production of hadrons with light (u,d,s) quarks at the QCD phase boundary

- introduction and perspective
- the hadron resonance gas
- (u,d,s) hadron production, Lattice QCD and the QCD phase structure
- comments on higher moments
- outlook

EMMI 2017 workshop

CCNU, Wuhan, China
Oct. 10 - 13, 2017
pbm

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG
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GSI

HUAZHONG UNIVERSITY

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

hadron production data from the ALICE collaboration
at the CERN LHC
see, e.g., M. Floris,

Nucl.Phys. A931 (2014) 103-112

and references there

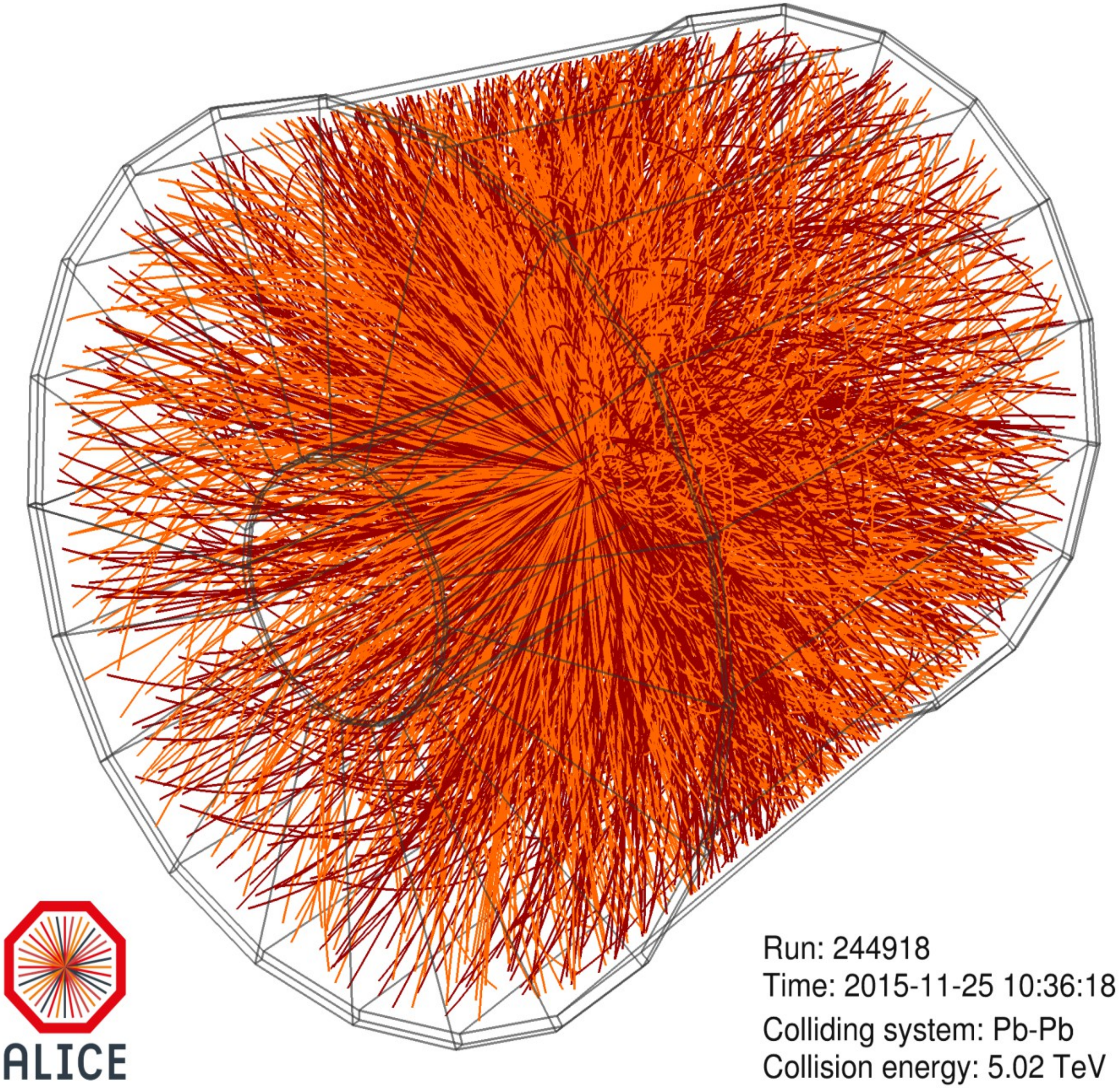
first PbPb collisions at LHC at $\sqrt{s}$ = 5.02 A TeV

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 running with 13 TeV pp

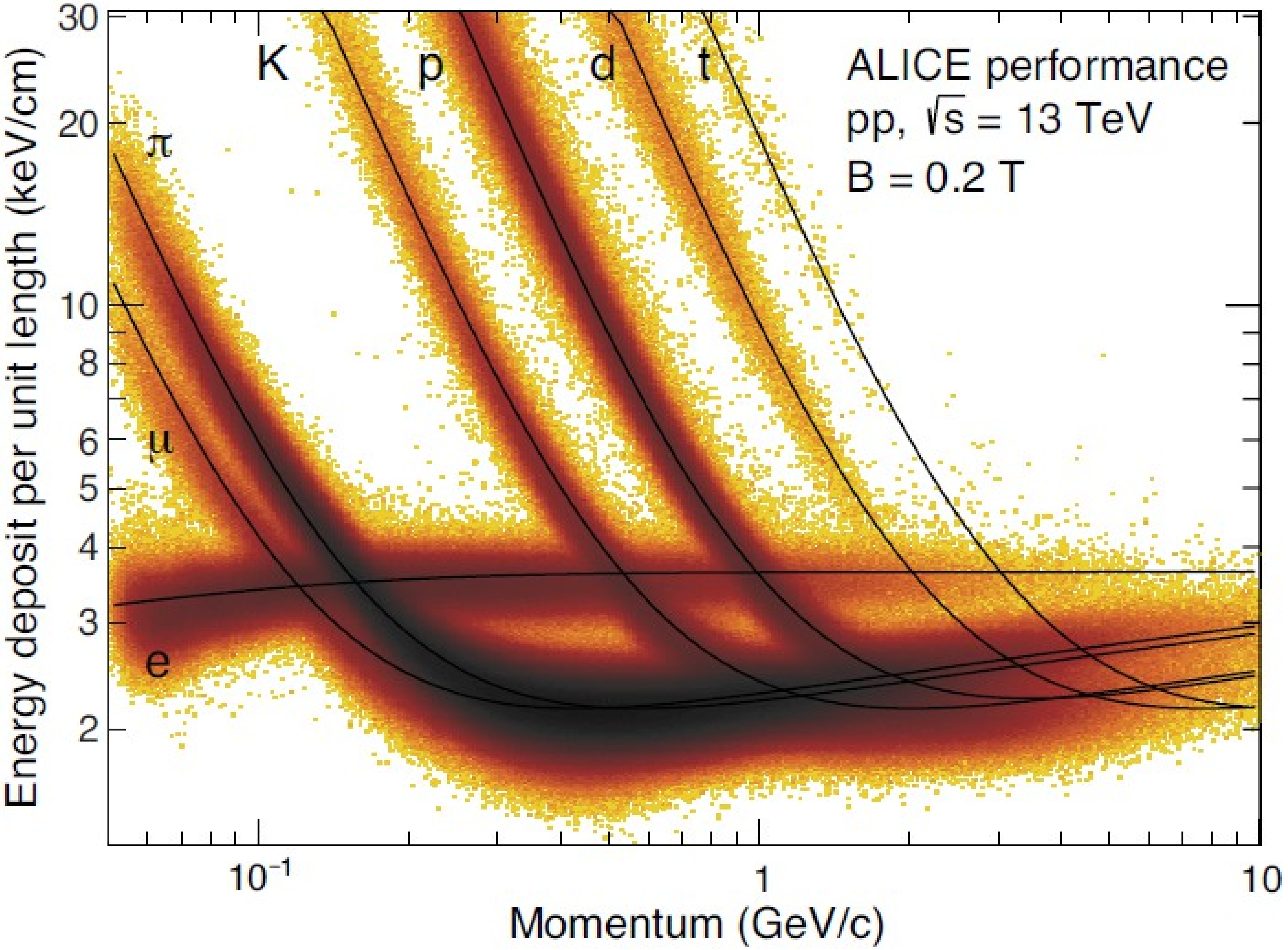
Nov. 2016: pPb 5 TeV



ALICE

particle identification with the ALICE TPC

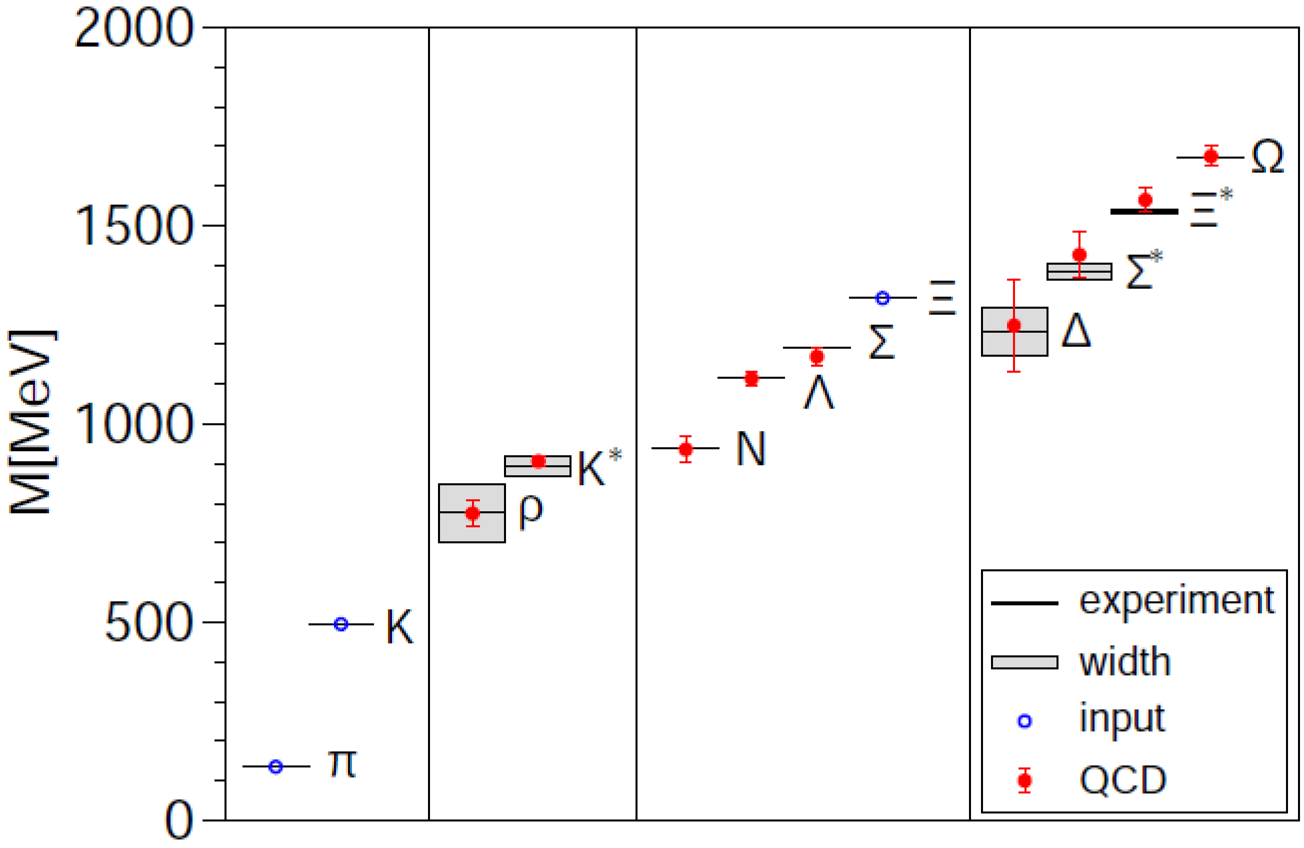
from 50 MeV to 50 GeV



hadron production and the QCD phase boundary

part 1: the hadron resonance gas

the hadron mass spectrum and lattice QCD



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

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

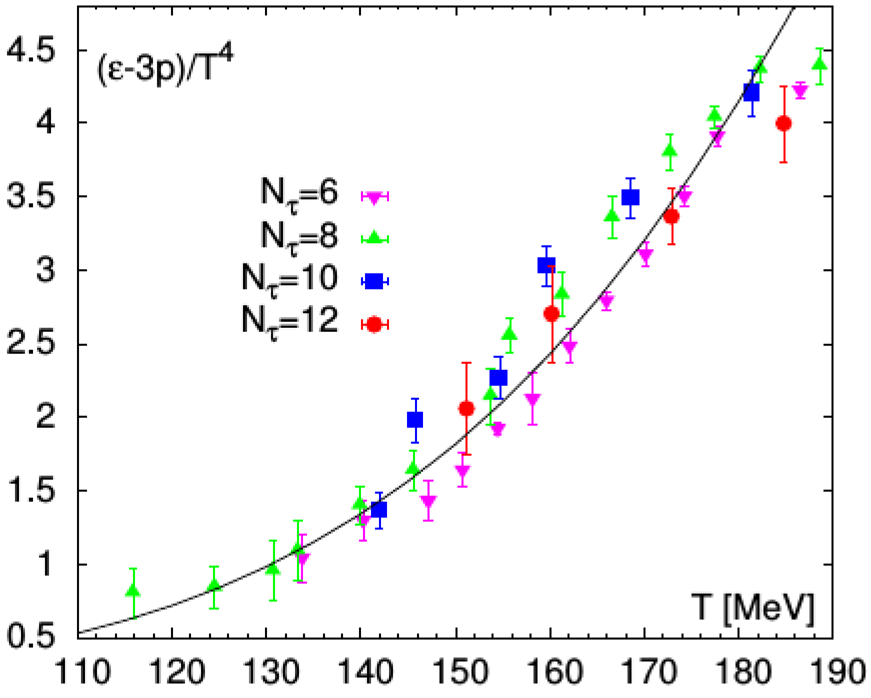
for the pressure we get:

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

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

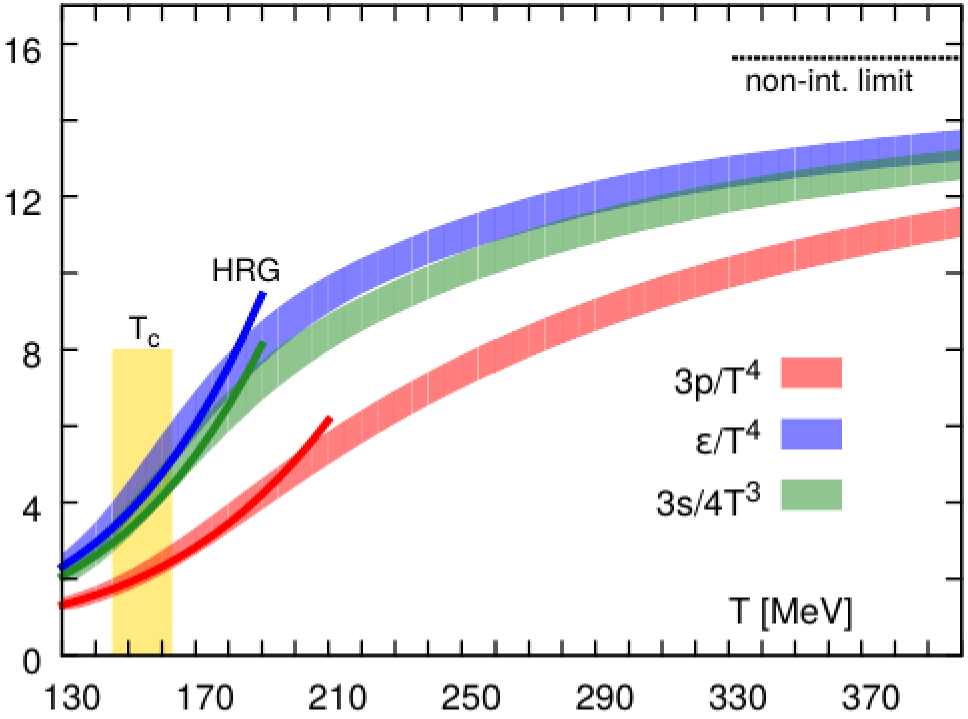


duality between hadrons and quarks/gluons (II)

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

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

$$\varepsilon_{\text{crit}} = (340 \pm 45)\ \text{MeV/fm}^3$$

$$\varepsilon_{\text{nucl}} = 450\ \text{MeV/fm}^3$$

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

hadron production and the QCD phase boundary

part 2: analysis with the statistical hadronization model

statistical hadronization 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

implementation

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

Latest PDG hadron mass spectrum ...quasi-complete up to m=2 GeV;
our code: 555 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i hadron yield, σ_i experimental uncertainty (stat.+syst.)

$\Rightarrow (T, \mu_B, V)$

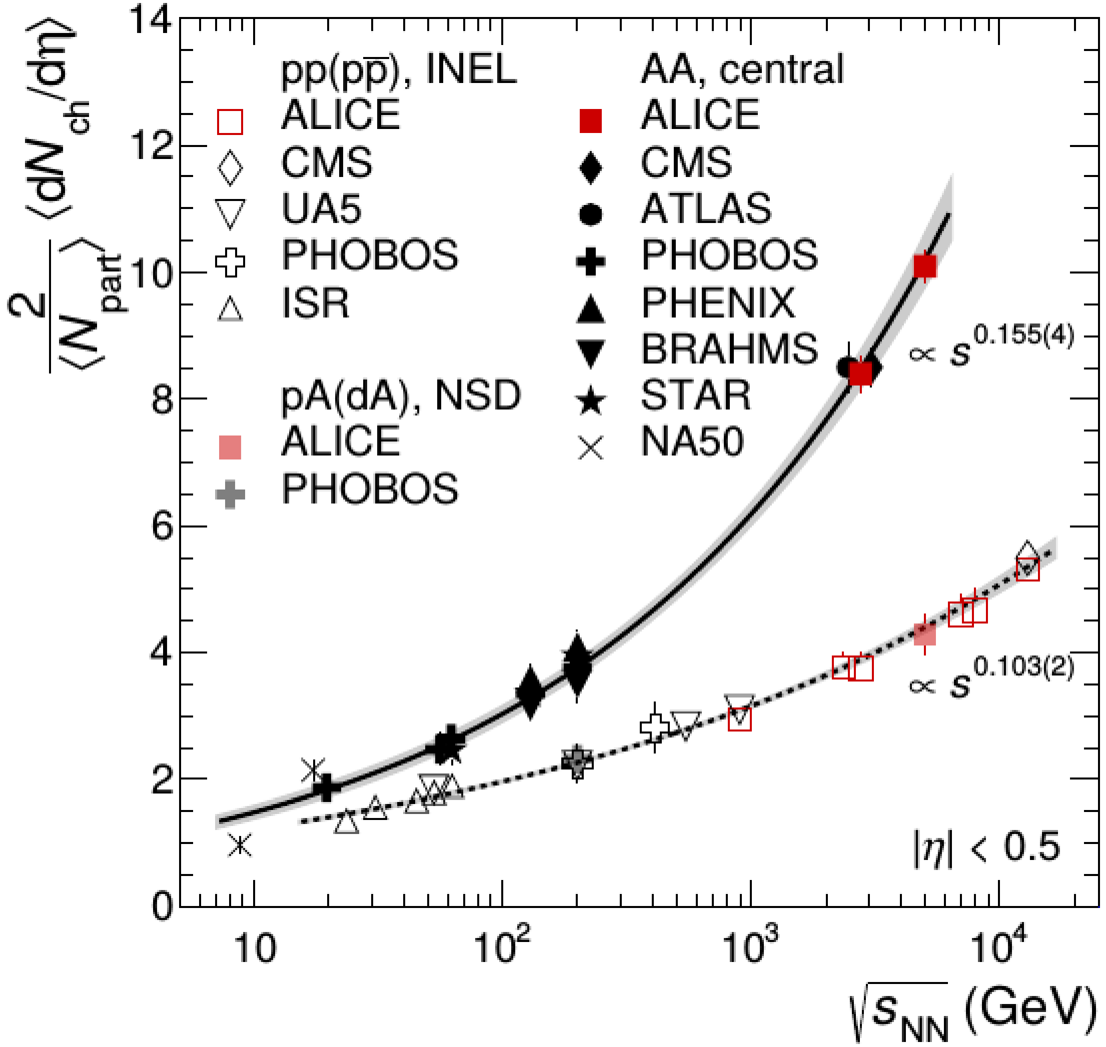
canonical treatment whenever needed (small abundances)

energy dependence of hadron production in central Pb-Pb (Au-Au) collisions

total number of hadrons produced

2.76 TeV $N_{had} = 25800$

5.02 TeV $N_{had} = 32300$

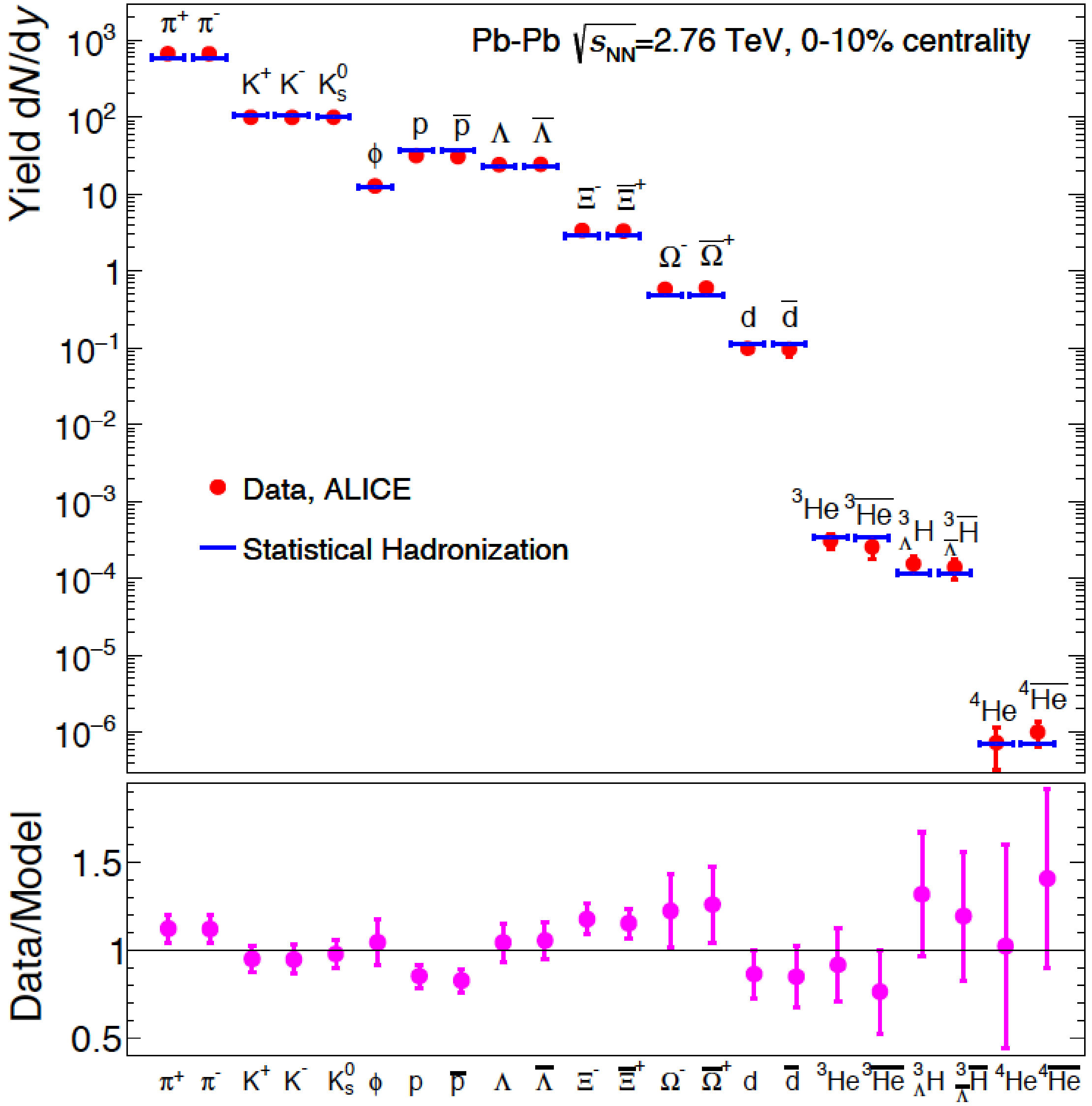


data from LHC run1 and run2

ALICE coll., Phys.Rev.Lett. 116 (2016) no.22, 222302

July 2017 update: excellent description of ALICE@LHC data

fit includes loosely bound systems such a
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

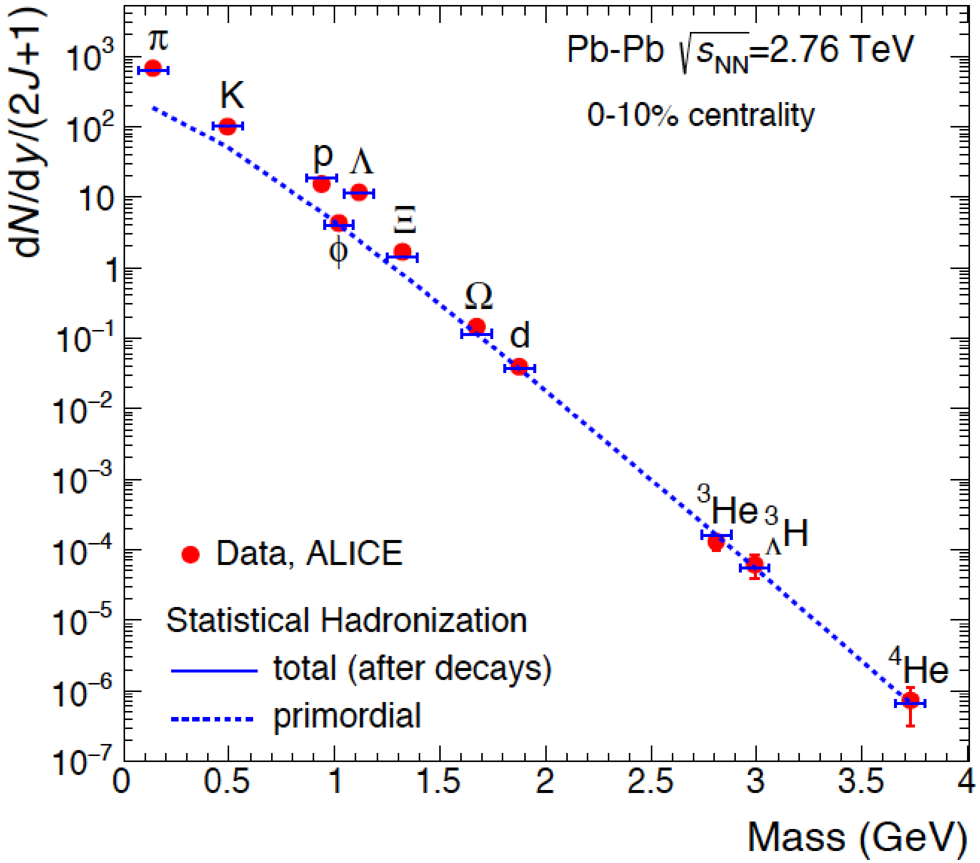


proton discrepancy 2.8 sigma

Xi discrepancy?

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].

excellent agreement over 9 orders of magnitude



agreement over 9 orders of magnitude with QCD statistical operator prediction

exponential decrease with mass and common temperature T = 159 MeV
of yields for light nuclei predicted from the thermal phenomenology discussed above

production near the phase boundary

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} = 156.5 ± 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} = 159 ± 5 MeV, independent of hadronic mass spectrum

an aside on loosely bound objects

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-

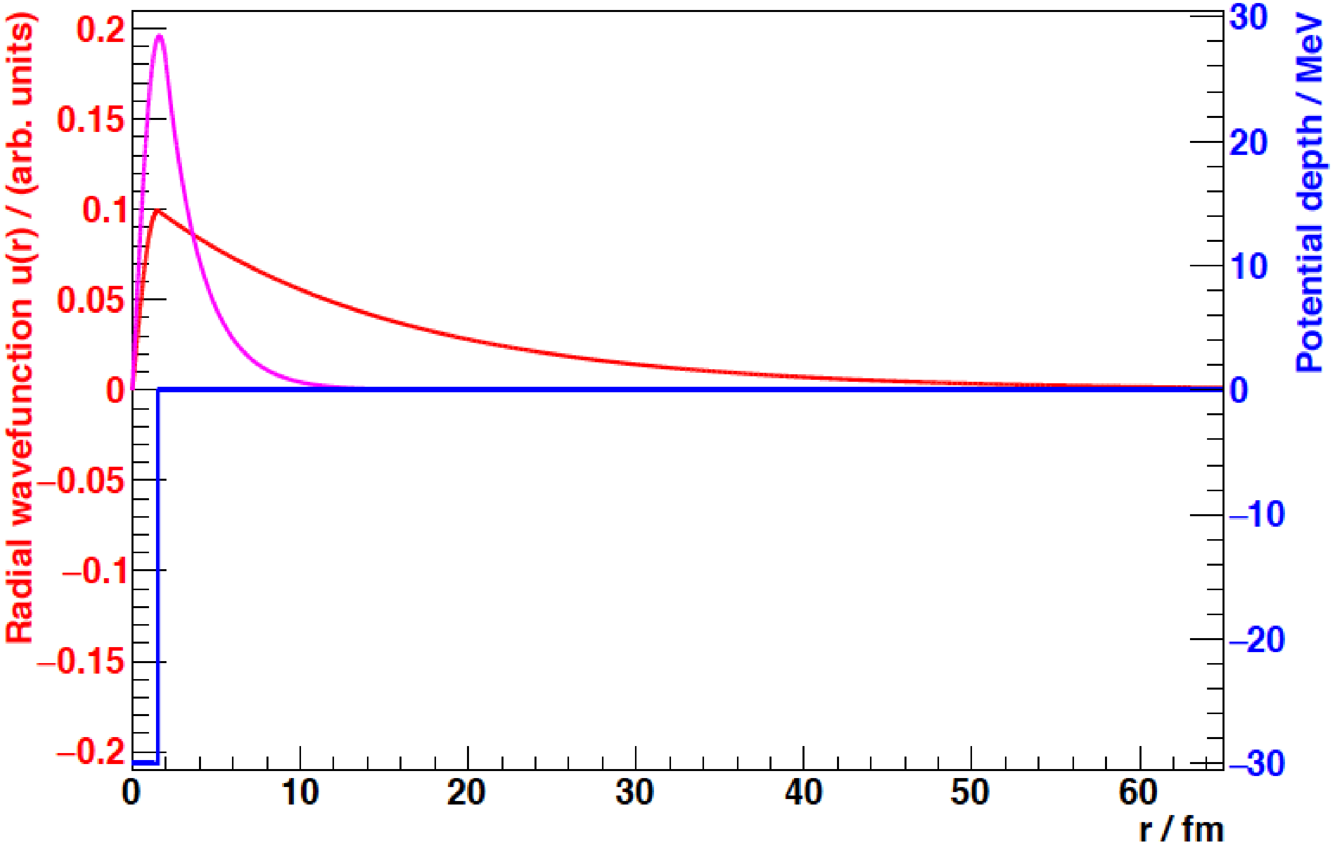
rms radius = $(4\ \text{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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.)

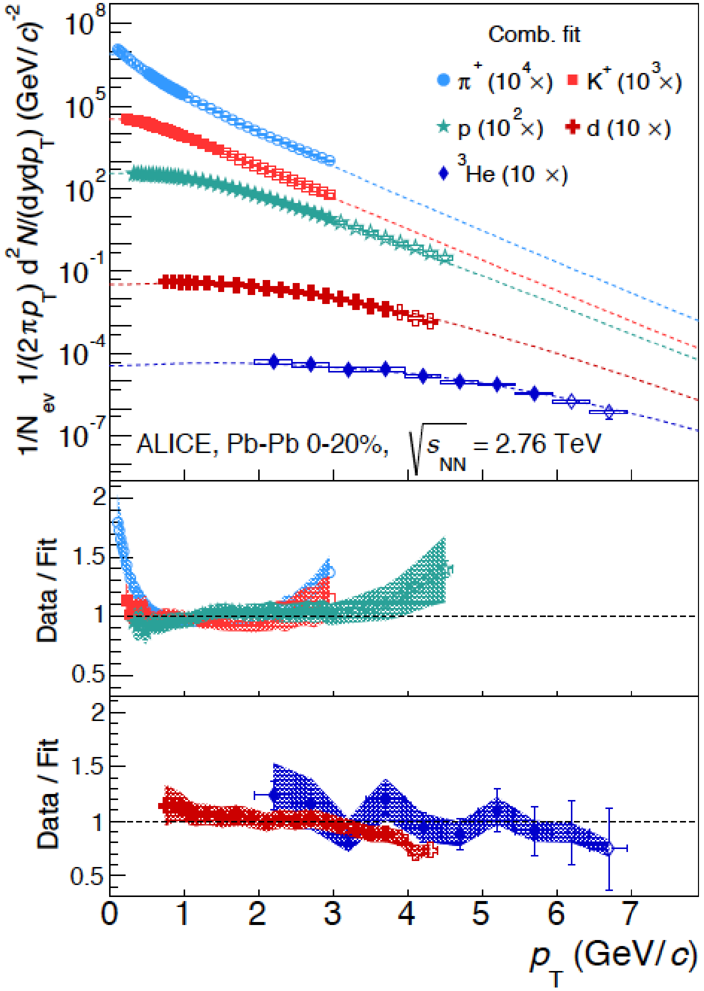
wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017

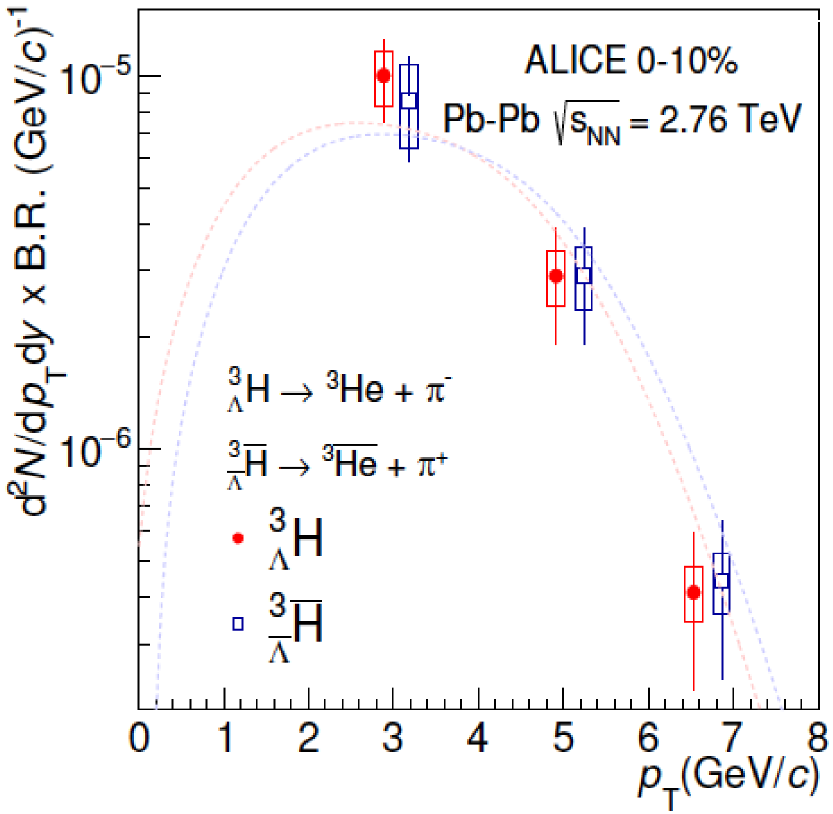


Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve shows a "triton" like object using a similar calculation as the hypertriton, namely a deuteron and an added nucleon, resulting in a much narrower object as the hypertriton.

light nuclei flow with same fluid velocity as pions, kaons, and protons



even hyper-triton flows with same common fluid velocity



Quark Model Spectroscopy

Why does the quark model work so well?

Why do M and B body plans dominate?

Why don't multibaryons make one big bag?

Frank Wilczek, QM2014 introductory talk

hypothesis:
all nuclei and hyper-nuclei are formed as compact multi-quark states at the phase boundary. Then slow time evolution into hadronic respresentation.

Andronic, pbm, Redlich, Stachel, in preparation

How can this be tested?

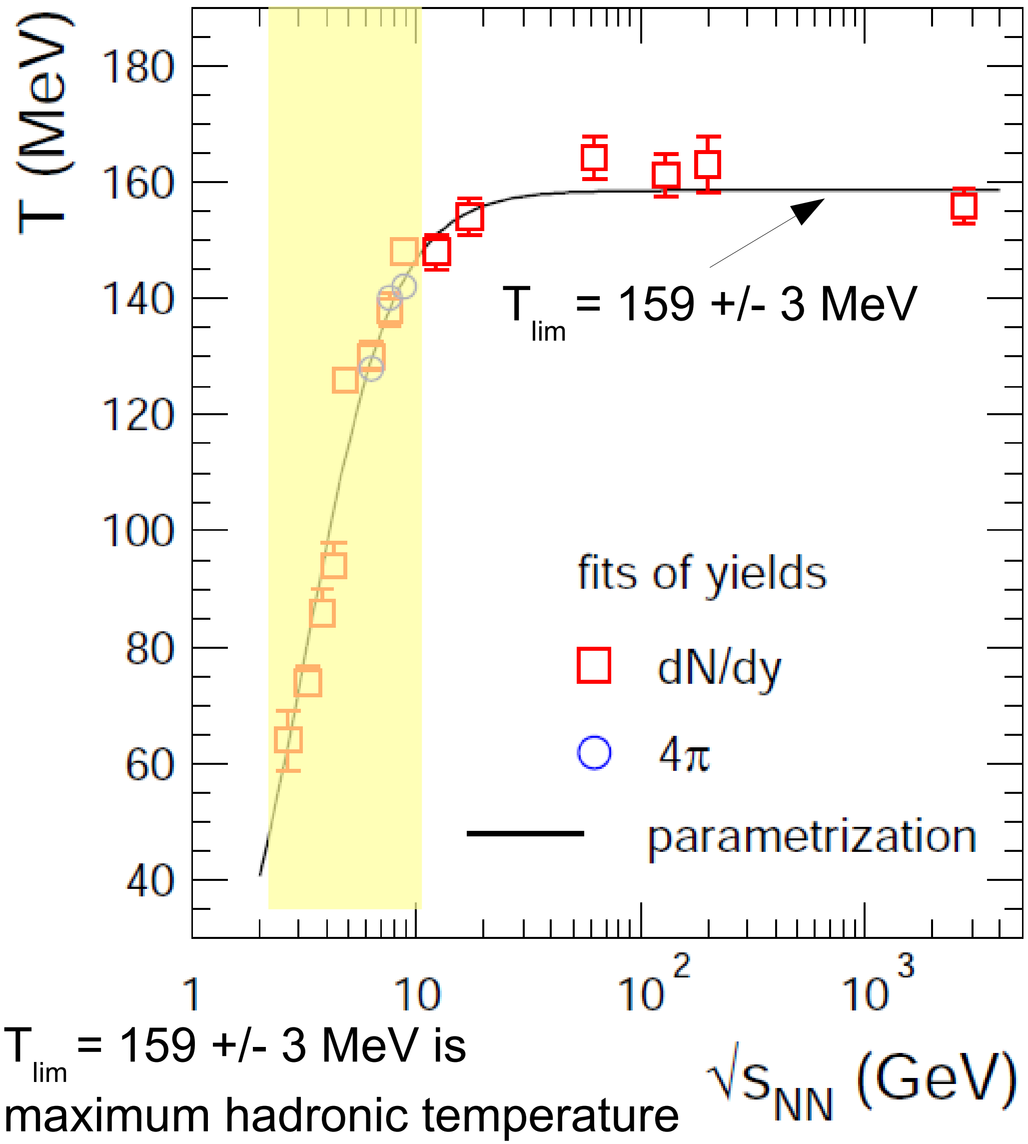
precision measurement of spectra and flow pattern for light nuclei and hyper-nuclei

a major new opportunity for ALICE Run3
and for CBM/NICA/JPARC/NA61

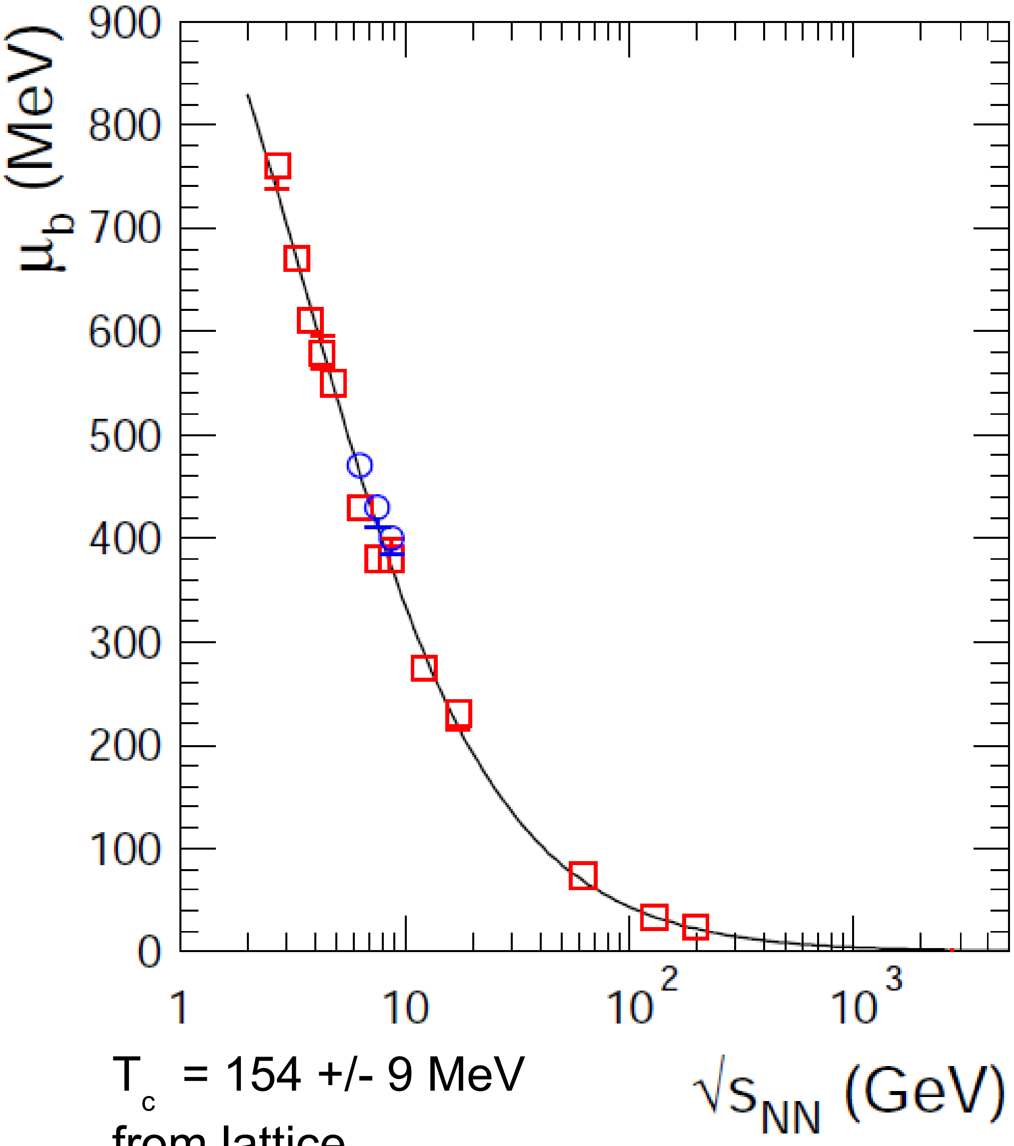
energy dependence of temperature and baryo-chemical potential

energy range from SPS down to threshold (FAIR)

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

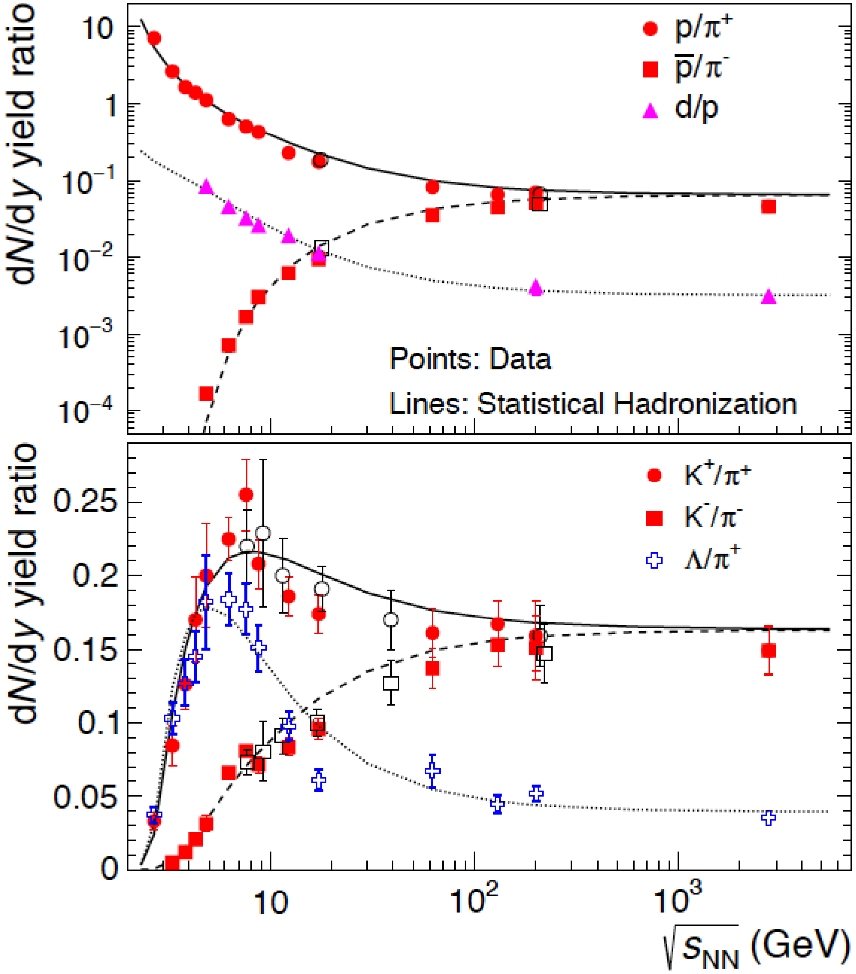


T_{lim} = 159 +/- 3 MeV is maximum hadronic temperature



T_c = 154 +/- 9 MeV from lattice

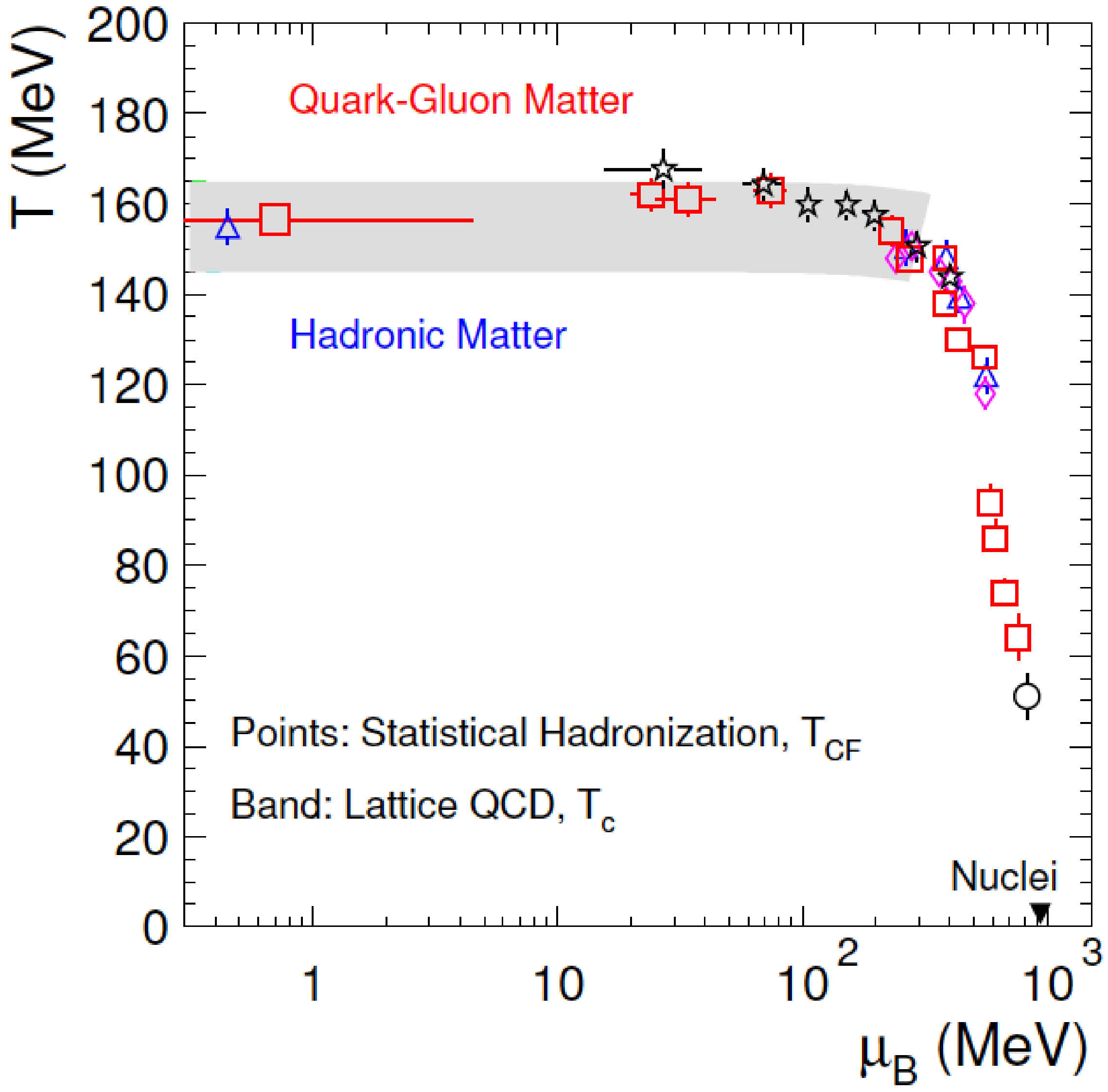
energy dependence of hadron production described quantitatively



together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

no new physics needed to describe K+/pi+ ratio
including the 'horn'

the QGP phase diagram, LQCD, and hadron production data



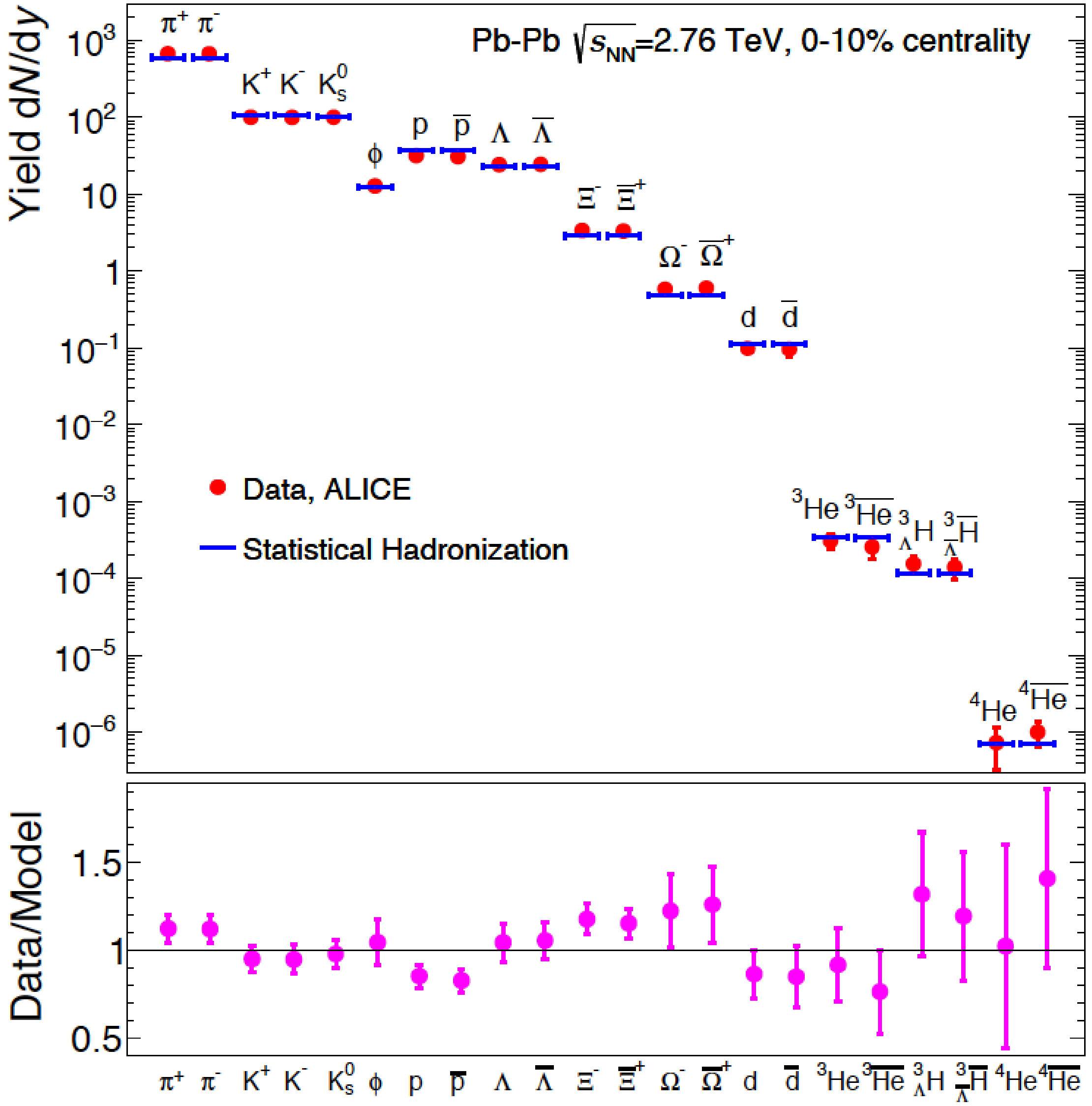
quantitative agreement of chemical freeze-out parameters with LQCD predictions for baryochemical potential < 300 MeV

open issues and questions

- why vacuum masses near phase boundary?
- transition from canonical to grand canonical regime
- are higher moments more sensitive to thermal parameters?
- incomplete hadron mass spectrum?
- uncertainty from statistical hadronization model

thermal fit with statistical hadronization model uses vacuum masses for all hadrons!

fit includes loosely bound systems such a
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



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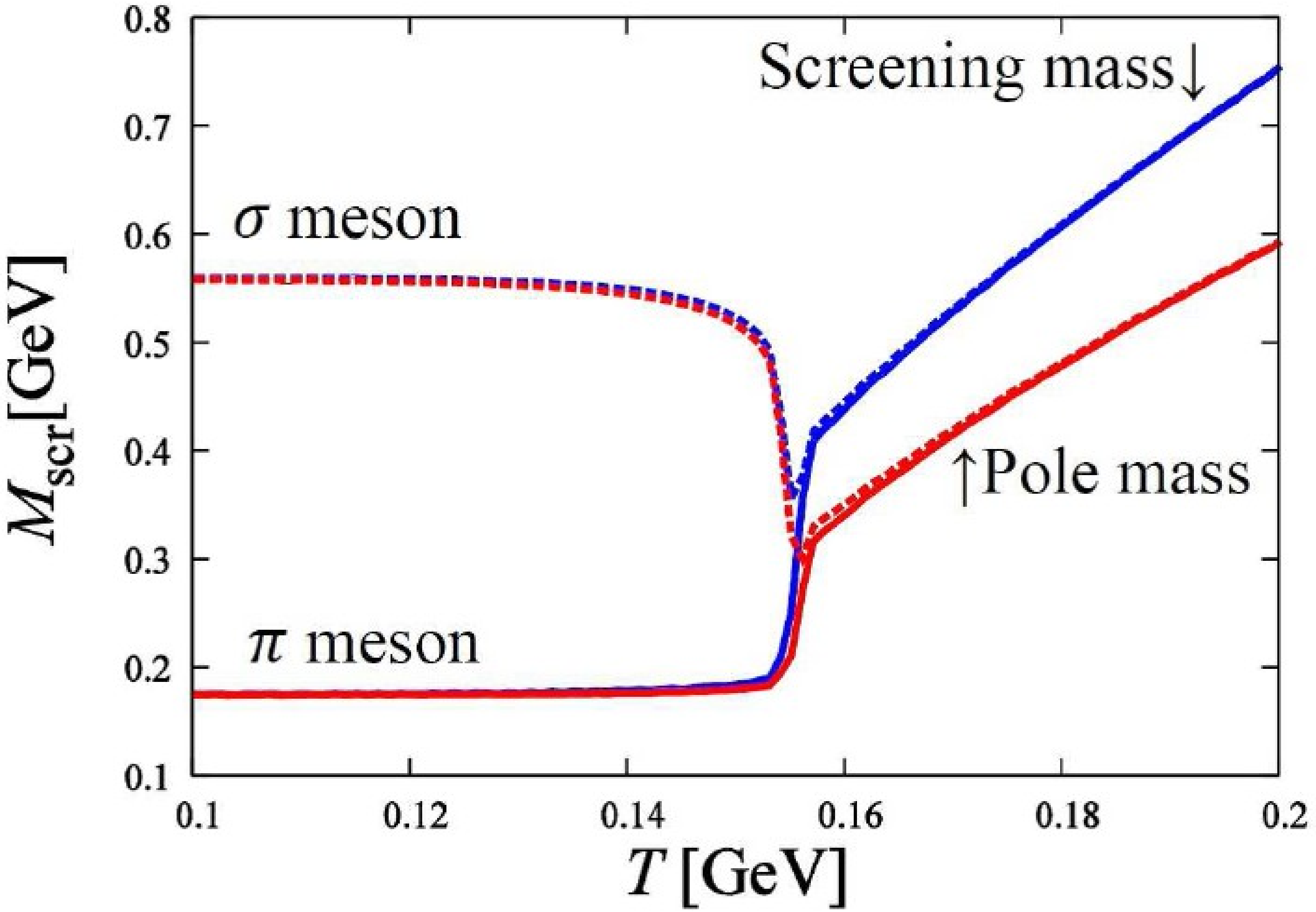
temperature dependence of meson masses in a NJL model



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.

Phys.Rev. D75 (2007) 065004

If the pion mass would be 300 MeV near T_c this would have drastic consequences, especially if nucleon mass is unchanged, see below

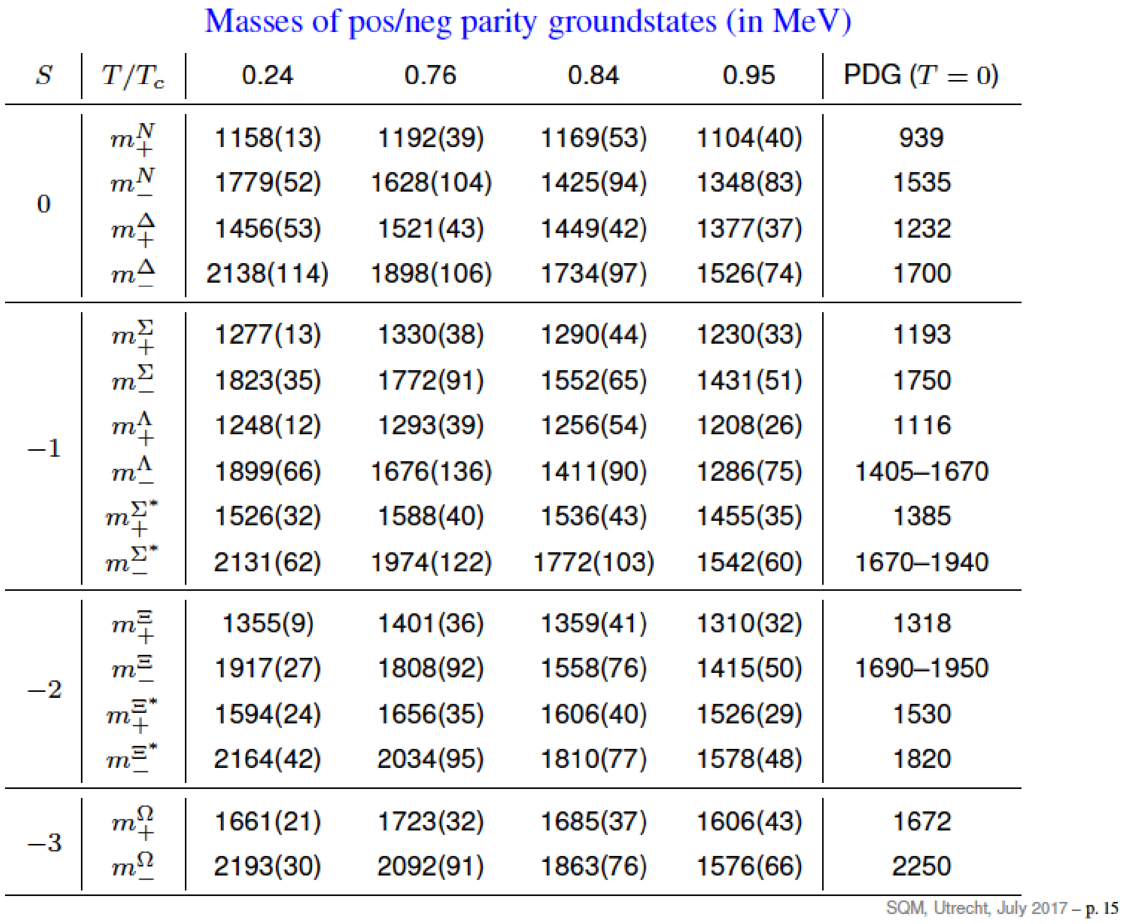
also: changing masses near $T_c = T_{chem}$ would invalidate the chemical freeze-out picture as it implies a dense hadronic phase below T_c
strong interactions are needed to bring masses back on the mass shell and adjust particle numbers

From G. Aarts, SQM2017

PRD 92 (2015) 014503, arXiv:1502.03603 [hep-lat]

JHEP 06 (2017) 034, arXiv:1703.09246 [hep-lat]

in preparation



Masses of pos/neg parity groundstates (in MeV)

S	T/T_c	0.24	0.76	0.84	0.95	PDG ($T=0$)
0	m_+^N	1158(13)	1192(39)	1169(53)	1104(40)	939
	m_-^N	1779(52)	1628(104)	1425(94)	1348(83)	1535
	m_+^Δ	1456(53)	1521(43)	1449(42)	1377(37)	1232
	m_-^Δ	2138(114)	1898(106)	1734(97)	1526(74)	1700
-1	m_+^Σ	1277(13)	1330(38)	1290(44)	1230(33)	1193
	m_-^Σ	1823(35)	1772(91)	1552(65)	1431(51)	1750
	m_+^Λ	1248(12)	1293(39)	1256(54)	1208(26)	1116
	m_-^Λ	1899(66)	1676(136)	1411(90)	1286(75)	1405–1670
	$m_+^{\Sigma^*}$	1526(32)	1588(40)	1536(43)	1455(35)	1385
	$m_-^{\Sigma^*}$	2131(62)	1974(122)	1772(103)	1542(60)	1670–1940
-2	m_+^Ξ	1355(9)	1401(36)	1359(41)	1310(32)	1318
	m_-^Ξ	1917(27)	1808(92)	1558(76)	1415(50)	1690–1950
	$m_+^{\Xi^*}$	1594(24)	1656(35)	1606(40)	1526(29)	1530
	$m_-^{\Xi^*}$	2164(42)	2034(95)	1810(77)	1578(48)	1820
-3	m_+^Ω	1661(21)	1723(32)	1685(37)	1606(43)	1672
	m_-^Ω	2193(30)	2092(91)	1863(76)	1576(66)	2250

SQM, Utrecht, July 2017 – p. 15

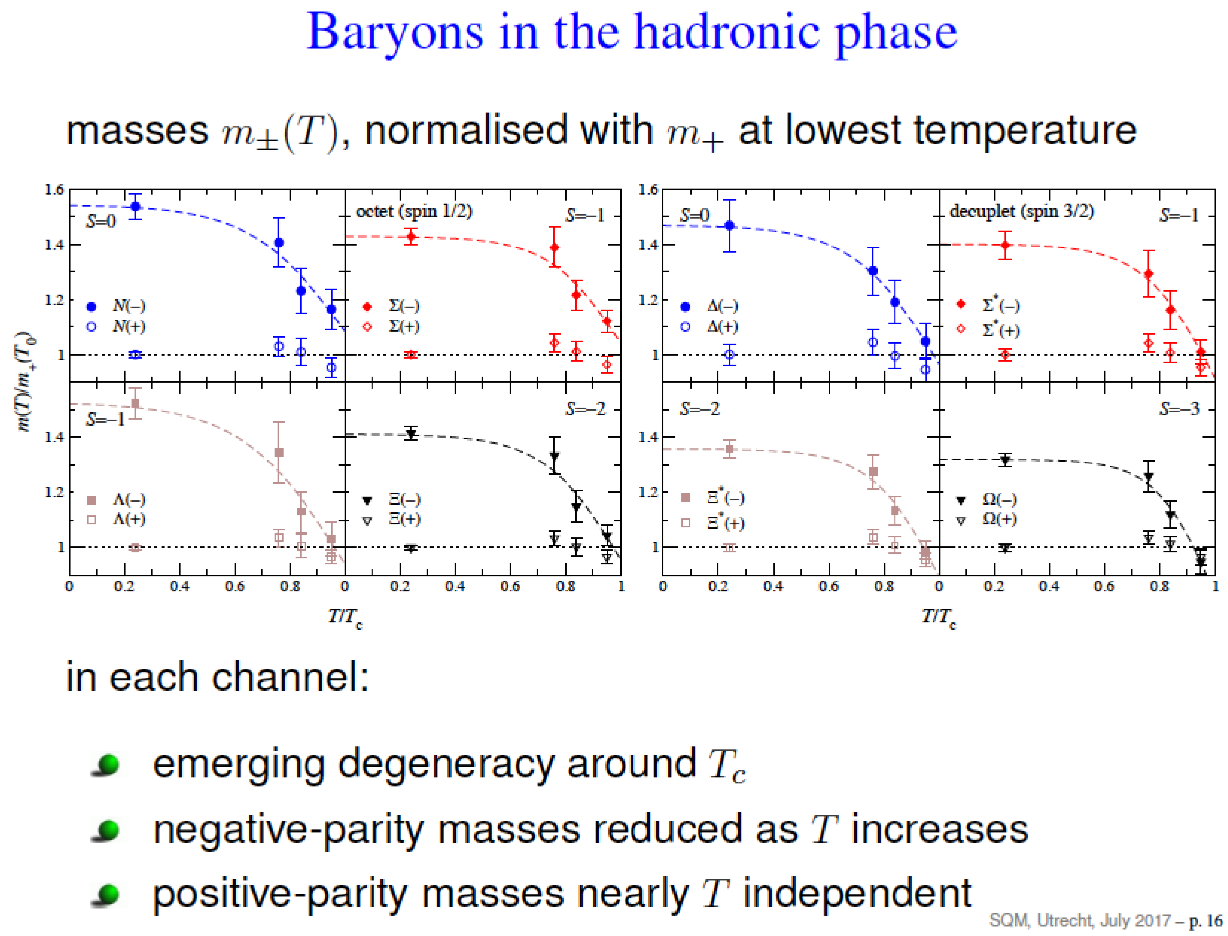
change of baryon masses near T_c

From G. Aarts, SQM2017

PRD 92 (2015) 014503, arXiv:1502.03603 [hep-lat]

JHEP 06 (2017) 034, arXiv:1703.09246 [hep-lat]

in preparation



Baryons in the hadronic phase

masses $m_{\pm}(T)$, normalised with m_+ at lowest temperature

in each channel:

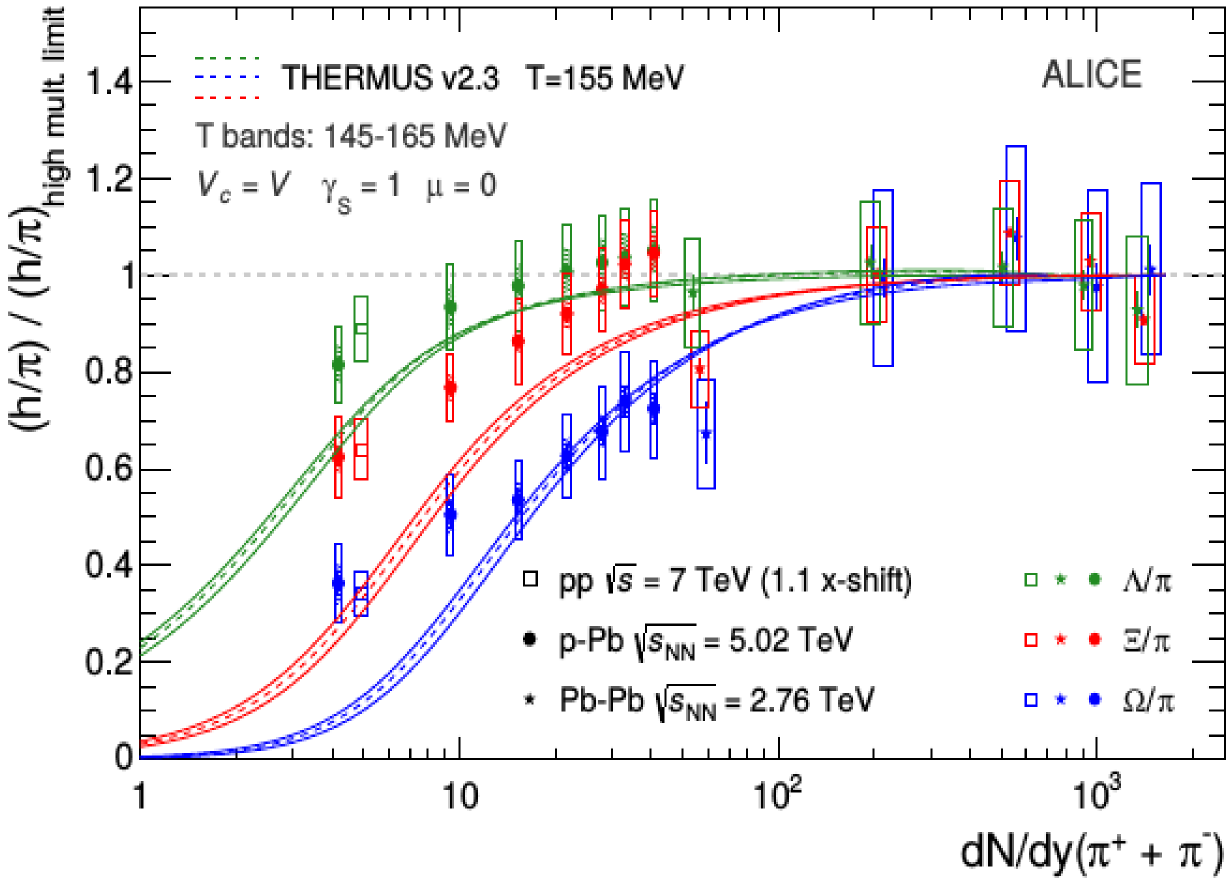
- emerging degeneracy around T_c
- negative-parity masses reduced as T increases
- positive-parity masses nearly T independent

SQM, Utrecht, July 2017 – p. 16

but negative parity baryons all lie higher up in the mass distribution
→ small effects on statistical hadronization results … to be tested

is multiplicity dependence described by canonical thermodynamics?

canonical approach developed by:
Hagedorn, Redlich, Z. Physik C27 (1985) 541
Cleymans, Redlich, Suhonen, Z. Physik C51 (1991) 137



main features, but not details, are captured well – needs further study
arXiv:1606.07424 ALICE data
actual calculations: Vislavicius and Kalweit, arXiv:1610.03001

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

- effect of purity in PID needs to be carefully studied, crucial for higher moment analysis – not yet done

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:

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

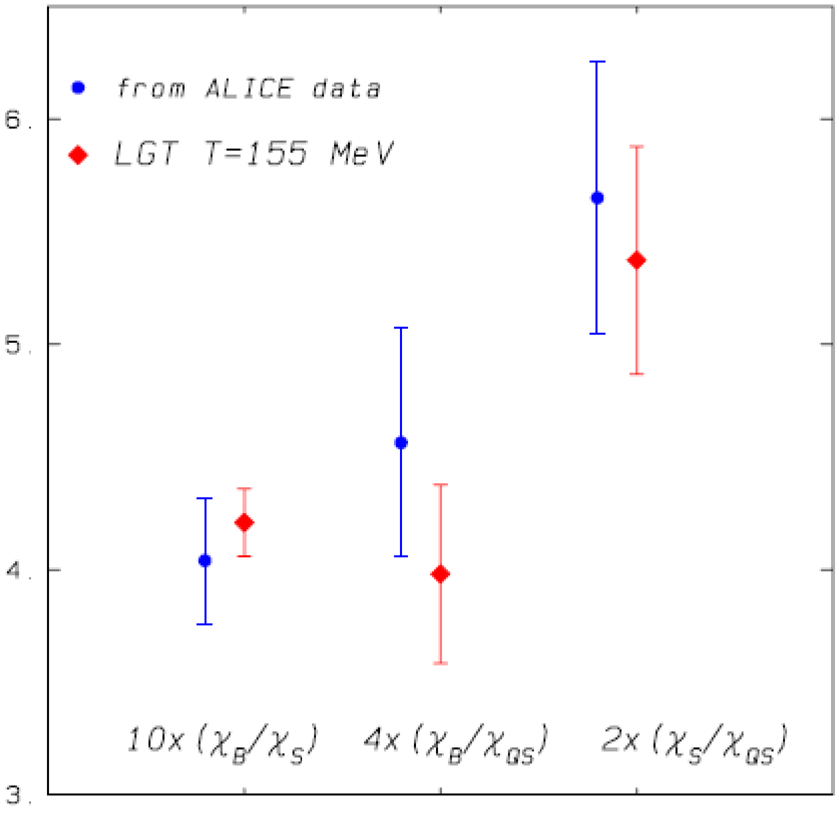
note: higher moments are derived from the same LQCD statistical operator as are first moments

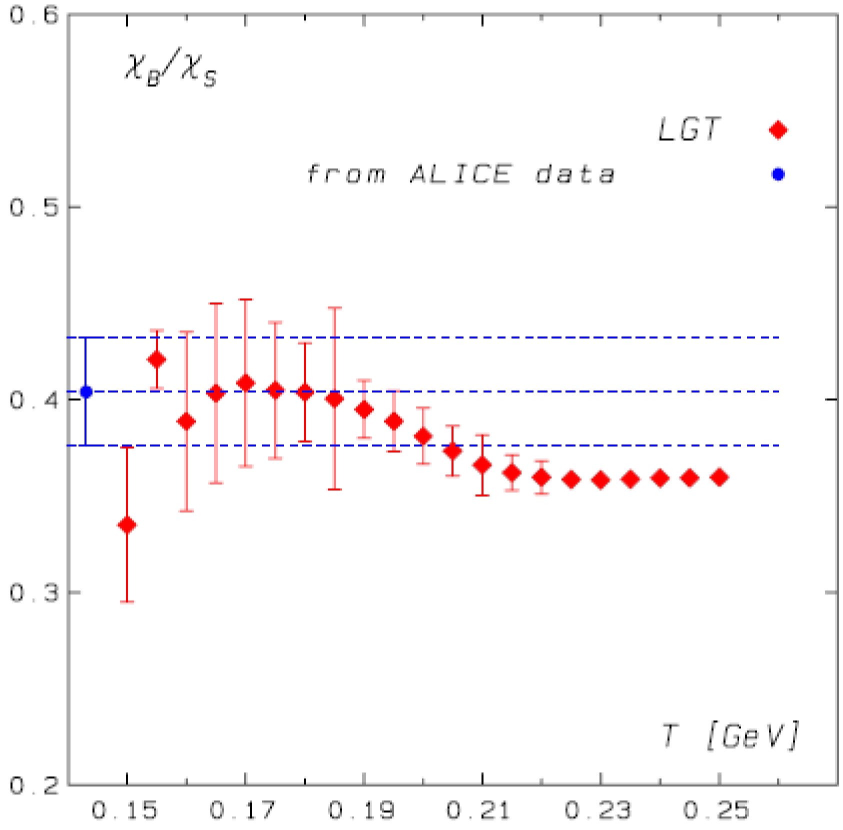
work based on arXiv:1412.8614, Phys. Lett. B747 (2015) 292,
pbm, A. Kalweit, K. Redlich, J. Stachel

expressed in terms of measurable quantities assuming a Skellam distribution for 2nd moments:

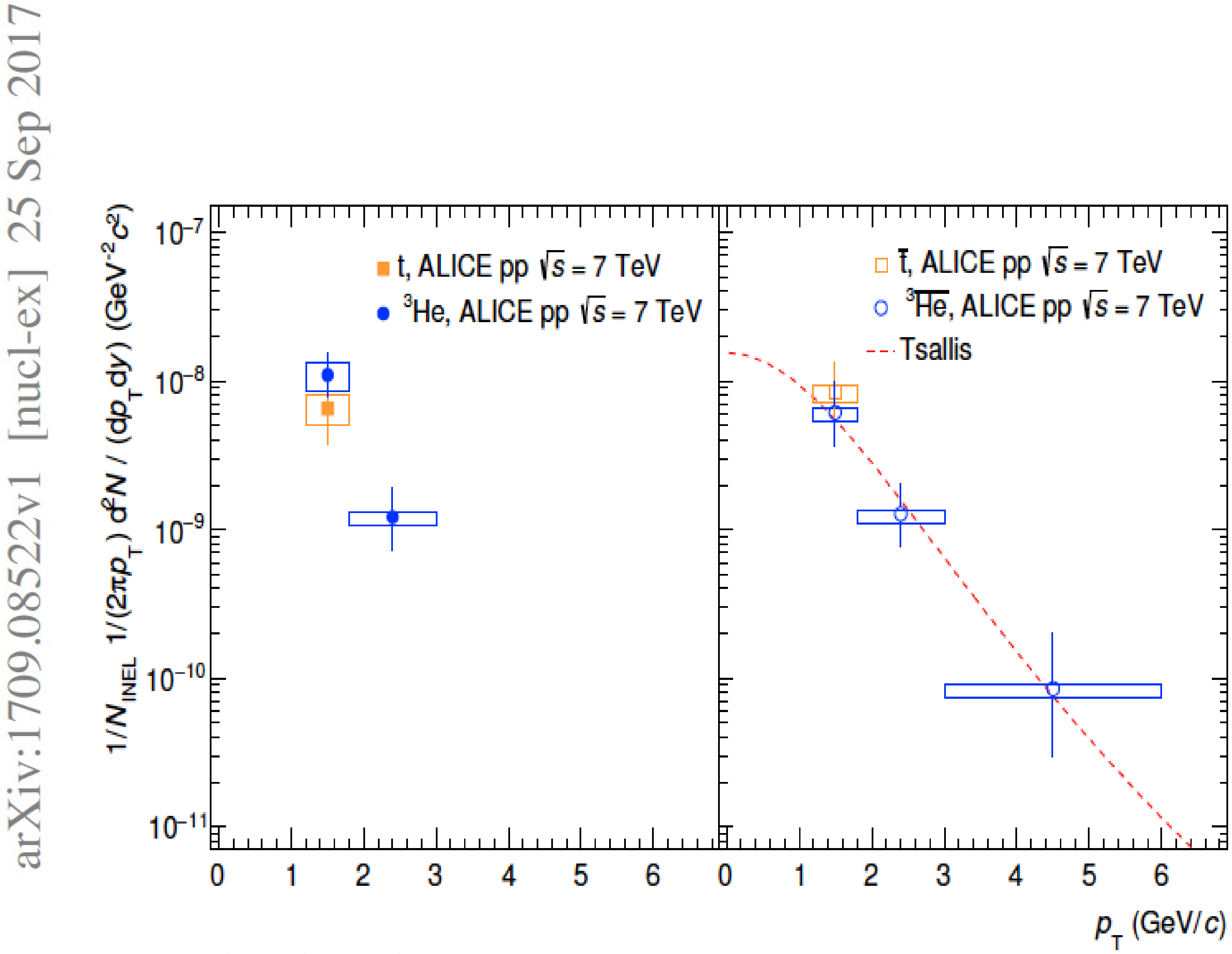
$$\frac{\chi_B}{T^2} = \frac{1}{VT^3}[\langle p \rangle + \langle N \rangle + \langle \Lambda + \Sigma^0 \rangle + \langle \Sigma^+ \rangle + \langle \Sigma^- \rangle \\ + \langle \Xi^- \rangle + \langle \Xi^0 \rangle + \langle \Omega^- \rangle + \text{antiparticles}],$$

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





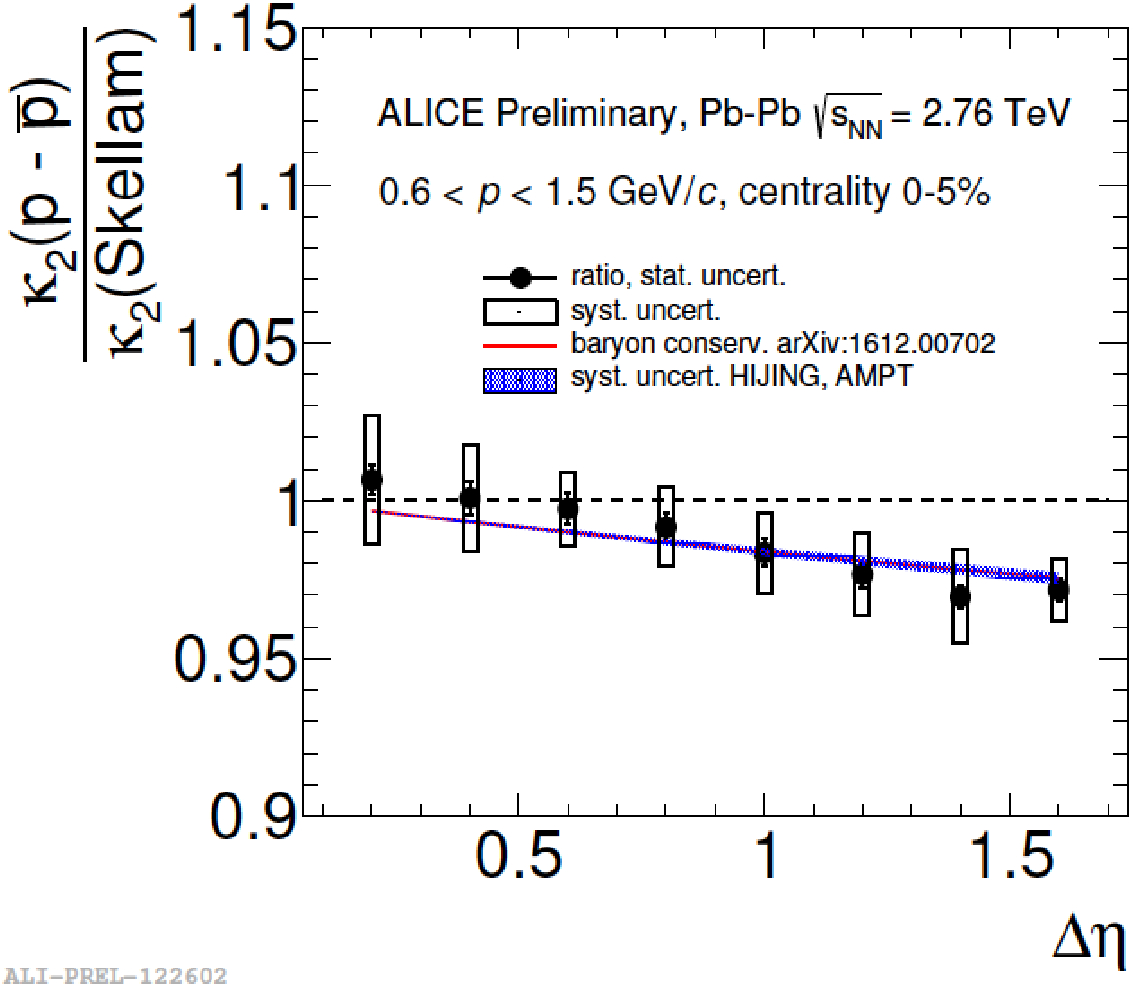
the LHC is a 'gluon collider' – isospin plays no role in particle production



3He = t, p=n, and anti-particles

so this method measures directly 2nd moment of the total baryon distribution

ALICE net proton data: second moments



deviation from the Skellam distribution is tiny and quantitatively described by baryon number conservation 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

thermal parameters from analysis of higher moments are consistent with those obtained from analysis of total yields (1st moments) but systematic uncertainty is much increased

need to correct for impact parameter fluctuations and baryon number conservation first

Systematic uncertainties in statistical hadronization model

in general, not easy to estimate

from analysis of uncertainties in mass spectrum, and in branching ratios, and considering the Boltzmann suppression, we get:

$\Delta T \leq 5$ MeV at $\mu_b = 0$ and $T = 156$ MeV

summary

- statistical hadronization model is effective tool to understand the phenomenology of hadron production in relativistic nuclear collisions from SIS to LHC energy
- deeply rooted in duality 'hadrons – quarks' near QCD phase boundary
- present precision is at the 10% level, mostly limited by incomplete knowledge of hadron mass spectrum and related branching ratios for decays
- measurements from ALICE at the 5% accuracy level shows deviations for protons and cascades at the 2 – 3 sigma level → need to be followed up
- yields of light nuclei and hyper-nuclei successfully predicted
  → maybe produced as quark bags?
- no evidence for mass changes of hadrons near the phase boundary
- results for higher moments must be consistent with 1st moment studies
- statistical hadronization approach also applies to the heavy quark sector – not covered here

key results:
experimental location of QCD phase boundary for $\mu_b < 300$ MeV:
$T_c = 156 \pm 5$ MeV
new insight into hadronization