SQM2022

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Lecture 3

Particle production and the statistical hadronization model

A. Andronic - University of Münster

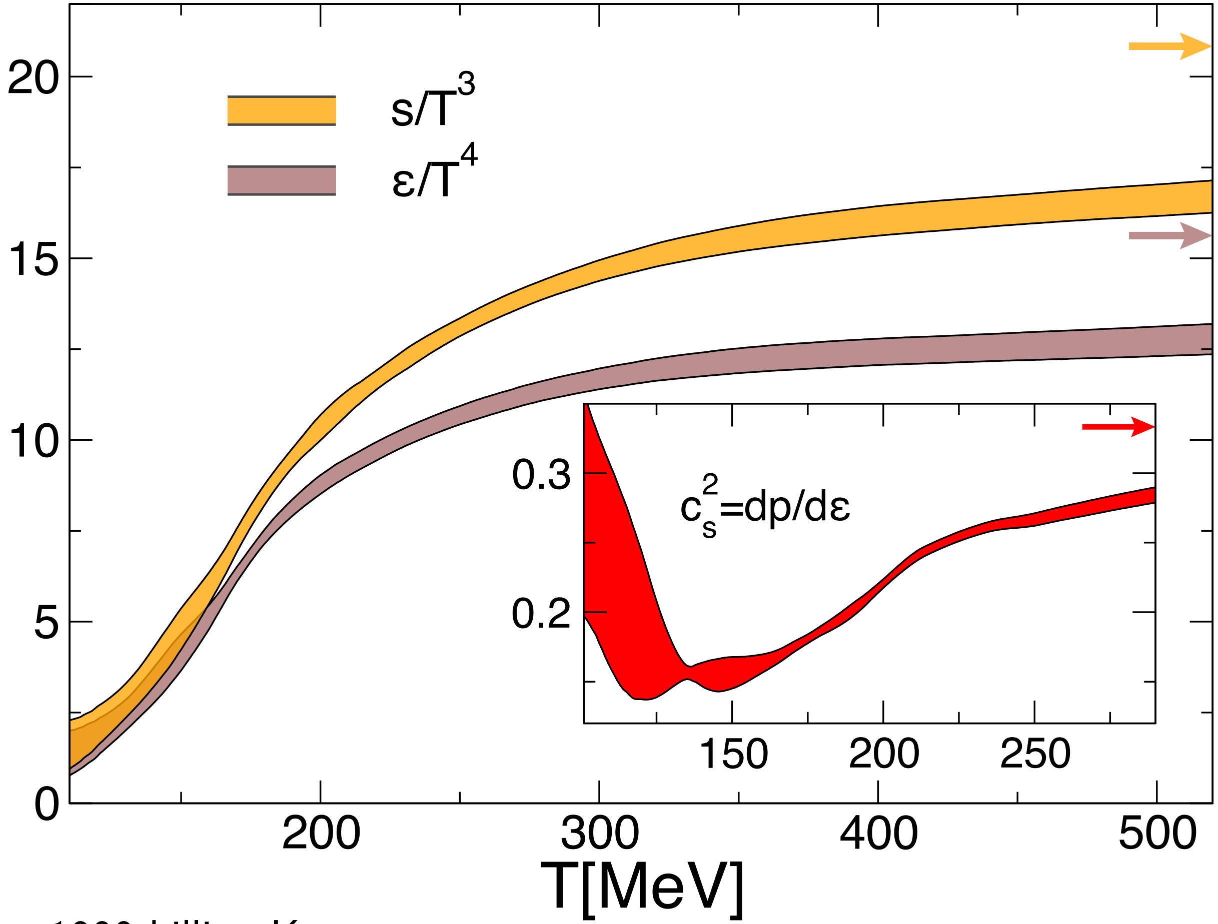
WWU MÜNSTER

Outline

- The context
- Measurement of hadron yields (central collisions)
- The statistical (thermal) model and the thermal fits
- Thermal fits and the QCD phase diagram
- "Small systems" (pp, p-Pb collisions)
- The heavy quarks (=charm)

Further (compact) reading: A.Andronic et al., Nature 561 (2018) 321 (and ref.therein)

Lattice QCD predicts a phase transition (μ_B=0)



(ideal gas)

quarks and gluons

$\varepsilon_{qg}/T^4 = (16 + \frac{7}{8}12N_f)\frac{\pi^2}{30}$

N_f=3 (u,d,s)

hadrons (pions)

$\varepsilon_{had}/T^4 = 3\frac{\pi^2}{30}$

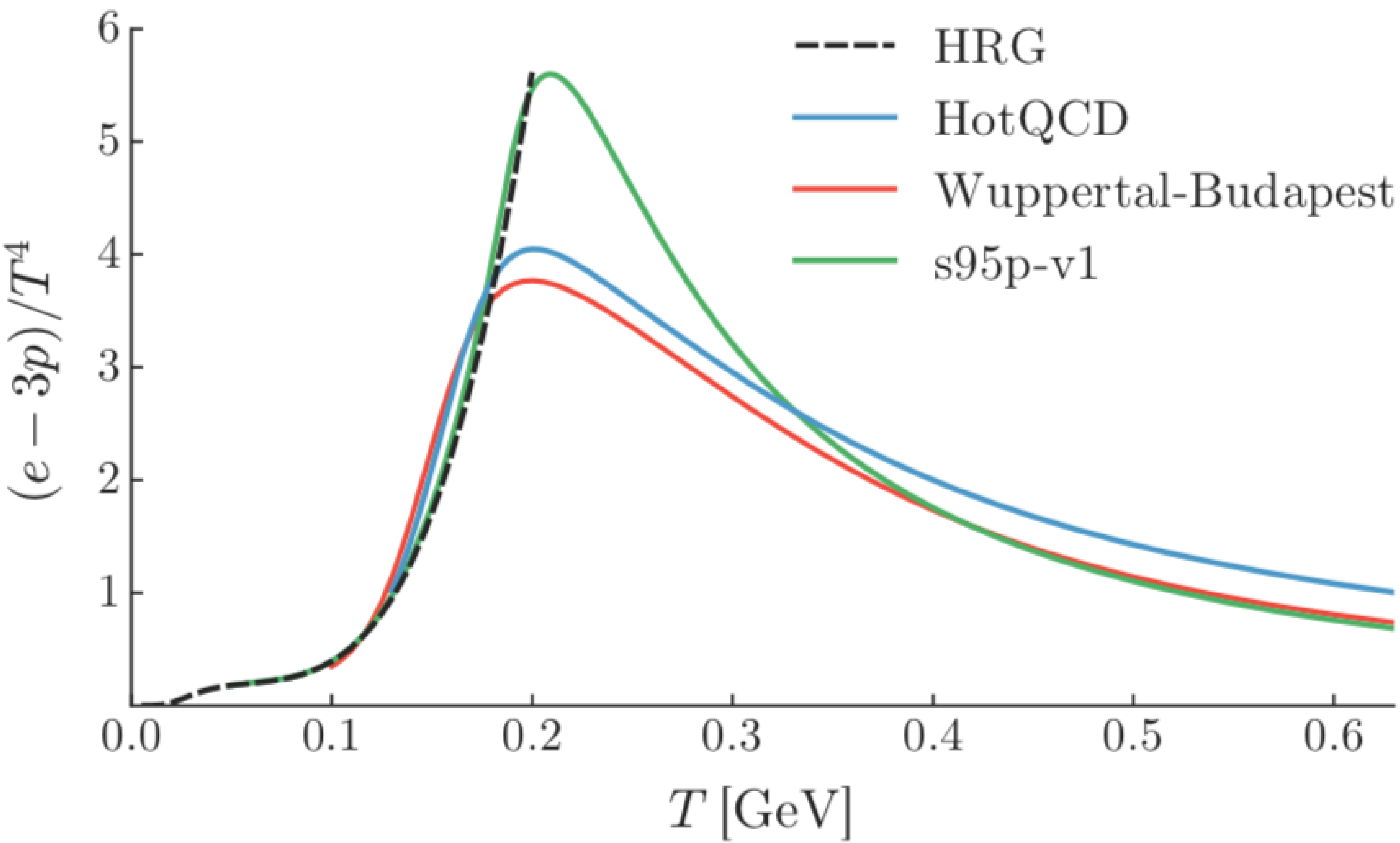
$\simeq$1000 billion K

Borsanyi et al., PLB 370 (2014) 99 , A. Bazavov et al., PLB 795 (2019) 15

T_c=156.5$\pm$1.5 MeV, $\varepsilon_c \simeq$0.4 GeV/fm^3, or 2.5$\varepsilon_{nuclear}$ *crossover*

ideal-gas limit not reached at very large temperatures (GeV range explored)

Lattice QCD: EoS

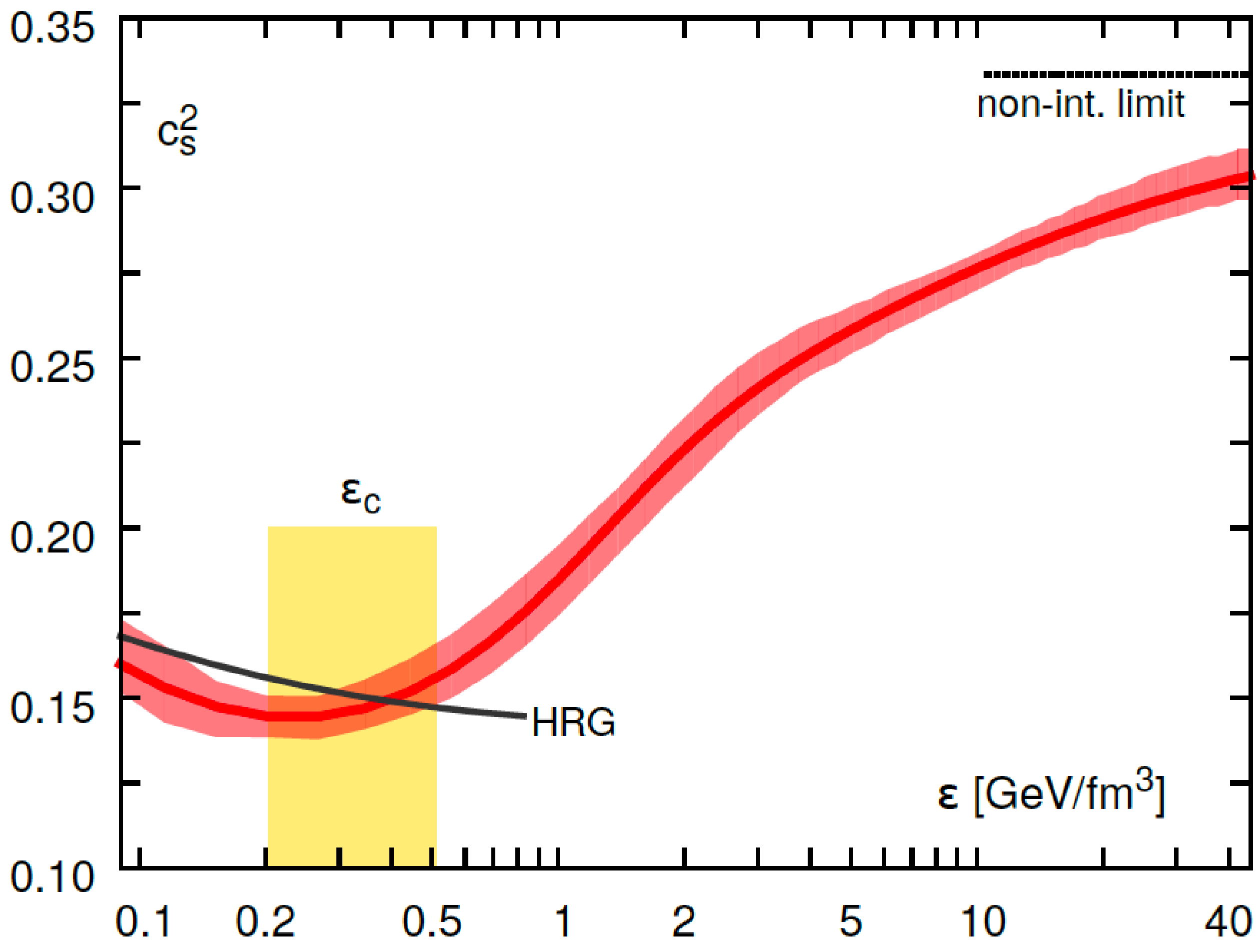


Moreland, Soltz, PRC 93 (2016) 044913

parametrization *s95p-v1* (used for some time) needs to be abandoned Lattice QCD quite precise

$(\varepsilon - 3P)/T^4$ the trace anomaly ...or *interaction measure*

Lattice QCD: EoS

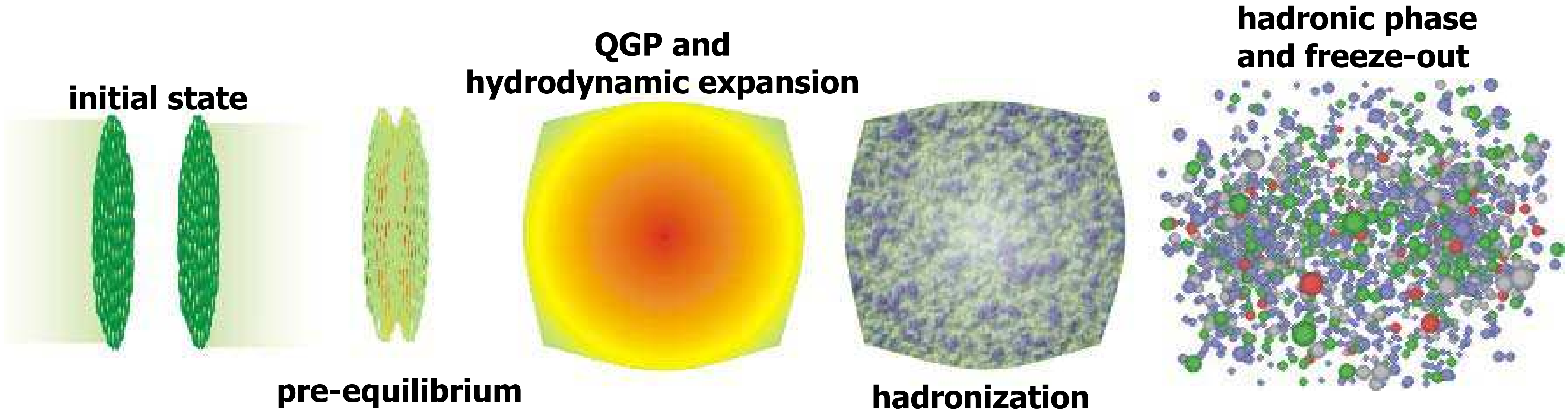


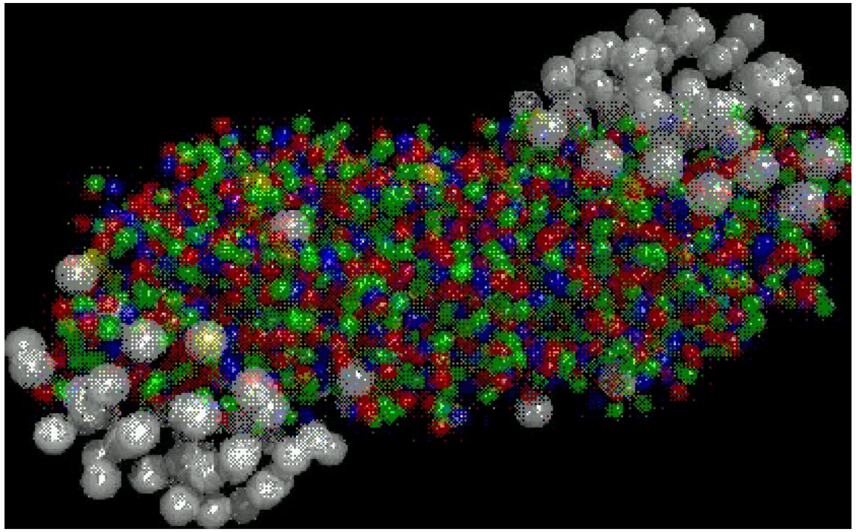
Ding, Karsch, Mukherjee, arXiv:1504.05274

$$c_s^2 = \frac{\mathrm{d}P}{\mathrm{d}\varepsilon} = \frac{\mathrm{d}P}{\mathrm{d}T} \Big/ \frac{\mathrm{d}\varepsilon}{\mathrm{d}T} = \frac{s}{C_V}, \qquad C_V \text{ specific heat}$$

HRG = Hadron Resonance Gas (this lecture)

From theory to experiment: QGP in the lab





SMASH animation

Stages of a high-energy nucleus-nucleus collision

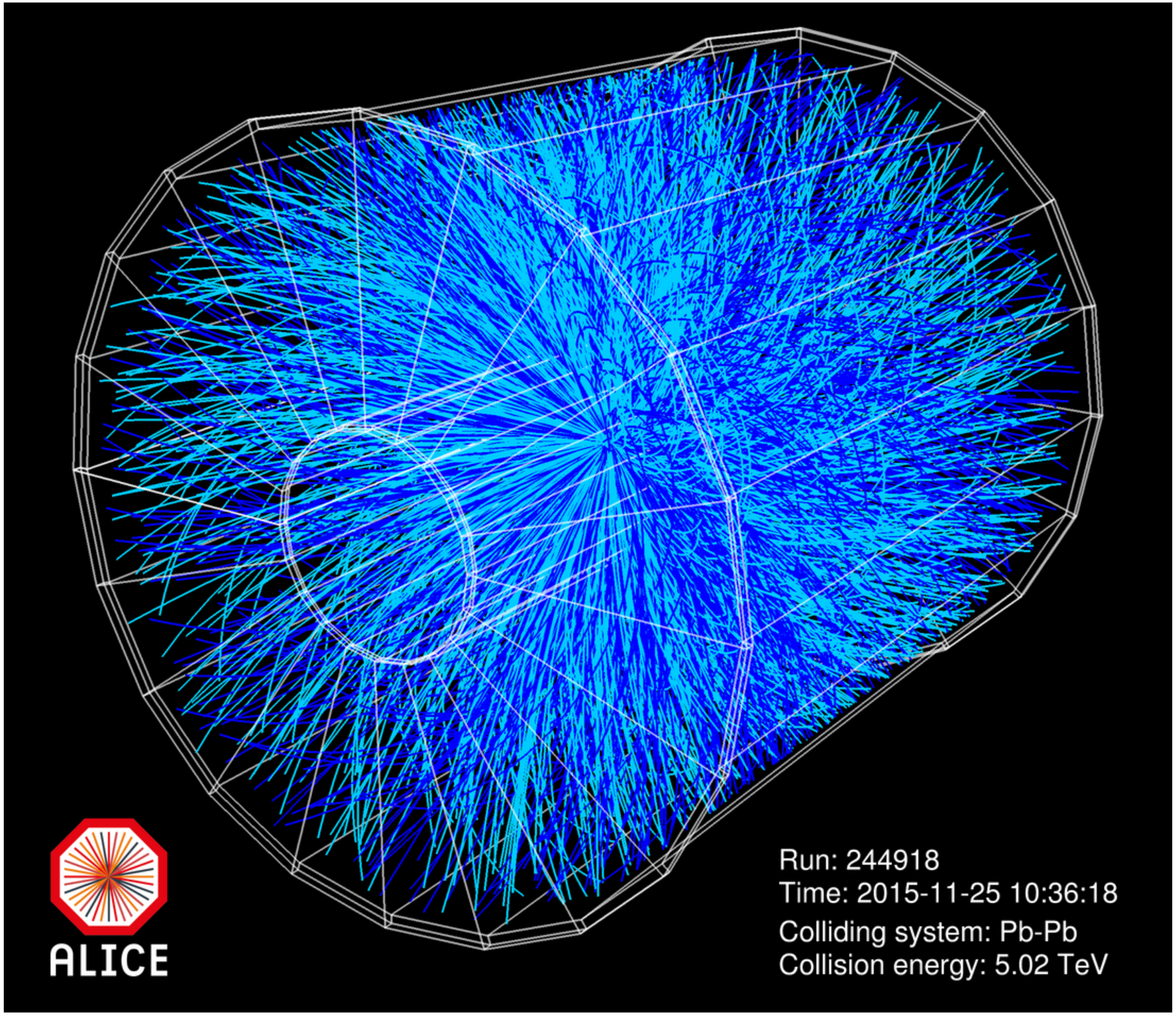
1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$)
2. thermalization: equilibrium is established ($t_{eq} \lesssim 1$ fm/c)
3. expansion and cooling ($t_{QGP} <$ 10-15 fm/c)
4. hadronization
5. chemical freeze-out: inelastic collisions cease (close to the phase boundary?); yields (and distribution over species) are frozen
6. kinetic freeze-out: elastic collisions cease; spectra and correlations are frozen ($t_{had} =$ 3-5 fm/c)

we measure 5. and 6. and want to determine properties at stages 2,3,4

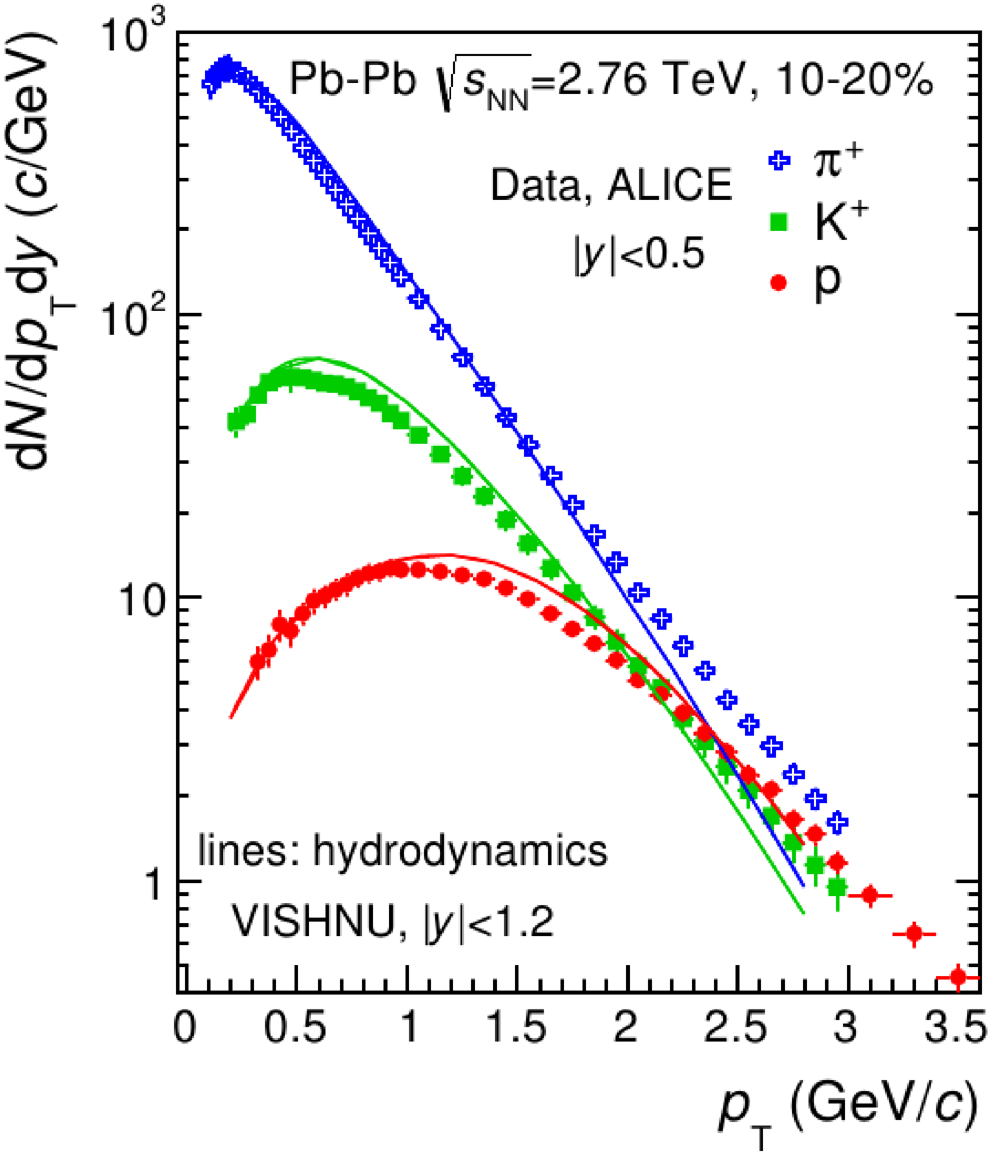
...only possible via models ("run the movie backwards")

We now try to characterize 5. via an analysis of hadron abundances ...
are they in equilibrium? connection to hadronization?

Nucleus-nucleus collisions at the LHC



a picture of a central collision (about 3200 primary tracks in $|\eta| < 0.9$); "Camera": Time Projection Chamber, 5 m length, 5 m diam.; 500 mil. pixels; we take a few 100 pictures per second (and are preparing to take 50000)



measuring spectra we observe strong collective flow ($\beta \simeq 0.6$), leading to marked mass dependence:

$$p = m\beta\gamma$$

NB: the decays (feed-down) complication

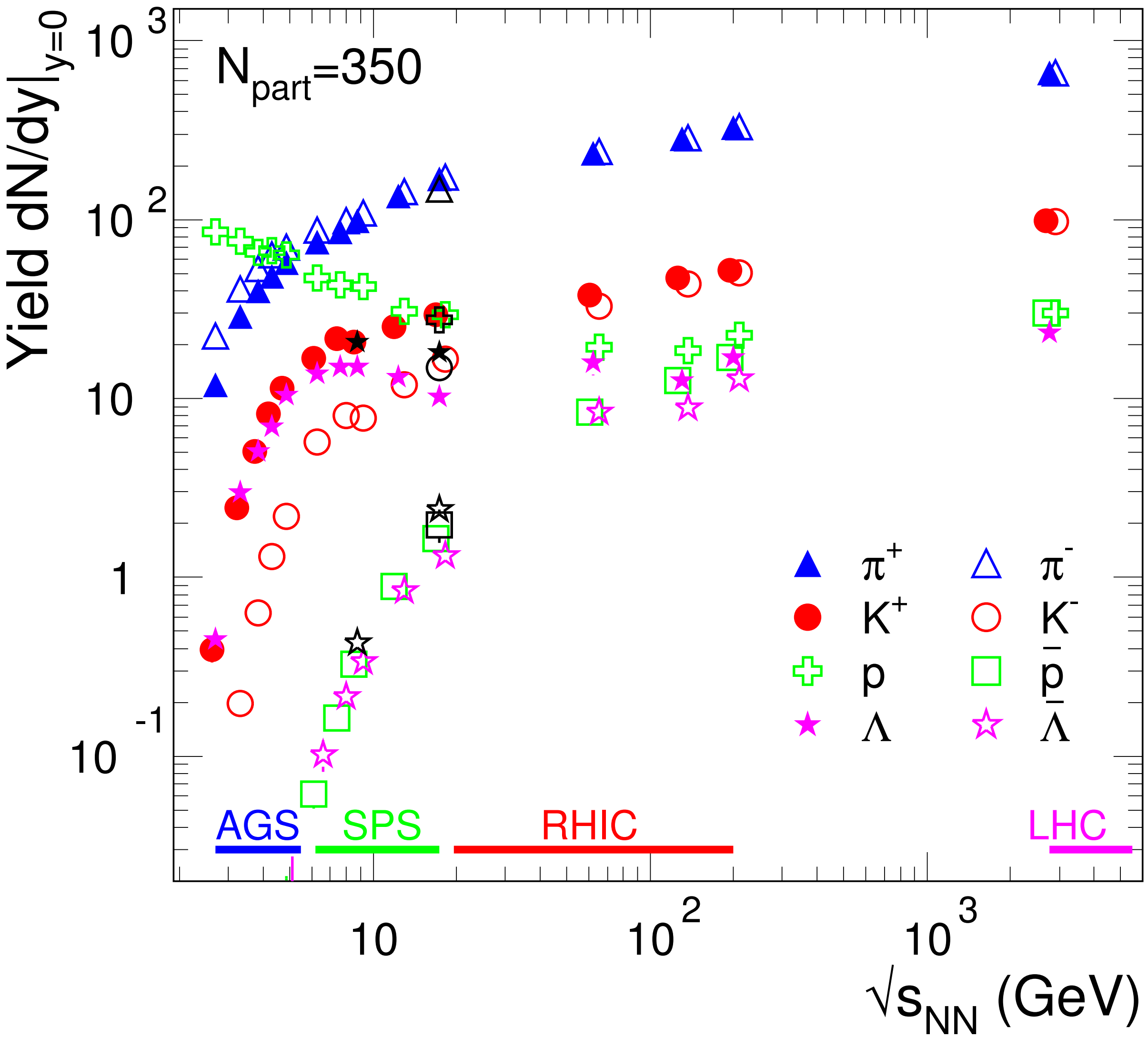
hydrodynamic models reproduce the data

$T_0 \simeq$500 MeV, expansion ($\Delta t \sim$10 fm$/c$)

from now on we will integrate on p_T

AA, IJMPA 29 (2014) 1430047

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 ($\mathrm{e}^{-m/T}$)

also known as: statistical / hadron resonance gas / statistical hadronization model (HRG / SHM)

...is in a way the simplest model

(*"All models are wrong, but some are useful"*, George Box)

The analysis of hadron yields within the thermal model provides a “snapshot” of a nucleus-nucleus collision at chemical freeze-out
(the earliest in the collision timeline we can look with hadronic observables)

Test hypothesis of hadron abundancies in equilibrium

...but the devil is in the details ...one needs:

- a complete hadron spectrum (all species of hadrons, see Particle Data Book)
- canonical approach at low energies (and smaller systems)
- to understand the data well (control fractions from weak decays)

microcanonical: describes an isolated system (E, V, T)

canonical and *grand canonical*: suppose a heat reservoir (temperature T)
the system (our collection of hadrons) exchange energy with that

canonical: no particles are exchanged (N, V, T)

grand canonical: the system exchanges particles ($\langle N \rangle$, V, T)
chemical potentials, or fugacities, are introduced to ensure conservation, on average, of particle numbers

here use *grand canonical*
(supplemented when needed with correction for canonical)

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: $V_{cons} \sum_i n_i I_{3i} = I_3^{tot}$, with $V_{cons} = N_B^{tot} / \sum_i n_i B_i$

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: $\sum_i n_i C_i = 0$.

Brief summary of cases

General ($\epsilon = +1$ for bosons, $\epsilon = -1$ for fermions; particle index i omitted):

$$N = -T\frac{\partial \ln Z}{\partial \mu} = \frac{gV}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E-\mu)/T] \pm 1}$$

$$N = \frac{g}{2\pi^2} T V m^2 \epsilon \sum_{k=1}^{\infty} \frac{\epsilon^k}{k} \mathrm{e}^{\frac{\mu}{T}k} K_2\left(\frac{m}{T}k\right)$$

Classical statistics:

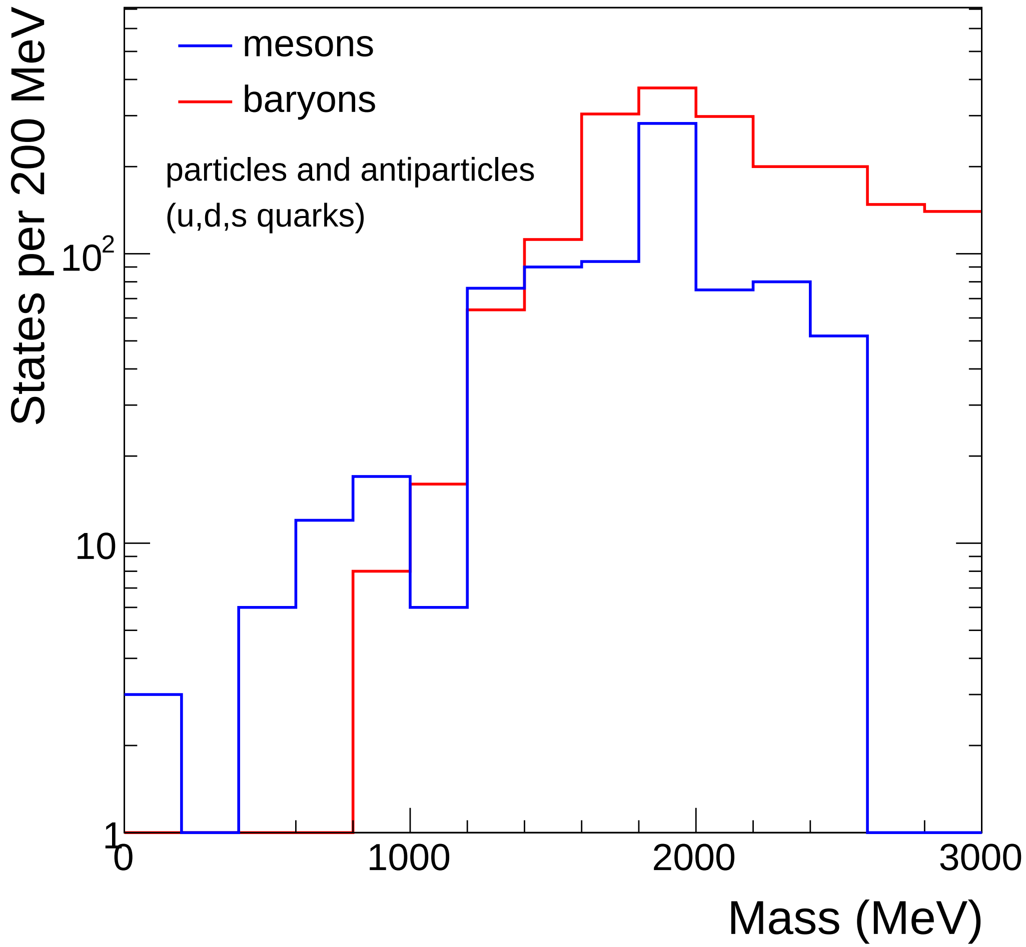
$$N = \frac{g}{2\pi^2} T V m^2 \mathrm{e}^{\frac{\mu}{T}} K_2\left(\frac{m}{T}\right) = gV\mathrm{e}^{\frac{\mu}{T}} \left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{e}^{-\frac{m}{T}} \left(1 + \frac{15T}{8m} + O(T^2/m^2)\right)$$

$$K_2(x) = \sqrt{\frac{\pi}{2x}}\mathrm{e}^{-x}\left(1 + \frac{15}{8x} + O(1/x^2)\right)$$

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

σ $[f_0(500)]$ meson proposed recently to be discarded (reduction of π densities by 3-4%)

Giacosa, Begun, Broniowski, arXiv:1603.07687

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

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

$(2J + 1)$ counted in

exponential form of mass spectrum (for large m): $\rho(m) = c \cdot m^{-a} \exp(m/T_H)$
in the statistical bootstrap model: Hagedorn, Lect.Notes Phys 221 (1985) 53)

"fireballs (hadrons) consist of fireballs, which consist of fireballs, which..."

consider Boltzmann statistics, non-relativistic approximation

$$\ln Z_i(T,V) = \frac{V}{(2\pi)^3}\int e^{-\sqrt{p^2+m^2}/T}\mathrm{d}^3p \simeq V\left(\frac{T}{2\pi}\right)^{2/3} m_i^{2/3} e^{-m_i/T}$$

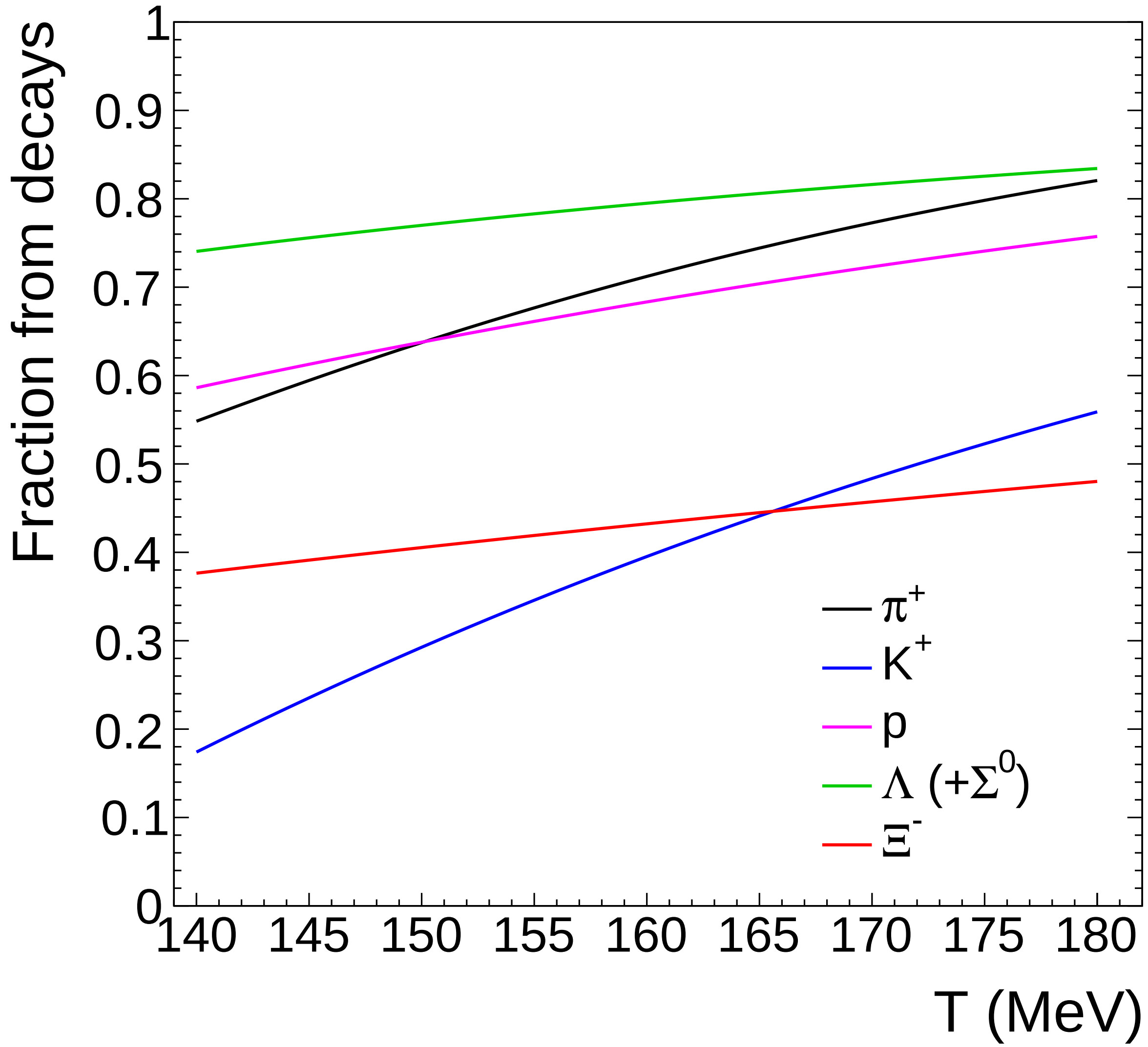
$\ln Z = \sum_i \ln Z_i = V\left(\frac{T}{2\pi}\right)^{2/3}\sum_i m_i^{2/3}e^{-m_i/T}$ (sum over all hadrons)

$$\ln Z = V\left(\frac{T}{2\pi}\right)^{2/3}\int_0^\infty \rho(m) m^{3/2} e^{-m/T}\mathrm{d}m$$

$$\varepsilon(T_H) = \frac{T^2}{V}\frac{\partial \ln Z}{\partial T}(T_H) \sim \frac{3T_H}{2}(m^{5/2-a})|_0^\infty + (m^{7/2-a})|_0^\infty + \mathrm{finite}$$

diverge at T_H for $a < 7/2$

T_H maximal temperature of hadronic systems; beyond: QGP (Cabibbo, Parisi) (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)

Considering widths of resonances

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

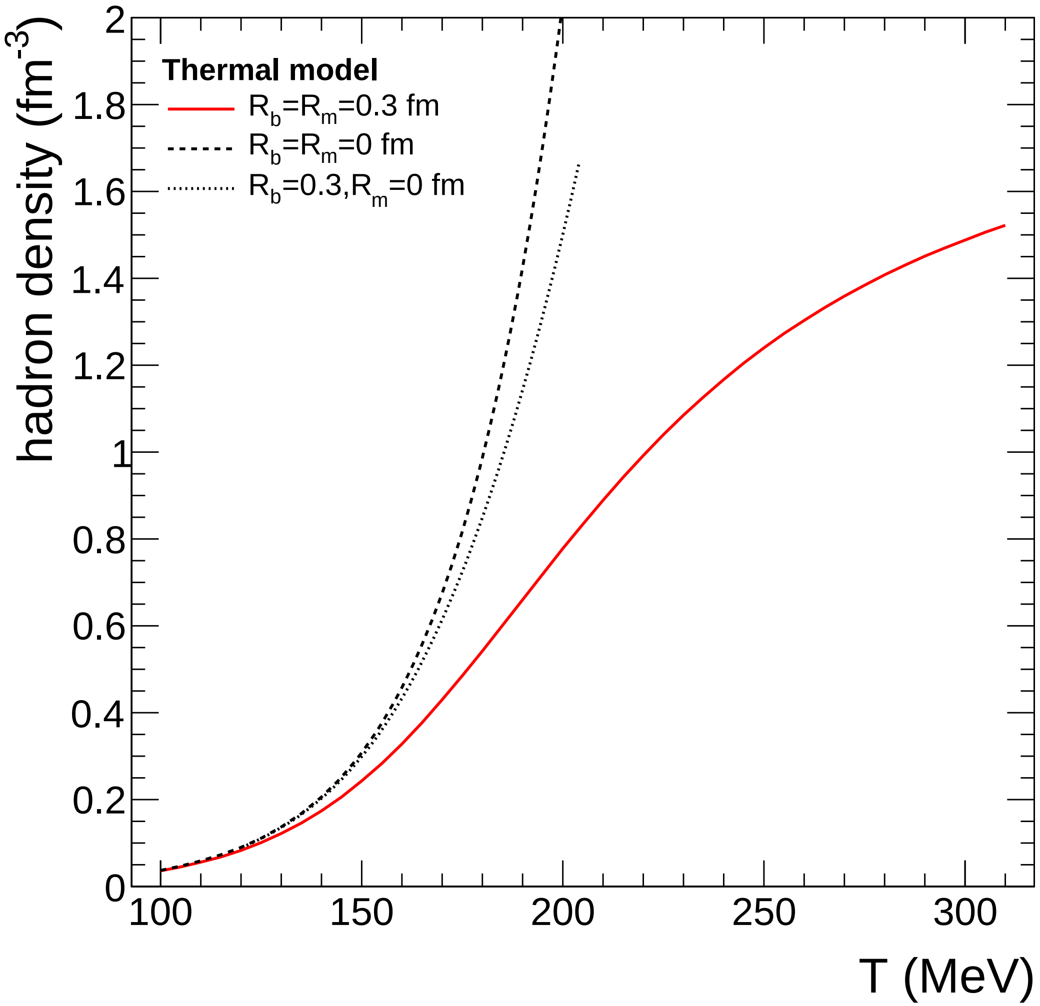
$$n_i = \frac{g_i}{2\pi^2}\frac{1}{N_{BW}}\int_{M_{thr}}^\infty \mathrm{d}m \int_0^\infty \frac{\Gamma_i^2}{(m-m_i)^2 + \Gamma_i^2/4} \cdot \frac{p^2 \mathrm{d}p}{\exp[(E_i^m - \mu_i)/T] \pm 1}$$

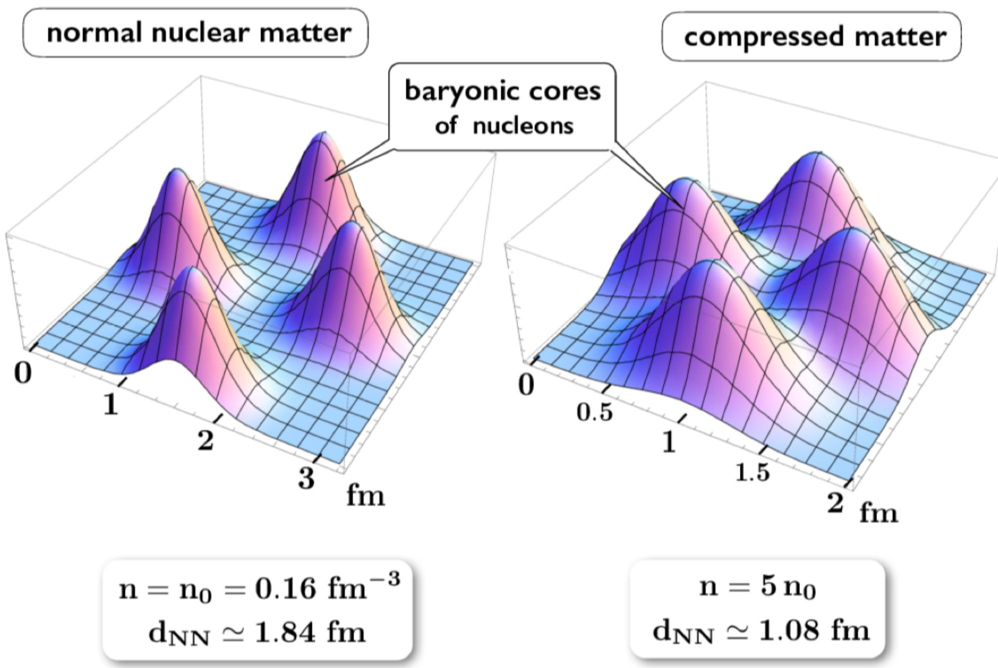
M_{thr} threshold mass for the decay channel.

Example: for $\Delta^{++} \rightarrow p + \pi^+$, M_{thr}=1.068 GeV ($m_{\Delta^{++}}$=1.232 GeV)

Important mainly at "low" temperatures ($T \lesssim$150 MeV)

Hadron densities





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 needed whenever the abundance of hadrons with a given quantum number is very small ...so that one needs to enforce exact quantum-number conservation in AA collisions; *Example: strangeness at low energies*

$$n_{i,S}^{C} = n_{i,S}^{GC} \cdot \frac{I_s(N_S)}{I_0(N_S)}$$

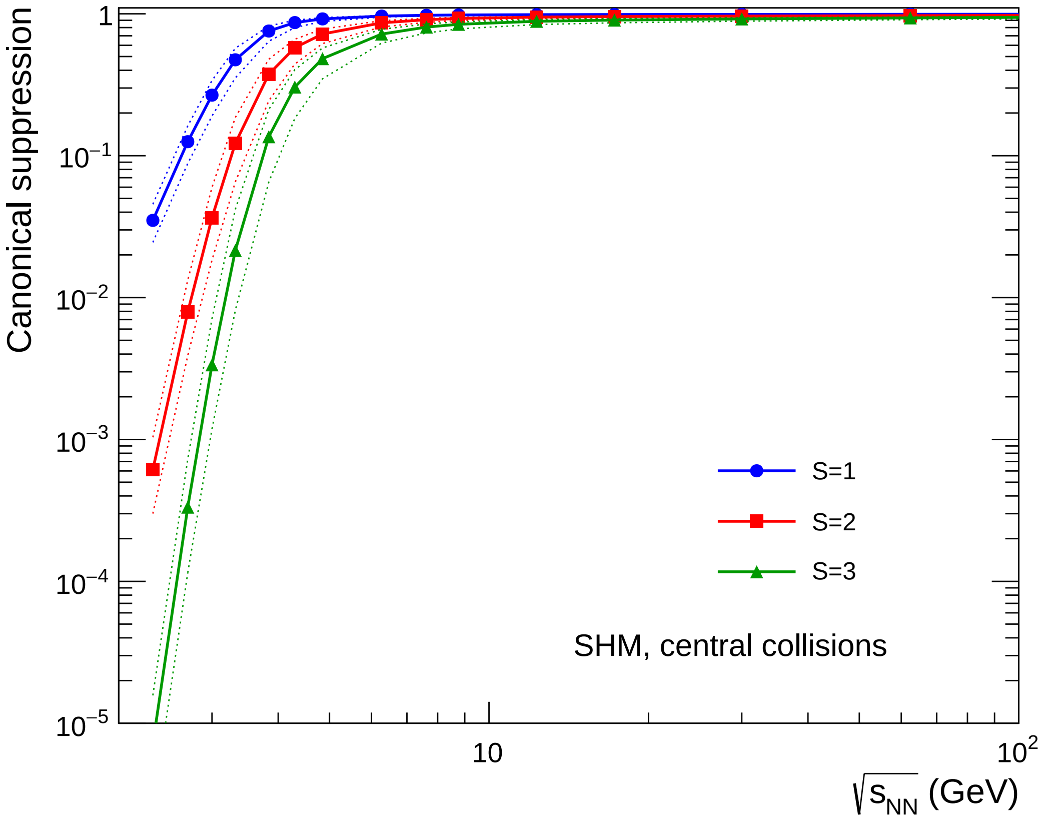
$$N_S = V_c \cdot \sum S \cdot n_{i,S},$$

total amount of strangeness-carrying hadrons (part.+antipart.)

$$n_{K,\Lambda}^{C} = n_{K,\Lambda}^{GC} \cdot \frac{I_1(N_S)}{I_0(N_S)},$$

$$n_{\phi}^{C} = n_{\phi}^{GC}$$

...negligible for $\sqrt{s_{NN}} \gtrsim 8$ GeV



relevant for small volumes (peripheral AA, pp, p–Pb collisions), $V_c \sim \mathrm{d}N_{ch}/\mathrm{d}y$

...a non-thermal fit parameter, to check possible non-thermal production of strangeness

for a hadron carrying "absolute" strangeness $s = |S - \bar{S}|$: $n_i \rightarrow n_i \gamma_s^s$

Examples: $K^{\pm}$ $(u\bar{s}, \bar{u}s)$: $n_K \gamma_s$, Λ (uds): $n_\Lambda \gamma_s$,

$\Xi(dss)$: $n_\Xi \gamma_s^2$, $\Omega(sss)$: $n_\Omega \gamma_s^3$, $\phi(s\bar{s})$: $n_\phi \gamma_s^2$

in principle, usage of γ_s is to be avoided if one tests the basic thermal model

even as some models employ it ($\Rightarrow \gamma_s = 0.6 - 0.8$), all agree that it is not needed at RHIC, LHC energies (for central collisions)

here (central AA collisions) we fix γ_s=1

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

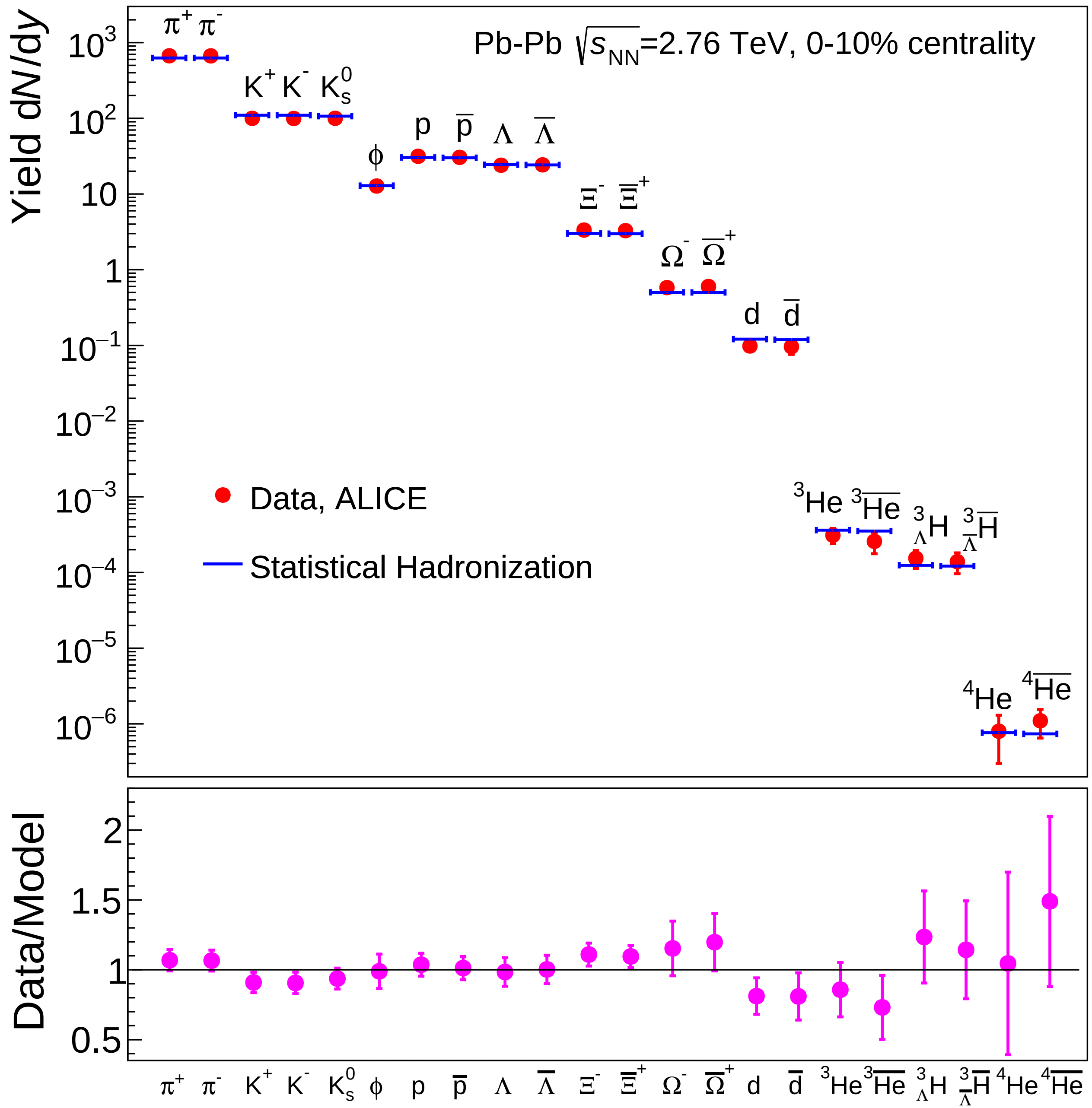
canonical treatment whenever needed (small abundances)

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%



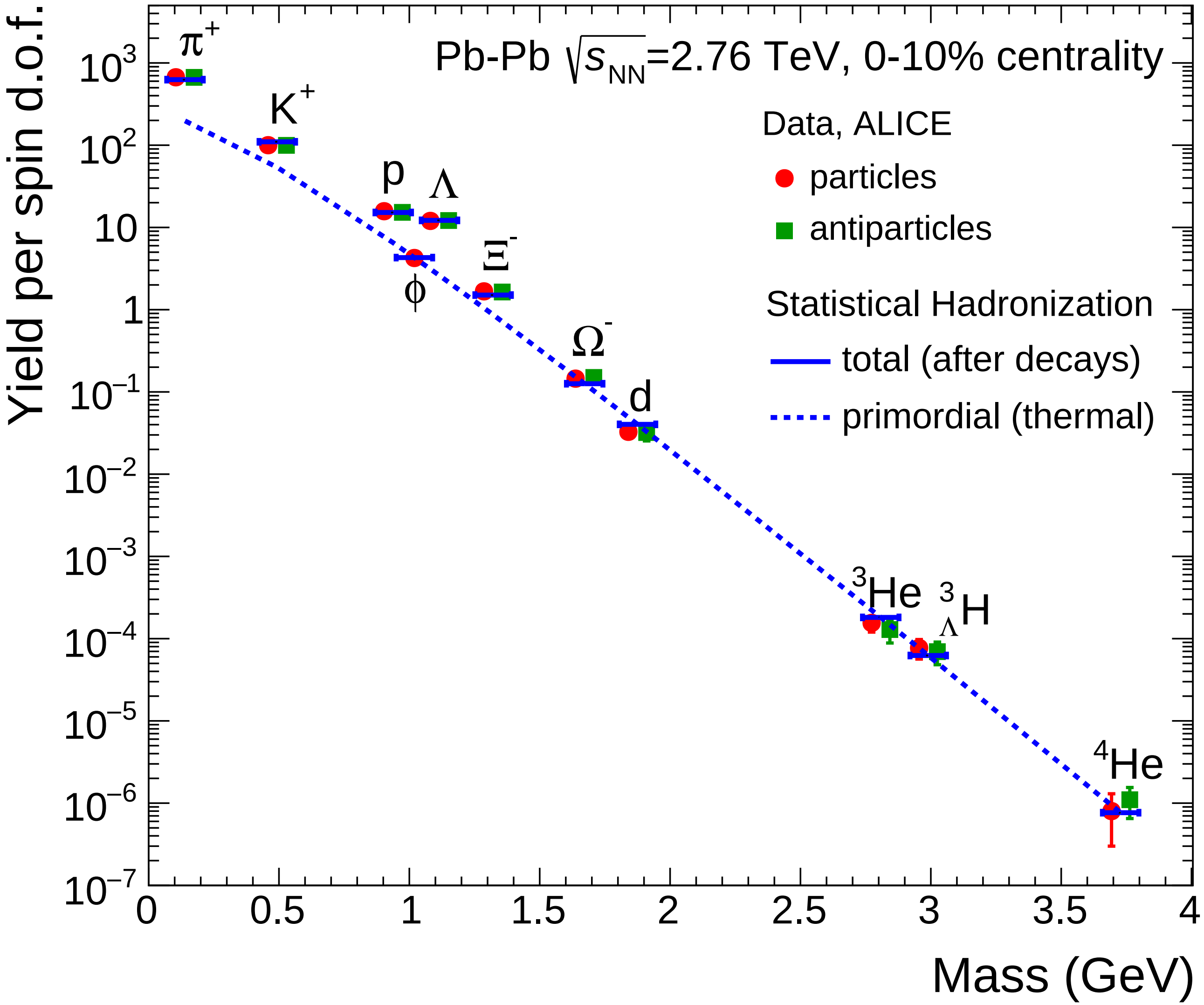
matter and antimatter produced in equal amounts

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

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

remarkably, loosely-bound objects (d, ${}^3_\Lambda H$) are also well described

Model uncertainties 1. 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

hadron eigenvolumes ...to mimick interactions (beyond low-density, Dashen-Ma)

$R_{meson} = 0.3, R_{baryon} = 0.3$ *fm is generally considered to be a reasonable case*

point-like hadrons lead to same T, but volume larger by 20-25%

an extreme case, $R_{meson} = 0, R_{baryon} = 0.3$ fm leads to

$T = 161.0 \pm 2.0$ MeV, $\mu_B = 0$ *fixed*, $V = 3470 \pm 280$ fm^3

NB: in this case, the result is rather sensitive on the set of hadrons in the fit

for instance, using hadrons up to Ω, cannot constrain T (unphysically large)

Vovchenko, Stöcker (et al.), JPG 44 (2017) 055103, arXiv:1606.06350

...and anything else can be imagined, see (R dependent on mass & strangeness)

Alba, Vovchenko, Gorenstein, Stöcker, NPA 974 (2018) 22, etc.

T-dependent Breit-Wigner resonance widths:

Vovchenko, Gorenstein, Stöcker, PRC 98 (2018) 034906

Interactions, rightly done

...for now only at the LHC

non-strange baryon sector treated in S-matrix formalism
(πN scattering phase shifts, *including non-resonant contributions*)

PLB 792 (2019) 304

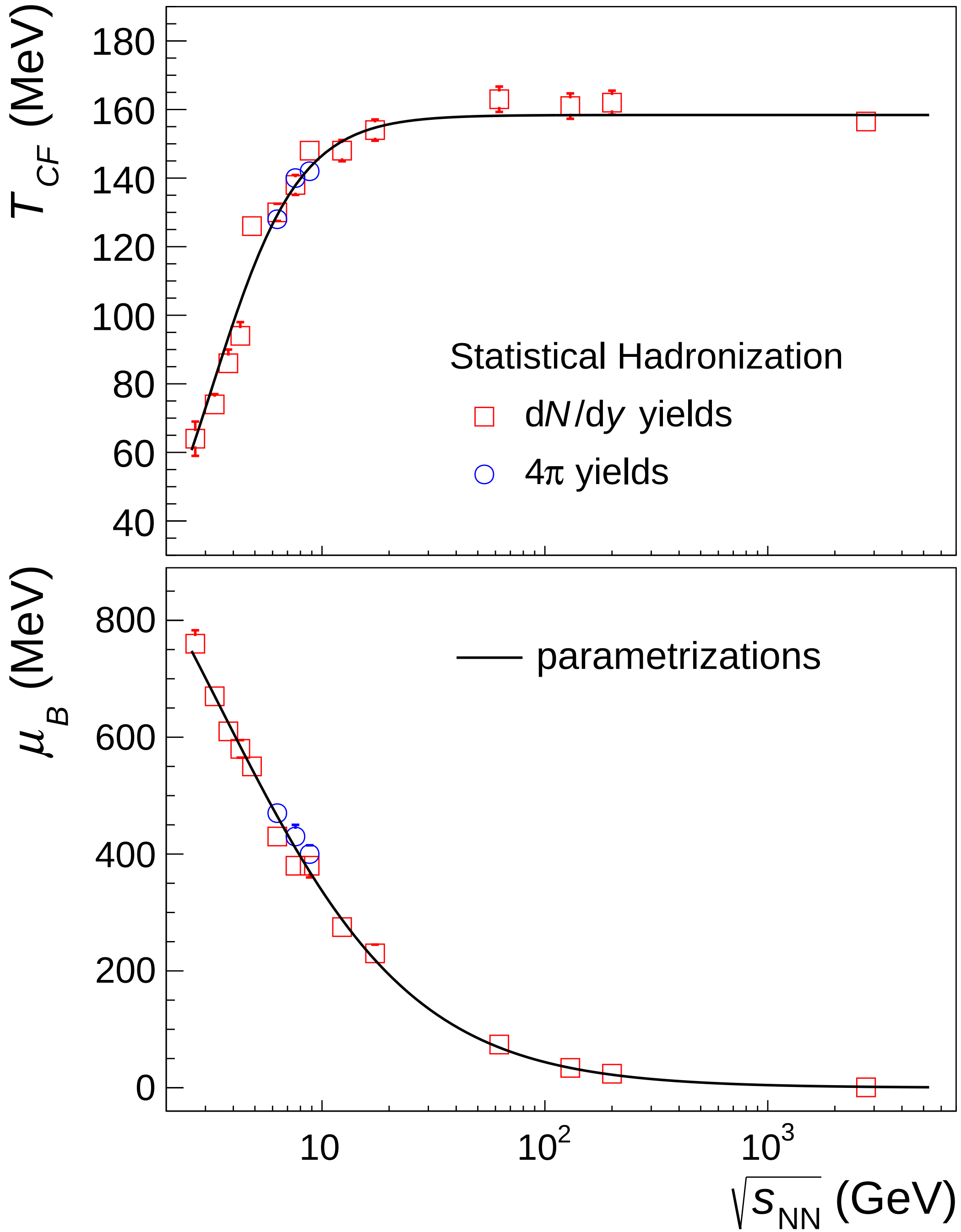
solved the so-called "proton puzzle" (too many protons in the statistical model)

for T=156 MeV, proton yield decreased by 17% compared to point-like

recently tackled: strange baryon sector, Cleymans et al., PRC 103 (2021) 014904

NB: presence of resonances implies interaction
(this is why moderate $R = 0.3$ fm is a reasonable choice)

Energy dependence of T, μ_B (central collisions)



thermal fits exhibit a limiting temperature:

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

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

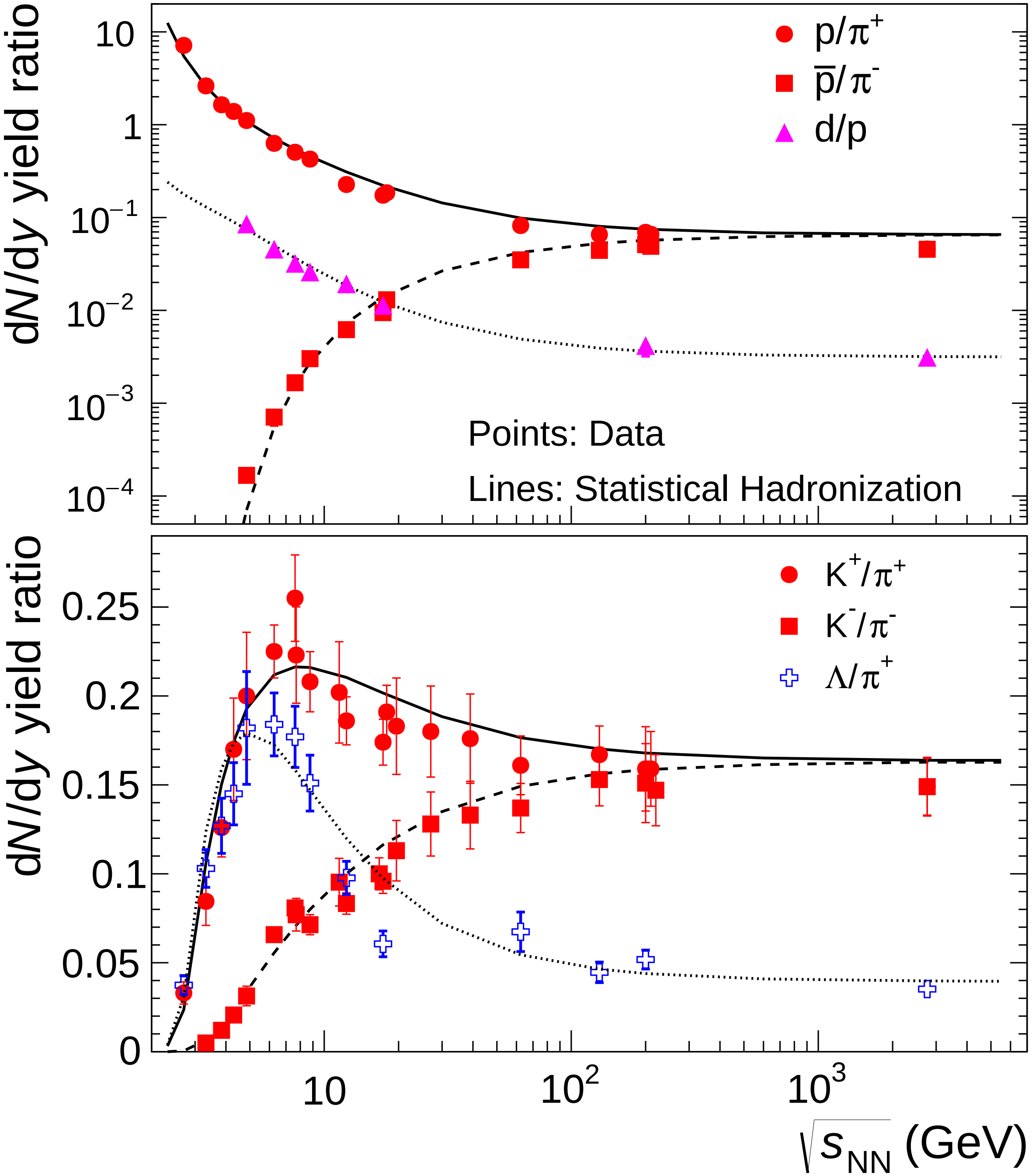
$$\mu_B[\text{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\text{GeV})}$$

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

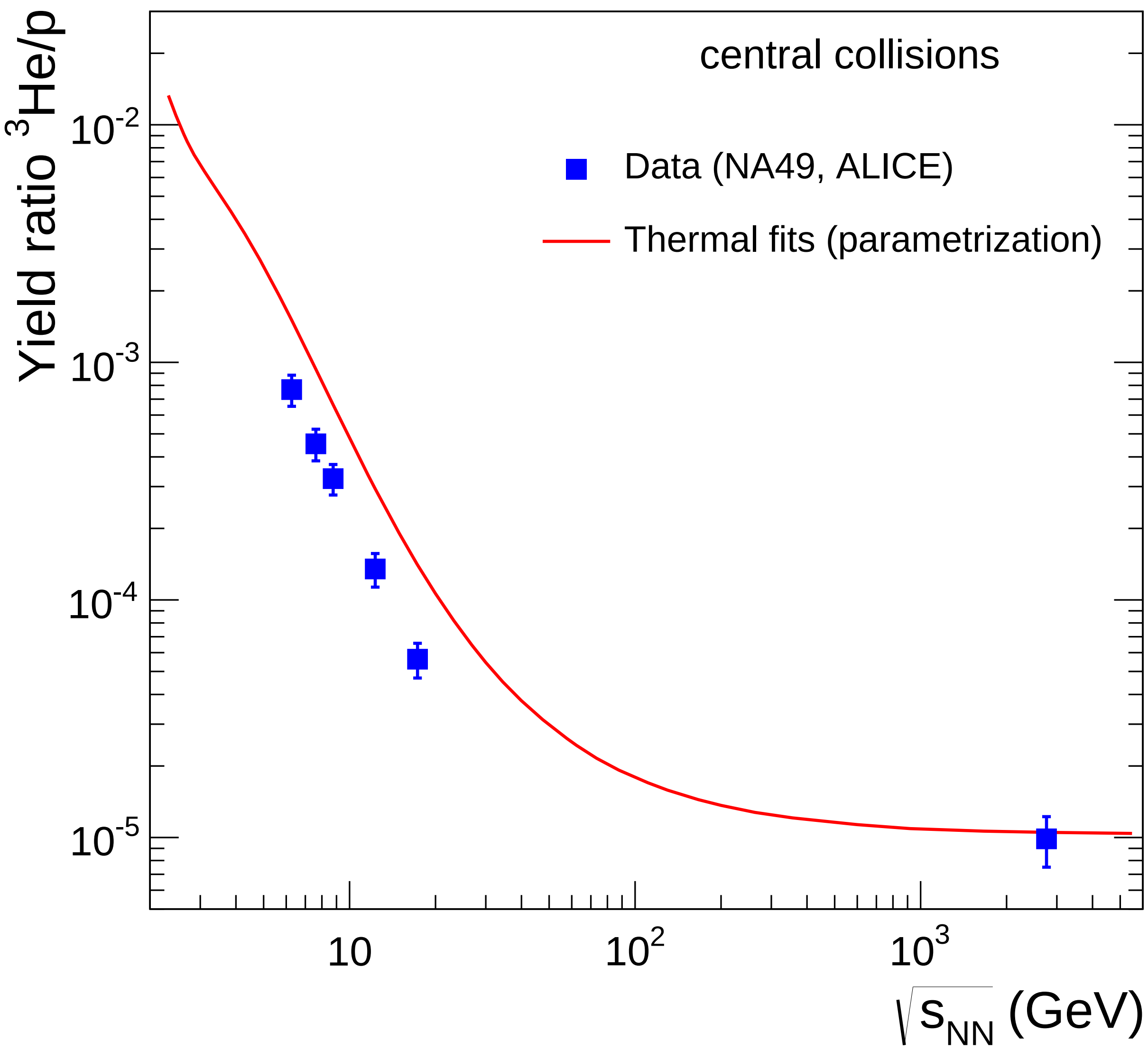
RHIC: STAR, BRAHMS

LHC: ALICE

NB: no contribution from weak decays

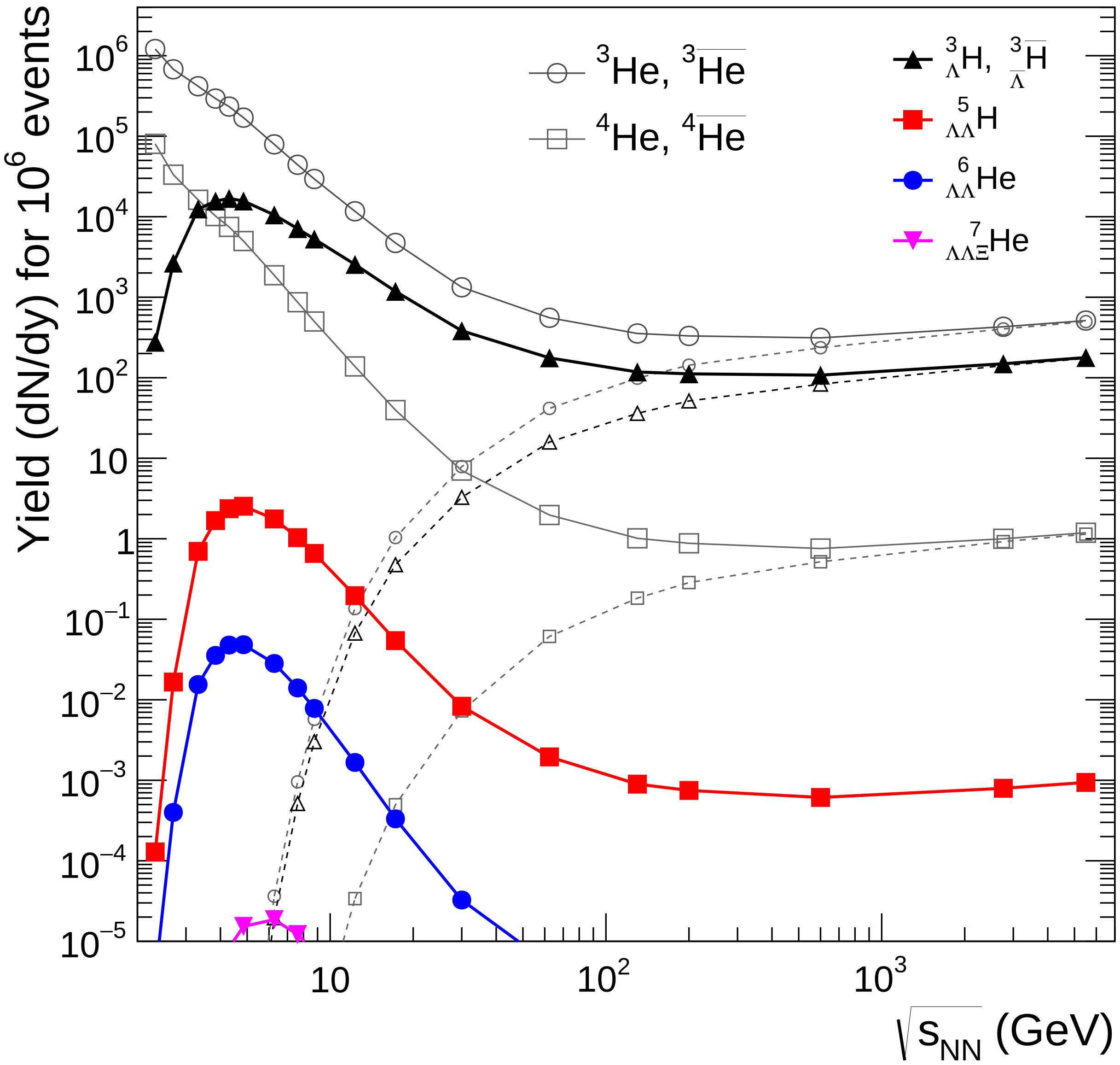
"structures" described by SHM (determined by strangeness conservation)

Something that doesn't work so well ?



(prelim.) STAR BES data confirm this discrepancy

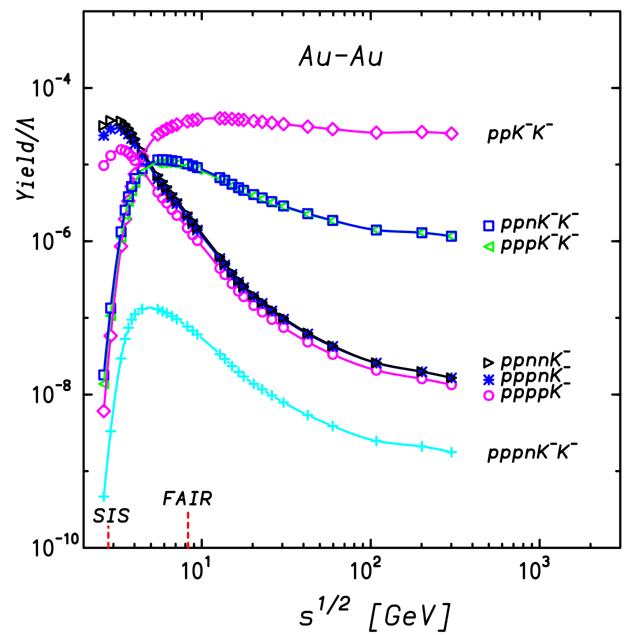
...are copiously produced at RHIC FT (and FAIR) energies



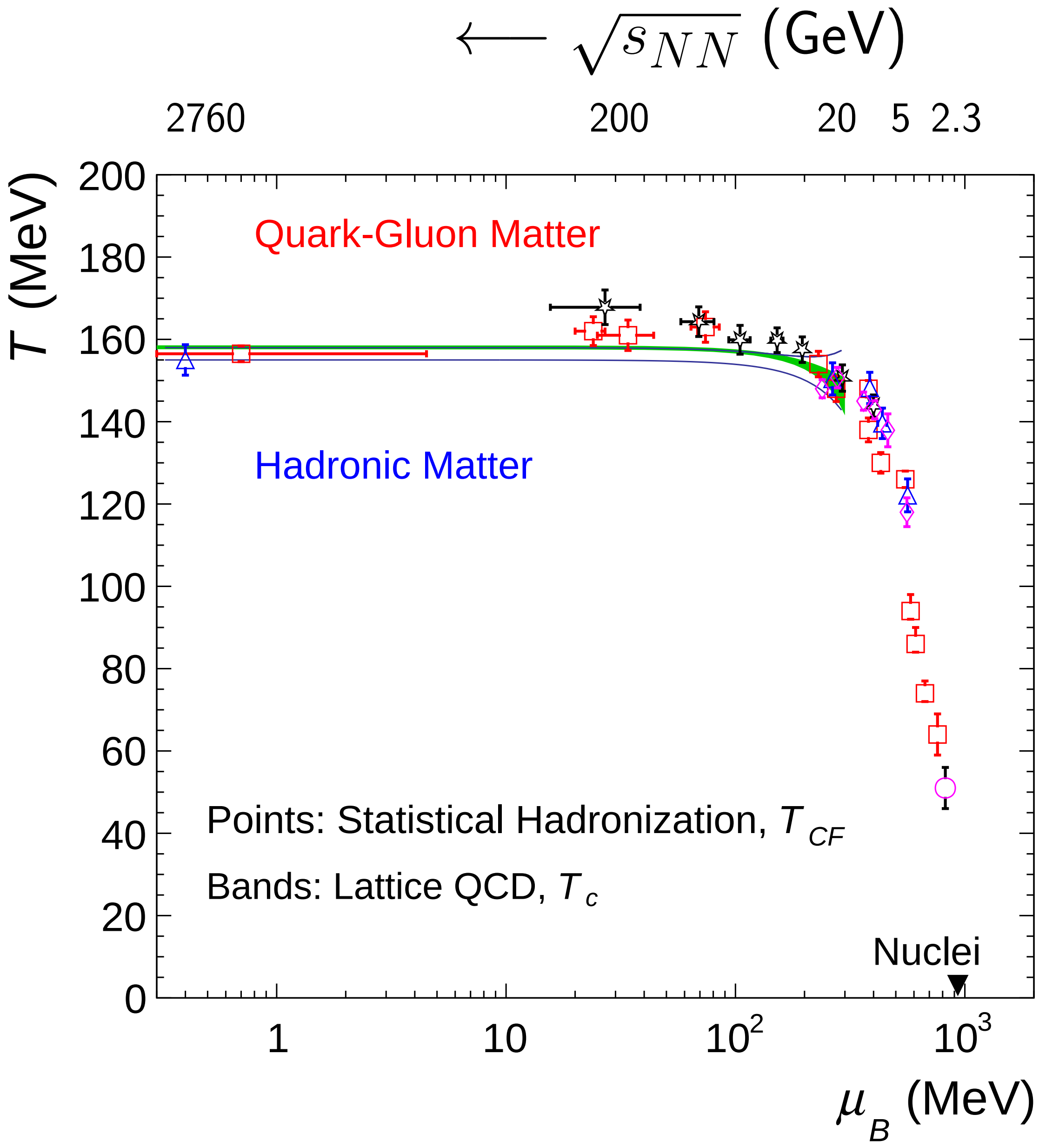
...some to be discovered

maybe also nucleon-K^- clusters?

AA, PBM, K.Redlich, NPA 765 (2006) 211



The phase diagram of QCD



LQCD: PRD 95 (2017); PRL 125 (2020)

at LHC, remarkable "coincidence" with Lattice QCD results

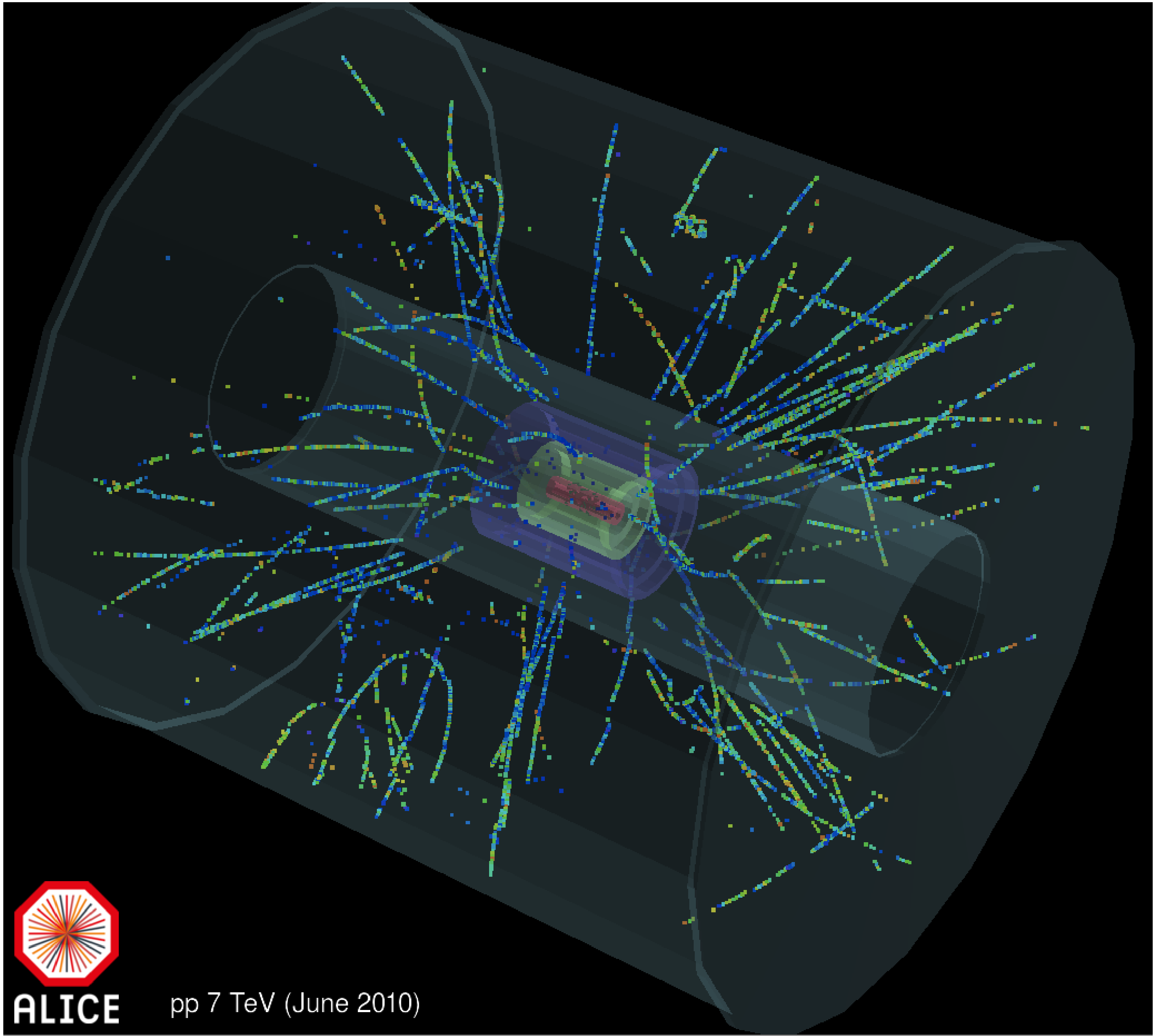
at LHC ($\mu_B \simeq 0$): purely-produced (anti)matter ($m = E/c^2$), as in the Early Universe

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

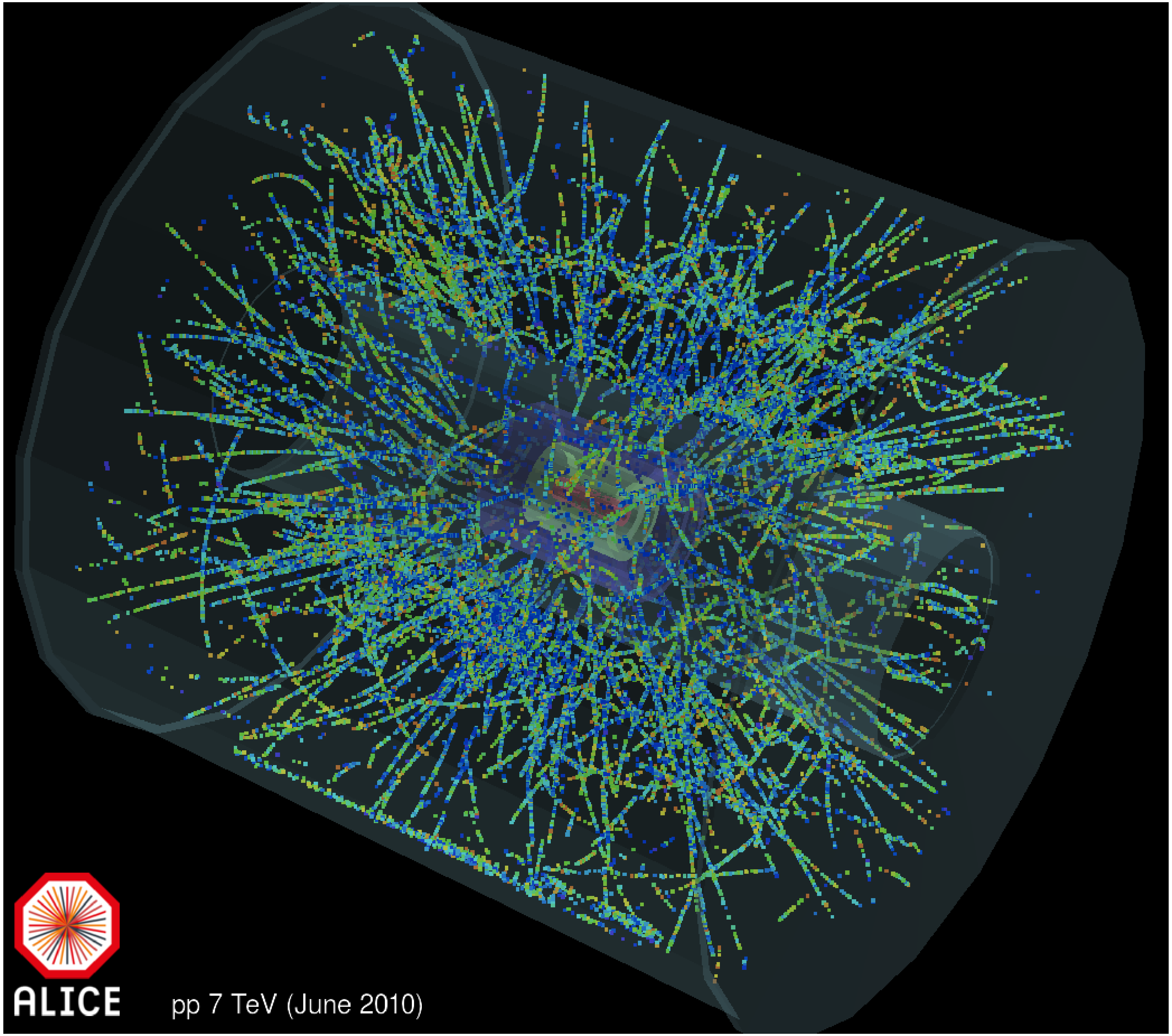
$\mu_B \gtrsim 400$ MeV: *the critical point awaiting discovery* (at FAIR?)

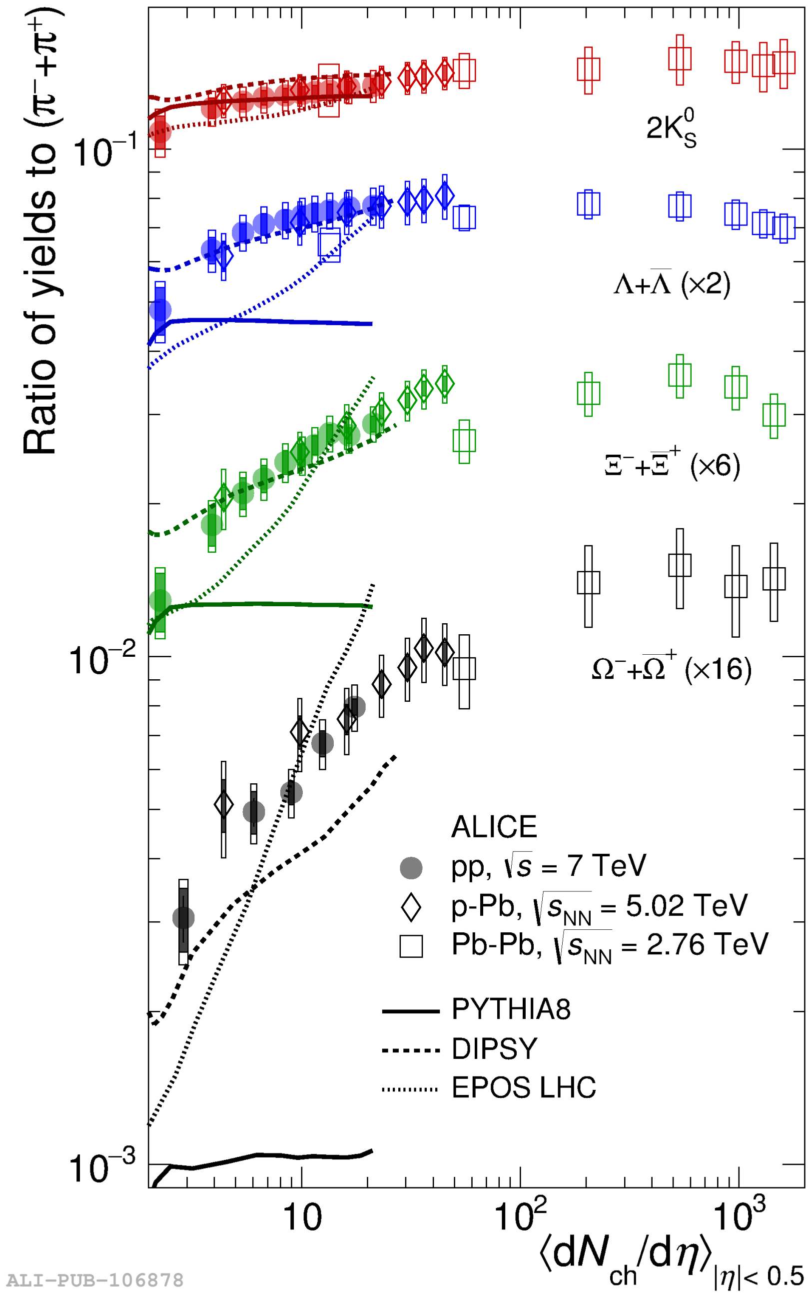
μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

The proton at low resolution ...in collisions at the LHC



The proton at high resolution ...in collisions at the LHC





ALICE, Nature Physics 13 (2017) 535

(big geometric) fireball in Pb–Pb reached with violent pp and p–Pb collisions

canonical to grand-canonical strangeness production regime

Vislavicius, Kalweit, arXiv:1610.03001

is the same mechanism at work in small systems (at large multiplicities)?

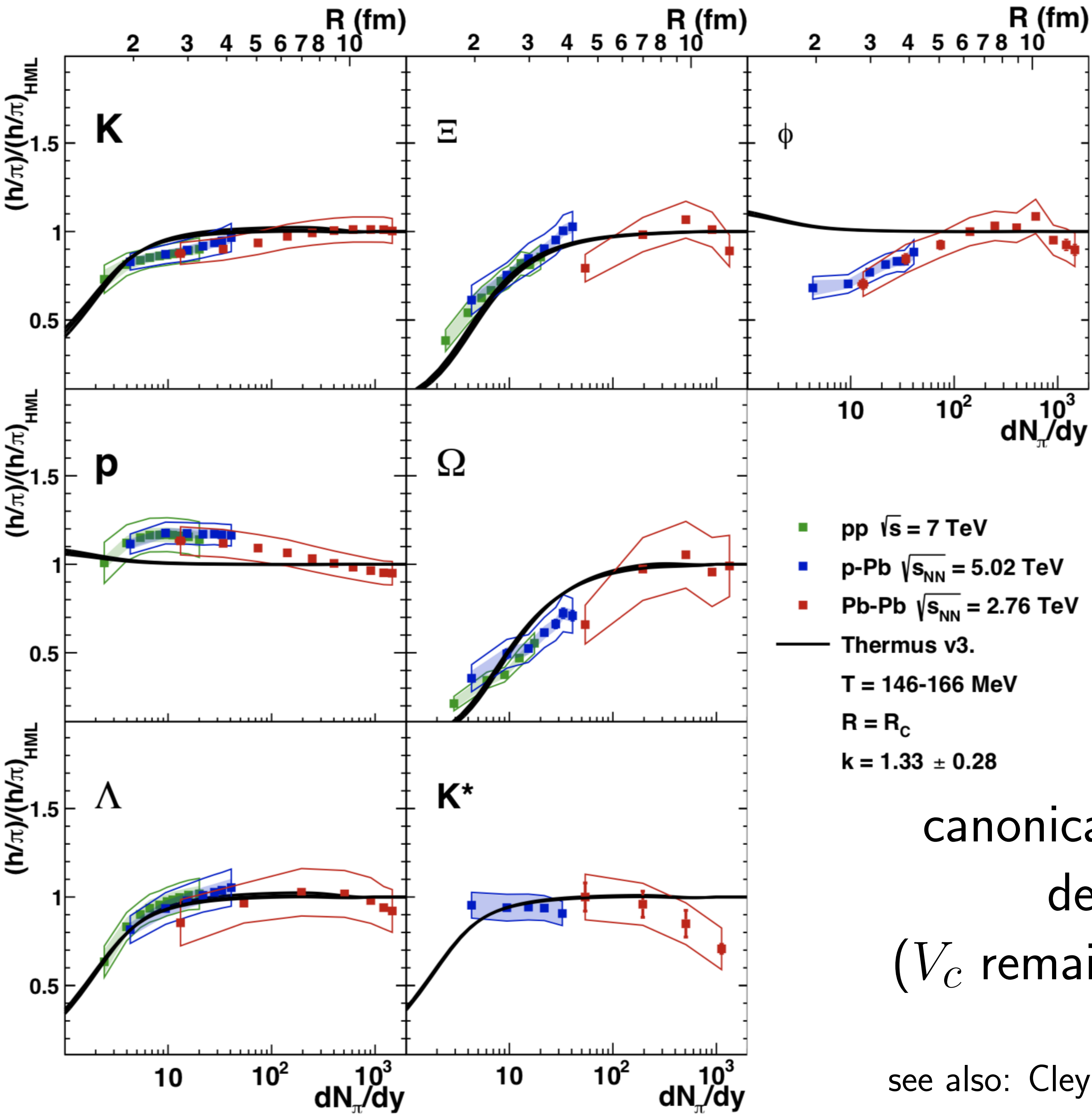
string hadronization models do not describe data well

...new ideas are being put forward

C.Bierlich et al, arXiv:2205.11170

(rope hadronization; no QGP)

Particle production - from small to large systems



Vislavicius, Kalweit,

arXiv:1610.03001

ratios to high multiplicity limit (HML)

canonical statistical hadronization describes data well
(V_c remains to be better constrained)

see also: Cleymans et al., PRC 103 (2021) 014904

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)

What about heavier ones?
...for instance *charm*, which weights about 1.2 GeV

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 (Lecture 1, Y.J. Lee)

- To what extent do charm (and beauty) quarks thermalize in QGP?

- Is charm-hadron formation at the QCD phase boundary a possibility?

SHM for charm (SHMc)

<u>*pQCD production*</u>, "throw in": $N_{c\bar{c}} = 13.8 \rightarrow g_c = 31.5$; $N_{J/\psi} \sim g_c^2$

LHC, central collisions, $\Delta y = 1$

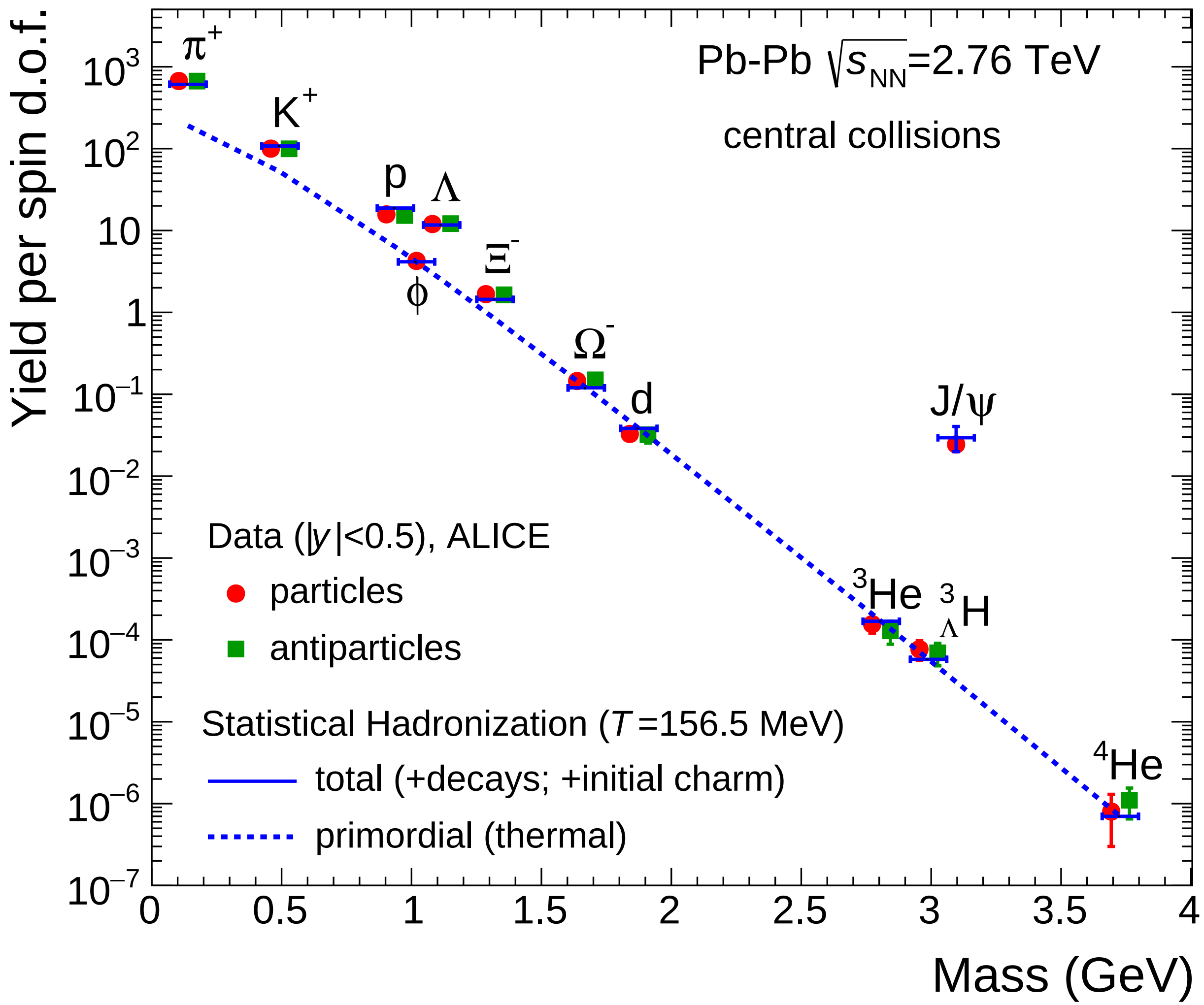
assume:

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

- full color screening
(Matsui-Satz)

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

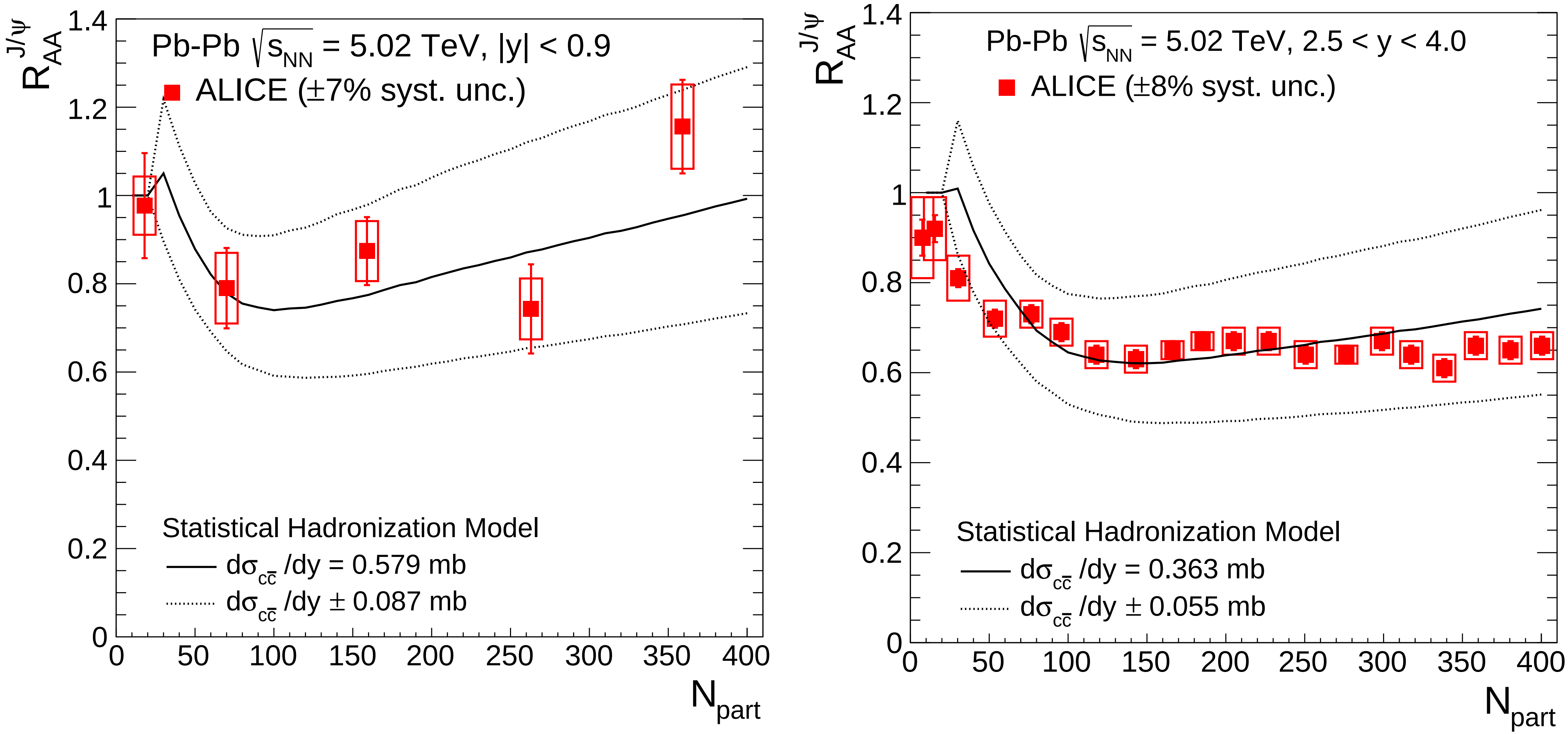
Model predicts all charm chemistry ($\psi(2S)$, $X(3872)$)



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

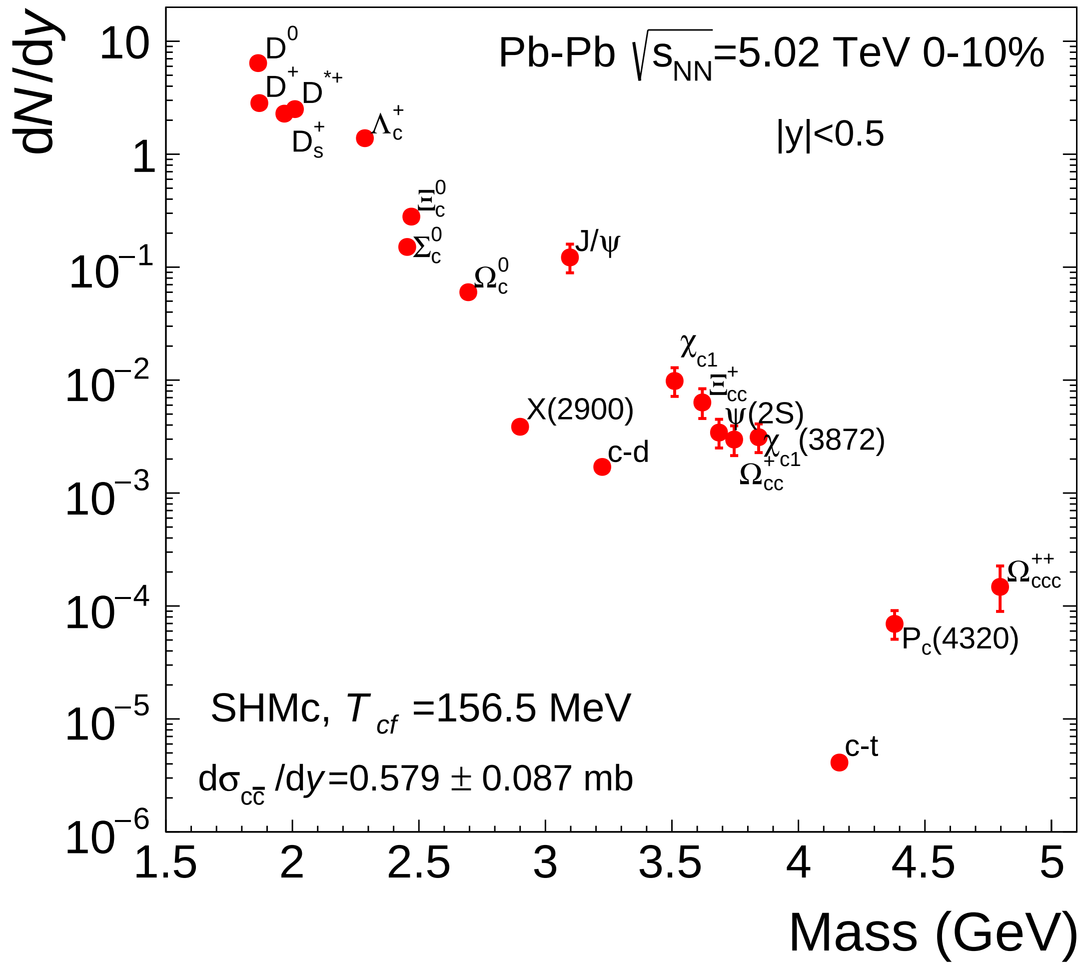
full thermalization of c quarks in QGP, hadronization at chemical freeze-out

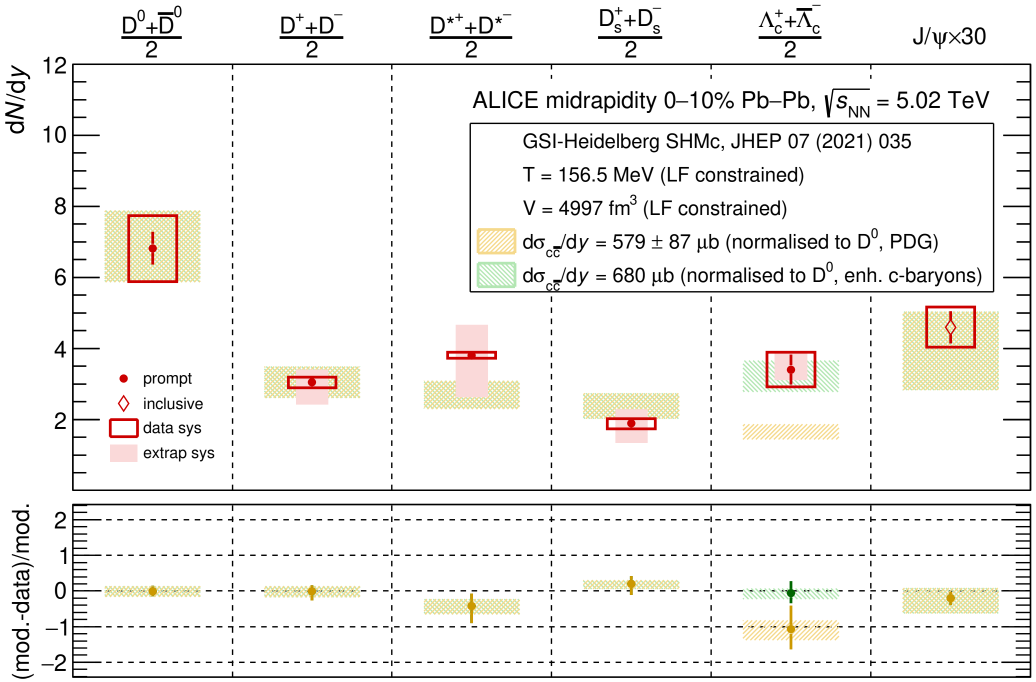


$d\sigma_{c\bar{c}}/dy$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, arXiv:2110.09420

dN/dy = 6.82±1.03 (and assuming hadronization fractions in data as in SHMc)

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





QM'22 talk, L. Vermunt (ALICE)

AA et al, JHEP 07 (2021) 035 (Updated slightly)

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

Summary

- 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?

  (as a dynamical process, understanding still missing)
- more insights from higher moments (B, S conservation)

  ... HRG: baseline against which critical fluctuations may be discovered
- Event the much heavier charm quarks appear to thermalize in bulk in QGP

  ...leading to charm-hadron production (largely) at the QGP phase boundary

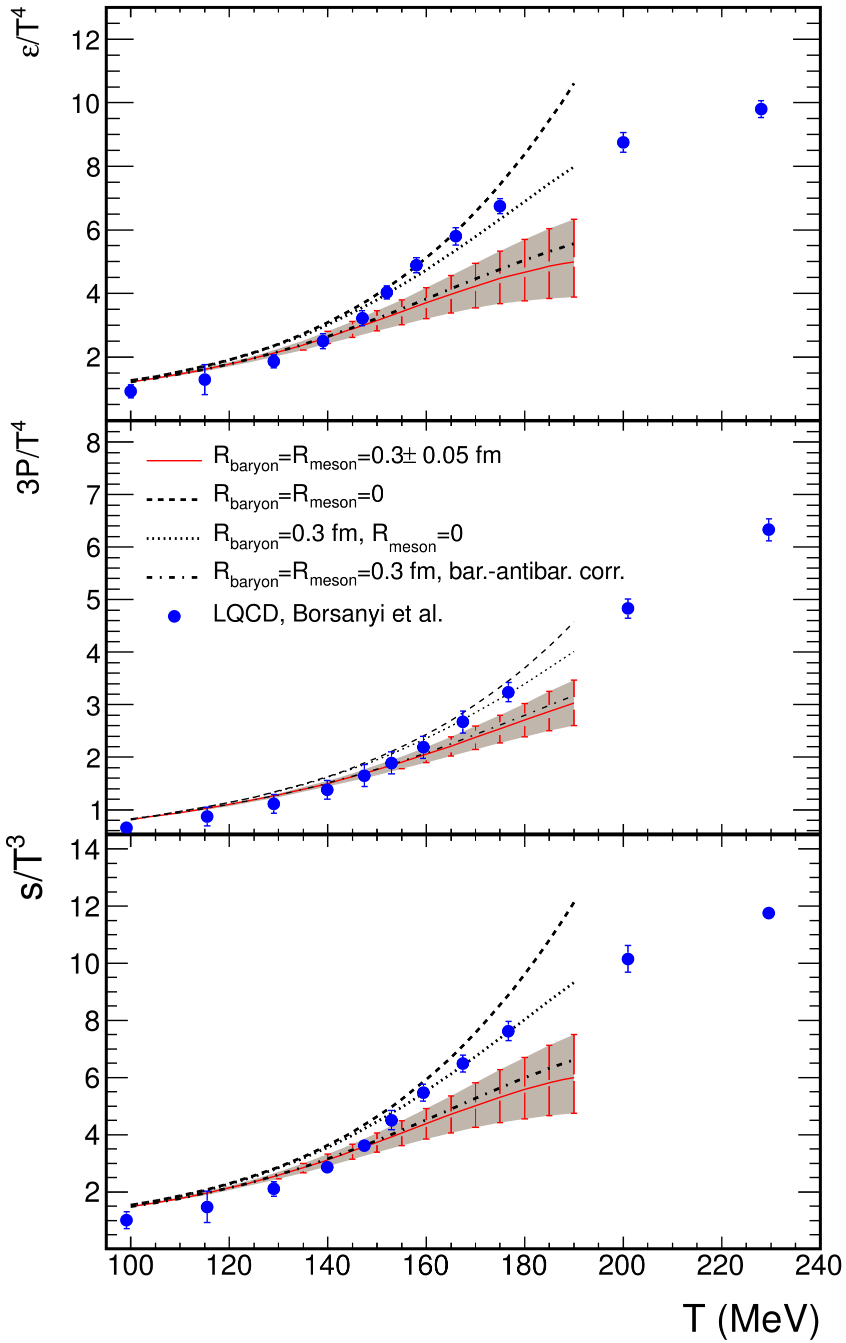
Supplementary material

a subject of quite some debate

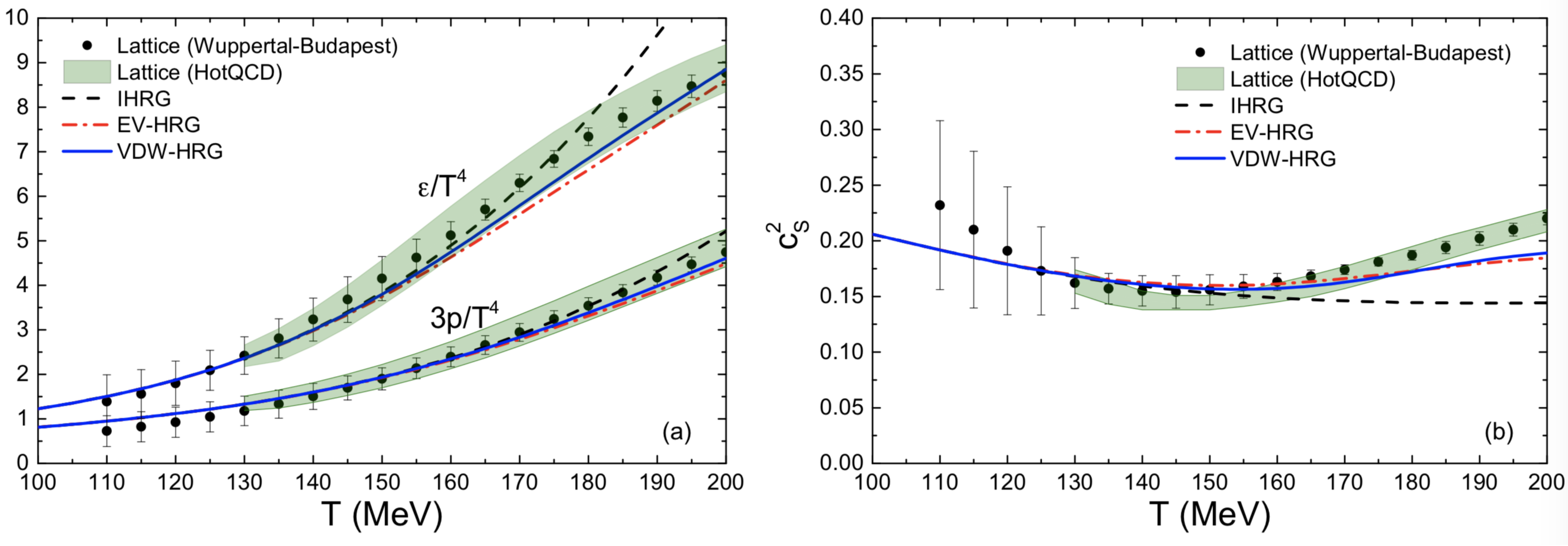
hadrons are not necessarily point-particles

an "excluded-volume" (hard sphere repulsion) is often employed

AA et al., PLB 718 (2012) 80



Matching HRG and LQCD - 2



Vovchenko, Gorenstein, Stöcker, PRL 118 (2017) 182301

$$c_s^2 = \mathrm{d}P/\mathrm{d}\varepsilon$$

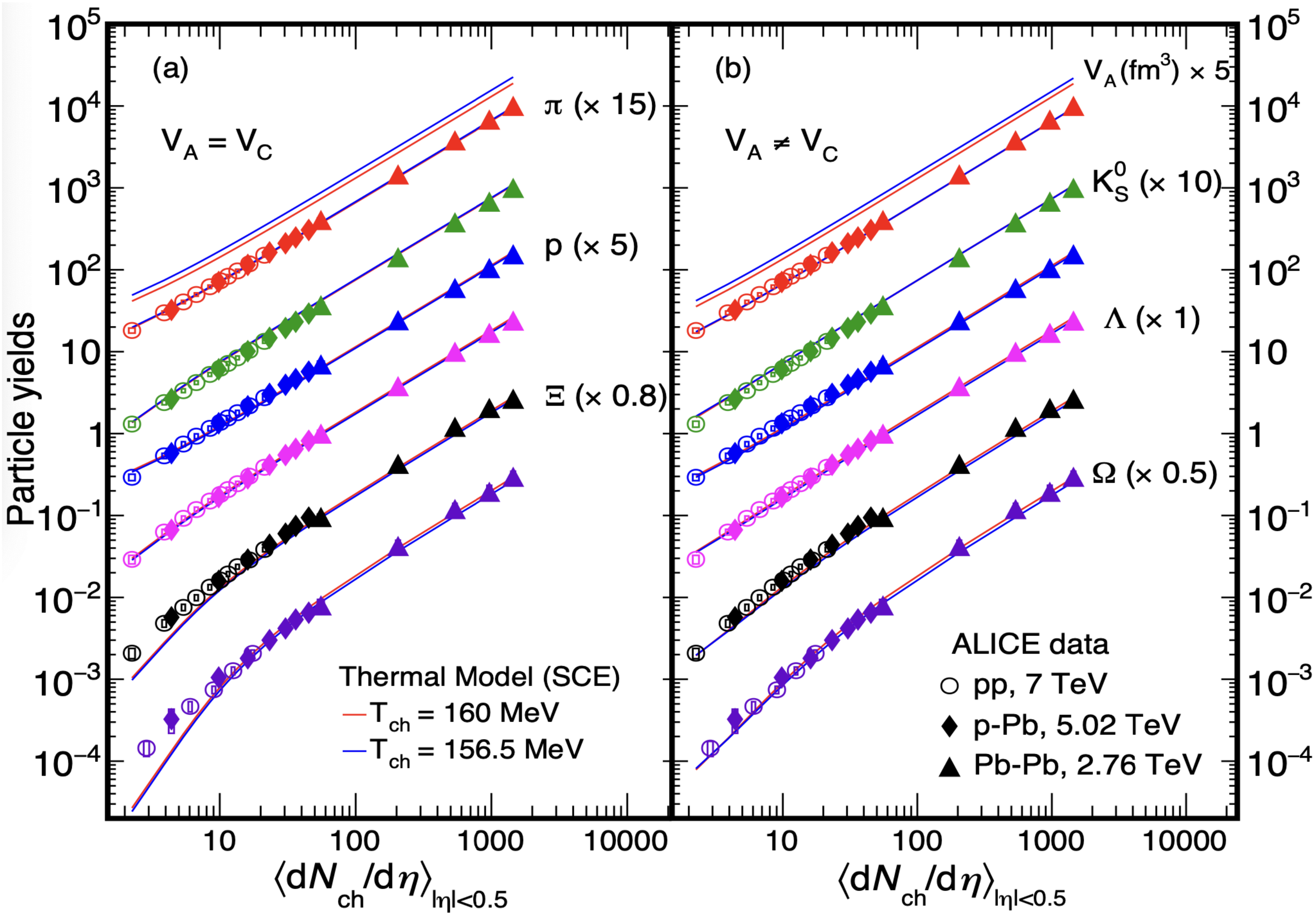
IHRG = ideal hadron resonance gas (model); EV-HRG = excluded-volume HRG

VDW = van der Waals, a=329 MeVfm^3, b=3.42 fm^3

critical point $T_c \simeq$19.7 MeV, $\mu_c \simeq$908 MeV ($n_c \simeq 0.45 n_0$)

describes LQCD χ_2 (susceptibilities) of conserved charges

SHM in pp, p-Pb, Pb–Pb collisions



Cleymans et al., PRC 103 (2021) 014904 $\quad V_c > V_A (= V_{\Delta y=1})$

SHM for charm: method and inputs

- 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 (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

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

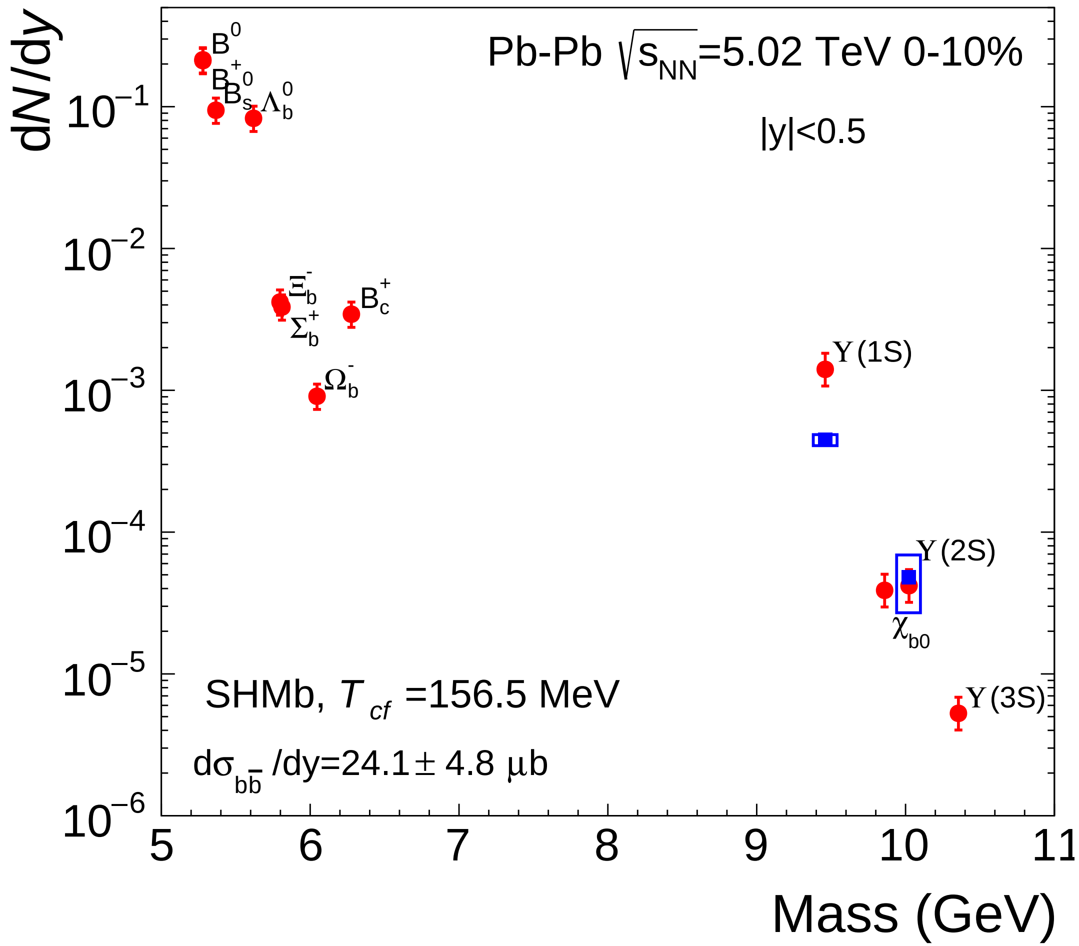
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

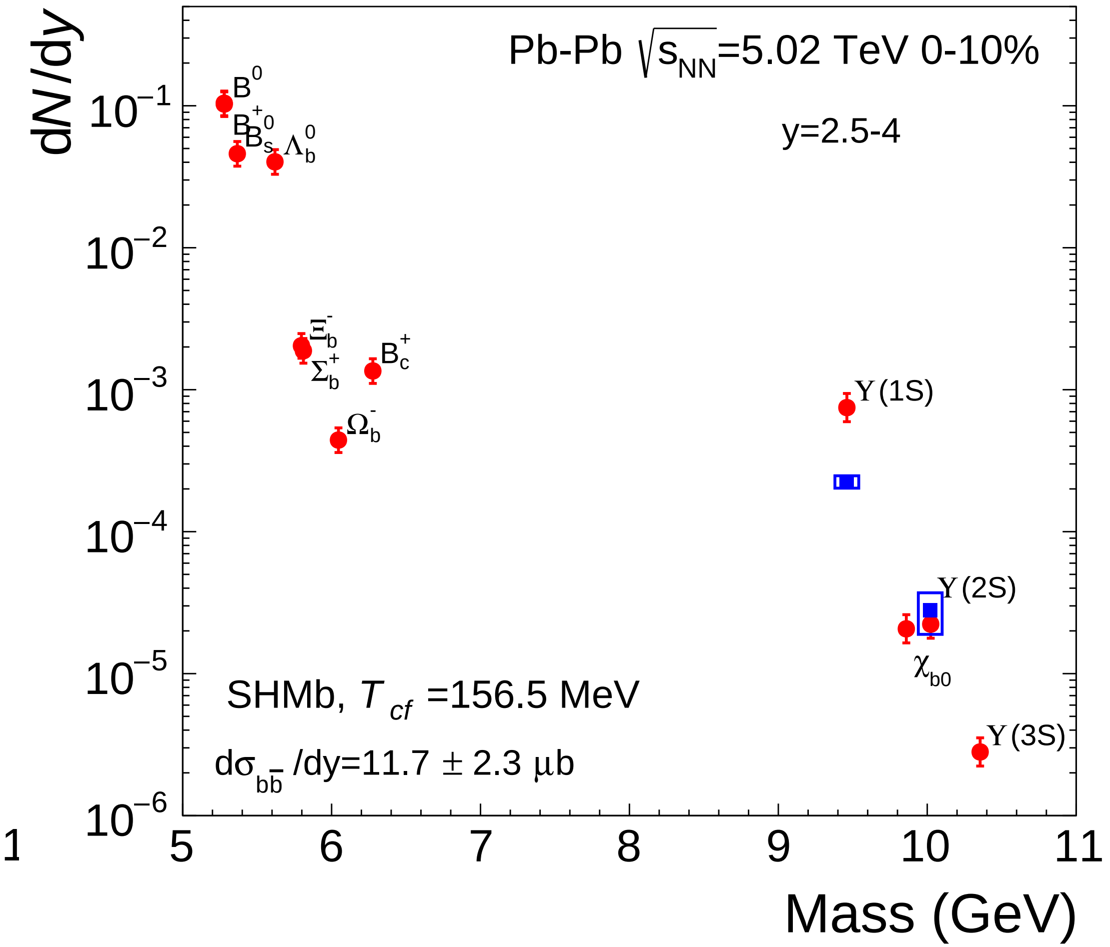
Inputs: T, μ_B, $V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{d}y)/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (exp. or pQCD)

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

SHMb: the beauty zoo (0-10%)

A. Andronic





$g_b = 1.05 \cdot 10^9$ $\quad$ $g_b = 0.86 \cdot 10^9$

$B_c : 3.44 \cdot 10^{-3}$ $\quad$ $B_c : 1.36 \cdot 10^{-3}$

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