Statistical model description of hadron yields in central AA collisions: the "minimalistic" approach

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- What is the "minimalistic" approach
- What results it gives
- What are the open issues
- Summary / Outlook

with P. Braun-Munzinger, K. Redlich, J. Stachel, JPG 38 (2011) 124081 [arXiv:1106.6321]; NPA 904 (2013) 535c [arXiv:1210.7724]; J. Phys. Conf. Ser. 509 (2014) 012019 [arXiv:1311.4662] (and refs. therein)

Hadron yields (central collisions)

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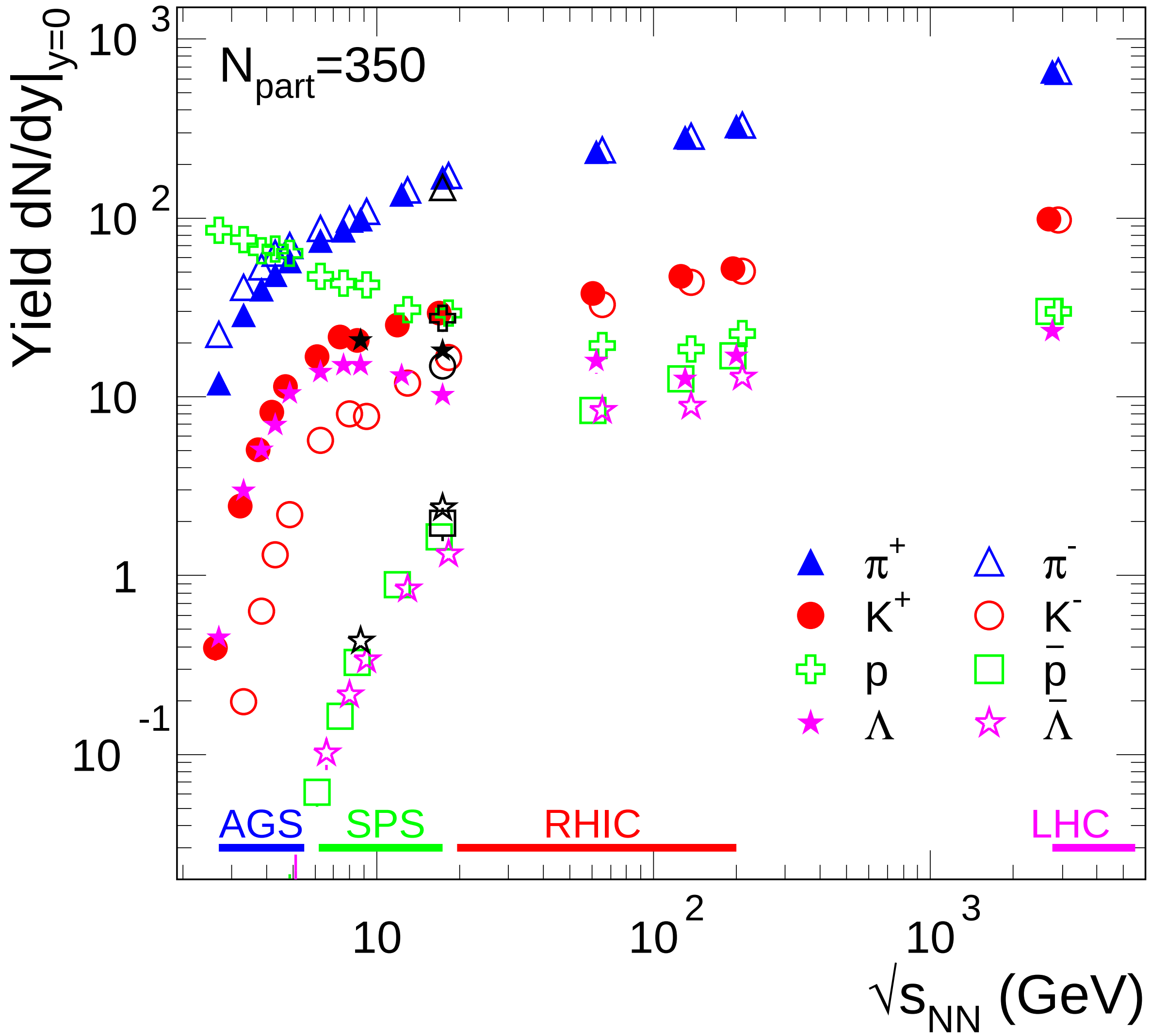

- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ ($u\bar{d}$, $d\bar{u}$), 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 low en.: u, d quarks remnants from the incoming nuclei)

what is this "chemistry" telling us?

The statistical (thermal) model

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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 (=0 at high energies)
ii) strangeness: $\sum_i n_i S_i = 0$
iii) charm: $\sum_i n_i C_i = 0$.

Thermal fits of hadron abundances

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

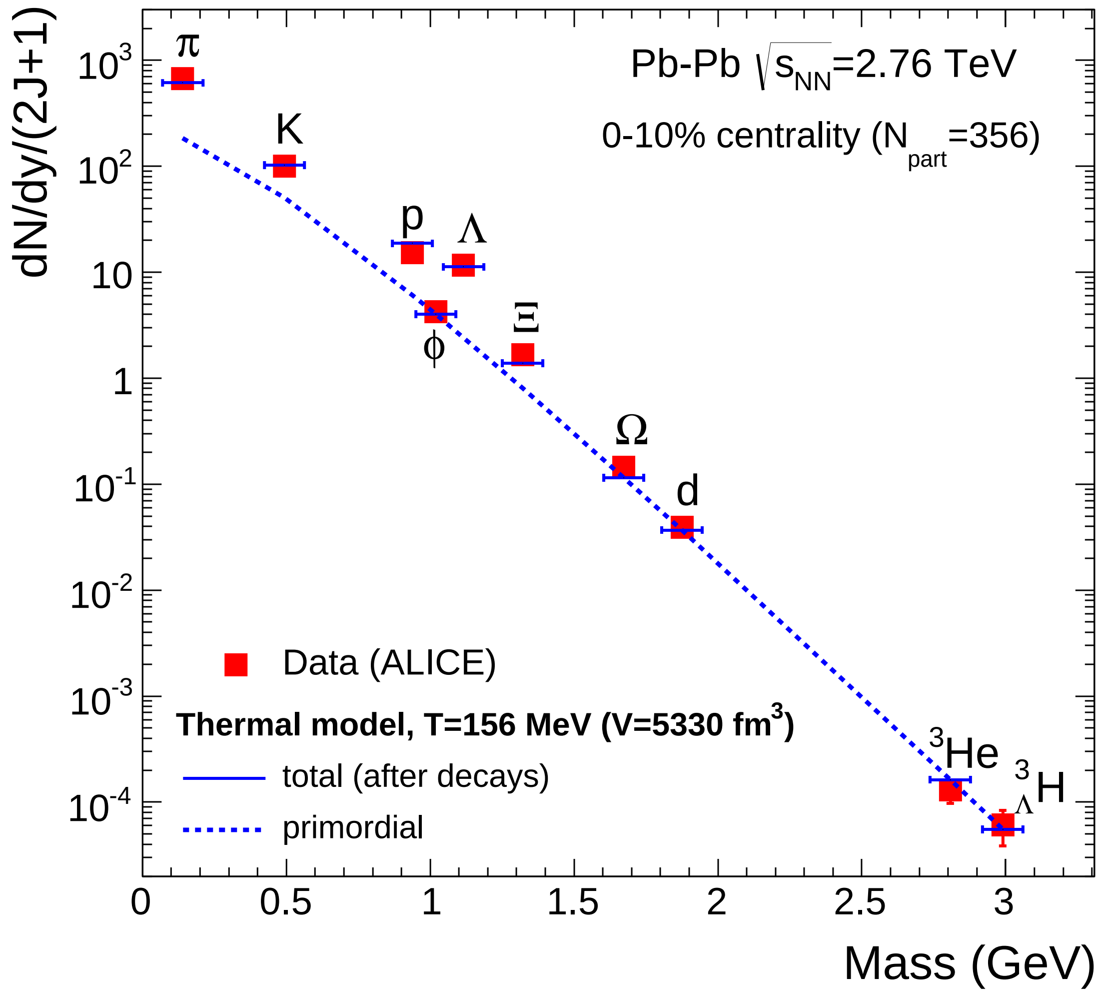
PDG hadron mass spectrum
(up to 3 GeV, 485 species)

includes resonance widths

interactions via “excluded volume”
(hard sphere radius $r = 0.3$ fm)

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

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



this is the minimalistic approach (no other parameters/assumptions)

Energy dependence of T, μ_B (central collisions)

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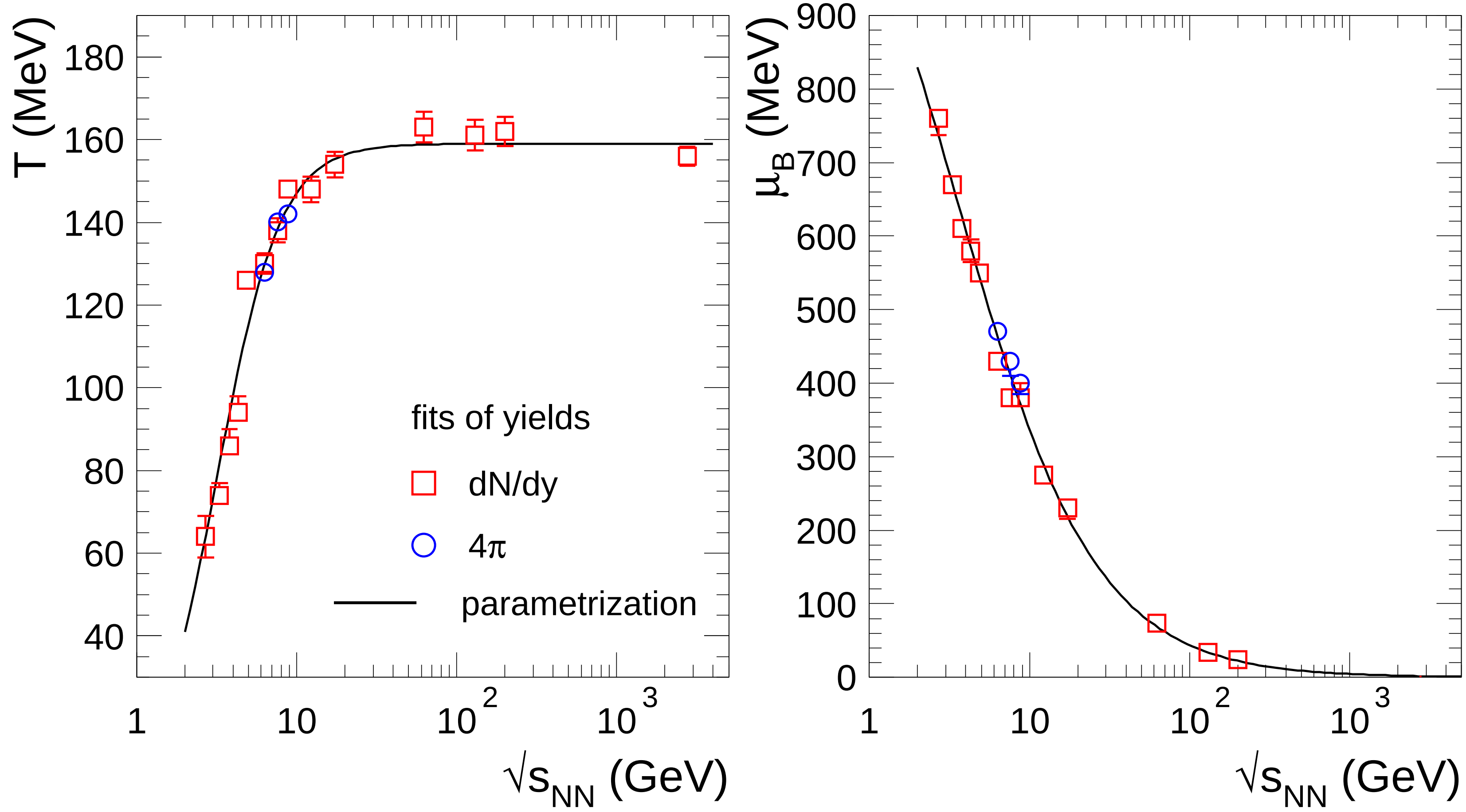

thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2$ MeV

$$T = T_{lim} \frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}, \qquad \mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

PLB 673 (2009) 142 ...with updates (T_{lim} was 164 ± 4 MeV)

Volume in central collisions

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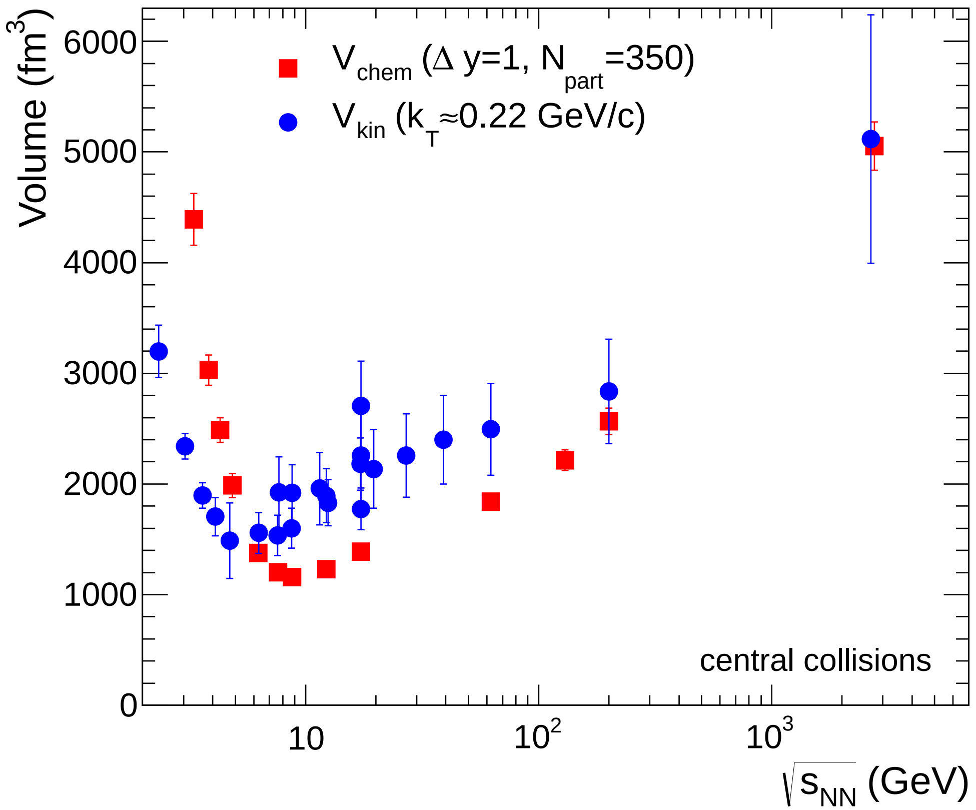
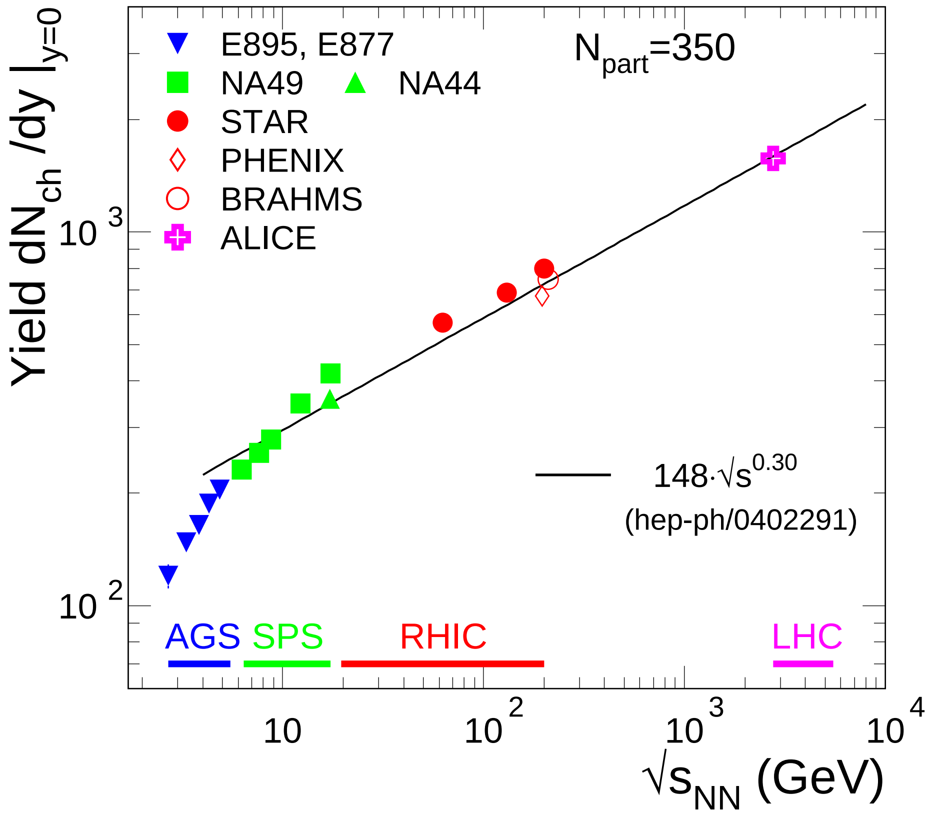
$$V_{chem}(\Delta y = 1) = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$





Predictive power

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

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

5.1 TeV: $V = 6400$ fm^3

40 TeV: $V = 12000$ fm^3 (2.2x $V_{2.76}$)

Connection to the phase diagram of QCD

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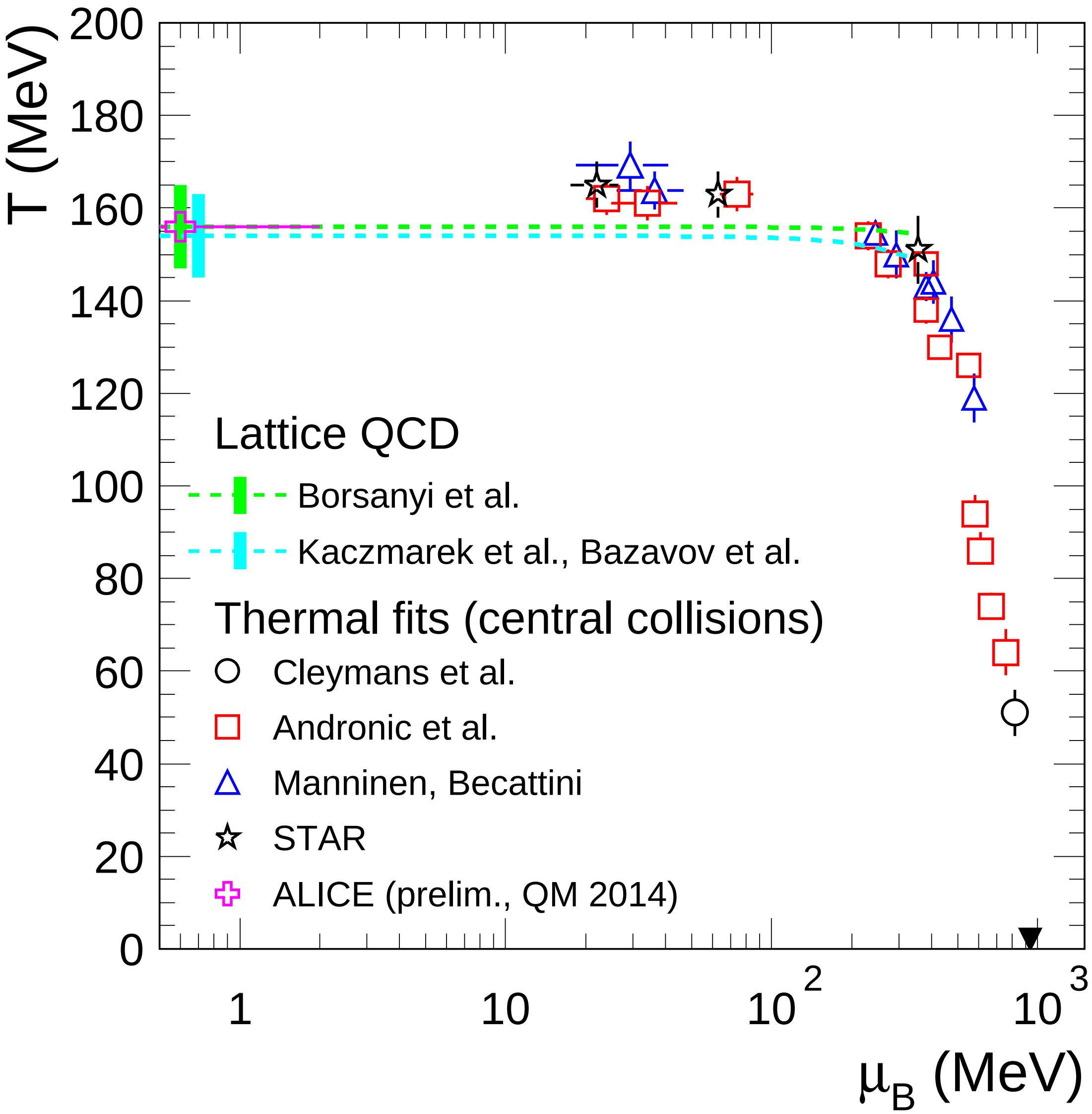

(as $T \rightarrow T_{lim}$) is chemical freeze-out a determination of the phase boundary?

Lattice QCD ($\mu_B = 0$)
crossover, T=145-165 MeV
curvature for $\mu_B > 0$

BW, JHEP 1009 (2010) 073; 1208 (2012) 053

HotQCD, arXiv:1407.6387; PRD 83 (2011) 014504

see discussions in

PBM, Stachel, Wetterich, PLB 596 (2004) 61
McLerran, Pisarski, NPA 796 (2007) 83
AA et al., NPA 837 (2010) 65
Floerchinger, Wetterich, NPA 890 (2012) 11

A "global" look (ratios)

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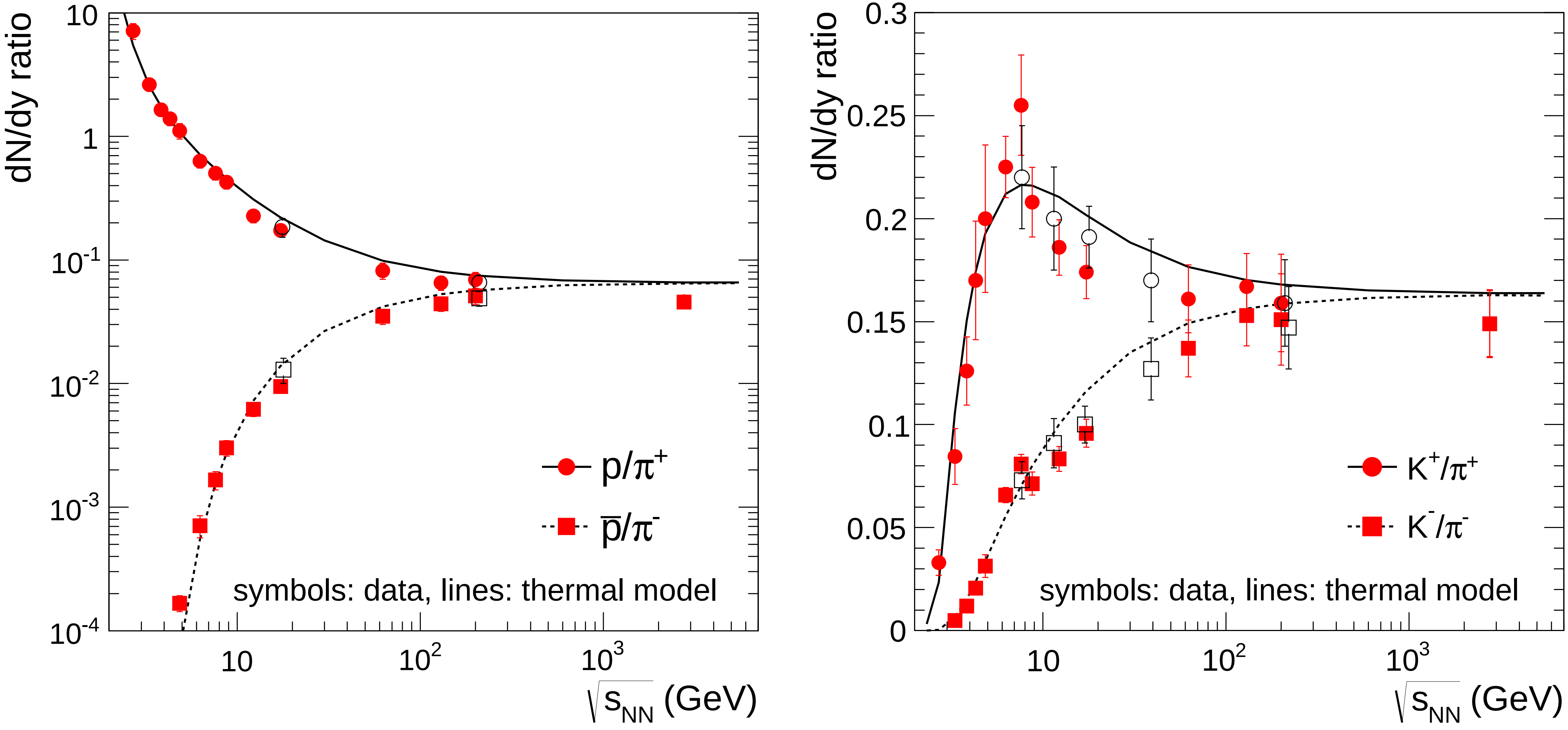

full: NA49 & STAR (p, $\bar{p}$ from w.d. subtracted); at 17 GeV open symbols NA44; at 200 GeV open symbols BRAHMS, lower energies STAR BES (prel.)

We turn now to the (gruesome:) details

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[....or can we defend the broad picture (success-story), beyond ''the 1st order''?]

Data handling [central collisions, unless mentioned otherwise, scaled to $N_{part} = 350$]

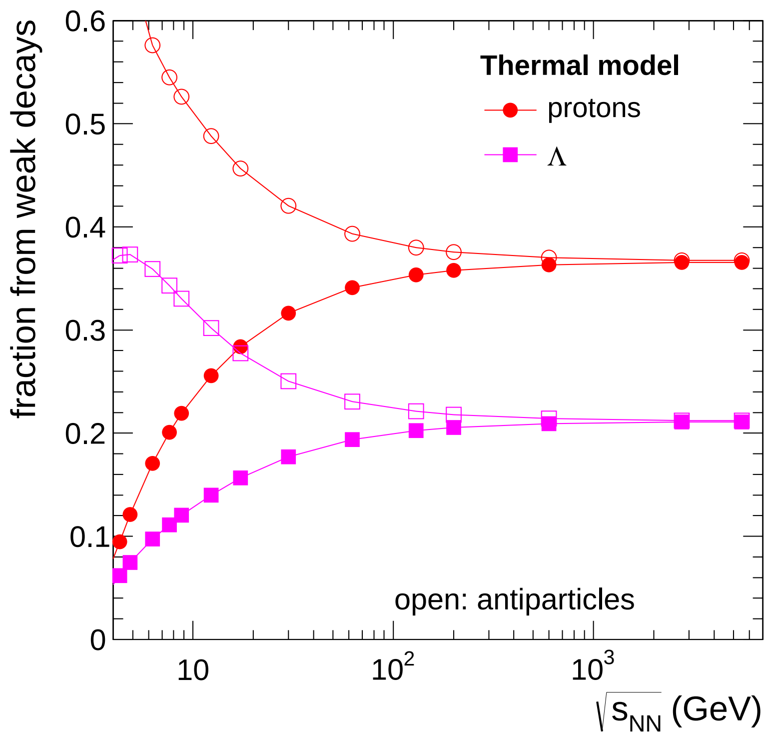
- ALICE: latest data (as of QM'14)
- STAR: all p from weak decays are in; PHENIX, BRAHMS: no π w.d. corr.

  (formerly: STAR: 2/3 p from w.d. subtracted; PHENIX, BRAHMS: 2/3 π w.d. subtracted)
- NA49: up-to-date data, July 2013

  https://edms.cern.ch/document/1075059

usually, resonances $(K^*, \Sigma^*, \Lambda^*)$ not in fit

weak decays contribution in the total yield $\Longrightarrow$
(including weak decays)



LHC, Pb–Pb, 0-10%

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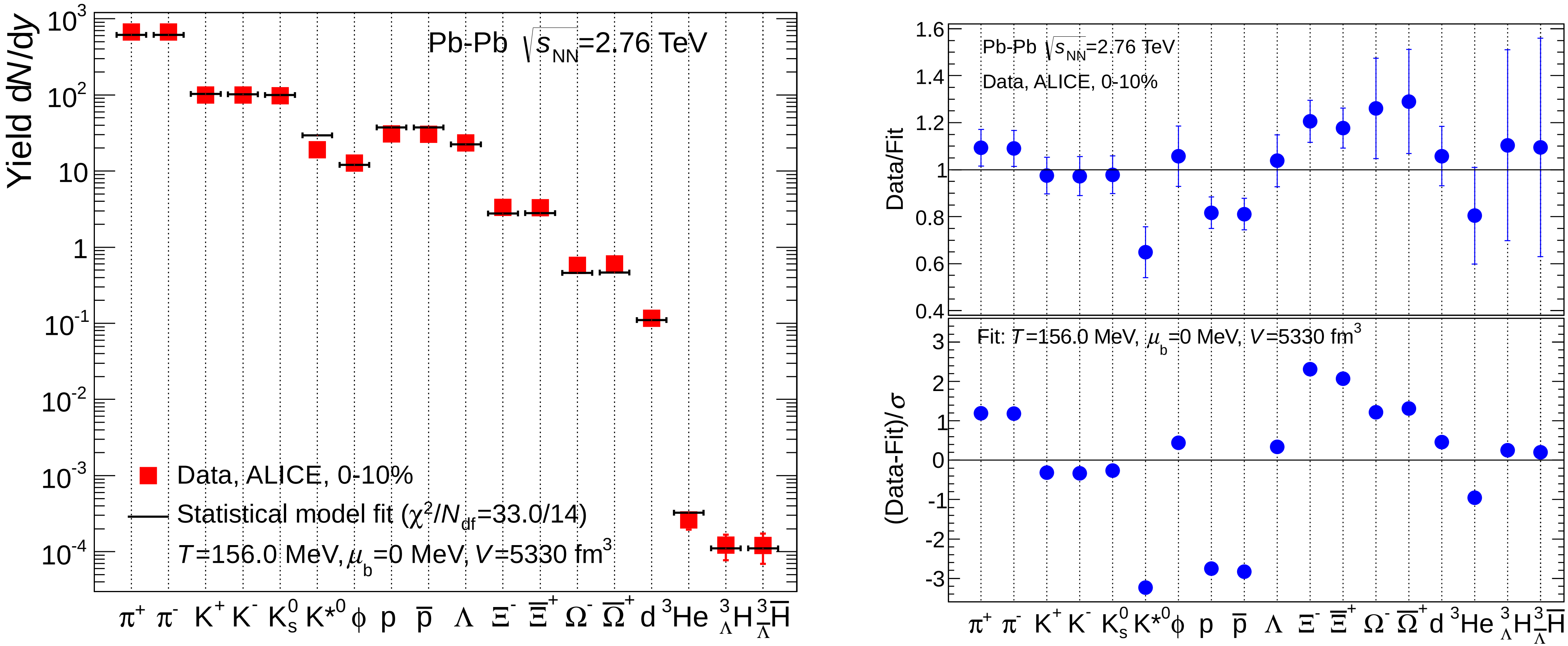

$$T = 156.0 \pm 1.5 \text{ MeV}, \ \mu_B = 0 \pm 2 \text{ MeV}, \ V = 5330 \pm 410 \text{ fm}^3$$

π, $K^{\pm}$, K^0 from charm included (0.7%, 2.6%, 2.9% for the best fit)

[no p,$\bar{\text{p}}$ in fit: $T = 158^{+1}_{-2}$ MeV, $V = 5170^{+450}_{-210}$ fm^3, χ^2/N_{df}=11.5/12]

RHIC, Au–Au 200 GeV, central

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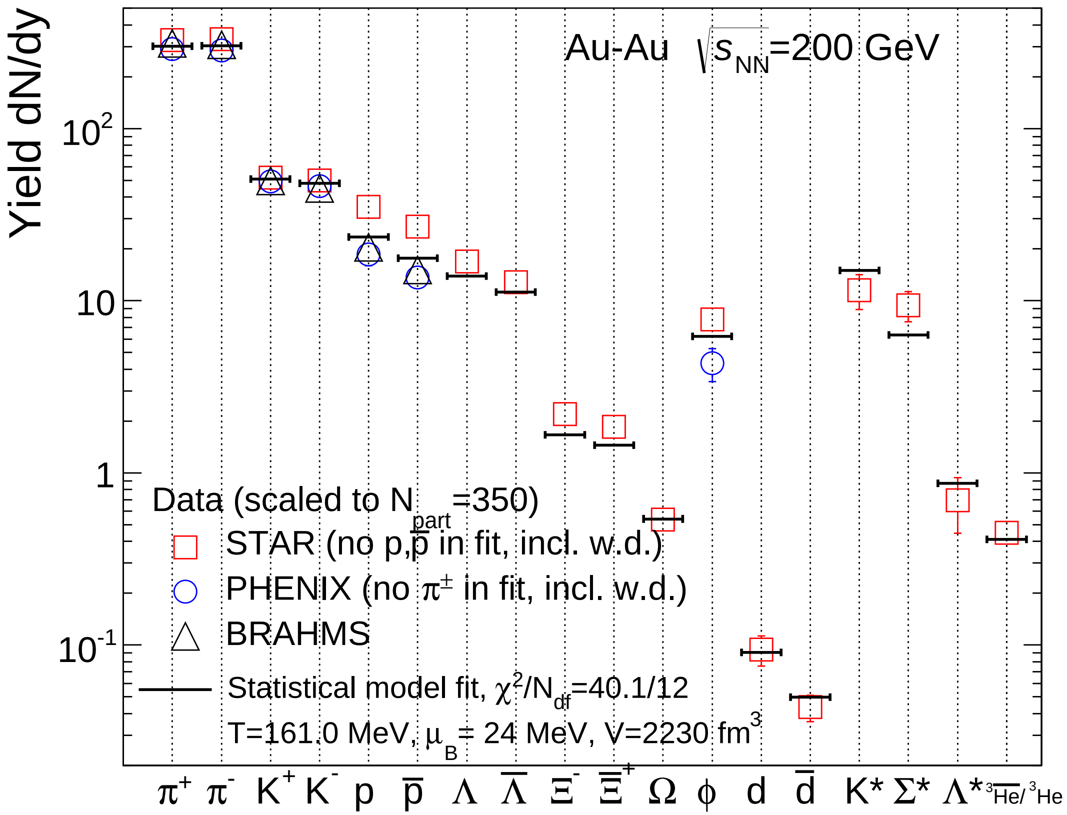

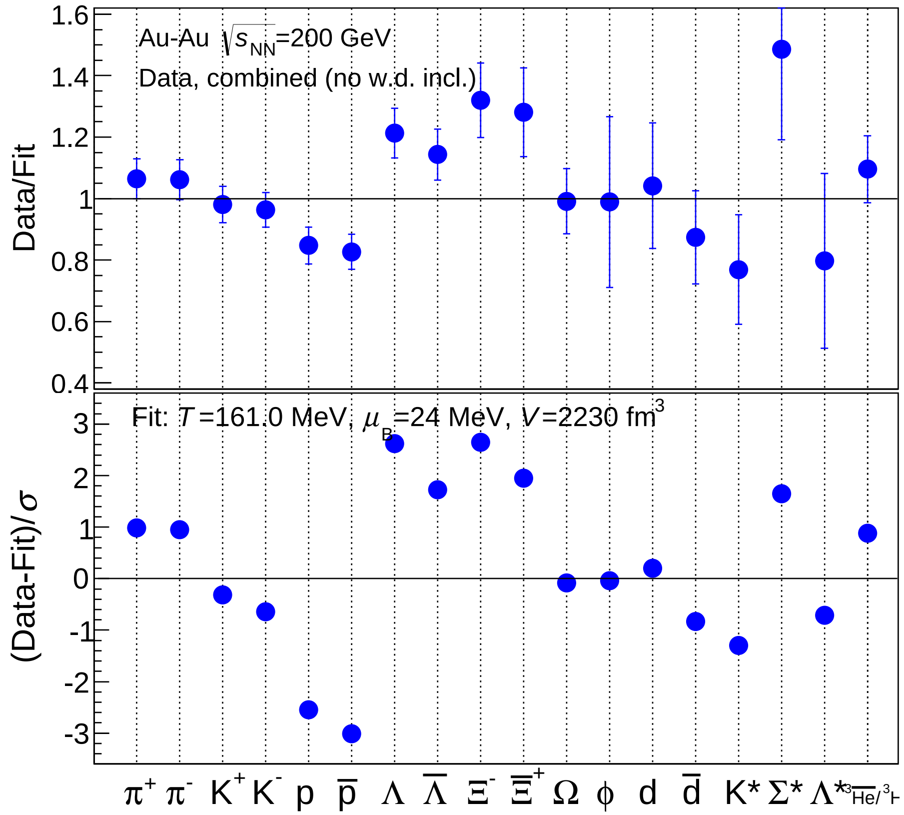

fit combined data (no w.d. contributions)

$$T = 161.0 \pm 1.5 \text{ MeV}, \ \mu_B = 24 \pm 3 \text{ MeV}, \ V = 2230 \pm 180 \text{ fm}^3$$

RHIC, Au–Au 200 GeV, central

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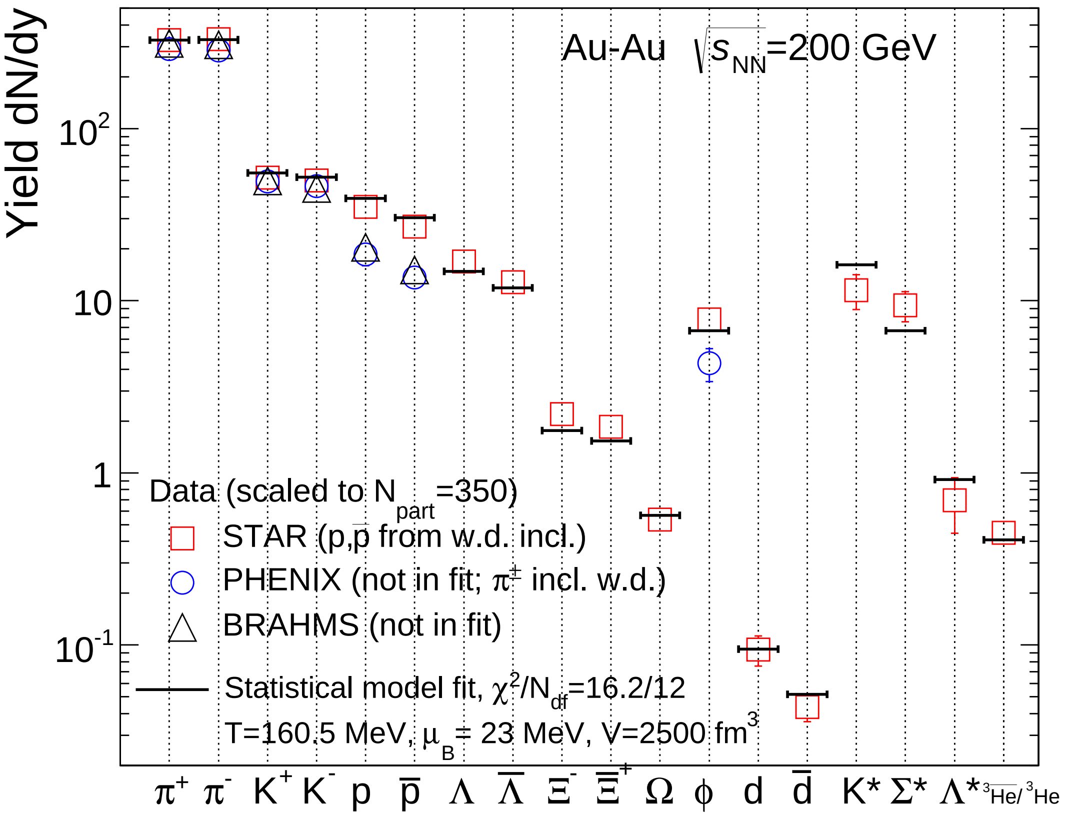

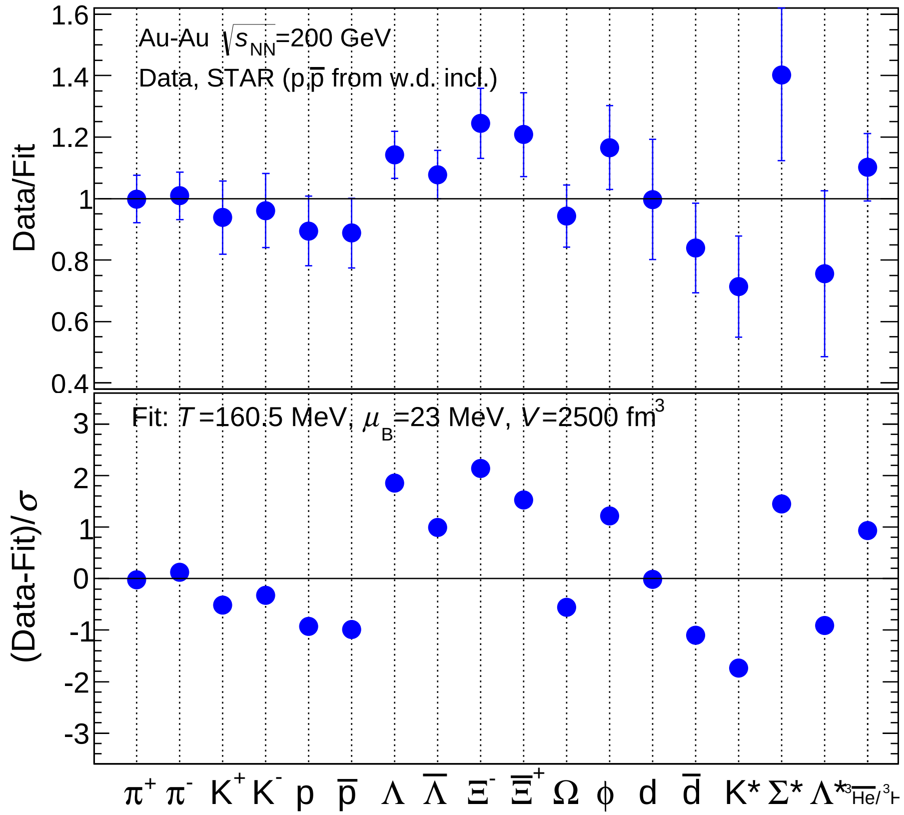

fit only STAR data (p, $\bar{p}$ from w.d. included)

$$T = 160.5 \pm 2.0 \text{ MeV}, \ \mu_B = 23 \pm 3 \text{ MeV}, \ V = 2500 \pm 260 \text{ fm}^3$$

RHIC, Au–Au 130 GeV, central

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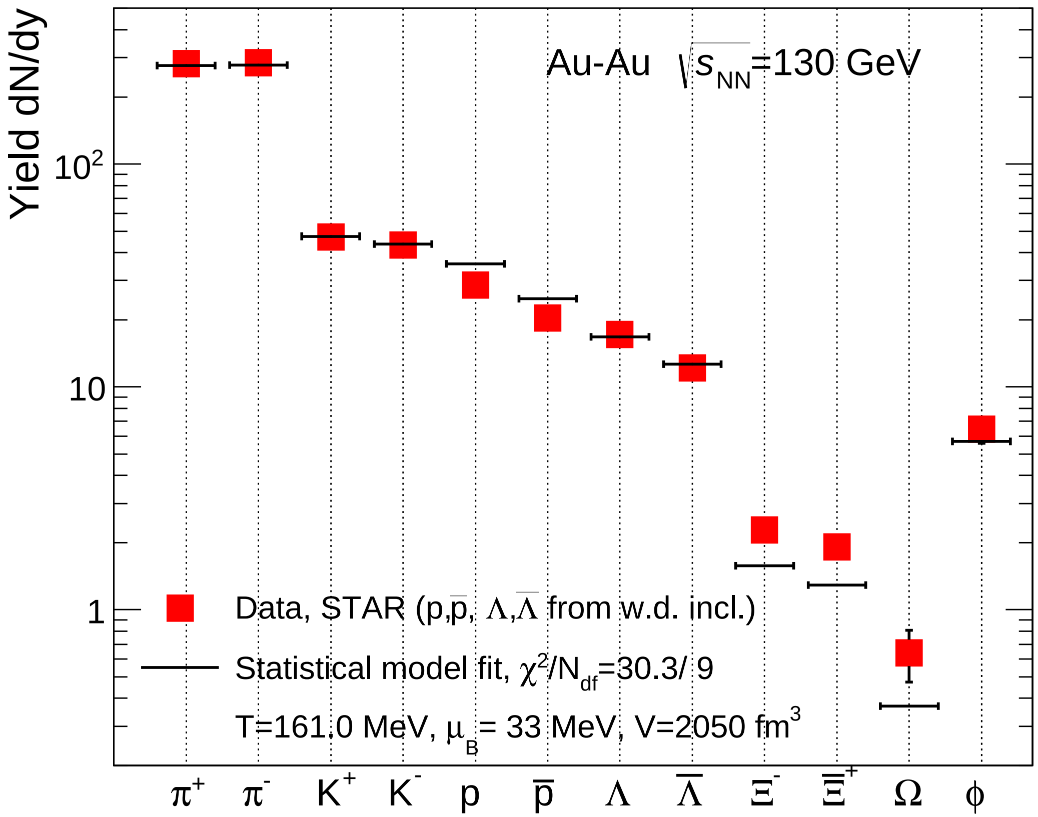

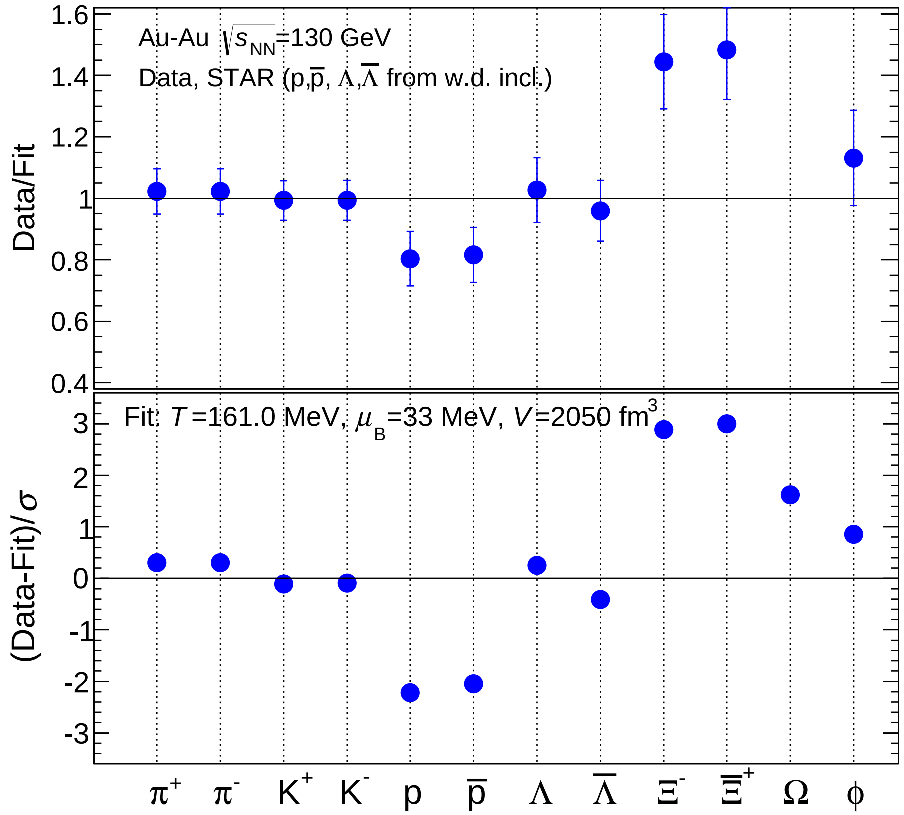

$$T = 161.0 \pm 2.5 \text{ MeV}, \; \mu_B = 33^{+11}_{-7} \text{ MeV}, \; V = 2050 \pm 230 \text{ fm}^3$$

RHIC, Au–Au 62.4 GeV, central

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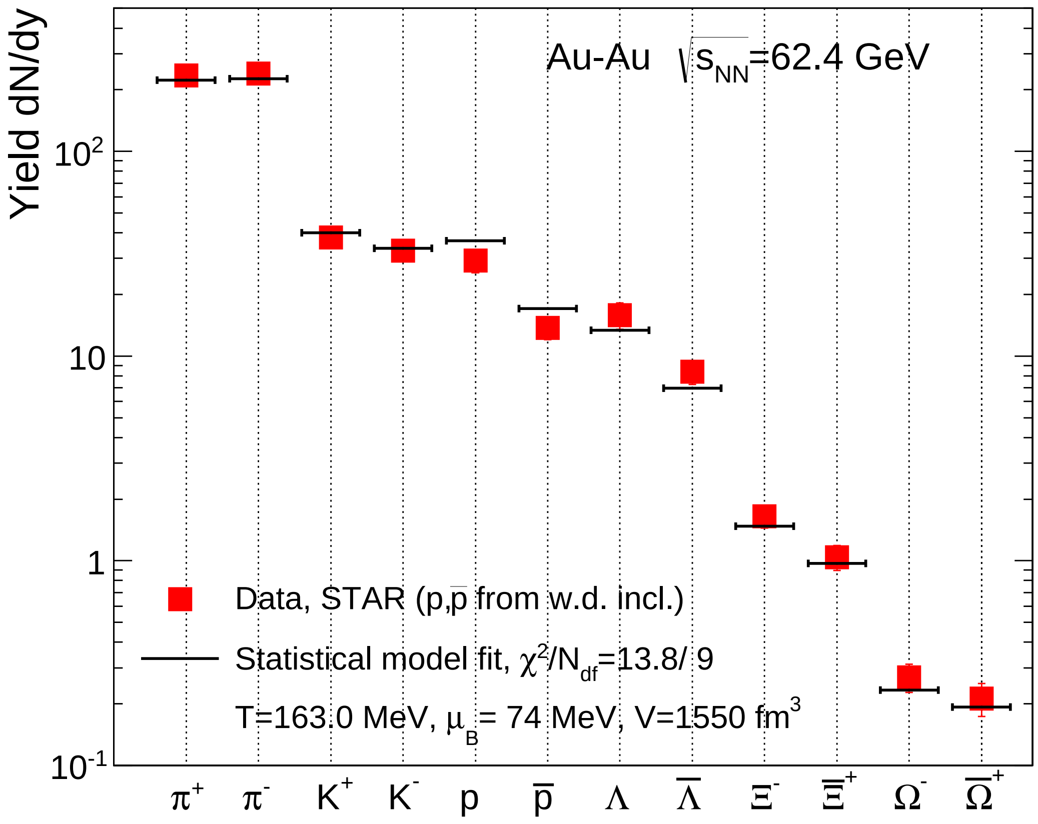

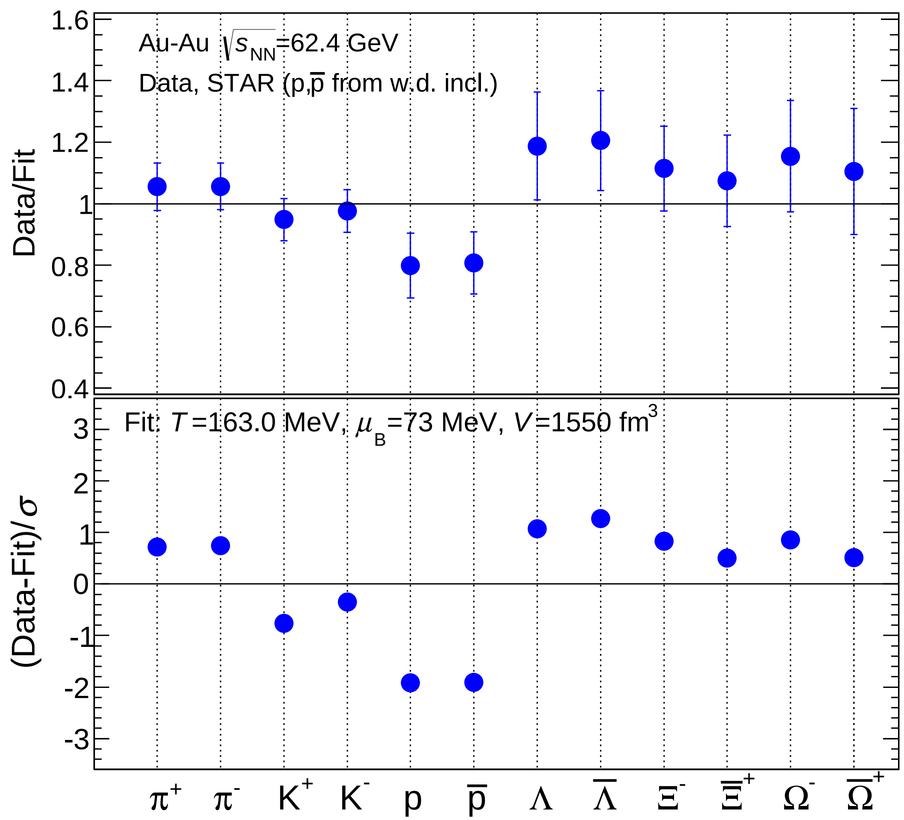

$$T = 163.0 \pm 2.5 \text{ MeV}, \ \mu_B = 74 \pm 10 \text{ MeV}, \ V = 1550 \pm 210 \text{ fm}^3$$

SPS, Pb–Pb 17.3 GeV, central

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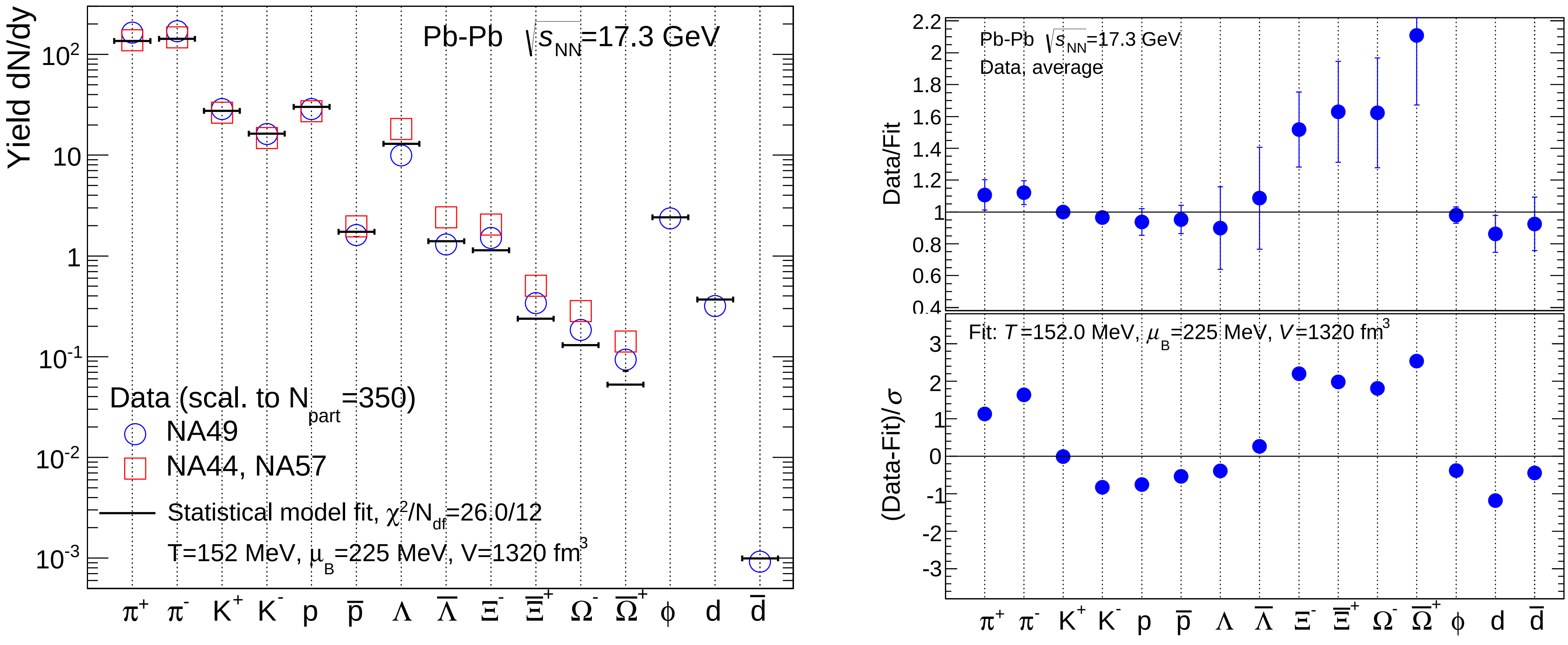

fit combined data (error-weighted averages, PDG-like)

$$T = 152.0 \pm 3.0 \text{ MeV}, \ \mu_B = 225 \pm 15 \text{ MeV}, \ V = 1320 \pm 220 \text{ fm}^3$$

SPS, Pb–Pb 17.3 GeV, central

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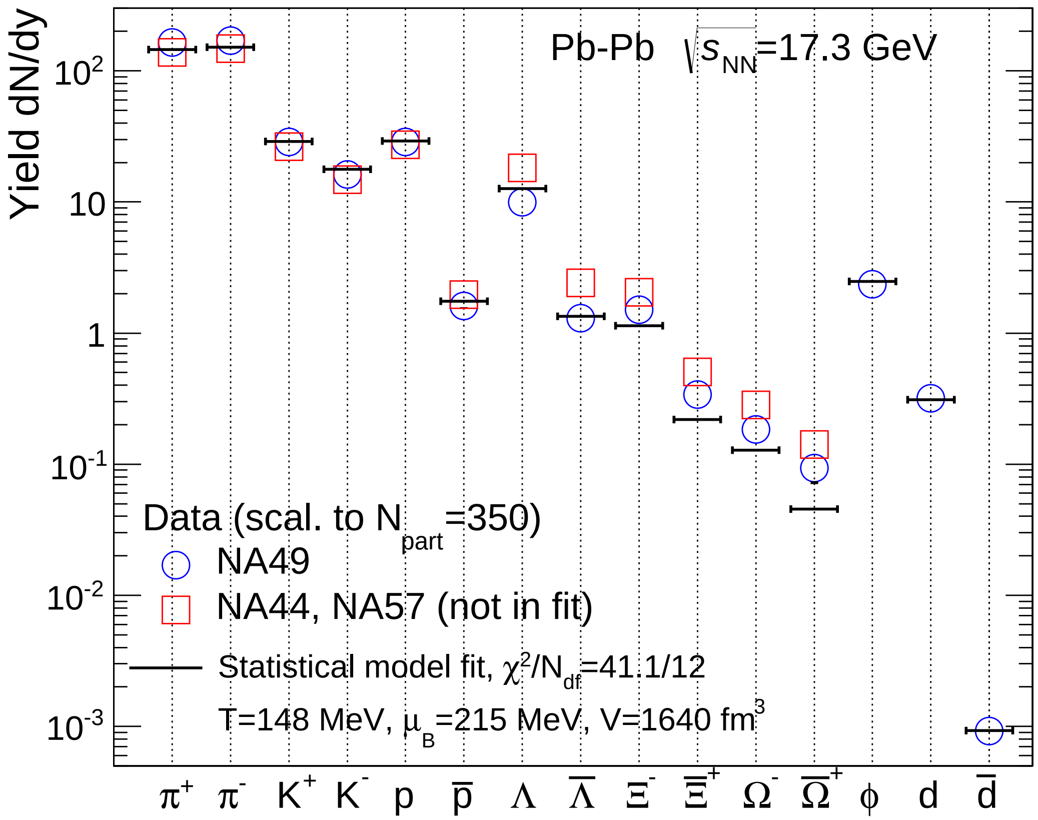

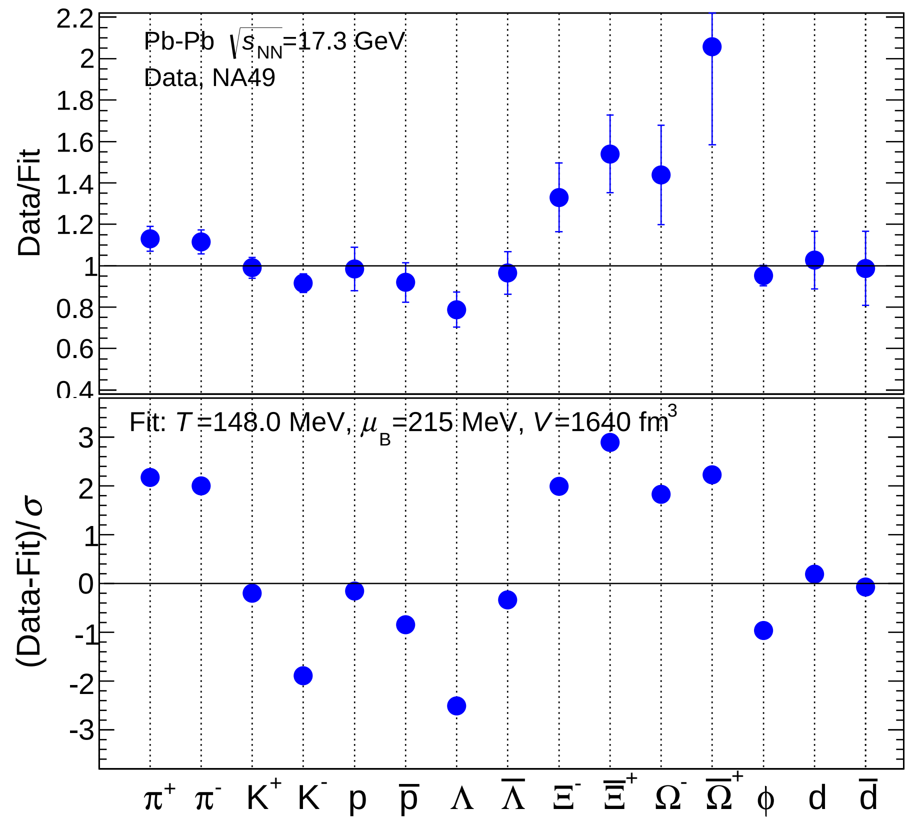

fit only NA49 data

$$T = 148.0 \pm 2.5 \text{ MeV},\ \mu_B = 215 \pm 15 \text{ MeV},\ V = 1650 \pm 210 \text{ fm}^3$$

AGS, Au–Au 4.9 GeV, central

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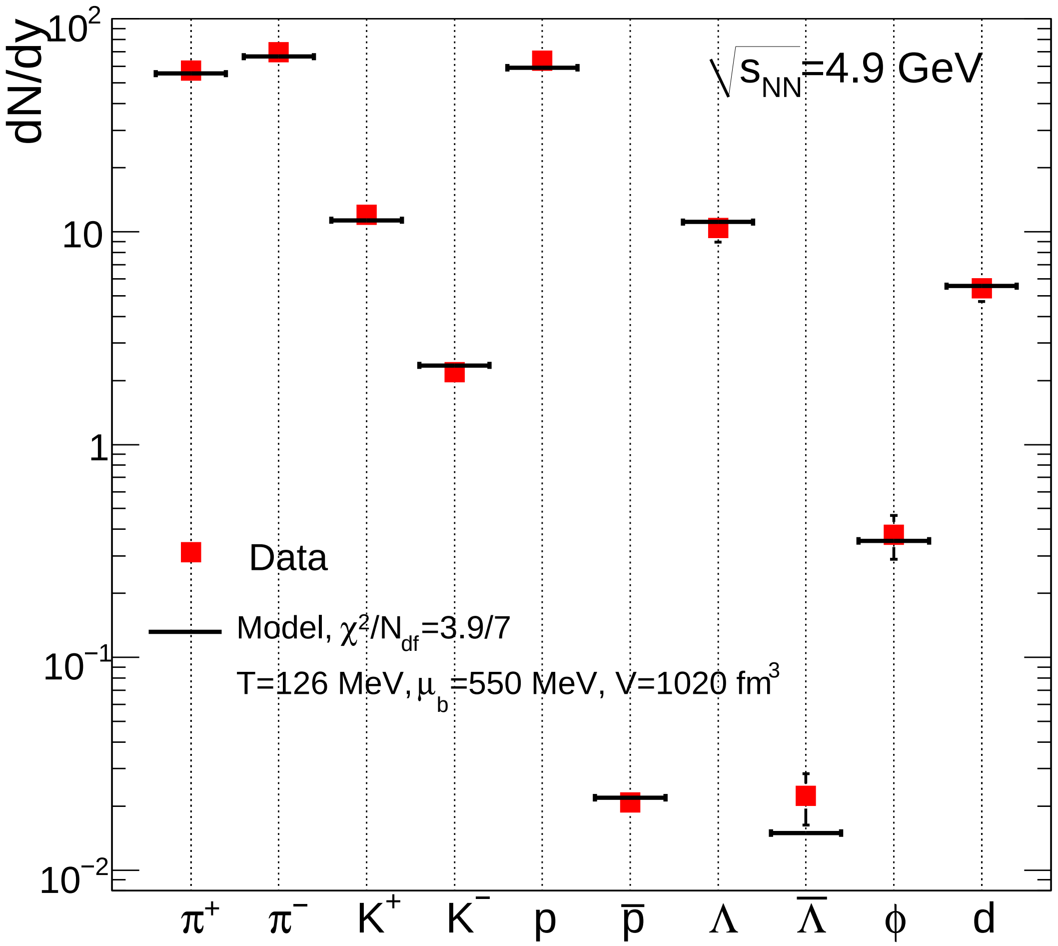

(...to close with a success case :)

fit as of 2018

Summary and outlook

the thermal model provides one clear way to obtain "experimental" points on the QCD phase diagram (via fits of u, d, s-hadron yields or fluctuations)

- thermal fits work well (AGS-LHC) with 3 parameters (T,μ_B,V)
- limiting temperature $\Rightarrow$ phase boundary ($T_{lim} \simeq T_c$)

Open issues

- proton "deficiency", most prominent at the LHC ... signals issue with (sudden) chemical freeze-out?

  there at RHIC too? why no deficit for Λ?
- significance of T decrease from RHIC to LHC?
- what will change if the still missing resonances are included (PDG 2014 and/or QM)?
- we need a better freeze-out line (phase boundary?) for μ_B >500 MeV