Production of weakly bound objects in high energy nuclear collisions

- introductory remarks and context
- hadron production, statistical model and the QCD phase boundary
- chemical freeze-out and the case of weakly bound objects
- production yields in high energy collisions

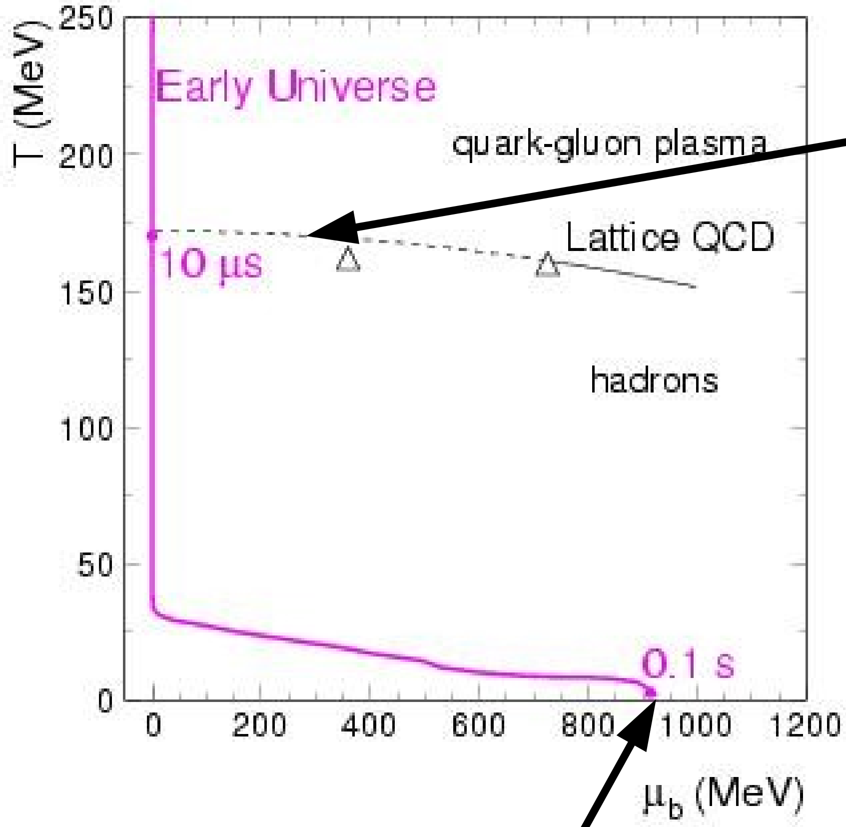
FIAS-Frankfurt

work based on collaboration with
A. Andronic, K. Redlich, and J. Stachel

Nuclear Theory Seminar
LBNL, May 2014

Peter Braun-Munzinger

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

The QCD phase diagram and chemical freeze-out

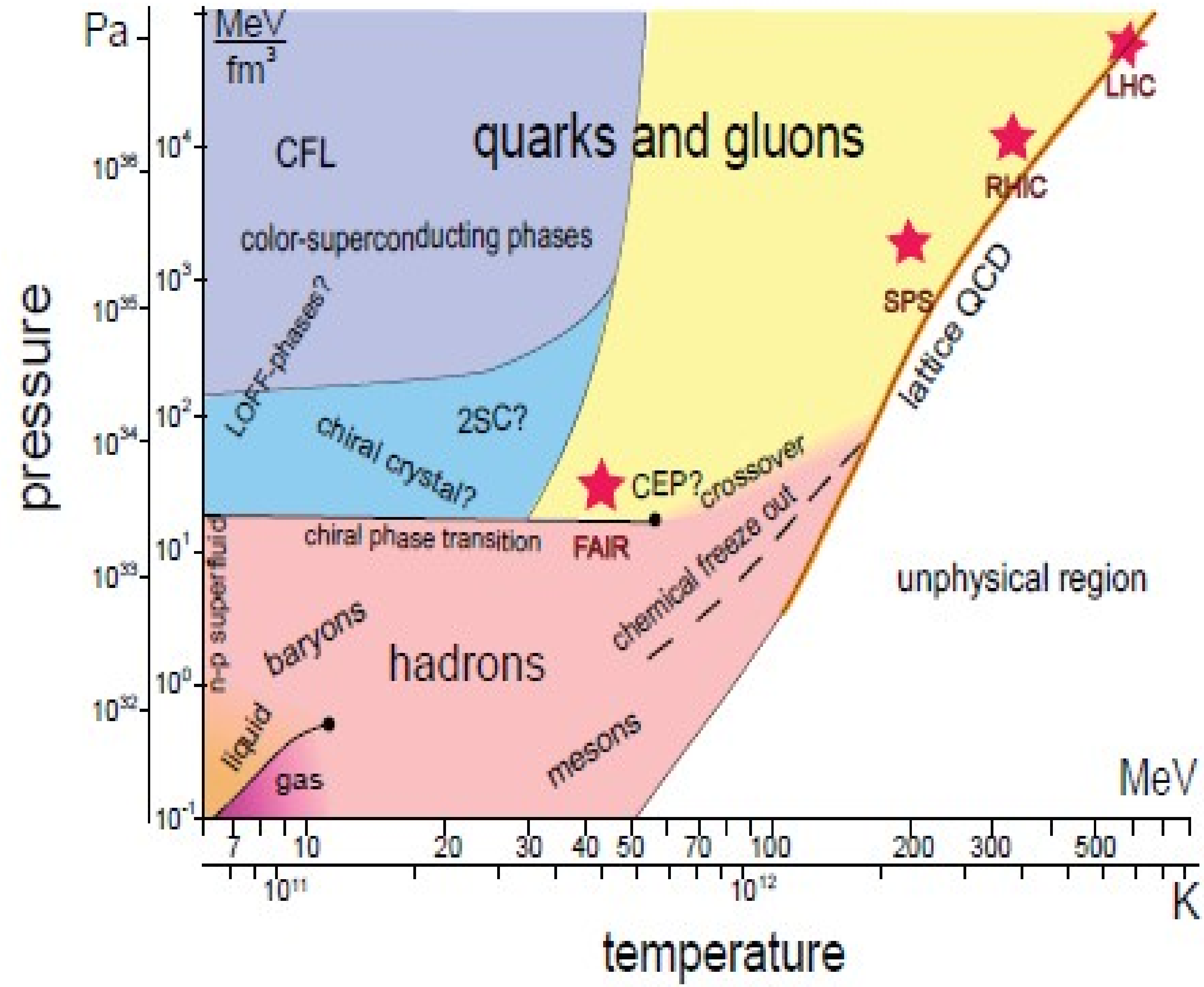
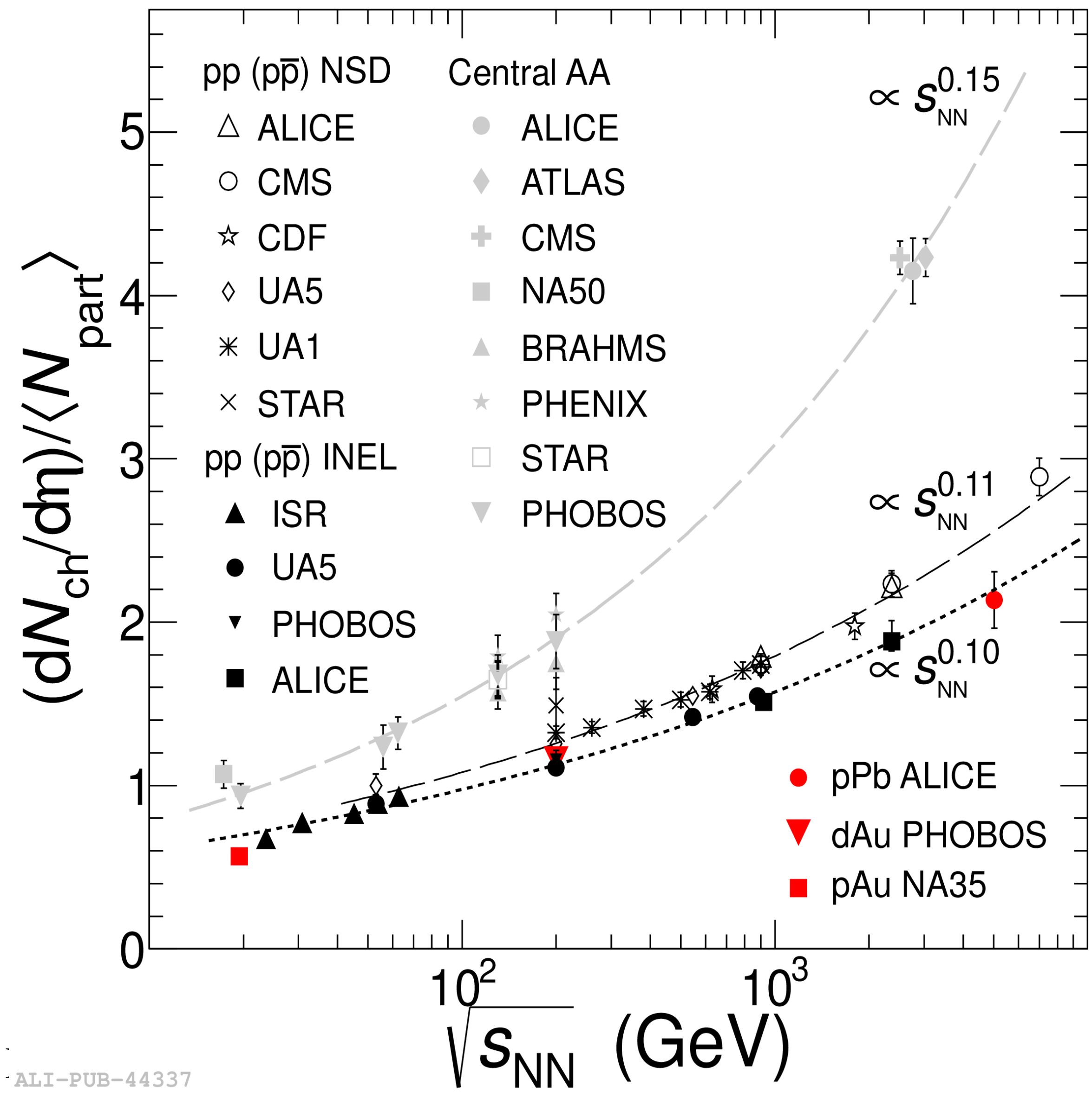


fig. from Wambach, Heckmann, Buballa, arXiv:1111.5475

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**

- Would also imply: 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

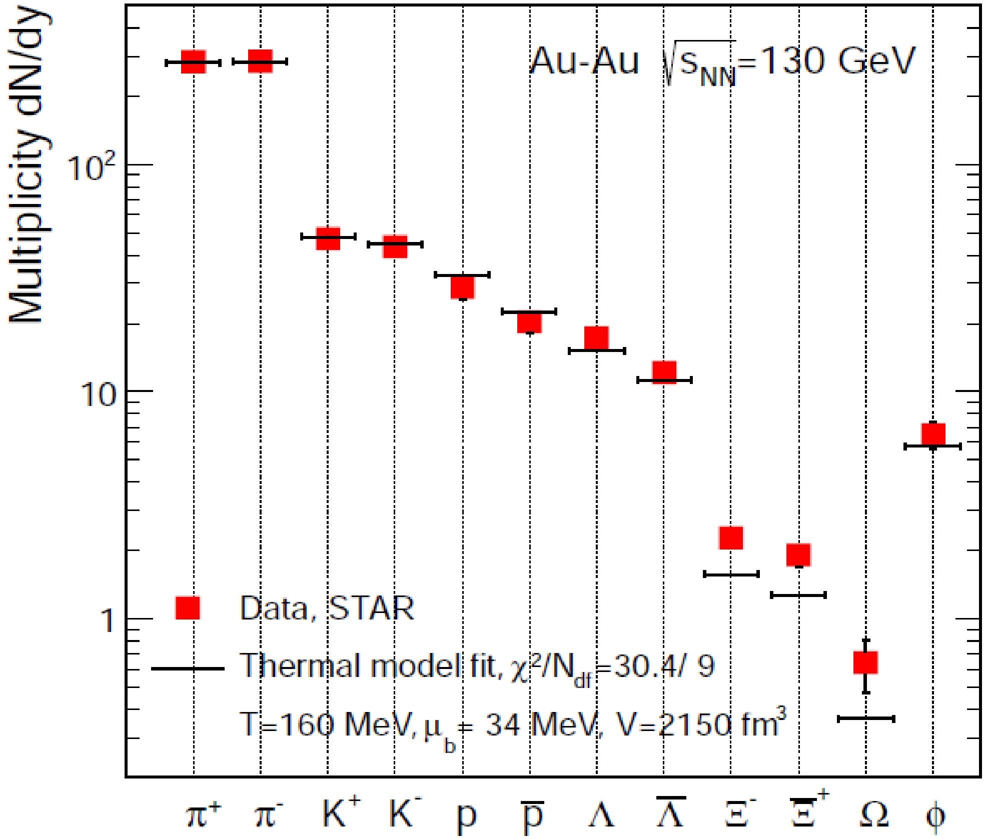
- This implies little energy dependence above RHIC energy

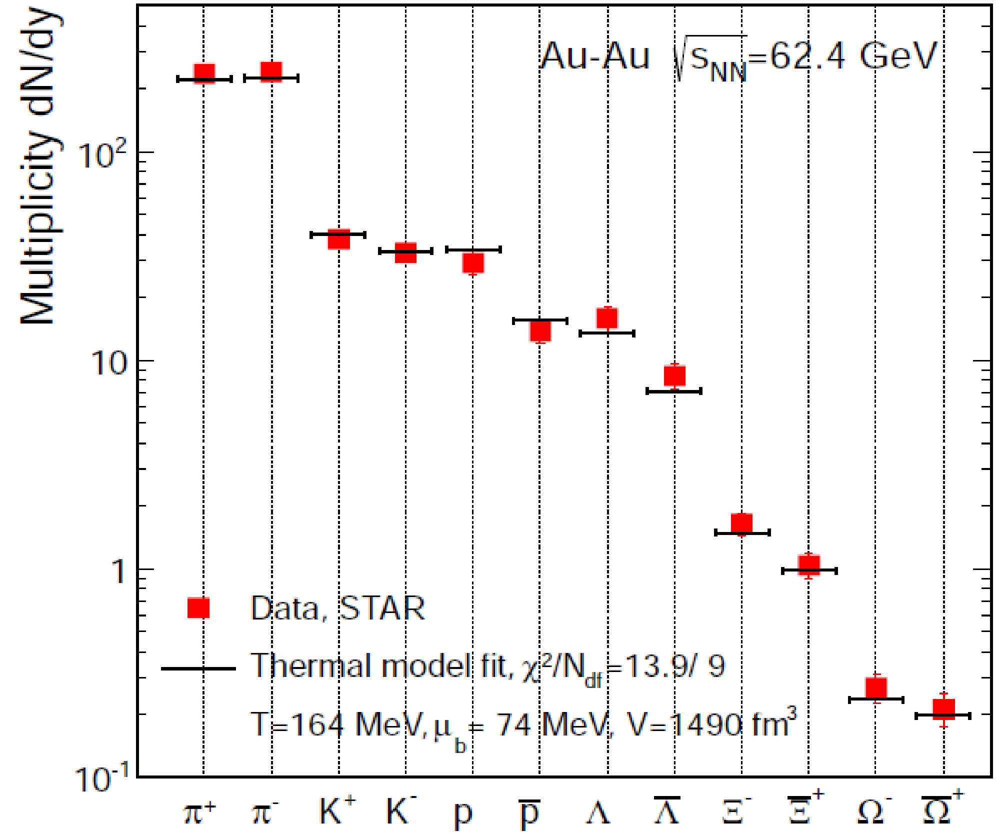
- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

Summary of pre-LHC era

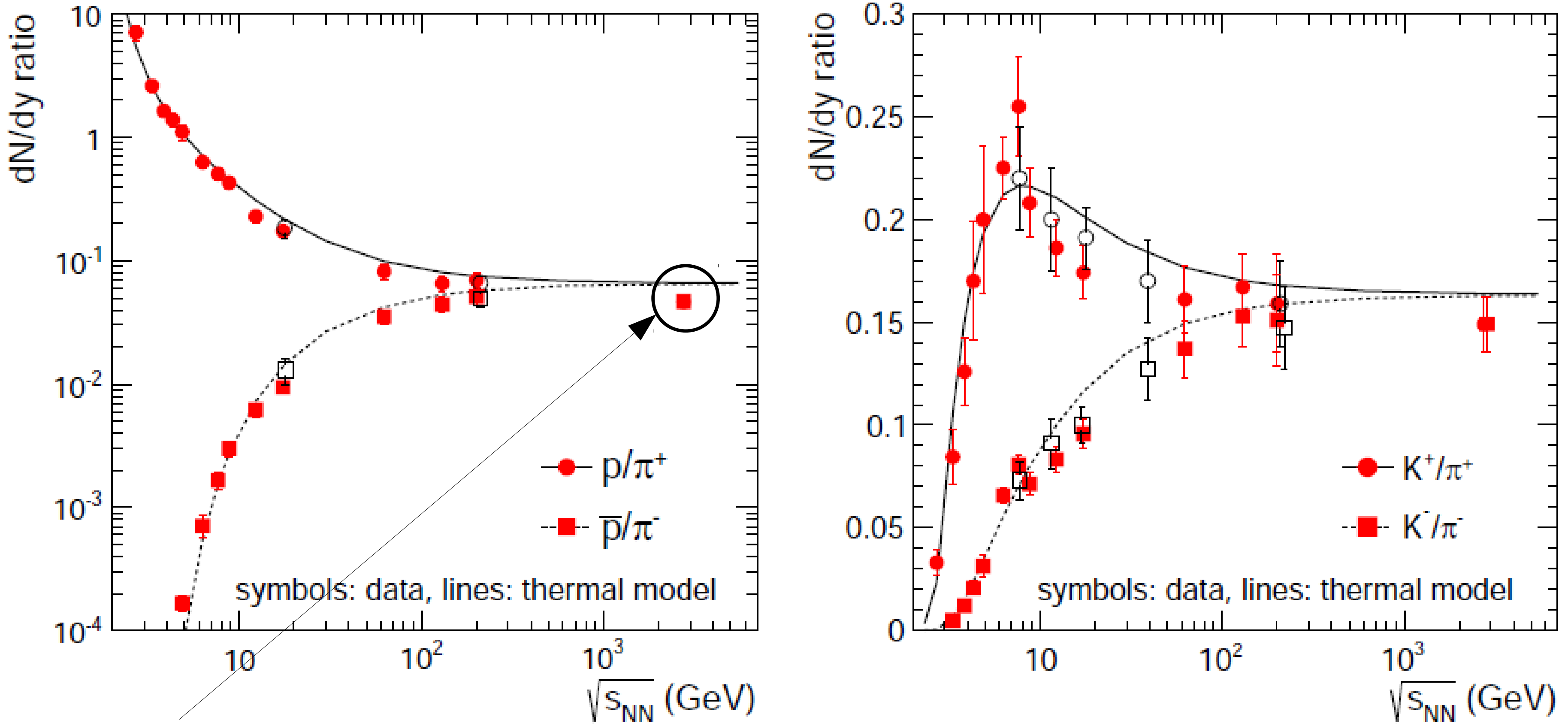
example of thermal fits: RHIC lower energies, STAR data alone





good fits, T = 160 – 164 MeV

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



proton anomaly?

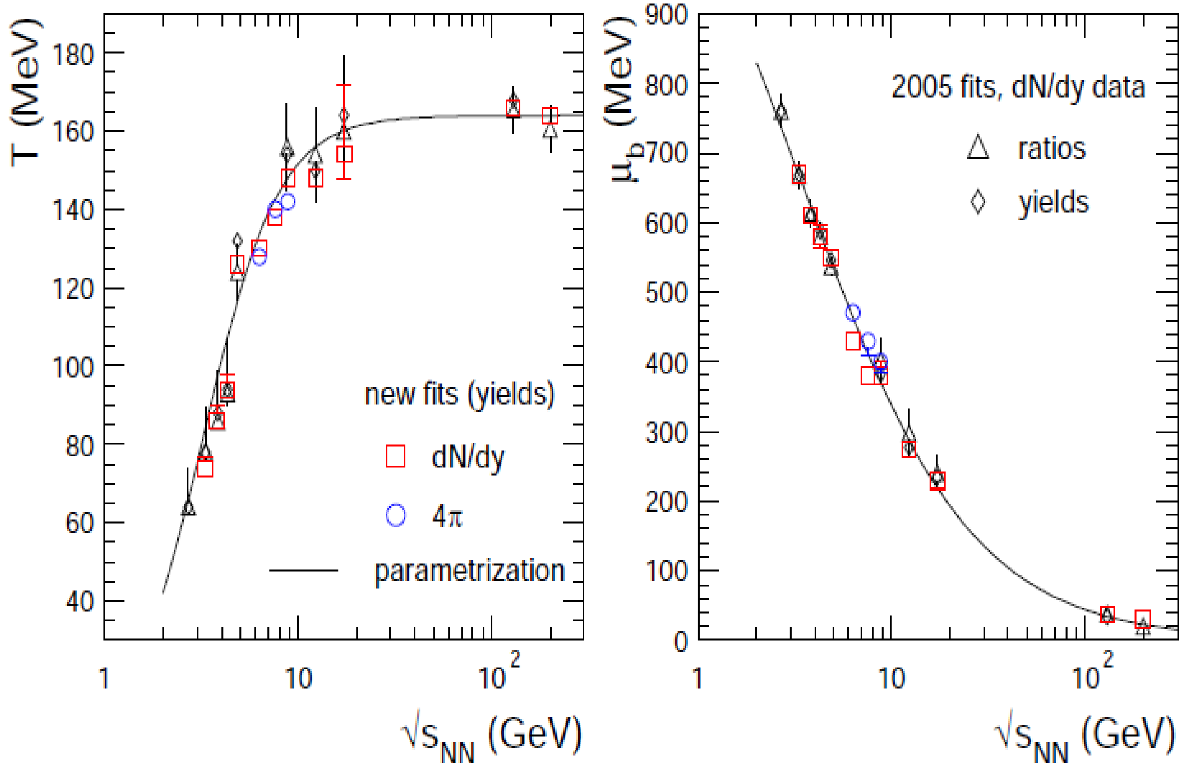
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 161 +/- 4 MeV

get T and μ_B for all energies

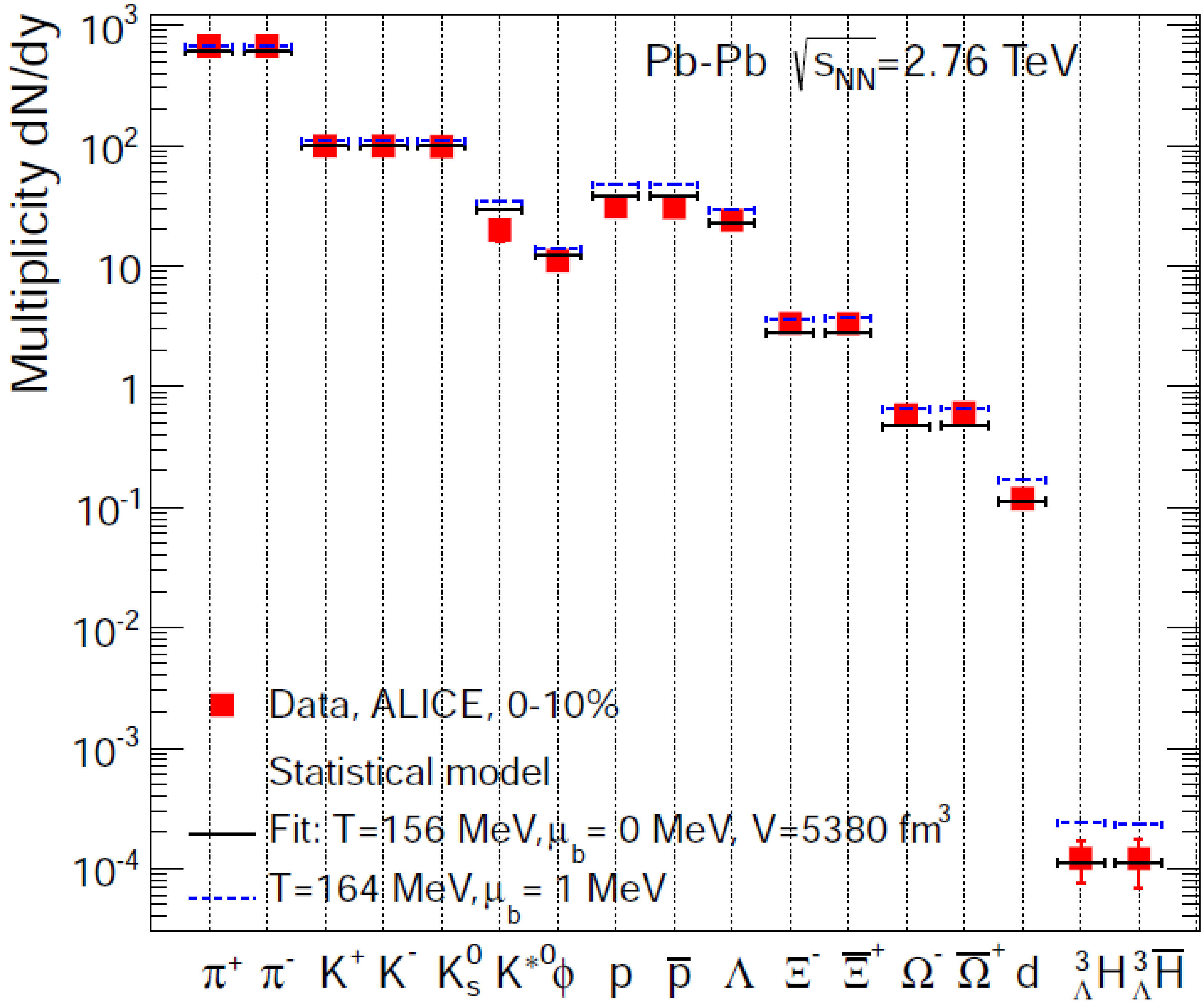
for LHC predictions we picked T = 161 MeV and, later, 164 MeV



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

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

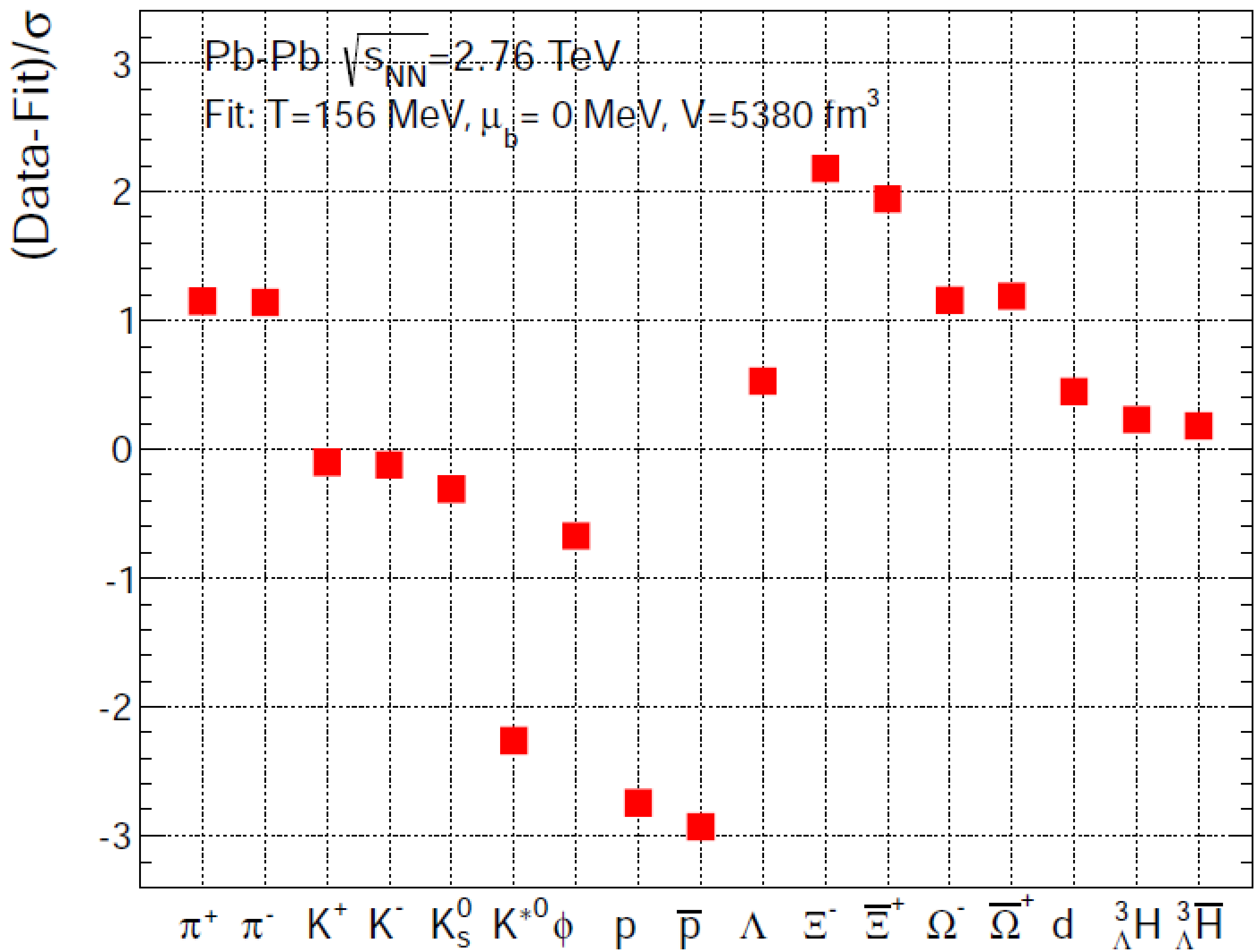
newest fit of Alice data including hypertriton, SQM2013



J. Stachel, A. Andronic, pbm, K. Redlich, arXiv:1311.4662

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

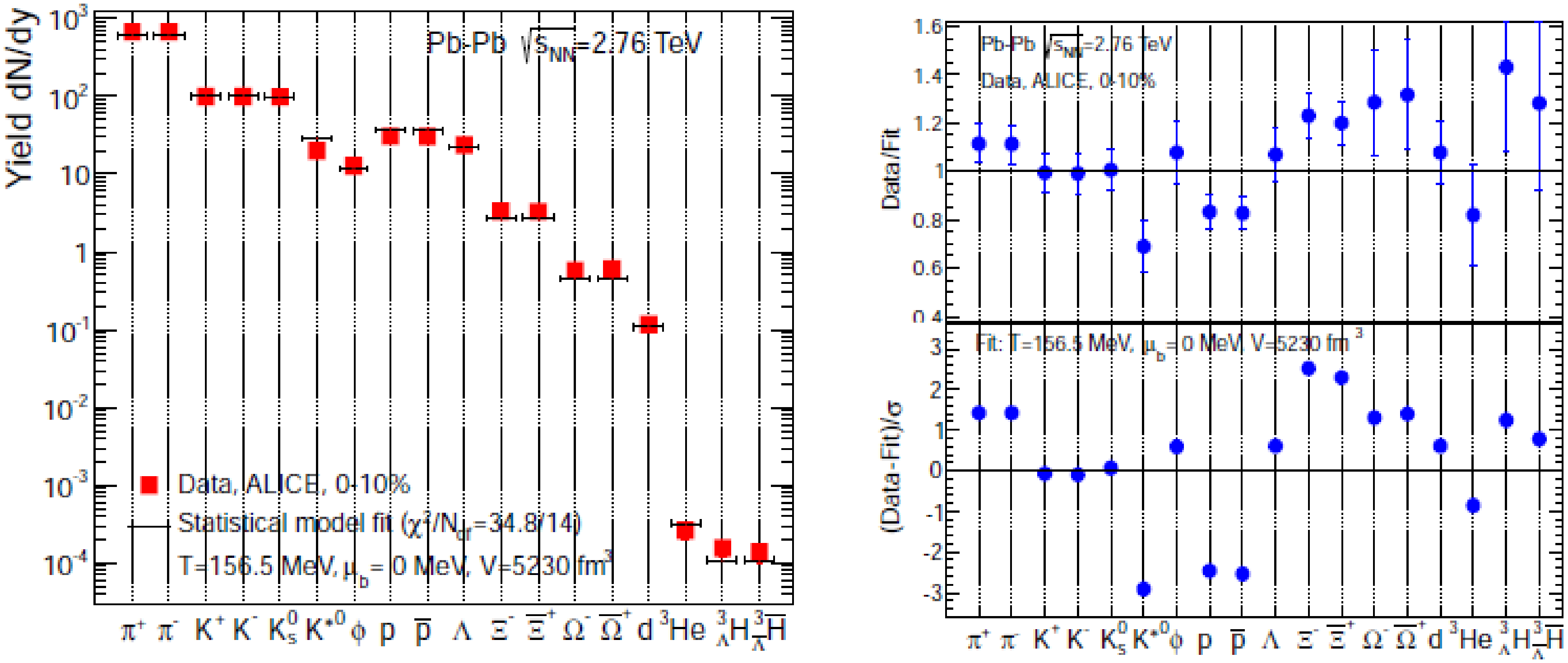
analyzing the deviations from the fit



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

update April 2014 incl. 3He

LHC, Pb–Pb, 0-10%



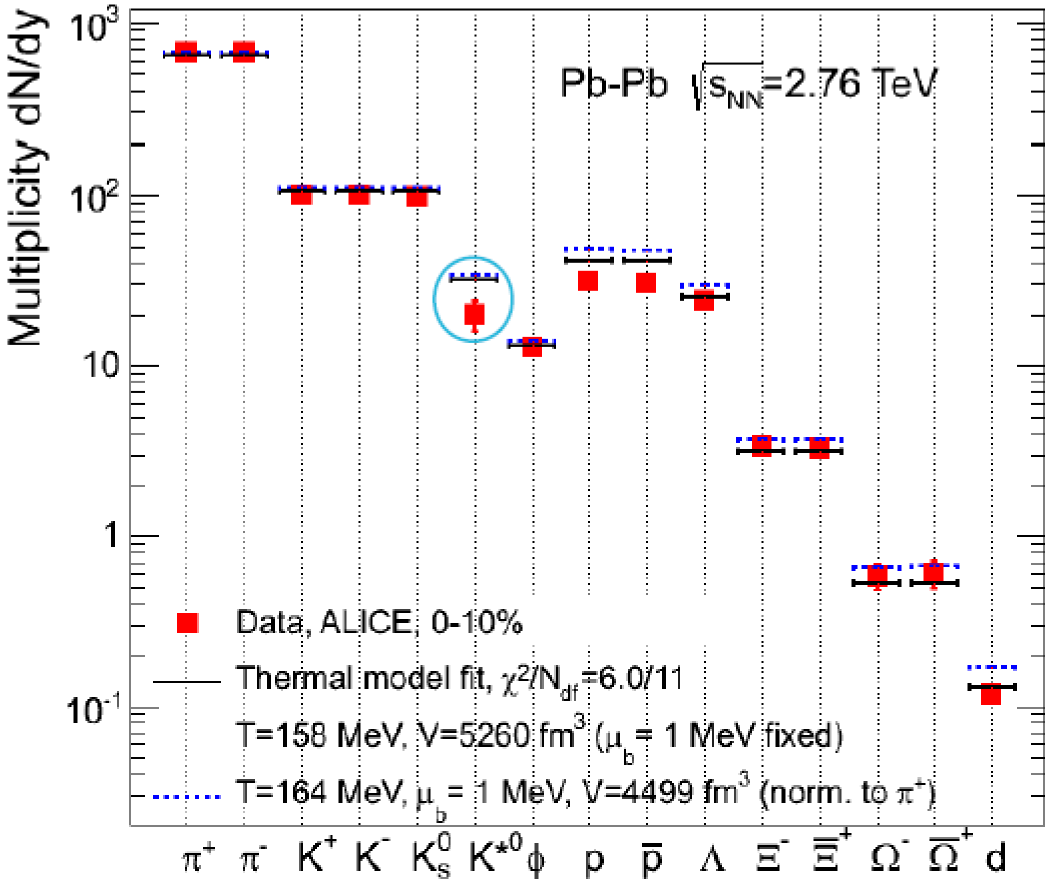
K^* not in fit

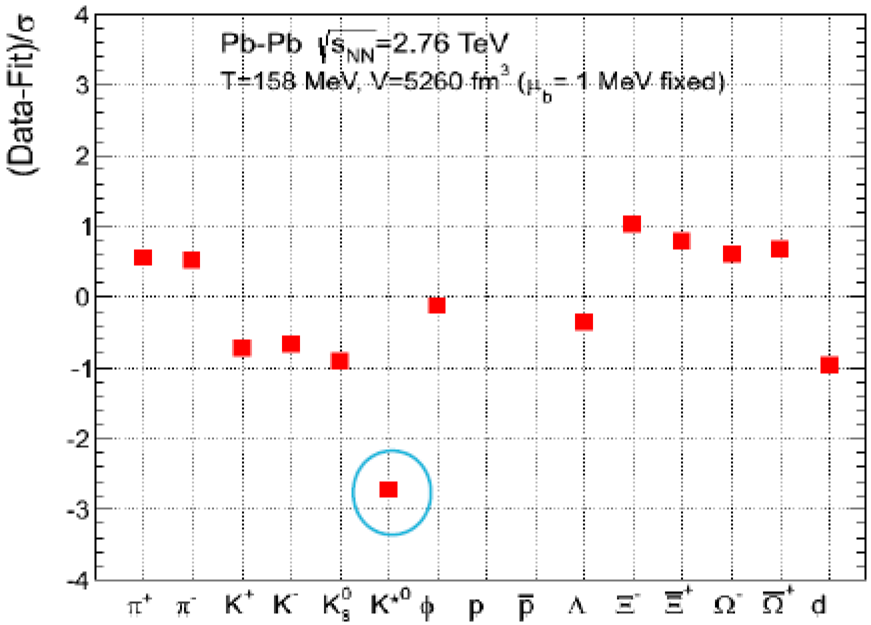
$T = 156.5 \pm 1.5$ MeV, $V = 5230 \pm 420$ fm^3

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

[no π in fit: $T = 158 \pm 1.5$ MeV, $V = 4730 \pm 380$ fm^3, χ^2/N_{df}=30.3/12]

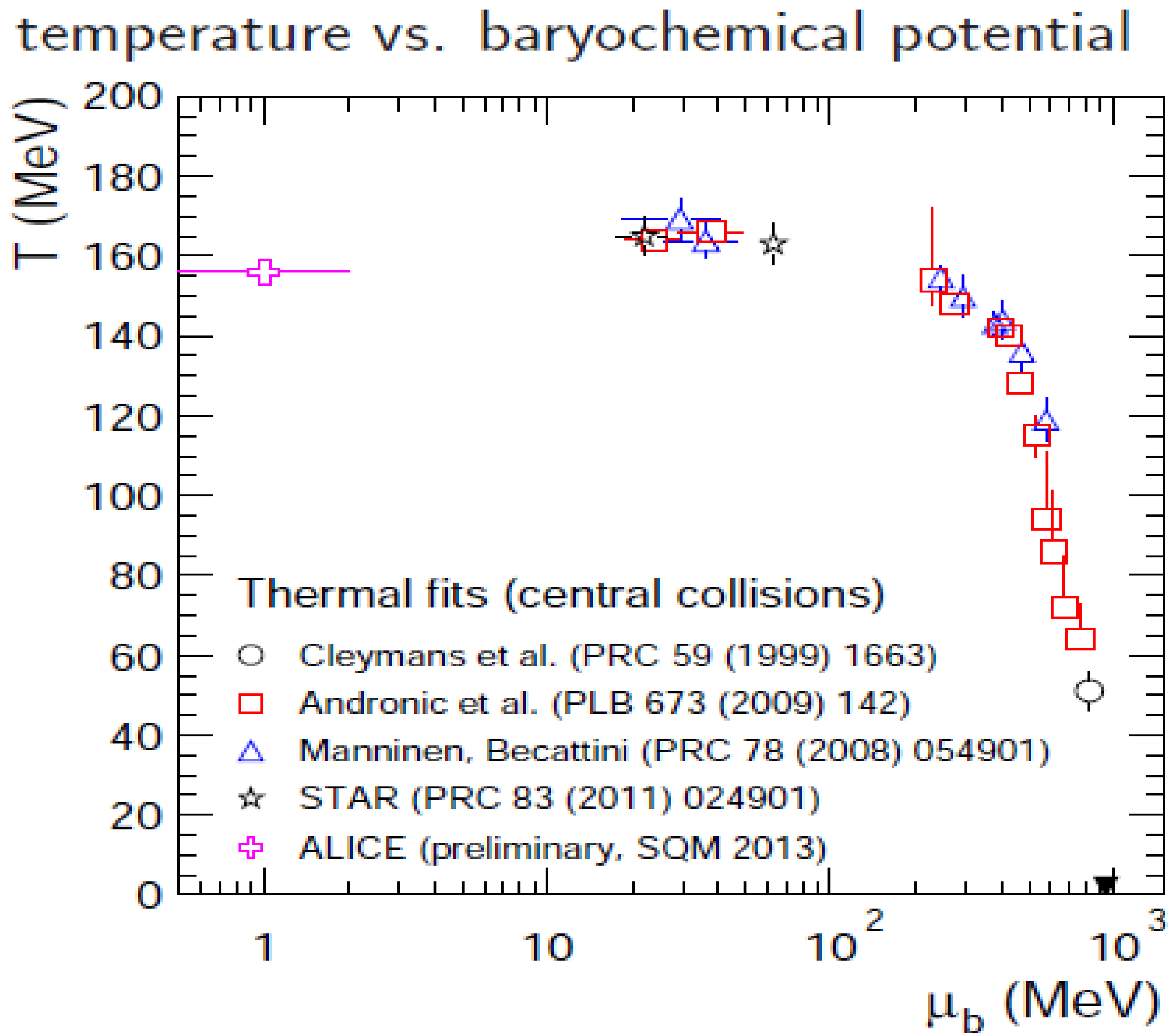
fit to data excluding protons





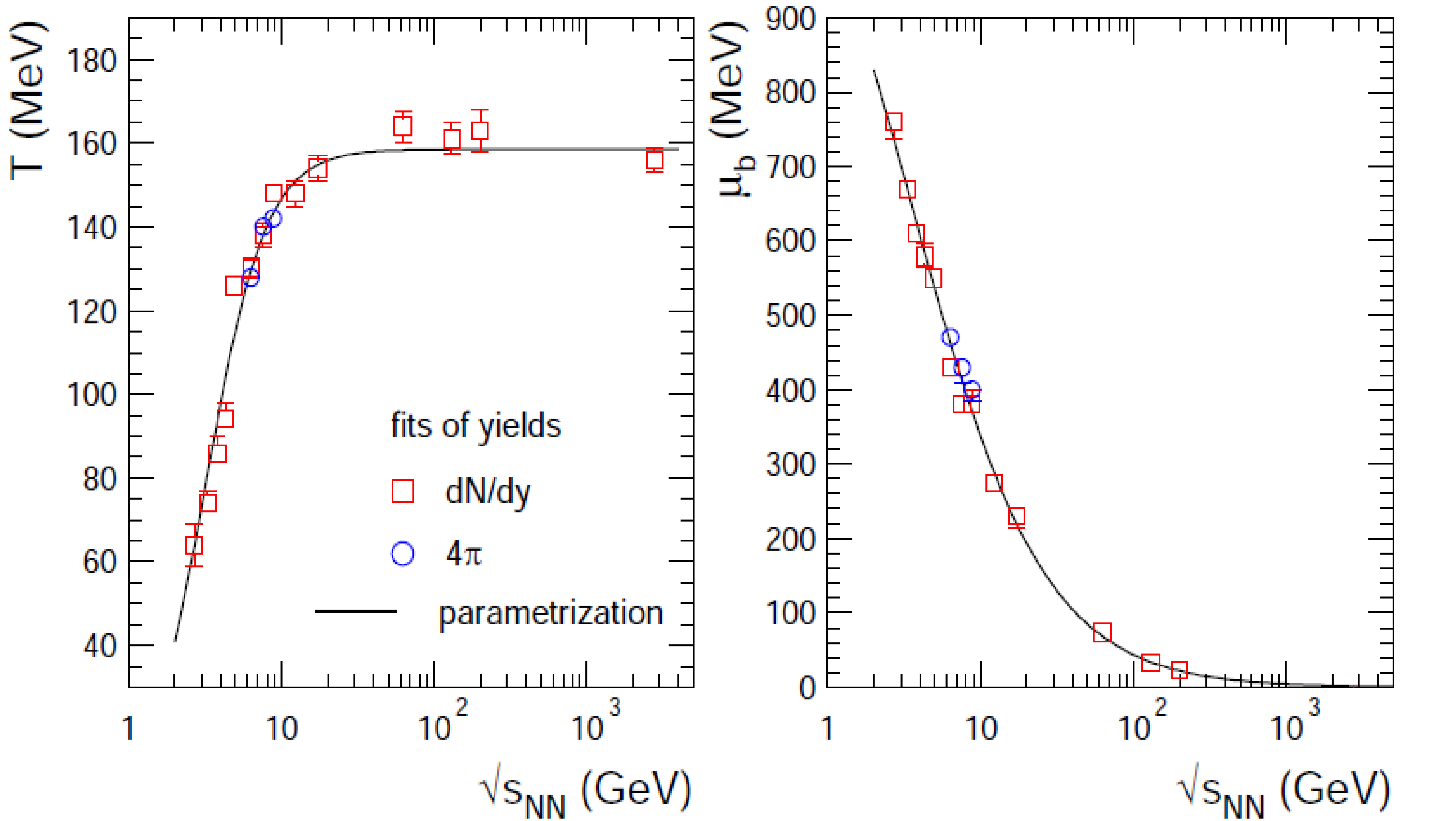
excellent fit, T = 158 MeV chi^2/ndf < 1

The newest T-mu plot including LHC data



Newest global fit

LHC data imply slightly lower T_{lim} compared to RHIC data extrapolations



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 156.5 MeV

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

important note: corrections for weak decays

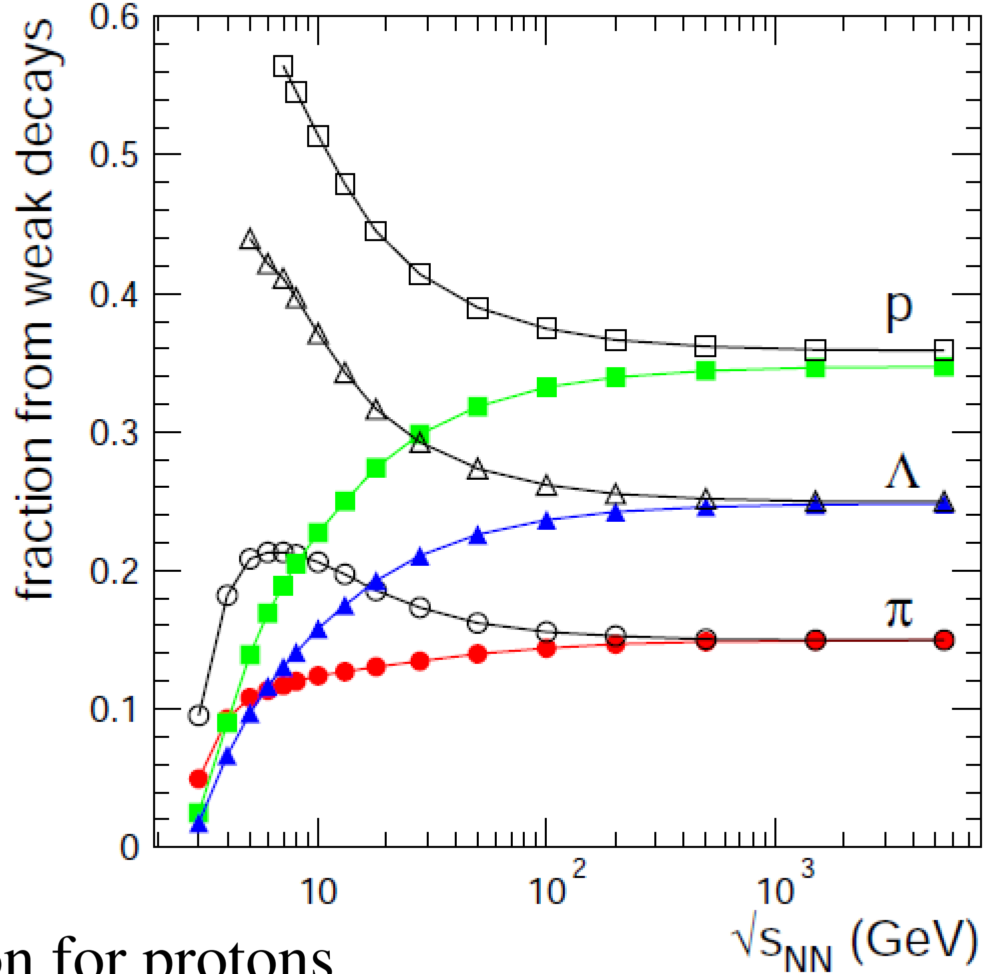
All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

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

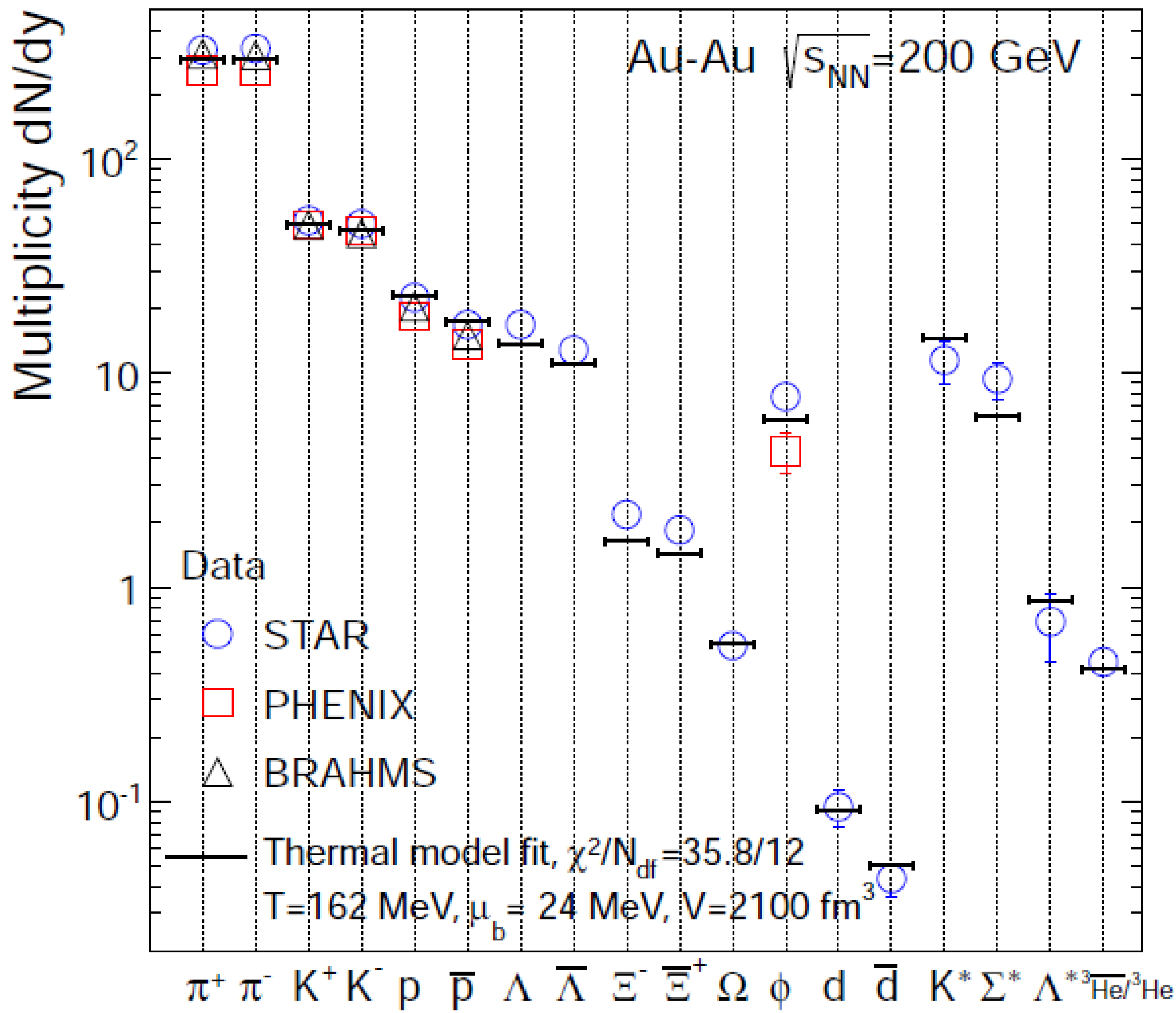
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

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

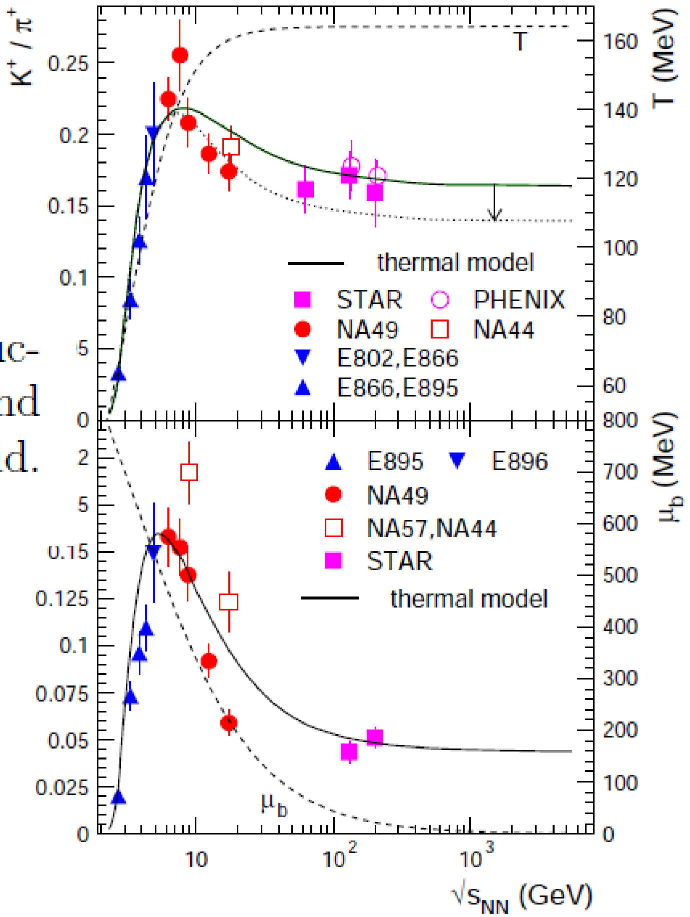
could it be incomplete hadron resonance spectrum?

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

An N* will decay 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

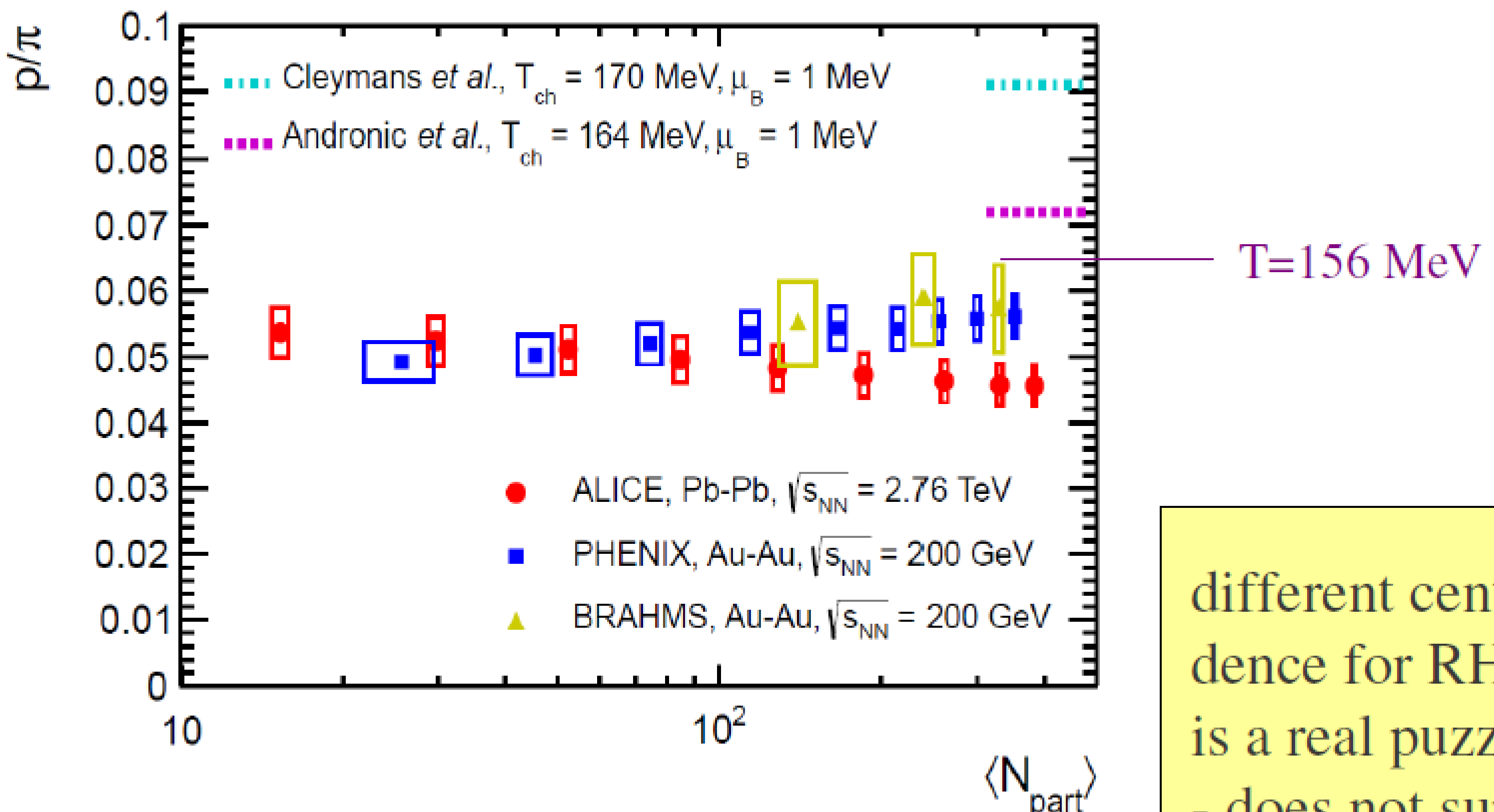
• need to incorporate detailed balance, 5pi → p p_bar
not included in current Monte Carlo codes (RQMD)

• 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

centrality dependence of proton/pion ratio



different centrality dependence for RHIC and LHC is a real puzzle
- does not support annihilation picture
- is it real? physics origin?

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 $E_B(d) = 2.23$ 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

The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, 3He hypertriton, …
implies no entropy production after chemical freeze-out

hypertriton binding energy is 130 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].

Some historical context on cluster production in relativistic nuclear collisions

P.J. Siemens and J.I. Kapusta, Phys. Rev. Lett. 43 (1979) 1486.

here the provocative statement was made that cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. for example:
entropy/baryon is proportional to -ln(d/p)

ENTROPY AND CLUSTER PRODUCTION IN NUCLEAR COLLISIONS

László P. CSERNAI* and Joseph I. KAPUSTA

PHYSICS REPORTS (Review Section of Physics Letters) 131, No. 4 (1986) 223–318.

Very concise summary, including an elucidation of the relation between thermal fireball model and coalescence model

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.

Thermal vs coalescence model predictions for the production of loosely bound objects in central Au—Au collisions

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7

	Thermal Model		
Particles	T=.120 GeV	T=.140 GeV	Coalescence Model
d	15	19	11.7
t+^{3}He	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
${}^{5}_{\Lambda\Lambda}$H	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
${}^{6}_{\Lambda\Lambda}$He	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
${}^{7}_{\Xi^0\Lambda\Lambda}$He	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
${}^{10}_{1}$St^{-8}	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
${}^{12}_{1}$St^{-9}	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
${}^{14}_{1}$St^{-11}	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
${}^{16}_{2}$St^{-13}	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
${}^{20}_{2}$St^{-16}	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

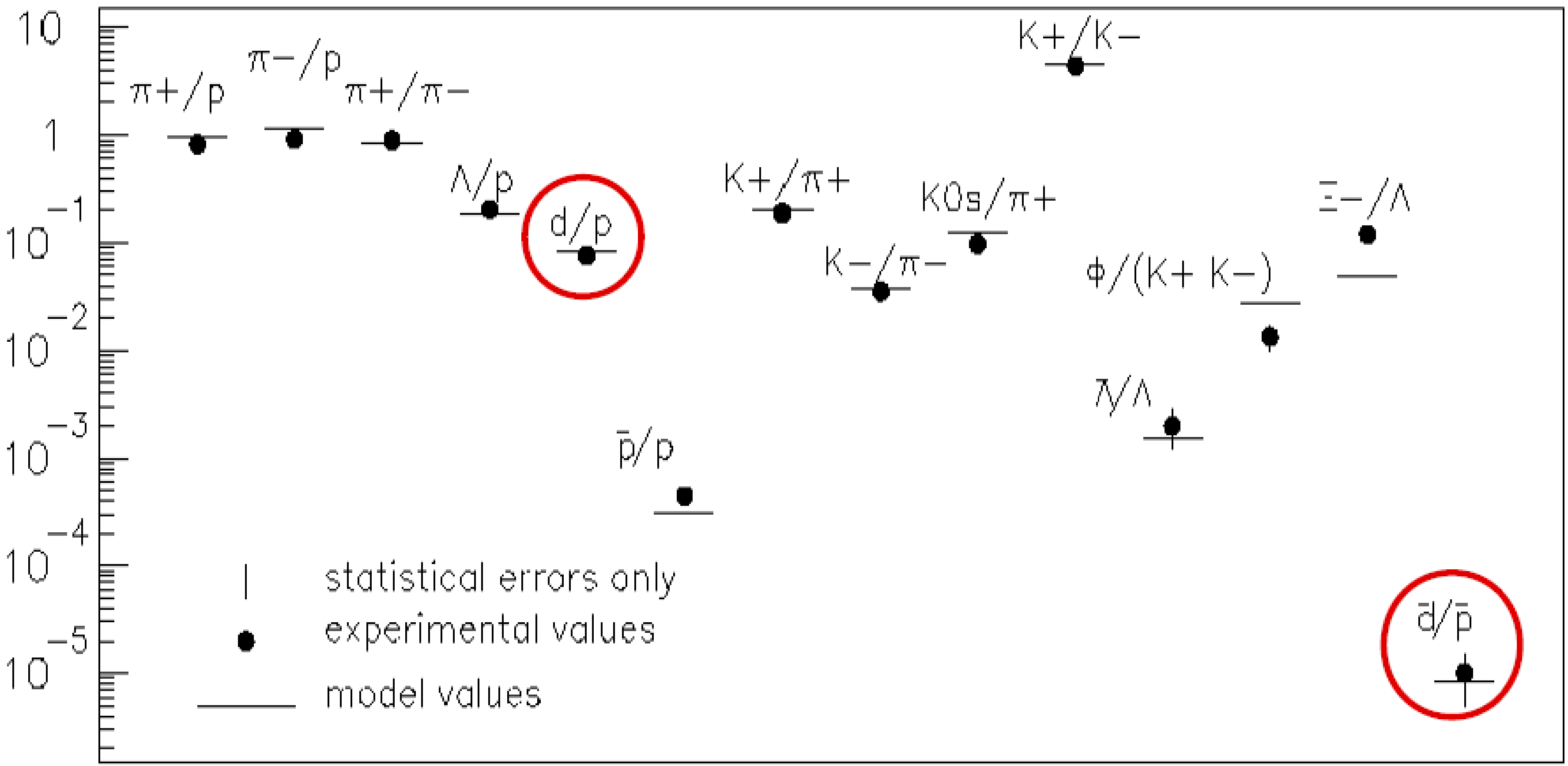
P. Braun-Munzinger, J. Stachel, J. Phys. G **28** (2002) 1971 [arXiv:nucl-th/0112051]

J.Phys. G21 (1995) L17-L20

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

Thermal model and production of light nuclei at AGS energy

<u>data cover 10 oom!</u>
addition of every nucleon
-> penalty factor $R_p = 48$
but data are at very low pt
use m-dependent slopes following
systematics up to deuteron
-> $R_p = 26$

<u>GC statistical model:</u>

$R_p \approx \exp[(m_n \pm \mu_b)/T]$
for T=124 MeV and μ_b= 537 MeV

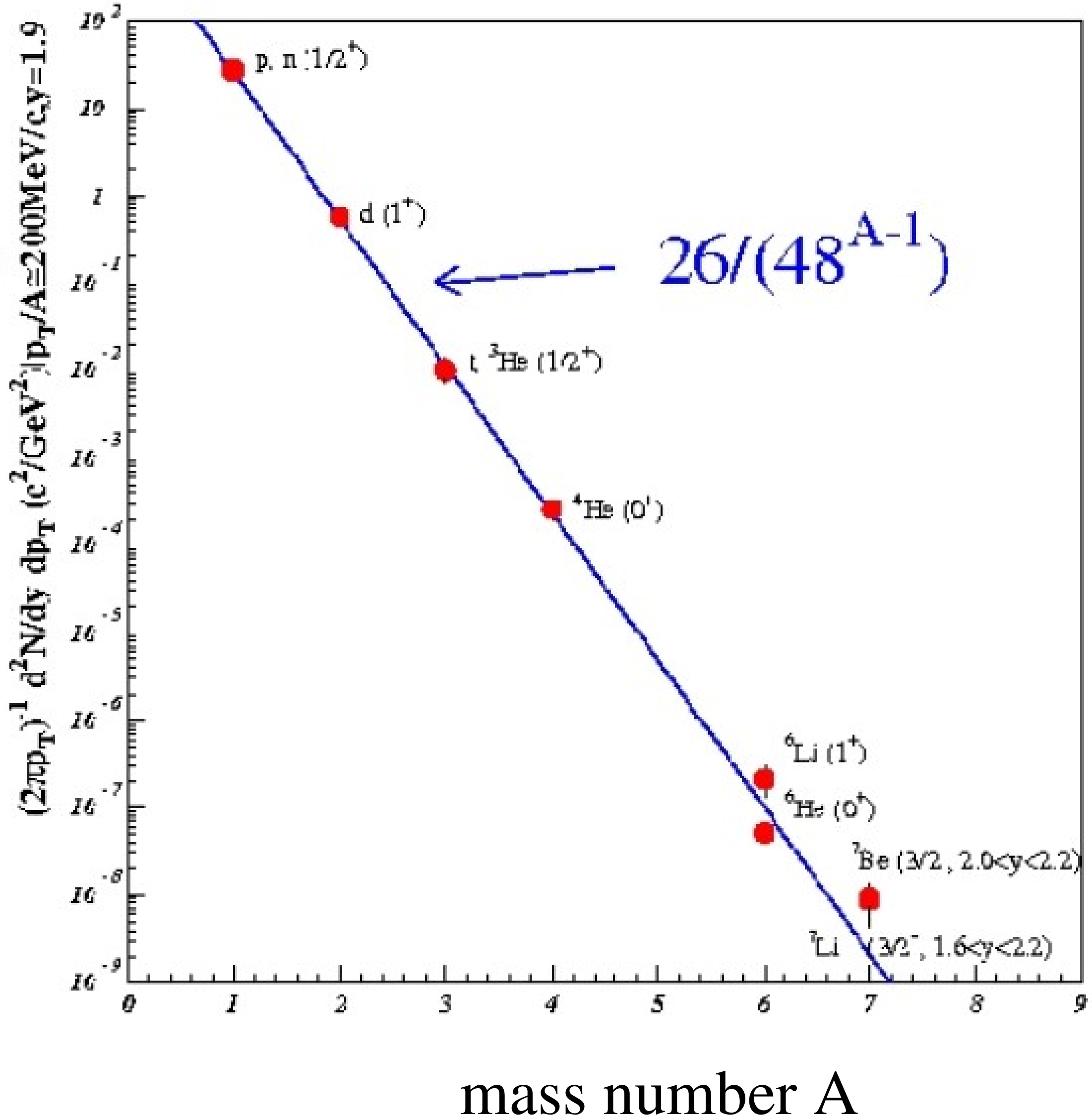
$R_p = 24$ good agreement

also good for **antideuterons**:

data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

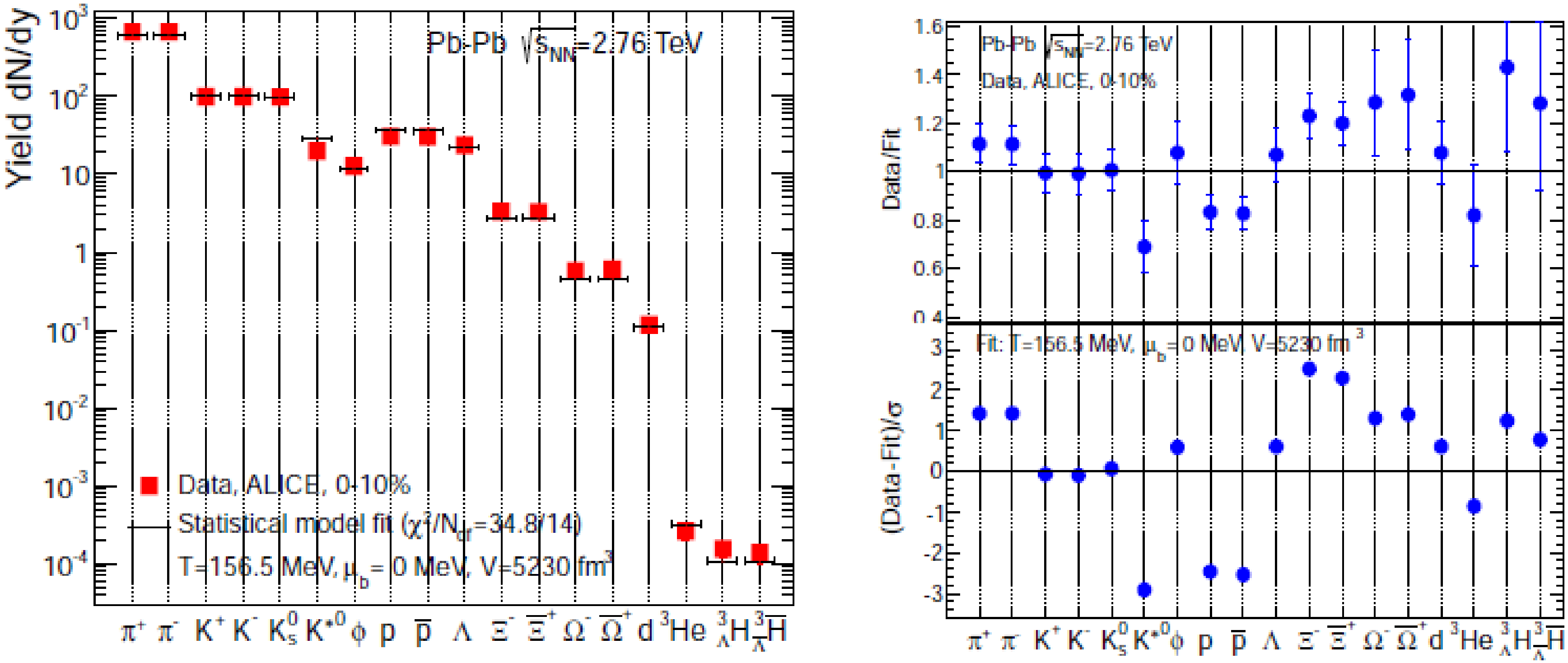
P. Braun-Munzinger, J. Stachel,
J. Phys. G28 (2002) 1971

E864 Coll., Phys. Rev. C61 (2000) 064908



update April 2014 incl. 3He

LHC, Pb–Pb, 0-10%



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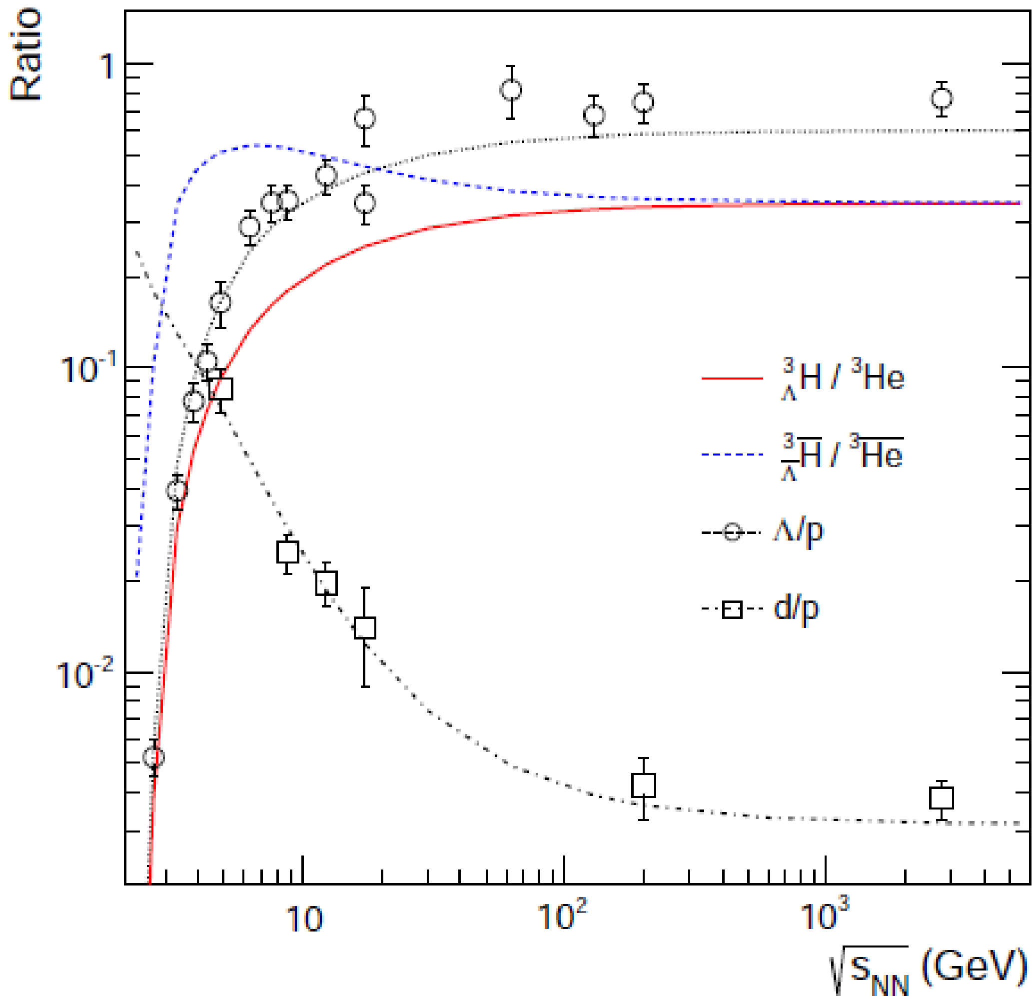
energy dependence of d/p ratio and thermal model prediction



agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy

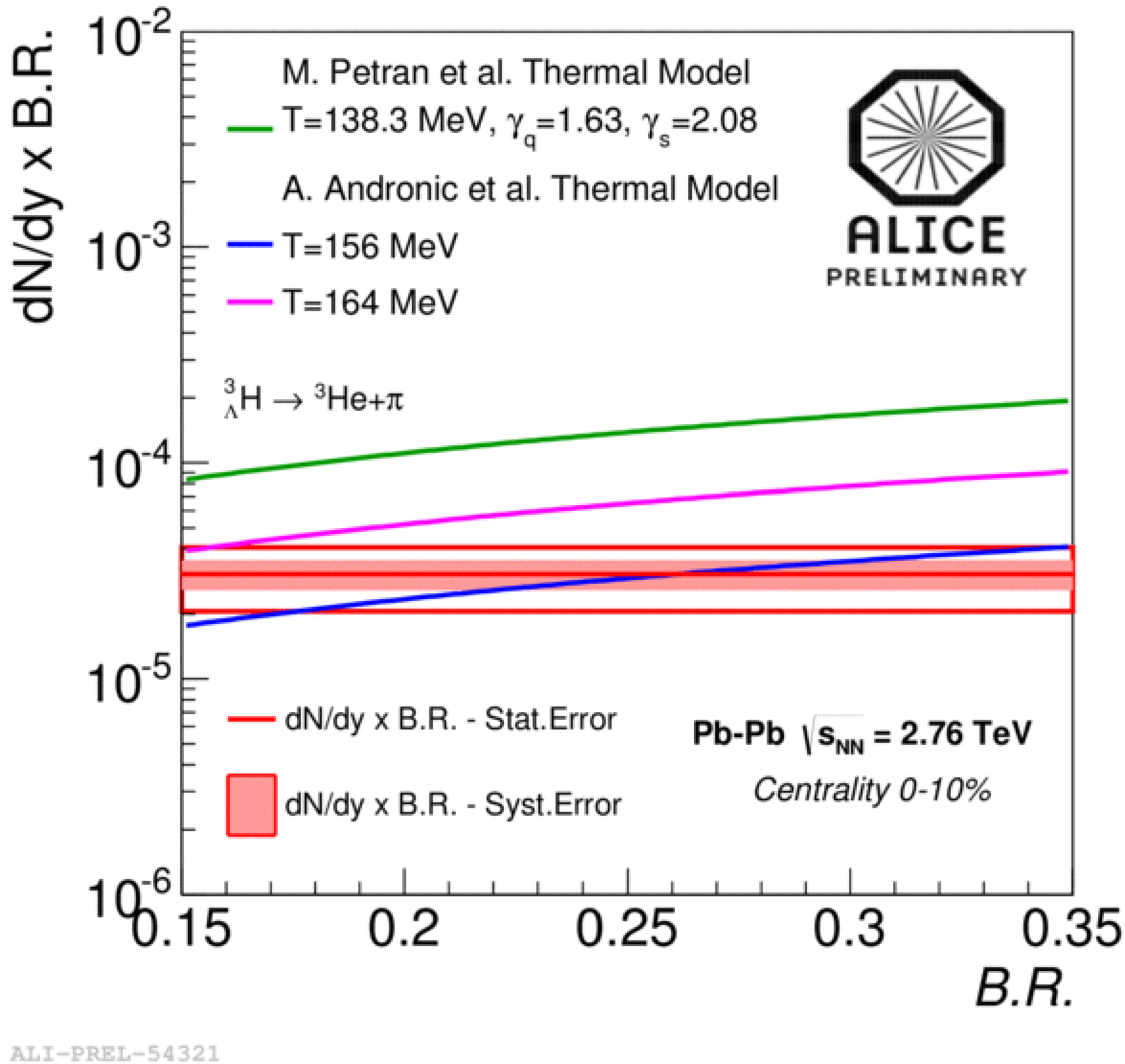
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase

Hypertriton yield x branching ratio and the thermal model

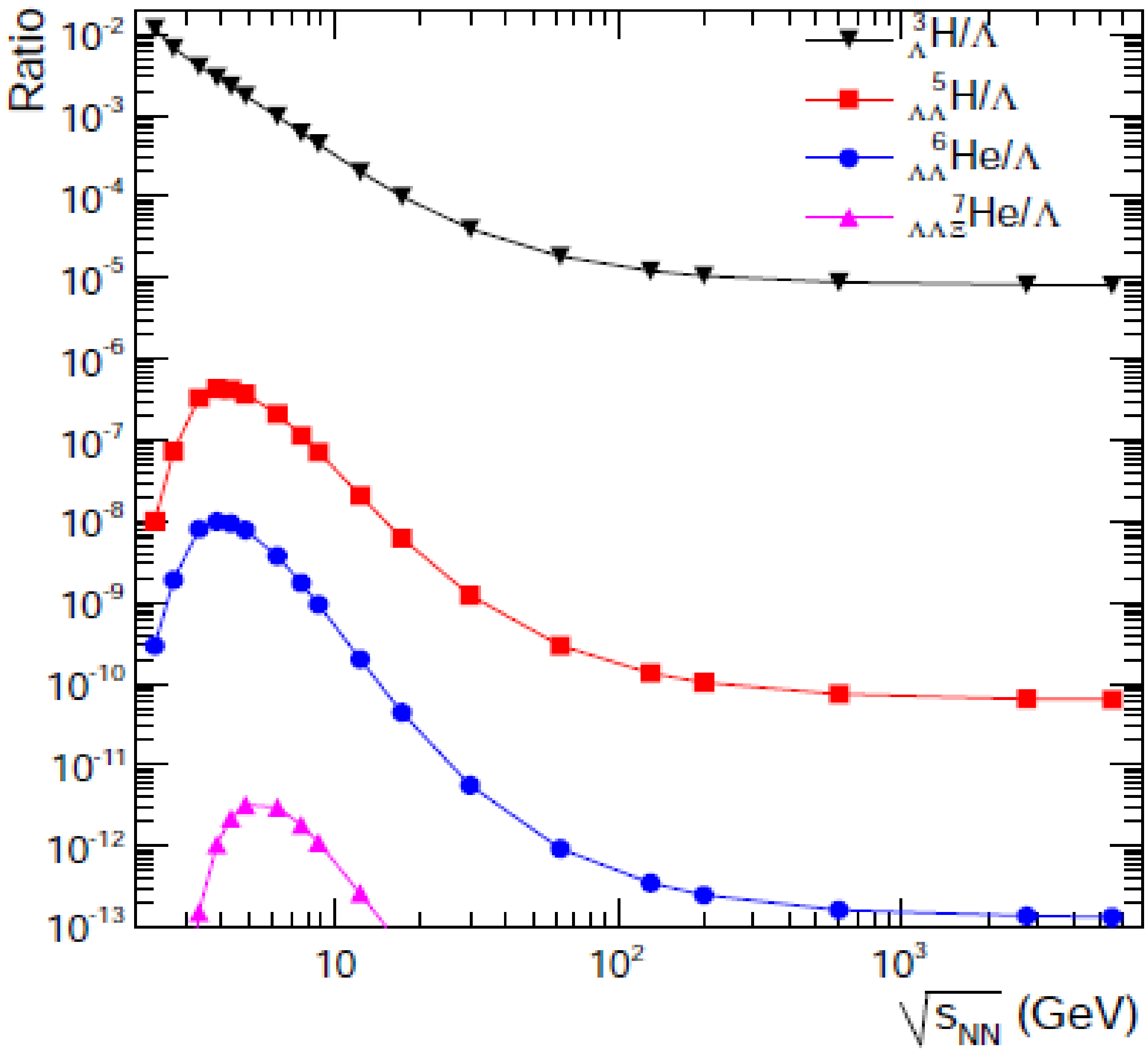


analysis spearheaded by Ramona Lea, ALICE

T = 156 MeV provides very good description

Note: binding energy of hypertriton is 130 keV!!
Most likely B.R. = 0.25 (also used by STAR)

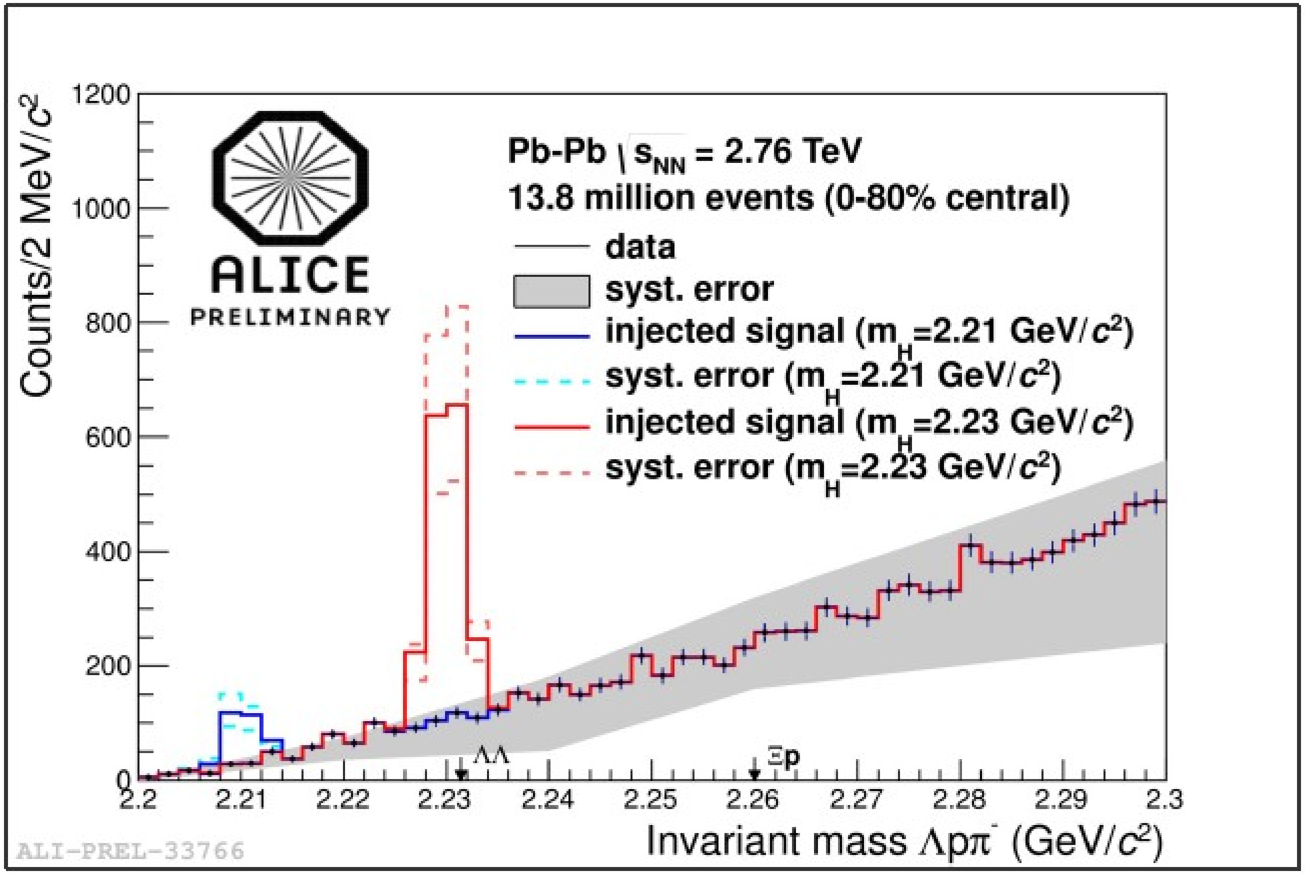
Energy dependence of the yields of exotic objects



note: yield peaks at low (SIS100) energies
an exciting but tough prospect for FAIR

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

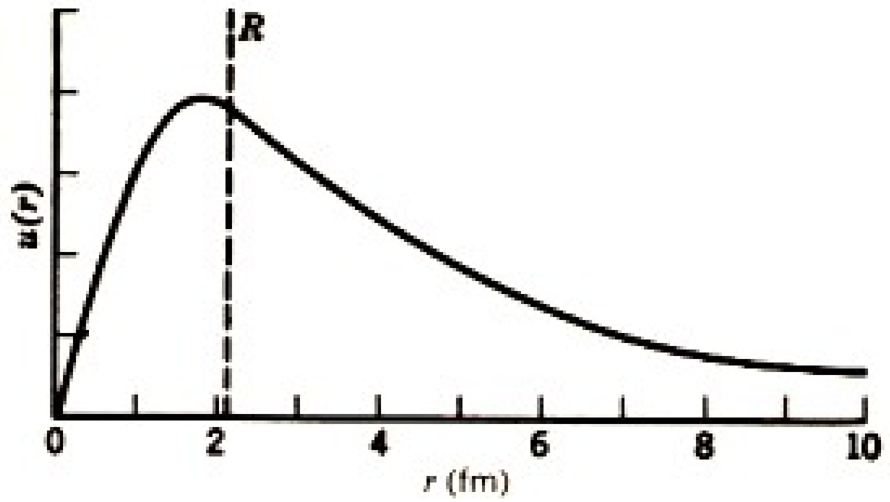
The size of loosely bound molecular objects

Examples: deuteron, hypertriton, XYZ 'charmonium states, molecules near Feshbach resonances in cold quantum gases

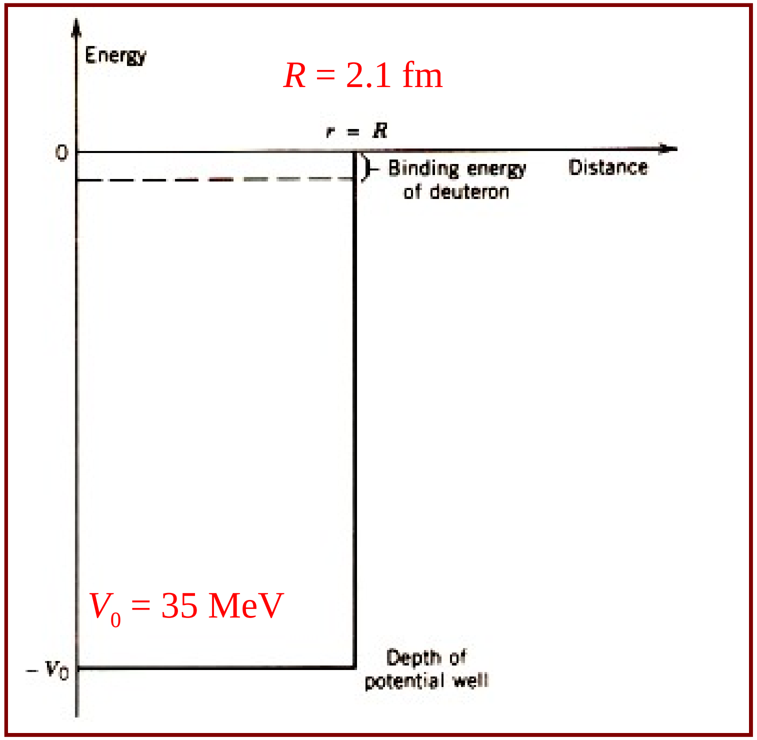
Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which the constituents are almost always separated by more than the range. One of the universal predictions is that the root-mean-square (rms) separation of the constituents is $(4\mu E_X)^{-1/2}$, where E_X is the binding energy of the resonance and μ is the reduced mass of the two constituents. As the binding energy is tuned to zero, the size of the molecule increases without bound. A classic example of a loosely-bound S-wave molecule is the deuteron, which is a bound state of the proton and neutron with binding energy 2.2 MeV. The proton and neutron are correctly predicted to have a large rms separation of about 3.1 fm.

Artoisenet and Braaten, arXiv:1007.2868

The deuteron as a loosely bound object



Mass = 1875 MeV
B.E. = 2.23 MeV
rms radius = 3 fm > range of potential



The Hypertriton

mass = 2.990 MeV

B.E. = 0.13 MeV

molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

rms radius = $(4\ \text{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

yet production yield is fixed at 156 MeV
temperature (about 1000 x E.B.)

The X(3872)

mass is below threshold of (D^{*0} D^0_{bar}) by (0.42 +/- 0.39) MeV

rms separation = 3.5 – 18.3 fm   structure: $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$

should be able to predict the X(3872) production probability in pp collisions at LHC energy with an accuracy of about 30%, uncertainty is due to not very precisely known number of charm quarks

result ready shortly

deuteron and anti-deuteron production in pp collisions at high energy
an important background for dark matter searches

Heavy dark matter states DM can decay via

$$DM \rightarrow d\ d_{bar} + X$$

Major experiments such as AMS-02 and GAPS search for anti-deuterons in cosmic rays

General Analysis of Antideuteron Searches for Dark Matter

Yanou Cui,[a,1] John D. Mason,[a,2] and Lisa Randall[a,3]

arXiv:1006.0983

background yield from $p + H \rightarrow d_{bar} + X$ and $p + He \rightarrow d_{bar} + X$ should also be well described (better than 50 % accuracy, much better than current coalescence estimates) within thermal model

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

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

success to describe also yields of loosely bound states provides strong evidence for isentropic expansion after chemical freeze-out

These results should be very useful also for dark matter searches and the nature of XYZ states

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

Exciting prospects for study of loosely bound objects