The statistical hadronization model and the QCD phase diagram: a flavor journey

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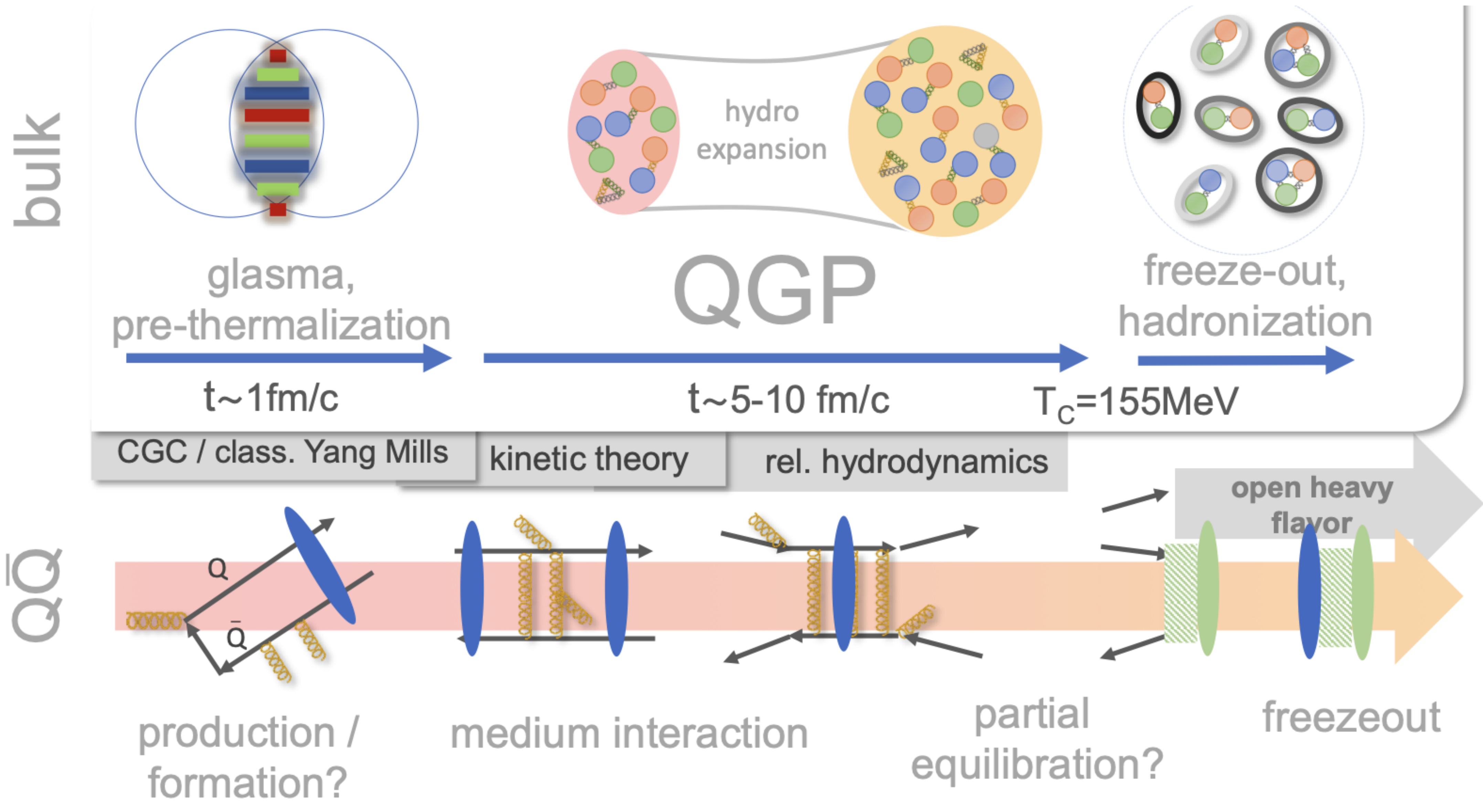
- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- The heavy quarks (quarkonium): data and models (SHM)
- The "sixth flavor"

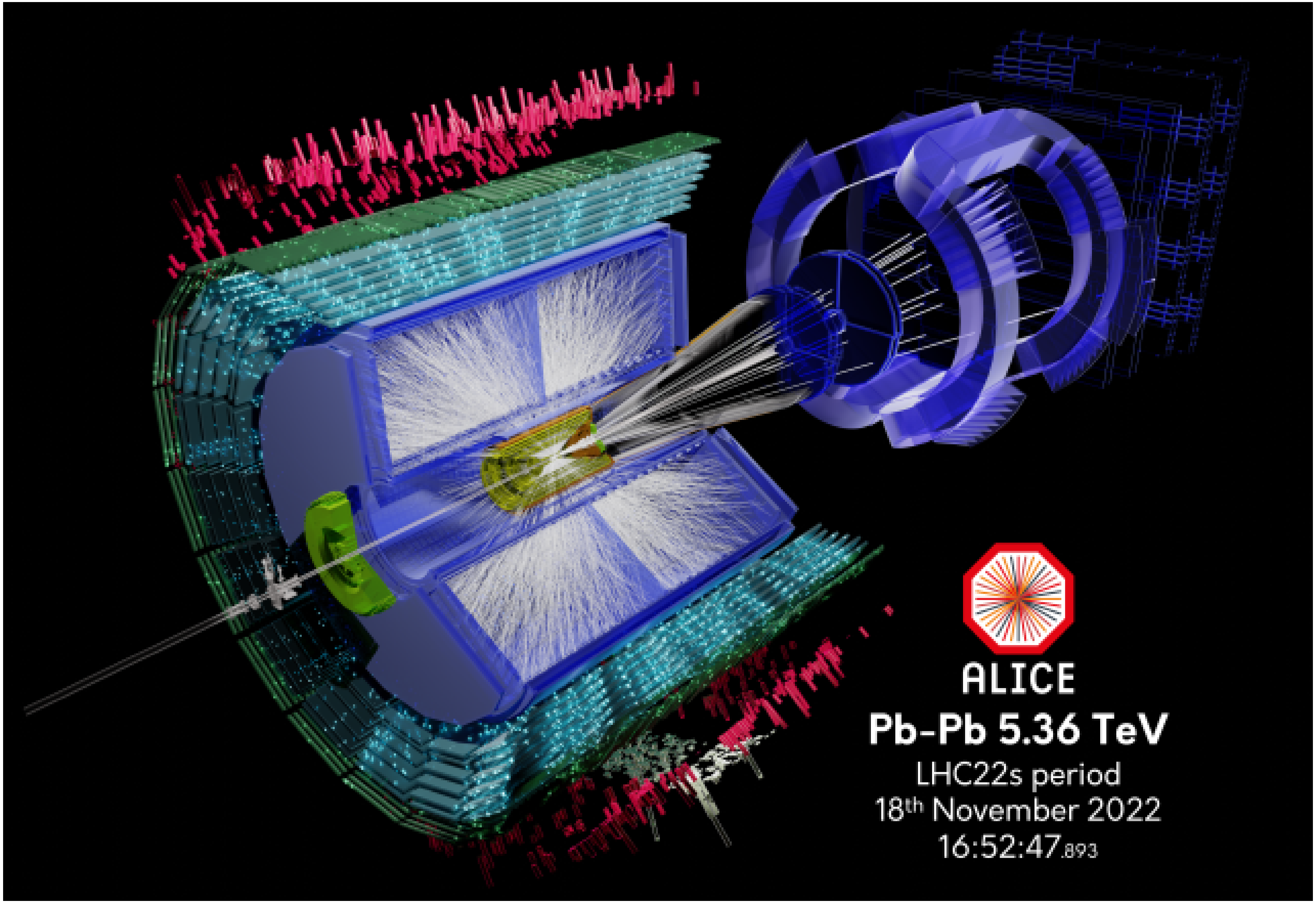
Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) 321, etc.

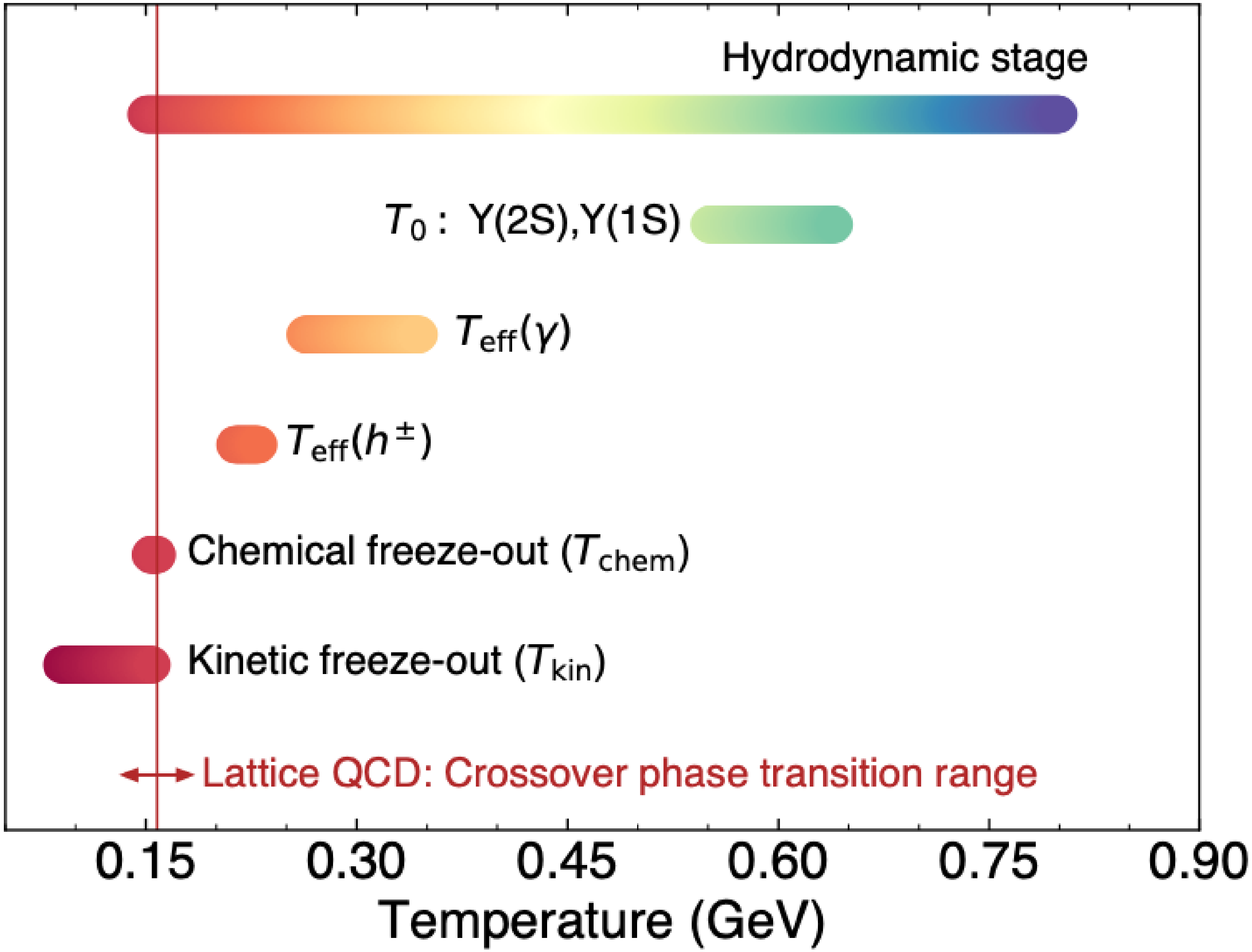
...+ Brunßen, Crkovská, Mazeliauskas, Vislavicius, Völkl, JHEP 07 (2021) 035; JHEP 10 (2024) 229; etc.



A. Rothkopf, Phys. Rep. 858 (2020) 1

The Quark-Gluon Plasma ...in Pb-Pb collisions





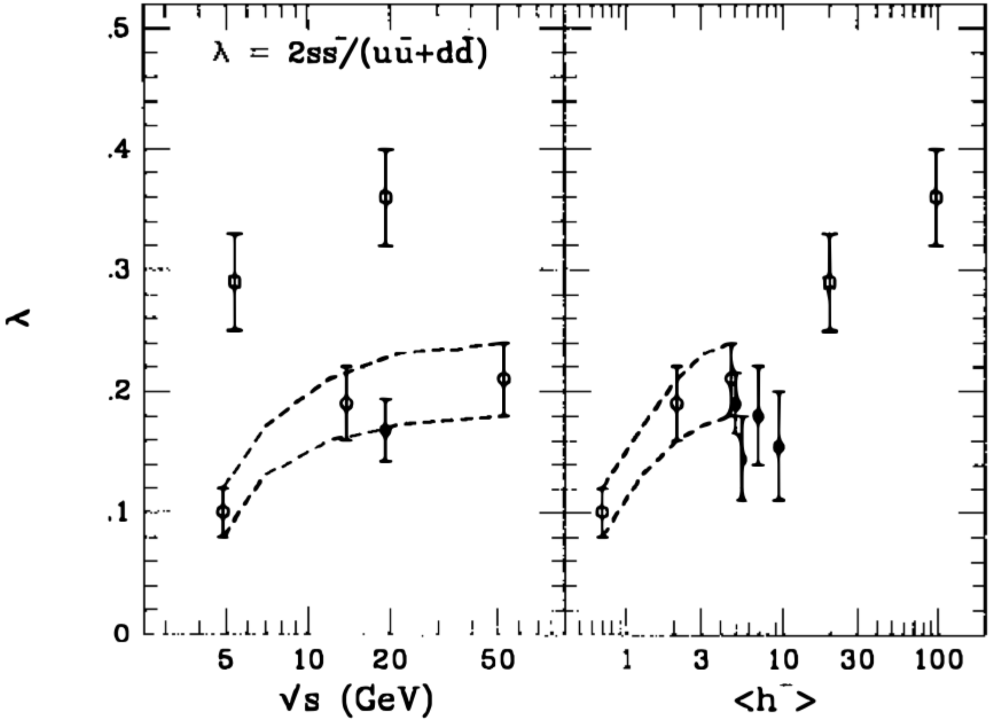
NB: Some values are probed ranges, some (T_{eff}) are measurement uncertainties

The ALICE experiment: a journey through QCD, EPJC 24 (2024) 813

J. Stachel, P. Braun-Munzinger, *Stopping in High-energy Nucleus Nucleus Collisions: Analysis in the Landau Hydrodynamic Model*, Phys. Lett. B 216 (1989) 1 [also: QM'88 review: Nucl. Phys. A 498 (1989) 33C]

Relativistic heavy ion physics at CERN and BNL

Stachel, Young, Ann. Rev. Nucl. Part. Sci. 42 (1992) 537-597 [Keywords: QCD, quark-gluon plasma, deconfined matter, restoration of chiral symmetry, relativistic heavy ion collisions, AGS, SPS, RHIC]



The desire to achieve significantly higher energy densities and temperatures and to create a QGP with low net baryon density led to the decision to build the Relativistic Heavy Ion Collider (RHIC) at BNL and to discussions concerning acceleration of heavy ions in the proposed Large Hadron Collider (LHC) at CERN. RHIC will attain cm energies per colliding nucleon-nucleon pair of $s^{1/2}$ = 250 GeV for light nuclei and 200 GeV for Au-Au collisions, while LHC might reach 3.8 TeV for Pb-Pb collisions. The construction of RHIC was begun in 1991, with the expectation of colliding beams operating by 1997. RHIC in particular offers operation as a dedicated facility for such research, an important consideration for experiment planning, for observation of several interesting signals of deconfinement (such as vector meson suppression and/or modification), and for modification of parton propagation, all of which have small cross sections and thus must be studied at large integrated luminosity. Present theoretical estimates indicate that only at these colliding beam facilities will the temperature significantly exceed the critical temperature, a likely requirement for the emission of observable amounts of thermal radiation.

squares: Si-Si, S-S; rest: pp, pA

ELSEVIER

26 January 1995

PHYSICS LETTERS B

Physics Letters B 344 (1995) 43–48

Thermal equilibration and expansion in nucleus-nucleus collisions at the AGS

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Received 20 October 1994; revised manuscript received 14 November 1994

Editor: G.F. Bertsch

Abstract

The rather complete data set of hadron yields from central Si + A collisions at the Brookhaven AGS is used to test whether the system at freeze-out is in thermal and hadro-chemical equilibrium. Rapidity and transverse momentum distributions are discussed with regards to the information they provide on hydrodynamic flow.

We have demonstrated that the presently available AGS data can be consistently described in a thermal model with chemical equilibrium and flow. This includes particle densities, ratios of produced particles, and rapidity and transverse momentum distributions. The thermal parameters describing freeze-out are T = 0.12–0.14 GeV, μ_b = 0.54 GeV, $\langle\beta_l\rangle$ = 0.52, and $\langle\beta_t\rangle = 0.39 - 0.33$. Earlier times in the evolution of the fireball need to be probed with different observables to determine the equation of state during the high density phase.

The fertile ground:

Cleymans, Satz, Suhonen, PLB 242 (1990) 111 (AGS: $93 \leq T \leq 112$ MeV, $0.2 \leq n_B \leq 0.12$ fm^{-3})

Davidson, Miller, Quick, Cleymans, PLB 255 (1991) 105 (SPS: $T \simeq 170$ MeV, $n_B \simeq 0.1$ fm^{-3})

Cleymans, Redlich, Suhonen, ZPC 51 (1991) 137 (canonical treatment)

Cleymans, Satz, ZPC 57 (1993) 135 (SPS: T, μ_B constraints)

Rischke, Gorenstein, Stöcker, Greiner, ZPC 51 (1991) 485 ("excluded volume")

Letessier, Tounsi, Rafelski, PLB 292 (1992) 417 (SPS, $T \simeq$ 200-210 MeV, $\lambda_s \simeq 1$), etc.

The Quark-Gluon Plasma: the early years

ELSEVIER

4 January 1996

PHYSICS LETTERS B

Physics Letters B 365 (1996) 1–6

Thermal and hadrochemical equilibration in nucleus-nucleus collisions at the SPS

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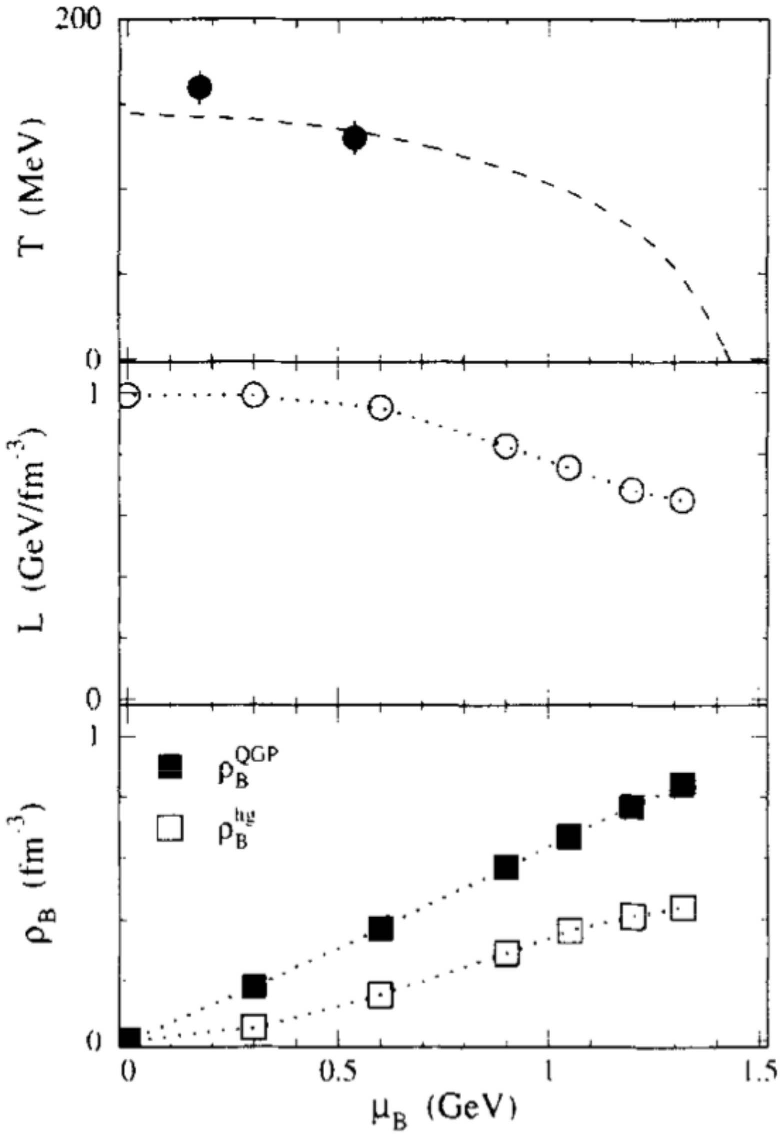
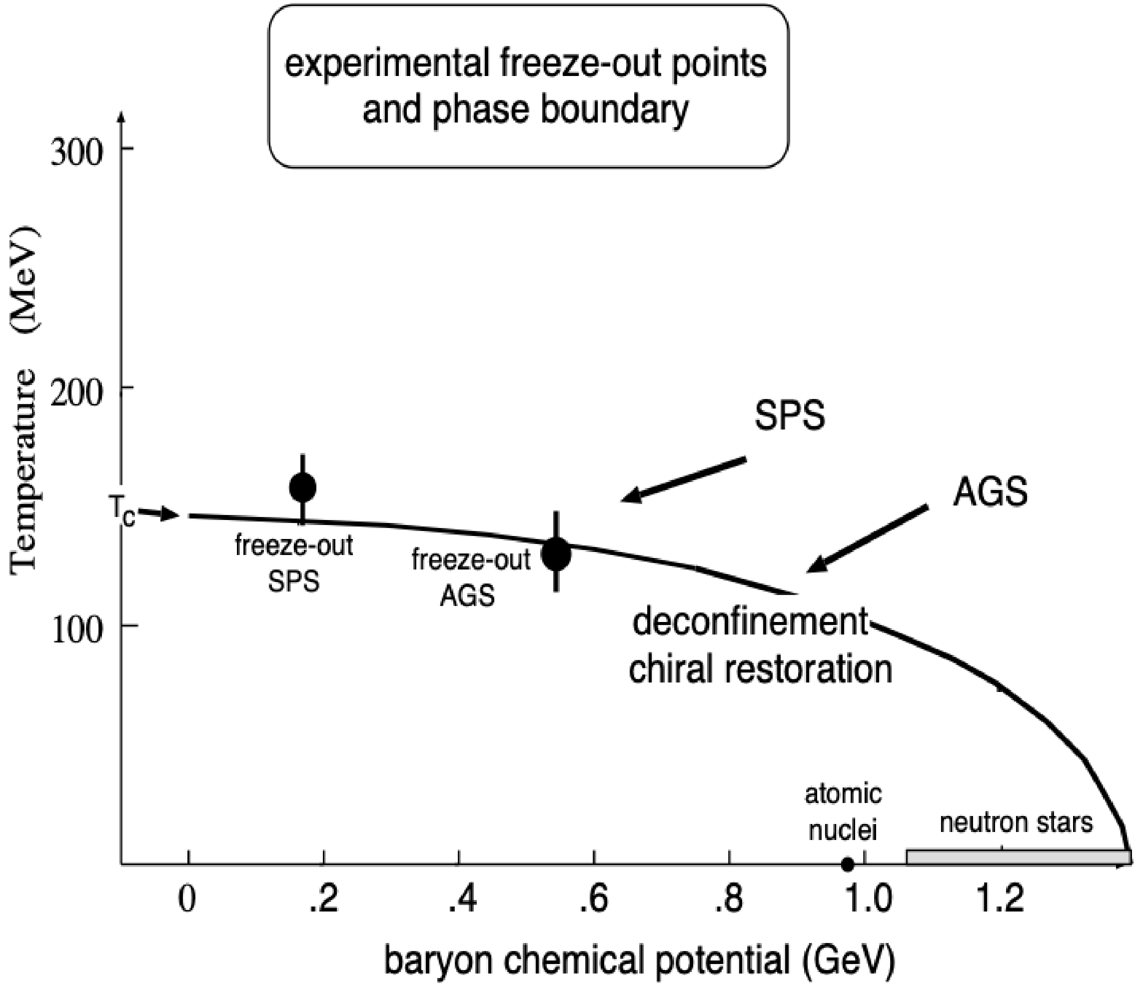
Received 14 August 1995; revised manuscript received 22 September 1995
Editor: G.F. Bertsch

Abstract

The currently available set of hadron abundances at the SPS for central S + Au(W,Pb) collisions is compared to predictions from a scenario assuming local thermal and hadrochemical equilibrium. The data are consistent with a freeze-out temperature $T = 160–170$ MeV. Spectra are consistent with this temperature range and a moderate transverse expansion. The freeze-out points at the AGS and SPS are found to be close to the phase boundary between a hadron gas and an ideal quark-gluon phase.

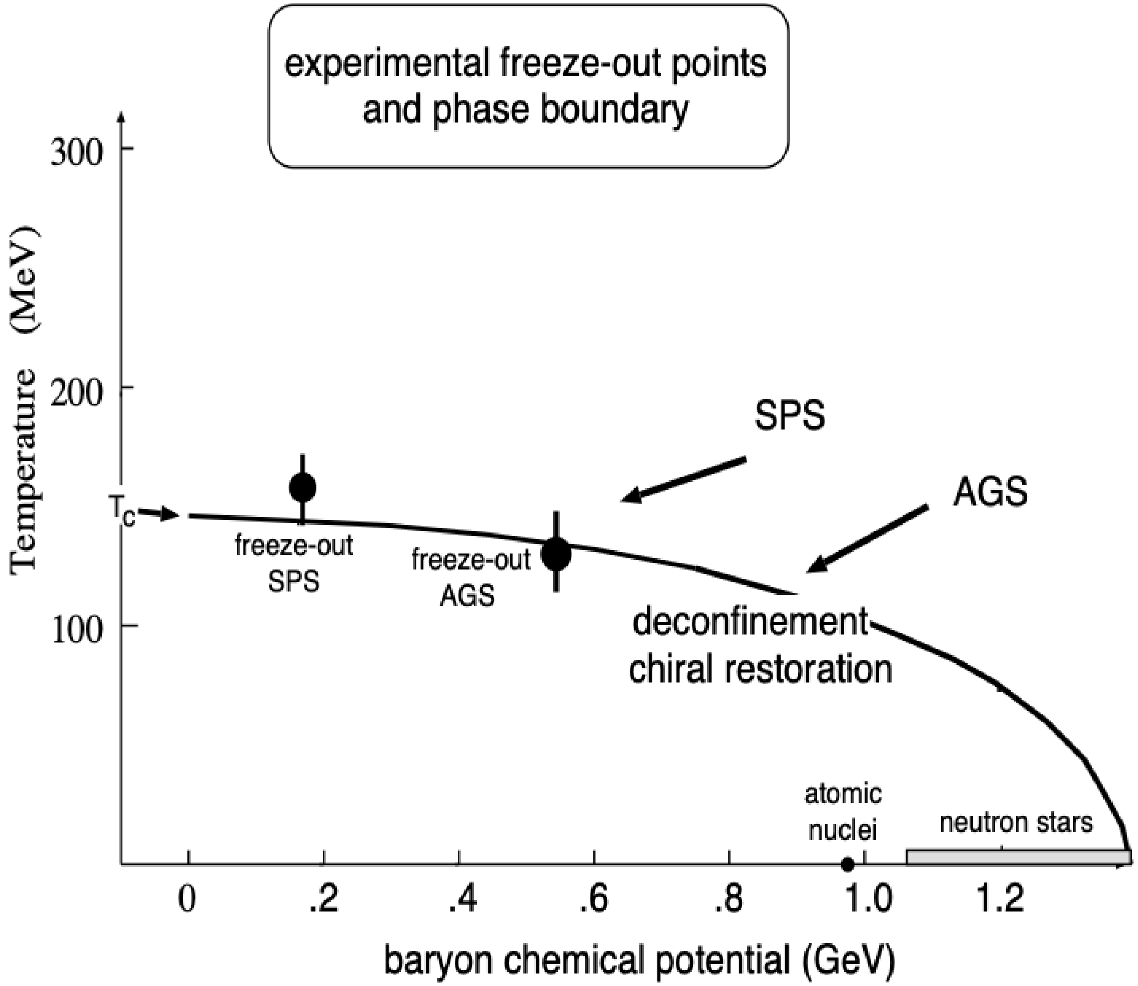
"...*after* expansion and cooling"





J.Stachel, *Tests of thermalization in relativistic nucleus nucleus collisions* (QM'96 review), Nucl.Phys.A 610 (1996) 509C ...see also: Braun-Munzinger, Stachel, Nucl.Phys. A606 (1996) 320

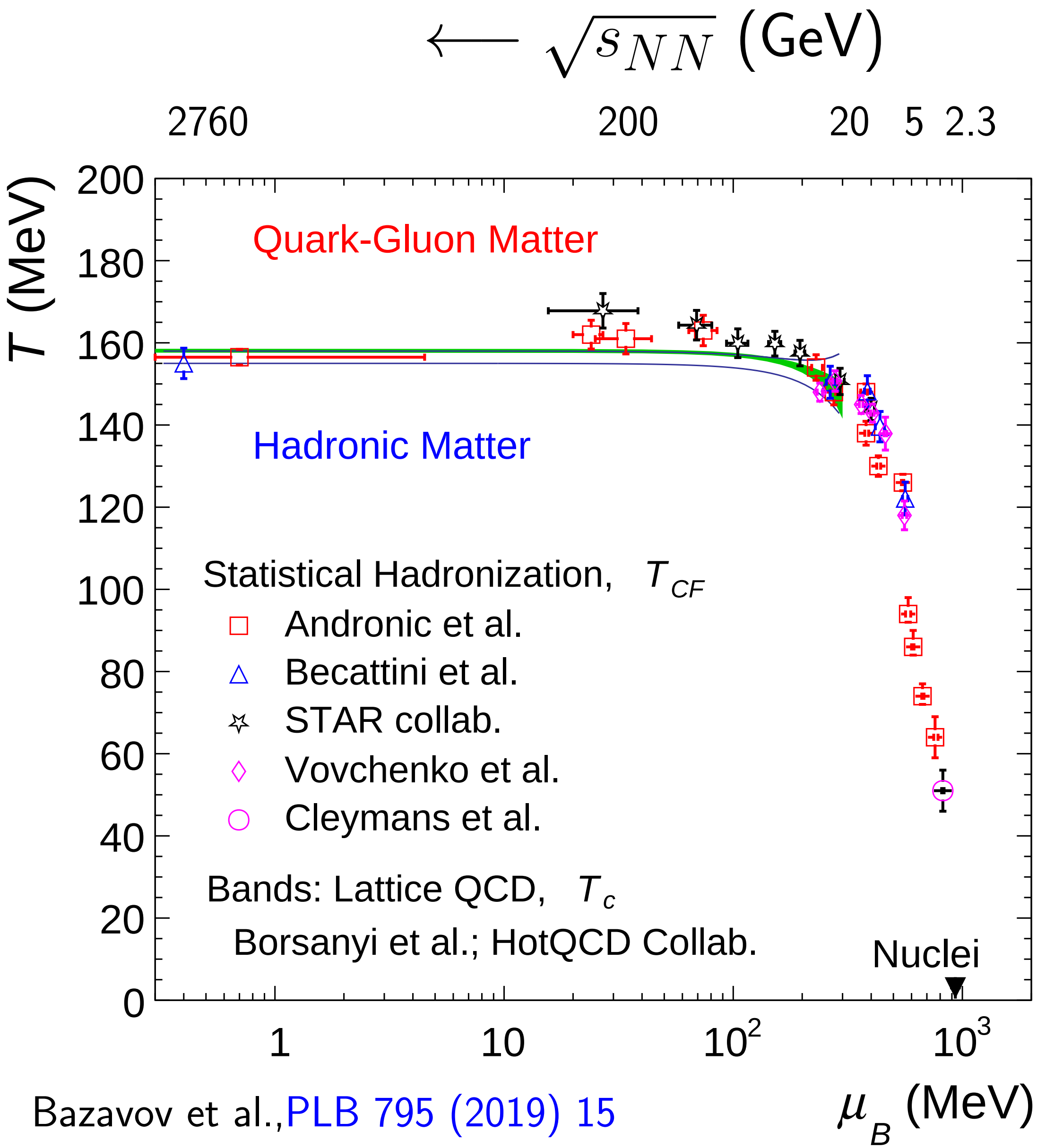
The Quark-Gluon Plasma: the early years



J.Stachel, *Tests of thermalization in relativistic nucleus nucleus collisions* (QM'96 review), Nucl.Phys.A 610 (1996) 509C ...see also: Braun-Munzinger, Stachel, Nucl.Phys. A606 (1996) 320

1996 is also the year I first-time met Johanna (and Peter) ...at the International Workshop *"Heavy Ion Physics at Low, Intermediate and Relativistic Energies using 4π Detectors"*, Poiana Brasov, Romania, October 7-14 (1996)

The phase diagram of QCD



Bazavov et al.,PLB 795 (2019) 15

Borsanyi et al., PRL 125 (2020) 052001

at LHC, remarkable "coincidence" with Lattice QCD results

at LHC ($\mu_B \simeq 0$): purely-produced (anti)matter ($m = E/c^2$), as in the Early Universe

$\mu_B > 0$: more matter, from "remnants"/stopping of the colliding nuclei

$\mu_B \gtrsim 400$ MeV: *the critical point awaiting discovery*

(RHIC BES / FAIR)

see refs. in Nature 561 (2018) 321

points: independent analyses of same data $\rightarrow$ "model/code uncert." are small

Statistical hadronization ("thermal") fits

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

quantum nr. conservation ensured via chemical potentials:

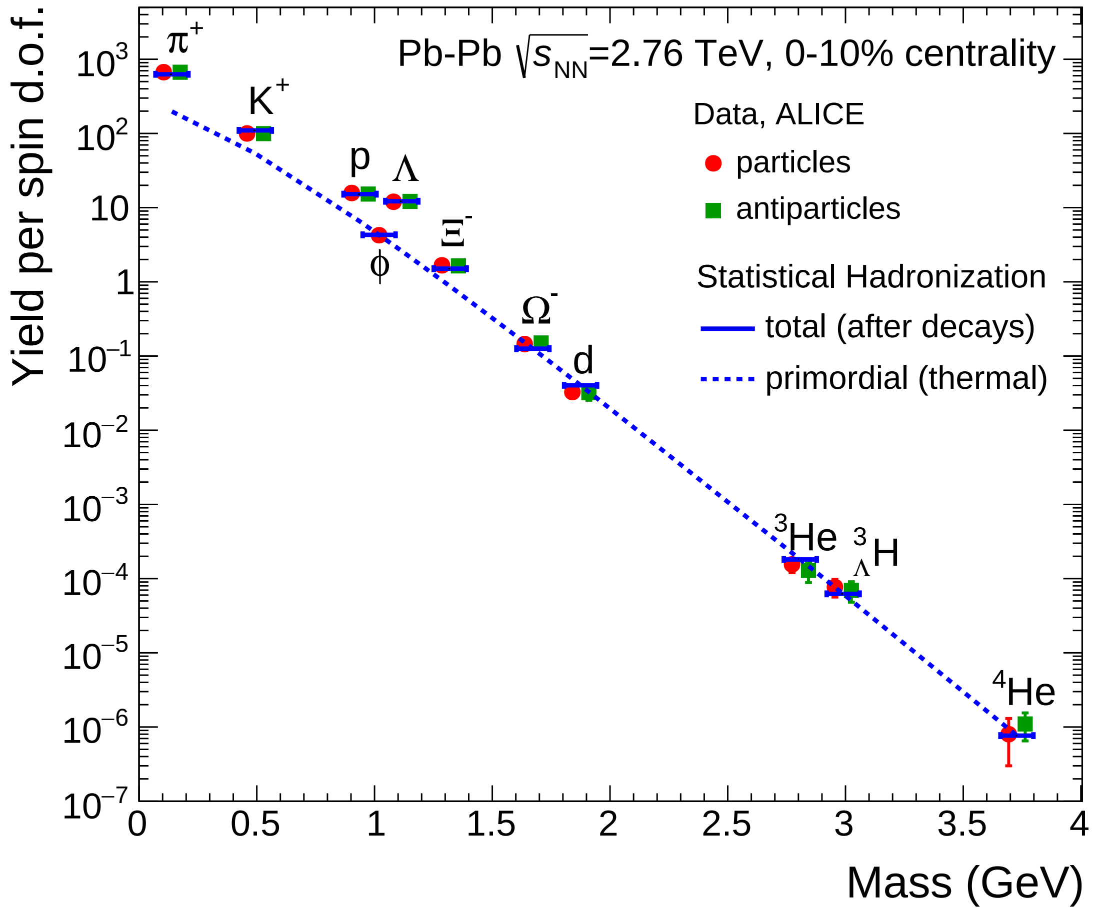
$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$

Initial conditions: $\mu_{I_3} \sim \mu_B$, S=0, C=0

Latest PDG hadron mass spectrum (up to 3 GeV, 600 species)

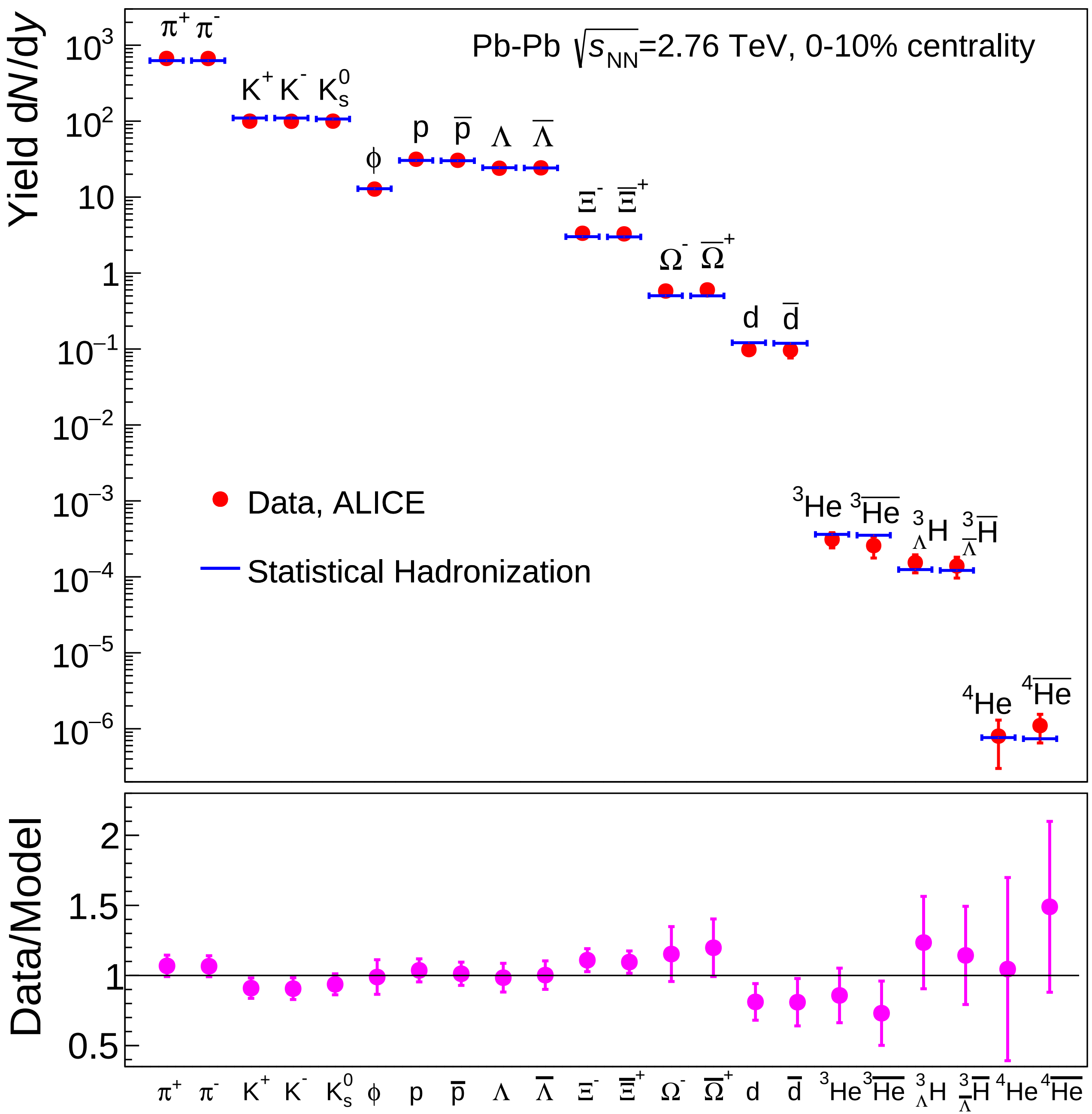
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i: hadron yield $\Rightarrow (T, \mu_B, V)$



Strong (and EM, for Λ) decays play a major role; approx.: $\ln N \sim \ln(mT) - \frac{m}{T}$

Even loosely-bound objects (d, ${}^3_\Lambda$H) seem produced at T=156 MeV (?)



matter and antimatter produced in equal amounts

$T_{CF} = 156.6 \pm 1.7$ MeV
$\mu_B = 0.7 \pm 3.8$ MeV
$V_{\Delta y=1} = 4175 \pm 380$ fm^3

$\chi^2/N_{df} = 16.7/19$

S-matrix treatment $(\mathrm{p}, \bar{\mathrm{p}})$

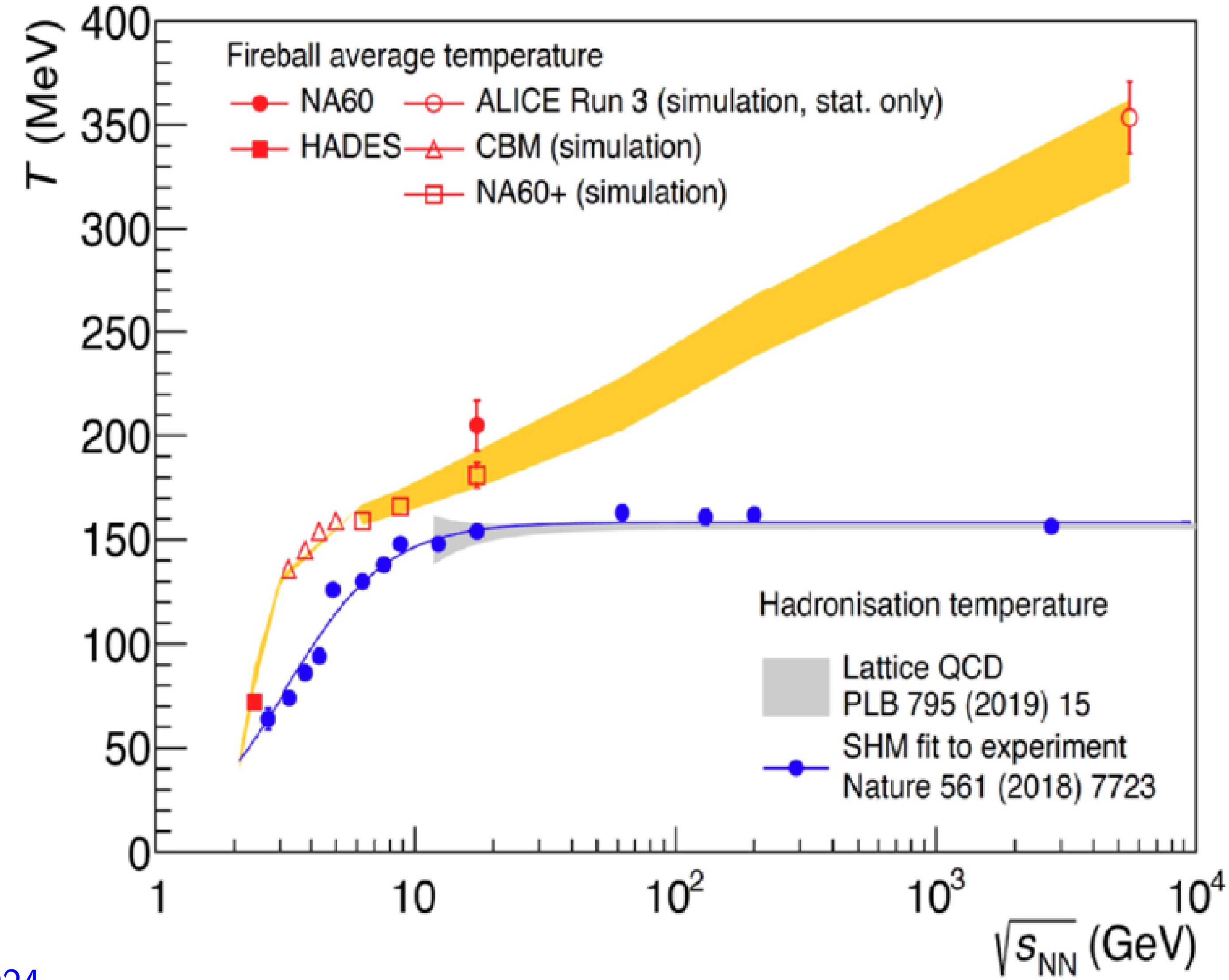
+Friman, Lo, Redlich, PLB 792 (2019) 304

remarkably, loosely-bound objects are also well described ($^3_\Lambda$H: 25% B.R.)

hadronization as bags of quarks and gluons?

hadron spectrum beyond PDG → same T_{CF} NPA 1010 (2021) 122176

Two temperatures



NuPECC LRP 2024

Fireball average temperature ...over the lifetime of the fireball (QGP+hadronic phase)

Fit of dilepton inv.mass data with: $\mathrm{d}N/\mathrm{d}M \sim M^{3/2}\exp(-M/T)$

Quark interlude

up to now we only considered hadrons built with *up, down, strange* quarks
...these are light, masses from a few MeV (u, d) to ∼90 MeV (s), $< T_{CF}$

what about heavier ones?
...for instance *charm*, which weights about 1.5 GeV, $\gg T_{CF}$

produced in pairs ($c\bar{c}$) in initial hard collisions, $t \sim 1/(2m_c) \leq 0.1$ fm/c

preserve their identity throughout the evolution of the fireball

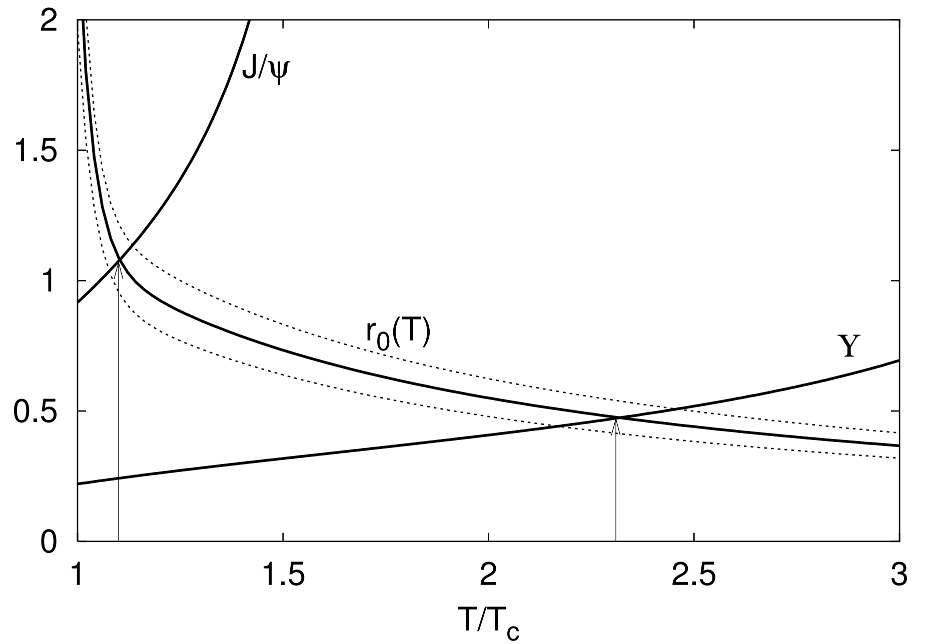
...ideal messengers of the early stage

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

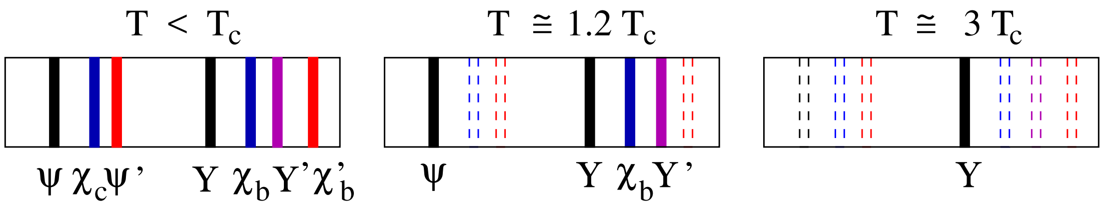
$\Rightarrow$ $\mathrm{q\bar{q}}$ "thermometer" of QGP

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

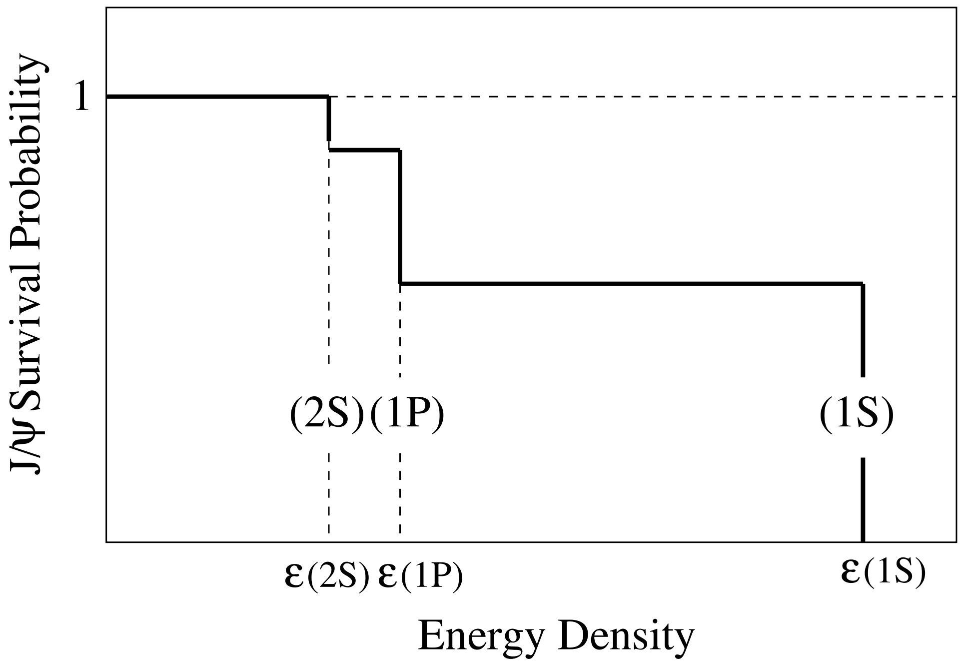
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi}$

Quarkonium and the QGP - "sequential suppression"

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



quantitative: lattice QCD



← 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}

$\sim \varepsilon$

quarkonium as thermometer

a new mechanism for charmonium production

Braun-Munzinger, Stachel, PLB 490 (2000) 196, NPA 690 (2001) 119 (+K.Redlich)

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, JHEP 10 (2024) 229

SHM for charm (SHMc)

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

LHC, central collisions

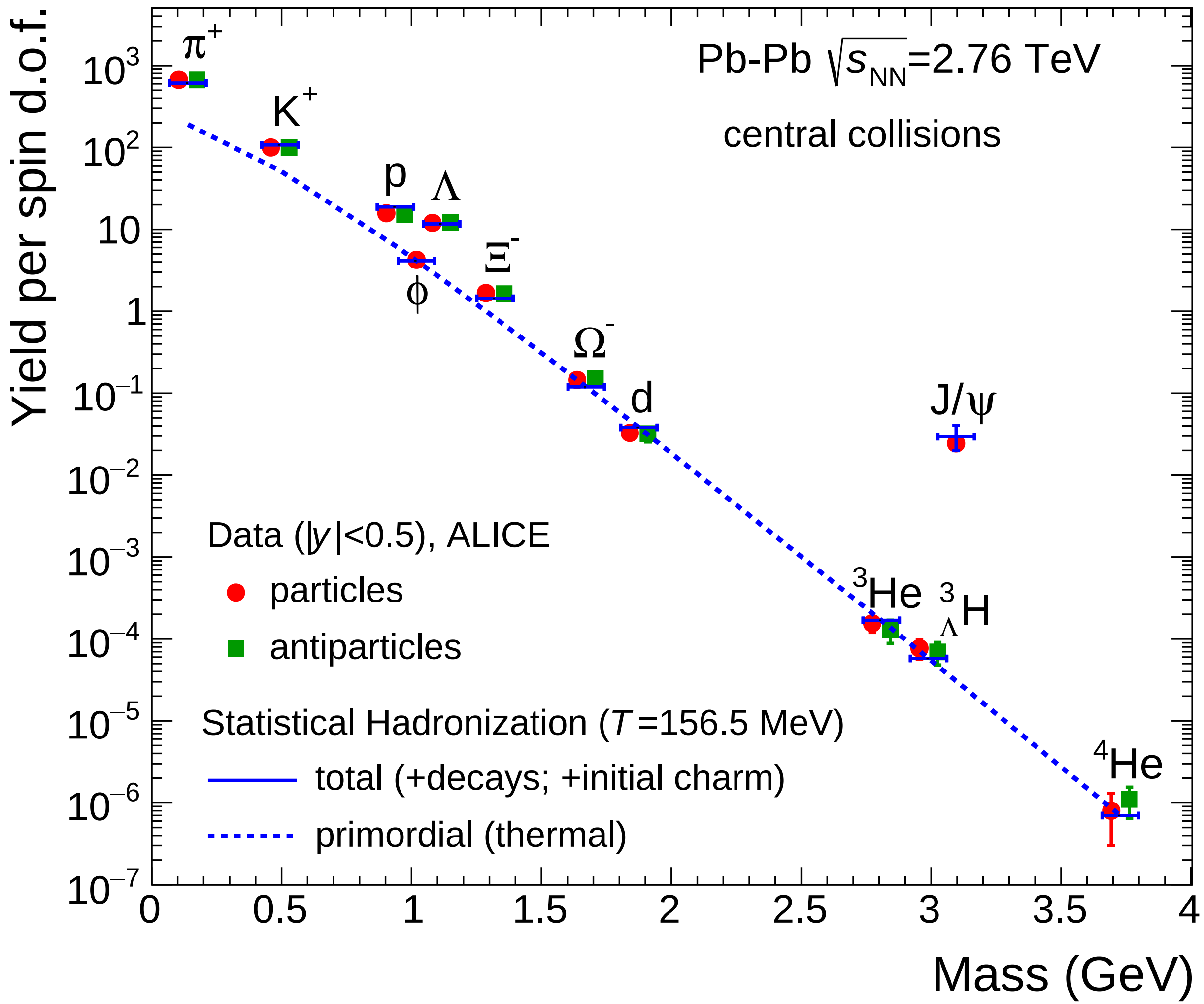
assume:

- full thermalization of $c, \bar{c}$ ("mobility" in V$\simeq$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

SHMc: method and inputs

Braun-Munzinger, Stachel, PLB 490 (2000) 196, NPA 690 (2001) 119 (+K.Redlich)

- Thermal model calculation (grand canonical) T,μ_B: $\rightarrow n_X^{th}$

- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$

- $N_{c\bar{c}} \ll 1 \rightarrow$ Canonical (Cleymans, Redlich, Suhonen, Z. Phys. C51 (1991) 137):

Gorenstein, Kostyuk, Stöcker, Greiner, PLB 509 (2001) 277

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c(N_{part}) \text{ (charm fugacity)}$$

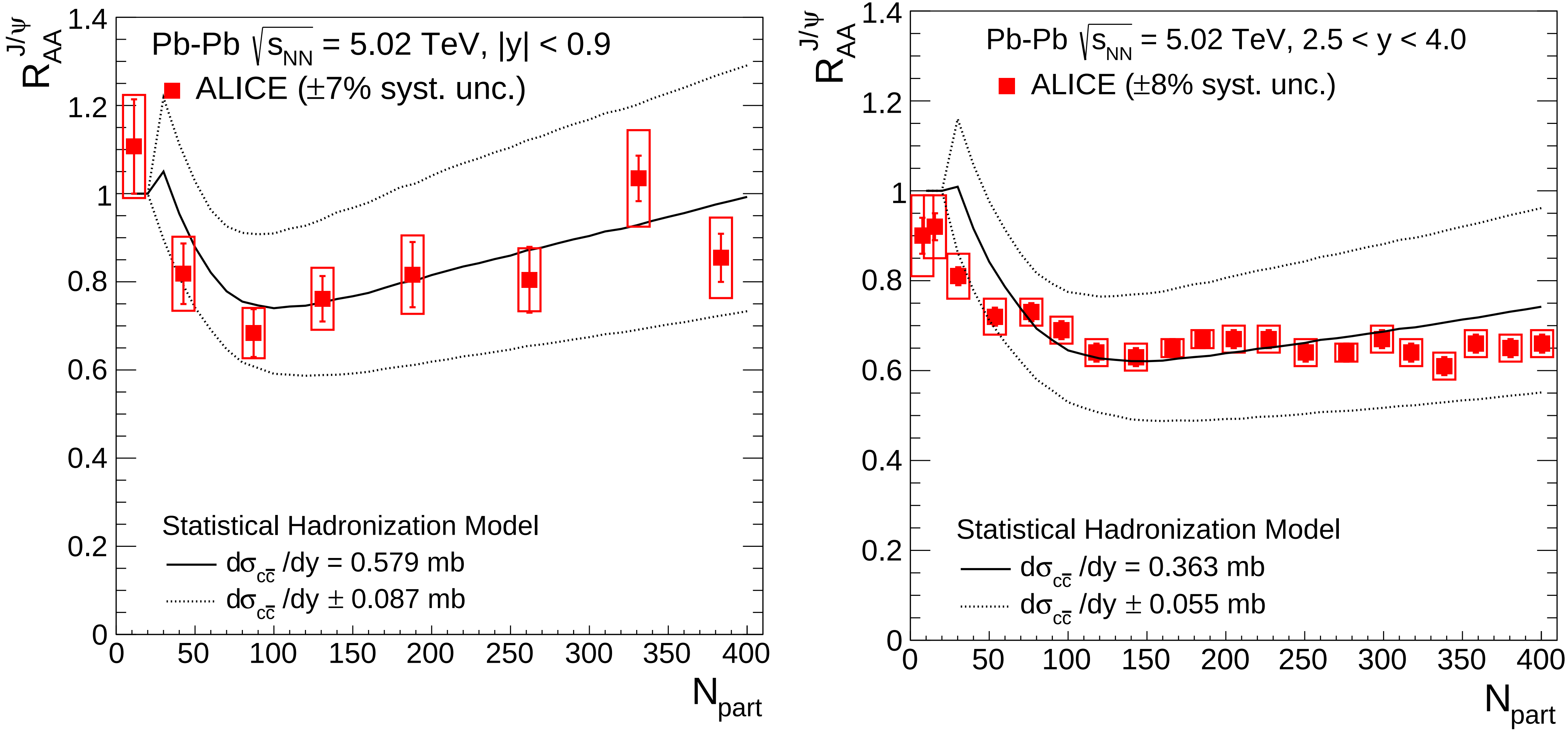
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 + N_D^{\text{corona}}, \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th} + N_{J/\psi}^{\text{corona}}$

Inputs: T, μ_B, $V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{d}y)/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (exp. or pQCD)

Assumed minimal volume for QGP: V_{QGP}^{min}=200 fm^3

SHMc and charmonium data at the LHC

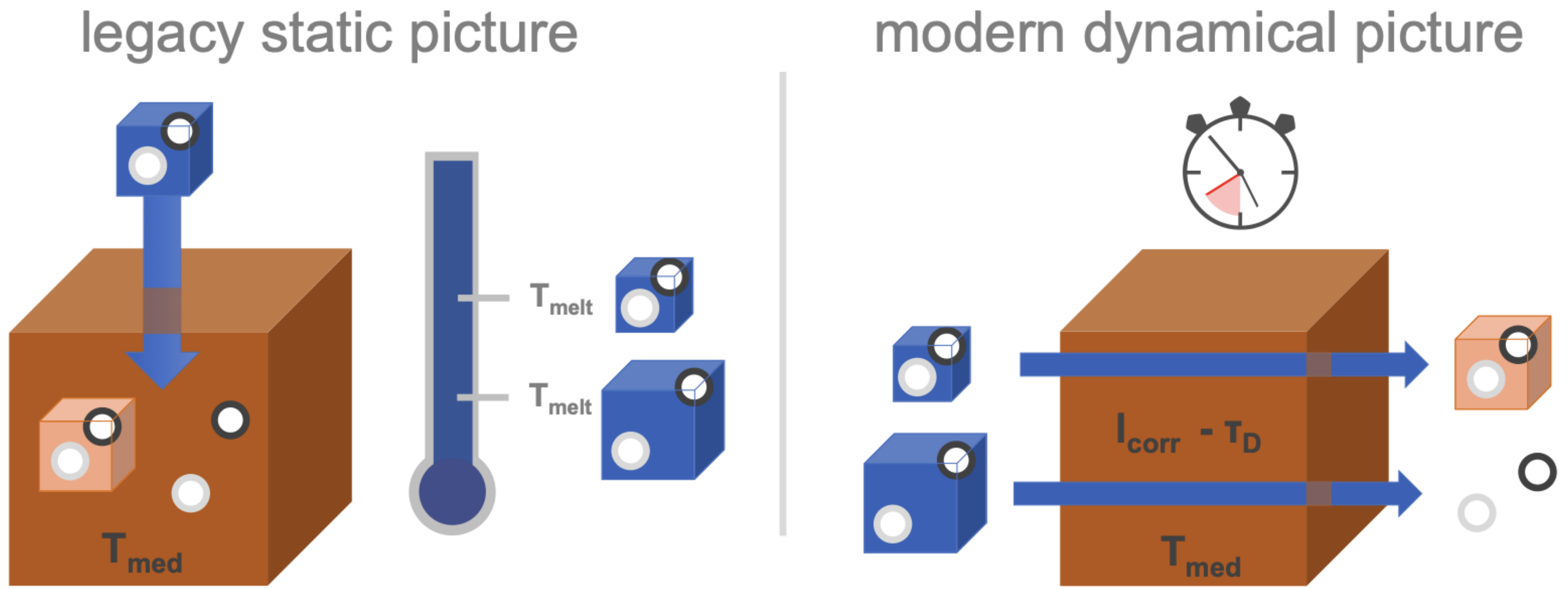
full thermalization of c quarks in QGP, hadronization at chemical freeze-out



$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, JHEP 01 (2022) 174

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

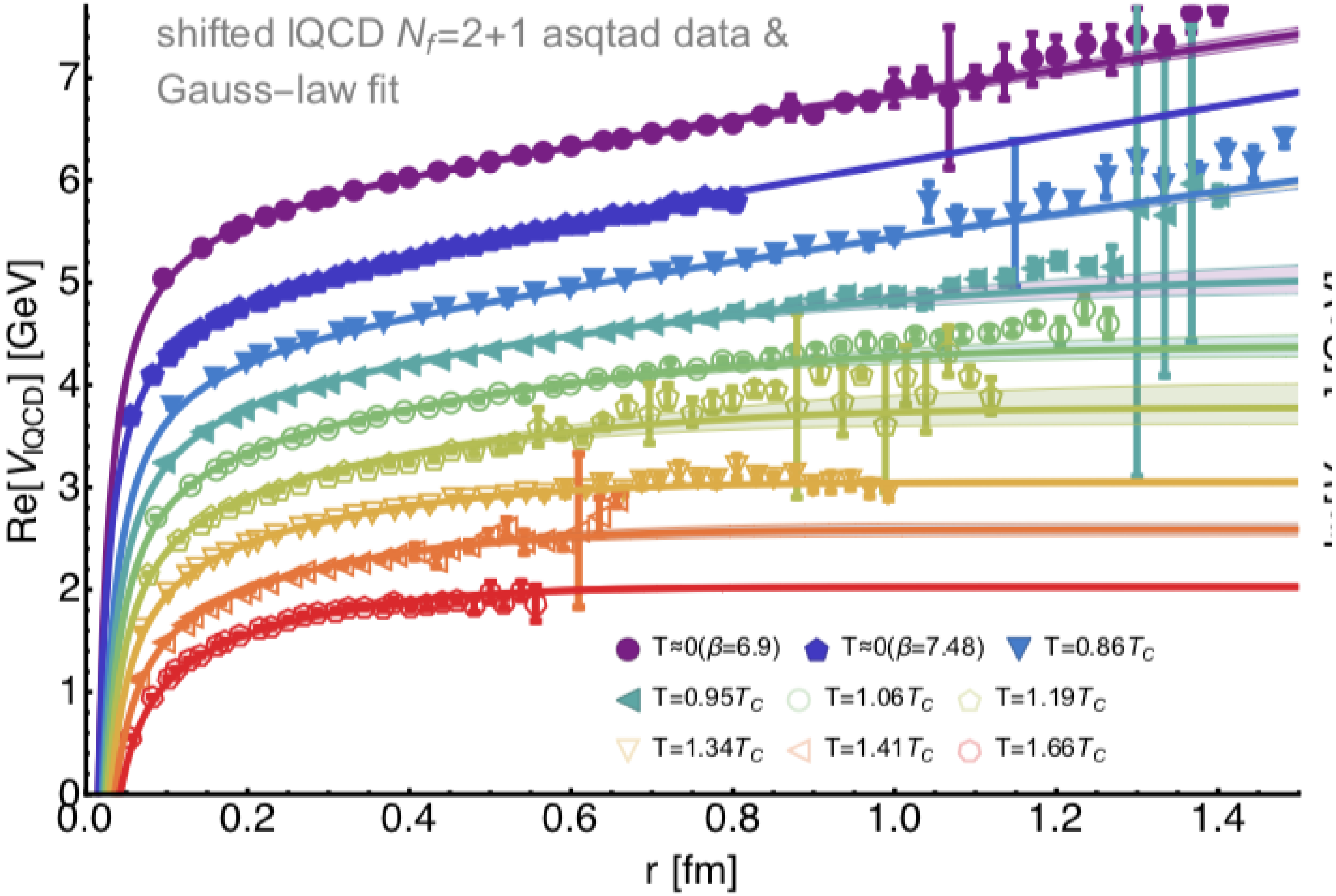
Quarkonium pictures



A. Rothkopf, Phys. Rep. 858 (2020) 1

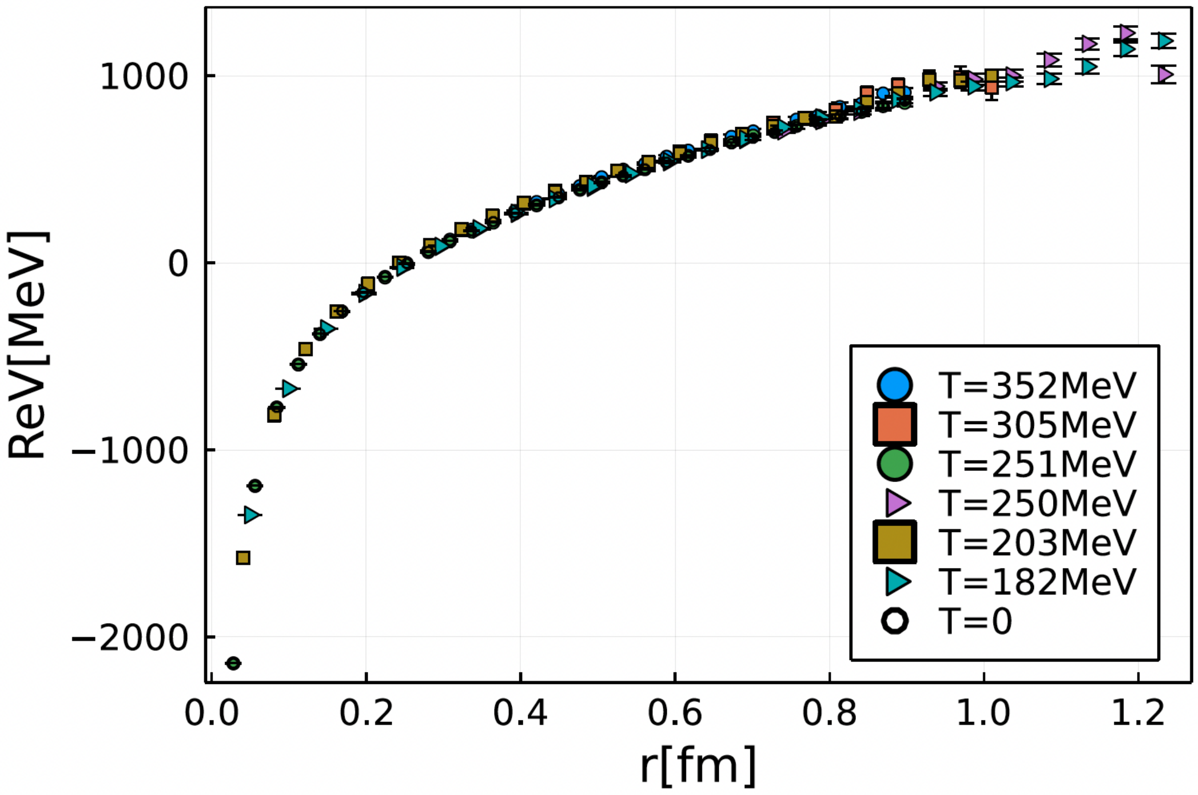
for $T(\tau)$ we anyway have more basic (bulk) observables (collective flow)

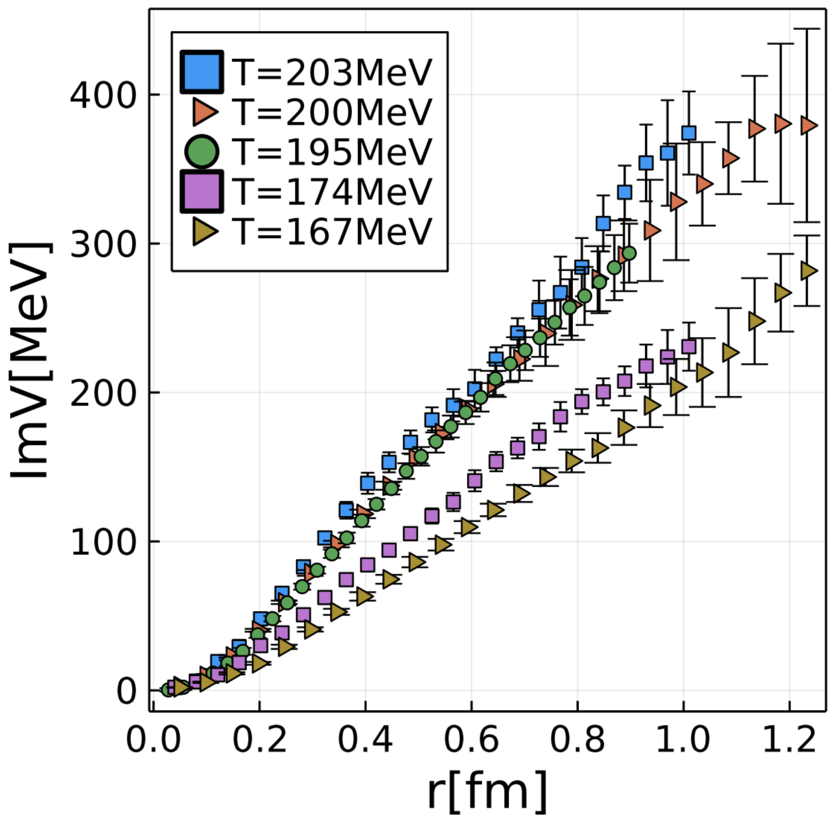
$$T \sim \Lambda_{QCD} \sim E^{vac}_{b,Q\overline{Q}} \; (m_Q \gg \Lambda_{QCD})$$



A. Rothkopf, Phys. Rep. 858 (2020) 1

$$(T_C \simeq 174 \text{ MeV})$$





HotQCD coll., PRD 109 (2024) 0745047

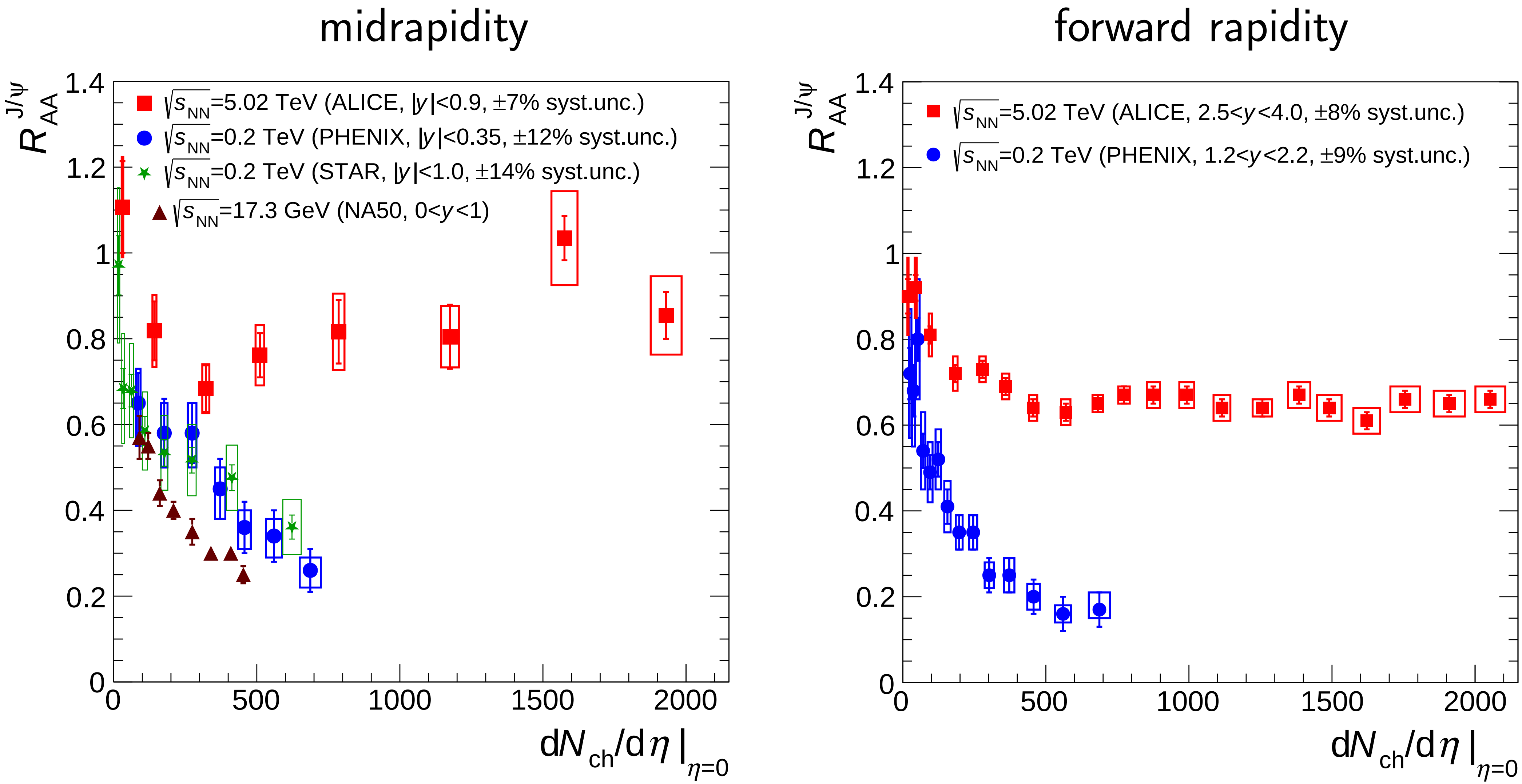
ReV: not screened!

ImV: large, increases with distance

$\rightarrow$ "melting of quarkonium is not related to color screening" (P.Petreczky)

Charmonium data: SPS, RHIC, LHC

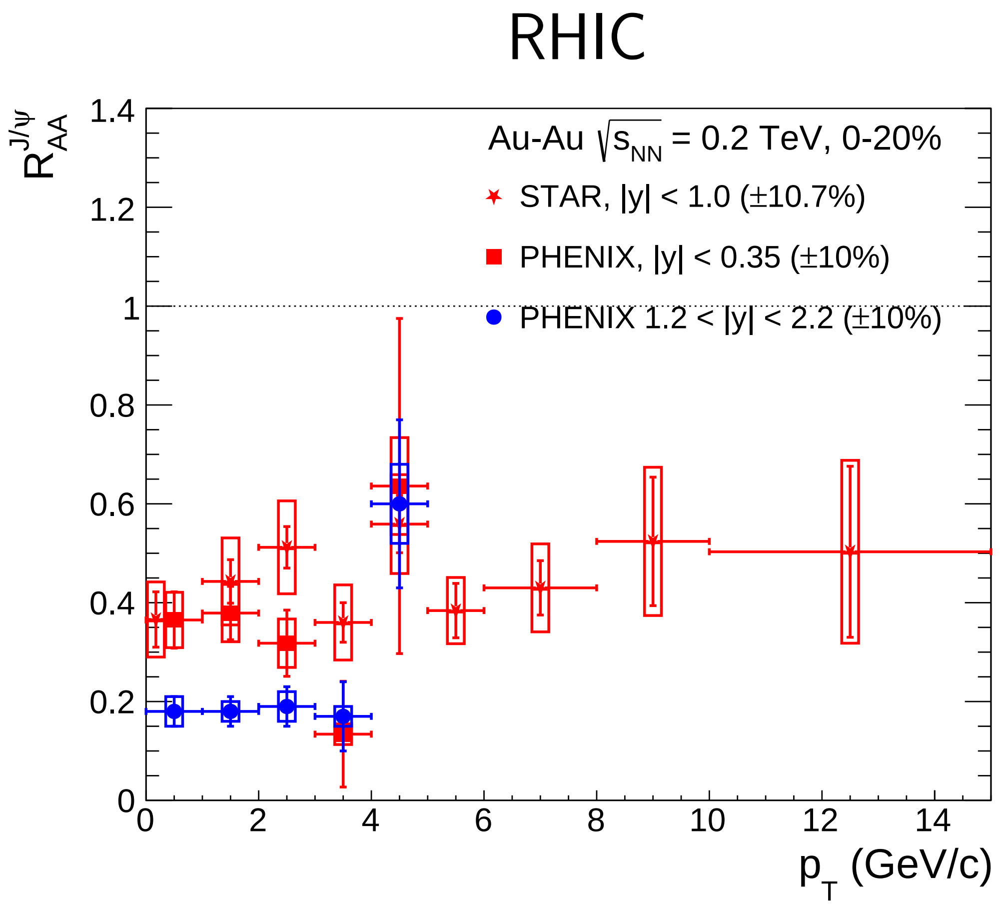
A. Andronic

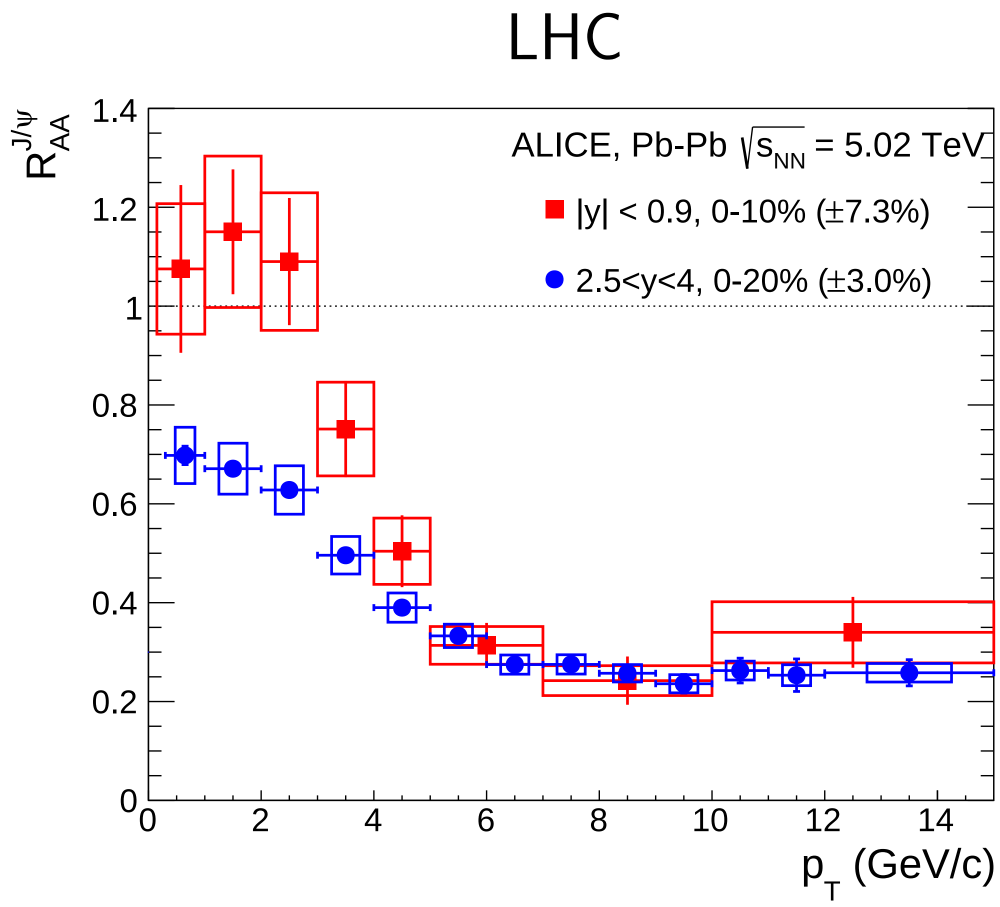


$$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$$

suppression at lower energies, but not obviously a sequential one

at the LHC: generation (at phase boundary), after (full) dissociation

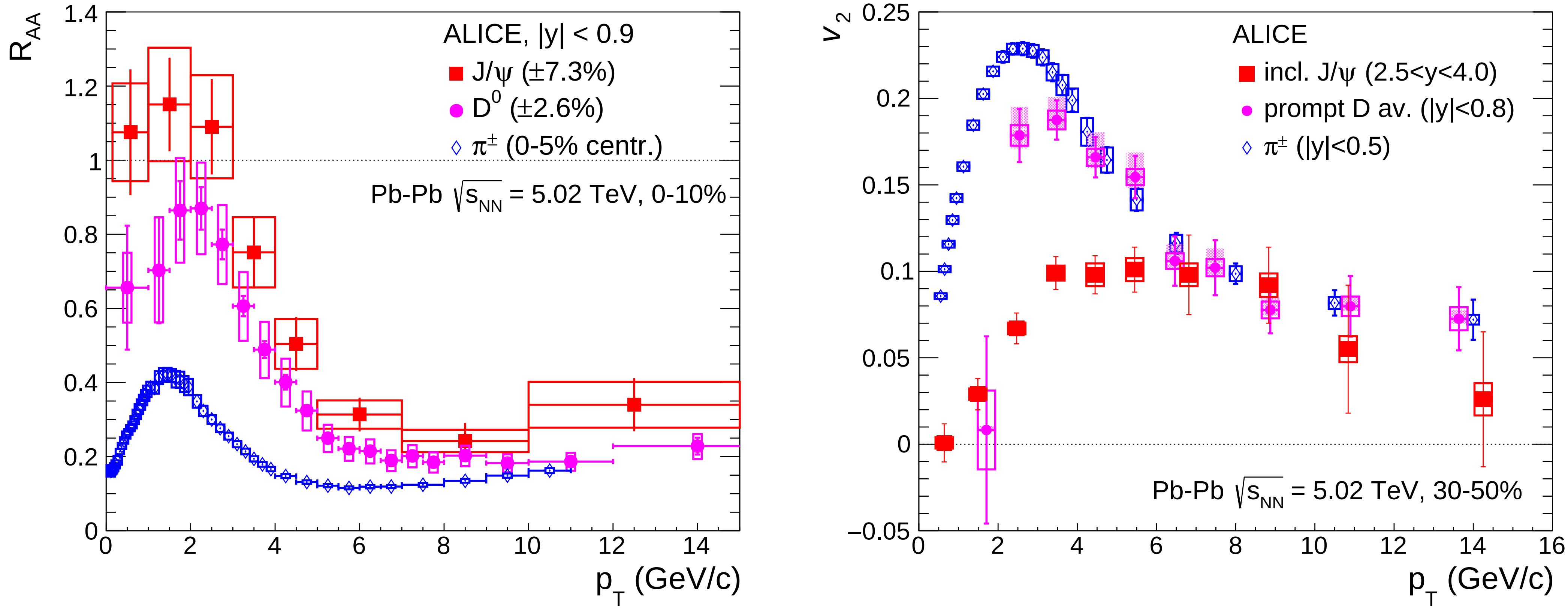




production at low p_{T} is enhanced at the LHC compared to RHIC

...stronger at midrapidity

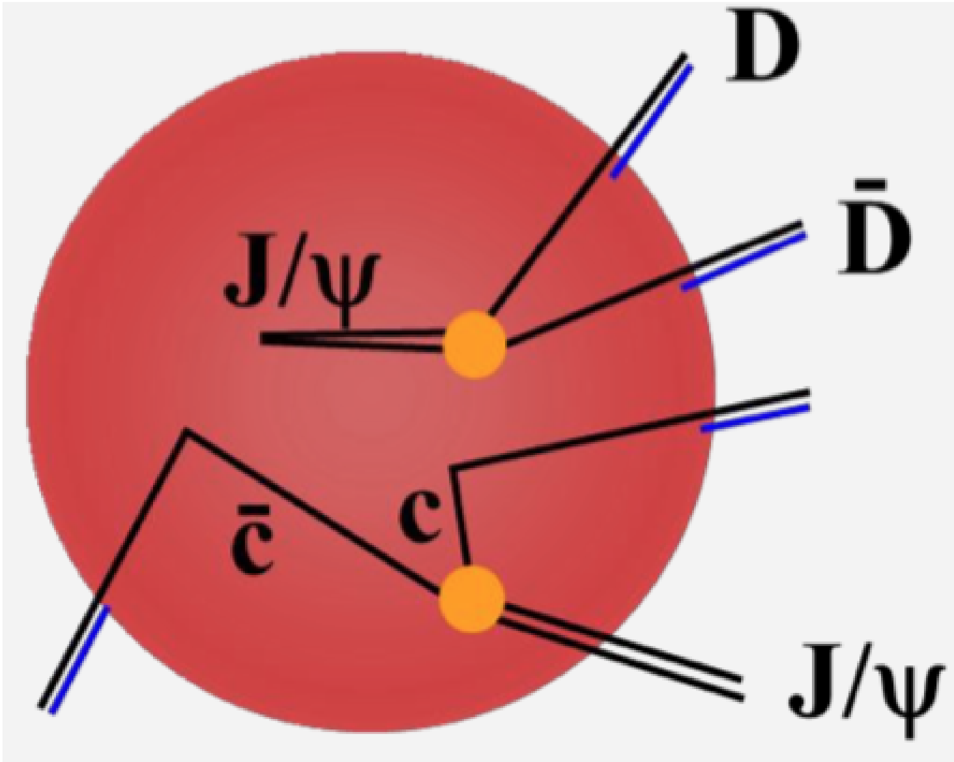
see quarkonium review: AA, R.Arnaldi, arXiv:2501.08290



ALICE, PLB 849 (2024) 138451, JHEP 01 (2022) 174, JHEP 11 (2018) 013

a very clear hierarchy at low/intermediate $p_{\rm T}$ (N_{coll}/N_{part} scaling; shadowing)

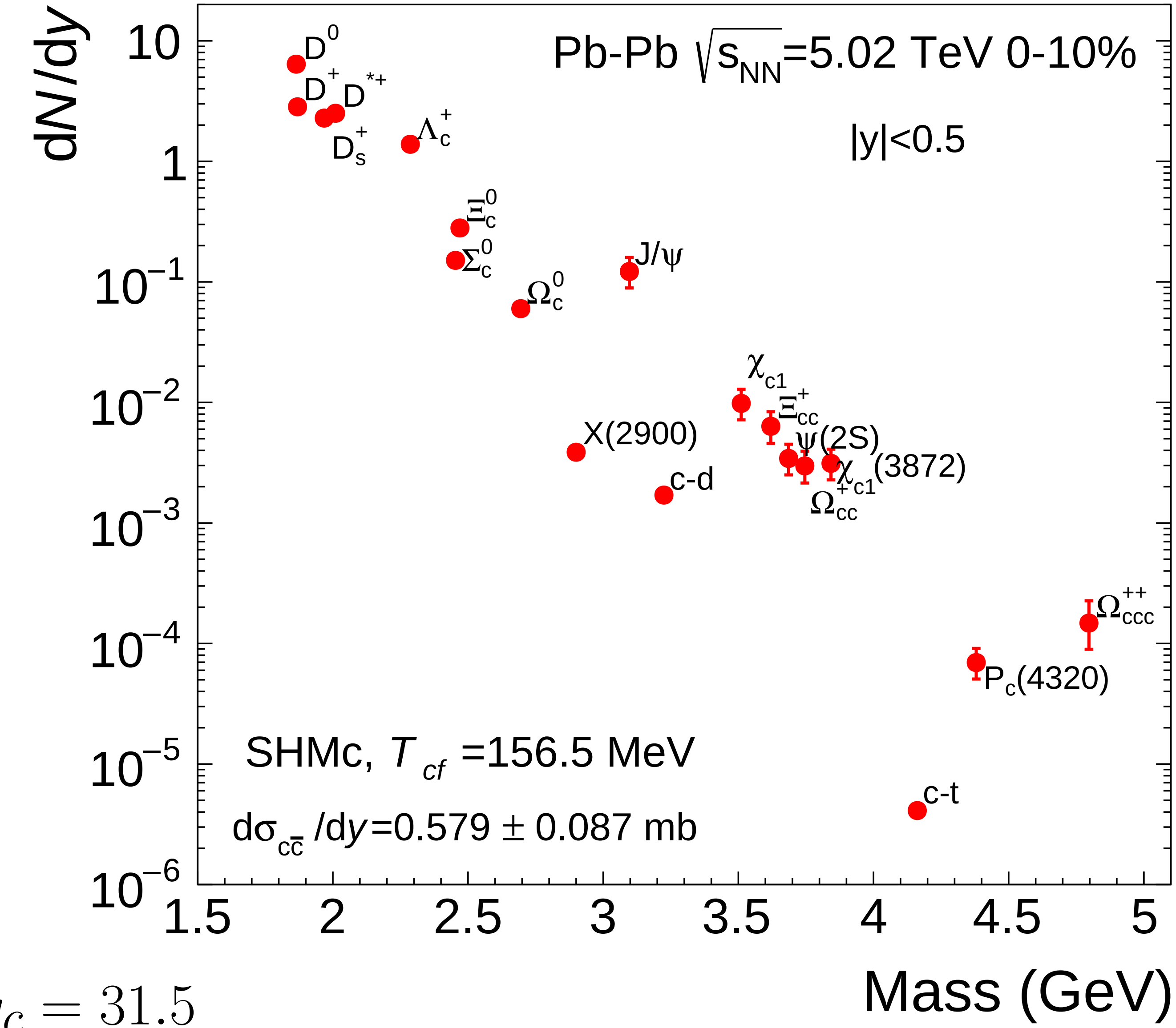
charm production is a pQCD process, pion production largely a thermal process



This picture is implemented in models in 2 basic ways:

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

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



$T_{cc}^{+} \simeq 0.9 \cdot \chi_{c1}(3872)$

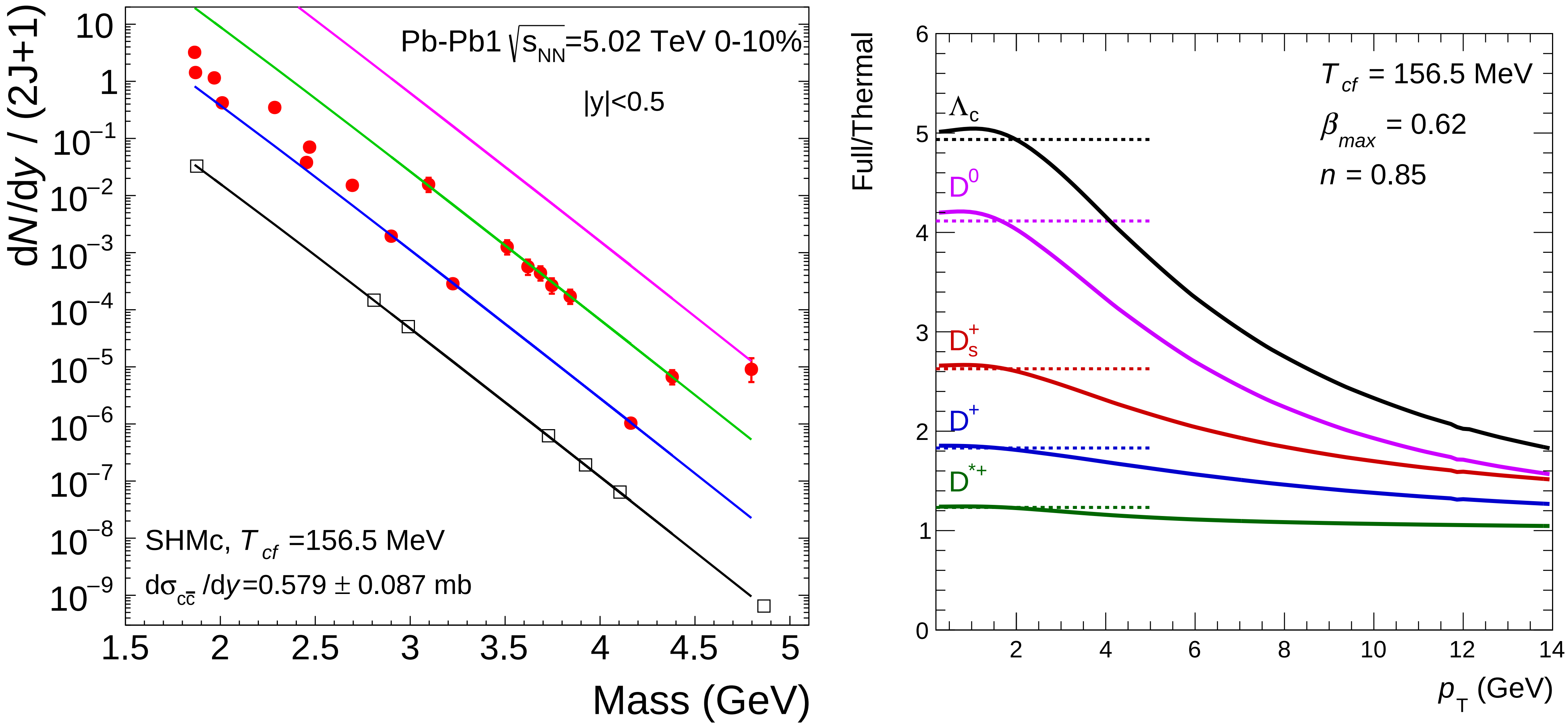
$X(6900) \sim 10^{-8}$

$\frac{dN_{c\bar{c}}}{dy} = 13.8$

$\rightarrow g_c = 31.5$

The power of the model: predicting the full suite of charmed hadrons

Full charm predictions for the LHC



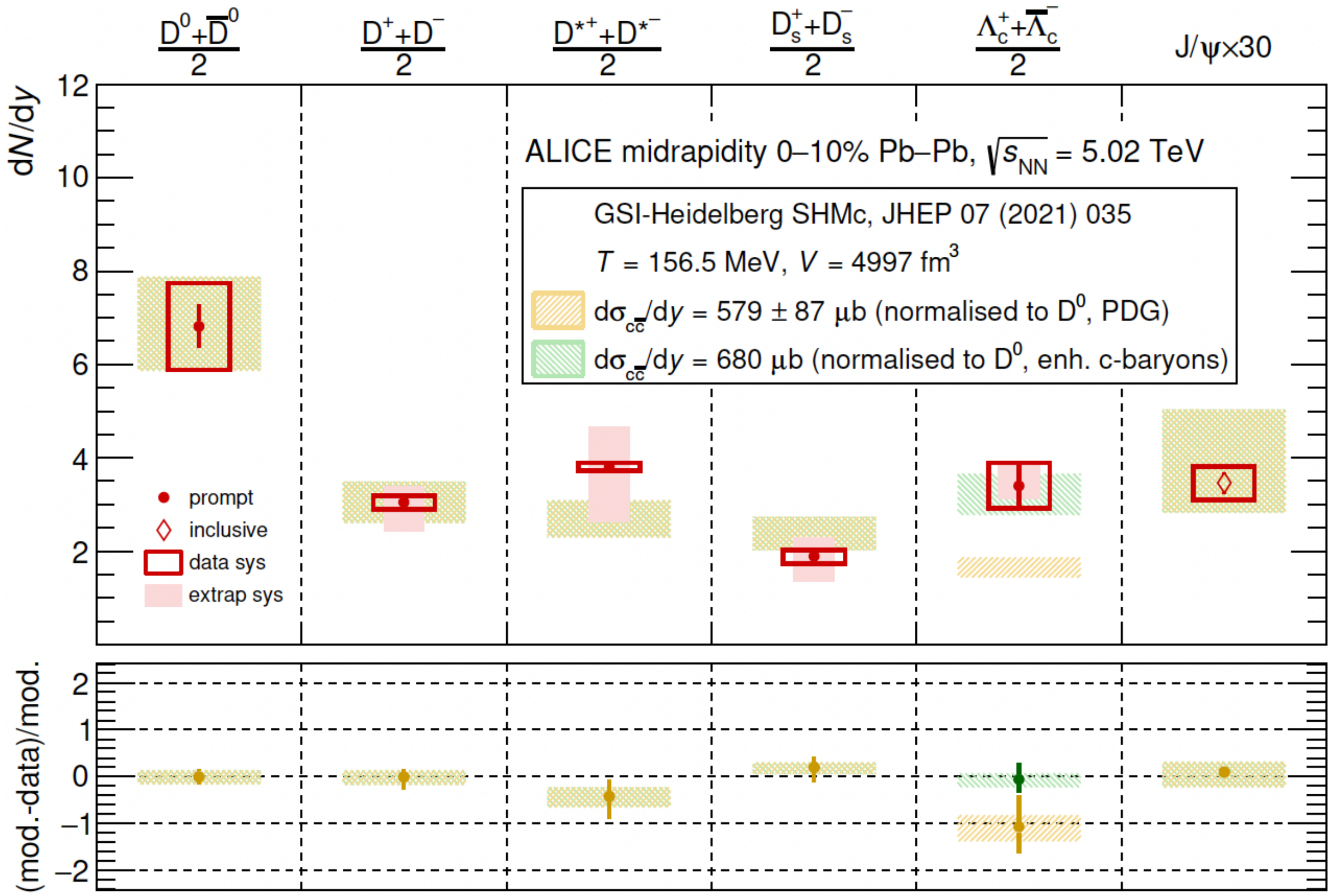
Charm-hadron spectrum as in PDG: 55 c-mesons, 74 c-baryons (part.+antipart.)

...large, but may not be complete

JHEP 07 (2021) 035

Charm data and SHMc model

A. Andronic



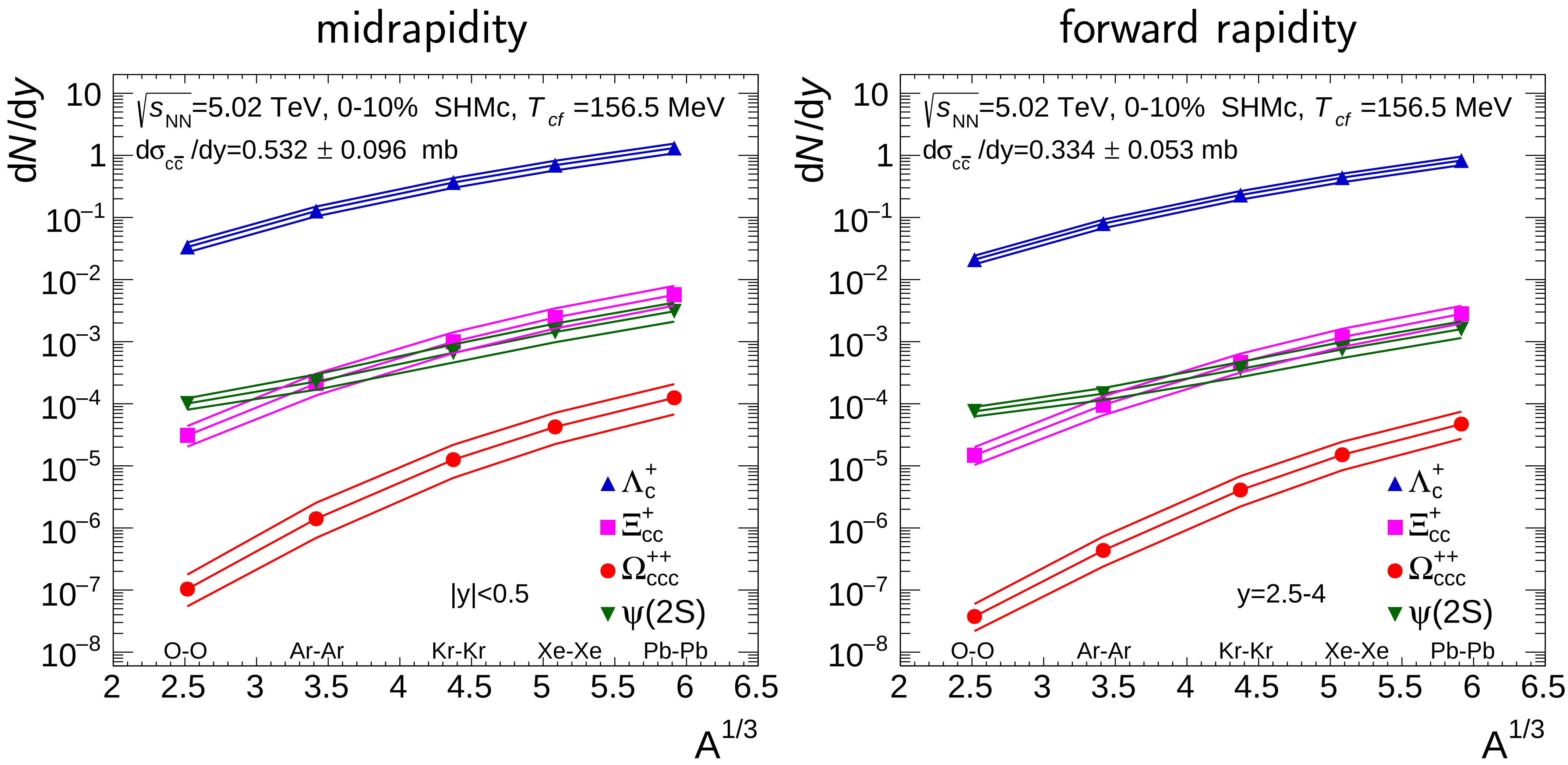
ALICE, EPJC 24 (2024) 813

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, PLB 850 (2024) 138520

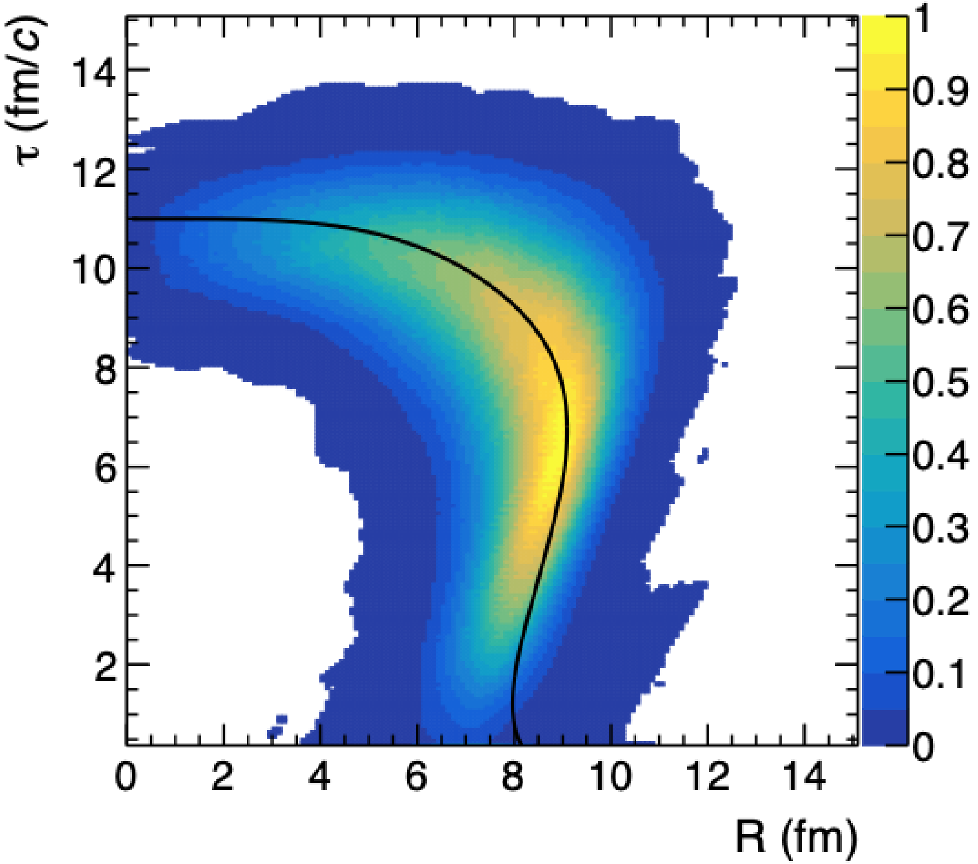
leaves the mesonic sector unaffected, for the commensurately larger $\sigma_{c\bar{c}}$

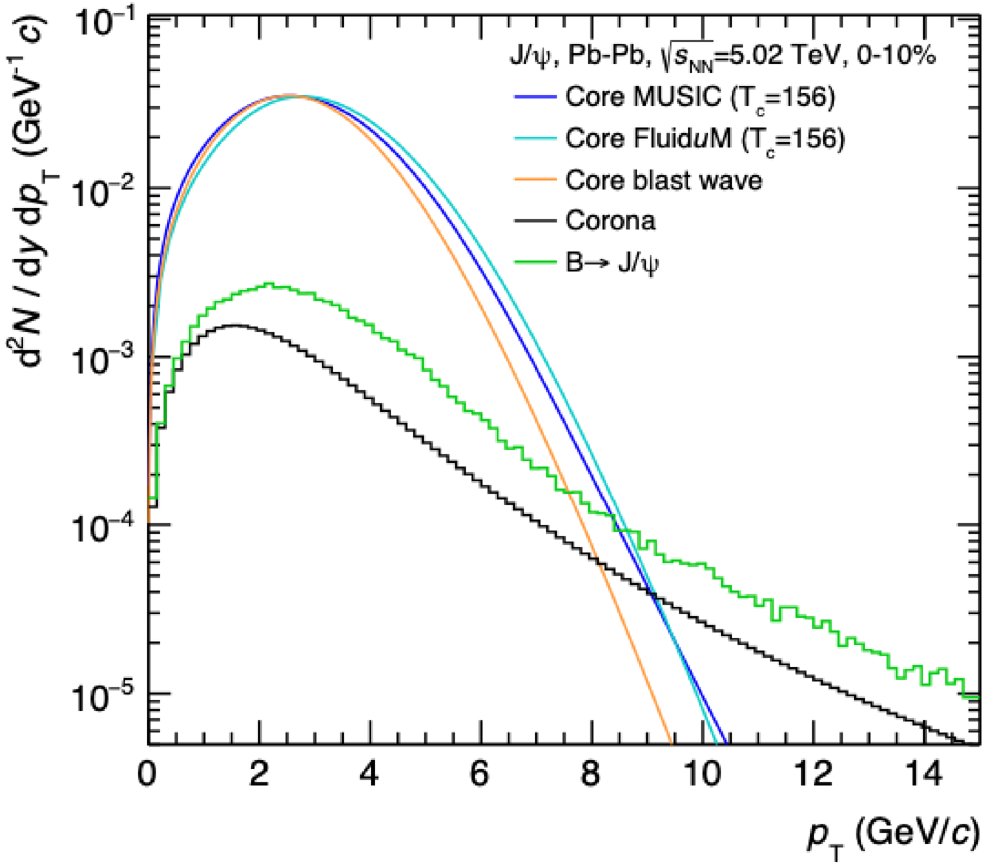
SHMc: system-size dependence (central, 0-10%)



JHEP 07 (2021) 035

SHMc describes pp data vs. N_{ch}, PBM, Redlich, Sharma, Stachel, arXiv:2408.07496

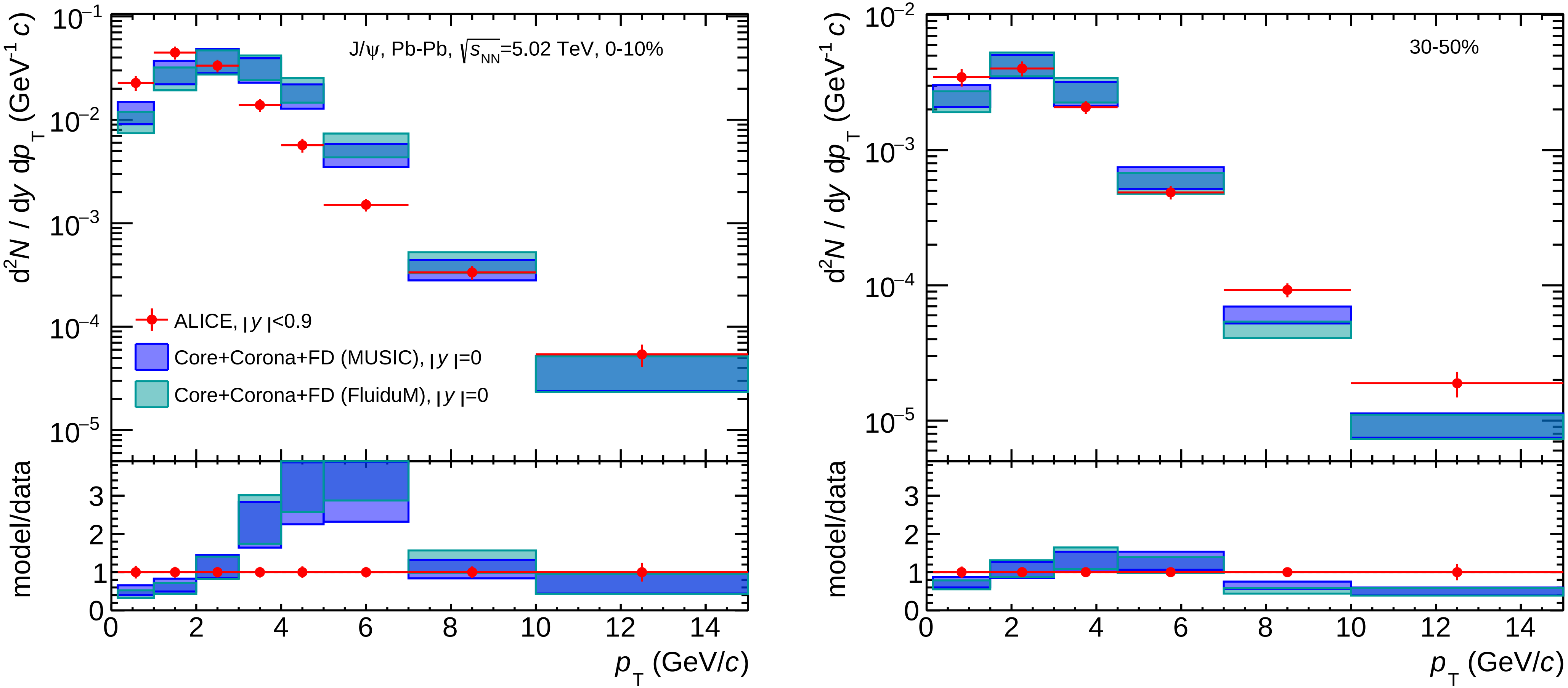




JHEP 10 (2024) 229

Distribution: MUSIC (IP-Glasma; τ_0=0.4 fm/c)
Line: Fluid$u$M (T$_{\rm R}$ENTO; τ_0=0.18 fm/c)

SHMc: p_T spectra

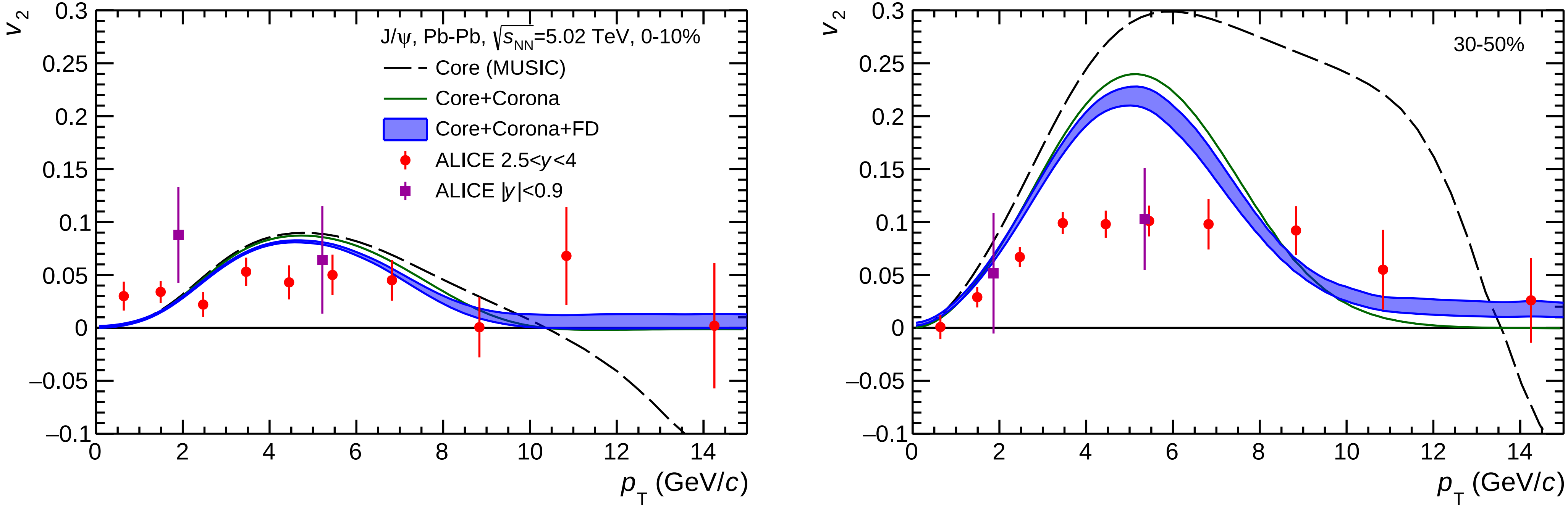


JHEP 10 (2024) 229

Too strong flow in 0-10% centrality

SHMc: v_2 distributions

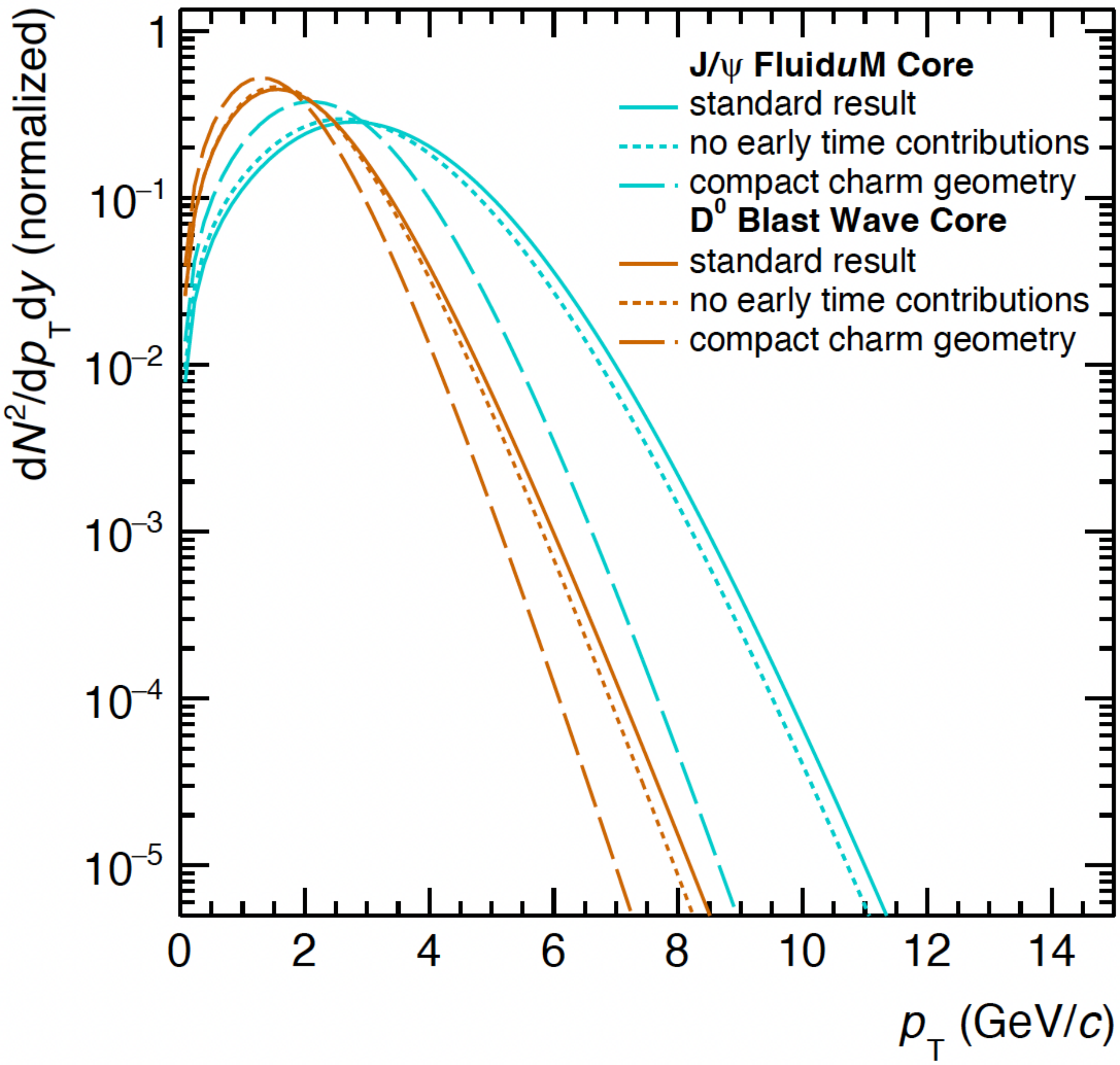
A. Andronic



JHEP 10 (2024) 229

again, we predict too much flow (v_3 is also overpredicted)

SHMc - coupling to hydrodynamics, refinements

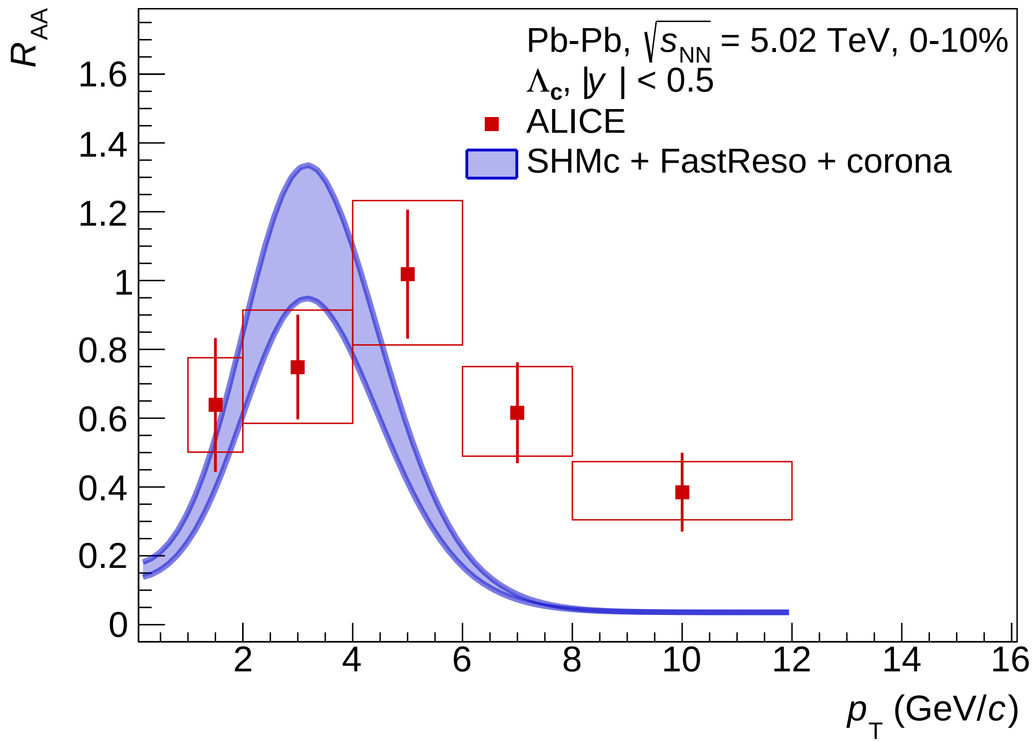


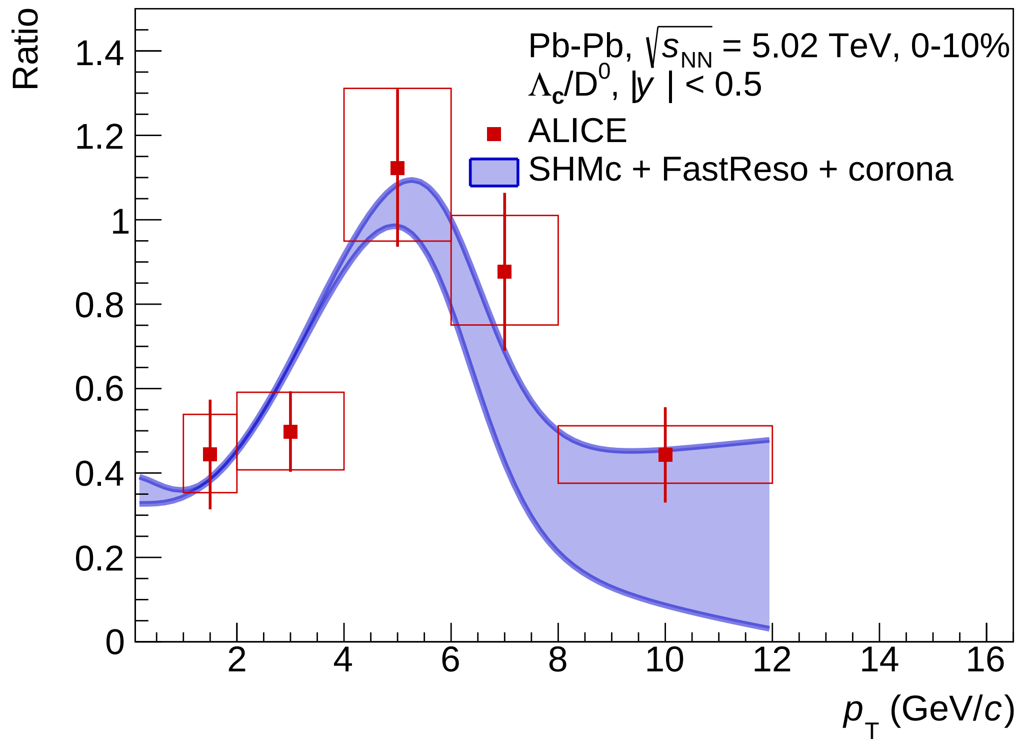
JHEP 10 (2024) 229

A spatially-mapped N_{coll} distribution needs to be implemented in addition.

SHMc: p_T, open charm

A. Andronic





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Implement screening picture with space-time evolution of the fireball (hydro-like)
Continuous destruction and "(re)generation" ("recombination")
Semi-classical: Boltzmann eq. (loss and gain terms) / Quantum transport

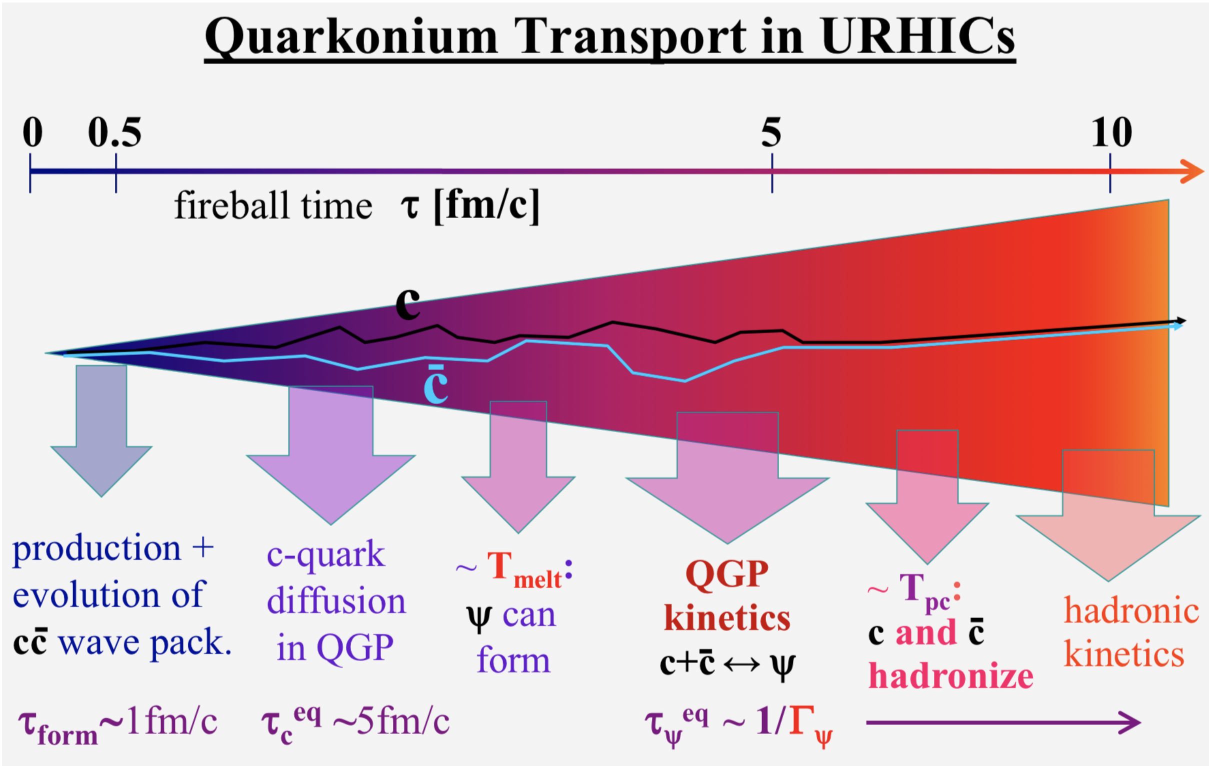
Thews et al., PRC 63 (2001) 054905 ...

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

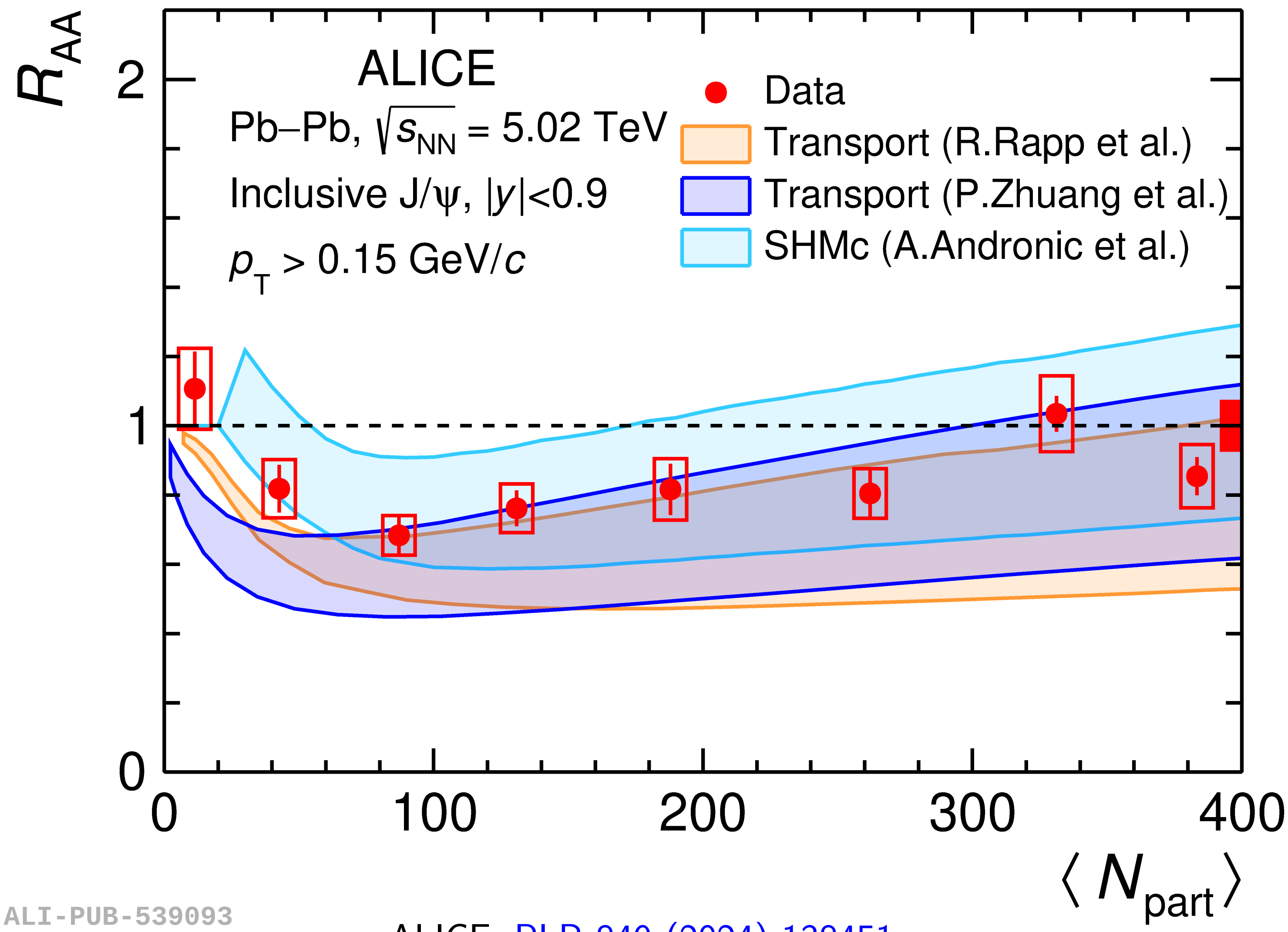
"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, PRC 89 (2014) 054911

Predict $R_{AA}, v_2(p_T)$

Model-intercomparison
EMMI RRTF, EPJA 60 (2024) 88



Rapp, Du, arXiv:1704.07923

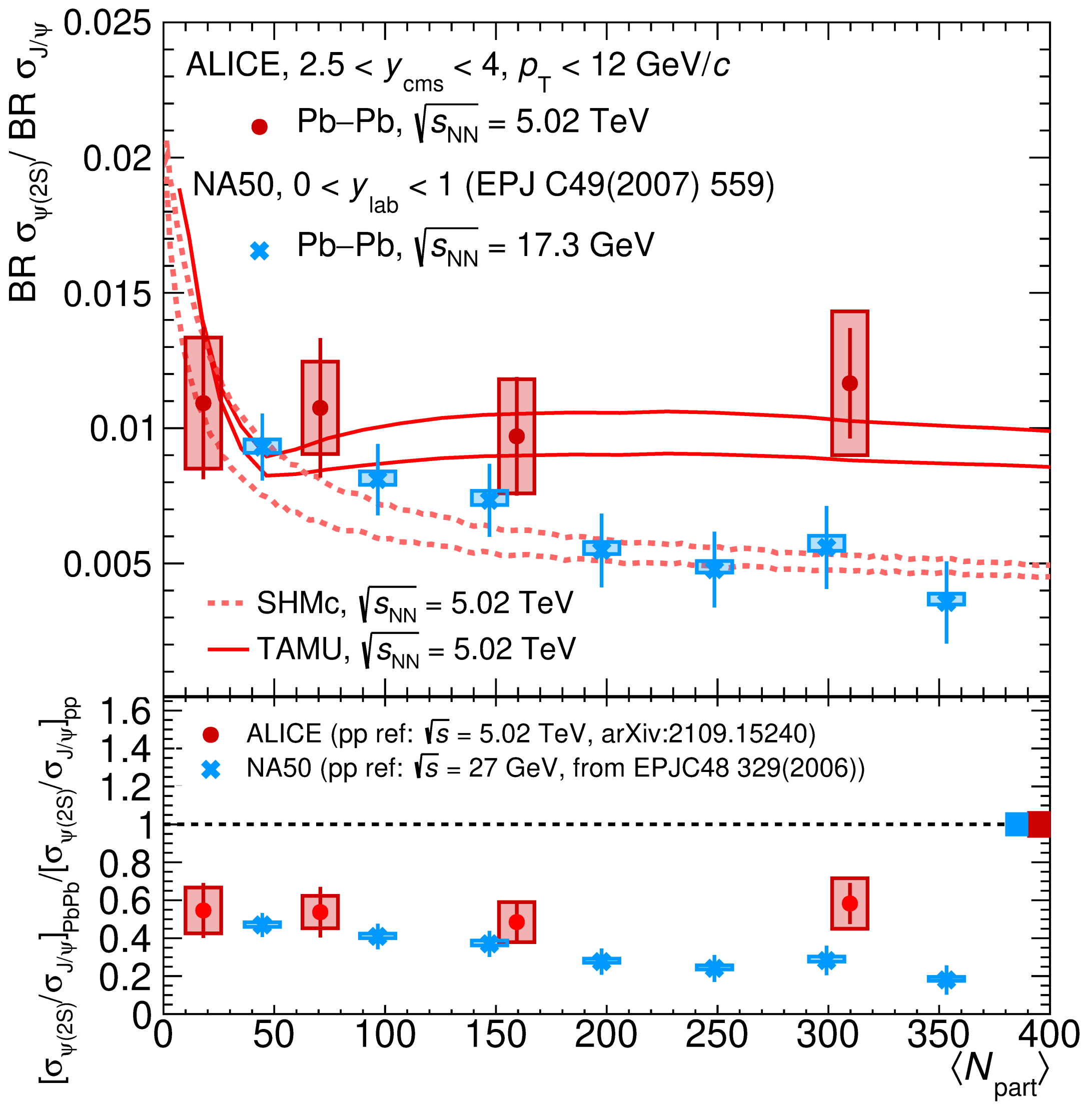


ALICE, PLB 849 (2024) 138451

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

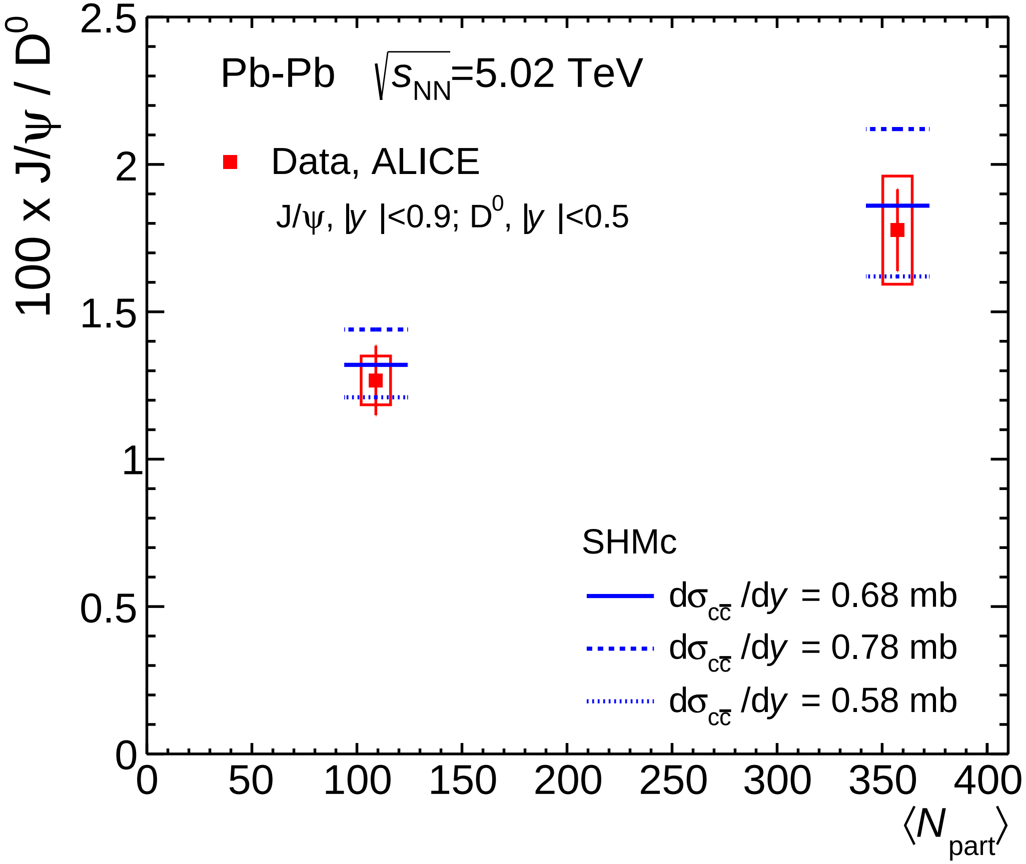
ALICE, JHEP 01 (2022) 174

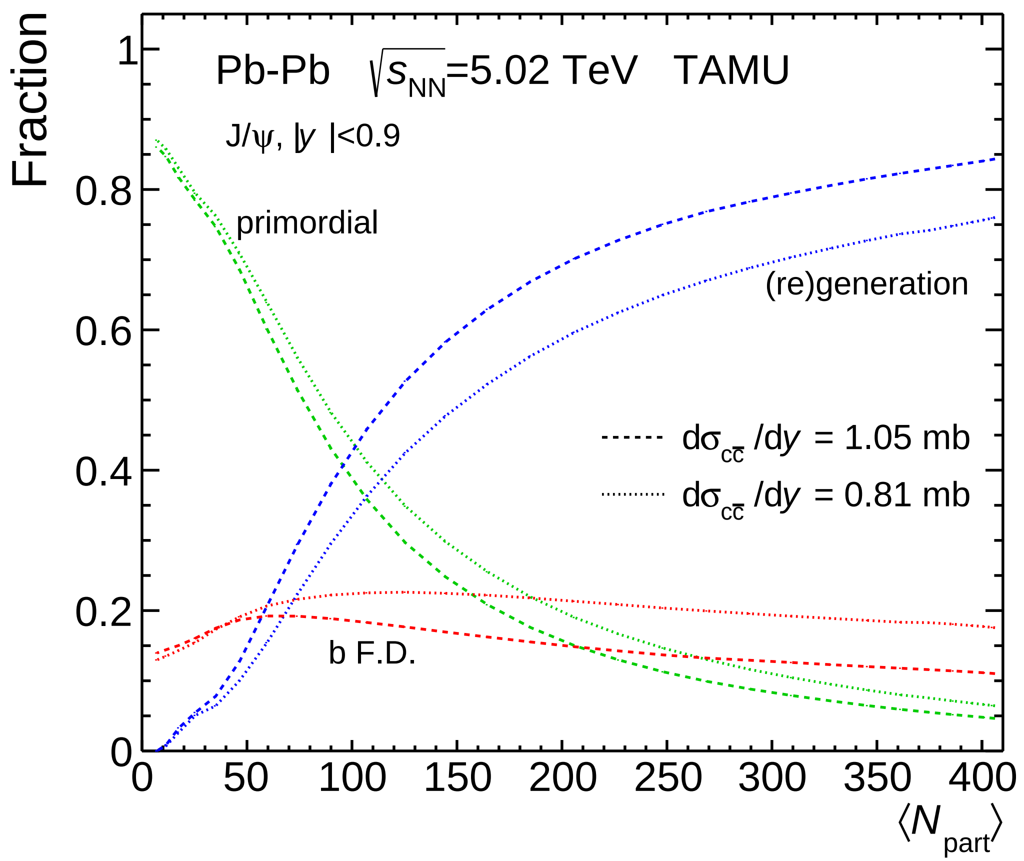
$\psi(2S)/J/\psi$ at the LHC (and SPS)



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

ALICE, PRL 132 (2024) 042301



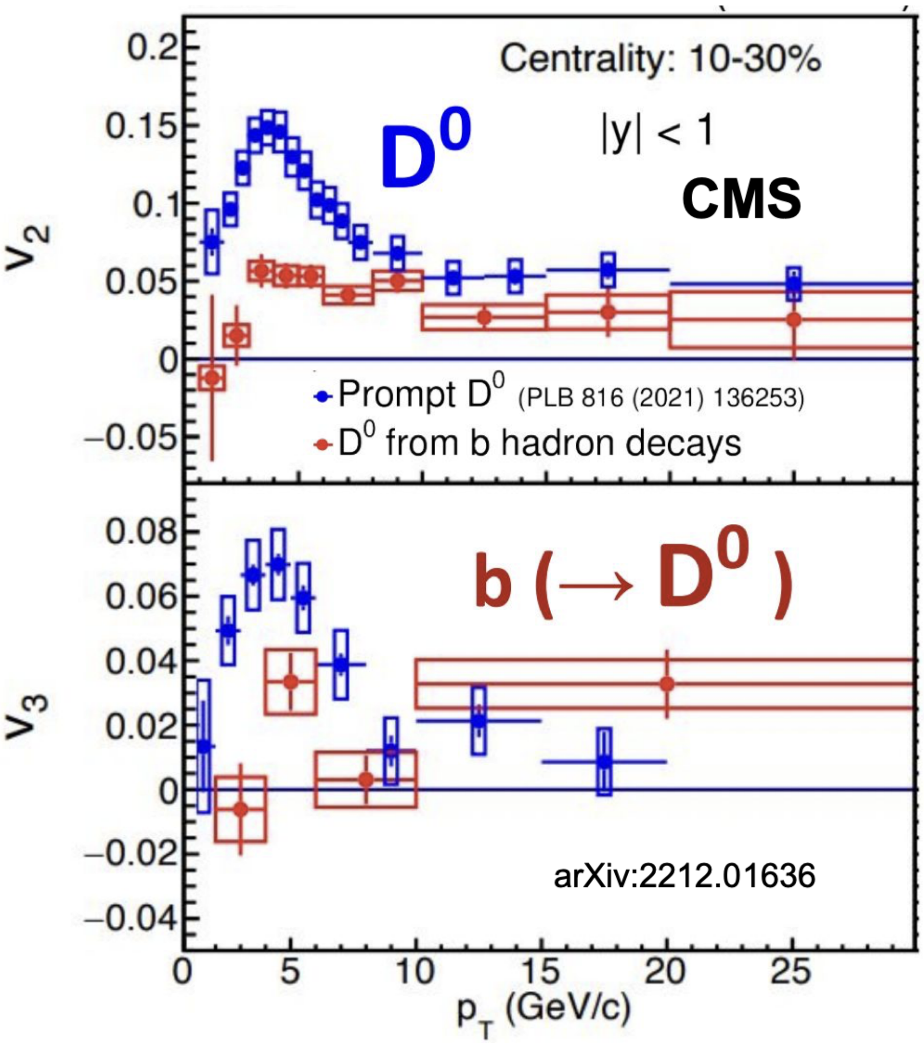


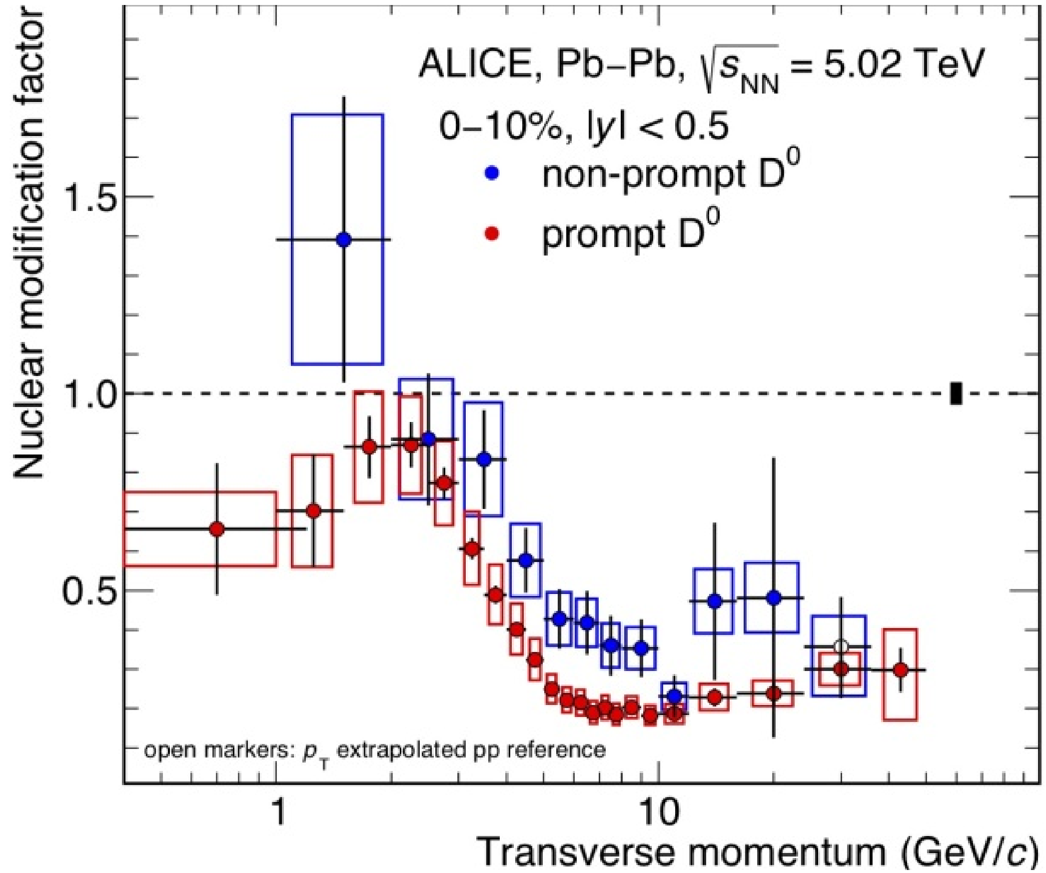
AA, R.Arnaldi, arXiv:2501.08290

Central collisions: (re)generation dominant in transport models (100% in SHMc)

Mid-central ($N_{part} \simeq 100$): 50-50 in transport, still 100% in SHMc

Beauty quark thermalization?



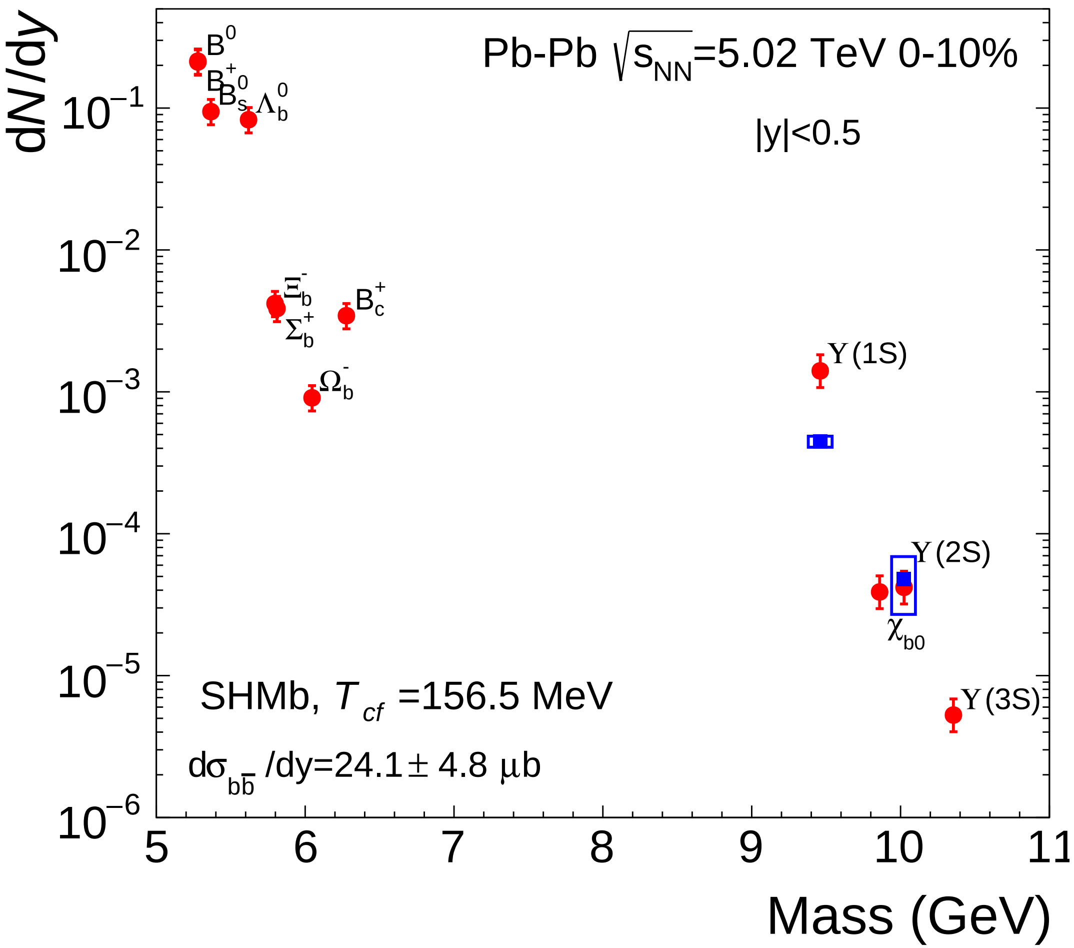


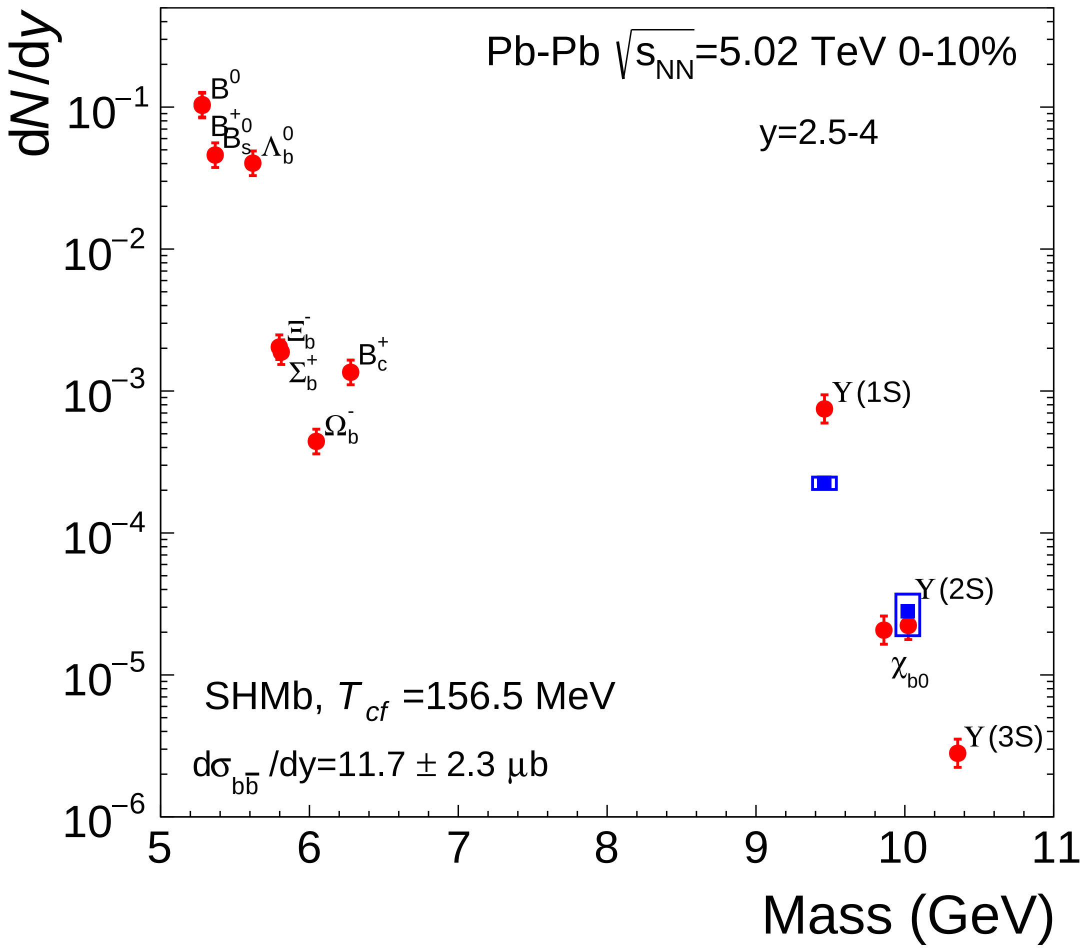
CMS, PLB 850 (2024) 138389, ALICE, JHEP 12 (2022) 126

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)

The limiting case: full beauty thermalization





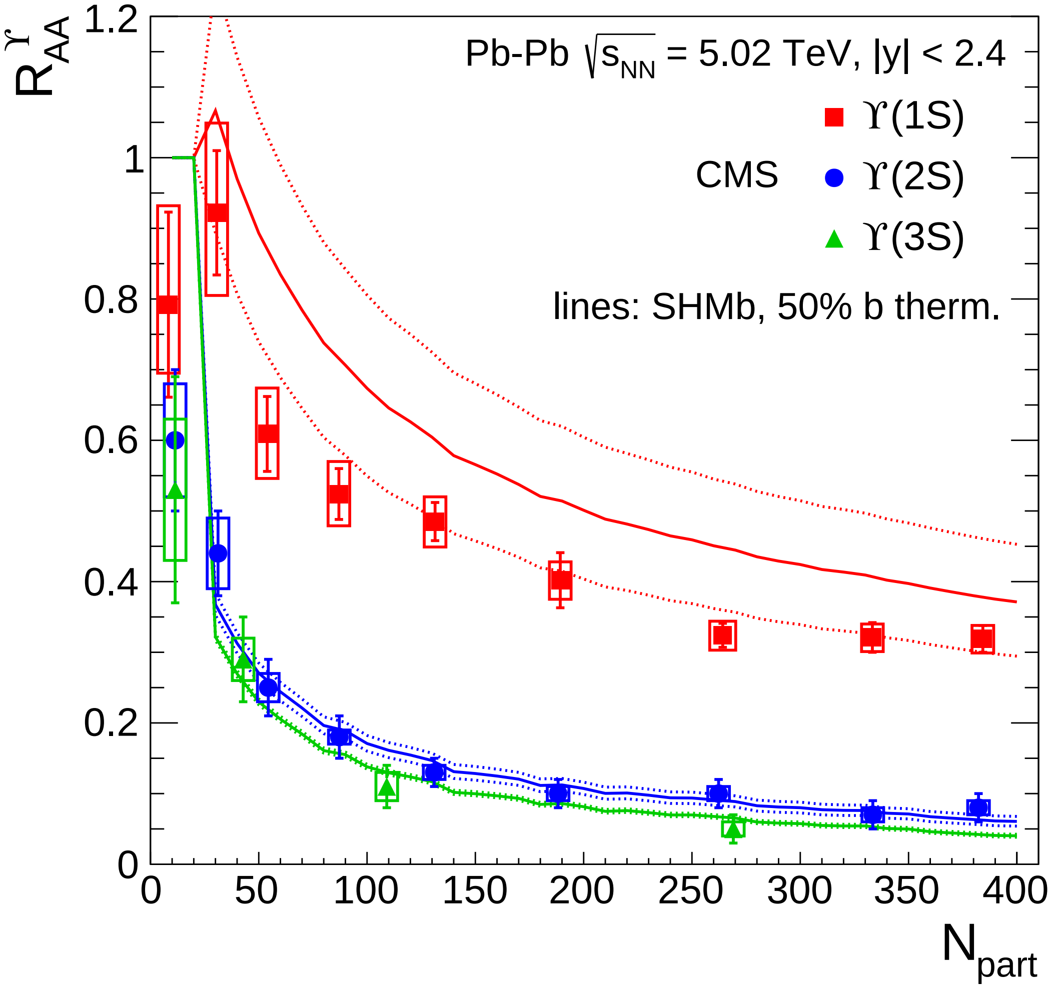
$g_b = 1.05 \cdot 10^9 \quad (\frac{\mathrm{d}N_{b\bar{b}}}{\mathrm{d}y} = 0.57)$

$B_c : \ 3.44 \cdot 10^{-3}$

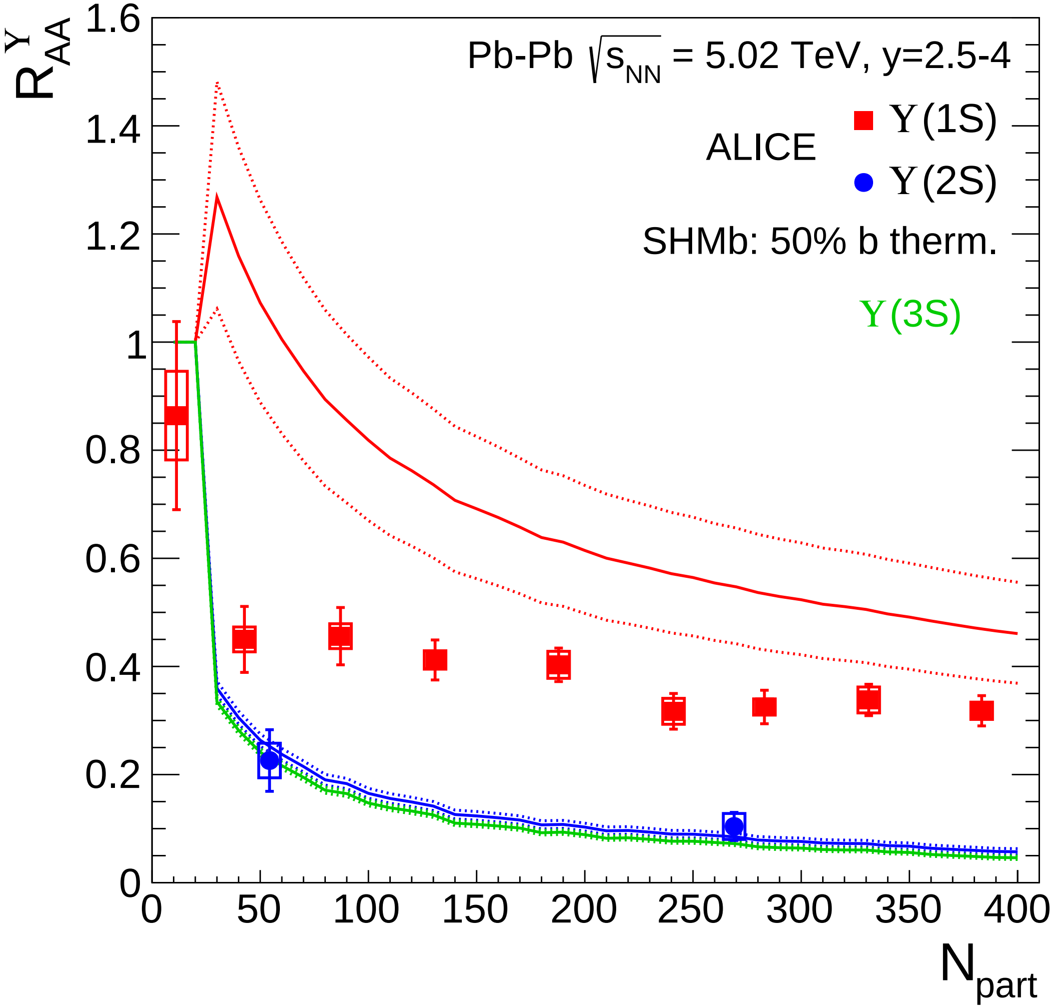
$g_b = 0.86 \cdot 10^9 \quad (\frac{\mathrm{d}N_{b\bar{b}}}{\mathrm{d}y} = 0.28)$

$B_c : \ 1.36 \cdot 10^{-3}$

Blue: Υ data (CMS, ALICE): calc. based on R_{AA} and pp (would be nice to include in publications $\mathrm{d}N/\mathrm{d}y$)



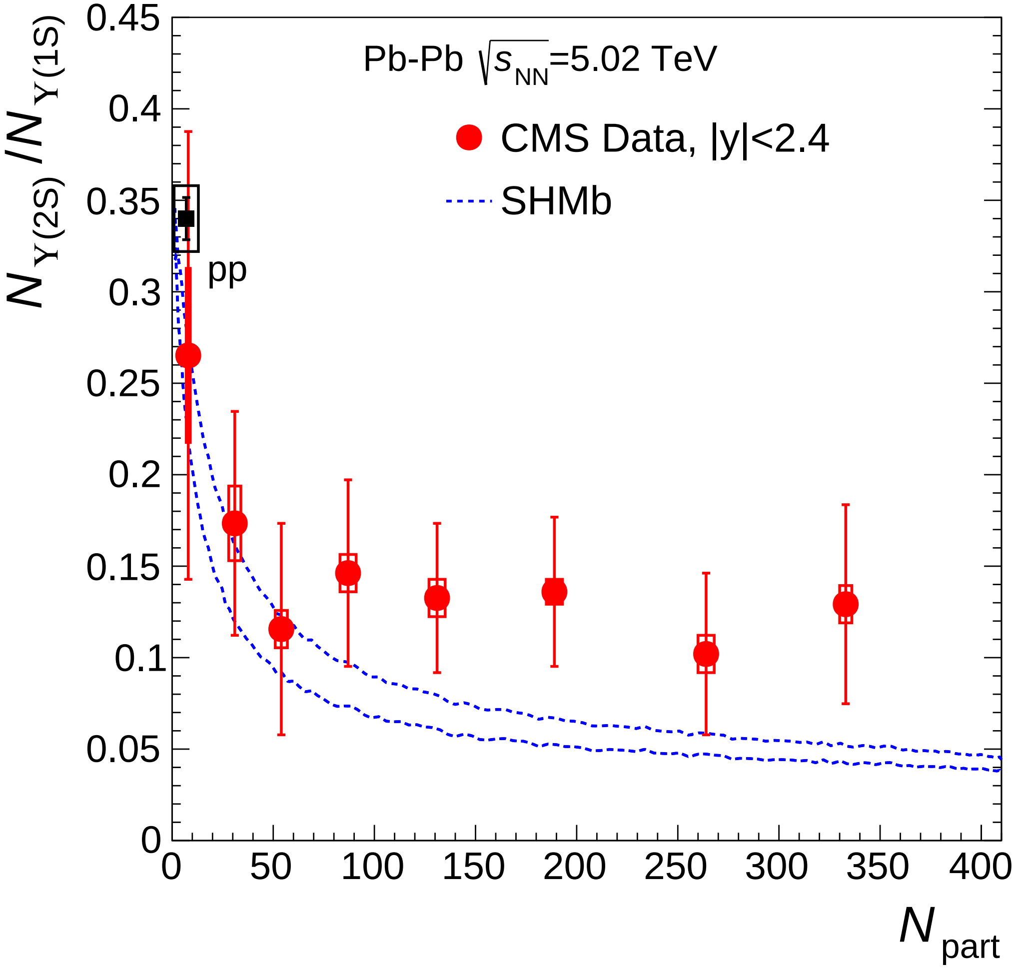
CMS, PRL 120 (2018) 142301



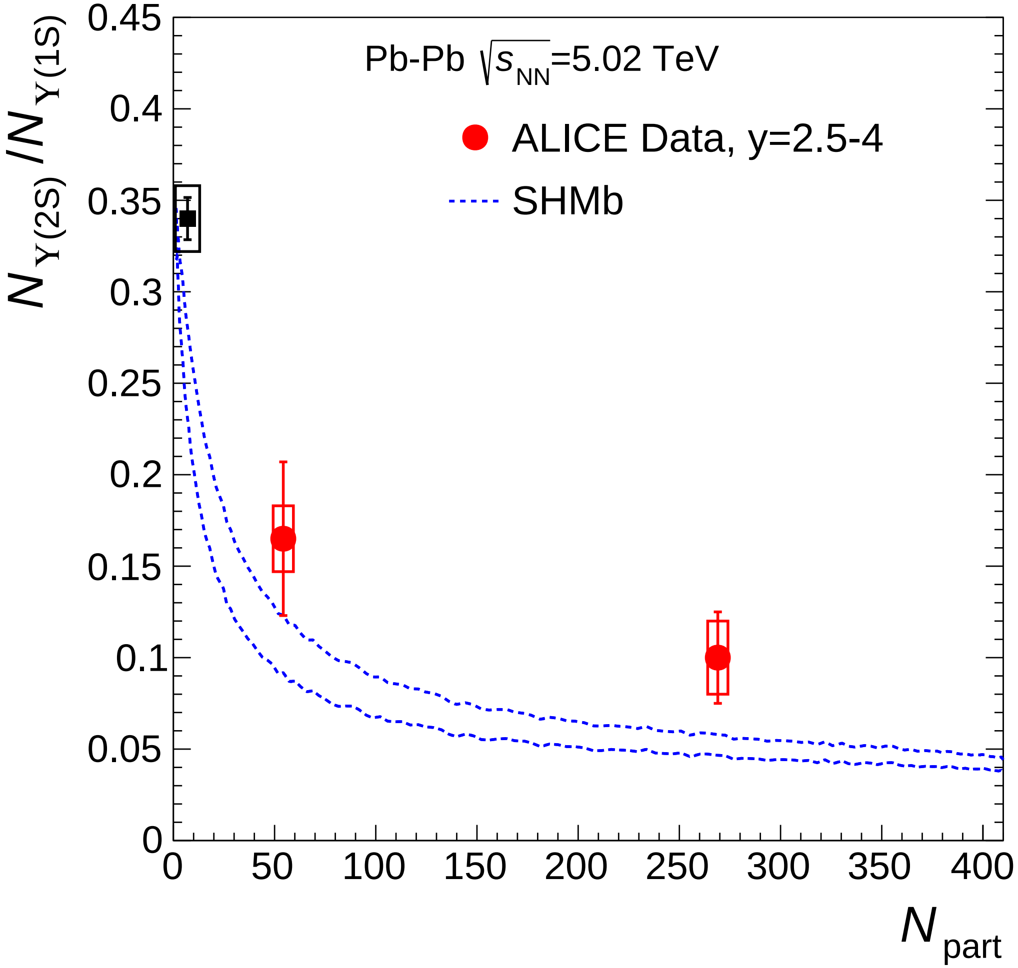
ALICE, PLB 822 (2021) 136579

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)

Summary / Conclusions: *up* to *charm*

- SHM describes *u,d,s*-hadron yields ...produced at the QCD phase boundary
- *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 reproducing the J/ψ and open charm data

  ...with c and $\bar{c}$ quarks deconfined in a volume of 5000 fm^3 ...QGP proof

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

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

  (up to 80% of the J/ψ yield at 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)

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

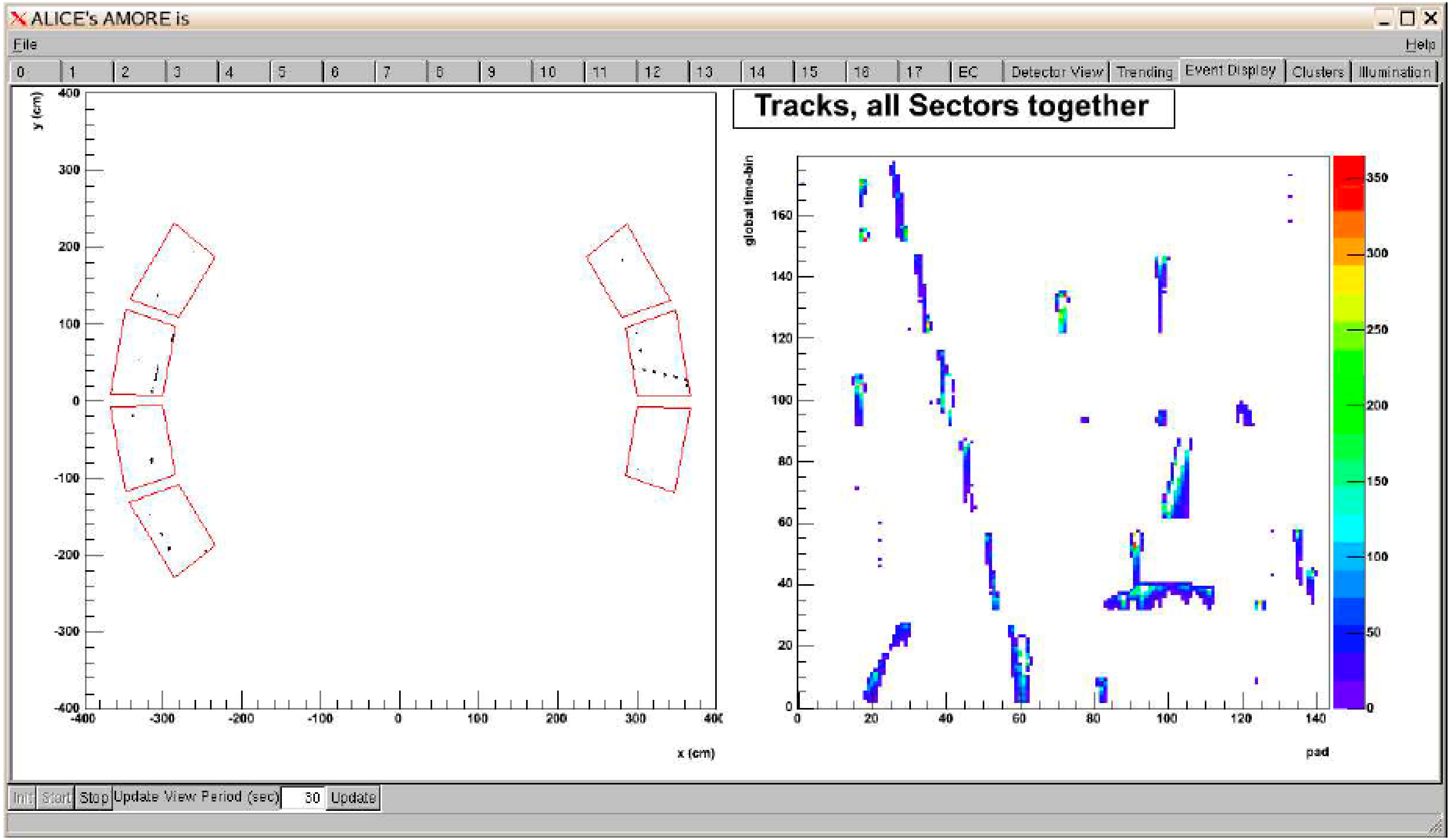
  Transport: regeneration important for $\Upsilon(2S)$ (at the LHC)

- Quantum approaches on strong rise

"getting hands dirty" ...by doing (transition radiation) detectors

Johanna was ALICE TRD's Project Leader (& ALICE MB member) for 25 years

Oct.2006, CERN, 1st TRD supermodule installation



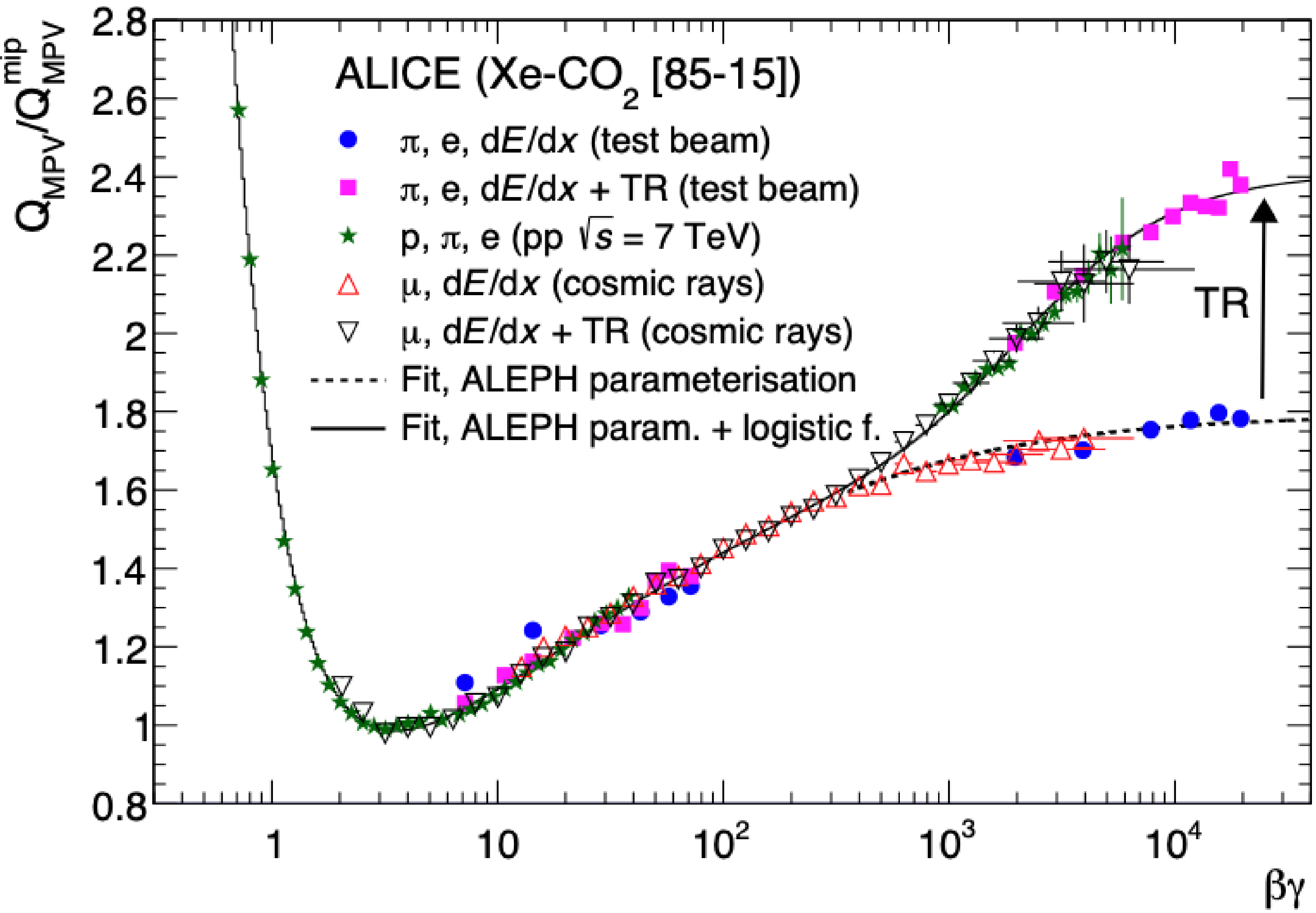
Johanna's energy pushed it through LoI, Sept. 1998; TDR, Oct. 2001; completion, Dec. 2014

(...the hidden part of the iceberg)

...although we did write papers on it:)

- *Prototype tests for the ALICE TRD*, A. Andronic et al. (ALICE Collaboration), IEEE Trans. Nucl. Sci. 48 (2001) 1259 [arXiv:nucl-ex/0102017]
- *Pulse height measurements and electron attachment in drift chambers operated with Xe,CO_2 mixtures*, A. Andronic et al. (ALICE Collaboration), Nucl. Instr. Meth. A 498 (2003) 143 [arXiv:physics/0303059]
- *Energy loss of pions and electrons of 1 to 6 GeV/c in drift chambers operated with Xe,CO_2(15%)*, A. Andronic et al. (ALICE TRD collaboration), Nucl. Instrum. Meth. A 519 (2004) 508 [arXiv:physics/0310122]
- *Space charge in drift chambers operated with the Xe,CO2(15%) mixture*, A. Andronic et al. (ALICE TRD collaboration), Nucl. Instrum. Meth. A 525 (2004) 447 [arXiv:physics/0402043]
- *Position reconstruction in drift chambers operated with Xe,CO_2(15%)*, C. Adler et al. (ALICE TRD Collaboration), Nucl. Instrum. Meth. A 540 (2005) 140 [arXiv:physics/0511233]
- *Electron/pion identification with ALICE TRD prototypes using a neural network algorithm*, C. Adler et al. (ALICE TRD Collaboration), Nucl. Instrum. Meth. A 552 (2005) 364 [arXiv:physics/0506202]
- *Transition radiation spectra of electrons from 1 to 10 GeV/c in regular and irregular radiators*, A. Andronic et al. (ALICE TRD Collaboration), Nucl. Instrum. Meth. A 558 (2006) 516 [arXiv:physics/0511229]
- *The ALICE Transition Radiation Detector: construction, operation, and performance*, ALICE Collaboration, Nucl. Instr. Meth. A 881 (2018) 88, [arXiv:1709.02743]

...our least-cited papers:)



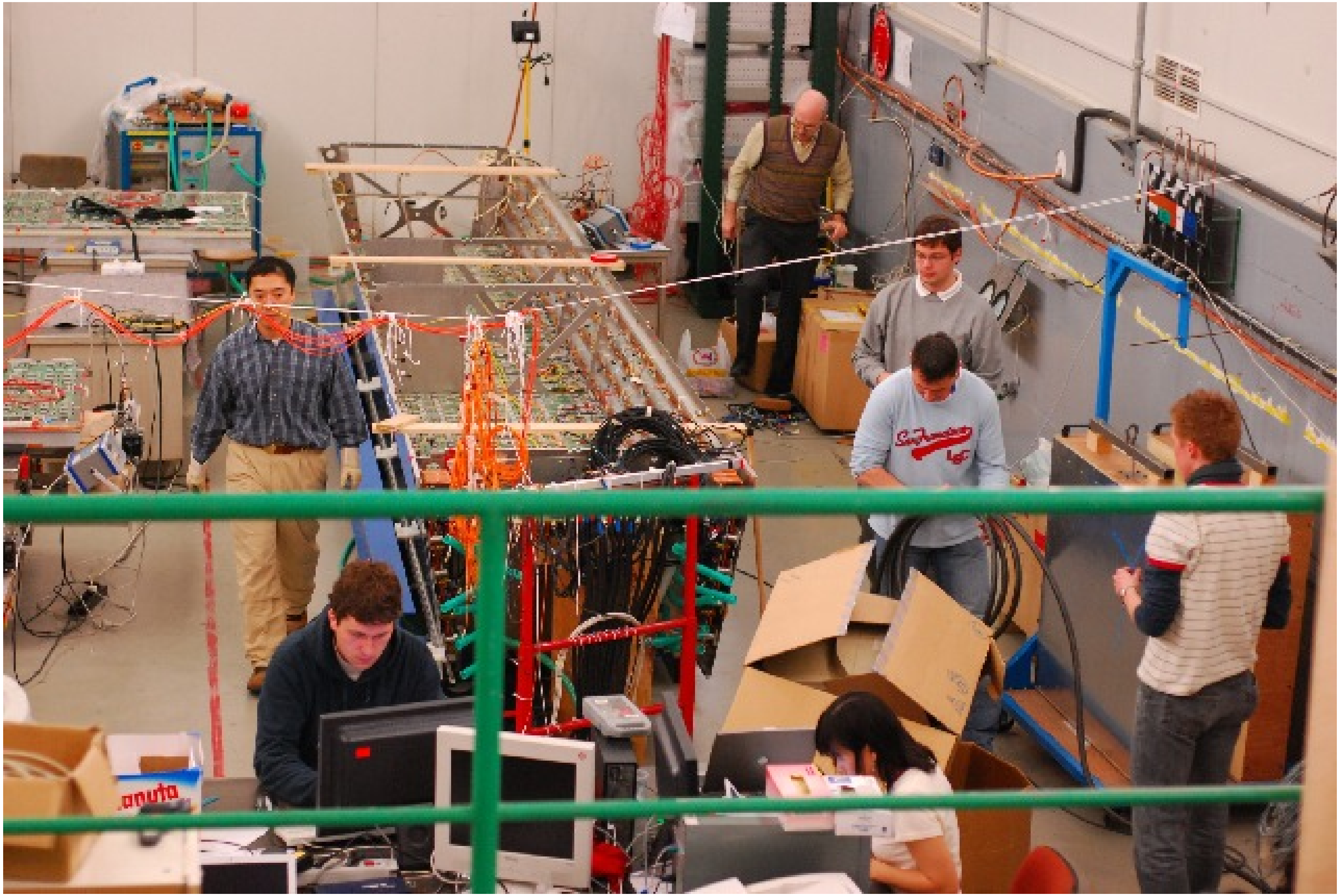
X-ray photons emitted by charged particles with $\gamma \gtrsim 1000$ at interface of 2 media

allows pion rejection in ALICE by a factor of up to 500 (momentum-dependent)

2005 - Cheile Gradistei (TRD workshop)

2008 - Jaipur

2008 - CERN, Point 2



2008 - Draisinentour (thanks Dariusz!)

2008 - GSI (chamber completion party)

2013 - Bautzen

2014 - Schmitten

2014 - CERN, Point 2 (last supermodule installed)

more photos

2015 - Münster (supermodule completion party)

2015 - München

2017 - Schloss Buchenau

2018 - "Nature quartet" (GSI)

“Never at rest”

Johanna served (and still serves/leads) in numerous scientific committees

President of the German Physics Society (DPG), 2012-2014
(first female in this prestigious role)

Lise Meitner Prize of EPS, 2014 (w. Jürgen S., Paolo G., Peter)

Stern-Gerlach Medal of DPG, 2019 (w. Peter)

Bundesverdienstkreuz 1. Klasse, 2021

Member of the Leopoldina Academy, since 2015

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Bundesverdienstkreuz 1. Klasse, 2021

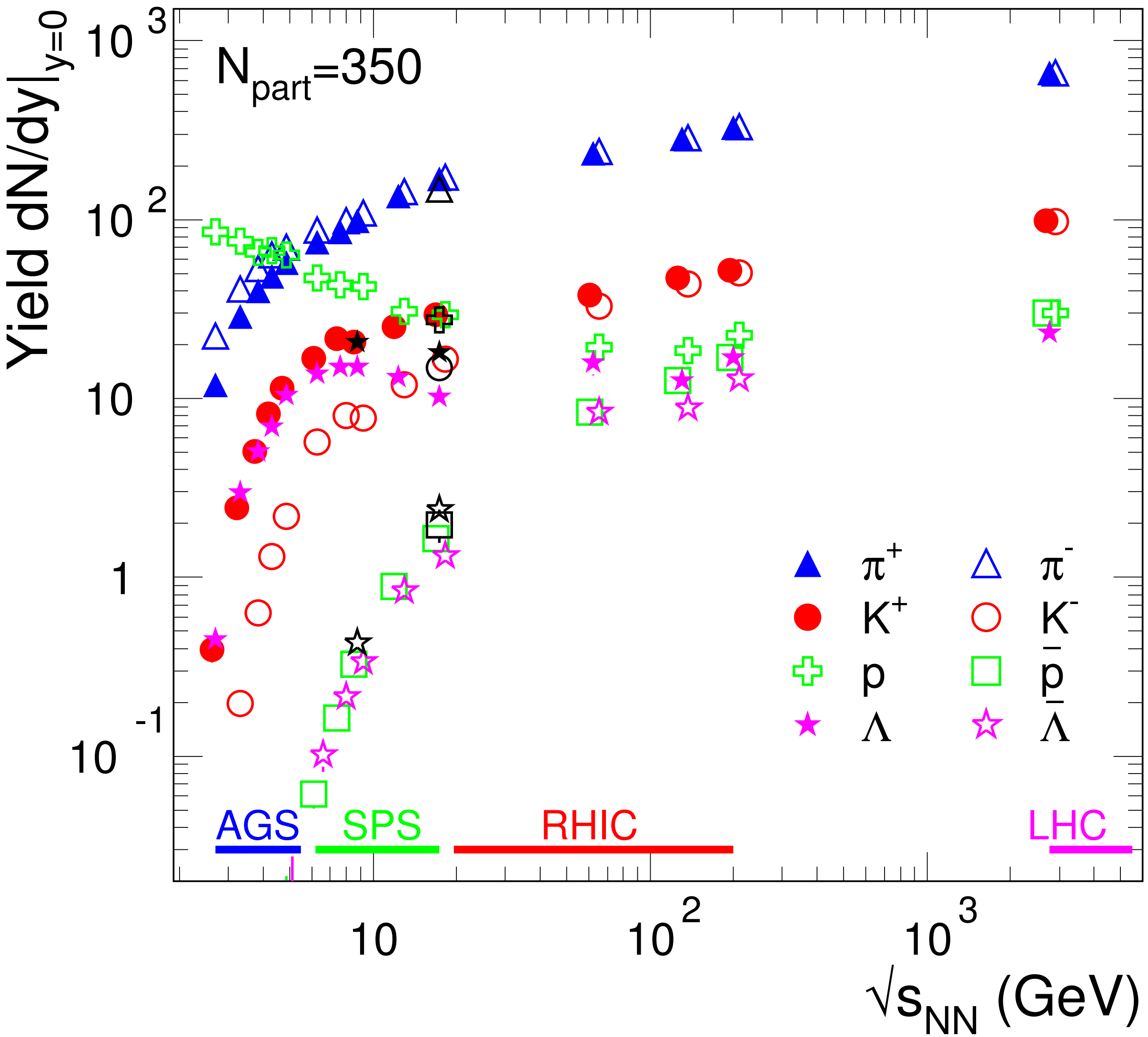
Member of the Leopoldina Academy, since 2015

Thank you for the wonderful time (working) together!

...and looking forward to our next projects!

Additional material

Hadron yields at midrapidity (central collisions)



AA, arXiv:1407.5003

- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

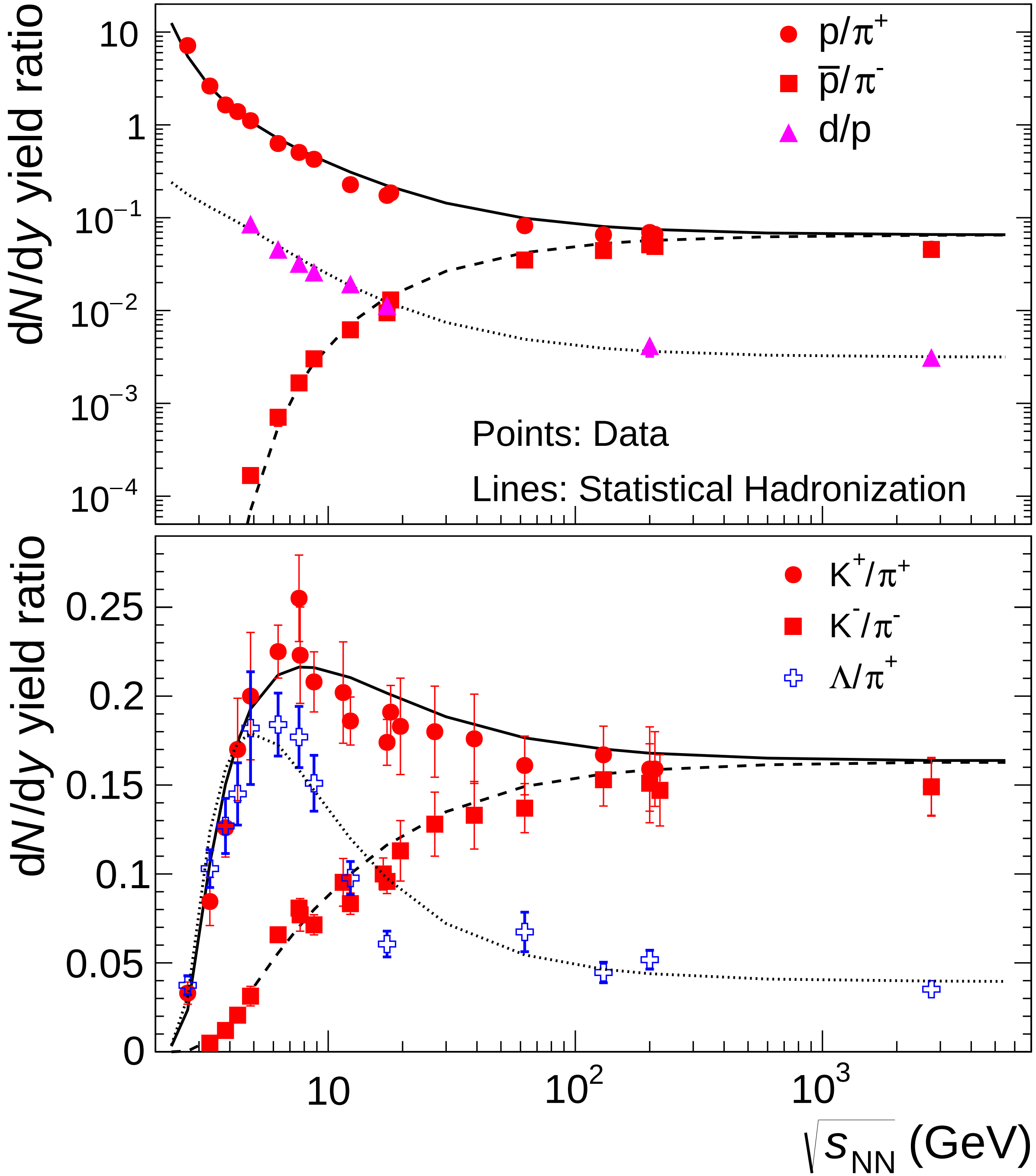
  $\pi^{\pm}$ $(u\bar{d}, d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s}, \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production at high energies ($\mathrm{e}^{-m/T}$)

at lower energies: u, d quarks as "remnants" (stopped) from the incoming nuclei

The grand (albeit partial) view

A. Andronic



Data:

AGS: E895, E864, E866, E917, E877

SPS: NA49, NA44

RHIC: STAR, BRAHMS

LHC: ALICE

NB: no contribution from weak decays

no S-matrix correction $(\mathrm{p}, \overline{\mathrm{p}})$

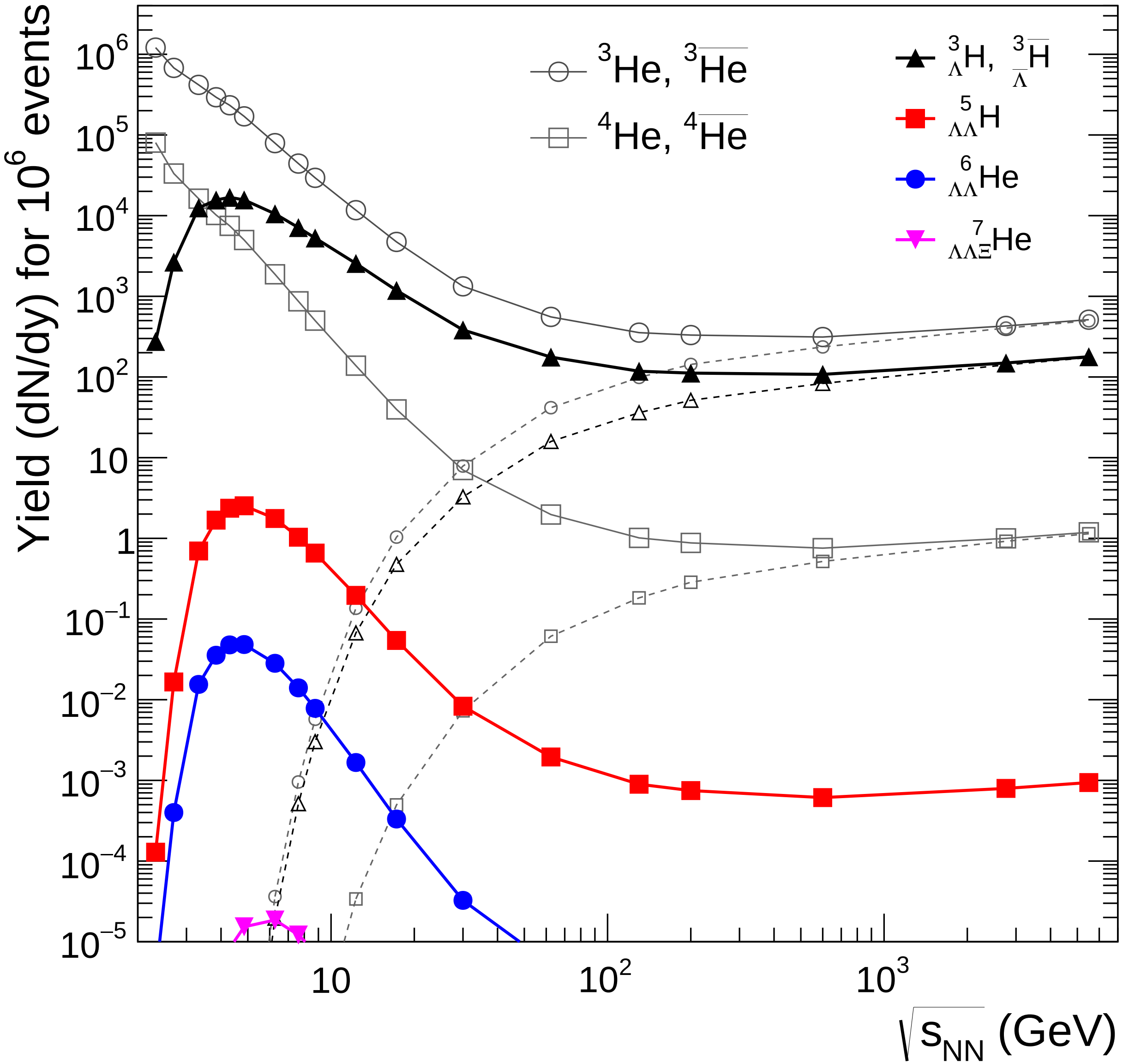
d/p ratio is well described for all energies

“structures” described by SHM

...determined by strangeness conservation

Λ/π peak reflects increasing T and decreasing μ_B

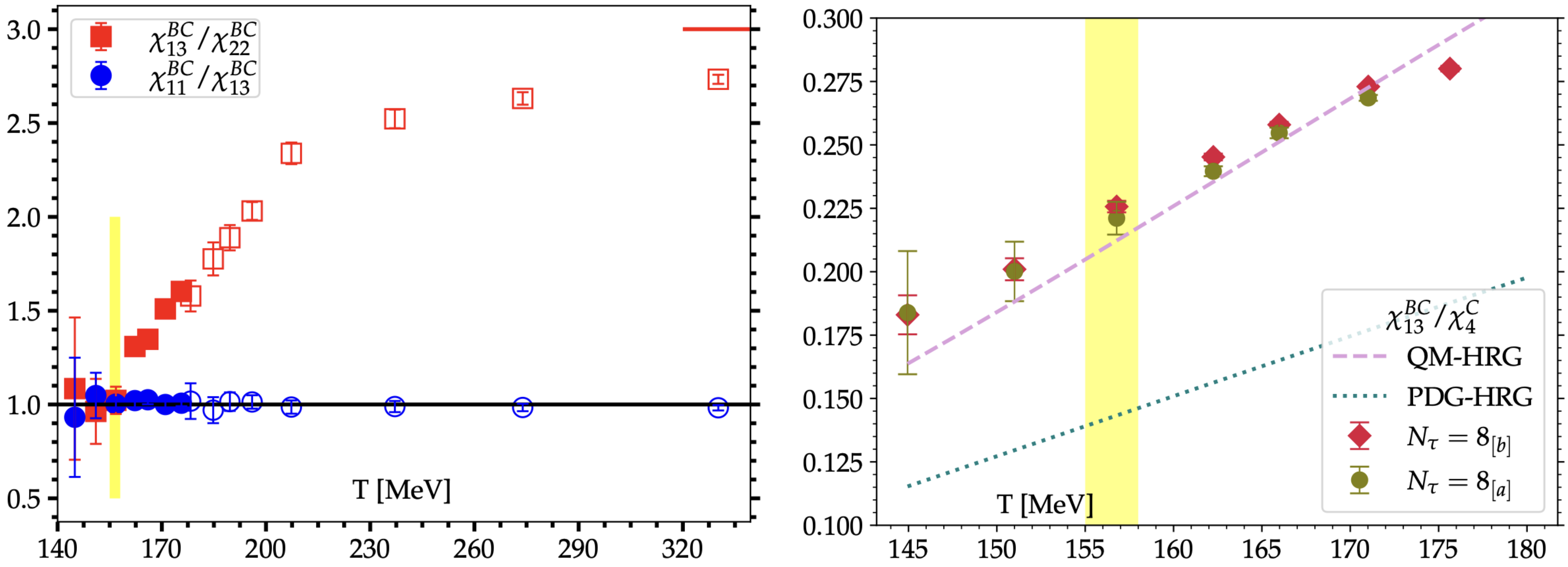
...are copiously produced at low (RHIC-BES/FAIR) energies



...some to be discovered

AA, PBM, JS, HS, PLB 697 (2011) 203

Charm in QGP - the LQCD view



Bazavov et al., PLLB 850 (2024) 138520

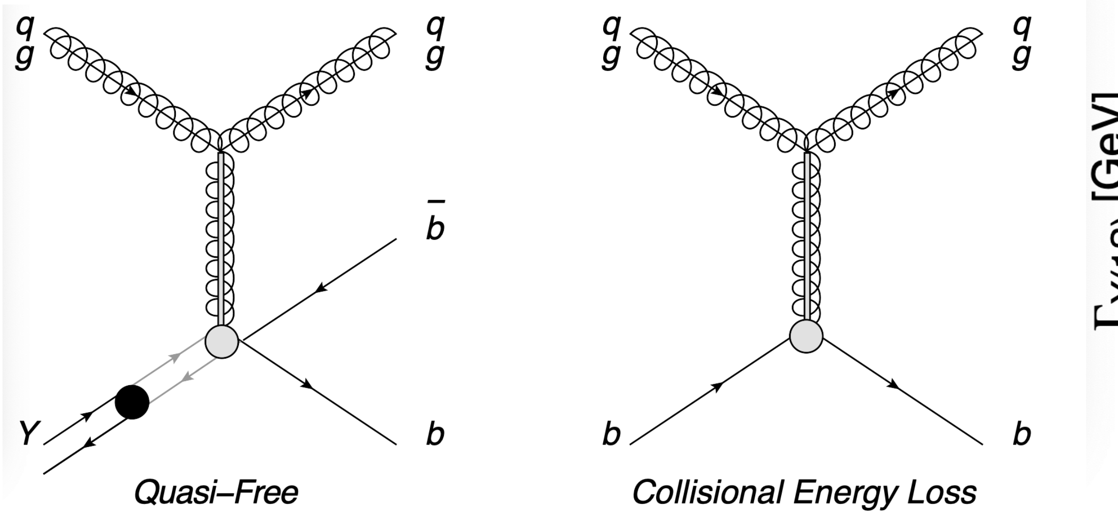
$\chi_{11}^{BC} = \chi_{1m}^{BC} = P_B^C$, m odd;

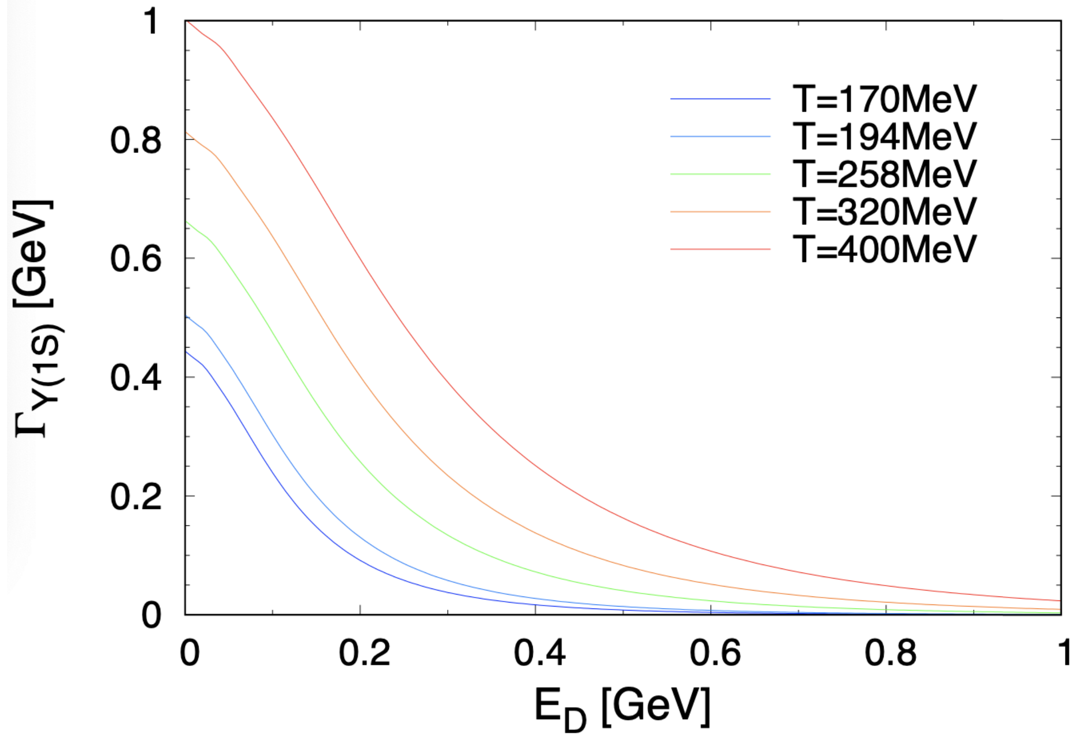
$\chi_{13}^{BC}/\chi_4^C \sim P_B^C/P^C$

Indication of charm-quark dofs at T_c, but "pure-quark" state at ≃200 MeV

Clear need of an enhanced charm-baryon spectrum wrt PDG

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



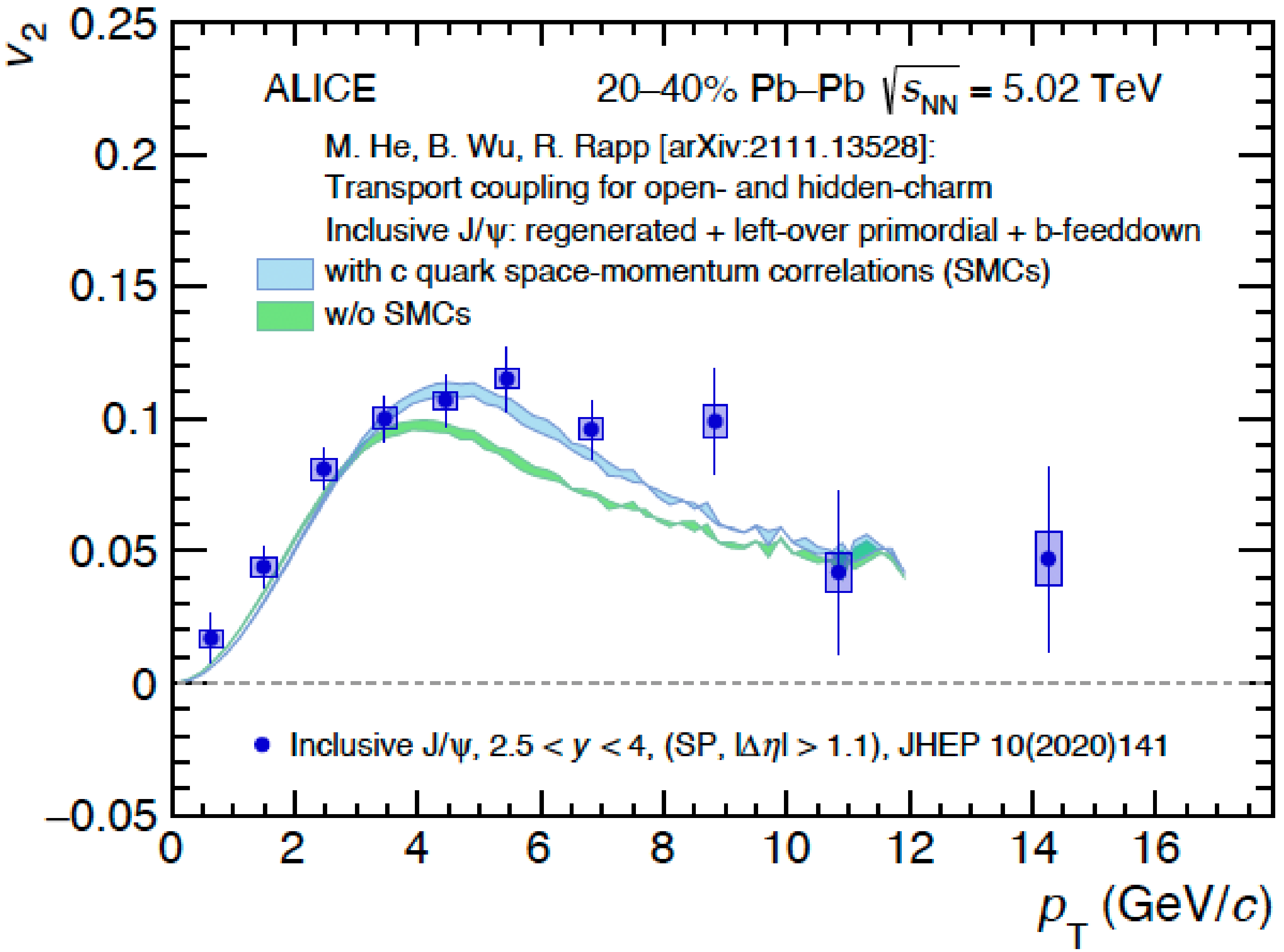


Du, Liu, Rapp, Phys. Lett. B 796 (2019) 20

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



ALICE, arXiv:2212.04348

a very good description of data by the TAMU model PRL 128 (2022) 162301

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

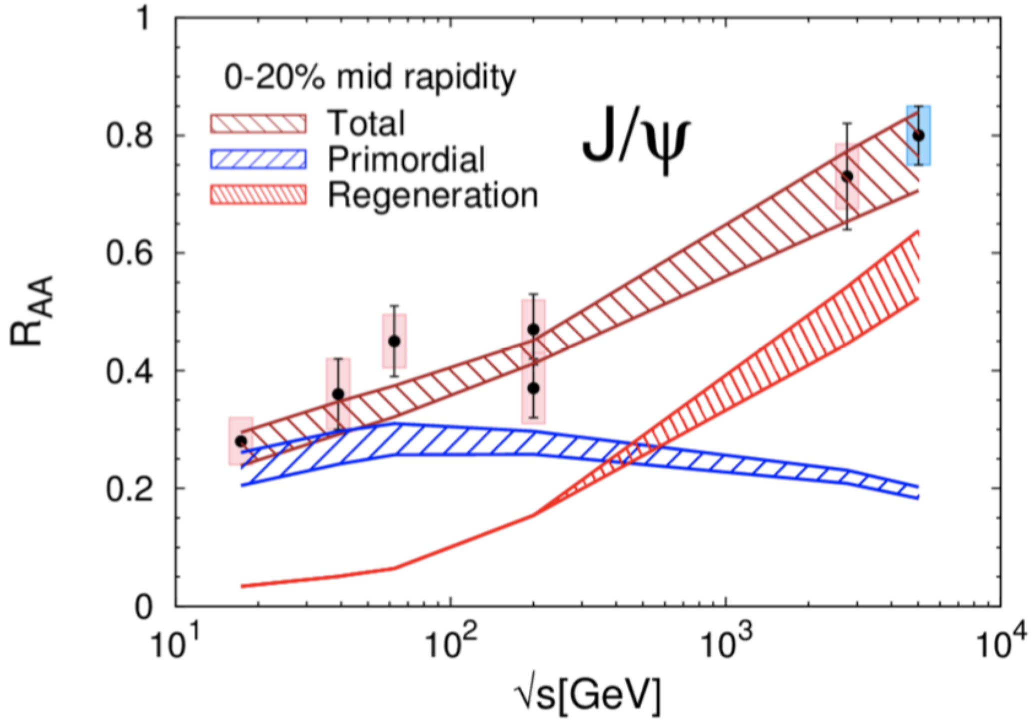
Open quantum systems description + Effective NRQCD theory

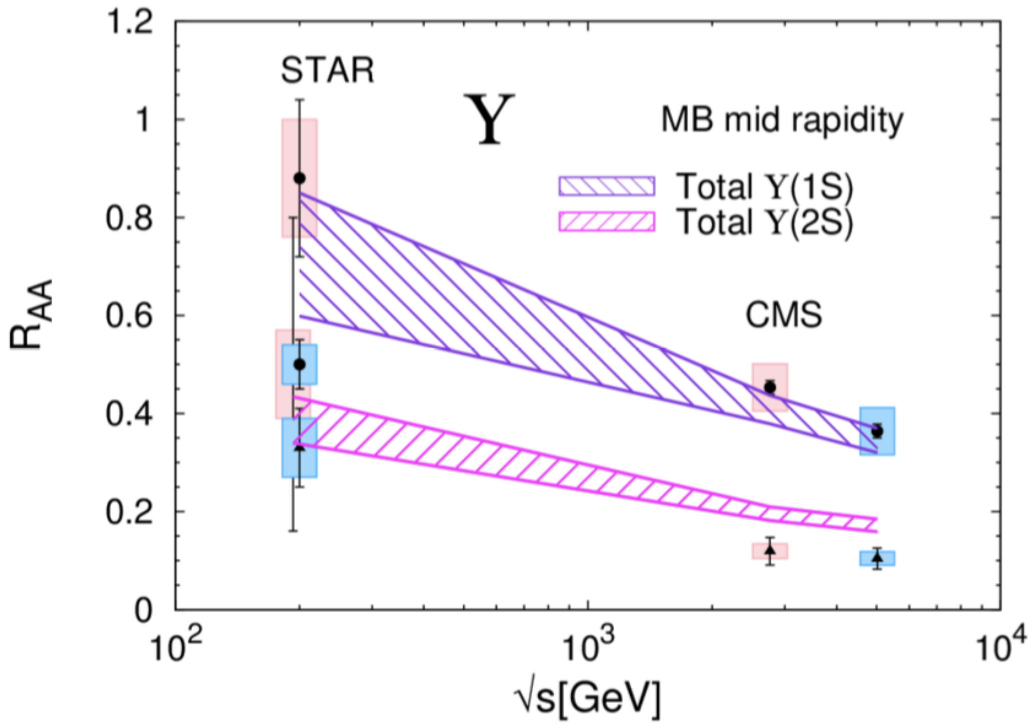
quantum evolution of the $b\bar{b}$ pair in QGP (heat bath; hydrodynamics)

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

Strickland, Thapa, PRD 108 (2023) 014031 and refs therein

Fractions primordial, (re)generated - energy dependence

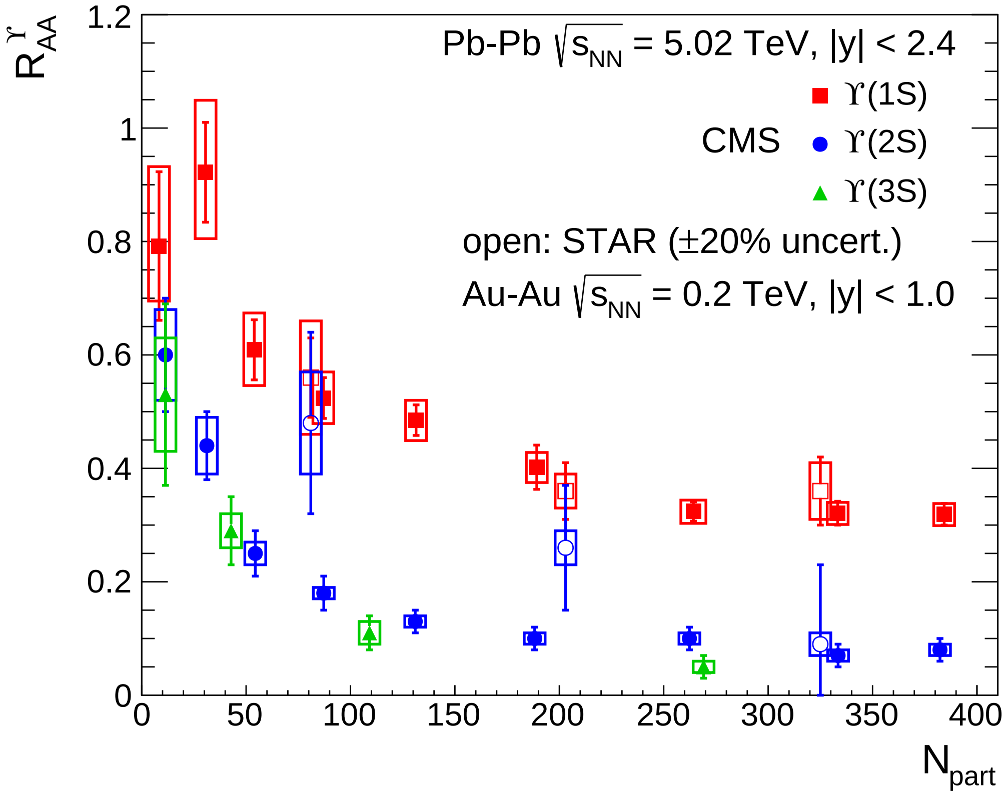




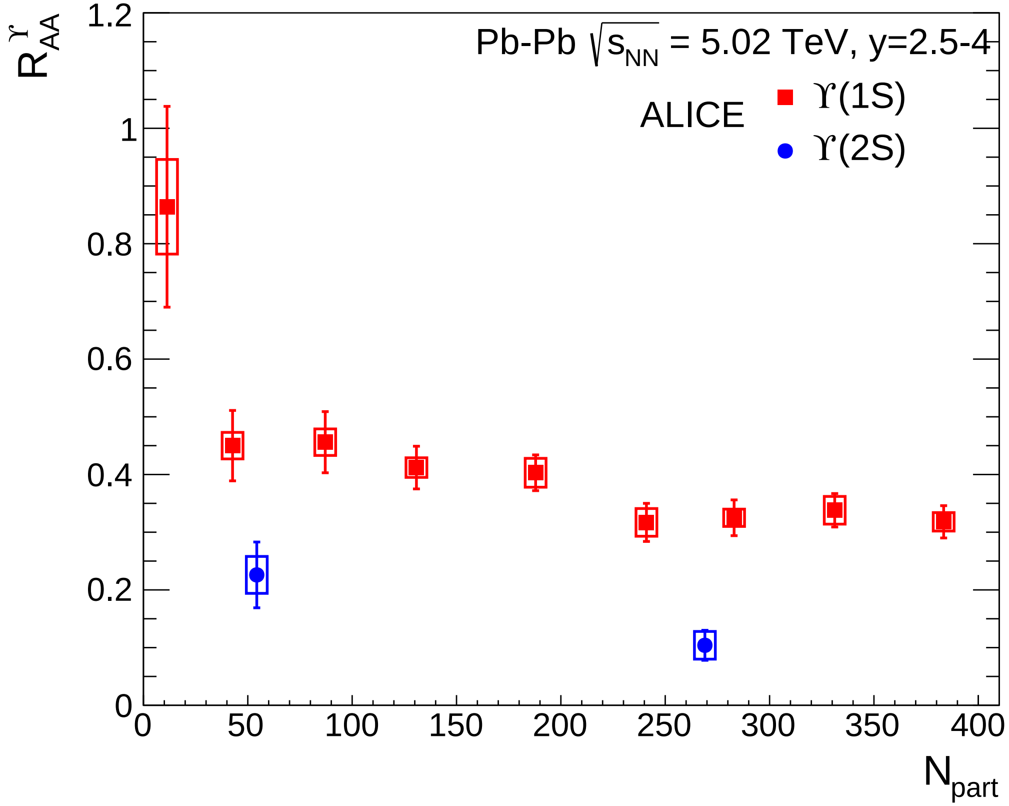
Rapp, Du, arXiv:1704.07923

Bottomonium data: RHIC and LHC

midrapidity



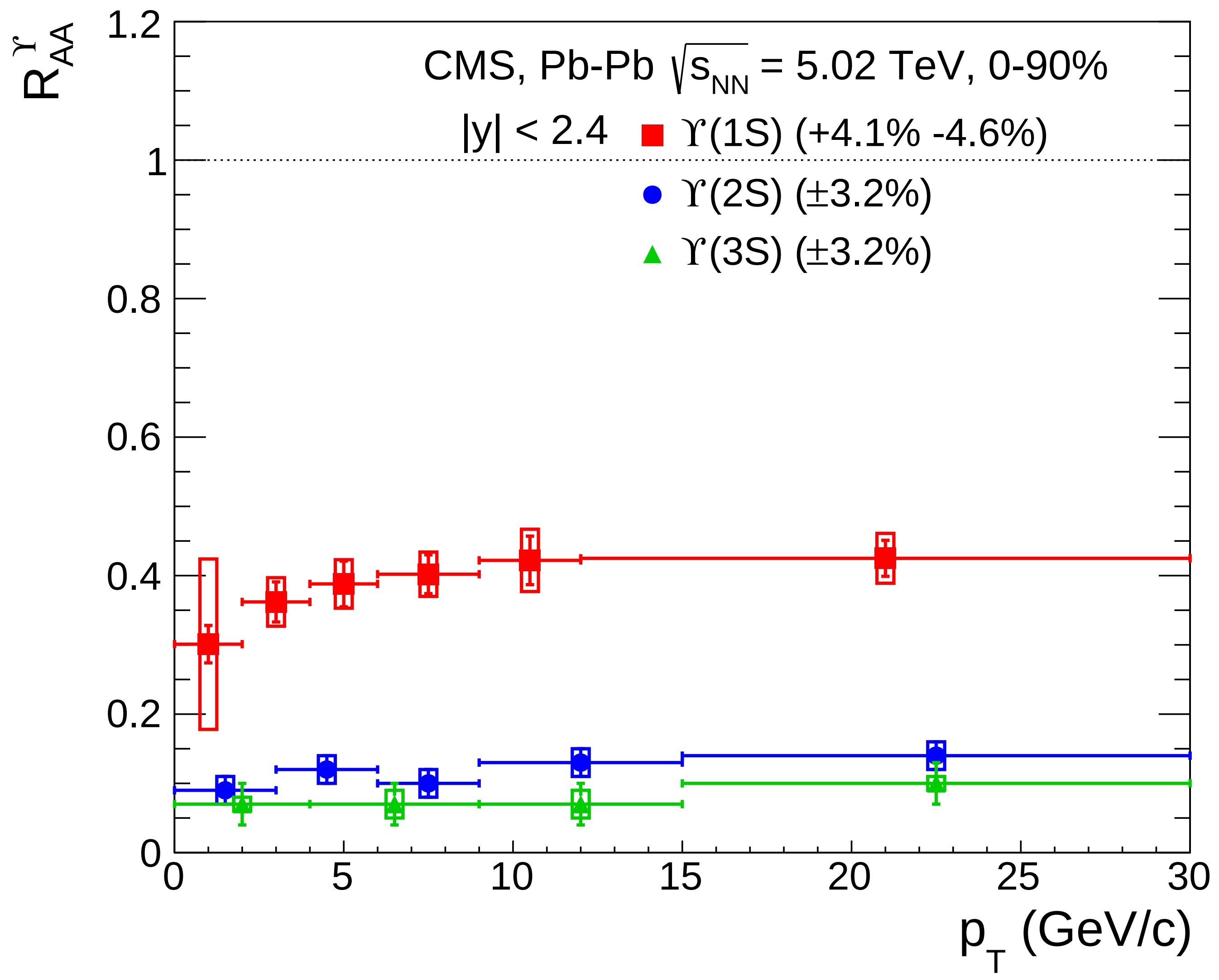
forward rapidity



significant suppression, hierarchy between states (sequential?)

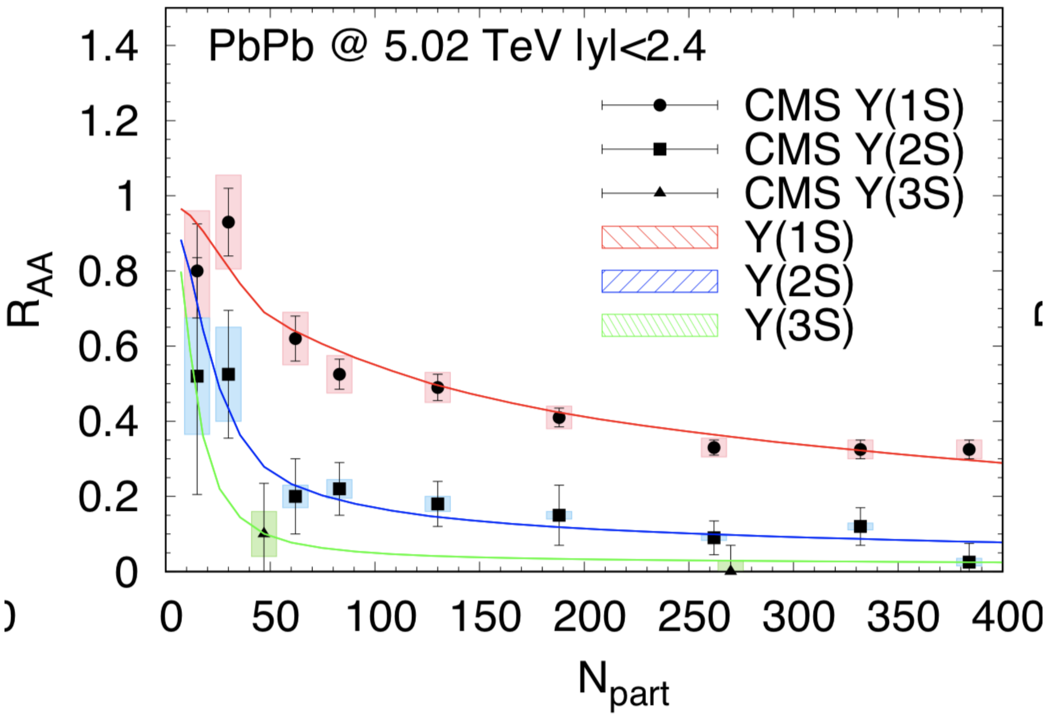
not significantly different at LHC and RHIC (except perhaps $\Upsilon(2S)$)

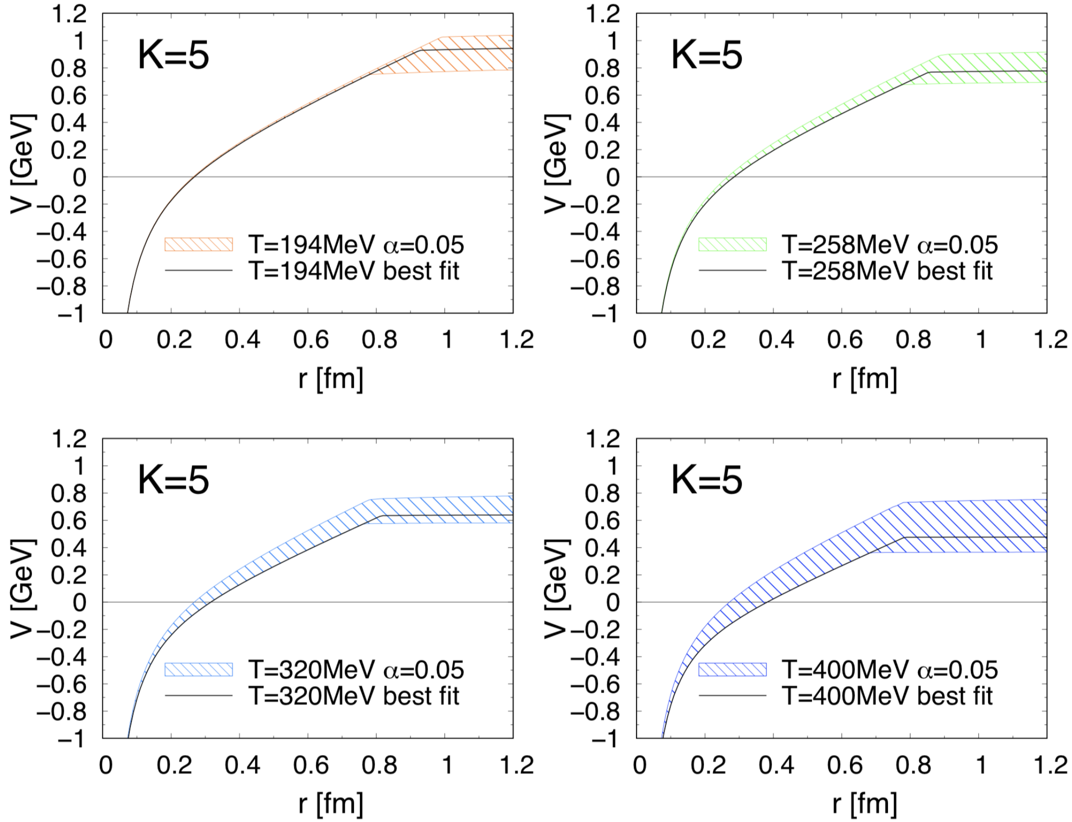
Bottomonium data at the LHC



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

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



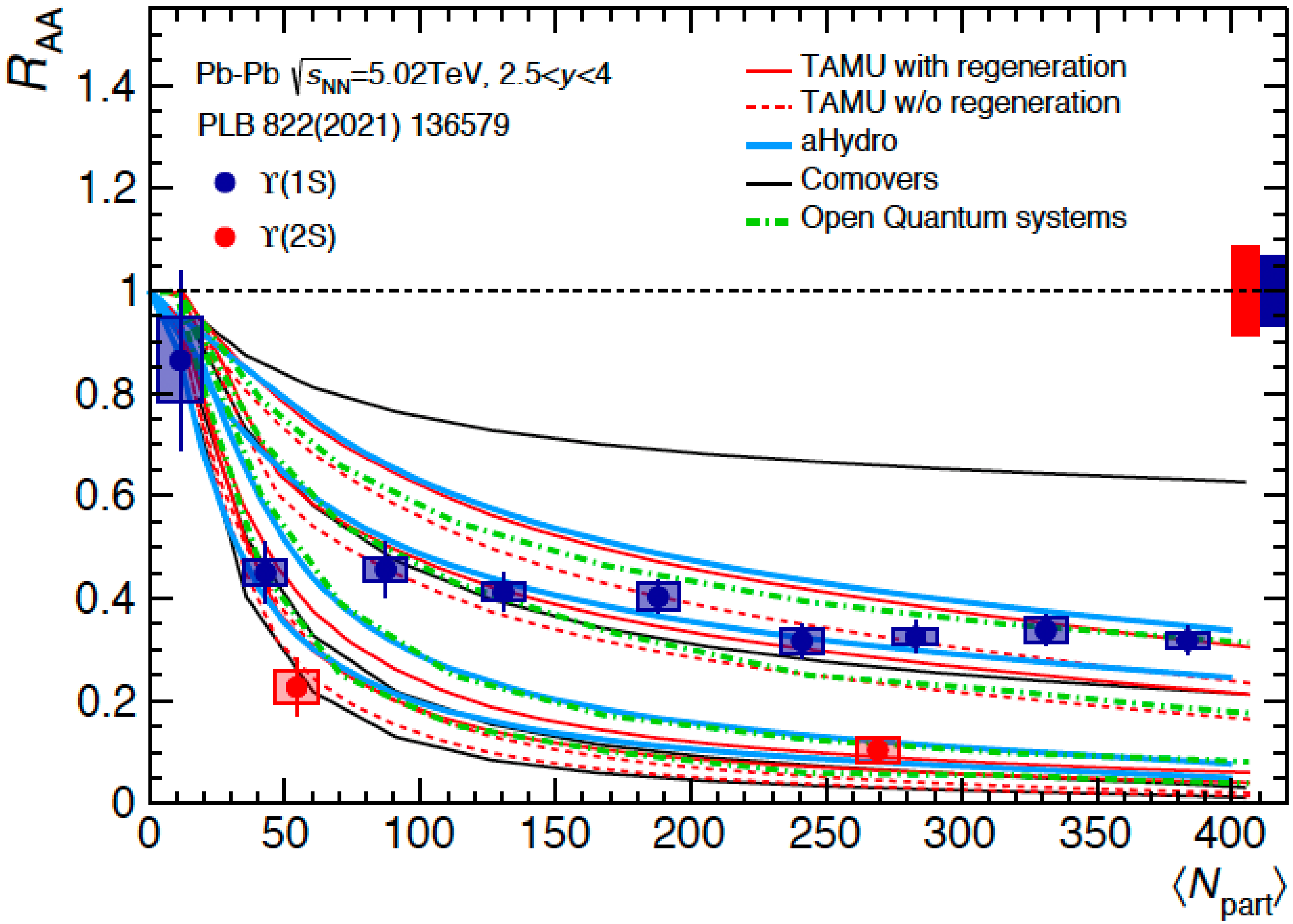


(re)generation important for $\Upsilon(2S)$

Transport Model (TAMU), Du, Liu, Rapp, PLB 796 (2019) 20

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

Υ suppression data and models

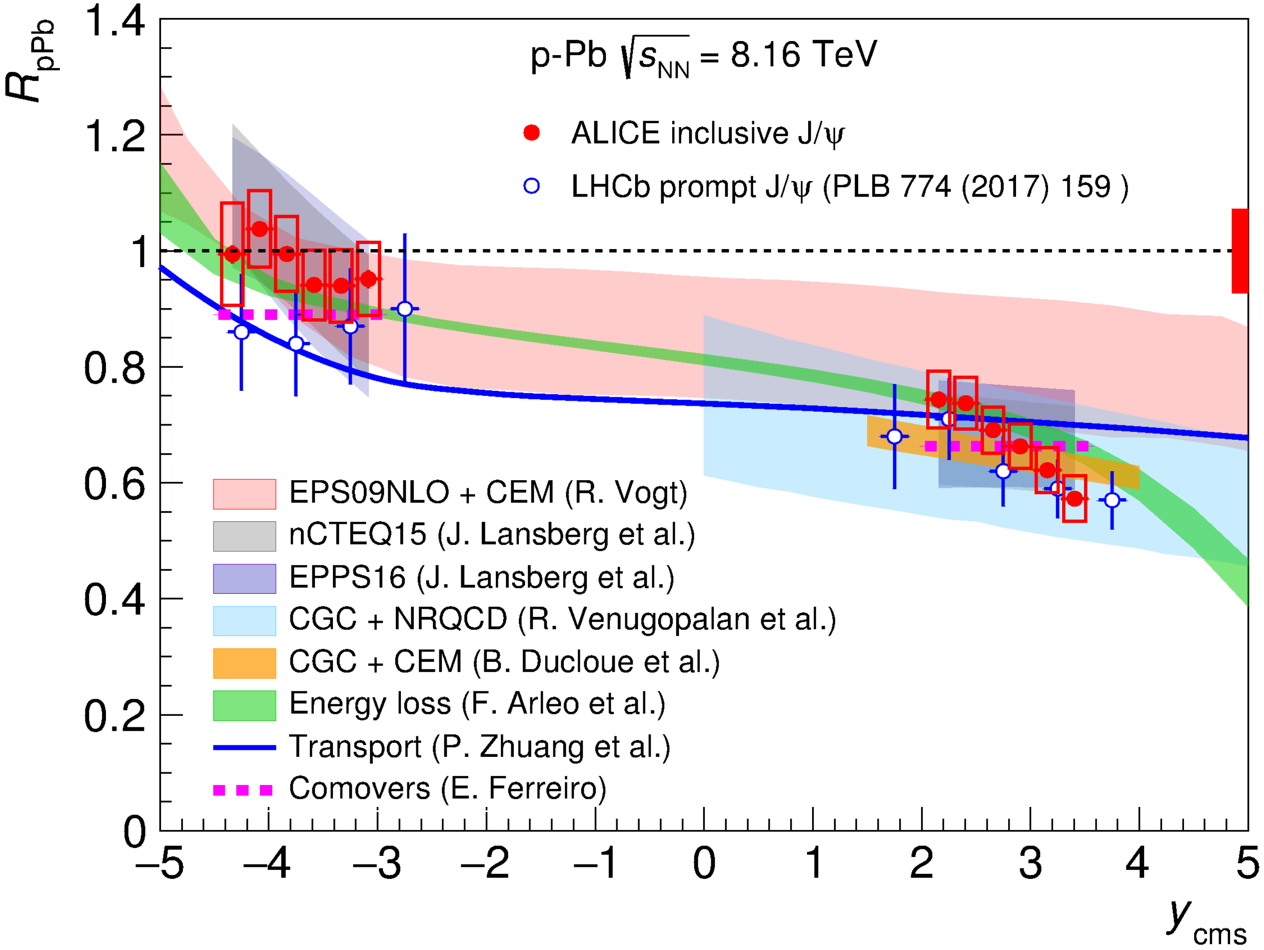


ALICE, arXiv:2212.04348

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

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

J/ψ production in p–Pb collisions



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

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}^{\mathrm{pPb}}\rangle \cdot \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

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

Shadowing describes data (shadowing uncert. are large)

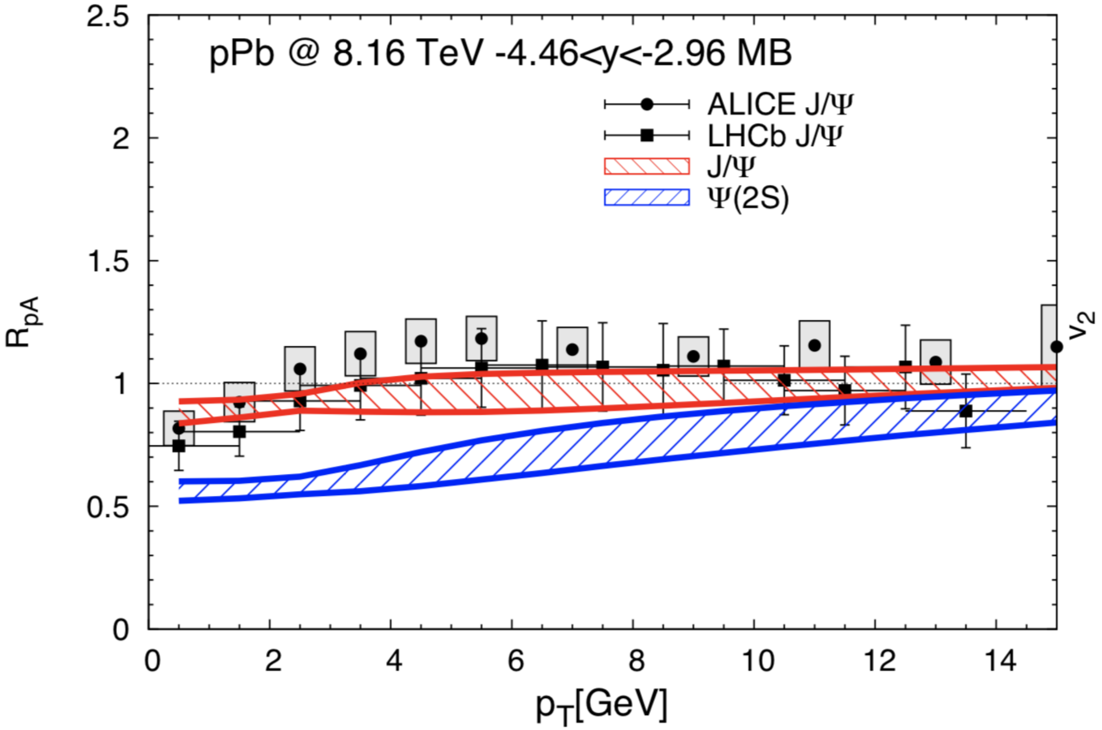
Color Glass Condensate also successful

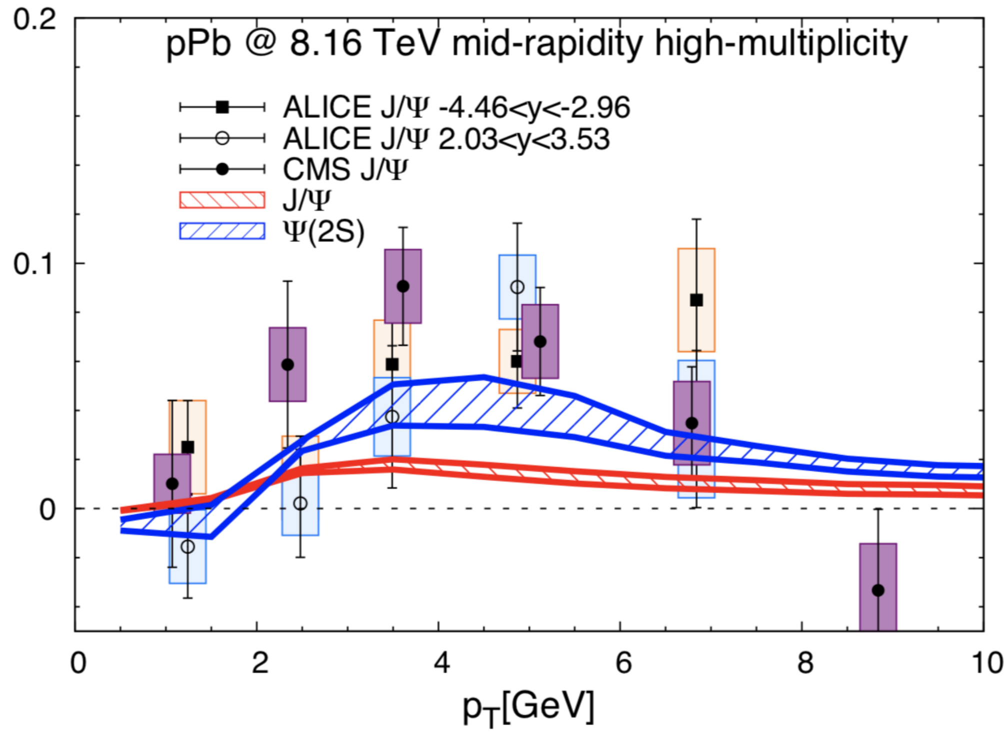
ALICE, JHEP 07 (2018) 160

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

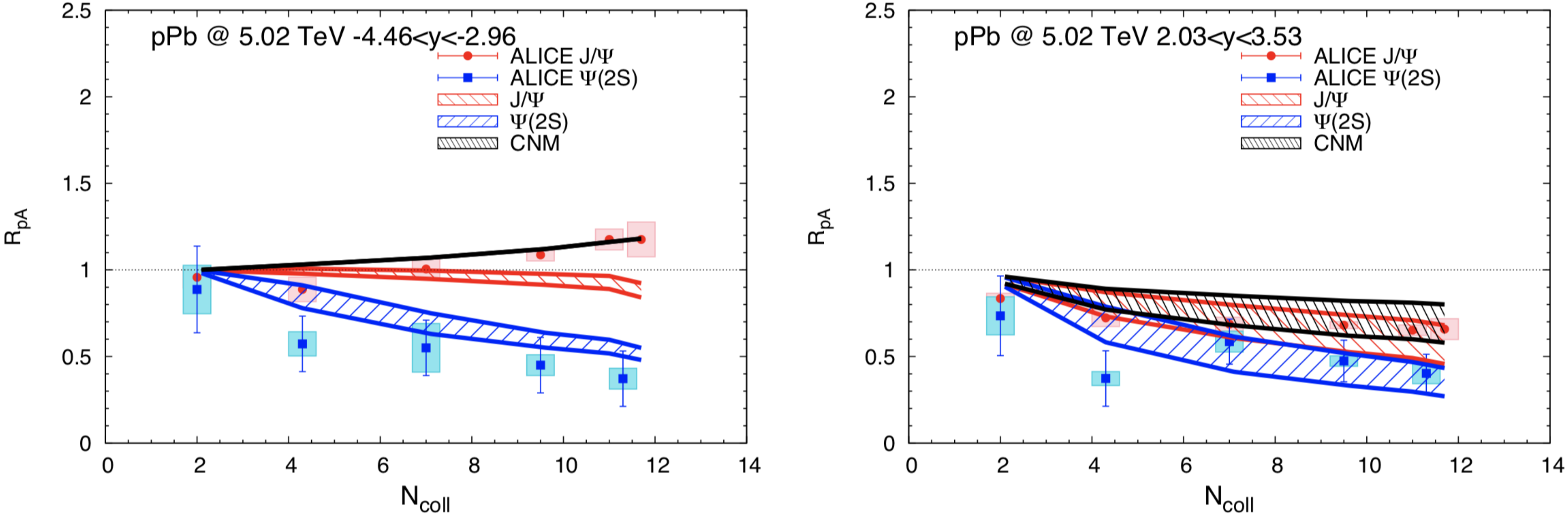




Bands: Transport Model, TAMU Du, Rapp, JHEP 1903 (2019) 015

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