Decoding the phase structure of QCD via particle production at high energy

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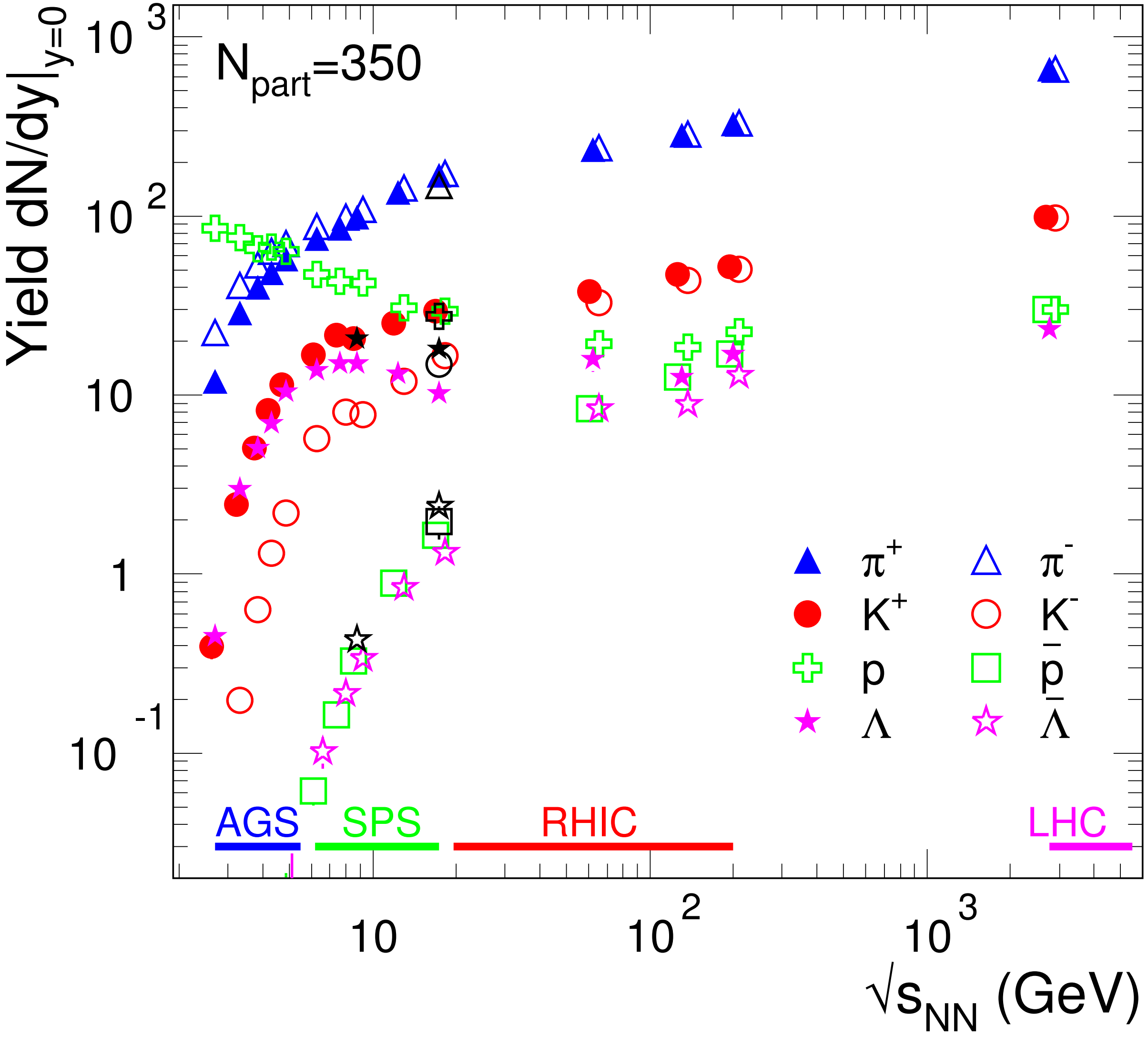
- Hadron production in nucleus-nucleus collisions
- The statistical model and the thermal fits
- Thermal fits and the QCD phase diagram
- Summary (and a glimpse of the charm quarks)

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

Hadron yields at midrapidity (central collisions)



A.Andronic, 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 (u, d quarks: remnants from the incoming nuclei)

...natural to think of the thermal (statistical) model ($e^{-m/T}$)

The statistical (thermal) model

grand canonical partition function for specie (hadron) i :

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

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;
$E_i = \sqrt{p^2 + m_i^2}$ total energy; $(+)$ for fermions (–) for bosons
$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

i) isospin: $\sum_i n_i I_{3i} / \sum_i n_i B_i = I_3^{tot} / N_B^{tot}, \quad N_B^{tot} \sim \mu_B$
I_3^{tot}, N_B^{tot} isospin and baryon number of the system (=0 at high energies)

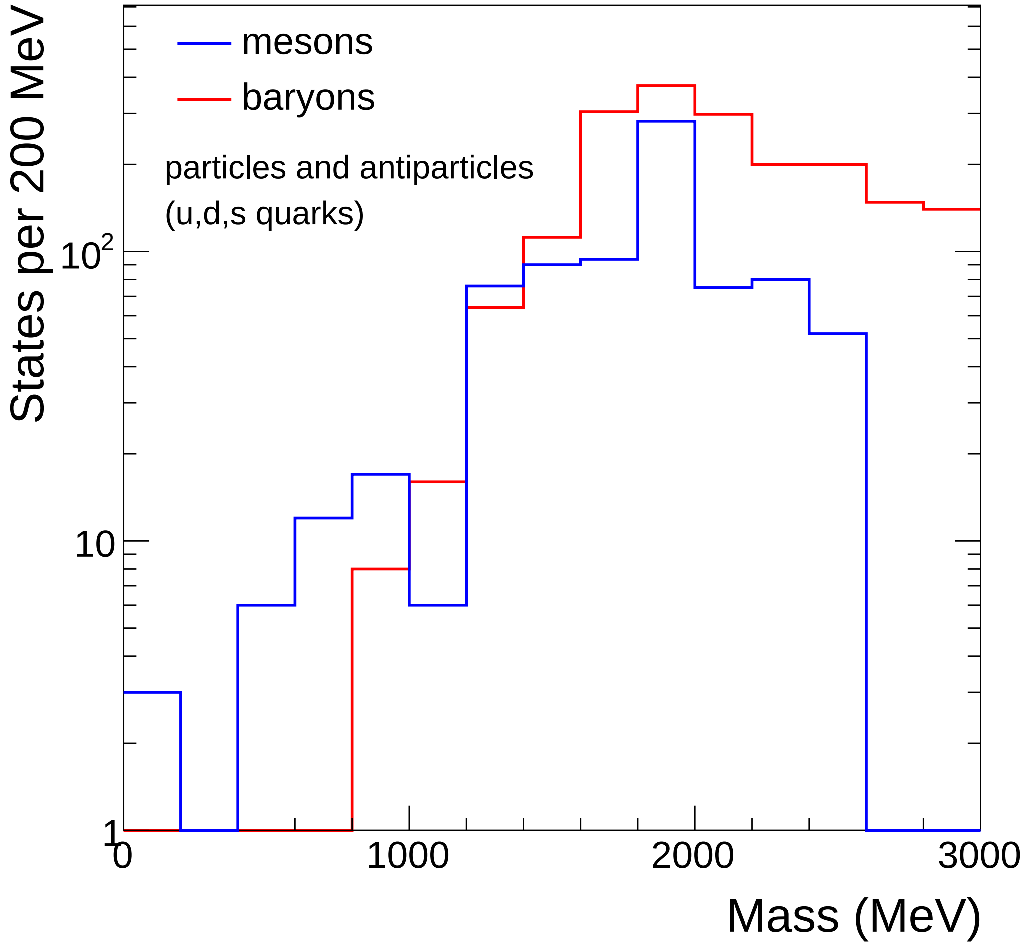
ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$.

Model input: hadron spectrum

...embodies low-energy QCD ...*vacuum masses*

well-known for $m < 2$ GeV; many confirmed states above 2 GeV, still incomplete



for high m, BR not well known, but can be reasonably guessed

T found to be robust in fits with spectrum truncated above 1.8 GeV

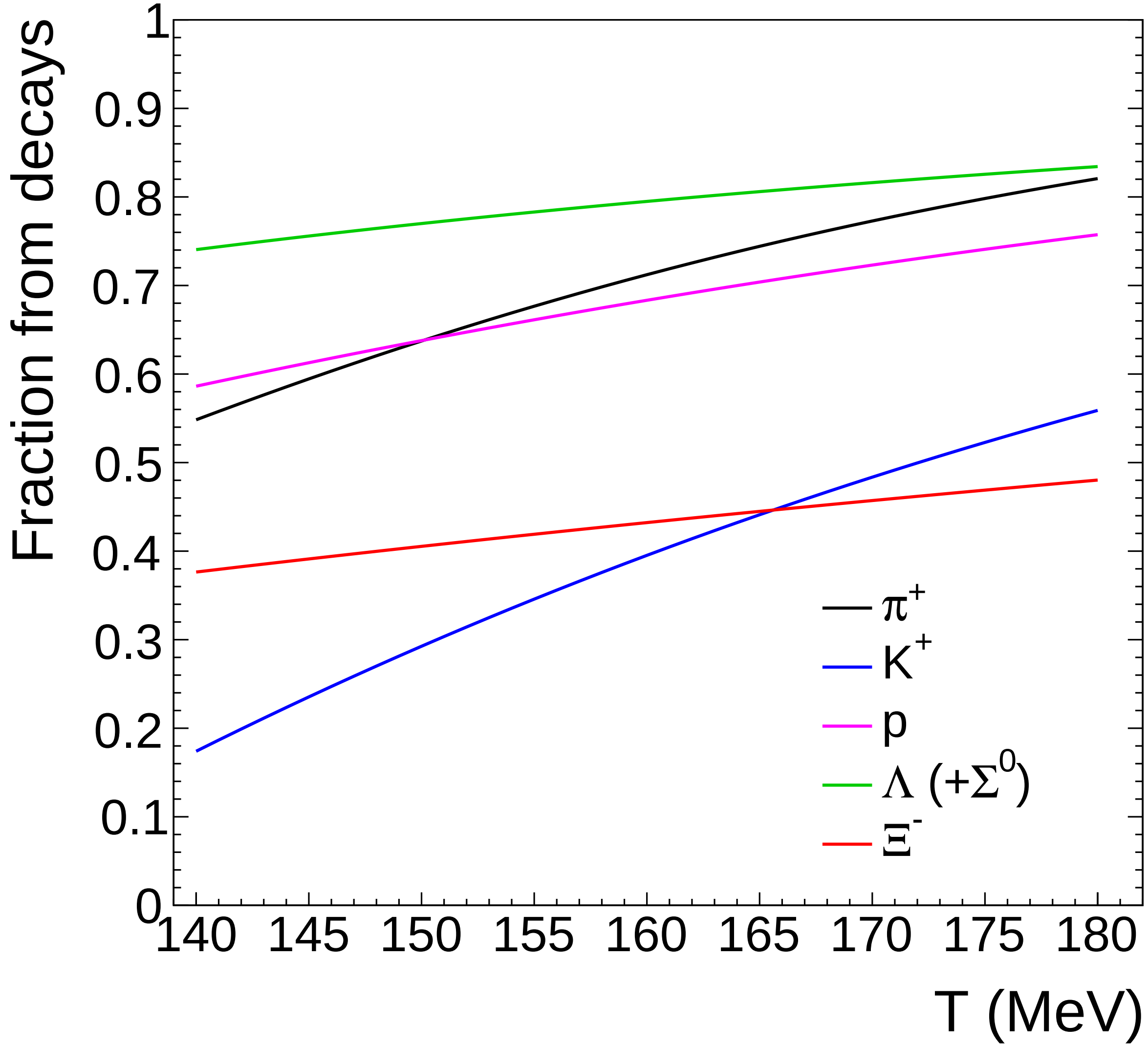
$$\rho(m) = c \cdot m^{-a} \exp\left(m/T_H\right)$$

$T_H \simeq 180$ MeV (max T for hadrons)

$(2J+1)$ counted in

Decays (feed-down)

(almost all) hadrons are subject to strong and electromagnetic decays



$\Delta \rightarrow p(n) + \pi$, $\rho \rightarrow \pi + \pi$

$\Sigma^0 \rightarrow \Lambda + \gamma$

weak decays can be treated as well ...to account for the exact experimental situation

contribution of resonances is significant (and particle-dependent)

(plot for μ_B=0)

The thermal model: other ingredients

- Canonical treatment (suppression): exact quantum-number conservation

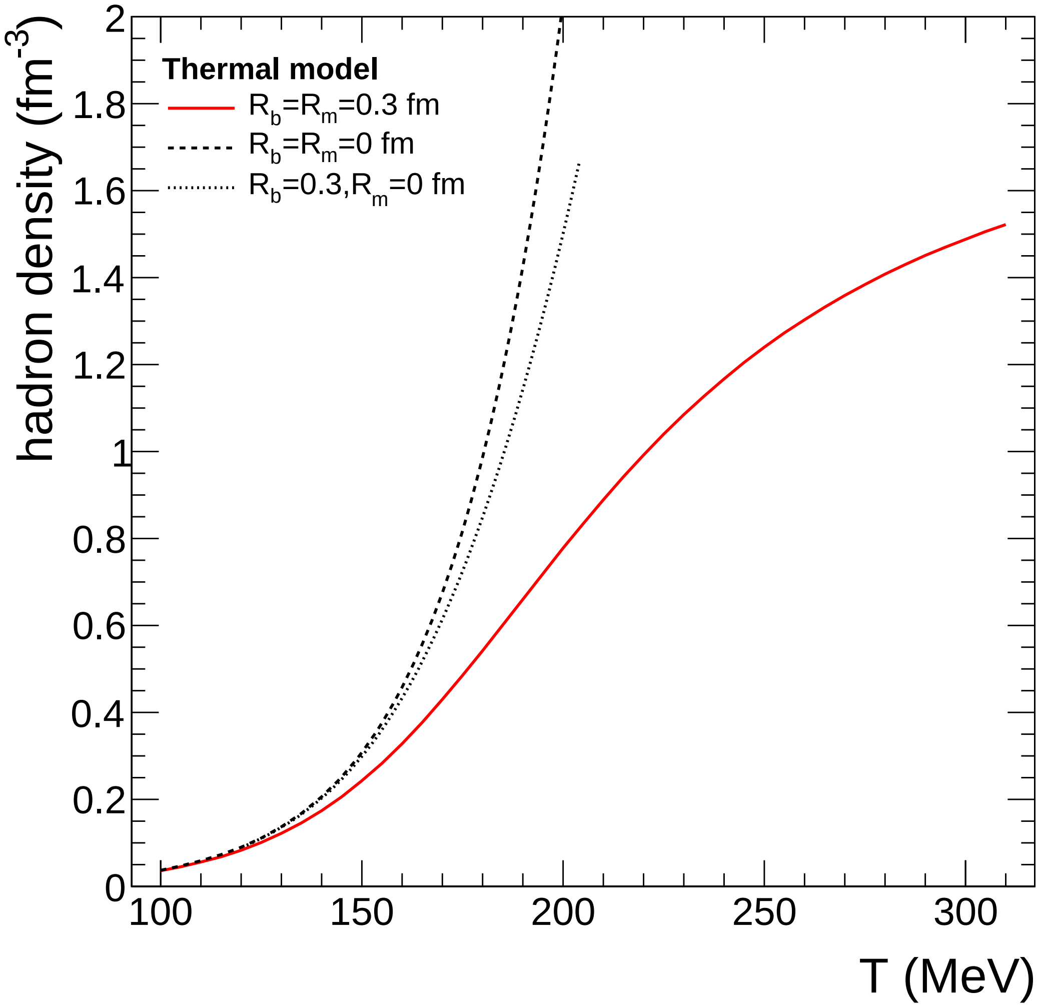
  important whenever the abundance of hadrons with a given quantum number is very small

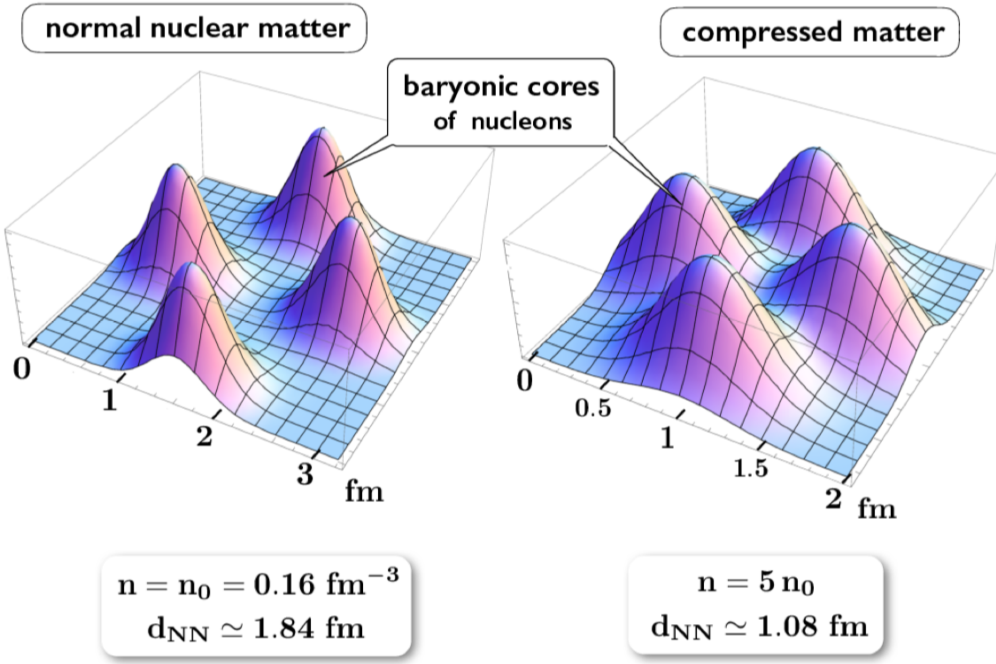
- Widths of resonances (Breit-Wigner)

- Interactions ...several ways tried:

  - hard-sphere
  - T-dependent Breit-Wigner resonance widths
  - S-matrix, based on scattering phase shifts (incl. non-resonant contrib.)

Hadron densities





$n = n_0 = 0.16$ fm^{-3}
$d_{NN} \simeq 1.84$ fm

$n = 5\, n_0$
$d_{NN} \simeq 1.08$ fm

Weise, arXiv:1811.09682

(baryons: gaussians, r=0.5 fm)

"hadron gas": a dense system (also nuclear matter is rather a liquid than a gas)

(the usual case is $R_{baryon} = R_{meson} = 0.3$ fm ...hard-sphere repulsion)

Air at NTP: intermolecule distance ≃50 × molecule size

Thermal fits of hadron abundances

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

Latest PDG hadron mass spectrum ...quasi-complete up to m=2 GeV;
our code: 555 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

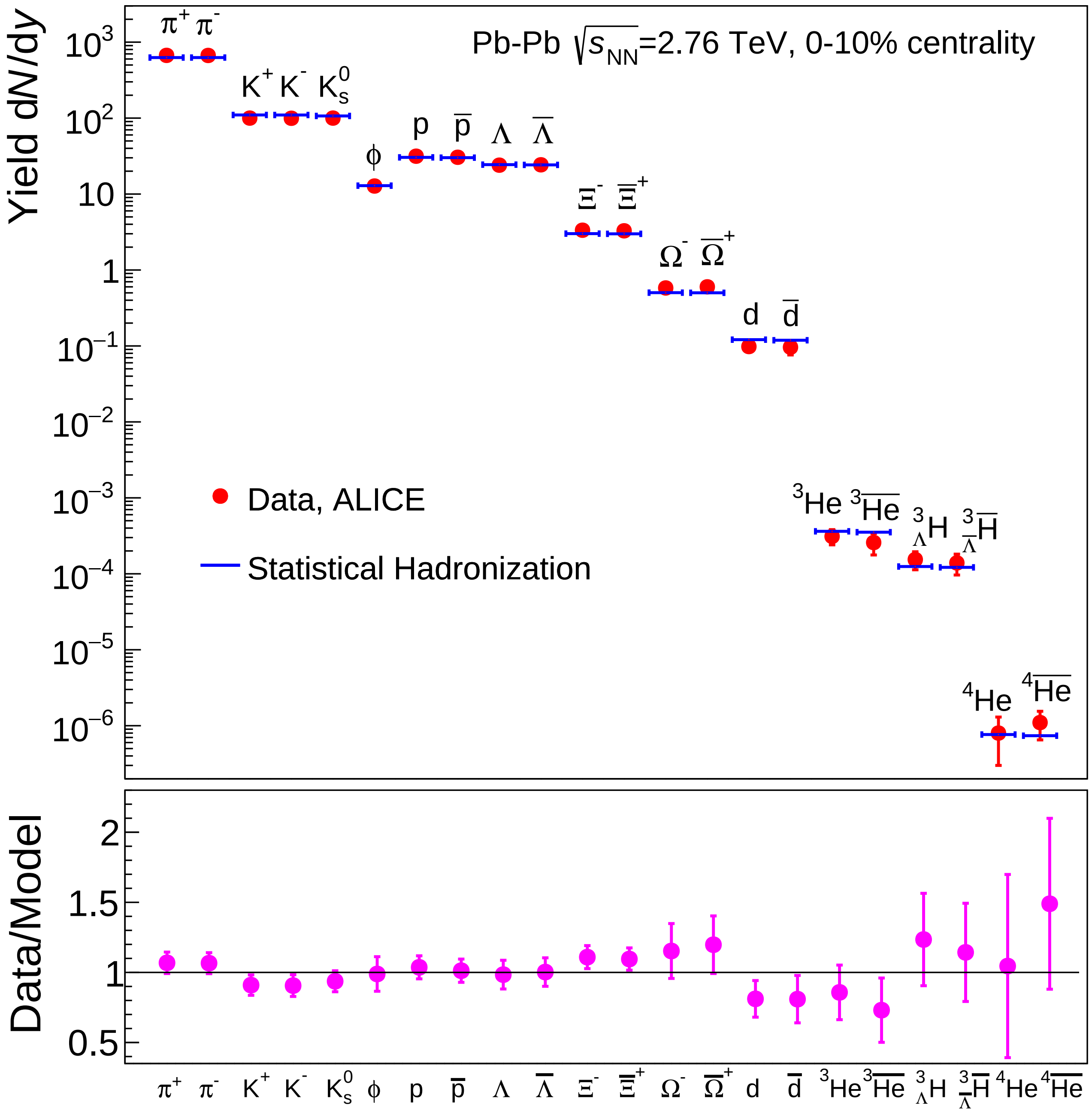
canonical treatment whenever needed (small abundances)

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

N_i hadron yield, σ_i experimental uncertainty (stat.+syst.)

$\Rightarrow (T,\ \mu_B,\ V)$ *...tests chemical freeze-out* (chemical equilibrium)

Thermal fit – LHC, Pb–Pb, 0-10%



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

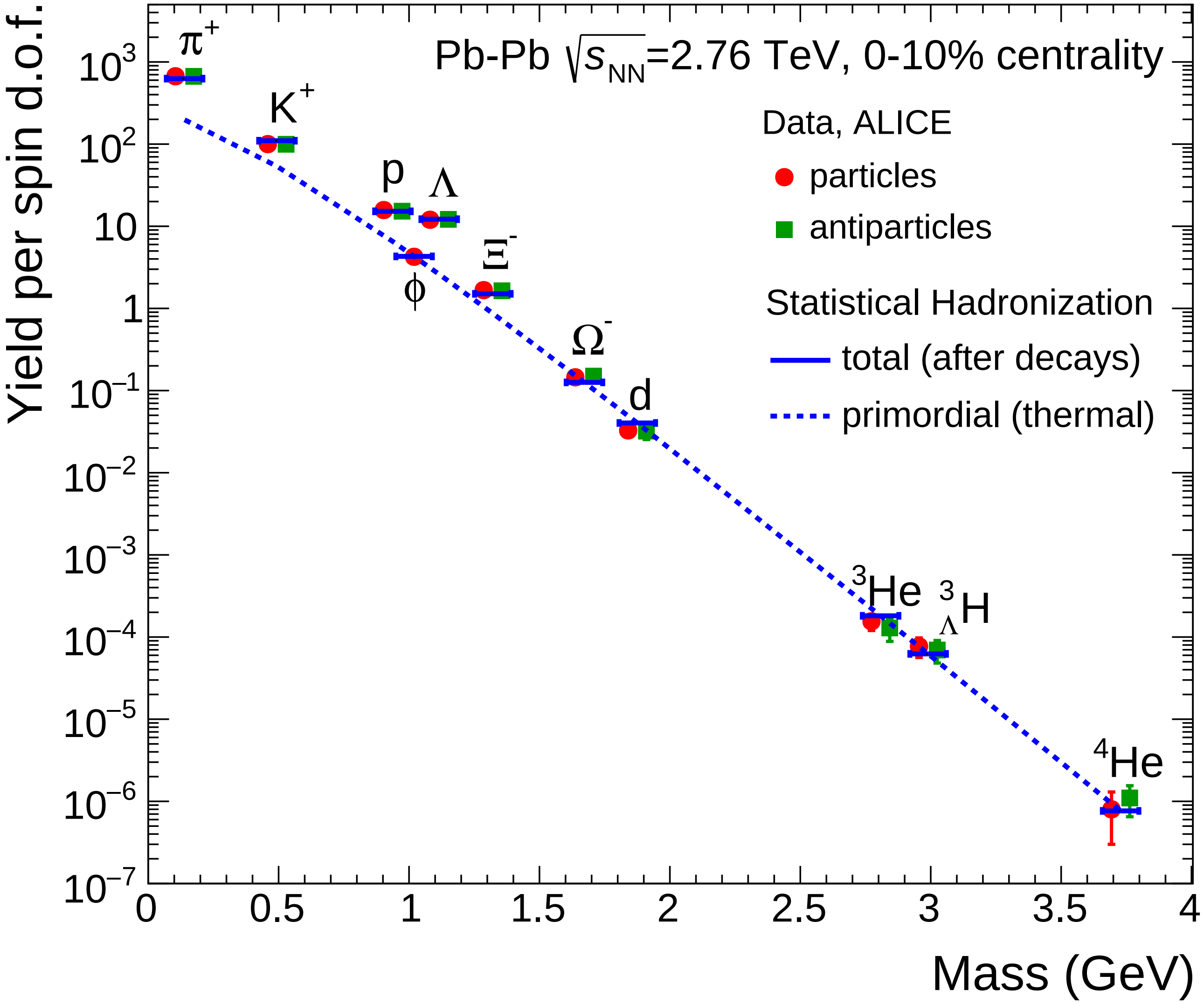
$\chi^2/N_{df} = 16.7/19$

S-matrix treatment

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

hadronization as bags of quarks and gluons?

Model uncertainties: hadron spectrum



contribution of resonances
is significant
(and particle-dependent)

Fit of ϕ, Ω, d, ^{3}He, $^3_\Lambda$H, ^{4}He:

$T_{CF} = 156 \pm 2.5$ MeV

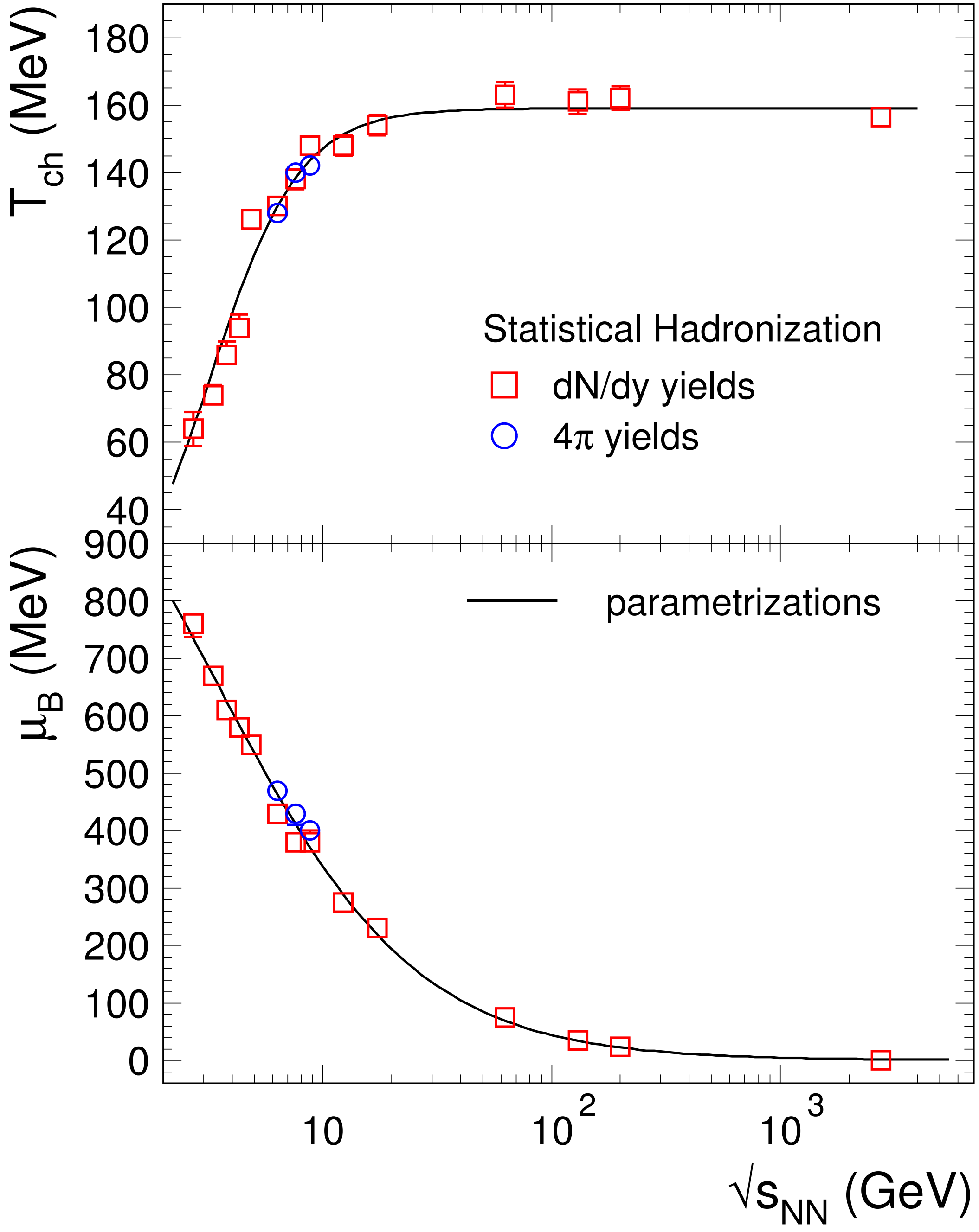
$(\chi^2/N_{df} = 7.4/8)$

Fit of nuclei (d, ^{3}He, ^{4}He):

$T_{CF} = 159 \pm 5$ MeV

3-4 MeV upper bound of systematic uncertainty due to hadron spectrum

Energy dependence of T, μ_B (central collisions)



thermal fits exhibit a limiting temperature:

$$T_{lim} = 158.4 \pm 1.4 \text{ MeV}$$

$$T_{CF} = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}$$

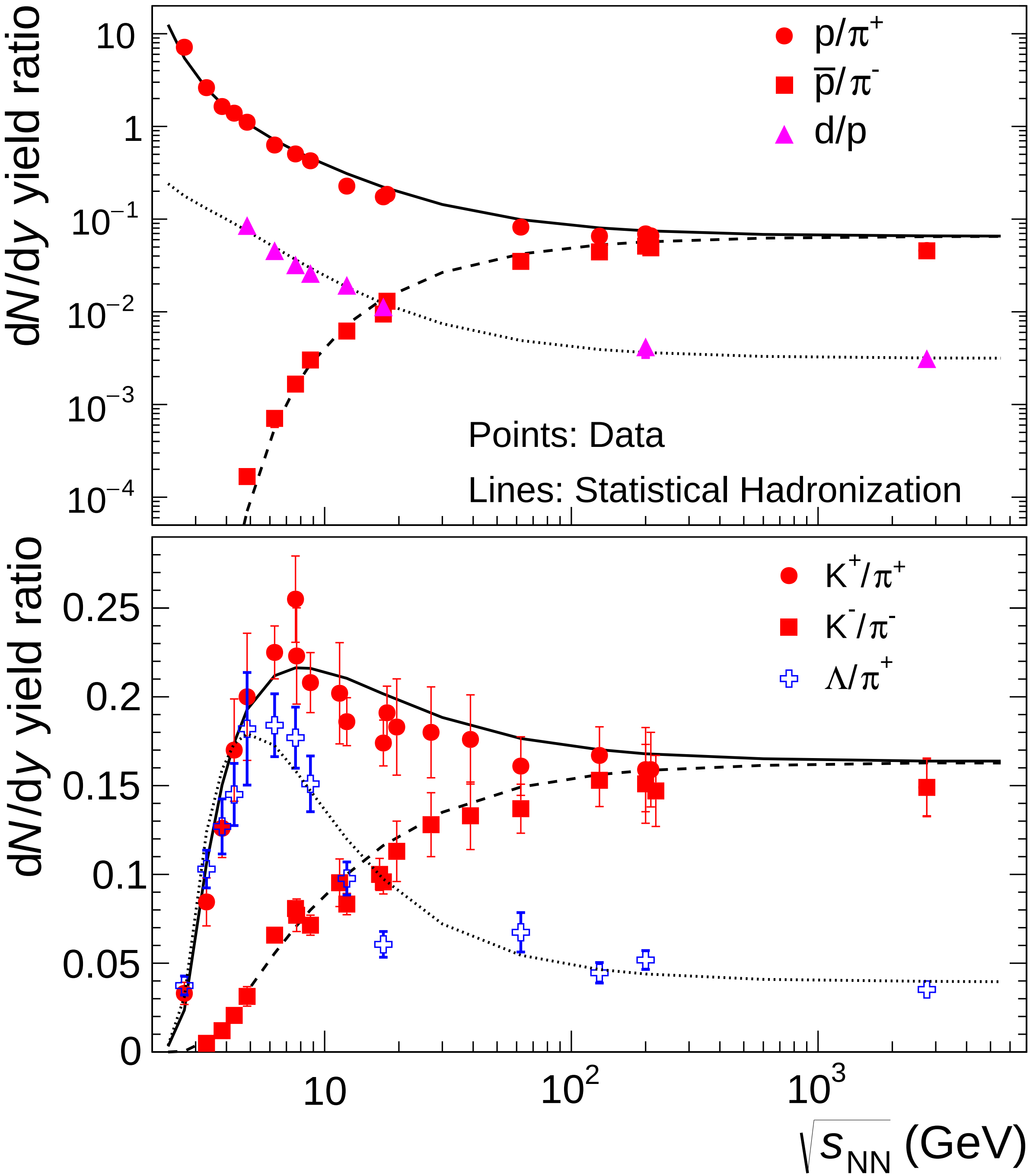
$$\mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

NPA 772 (2006) 167, PLB 673 (2009) 142

μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

determined by the "stopping" of the colliding nuclei

The grand (albeit partial) view



Data:

AGS: E895, E864, E866, E917, E877

SPS: NA49, NA44

RHIC: STAR, BRAHMS

LHC: ALICE

NB: no contribution from weak decays

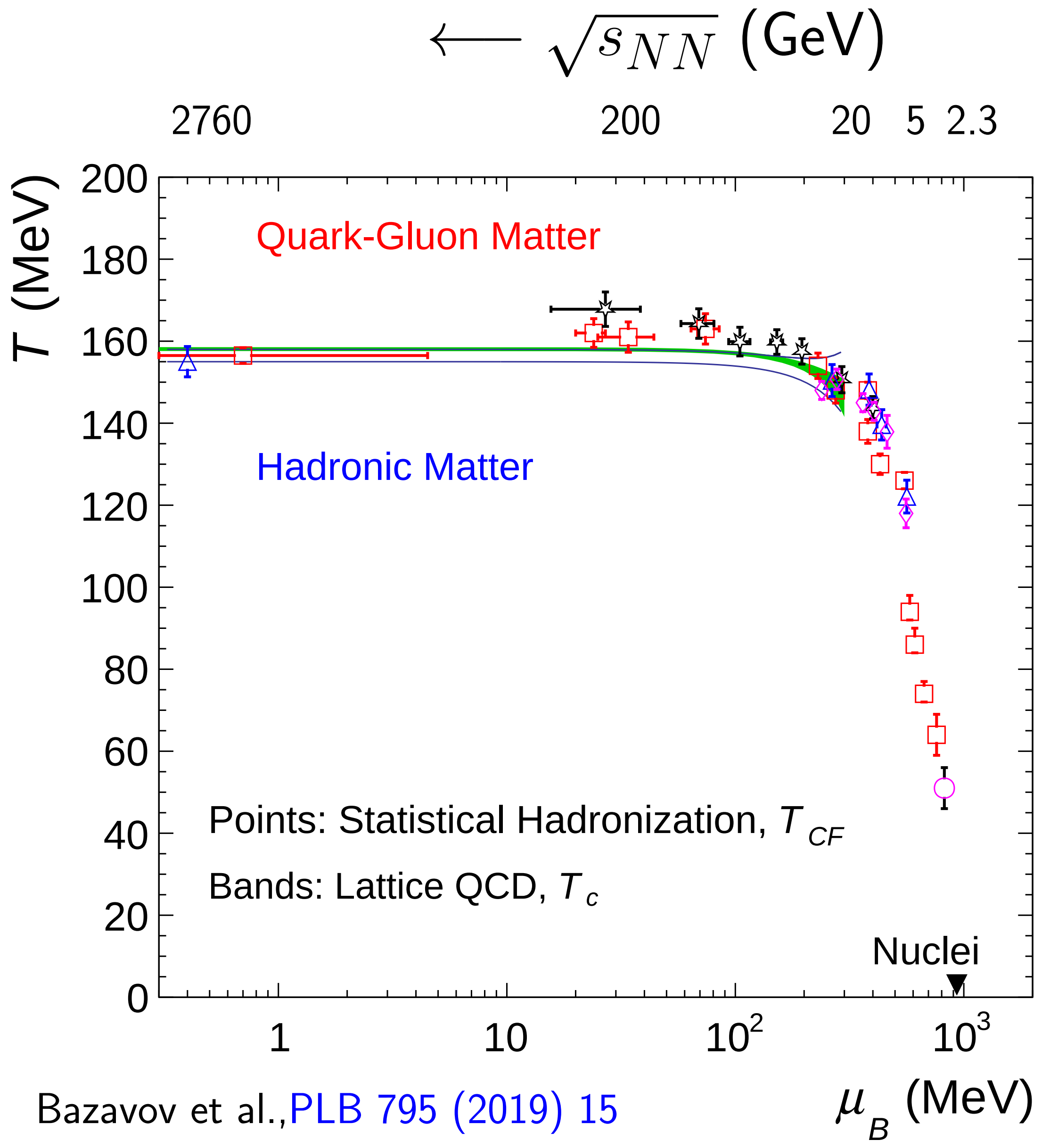
d/p ratio is well described for all energies

"structures" described by SHM

...determined by strangeness conservation

Λ/π peak reflects increasing T and decreasing μ_B

The phase diagram of QCD



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" of the colliding nuclei

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

(RHIC BES / FAIR)

Bazavov et al.,PLB 795 (2019) 15
Borsanyi et al., PRL 125 (2020) 052001

see refs. in Nature 561 (2018) 321

points: independent analyses of same data → "model/code uncert." are small

Summary

- Hadronization: rapid process in which all quark flavors take part concurrently
- Abundance of hadrons with light quarks consistent with chemical equilibration
- There is a variety of approaches ... *a personal bias: the "minimal model"*

  a minimal set of parameters, means a well-constrained model
- The thermal model provides a simple way to access the QCD phase boundary

  ...at high energies (at low energies canonical suppression needs more care)

  ...but is it more than a 1st order description (of loosely-bound objects)?

  ...and what fundamental point does it make about hadronization?

  (statistical features dominate, but understanding still missing as a dynamical process)
- More insights from higher moments and from heavier (charm) quarks

  ...(at the LHC) a handle for hadronization T *with a mass scale* ($m_{c\bar{c}}$) *well above* T

  ($T > T_{ch}$ measured with (virtual) photons and through flow via hydrodynamics)

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

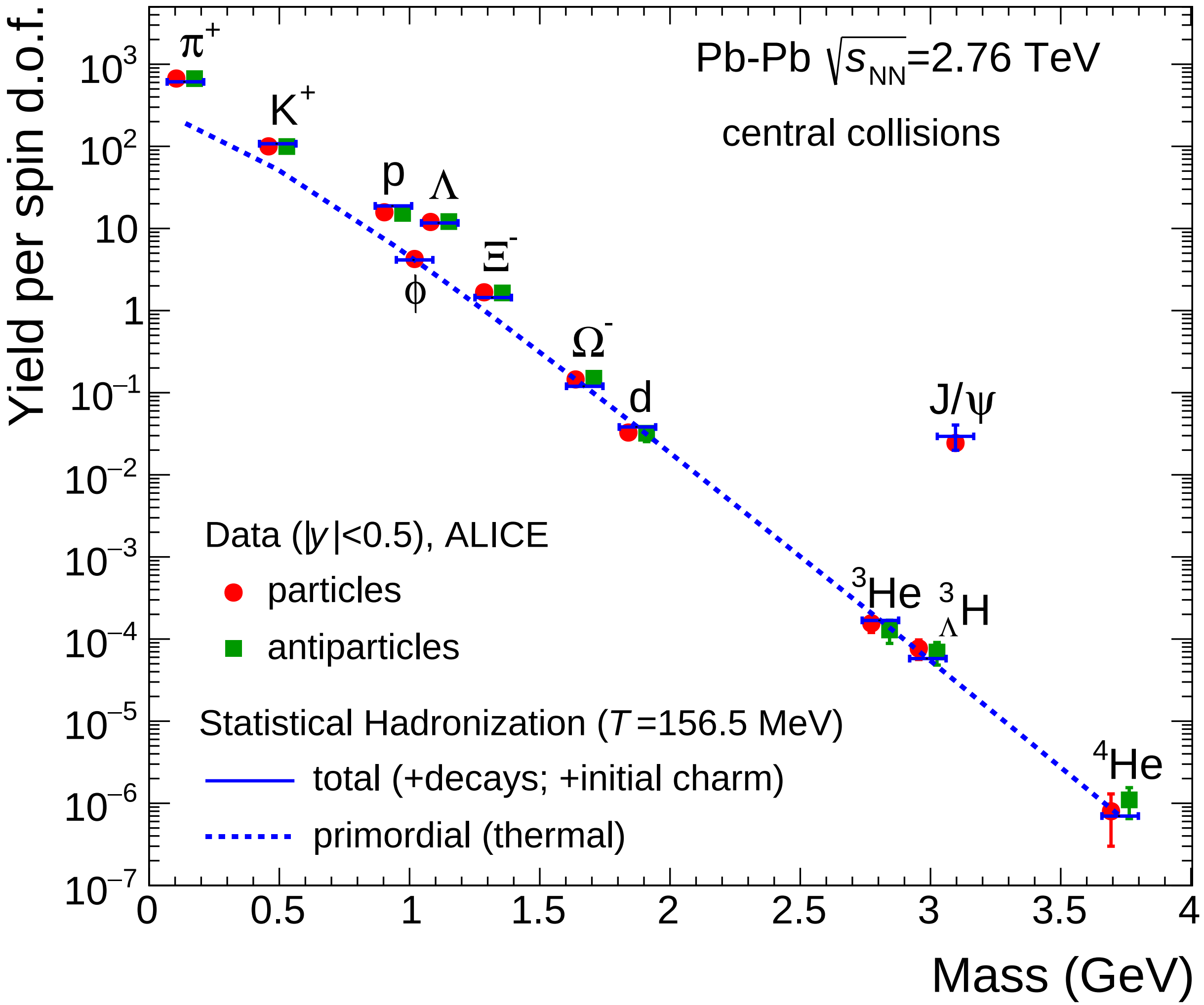
assume:

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

Additional material

SHMc: method and inputs

Braun-Munzinger, Stachel, PLB 490 (2000) 196, NPA 690 (2001) 119

- Thermal model calculation (grand canonical) T,μ_B: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$Canonical (Cleymans, Redlich, Suhonen, Z. Phys. C51 (1991) 137):

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

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

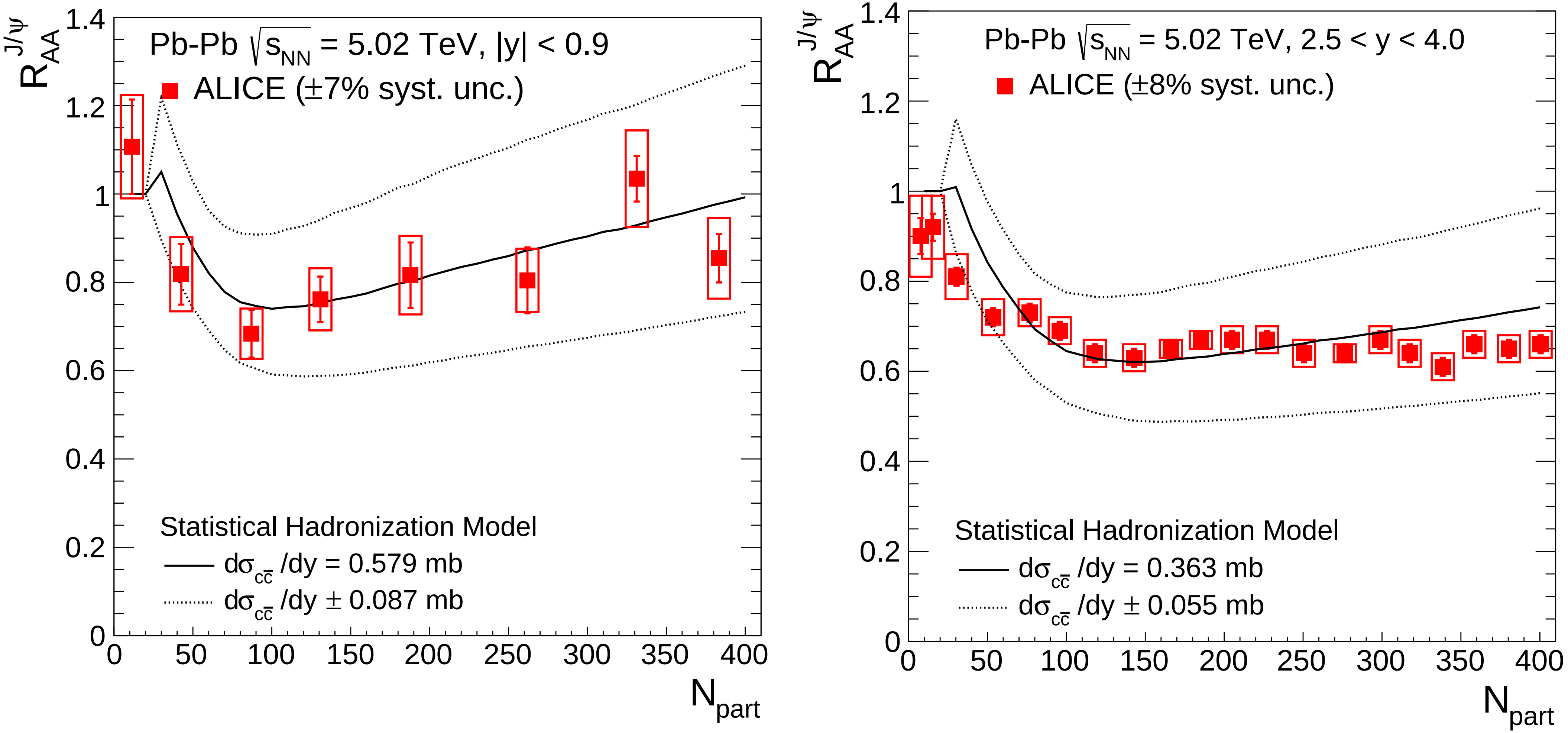
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 + N_D^{\mathrm{corona}}$, $N_{J/\psi} = g_c^2 V n_{J/\psi}^{th} + N_{J/\psi}^{\mathrm{corona}}$

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

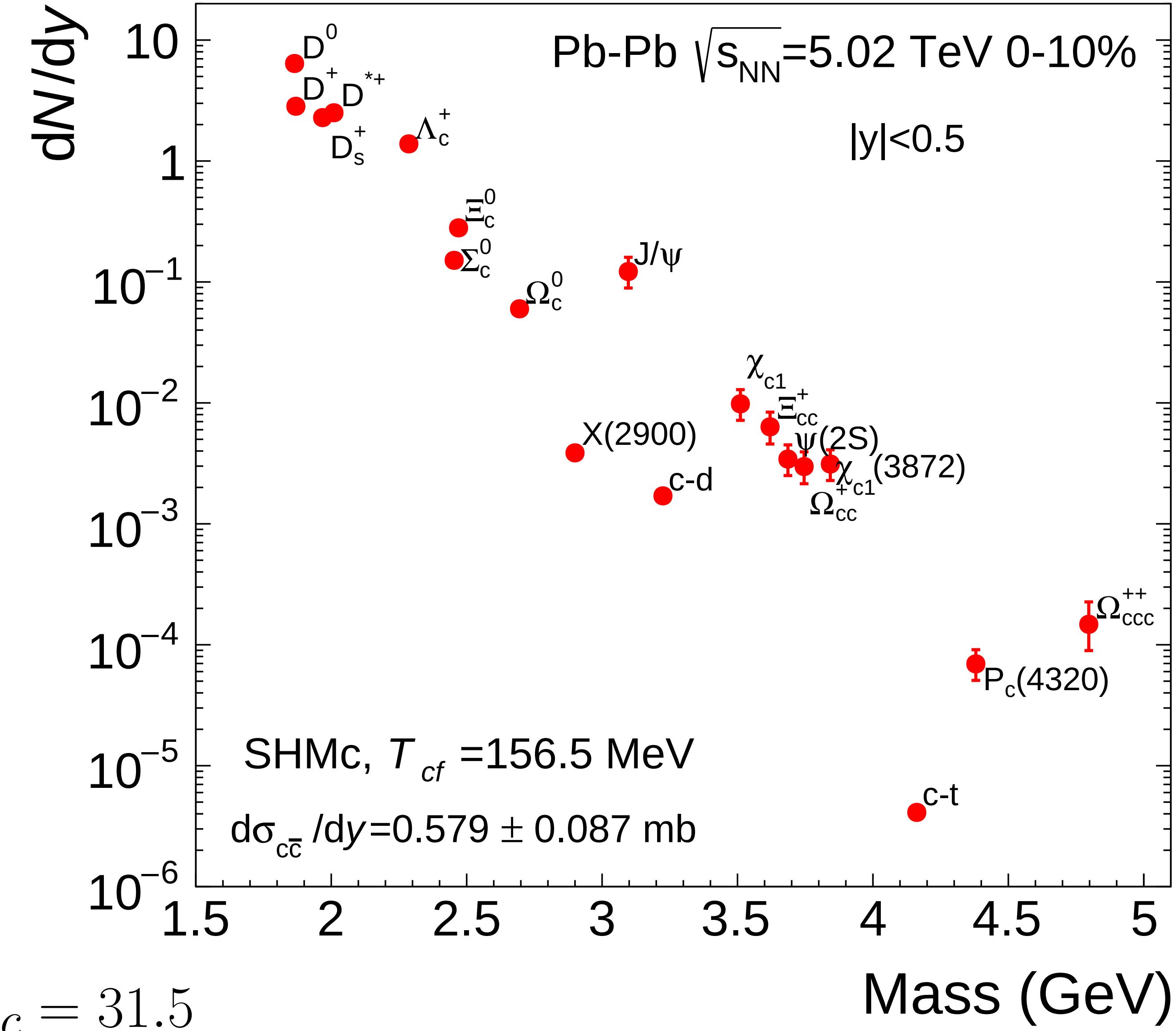
full thermalization of c quarks in QGP, hadronization at chemical freeze-out



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

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

SHMc: the full charm zoo



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

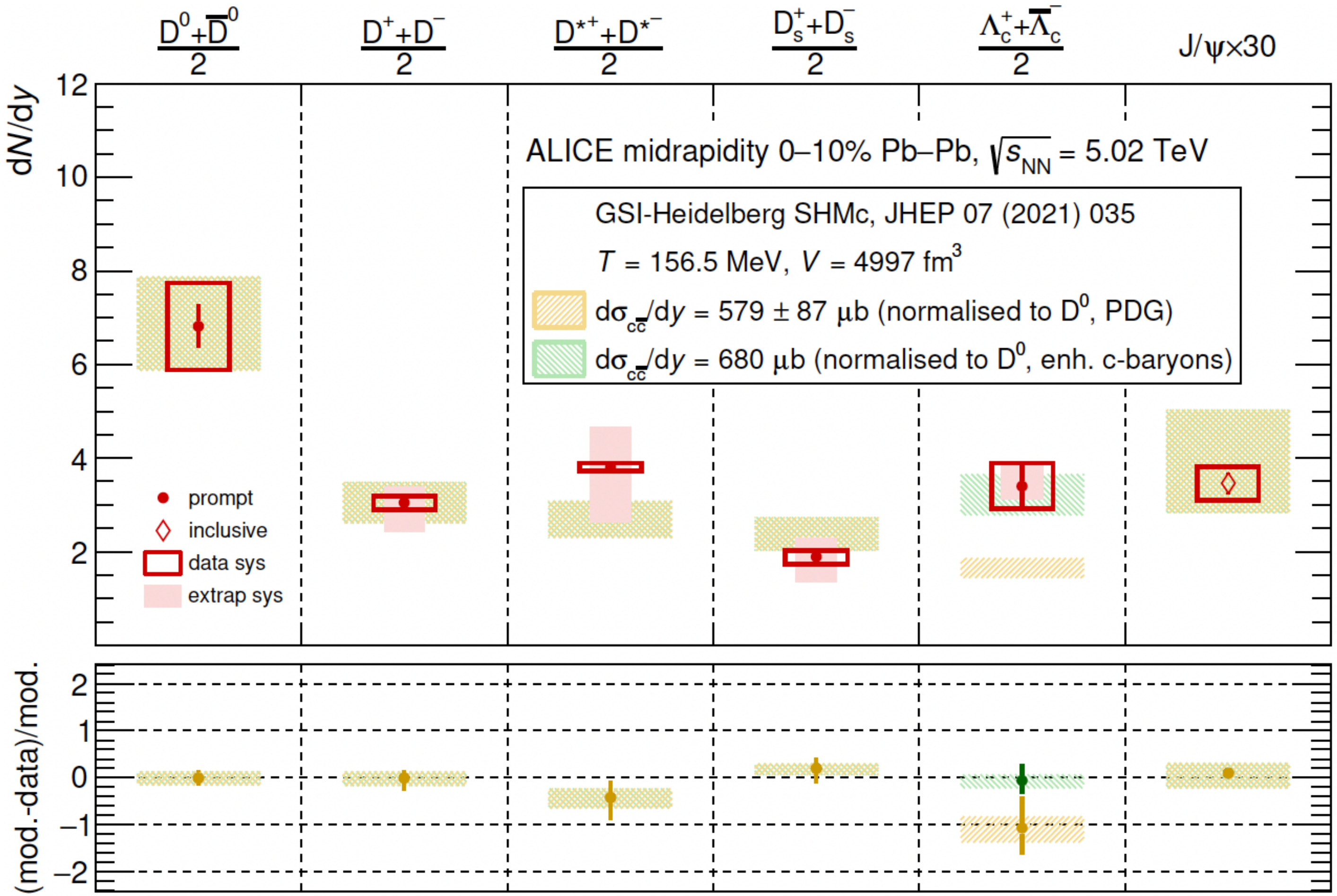
$$X(6900) \sim 10^{-8}$$

$$\frac{\mathrm{d}N_{c\bar{c}}}{\mathrm{d}y} = 13.8$$

$$\to g_c = 31.5$$

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

Charm data and SHMc model



ALICE, arXiv:2212.04348

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

Summary / Conclusions: charm

In the (our) statistical hadronization model:

- The hadronization is a rapid process in which all quark flavors take part concurrently
- 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

"The competition":

the kinetic model, continuous J/ψ destruction and (re)generation in QGP

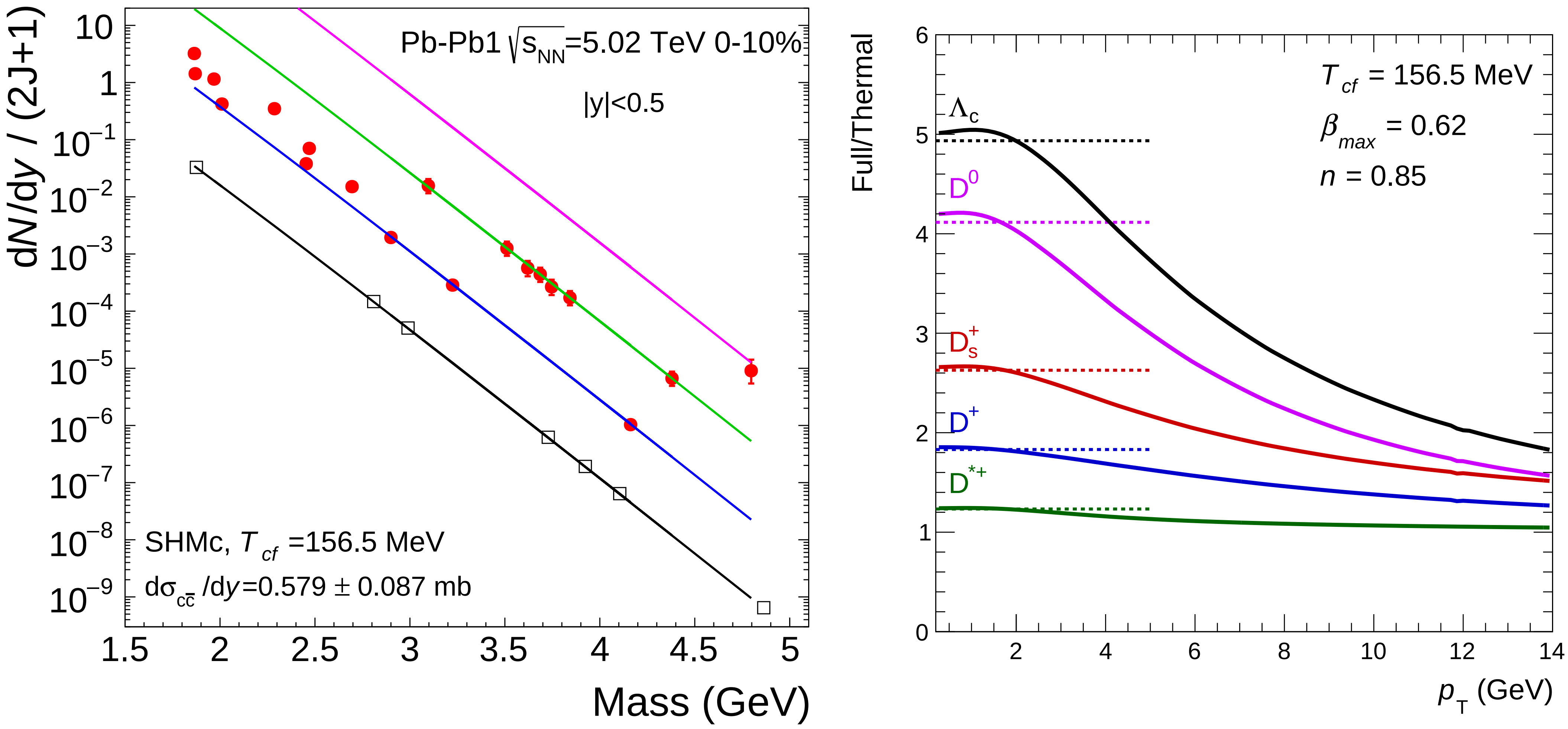
(only up to 2/3 of the J/ψ yield (LHC, central collisions) originates from deconfined c and $\bar{c}$ quarks)

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

A precision (±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)

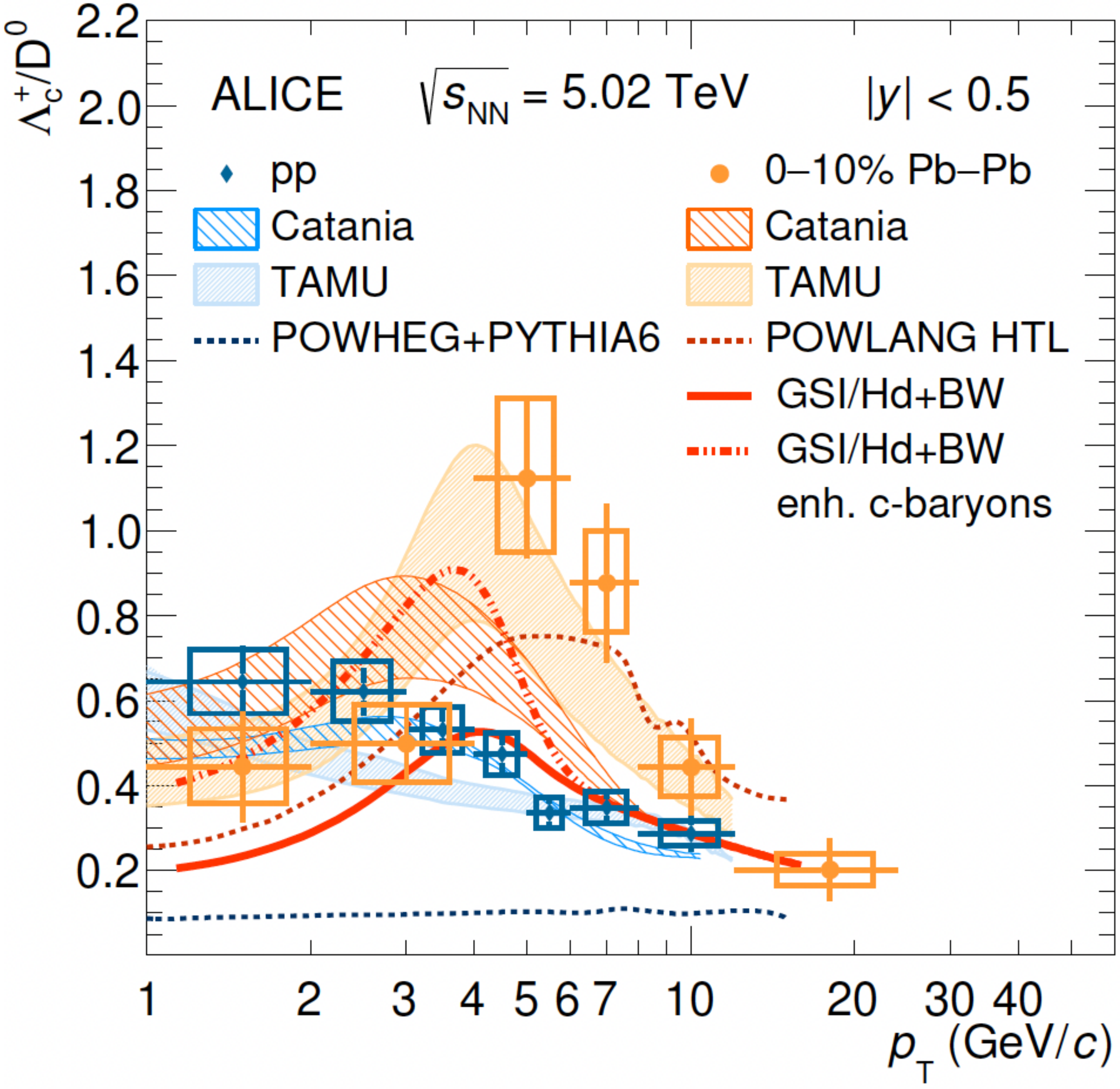
Full charm predictions for the LHC



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

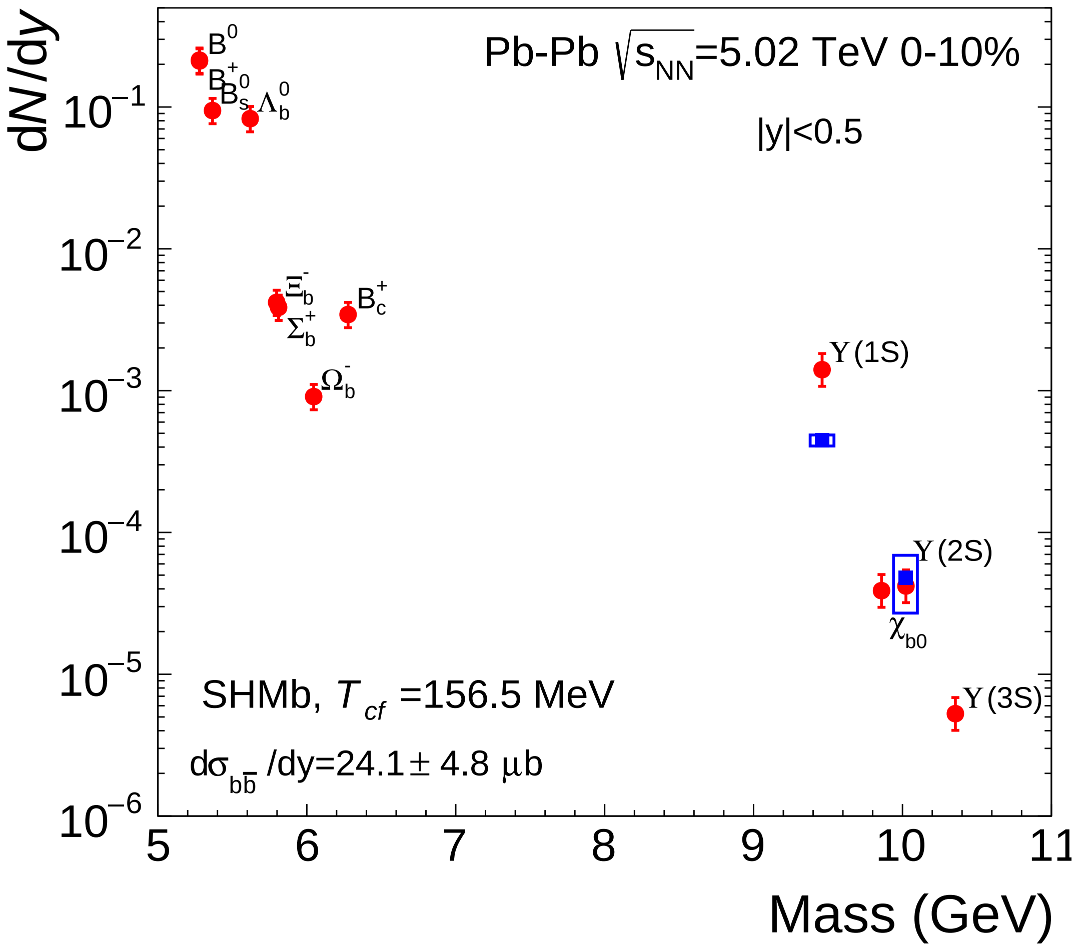
...large, but may not be complete (LQCD)

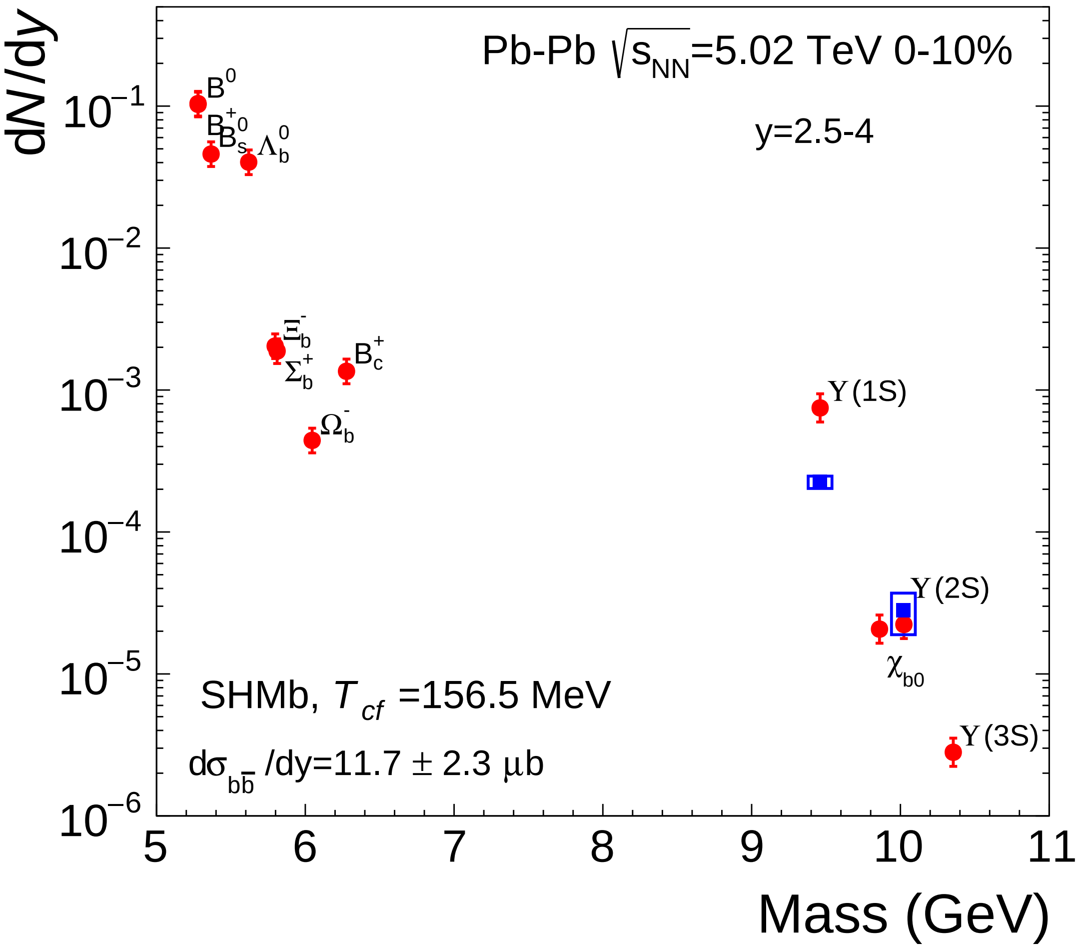
Open charm data vs. models at the LHC



ALICE, arXiv:2212.04384

The limiting case: full beauty thermalization





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

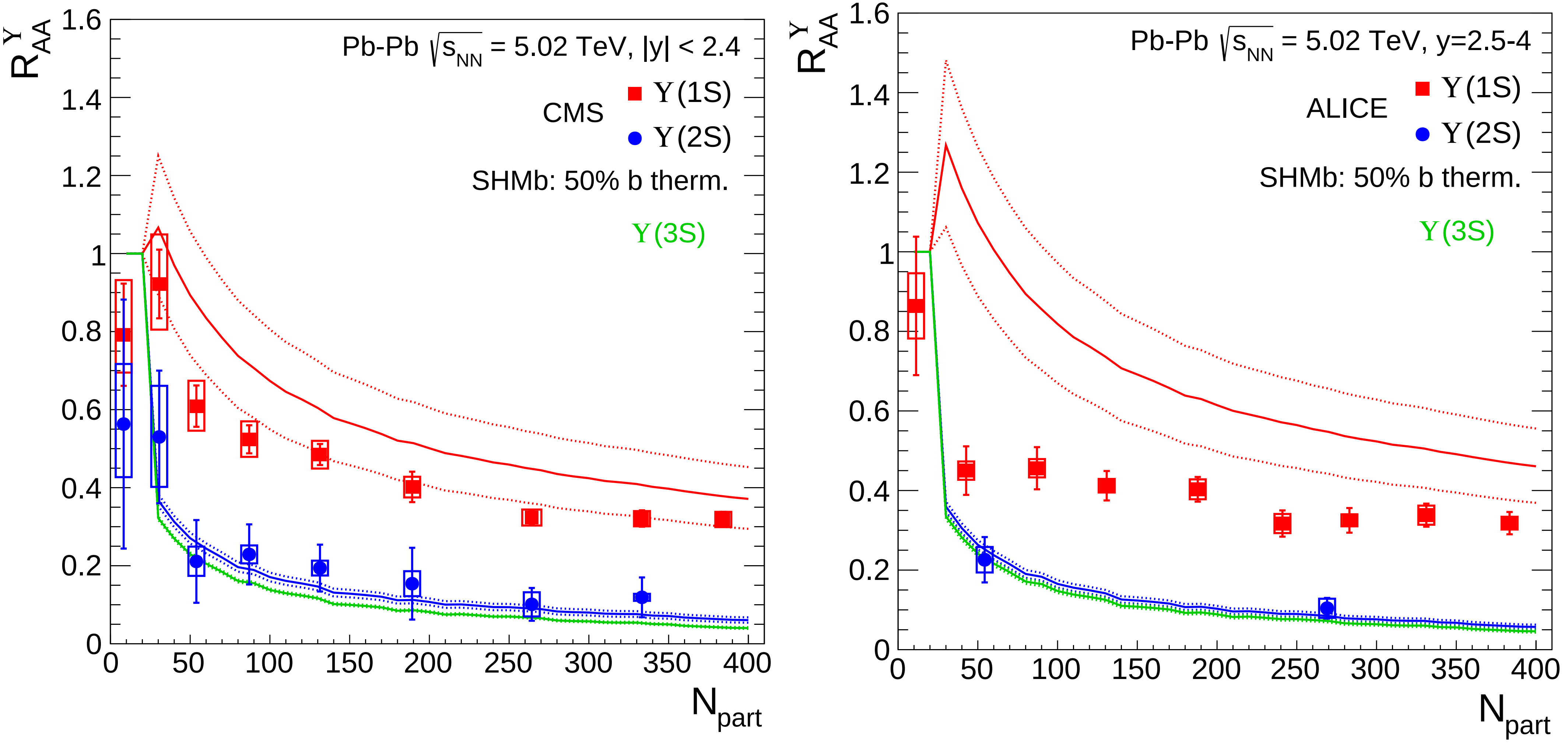
$$B_c : \ 3.44 \cdot 10^{-3}$$

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

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

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

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



CMS, PRL 120 (2018) 142301

ALICE, PLB 822 (2021) 136579

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