Hadron production in nuclear collisions and the QCD phase boundary

HELMHOLTZ GEMEINSCHAFT

- introductory remarks – quark matter and the early universe
- hadron production, statistical model and the QCD phase boundary
- chemical freeze-out and the case of weakly bound objects
- turning things upside-down: quark matter and exotica

FIAS-Frankfurt

work based on collaboration with

A. Andronic, K. Redlich, and J. Stachel

EMMI

remembering Gerry Brown

Stony Brook, Nov. 2013

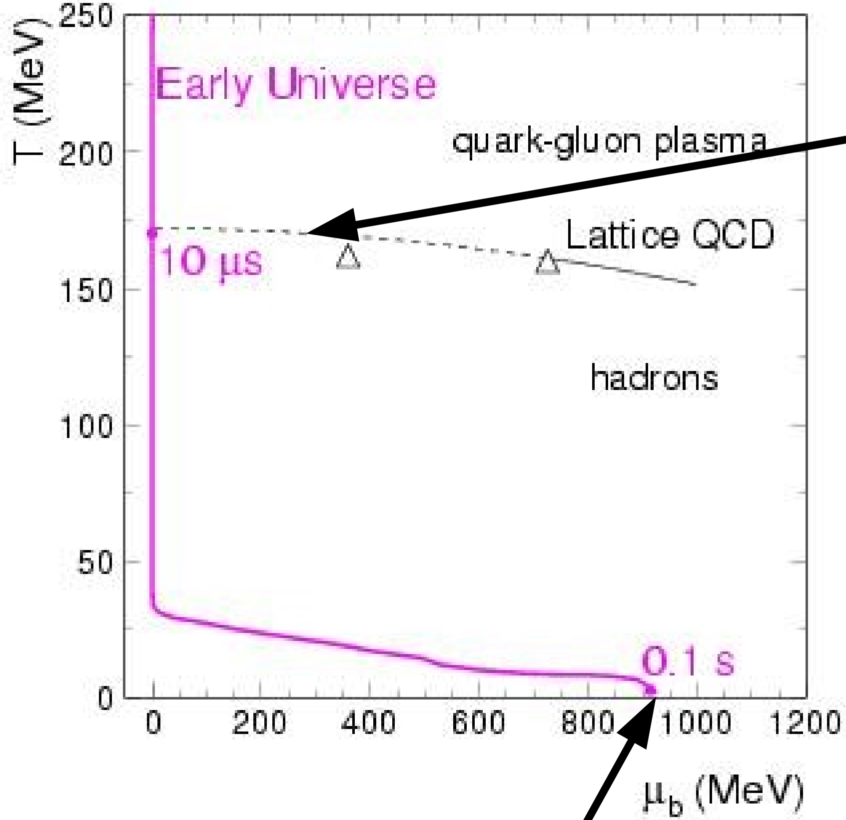
Peter Braun-Munzinger

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT


PHYSICS REPORTS
NUCLEAR PHYSICS A
THE NORTH FACE

Evolution of the Early Universe



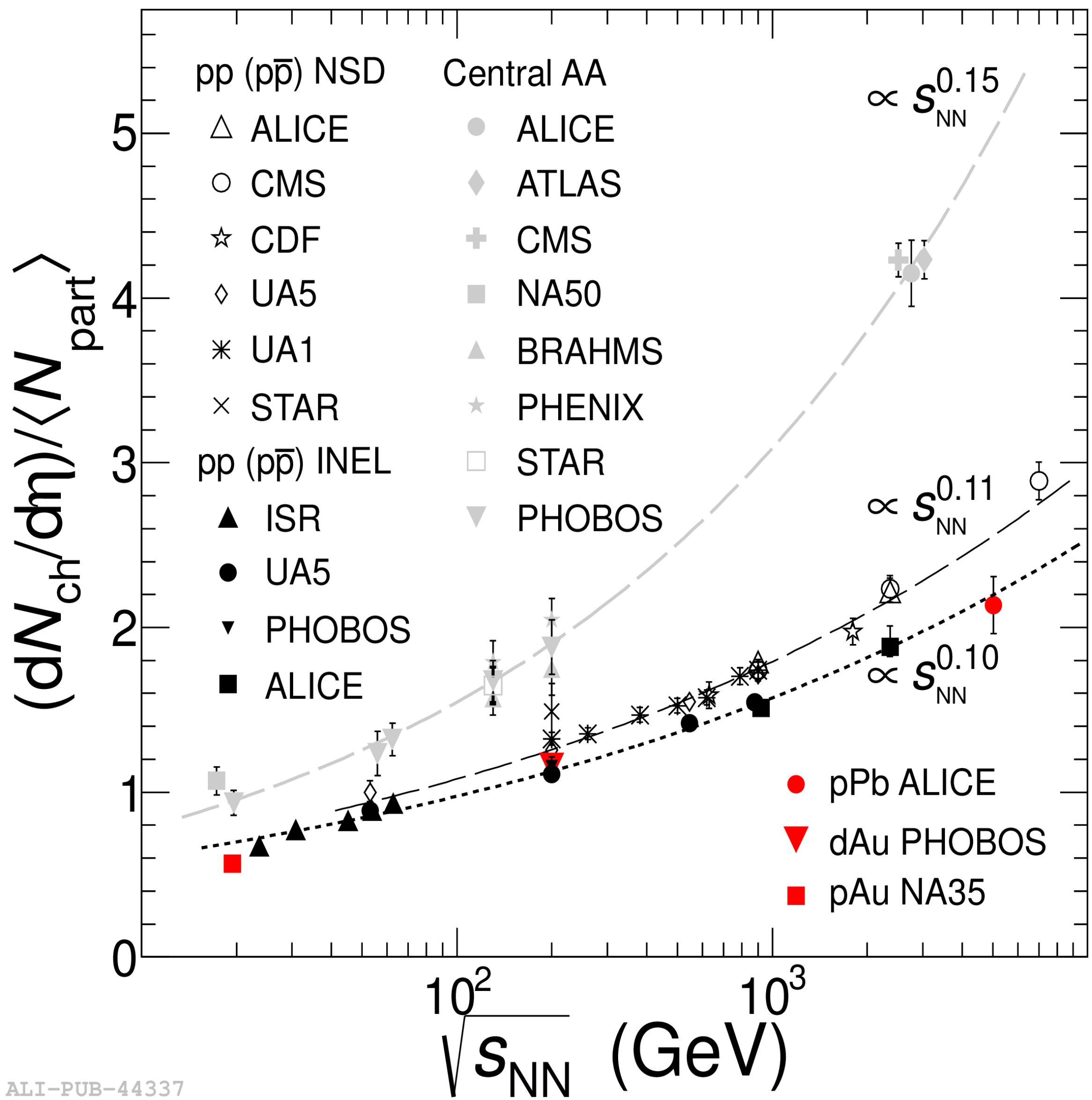
QCD Phase Boundary

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

Charged particle multiplicity in pp, pPb and central PbPb collisions



increase with beam energy significantly steeper than in pp

can the fireball formed in central nuclear collisions be considered matter in equilibrium?

Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: an important test of equilibration of quark matter near the phase boundary, **no equilibrium → no QGP matter**

- No (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis

pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69

- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

Gerry and the QCD phase boundary

The Vector Manifestation of Hidden Local Symmetry, Hadronic Freedom and the STAR ρ^0/π^- Ratio

G.E. Brown,[1] Chang-Hwan Lee,[2] and Mannque Rho[3]

Model of the thermodynamics of the chiral restoration transition

V. Koch, G.E. Brown (SUNY, Stony Brook). 1993. 20 pp.

The Vector Manifestation of Hidden Local Symmetry, Hadronic Freedom and the STAR ρ^0/π^- Ratio

G.E. Brown,[1] Chang-Hwan Lee,[2] and Mannque Rho[3]

E.V. Shuryak and G.E.Brown

Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA

(February 1, 2008)

The cooling of anti-protons in nuclear matter
G.E. Brown, V. Koch (SUNY, Stony Brook),
C.M. Ko (Texas A-M).

Medium effects on kaon and antikaon spectra in heavy-ion collisions
X.S. Fang, C.M. Ko (Texas A-M, Cyclotron Inst. & Texas A-M),
G.E. Brown, V. Koch (SUNY, Stony Brook). Apr 1993. 4 pp. Published in Phys.Rev. C47 (1993) 1678-1682

The QCD phase diagram and chemical freeze-out

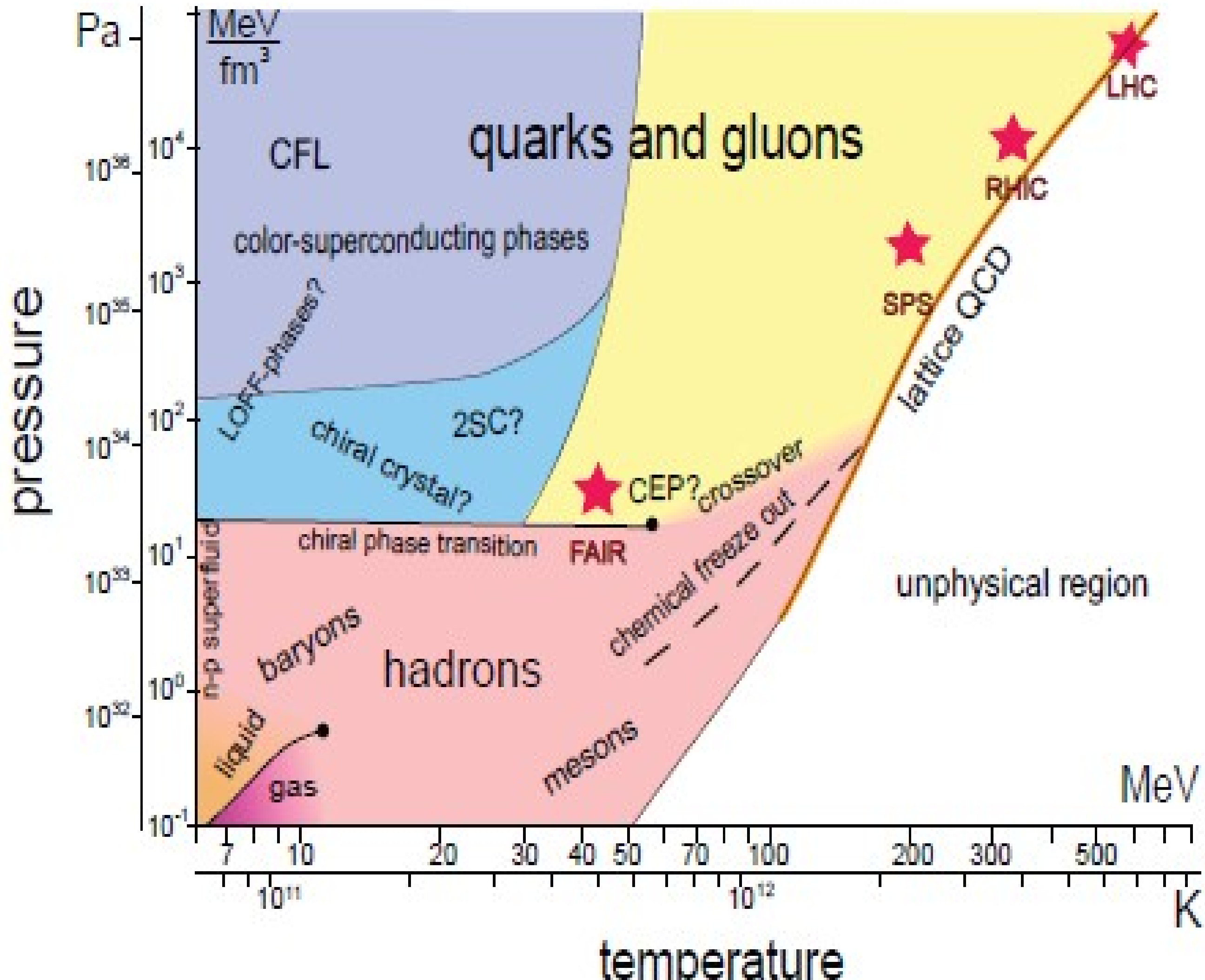
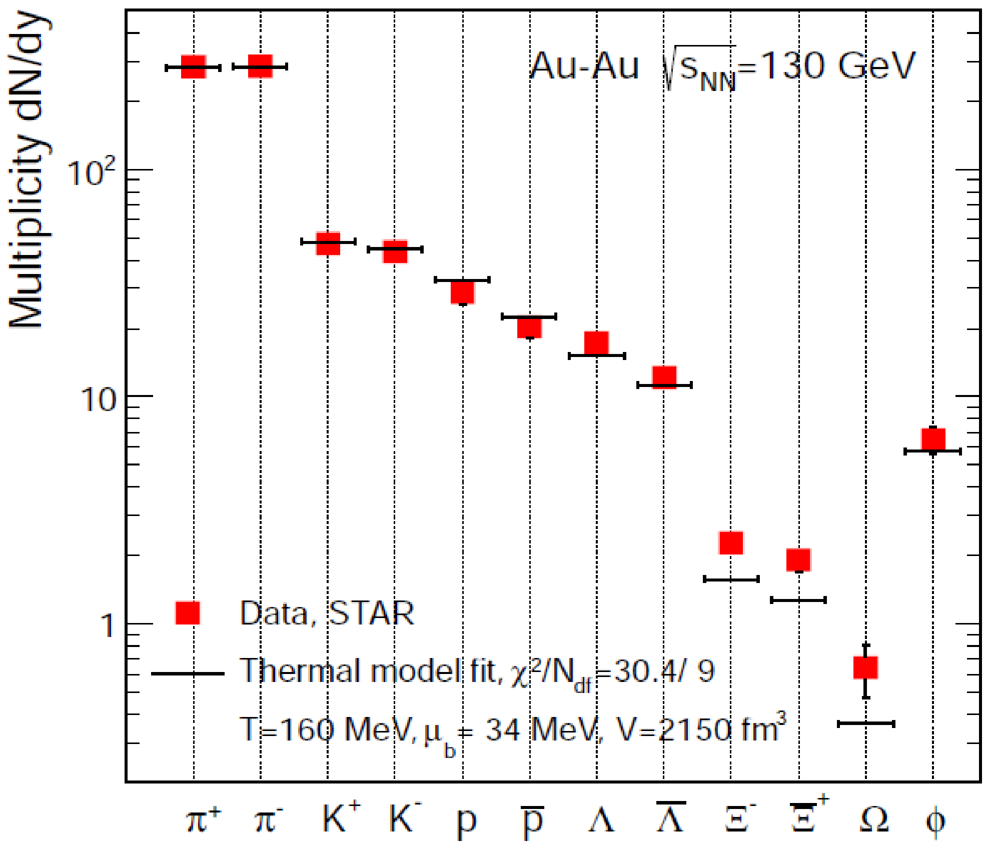
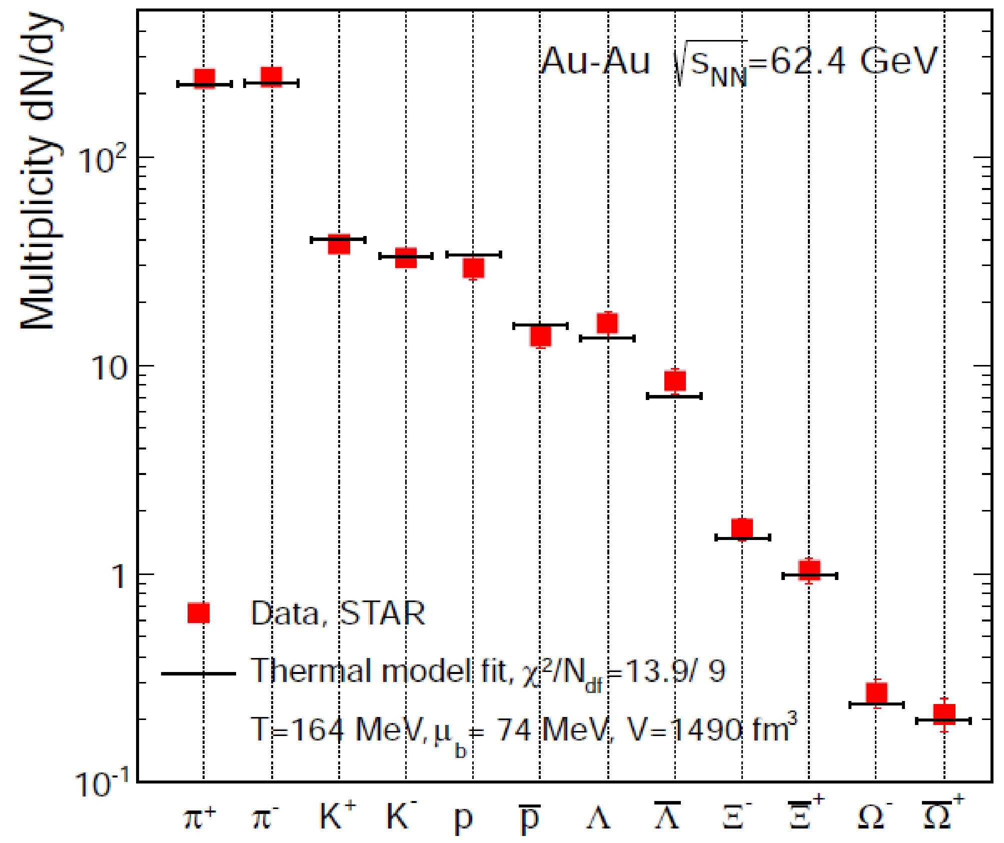


fig. from Wambach, Heckmann, Buballa, arXiv:1111.5475

Summary of pre-LHC era

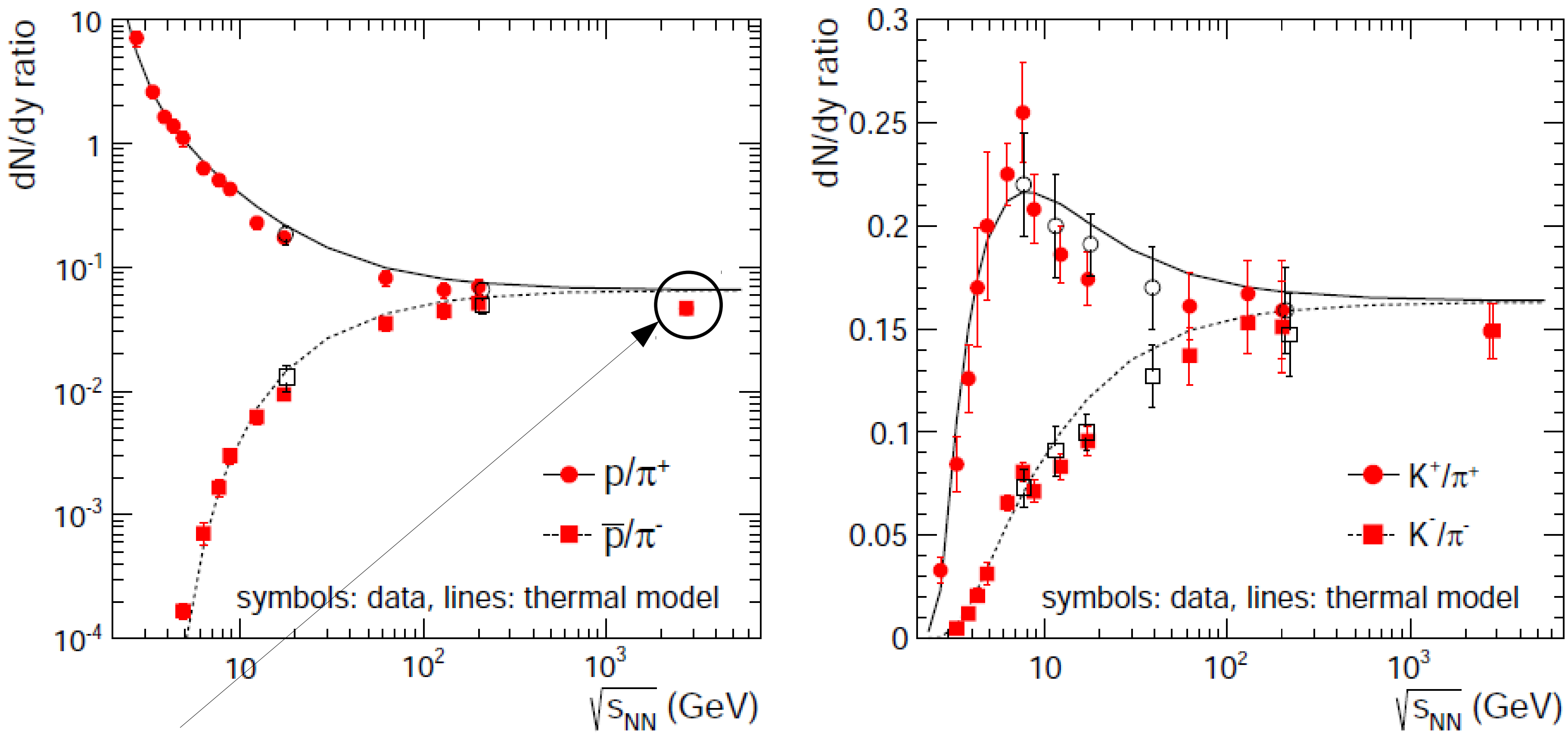
example of thermal fits: RHIC lower energies, STAR data alone





good fits, T = 160 – 164 MeV

overall systematics, including ALICE data, on proton/pion and kaon/pion ratios



proton anomaly?

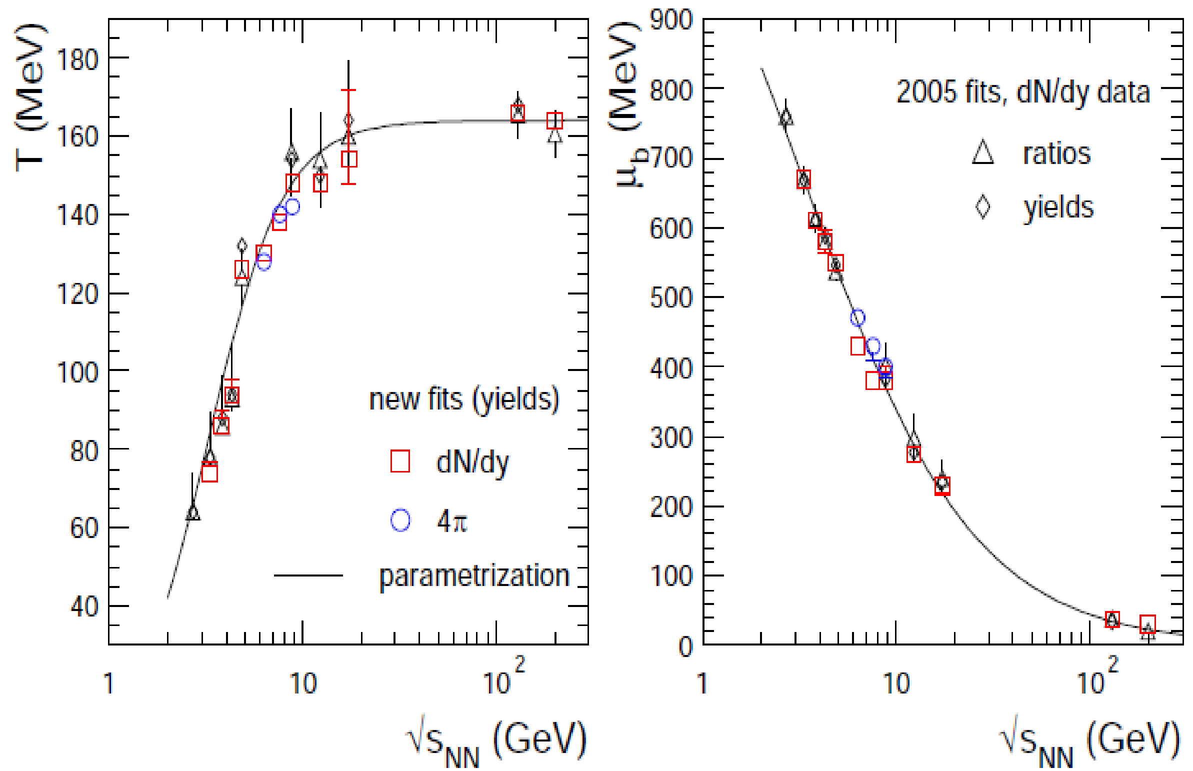
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 161 +/- 4 MeV

get T and μ_B for all energies

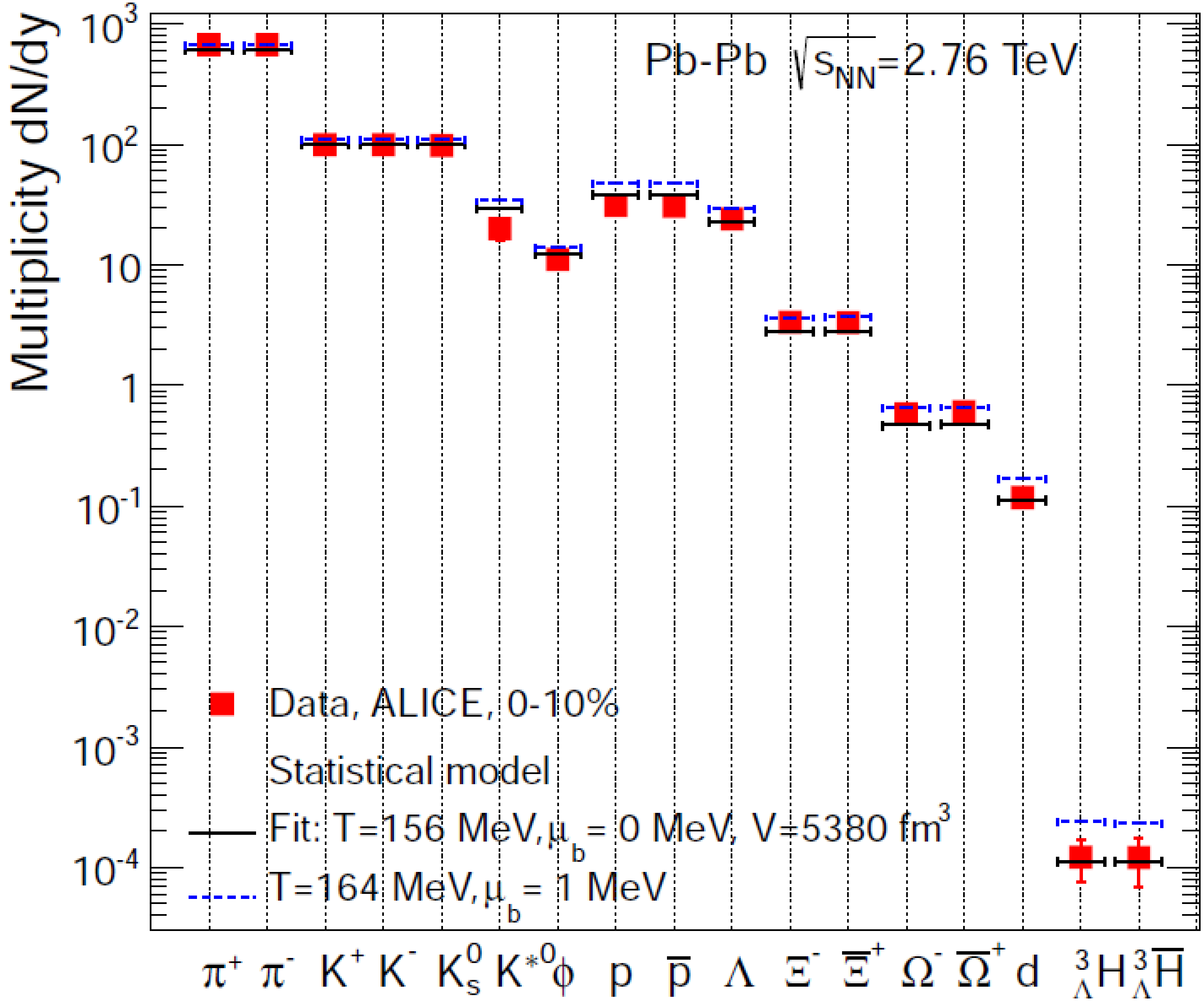
for LHC predictions we picked T = 161 MeV and, later, 164 MeV



A. Andronic, pbm, J. Stachel,
Nucl. Phys. A772 (2006) 167, nucl-th/0511071 ,
J. Phys. G38 (2011) 124081

T_{lim} = 161 MeV is the QCD phase transition temperature

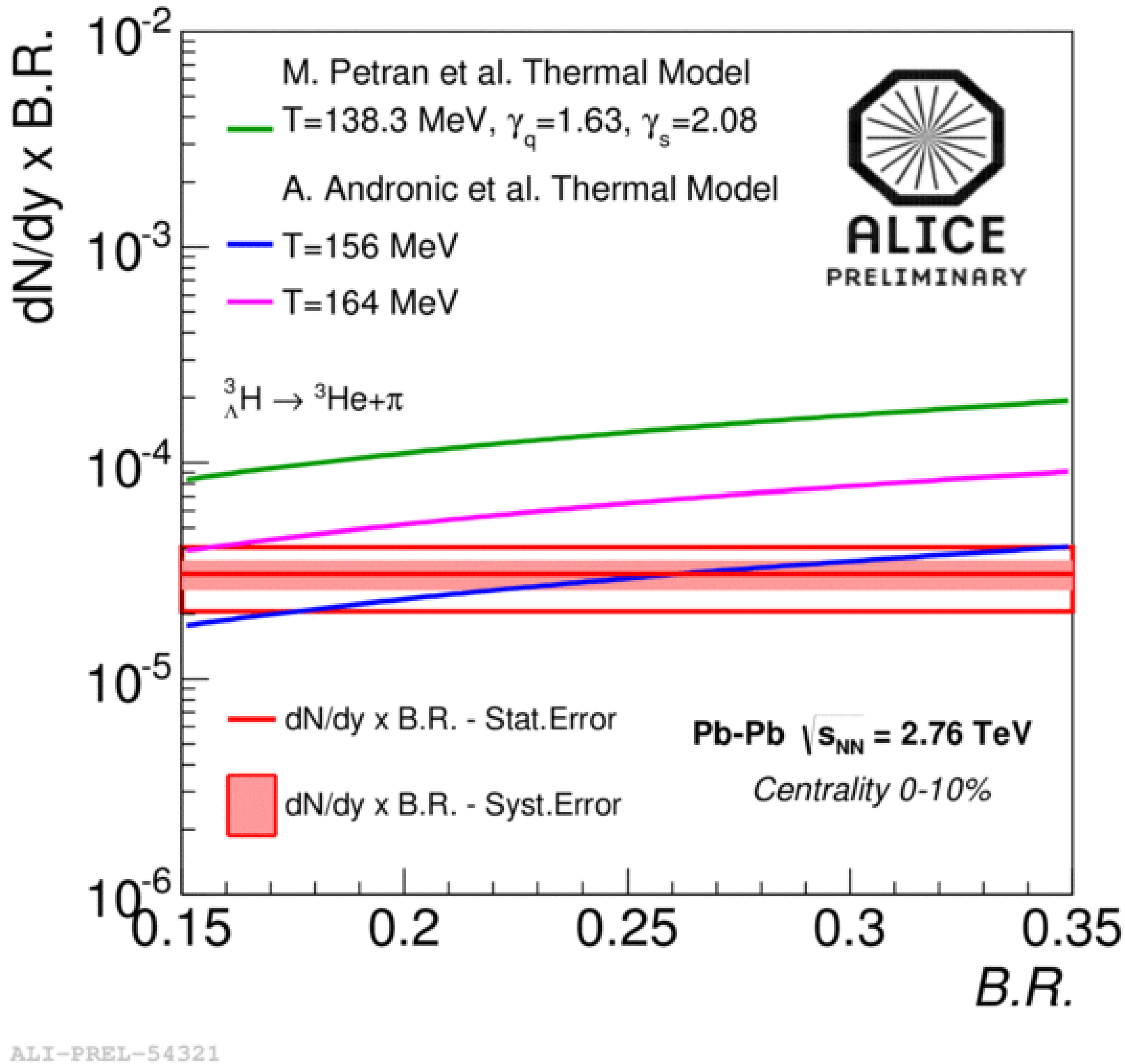
newest fit of Alice data including hypertriton



J. Stachel, A. Andronic, pbm, K. Redlich, arXiv:1311.

very good fit for T = 156 MeV also works for hypertriton
good agreement over nearly 7 orders of magnitude

Hypertriton yield x branching ratio and the thermal model

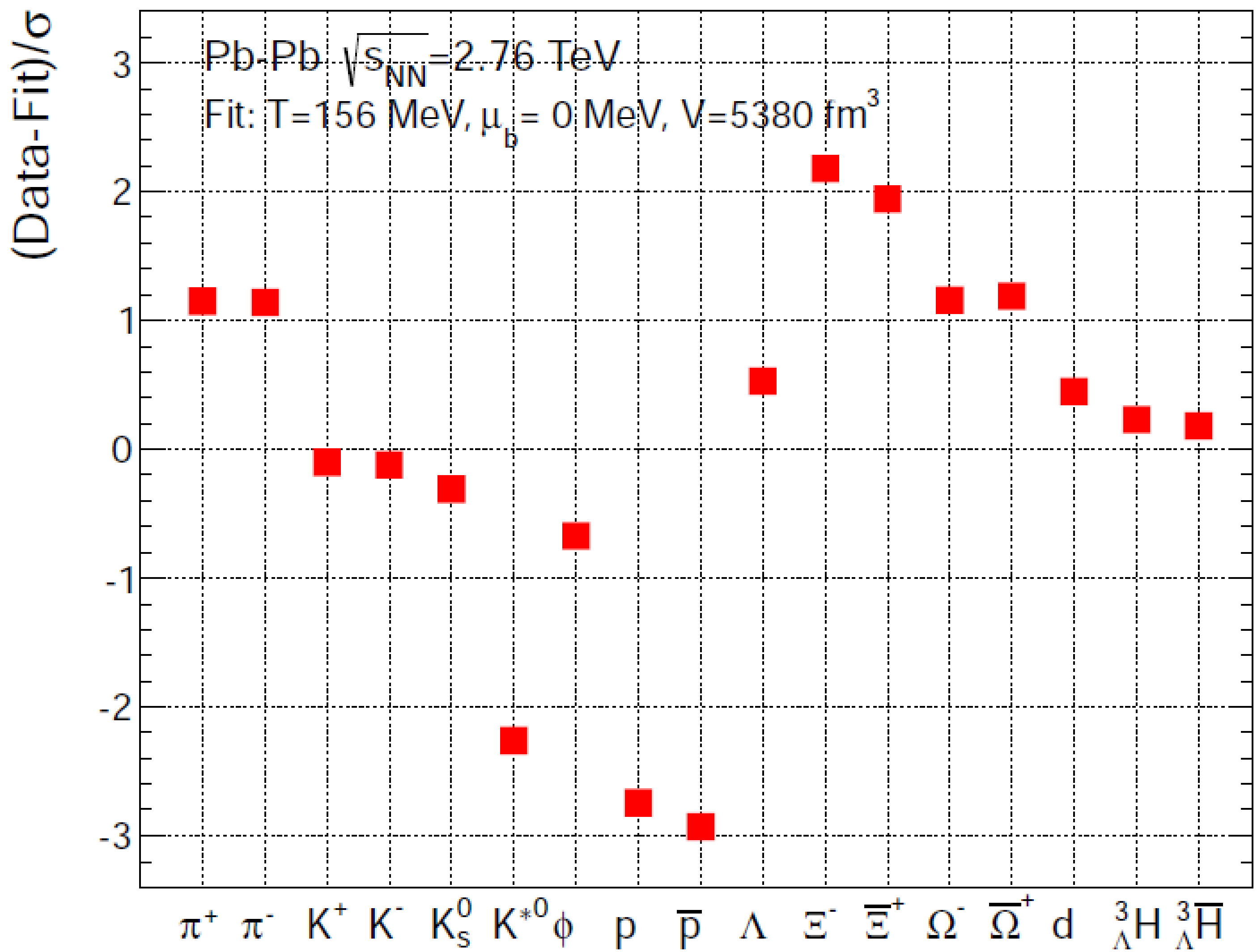


analysis spearheaded by Ramona Lea, ALICE

T = 156 MeV provides very good description

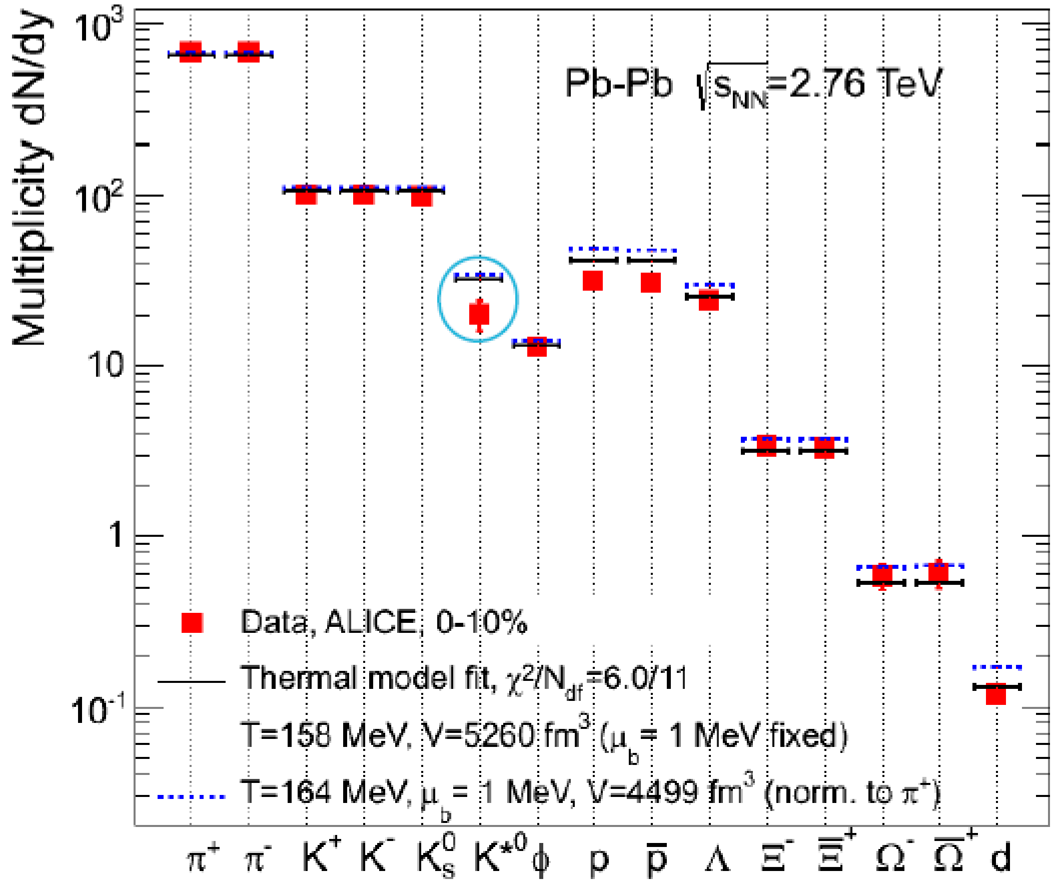
Note: binding energy of hypertriton is 100 keV!!
Most likely B.R. = 0.25 (also used by STAR)

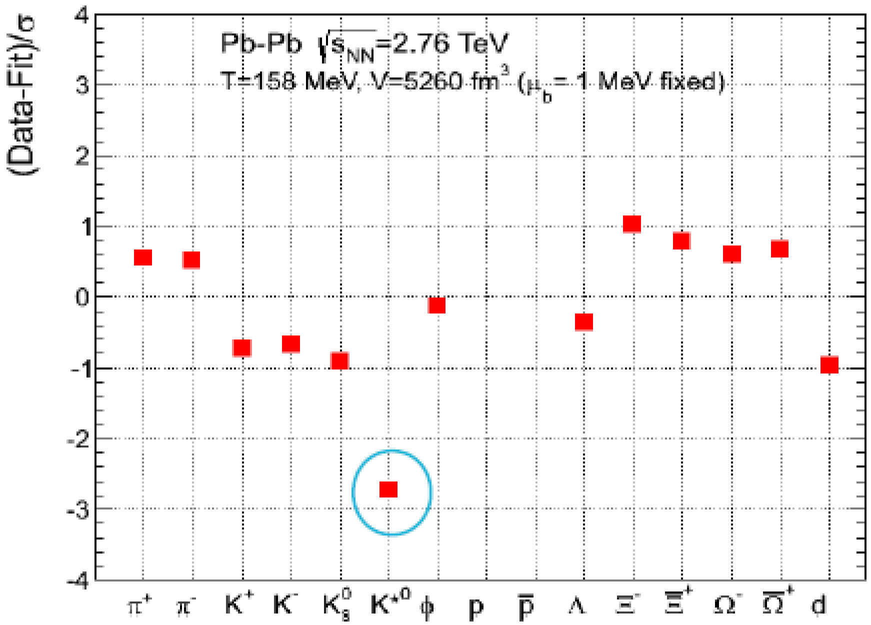
analyzing the deviations from the fit



chi^2/ndf = 2.4 (anti)protons differ from fit by (19.4%) 18%
corresponding to (2.9 sigma) 2.7 sigma

fit to data excluding protons





excellent fit, T = 158 MeV chi^2/ndf < 1

where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156 MeV

fit without protons yields slighty higher T = 158 MeV, driven by hyperons

important note: corrections for weak decays

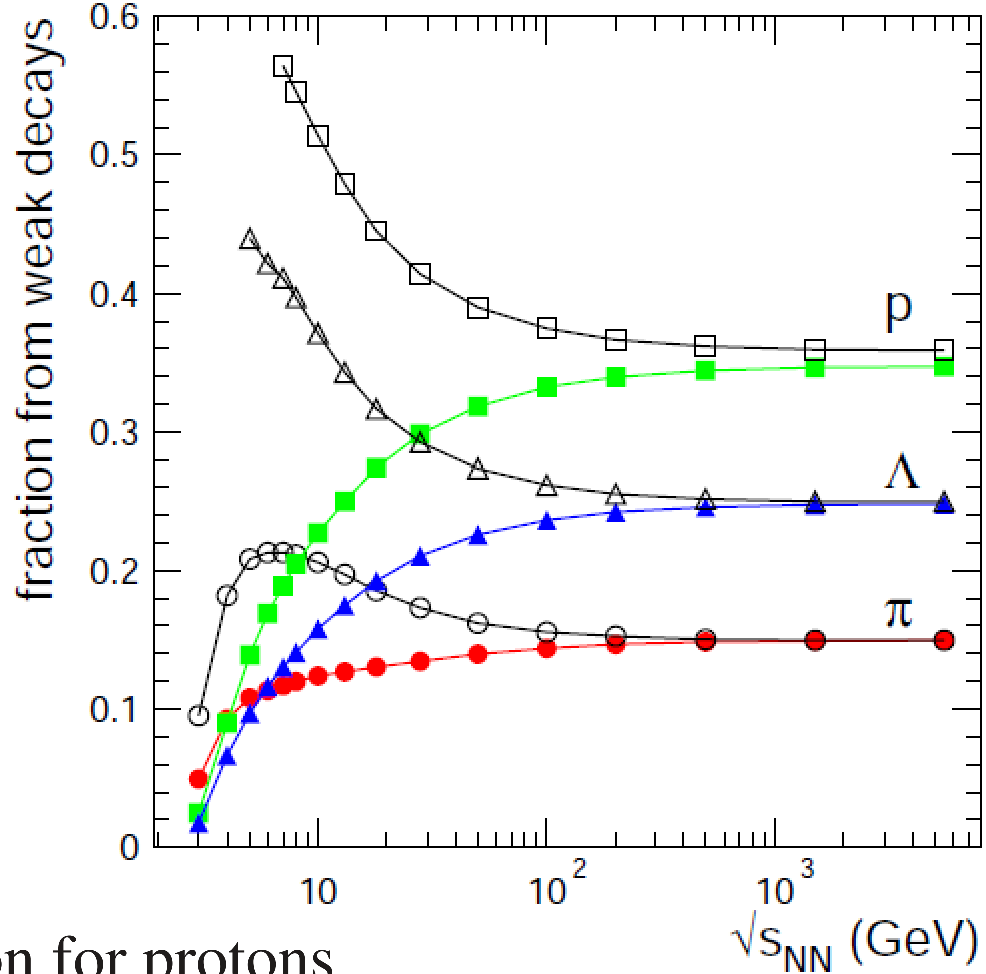
All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

in light of high precision LHC data the corrections done at RHIC may need to be revisited.

treatment of weak decays

fraction of yield from weak decays



biggest correction for protons
done in hardware (vertex cut) at ALICE
software corrections at all lower energies

Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

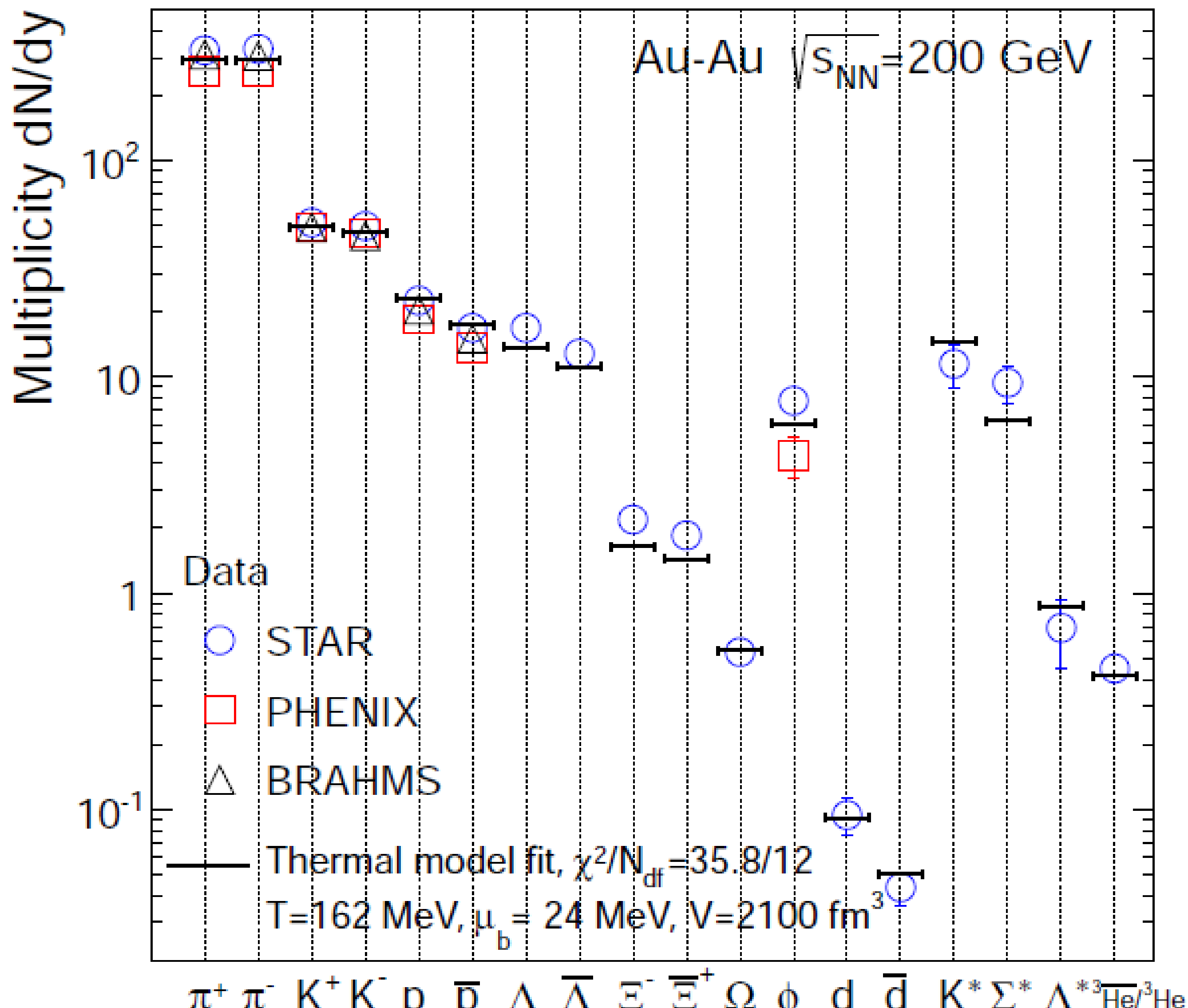
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments

Au+Au central at 200 GeV, all experiments combined

T = 162 MeV



could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation

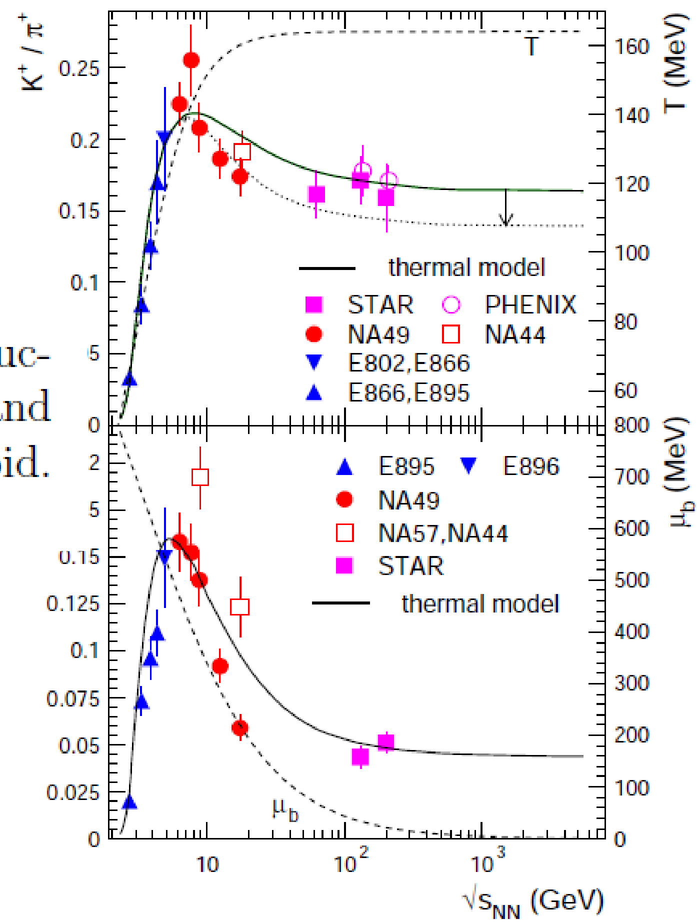
could it be incomplete hadron resonance spectrum?

Note: because of baryon conservation, adding more baryon resonances will decrease in the model the p/pi ratio

An N* will decrease dominantly into 1 N + a number (depending on the N* mass) of pions

Same effect seen in
K/pi ratio because of strangeness conservation

A. Andronic, P. Braun-Munzinger, J. Stachel, Thermal hadron production in relativistic nuclear collisions: the sigma meson, the horn, and the QCD phase transition, Phys. Lett. **B673** (2009) 142, erratum ibid. **B678** (2009) 516, arXiv:0812.1186.



could it be proton annihilation in the hadronic phase?

F. Becattini et al., Phys. Rev. C85 (2012) 044921 and arXiv: 1212.2431

• need to incorporate detailed balance, 5pi → p p_bar
not included in current Monte Carlo codes (RQMD)

• taking detailed balance into account reduces effect strongly,
see Rapp and Shuryak 1998

• see also W. Cassing, Nucl. Phys. A700 (2002) 618
and recent reanalysis, by Pan and Pratt, arXiv:

• agreement with hyperon data would imply strongly reduced
hyperon annihilation cross section with anti-baryons → no
evidence for that

the 'proton anomaly' and production of light nuclei

can the measurement of d, t, 3He and 4He settle the issue?
what about hypertriton?

important to realize: production yield of deuterons is fixed at $T = T_{chem} = 156$ MeV even if $E_B(d) = 2.3$ MeV!

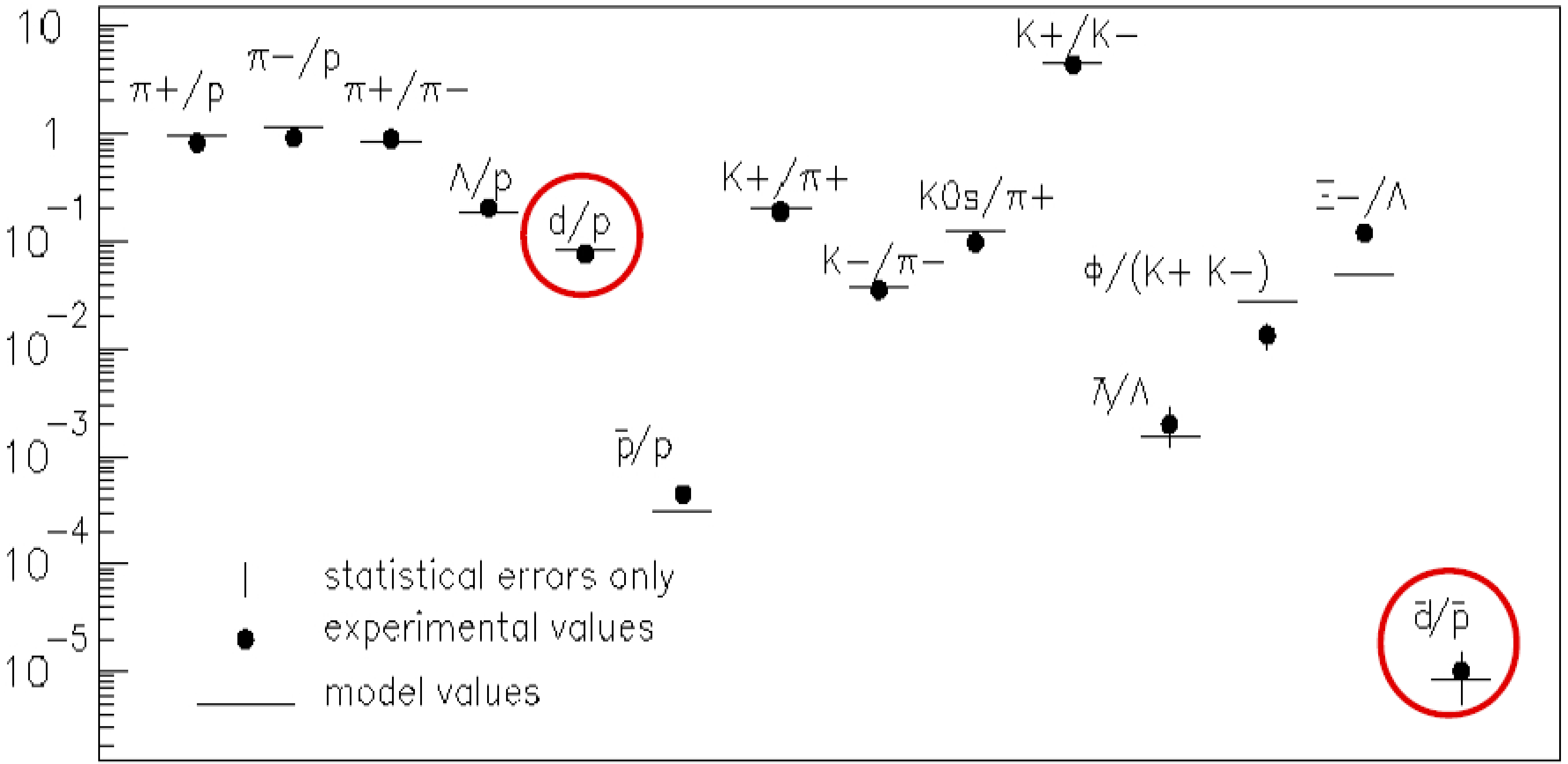
entropy/baryon is proportional to $-\ln(d/p)$ and is conserved after T_{chem}

good agreement with LHC d and hyper-triton yield implies: there is no shortage of protons and neutrons at chemical freeze-out, inconsistent with annihilation scenario

deuterons and anti-deuterons also well described at AGS energy

14.6 A GeV/c central Si + Au collisions and GC statistical model

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994



dynamic range: 9 orders of magnitude! No deviation

The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, hypertriton, …
implies no entropy production after chemical freeze-out

hypertriton binding energy is 100 keV << T_chem = 156 MeV

use relativistic nuclear collision data and thermal model predictions to search for exotic objects

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

The 'snowball in hell' story

Production of strange clusters and strange matter in nucleus-nucleus collisions at the AGS

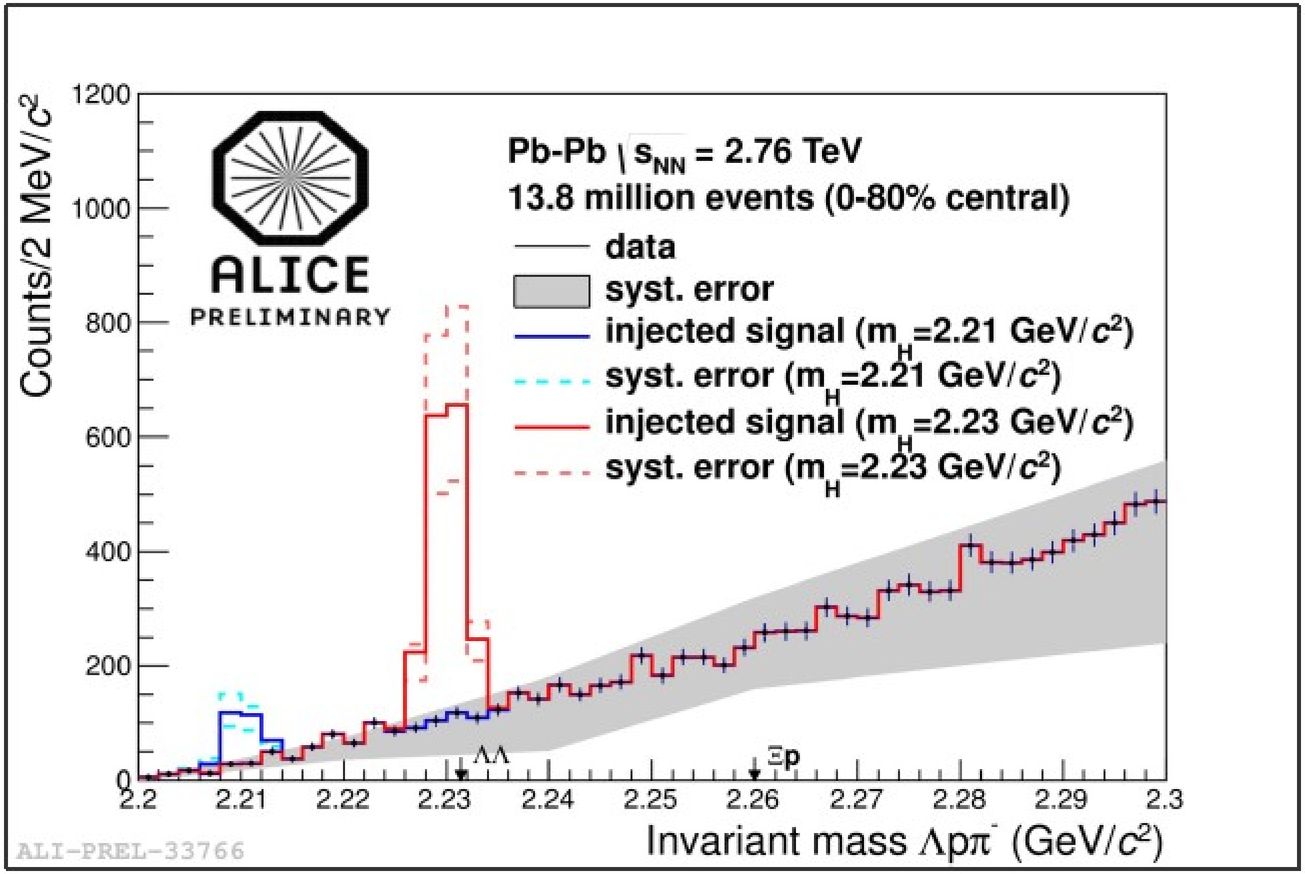
P. Braun-Munzinger, J. Stachel (SUNY, Stony Brook). Dec 1994. 9 pp.

Published in J.Phys. G21 (1995) L17-L20

In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, α ...) and for for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.

example: search for H-Dibaryon

Ramona Lea, SQM2013



No signal observed, H yield is < 0.1 x (thermal model prediction)
Much more stringent limits to come soon

summary

the Pb-Pb central collision hadron yields from LHC run1 are well described by assuming equilibrated matter at T = 156 MeV and mu_b < 1 MeV, very close to predictions from lattice QCD for T_c

the original > 7 sigma proton anomaly is now 2.9 (2.7) sigma

reproduction of the deuteron and hypertriton yield does not lend support to annihilation scenarios after chemical freeze-out

implementation of additional baryon resonances will be the next step

overall the LHC data provide strong support for chemical freeze-out driven by the (cross over) phase transition at T_c = 156 MeV

The thermal model is alive and well

Thank you, Gerry, for more than 30 years of strong personal and scientific interactions. You have enriched our life enormously.