Conference Highlight: Heavy flavors

Lijuan Ruan (BNL)

September 27, 2024

Why heavy flavor?

$m_Q >> T_{pc}$, $\Lambda_{QCD;}$ production controlled as a hard initial-state process

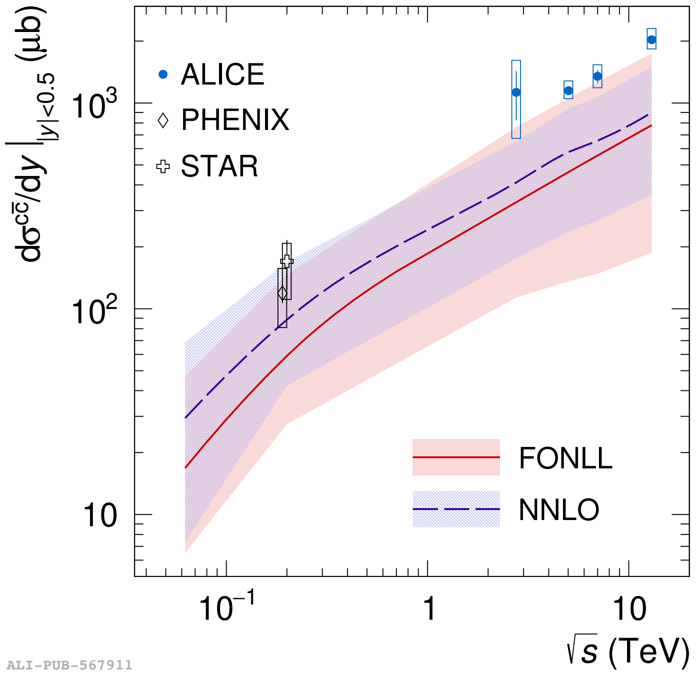
Dynamic evolution

- Propagation at low momenta: Brownian motion, spatial diffusion coefficient D_S
- At high momenta: in-medium parton shower evolution; suppression of forward radiation
- In-medium hadronization: recombination and fragmentation

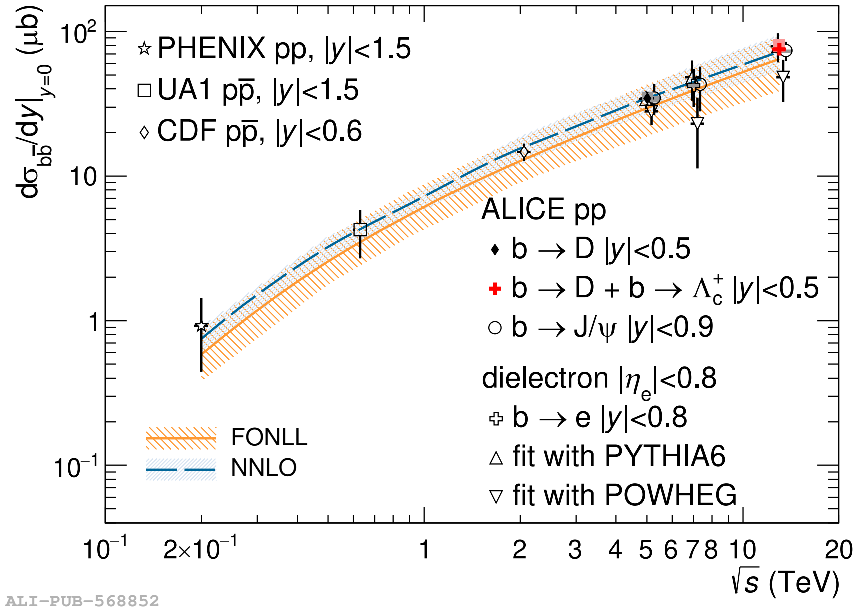
Cold nuclear matter effects

Heavy flavor cross section in p+p

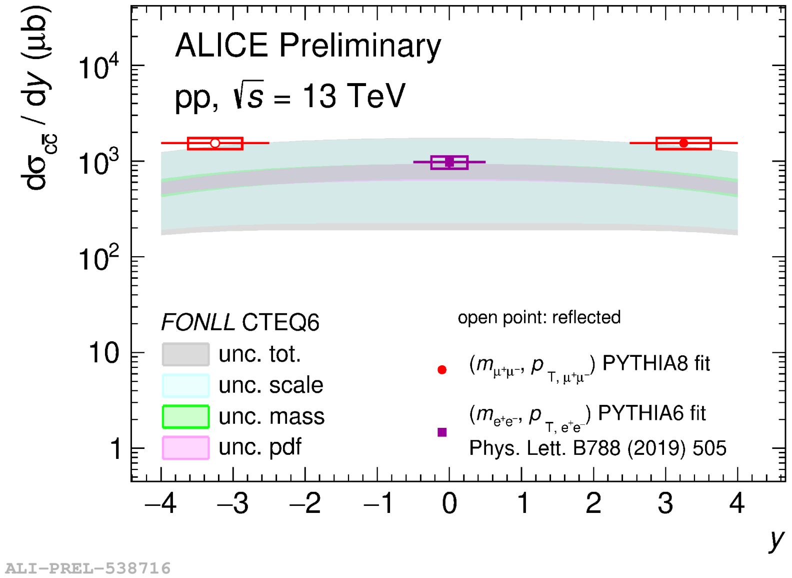
Charm

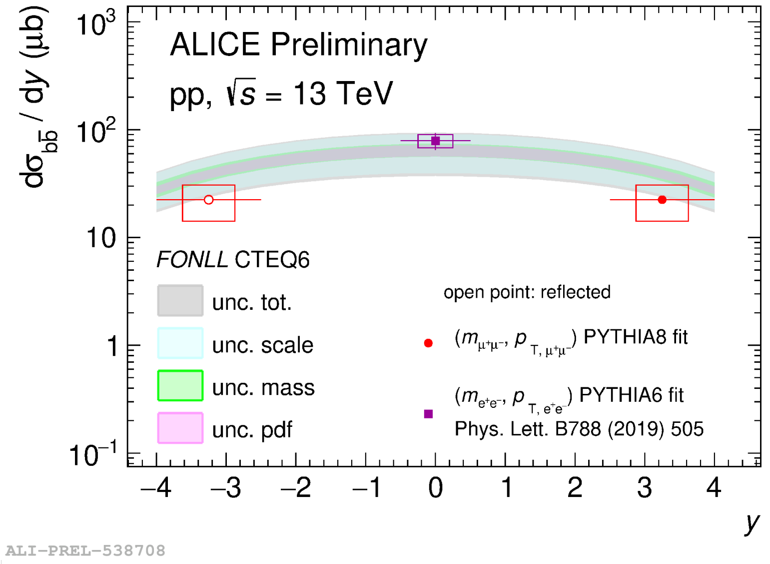


Beauty



Constrain recombination contribution to quarkonia

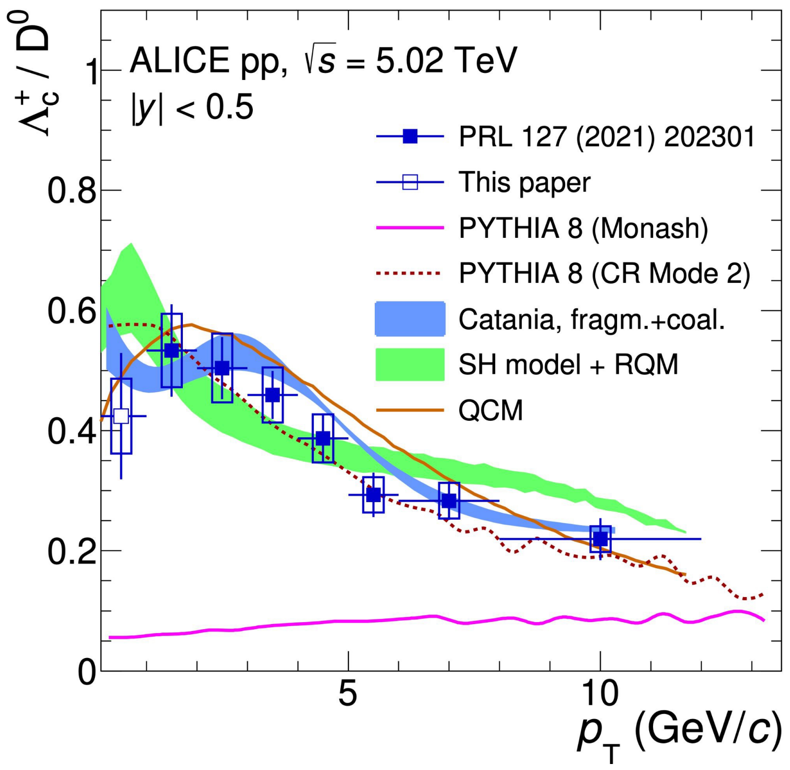


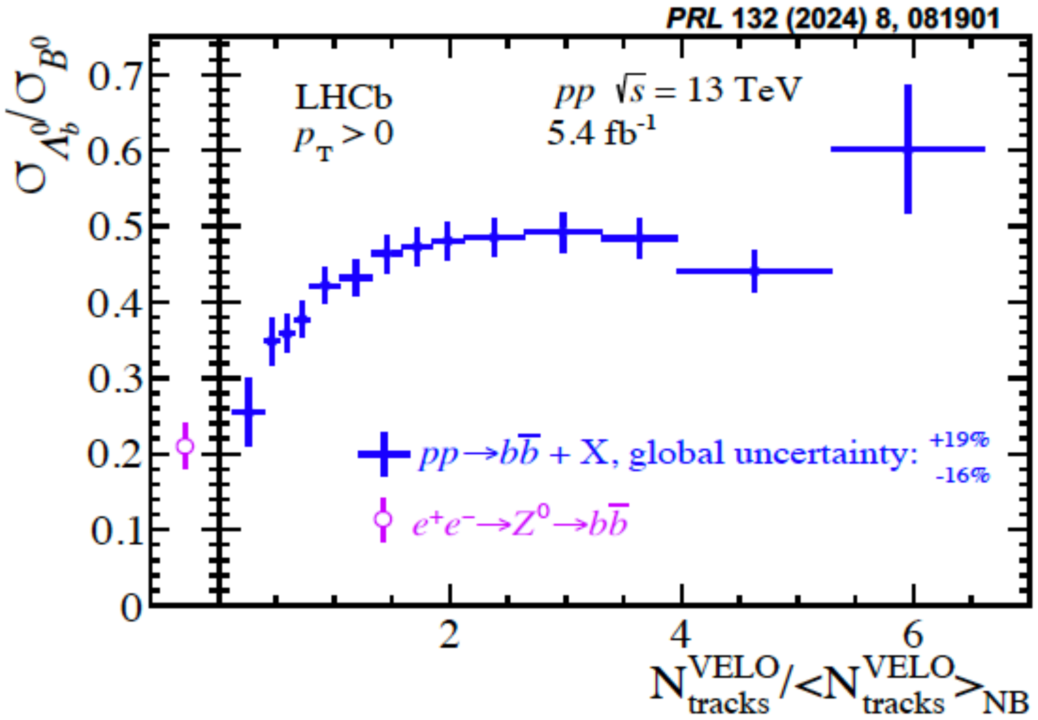


M. Pennisi

Baryon enhancement in p+p

ALICE, PRC 107 (2023) 064901

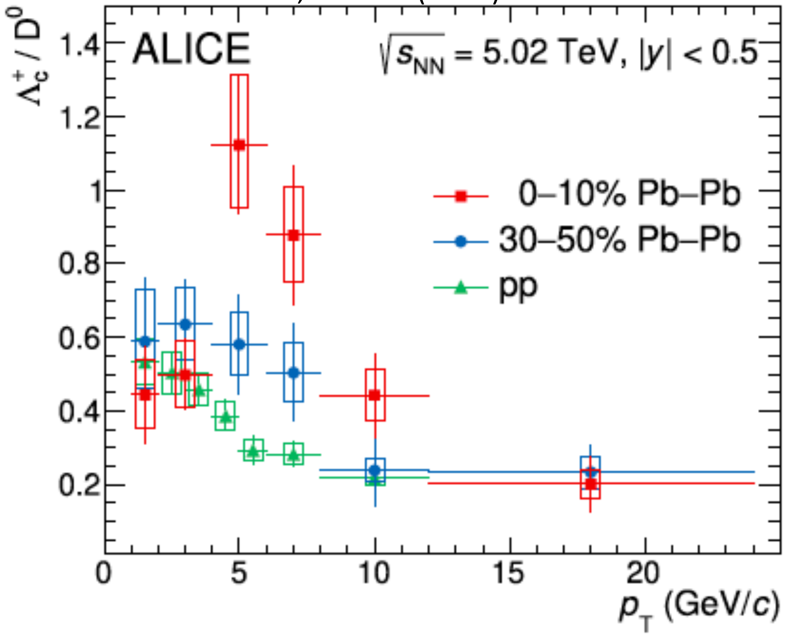


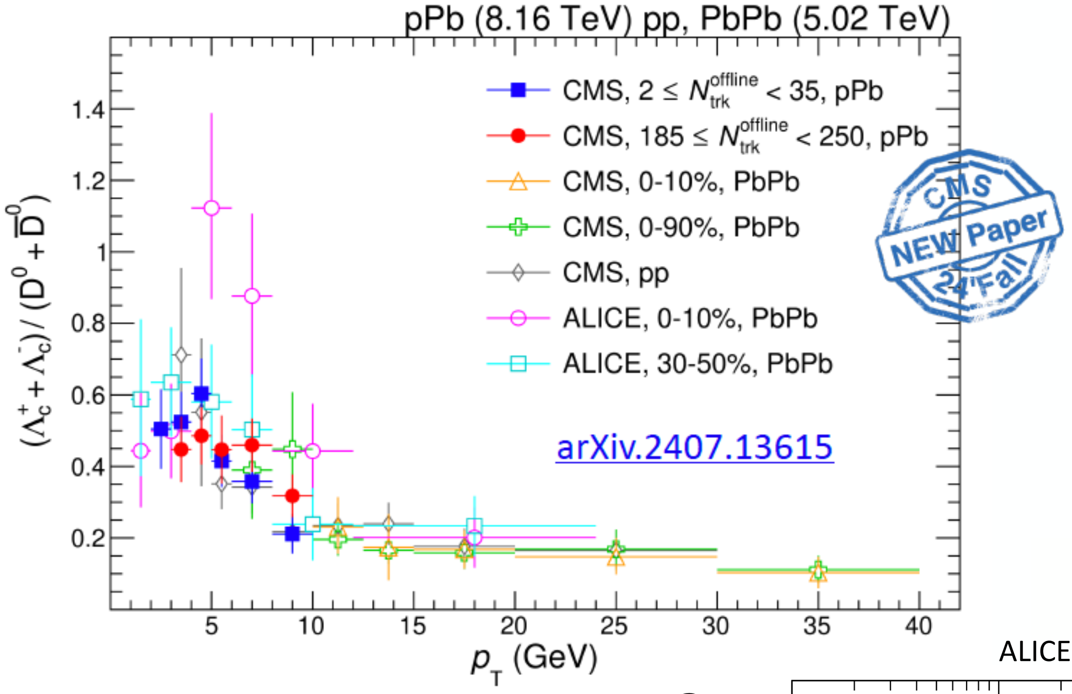


Baryon/meson ratio enhanced in p+p compared to e^+e^-, ep

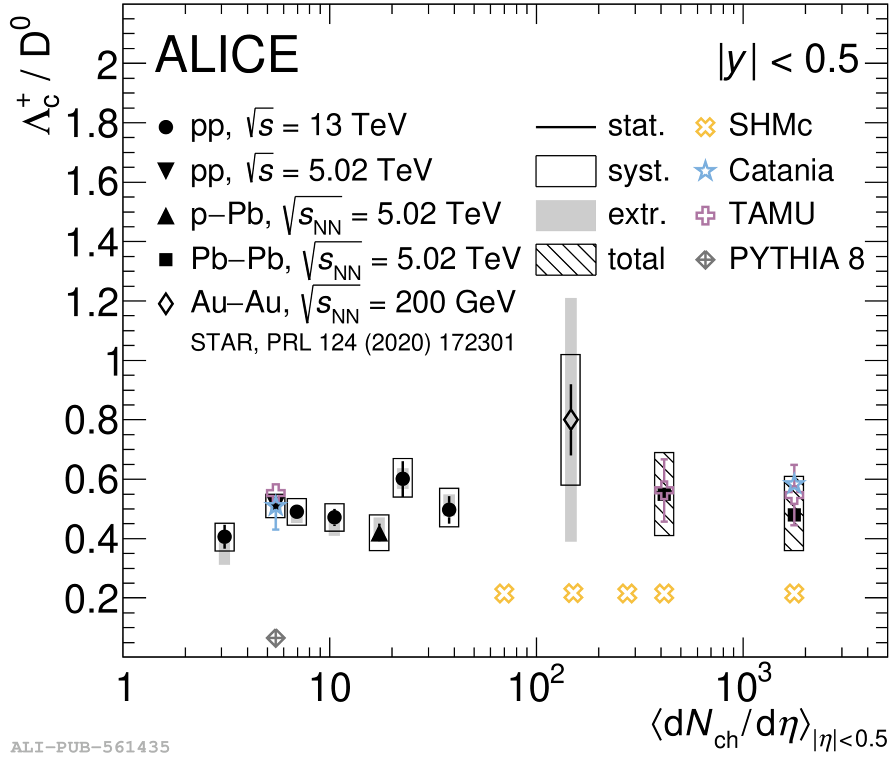
Baryon enhancement in pA, AA

ALICE, PLB839 (2023) 137796





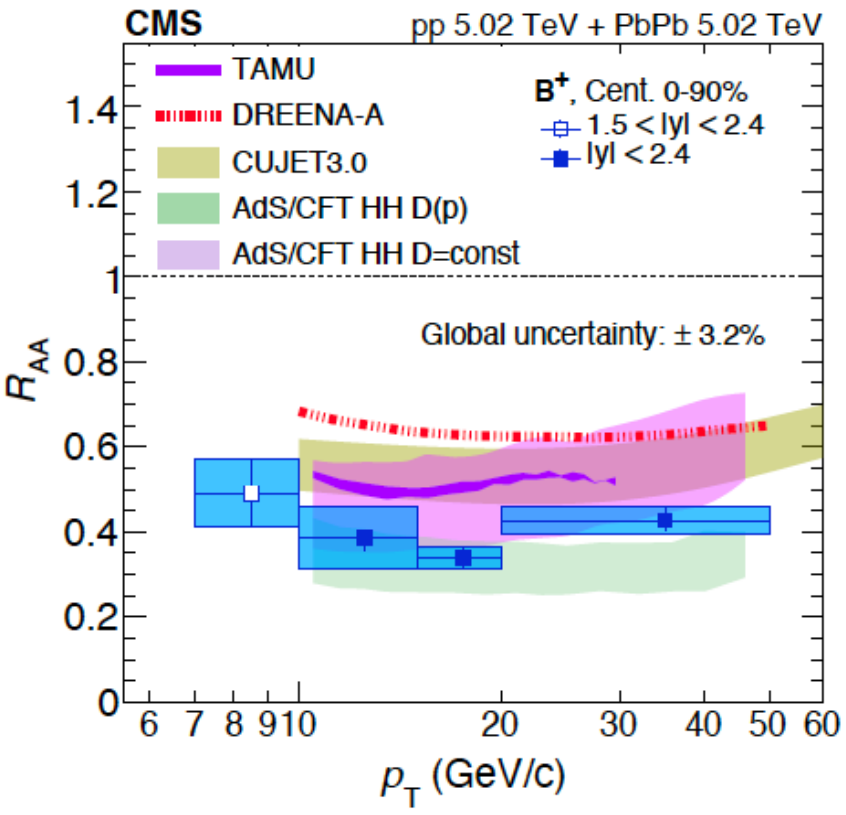
ALICE, PLB 839 (2023) 137796

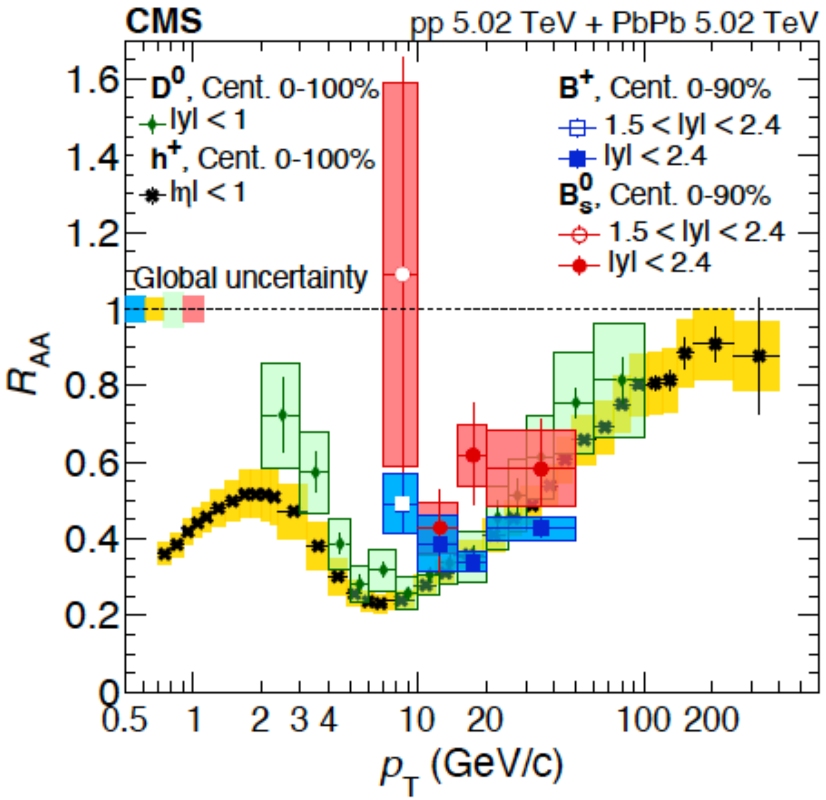


Baryon/meson ratio enhanced in AA, pA compared to p+p

Probe flavor dependence of energy loss: R_{AA}

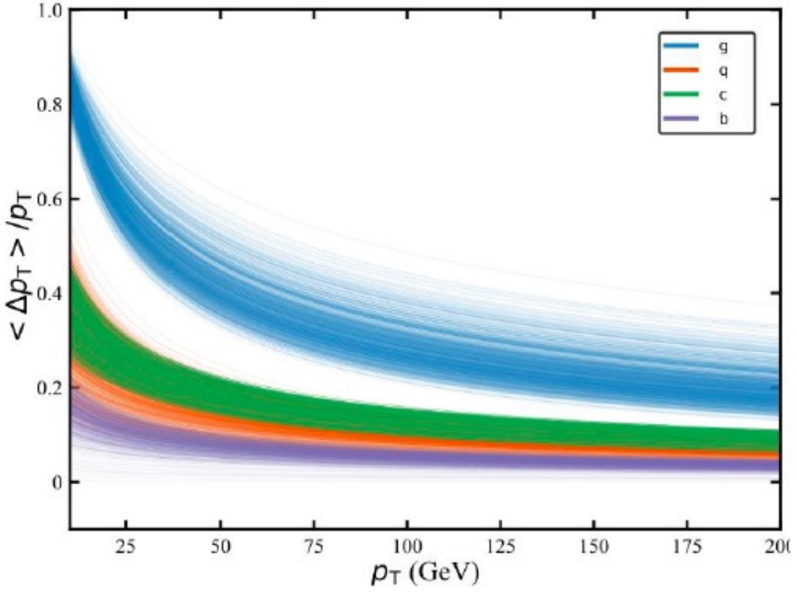
CMS, arXiv:2409.07258





Mass hierarchy

G. Qin

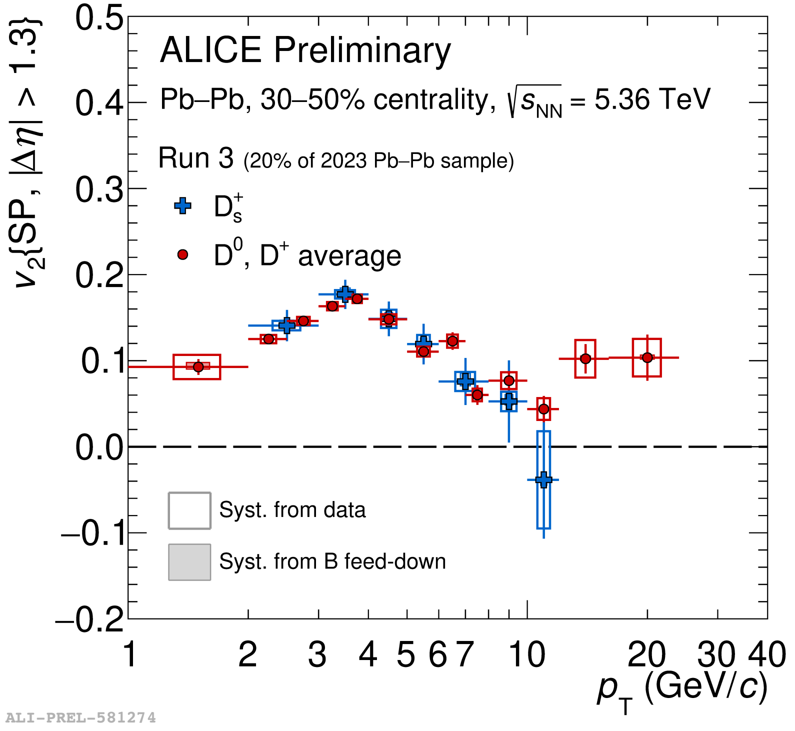


Bayesian analysis:

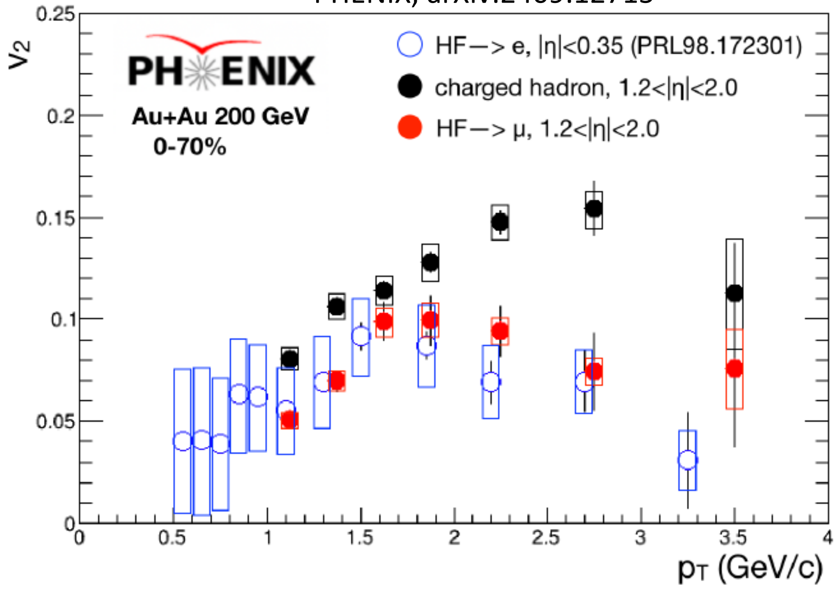
$$\langle \Delta E_g \rangle > \langle \Delta E_q \rangle \sim \langle \Delta E_c \rangle > \langle \Delta E_b \rangle$$

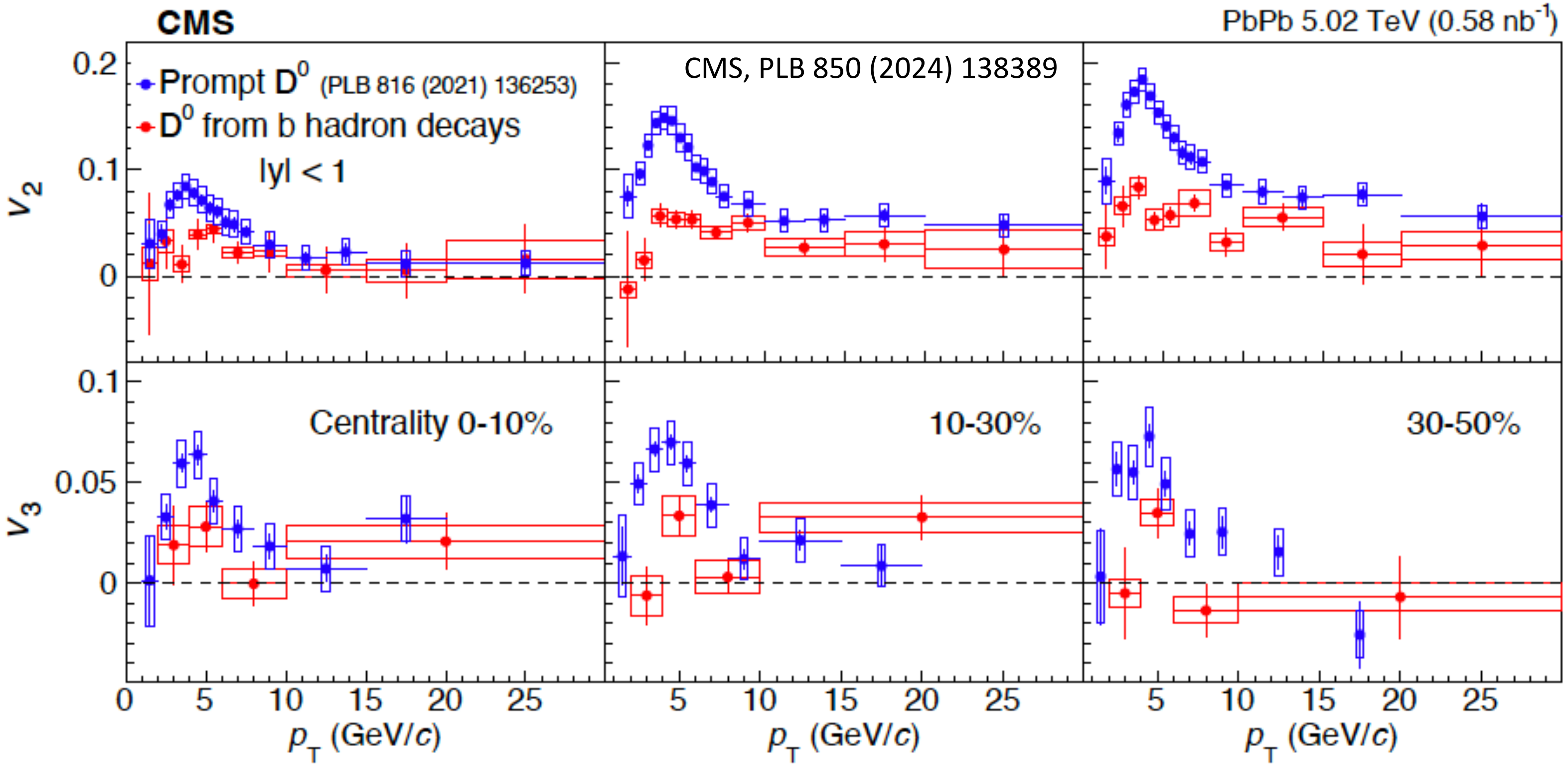
Mass dependence of flow: v_n

B. Zhang



PHENIX, arXiv:2409.12715



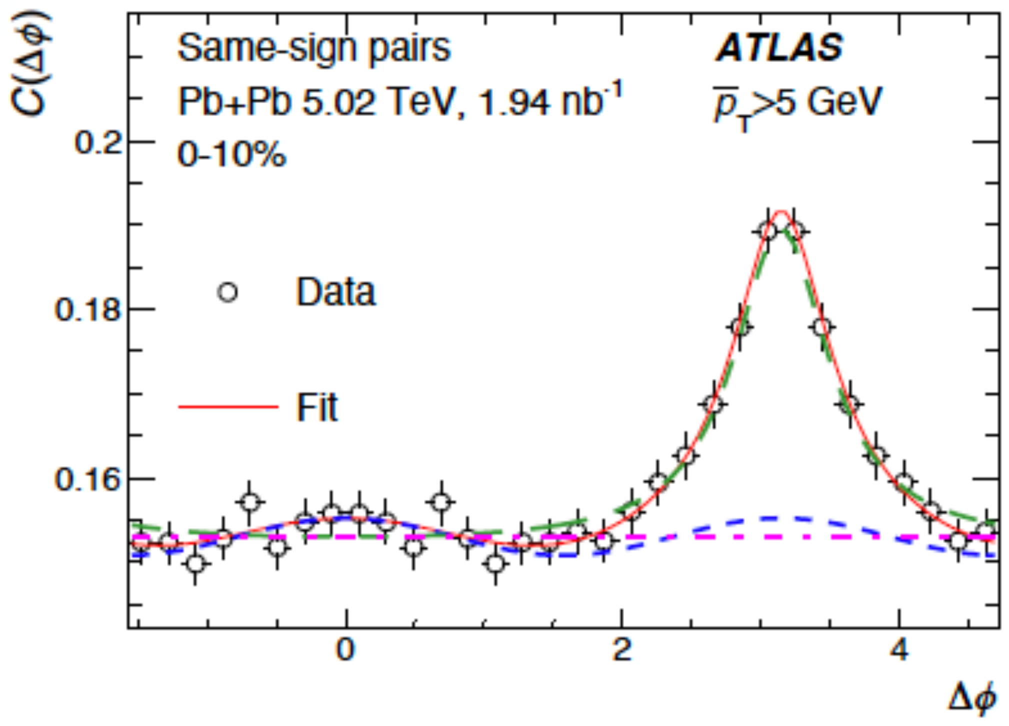


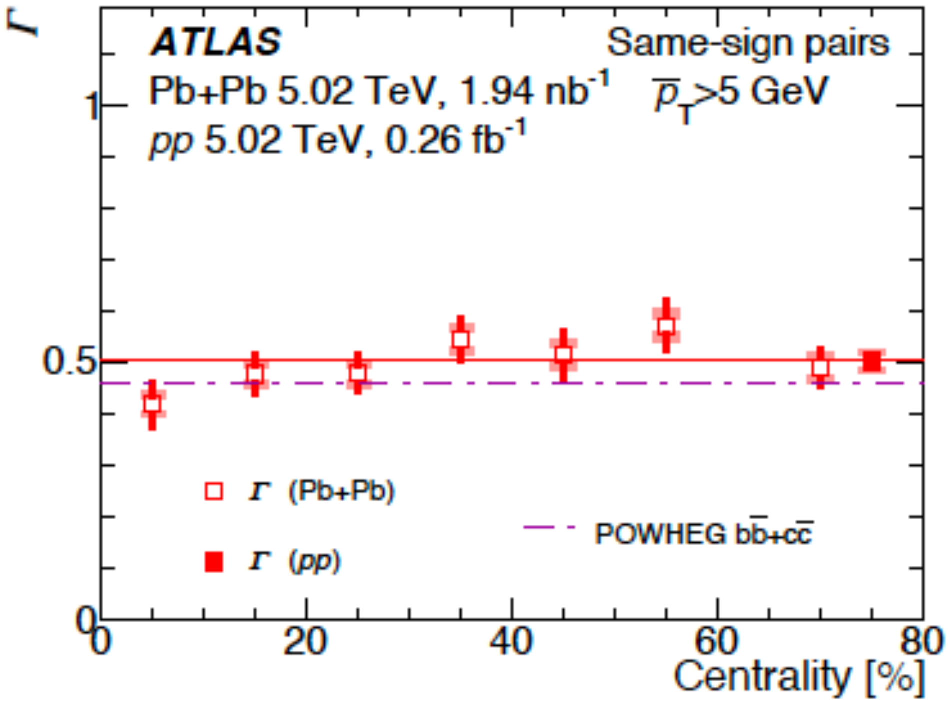
Precise D meson v_n measurement

Significant flow observed for b hadrons

Azimuthal angle correlation of heavy flavor pairs

ATLAS, PRL 132 (2024) 202301



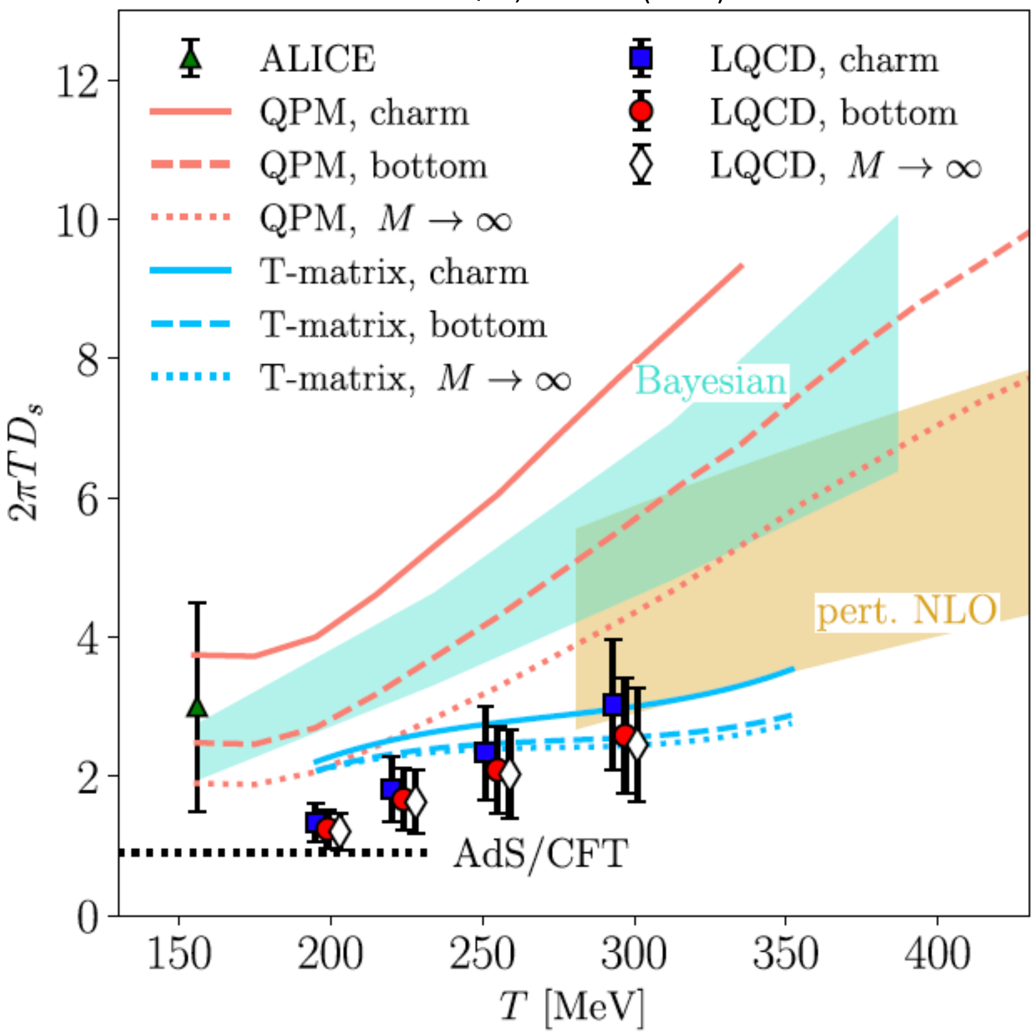


No away-side broadening observed

Model calculations? Lower the p_T cut?

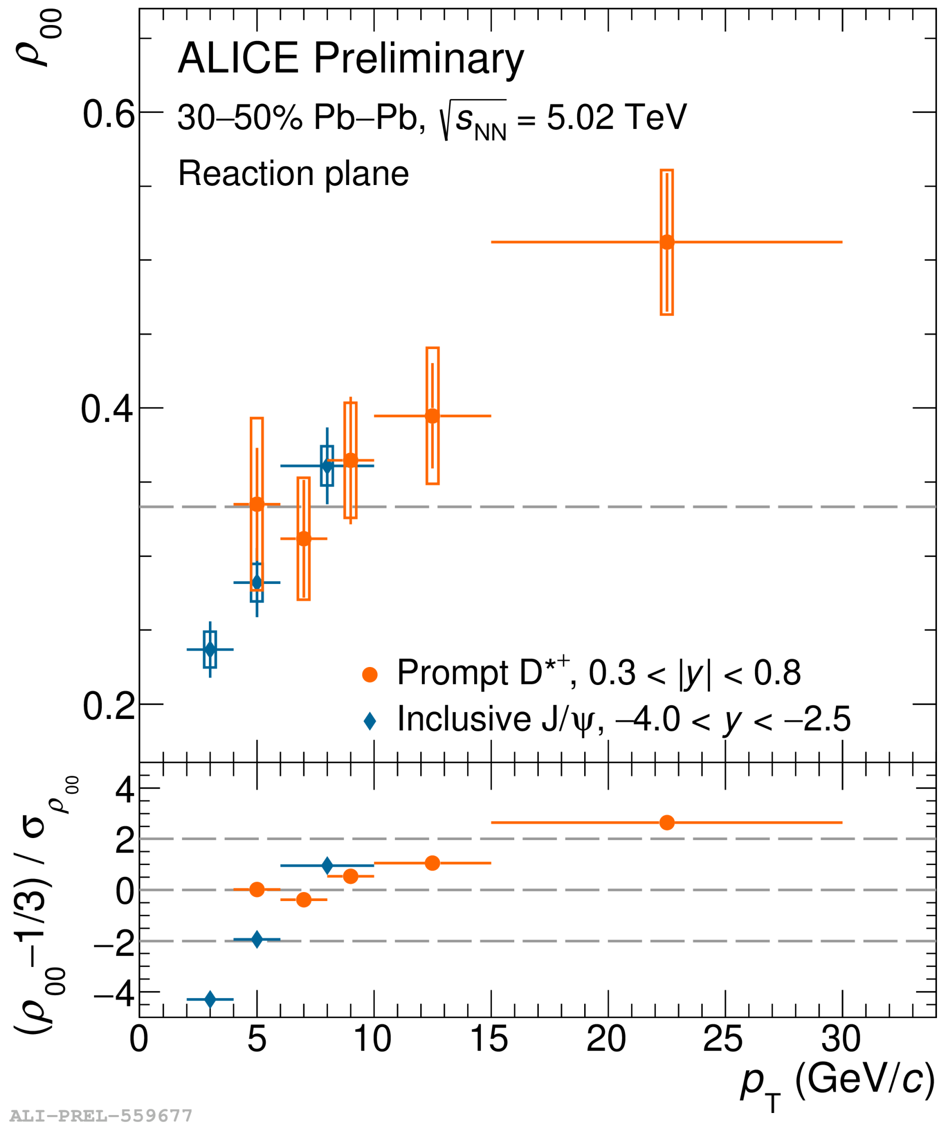
Spatial diffusion coefficient D_S

Hot QCD, PRL 132 (2024) 051902



The models that qualitatively describe the data suggest small values for D_S.

Spin alignment of D meson

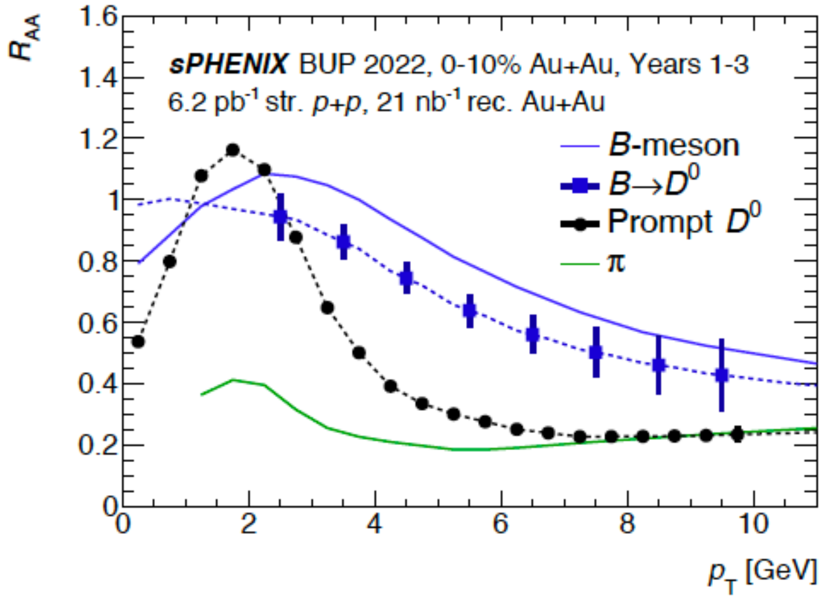


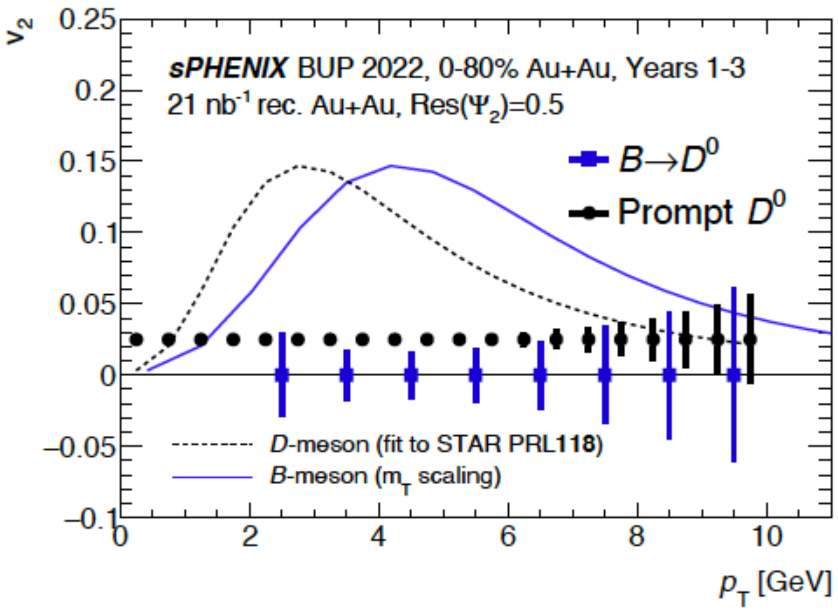
Do we have a consistent picture to describe vector meson spin alignment results?

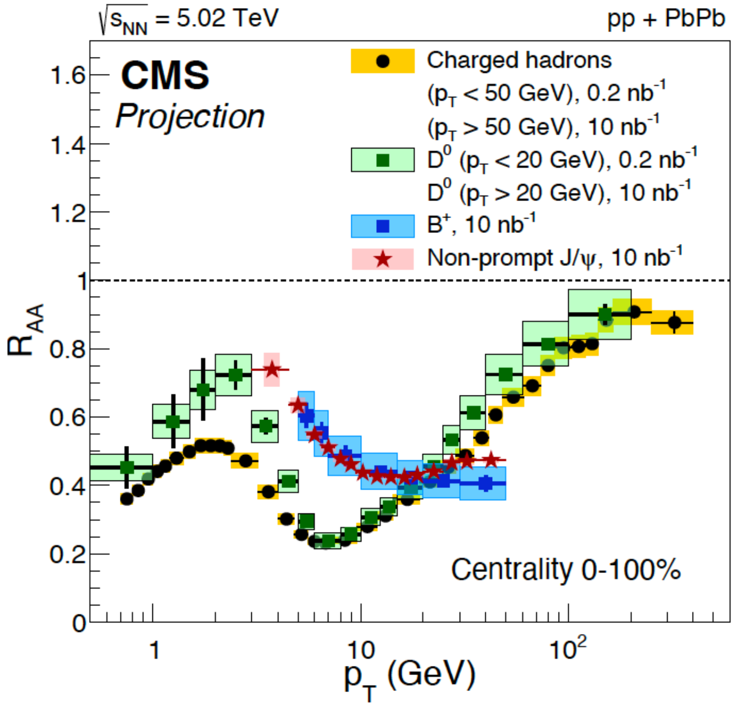
Need more precise measurements and more theory efforts

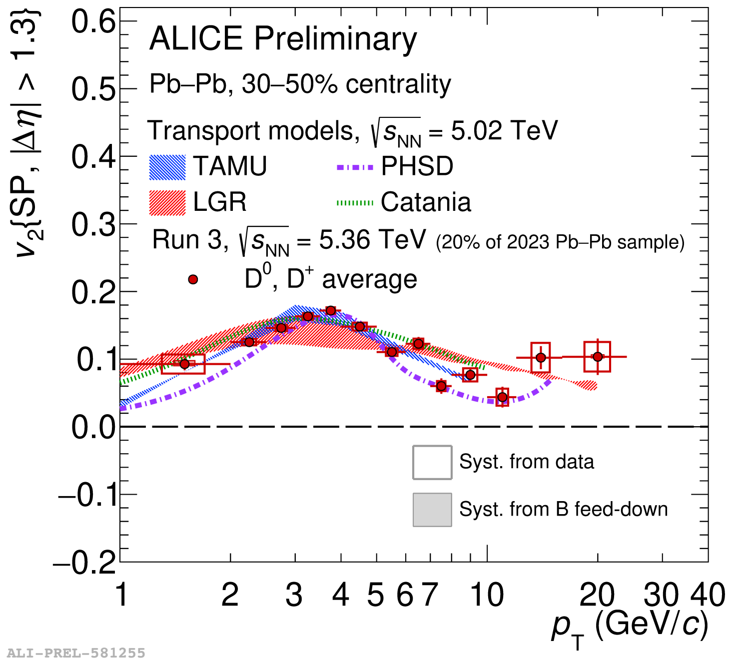
M. Li

Towards the future









B. Zhang

What do we learn from open heavy flavor

Experiment

Measurements much more precise

- Baryon enhancement, strangeness enhancement
- Elliptic flow, R_{AA}

Spin alignment

Energy-energy correlator

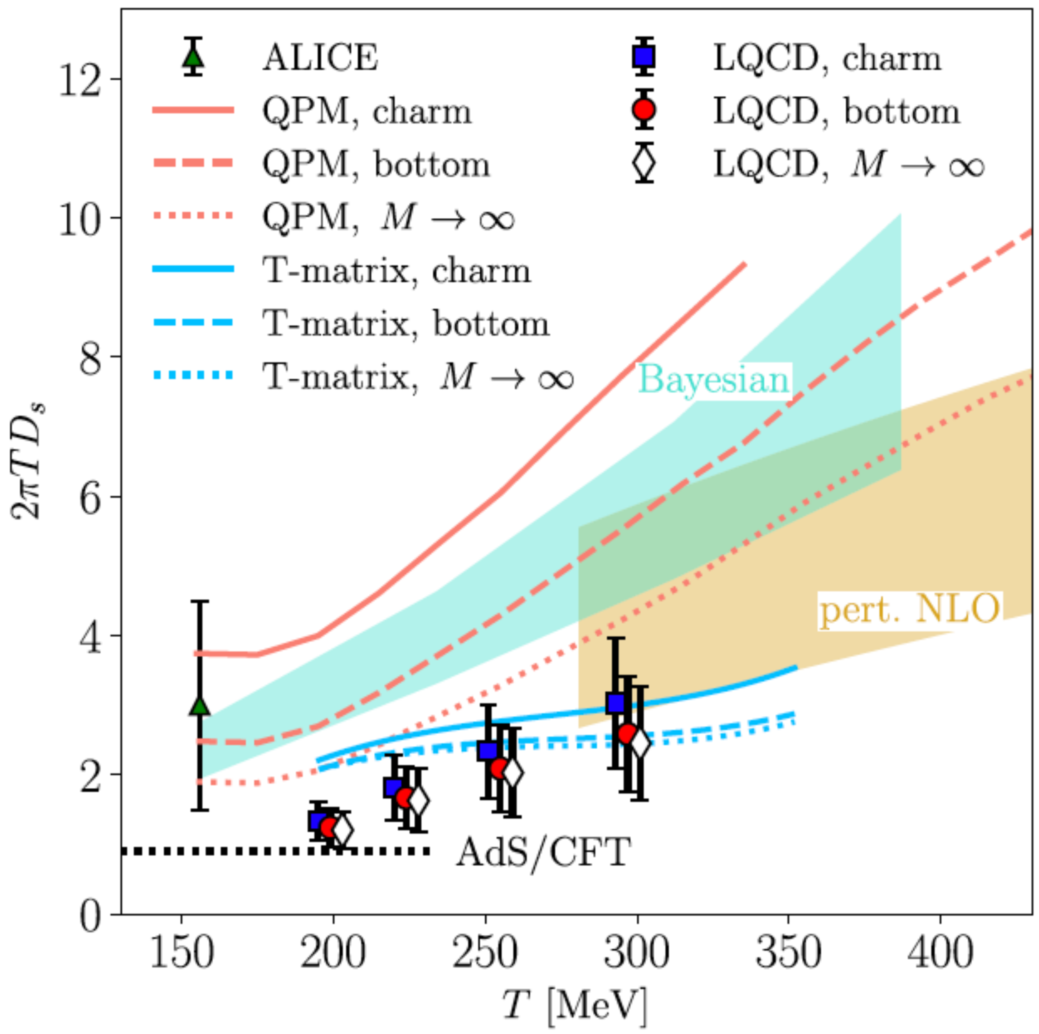
Dead-cone effect in heavy flavor jets

Higher mass states from Run 3:

$\Sigma_c^{0,++}(2520)$ $\Sigma_c^{0,++}(2455)$

…

Theory



How do we move forward

Need strong theory collaboration

- Heavy Flavor EMMI Rapid Reaction Task Force 2016, arXiv: 1803.03824
  - Initial heavy flavor spectra including initial c quark pt distribution and D meson FFs
  - Cold nuclear matter effects
  - Bulk evolution models
  - Hadronization
  - Transport coefficients and implementation
  - High-p_T energy loss and qhat

Extraction of Heavy-Flavor Transport Coefficients in QCD Matter

R. Rapp[*1], P.B. Gossiaux[*2], A. Andronic[*3,4], R. Averbeck[*3], S. Masciocchi[*3], A. Beraudo[5], E. Bratkovskaya[3,6], P. Braun-Munzinger[3,7], S. Cao[8], A. Dainese[9], S.K. Das[10,11], M. Djordjevic[12], V. Greco[11,13], M. He[14], H. van Hees[6], G. Inghirami[3,6,15,16], O. Kaczmarek[17,18], Y.-J. Lee[19], J. Liao[20], S.Y.F. Liu[1], G. Moore[21], M. Nahrgang[2], J. Pawlowski[22], P. Petreczky[23], S. Plumari[11], F. Prino[5], S. Shi[20], T. Song[24], J. Stachel[7], I. Vitev[25], and X.-N. Wang[26,18]

Recommendations from the task force

Recommend future modeling efforts

1. Adopt FONLL baseline HQ spectra with EPS09 shadowing for the initial conditions in transport simulations.

2. Employ publicly available hydrodynamic or transport evolution models which have been tuned to data, with a maximal range of viable initial conditions and model parameters; or even a single one with a pre-specified tune as a single point of contact of all approaches.

3. Use recombination schemes of heavy quarks with light medium partons which satisfy 4-momentum conservation and recover equilibrium distributions in the long-time limit for the resulting hadron distributions.

4. Incorporate nonperturbative interactions in the modeling of heavy-flavor transport in a QGP at moderate temperatures as established and constrained by information from lattice QCD; utilize resummed interactions leading to bound-state formation near Tc to facilitate a seamless transition into coalescence processes.

5. Include diffusion through the hadronic phase of heavy-ion collisions.

Recommendations from the task force

Suggest future experimental efforts

A. Bottom observables as the theoretically cleanest probe of a strongly-coupled QGP, in terms of the implementation of both microscopic interactions and transport, and as a measure of coupling strength without saturation due to thermalization;

B. v_2 peak structures and maximal values for D and B mesons to gauge the heavy-flavor interaction strength and delineate elastic and radiative regimes;

C. Precision R_{AA} and v_2 of D and B mesons at various beam energies to extract temperature and mass dependence of transport coefficients;

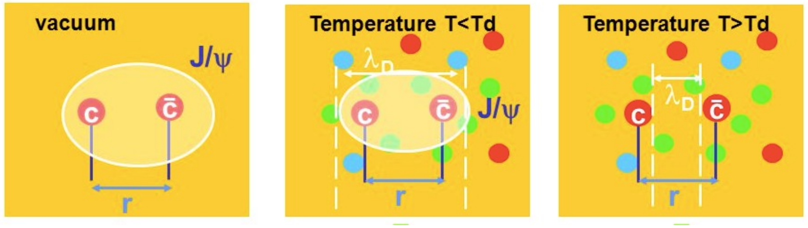
D. D_s and Lambda_c hadron observables at low and intermediate p_T to unravel the in-medium charm-quark chemistry, specifically its role in hadronization processes and reach in p_T;

E. Heavy-flavor (especially bottom) in jets to disentangle gluon vs. heavy-flavor energy loss and production mechanisms (direct vs. gluon splitting).

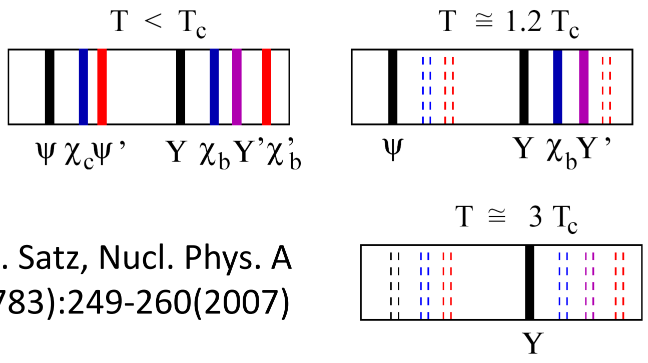
F. Correlation measurements of heavy-flavor pairs to delineate collisional from radiative interactions and test Langevin against Boltzmann transport approaches.

Quarkonia as thermometer?

Color screening



$r_{q\bar{q}} \sim 1/E_{binding}$ vs. $\lambda_D \sim 1/T$



H. Satz, Nucl. Phys. A (783):249-260(2007)

Dissociation: dynamic screening

Recombination

Cold nuclear matter effects

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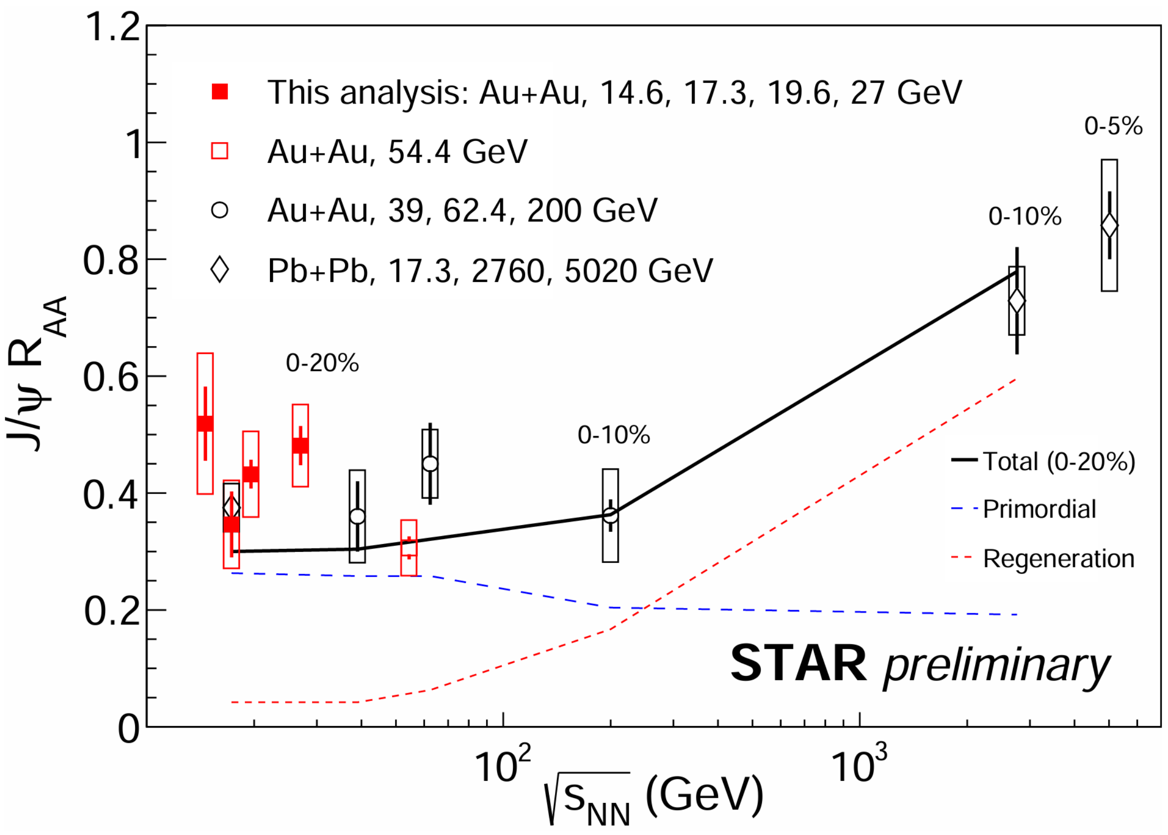
J/psi suppression from SPS to LHC

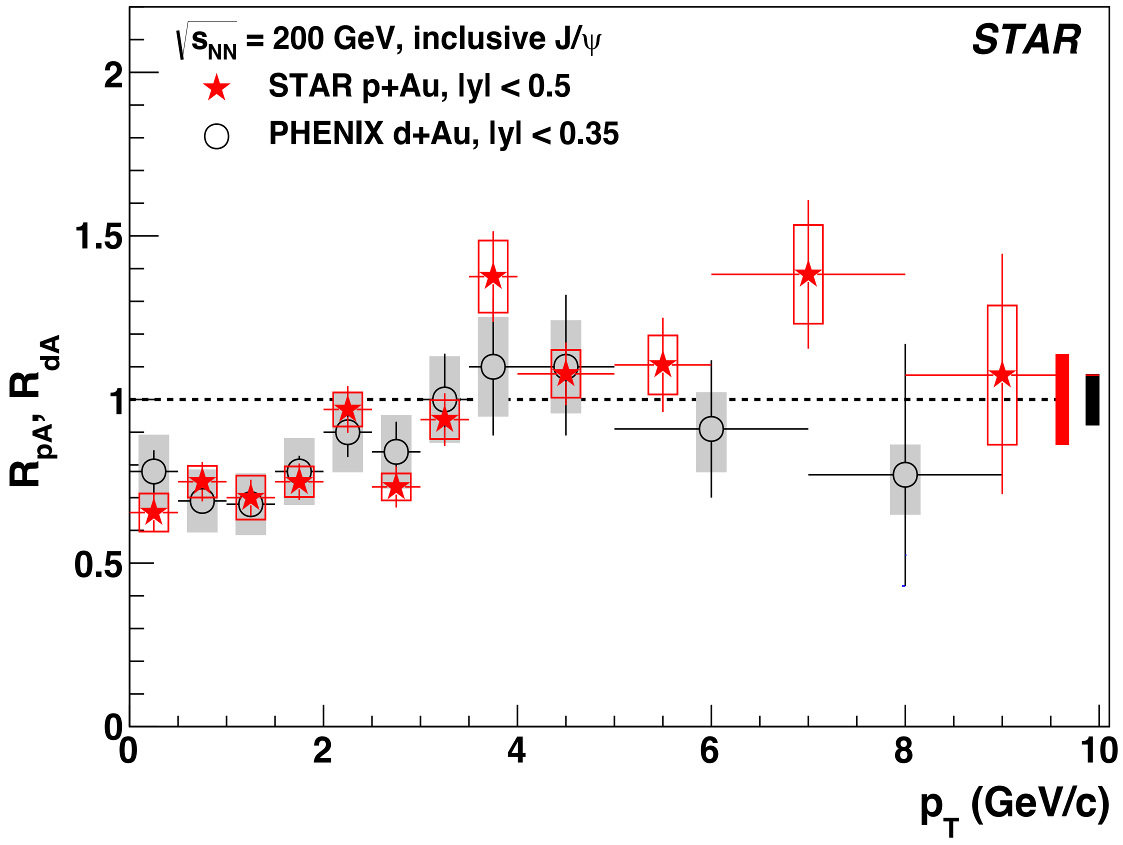


X. Zhao, R. Rapp, PRC 82 (2010) 064905
NA50, PLB 477 (2000) 28, STAR, PLB 771 (2017) 13, STAR, PLB 797 (2019) 134917
ALICE, PLB 734 (2014) 314, ALICE, NPA 1005 (2021) 121769

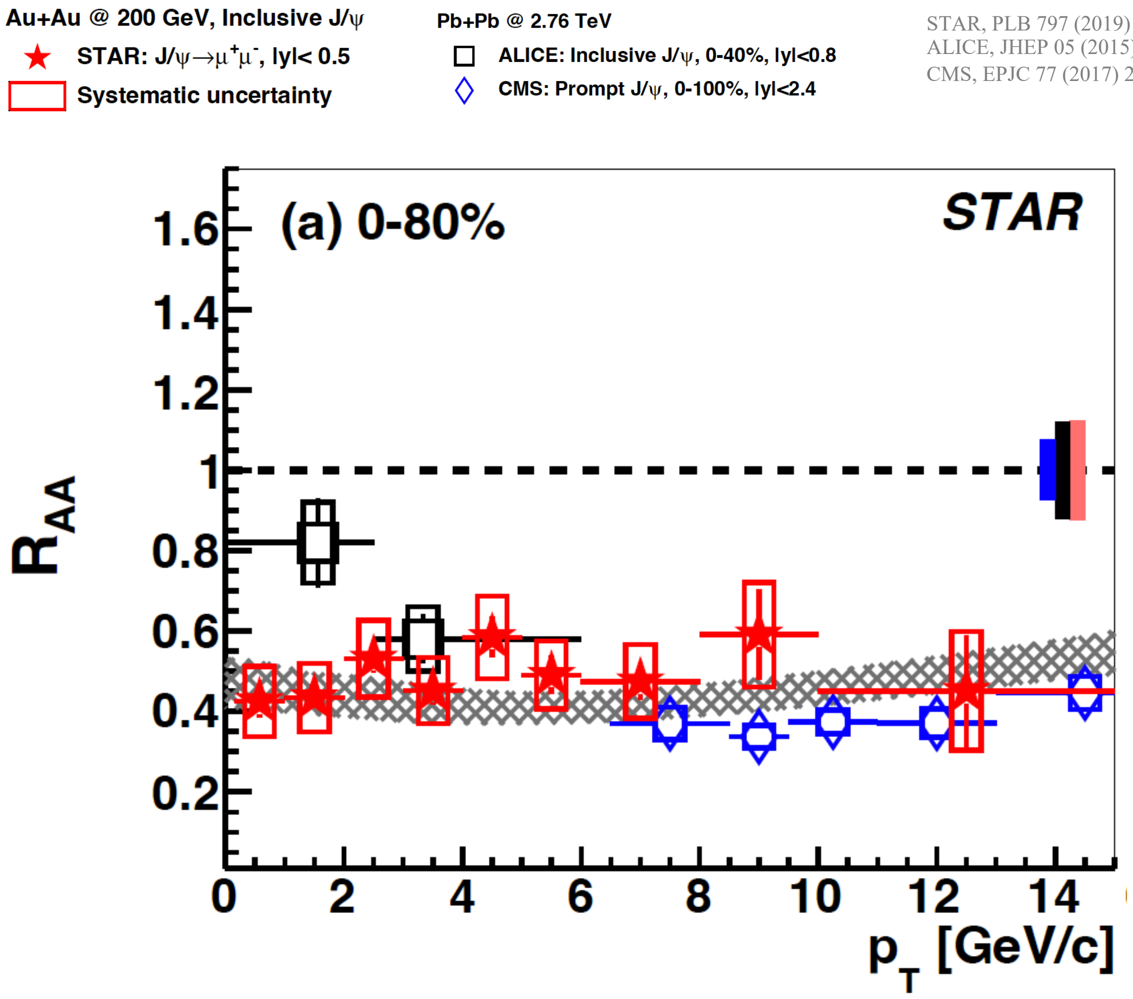
Interplay between CNM, color screening, dissociation, and recombination

W. Zhang

J/psi suppression: p_T dependence



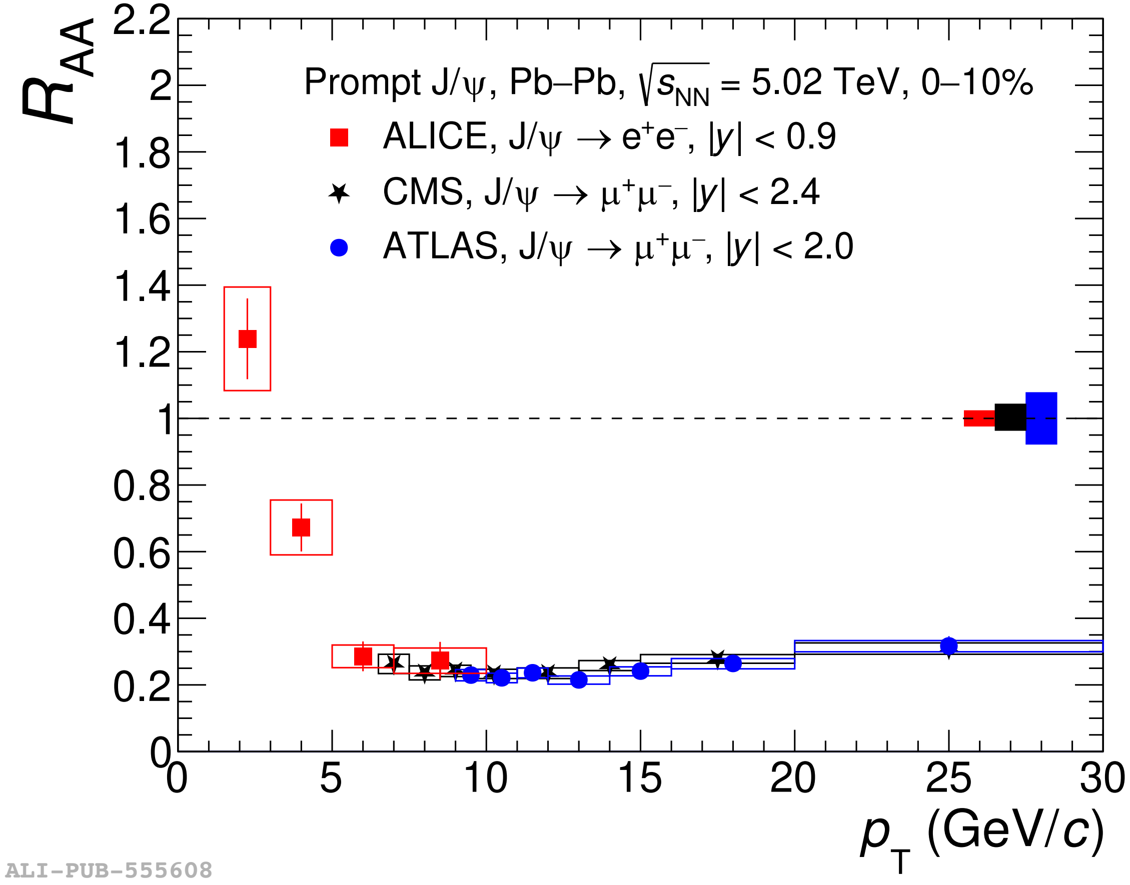
PHENIX, PRC 87 (2013) 034904; STAR, PLB 825 (2022) 136865



STAR, PLB 797 (2019) 134917
ALICE, JHEP 05 (2015) 051
CMS, EPJC 77 (2017) 252

High p_T suppression: evidence of color screening and dissociation

J/psi suppression: p_T dependence

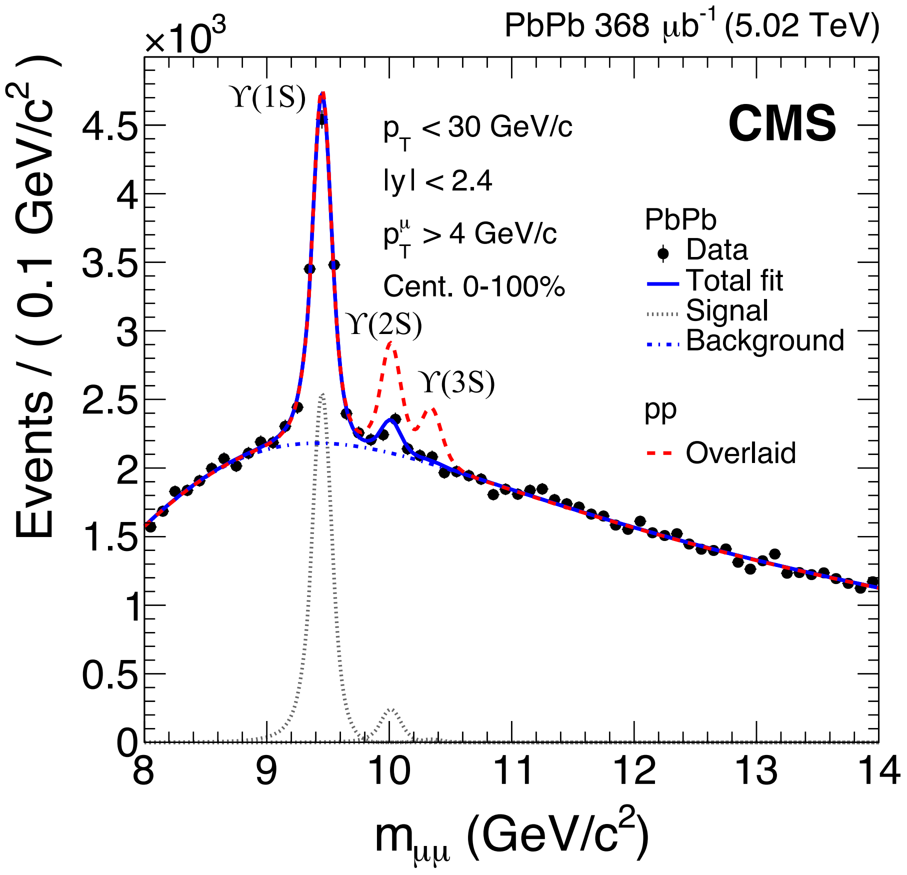


ALICE, JHEP 02 (2024) 066
ATLAS, EPJC 78 (2018) 762
CMS, EPJC 78 (2018) 509

High p_T suppression: evidence of color screening and dissociation

Sequential Upsilon suppression

CMS, PRL 120 (2018) 142301



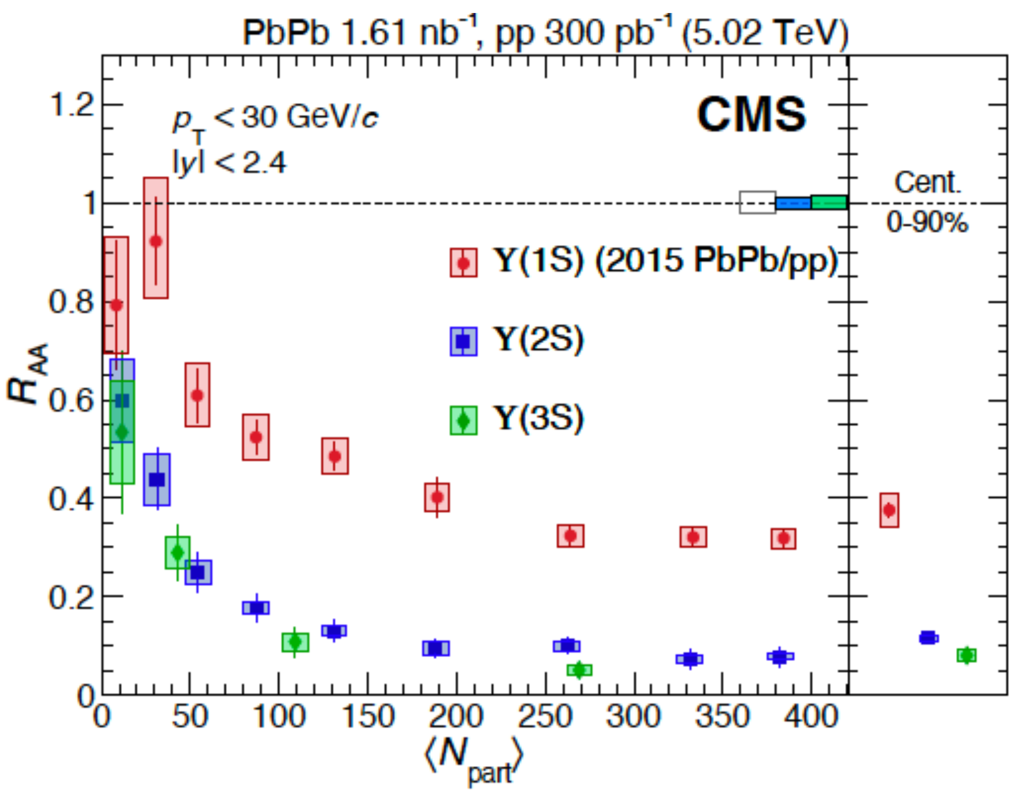
ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

Much less contribution from b and bbar recombination

Sequential ϒ suppression at LHC

Sequential Upsilon suppression

CMS, PRL 133 (2024) 022302



ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

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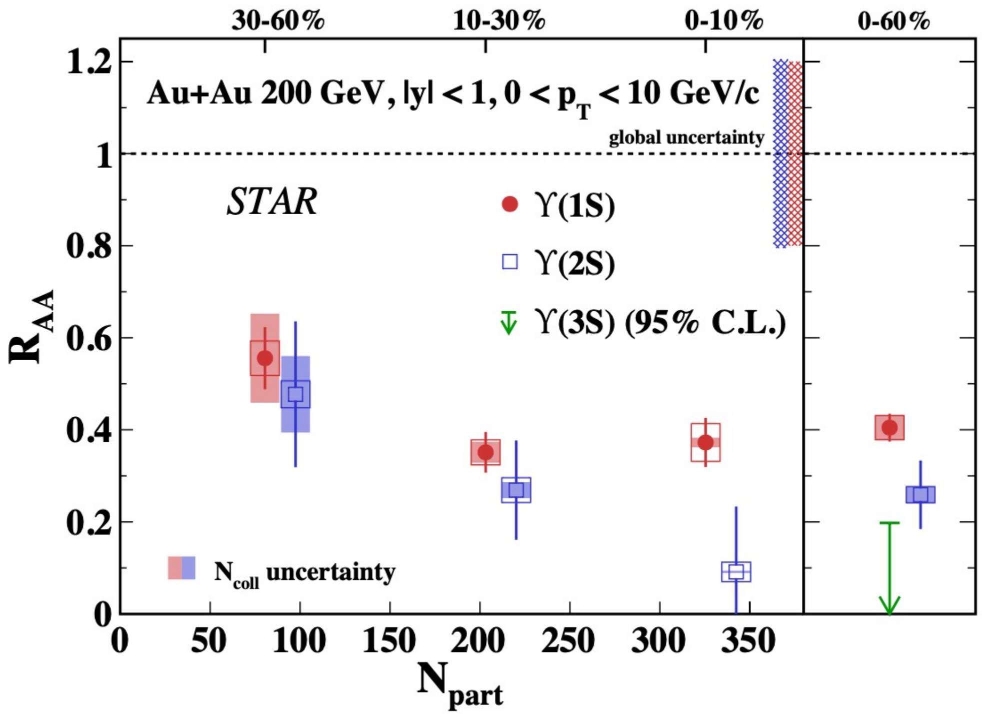
Sequential ϒ suppression at LHC

Sequential Upsilon suppression

STAR, PRL 130 (2023) 112301



ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

Negligible contribution from b and bbar recombination at RHIC

ϒ(1S) R_{AA} = 0.40 ± 0.03 (stat.) ± 0.03 (sys.) ± 0.07 (norm.)

ϒ(2S) R_{AA} = 0.26 ± 0.07 (stat.) ± 0.02 (sys.) ± 0.04 (norm.)

ϒ(3S) R_{AA} upper limit: 0.20 at a 95% confidence level

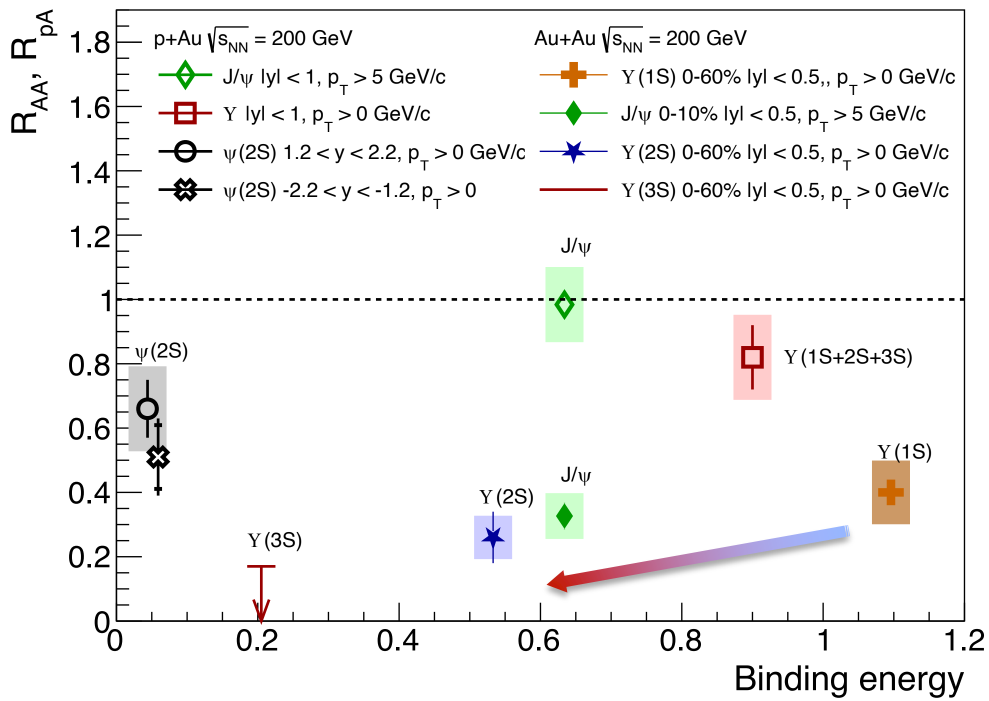
Sequential ϒ suppression at RHIC

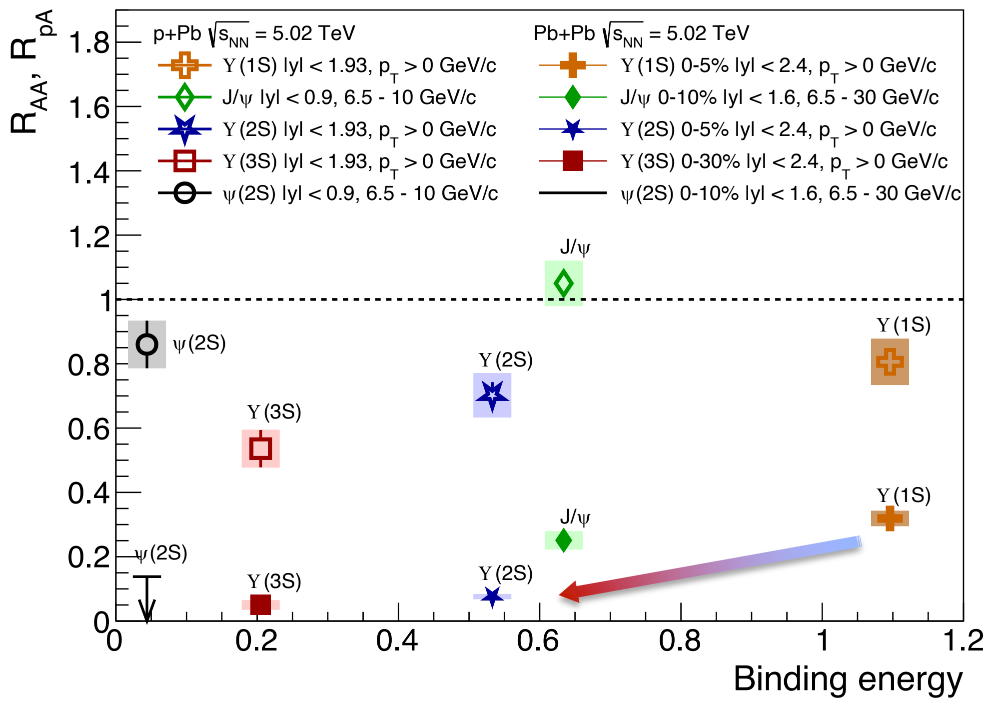
Quarkonium suppression vs. binding energy

RHIC

Hot QCD White Paper, arXiv:2303.17254

LHC



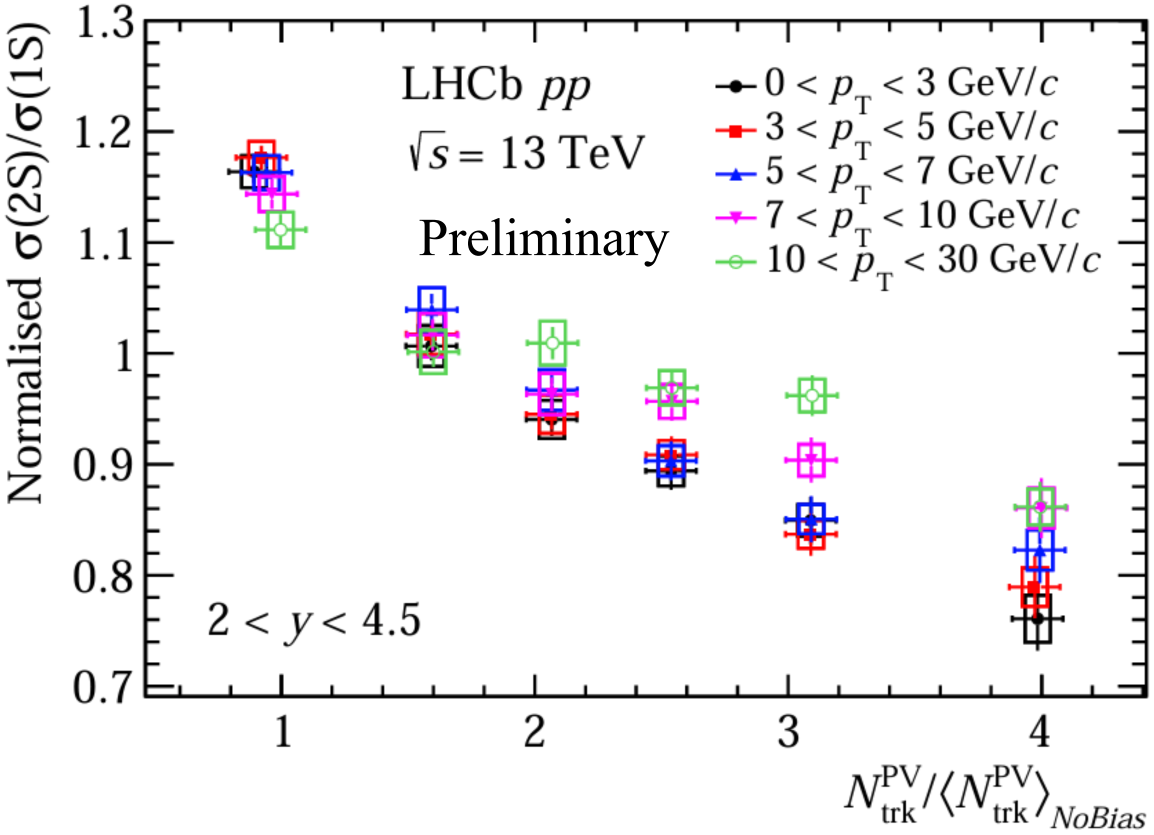


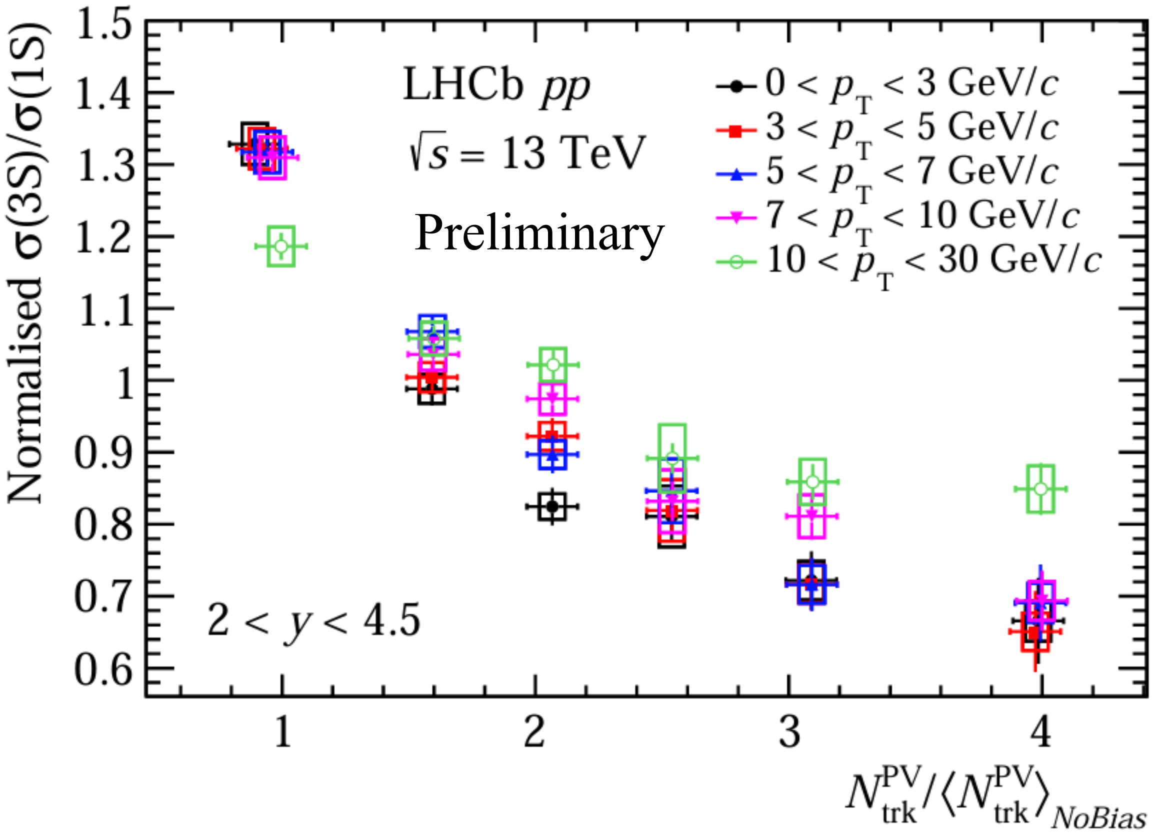
Sequential suppression pattern observed

Caveats: p+A measurements, feed-down contributions

Need to measure higher excited states and improve precision

Upsilon suppression in p+p collisions





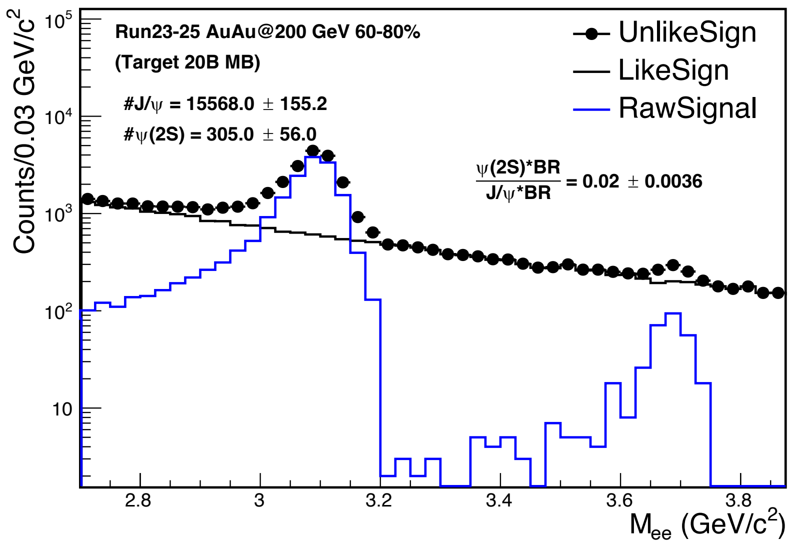
Sequential suppression pattern observed

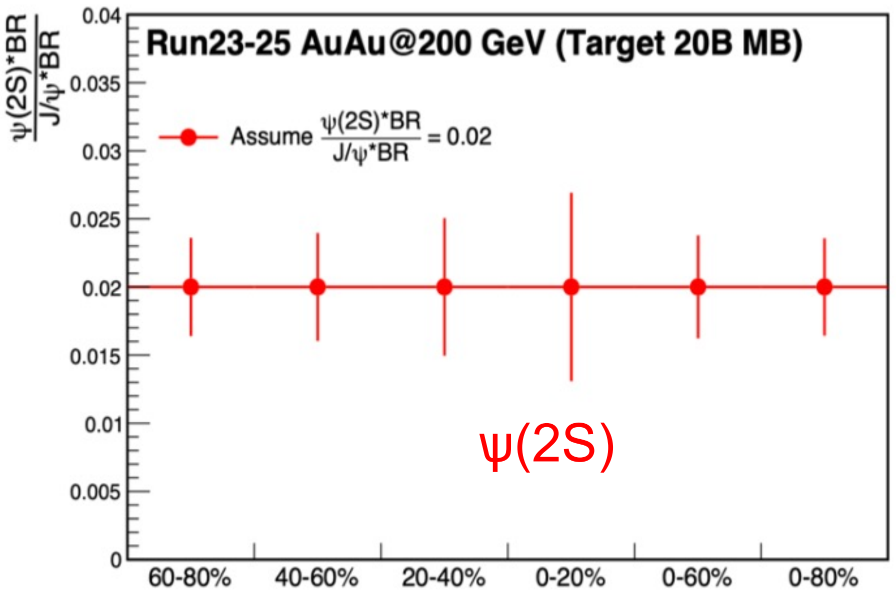
- 35% of $\Upsilon(2S)$ comes from $\chi_b(2P)$
- high-p_T $\Upsilon(3S)$ has about 35% dissociation, also consistent with the high-p_T $\chi_b(3P)$ feed-down fraction

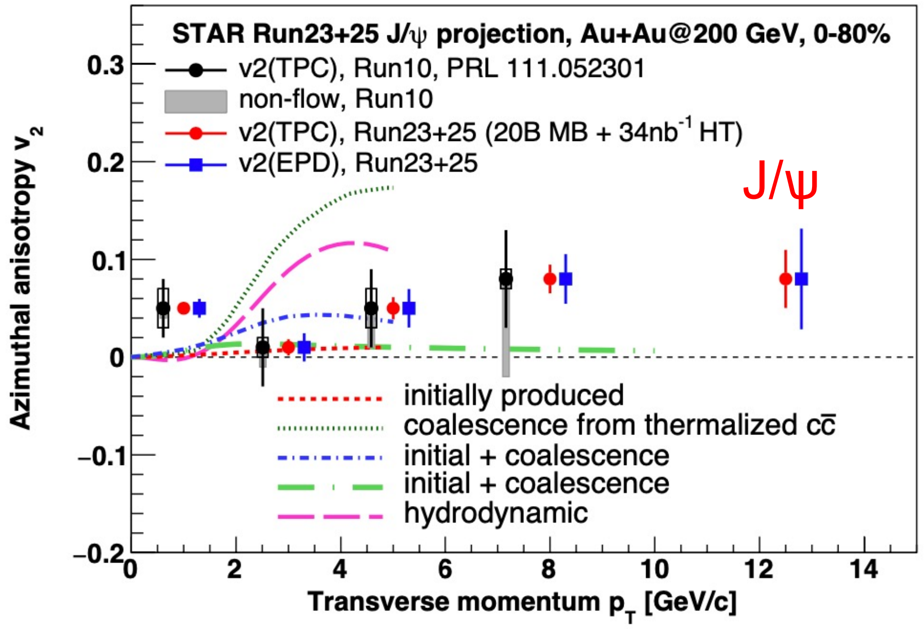
C. Dong's poster, C. Luiz Da Silva's talk

Towards the future

[STAR Beam Use Request](#)





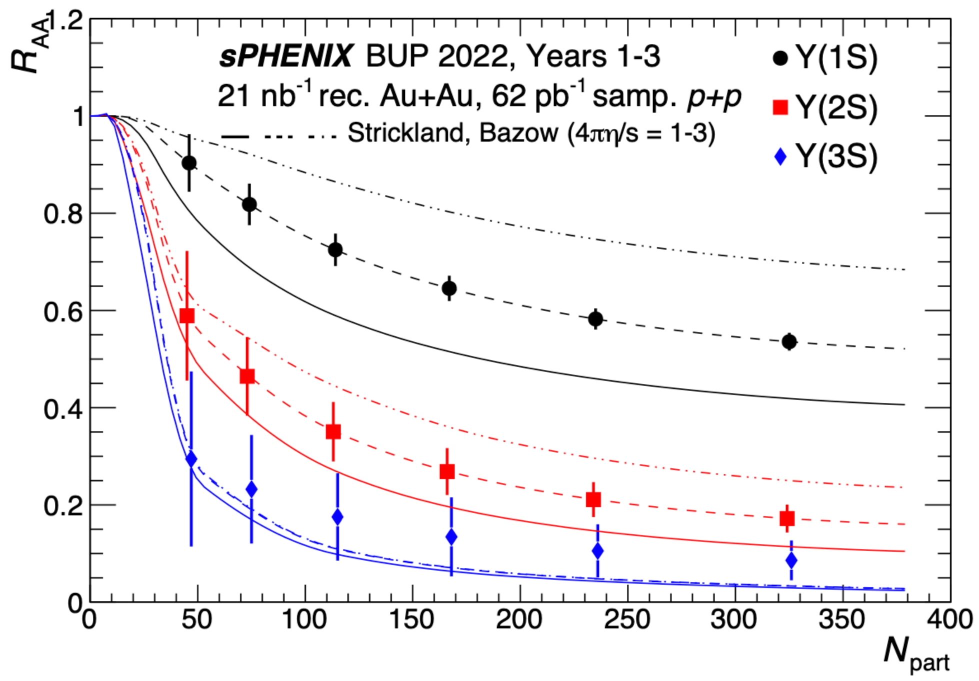


2023+2024+2025 data:
Enable first ψ(2S) measurement in Au+Au at RHIC

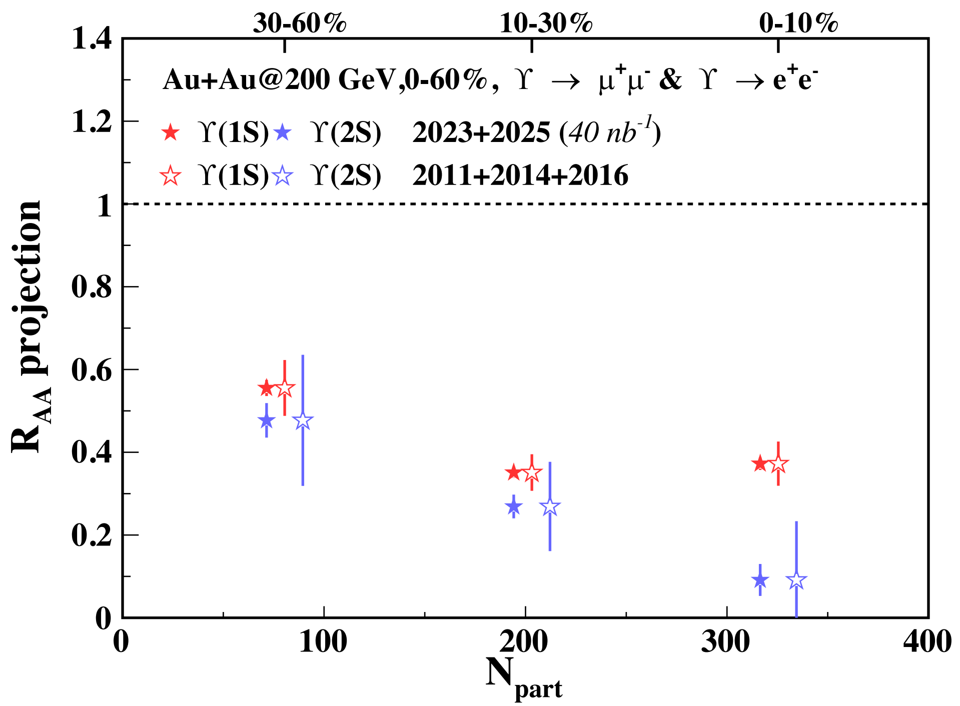
Improve J/ψ measurement significantly

Towards the future

sPHENIX Beam Use Proposal



STAR Beam Use Request



2023+2024+2025 data:

Enable first Upsilon(3S) R_{AA} measurement in Au+Au at RHIC

Improve Upsilon(1S) and Upsilon(2S) measurement significantly

What do we learn from quarkonia

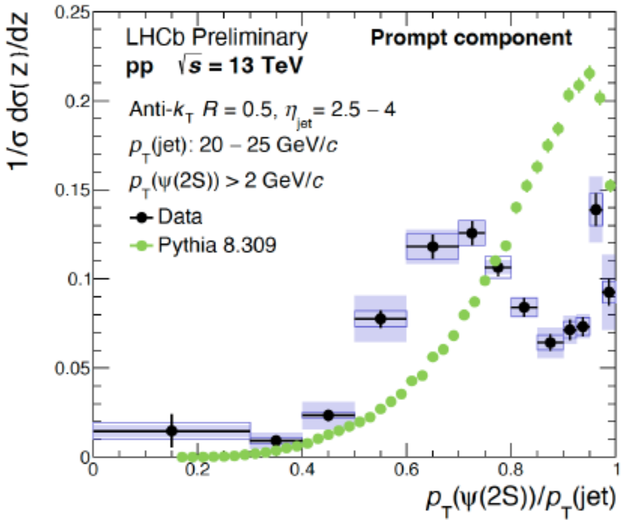
Despite all the other effects, color screening and dissociation effects were observed, evidence of the in-medium strong force modification

Not a direct thermometer, but can constrain medium temperature (> 1.5 T_c)

Important tool to understand deconfinement and hadronization

Call for a coherent picture to systematically understand quarkonium production in heavy ion collisions. Open quantum system? How about p+p, p+A?

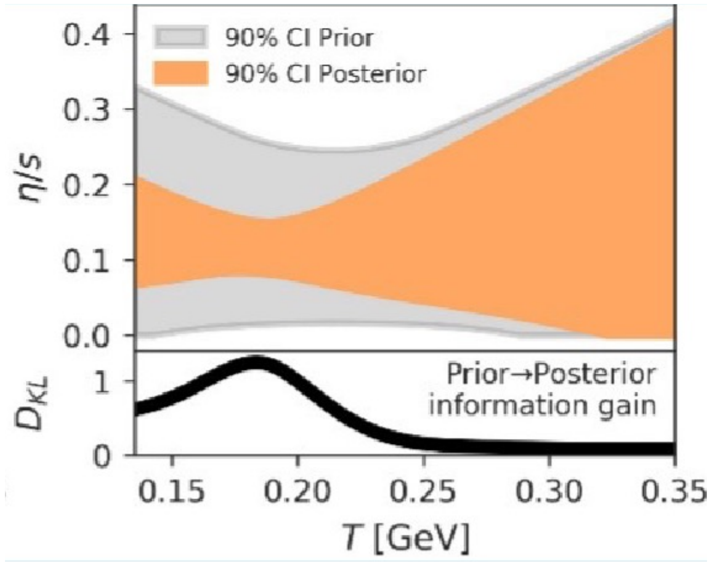
HEFTY
COLLABORATION



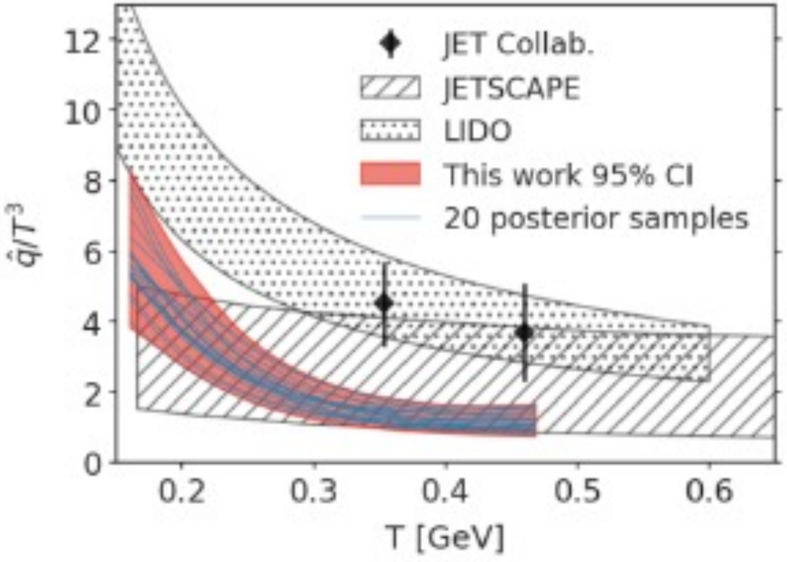
M. Durham

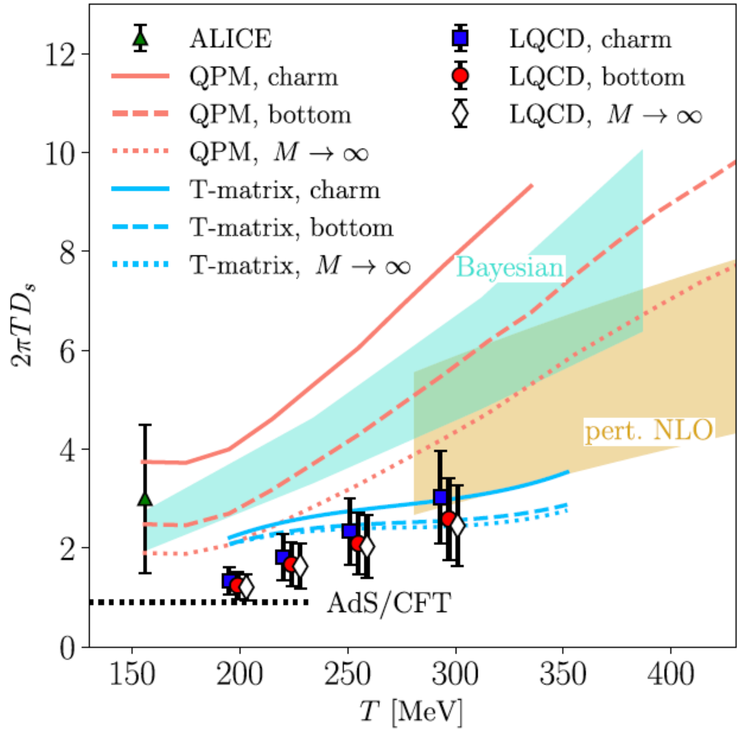
Summary

JETSCAPE Collaboration, PRL 126 (2021) 242301



Man Xie et al., Phys. Rev. C **108** (2023) L011901





The newly built sPHENIX detector and upgraded STAR detector at RHIC, together with increased luminosity at the LHC and upgraded ALICE, ATLAS, CMS and LHCb detectors, will enable a multi-messenger era for hot QCD based on the combined constraining power of precise measurements using soft, hard, and electro-magnetic probes. --> Establish a coherent picture of heavy ion collisions and inform properties of quark-gluon matter with strong theory collaboration.