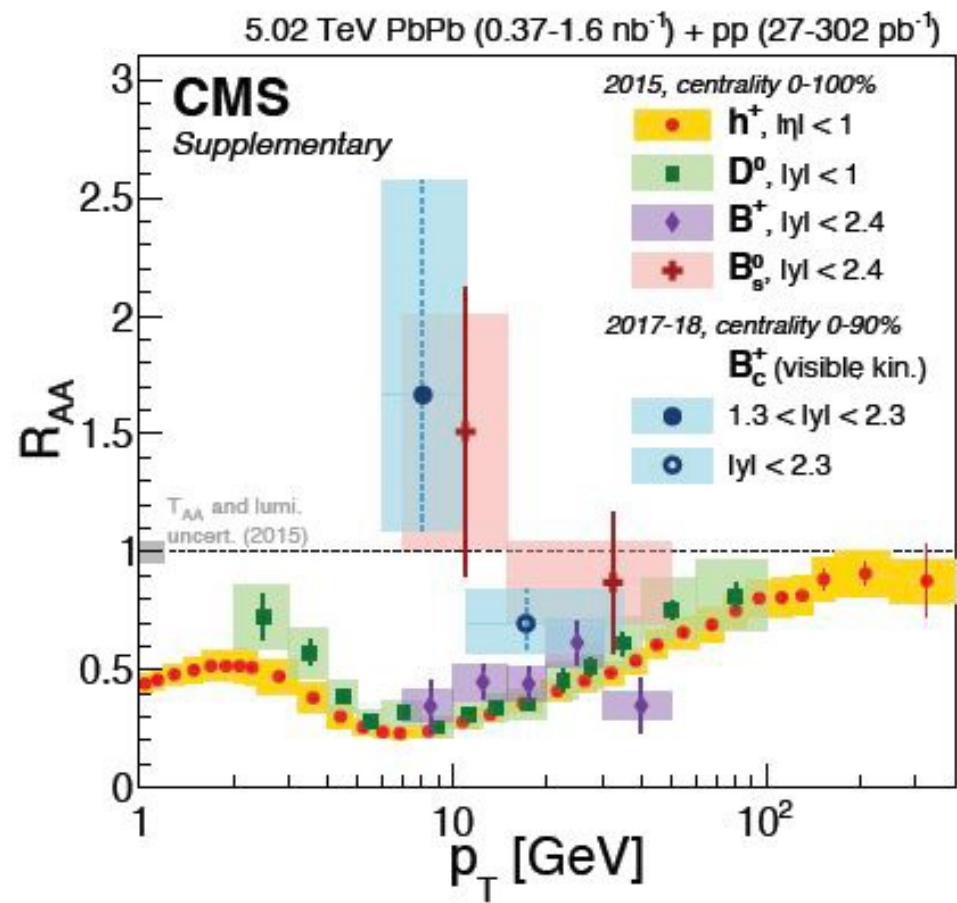
J/ψ vs $\Upsilon(1S)$



• How is quarkonium production modified by QGP?

- Sequential suppression observed for both charmonia and bottomonia
- Significant charmonium flow, while that of bottomonium is consistent with zero
- Models including both **color-screening and regeneration effects** describe data
- Improvement to the measurement precision for Psi(2S) and bottomonia especially v_2 is needed

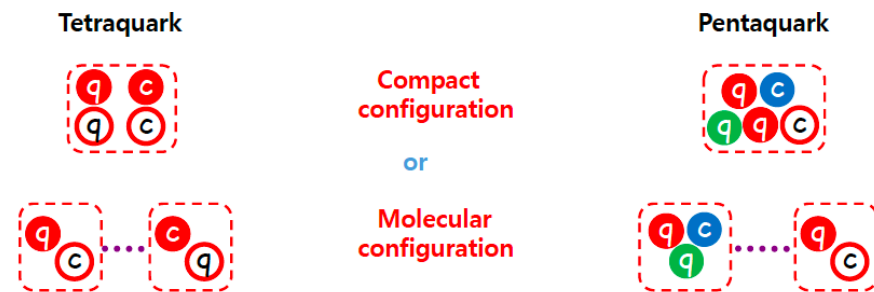
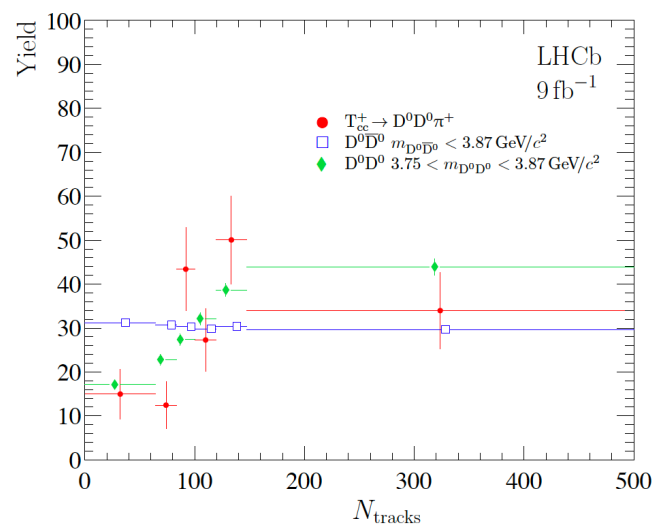
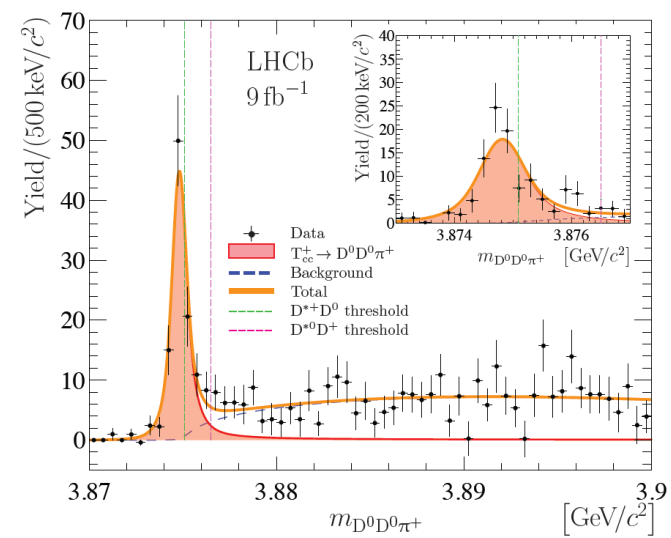
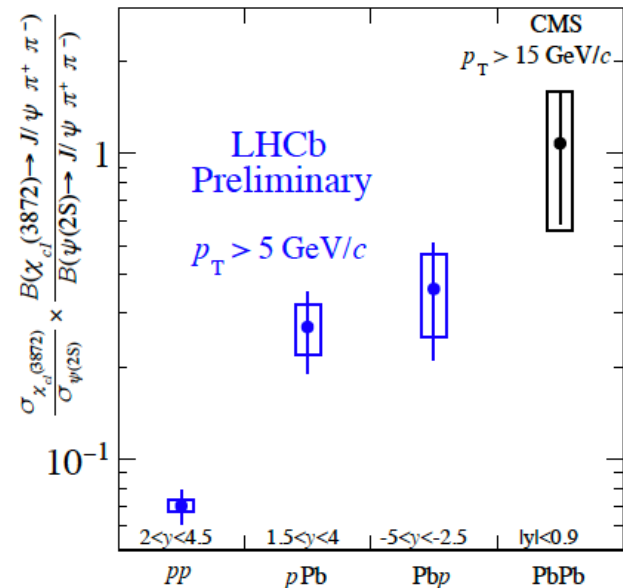
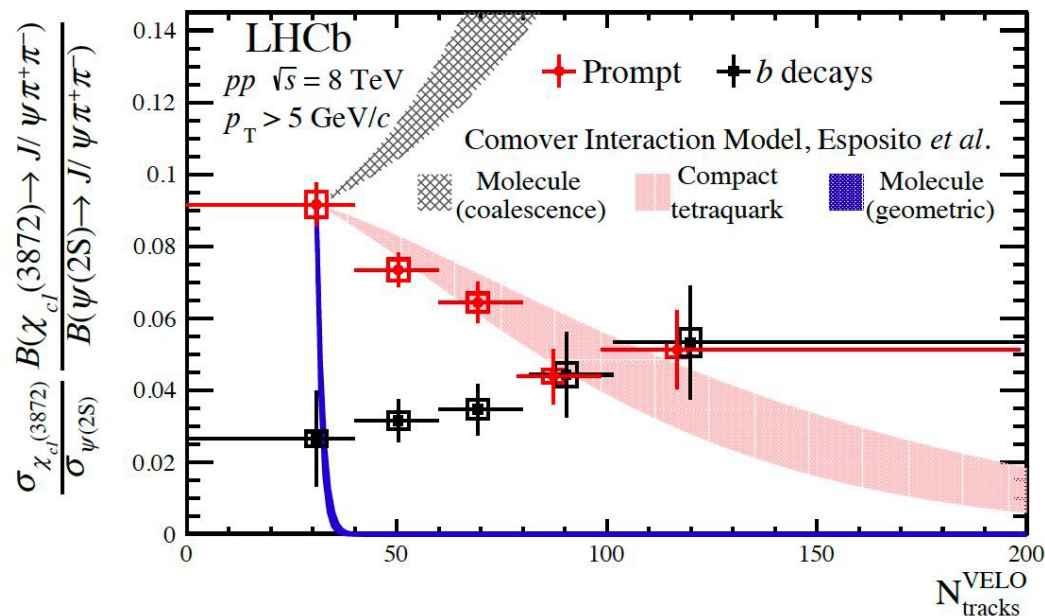
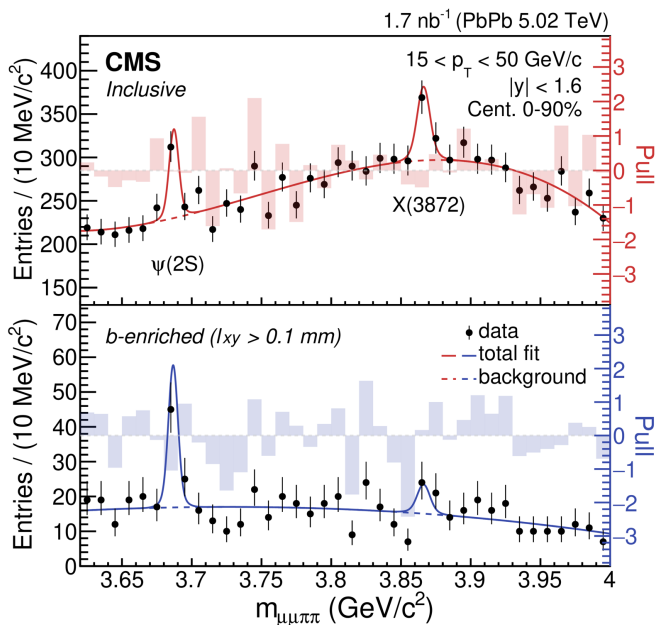
Bc Production in AA Collisions



- **Hint of B_c enhancement**

- Due to **recombination of uncorrelated b and c quark in QGP?**
- Need to improve the measurement precision to make more definitive statements

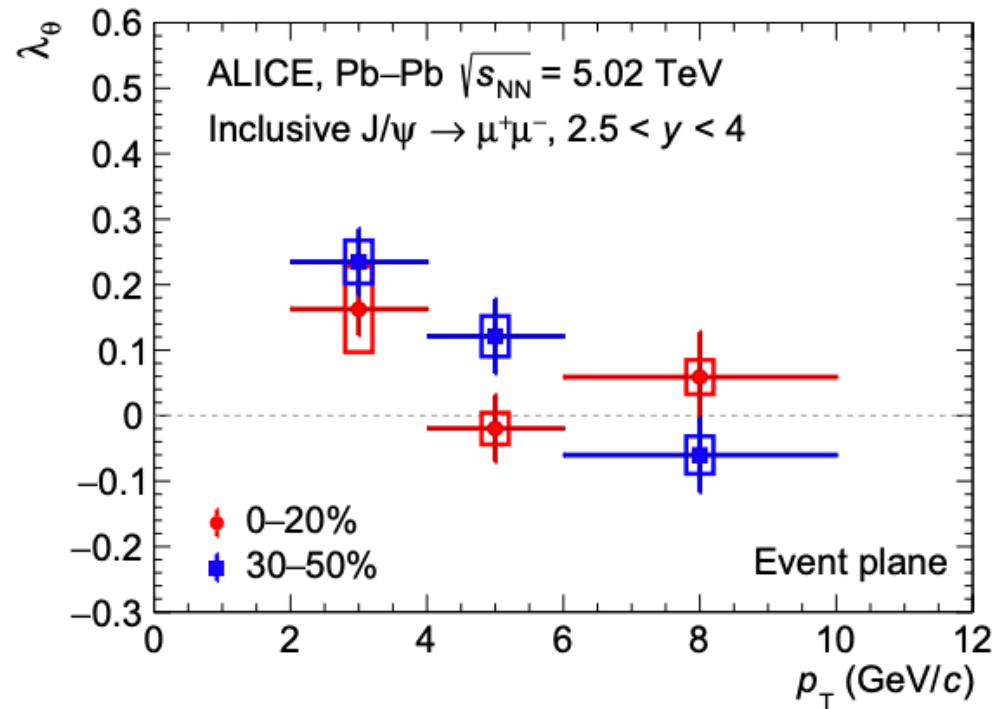
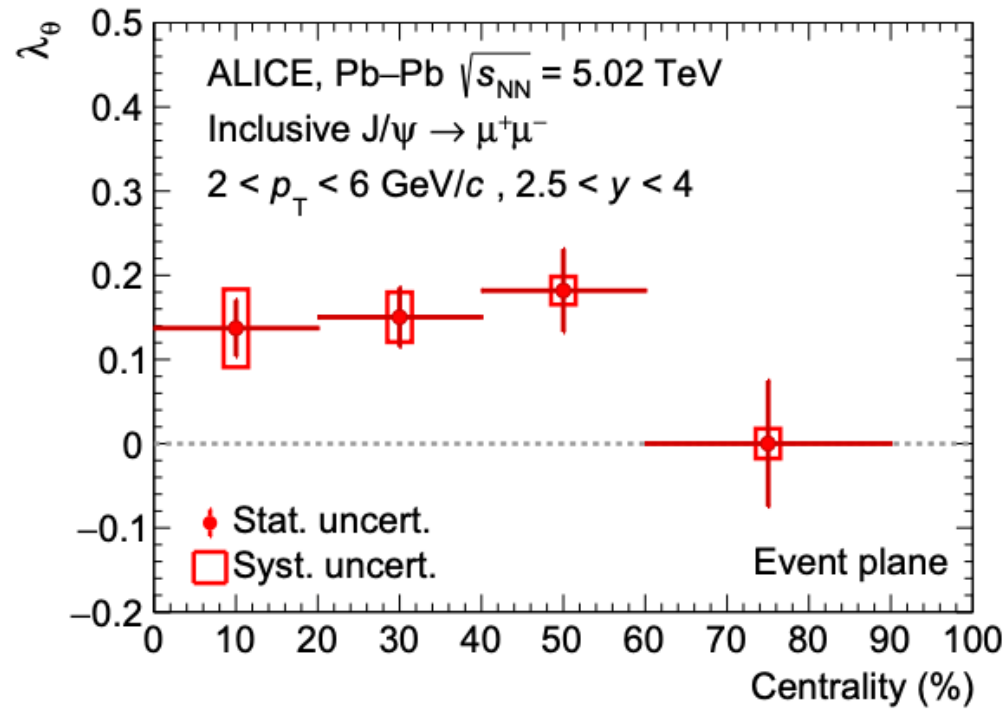
Exotic Particles



Which structure? → short distance vs long distance interaction

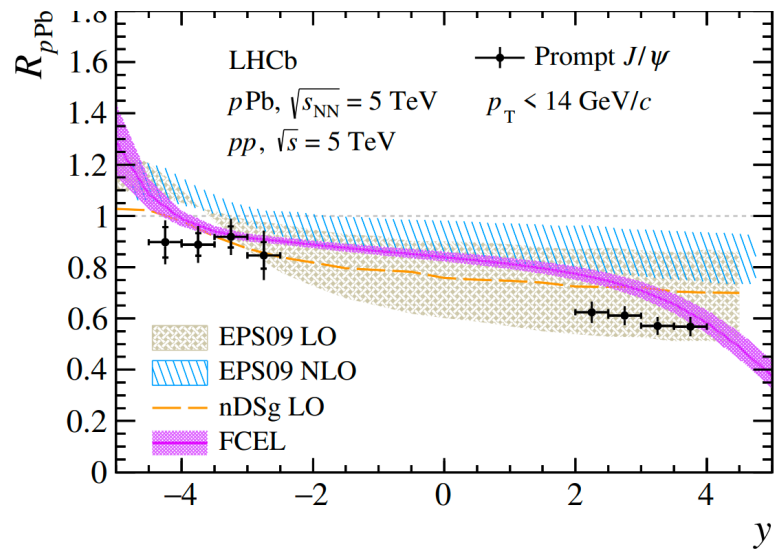
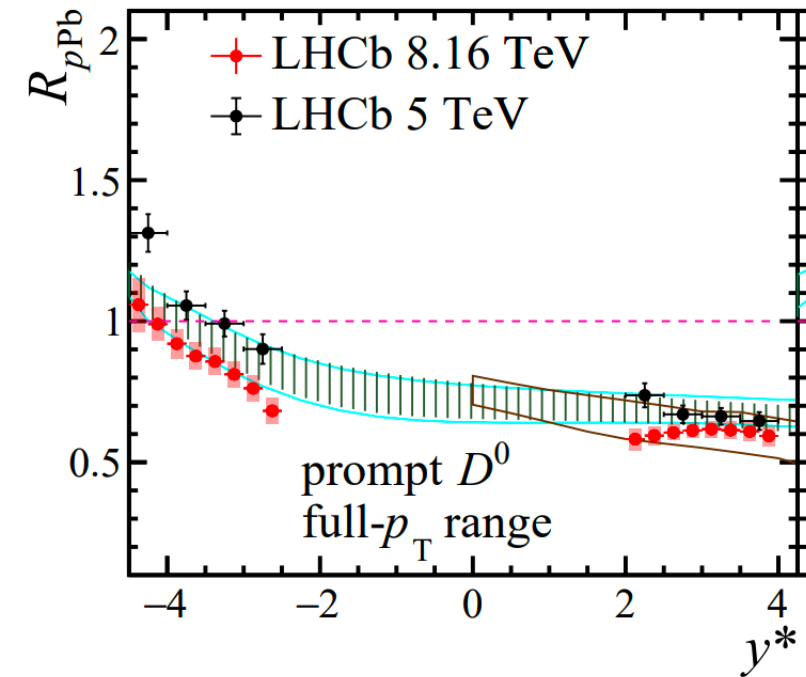
Exotic	X(3872)	Tcc(3875)	X(5568)	Pc(4312)
Quark	(uc)(ūc)	(ud)(c̄c̄)	(bu)(d̄s̄)	(udc)(ūc̄)
Threshold	D ⁻ D ⁰	D ⁻ D ^{*0}	Non near	→

J/psi Polarization in AA Collisions

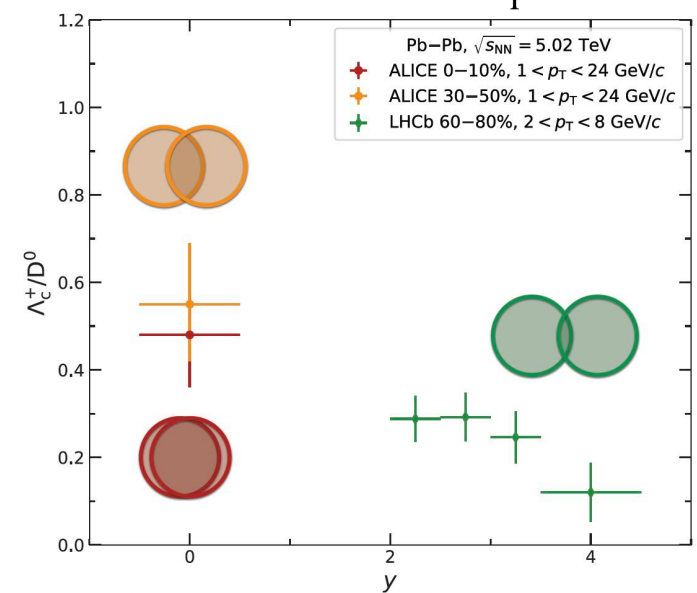
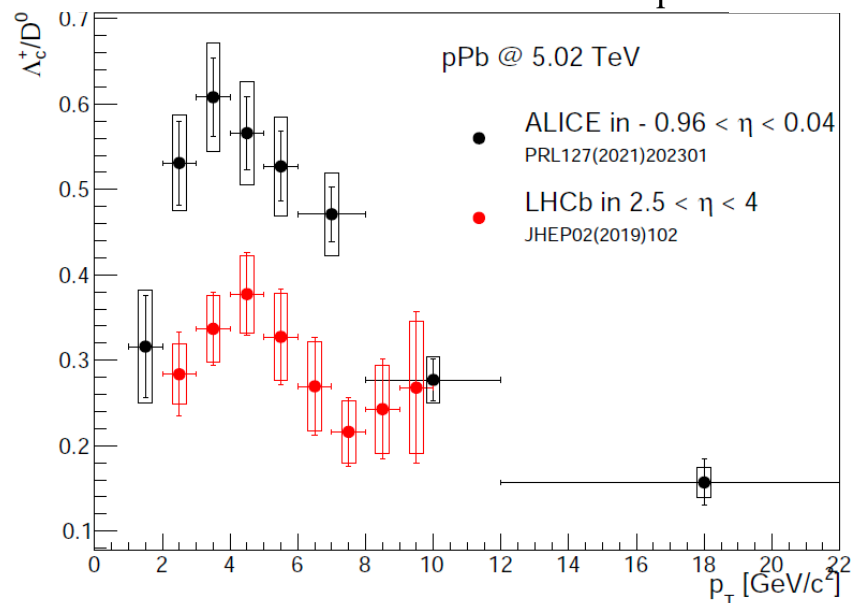
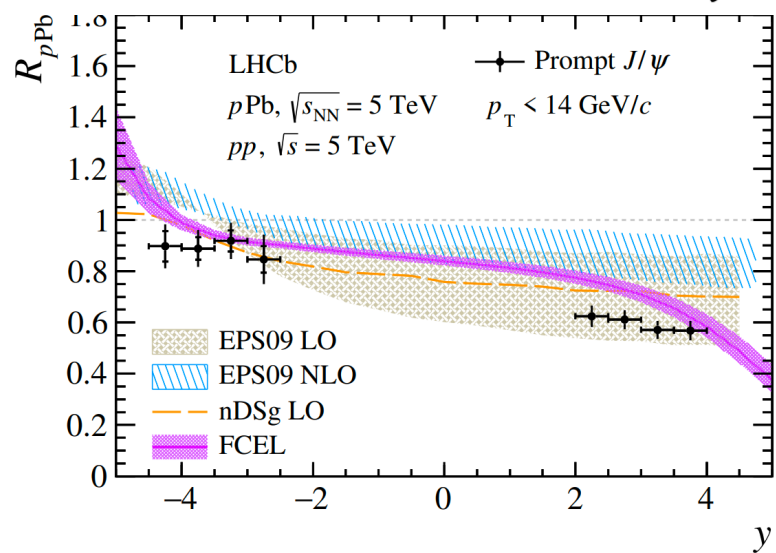
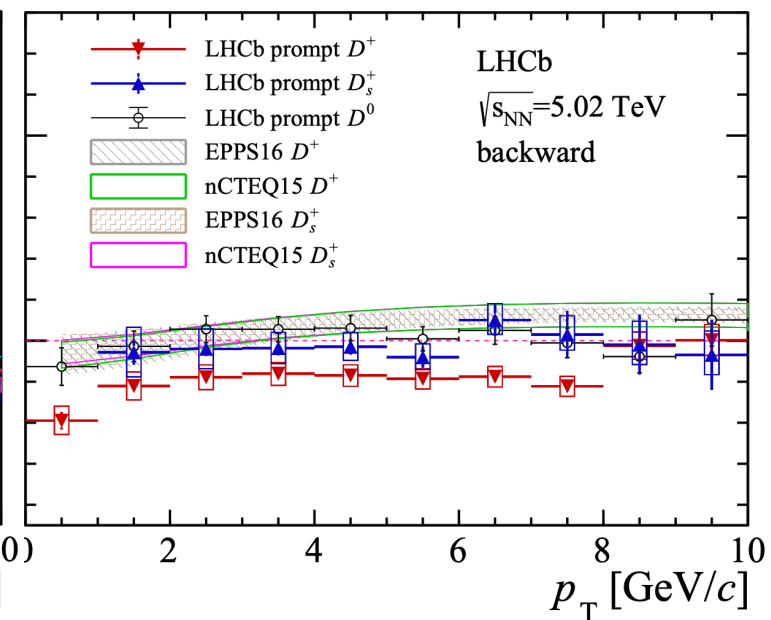
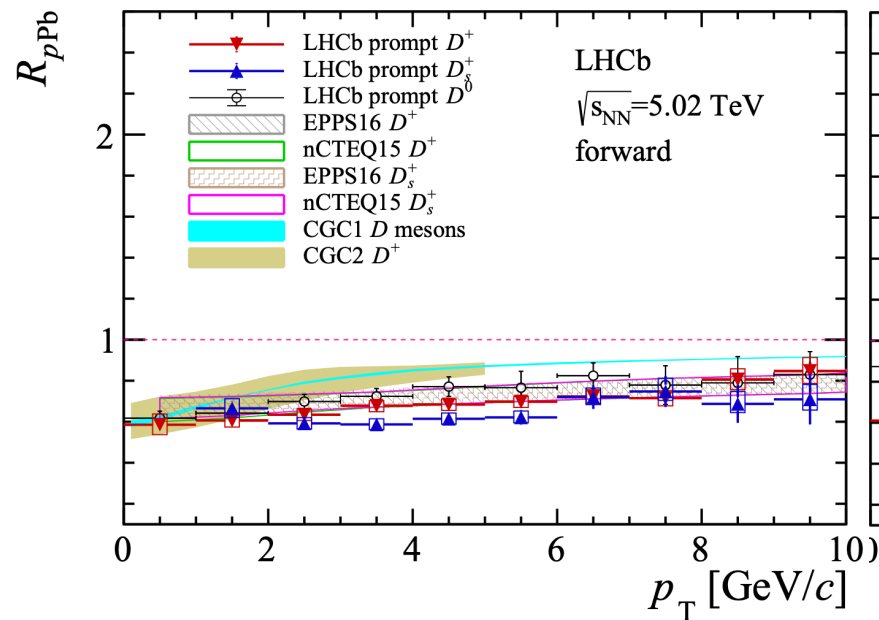
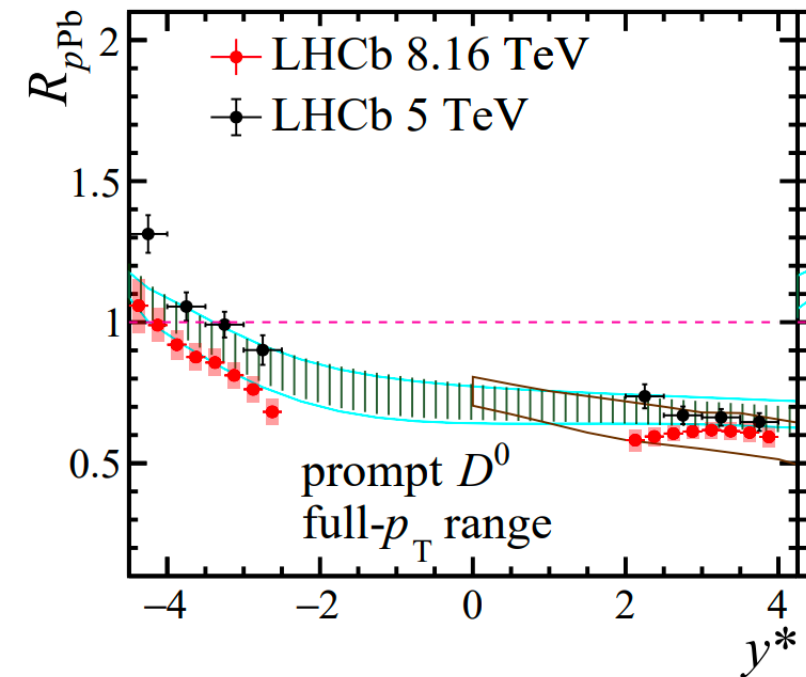


- Interpretation of these results is unclear

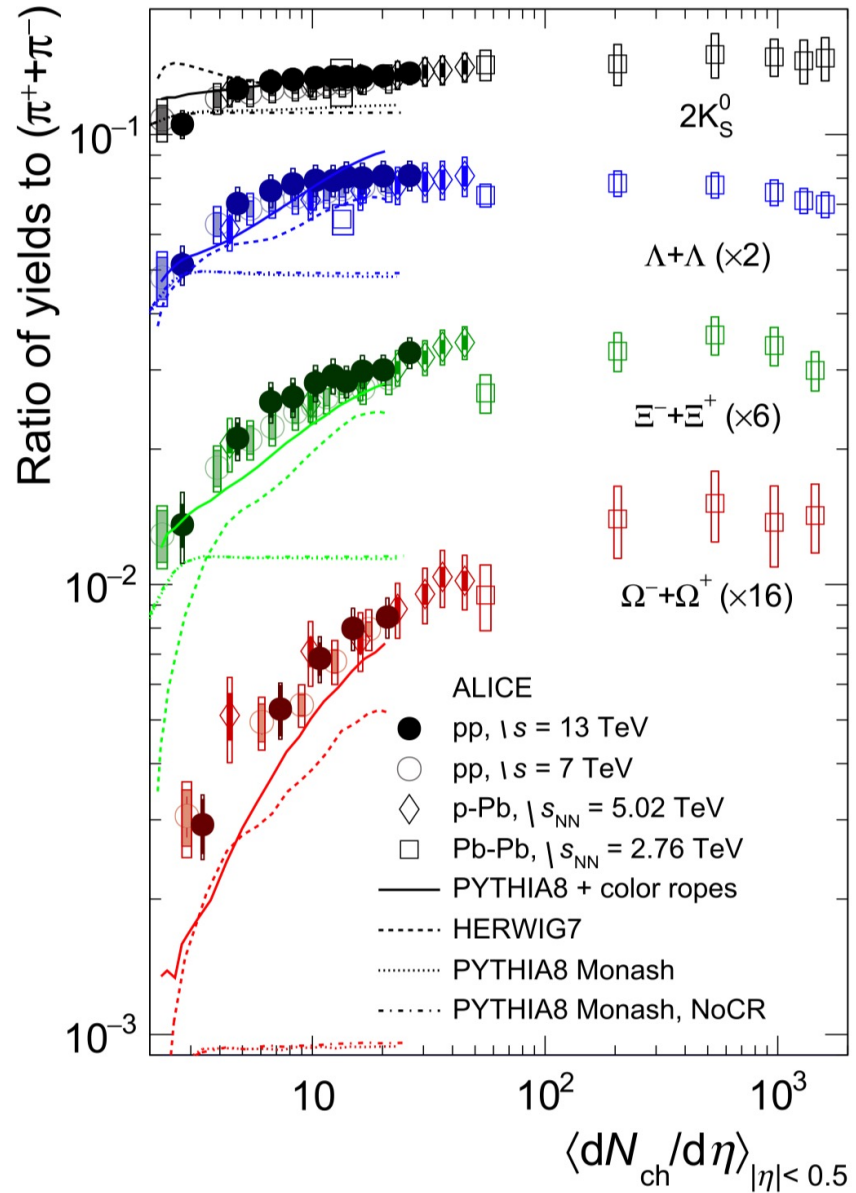
Rapidity Puzzles



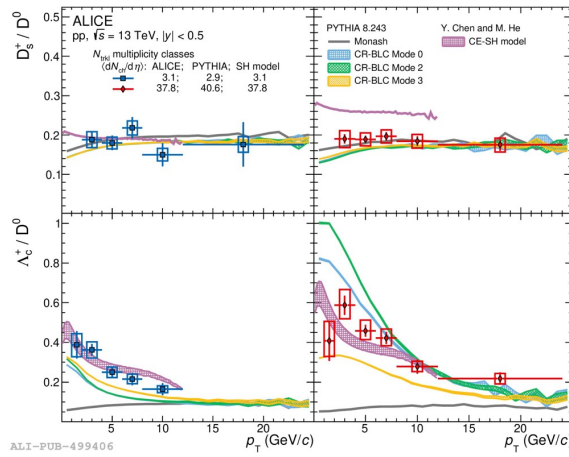
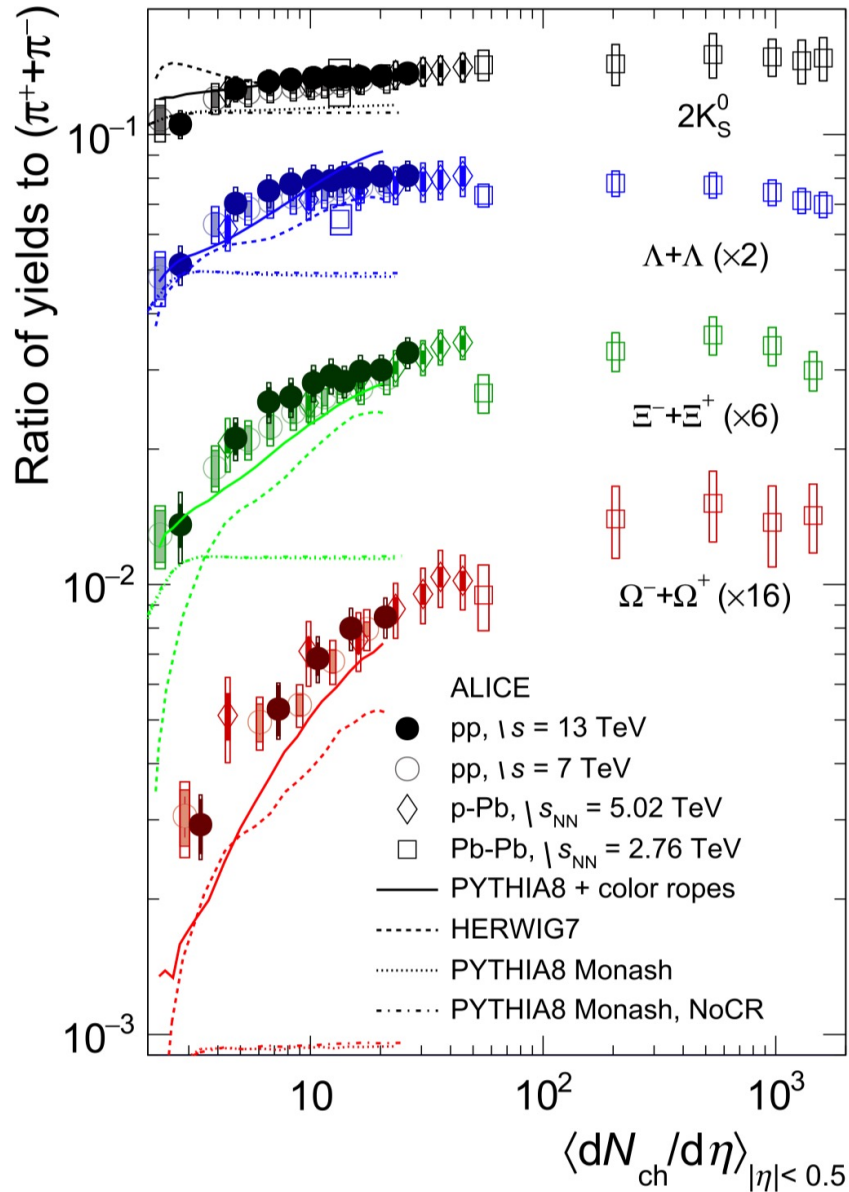
Rapidity Puzzle



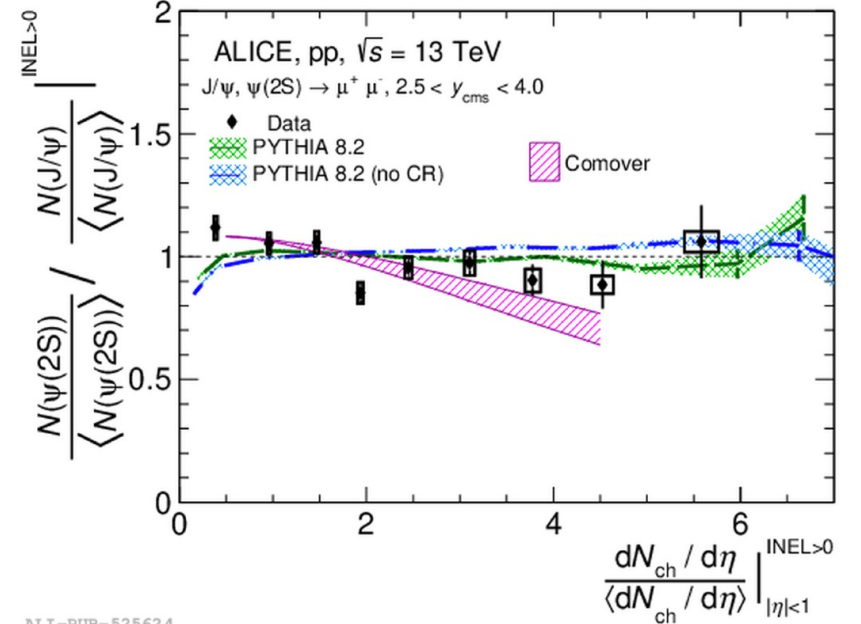
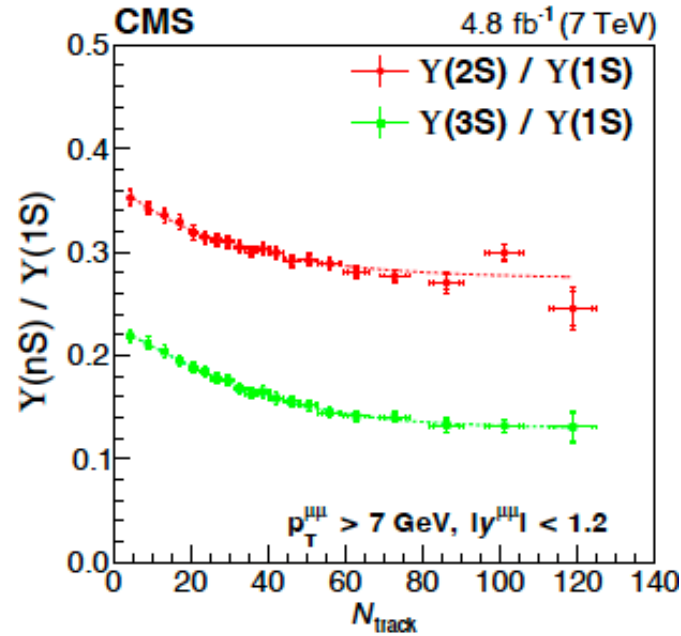
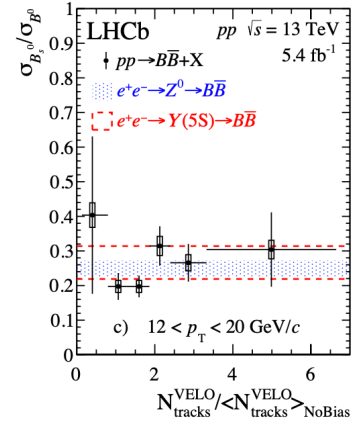
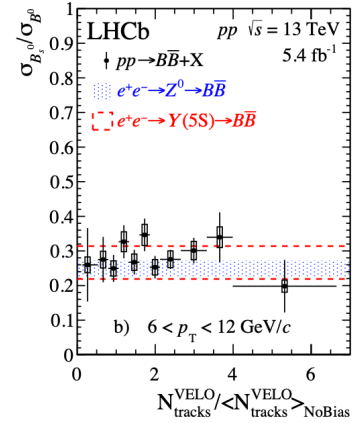
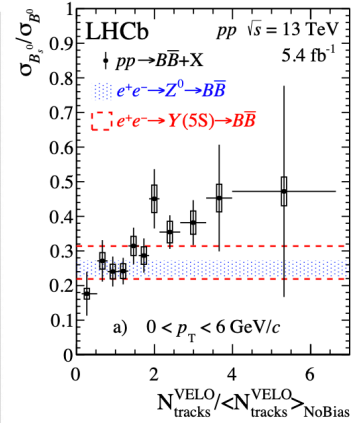
N_{trk} Puzzle



N_{trk} Puzzle

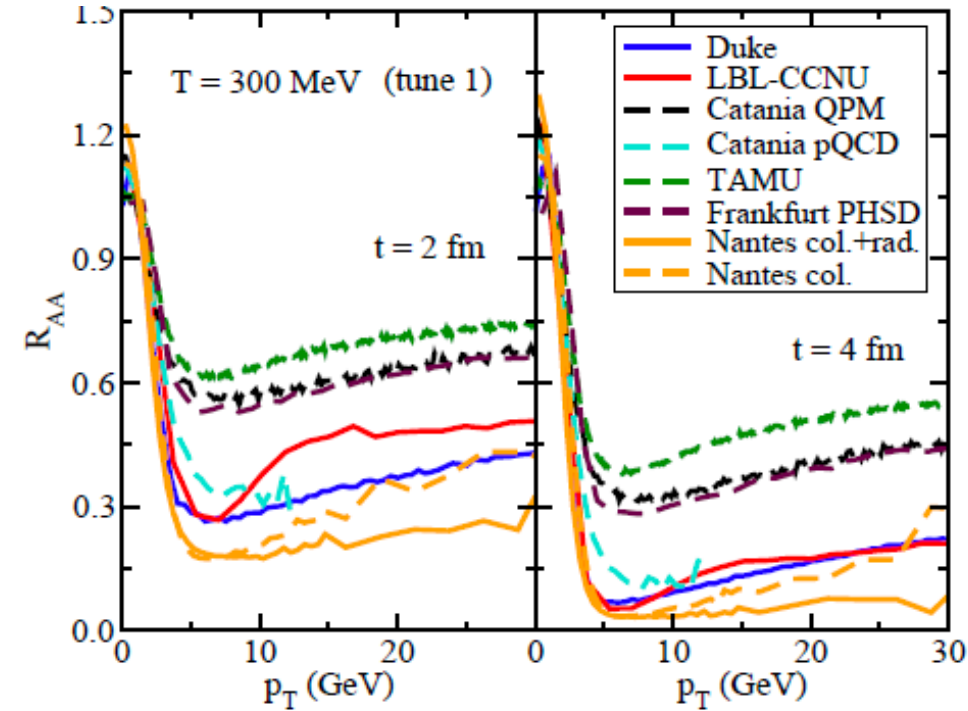
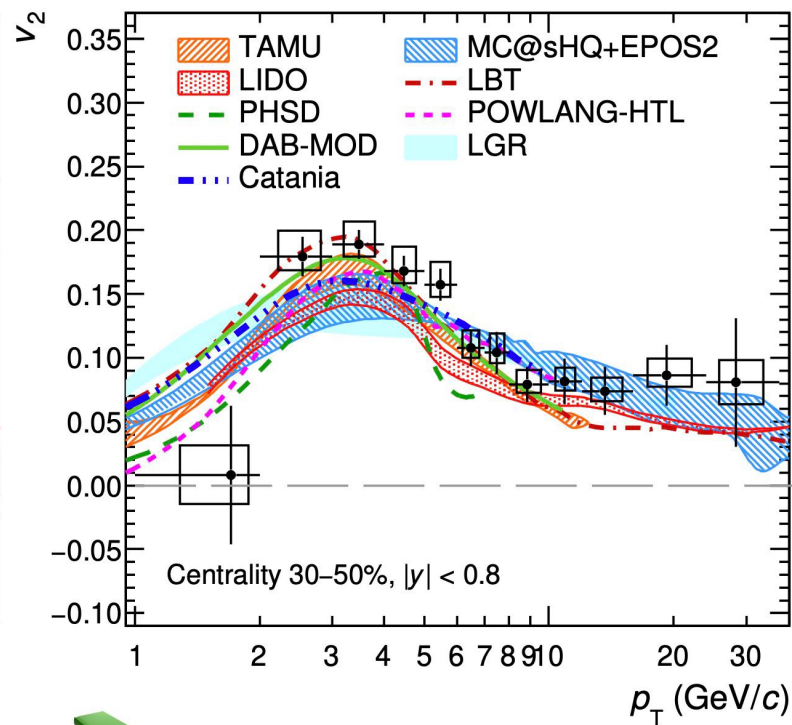
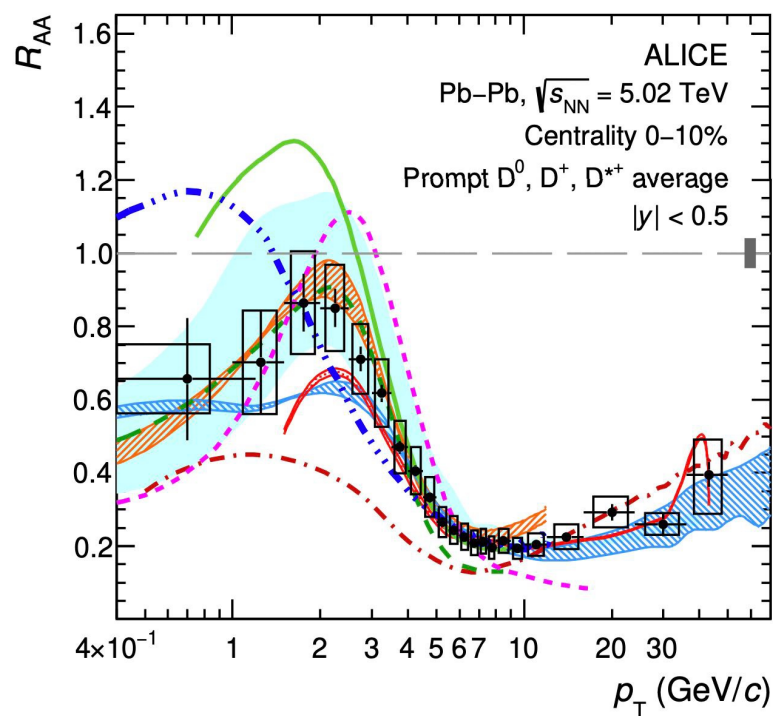


ALI-PUB-499406



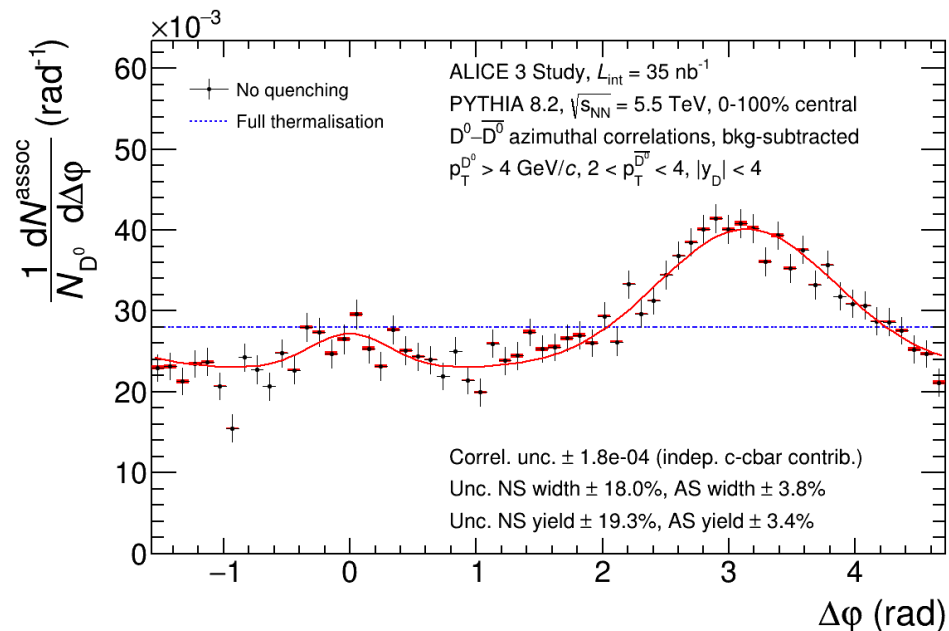
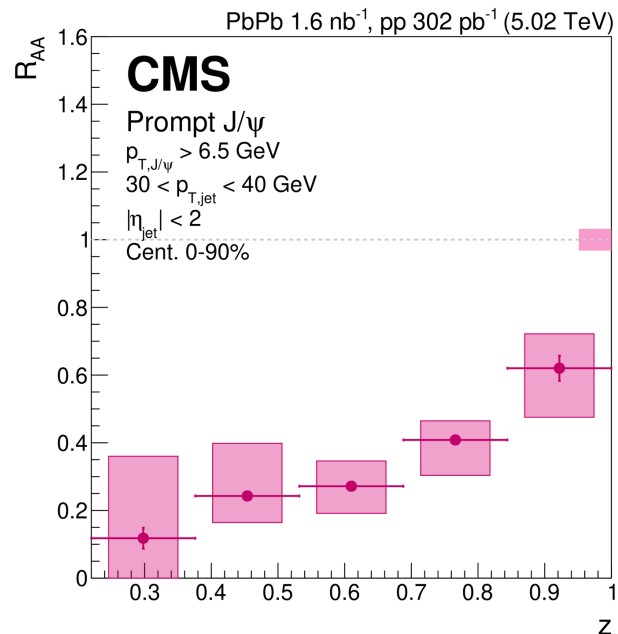
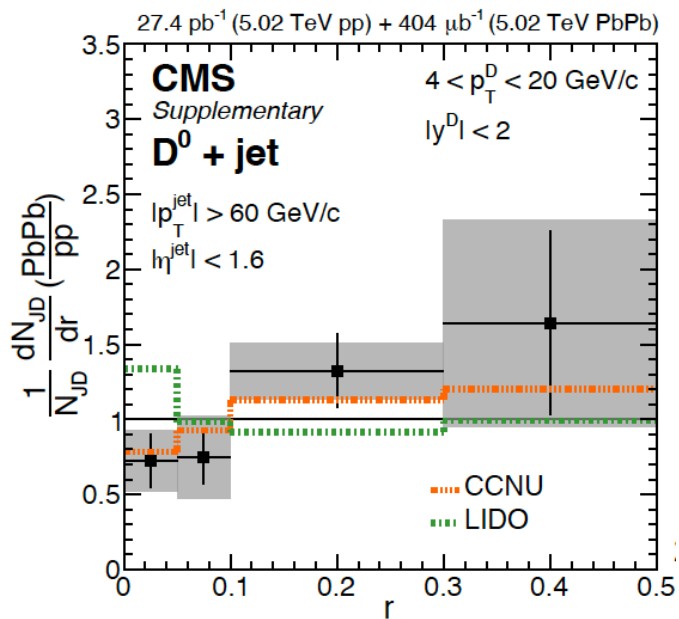
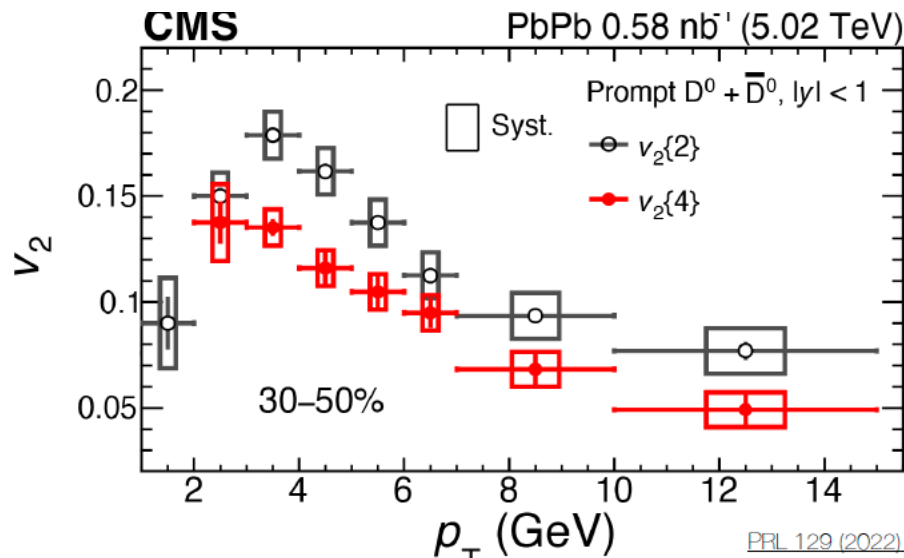
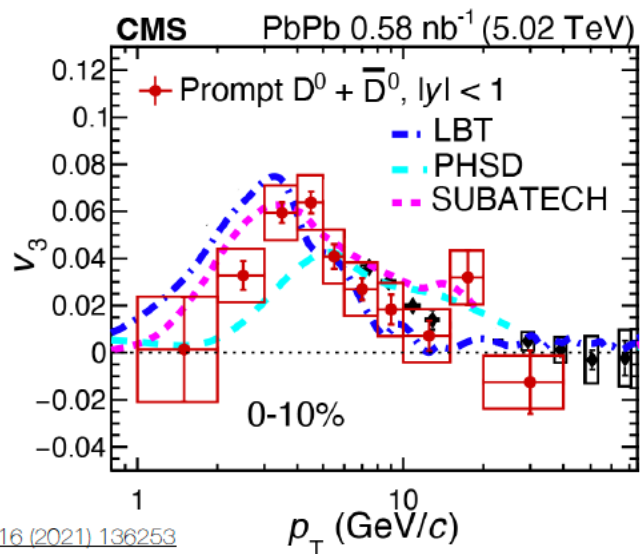
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Model Puzzle



- Models with different initial conditions, CNM effects, medium evolution, energy loss or hadronization mechanisms can describe R_{AA} and v_2 data

Model Puzzle



Summary

- **Findings from heavy flavor measurements at LHC so far:**
 - **Energy loss:** measured R_{AA} and flow consistent with **mass hierarchy of energy loss $\Delta E_c > \Delta E_b$** . Need to improve measurement precision for **low p_T charm hadrons, charm baryons and bottom hadrons and new observables** to better understand energy loss mechanisms.
 - **Hadronization:** **coalescence is important for hadronization in pp/pA/AA collisins, modification to charm quark hadronization in QGP observed**. Need to improve measurement precision and kinematic coverage for **charm baryons and bottom hadrons** to better understand heavy quark hadronization mechanisms.
 - **Quarkonia:** **sequential suppression observed for both charmonia and bottomonia**. Need to improve measurement precision and kinematic coverage for **excited charmonium and bottomonium states** to understand feed-down, color screening and regeneration
 - **Studies started:** exotic particles, D and J/psi in jets, correlations ...
- **LHC Run3+4 with newly upgraded detectors and much larger data samples will help us to better understand HQ, QGP and more!**

