moments of truth: hadron production in ultra-relativistic nuclear collisions and the QCD phase diagram

- introduction and perspective
- hadron production, Lattice QCD and the QCD phase structure
  - first moments
  - higher moments and susceptibilities for conserved quantum numbers
- remarks on quarkonia
- outlook

Ultra-RelatIvistiCH HEavy IoNZ 2016
CERN, July 18-20, 2016

Peter Braun-Munzinger

Dear Uli,

Happy Birthday

...and many more seminal papers such as the one below
(my favorite Heinz paper)

Hydrodynamic description of ultrarelativistic heavy ion collisions

Peter F. Kolb (SUNY, Stony Brook), Ulrich W. Heinz (Ohio State U.). May 2003. 82 pp.

Published in In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 634-714

SUNY-NTG-03-06

e-Print: nucl-th/0305084 | PDF
Cited by 747 records

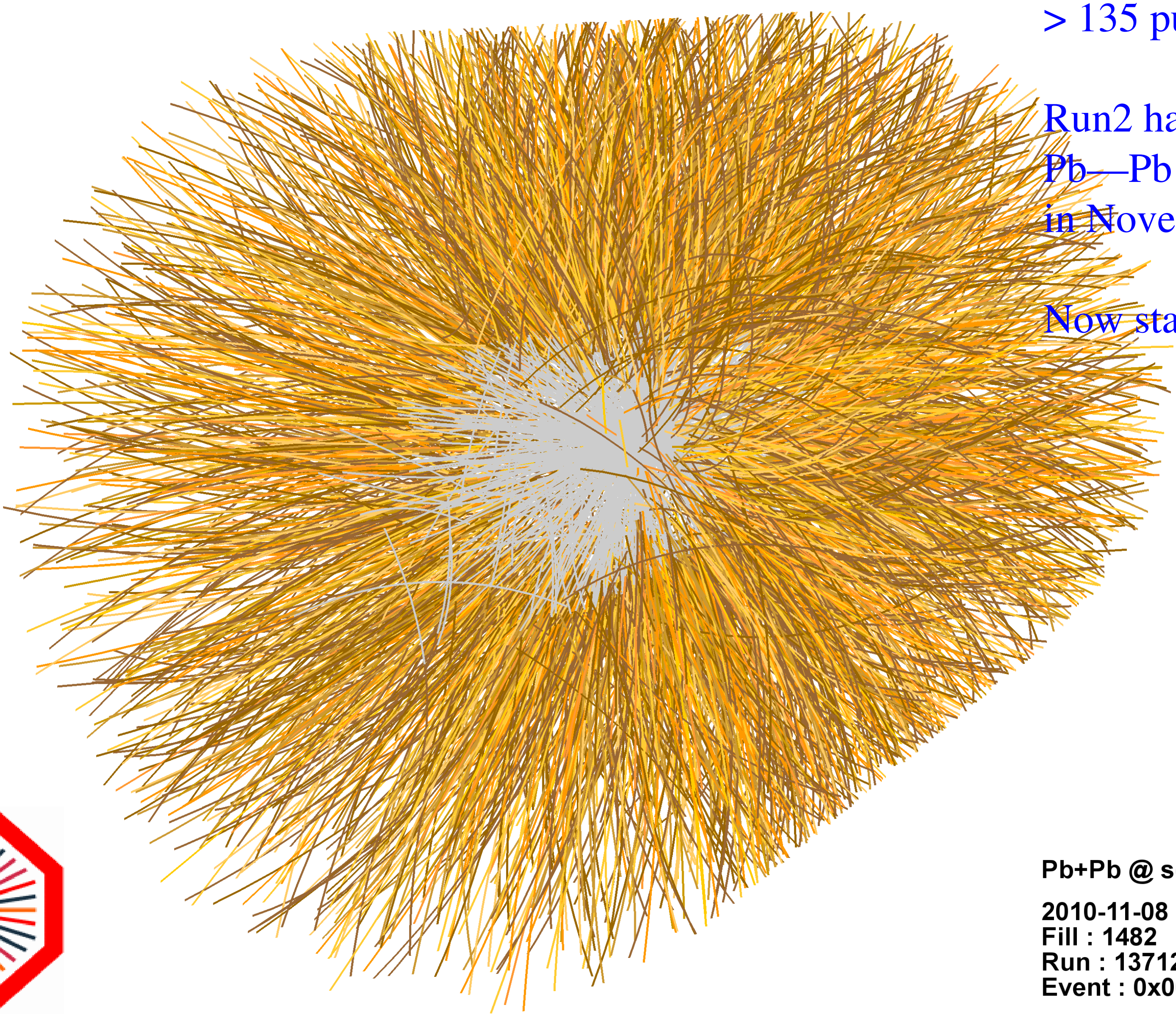
results obtained in collaboration with
Anton Andronic,
Krzysztof Redlich, and Johanna Stachel

first PbPb collisions at LHC at √s = 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



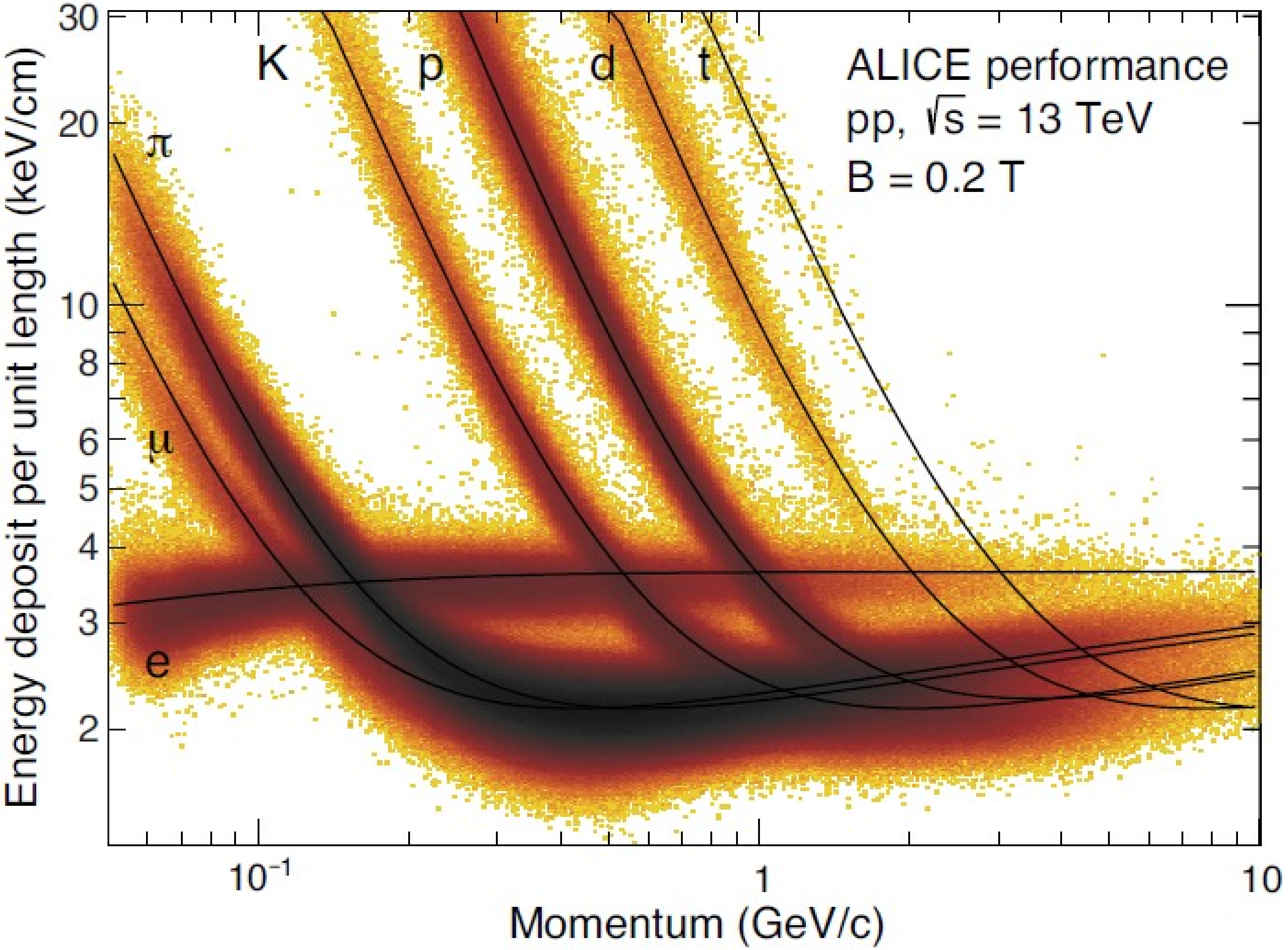
Pb+Pb @ sqrt(s) = 2.76 ATeV

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

and the fun started

particle identification with the ALICE TPC

from 50 MeV to 50 GeV



PDG2016

hadron production, 1st moments and the QCD phase boundary

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

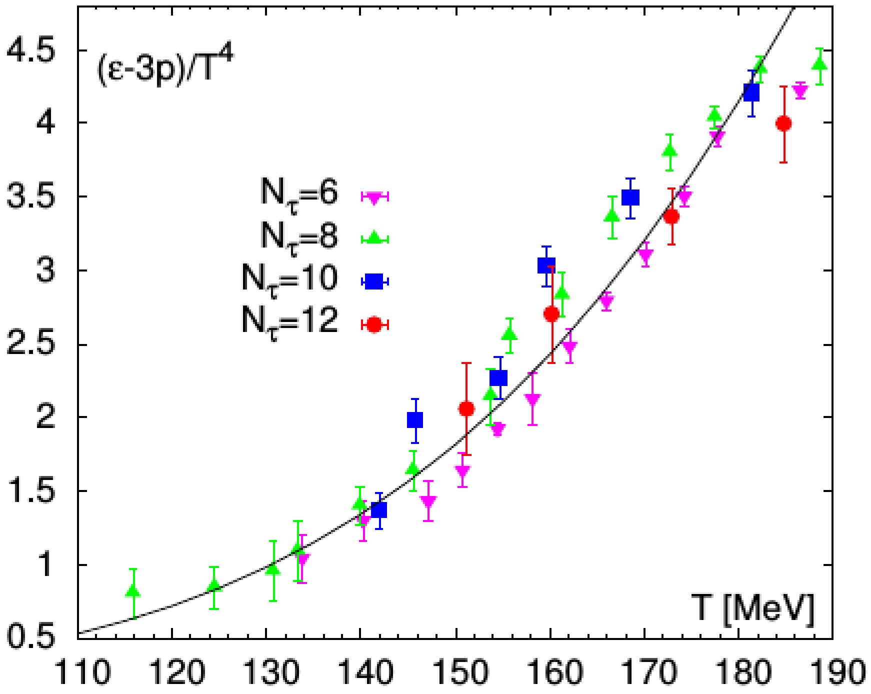
for the pressure we get:

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

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)

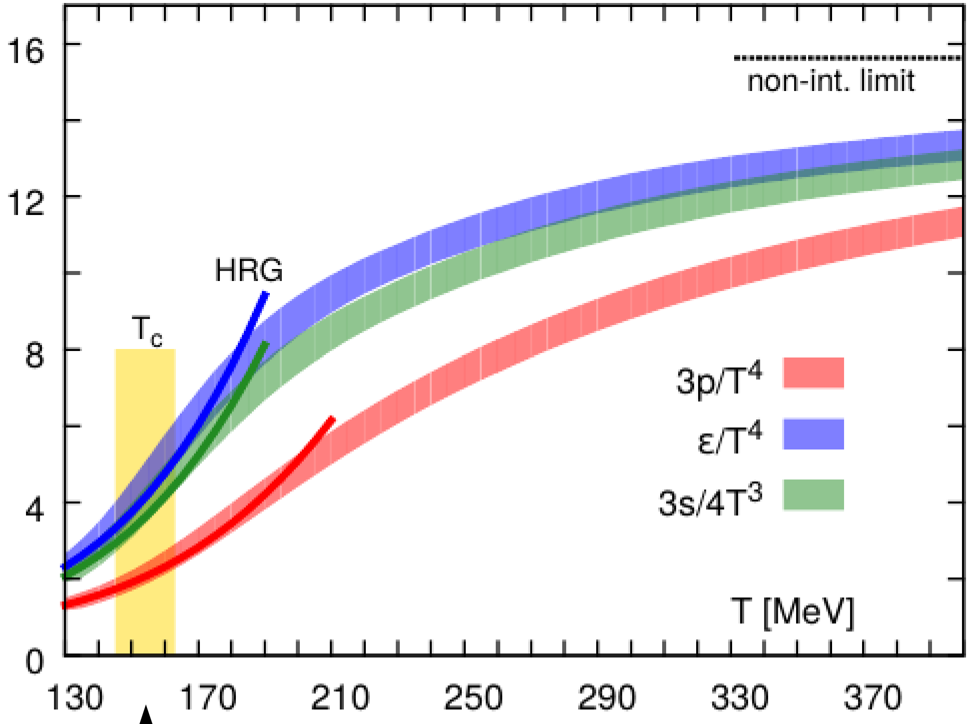
makes sense only in the low T,
low density phase

interactions can only be a small
perturbation
T < 165 MeV
$n < 0.4/\mathrm{fm}^3$

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

with hadron resonance gas predictions (colored lines)

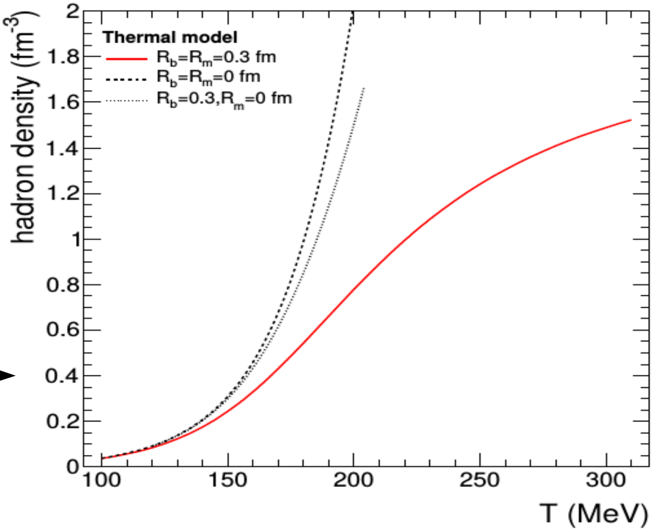
essentially the same results also from
Wuppertal-Budapest coll.
Phys.Lett. B730 (2014) 99-104



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

pseudo-critical
temperature

low density →



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 $\mu = (\mu_b, \mu_Q, \mu_S)$.

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:

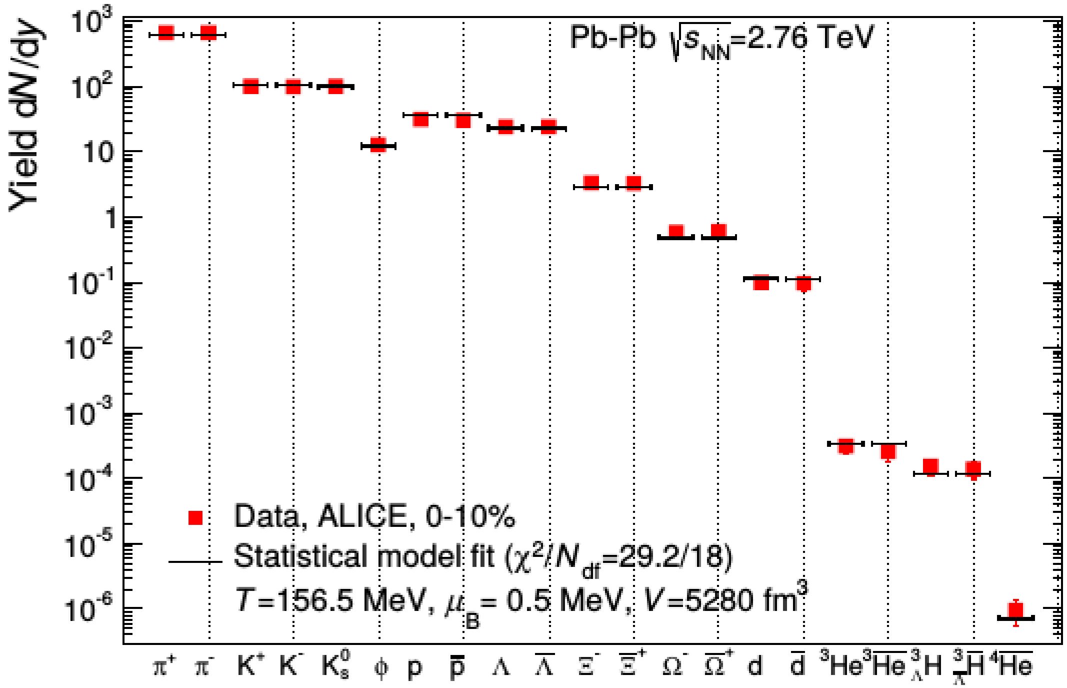
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

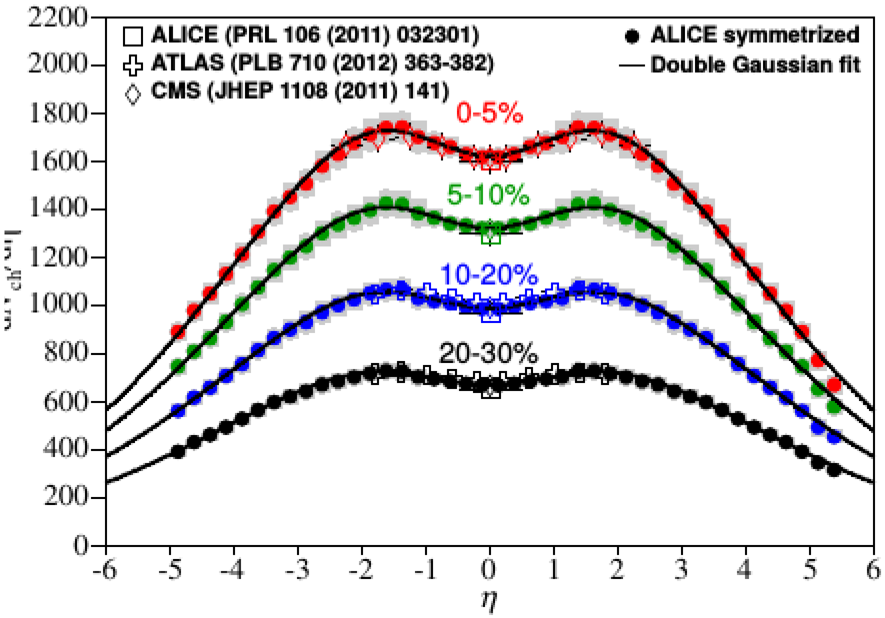
from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

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


$dN_{ch}/d\eta$ data

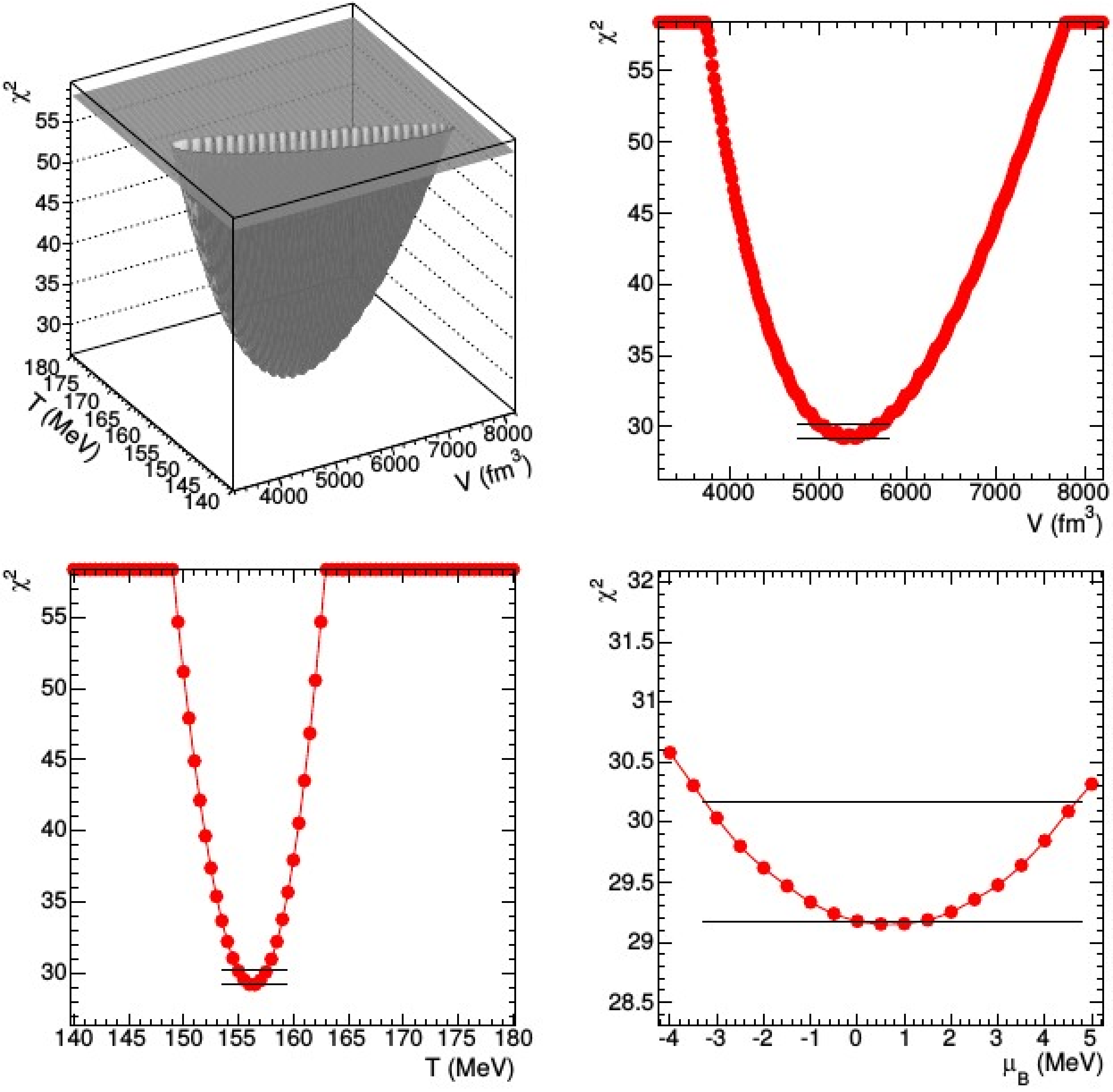
ALICE, PLB 726 (2013) 610

proton discrepancy 2.8 sigma

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

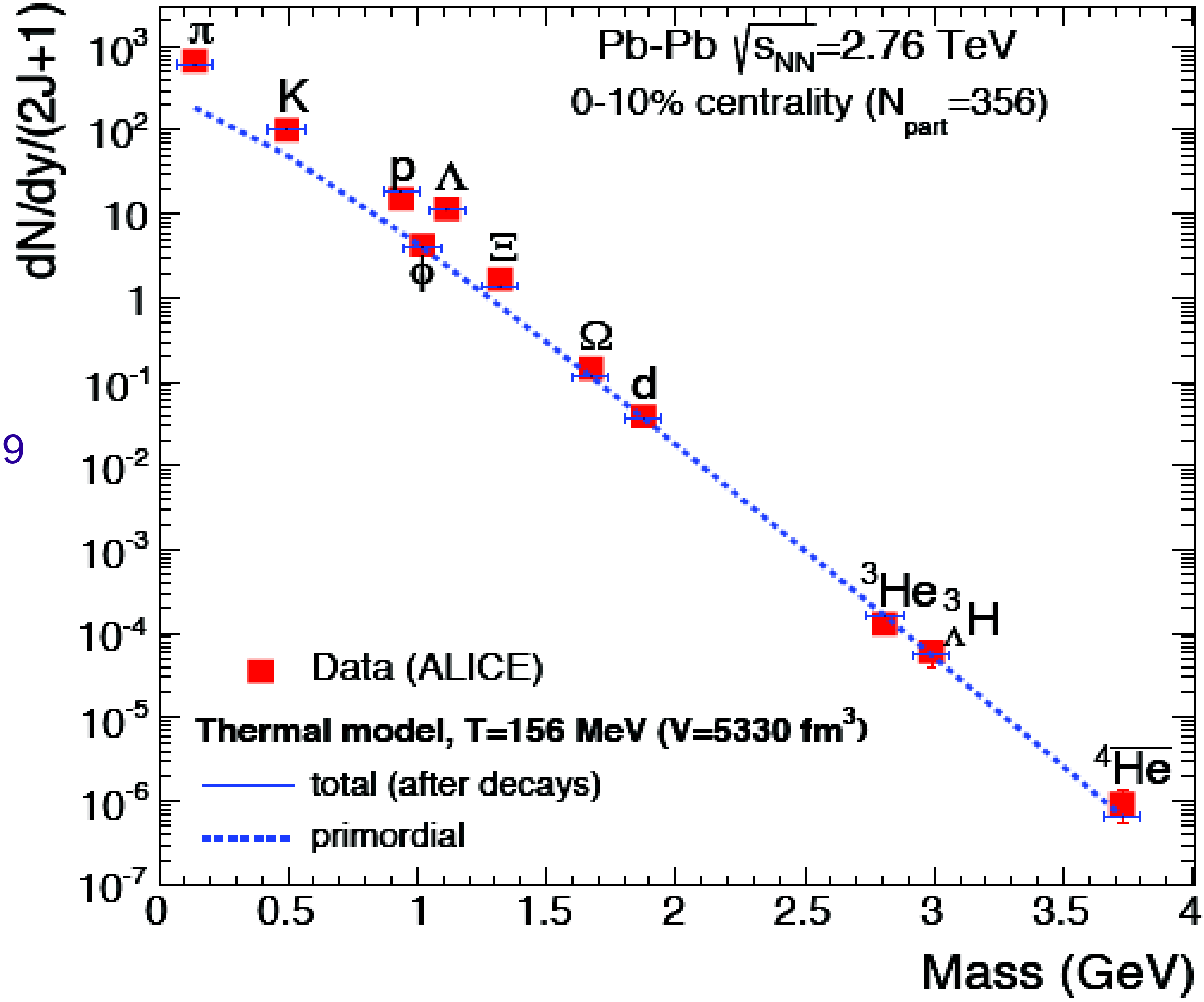
J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

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



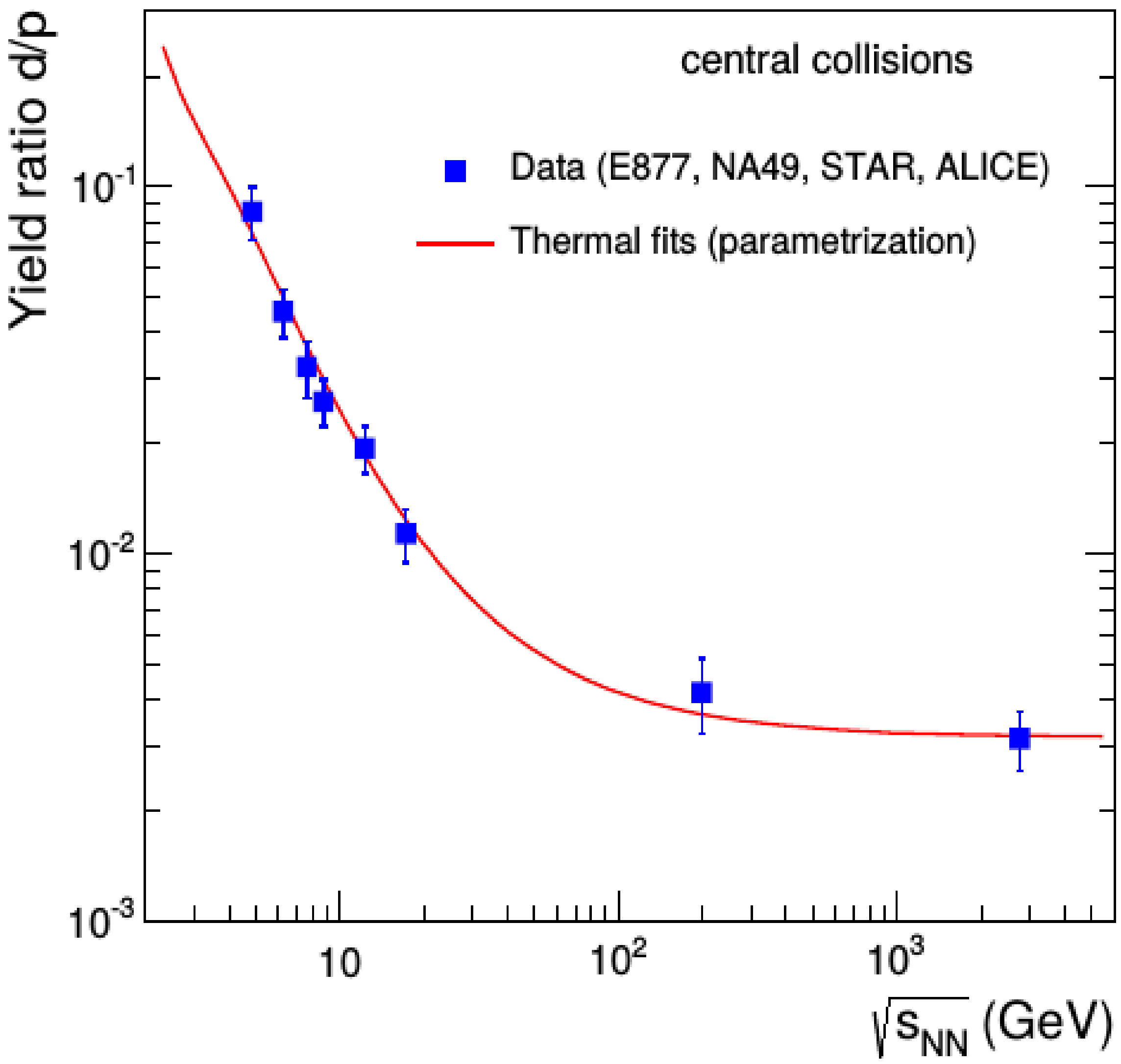
excellent agreement over 9 orders of magnitude

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

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



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-

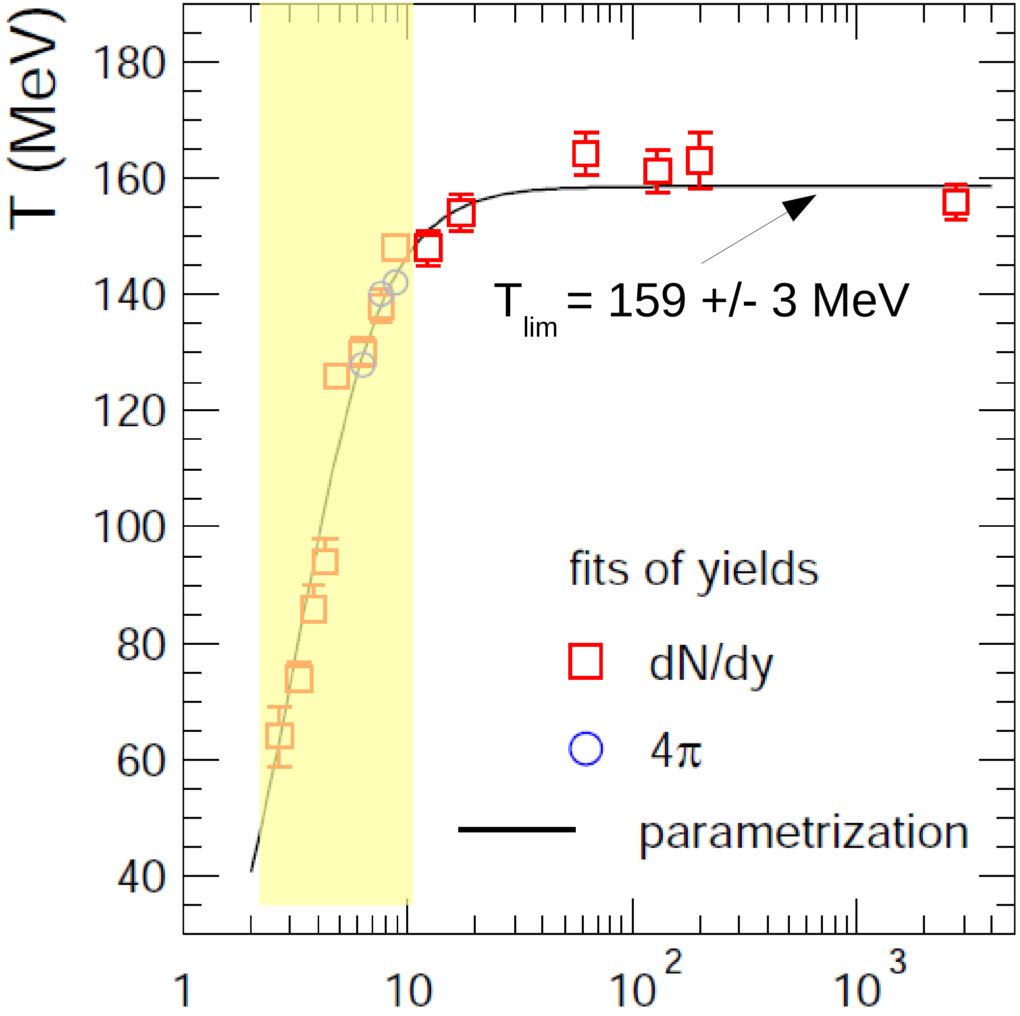
rms radius = $(4\ \mathrm{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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 separation energy.)

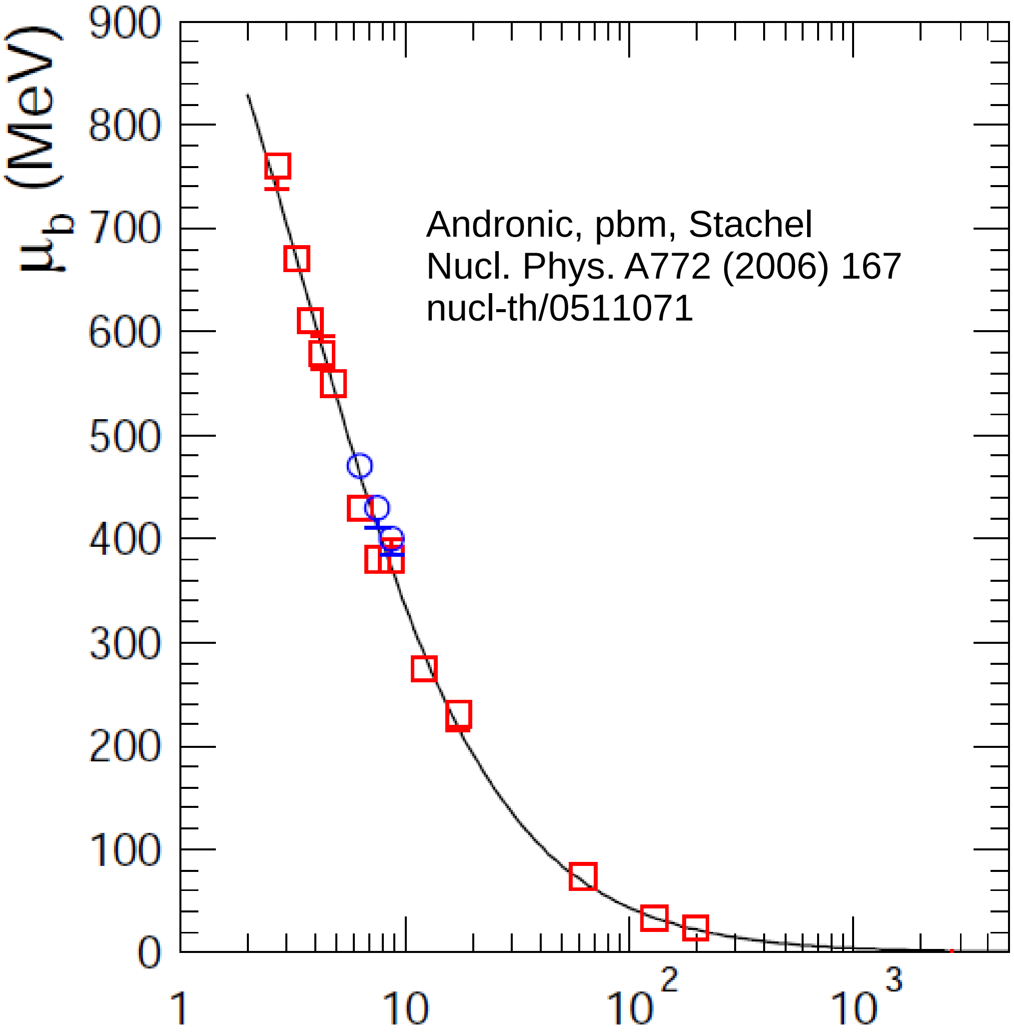
energy dependence of temperature and baryo-chemical potential

energy range from SPS down to threshold



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

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

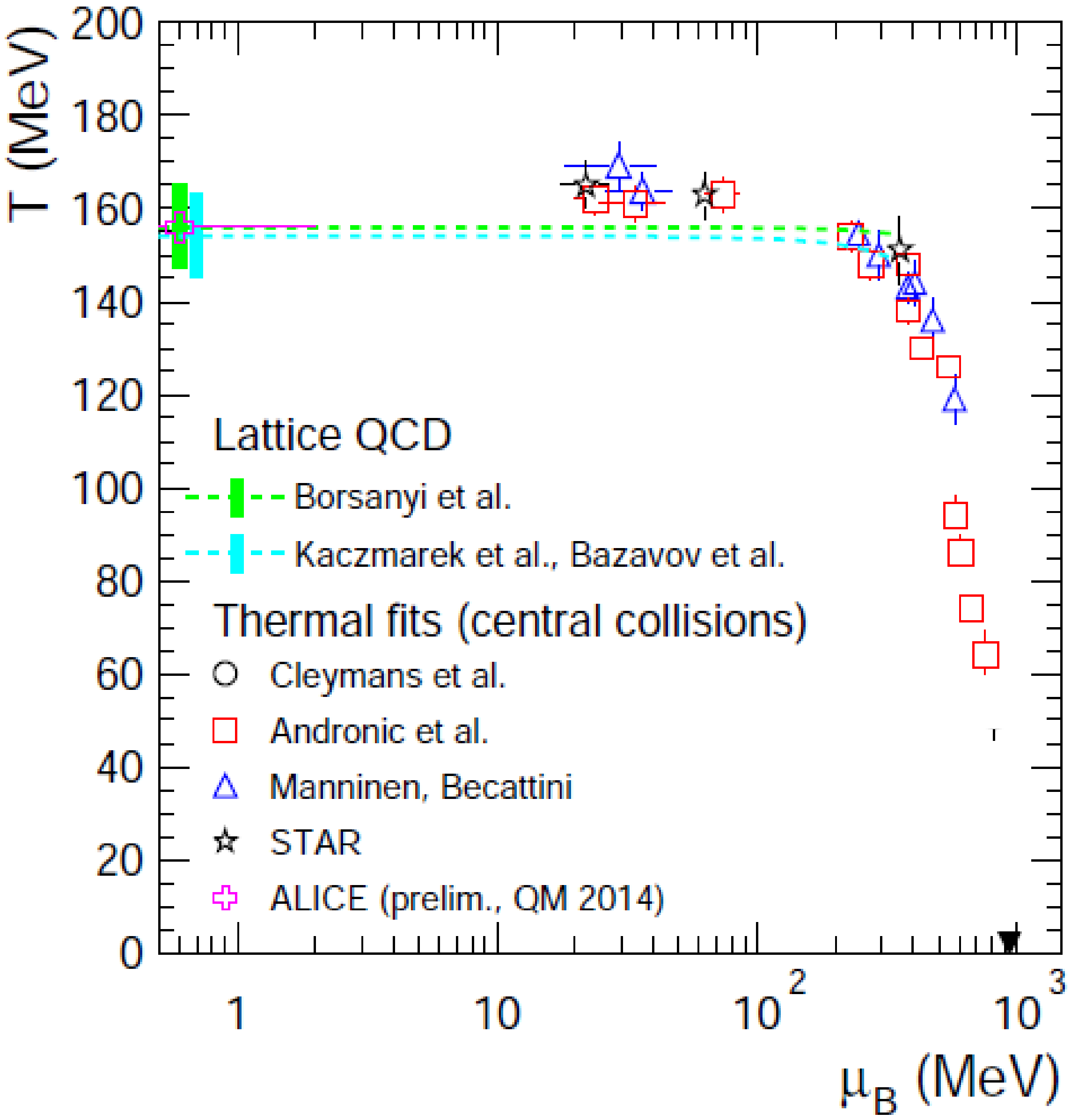


Andronic, pbm, Stachel
Nucl. Phys. A772 (2006) 167
nucl-th/0511071

T_c = 154 +/- 9 MeV from lattice

the QGP phase diagram, LQCD, and hadron production data

hadron production data tightly constrain the QCD phase diagram



second moments

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:

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

susceptibilities can be measured via 1st and 2nd order fluctuation measurements

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

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

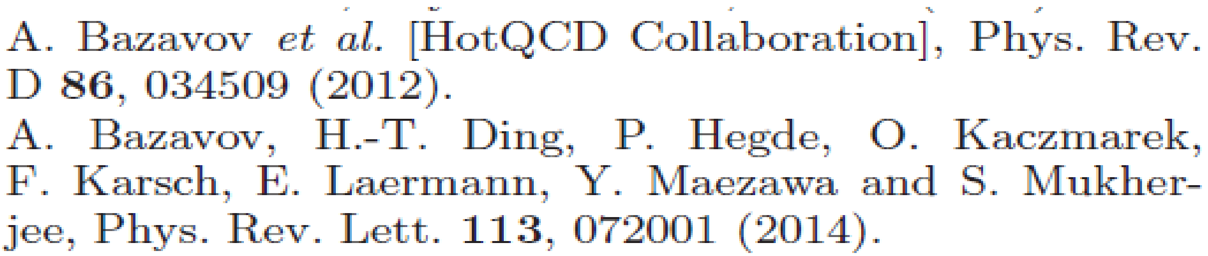
in this limit, we can make a direct comparison between the susceptibility from LQCD, and the experimentally measured total mean number of baryons and anti-baryons.

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).

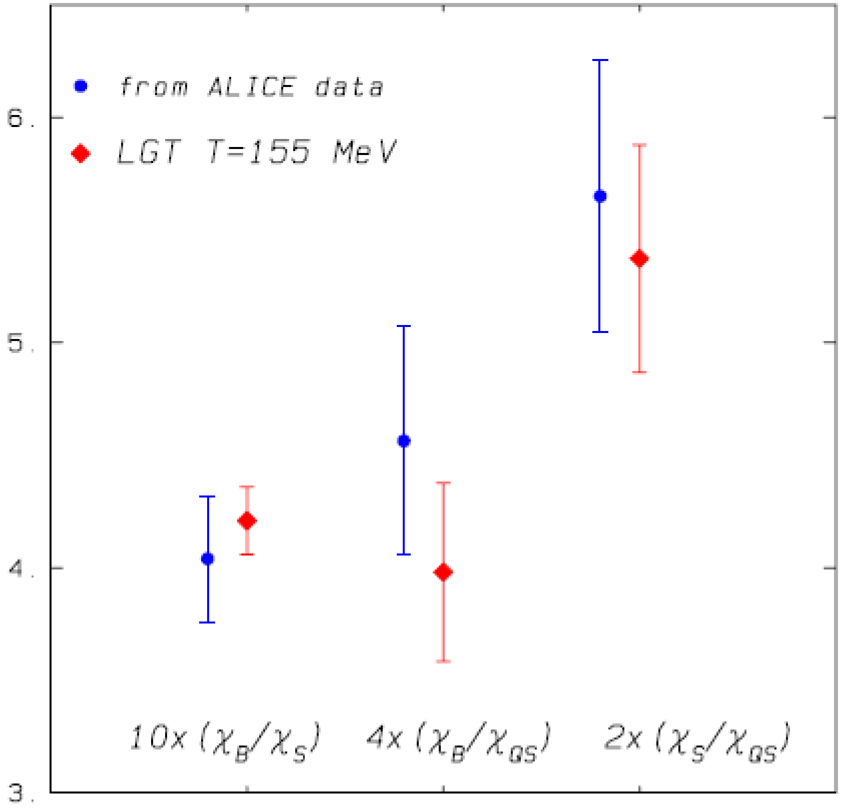
A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa and S. Mukherjee, Phys. Rev. Lett. **113**, 072001 (2014).

expressed in terms of measurable quantities:

big advantage:
not cuts
in transverse momentum

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

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



charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{ccbar})^2$

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

the idea

heavy quarks are not thermally produced, since their mass m >> T

at collider energies, heavy quarks are copiously produced through QCD hard scattering

the developing hot fireball formed in the collision thermalizes the heavy quarks

all charmed hadrons and charmonia are deconfined near T_c

the fireball expands and cools until it reaches the phase boundary

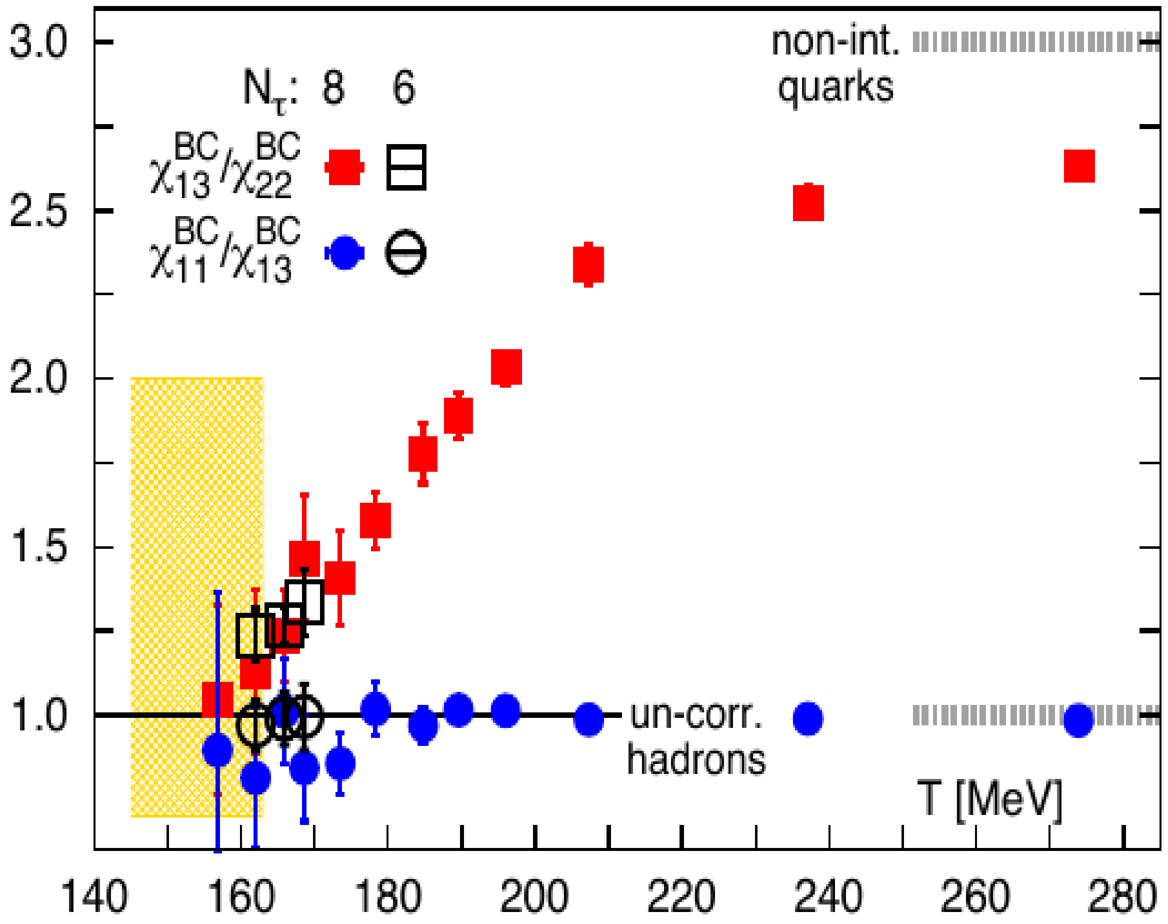
there, charmonia are formed with thermal/statistical weights

since charmonium formation scales with $N(_{ccbar})^2$ and since the charm cross section increases strongly with energy, we expect enhanced charmonium production at collider energy

this brings the thermal model into the heavy quark era with a large heavy quark fugacity

note: mass of charm quark is about 300 times heavier than mass of light quarks

from lattice: charmed hadrons deconfine near T_c

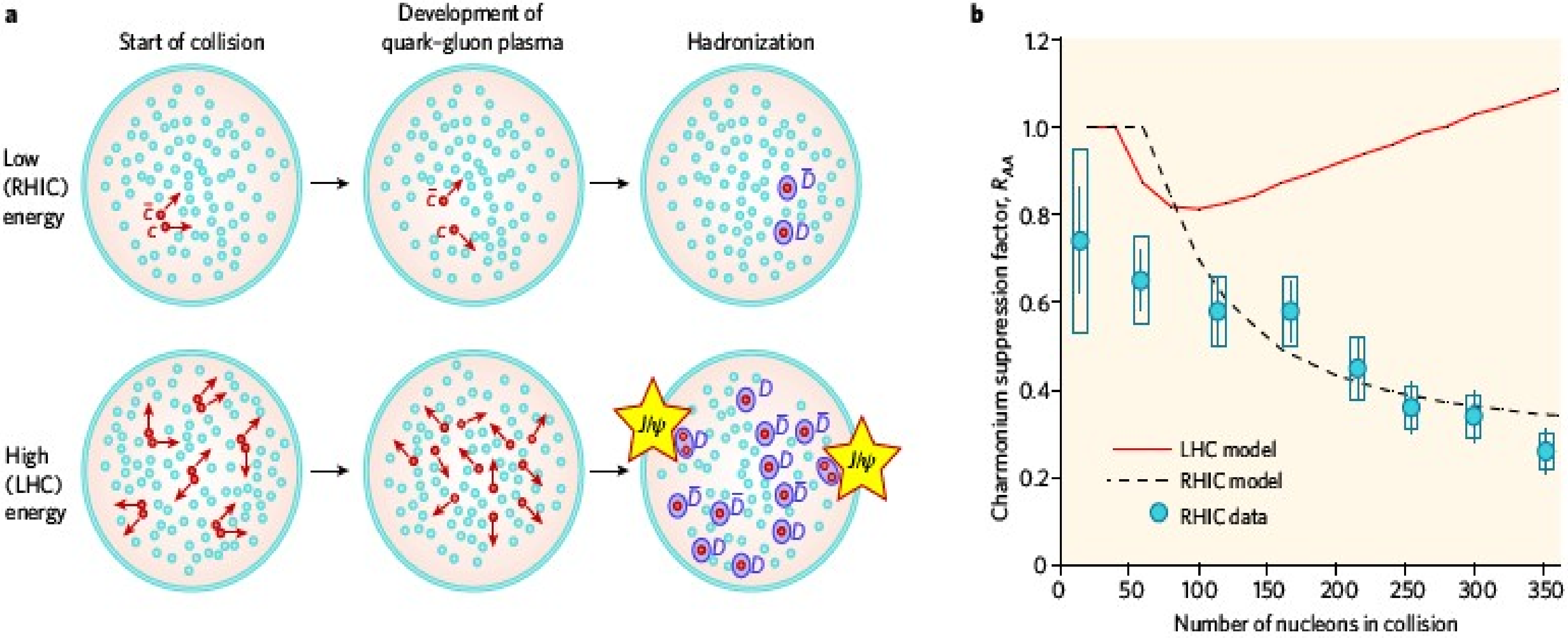


Bazavov et al, PLB 737 (2014) 210

figure courtesy Peter Petrezky

quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

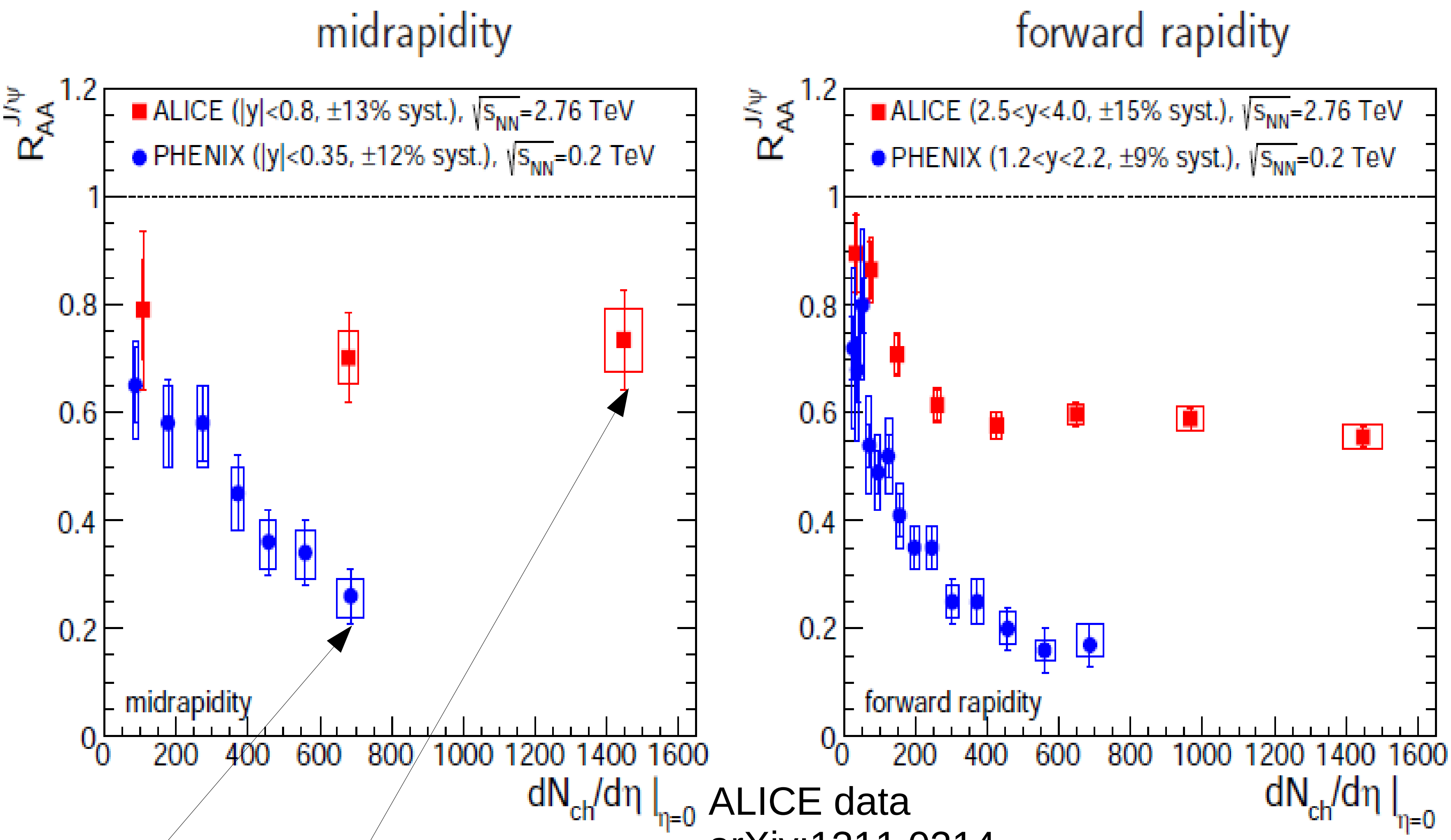
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma,
Nature **448** Issue 7151, (2007) 302-309.



charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

less suppression when increasing the energy density

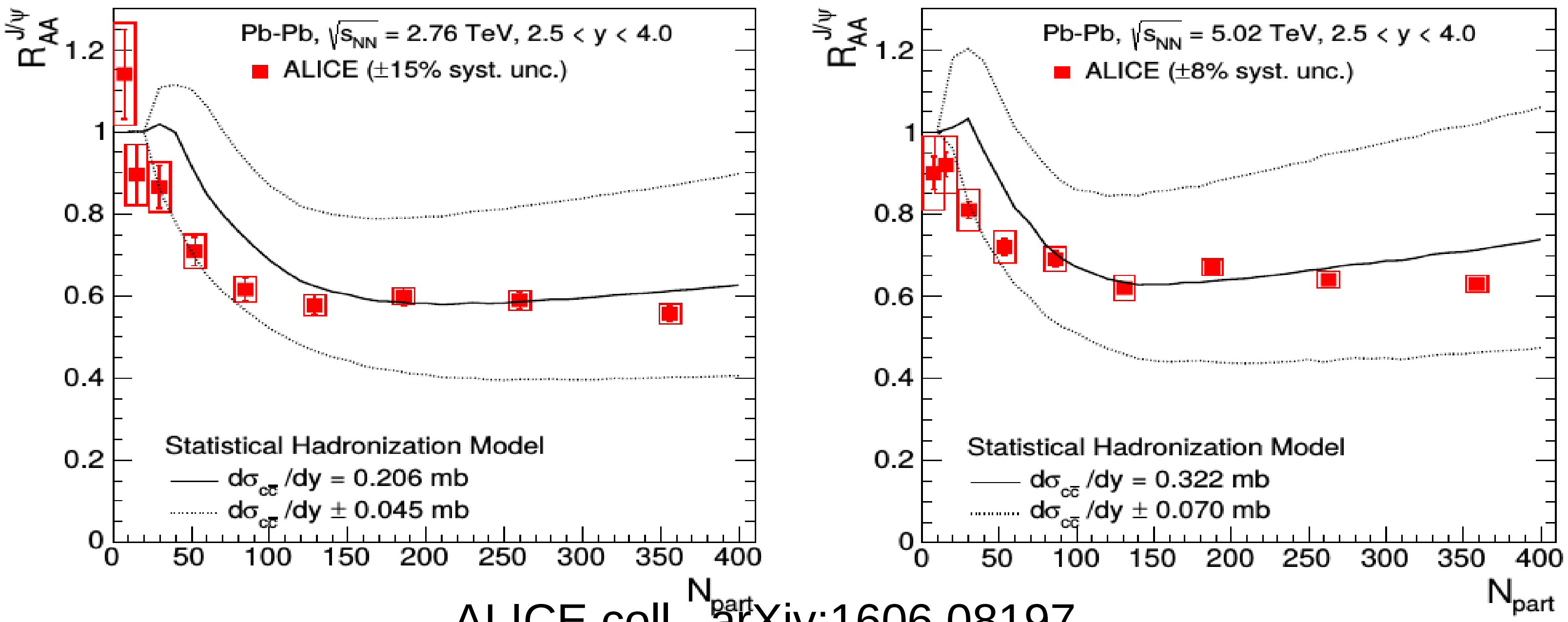


ALICE data
arXiv:1311.0214
Phys.Lett. B734 (2014) 314-327

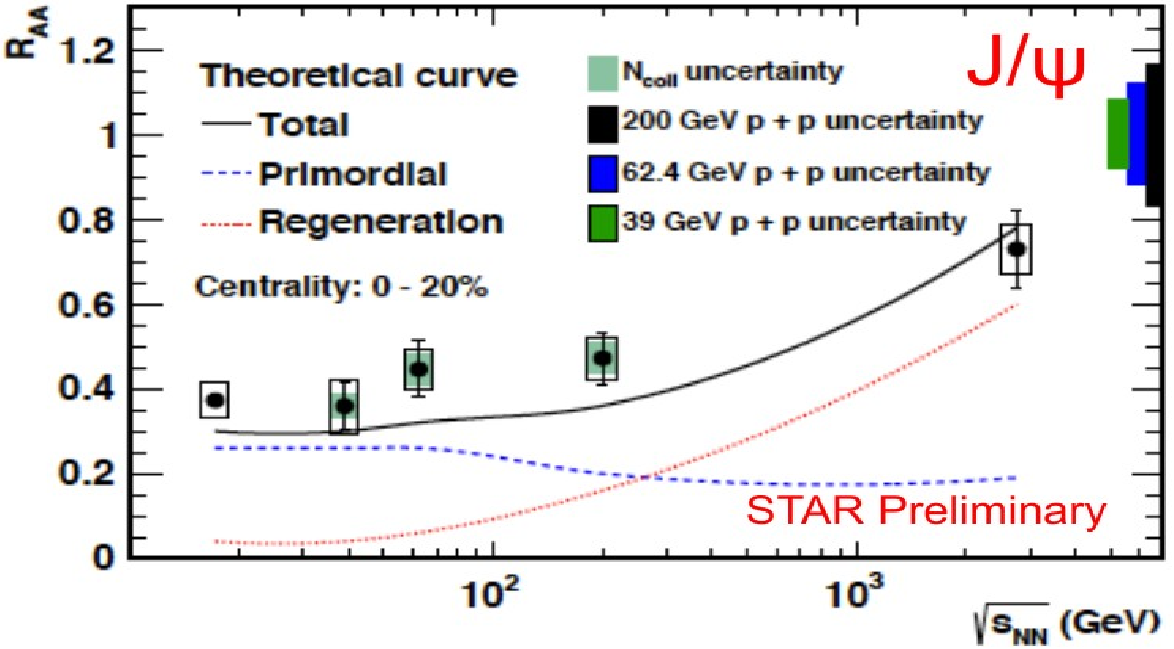
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

2007 prediction impressively confirmed by LHC data

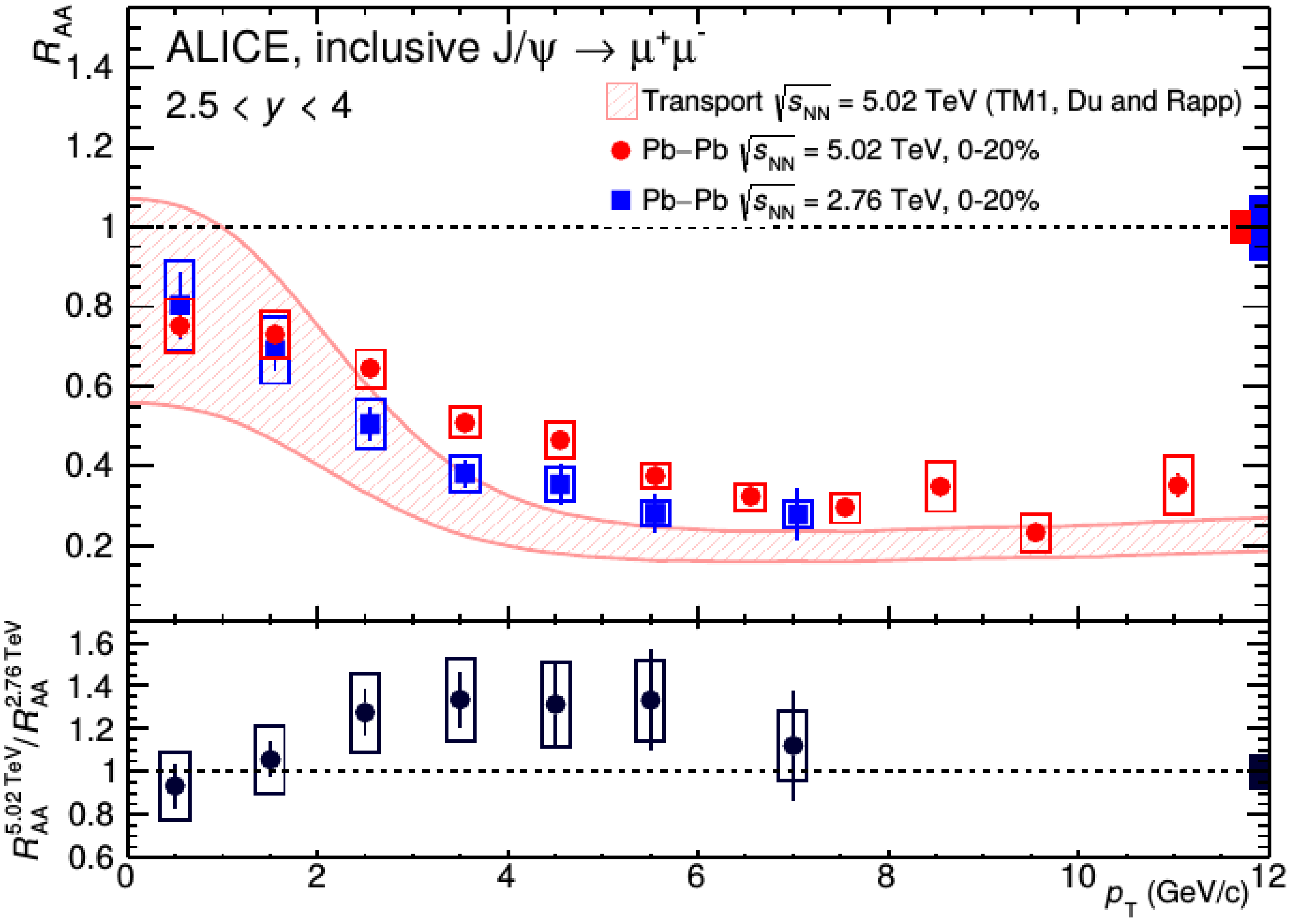
predictions from 2000/2007 beautifully confirmed by RHIC and LHC data



ALICE coll., arXiv:1606.08197



...and the dependence on transverse momentum



ALICE coll., arXiv:1606.08197

summary

thermal approach describes well hadron production in relativistic nuclear collisions from $\sqrt{s_{NN}}$ = 5 GeV to $\sqrt{s_{NN}}$ = 5 TeV

direct connection to QCD statistical operator

chemical freeze-out is closely connected to (pseudo)critical temperature

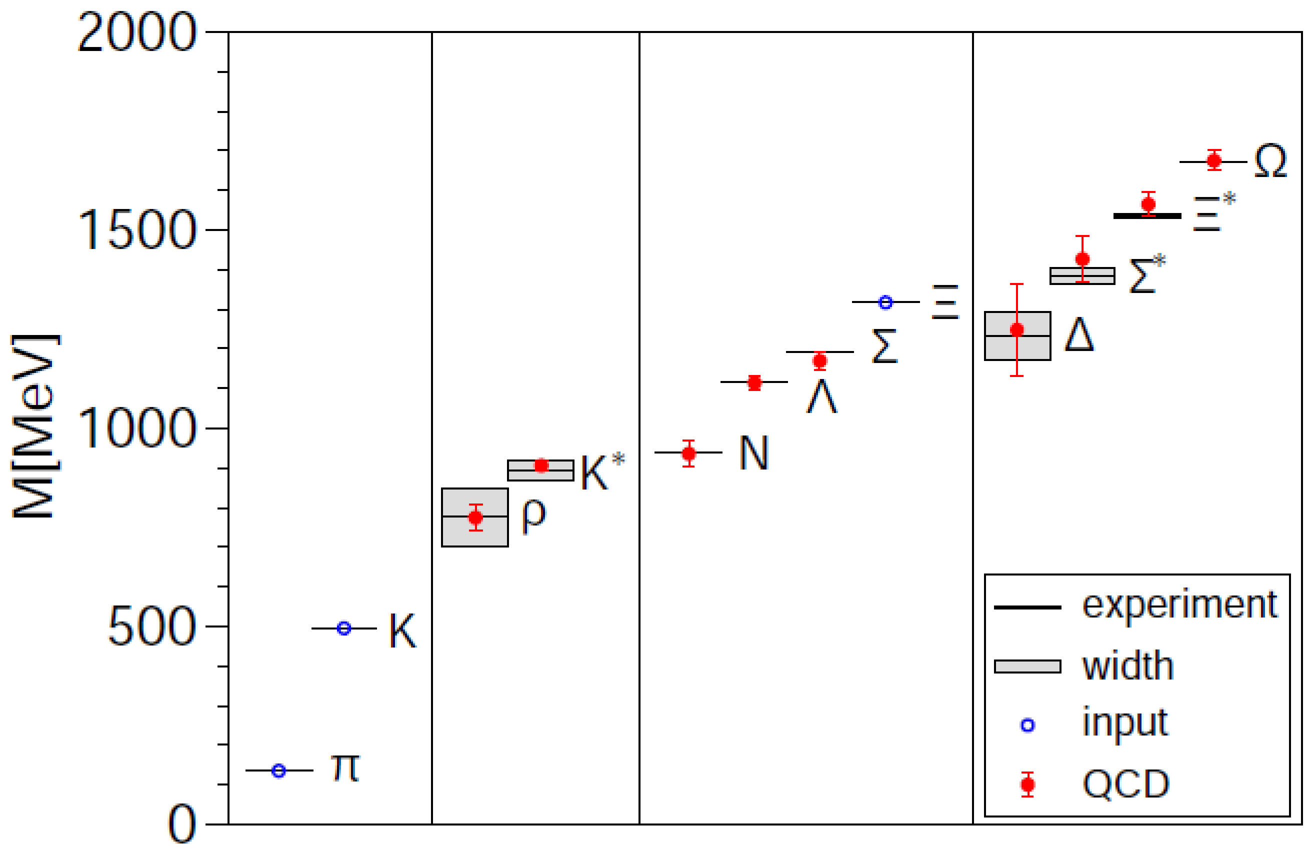
production of loosely bound and exotic objects well described

first attempt at 2nd moments, higher moments to come soon

enhancement of charmonia at collider energies: signature of deconfined and thermalized heavy quarks

additional slides

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?

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

...more details

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

  derived anti-particles from published ratios:

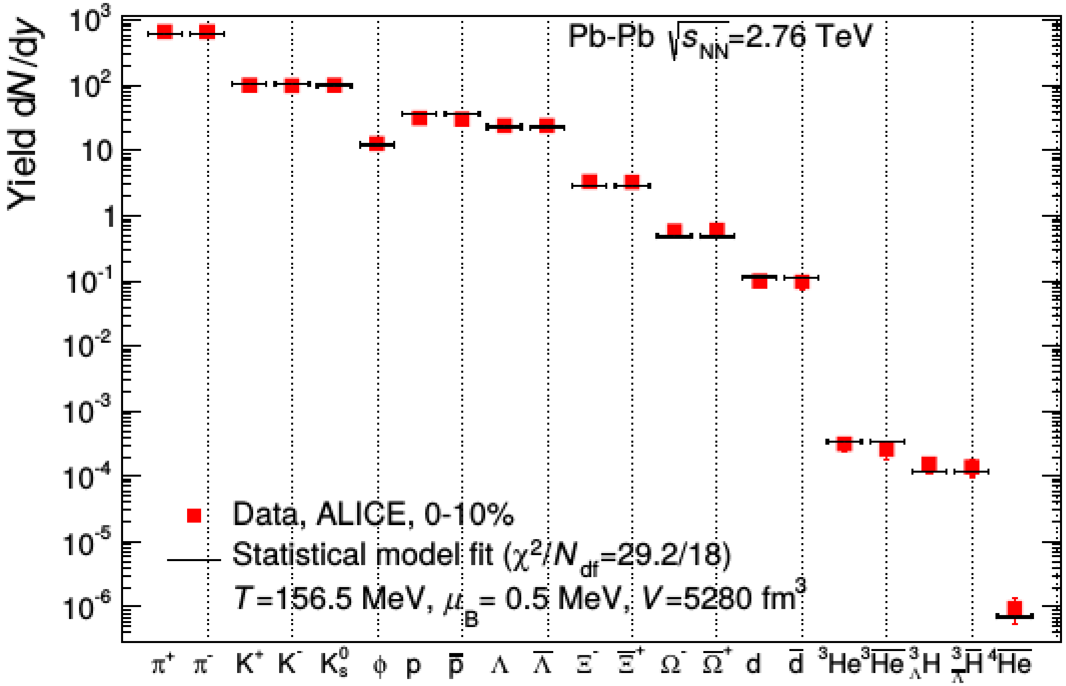
  d: (9.82±1.58)$\times 10^{-2}$, $\bar{\mathrm{d}}/\mathrm{d} =$ 0.98±0.13 → $\bar{\mathrm{d}}$: (9.62±2.01)$\times 10^{-2}$

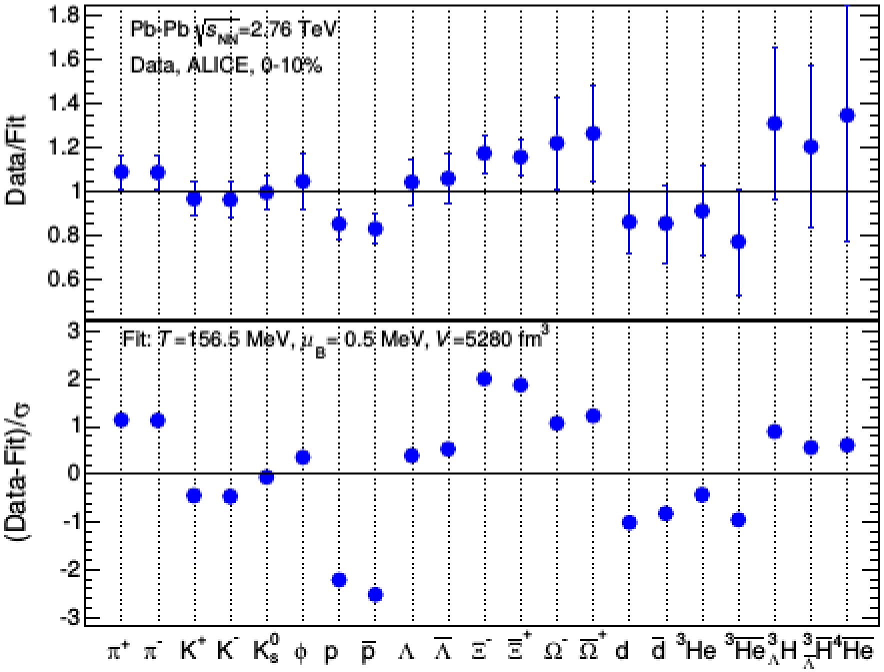
  $^3\mathrm{He}$: rescale from 0-20% to 0-10% using d, factor 1.127 → (3.11±0.706)$\times 10^{-4}$
  $^3\bar{\mathrm{He}}/^3\mathrm{He} =$ 0.83±0.08±0.16 → $^3\bar{\mathrm{He}}$: (2.58±0.81)$\times 10^{-4}$

excluded volume correction:

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

details on thermal description





all species in fit

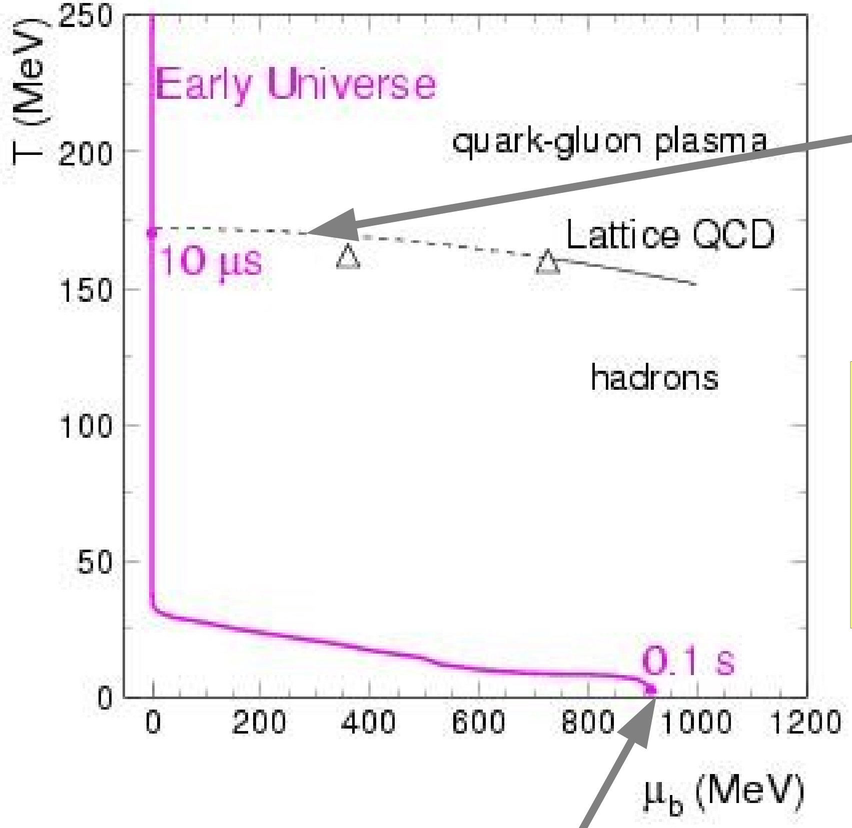
π, $K^{\pm}$, K^0 from charm included (0.7%, 2.9%, 3.1% for best fit)

$T = 156.5 \pm 1.5$ MeV, $\mu_B = 0.5 \pm 3.8$ MeV, $V = 5280 \pm 410$ fm^3

QCD pseudo-critical temperature $T_c = (154 \pm 9)$ MeV

chemical freeze-out very close to QCD phase boundary

evolution of the early universe and the QCD phase diagram



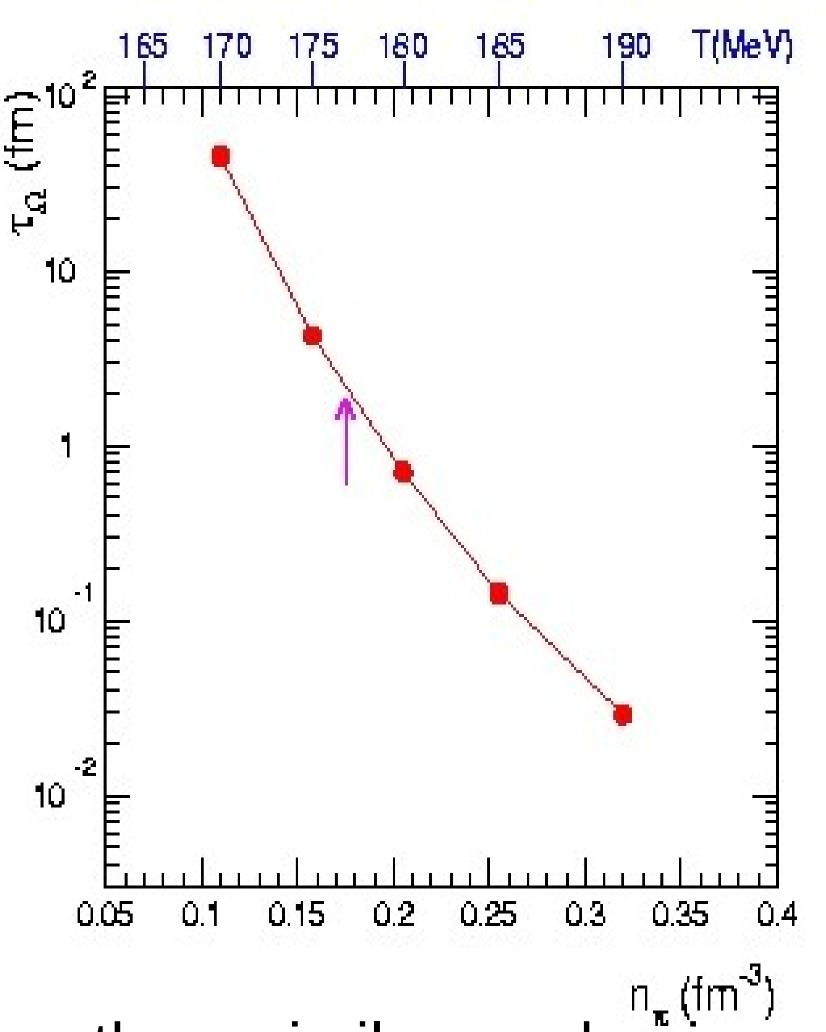
QCD phase boundary

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



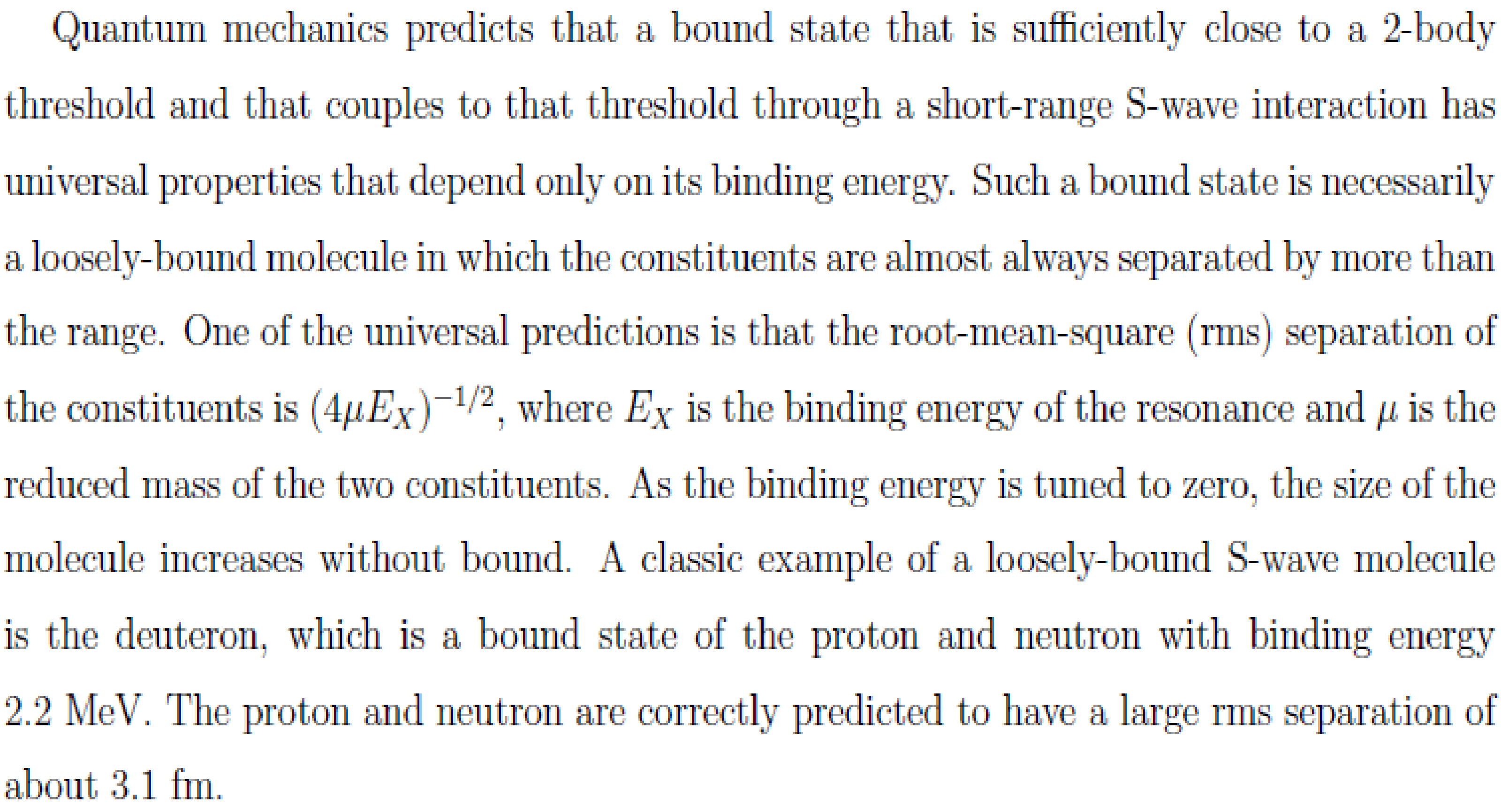
- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within the same very narrow temperature window.

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

are there similar mechanisms for large μ_b?

The size of loosely bound molecular objects

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

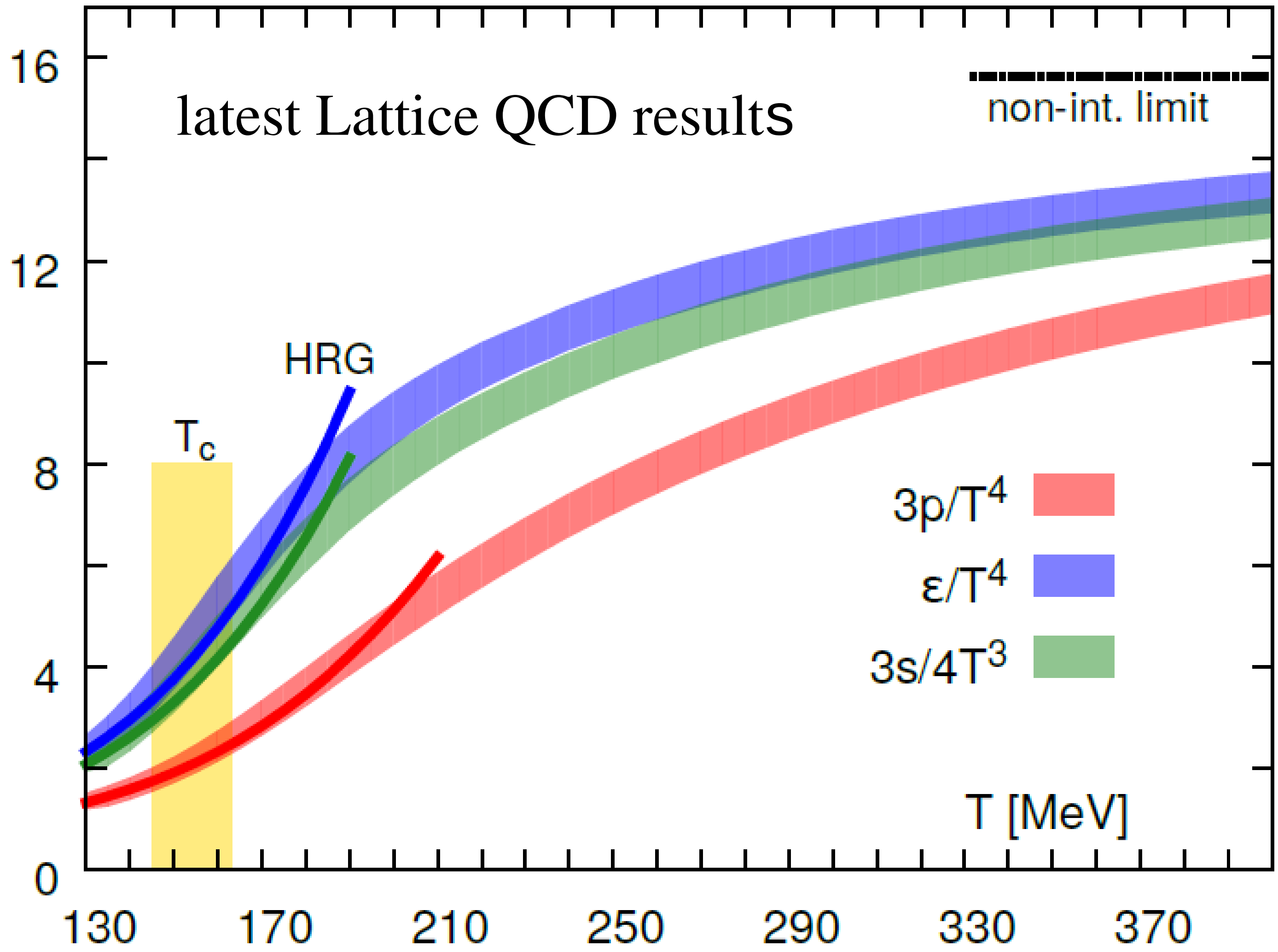


Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which 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 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

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)

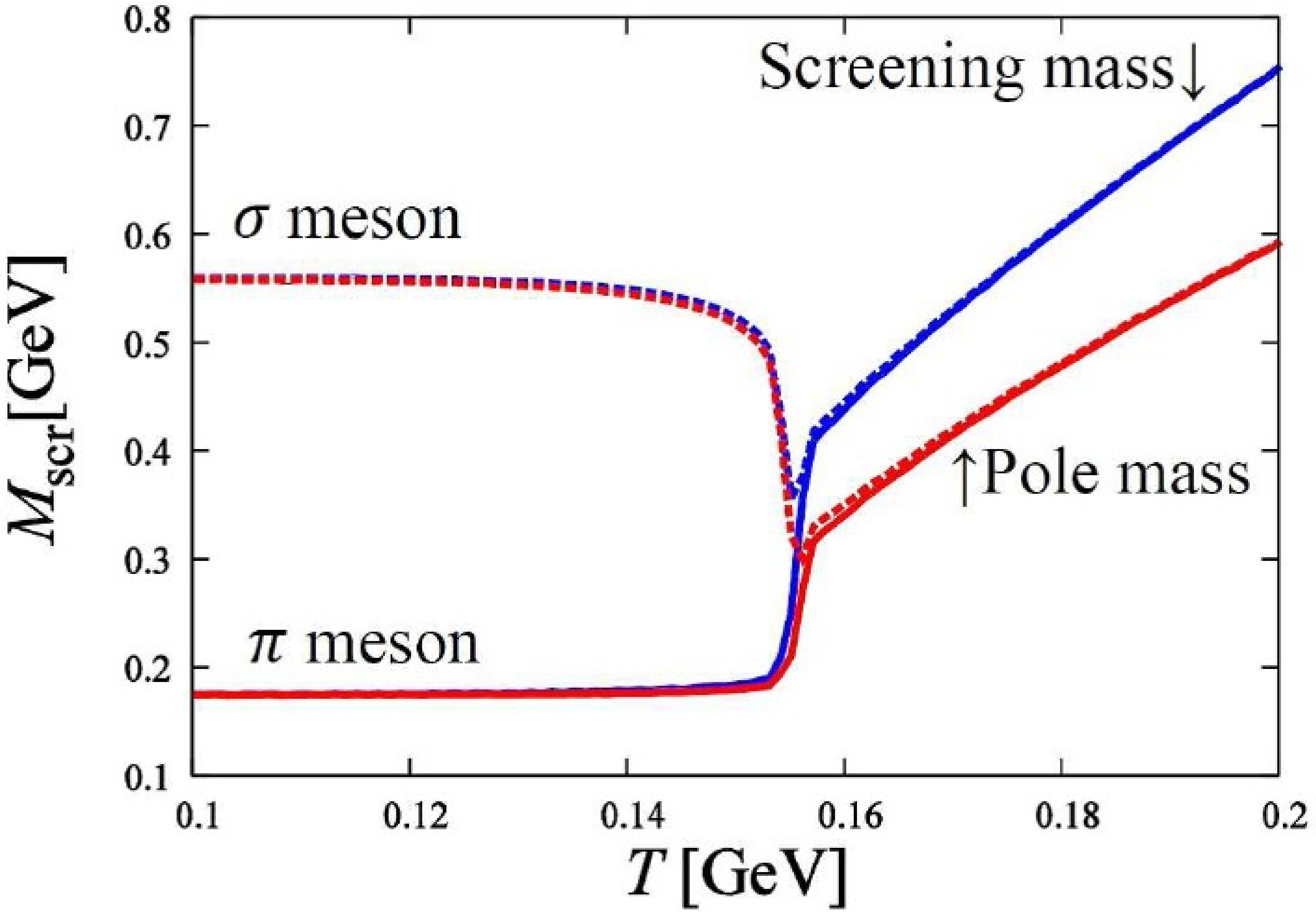
LQCD results cannot be described by hadronic degrees of freedom for T > 163 MeV.

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

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