Ultra-relativistic nuclear collisions, the quark-gluon plasma, and QCD

HELMHOLTZ
GEMEINSCHAFT

- introduction and perspective
- thermal model and the QCD statistical operator
- hadron data, Hagedorn limiting temperature, and the QCD phase boundary
- production of loosely bound objects
- summary

FIAS-Frankfurt

EMMI

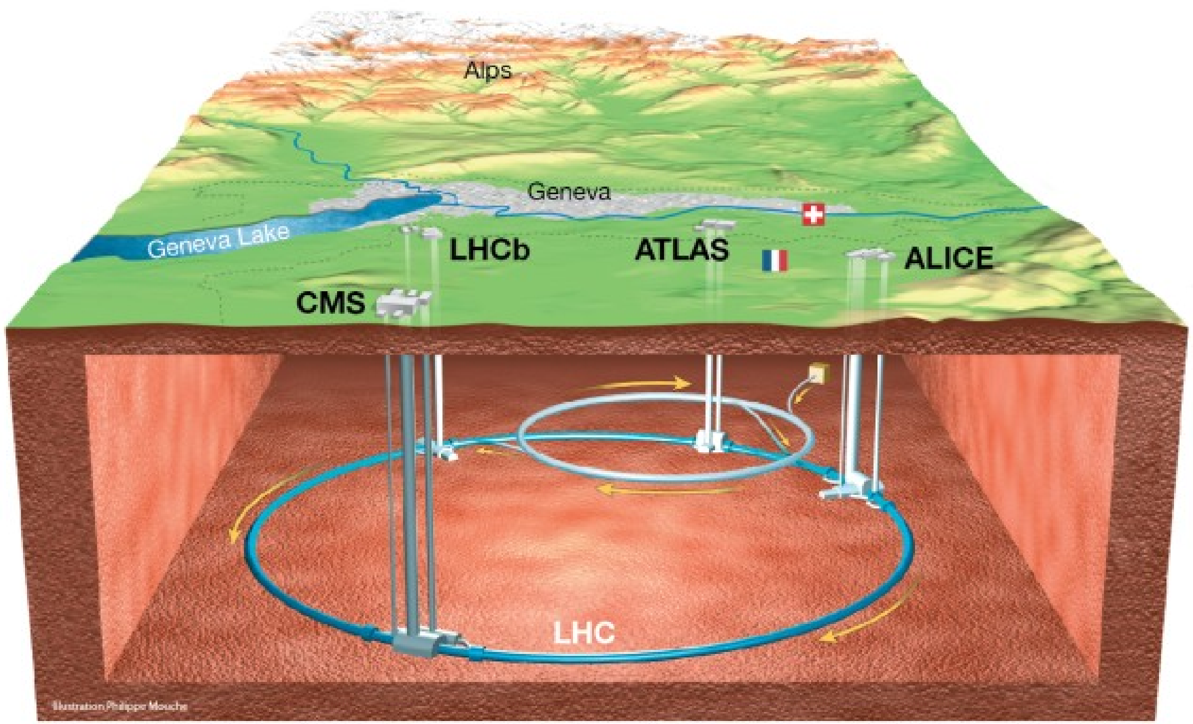
ICNFP workshop
Kolymbari, Crete, Aug. 5, 2014

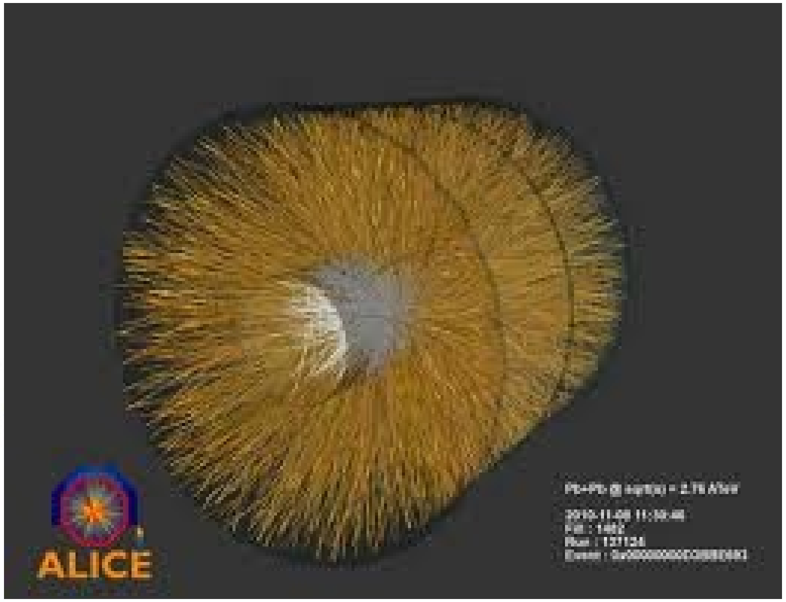
GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

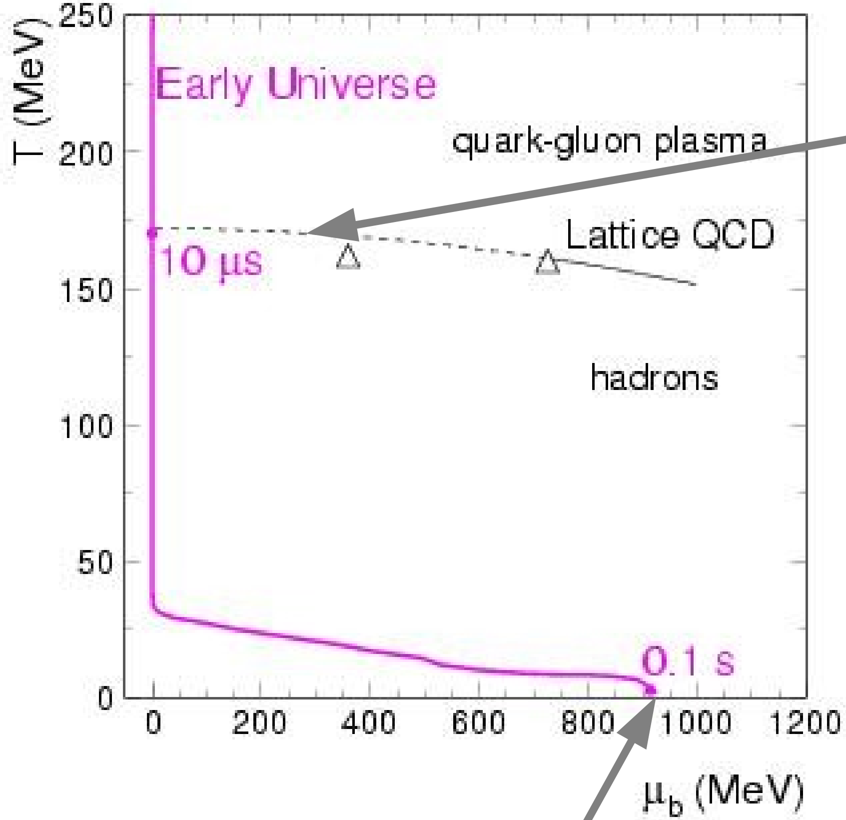
Peter Braun-Munzinger

YEARS / ANS CERN





Evolution of the Early Universe



QCD Phase Boundary

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

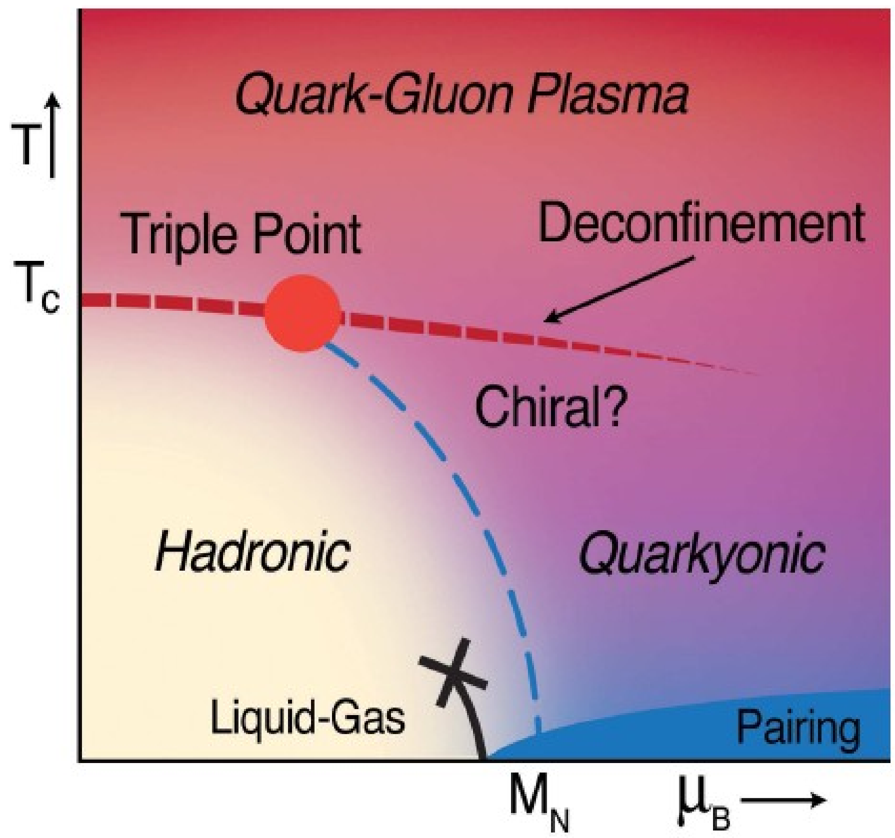
- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

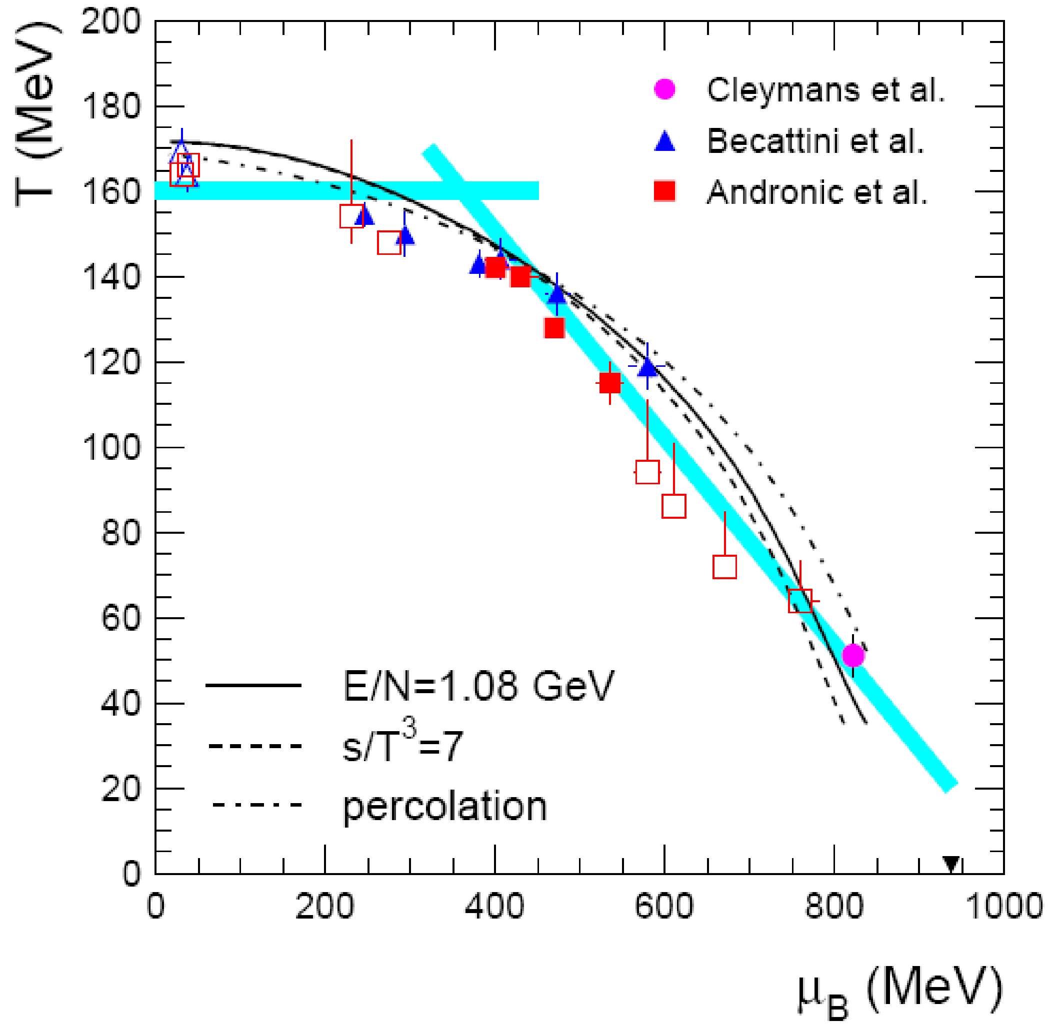
neutrinos decouple and light nuclei begin to be formed

the QCD phase diagram

Andronic et al.,, arXiv:0911.4806
Nucl. Phys. A837 (2010) 65

data points:
'chemical' freeze-out of hadrons





all lattice groups now agree: T_c(mu=0) is close to 155 MeV
T. Battacharya et al, arXiv:1402.5175 [hep-lat]
S. Borsanyi et al., arXiv:1312.2193 [hep-lat]

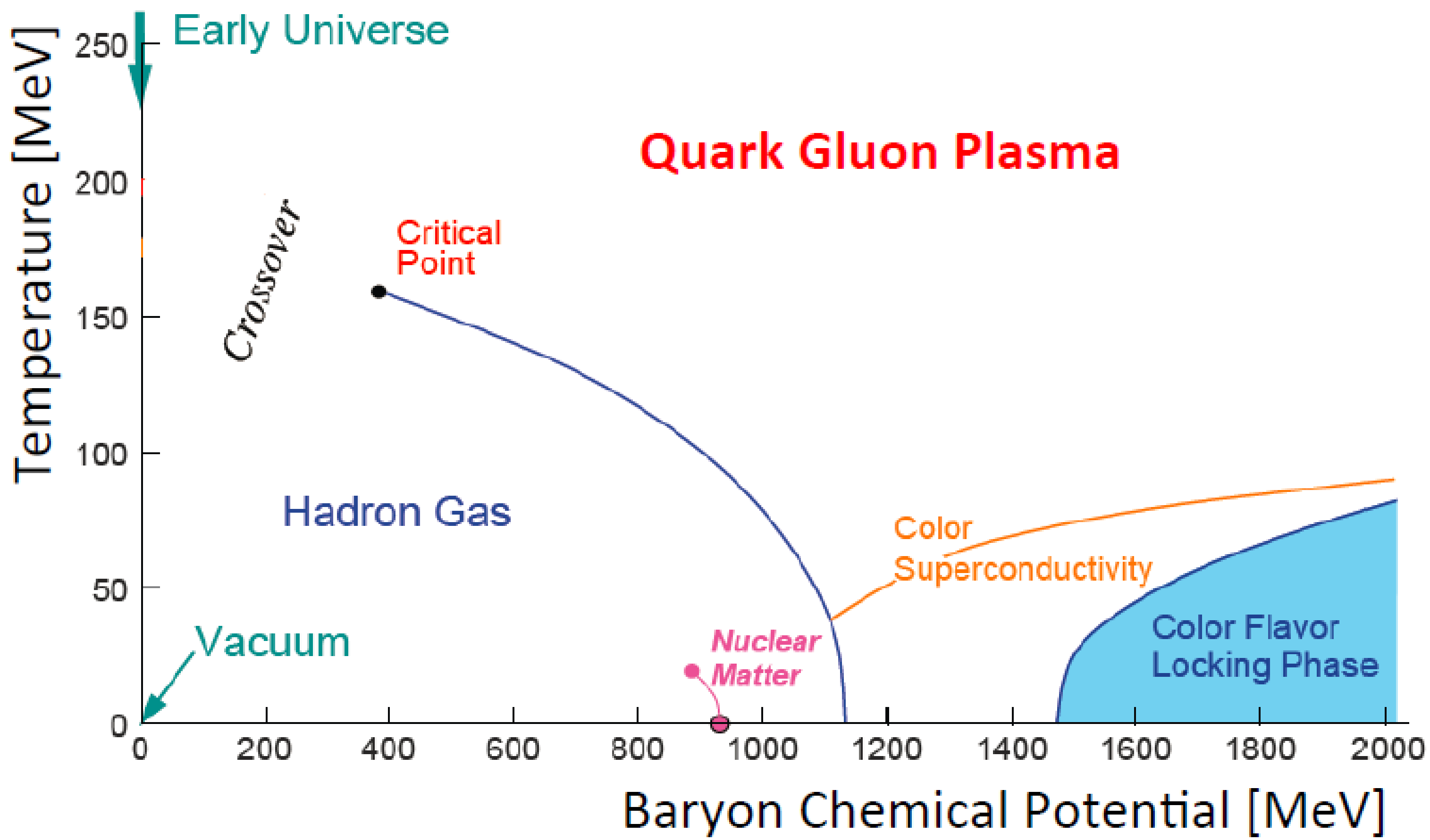
review: pbm, wambach
RMP 81 (2009) 1031

The 'condensed matter' phases of QCD – F. Wilczek, 2000
fundamental questions about extreme matter

- what are the properties of deconfined matter at extreme temperatures and densities, is chiral symmetry restored?
- can the transition temperature to the QGP be measured?
- what are its macroscopic transport parameters and equation of state?
- what is the nature of microscopic excitations and quasi-particles?
- is the QGP a strongly coupled liquid? how is its structure related to other strongly coupled systems?
- is there a critical endpoint in the phase diagram?

Relativistic nuclear collisions:
a tool to study bulk properties of non-abelian matter in the laboratory

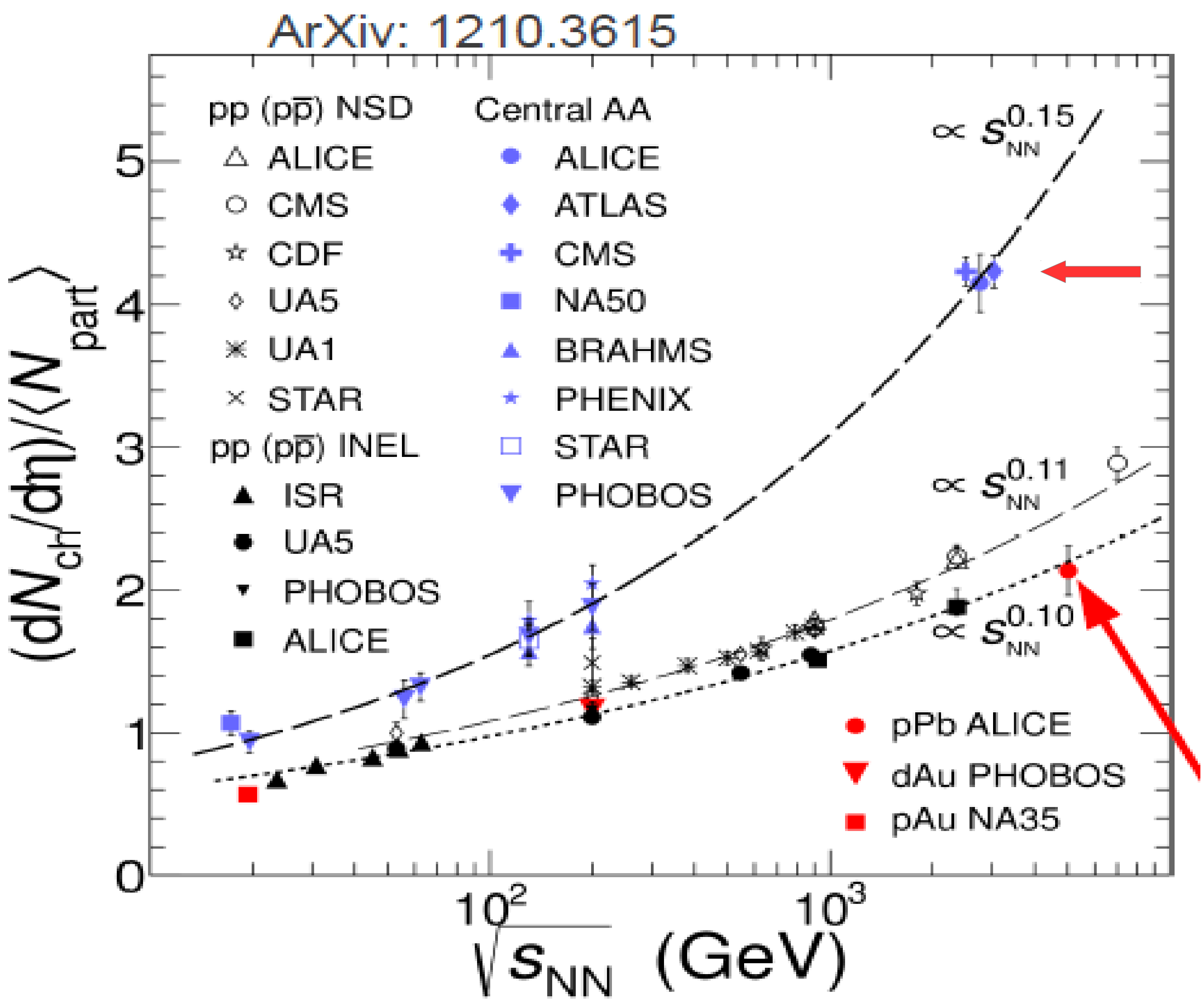
High baryon densities



Hadron production and the QCD phase boundary

Work performed in collaboration with Anton Andronic, Krzysztof Redlich and Johanna Stachel

Charged particle multiplicity in pp, pPb and central PbPb collisions



increase with beam energy significantly steeper than in pp

pPb similar to pp inelastic

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

Phys. Rev. Lett. 105(2010)252301

Quark-gluon plasma and hadron yields in central nuclear collisions

QCD implies duality between (quarks and gluons) – hadrons

Hadron gas is equilibrated state of all known hadrons

QGP is equilibrated state of deconfined quarks and gluons

at a critical temperature T_c a hadronic system converts to QGP

consequence:

QGP in central nuclear collisions if:

1. all hadrons in equilibrium state at common temperature T
2. as function of cm energy the hadron state must reach a limiting temperature T_{lim}
3. all hadron yields must agree with predictions using the full QCD partition function at the QCD critical temperature $T_c = T_{lim}$

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

- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

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

At what energy is phase boundary reached?

Thermal model of particle production and QCD

Partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

For each particle i, the statistical operator is:

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

Particle densities are then calculated according to:

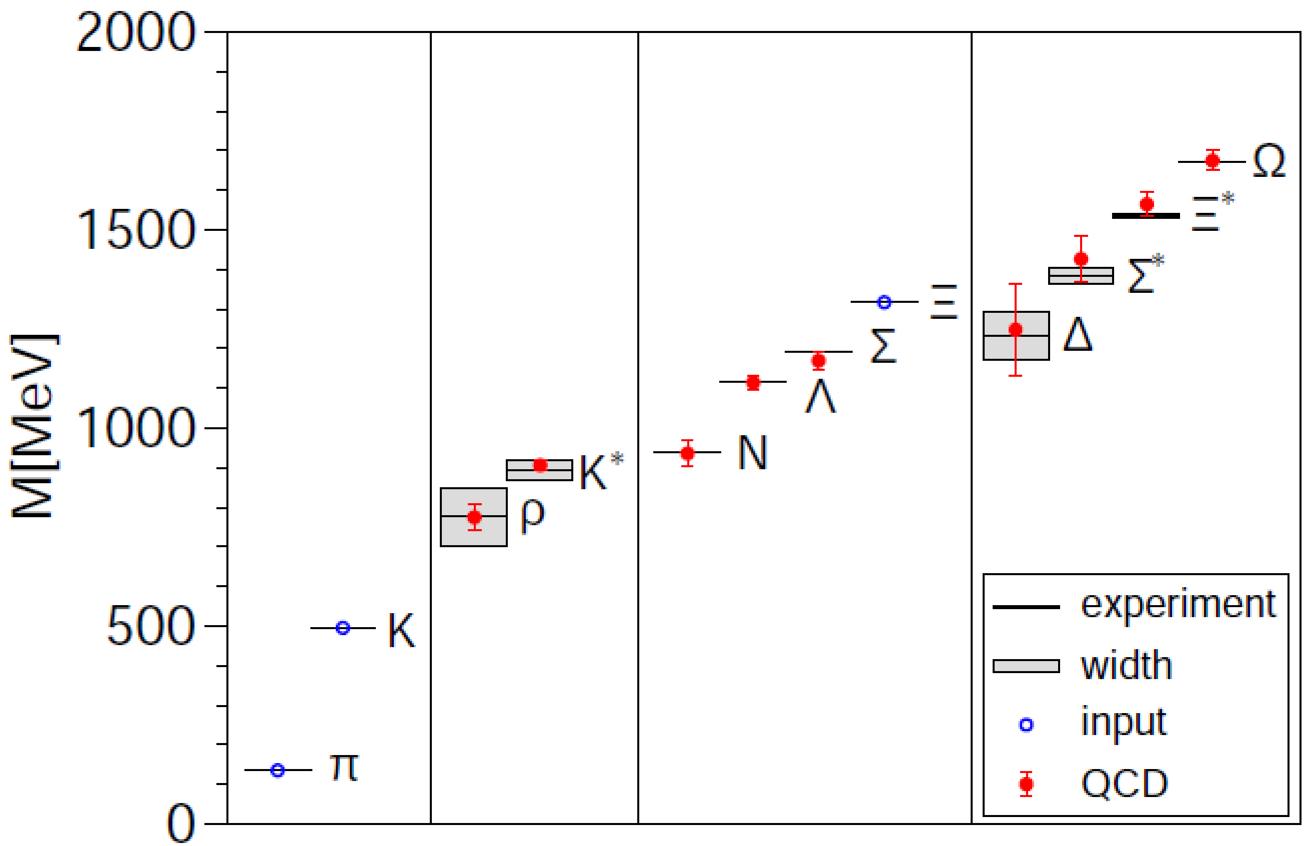
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

From analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

In practice, we use the full experimental hadronic mass spectrum from the PDG compilation to compute the 'primordial yield'

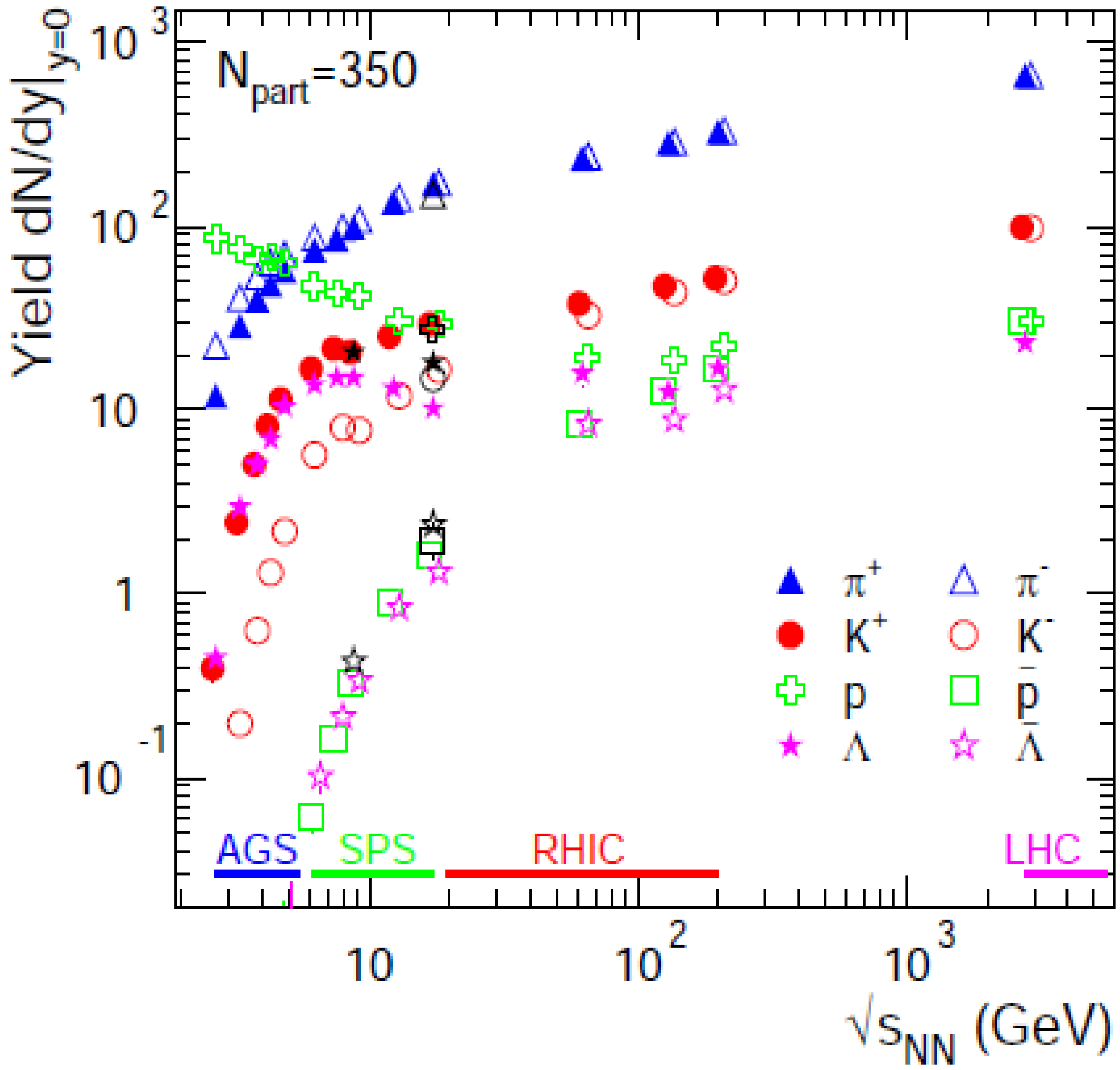
Comparison with measured hadron yields needs evaluation of all strong decays

The hadron mass spectrum and lattice QCD



S. Duerr et al., Science 322 (2008) 1224-1227

The experimental input: 25 years of data from the GSI, AGS, SPS, RHIC and LHC collaborations



CERN experiments:

SPS:
NA35, NA36, NA44, NA45, NA49, NA50, NA57, NA60, NA61 WA80. WA87, WA98

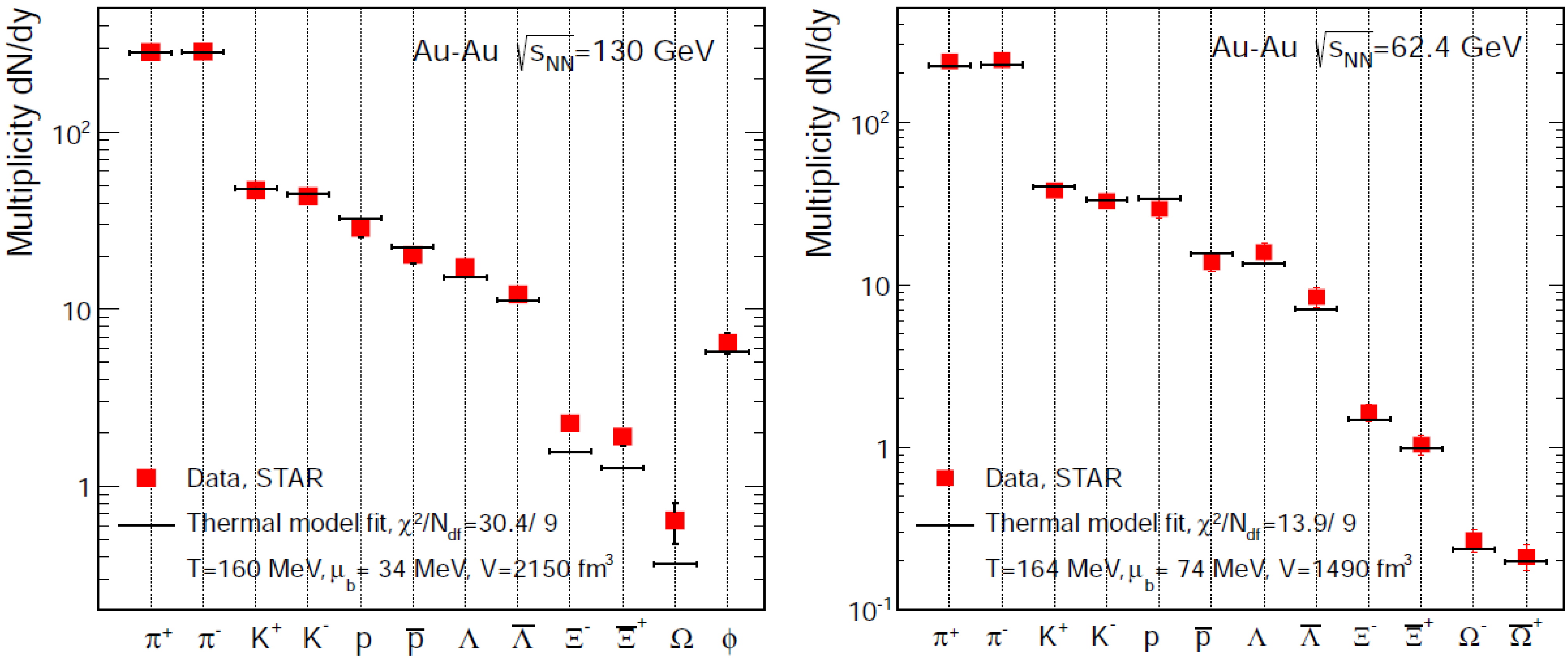
LHC:
ALICE, ATLAS, CMS, LHCb

GSI experiments:
FOPI, KAOS

BNL experiments:
AGS:
E802/E859/E866, E810, E814/E877, E864, E895

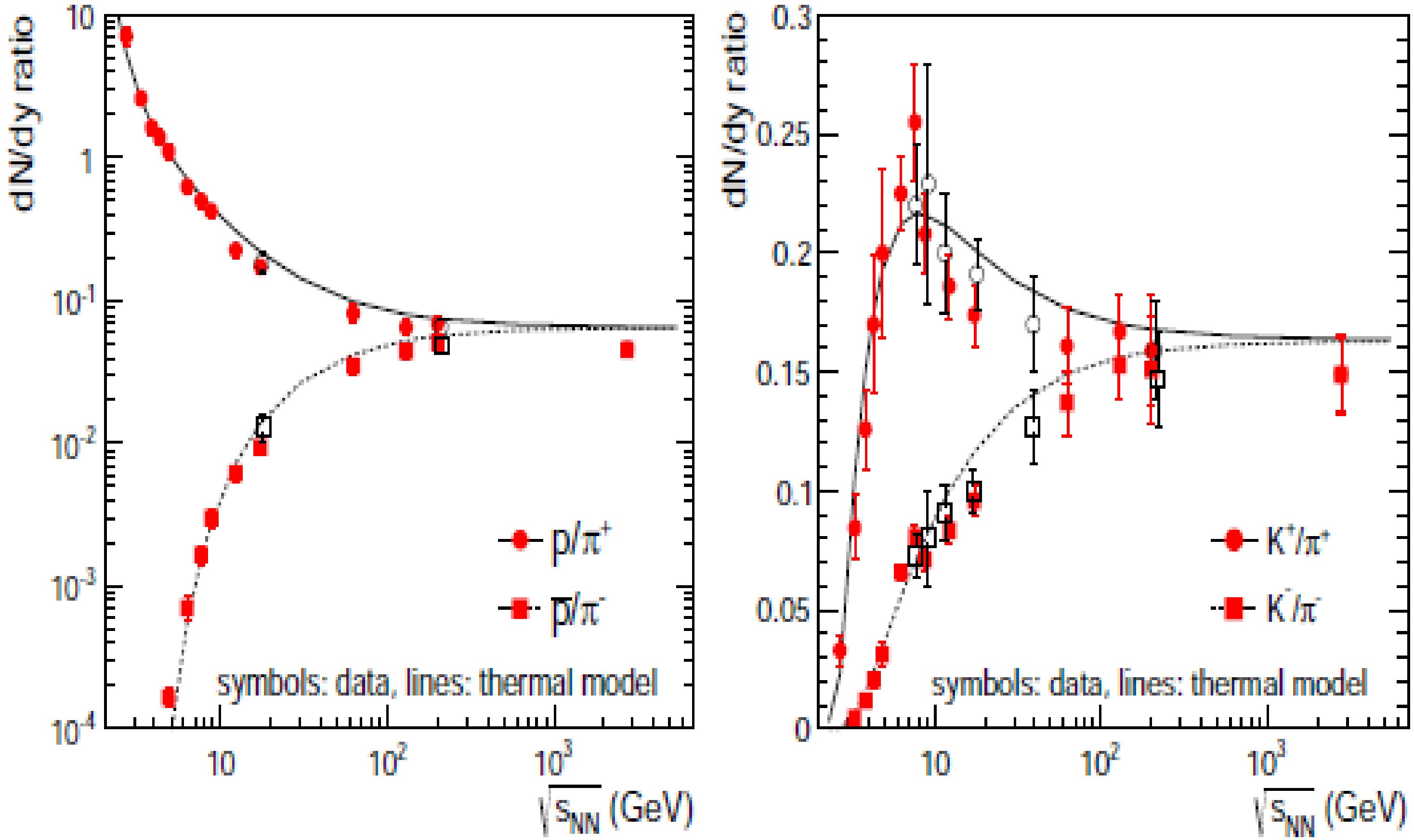
RHIC:
BRAHMS, PHENIX, PHOBOS, STAR

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

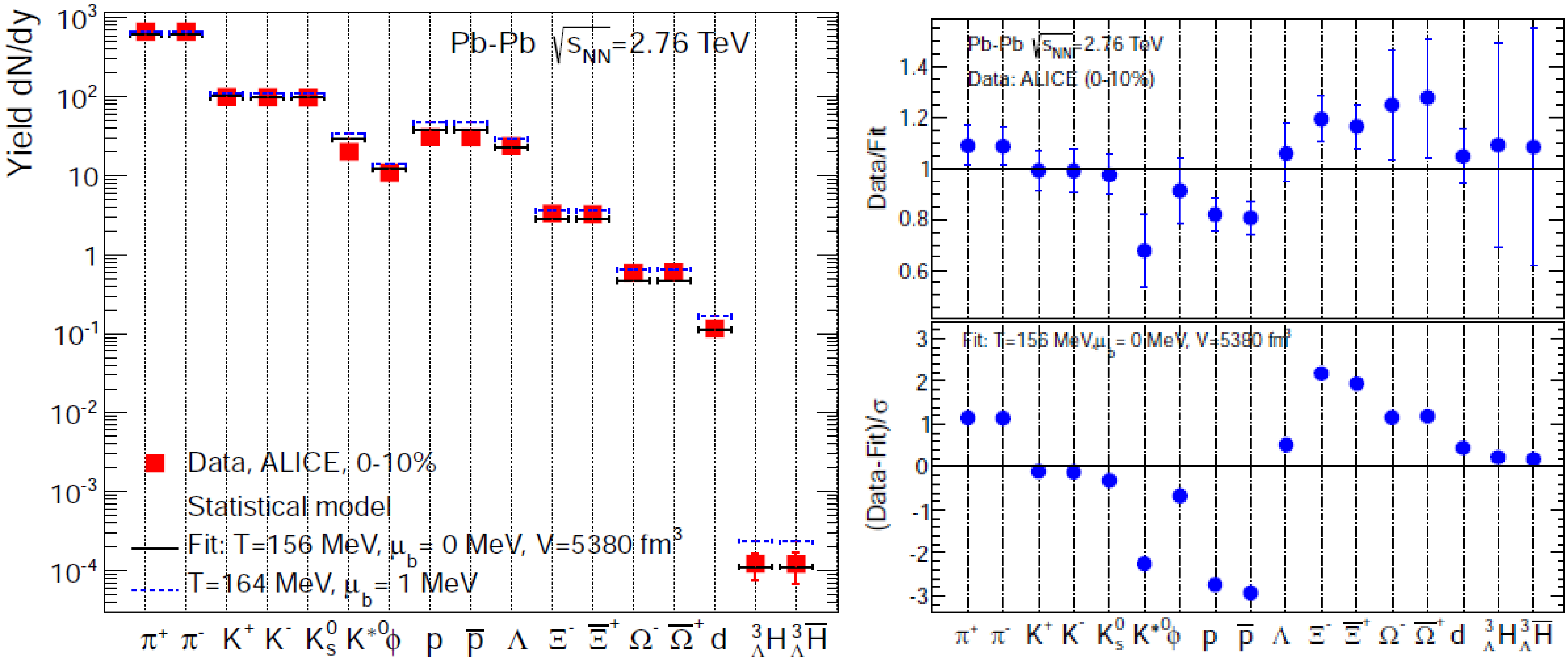


good fits, T = 160 – 164 MeV

Energy dependence of particle yields and thermal model



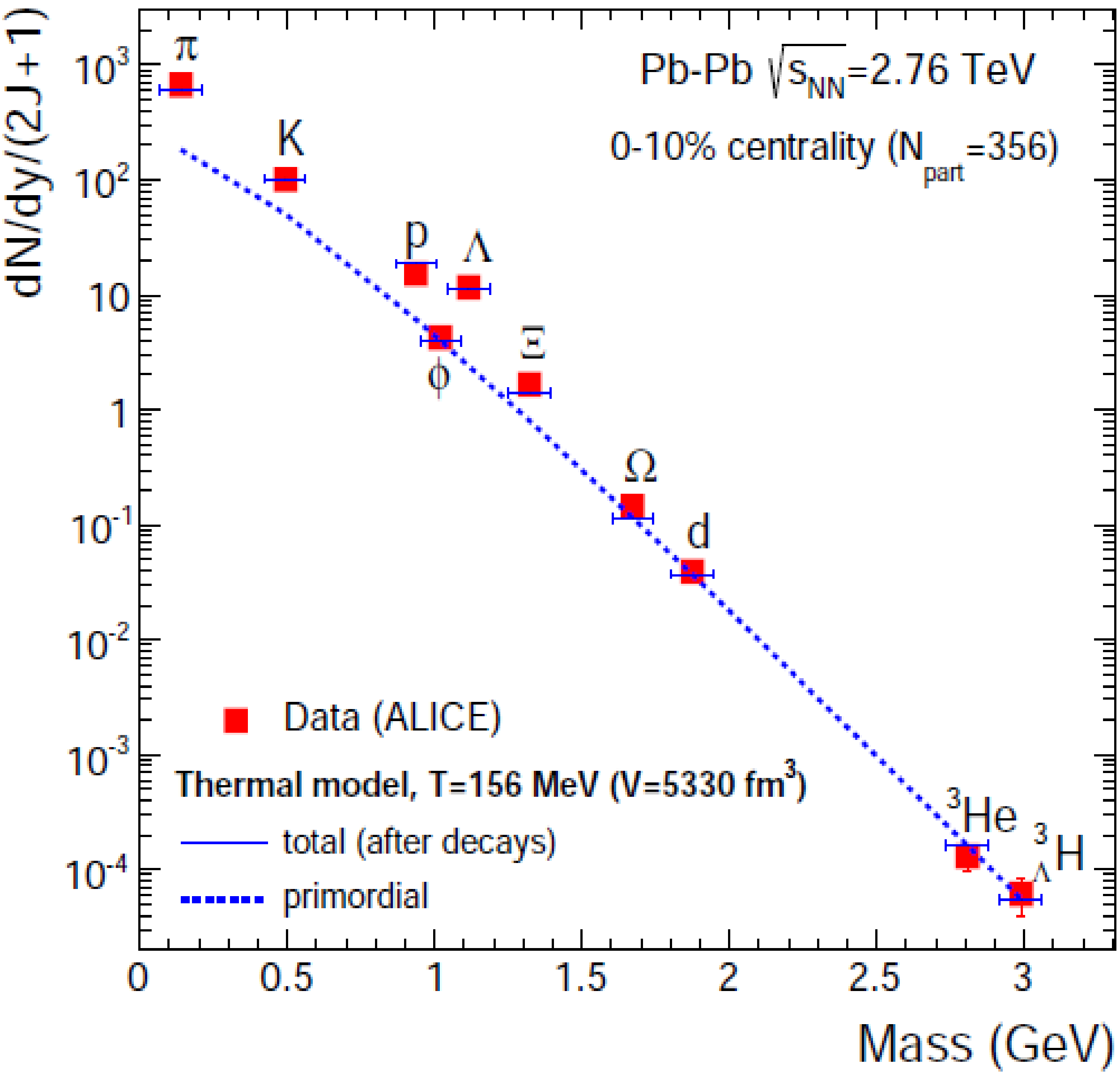
Excellent description of LHC data



fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound by only 100 keV, it is the **ultimate halo nucleus,**
produced at T=156 MeV.

This result is important for the understanding of the production of exotica, see below.

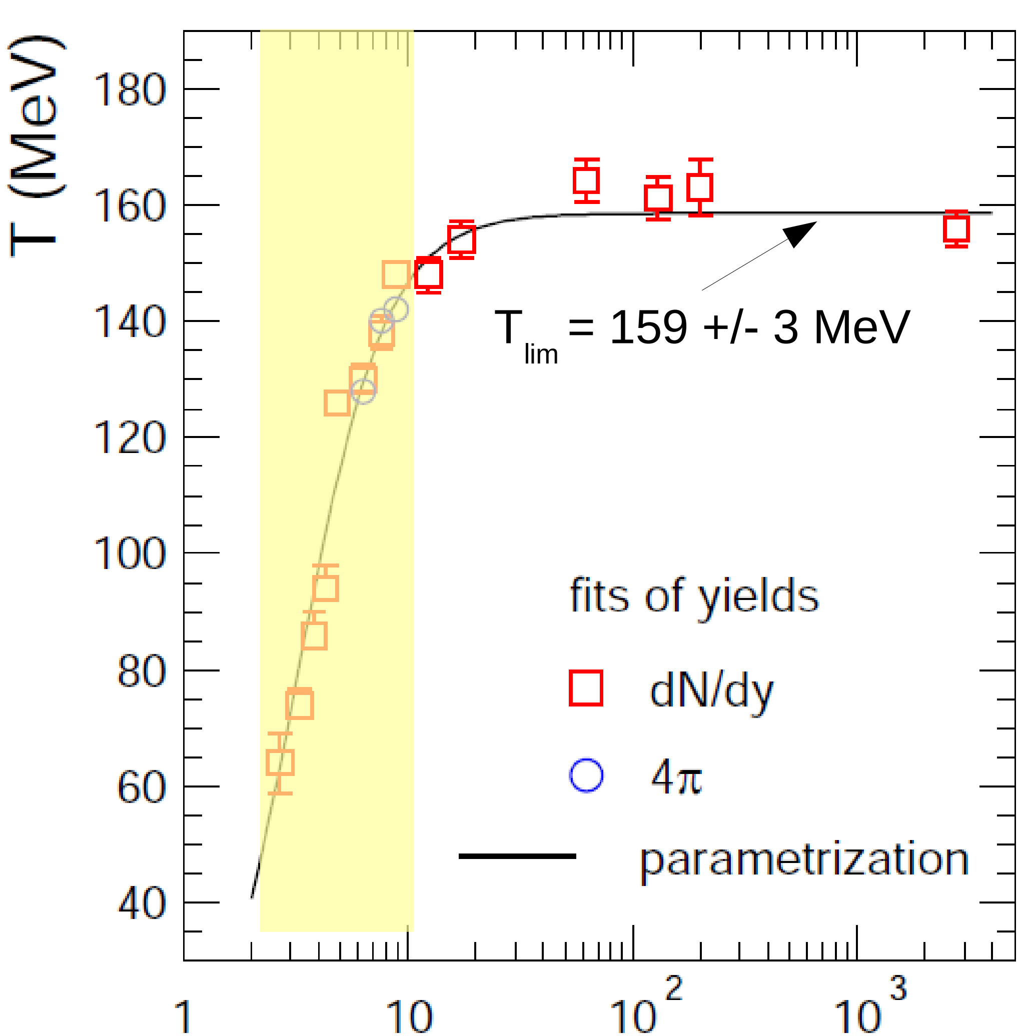
Mass dependence of primordial and total yield compared to LHC data

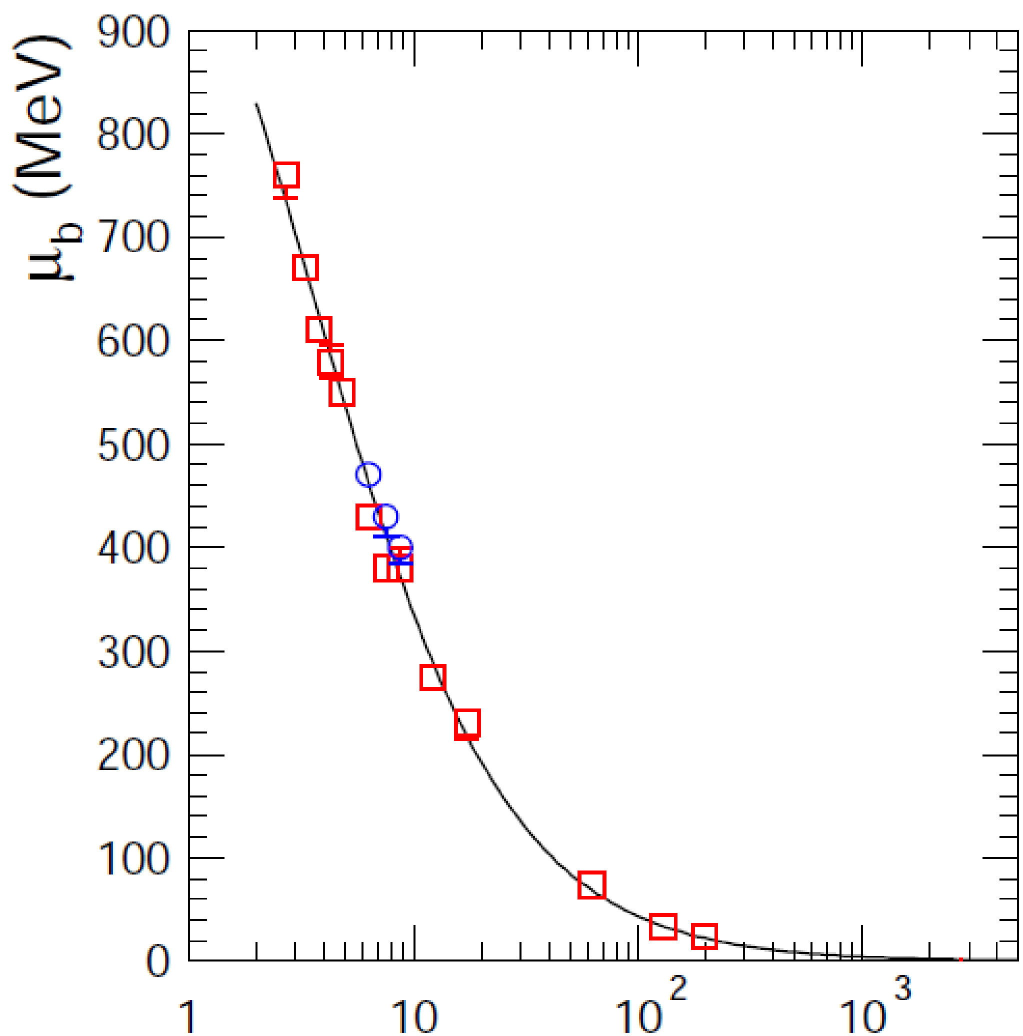


Energy dependence of temperature and baryo-chemical potential

energy range from SPS down to threshold

is phase boundary ever reached for $\sqrt{s_{NN}}$ < 10 GeV?

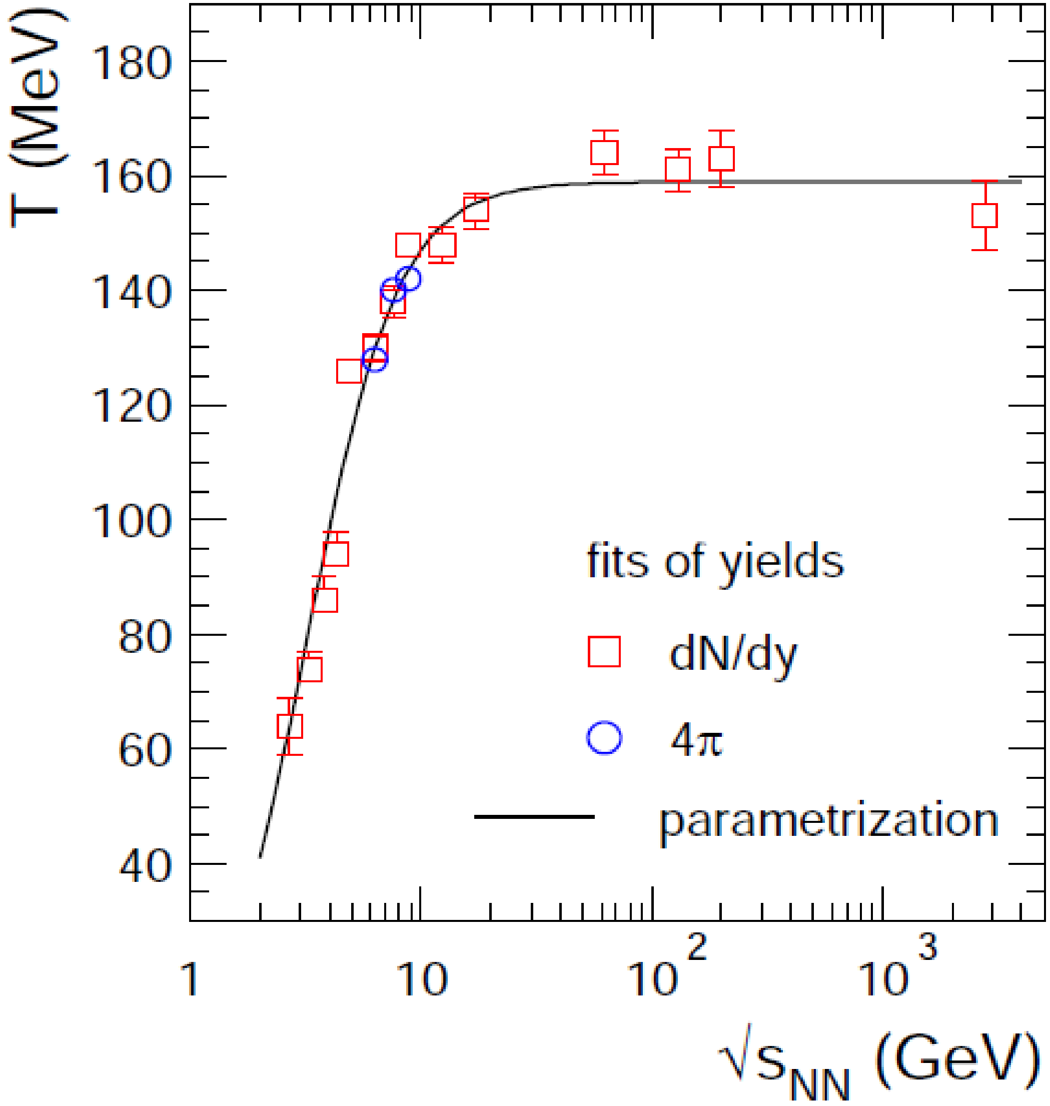




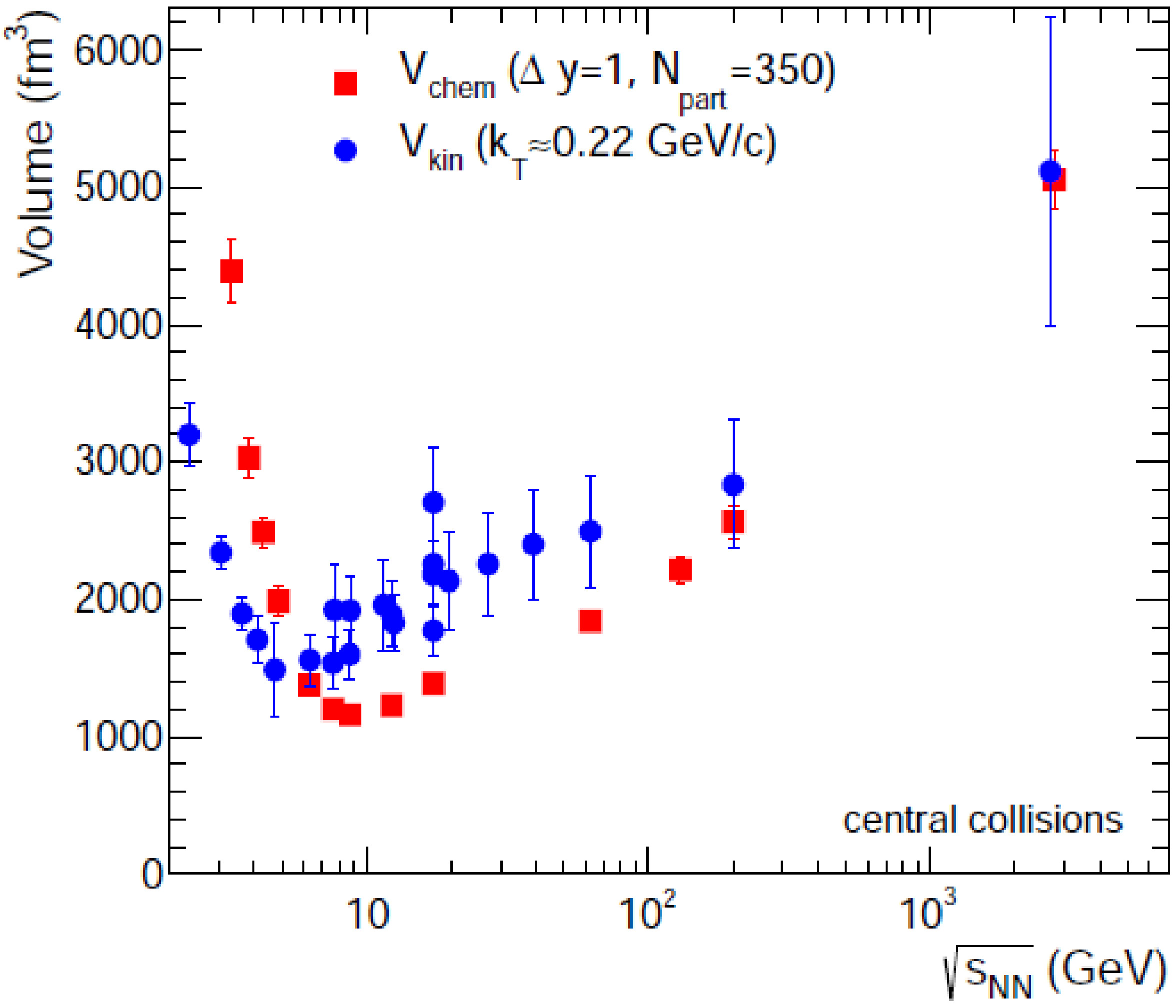
T_{lim} = 159 +/- 3 MeV is lower limit for phase boundary

T_c = 155 +/- 8 MeV from lattice

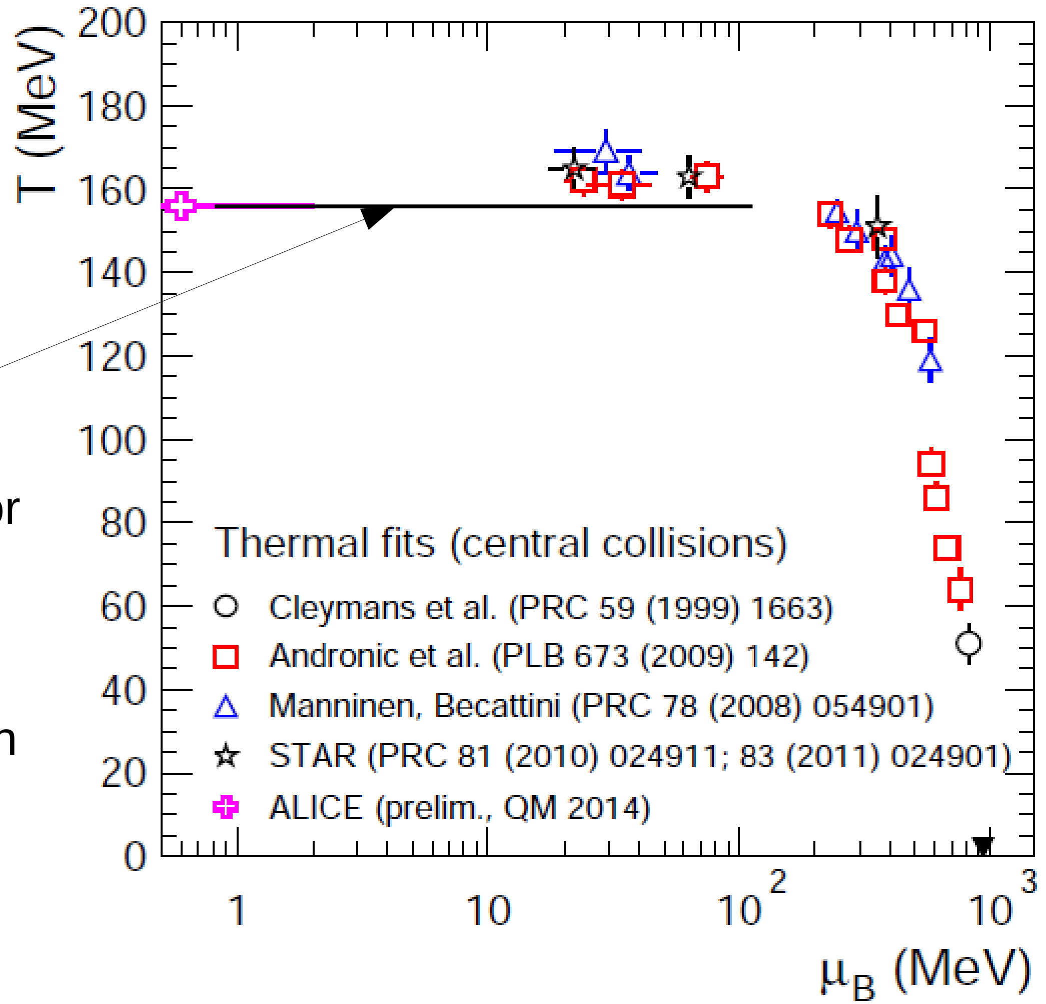
QGP limits the maximum temperature of a hadronic system



Energy dependence of (chemical freeze-out) volume



central nucleus-nucleus collision data and the QCD phase boundary



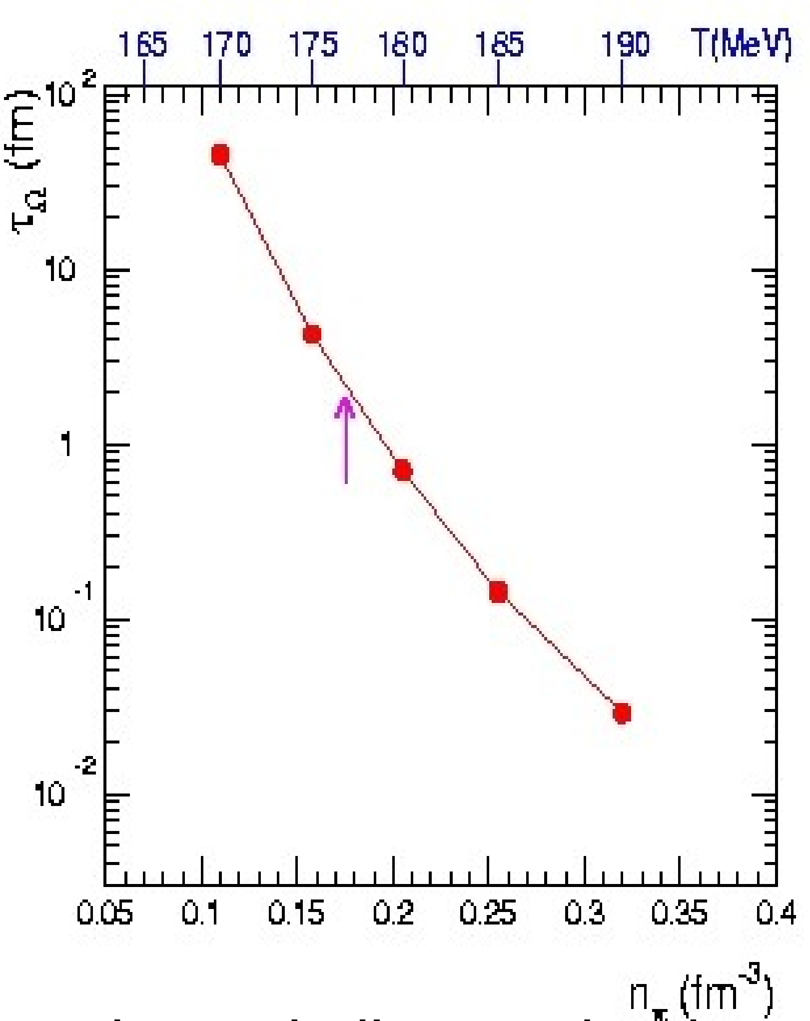
Lattice QCD,
T_c = 155 +/- 8 MeV for
mu_b = 0

mu_b dependence
from Taylor expansion
HOT-QCD coll.

Limiting temperature predicted by Hagedorn 50 years ago and oberserved in the data is very close to critical temperature from lattice QCD

This includes mu_b dependence for mu_b < 250 MeV (top SPS energy)

The QGP phase transition drives chemical equilibration for small mu$_b$

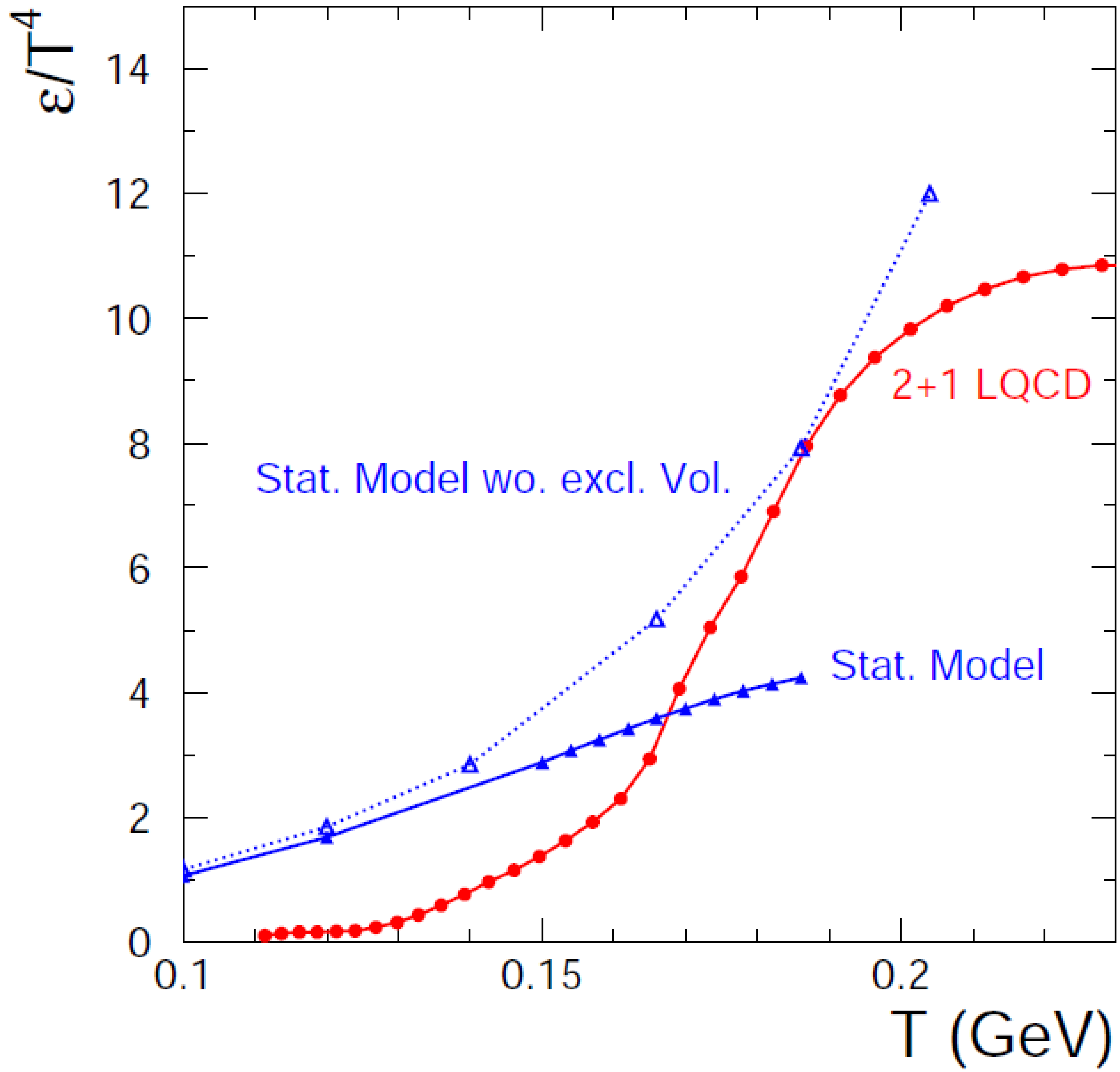


- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window.

are there similar mechanisms for large μ_b?

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

Temperature dependence of energy density near T_c



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 A

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	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}\mathrm{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}\mathrm{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}\mathrm{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}\mathrm{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}\mathrm{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

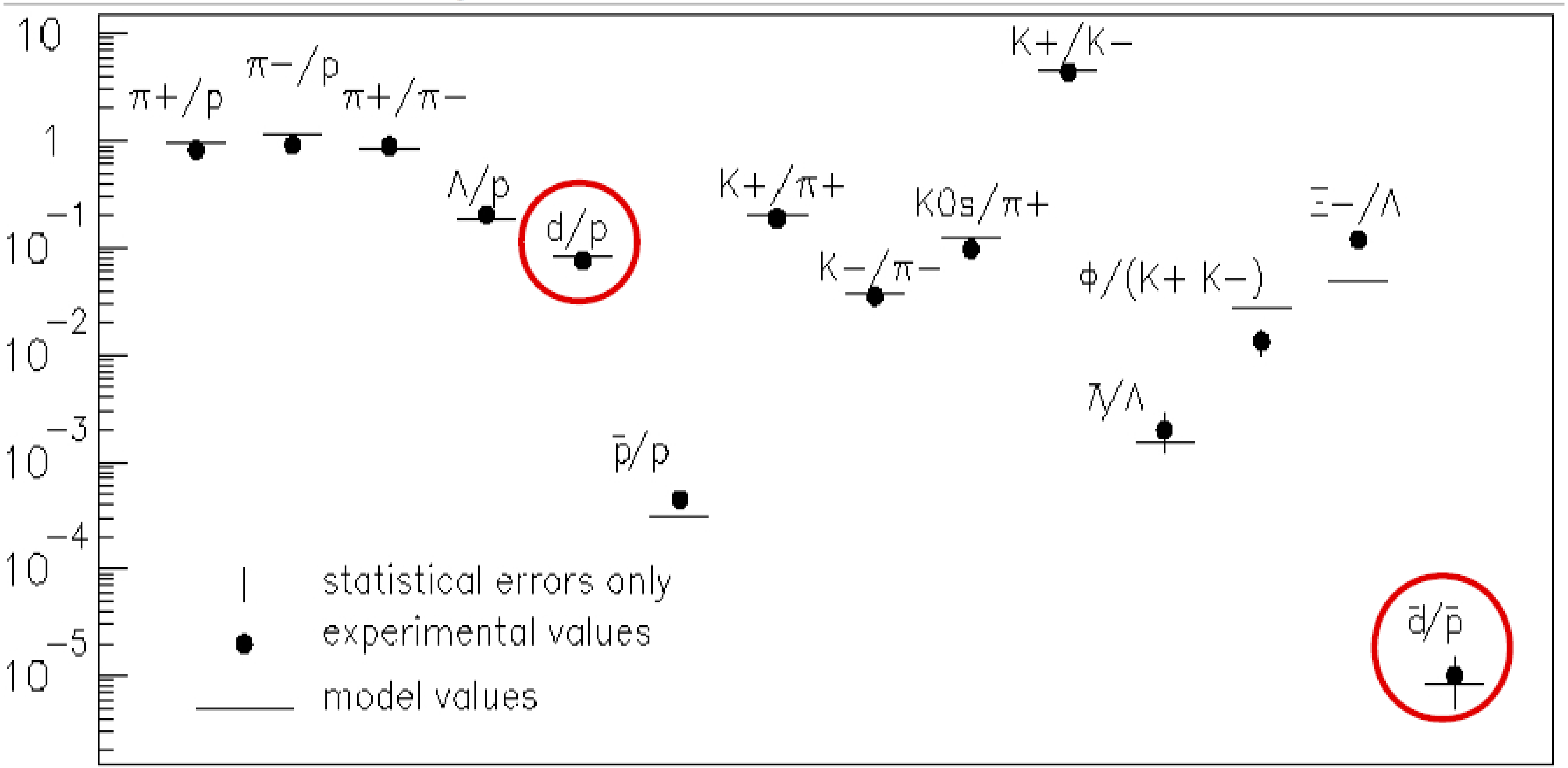
P. Braun-Munzinger, J. Stachel, J. Phys. G **28** (2002) 1971 [arXiv:nucl-th/0112051]

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

data cover 10 oom!
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
-> $R_p = 26$

GC statistical model:

$$R_p \approx \exp[(m_n \pm \mu_b)/T]$$

for T=124 MeV and μ_b= 537 MeV

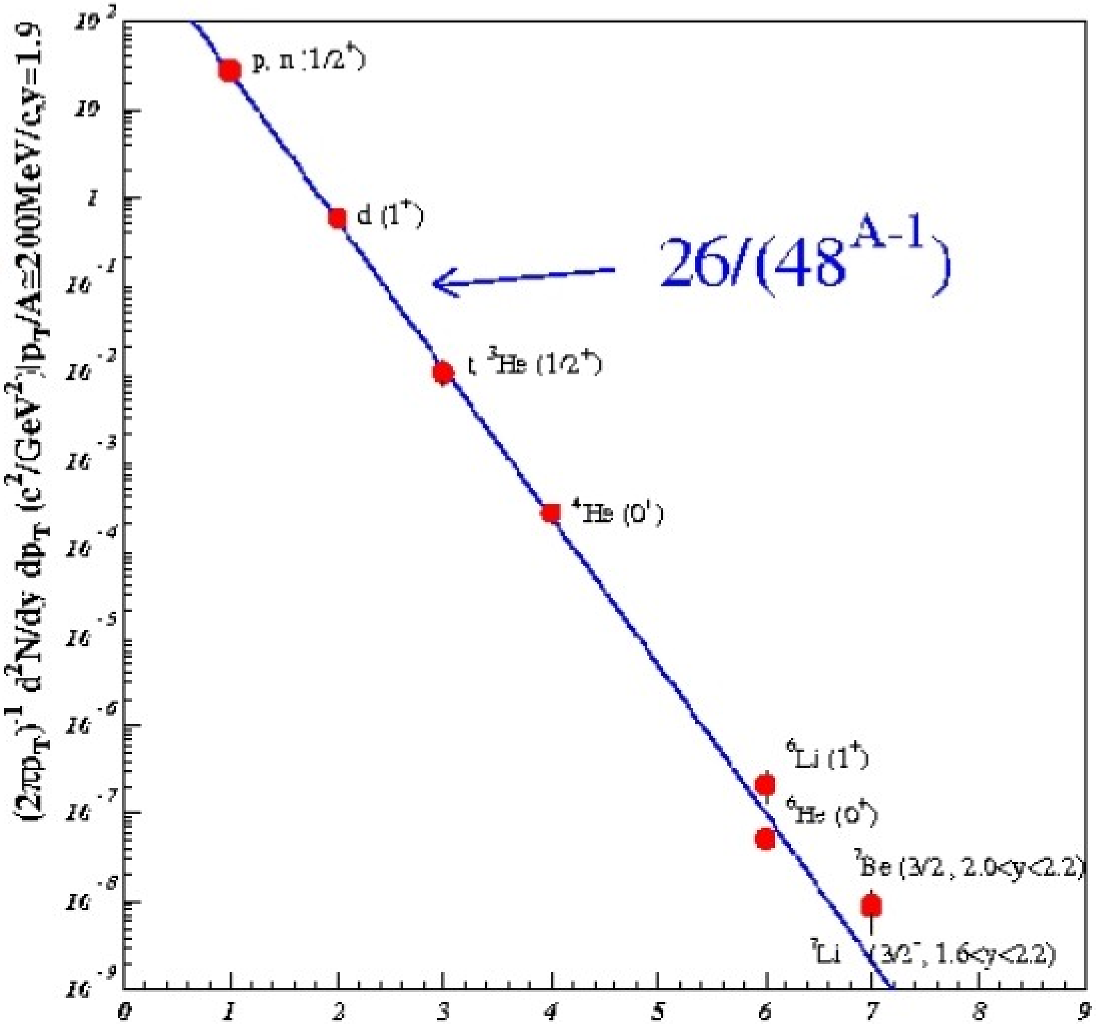
$R_p = 24$ good agreement

also good for **antideuterons**:

data: $R_p = 2\pm1\cdot10^5$ SM: $1.3\cdot10^5$

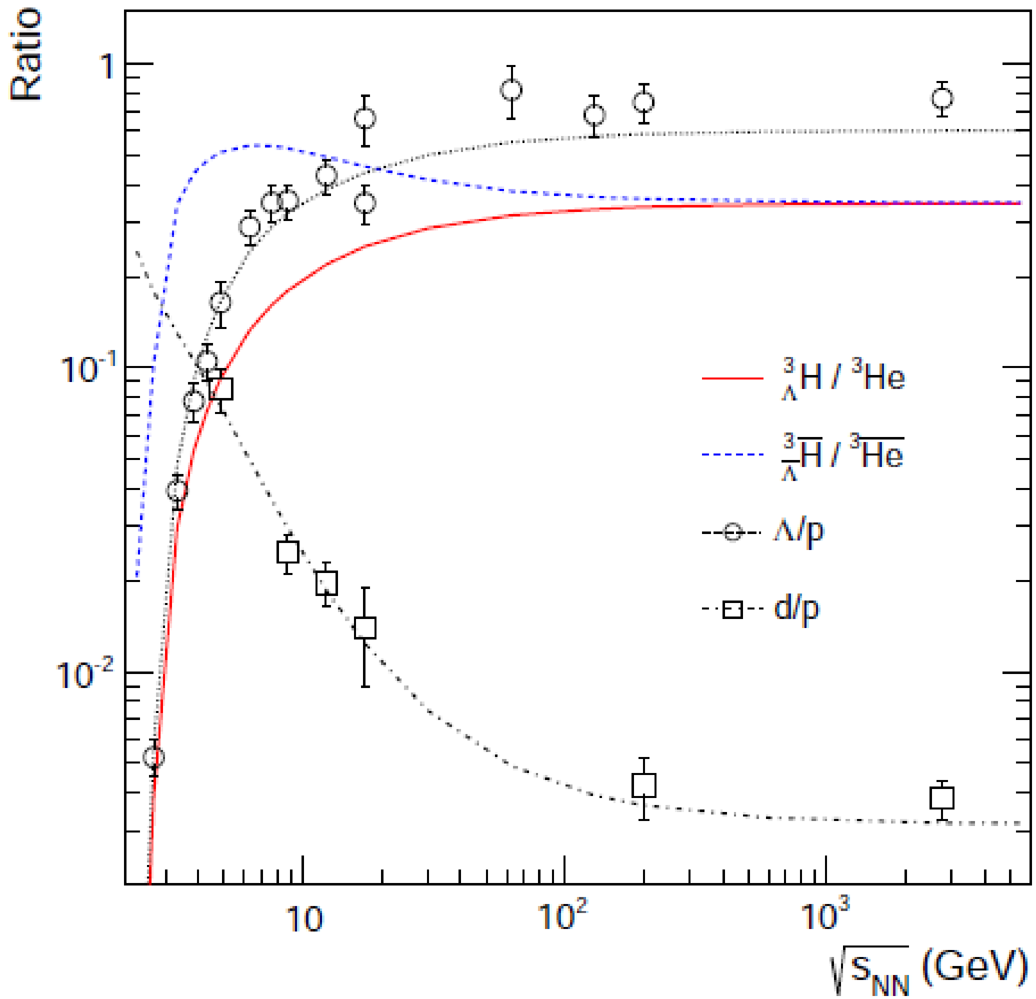
P. Braun-Munzinger, J. Stachel, J. Phys. G28 (2002) 1971

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



mass number A

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

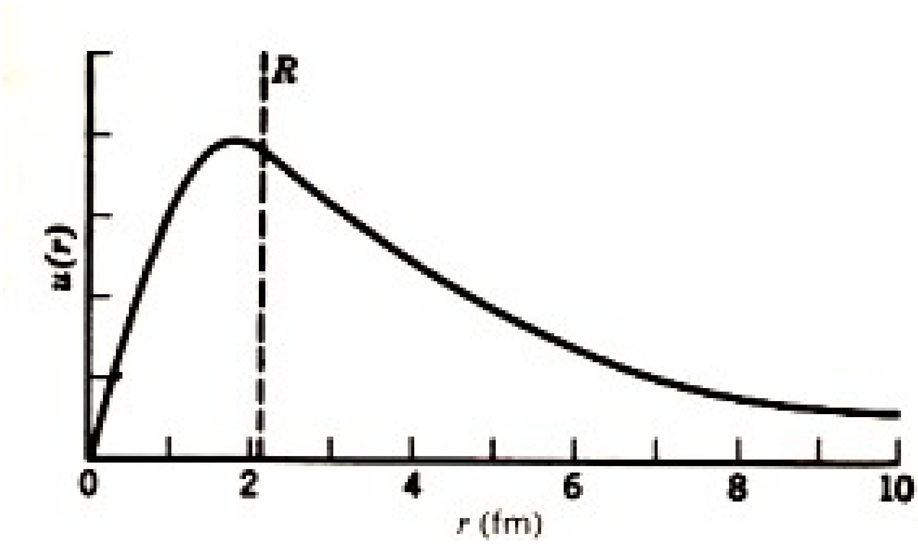
The size of loosely bound molecular objects

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

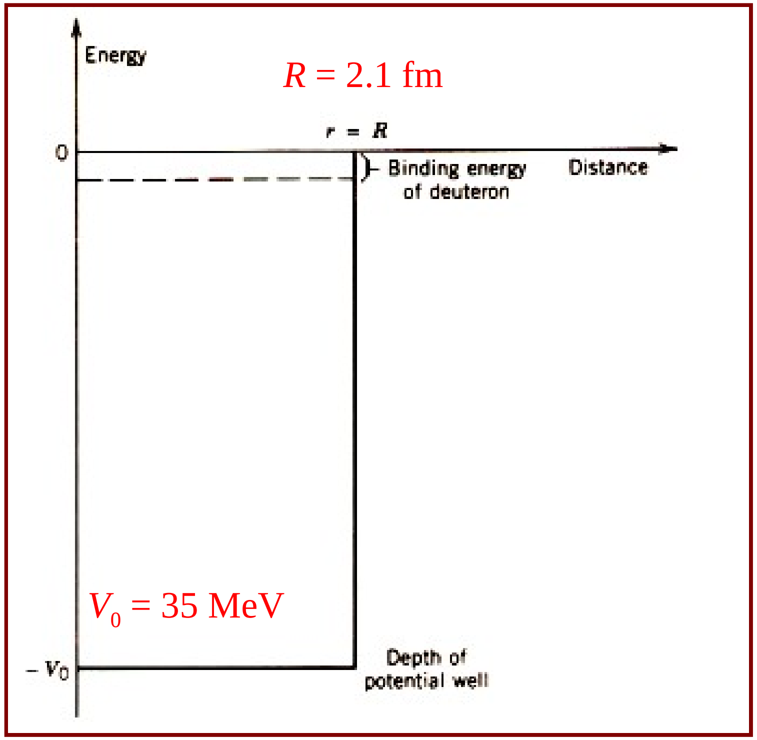
Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which 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 = $(4\ \mathrm{B.E.}\ \ M_{red})^{-1/2}$ = 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 1

all so far measured hadron multiplicity data from central nuclear collisions are in agreement with thermal model predictions

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 results provide strong evidence for a limiting temperature near 156 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

Summary 2

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

the full QCD statistical operator is encoded in the nuclear collision data on hadron multiplicities

energy dependence of hadron yields provides strong connection to fundamental QCD prediction of hadronic and quark-gluon matter at high temperature

Additional slides

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

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

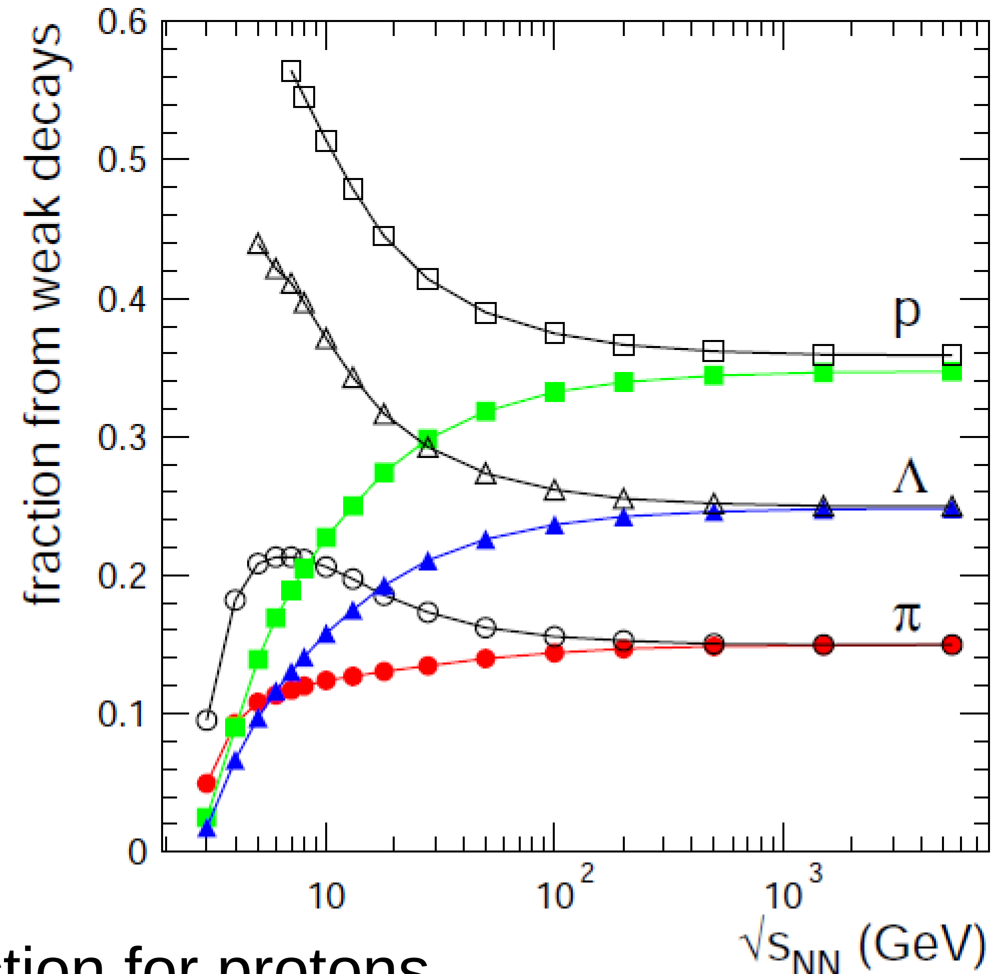
All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

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

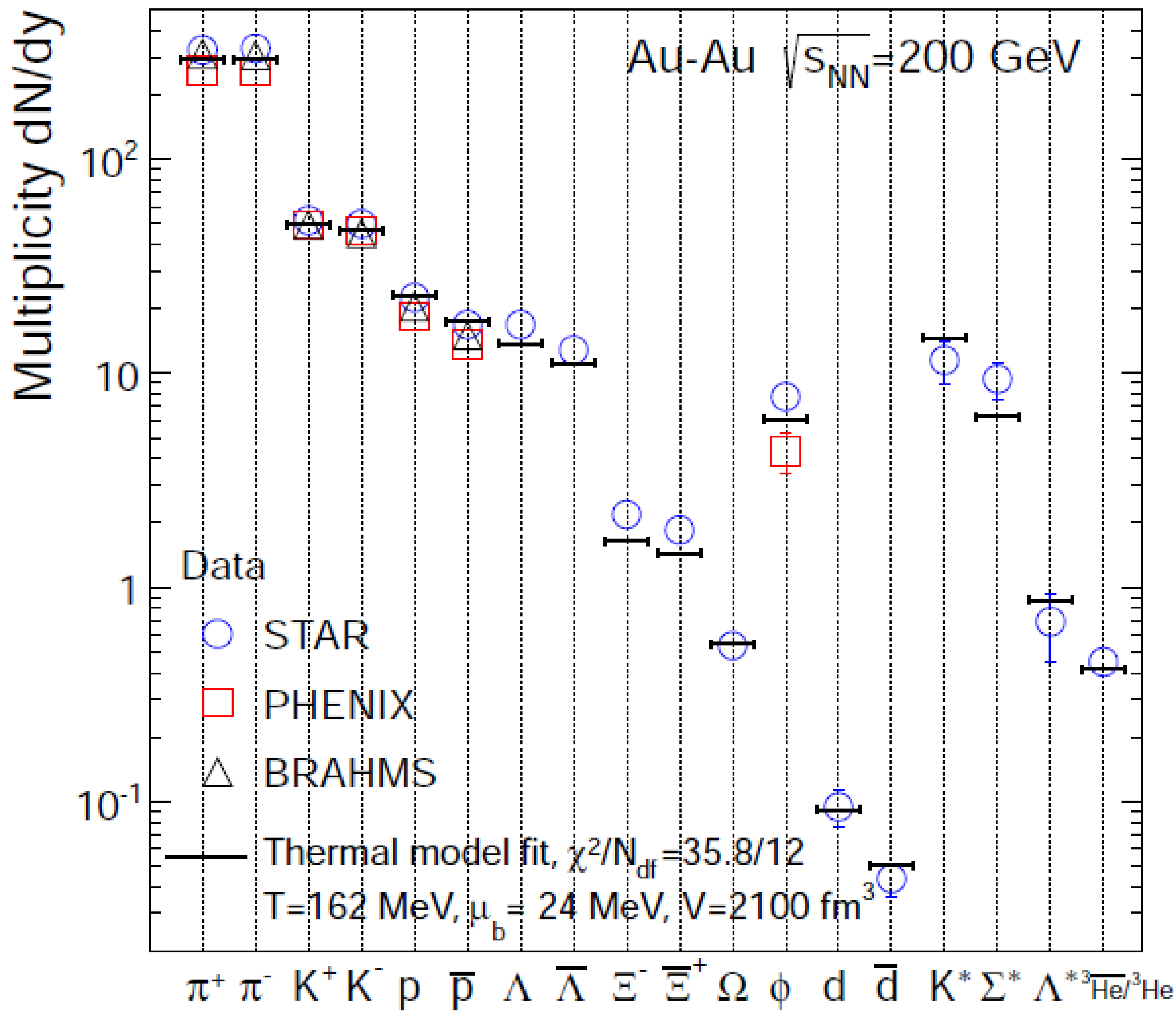
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

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 Me'



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

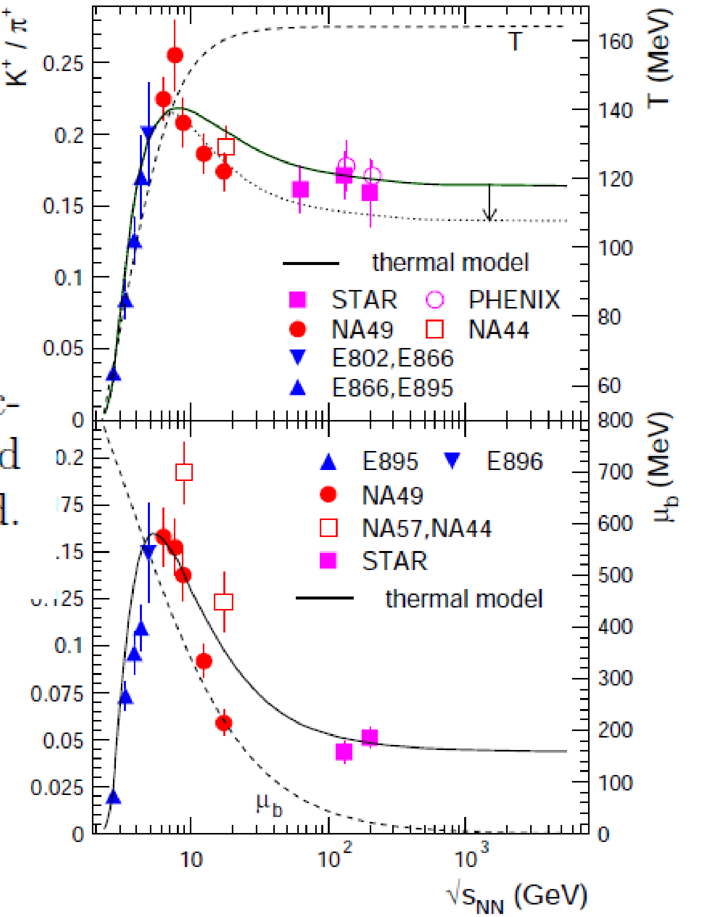
could it be incomplete hadron resonance spectrum?

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

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

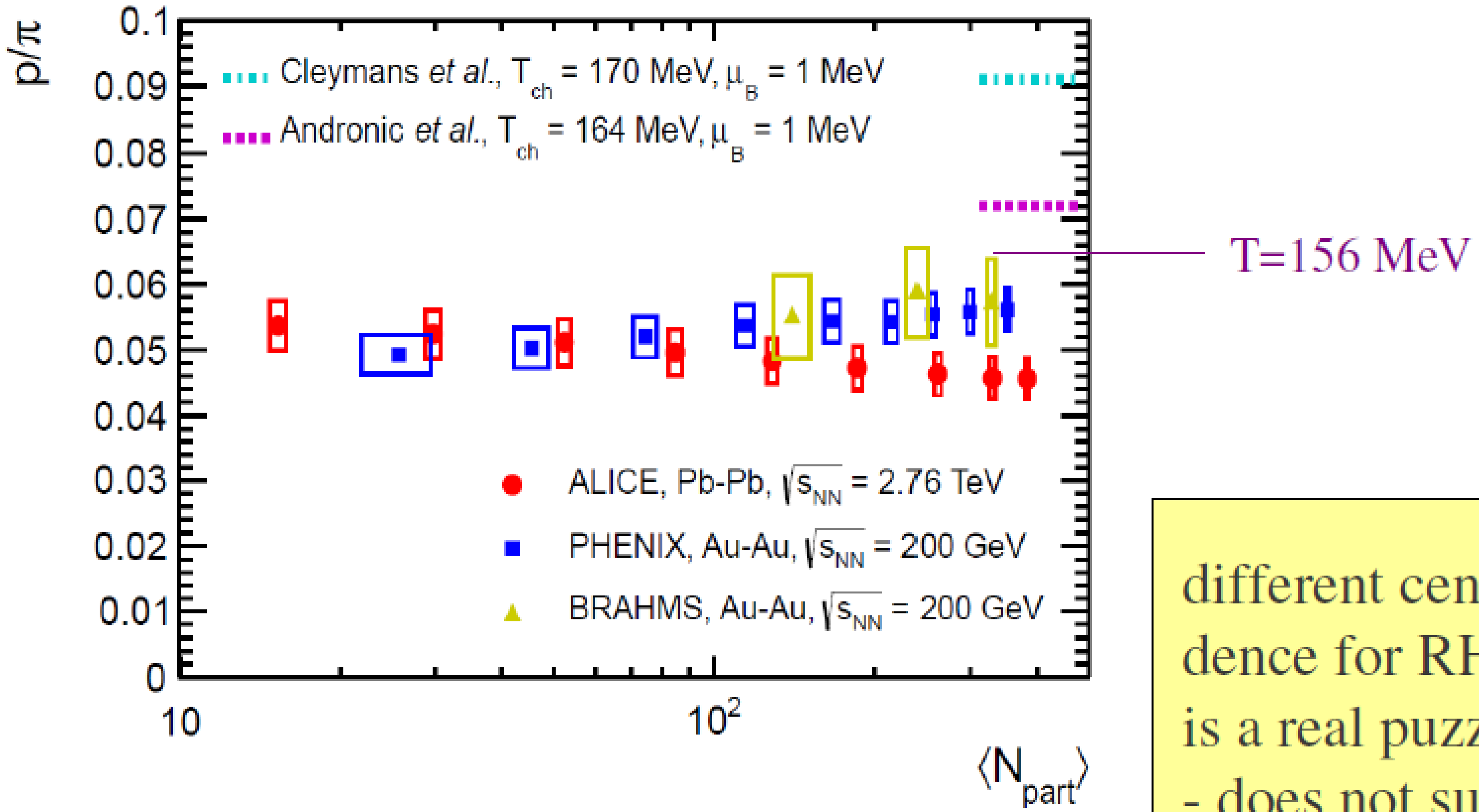
• need to incorporate detailed balance, 5pi → p p_bar not included in current Monte Carlo codes (RQMD)

• 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

Nuclear collisions, open and hidden charm hadrons, and QCD

Hadrons containing charm quarks can also be described provided open charm cross section is known

Recent ALICE data imply Debye screening near T_c for charmonium and deconfined heavy quarks, see talk by Johanna Stachel

Could it be that increasing number of charm quarks changes (lowers) T_c? An issue for the FCC!

Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at T_c

- Debye screening length < 0.4 fm near T_c

- Combination of uncorrelated charm quarks into J/psi → deconfinement

statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP

Debye mass, LQCD, and J/psi data

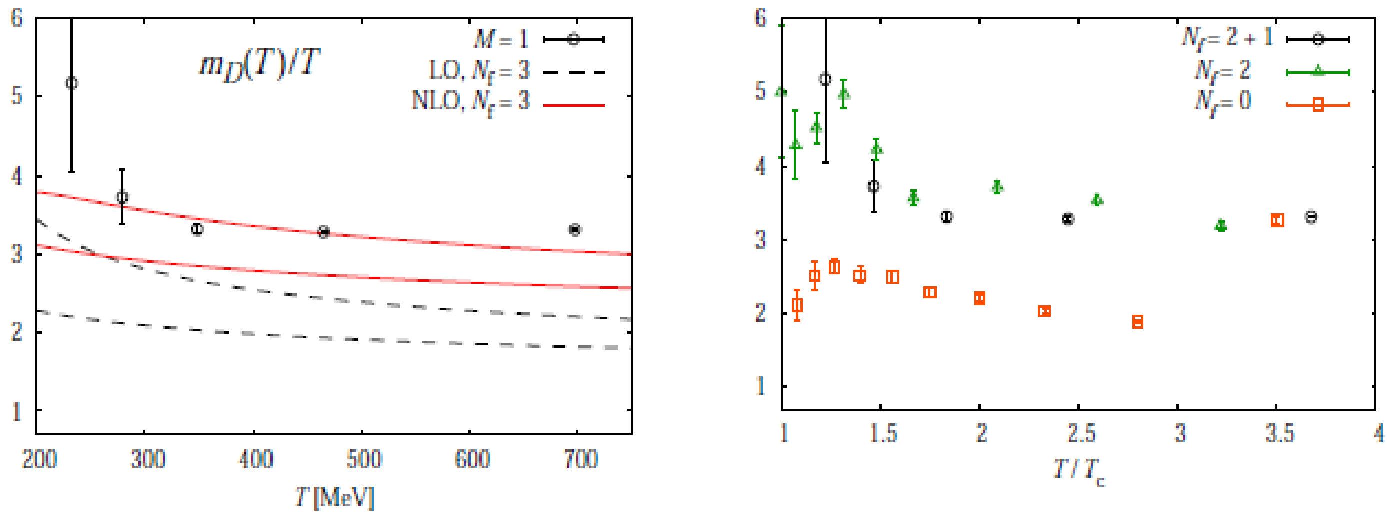


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, where μ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for $2+1$-flavor QCD as $T_c \sim 190$ MeV.

arXiv:1112.2756 WHOT-QCD Coll.

from J/psi data and statistical hadronization analysis:

$m_{Debye}/T > 3.3$

at T = 0.15 GeV