Particle production in relativistic nuclear collisions and the phase structure of QCD

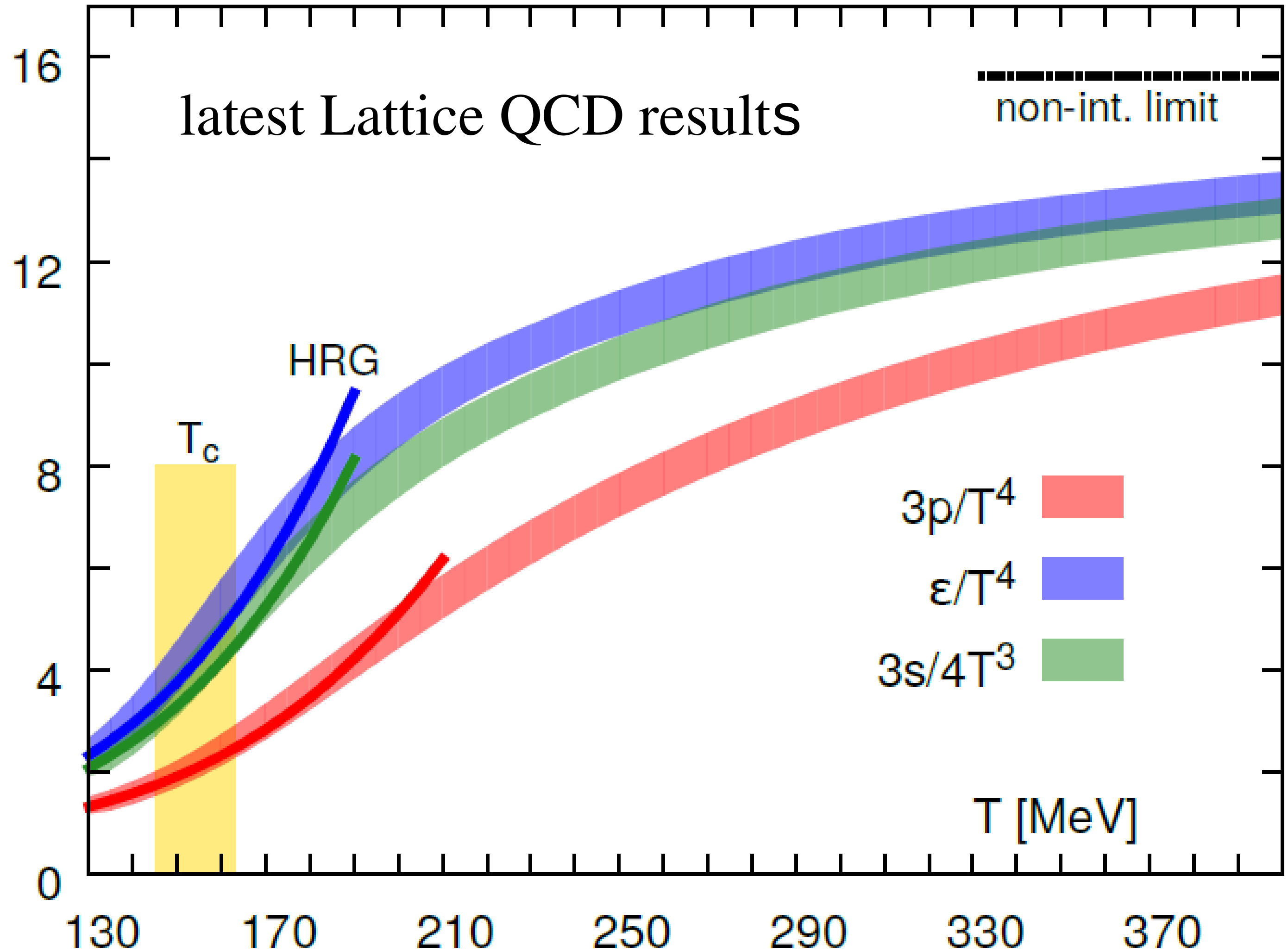
- introduction and perspective
- hadron production, Lattice QCD and the QCD phase structure
- remarks on fluctuations at LHC energy
- outlook

CPOD2016
Wroclaw
June1, 2016

Peter Braun-Munzinger

results obtained in collaboration with
Anton Andronic,
Krzysztof Redlich, and Johanna Stachel

the equation of state of hot QCD matter – a chiral (cross over) phase transition between hadron gas and the QGP



are there free quarks at T << Tc ???

critical region: $T_c = (154 \pm 9)$ MeV $\varepsilon_{crit} = (340 \pm 45)$ MeV/fm^3

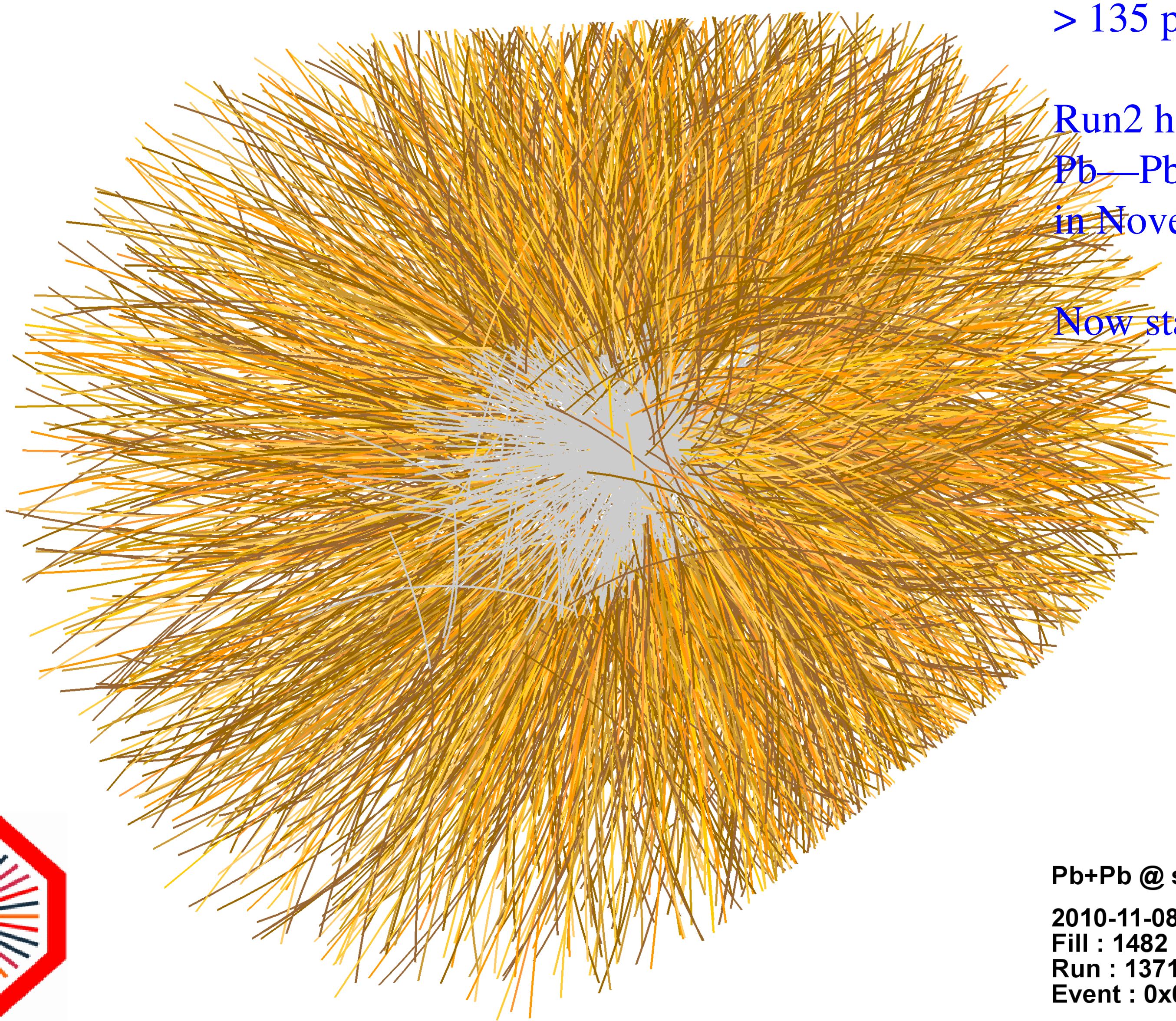
HOTQCD coll., Phys.Rev. D90 (2014) 9, 094503

first PbPb collisions at LHC at Ös = 2.76 A TeV

Run1: 3 data taking campaigns
pp, pPb, Pb—Pb
> 135 publications

Run2 has started with 13 TeV pp
Pb—Pb run
in November 2015

Now starting again with 13 TeV pp



Pb+Pb @ sqrt(s) = 2.76 ATeV

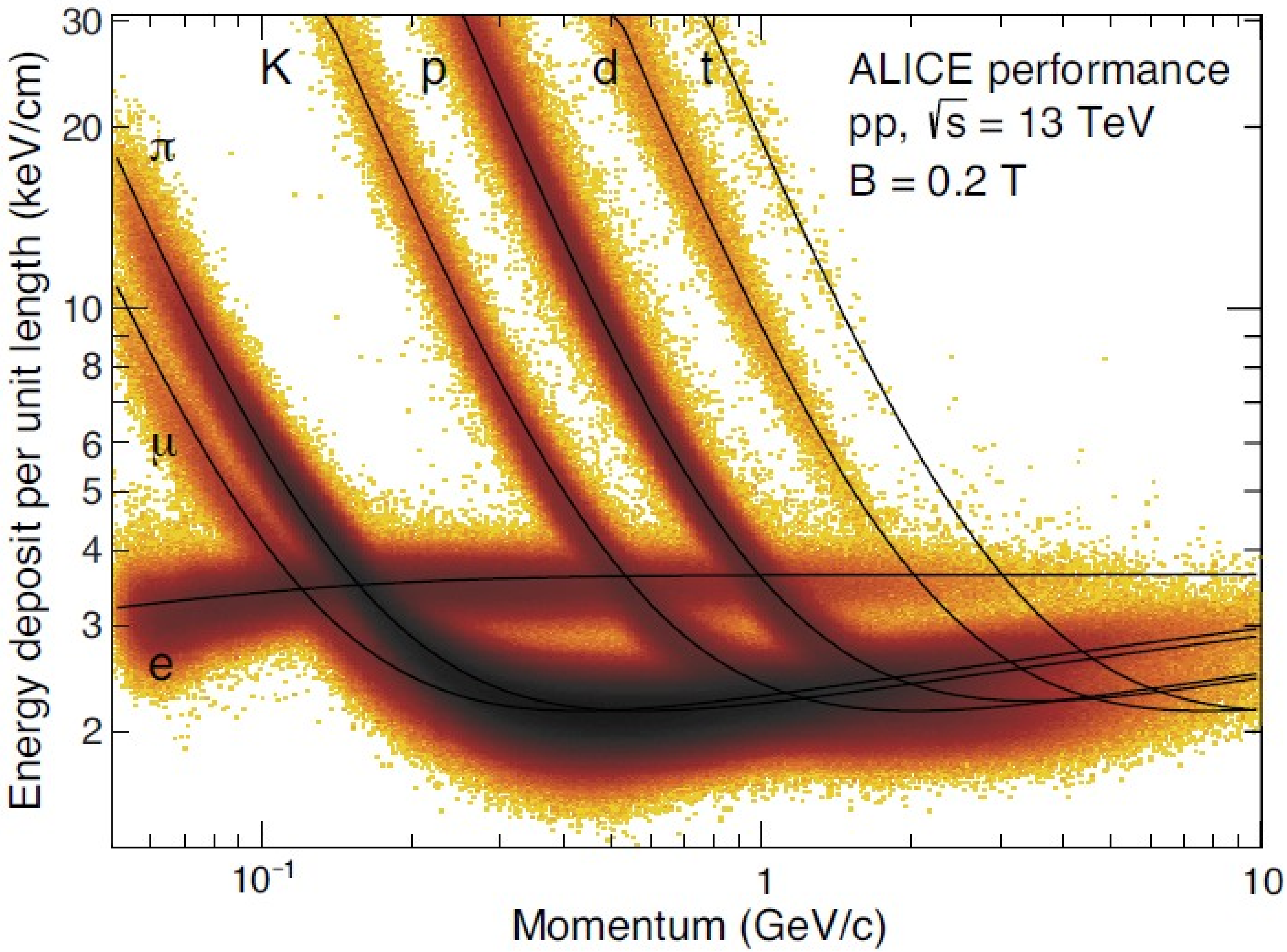
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

and the fun started

particle identification with the ALICE TPC

from 50 MeV to 50 GeV



hadron production and the QCD phase boundary

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 $T_c = T_{lim}$

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

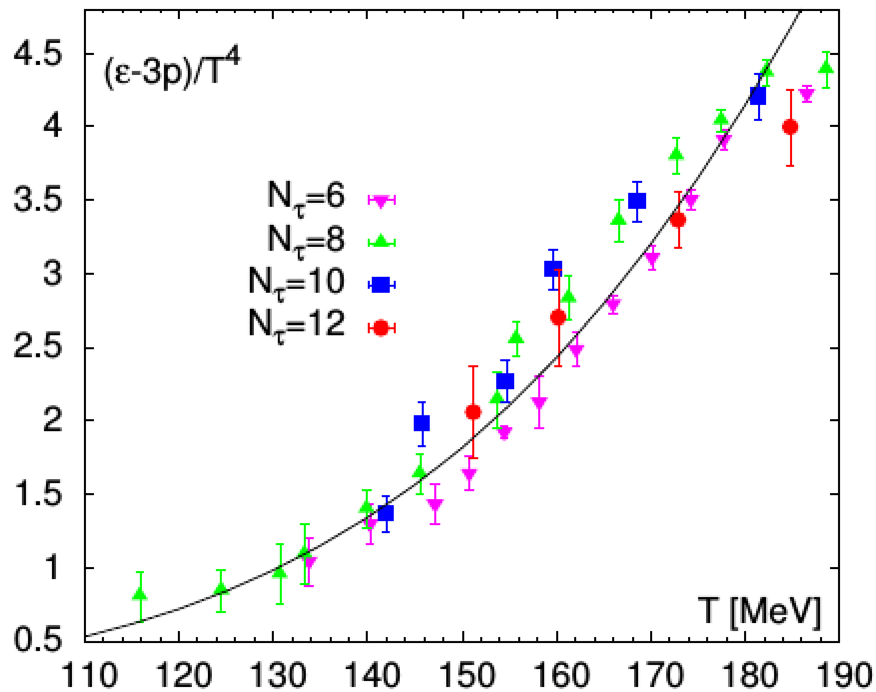
for the pressure we get:

$$\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z(V,T,\mu)$$

comparison of trace anomaly from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

with hadron resonance gas prediction
(solid line)

LQCD: full dynamical quarks with realistic
pion mass

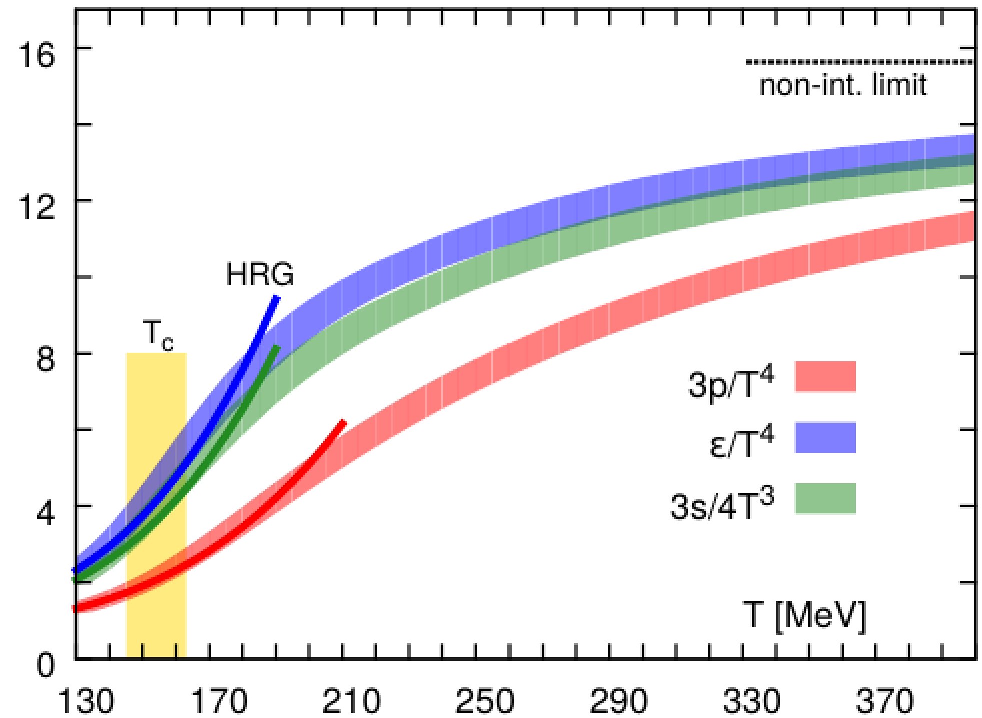


duality between hadrons and quarks/gluons (II)

comparison of equation of state from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

with hadron resonance gas predictions (colored lines)

essentially the same results also from Wuppertal-Budapest coll.
Phys.Lett. B730 (2014) 99-104



pseudo-critical temperature

$$T_c = (154 \pm 9)\ \mathrm{MeV}$$

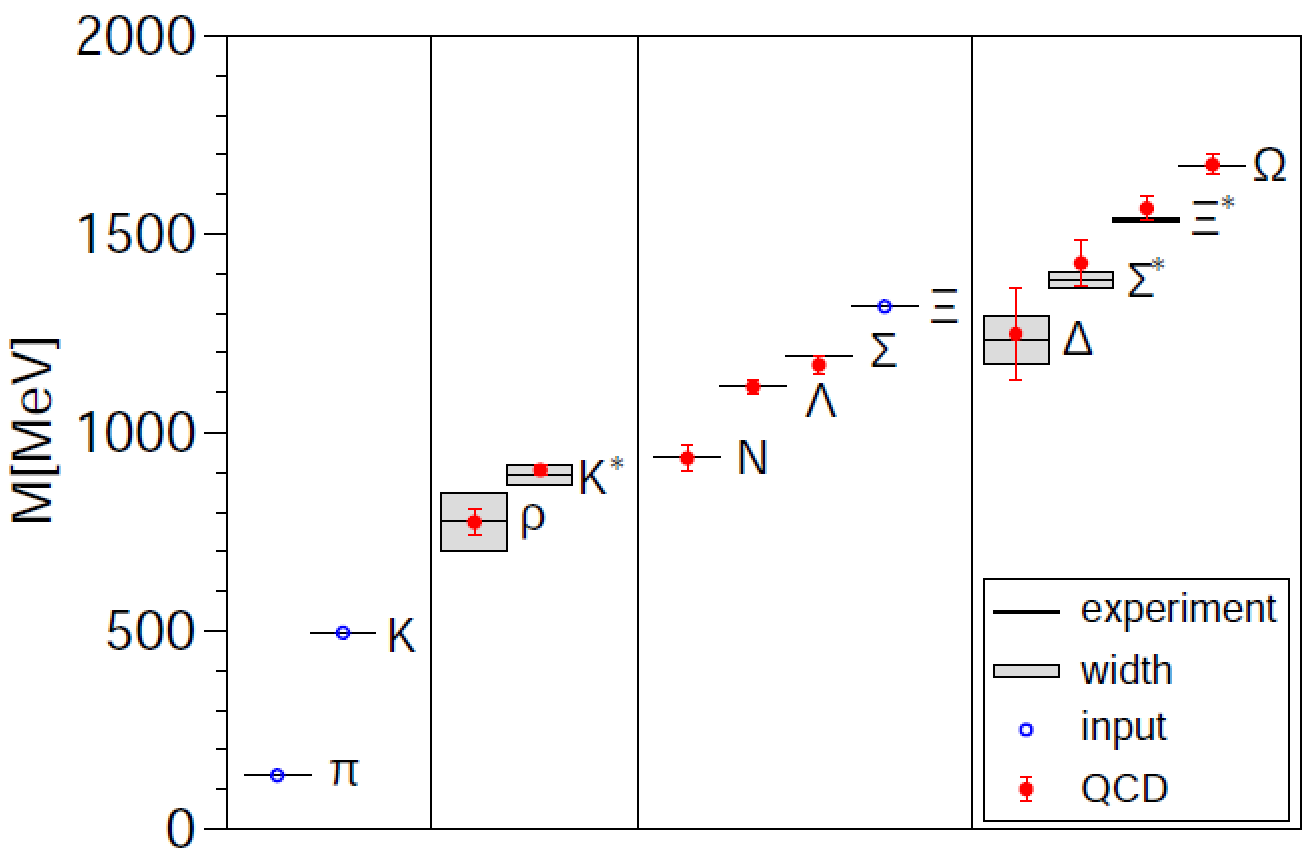
duality between hadrons and quarks/gluons (III)

in the dilute limit T < 165 MeV:

$$\ln Z(T,V,\mu) \approx \sum_{i\in\ mesons} \ln \mathcal{Z}^M_{M_i}(T,V,\mu_Q,\mu_S) + \sum_{i\in\ baryons} \ln \mathcal{Z}^B_{M_i}(T,V,\mu_b,\mu_Q,\mu_S)$$

where the partition function of the hadron resonance model is expressed in mesonic and baryonic components. The chemical potential μ reflects then the baryonic, charge, and strangeness components $\mu = (\mu_b, \mu_Q, \mu_S)$.

the hadron mass spectrum and lattice QCD



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

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:

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

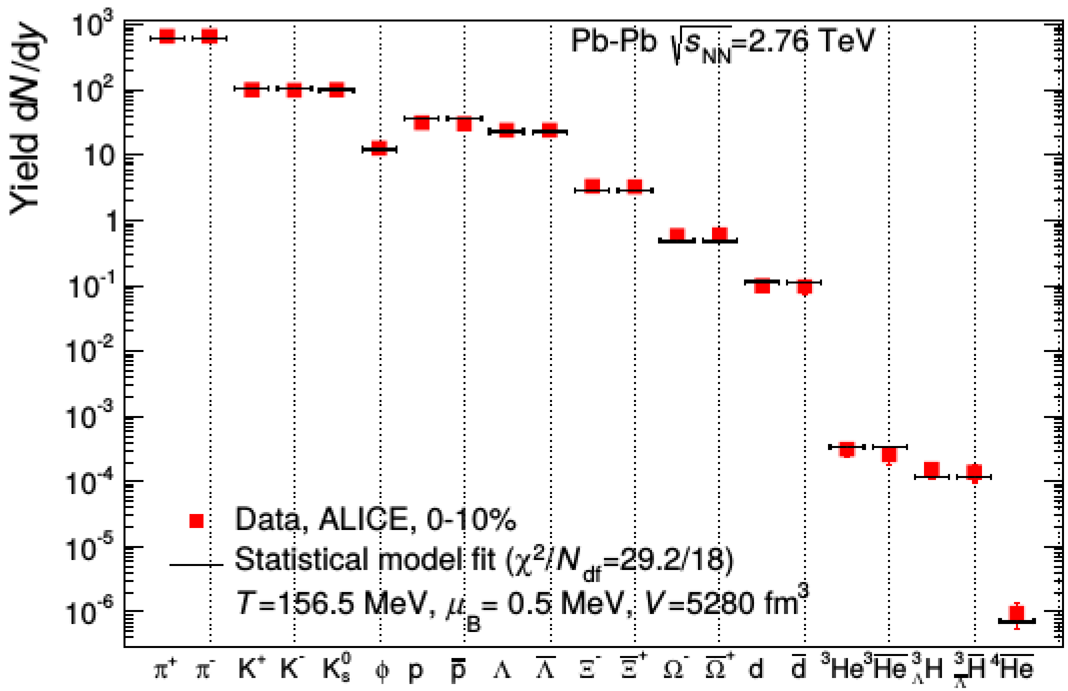
from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

in practice, we use the full experimental hadronic mass spectrum from the PDG compilation (vacuum masses) to compute the 'primordial yield'

comparison with measured hadron yields needs evaluation of all strong decays

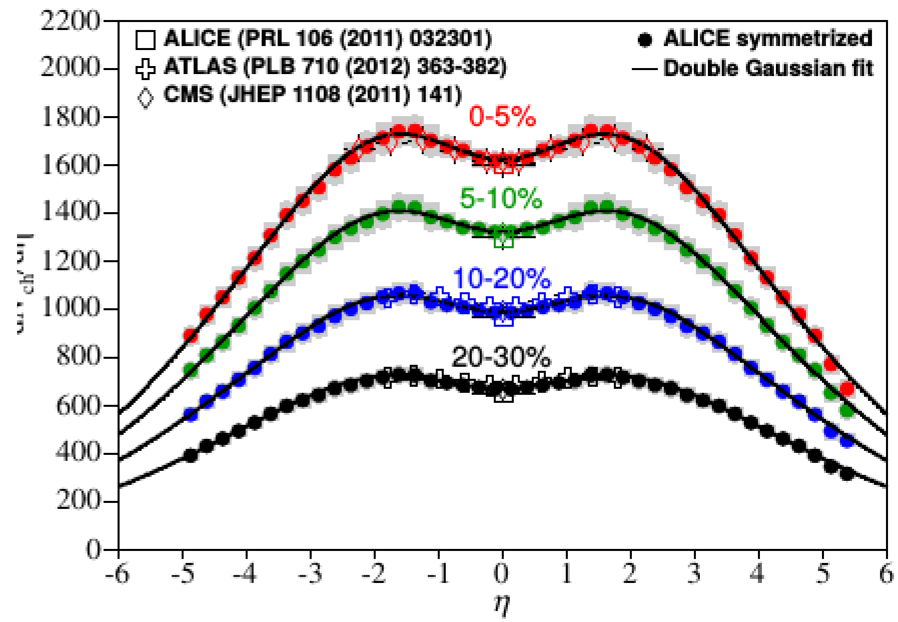
May 2016 update: excellent description of LHC data

T, $V(\Delta y = 1)$ from thermal fit



proton discrepancy 2.8 sigma

$dN_{ch}/d\eta$ data

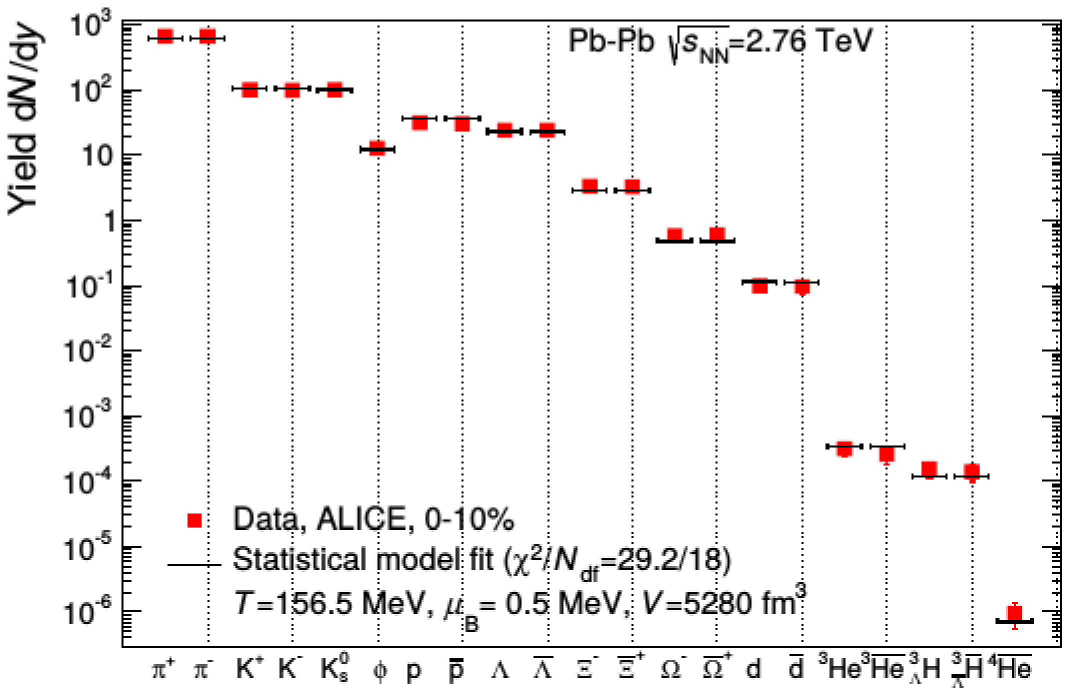


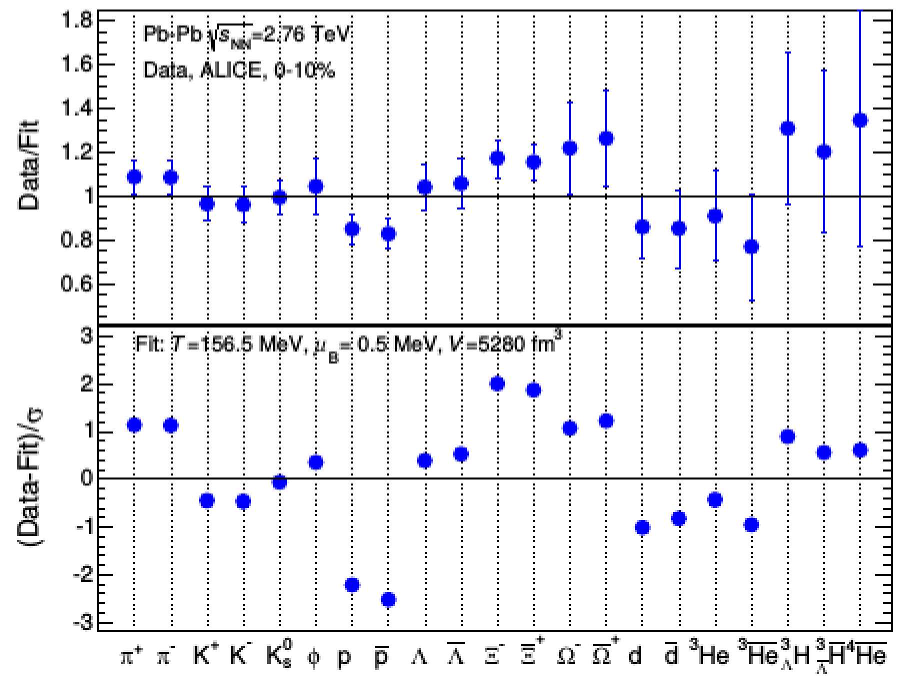
ALICE, PLB 726 (2013) 610

fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n), Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156 MeV. close to an Efimov state

J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

details on thermal description





all species in fit

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

$T = 155.5 \pm 1.5$ MeV, $\mu_B = 0.5 \pm 3.8$ MeV, $V = 5280 \pm 410$ fm^3

...more details

- $\bar{\Lambda}$ from S.Schuchmann, PhD Thesis (Jul.2015)
- fragments from ALICE, arXiv:1506.08951

  derived anti-particles from published ratios:

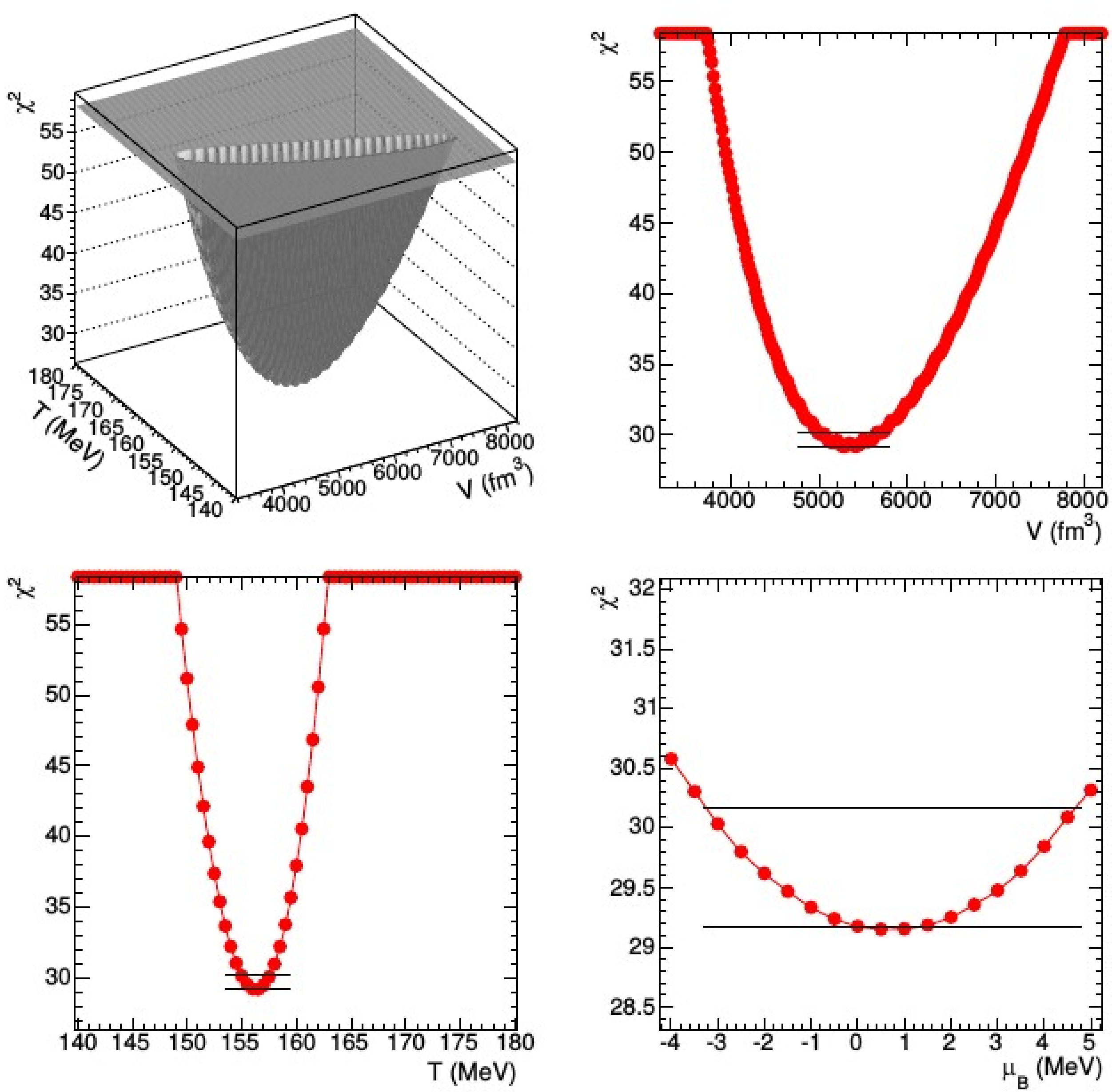
  d: (9.82±1.58)$\times 10^{-2}$, $\bar{\mathrm{d}}/\mathrm{d} =$ 0.98±0.13 $\rightarrow$ $\bar{\mathrm{d}}$: (9.62±2.01)$\times 10^{-2}$

  $^3\mathrm{He}$: rescale from 0-20% to 0-10% using d, factor 1.127 $\rightarrow$ (3.11±0.706)$\times 10^{-4}$
  $^3\bar{\mathrm{He}}/^3\mathrm{He} =$ 0.83±0.08±0.16 $\rightarrow$ $^3\bar{\mathrm{He}}$: (2.58±0.81)$\times 10^{-4}$

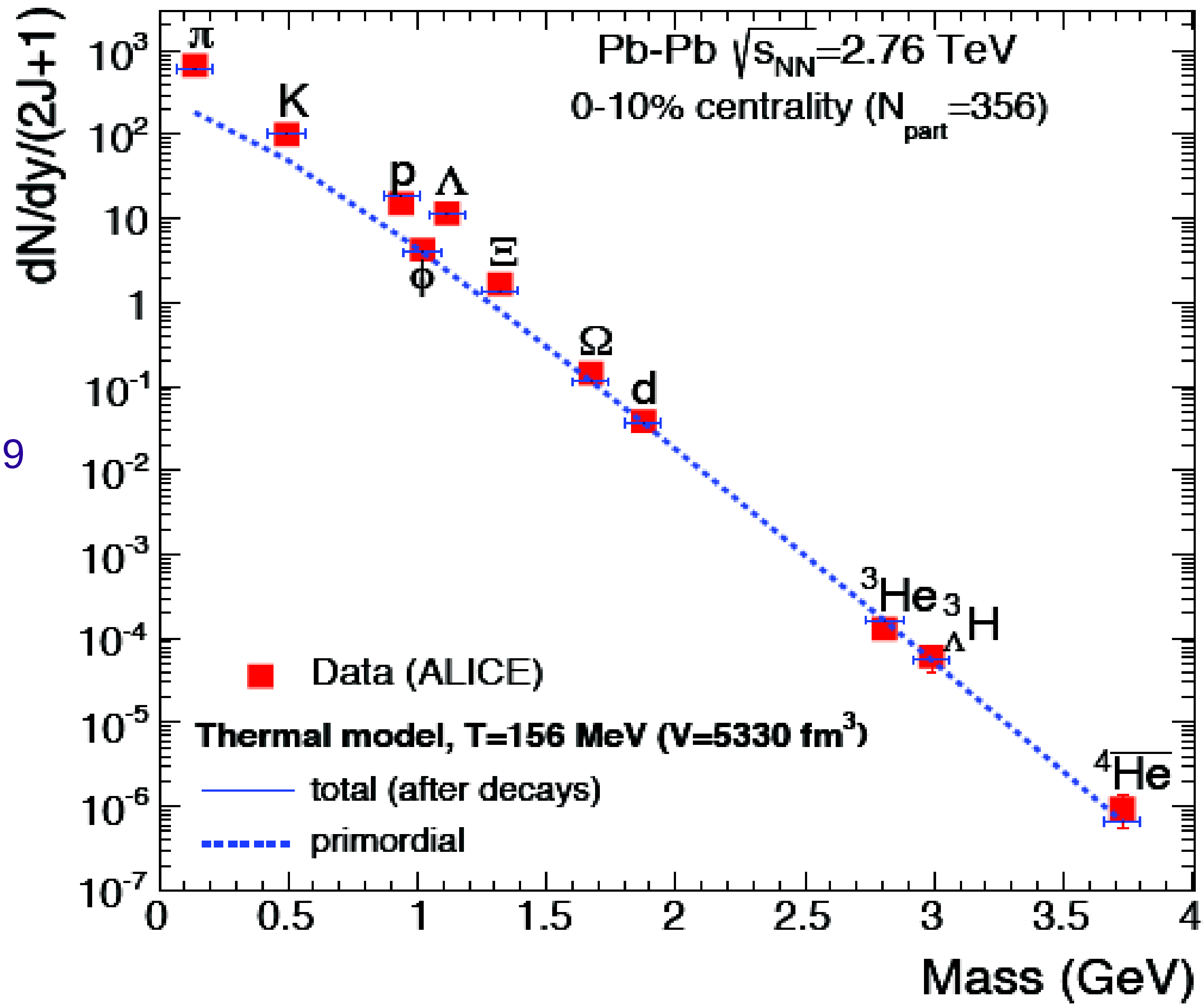
excluded volume correction:

our standard case: $R_b = R_m = 0.3$ fm

chi^2 curves in (T,V) for fit



excellent agreement over 9 orders of magnitude



agreement over 9 orders of magnitude with QCD statistical operator prediction

yield of light nuclei predicted in: pbm, J. Stachel, J.Phys. G28 (2002) 1971-1976,
J.Phys. G21 (1995) L17-L20

a note on the chemical freeze-out temperature

T_{chem} = 155 ± 1.5 MeV from fit to all particles

there is an additional uncertainty because of the poorly known hadronic mass spectrum for masses > 2 GeV

for d, 3He, hypertriton and alpha, there is very little feeding from heavier states and none from high mass states in the hadronic mass spectrum, for these particles the temperature T_{nuc} can be determined 'on the back of an envelope' :

T_{nuc} = 154 ± 5 MeV, independent of hadronic mass spectrum

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 Hypertriton

mass = 2.990 MeV

Lambda sep. energy. = 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

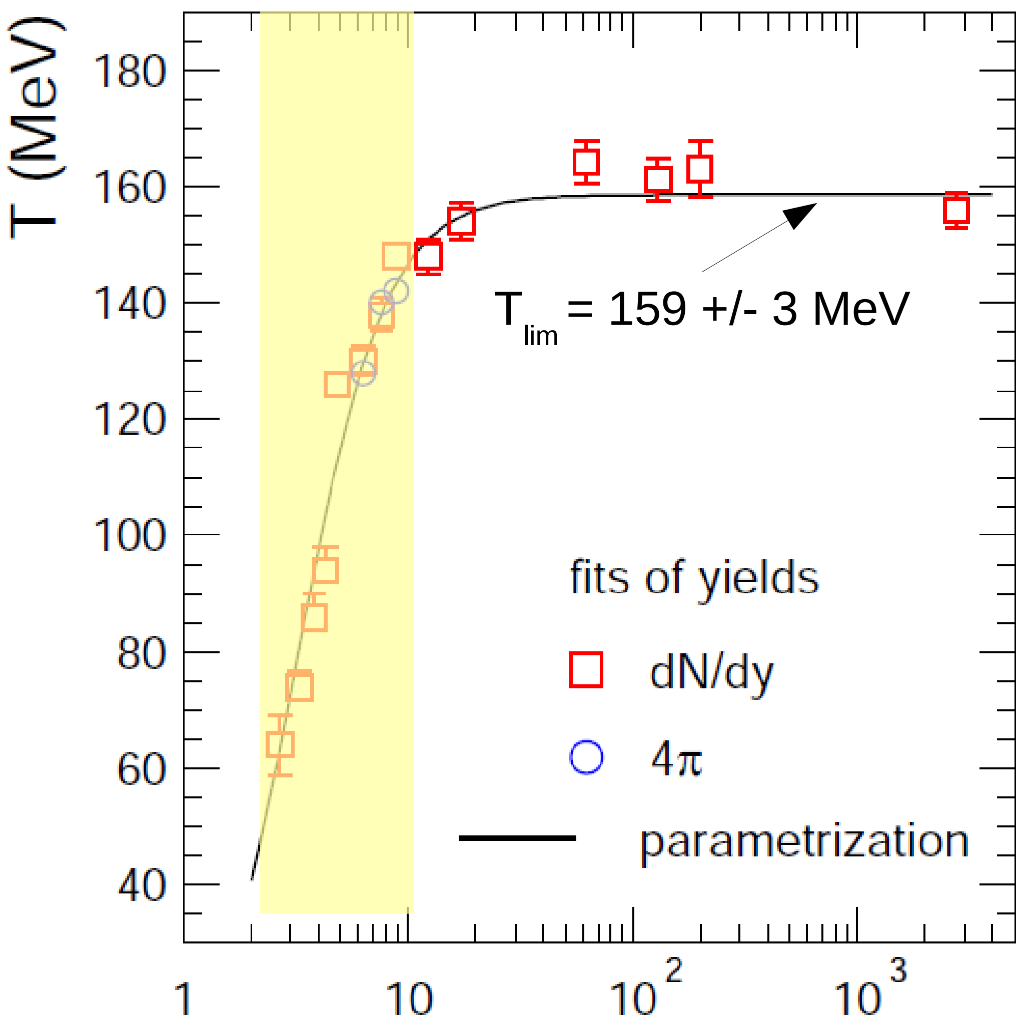
in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

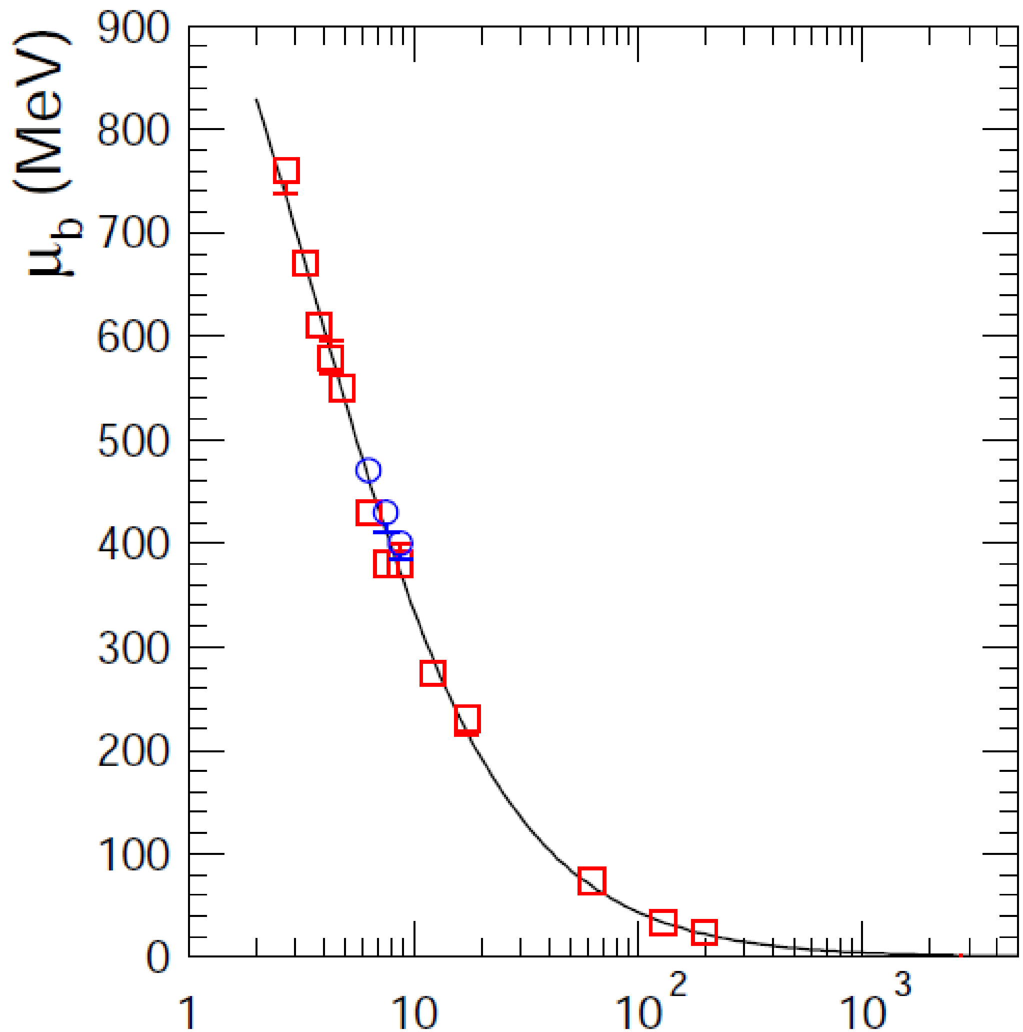
yet production yield is fixed at 156 MeV temperature
(about 1000 x separation energy.)

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?

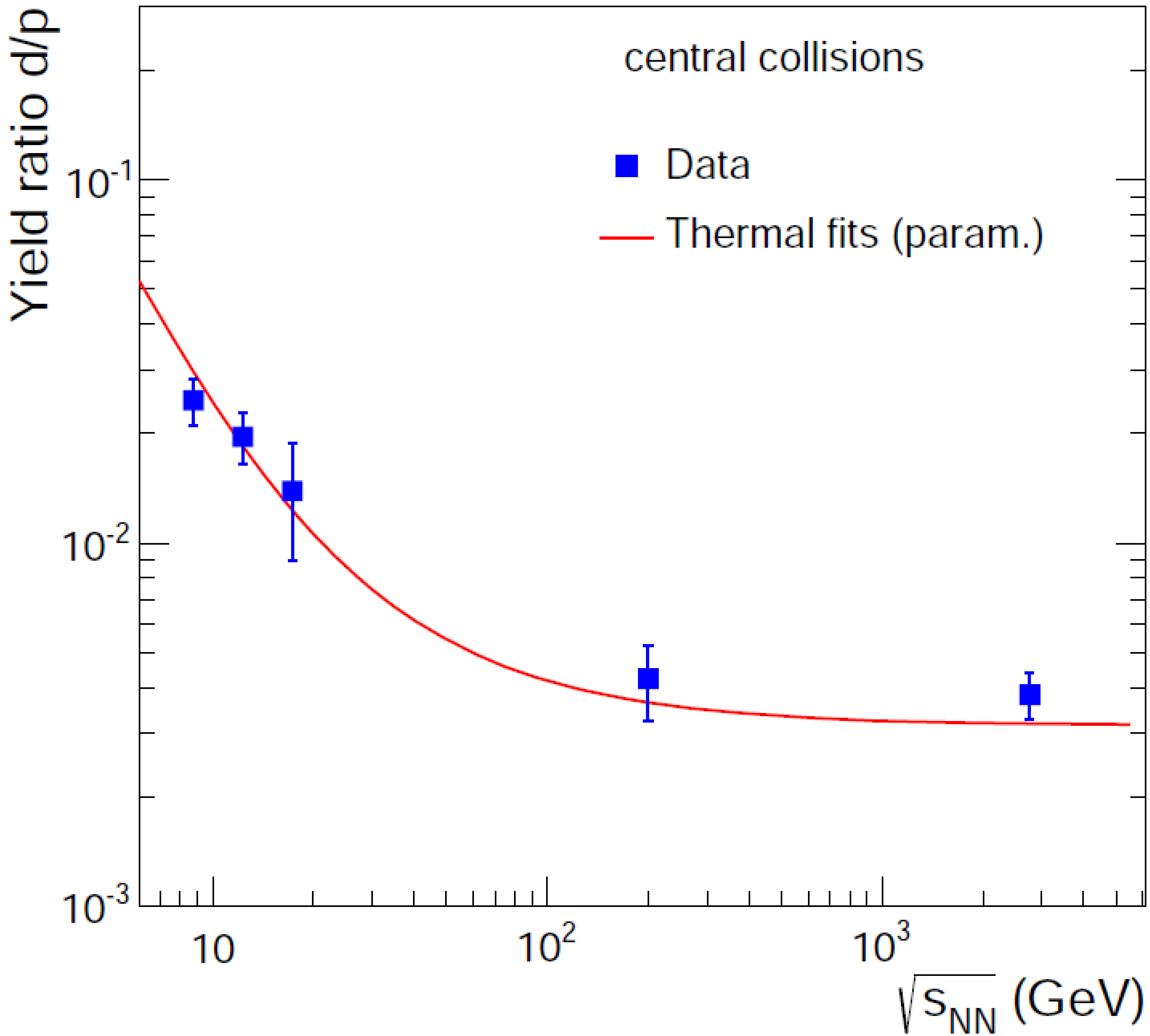




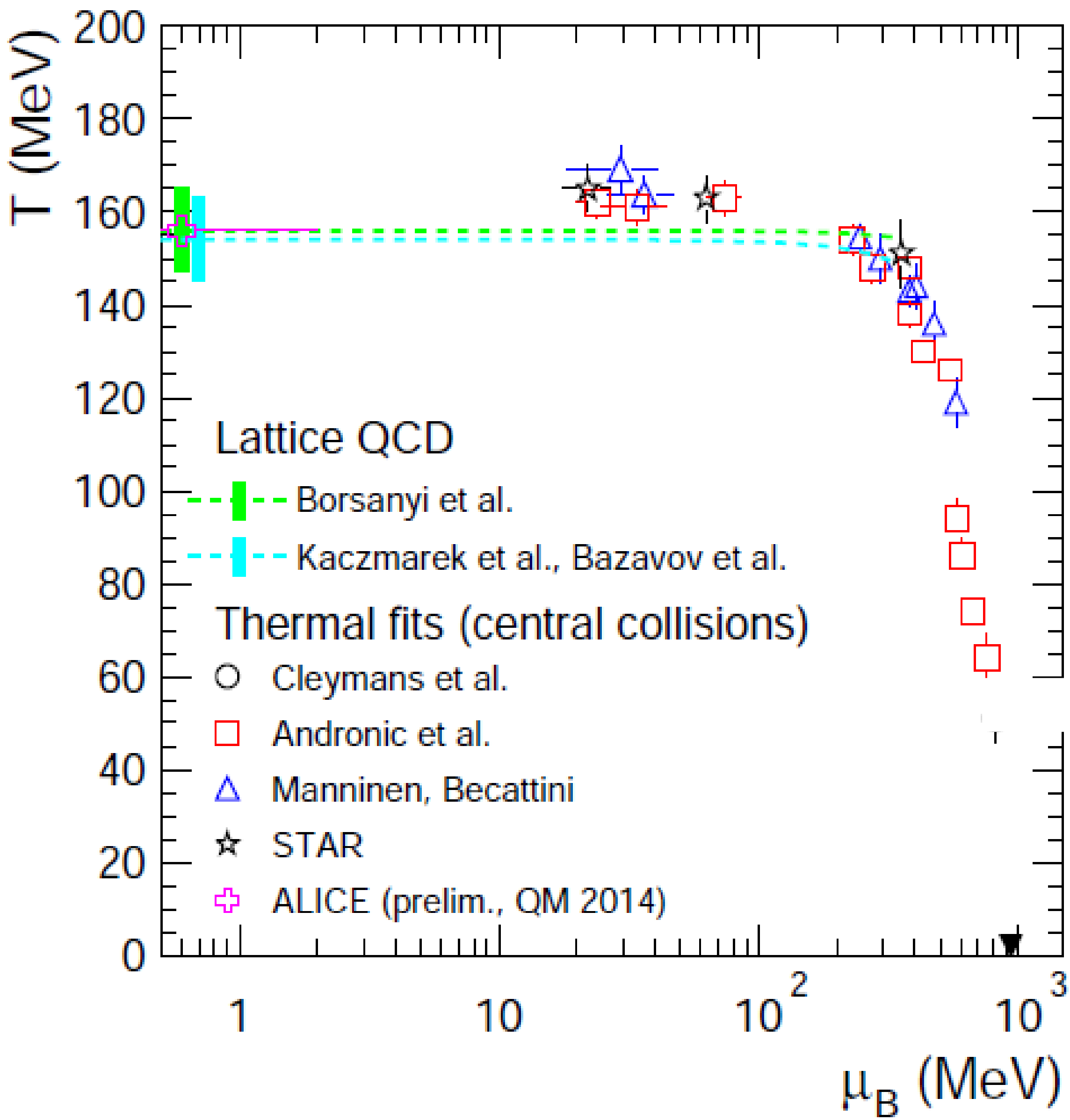
T_{lim} = 159 +/- 3 MeV is maximum hadronic temperature

T_c = 154 +/- 9 MeV from lattice

d/p ratio as function of energy – Pb—Pb collisions



the QGP phase diagram, LQCD, and hadron production data



lattice QCD, net 'charges', susceptibilities, and ALICE data

main idea: at LHC energy, $\mu_b = 0$, no sign problem, LQCD approach reliable

in a thermal medium, fluctuations or correlations of net 'charges' N are expressed in terms of susceptibilities as:

$$\hat{\chi}_N \equiv \frac{\chi_N}{T^2} = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_N^2} \qquad \hat{\chi}_{NM} \equiv \frac{\chi_{NM}}{T^2} = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_N \partial \hat{\mu}_M}$$

here, the reduced pressure and chemical potential are, with N,M =(B,S,Q):

$$\hat{P} = P/T^4 \qquad \hat{\mu}_N = \mu_N/T$$

thermodynamically, the susceptibility for the conserved charge N is related to its variance via:

$$\hat{\chi}_N = \frac{1}{VT^3}(\langle N^2 \rangle - \langle N \rangle^2)$$

work based on arXiv:1412.8614, Phys. Lett. B747 (2015) 292, pbm, A. Kalweit, K. Redlich, J. Stachel for the special case of uncorrelated emission (Skellam distribution) and net baryon number N = B, the susceptibility is related to the total mean number of baryons + anti-baryons via

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(\langle N_q \rangle + \langle N_{-q} \rangle)$$

in this limit, we can make a direct comparison between the susceptibility from LQCD, and the experimentally measured total mean number of baryons and anti-baryons.

for N = strangeness S or charge Q, similar expressions, with |q| = (1,2) and |q| = (1,2,3) hold:

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}\sum_{n=1}^{|q|} n^2(\langle N_n \rangle + \langle N_{-n} \rangle)$$

within this approach, a direct link between ALICE LHC data and LQCD predictions can be established

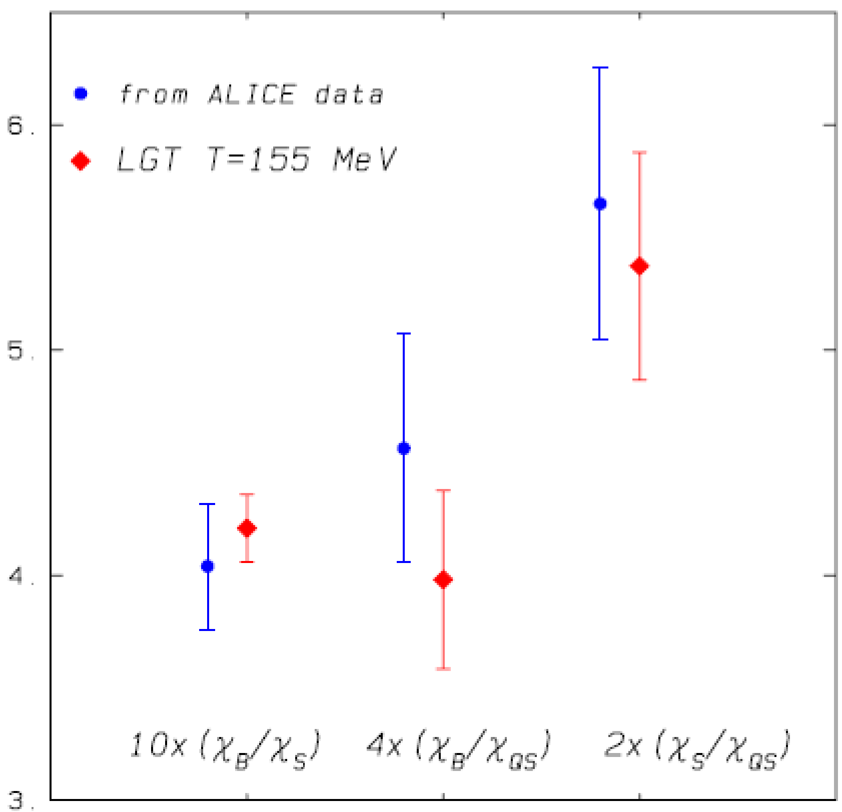
LQCD predictions from:

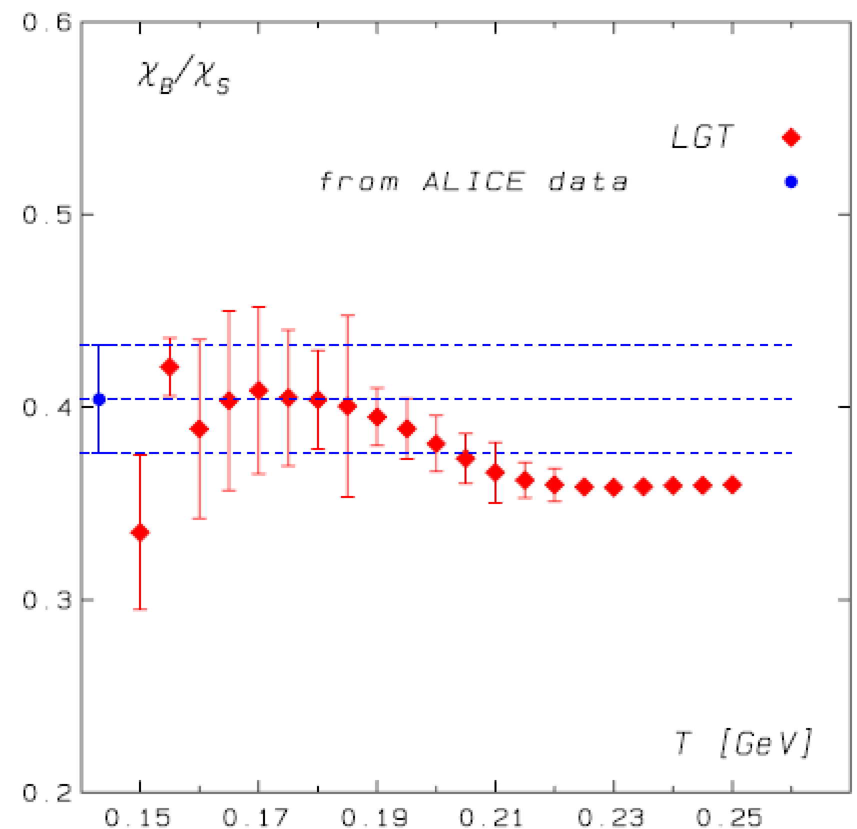
A. Bazavov *et al.* [HotQCD Collaboration], Phys. Rev. D **86**, 034509 (2012).
A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa and S. Mukherjee, Phys. Rev. Lett. **113**, 072001 (2014).

expressed in terms of measurable quantities:

$$\frac{\chi_B}{T^2} = \frac{1}{VT^3}[\langle p\rangle + \langle N\rangle + \langle \Lambda + \Sigma^0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle$$
$$+ \langle \Xi^-\rangle + \langle \Xi^0\rangle + \langle \Omega^-\rangle + \text{antiparticles}],$$

$$\frac{\chi_S}{T^2} \simeq \frac{1}{VT^3}[(\langle K^+\rangle + \langle K^0\rangle + \langle \Lambda + \Sigma^0\rangle + \langle \Sigma^+\rangle \quad (9)$$
$$+ \langle \Sigma^-\rangle + 4\langle \Xi^-\rangle + 4\langle \Xi^0\rangle + 9\langle \Omega^-\rangle + \text{antiparticles})$$
$$- (\Gamma_{\phi\to K^+} + \Gamma_{\phi\to K^-} + \Gamma_{\phi\to K^0} + \Gamma_{\phi\to \bar{K}^0})\langle \phi\rangle].$$





from the above figures, one concludes that LQCD predictions and data agree for (pseudo-)critical temperatures T > 150 MeV.

however, as shown in F. Karsch, Acta Phys. Polon. Supp. **7**, no. 1, 117 (2014)

LQCD results cannot be described by hadronic degrees of freedom for T > 163 MeV.

hence we conclude that

150 < T < 163 MeV

from the comparison of ALICE hadron yields with LQCD predictions, completely consistent with the chemical freeze-out analysis

a few remarks about analysis of higher moments of conserved charges

- already for second moments there is a delicate balance between influence of conservation laws (at large acceptance) and trivial fluctuations (at small acceptance
  - for small acceptance, delta_eta << 1, probability distributions become Poisson and are not sensitive to critical behavor.
    in this limit all efficiencies are binomially distributed.
  - for large acceptance, delta_eta > 1, effect of conservation laws becomes large. Efficiencies are not anymore binomially distributed. But data are sensitive to dynamical behavior.
  - corrections for baryon number conservation become mandatory
  - for large values of mu_b, impact parameter (volume) fluctuations become largest source of 'trivial' fluctuations, very unpleasant for search for critical endpoint (details see below)
- for higher moments, situation becomes more difficult.
- effect of purity in PID needs to be carefully studied, crucial for higher moment analysis

a few remarks about analysis of higher moments of conserved charges

- volume fluctuations

  - independent source model:

  - for N: total number of particles, N_s: number of sources, n: number of particles from a single source

$$c_2(N) = \langle N_s \rangle c_2(n) + \langle n \rangle^2 c_2(N_s)$$

stay tuned for more results in Anar Rustamov's talk on Friday

also ALICE higher moments results soon

- 2 limits:
  - (i) <n> = N_p low energy limit, fluctuations dominated by trivial volume fluctuations
  - (ii) <n> = <N_p – N_pbar> = 0 high energy (LHC) limit, volume fluctuations drop out

major advantage at LHC energy: EbE measurements of conserved quantities sensitive to dynamical fluctuations

summary

overall the LHC data provide strong support for chemical freeze-out driven by the 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

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

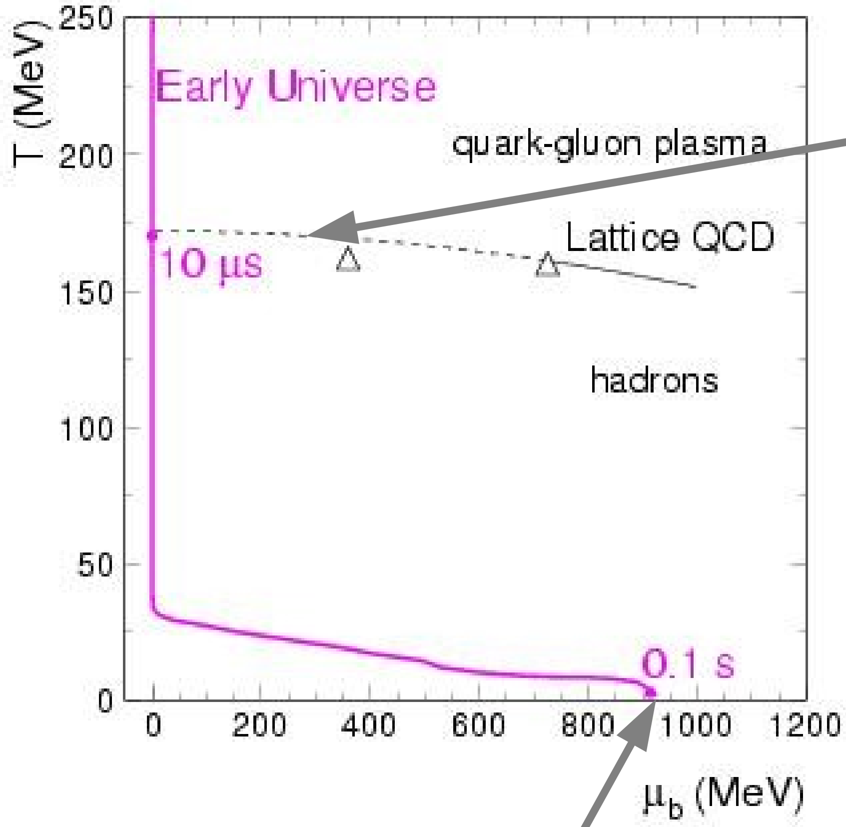
first results on 2nd moments consistent and encouraging

search for critical behavior near phase boundary at LHC energy is underway

connection between LQCD and data

additional slides

evolution of the early universe and the QCD phase diagram



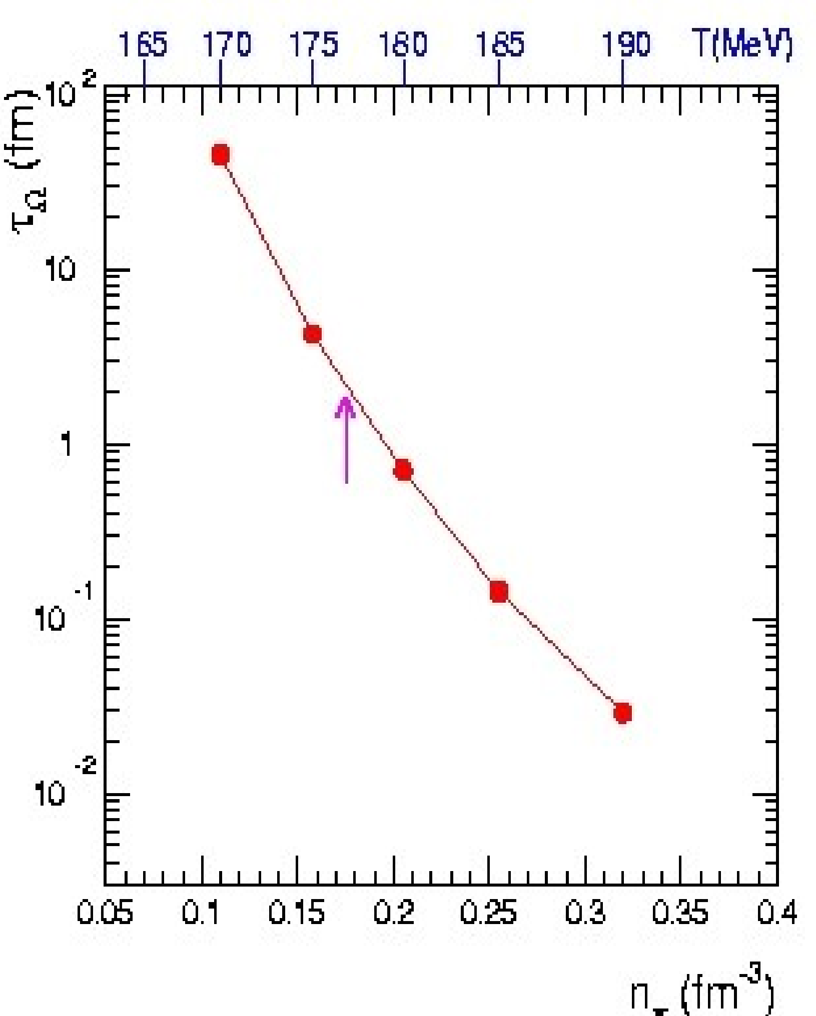
QCD phase boundary

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 QGP phase transition drives chemical equilibration for small μ_b

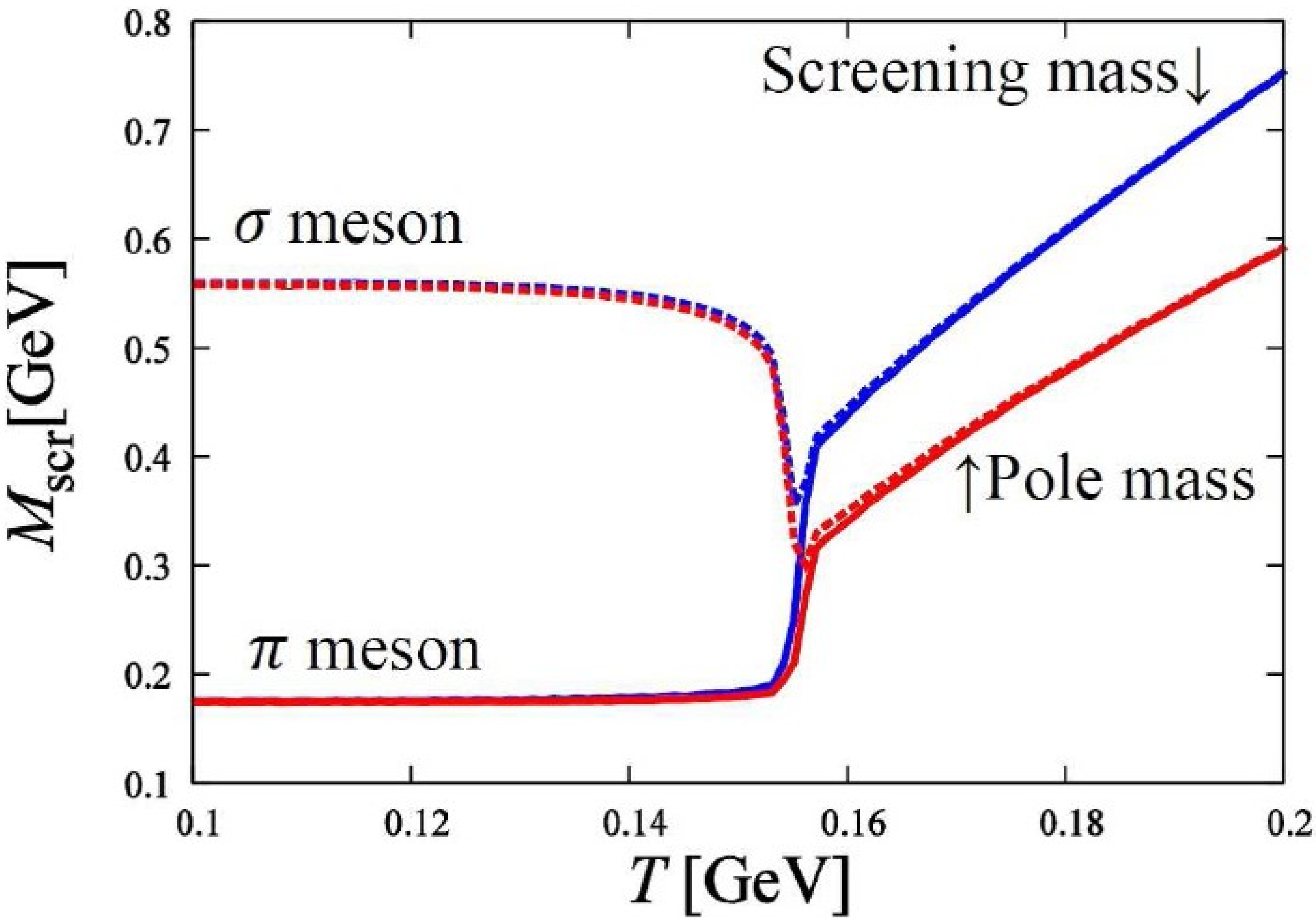


- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within the same very narrow temperature window.

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

are there similar mechanisms for large μ_b?

temperature dependence of meson masses in a NJL model



Mesonic correlation functions at finite temperature and density in the Nambu-Jona-Lasinio model with a Polyakov loop

H. Hansen, W.M. Alberico (INFN, Turin & Turin U.), A. Beraudo (Saclay, SPhT), A. Molinari, M. Nardi (INFN, Turin & Turin U.), C. Ratti (ECT, Trento & INFN, Trento). Sep 2006. 26 pp.

Published in Phys.Rev. D75 (2007) 065004