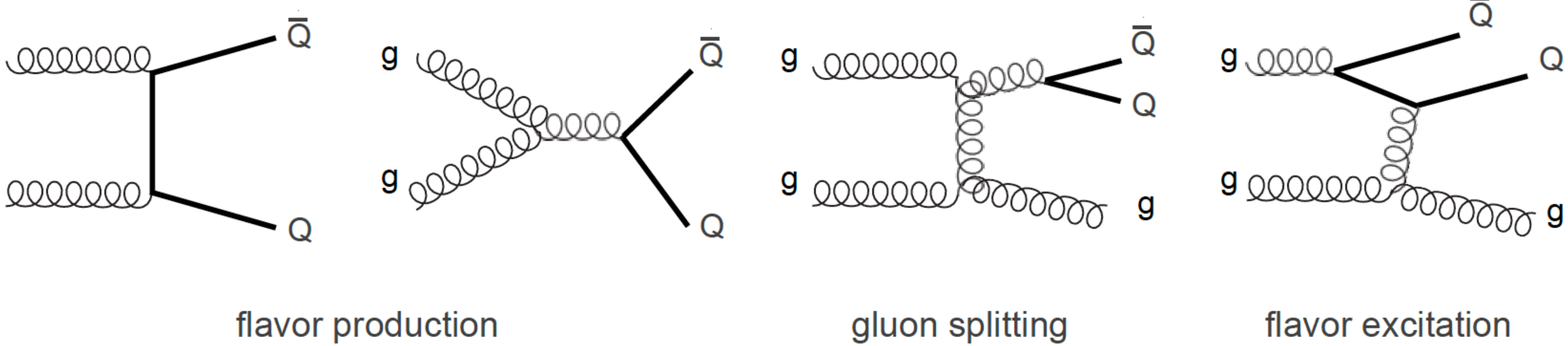
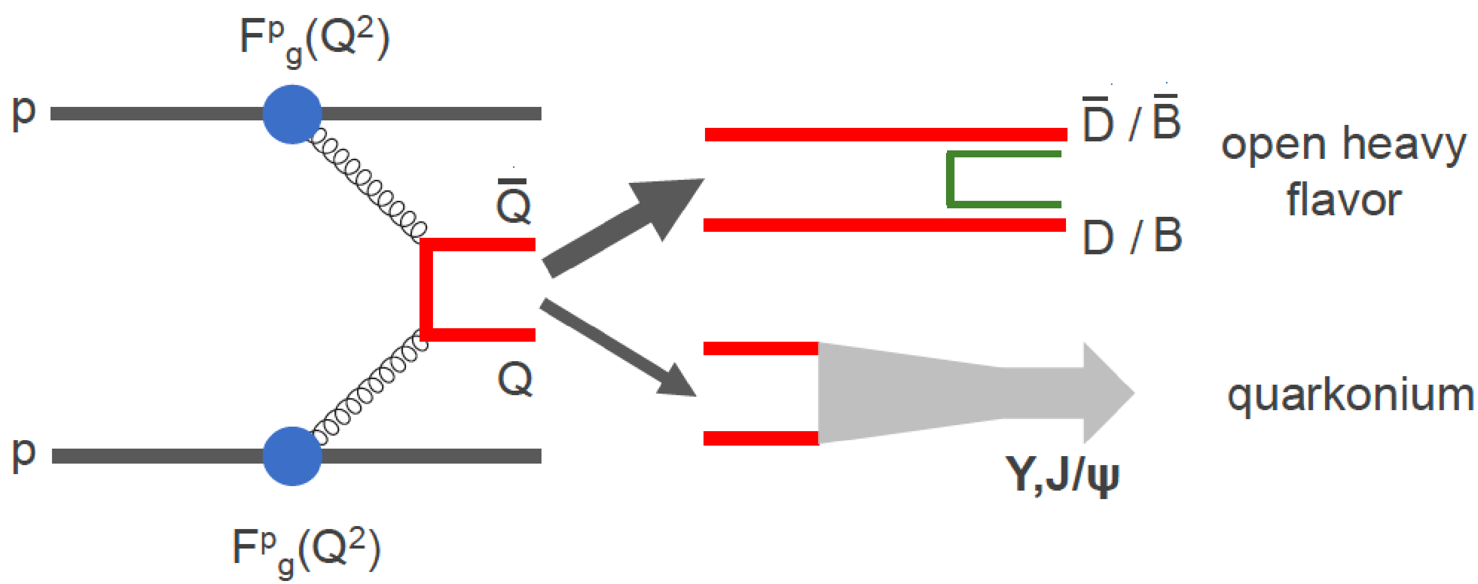
Quarkonium production at the LHC: experiment and theory overview

A. Andronic - University of Münster

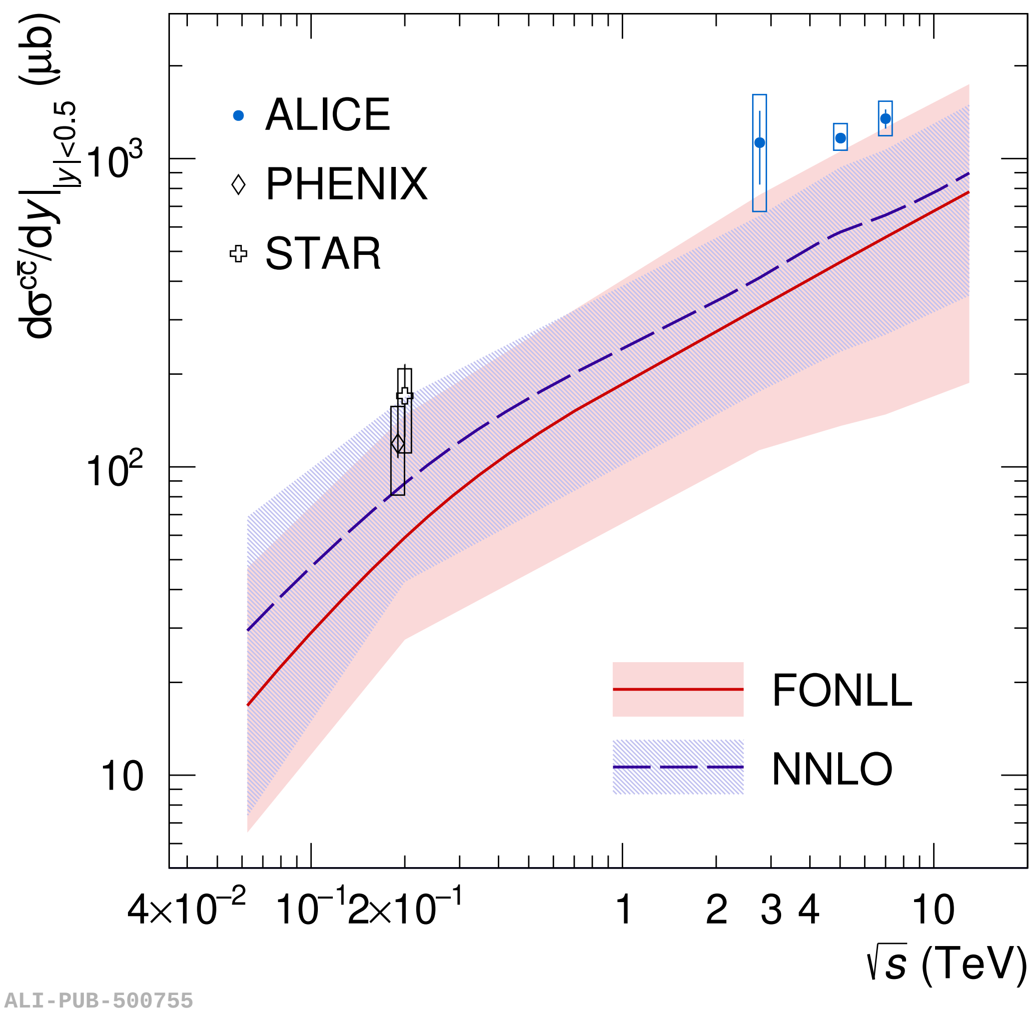
- Measurements and models in pp collisions (brief)
- Data and models in Pb-Pb collisions (compared to RHIC data)

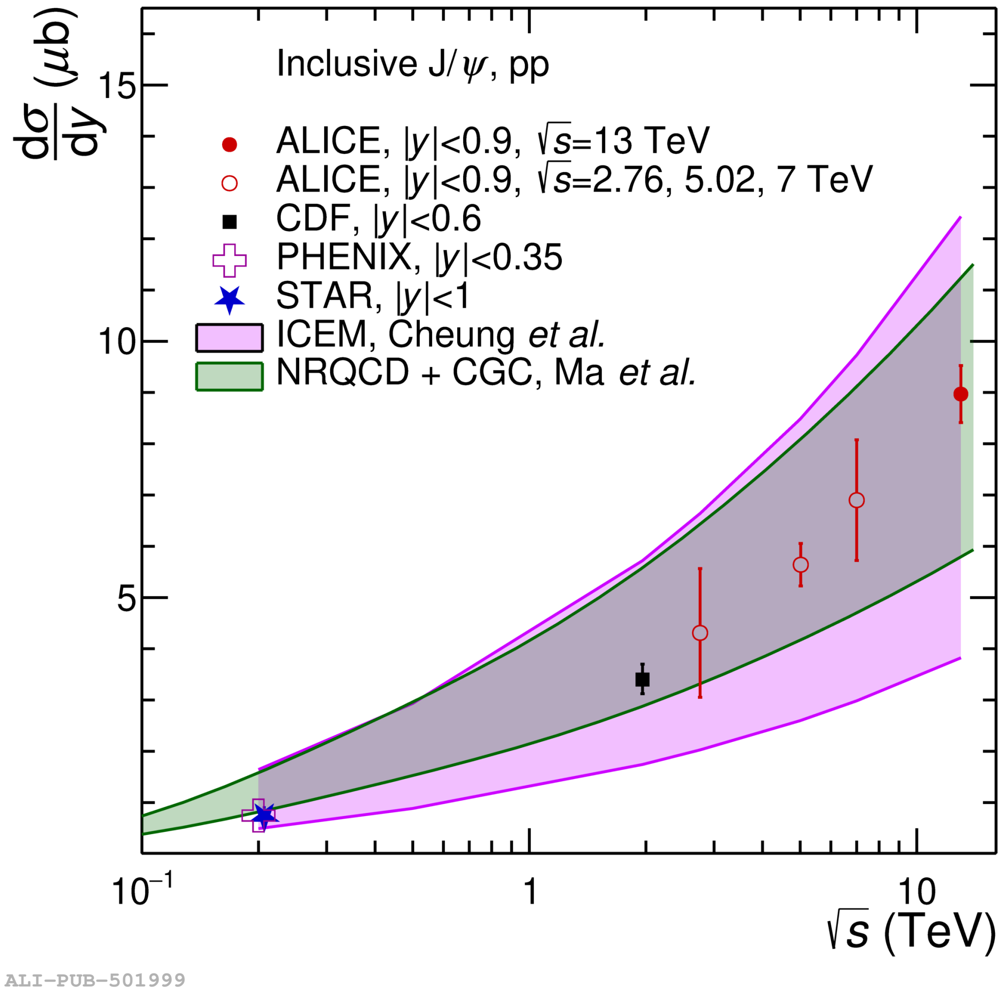
Heavy-quark and quarkonium production





A. Rothkopf, arXiv:1912.02253





ALICE, PRD 105 (2022) L011103

ALICE, Eur. Phys. J. C 81 (2021) 1121

FONLL, NNLO: perturbative QCD calculations

abundant charm(onium) production at the LHC; charmonium/charm ∼1%

Quarkonium models

Non-relativistic QCD (NRQCD):

as Q, $\bar{Q}$ move slowly (in quarkonium c.m.s., v), exploits hierarchy of scales $m_Q \gg m_Q v, m_Q v^2, \Lambda_{QCD}$ (≃200 MeV)

sum over all states (singlet, octet) of the product of $\sigma_{Q,\bar{Q}}$ (pQCD) times the long-distance matrix elements that describe the non-perturbative formation process (derived from fits of data or calculated in lattice QCD)

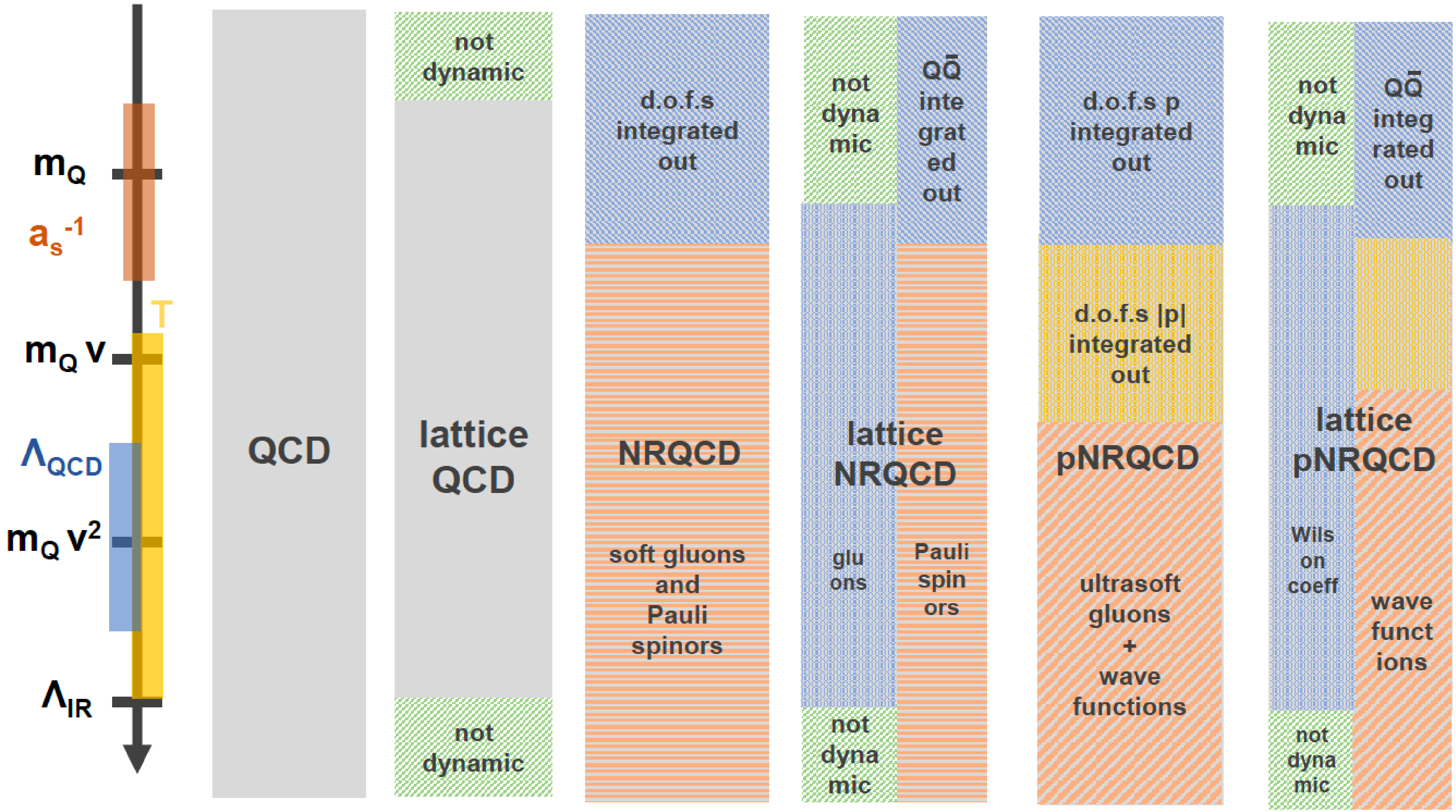
Color Evaporation Model, CEM: $\sigma_{CEM}^{pp \to H+X} = k_H \cdot \sigma_{Q,\bar{Q}}$ (quarkonium H)

Color Singlet Model, GSM: $\sigma_{CSM}^{pp \to H+X} \sim \sigma_{Q,\bar{Q}}(v=0)|R_H(0)|^2$ (S states)

$R_H(0)$ is the radial wavefunction at origin for hadron (quarkonium) H

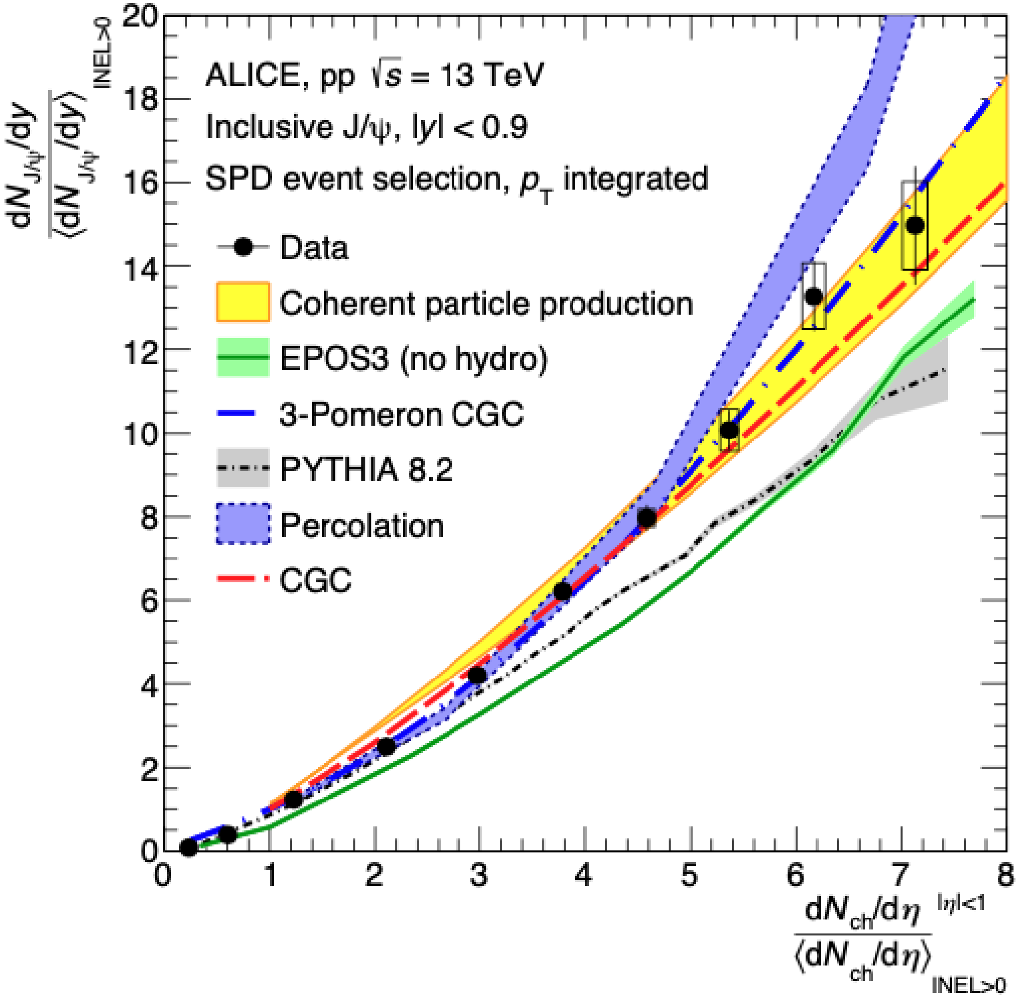
Bodwin, arXiv:1012.4215; Soto, arXiv:1101.2392;

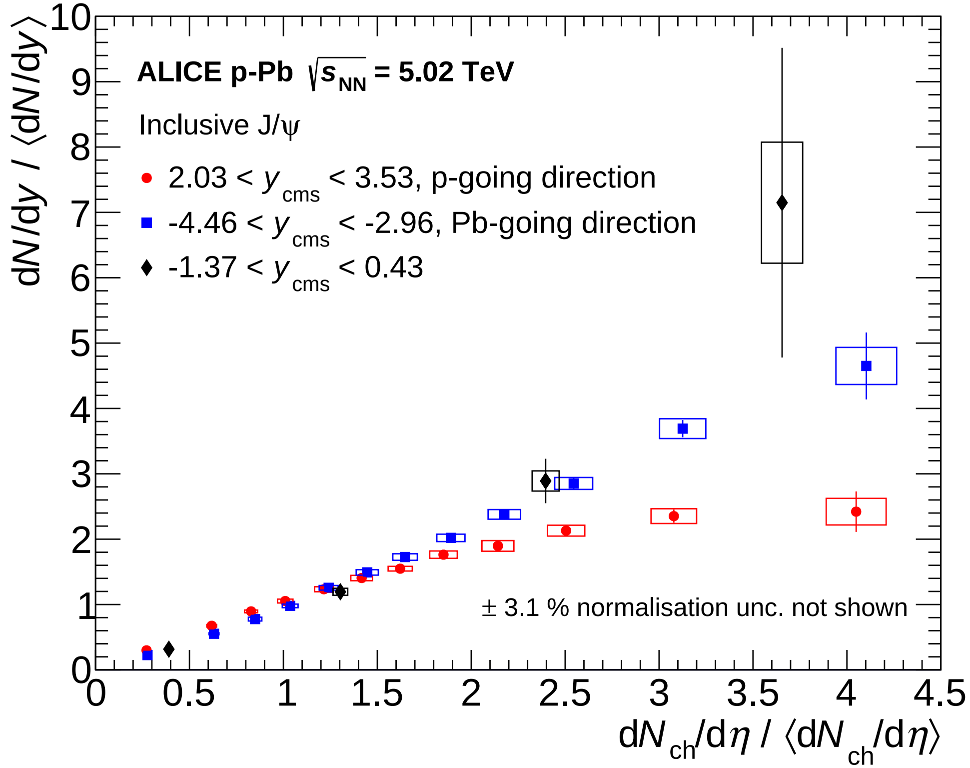
...is a rich theory field



A. Rothkopf, arXiv:1912.02253

J/ψ vs. event activity





What is trivial here? (1st diagonal?)

"Energy cost" similar for MB event (Δy=1) and J/ψ ($\simeq$6 GeV)

Similar behaviour measured for D mesons; Υ; charged part. p_T=5-6 GeV/c

the original idea: Matsui & Satz, Phys.Lett. B 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

Refinements: "sequential suppression":

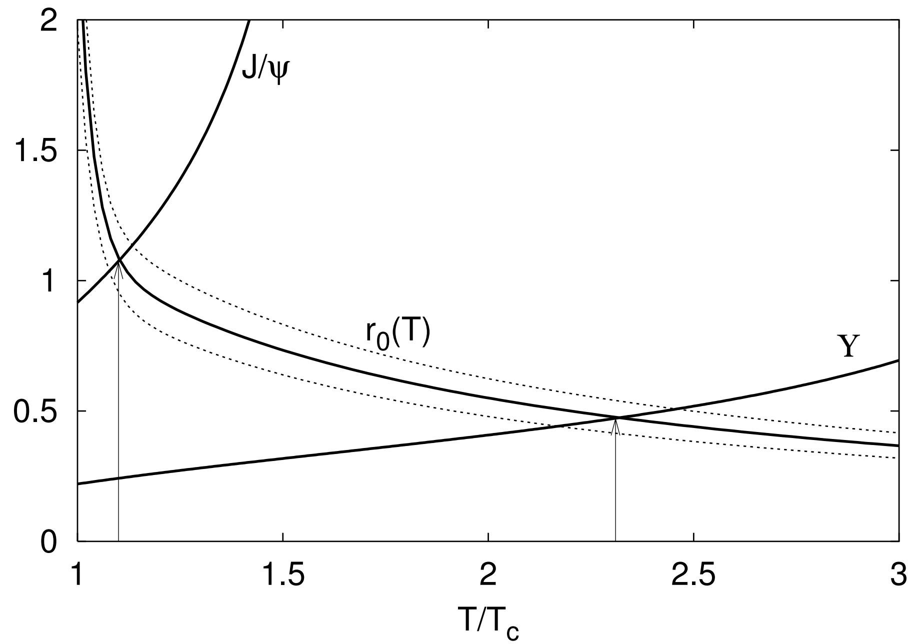
Digal et al., PRD 64 (2001) 75

no $\mathrm{q\bar{q}}$ bound state if

$r_{\mathrm{q\bar{q}}}(T) > r_0(T) \simeq \frac{1}{g(T)T}$

r_0 Debye length in QGP

$\Rightarrow$ $\mathrm{q\bar{q}}$ "thermometer" of QGP

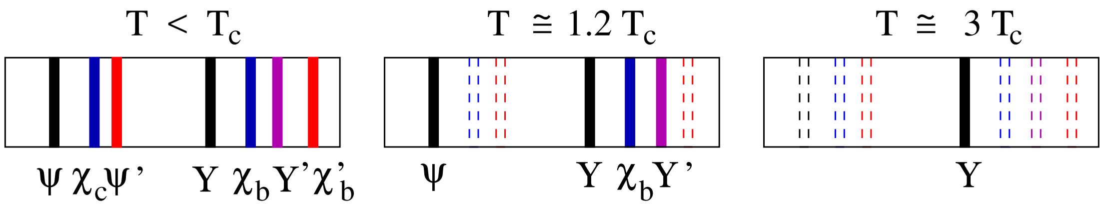


Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

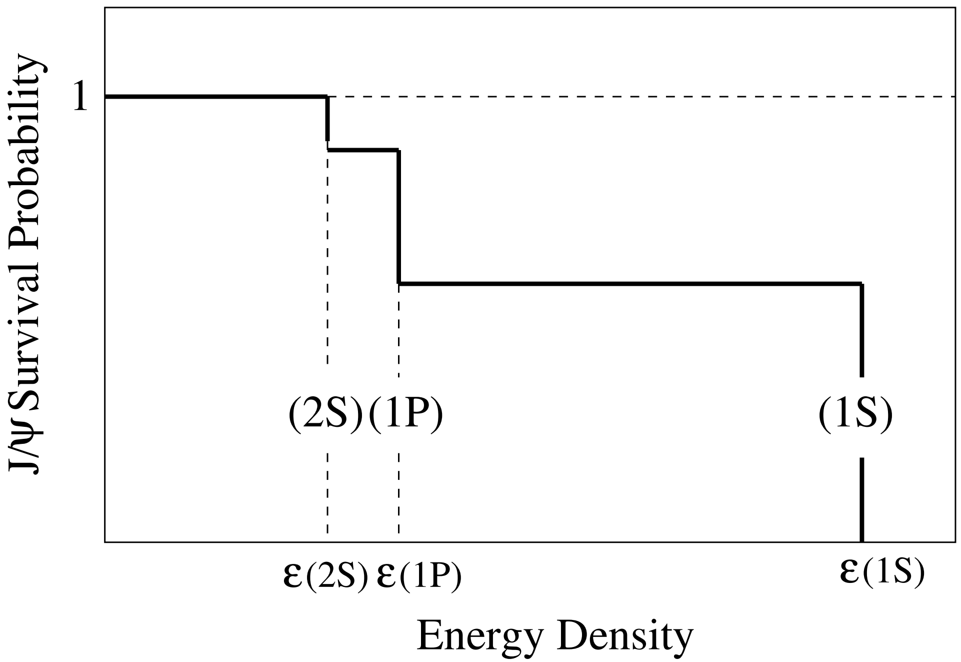
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi}$

Quarkonium and the QGP - “sequential suppression”

Digal et al., PRD 64 (2001) 75; H.Satz, arXiv:1310.1209



quantitative: lattice QCD
(next talk, by P. Petreczky)



← assumed feed-down to J/ψ:
10% from $\psi(2S)$ and 30% from χ_c

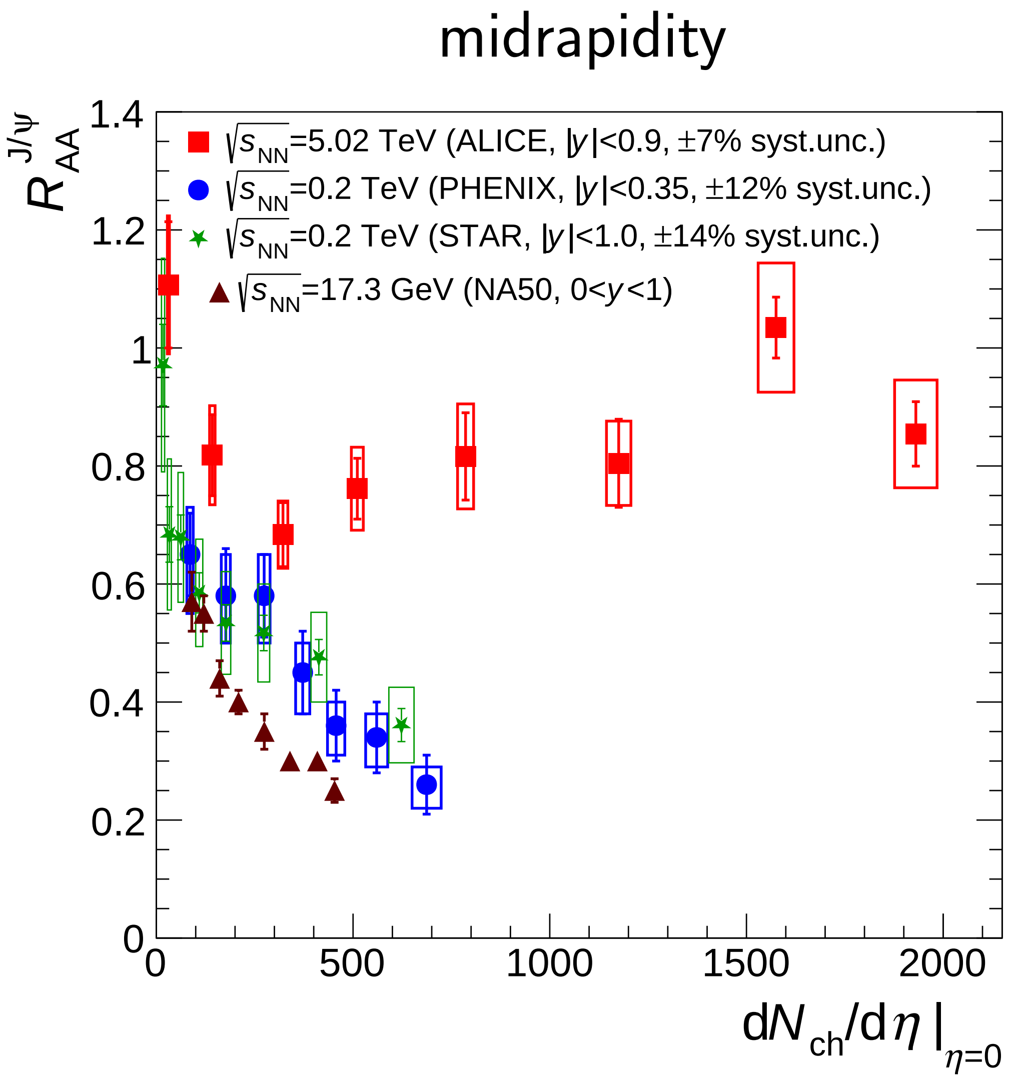
Experimentally:

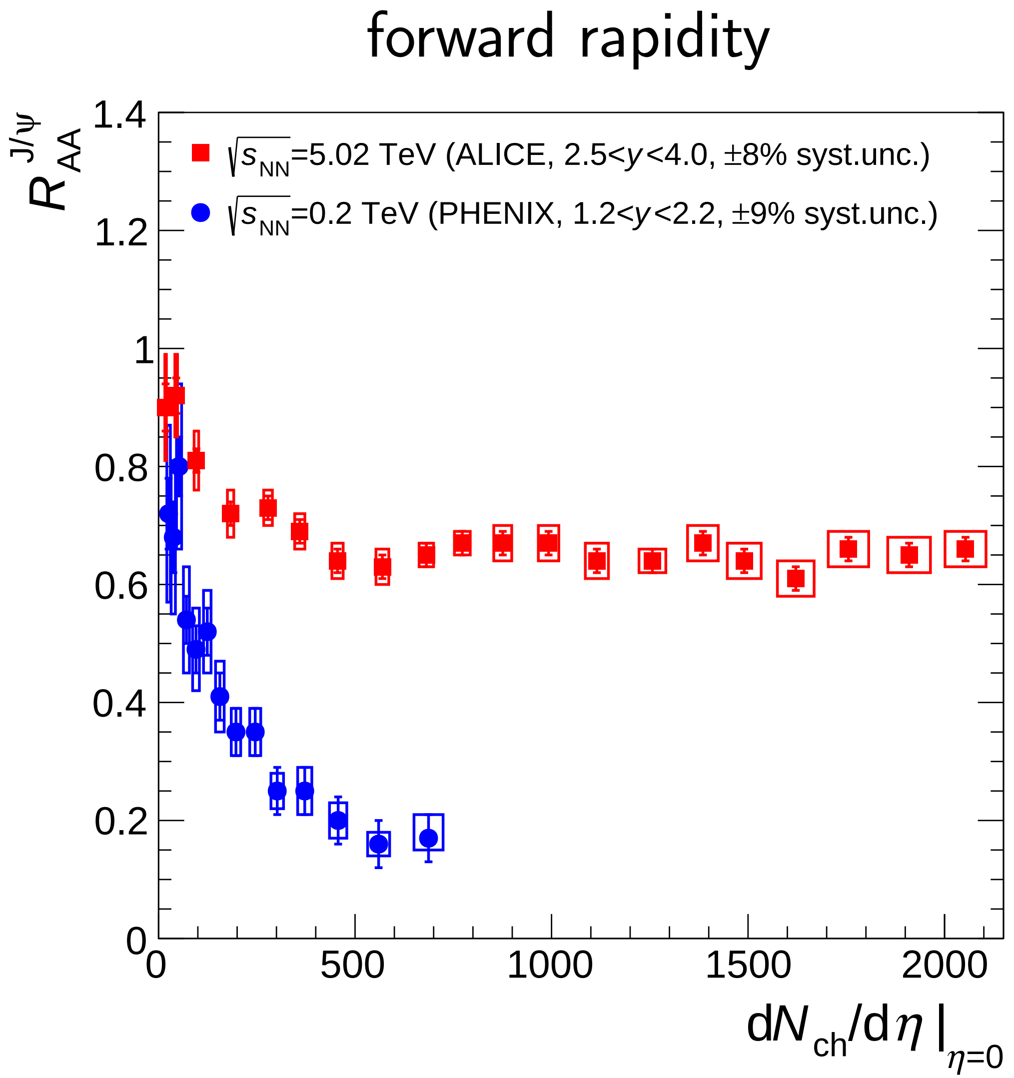
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AA}/\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$ vs. N_{part}

or N_{ch}

quarkonium as thermometer

Charmonium data: SPS, RHIC, LHC





suppression at lower energies, but not obviously a sequential one

at the LHC another effect offsets the dissociation

Charmonium data: RHIC and LHC

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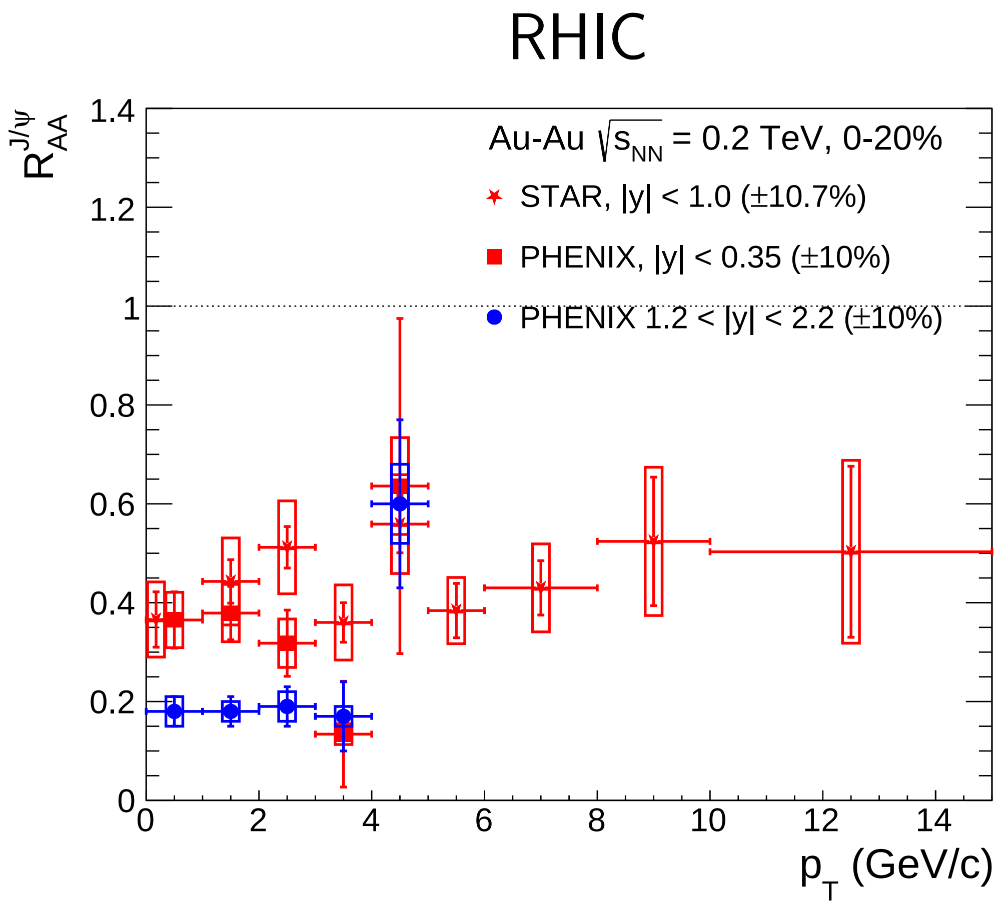
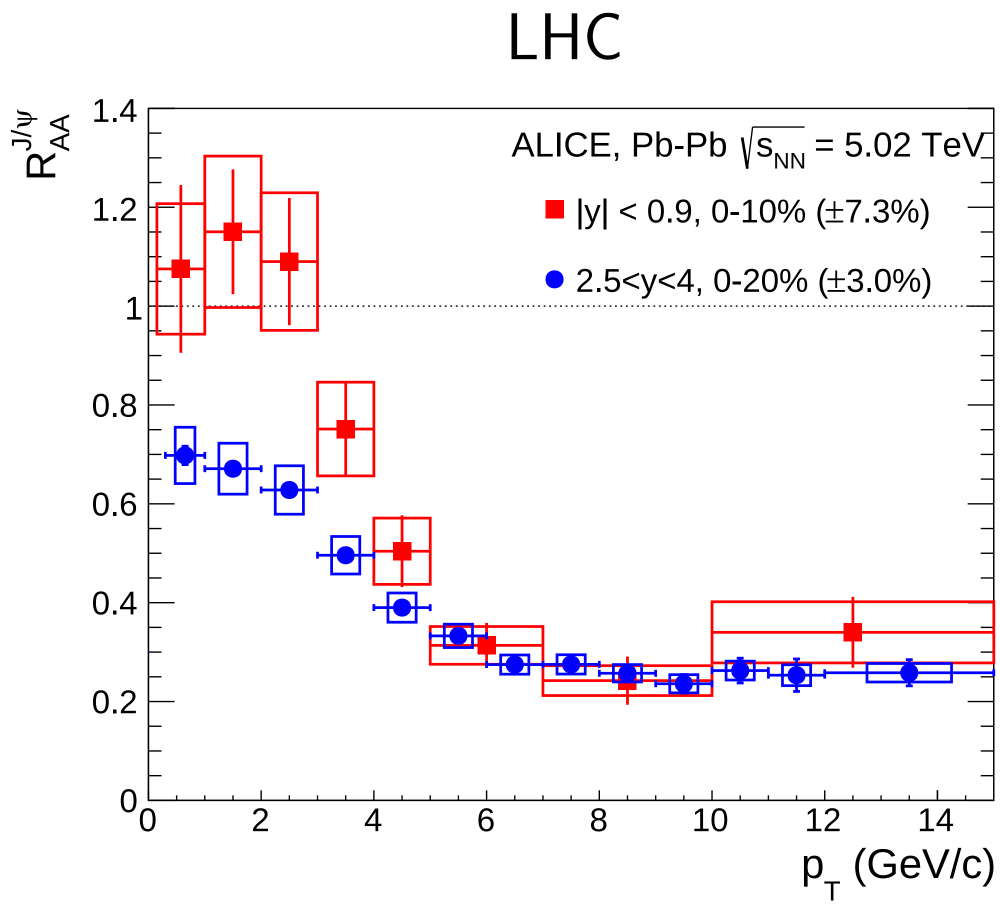
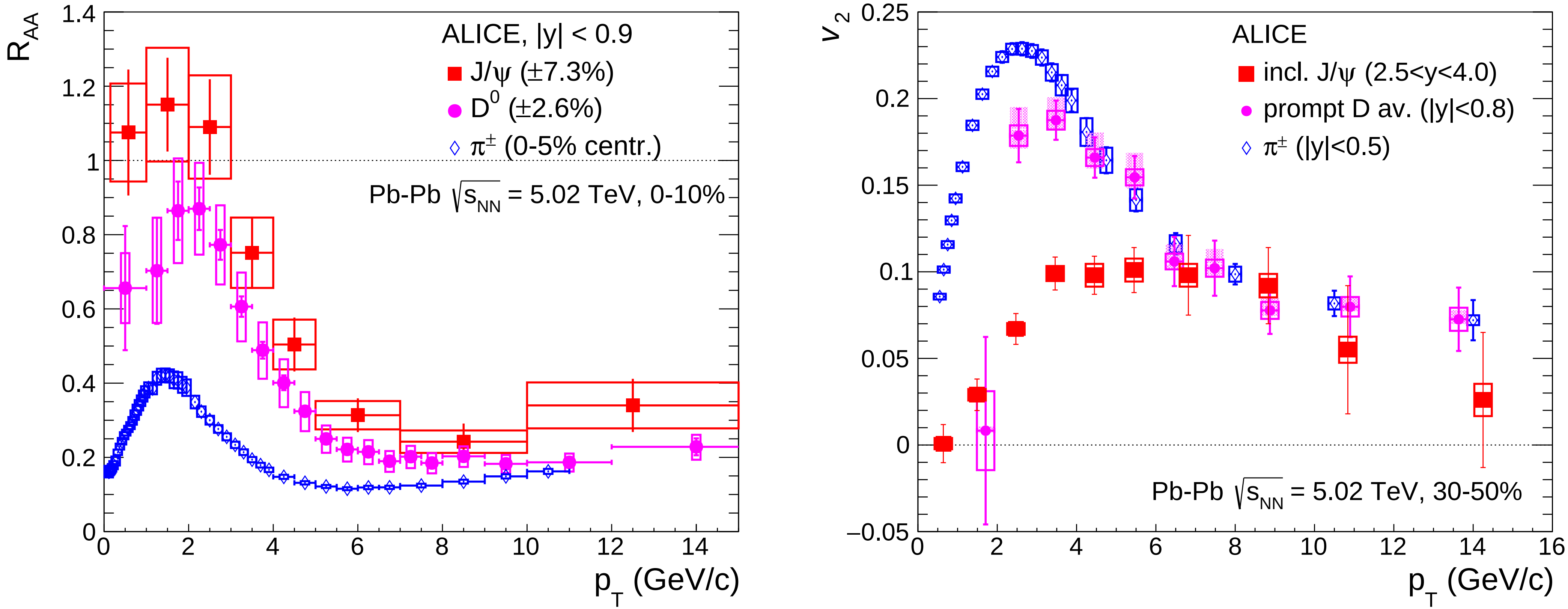




production at low p_{T} is enhanced at the LHC compared to RHIC

...stronger at midrapidity

Charmonium data at the LHC: in perspective

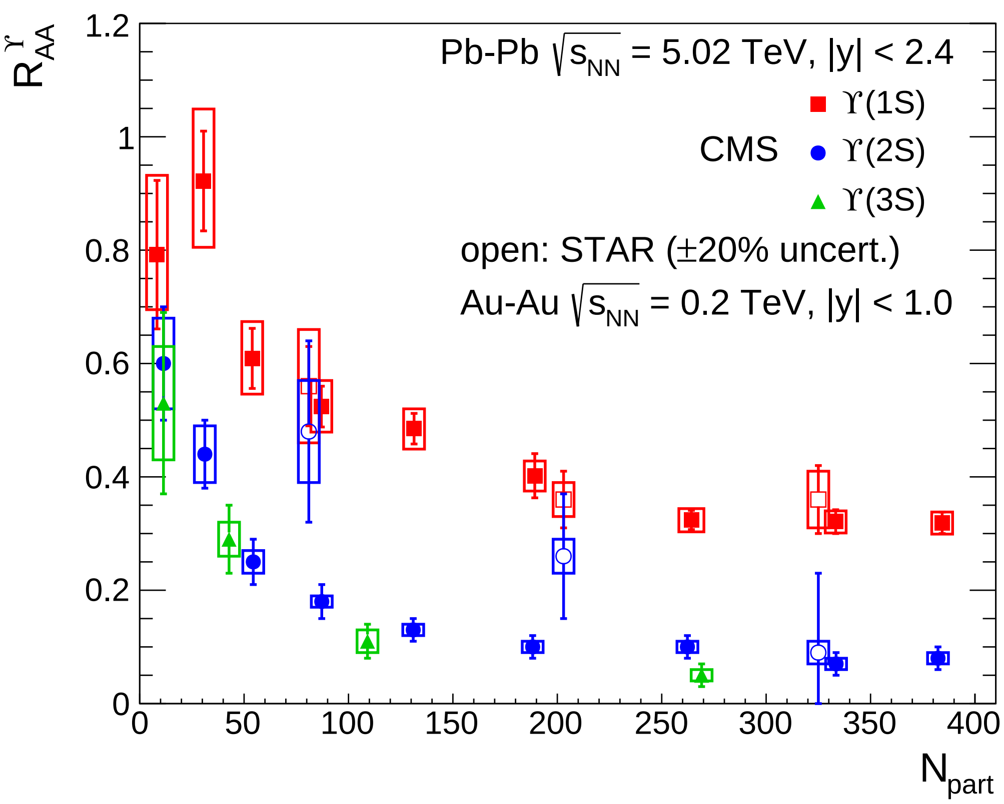


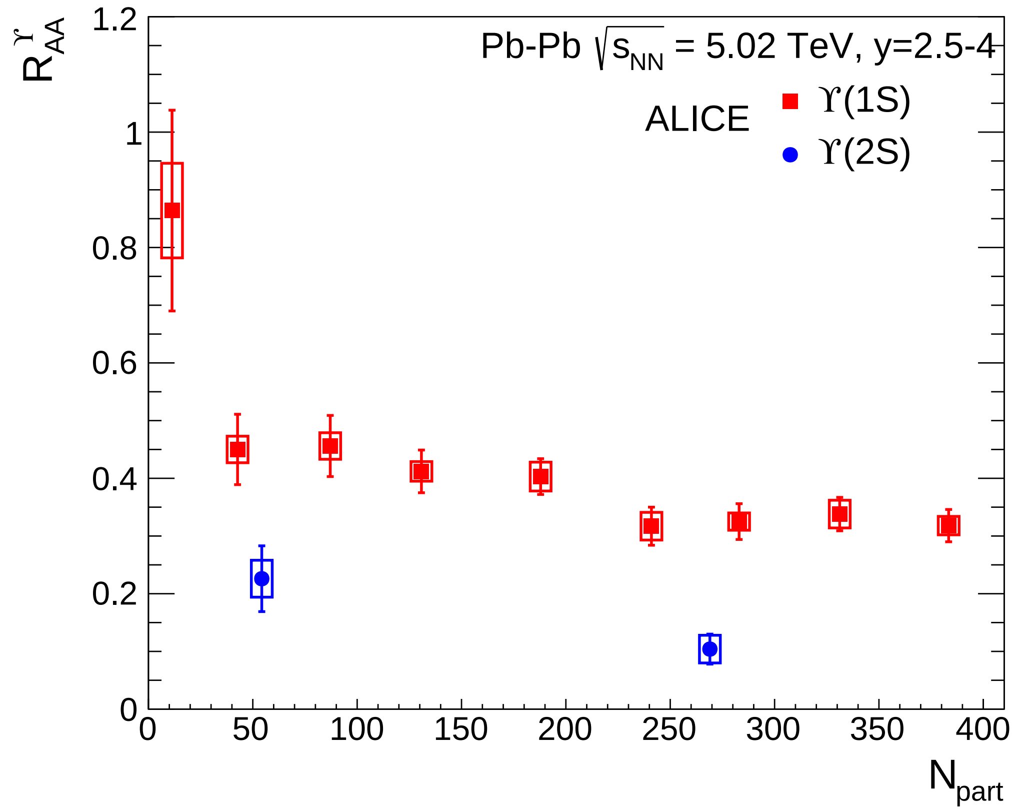
ALICE, arXiv:2303.13361, arXiv:2110.09420, arXiv:1802.09145

a very clear hierarchy at low/intermediate p_T

charm production is a pQCD process, pion production largely a thermal process

Bottomonium data: RHIC and LHC

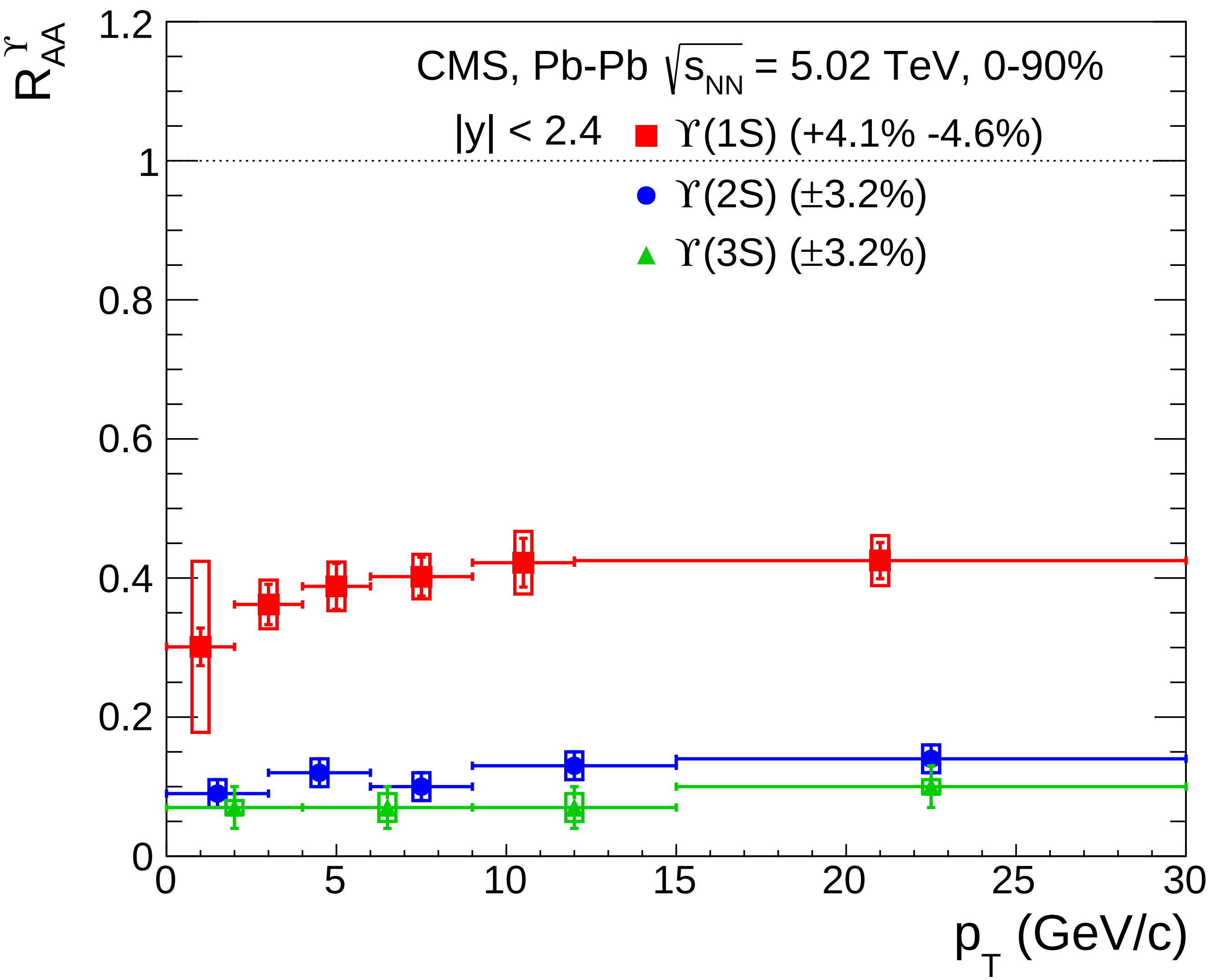




significant suppression, hierarchy between states (sequential?)

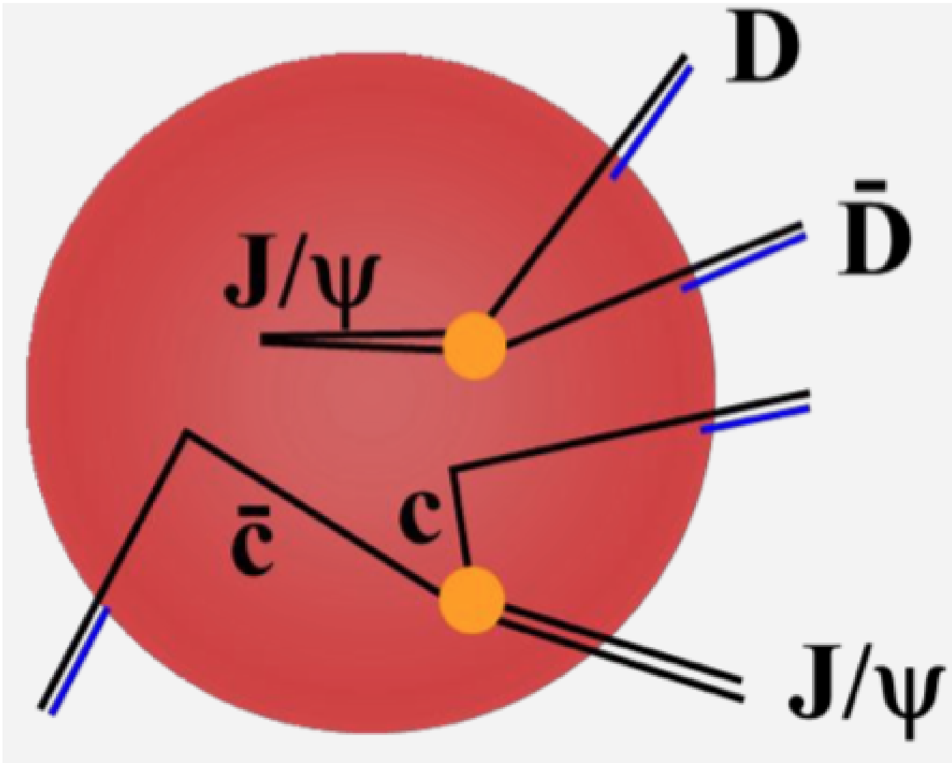
not significantly different at LHC and RHIC (except perhaps $\Upsilon(2S)$)

Bottomonium data at the LHC



weak $p_{\rm T}$ dependence (dissociation expected to be stronger at low $p_{\rm T}$)

There is dissociation and there is (re)generation



This picture is implemented in models in 2 basic ways:

1) statistical hadronization: full screening, generation at hadronization
   (c,$\bar{\mathrm{c}}$ produced in initial scattering and fully thermalized in QGP)

2) transport: continuous destruction and (re)generation, also from different c,$\bar{\mathrm{c}}$
   (time evolution of T constrained by other measurements)

The statistical hadronization model

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259

all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)
...survive and thermalize **in QGP** (thermal, but not chemical equilibrium)

charmed hadrons are formed at chemical freeze-out together with all hadrons
"generation" ...no J/ψ survival in QGP (full screening)

(if supported by data) J/ψ looses status as "thermometer" of QGP
...and gains status as a powerful observable for the QCD phase boundary

Predicts p_T spectra too: hydrodynamics (MUSIC) (input for β_T in blast-wave formula)
JHEP 07 (2021) 035, arXiv:2308.14821

SHM for charm (SHMc)

pQCD production, "throw in": $N_{c\bar{c}} = 9.6 \rightarrow g_c = 30.1$ $(I_1/I_0 = 0.974)$

LHC, central collisions

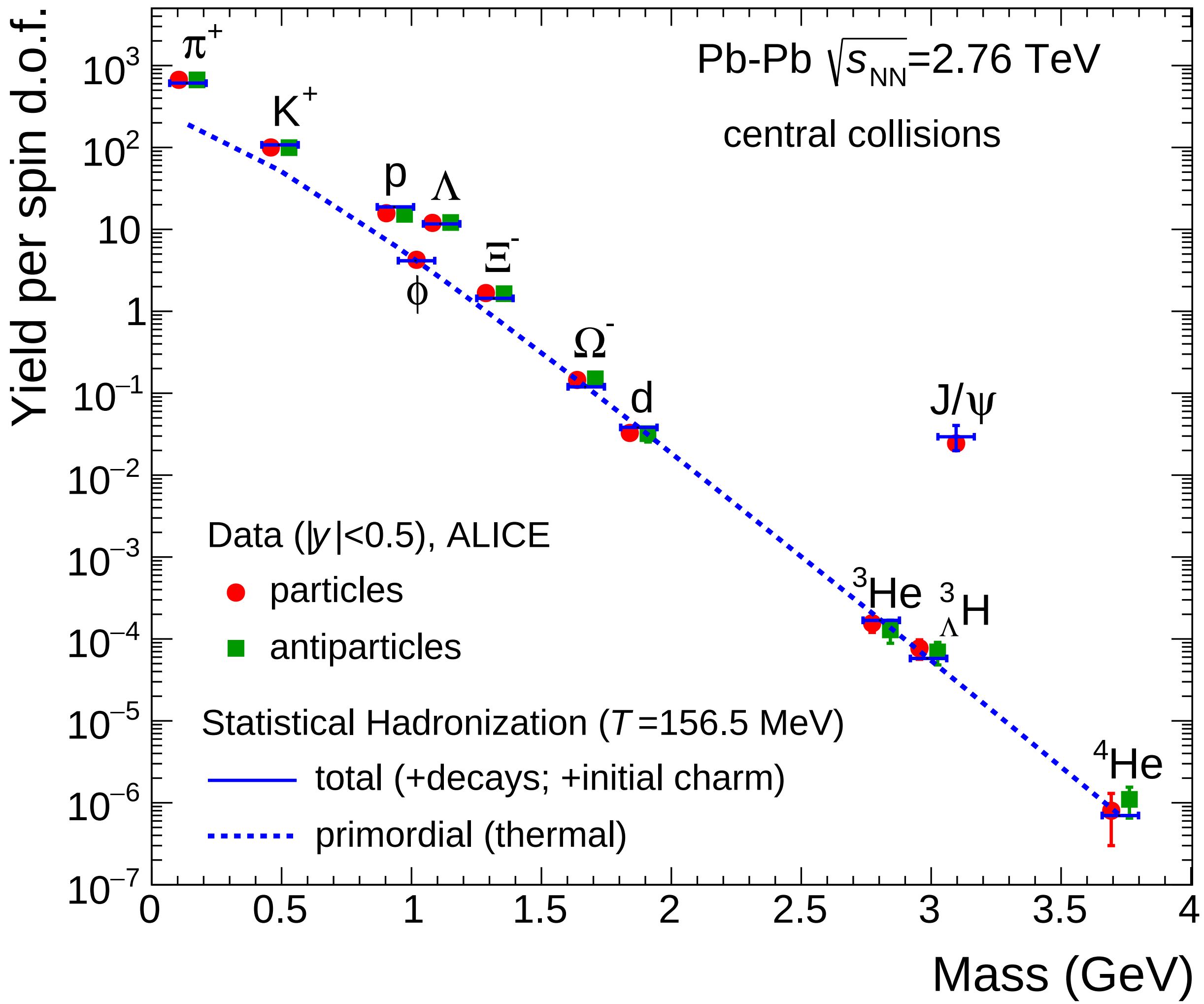
assume:

- full thermalization of $c, \bar{c}$ ("mobility" in V≃4000 fm^3)

- full color screening (Matsui-Satz)

Braun-Munzinger, Stachel, PLB 490 (2000) 196

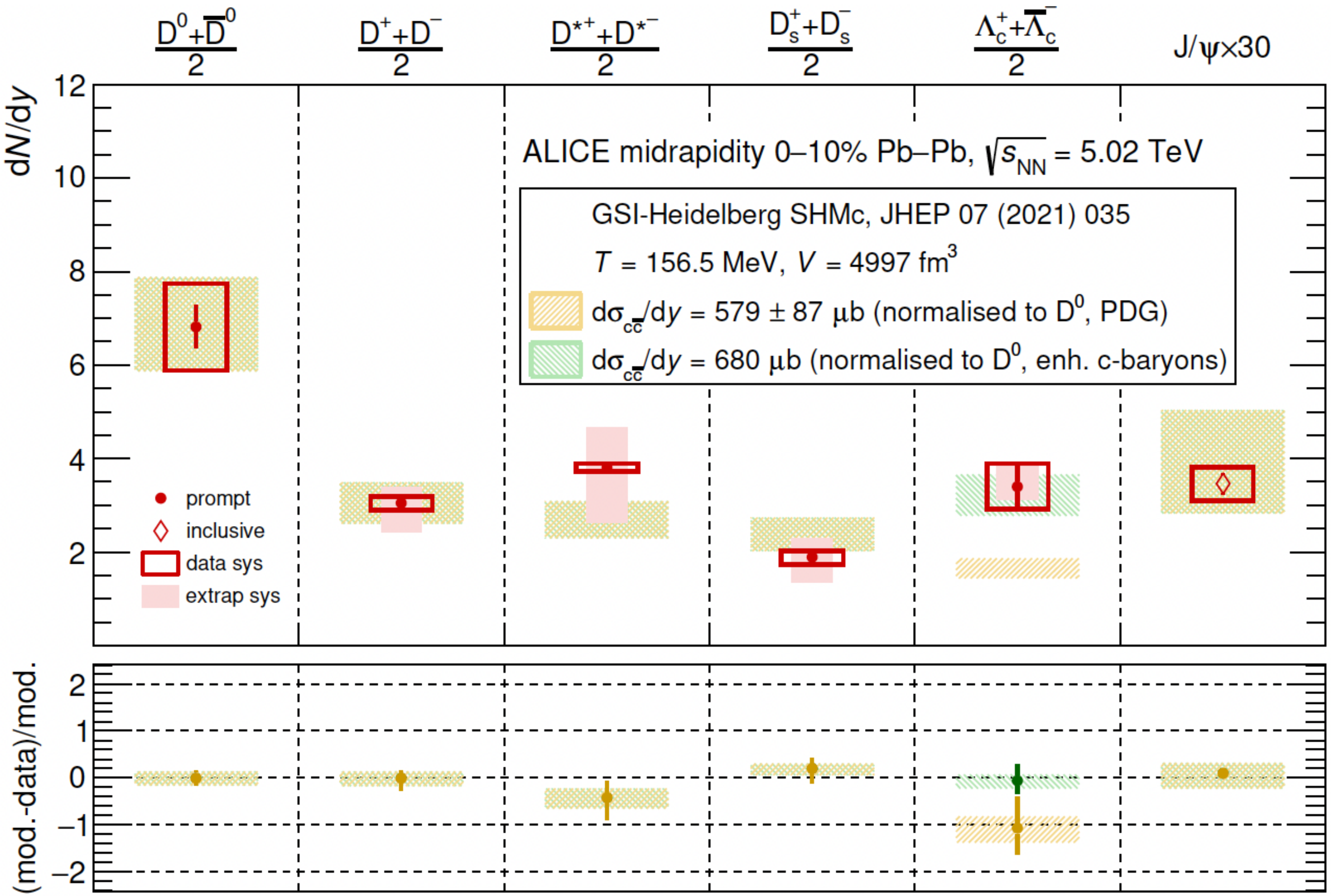
Model predicts all charm chemistry ($\psi(2S)$, $X(3872)$)



π, $K^{\pm}$, K^0 from charm included in the thermal fit (0.7%, 2.9%, 3.1% for T=156.5 MeV)

PLB 797 (2019) 134836

Charm data and SHMc model



ALICE, arXiv:2212.04348

Enh. c-baryons: *tripled* the excited charm-baryon states, *and* $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$: +19%

RQM: He,Rapp, PLB 795 (2019) 117; LQCD, Bazavov et al., PLB 737 (2014) 210

leaves the mesonic sector unaffected, for the commensurately larger $\sigma_{c\bar{c}}$

Transport models

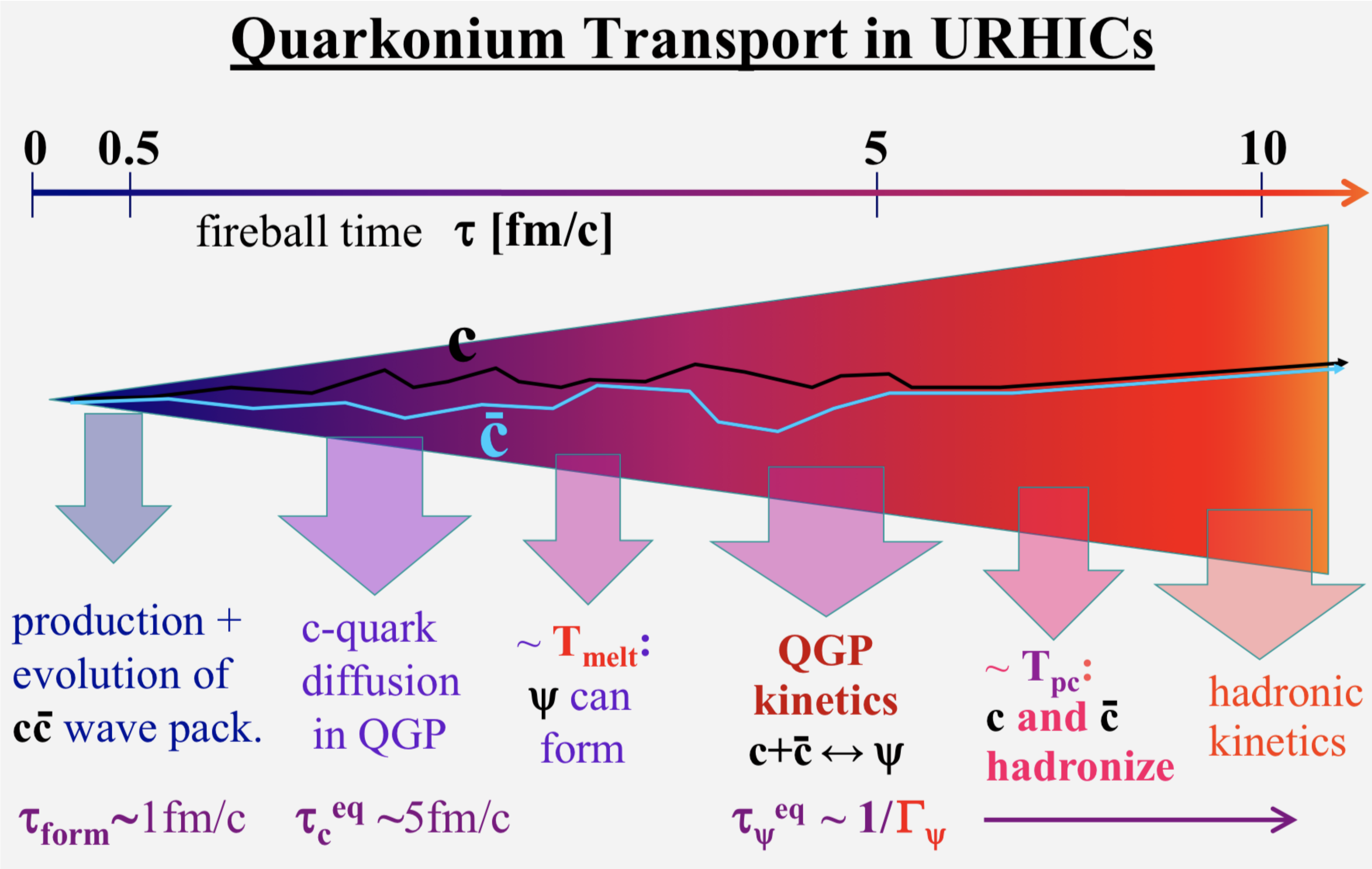
implement screening picture with space-time evolution of the fireball (hydro-like)
continuous destruction and "(re)generation" ("recombination")
Boltzmann equation (loss and gain terms)

Thews et al., PRC 63 (2001) 054905 ...

"TAMU", PLB 664 (2008) 253, NPA 859 (2011) 114, EPJA 48 (2012) 72

"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, arXiv:1401.5845

Predicts $R_{AA}, v_2(p_T)$ (TAMU describes D mesons too)



Rapp, Du, arXiv:1704.07923

Transport models - the essentials

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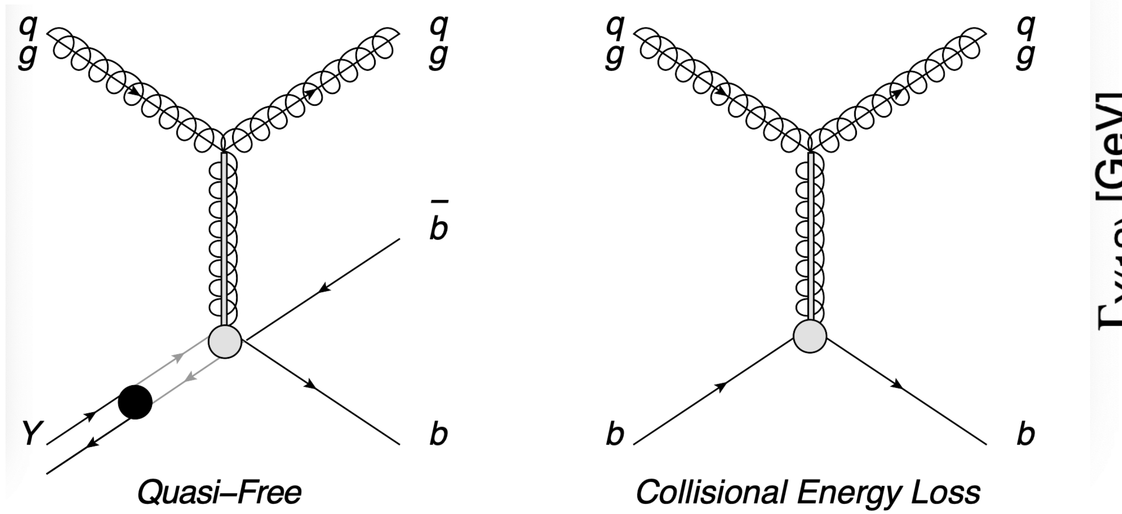
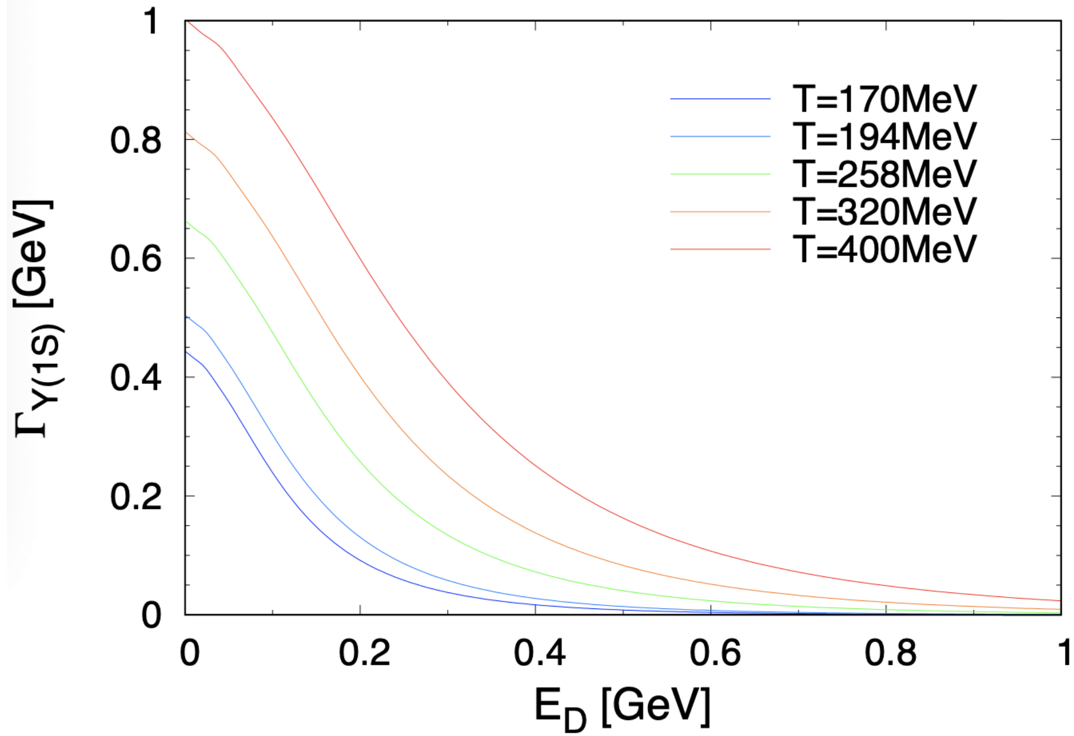
$$\frac{\mathrm{d}N_{\Upsilon}}{\mathrm{d}\tau} = -\Gamma(T(\tau))\left[N_{\Upsilon}(\tau) - N_{\Upsilon}^{eq}(T(\tau))\right]$$





Du, Liu, Rapp, Phys. Lett. B 796 (2019) 20

Quasi-free = inelastic (dissociation) = imaginary part of HQ potential

K factor: enhancement over perturbative results ($K = 5$ in $\Gamma_{\Upsilon(1S)}$ above)

N^{eq}: SHM generation

2 other models

- "Comovers" model (Santiago):
  (invented to describe suppression in the (final-state) hadronic medium at SPS
  $J/\psi + \pi \rightarrow D + \bar{D}$)

  at LHC: gluo-dissociation and a (re)generation component (dominant for J/ψ)
  (the Boltzmann equation of the transport model is also in the comoving system)

  E. Ferreiro at al., PLB 731 (2014) 57

- Hydrodynamic model (Kent State Univ.)
  hydro gives energy density vs. space-time
  suppression probability vs. ε gives R_{AA} (of Y)

  Strickland, Bazow, NPA 879 (2012) 25

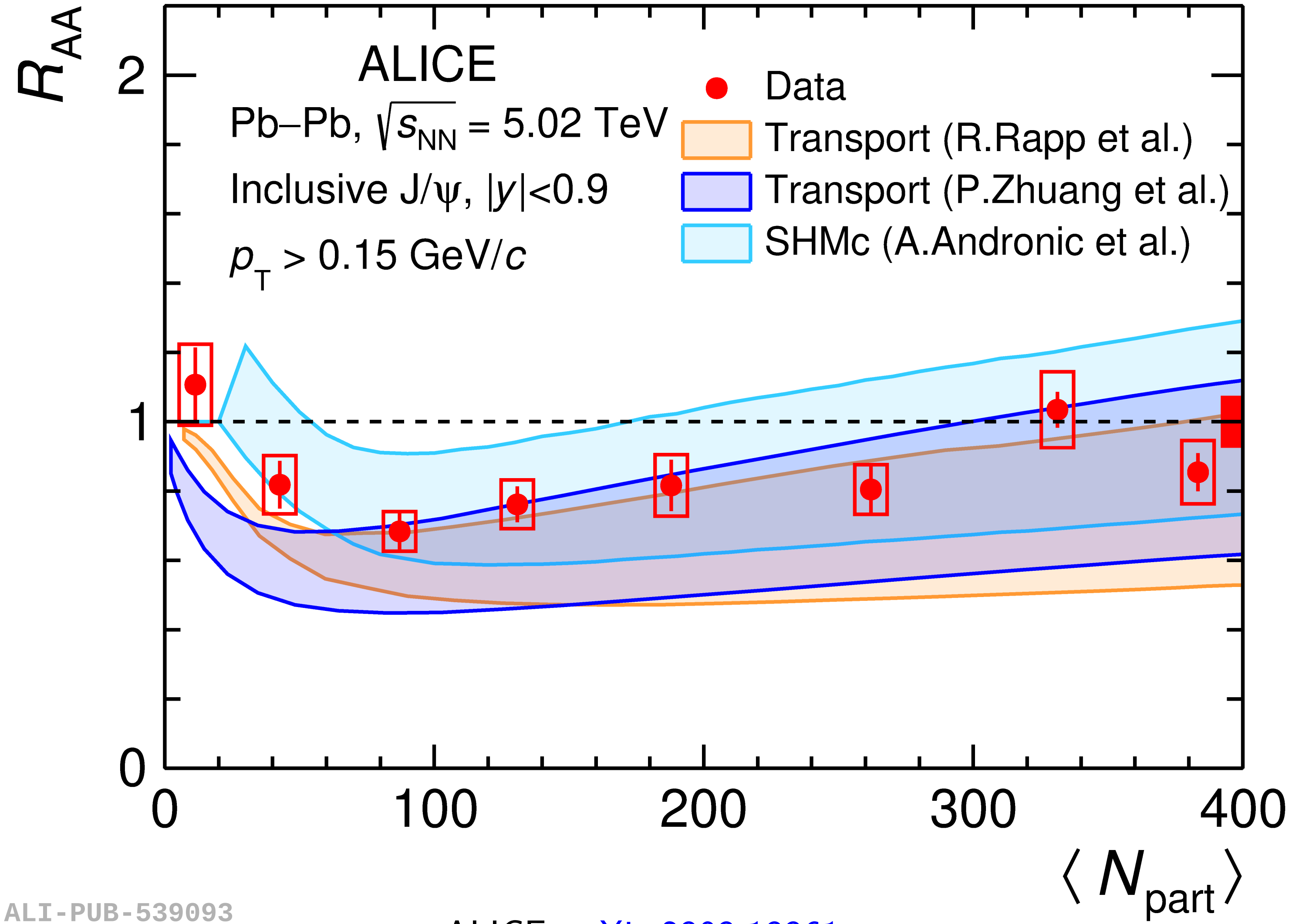
...and one more: the quantum approach

Open quantum systems description + Effective NRQCD theory

quantum evolution of the $\mathrm{b\bar{b}}$ pair in QGP (heat bath; hydrodynamics)

Lindblad equation (accuracy: at NLO in the binding energy over temperature)

Strickland, Thapa, PRD 108 (2023) 014031

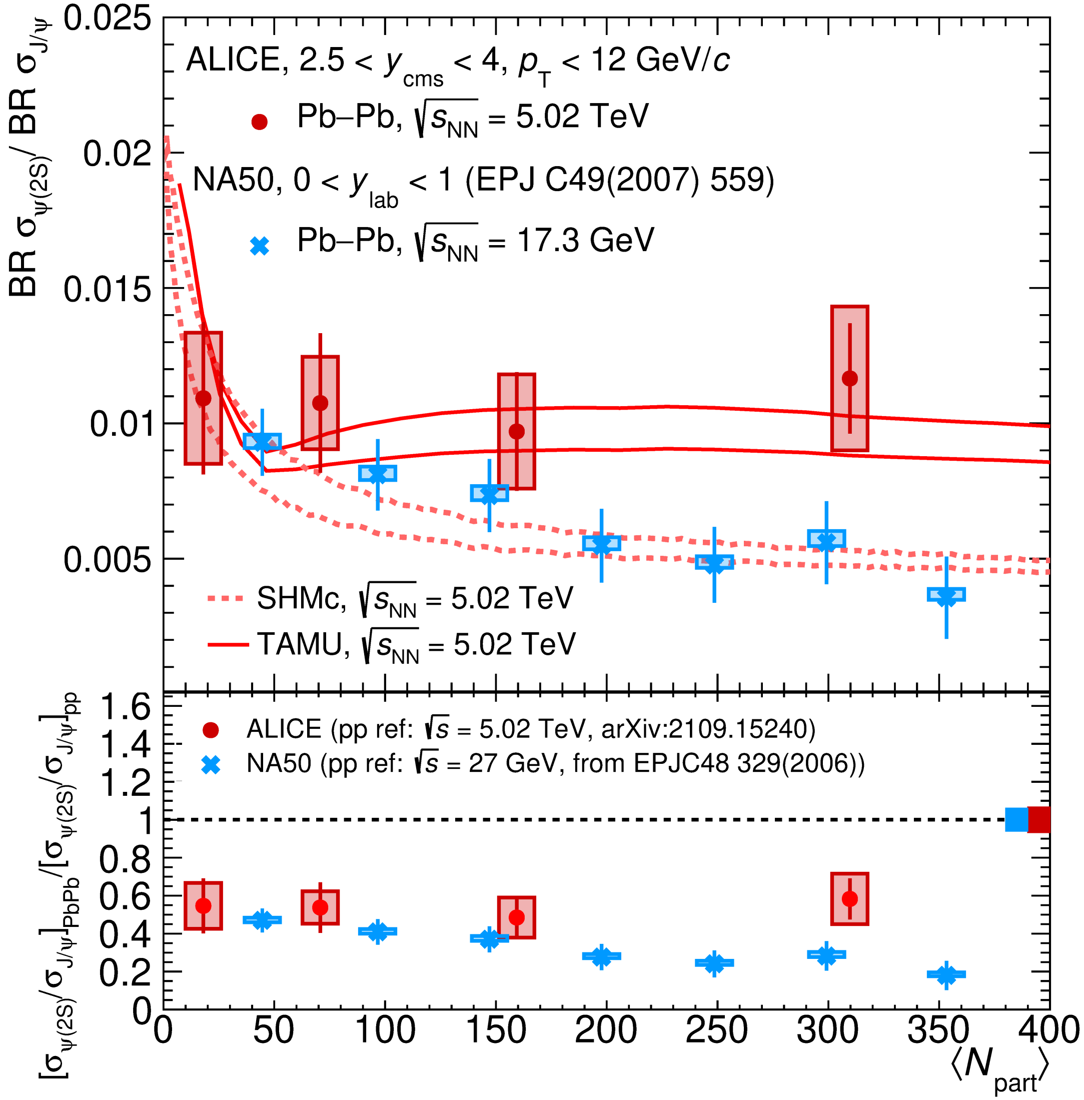


ALICE, arXiv:2303.13361

SHMc: $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, arXiv:2110.09420

$\mathrm{d}N/\mathrm{d}y = 6.82 \pm 1.03$ ($|y| < 0.5$; FONLL for y=2.5-4; assuming hadronization fractions in data as in SHMc)

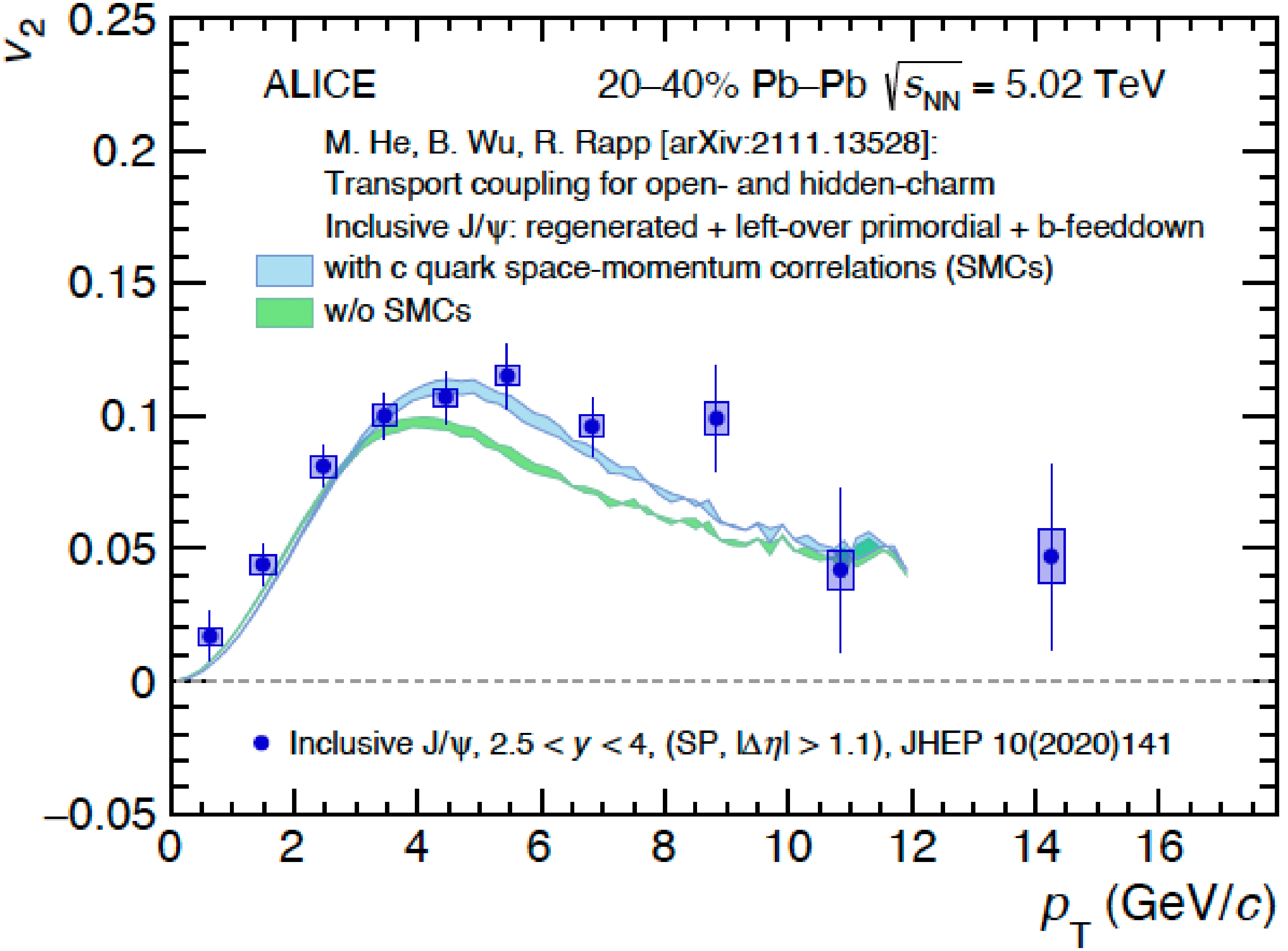
$\psi(2S)/J/\psi$ at the LHC (and SPS)



ALICE, arXiv:2210.08893

In SHMc uncertainty only due to nuclear-corona ($\sigma_{c\bar{c}}$ cancels out completely)

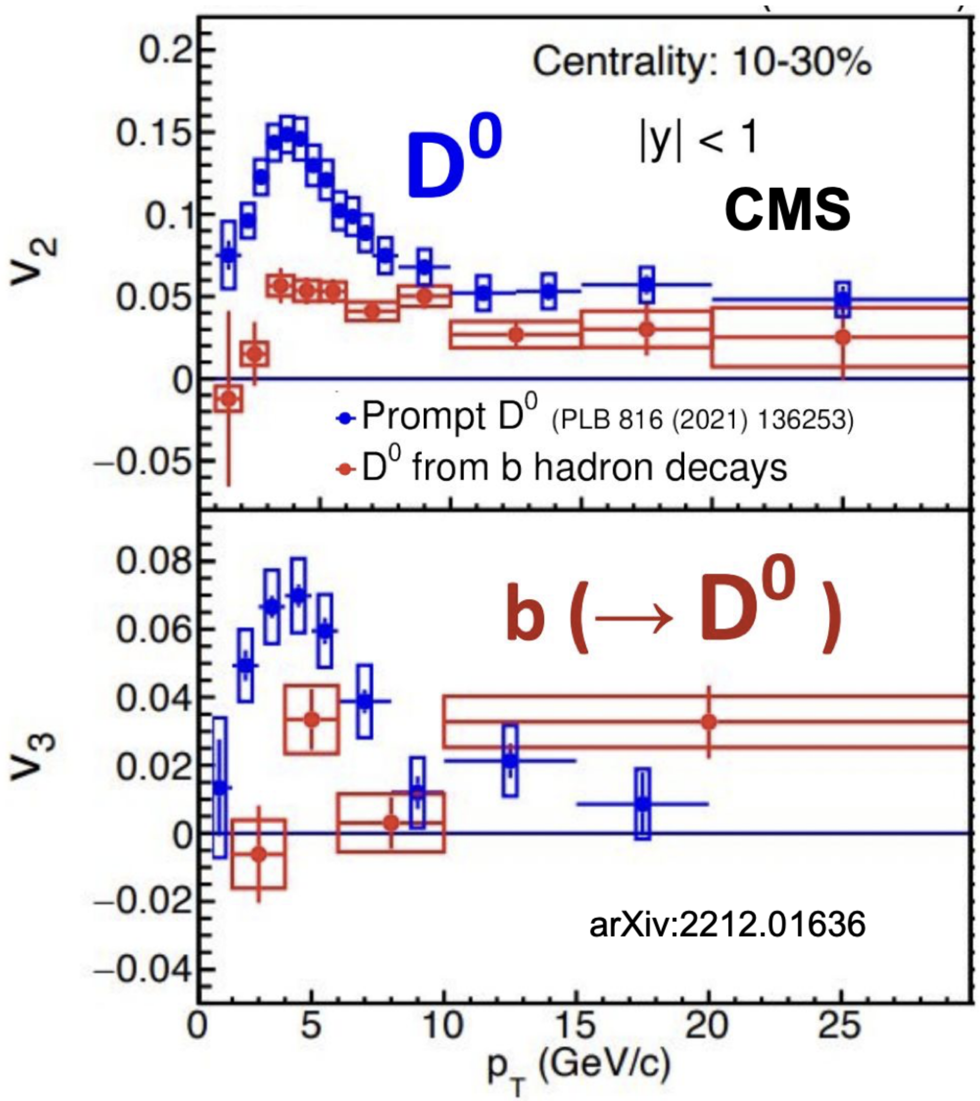
J/ψ elliptic flow: data and transport model

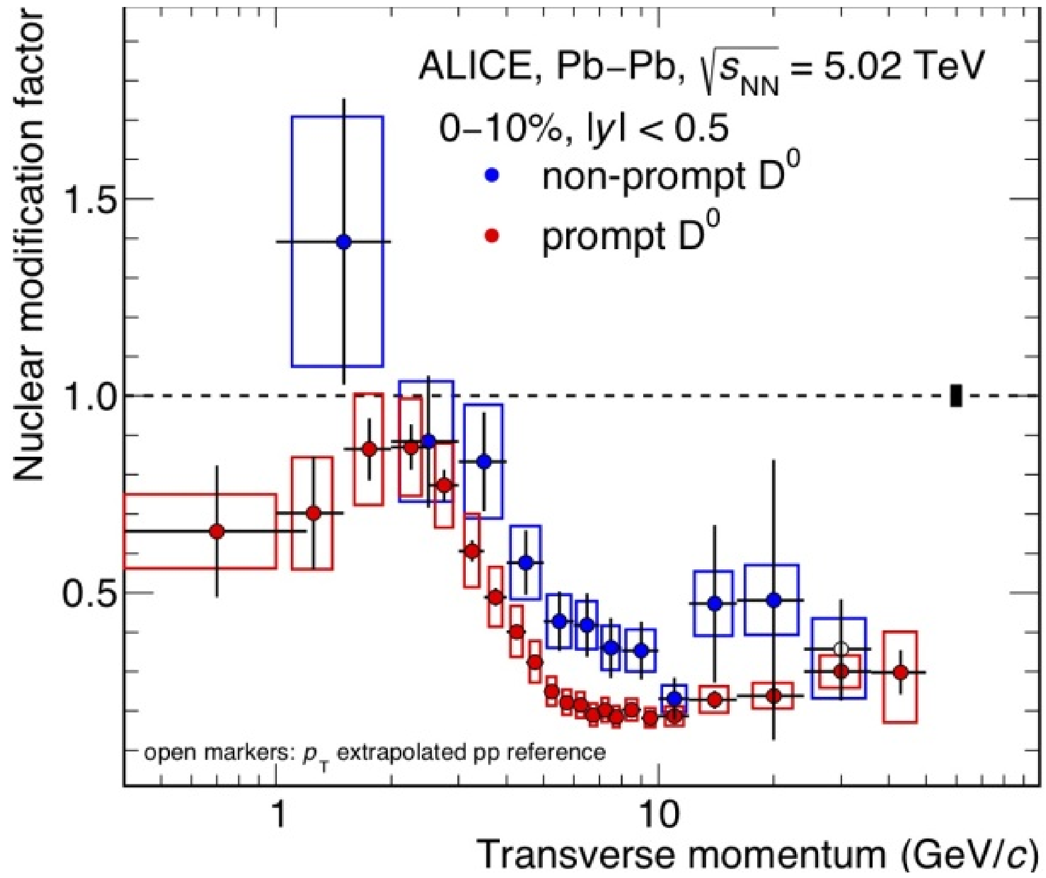


ALICE, arXiv:2212.04348

a very good description of data by the TAMU model

Beauty quark thermalization?





ALICE, arXiv:2202.00815, ATLAS

definitely strong flow but clearly less strong than for charm (CMS, QM'22, HIN-21-003)

...and a strong coupling with the medium (less energy loss than charm, $p_T \simeq 10$ GeV$/c$)

R_{AA}, 50% $b\bar{b}$ thermalized

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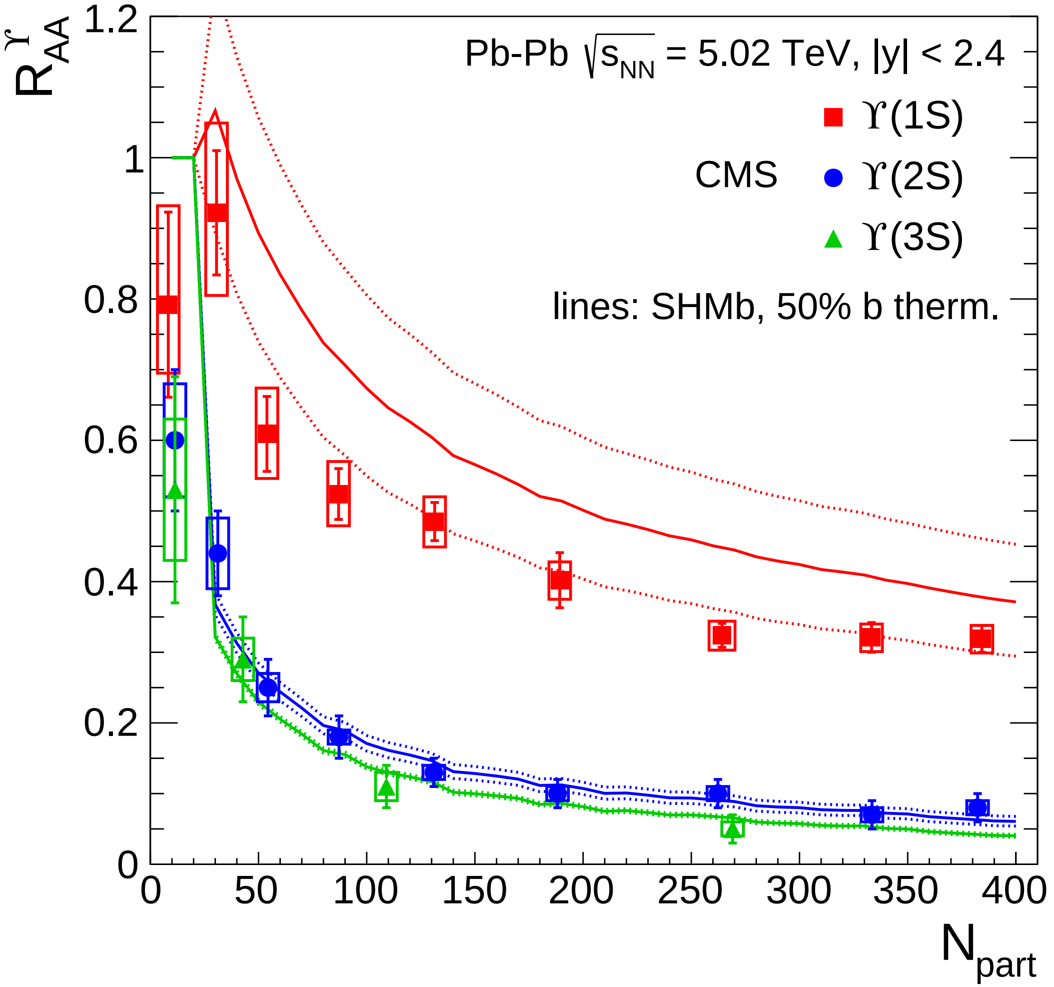
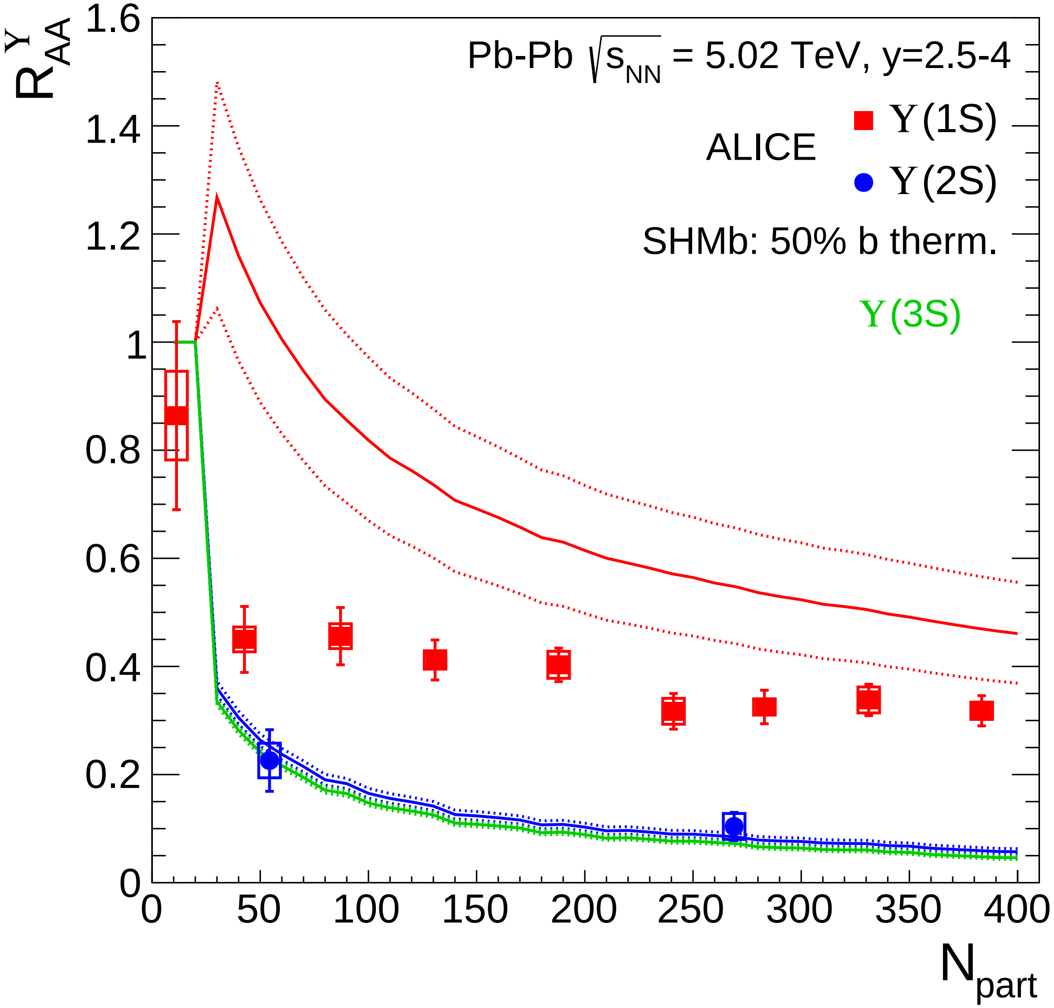


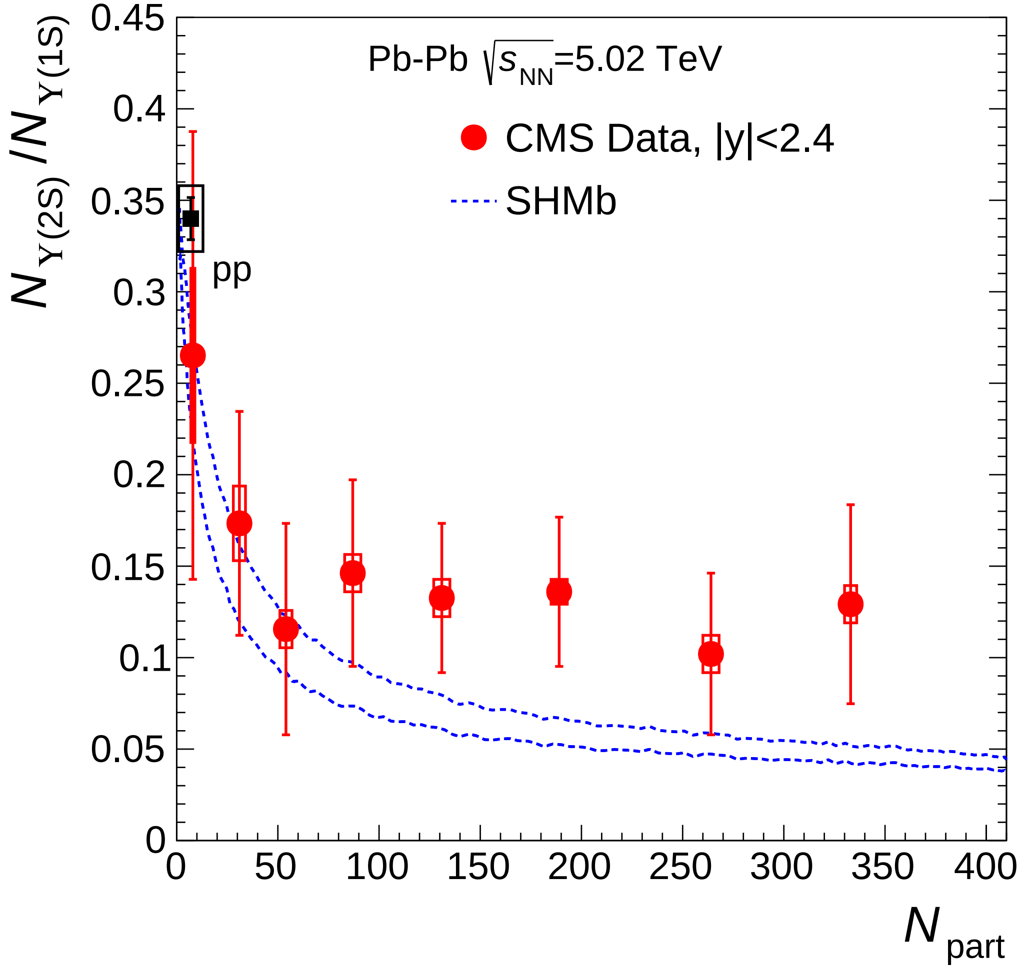
CMS, PRL 120 (2018) 142301



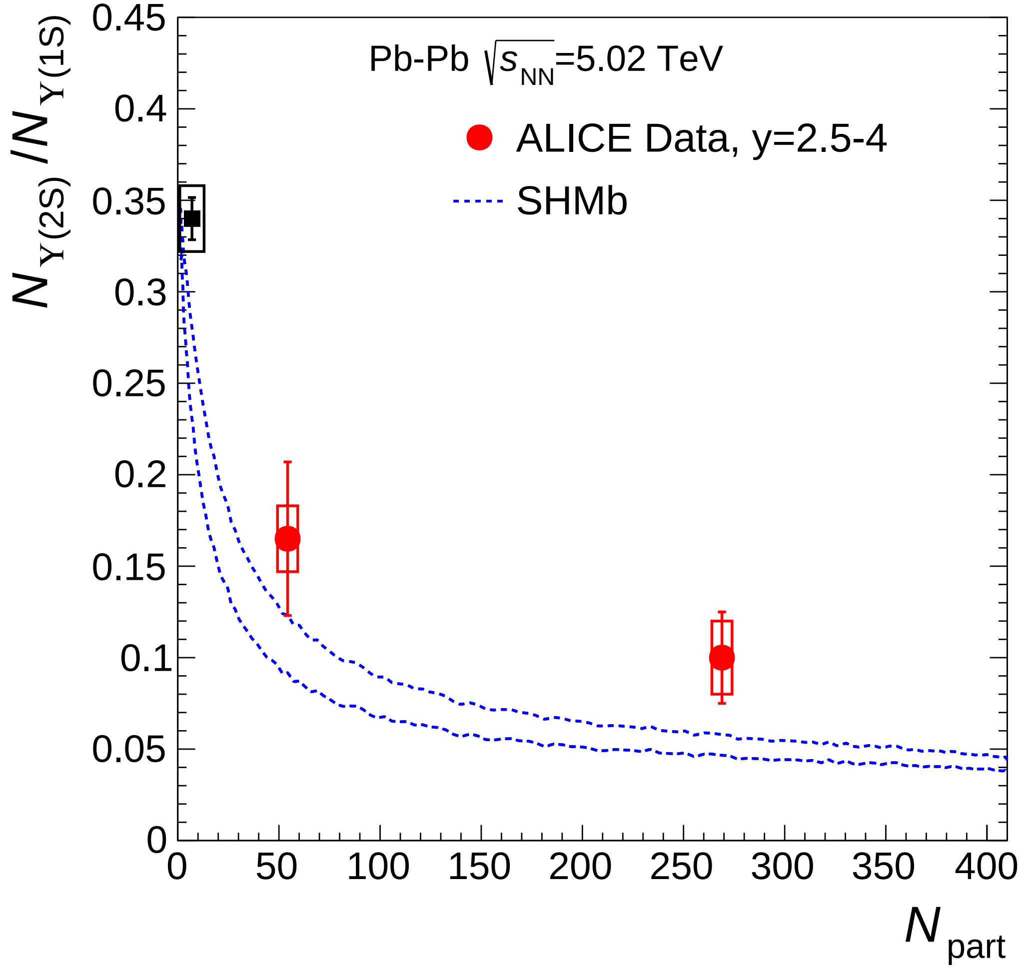
ALICE, PLB 822 (2021) 136579

What does non-thermalized beauty produce? (no room for it in SHMb)

$\Upsilon(2S)/\Upsilon(1S)$ ratio (100% b thermalization)



CMS, PRL 120 (2018) 142301

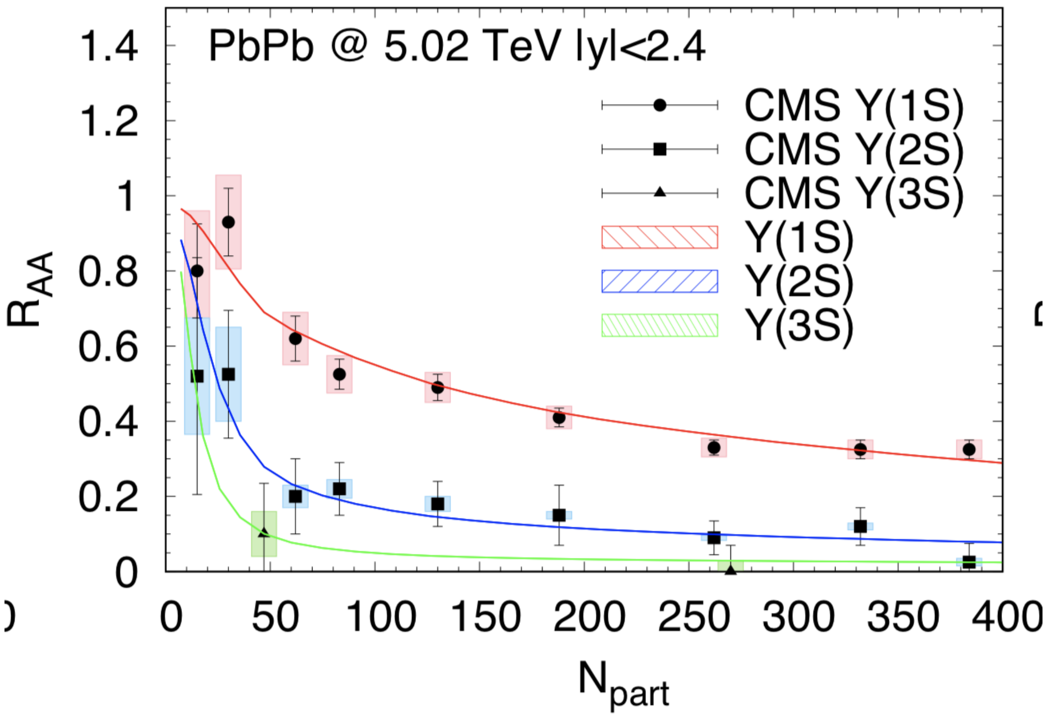


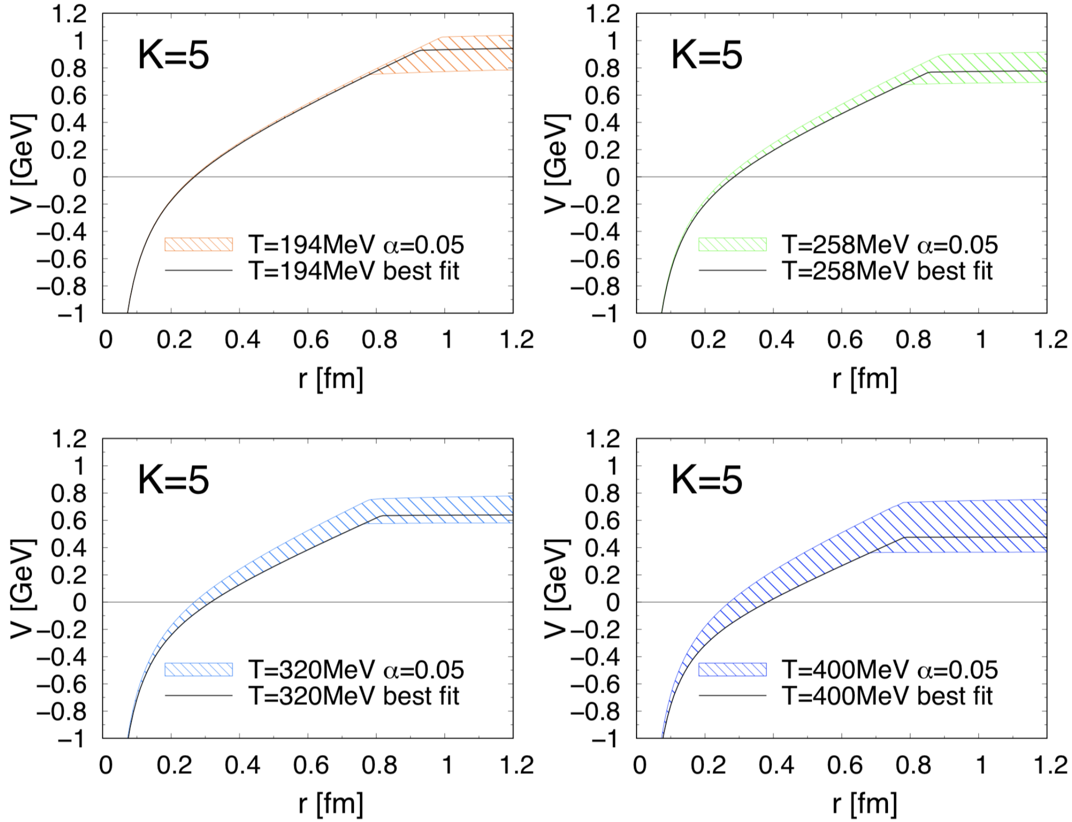
ALICE, PLB 822 (2021) 136579

ALICE pp: $\Upsilon(2S)/\Upsilon(1S) = 0.5 \pm 0.1$, arXiv:2109.15240

SHMb uncert.: nuclear-corona (fraction)

...is very good; allows extraction of in-medium (Cornell) potential



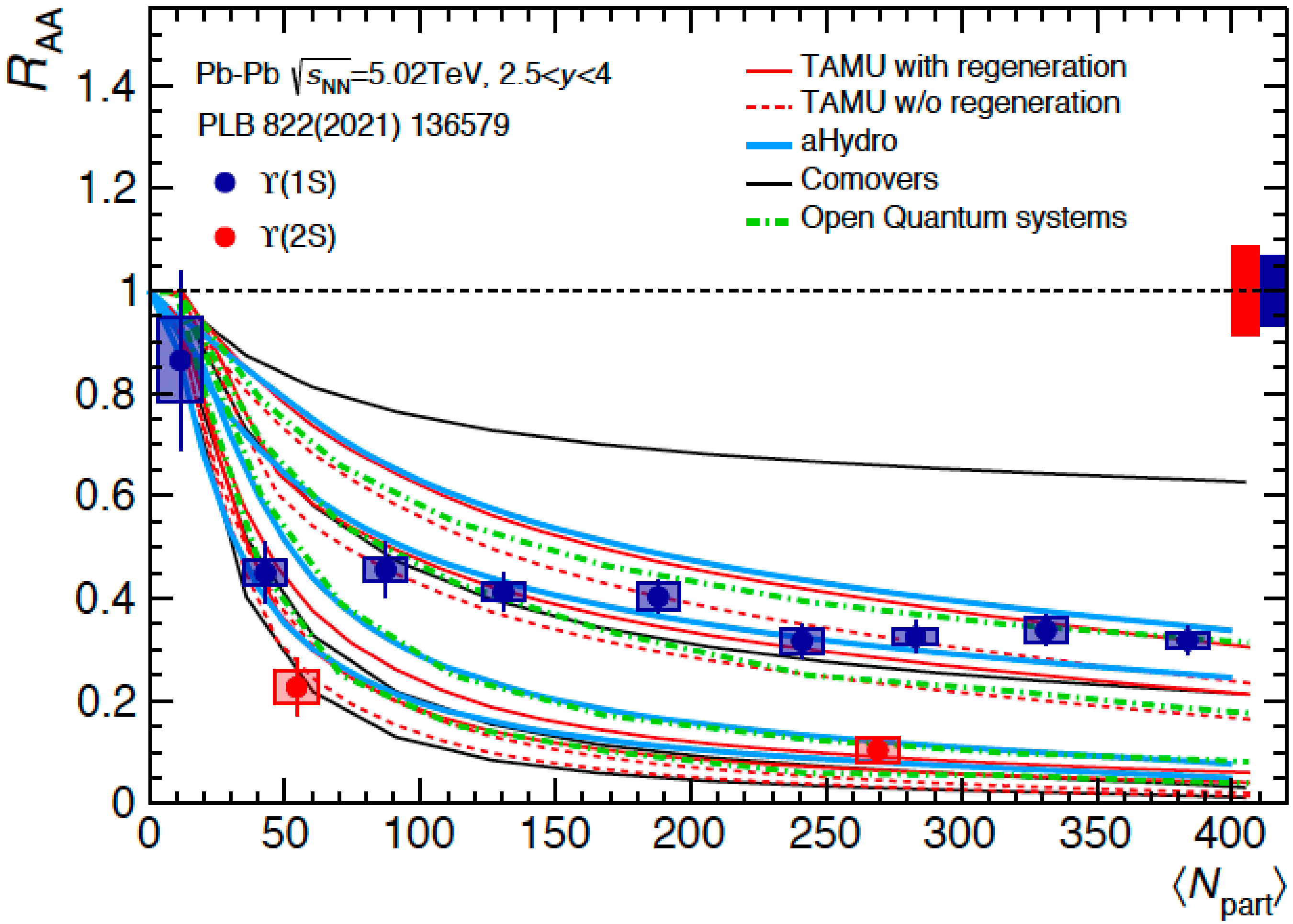


(re)generation important for $\Upsilon(2S)$

Transport Model (TAMU), Du, Liu, Rapp, Phys. Lett. B 796 (2019) 20

Substantial remnants of the long-range color confining force in QGP

Υ suppression data and models



ALICE, arXiv:2212.04348

All models (except perhaps Comovers ...large uncert.) reproduce the data well

TAMU: Regeneration important for $\Upsilon(2S)$

Summary / Conclusions: charm

- Charm quarks seem to thermalize very effectively (close to 100%) in QGP
- SHM: all charmonium *and open charm states* are generated exclusively at hadronization (chemical freeze-out) ...full color screening

  The model is very successful in reproducting the J/ψ and open charm data

  A handle for hadronization T with a mass scale well above T

- Transport models: continuous J/ψ destruction and (re)generation in QGP

  (only up to 2/3 of the J/ψ yield (LHC, central collisions) originates from deconfined c and $\bar{c}$ quarks)

  Discriminating the two pictures implies providing an answer to fundamental questions related to the fate of hadrons in a hot deconfined medium.

  A precision ($\pm$10%) measurement of $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ in Pb-Pb (Au-Au) collisions needed for a stringent test

  (within reach with the upgraded detectors at the LHC and RHIC)

Summary / Conclusions: beauty

- Full beauty thermalization seems not realized in nature

  ...with 30-50% of beauty quarks fully thermalized SHM can explain the Υ data

  ...but this fraction is (significantly) dependent on the b-hadron spectrum

  What does non/partially-thermalized beauty produce?

  no Υ because strong coupling with the medium destroys the b-$\bar{b}$ correlation?

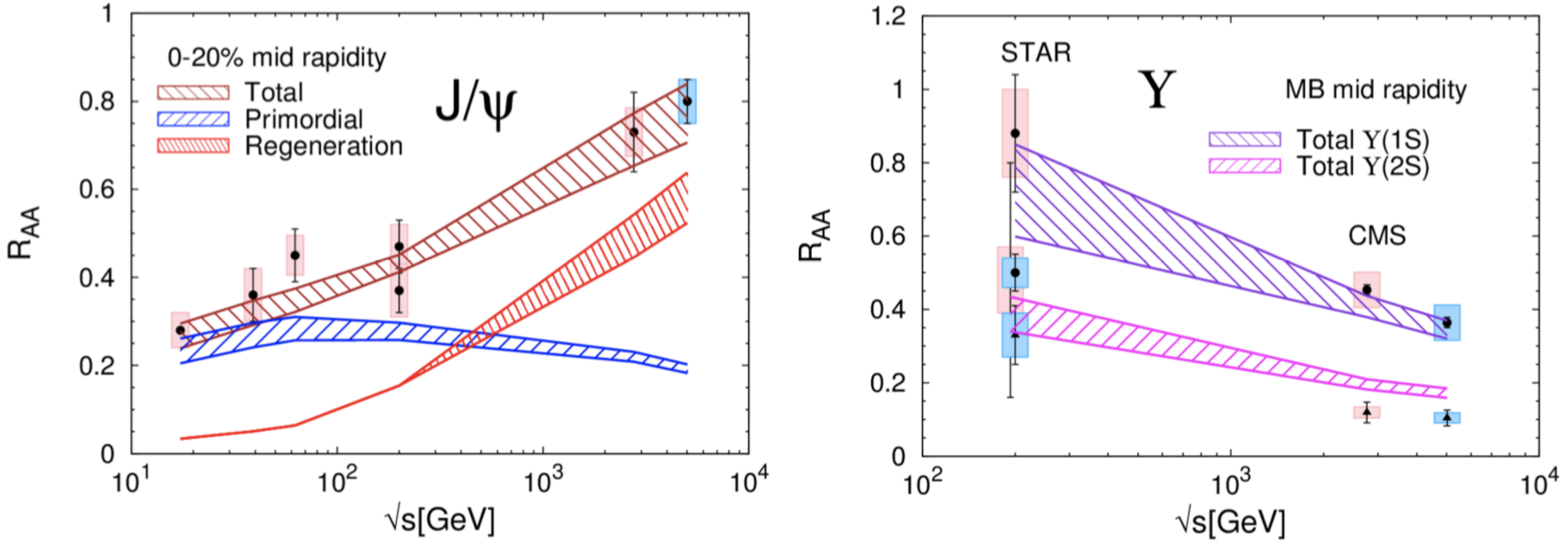
- Transport and Hydro models are successfully reproducing Υ suppression

  Transport: regeneration important for $\Upsilon(2S)$ (at the LHC)

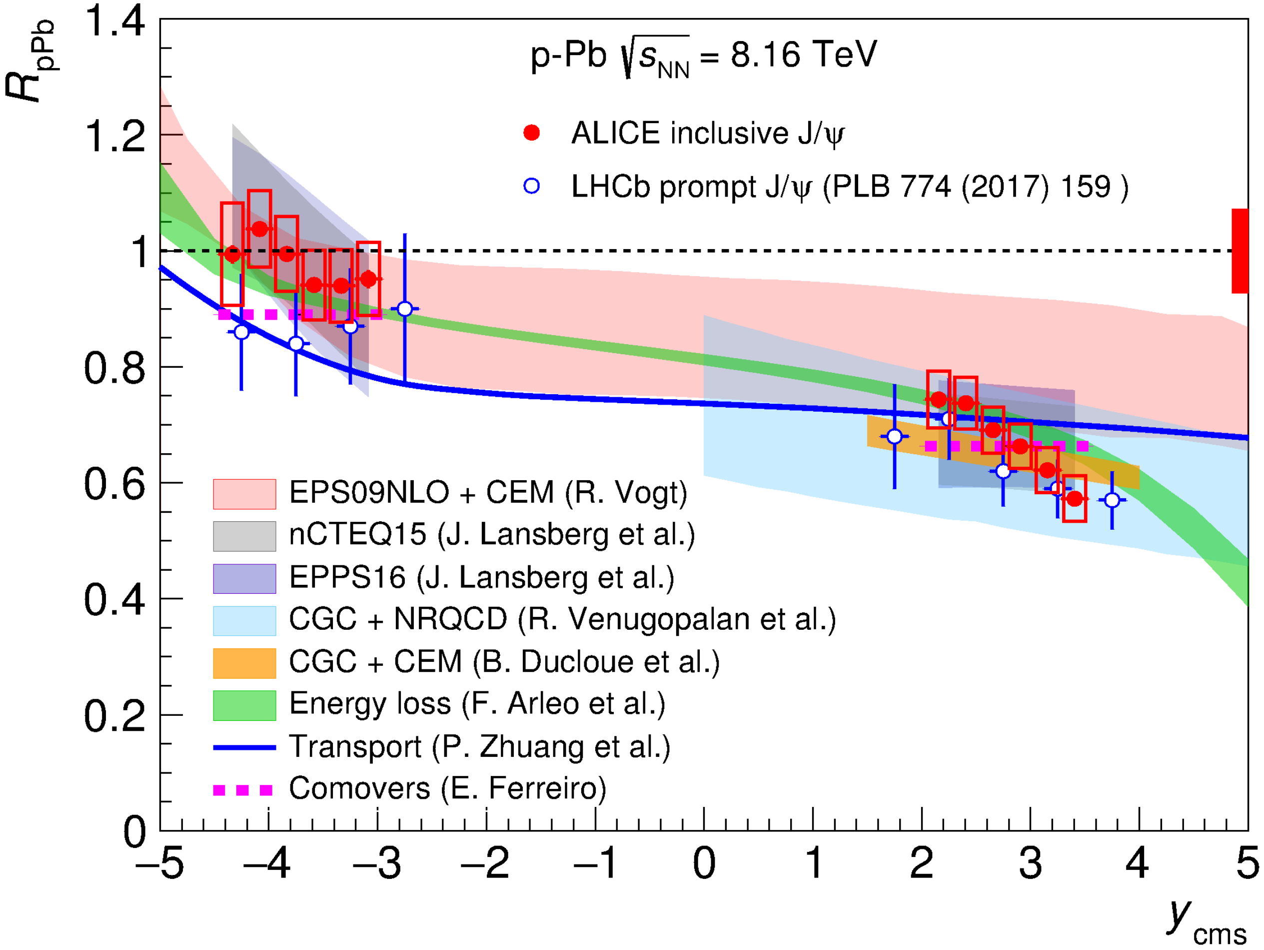
- Quantum approaches on strong rise

Additional material

Fractions primordial, (re)generated - energy dependence



Rapp, Du, arXiv:1704.07923



$7 \cdot 10^{-3} \lesssim x \lesssim 3 \cdot 10^{-2}$ $10^{-5} \lesssim x \lesssim 5 \cdot 10^{-5}$

$$R_{pPb} = \frac{dN_{pPb}/dp_T dy}{\langle N_{coll}^{pPb} \rangle \cdot dN_{pp}/dp_T dy}$$

$$\langle N_{coll}^{pPb} \rangle \simeq 7$$

Shadowing describes data (shadowing uncert. are large)

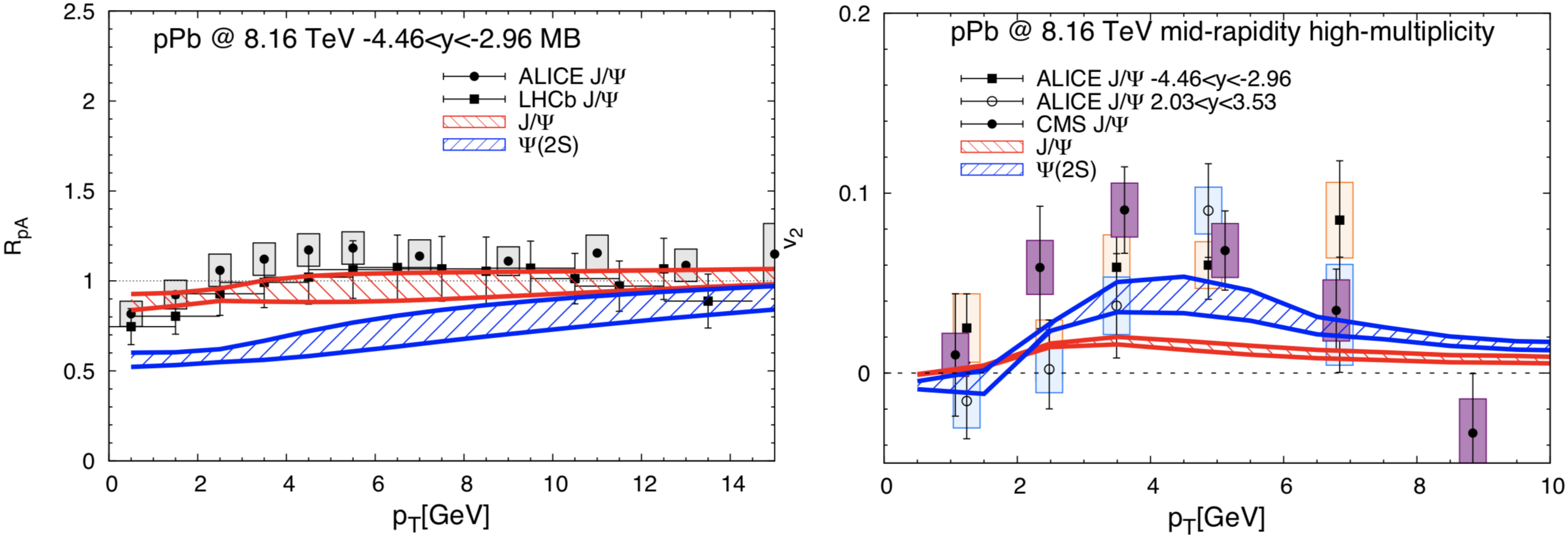
Color Glass Condensate also successful

ALICE, JHEP 07 (2018) 160

LHCb, PLB 774 (2017) 159

Seen also with Run 1 data (5.02 TeV): ALICE, JHEP 02 (2014) 073, 06 (2015) 55

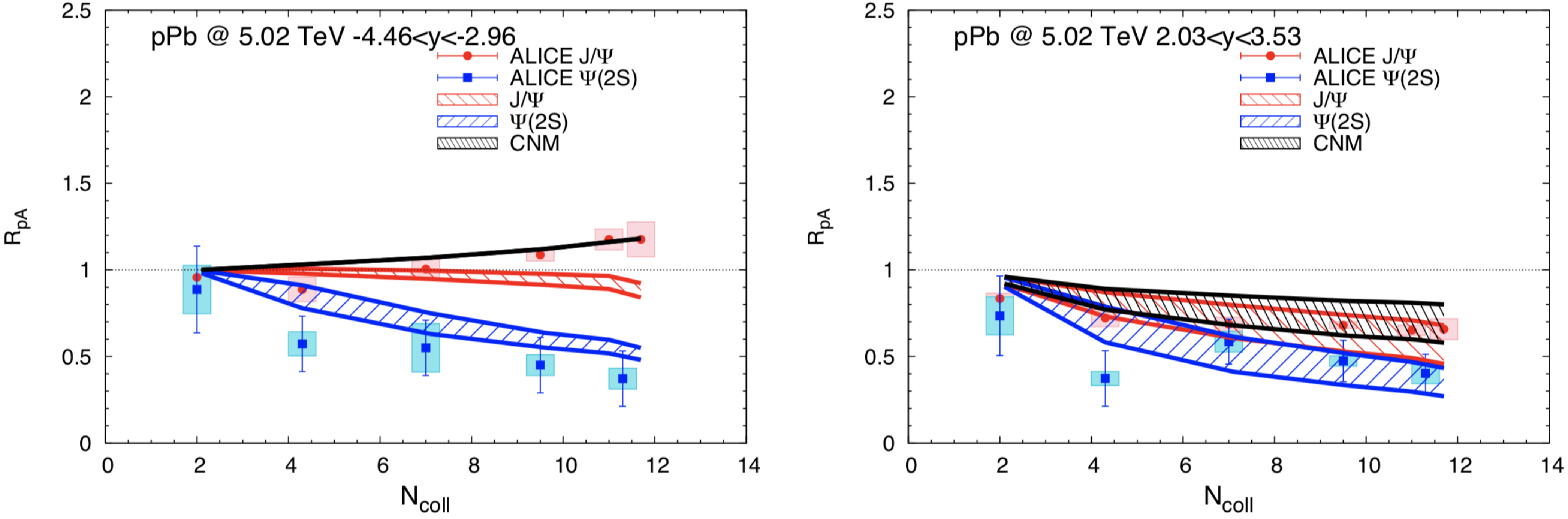
J/ψ production in p–Pb collisions



Bands: Transport Model, TAMU Du, Rapp, JHEP 1903 (2019) 015

Need experimentally (in reach for Run 3,4): better precision; also v_3; separate B component; v_2 of $\psi(2S)$?

J/ψ and $\psi(2S)$ production in p–Pb collisions



Du, Rapp, JHEP 1903 (2019) 015