Hadron production in high-energy nuclear collisions and the QCD phase diagram

A. Andronic – GSI Darmstadt

- The statistical (hadronization) model
- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram

work in collaboration with P. Braun-Munzinger, K. Redlich, J. Stachel

arXiv:1710.09425

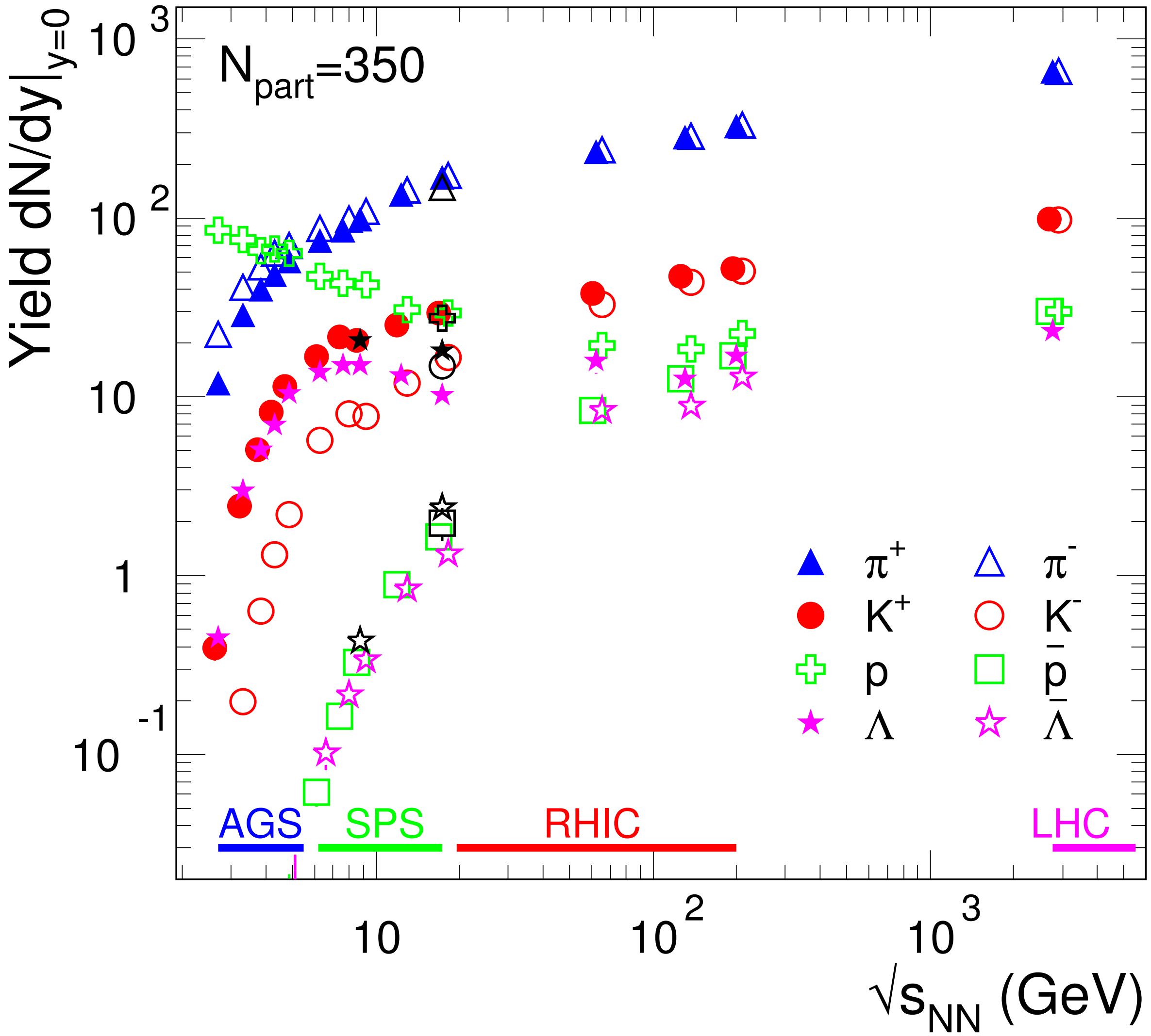
in memoriam

Helmut Oeschler

(3.3.1945 - 3.1.2017)

photo gallery

Hadron yields - central collisions



- 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: $\Xi(dss)$, $\Omega(sss)$...

- 3 decades in energy and

  3 decades of experimental effort

mass hierarchy in production ...natural to think of the thermal model grand canonical partition function for specie i ($\hbar = c = 1$):

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

$g_i = (2J_i + 1)$ 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

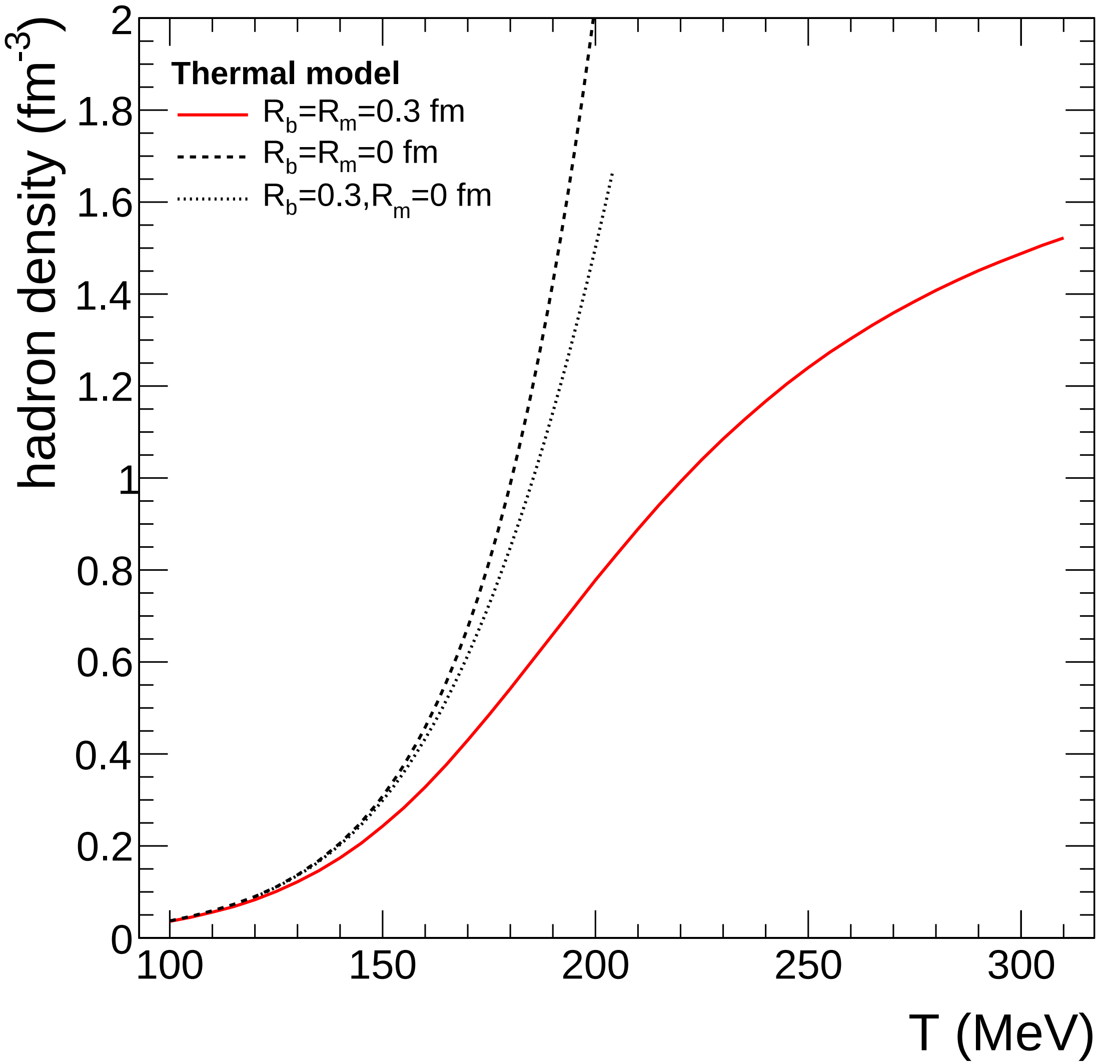
μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

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 ($\simeq$0 at high energies)

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

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

Hadron densities



a dense system for $T \gtrsim 170$ MeV (for point-like hadrons)

the usual case is $R_b = R_m = 0.3$ *fm*

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

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

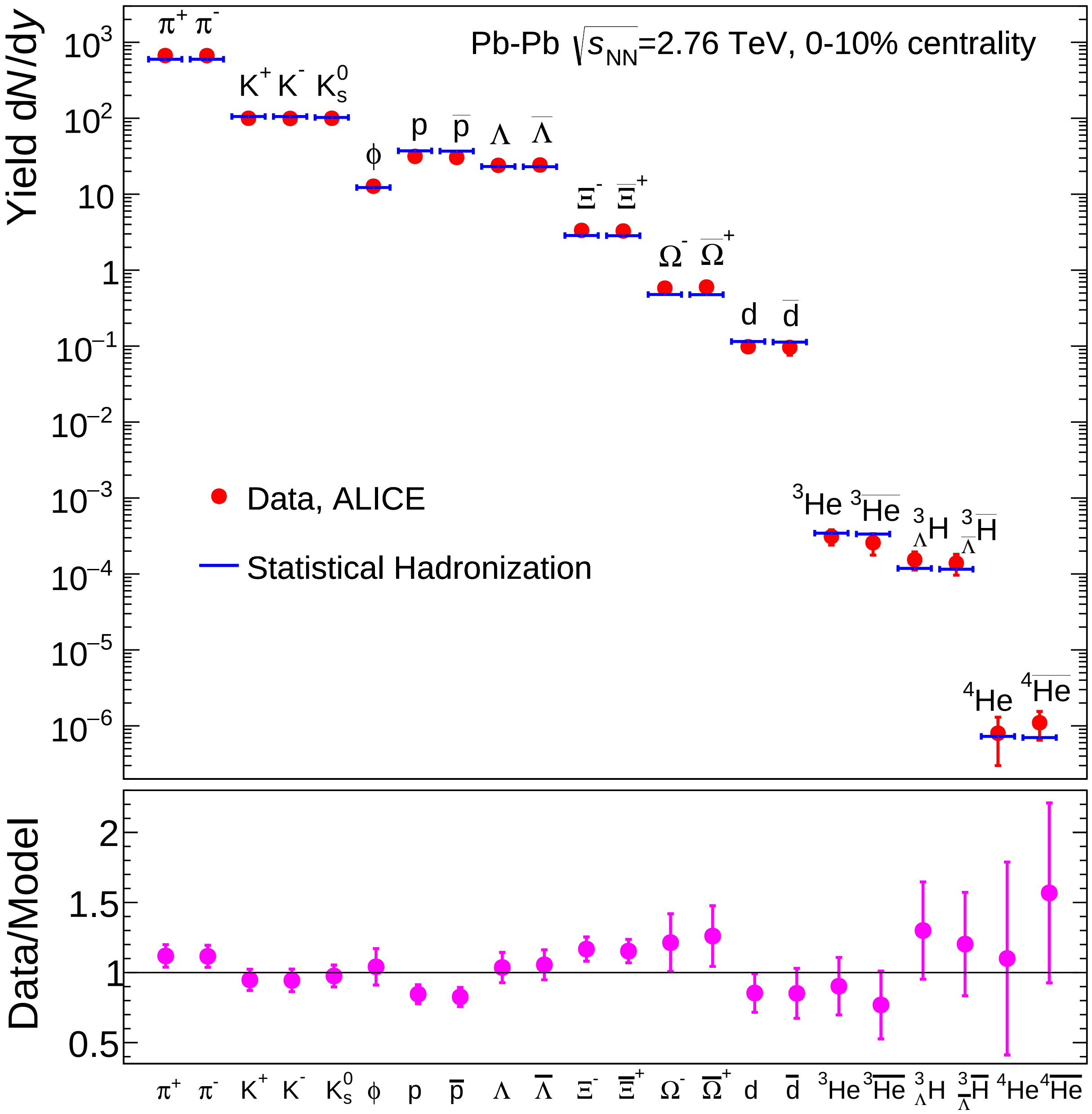
canonical treatment whenever needed (small abundances)

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, μ_B, V) *...tests chemical freeze-out* (chemical equilibrium)

Thermal fit – LHC, Pb–Pb, 0-10%



all species in fit

π, $K^{\pm}$, K^0 from charm included (0.7%, 2.9%, 3.1% for the best fit)

$T_{CF} = 156.5 \pm 1.5$ MeV
$\mu_B = 0.7 \pm 3.8$ MeV
$V_{\Delta y=1} = 5280 \pm 410$ fm^3

$\chi^2/N_{df} = 29.3/19$

remarkably, loosely-bound objects are well described

Thermal fit – LHC, Pb–Pb, 0-10%

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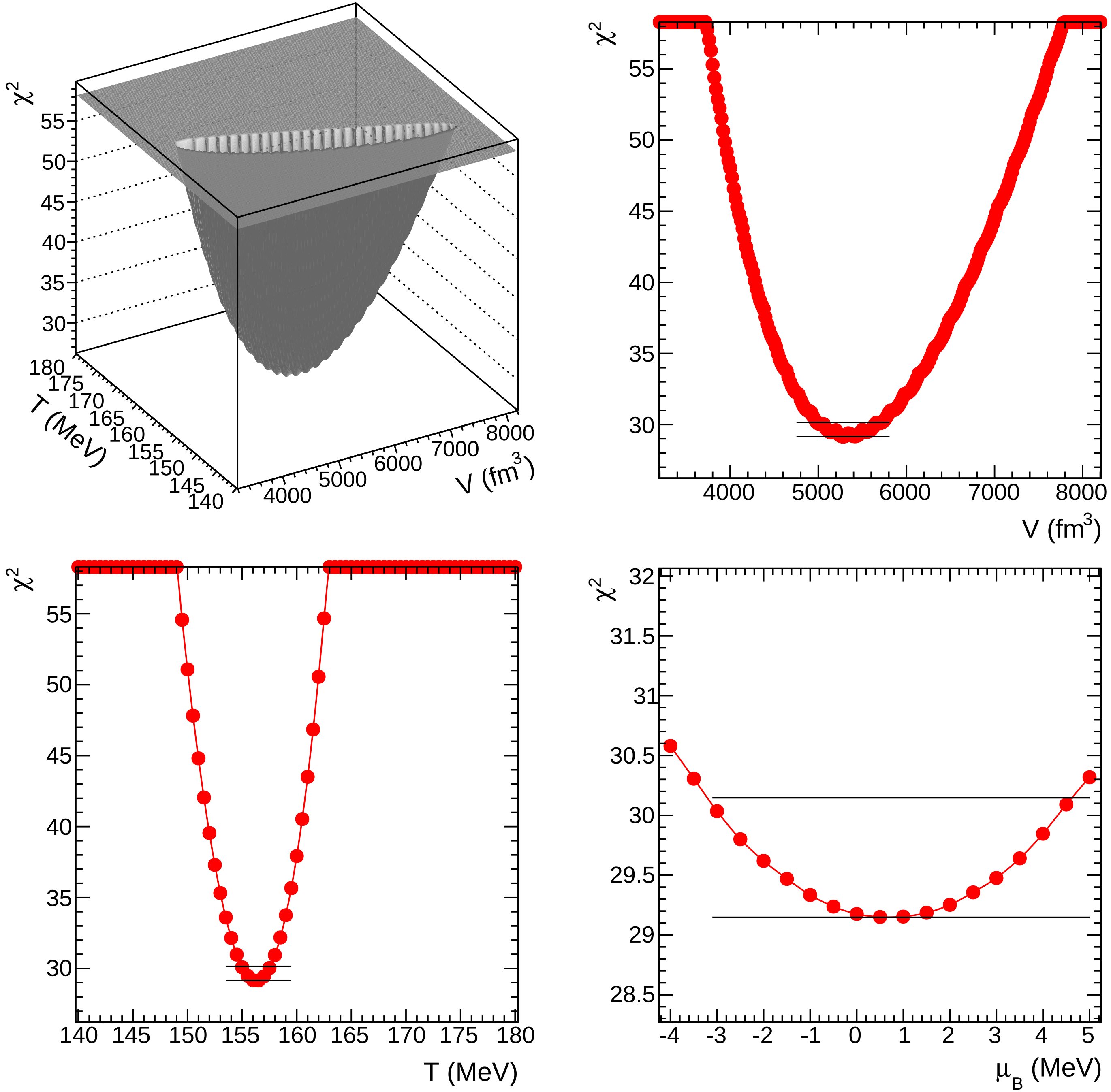
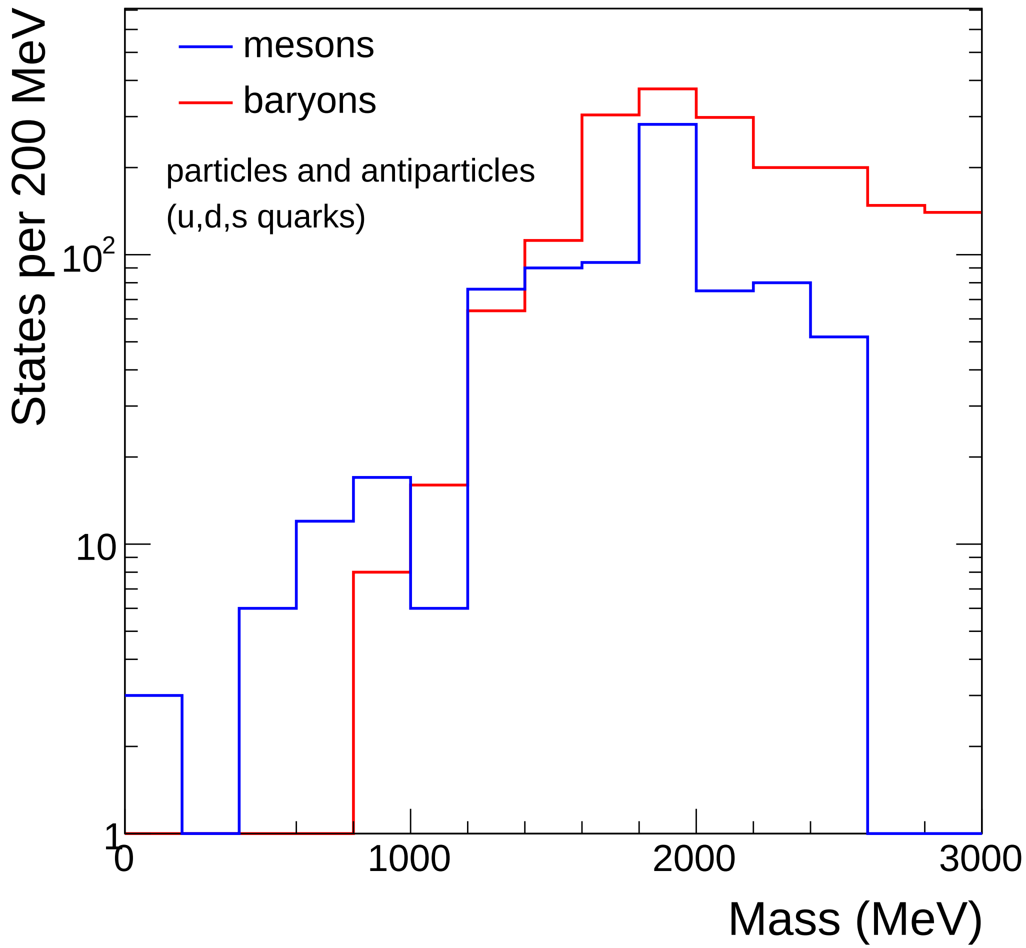


hadron spectrum ...embodies low-energy QCD ...*vacuum masses*

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

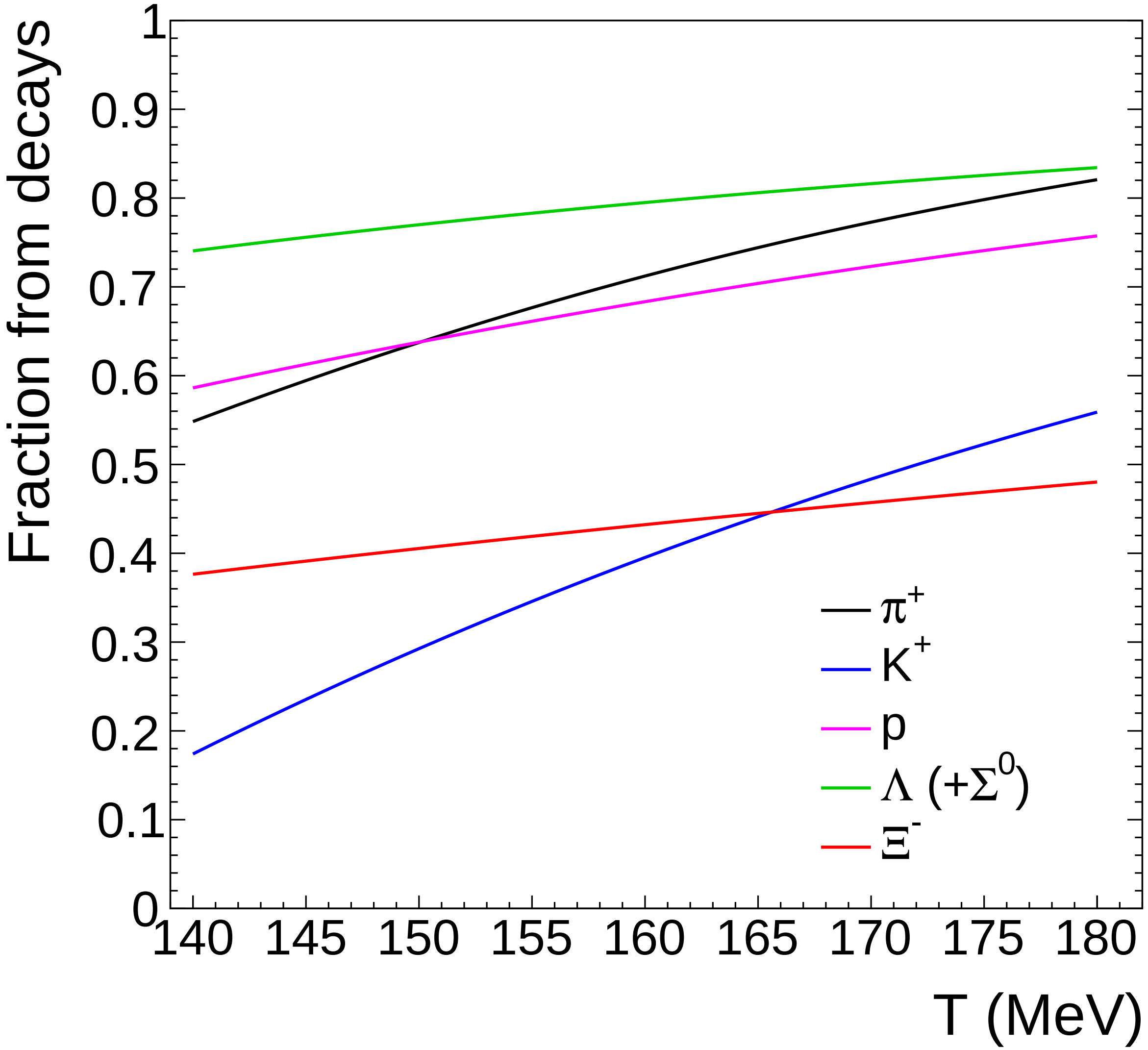
T found to be robust in fits with spectrum truncated above 1.8 GeV

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

Giacosa, Begun, Broniowski, arXiv:1603.07687

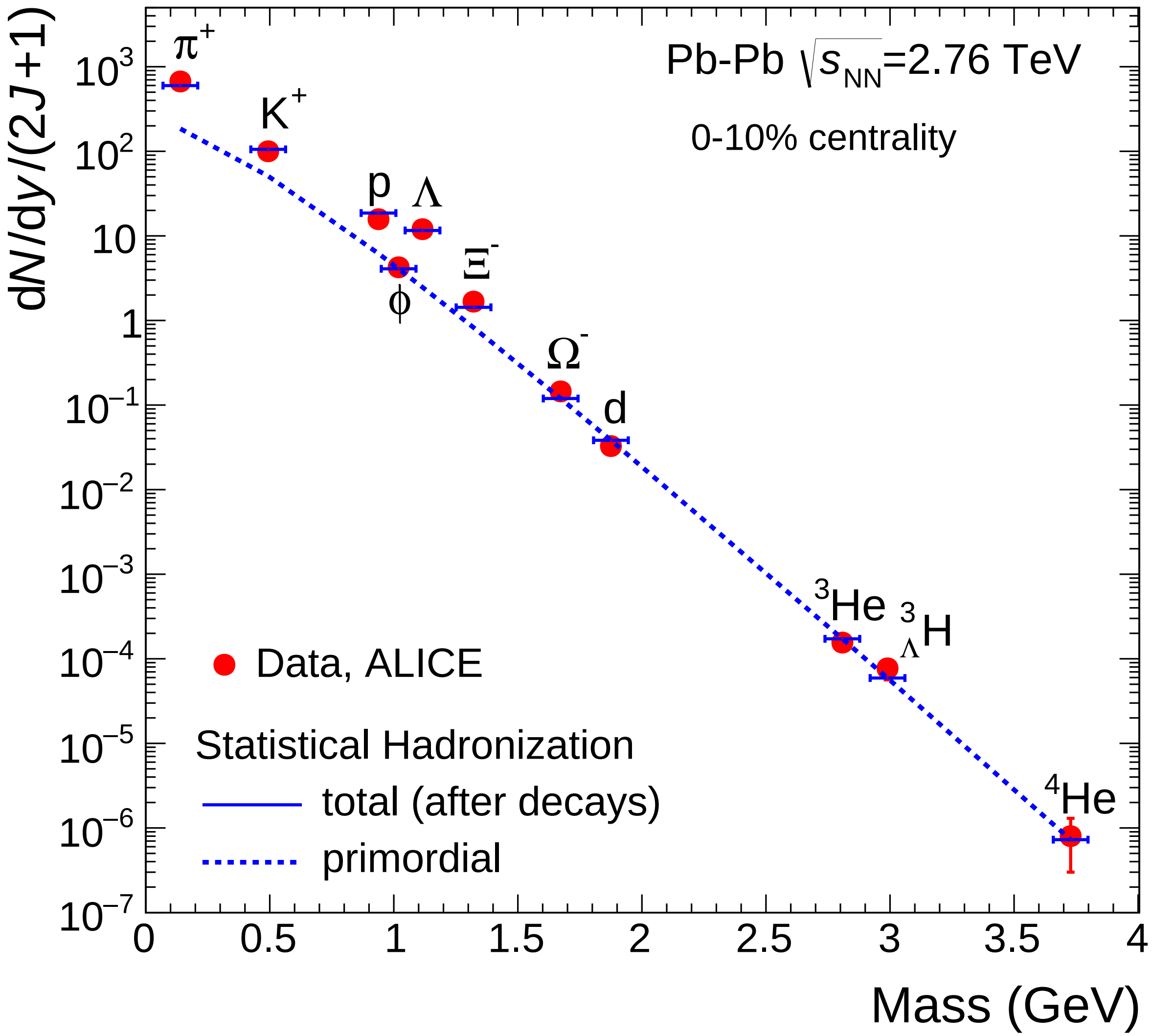
$(2J + 1)$ counted in

Systematic uncertainties - hadron spectrum



contribution of resonances is significant (and particle-dependent)

Systematic 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 syst. uncert. due to hadron spectrum

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

we consider that $R_{meson} = 0.3, R_{baryon} = 0.3$ *fm is 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, arXiv:1606.06542 , etc.

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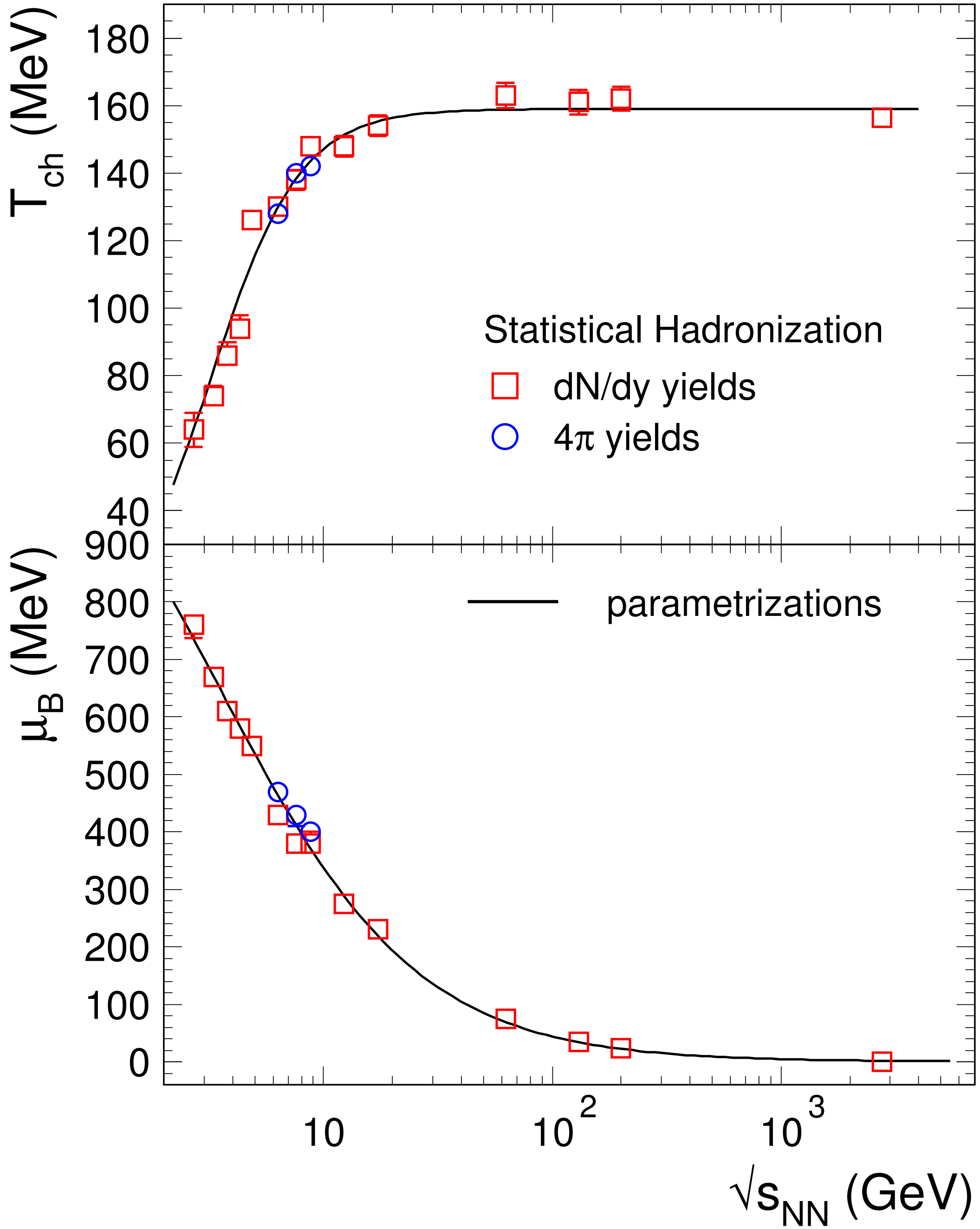

thermal fits exhibit a limiting temperature:

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

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

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

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

The grand (albeit partial) view

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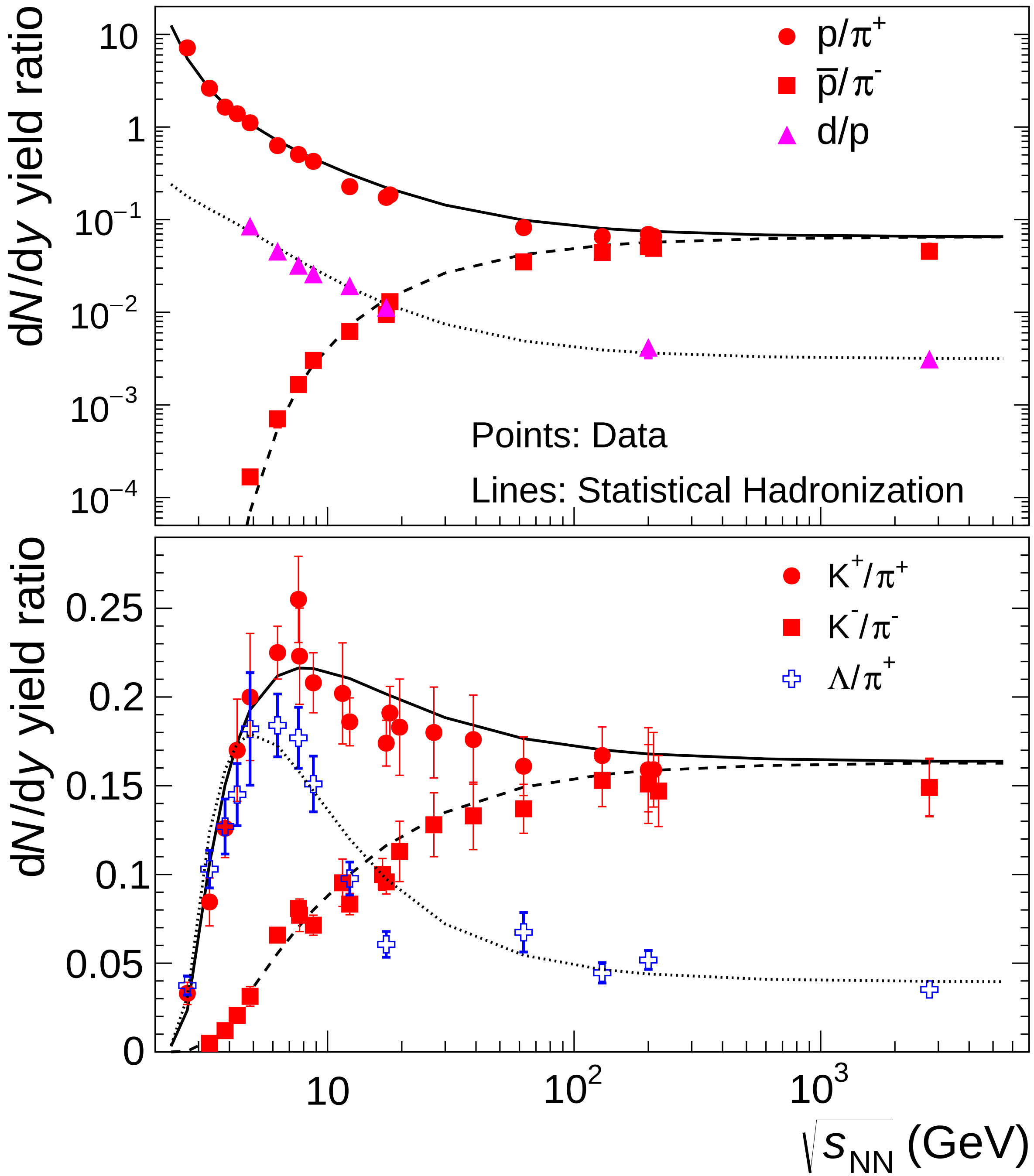


Data:

AGS: E895, E864, E866, E917, E877

SPS: NA49, NA44

RHIC: STAR, BRAHMS

LHC: ALICE

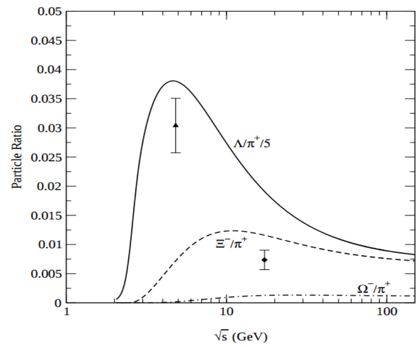
NB: no contribution from weak decays

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

the first insight:

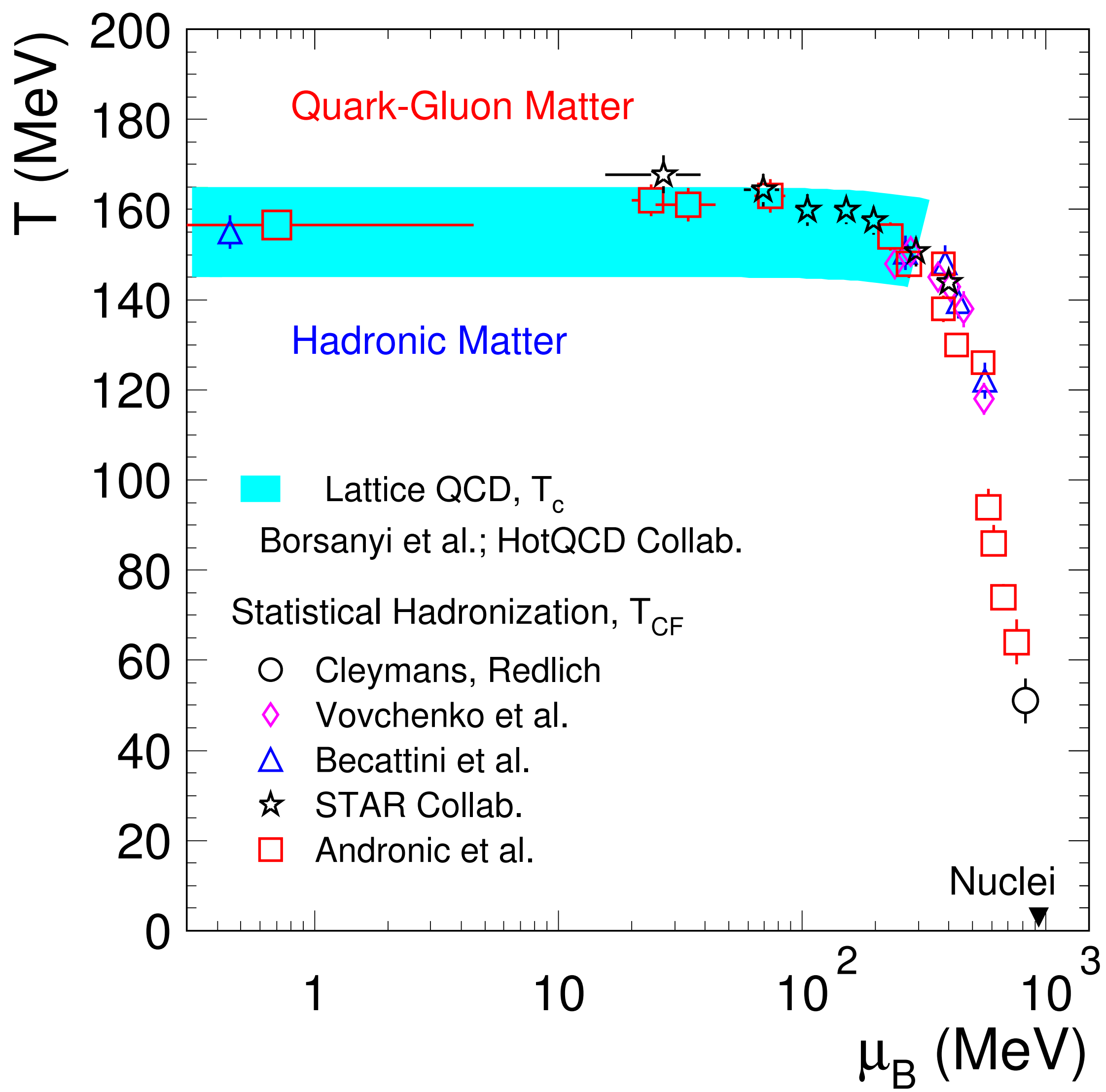
Braun-Munzinger, Cleymans, Oeschler, Redlich, *Maximum Relative Strangeness Content in Heavy Ion Collisions Around 30 AGeV*

NPA 697 (2002) 902



Connection to the phase diagram of QCD

$T_{CF} \to T_{lim}$ ...is chemical freeze-out a determination of the phase boundary?



...Yes, at low μ_B

Lattice QCD:

Borsanyi et al., JHEP 1009 (2010) 073, JHEP 1208 (2012) 053

HotQCD, PRD 90 (2014) 094503, PRD 83 (2011) 014504

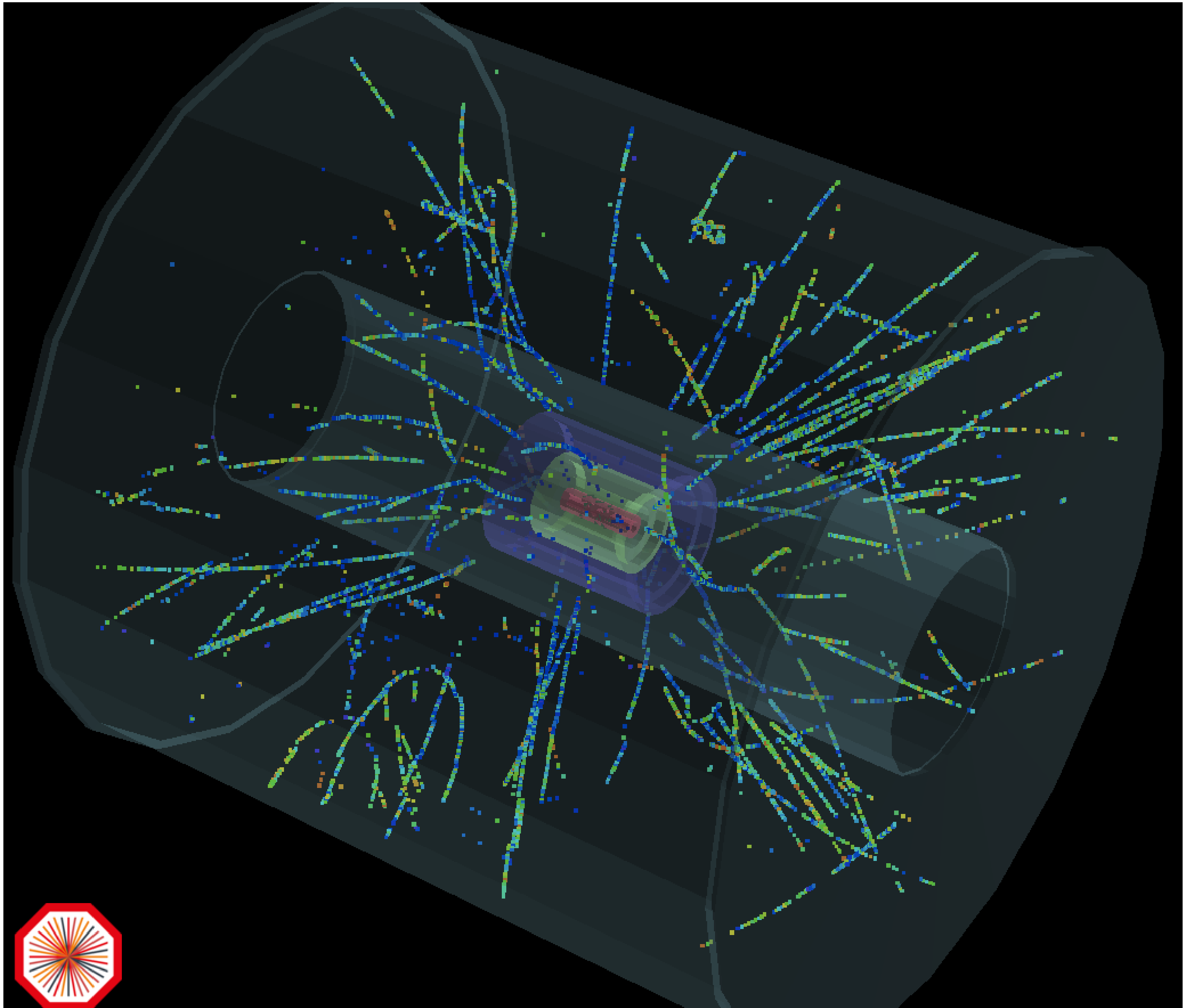
Statistical model

Cleymans, Redlich, PRC 59 (1999) 1663
Vovchenko et al., PRC 93 (2016) 064906
Becattini et al., PLB 764 (2017) 241
STAR, PRC 96 (2017) 044904

Andronic et al., arXiv:1710.09425

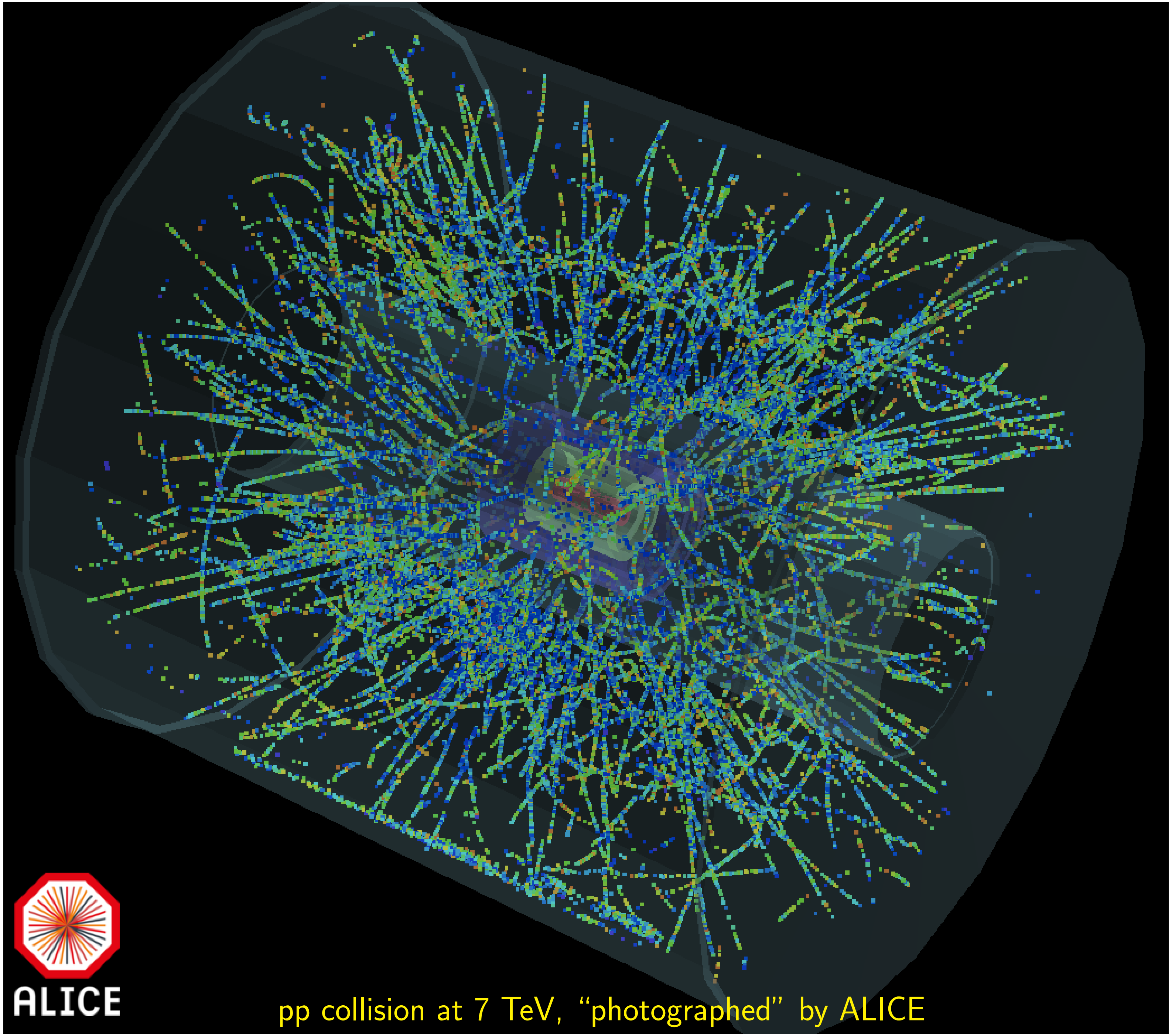
Are the larger T values at RHIC significant (physics)?

Proton collisions at the LHC



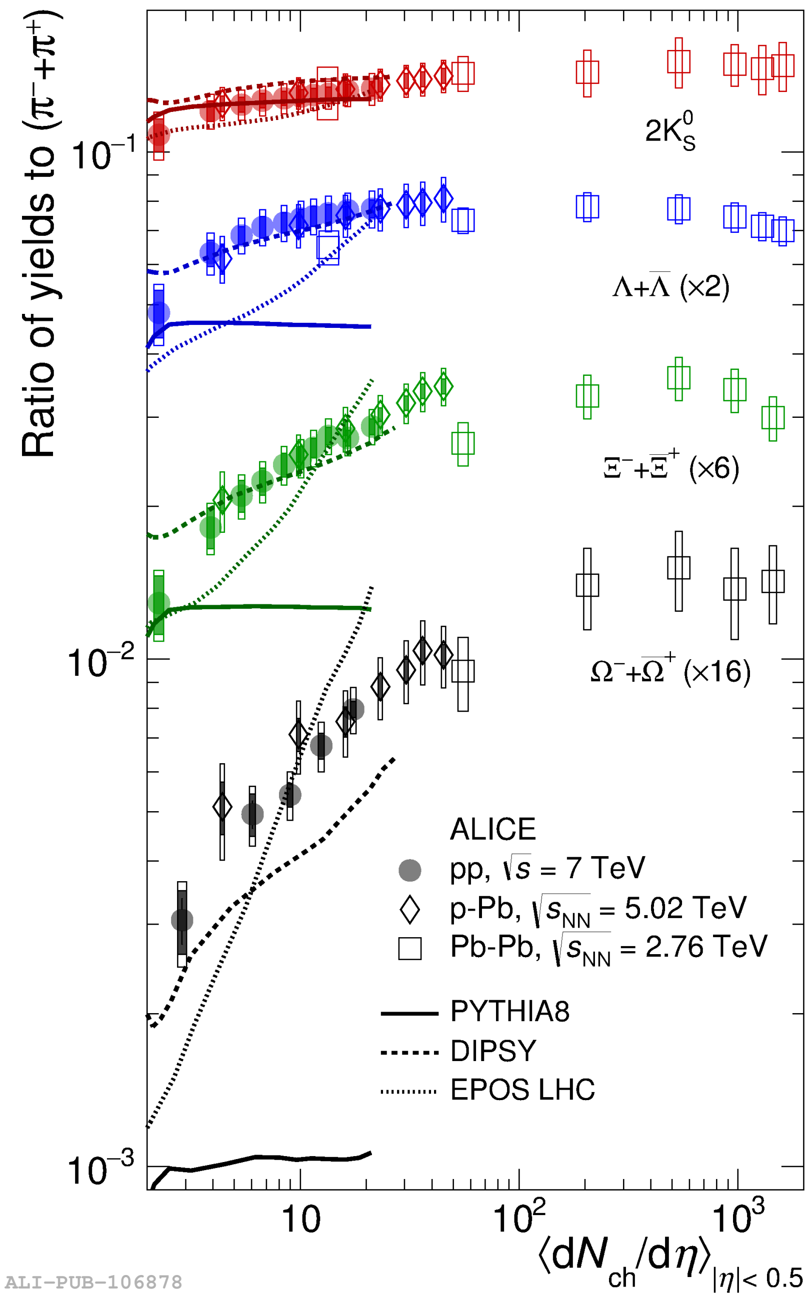
pp collision at 7 TeV, "photographed" by ALICE

Proton collisions at the LHC



pp collision at 7 TeV, "photographed" by ALICE

Strangeness production - from small to large systems



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

Fischer, Sjöstrand, arXiv:1610.09818

"thermodynamical string fragmentation"

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

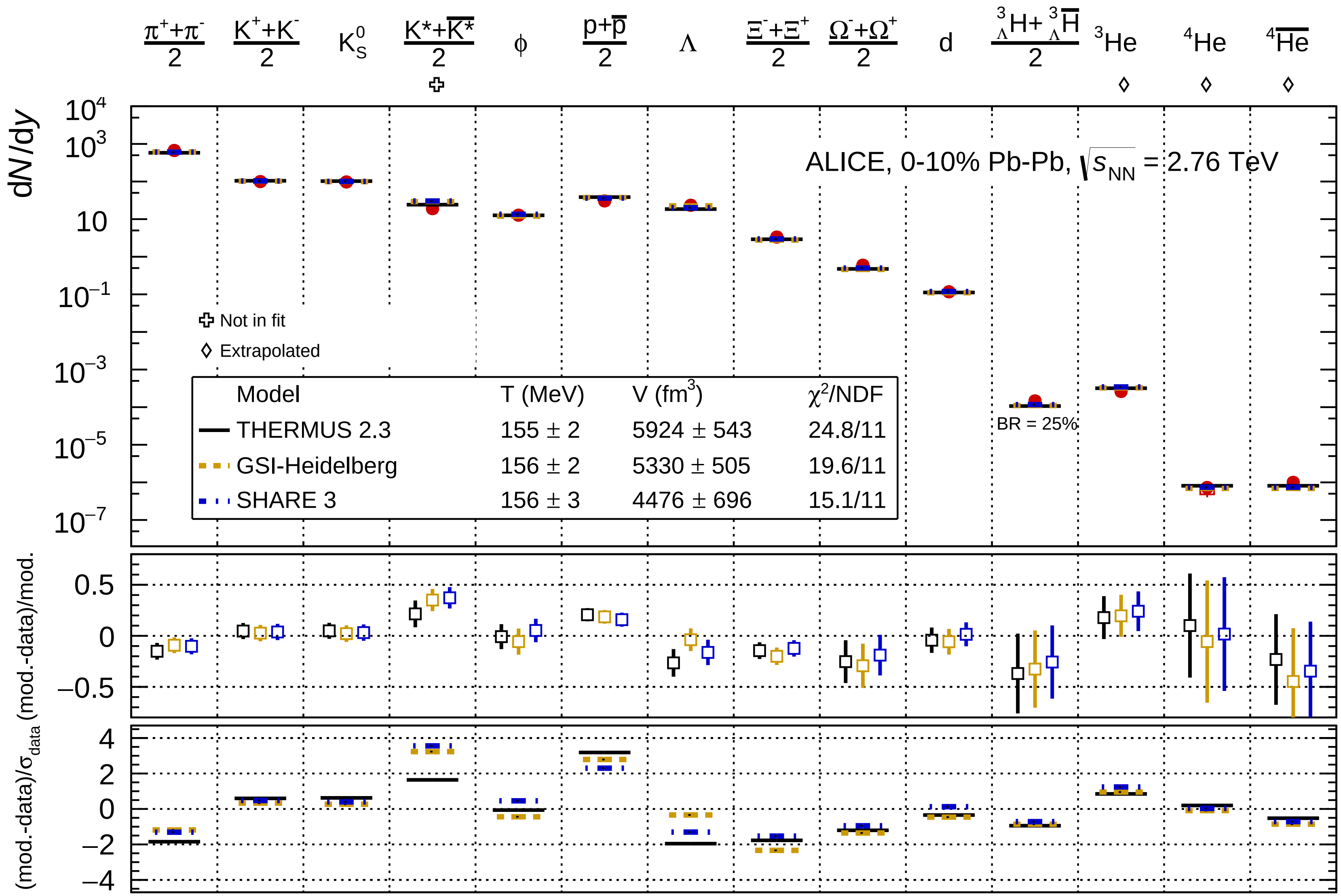
  ...at high energies (at low energies canonical suppression needs more care)

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

  ...and what fundamental point does it make about hadronization?
- more insights from higher moments and from heavier (charm) quarks

Backup slides

LHC, Pb–Pb, 0-10% - 3 models



ALICE, arXiv:1710.07531

LHC, Pb–Pb, 0-10% - ALICE data

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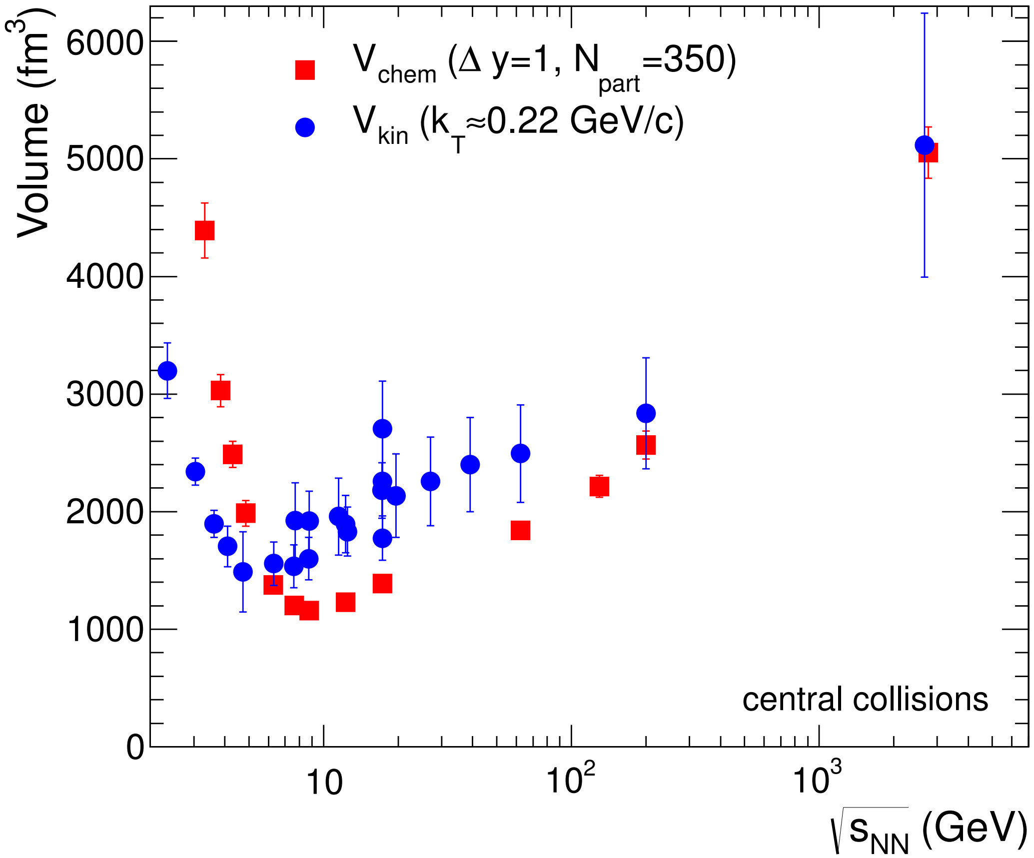
- $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, PRC 88 (2013) 044910
- ϕ, PRC 91 (2015) 024609
- K_s^0, Λ, PRL 111 (2013) 222301
  $\bar{\Lambda}$ from S.Schuchmann, PhD Thesis, Goethe-University Frankfurt (July 2015)
- Ξ, Ω, PLB 728 (2014) 216
- d, ^{3}He, PRC 93 (2015) 024917
  derive anti-particles from published ratios
- $^3_\Lambda\mathrm{H}$, $^3_{\bar{\Lambda}}\bar{\mathrm{H}}$, PLB 754 (2016) 360, assume B.R.=25%
- $^4\mathrm{He}$, $^4\bar{\mathrm{He}}$, arXiv:1710.07531

Volume in central collisions

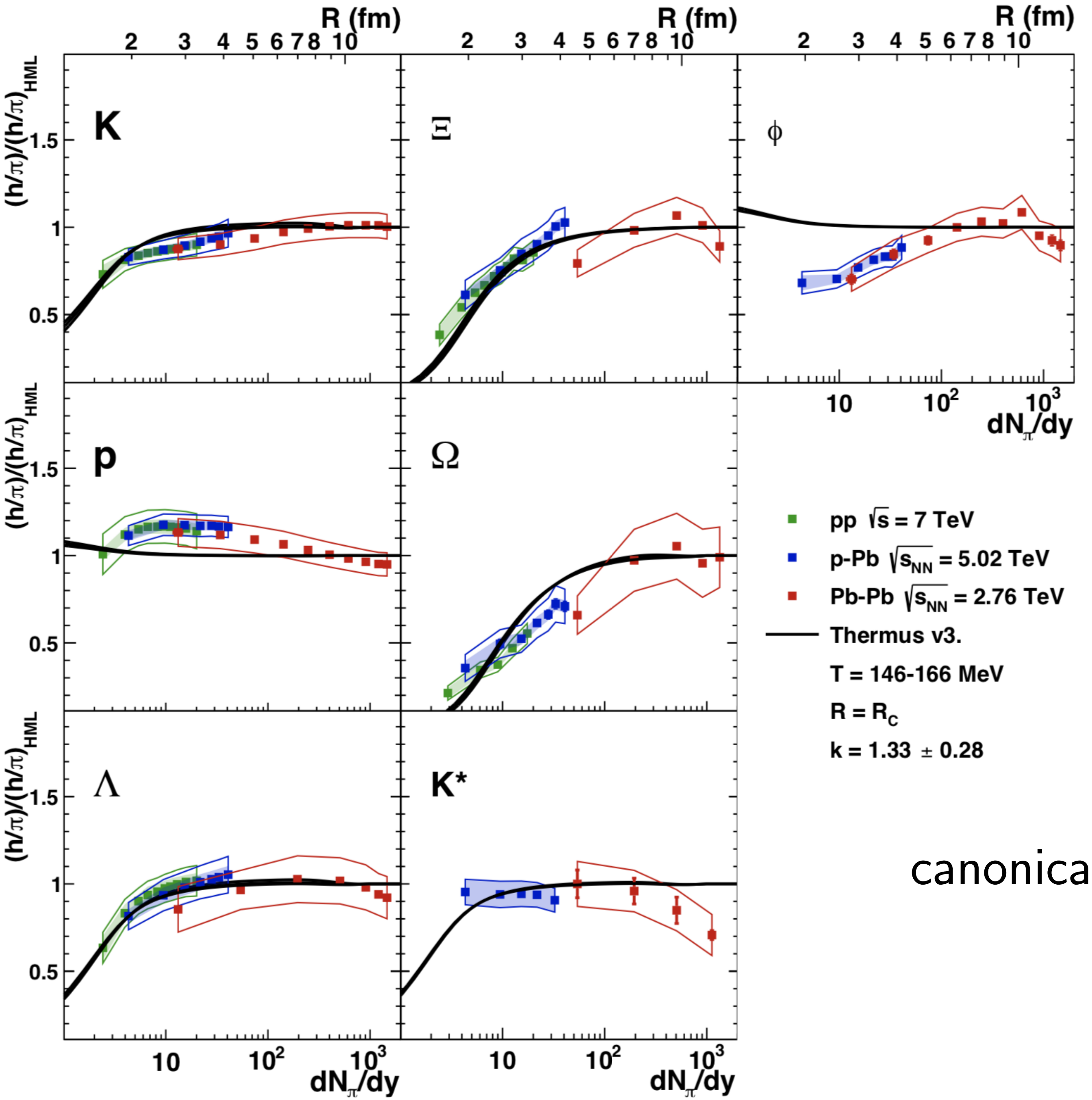


$$V_{chem}^{\Delta y=1} = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$

$$V_{kin} = V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$$

HBT data: ALICE, PLB 696, 328 (2011)

Strangeness production - from small to large systems



Vislavicius, Kalweit,

arXiv:1610.03001

ratios to high multiplicity limit (HML)

canonical statistical hadronization describes data well