decoding the QCD phase structure with relativistic nuclear collisions

- introduction and perspective
- the hadron resonance gas
- (u,d,s) hadron production, Lattice QCD and the QCD phase structure
- quarkonia and heavy quark hadrons – window to understand deconfinement
- outlook

pbm

Seminar, LHEP, JINR

Dubna
Jan. 25, 2018

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

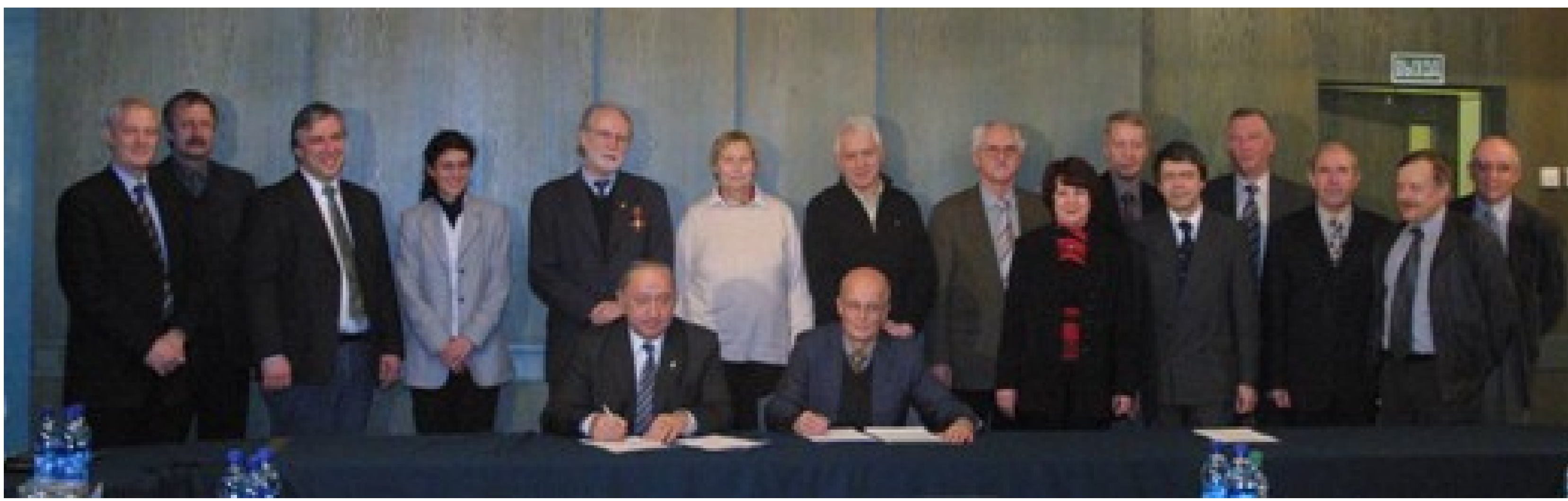
EMMI

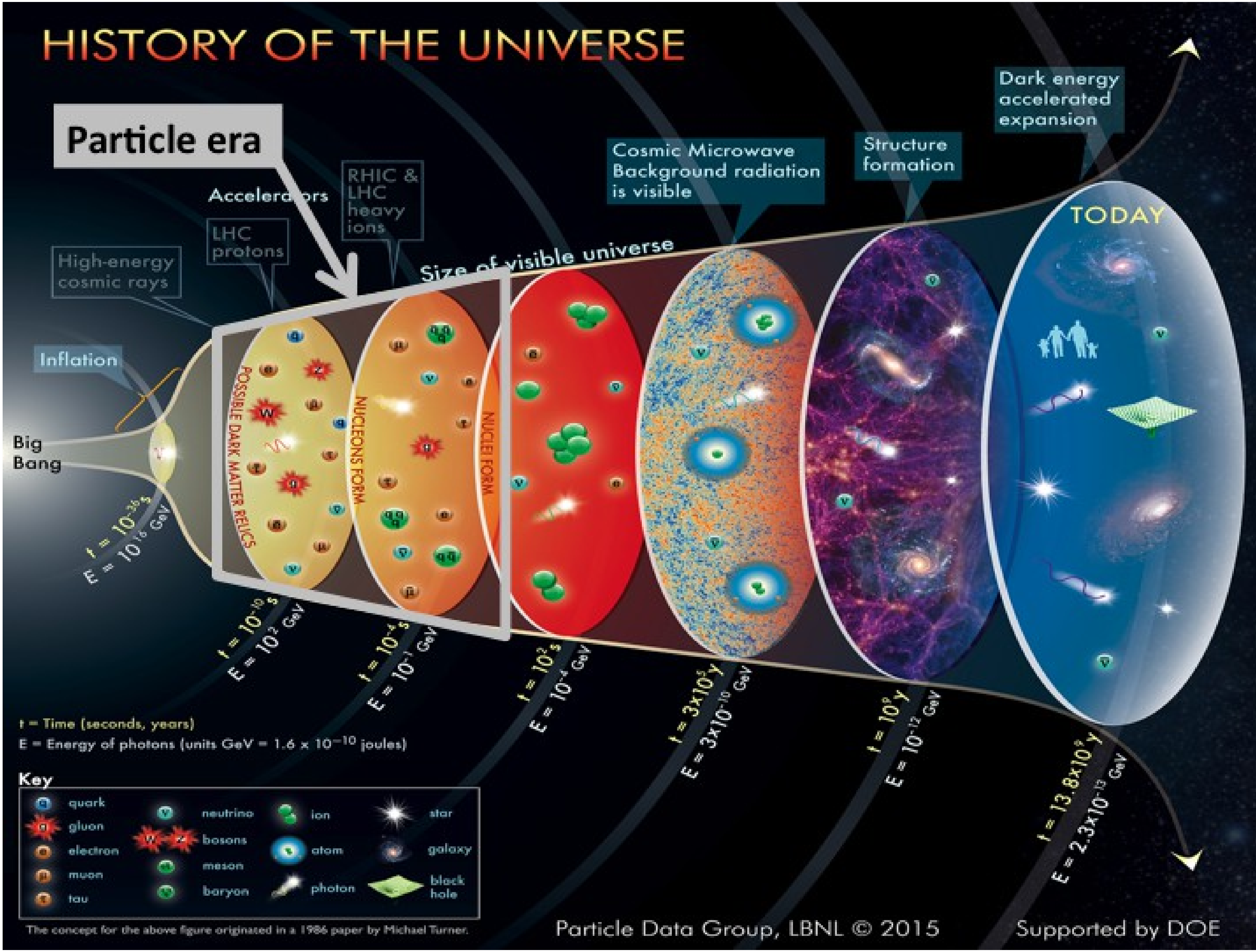
GSI

HUAZHONG UNIVERSITY

phenomenology results obtained in collaboration with
Anton Andronic, Krzysztof Redlich, and Johanna Stachel
arXiv:1710.09425
and with Anar Rustamov, Johanna Stachel
Nucl.Phys. A967 (2017) 453-456
Nucl.Phys. A960 (2017) 114-130

my last visit to JINR: January 2004
BMBF-JINR Bilateral Agreement meeting



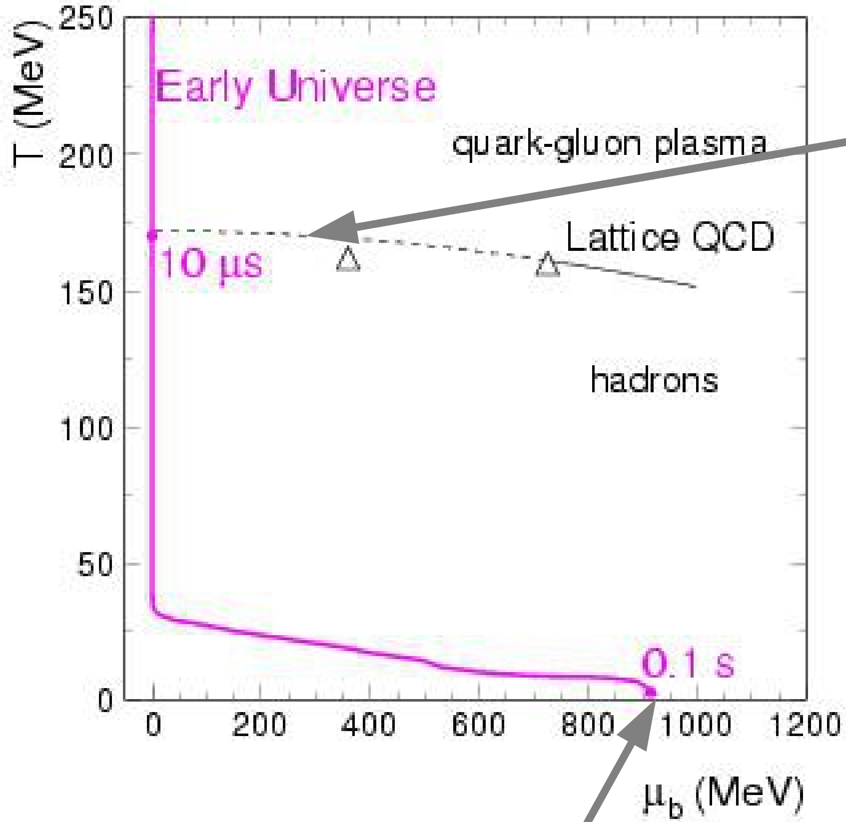


HISTORY OF THE UNIVERSE
Particle era
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10−10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

time line and matter in the early universe

- inflation up to 10^{-32} s
- 10^{-32} to 10^{-12} s: cosmic matter consists of **massless** particles and fields quarks, leptons, neutrinos, photons, Z, $W^{\pm}$, H ??? lots of speculations
- 10^{-12} s: electroweak phase transition, T $\approx$ 100 GeV
- $10^{-12} - 10^{-5}$ s quark-gluon plasma phase
  particles acquire mass through Higgs mechanism, QGP consists of:
  $\overline{q}qg\overline{l}l\gamma ZW^{\pm}H$, all in equilibrium
- 10^{-5} s QCD phase transition, T = 155 MeV
- 10^{-5} s to 1 s annihilation phase, T(1 s) $\approx$ 1 MeV
  cosmic matter converts into protons, neutrons, leptons, neutrinos, photons
- t > 1 s: leptons annihilate and reheat universe, neutrinos decouple, light element production commences

evolution of the early universe and the QCD phase diagram



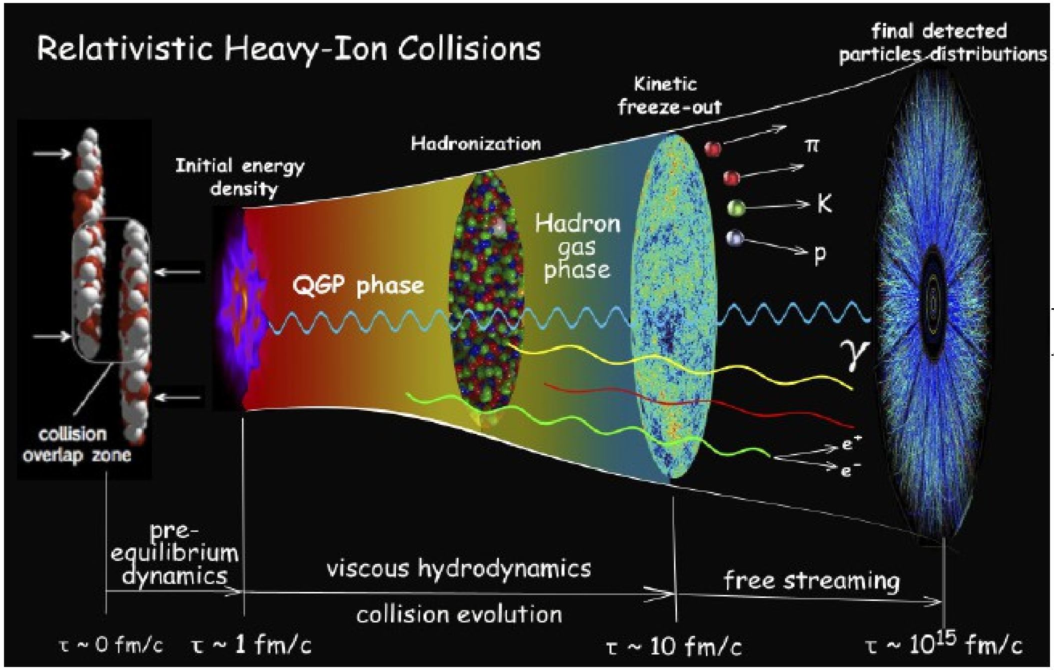
QCD phase boundary

homogeneous Universe in equilibrium, this matter can only be investigated in nuclear collisions

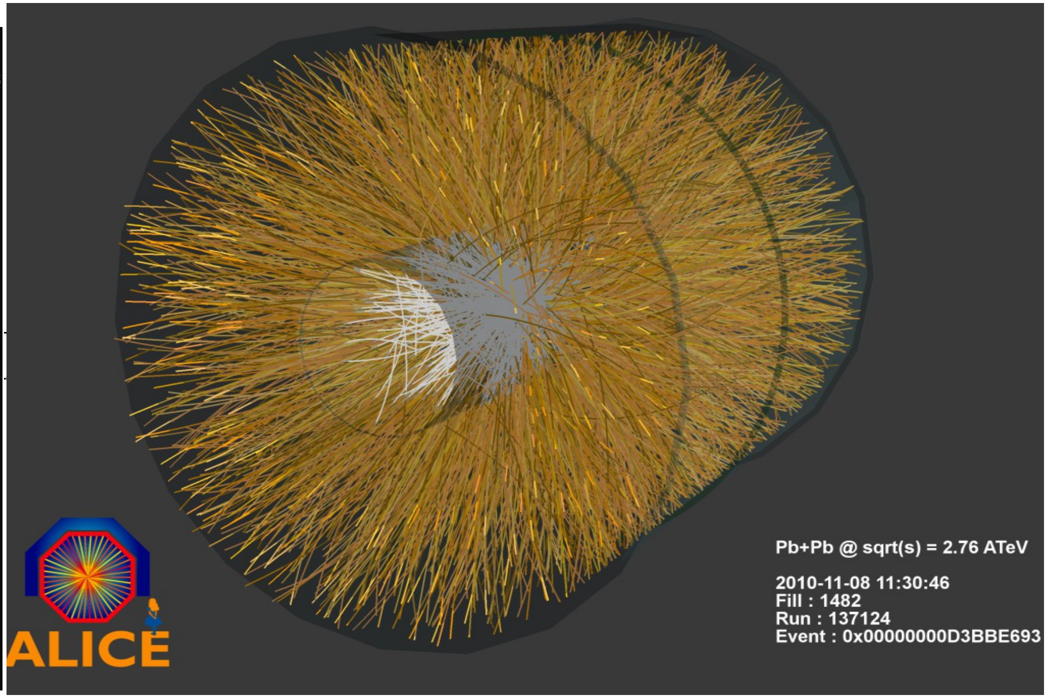
- charge neutrality
- net lepton number = net baryon number
- constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

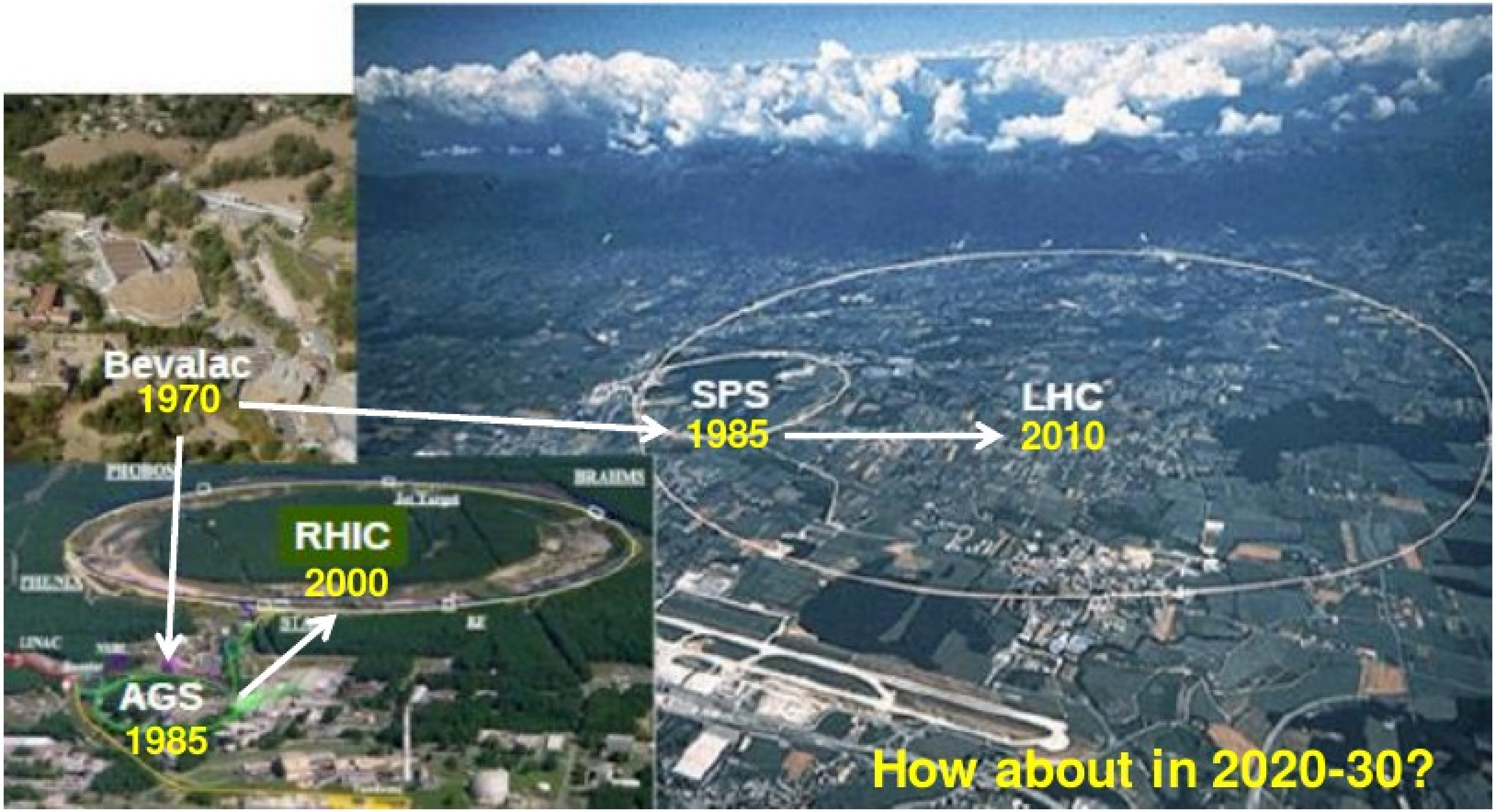
the Quark-Gluon Plasma formed in nuclear collisions at very high energy



Paul Sorensen and Chun Shen

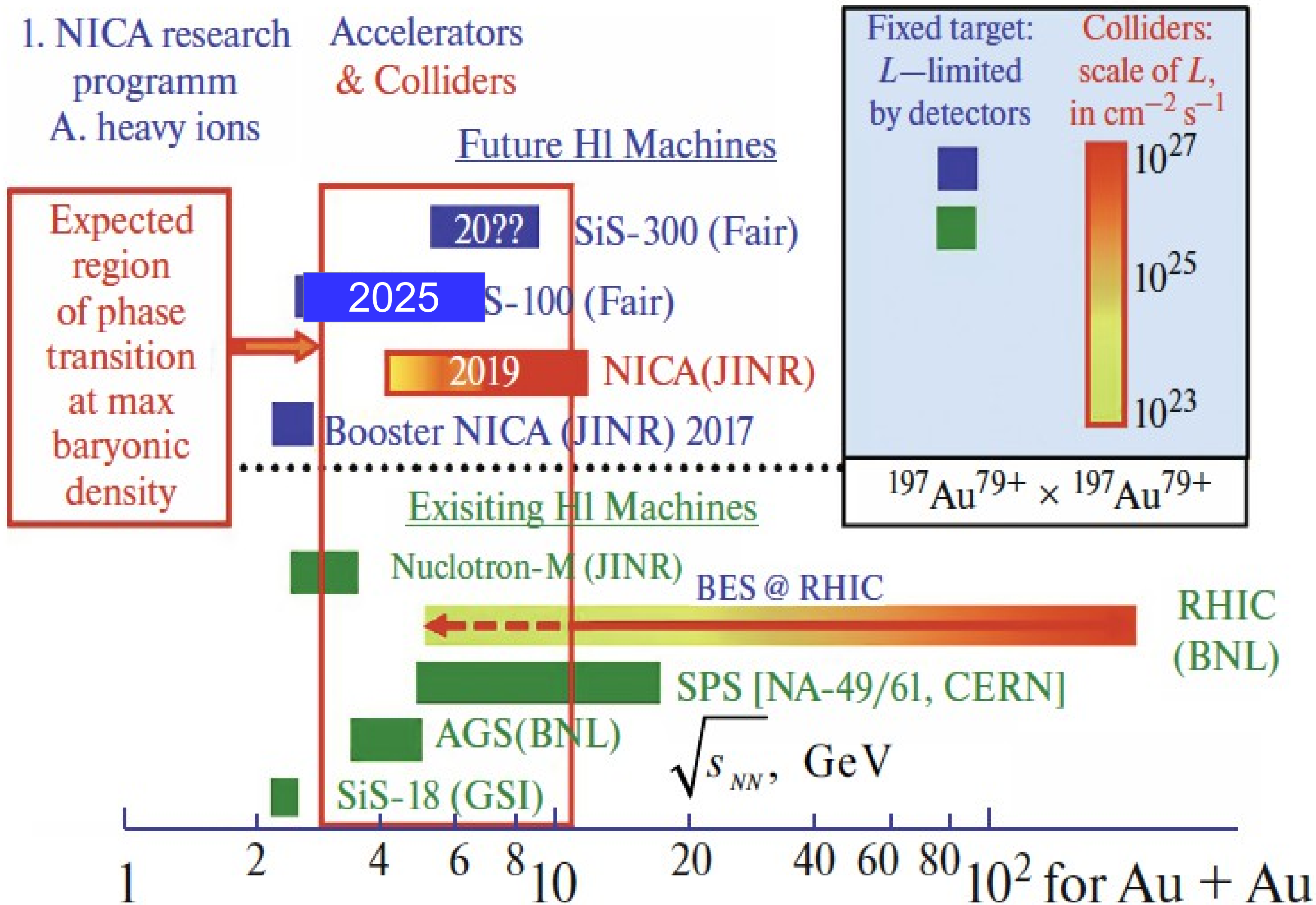


The landscape of accelerators



(Figure provided by M. Gyulassy)

NICA: 2019
FAIR: 2024
JPARC
CERN SPS


1. NICA research programm A. heavy ions
Accelerators & Colliders
Future HI Machines
Fixed target: L—limited by detectors
Colliders: scale of L, in cm^−2 s^−1
10^27
10^25
10^23
Expected region of phase transition at max baryonic density
20??
SiS-300 (Fair)
2025
S-100 (Fair)
2019
NICA(JINR)
Booster NICA (JINR) 2017
197Au79+ × 197Au79+
Exisiting HI Machines
Nuclotron-M (JINR)
BES @ RHIC
RHIC (BNL)
SPS [NA-49/61, CERN]
AGS(BNL)
SiS-18 (GSI)
√s_NN, GeV
1
2
4
6
8
10
20
40
60
80
10^2 for Au + Au

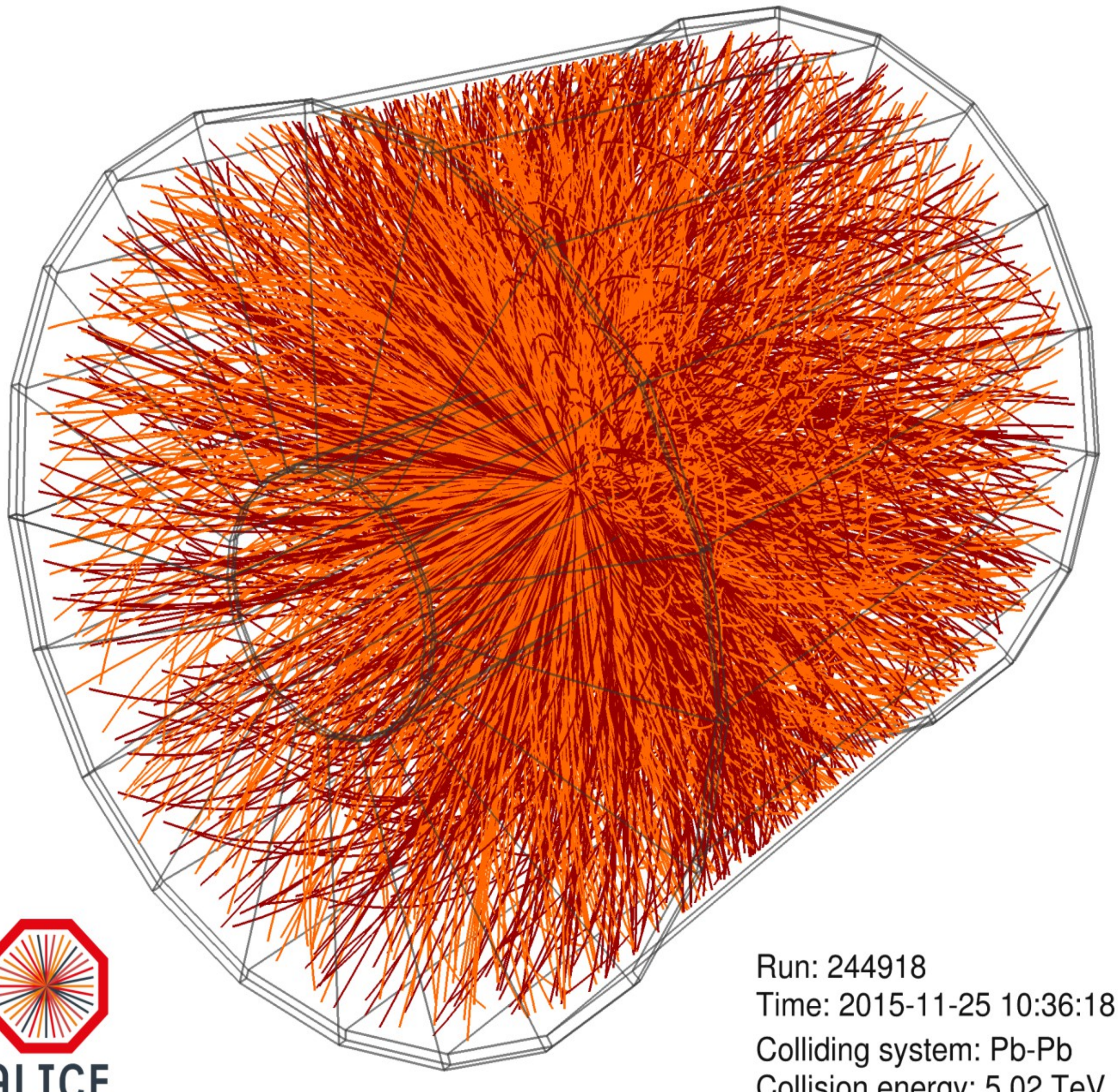
first PbPb collisions at LHC at √s = 5.02 A TeV

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

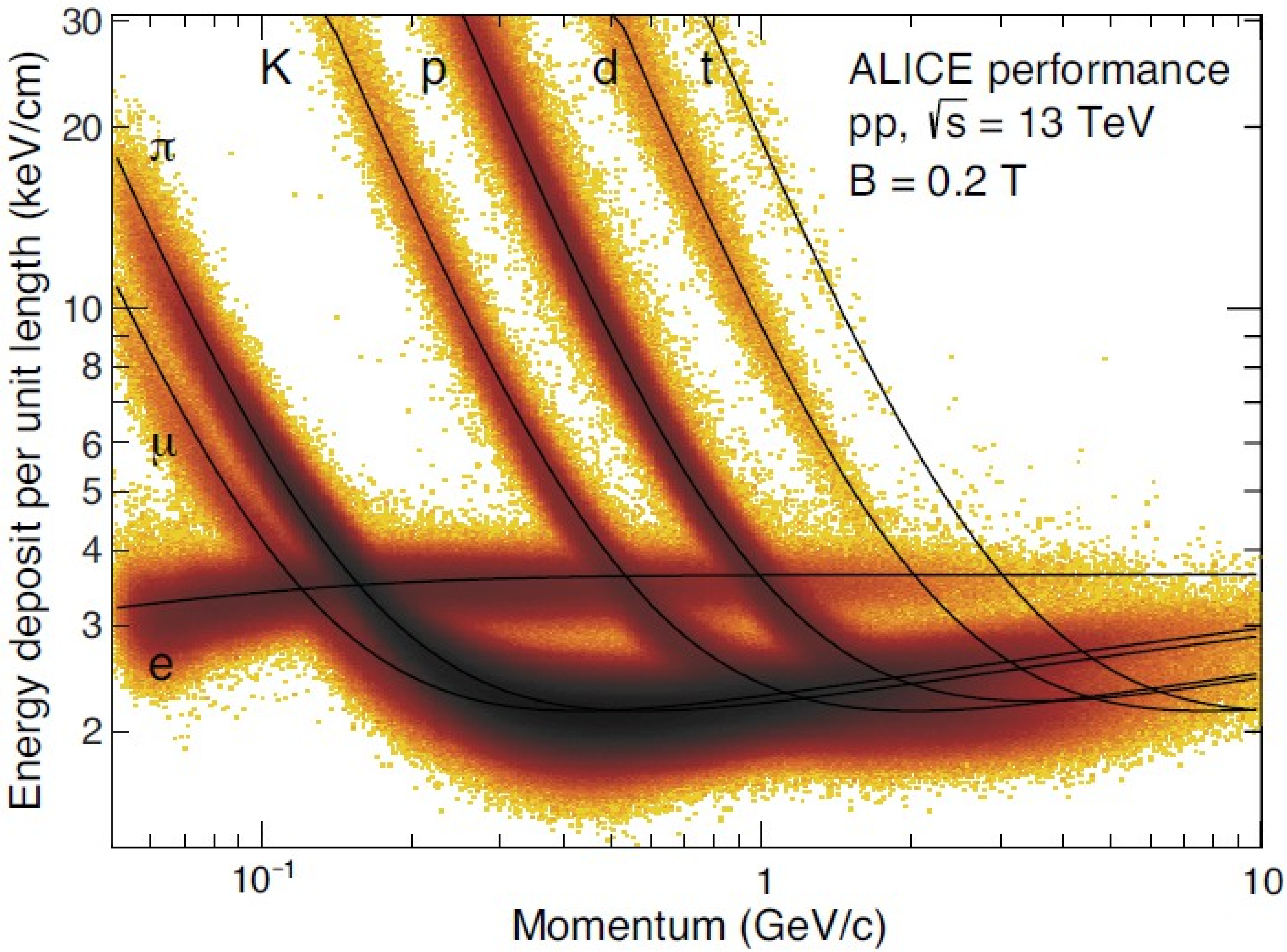
Nov. 2016: pPb 5 TeV



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

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

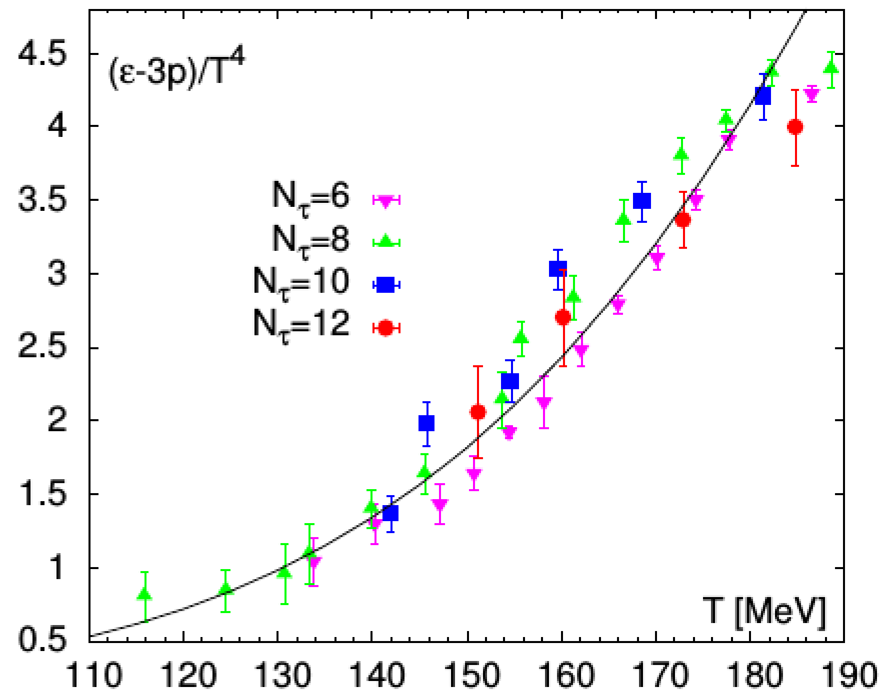
for the pressure we get:

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

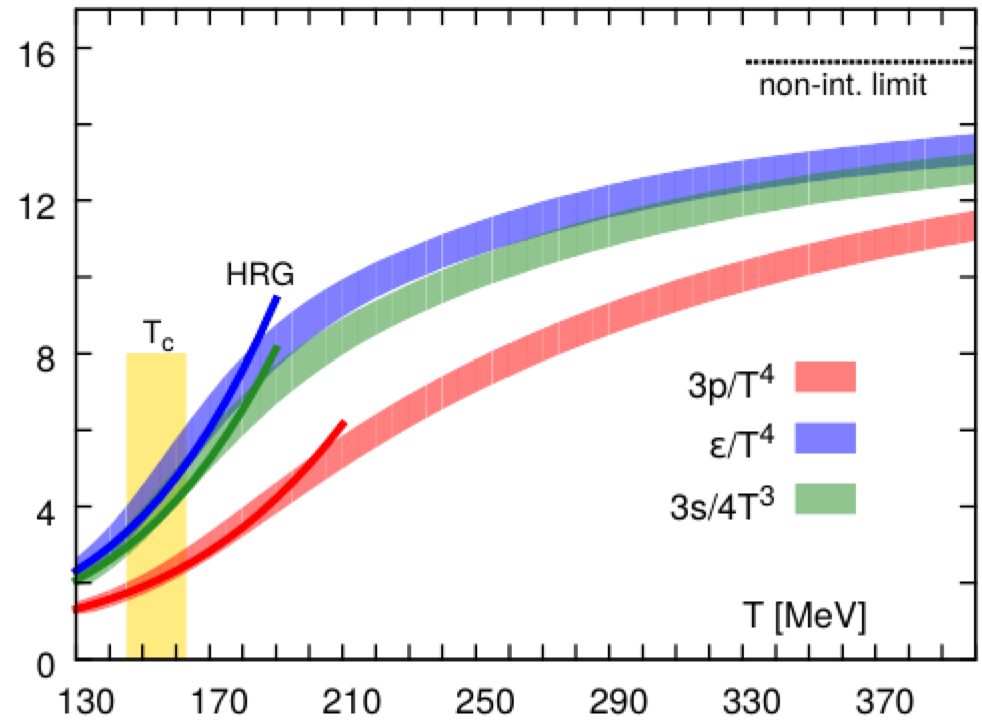
comparison of trace anomaly from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

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

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

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

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

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

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

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.)

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

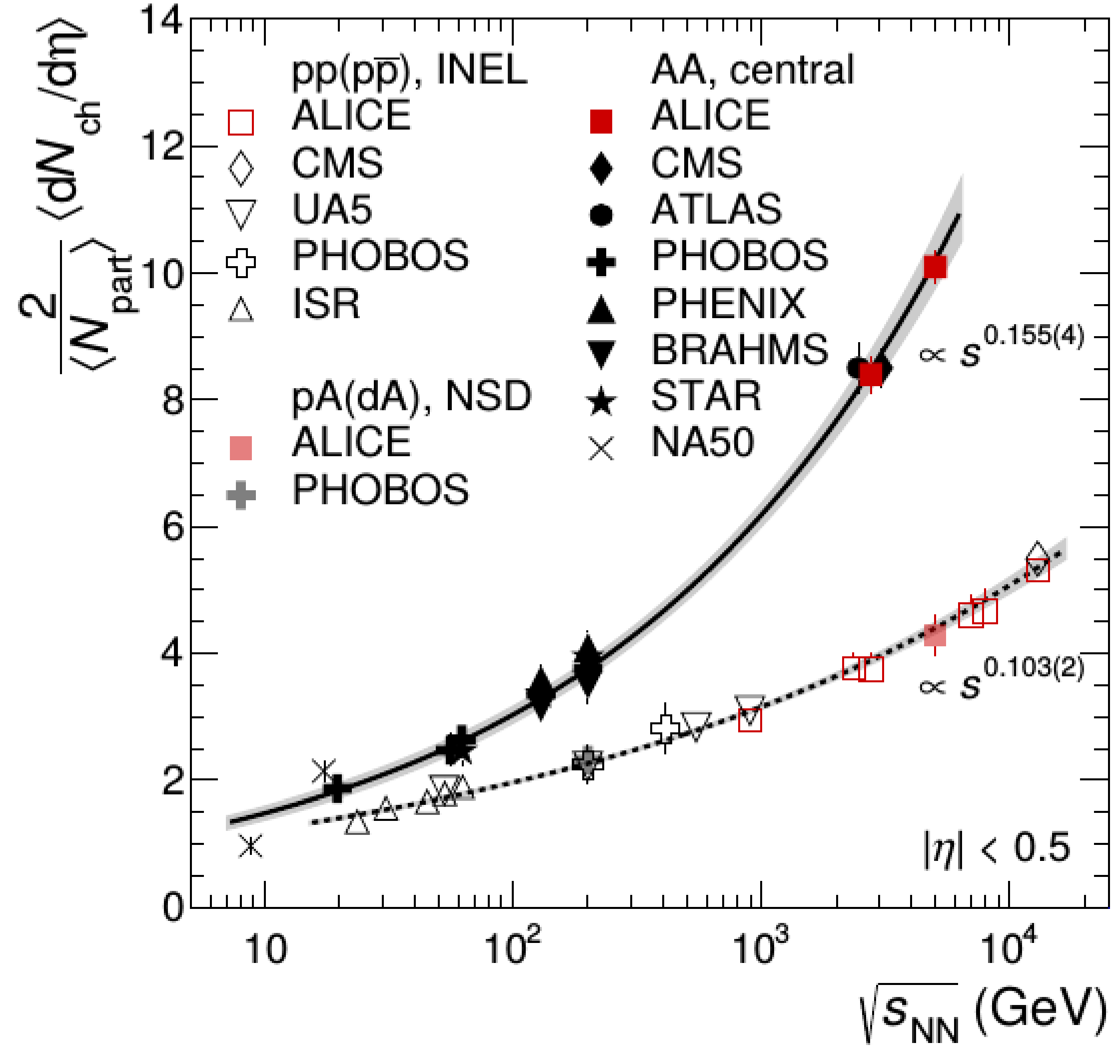
canonical treatment whenever needed (small abundances)

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



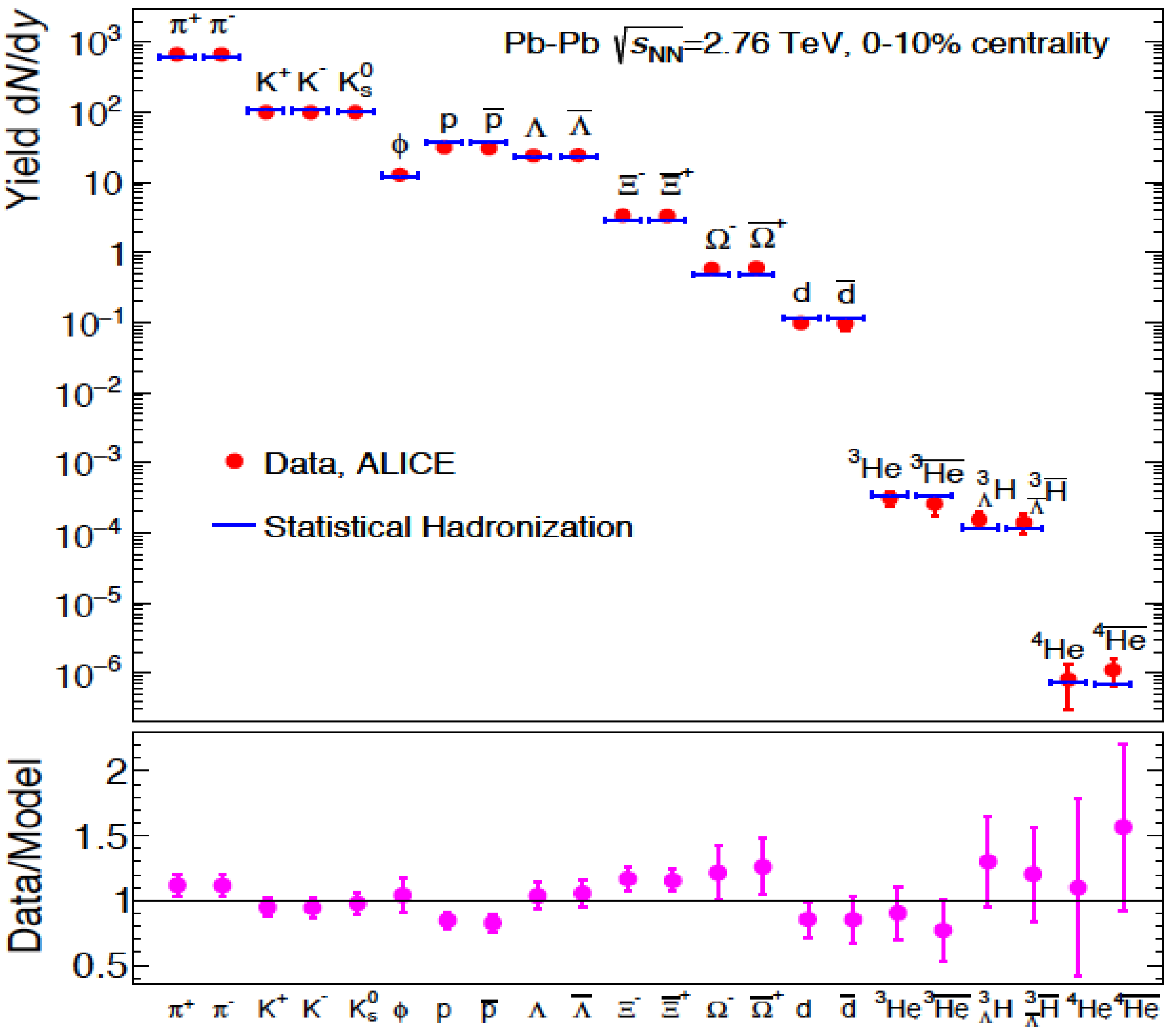
data from LHC run1 and run2

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

Oct. 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 nucl**
produced at T=156 MeV. close to an Efin
state

proton discrepancy about 2.8 sigma

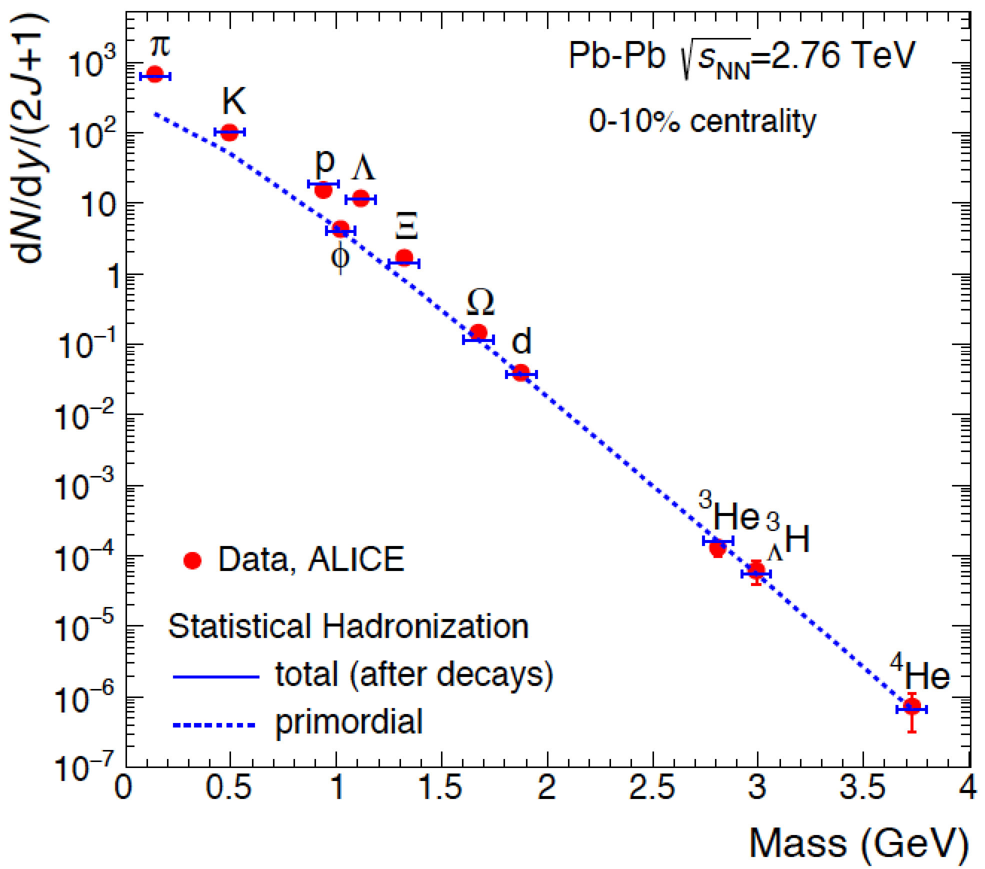


Andronic, pbm, Redlich, Stachel, arXiv:1710.09425

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



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

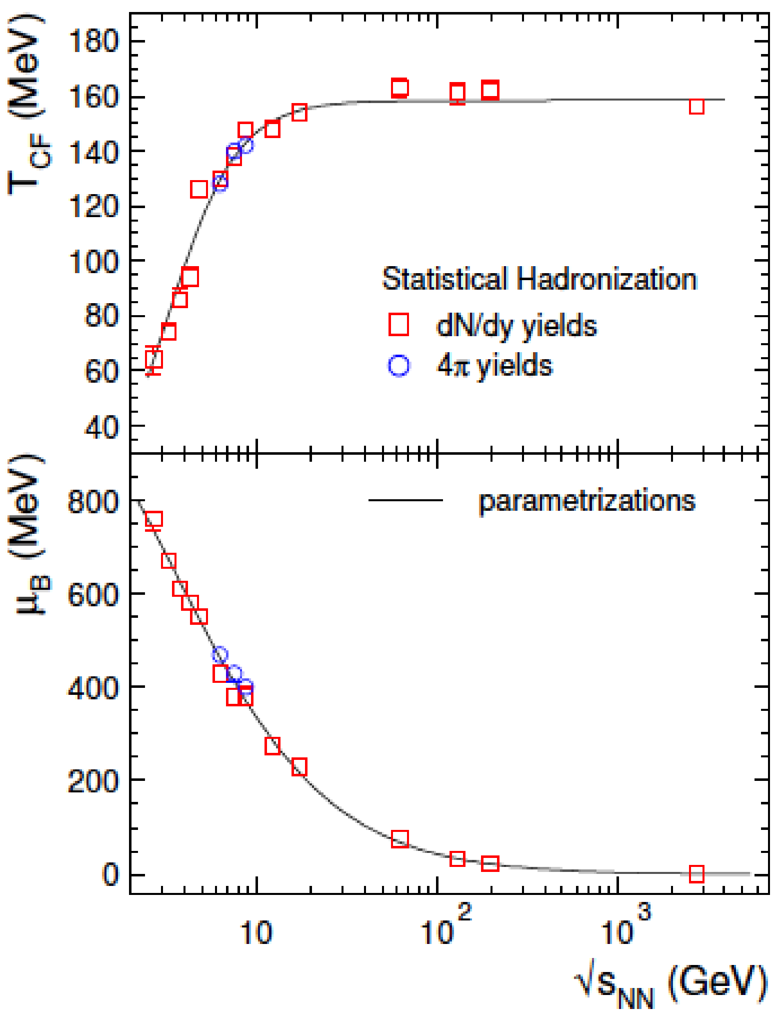
T_{chem} = 156.5 ± 1.5 MeV from fit to all particles

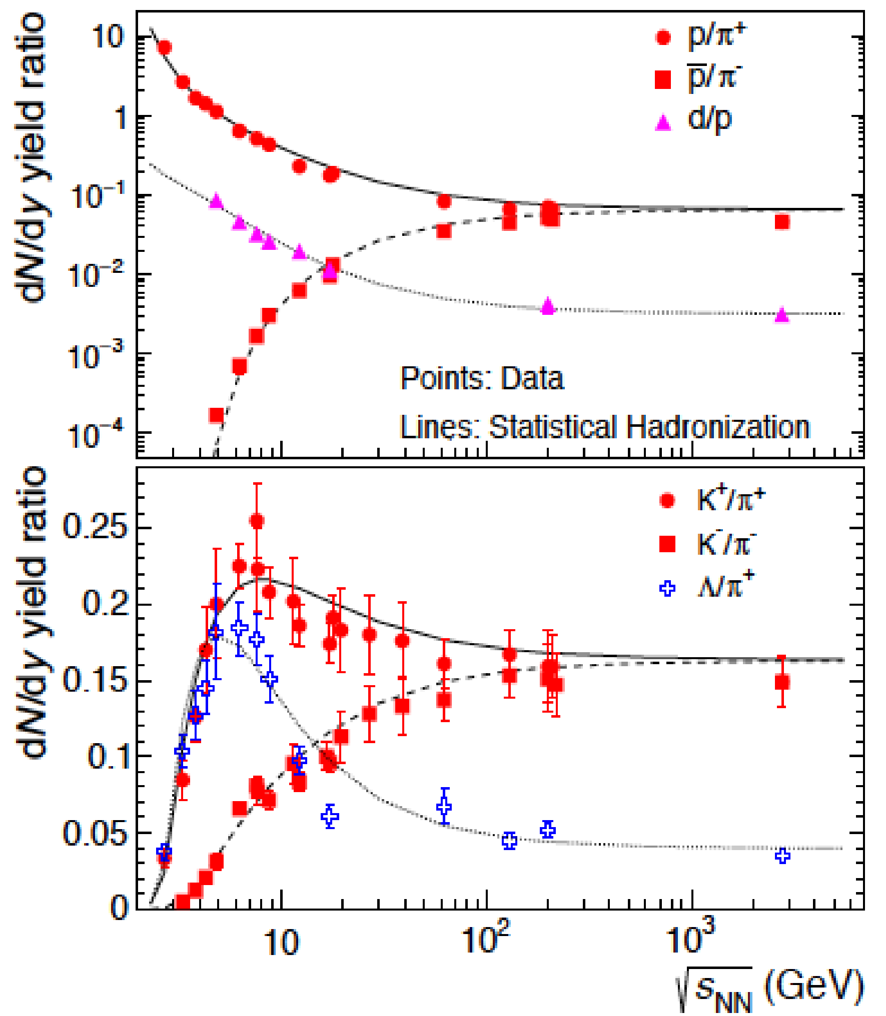
there is an additional uncertainty because of the poorly known hadronic mass spectrum for masses > 2 GeV

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

energy dependence of hadron production described quantitatively

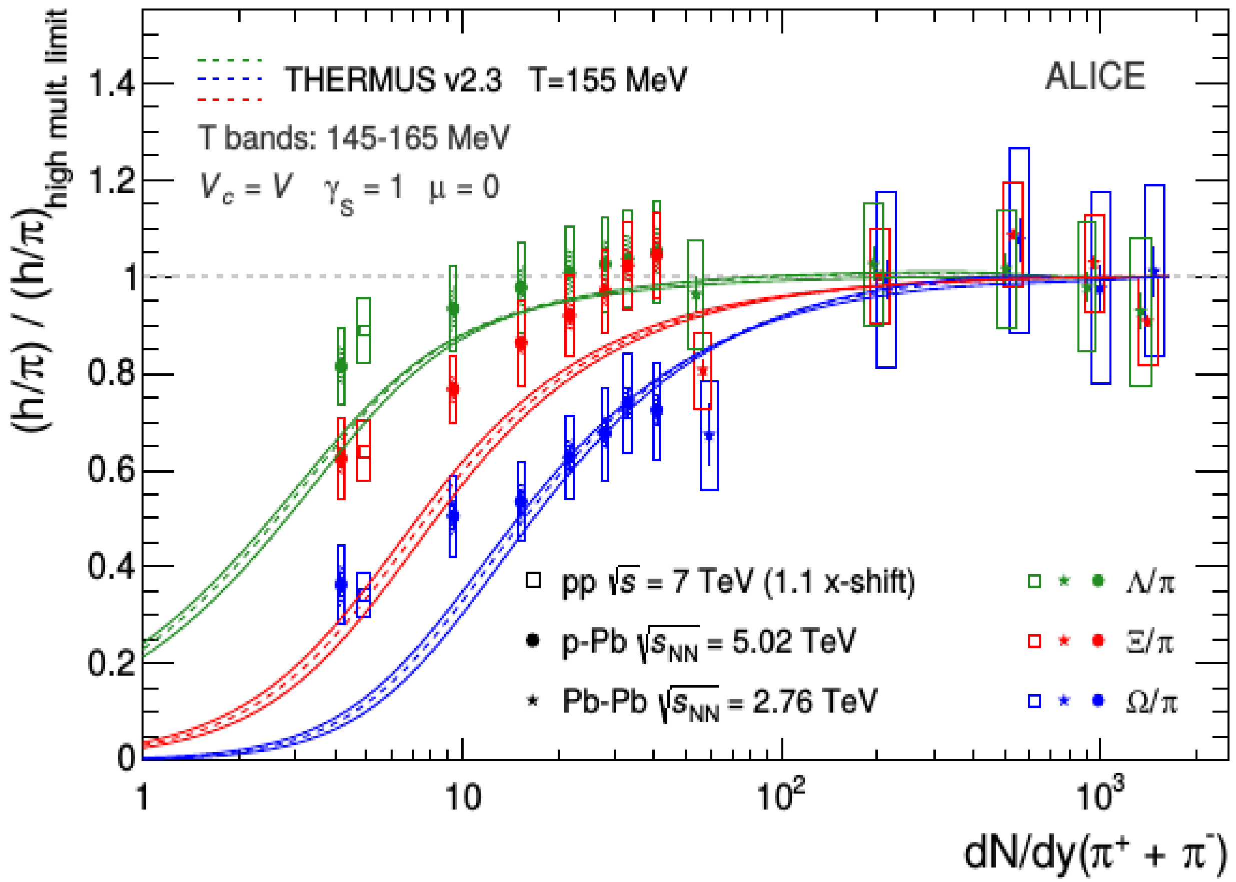




together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

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

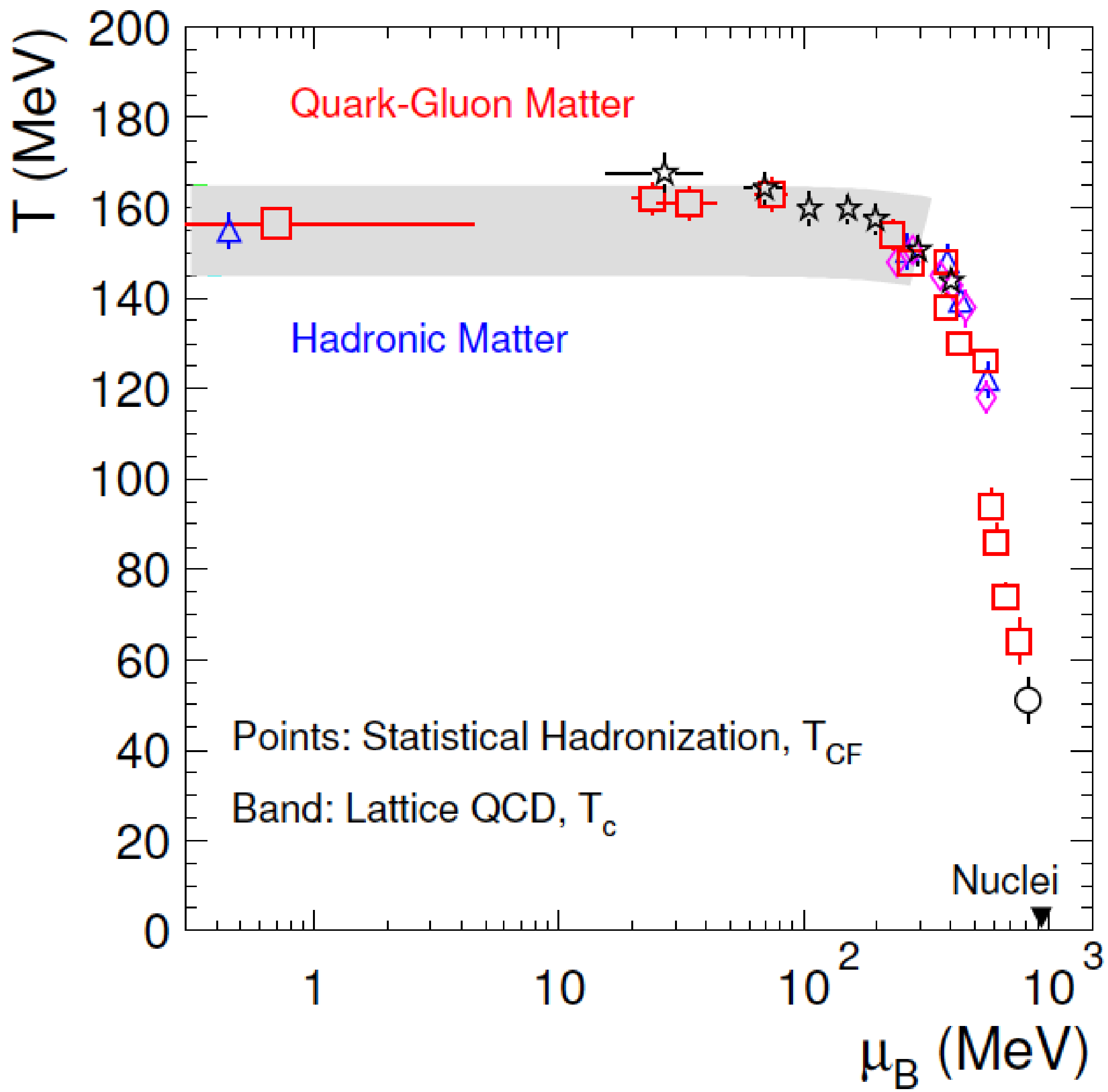
is multiplicity dependence described by canonical thermodynamics?



main features, but not details, are captured well – needs further study

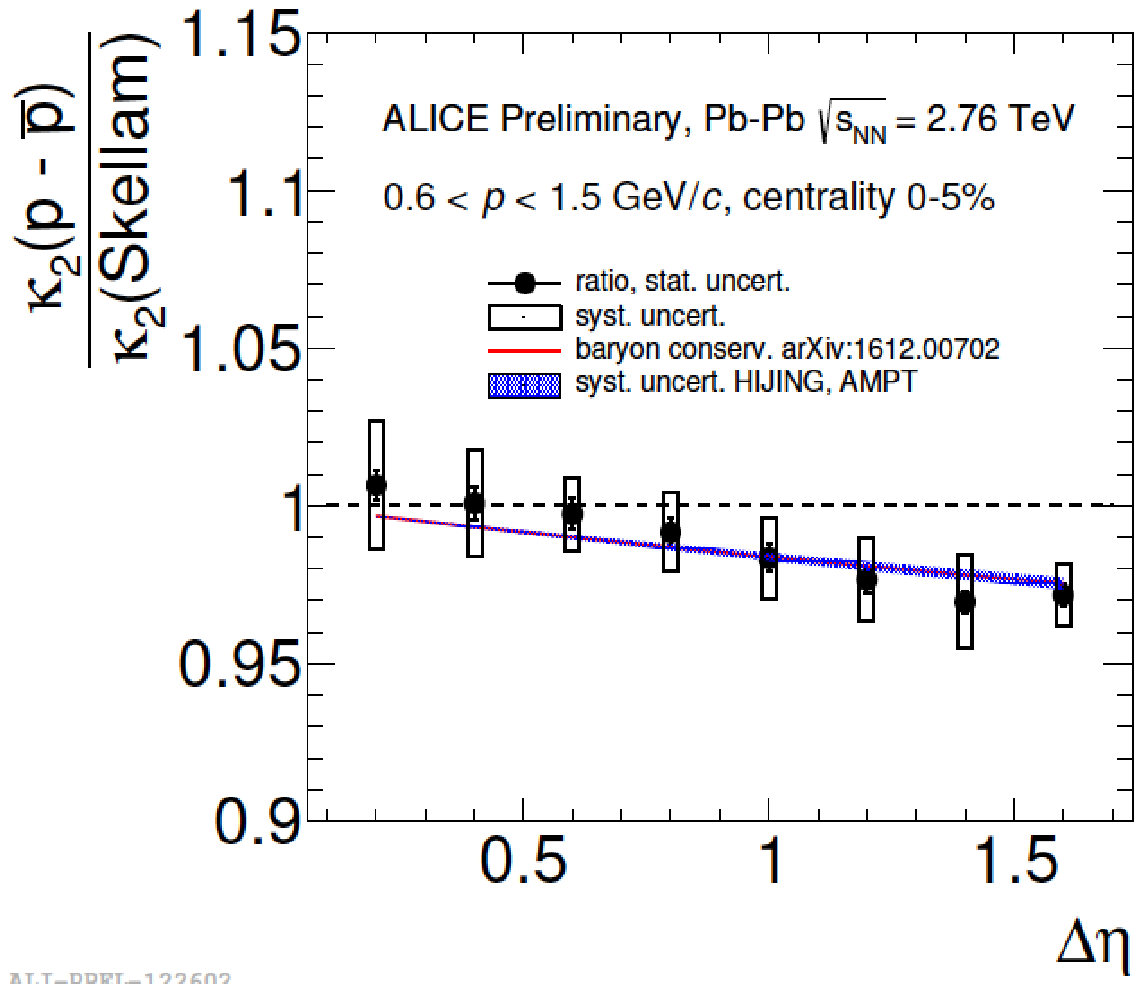
arXiv:1512.07227 ALICE

the QGP phase diagram, LQCD, and hadron production data



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

ALICE net proton data: second moments



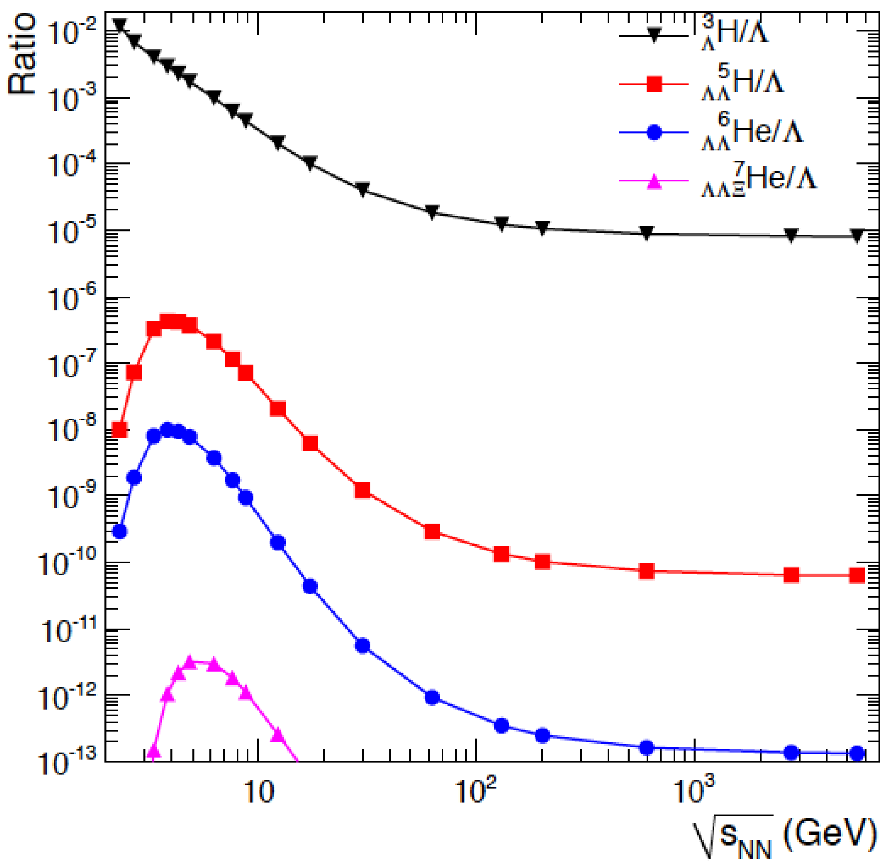
deviation from the Skellam distribution is small and quantitatively described by baryon number conservation

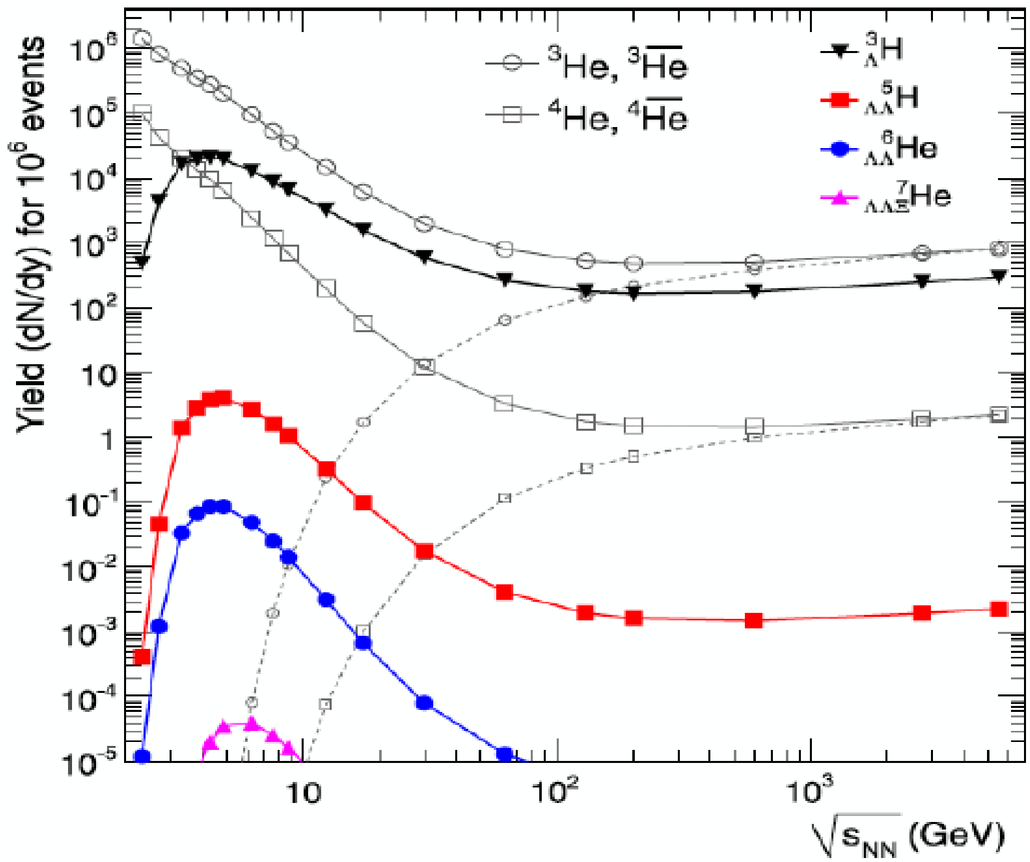
Anar Rustamov, ALICE coll., Nucl.Phys. A967 (2017) 453-456
pbm, Rustamov, Stachel, Nucl.Phys. A960 (2017) 114-130

this work has prepared the ground for quantitative analysis of higher moments and comparison the LQCD

now special section on loosely bound objects

exciting opportunities for the upcoming accelerator facilities
NICA, FAIR/CBM, J-Parc





Andronic, pbm, Stachel, Stoecker
Phys.Lett. B697 (2011) 203-207

The Hypertriton

mass = 2990 MeV, binding energy = 2.3 MeV

Lambda sep. energy = 0.13 MeV

molecular structure: (p+n) + Lambda

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

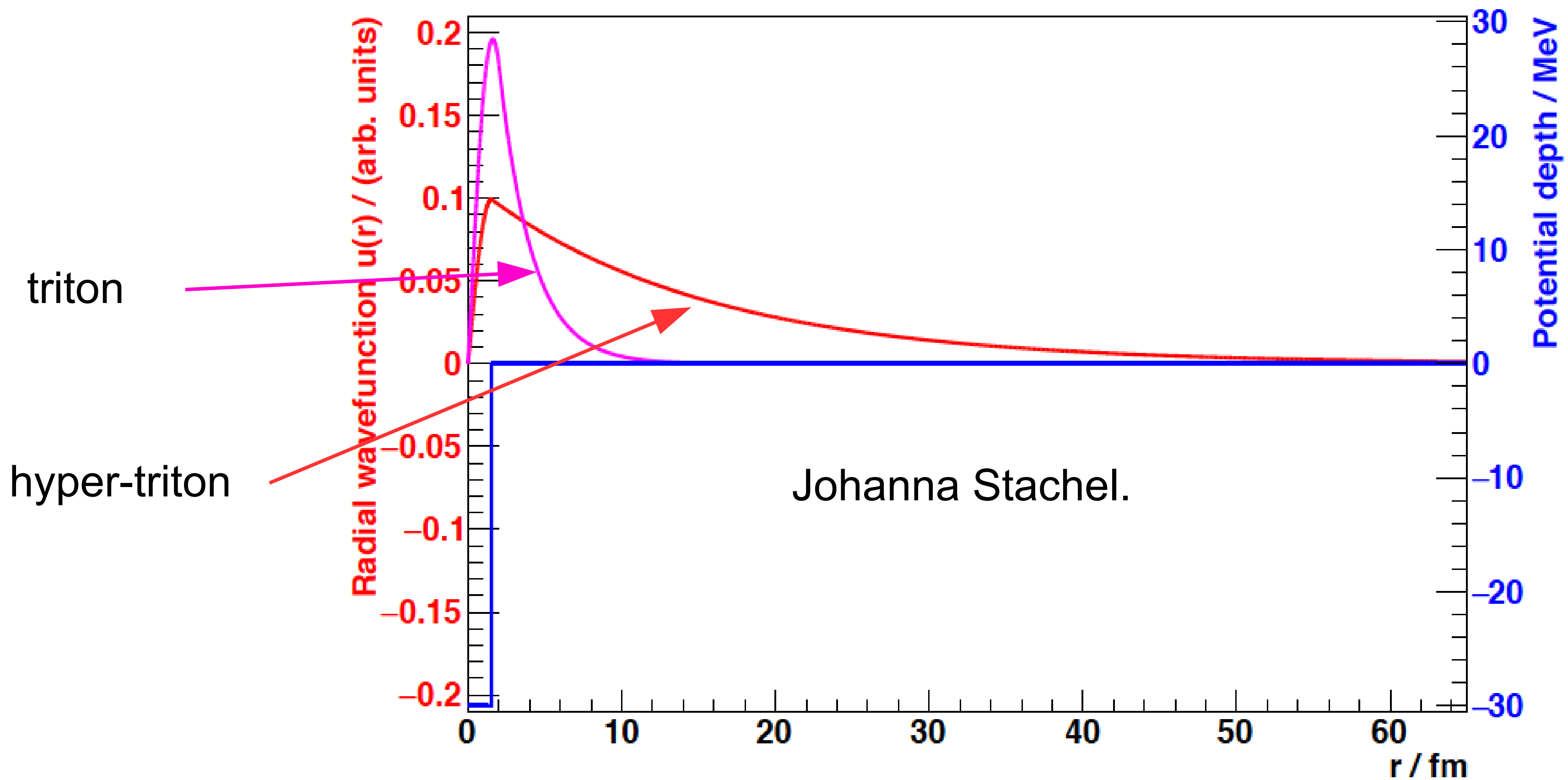
rms radius = $(4\ \text{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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.)

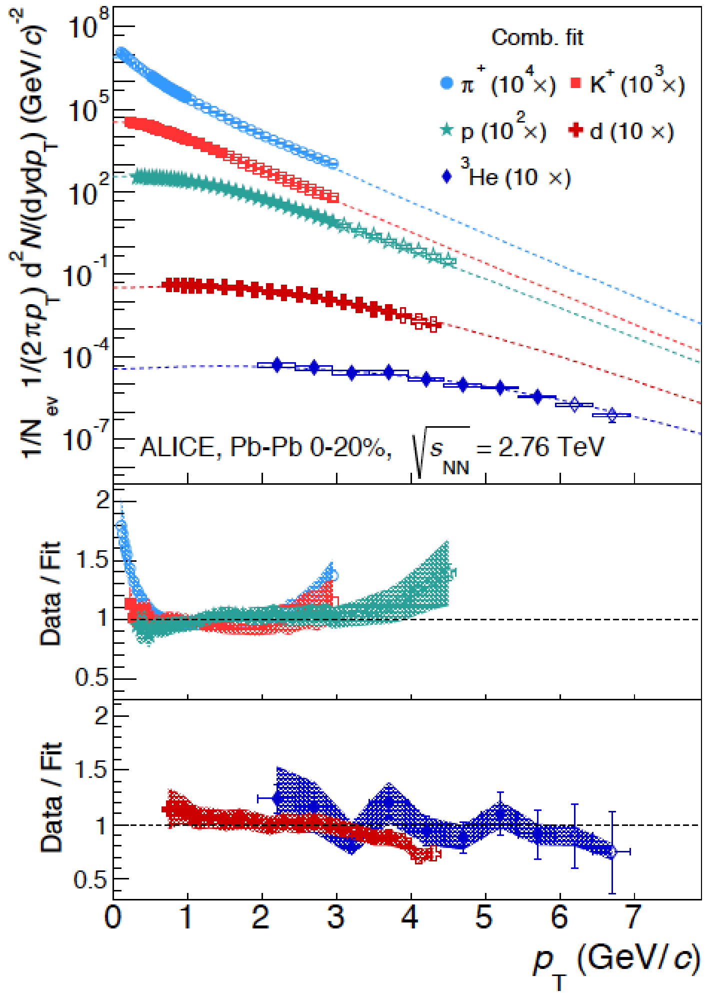
wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017

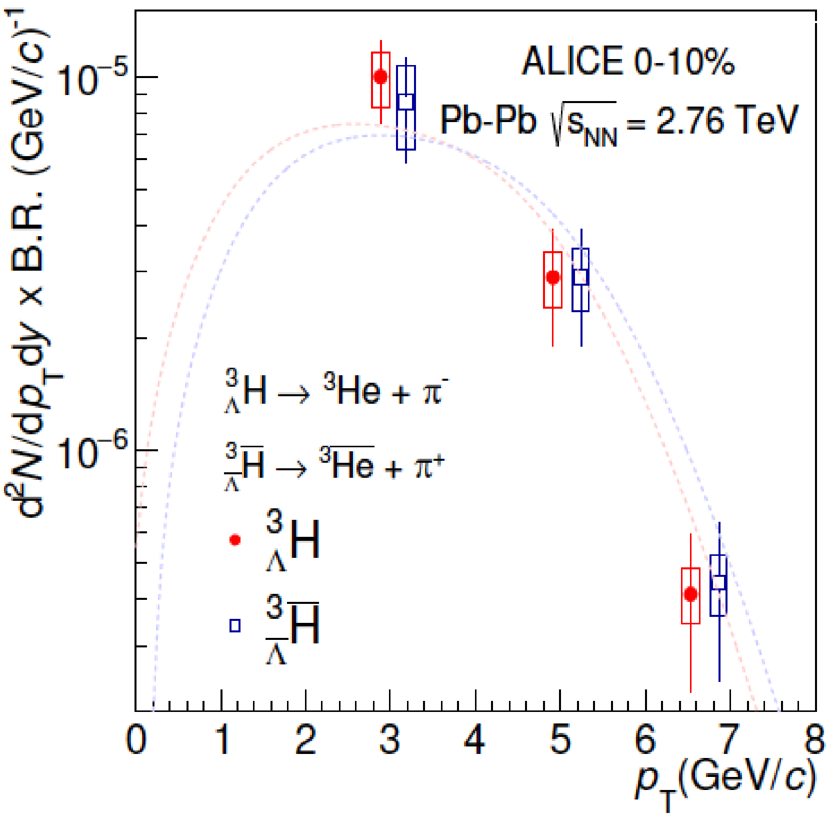


Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve 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

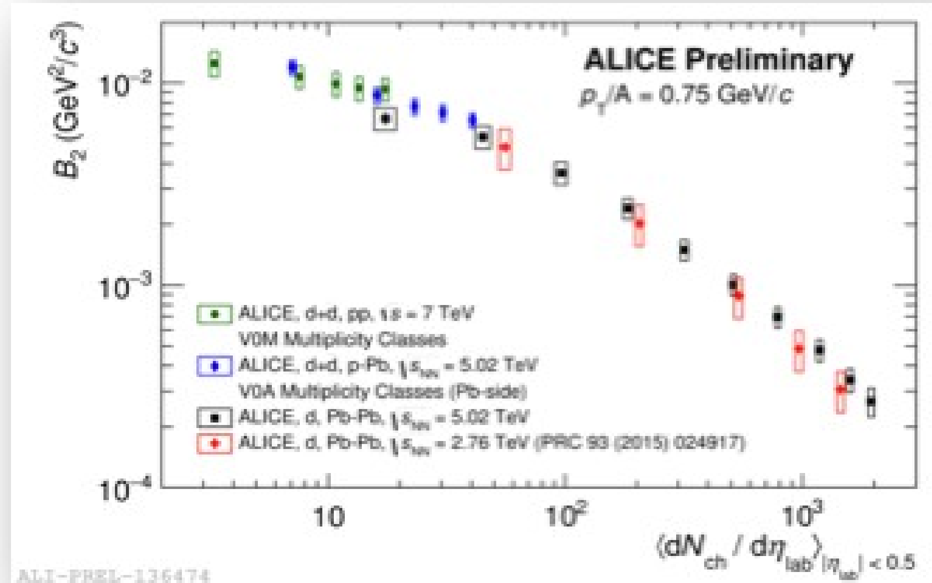


even hyper-triton flows with same common fluid velocity



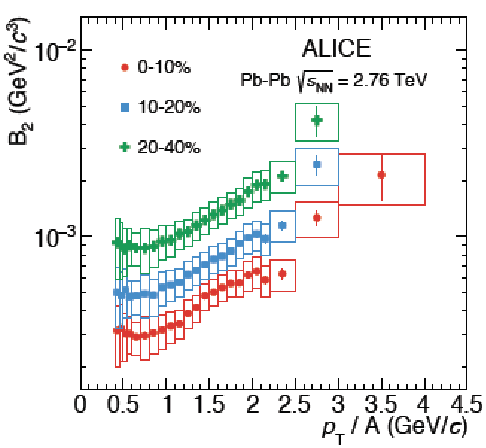
is coalescence approach an alternative?

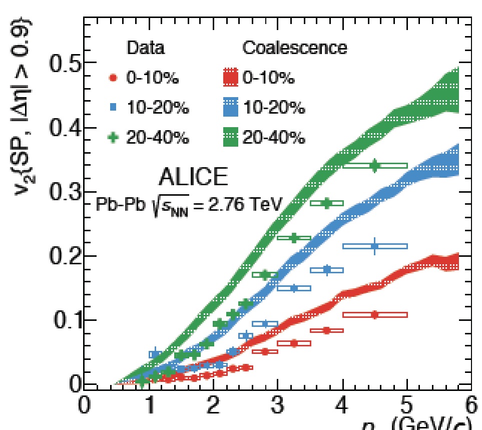
$$E_i \frac{d^3N_i}{dp_i^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^A \qquad B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\frac{M}{m^A}$$

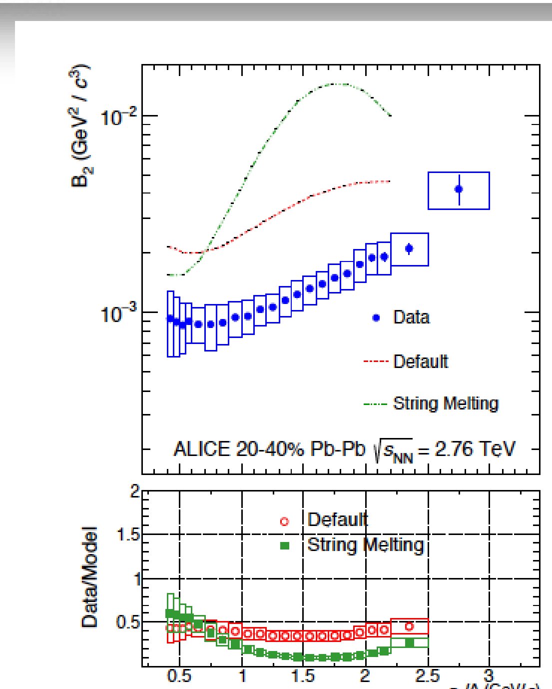


centrality and p_T dependence of coalescence parameter not understood and not well reproduced by models such as AMPT

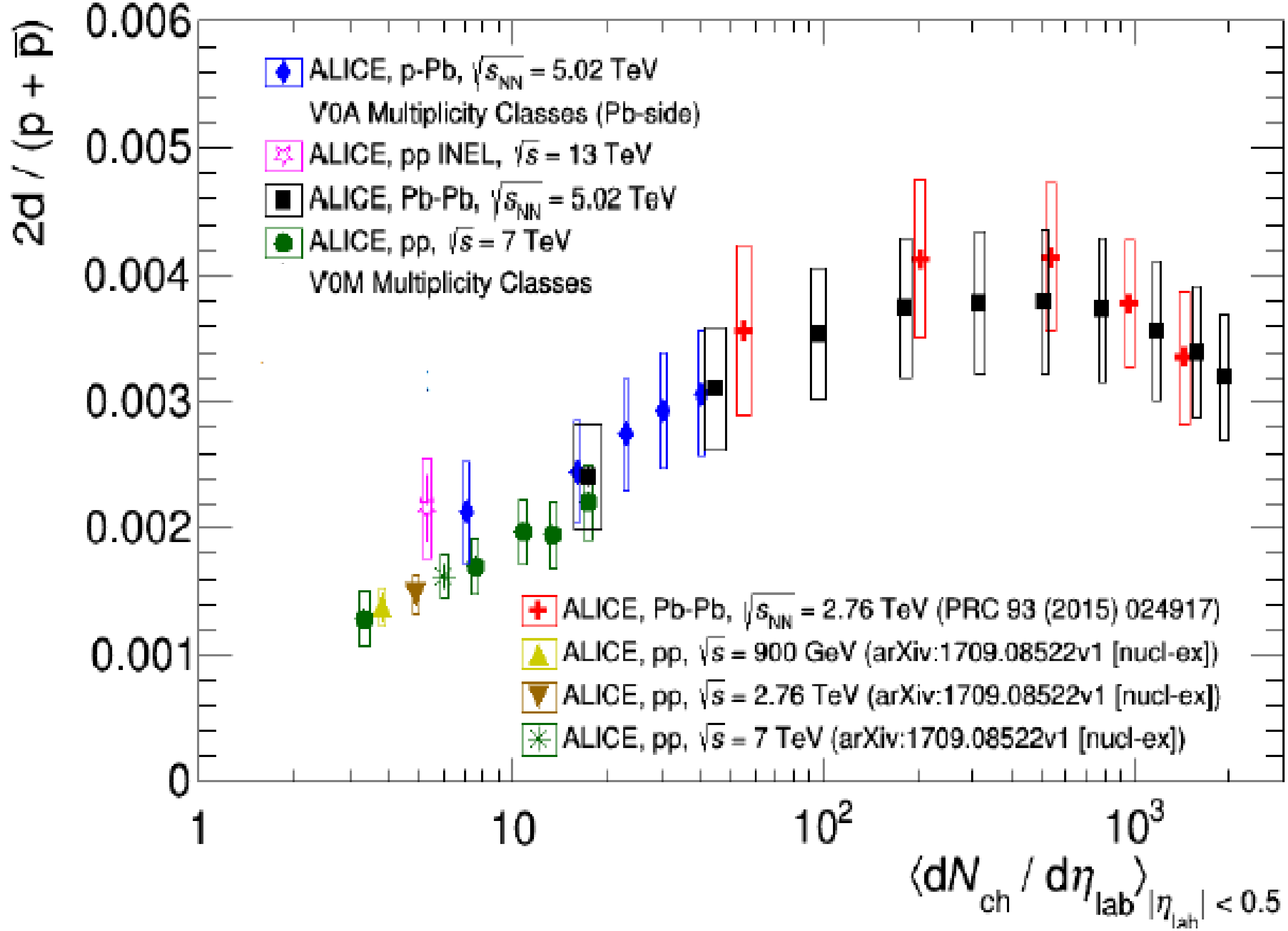
ALICE: arXiv:1707.07304







deuteron/proton ratio vs charged-particle multiplicity



d/p ratio not consistent with 'coalescence' expectations where ratio is expected to increase with volume of the firebal
see, e.g., S. Mrowczynski, arXiv:1607.02267

coalescence approach, general considerations for loosely bound states

- production yields of loosely bound states is entirely determined by mass, quantum numbers and fireball temperature.

- hyper-triton and 3He have very different wave functions but essentially equal production yields.

- energy conservation needs to be taken into account when forming objects with baryon number A from A baryons.

- delicate balance between formation and destruction; maximum momentum transfer onto hyper-triton before it breaks up: ΔQ_{max} < 20 MeV/c, typical pion momentum p_pi = 250 MeV/c, typical hadronic momentum tranfer > 100 MeV/c.

- hyper-triton interaction cross section with pions or nucleons at thermal freeze-out is of order σ > 70 fm^2. For the majority of hyper-tritons to survive, the mfp λ has to exceed 15 fm → density of fireball at formation of hyper-triton $n < 1/(\lambda\, \sigma) = 0.001/fm^3$. Completely inconsistent with formation at kinetic freeze-out, where $n \approx 0.05/fm^3$.

- description of centrality dependence of spectra and d/p ratio not consistent with coalescence predictions.

a possible way out

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, arXiv :1710.09425

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

summary 1

- 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?

- coalescence approach not well suited for loosely bound states

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156 ± 5 MeV
new insight into hadronization

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

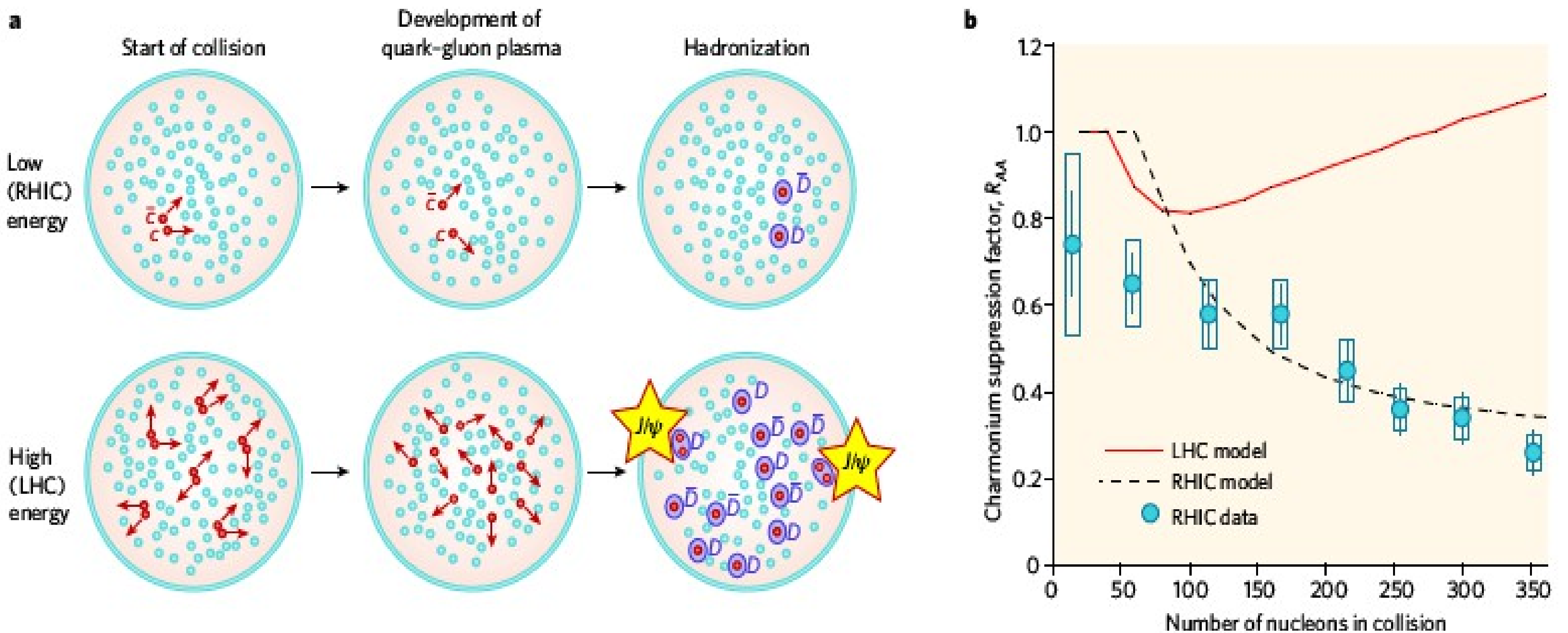
since charmonium formation scales with $N(_{ccbar})^2$ and since the charm cross section increases strongly with energy, we expect enhanced charmonium production at collider energy

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

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

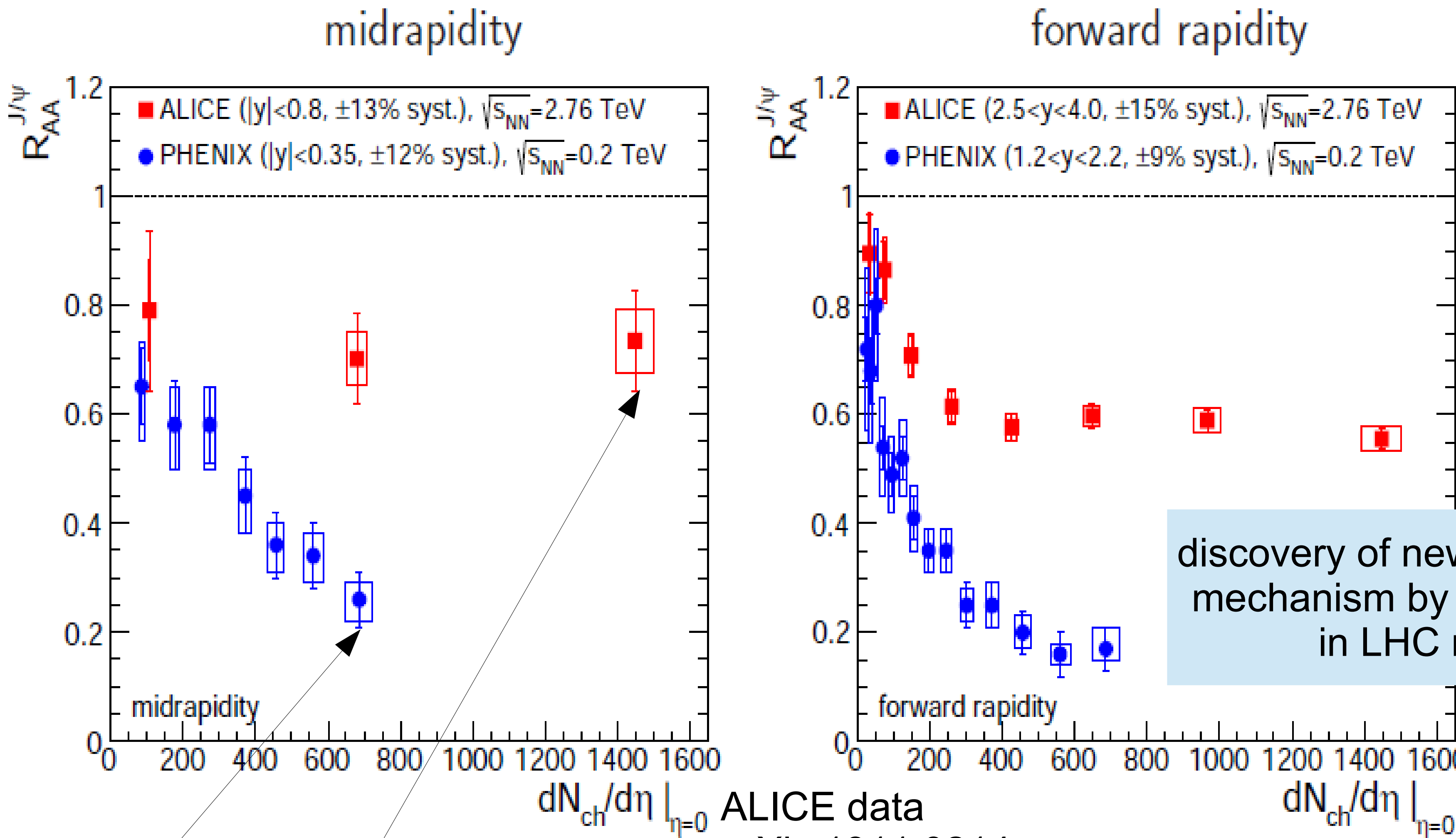
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



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



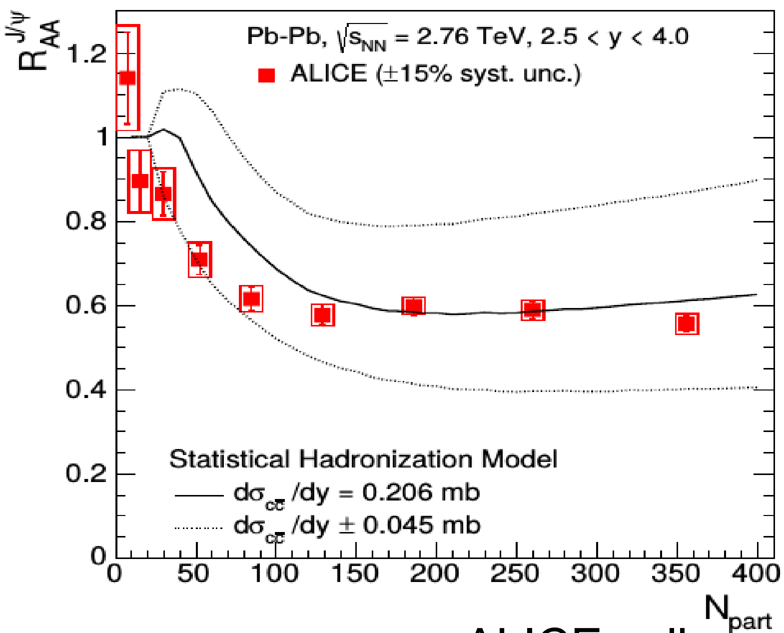
discovery of new production mechanism by ALICE coll. in LHC run1

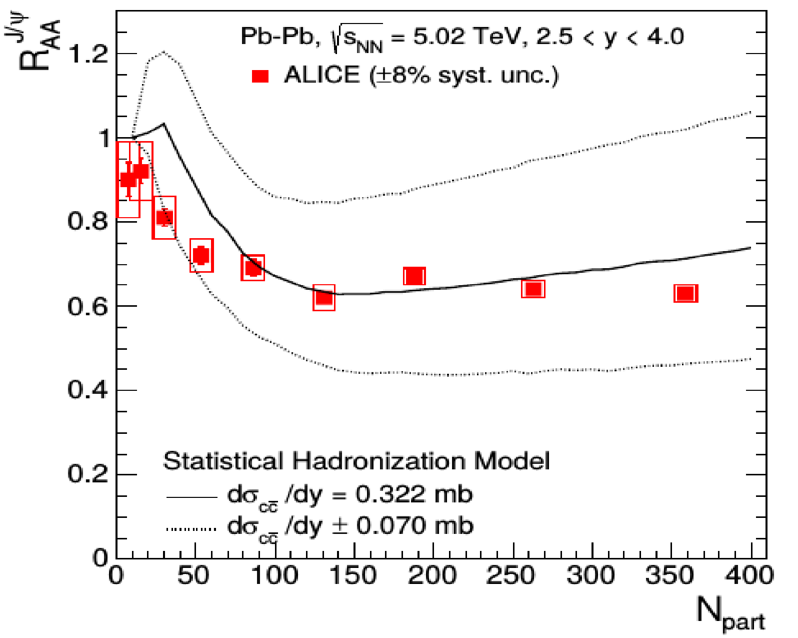
ALICE data
arXiv:1311.0214
Phys.Lett. B734 (2014) 314-327

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

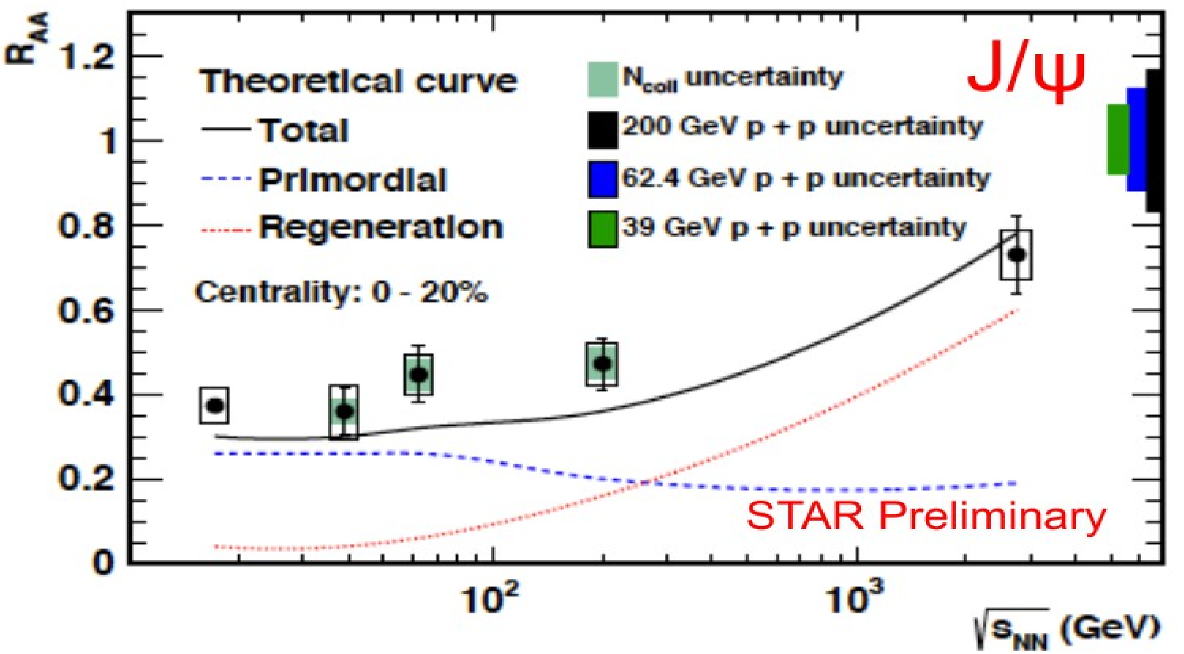
2007 prediction impressively confirmed by LHC data

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

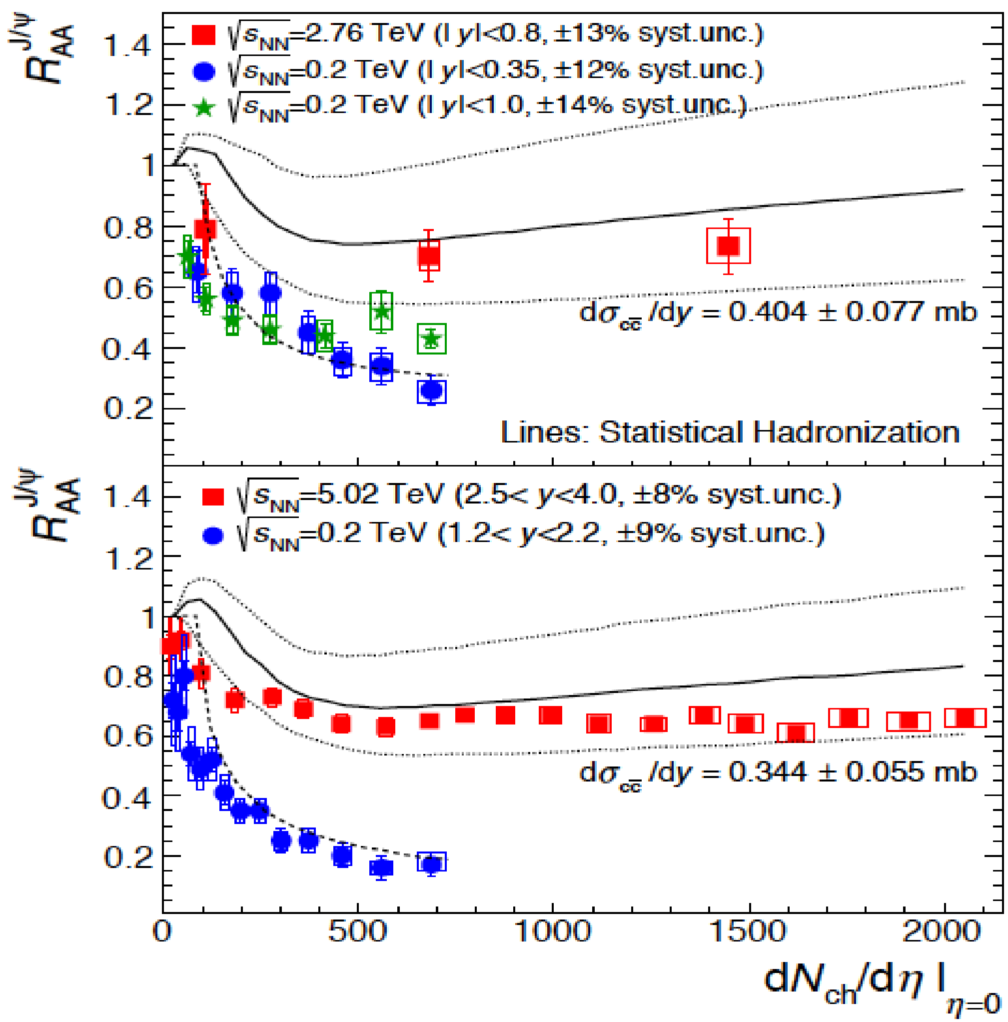




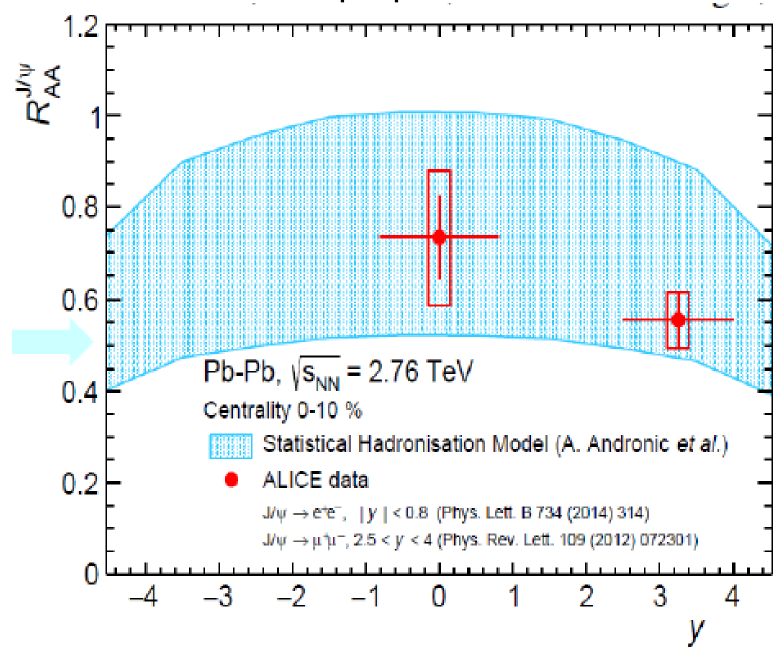
ALICE coll., arXiv:1606.08197



latest statistical hadronization model calculations



M. Koehler, Andronic, pbm, Stachel
in preparation



data exhibit maximum at y=0

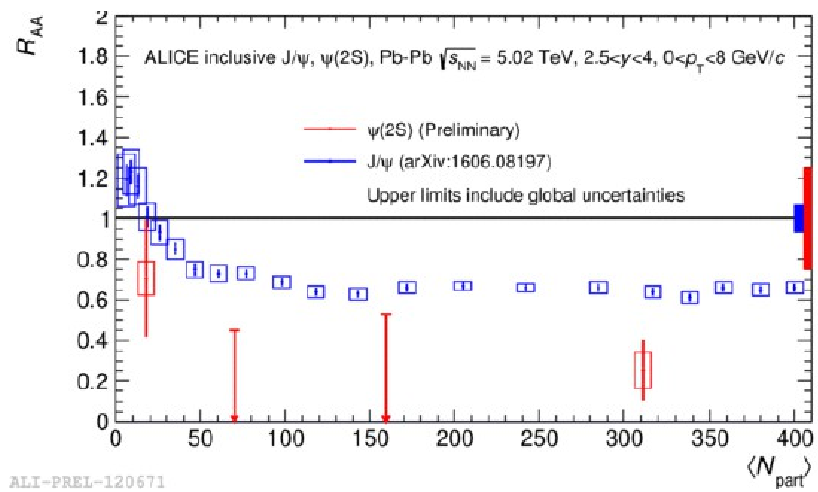
Andronic, pbm, Stachel, Redlich, arXiv:1710.09425

comparison to ALICE, STAR, PHENIX data at 0.2, 2.76 and 5.02 TeV
calculation uses most recent info on open charm cross section

the psi'/psi ratio and colorless bound states in the QGP

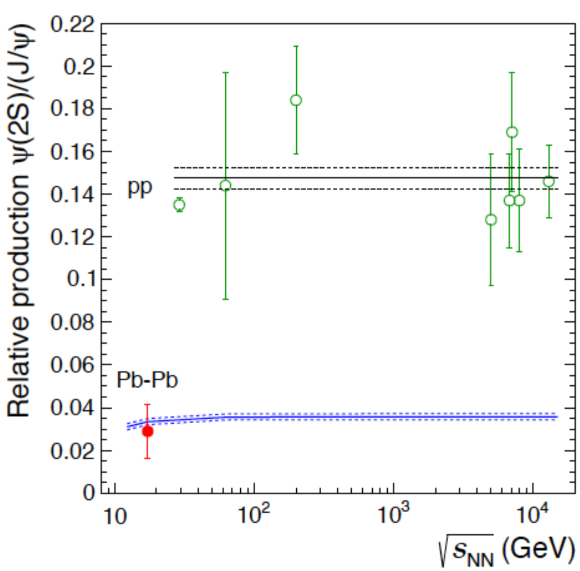
data not yet conclusive – much more to come

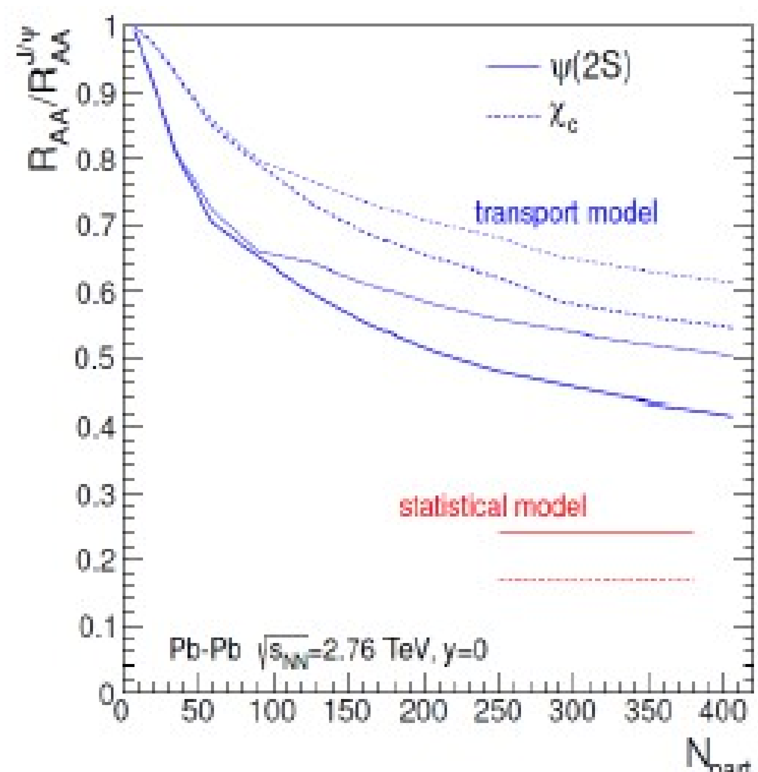
If substantiated → no colorless bound states in QGP

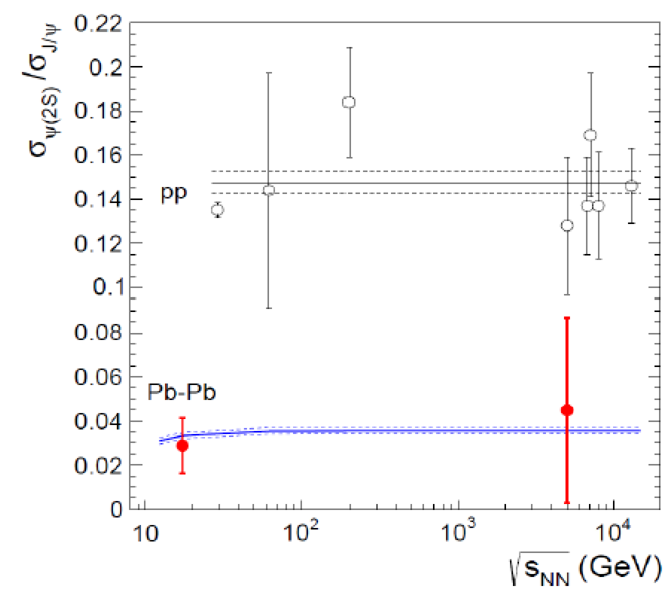


latest ALICE data - Scomparin-QM2017

ALICE preliminary central collisions

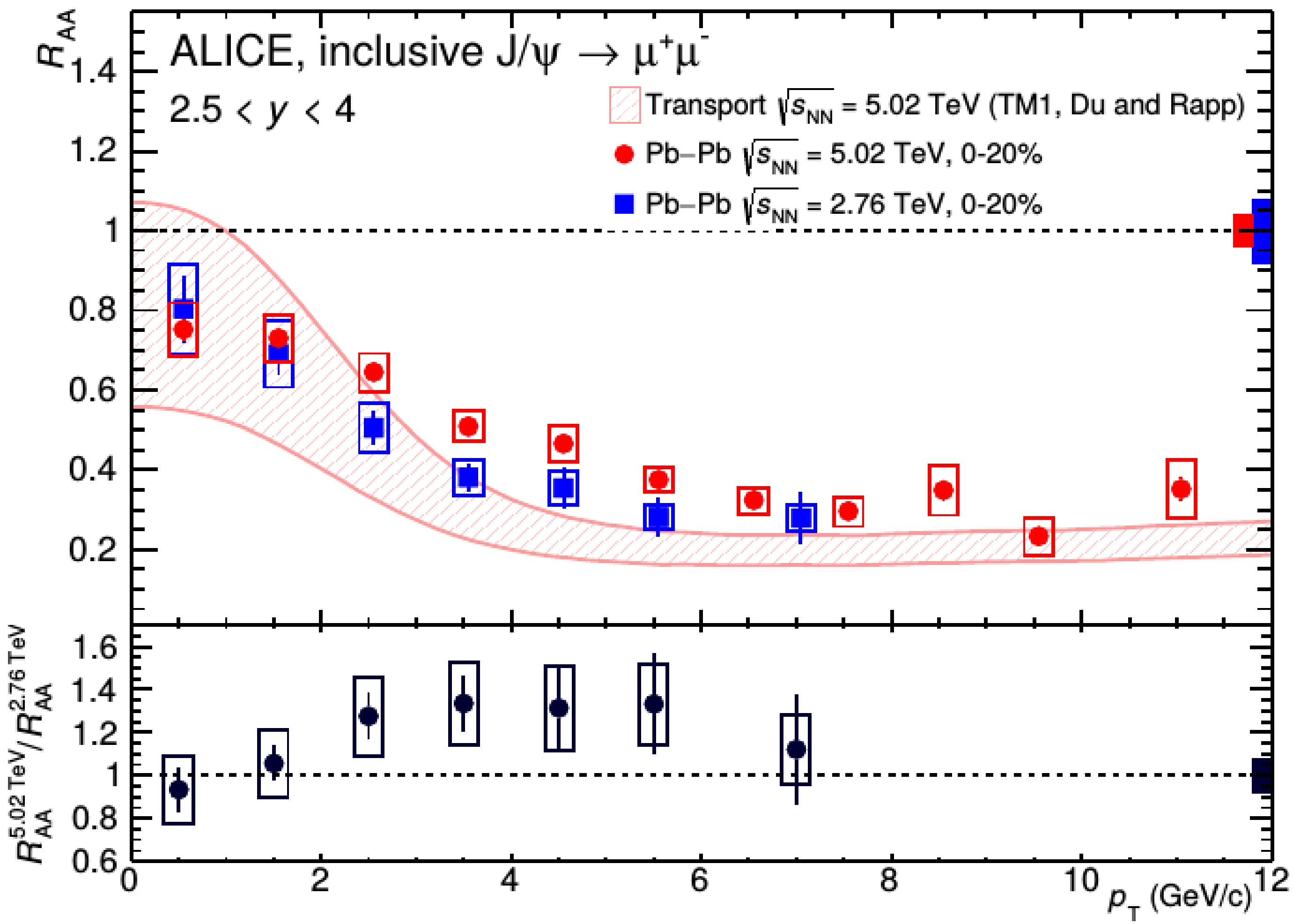






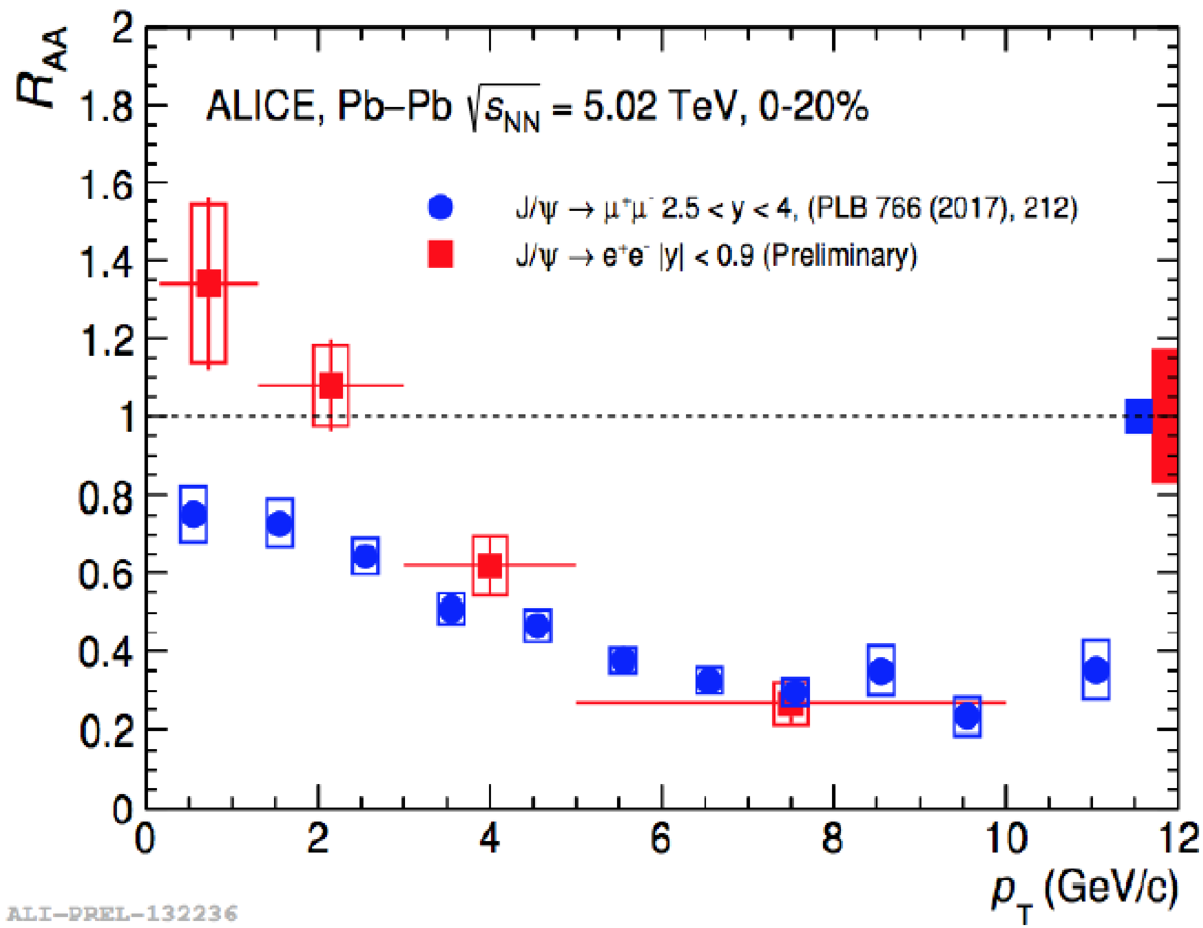
Andronic, pbm, Stachel, Redlich, arXiv:1710.09425

dependence on transverse momentum (1)
forward rapidity



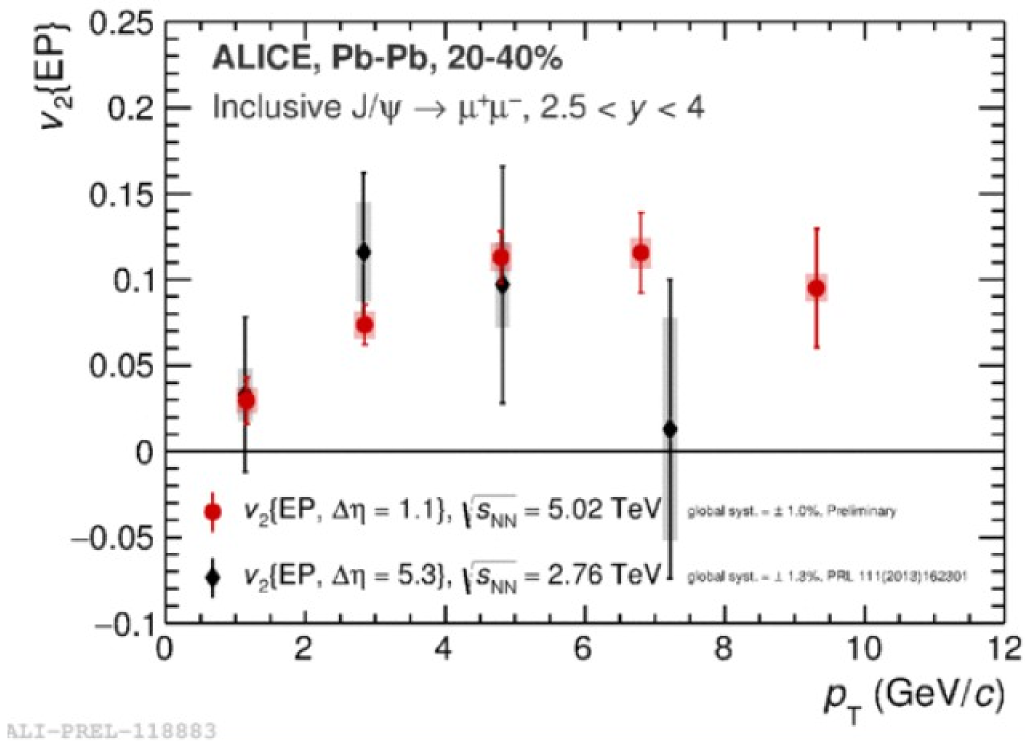
ALICE coll., arXiv:1606.08197

dependence on transverse momentum (2)
mid-rapidity vs forward rapidity



indication of J/psi enhancement at low p_t near mid-rapidity

elliptic flow of charmonium

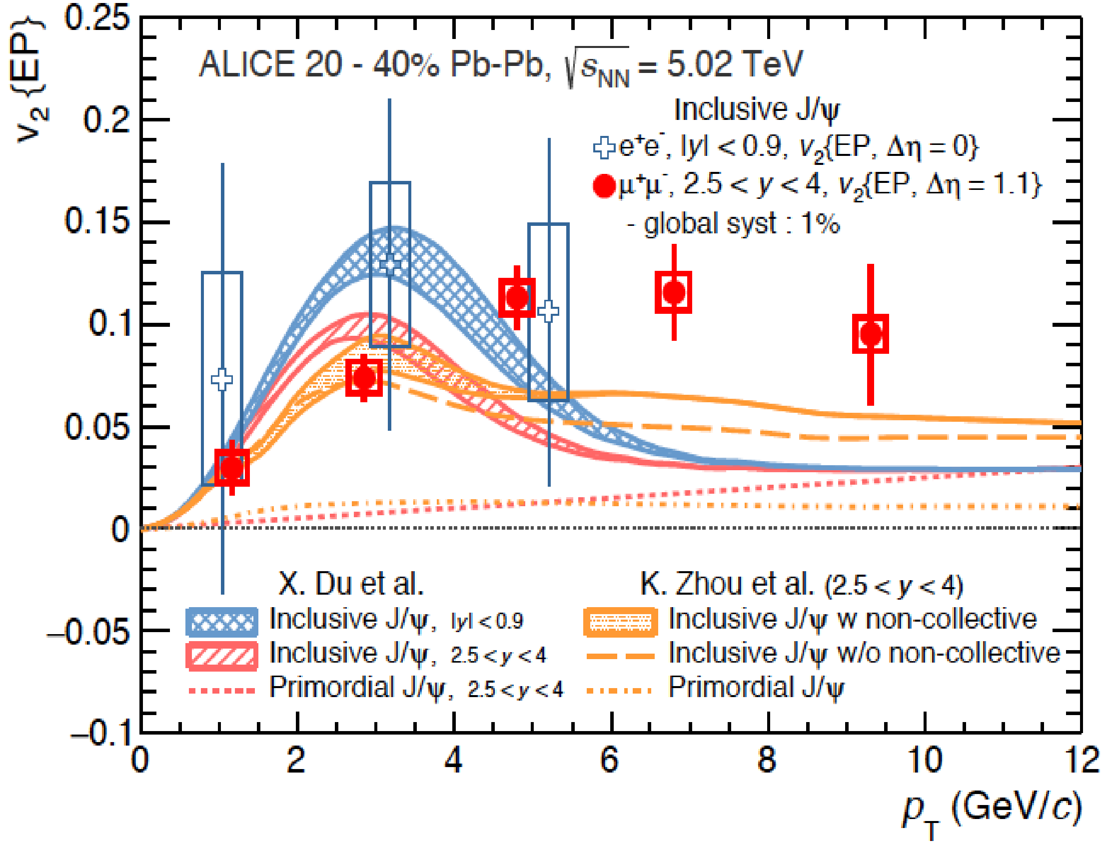


arXiv:1709.05260

p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
Δη=1.1	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
Δη=5.3	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ

most recent LHC Run2 result,
charm quarks participate in the hydrodynamical evolution of the QGP fireball
support for statistical hadronization of deconfined charm quarks

J/psi flow at mid-rapidity and forward rapidity



J/psi flow larger than expected at high transverse momentum transition from hydrodynamic flow to energy loss?

arXiv:1709.05260

statistical hadronization analysis → Debye mass determination near T_{pc}= 156 MeV

J/psi formation via statistical hadronization at T_c implies
experimental determination of Debye length (mass) and temperature
$\lambda_D < 0.4$ fm at T = 156 MeV or $\omega_D/T > 3.3$
can compare to theory:

quite ok

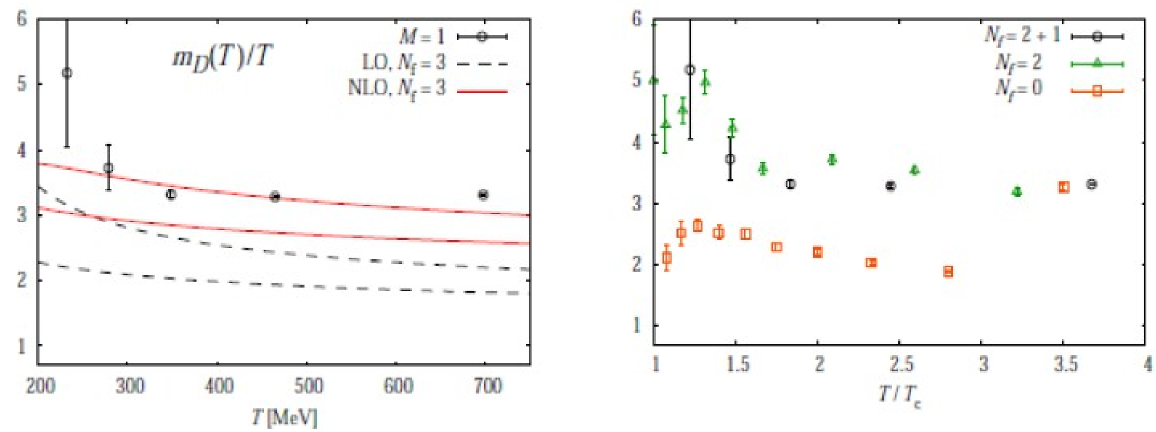


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ ($3\pi T$), 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.

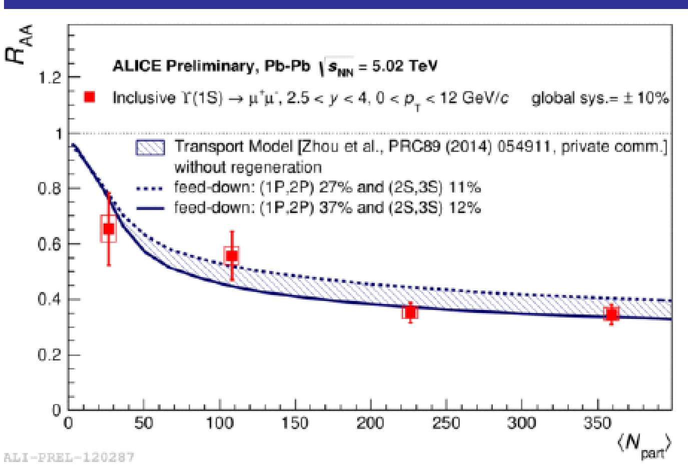
bottomonia

issues and questions

- is there suppression for Y(1s)?
- is there sequential suppression?
- role of (re-)generation
- p_T and rapidity distributions

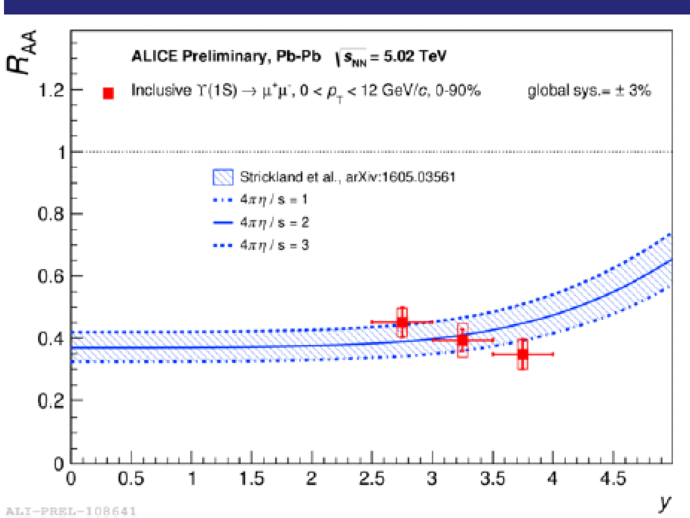
note: (re-)generation effects are vsible even if there is only 1 b bbar pair
diagonal term

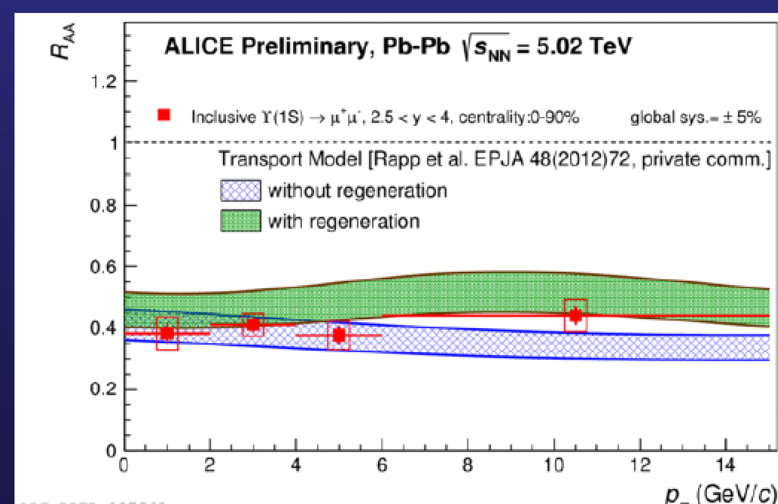
ϒ results in Pb-Pb: run 2



- Transport and anisotropic hydrodynamical models **qualitatively describe** the centrality and p_T–dependence of ϒ(1S) R_{AA}
- Some tension in the y-dependence ?
- **Contribution of regeneration is small**

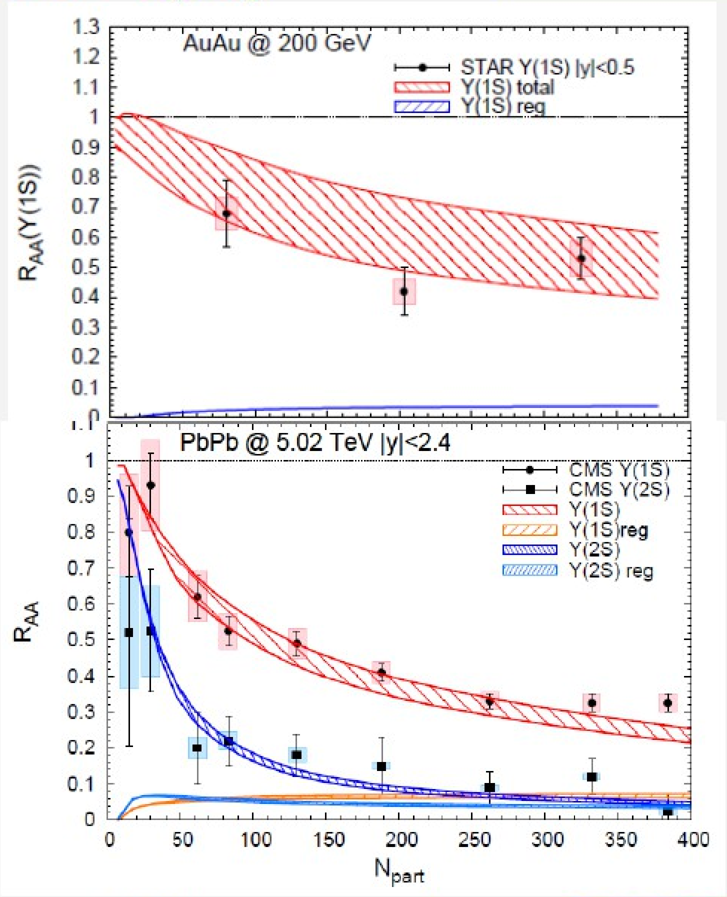
- **R_{AA} (ϒ(2S))** = 0.26± 0.12 ± 0.06(sys.)
  < R_{AA} (ϒ(1S)) = 0.40 ± 0.03 ± 0.04(sys.)

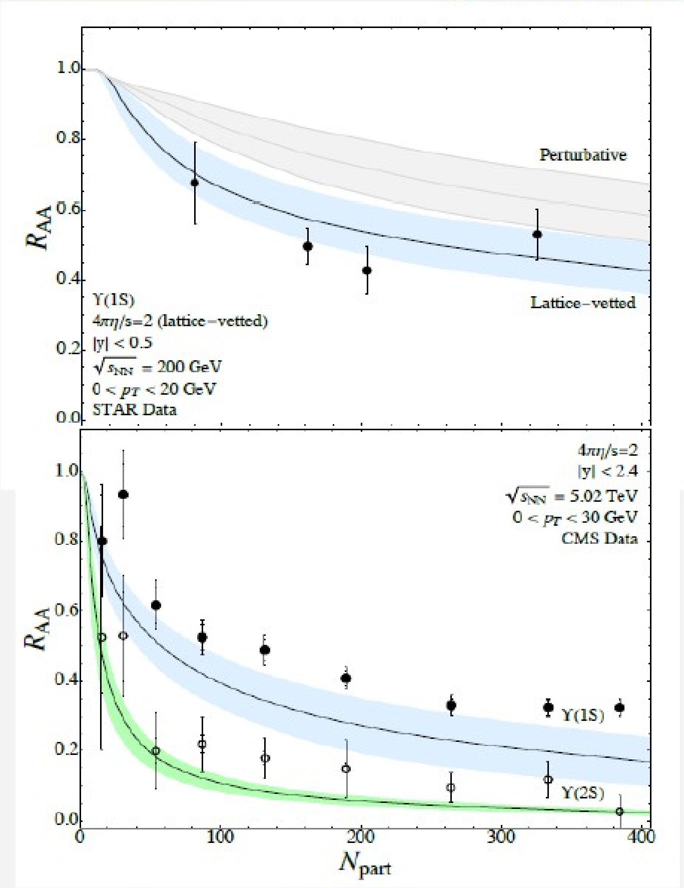




new analysis from Ralf Rapp

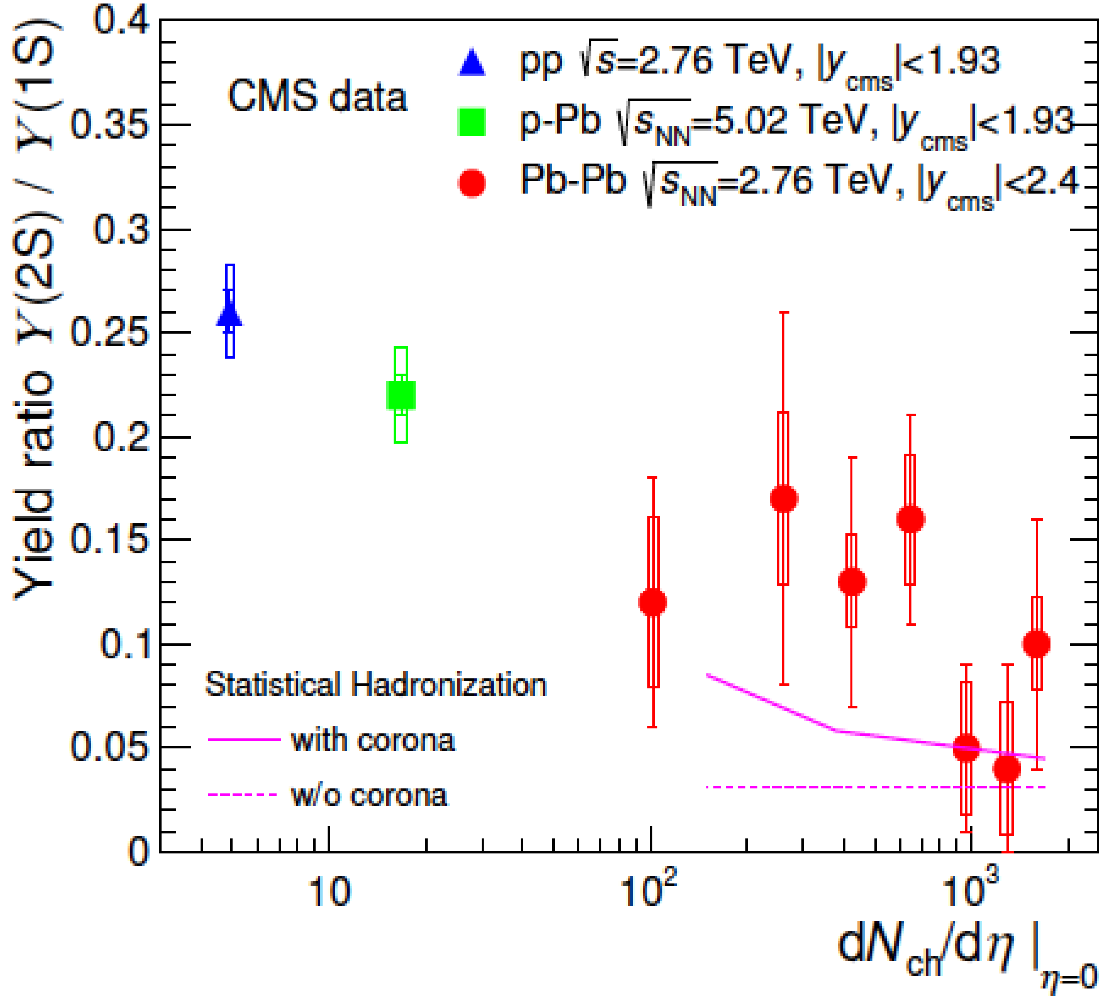
[TAMU '11,'17] **Lattice-based potentials** [Kent St '17]





- Υ(1S) suppression at **RHIC** → regeneration at **LHC**
- Regeneration dominant for **Υ(2S)** in central **PbPb** at **LHC**?

statistical hadronization model prediction



Andronic, pbm, Stachel, Redlich, arXiv:1710.09425

calculation assumes full suppression of all Y states at T_pc and production at the phase boundary

summary 2

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

statistical hadronization model also describes hadrons including charmonia formed from deconfined charm quarks

1st evidence for deconfined charm quarks in the QGP

are there colorless bound states inside the QGP? The psi(2s)/psi ratio will tell.

recombination also for Y states?

connection between LQCD and data

experimental evidence for:
QCD phase boundary
deconfinement of charm quarks

additional slides

The Hypertriton

mass = 2.990 MeV

Lambda sep. energy. = 0.13 MeV

molecular structure: (p+n) + Lambda

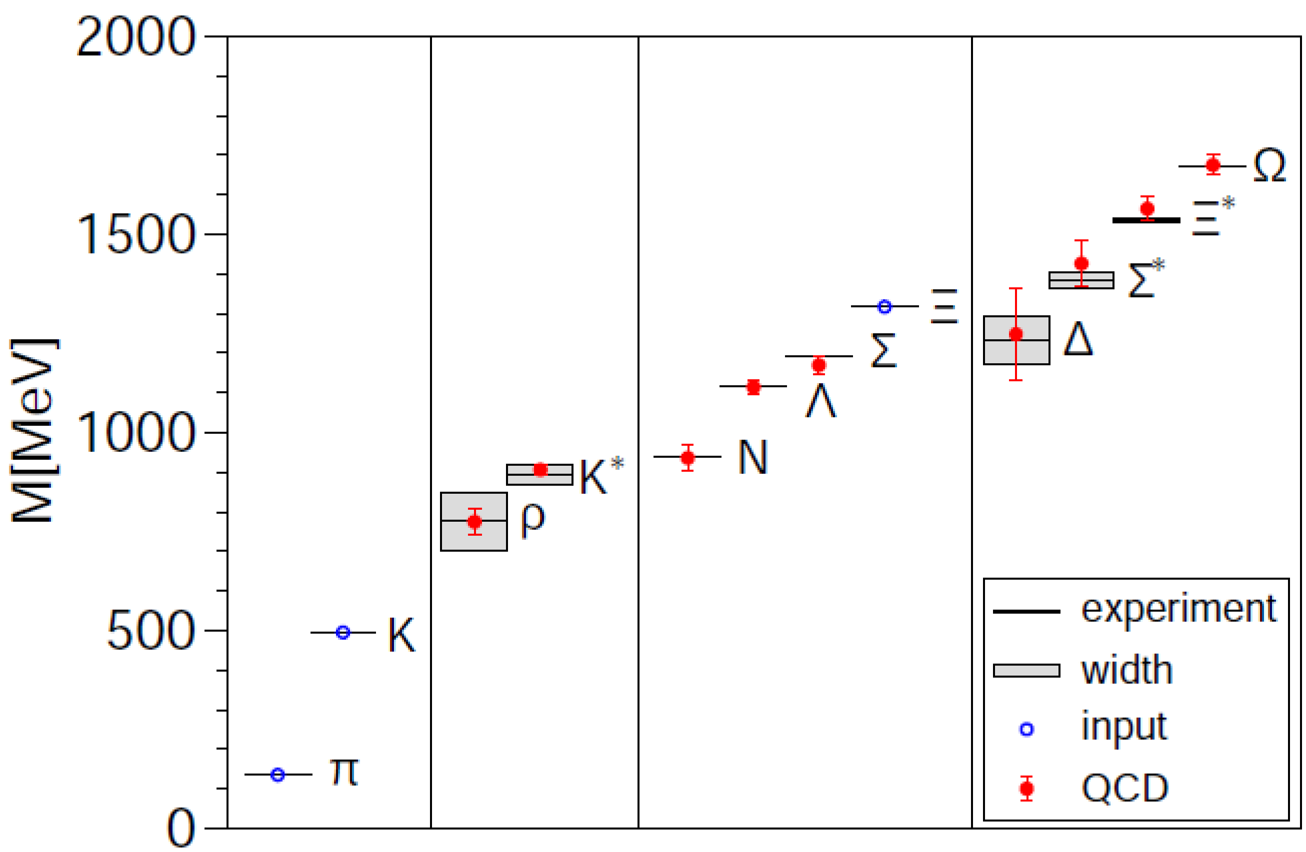
2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

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

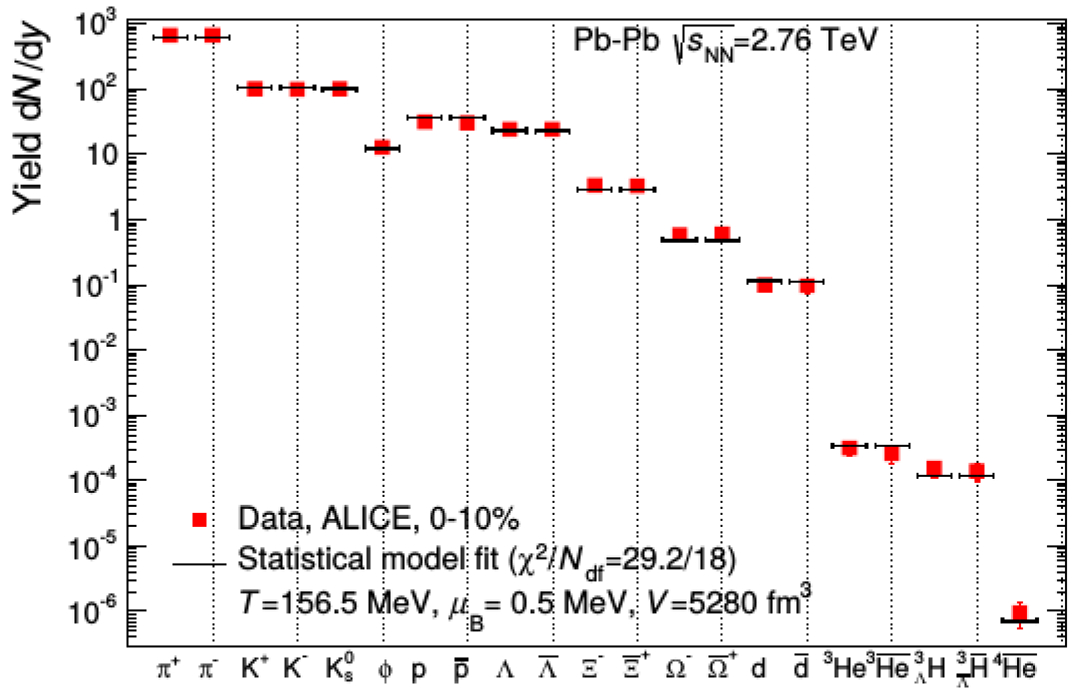
yet production yield is fixed at 156 MeV temperature
(about 1000 x separation energy.)

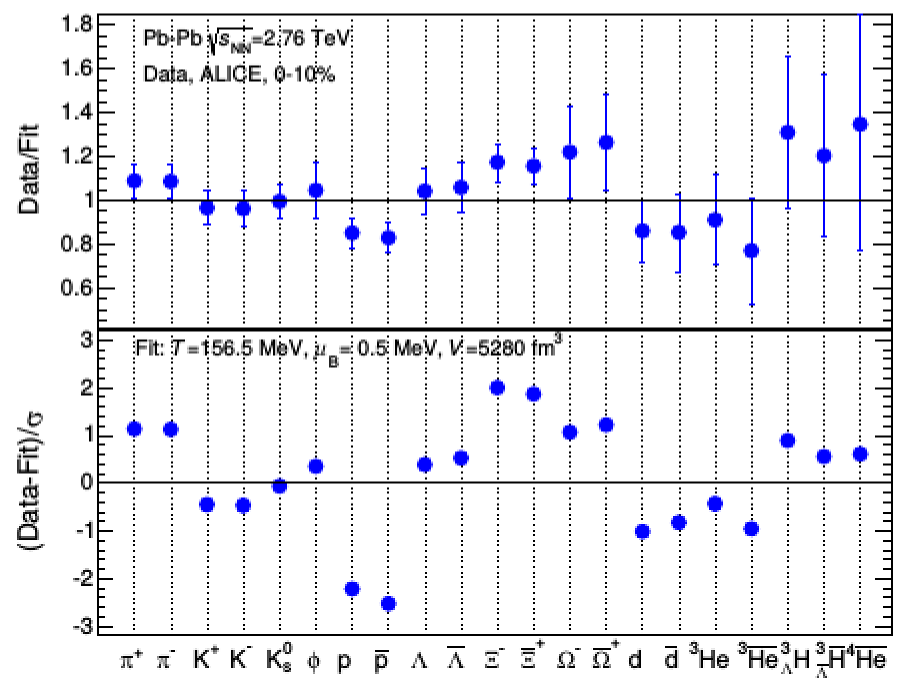
the hadron mass spectrum and lattice QCD



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

details on thermal description



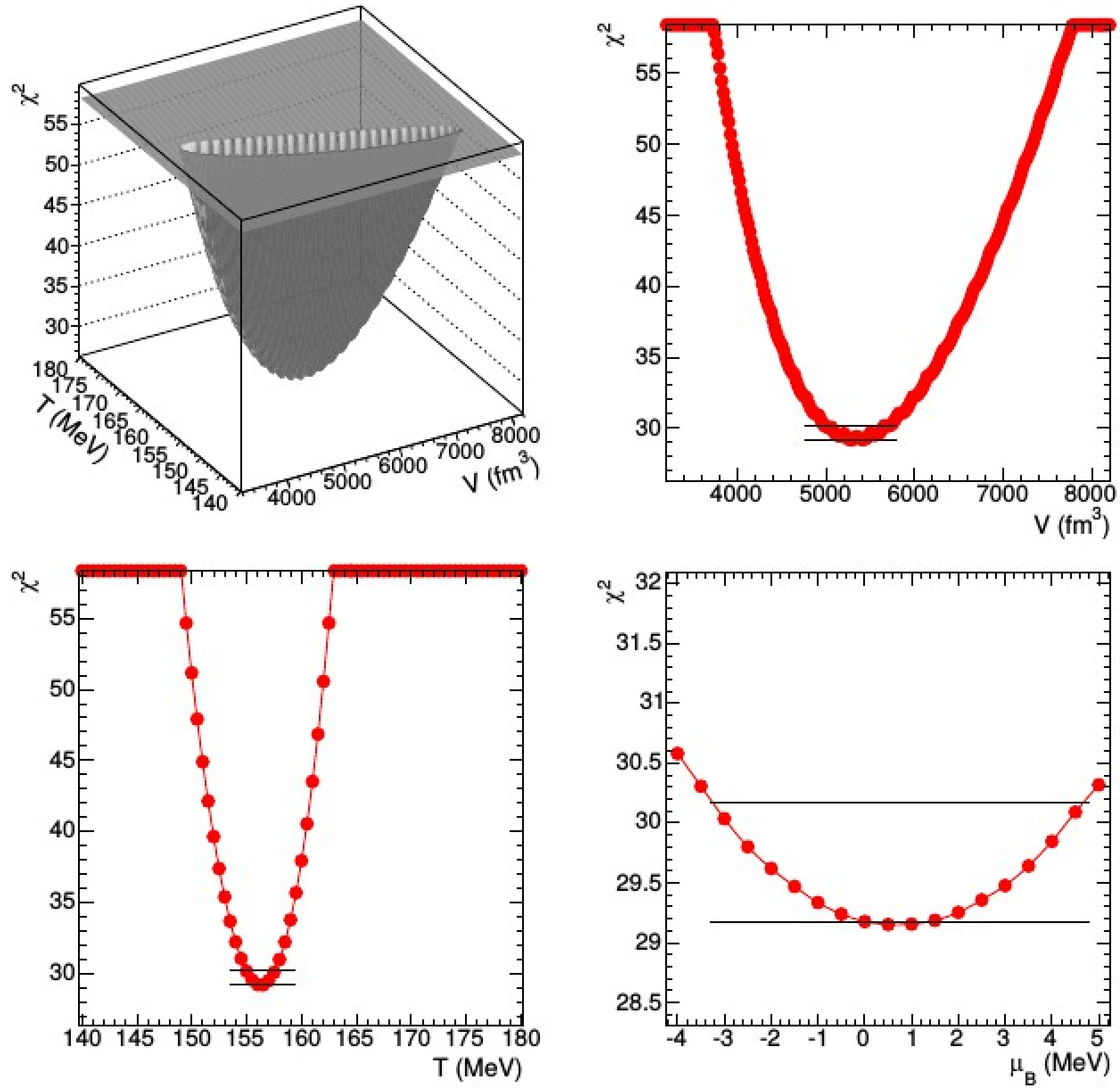


all species in fit

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

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



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:

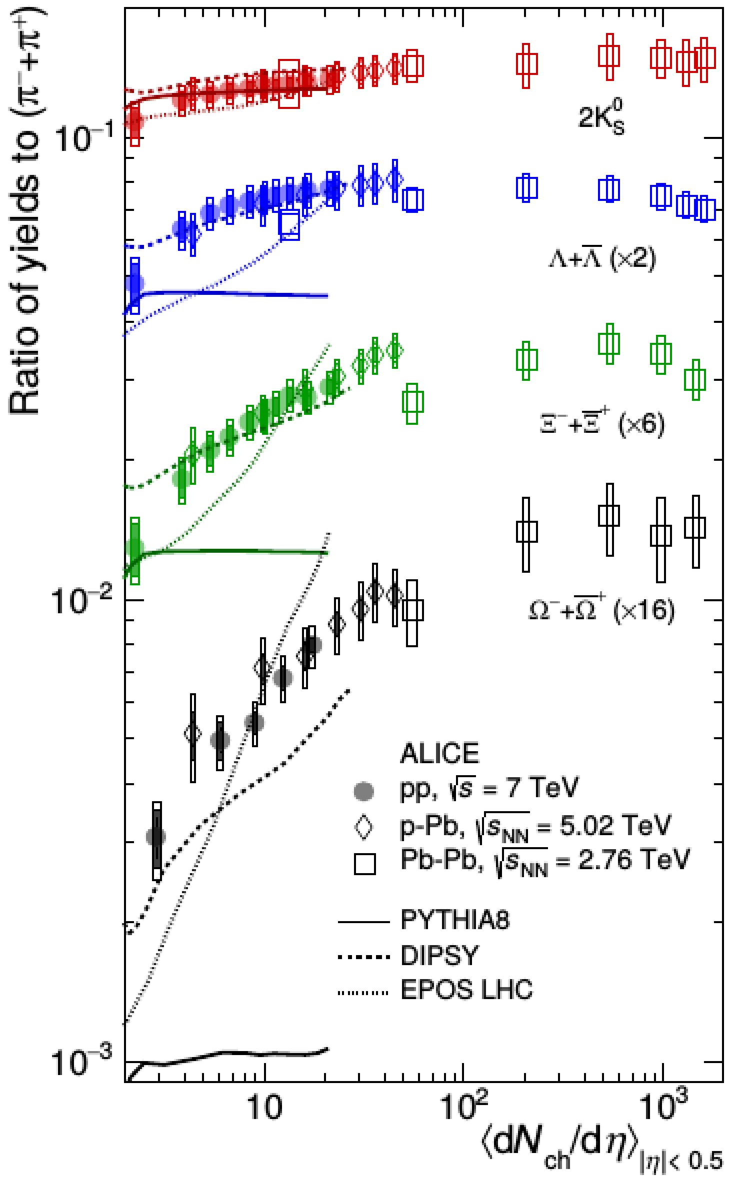
$$\frac{\chi_N}{T^2} = \frac{1}{VT^3} \sum_{n=1}^{|q|} n^2(\langle N_n \rangle + \langle N_{-n} \rangle)$$

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).

multiplicity dependence of yield ratios
approach to grand-canonical limit observed



grand-canonical
Omega/pi

arXiv:1606.07424
ALICE

...more details

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

  derived anti-particles from published ratios:

  d: $(9.82\pm1.58)\times10^{-2}$, $\bar{\mathrm{d}}/\mathrm{d} = 0.98\pm0.13 \rightarrow \bar{\mathrm{d}}$: $(9.62\pm2.01)\times10^{-2}$

  $^3\mathrm{He}$: rescale from 0-20% to 0-10% using d, factor 1.127 $\rightarrow (3.11\pm0.706)\times10^{-4}$
  $^3\bar{\mathrm{He}}/^3\mathrm{He} = 0.83\pm0.08\pm0.16 \rightarrow {}^3\bar{\mathrm{He}}$: $(2.58\pm0.81)\times10^{-4}$

excluded volume correction:

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

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 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

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 $T_c = T_{lim}$

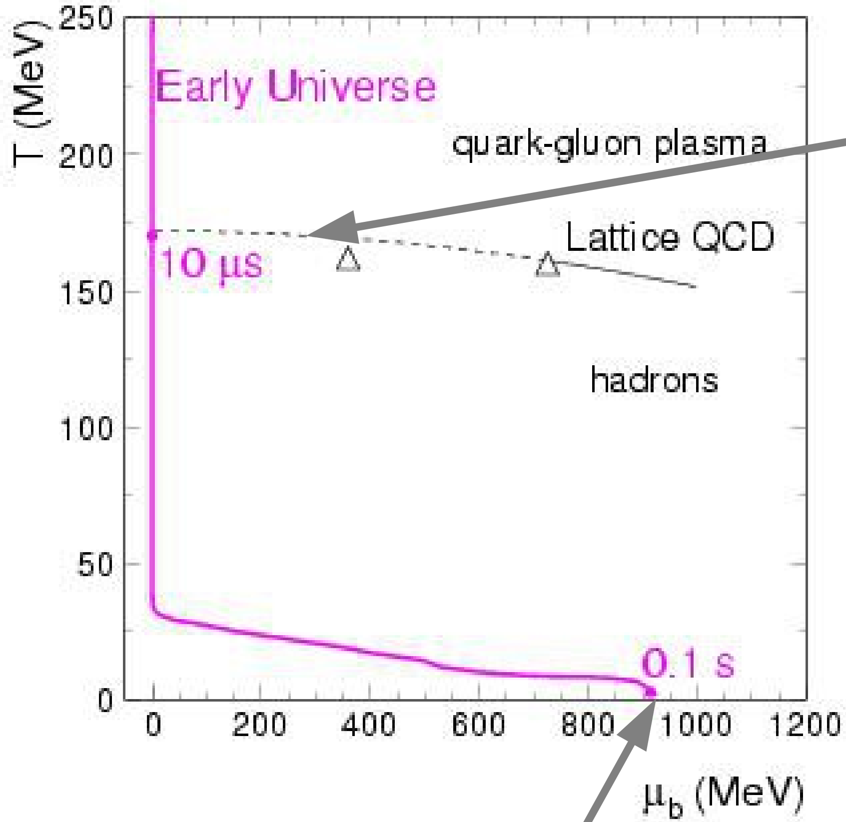
The size of loosely bound molecular objects

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

evolution of the early universe and the QCD phase diagram



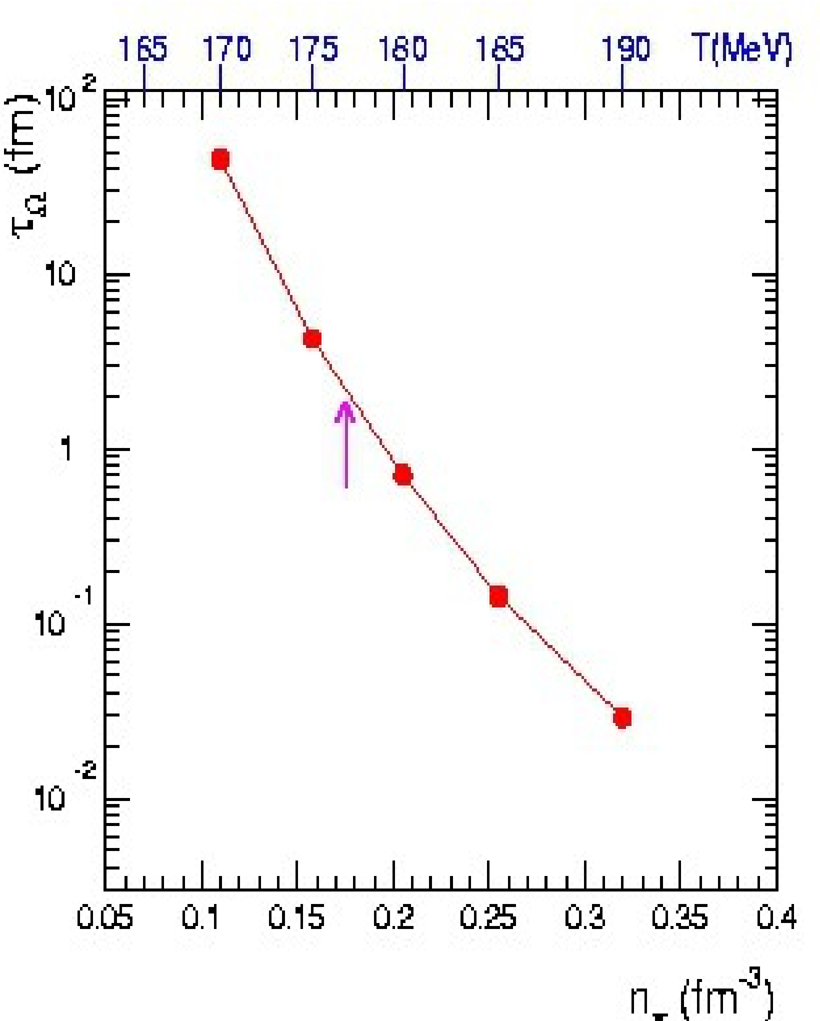
QCD phase boundary

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 ! b

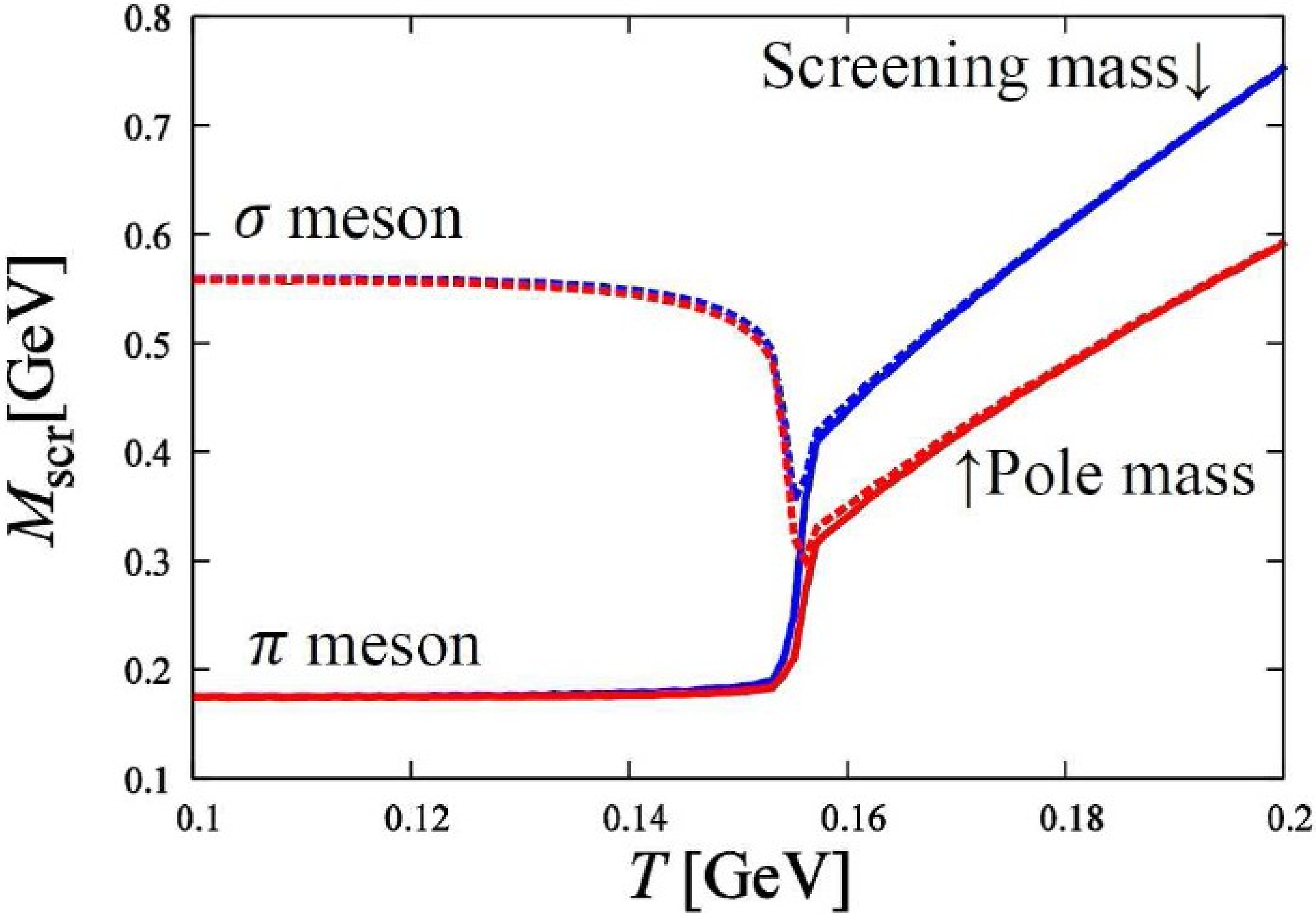


- Near phase transition particle density varies rapidly with T.
- For small ! b, reactions such as KKK! ! ! ! N_{bar} bring multi-strange baryons close to equilibrium.
- Equilibration time ! ! T^{-60} !
- All particles freeze out within the same very narrow temperature window.

are there similar mechanisms for large ! b?

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

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

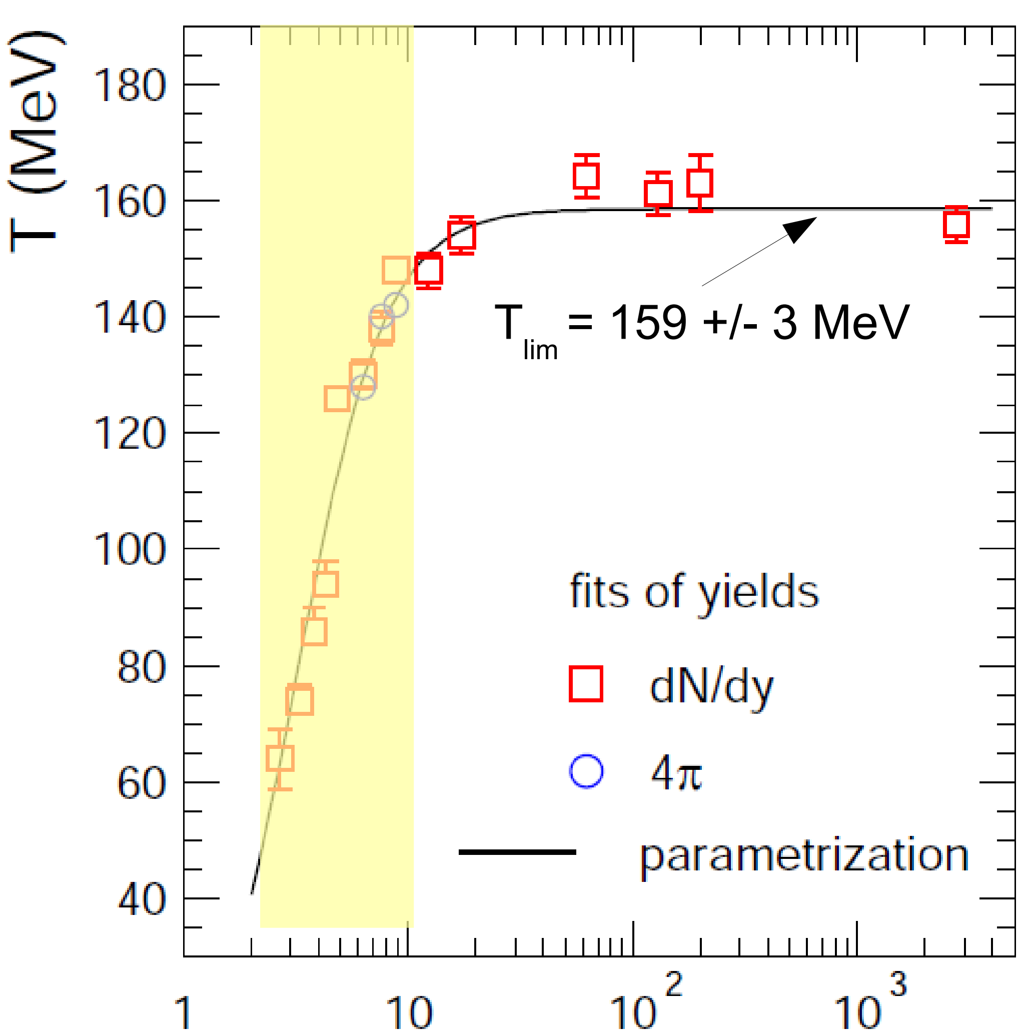
H. Hansen, W.M. Alberico (INFN, Turin & Turin U.), A. Beraudo (Saclay, SPhT), A. Molinari, M. Nardi (INFN, Turin & Turin U.), C. Ratti (ECT, Trento & INFN, Trento). Sep 2006. 26 pp.

Published in Phys.Rev. D75 (2007) 065004

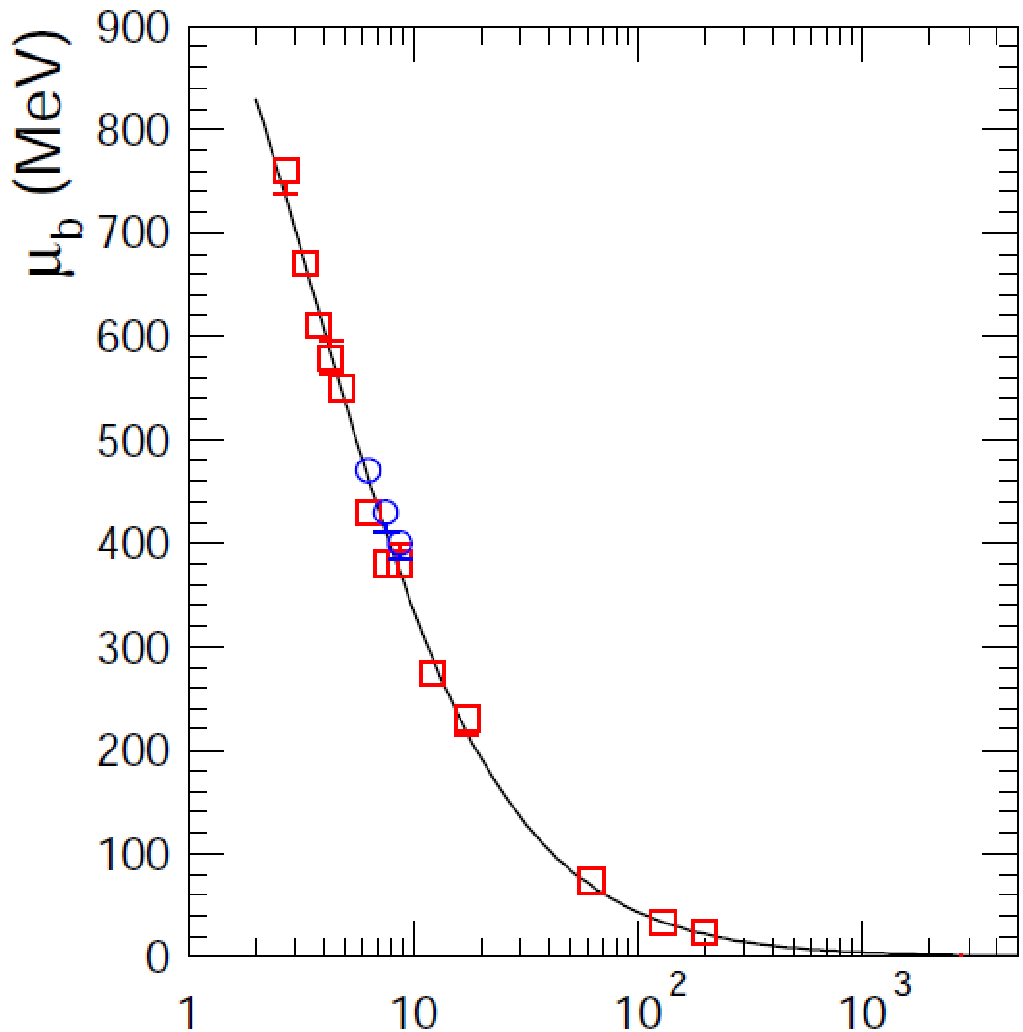
energy dependence of temperature and baryo-chemical potential

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