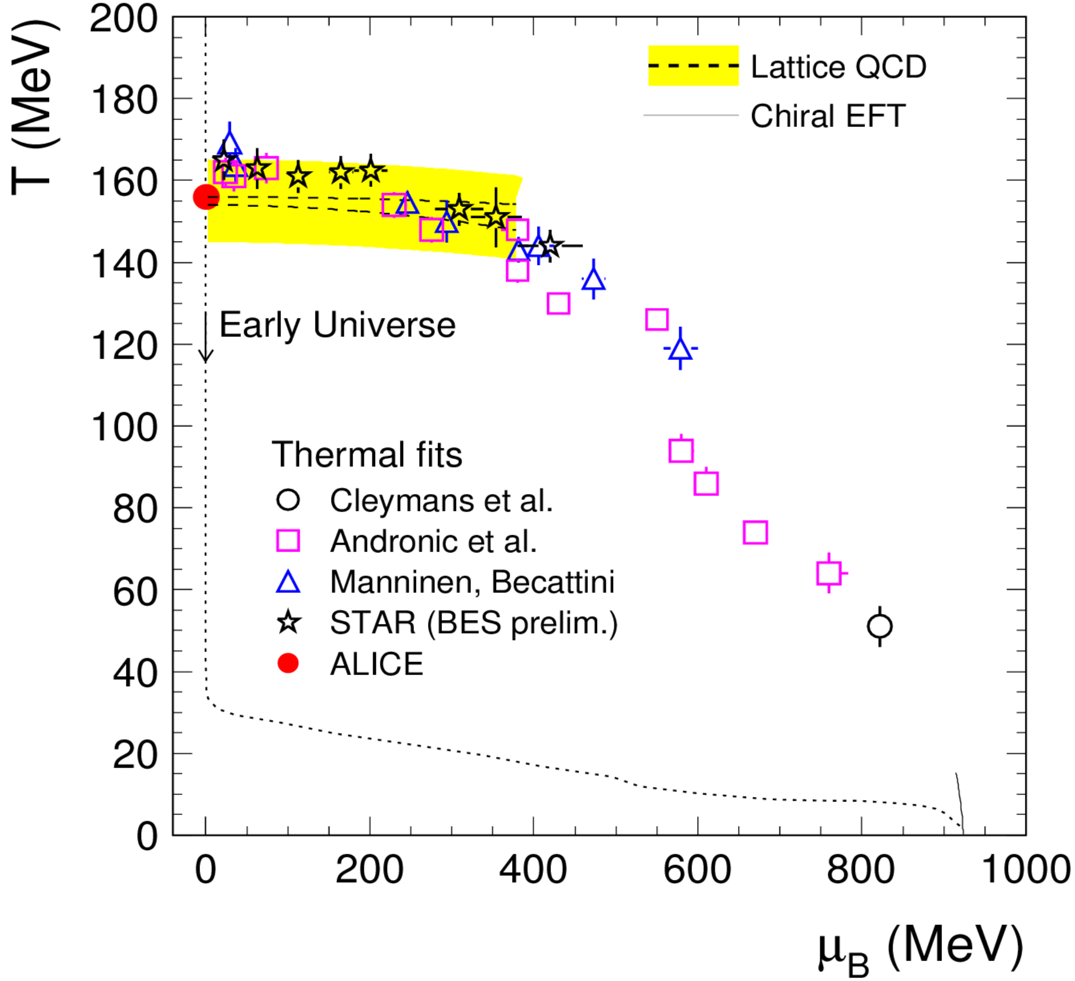
Hadron production in high energy nuclear collisions and the QCD phase diagram

Outline:
- the QCD phase diagram in lattice QCD
- hadron production at the LHC
- production of nuclei, anti-nuclei and exotica
- hadron yields and statistical model from AGS to SPS to RHIC
- connection to phase boundary
- direct connection of LHC data to lattice QCD on 2nd order critical fluctuations

work done in collaboration with
A. Andronic, P. Braun-Munzinger, und K. Redlich

Johanna Stachel, Physikalisches Institut, U. Heidelberg
CCNU Wuhan, July 28, 2015

Phase diagram of strongly interacting matter - today



Theoretical knowledge of the phase diagram

theory of strong interaction: QCD

Lagrangian density: $\mathcal{L}_{\mathrm{QCD}} = \frac{1}{2g^2}\mathrm{Tr}\left(F_{\mu\nu}(x)^2\right) + \overline{q}(x)\left(i\gamma_\mu D_\mu + m\right)q(x)$

in limit where renormalized running coupling constant $\alpha(q^2) = g^2(q^2)/4\pi$ small, QCD perturbation theory gives precise results (cf. QED)

- in hadronic matter and in QGP at T a few times T_c, coupling not small!

already in 1974 proposed by Wilson: put field theory (e.g. QCD) on 4 d lattice in Euclidian space-time

from 1979 possibility to numerically calculate observables on a computer "birth of lattice QCD"

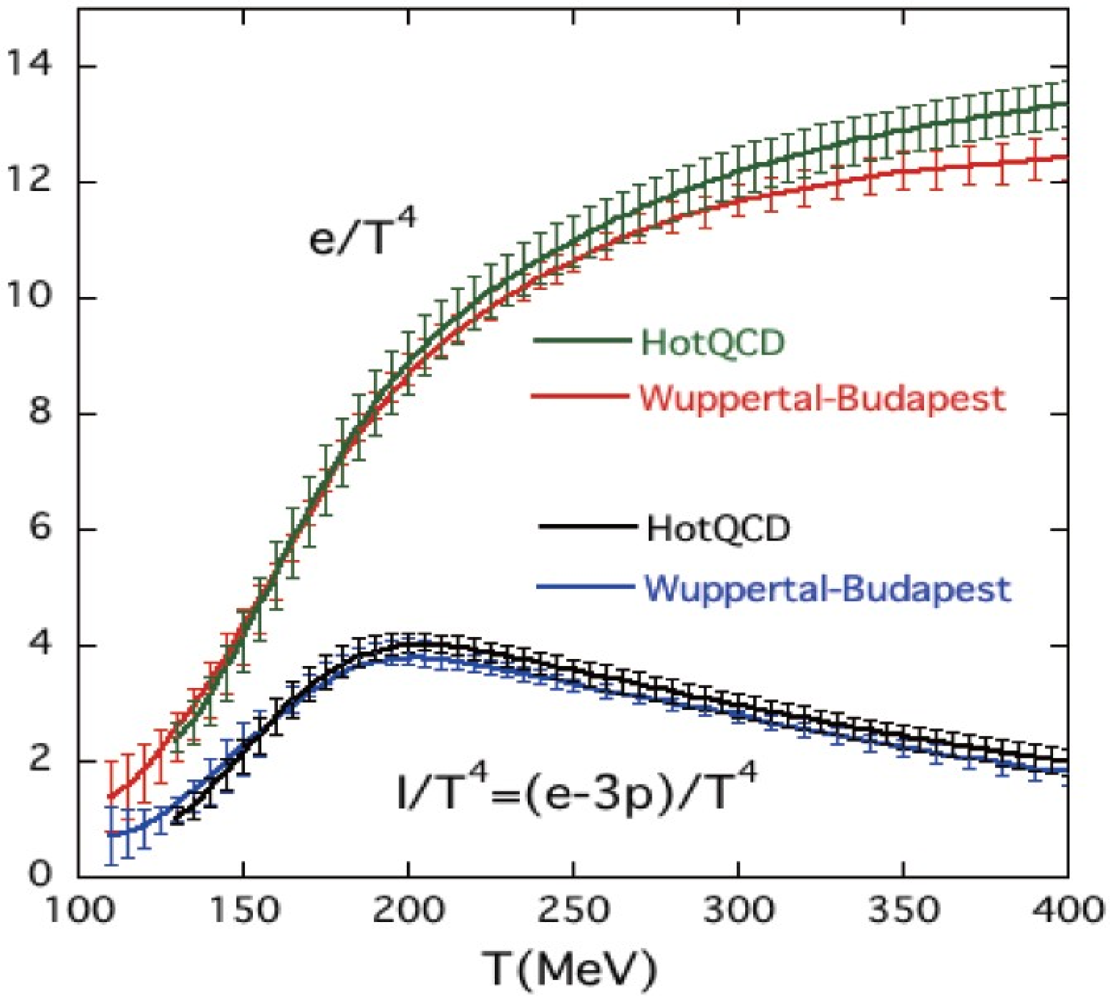
in the past 35 years tremendous development due to availability of parallel super computers (to good part also driven by lQCD community) and better algorithms

- now lattice QCD is a mature technique with increasingly reliable results

Equation of state of hot QCD matter in lattice QCD

computation of QCD EoS one of the major goals in lQCD community since 1980

A.Ukawa, arXiv:1501.04215



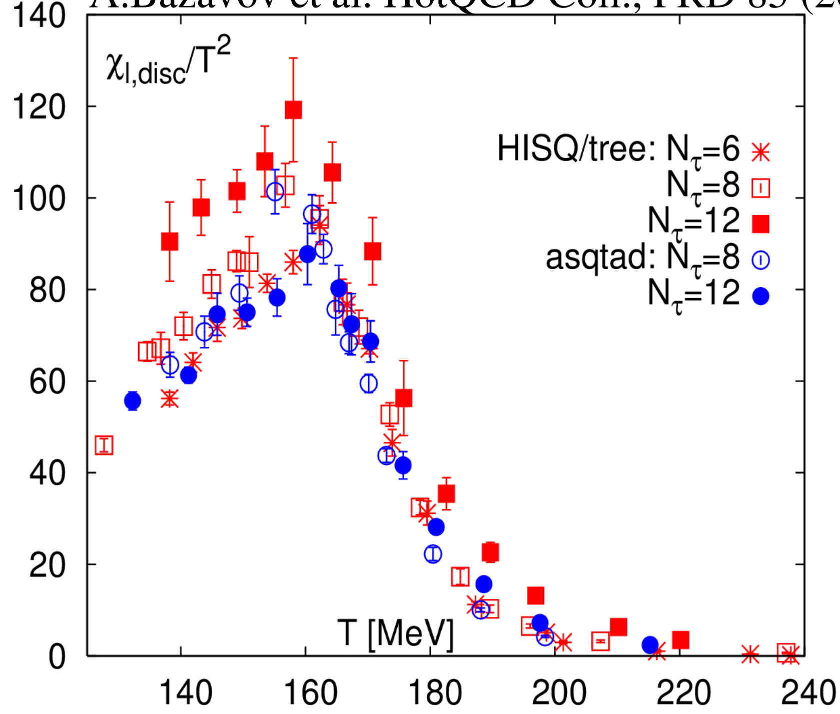
consolidated results on EoS from different groups, extrapolated to continuum and chiral limit

rapid rise of energy density (normalized to T^4 rise for relativistic gas)
- signals rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons
- lQCD points to continuous cross over transition

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

S.Borsayi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073
A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



$$\langle \bar{\Psi}\Psi \rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial m}$$

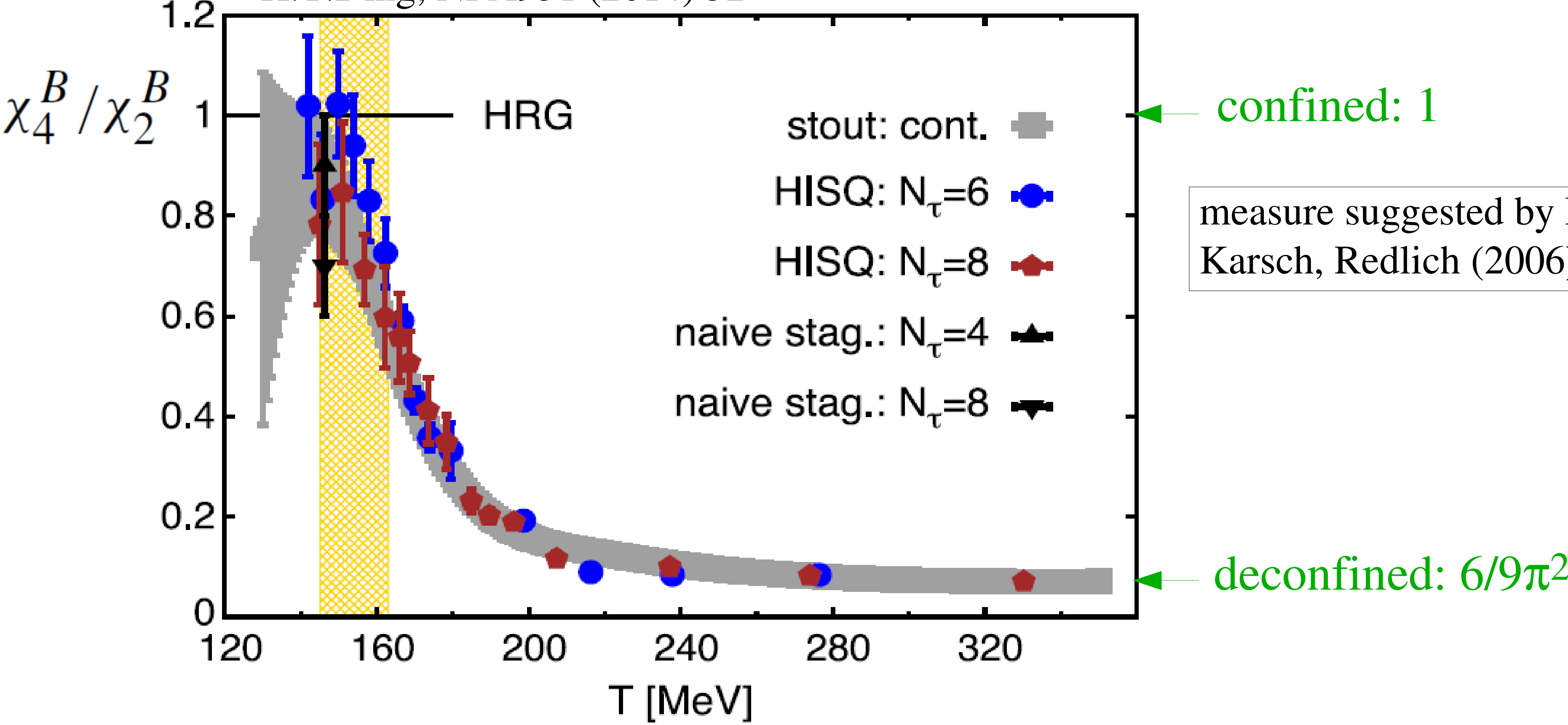
$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

comparing different measures and different fermion actions, consensus:
T_c = 150 – 160 MeV for chiral restoration

Measure of deconfinement in lQCD

$\chi_4^B/\chi_2^B \propto \text{baryon number}^2$

H.T.Ding, NPA931 (2014) 52



measure suggested by Ejiri, Karsch, Redlich (2006)

rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

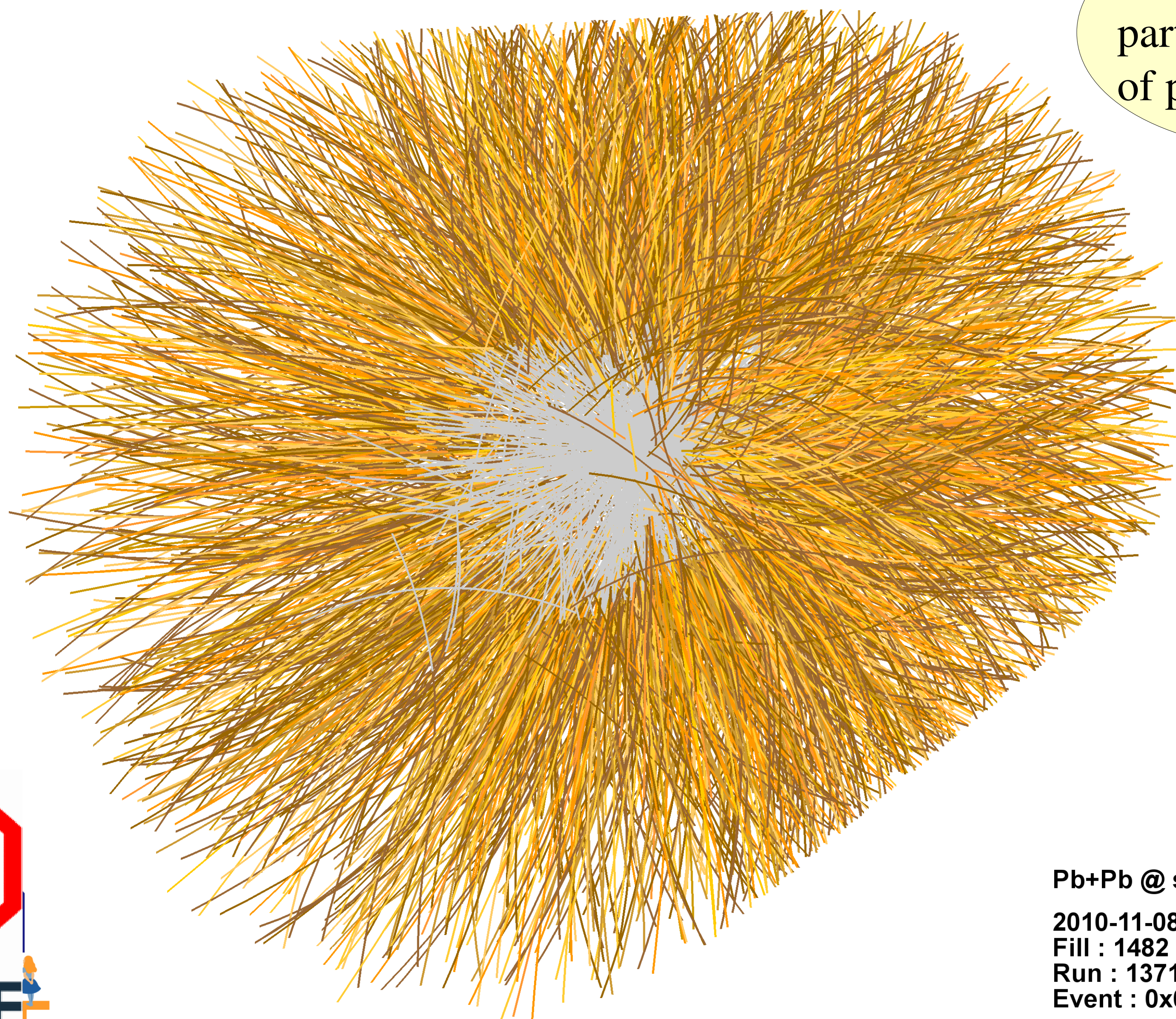
Experiment

QGP and phase diagram studied in high energy collisions of nuclei since 1987 at AGS/SPS, since 2000 at RHIC, since 2010 at the LHC at $\sqrt{s_{NN}}$ = 2.76 TeV

a central PbPb collision at LHC at $\sqrt{s}$ = 2.76 A TeV

first collisions with stable beams:
Nov 8 - Dec 6, 2010

about 3000 charged particles in 1.8 units of pseudorapidity



Pb+Pb @ sqrt(s) = 2.76 ATeV

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

ALICE

Charged Particle Multiplicity

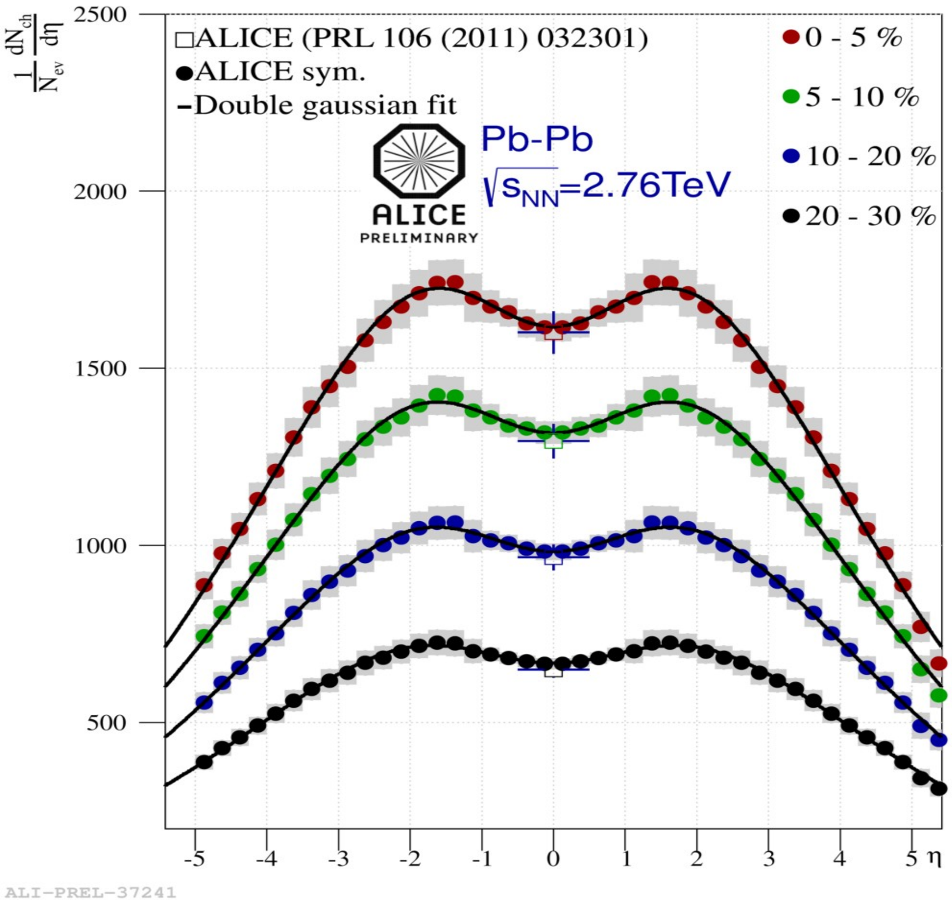
probes density of gluons initially liberated from the colliding nucleons

expect order of 10 000 (question of shadowing and of gluon saturation)

in a statistical ensemble measure of initial entropy density

each gluon (boson) contributes 3.6 units to the entropy

preserved for isentropic expansion



central PbPb at 2.76 TeV

$dN_{ch}/d\eta = 1600$

using arguments by Bjorken

initial energy density

$\varepsilon_0 = 146$ GeV/fm^3

$T \approx 0.68$ GeV $\approx 4\ T_c \approx 10^{13}$ K

pressure P ≈ 49 GeV/fm^3 = 7.9 10^{36} Pa

entropy density ≈ 290/fm^3

total entropy of fireball: 36 000

the Hadro-Chemical Composition of the Fireball

what are the 20 000 hadrons observed in final state at LHC?

QGP and hadron yields

QCD implies duality between quarks/gluons and hadrons

- hadron gas: equilibrated state of all known hadrons
- QGP: equilibrated state of quarks and gluons

at pseudocritical temperature T_c, QGP converts to hadrons

existence of QGP in central nuclear collisions implies that:

- hadron yields correspond to equilibrium state of common temperature T
- hadron yields must agree with predictions using the full QCD partition function at this temperature T

near T_c, hadron densities very large, can rapidly drive system into equilibrium between hadronic species by multi-particle reactions (critical opalescence)

- conversely, rapidly dropping densities (reduction of dof and T^3 drop of entropy density) imply cooling system falls out of equilibrium, i.e. freezes out
  T bounded by T_c within a few MeV

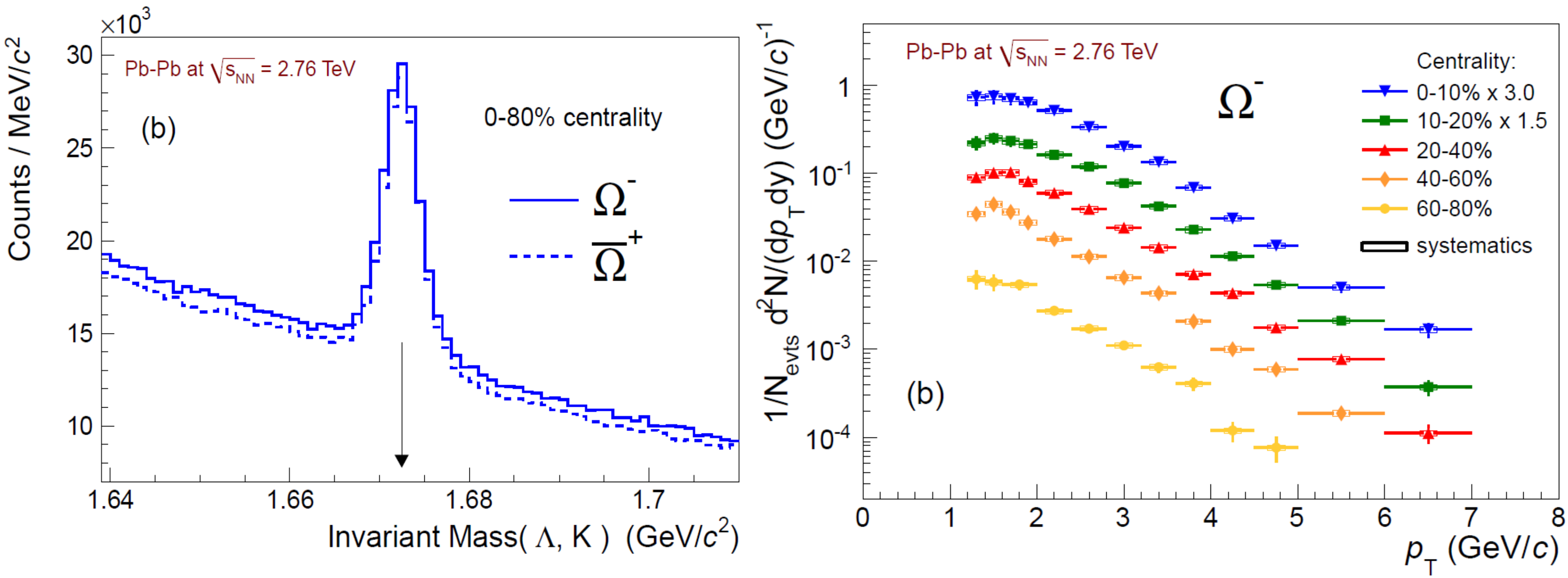
analysis of hadron production $\rightarrow$ experimental determination of T_c

P. Braun-Munzinger, J.S., C. Wetterich, PLB 596 (2004) 61

Production of different hadron species

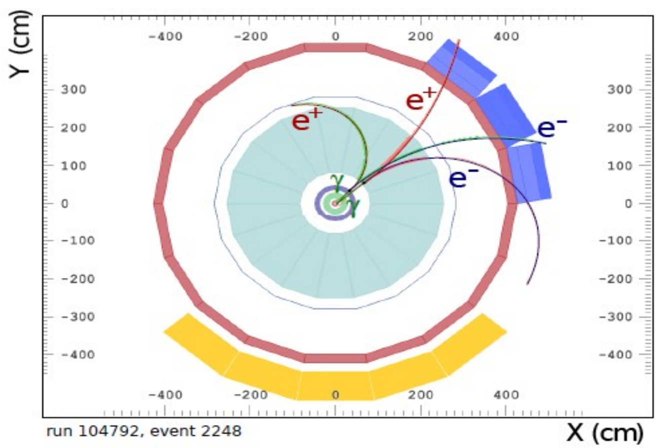
measure and integrate spectra of identified hadrons

- hadrons reconstructed from weak decay products (Λ, Ξ, Ω)
- specific energy loss dE/dx and time-of-flight

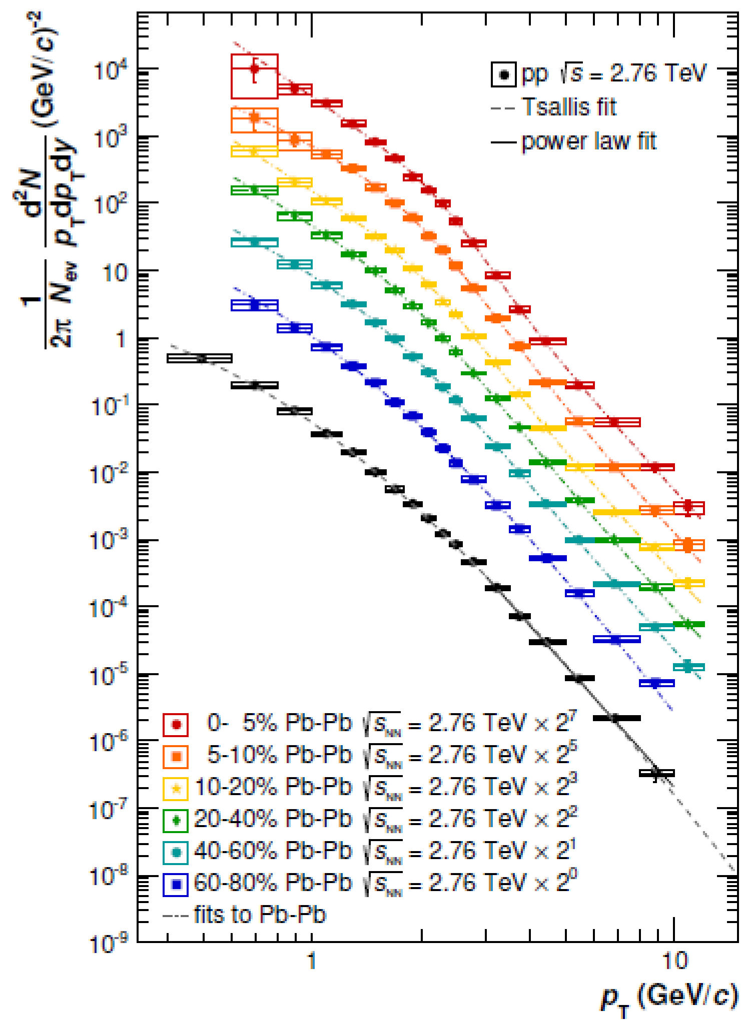


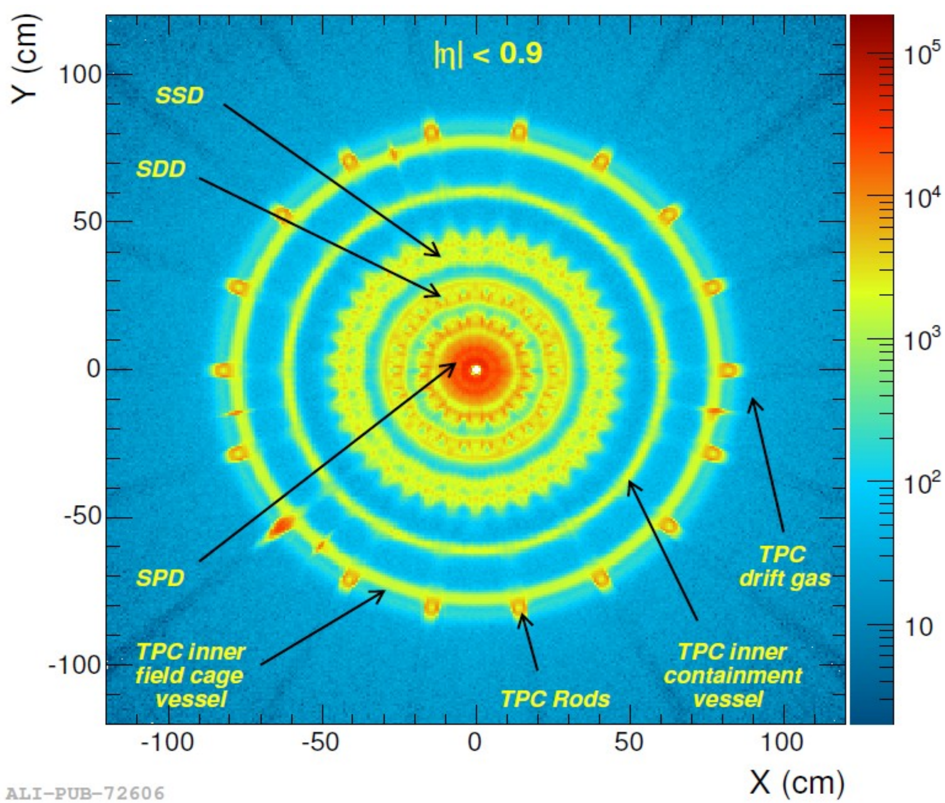
data: ALICE PLB 728 (2014) 216

Neutral pions from decay photon conversion in detector



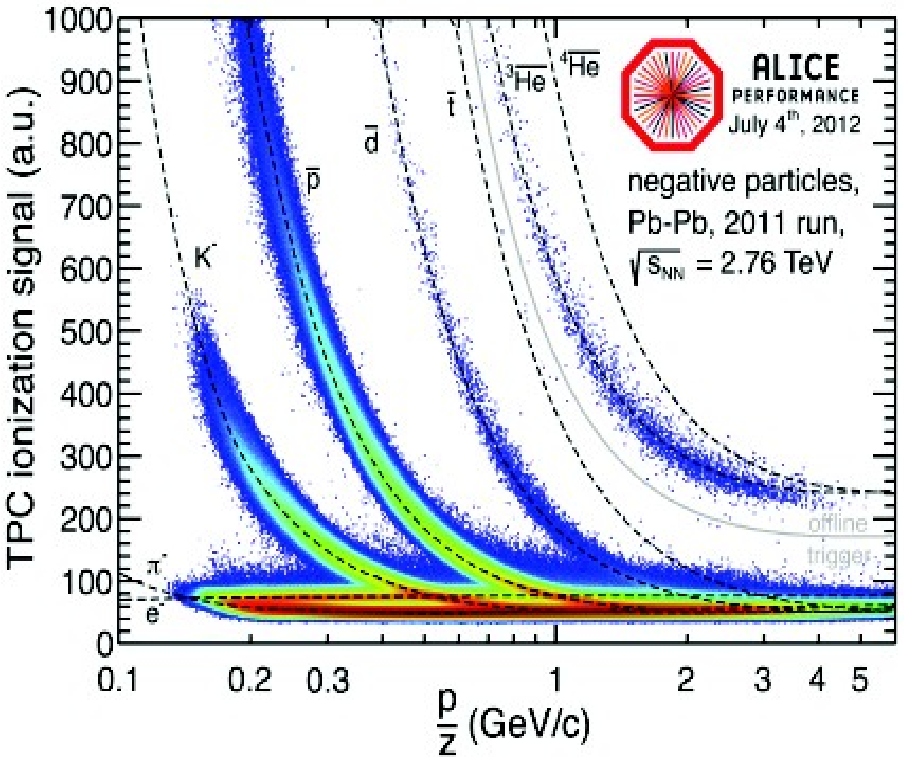
ALICE, EPJ C74 (2014) 10, 3108

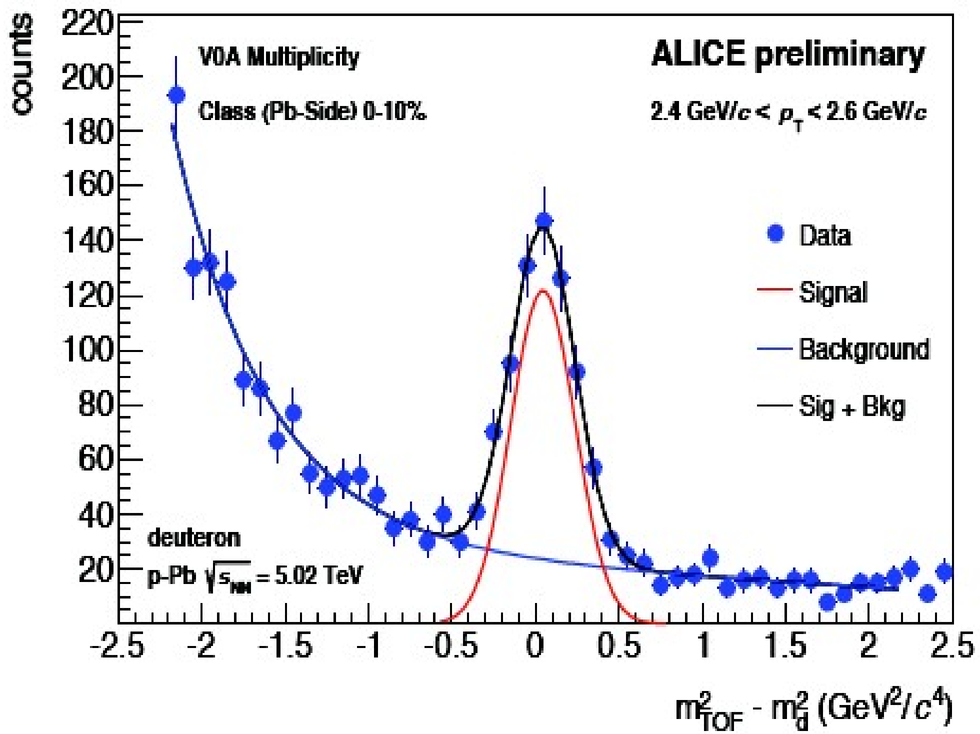




allows to determine the material thickness up to middle of TPC of 11% X_0 with accuracy of 4.5%

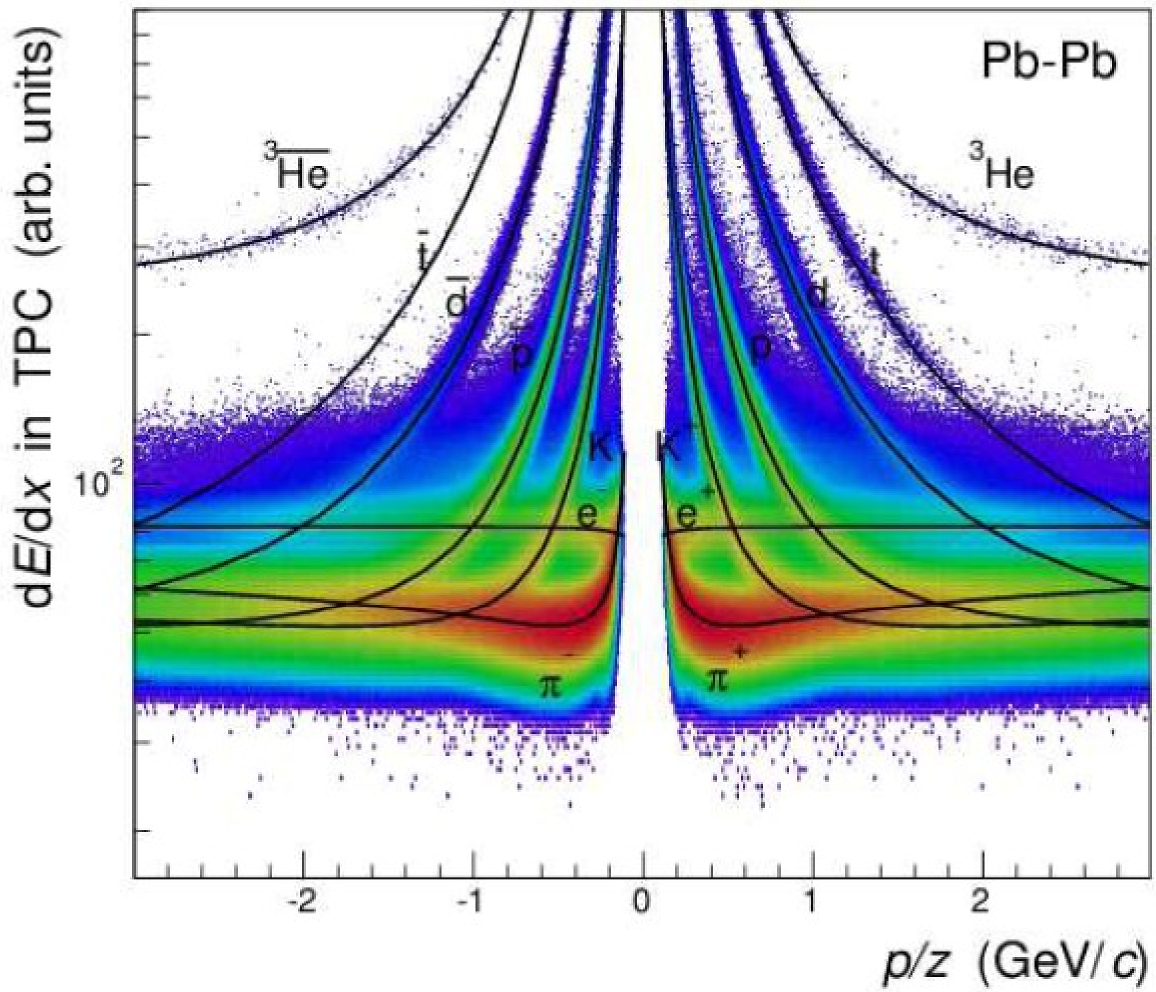
Particle identification via dE/dx in the TPC and TOF





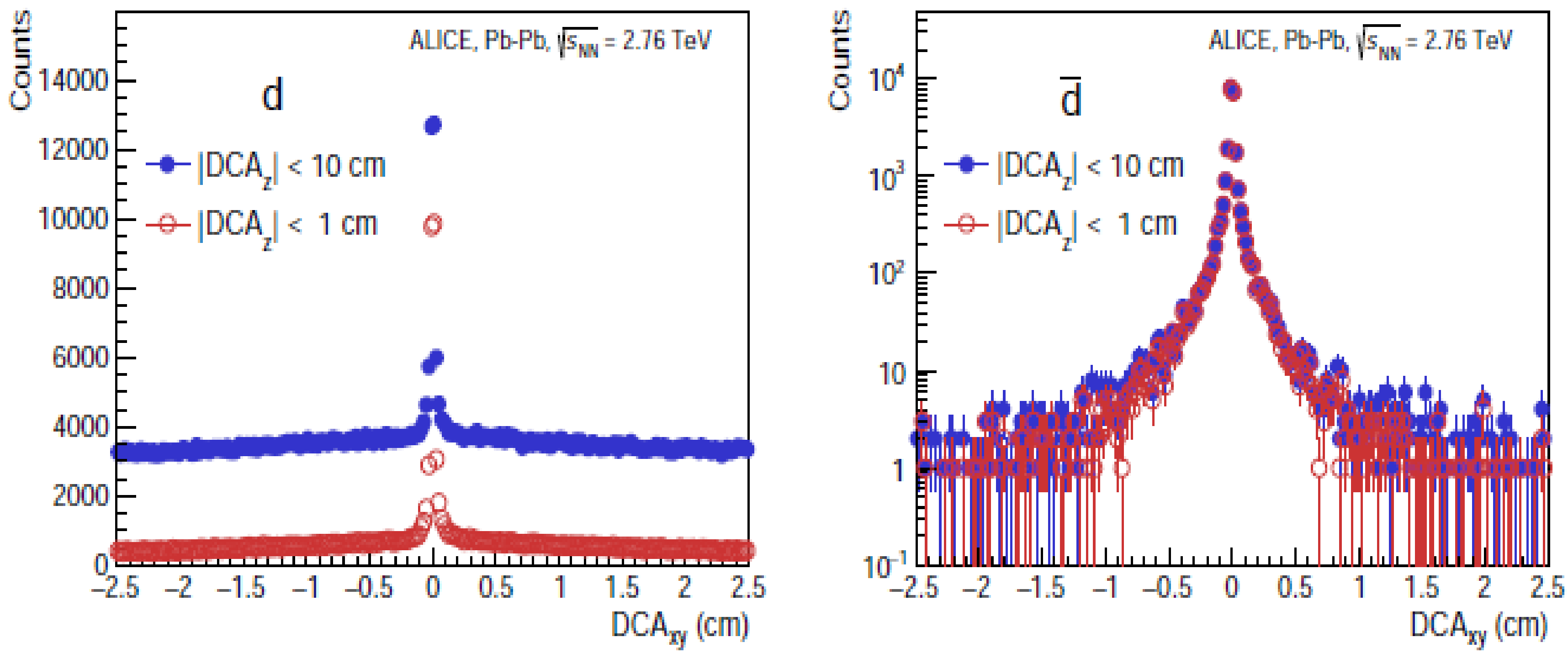
- all particles from e to ^{4}He identified via the TPC specific energy loss (resol 6 %) plus TOF at crossings
- 2011 run 2.3 10^7 events and in those 10 anti-^{4}He

Difficulty for production of nuclei: secondaries from spallation



data ALICE - arXiv:1506:08951
loose vertex cuts
centrality: 0-80%
apparent asymmetry between t and anti-t is caused by large spallation background at low momentum for tritons
anti-t/t yield consistent with 1 after final cuts

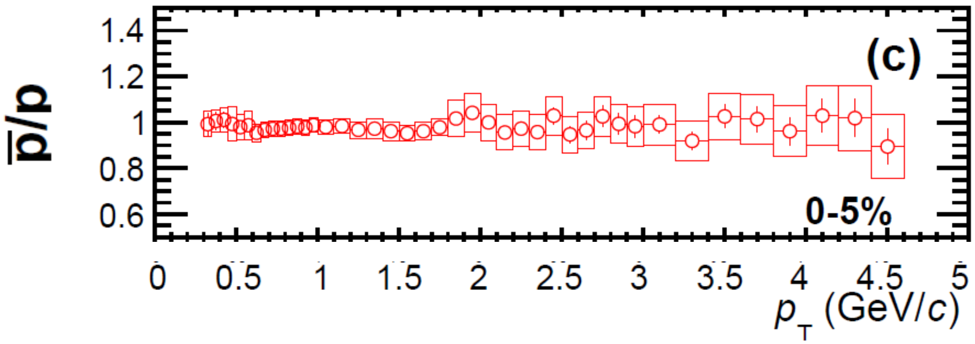
Separation of secondaries from primaries



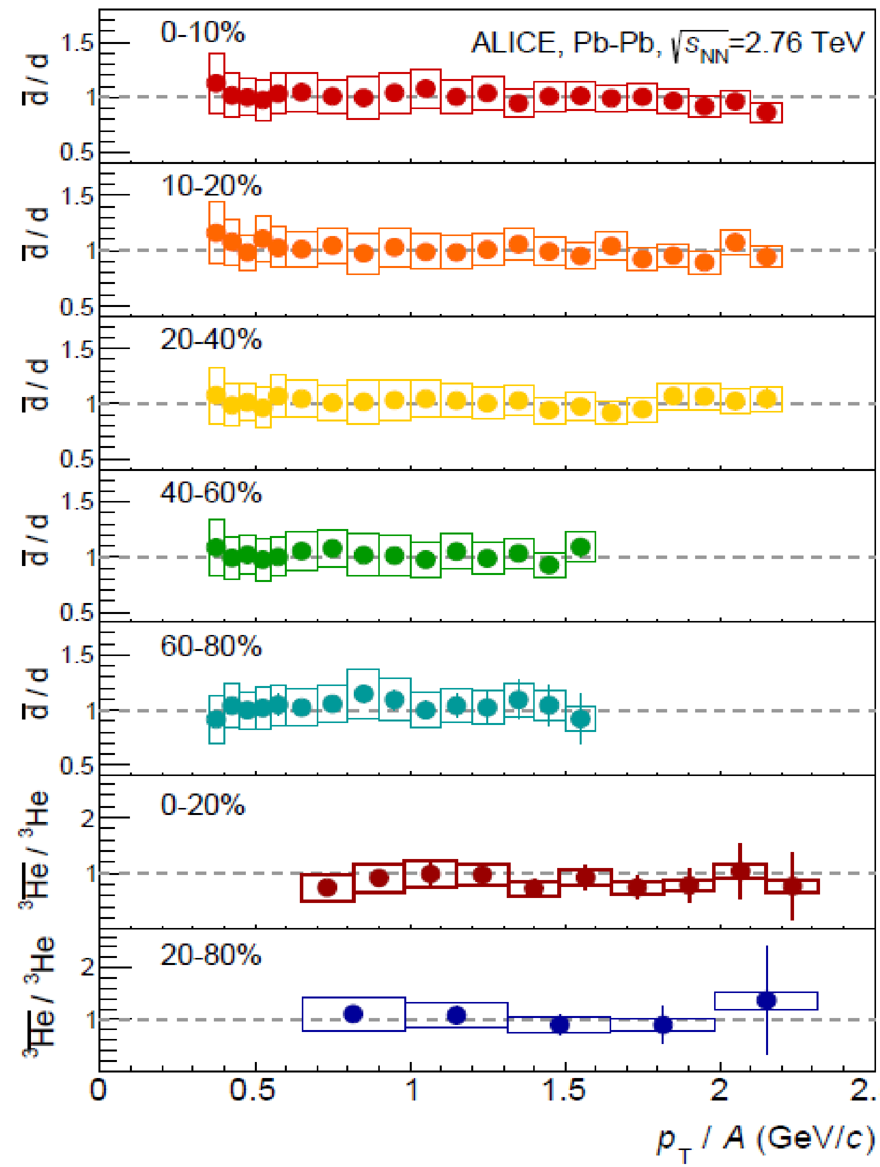
DCA = distance of closest approach of a track from the primary vertex
separation of primaries from secondaries through vertex cut -
important for particles, not anti-particles

Production of nuclei and anti-nuclei at the LHC

ALICE PRC88 arXiv:1303.0737

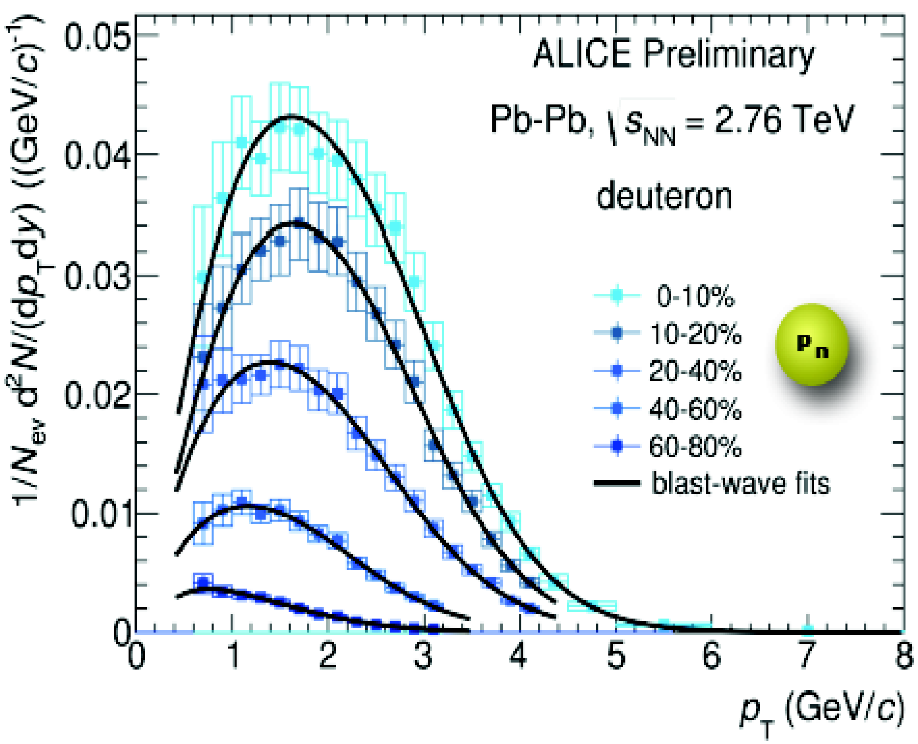


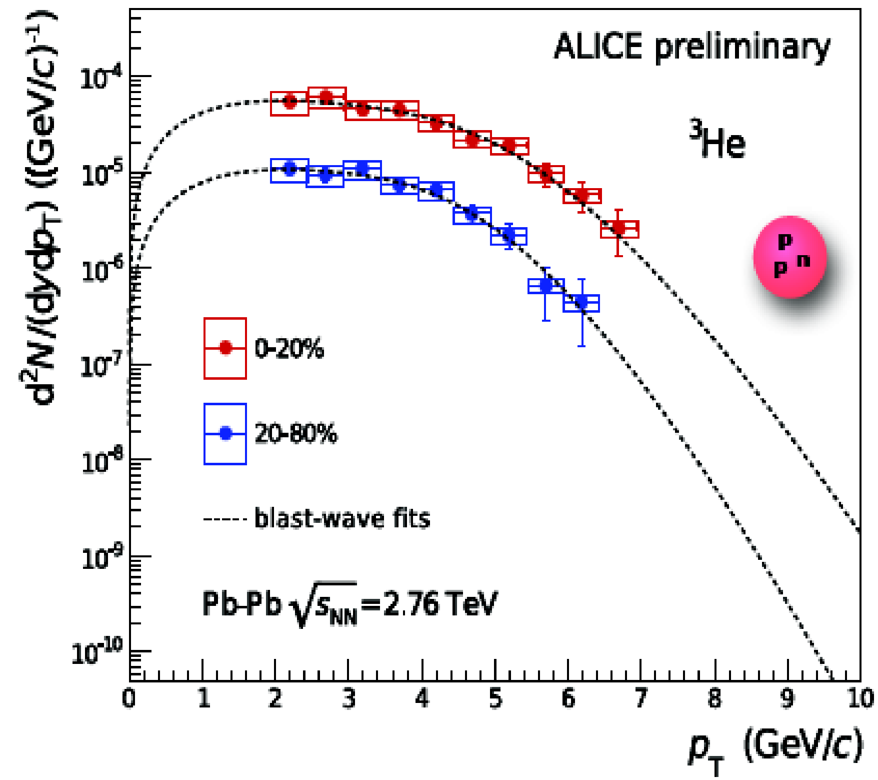
arXiv: 1506.08951



- matter and anti-matter produced in equal proportions at LHC
- consistent with net-baryon free central region, (μ_b < 1 MeV)

Measurement of transverse momentum spectra





composite objects participate in hydrodynamic flow
spectra described by hydro-inspired 'blast wave' approach
obtain $\langle\beta\rangle \approx 0.6$

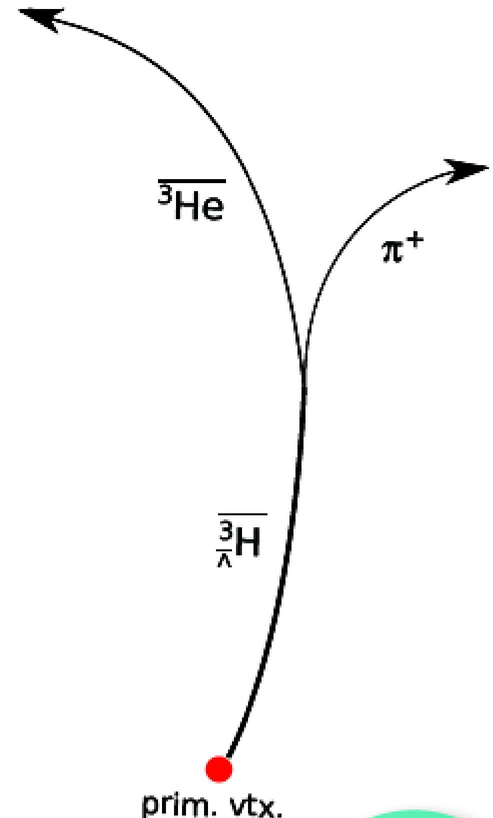
Hypertriton identification via particle ID and vertex measurements

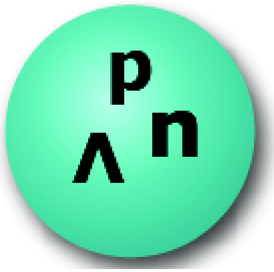
Identification of light nuclei which are daughter tracks originating from decay vertices

Lifetime similar to lifetime of free Λ

m(Hypertriton) = 2.991 ± 0.002 GeV/c^2

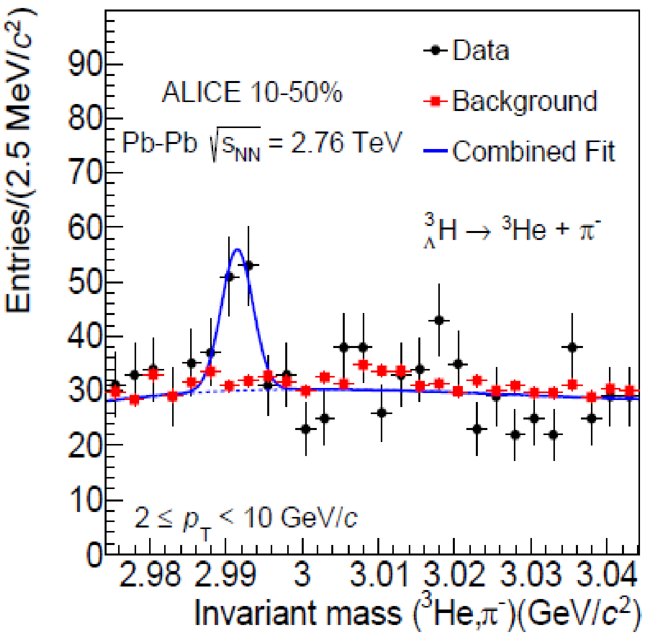
investigated decay channel:
Hypertriton → ^{3}He + π^-

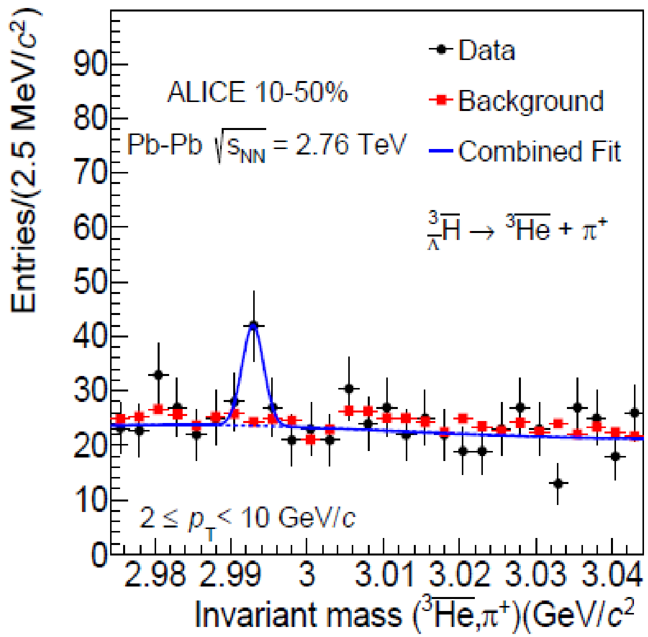


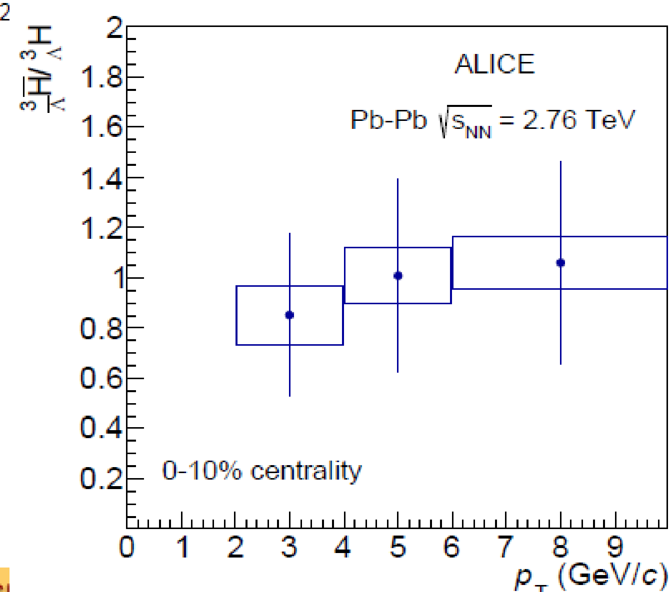


Hypertriton results

arXiv:1506.08453







Statistical hadronization model and experimental data

starting point: the statistical model – grand canonical

partition function: $\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$

particle densities: $n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i-\mu_i)/T) \pm 1}$

for every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **fit at each energy provides values for T and μ_b**

- get yields of all hadrons

for dN/dy need in addition volume per unit y - fix to dN_{ch}/deta

good fit to data for central collisions of heavy nuclei at AGS, SPS, RHIC, LHC

see e.g. A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A722(2006)167 nucl/th/0511071

implementation of our statistical model

in total 426 hadrons and composites (nuclei etc.) included – all states considered confirmed by PDG
precision of e+e- data and LHC data requires this
(currently updating for newly found states)

finite volume correction

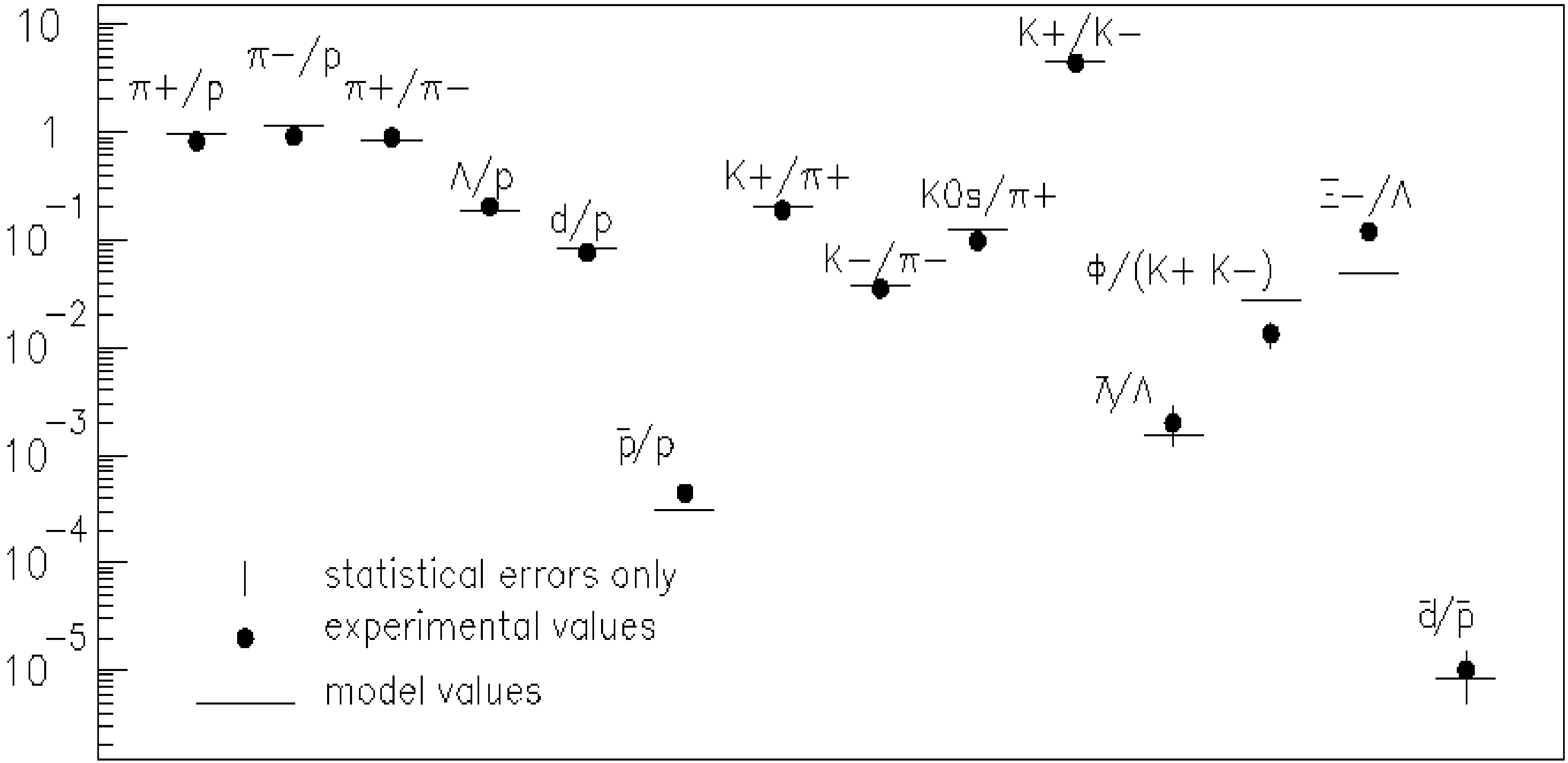
interactions as Van der Waals gas via excluded volume

for inclusion of charm-quarks canonical correction factors

first successful application of thermal model - AGS data

14.6 A GeV/c central Si + Au collisions and GC statistical model

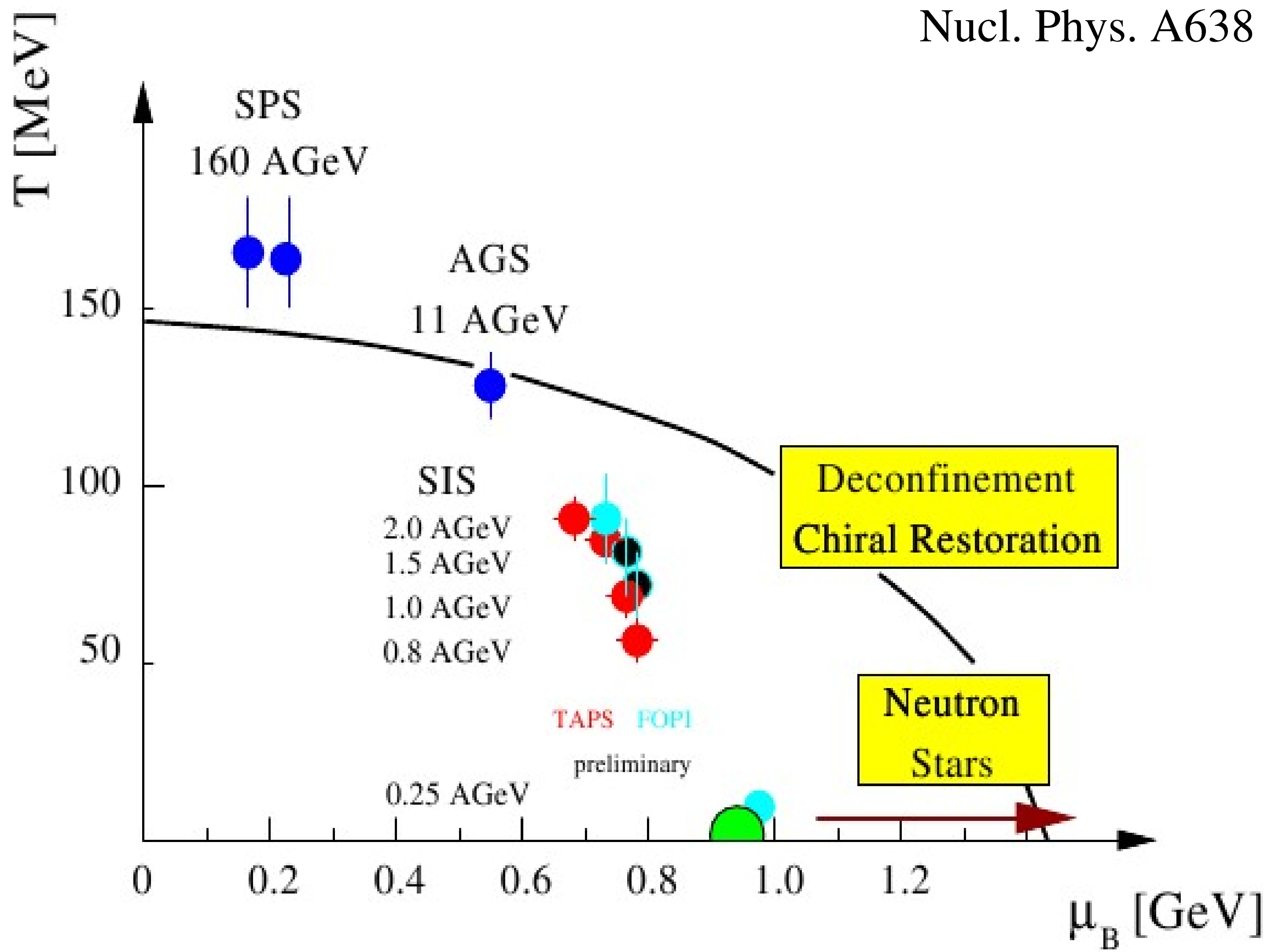
P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994



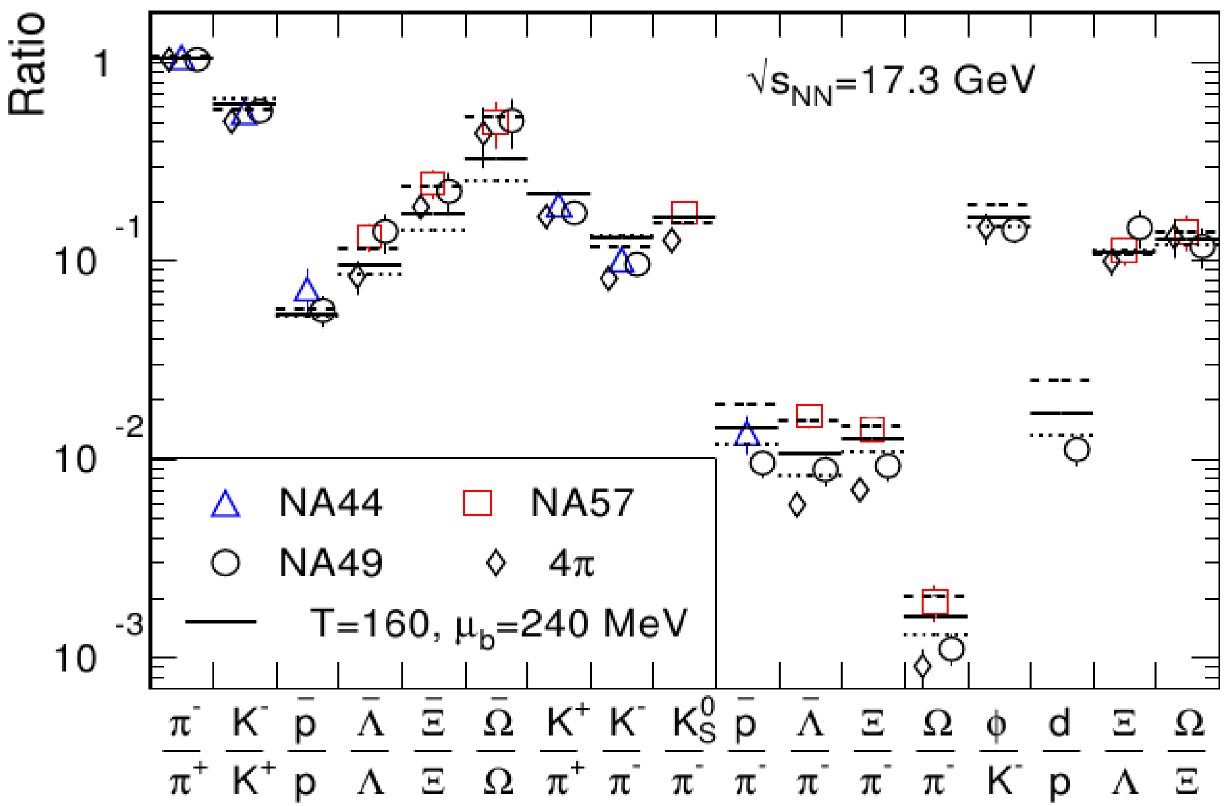
dynamic range: 9 orders of magnitude! No deviation

leading to the first phase diagram with experimental points

P.Braun-Munzinger and J. Stachel, nucl-th/9803015,
Nucl. Phys. A638 (1998) 3



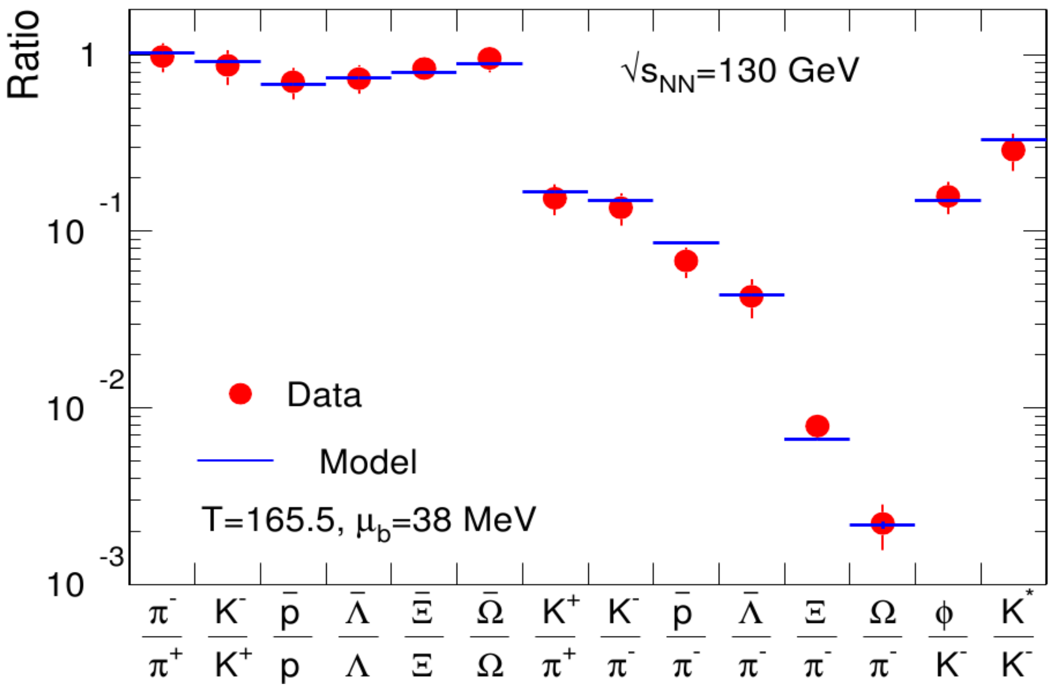
SPS data and thermal model

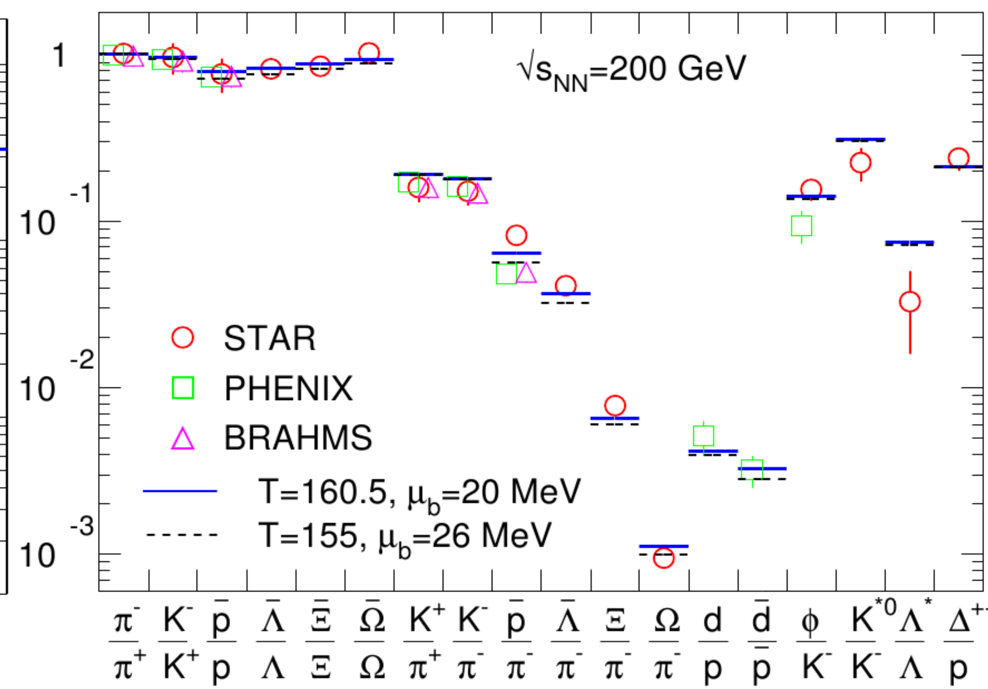


RHIC hadron yields reproduced really well compared to statistical model (GC)

130 GeV data in excellent agreement with thermal model predictions

prel. 200 GeV data fully in line still some experimental discrepancies

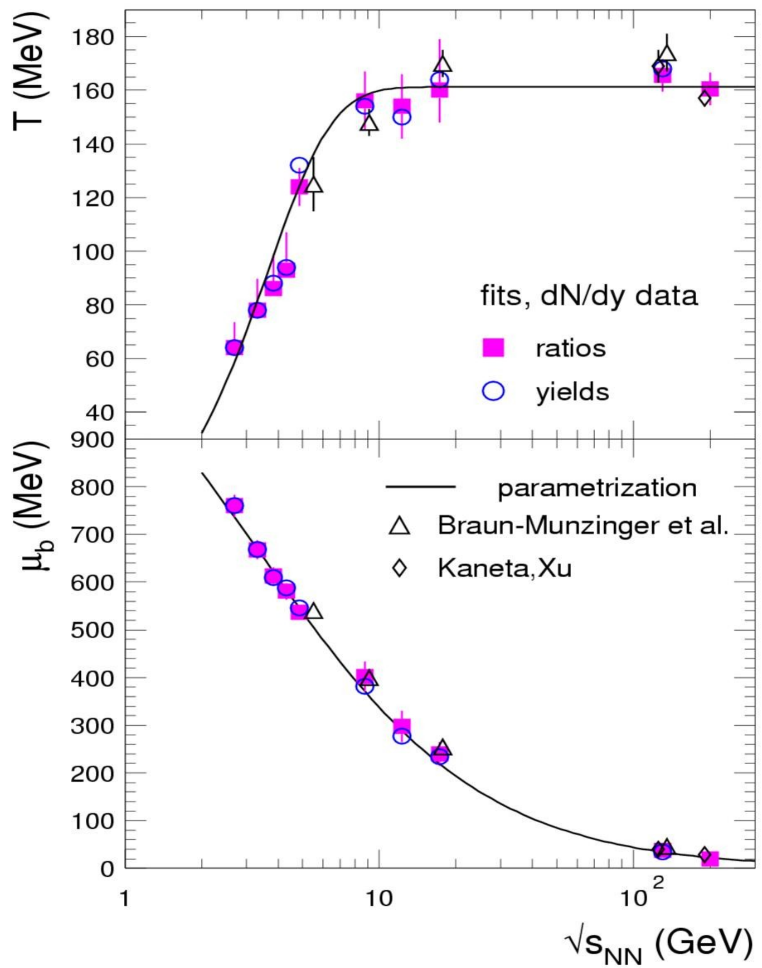




chemical freeze-out at: T = 165 ± 5 MeV

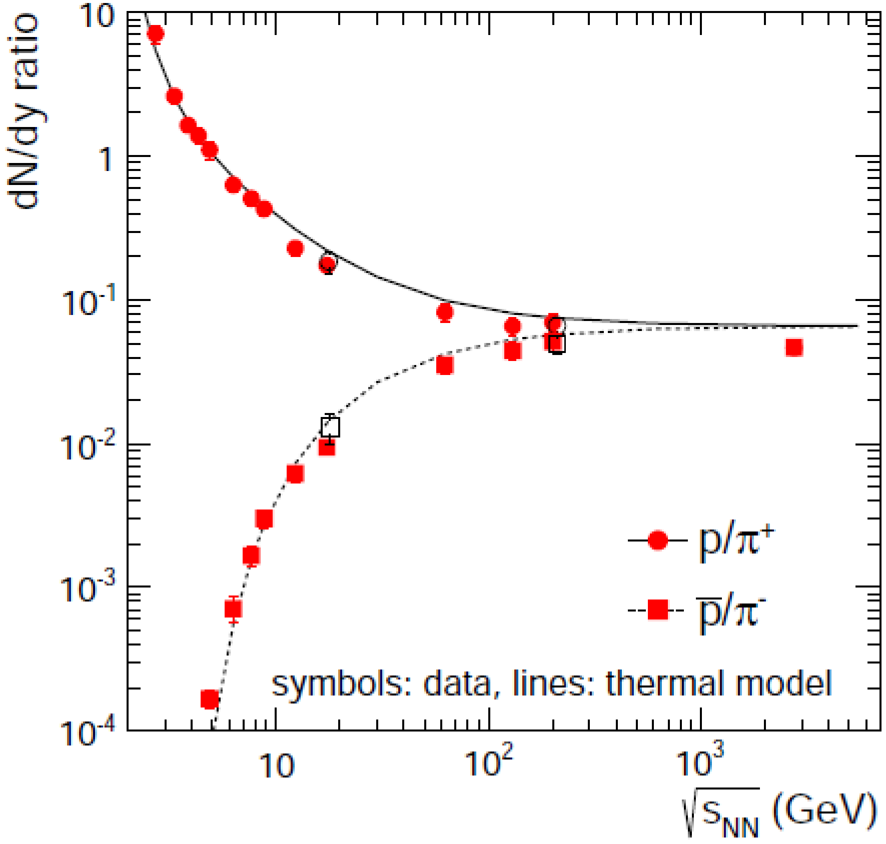
P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167
confirmed by Xu and Kaneta and by F. Becattini

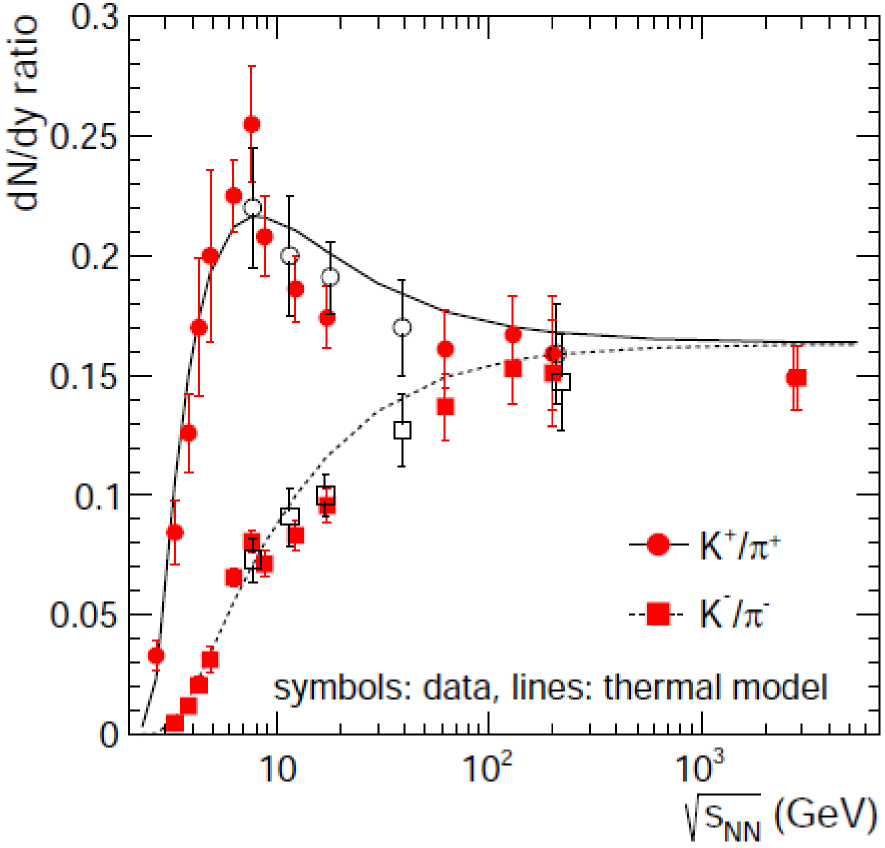
Systematic evolution of T and mu_b with beam energy



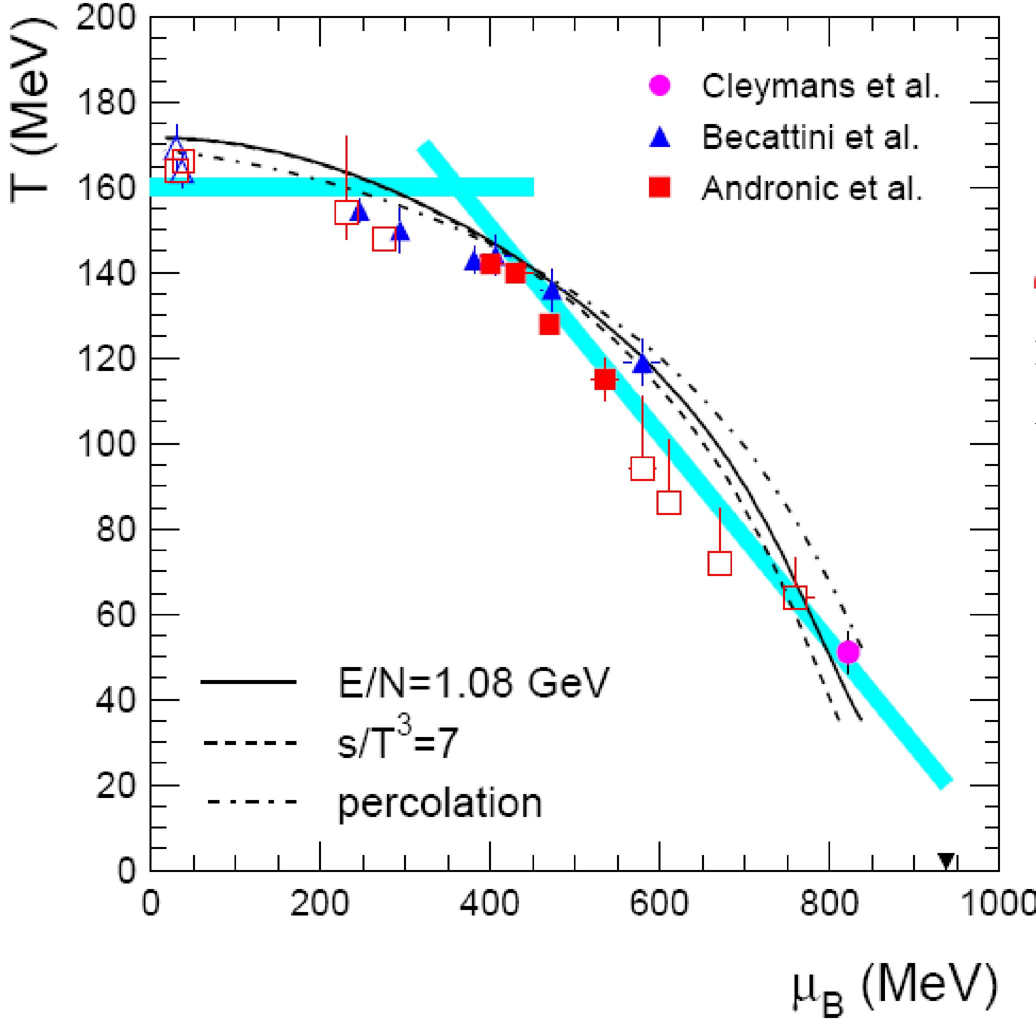
beam energy dependence of hadron yields from AGS to LHC

following the observed evolution of T and μ_b, detailed features of proton/pion and kaon/pion ratios reproduced in detail





experimental knowledge of the QCD phase diagram



- agreement between groups doing finite temperature lattice gauge theory:
  $T_c(\mu=0)$ = 150-160 MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat] S. Borsanyi et al., arXiv:1005.3508 [hep-lat]

- data points 'chemical' freeze-out of hadrons from abundancies

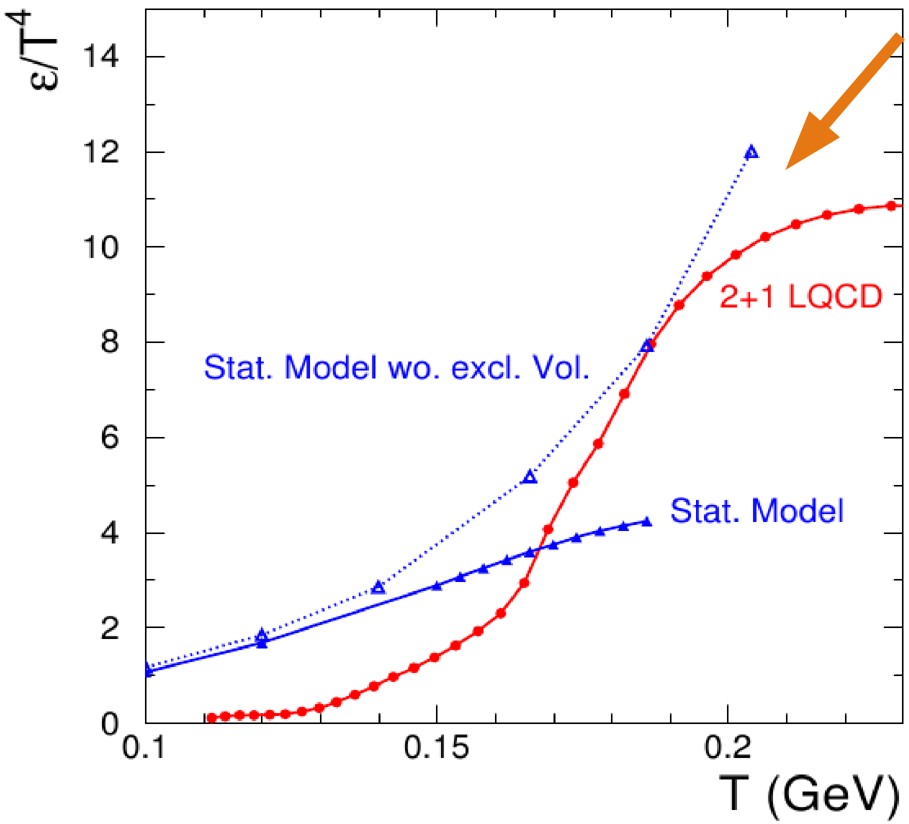
A. Andronic, P. Braun-Munzinger, J. S., Nucl. Phys. A772 (2006) 167

T_{chem} saturates apparently at T_c not trivial

equilibration driven by high densities near T_c

rapid equilibration within a narrow temperature interval around T_c by multi-particle collisions due to steep temperature dependence of densities

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

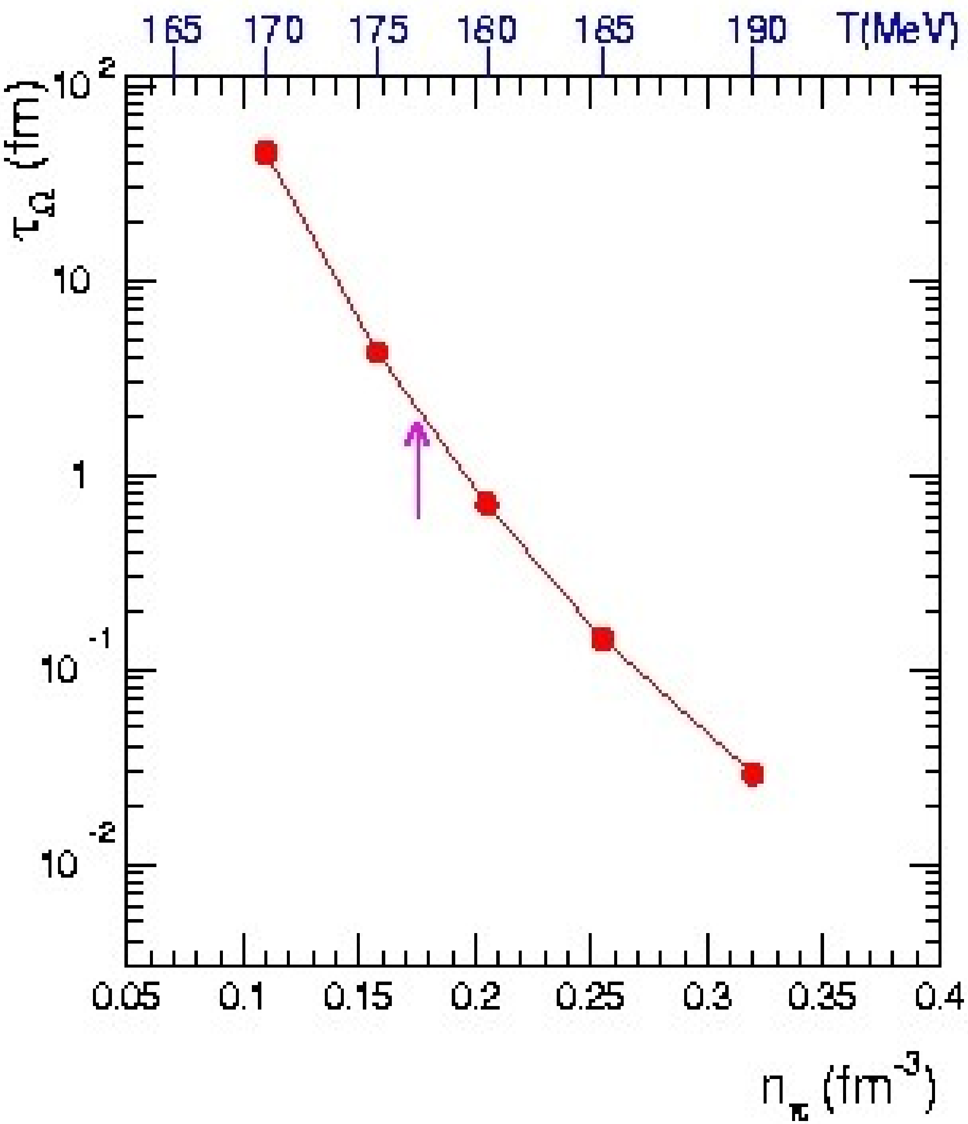


for T_{ch} 20-30 MeV below T_c very hard to maintain scenario of simultaneous freeze-out of all hadron species

estimate upper limit of $T_c - T_{ch} = 5$ MeV

⇒ requires $T_c \approx 160$ MeV experimental determination!

density dependence of characteristic time for strange baryon production



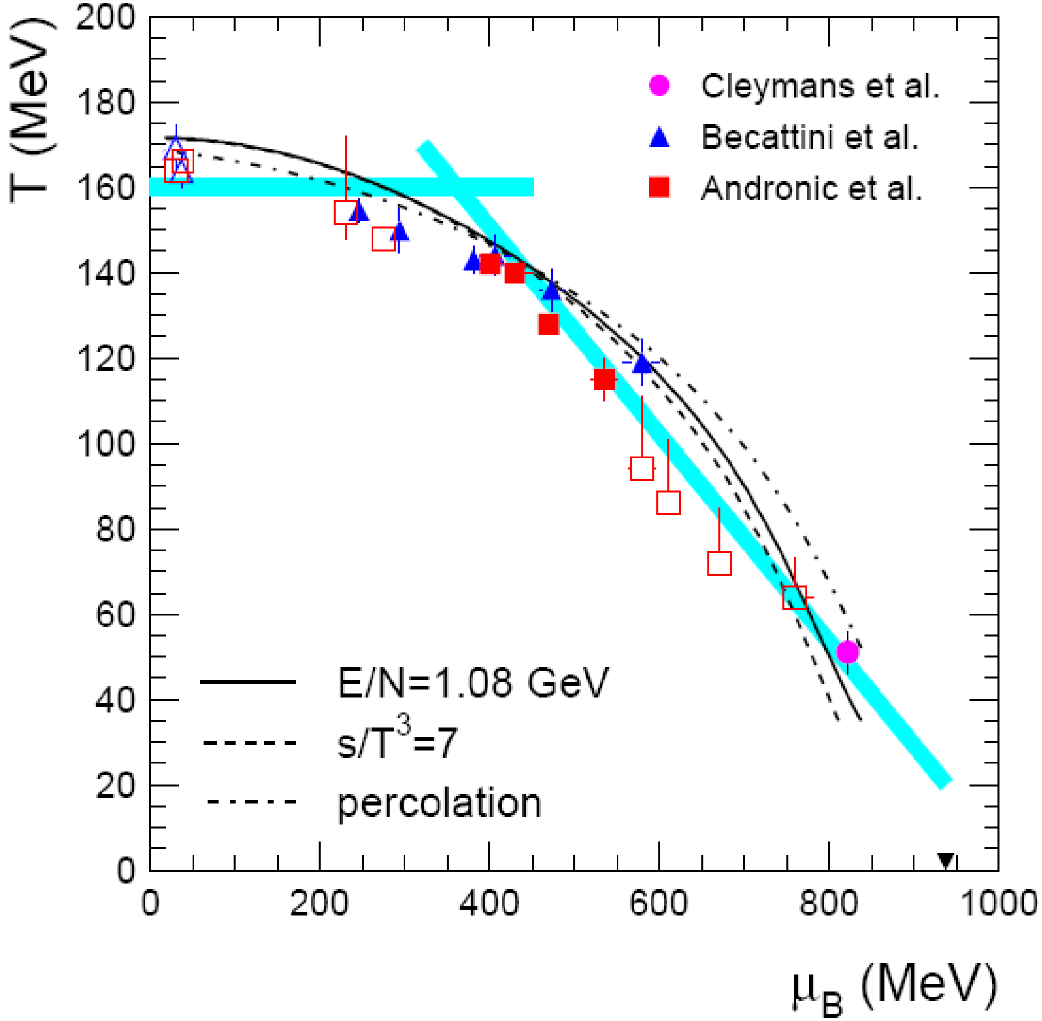
- near phase transition particle density varies rapidly with T (see previous slide)
- for SPS energies and above reaction such as 2π+KKK$\rightarrow$ Ω Nbar bring multi-strange baryons close to equilibrium rapidly
- in region around T_c equilibration time $\tau_\Omega \propto T^{-60}$!
- increase n_π by 1/3: τ = 0.2 fm/c (corresponds to increase in T by 8 MeV) decrease n_π by 1/3: τ = 27 fm/c

$\rightarrow$ all particles freeze out within a very narrow temperature window due to the extreme temperature sensitivity of multi-particle reactions

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

phase diagram and chemical freeze-out points 2009

A. Andronic et al. ArXiv 0911.4806[hep-ph]



based on this prediction for LHC:

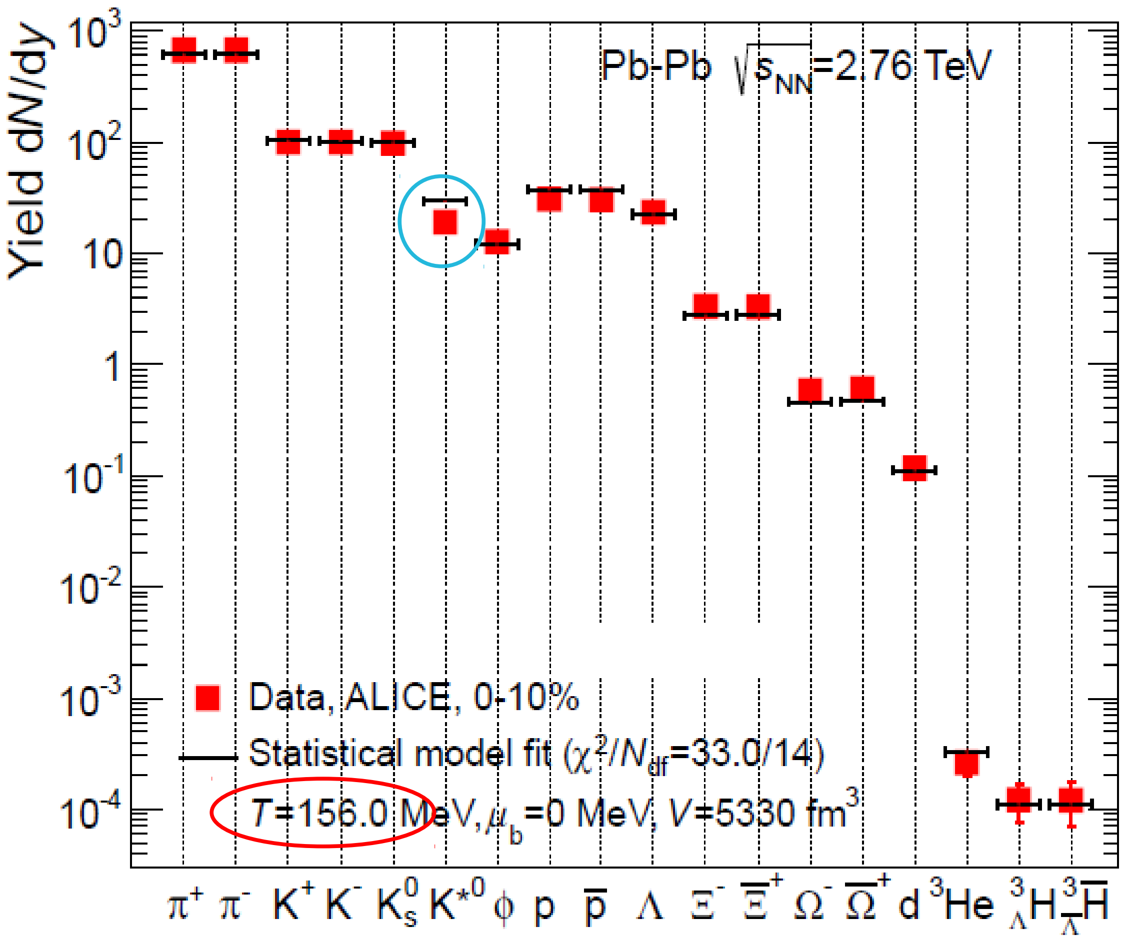
$T = 161 \pm 4$ MeV and $\mu_b = 0.8^{+1.2}_{-0.6}$ MeV

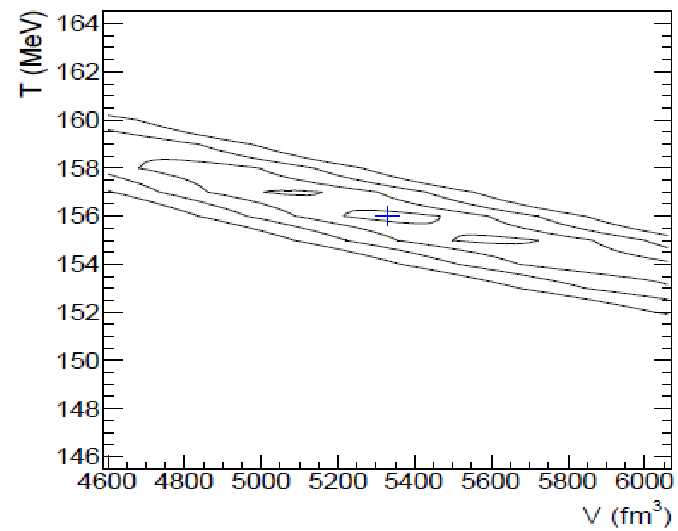
A. Andronic, P. Braun-Munzinger, J.S. arXiv:0707.4076 [nucl-th]

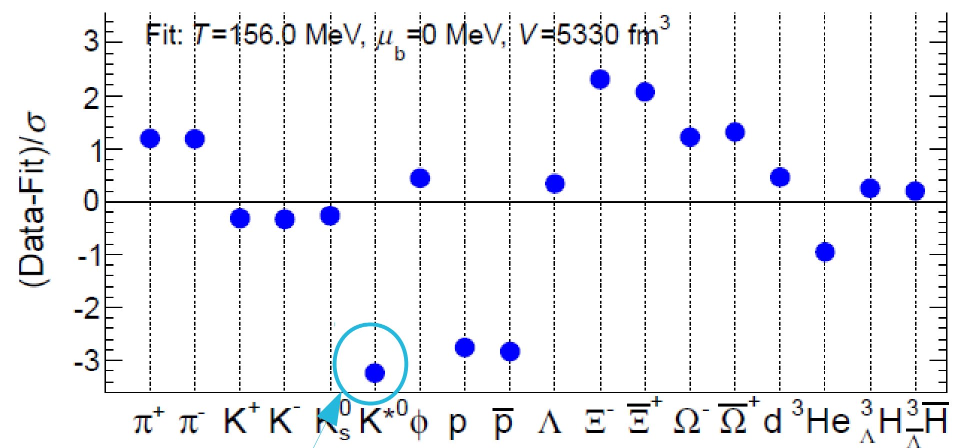
over the coming years these numbers moved a little due to RHIC data

LHC data

Fit to data from ALICE at the LHC





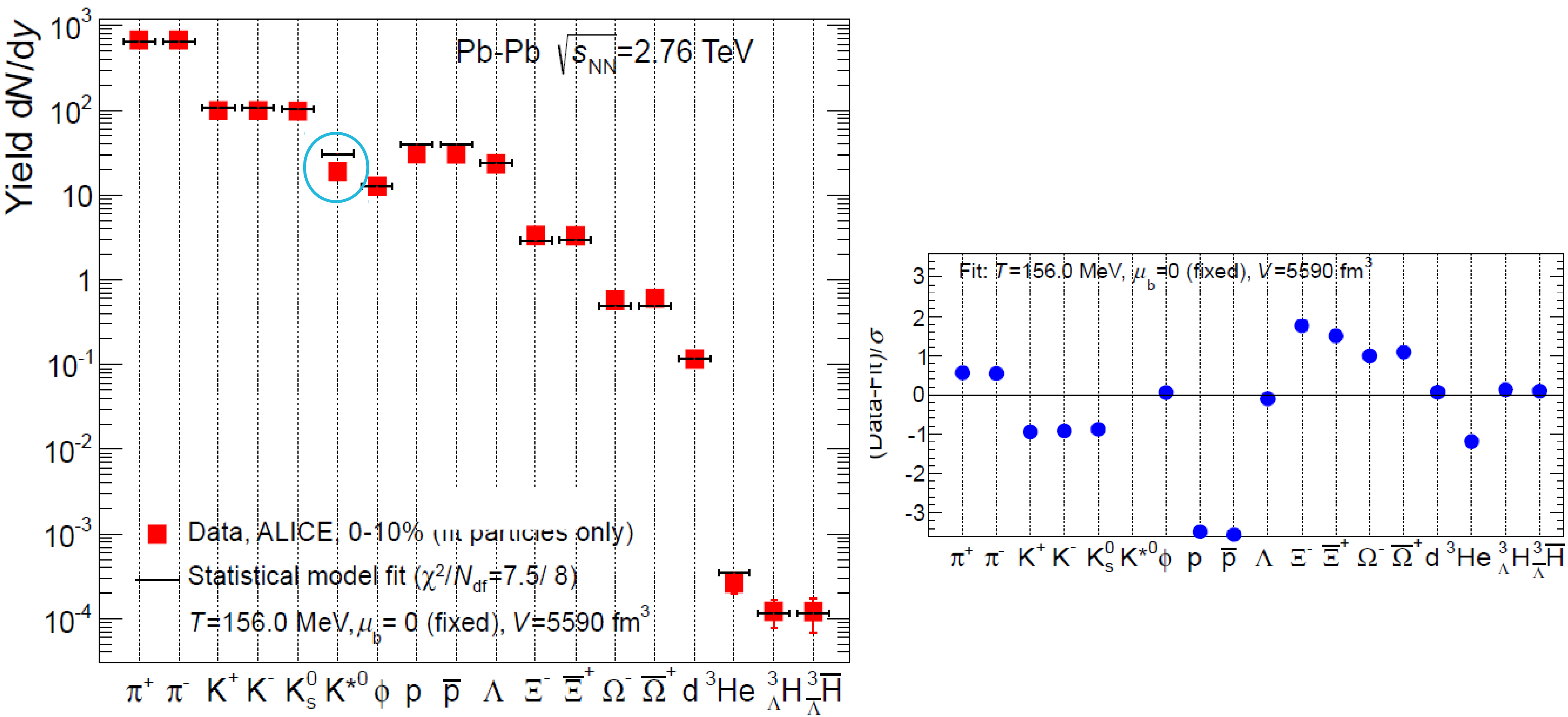


T = 156 MeV
red. $X^2 = 2.33$

protons low by 2.8 σ

strongly decaying resonance

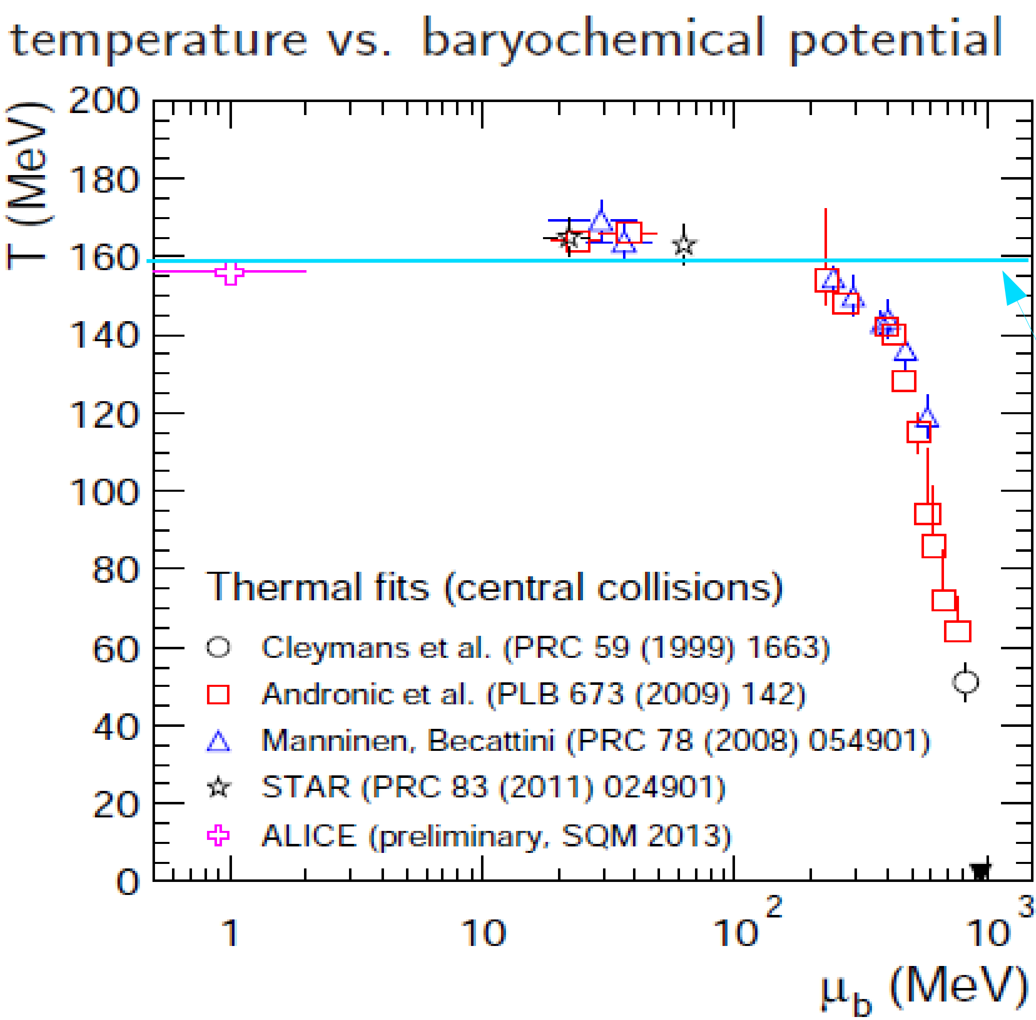
fit excluding protons



<u>excluding protons:</u> T unchanged

perfect fit for other hadrons

Energy dependence of temperature and baryochem pot.



hadron yields for Pb-Pb central collisions from LHC down to RHIC, SPS, AGS and even SIS energies well described by a statistical ensemble

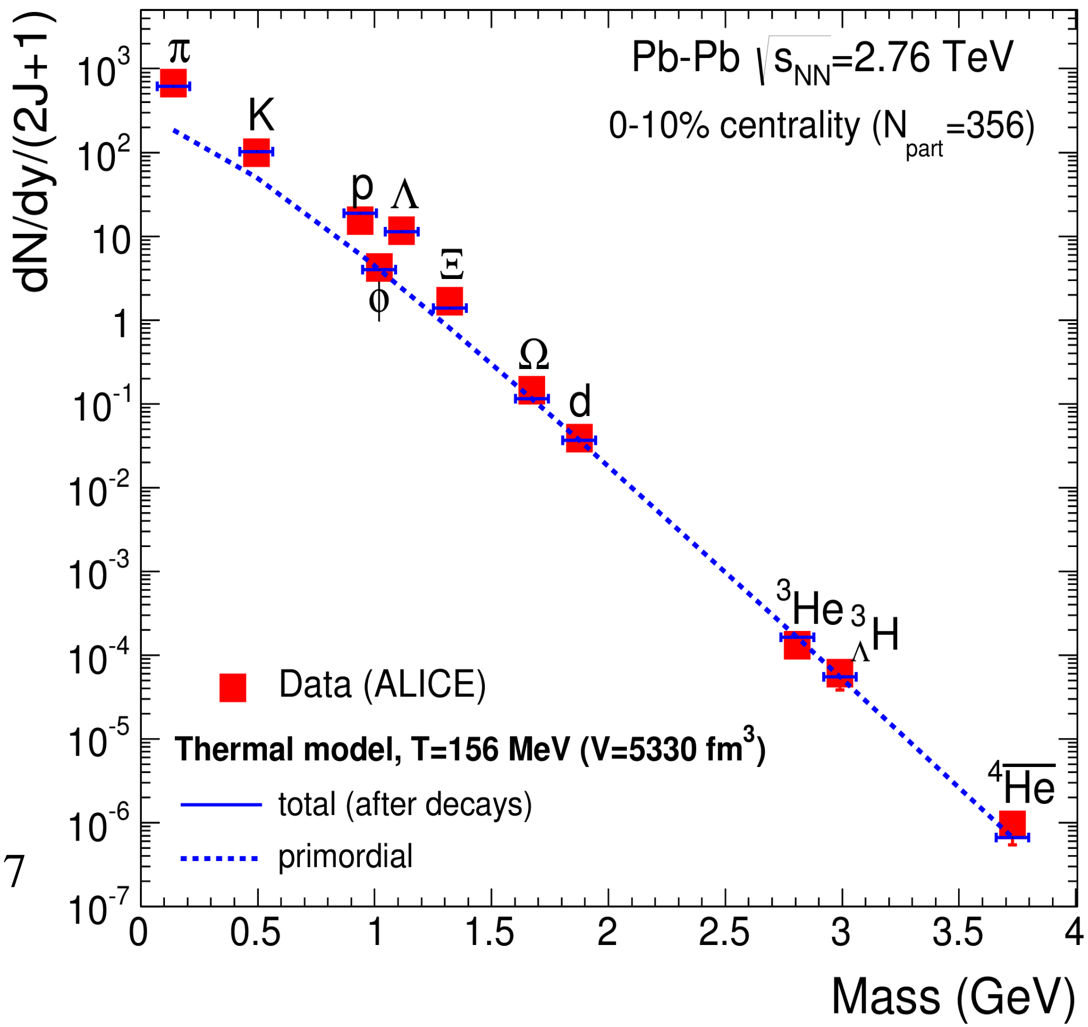
- there is a limiting temperature for a hadronic system

$T_{lim} = 159 \pm 3$ MeV

reached for $\sqrt{s_{NN}} \geq 10$ GeV

Quark- hadron duality

agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)



works equally well for nuclei and loosely bound (anti)hyper-nuclei

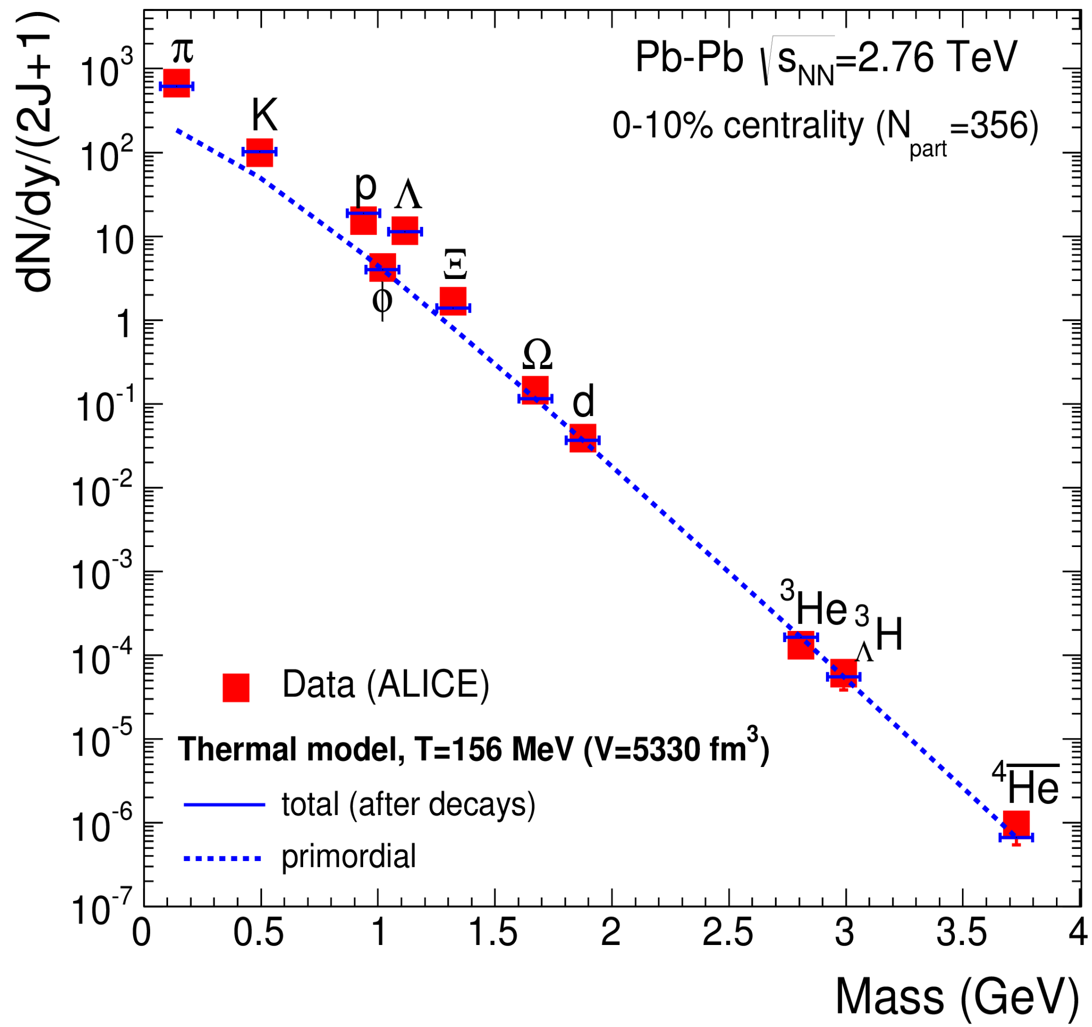
prediction P. Braun-Munzinger, J.S., J.Phys. G28 (2002) 1971-1976, J.Phys. G21 (1995) L17

strong indication of isentropic expansion in hadronic phase

Loosely bound states in PbPb collisions

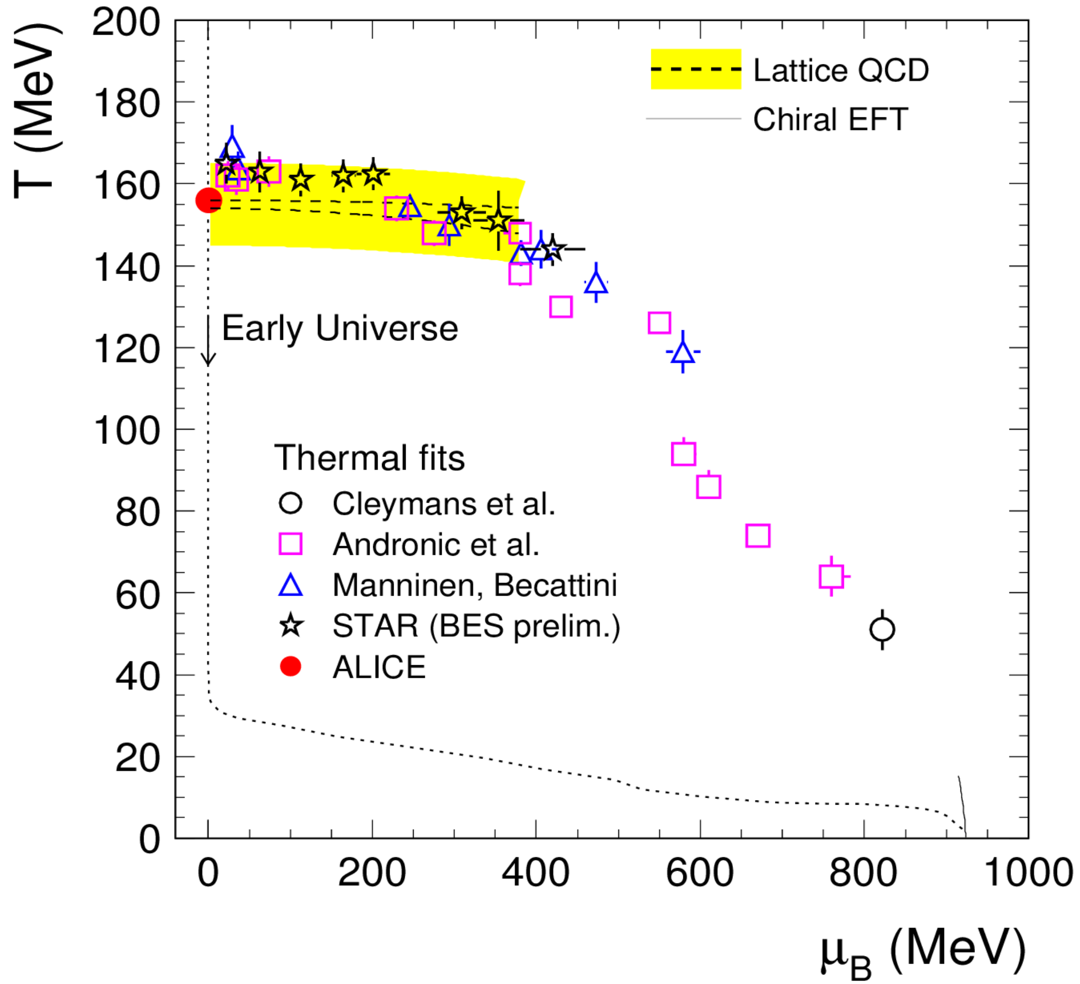
PbPb central collisions: even Efimov-like states (hypertriton) produced with yields fixed at the phase boundary

T 3 oom higher than Lambda separation energy



The QCD phase diagram – experiment and lattice QCD

experimental hadronic freeze-out points coincide with pseudocritical temperature T_c from state-of-the-art lattice QCD for high collision energies

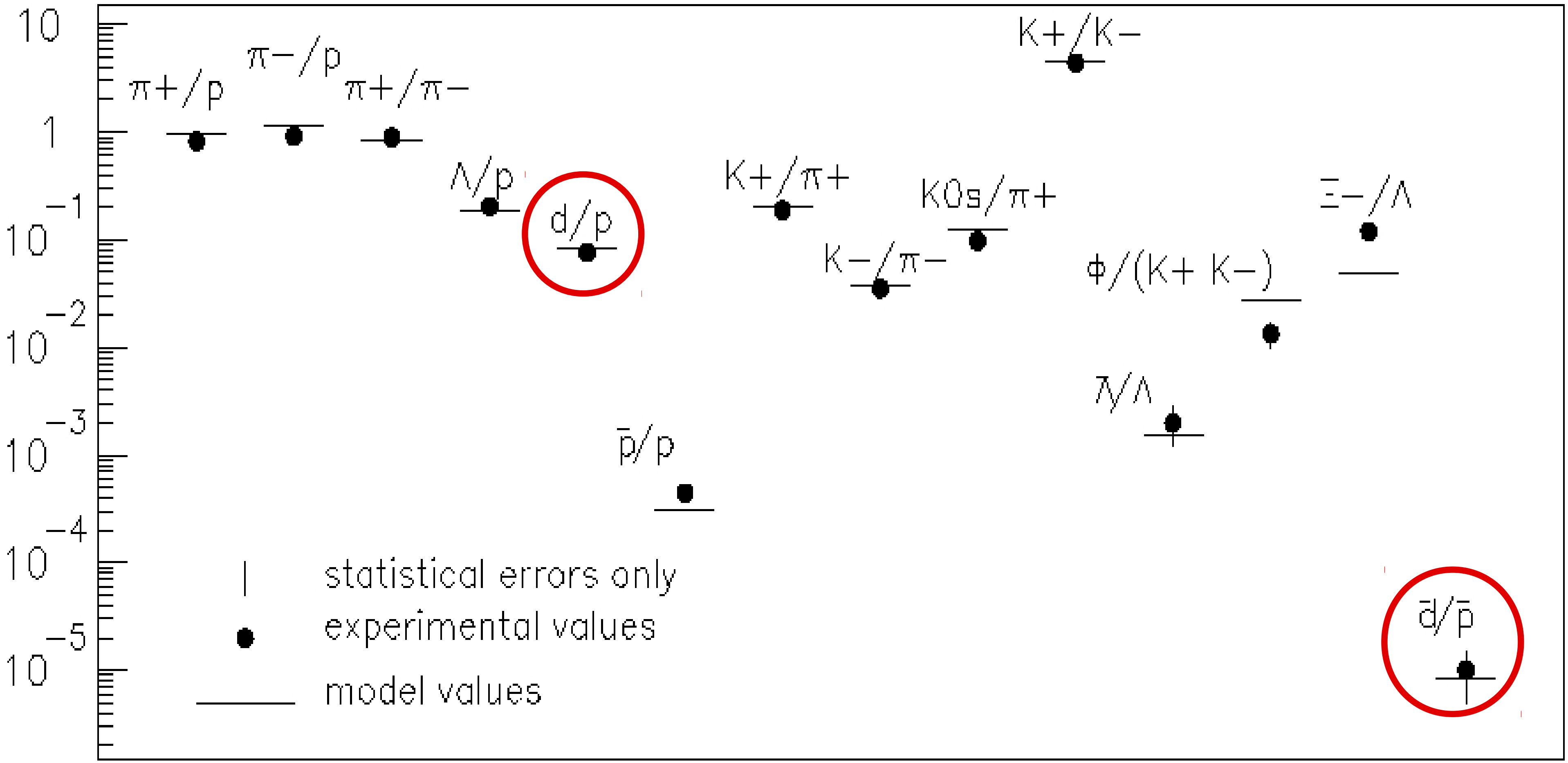


Revisit formation of (anti-)nuclei

first fit to AGS data – reproduces yields of d and dbar

14.6 A GeV/c central Si + Au collisions and GC statistical model

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994



dynamic range: 9 orders of magnitude! No deviation

Should nuclei follow prediction of statistical hadronization at all?

Argument has been made, that coalescence is responsible for their formation and this is different mechanism

However: for system in thermal equilibrium, statistical ensemble and coalescence results agree
d/p is given by entropy per baryon (see already Siemens and Kapusta PRL 43 (1979) 1486 - S/A μ -ln(d/p))
while lightly bound nuclei may well be destroyed and built again during isentropic expansion, ratio of their abundance is frozen in by S/B and doesn't change

for system in thermal equilibrium statistical and coalescence yields agree

P. Braun-Munzinger, J. Stachel, J. Phys. G21 (1995) L17

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7

	Thermal Model		
Particles	T=.120 GeV	T=.140 GeV	Coalescence Model
d	15	19	11.7
t+^{3}He	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
$^{5}_{\Lambda\Lambda}$H	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
$^{6}_{\Lambda\Lambda}$He	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
$^{7}_{\Xi^0\Lambda\Lambda}$He	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}\mathrm{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}\mathrm{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}\mathrm{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}\mathrm{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}\mathrm{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

Production of light nuclei and antinuclei at the AGS

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

<u>data cover 10 oom!</u>

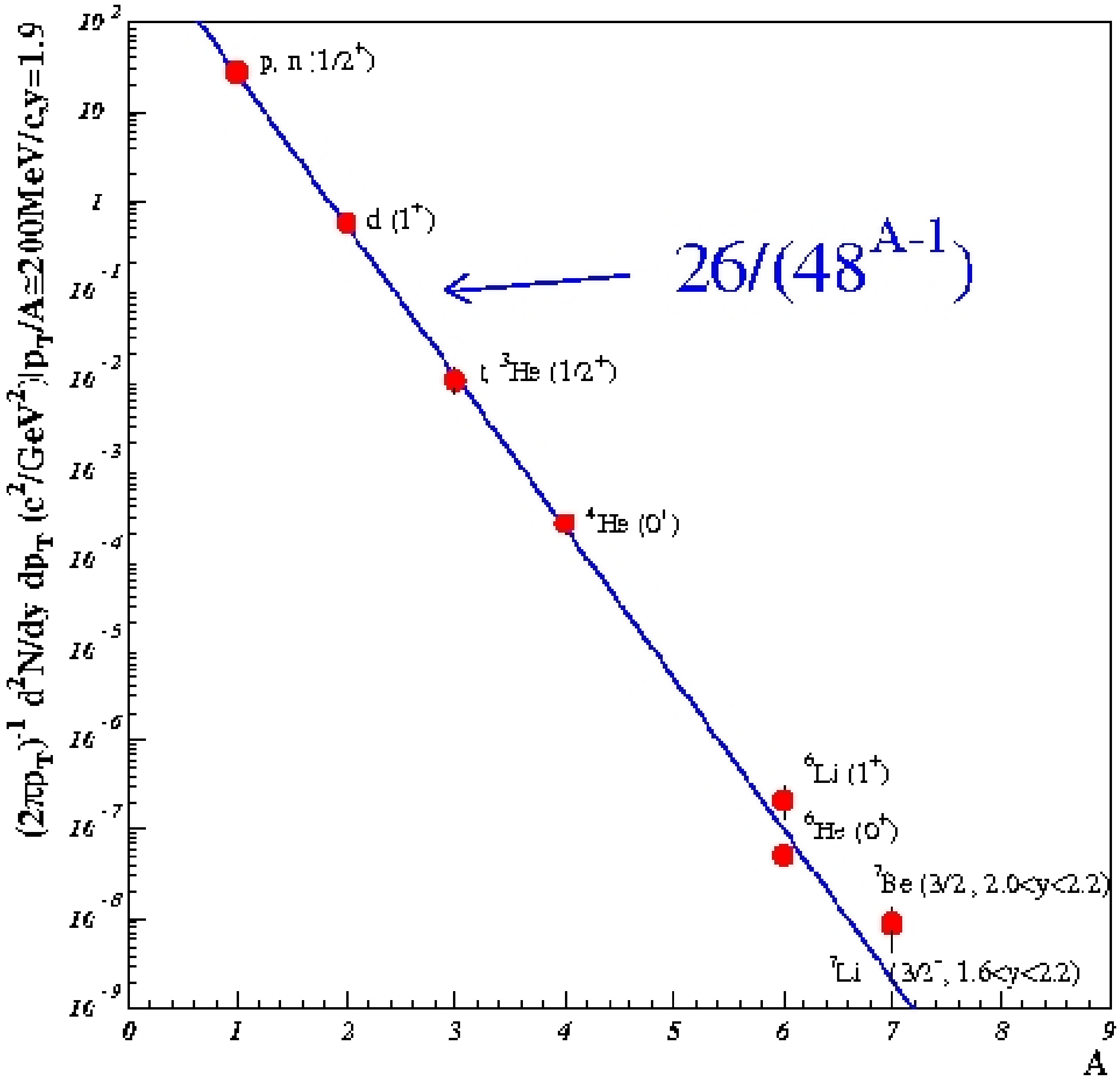
addition of every nucleon

-> penalty factor $R_p = 48$

but data are at very low pt

use m-dependent slopes following systematics up to deuteron

-> $R_p = 26$



<u>GC statistical model:</u>

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

for T=124 MeV and μ_b= 537 MeV

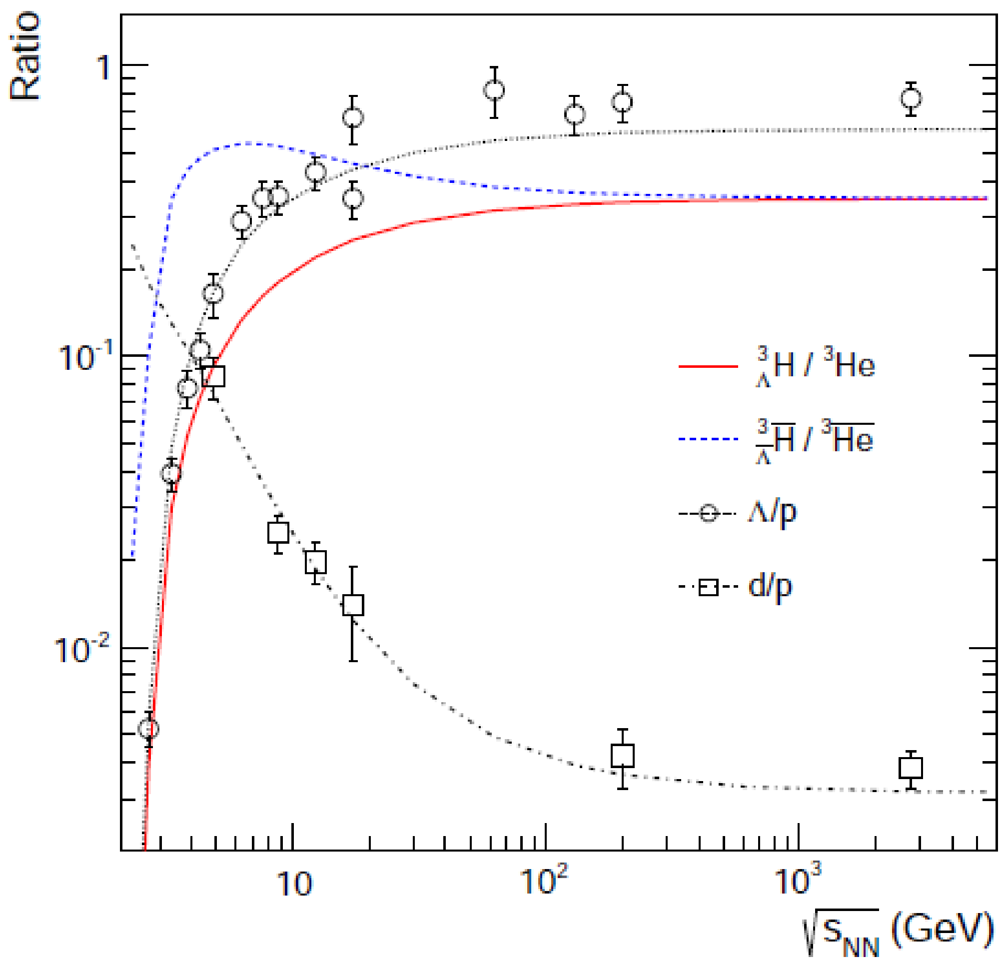
$R_p = 24$ good agreement

also good for **antideuterons**:

data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

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

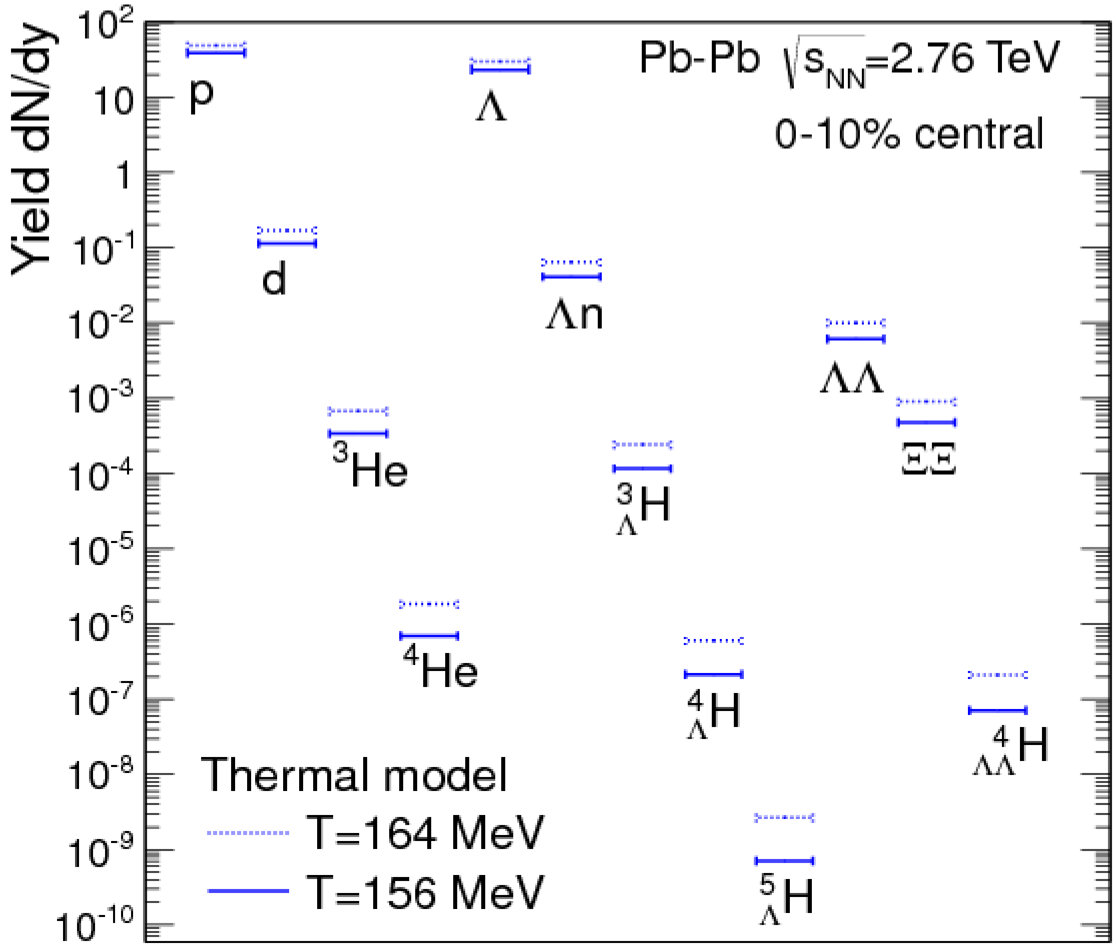
energy dependence of d/p ratio and themal model prediction



agreement of data from Bevalac/SIS energies up to LHC
with thermal model prediction

A.Andronic, P.Braun-Munzinger, J.S., H. Stöcker, PLB697 (2011)203

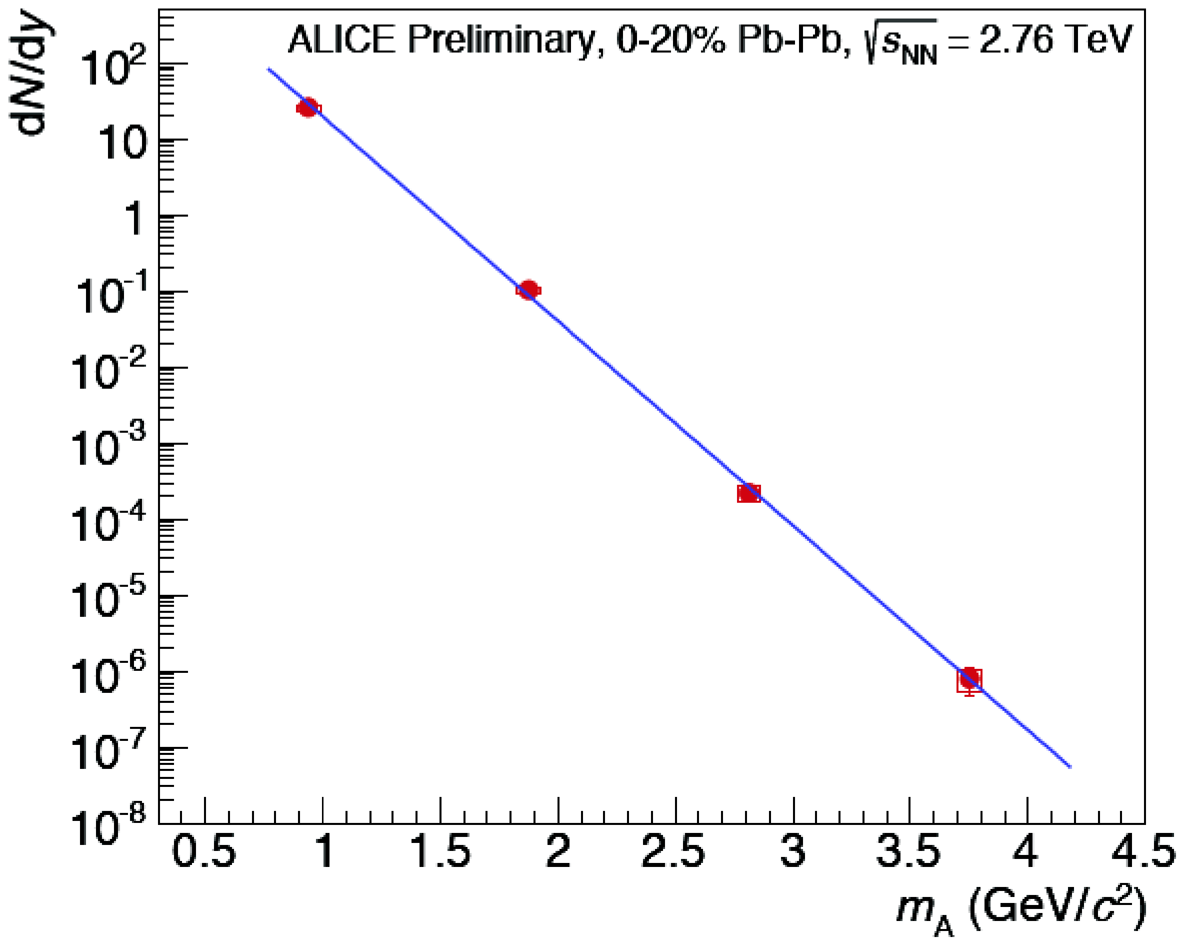
Predictions for nuclei and hypernuclei and exotica



values for ^{4}He, ^{3}He and $^3{}_\Lambda$H were predictions and are in excellent agreement with new data from ALICE

test of statistical hadronization model over another 3 orders of magnitude

Production of light anti-nuclei at LHC energy



penalty factor exp(-m/T) ≈ 300

a direct comparison of LHC data and lattice QCD

fluctuations of conserved charges (baryon number, strangeness, charge) sensitive to criticality related to spontaneous breaking of chiral symmetry

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

with $\hat{P} = P/T^4$, $\hat{\mu}_N = \mu_N/T$ and $N, M = (B, S, Q)$

- exhibit characteristic properties governed by universal part of free energy in lQCD chiral transition in O(4) critical region

  can we see signs of this criticality in experimental data?
- direct measurement of higher moments of fluctuations of conserved charges very challenging, for LHC under way (very statistics hungry!)
- 2nd order cumulants of conserved charges can be obtained from measured inclusive distributions in case probability distribution of number of particles and antiparticles are Poissonian and uncorrelated

P. Braun-Munzinger, A. Kalweit, K. Redlich, J.S. PLB in print, arXiv:1412.8614

Fluctuations of net charges

susceptibilities of a conserved charge related to variance of net charge distribution

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

if e.g. baryon and antibaryon distributions are Poisson, the net baryon distribution is a Skellam distribution

variance of Skellam distribution given by mean of total number of baryons + antibaryons

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

can be directly computed from measured ALICE data using rapidity densities of measured baryon and antibaryon yields:

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

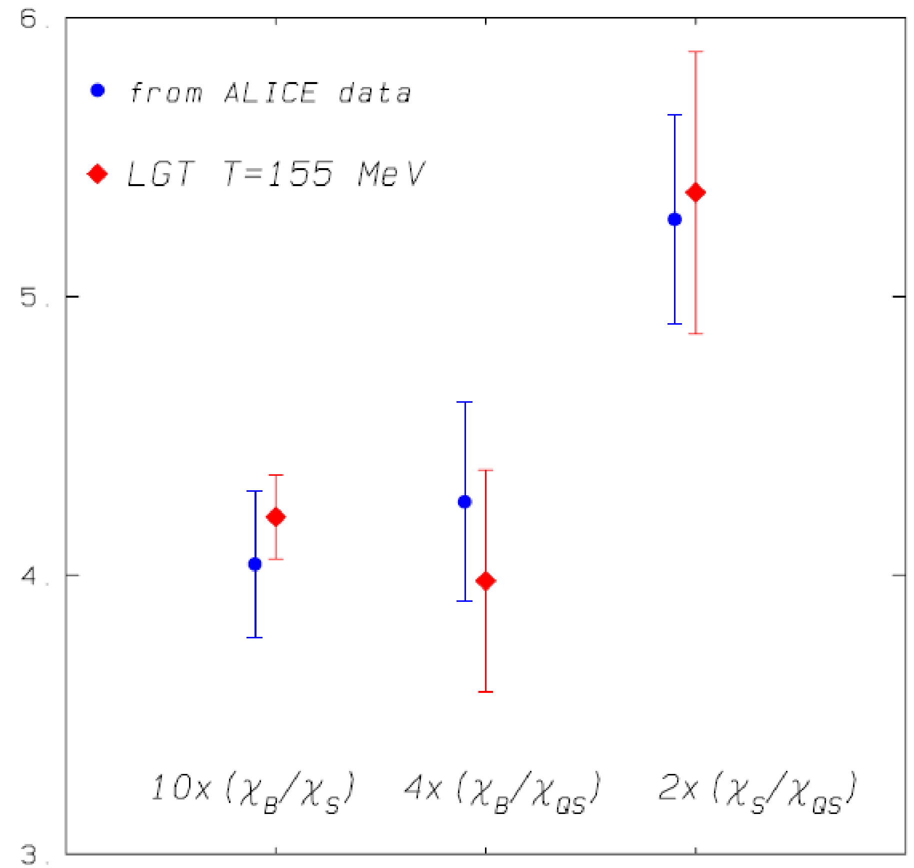
and equivalent for strangeness using strange hadron yields or electric charge/strangeness correlations using charged strange hadron yields

Comparison chiral susceptibilities data and lQCD

ALICE data: $$\frac{\chi_B}{T^2} \simeq \frac{1}{VT^3}(203.7 \pm 11.4)$$
$$\frac{\chi_S}{T^2} \simeq \frac{1}{VT^3}(504.2 \pm 16.8)$$
$$\frac{\chi_{QS}}{T^2} \simeq \frac{1}{VT^3}(191.1 \pm 12).$$

- in ratios of susceptibilities volume and temperature drop out
- compare to lattice QCD at pseudo-critical temperature for $\mu_b = 0$ and extrapolated to continuum limit

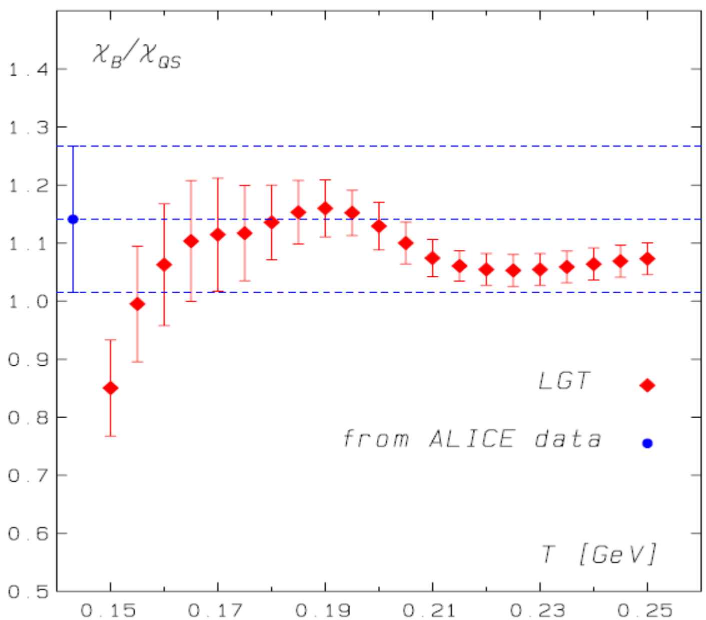
A.Basavov et al., PRL 113 (2014) 072001 and PRD 86 (2012) 034509

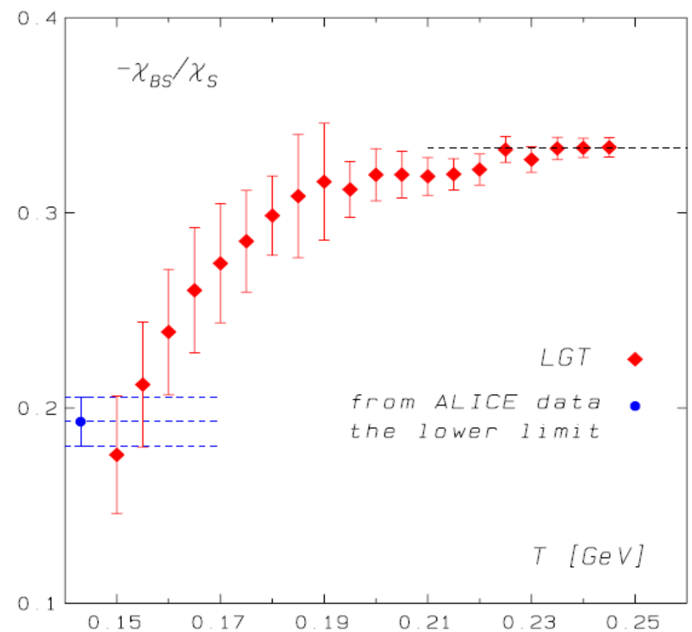


very good agreement data and lQCD
strongly suggests: fluctuations are of thermal origin and indeed established at the phase boundary

Can one limit temperature range by comparison to data?

evaluate susceptibilities from lQCD for a range of temperatures and compare to data





combination of these two plots: T > 150 MeV and T < 165 MeV
and independently: for T > 163 MeV, lQCD thermodynamics cannot be described by hadronic degrees of freedom (Karsch 2014)

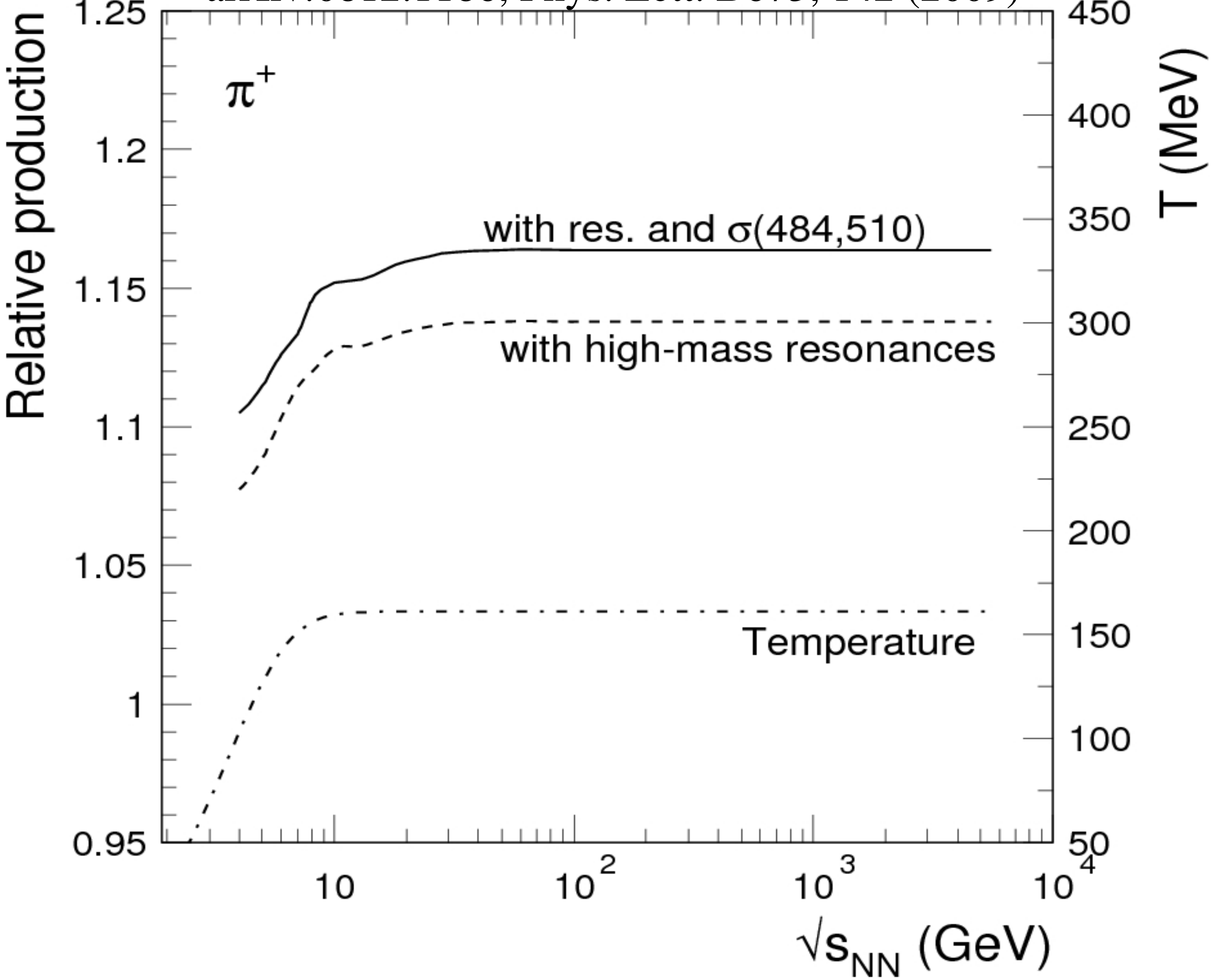
summary

- good knowledge of QCD phase diagram from lattice QCD close to μ_b=0
- comprehensive set of data on hadron yields from AGS to LHC energies
  data consistent with QCD statistical operator over 9 oom, chemical freeze-out very close to pseudocritical temperature from lQCD
- same pictures applies to the formation of (anti-)nuclei and hypernuclei
- fluctuations of conserved charges: linked to mean multiplicities
  values consistent with lQCD, indicative of thermal fluctuations at phase boundary

backup

relative change in pion yield with more high mass resonances and the σ

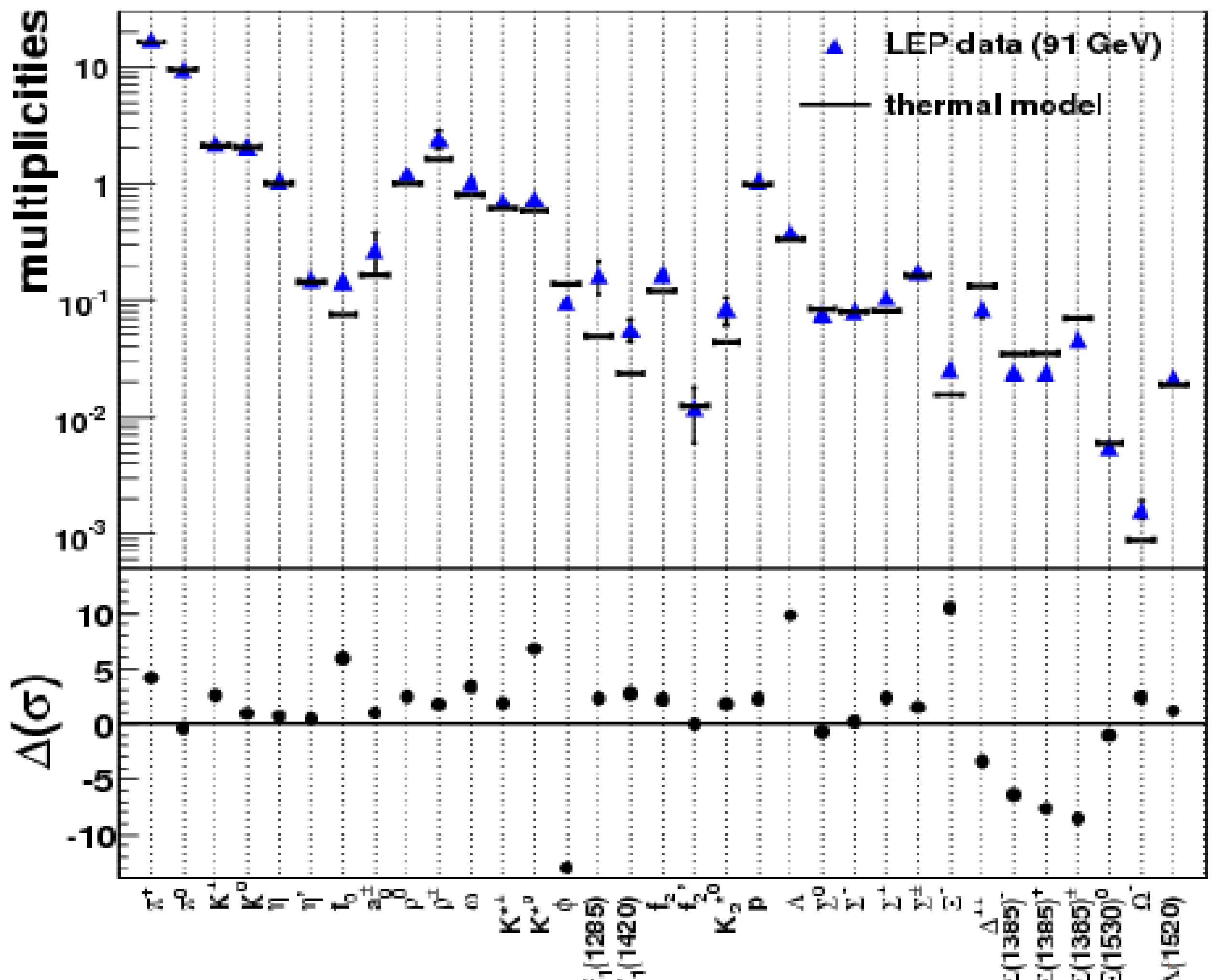
A. Andronic, P. Braun-Munzinger, J. Stachel,
arXiv:0812.1186, Phys. Lett. B673, 142 (2009)



as T levels off,
so does the increase in
pion yield

e+e- collisions: initialize thermal model with u,d,s,c,b – jets according to measurement (weak isospin)

A. Andronic, P. Braun-Munzinger, F. Beutler, K. Redlich, J. Stachel, Phys. Lett. B678 (2009)
arXiv 0804.4132

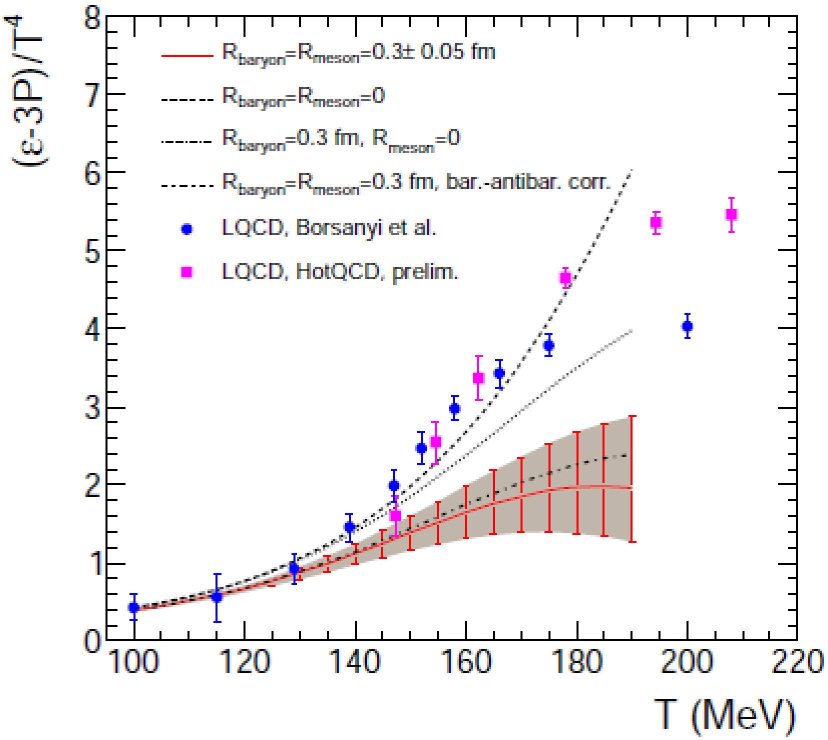


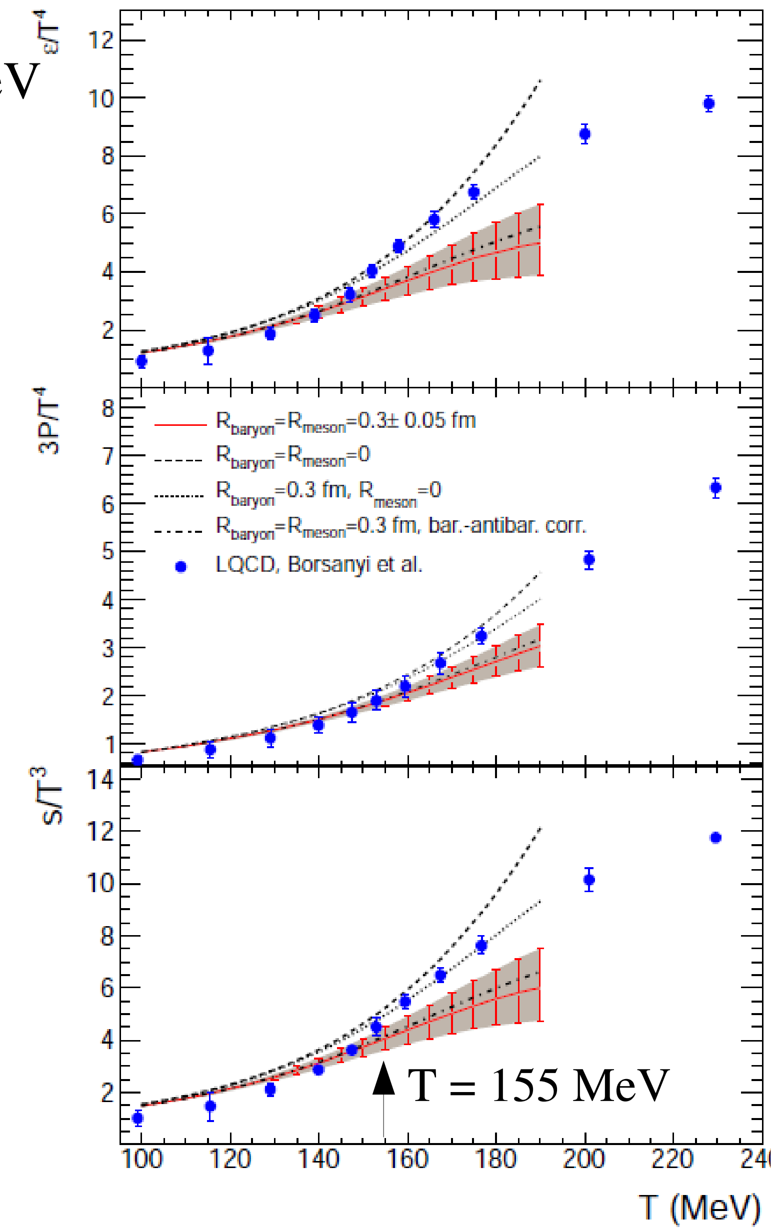
strangeness supressed – fit still not good!

parameter set: T=164 MeV, V=20 fm^3, $\gamma_s=0.72$ with $\chi^2=718/30$

Lattice QCD and various hadron resonance gas predictions for thermodynamic quantities

interactions become visible around T = 140 MeV but no well constrained; modeled here with excluded volumes





Andronic, Braun-Munzinger, JS, Winn,
Phys. Lett. B718 (2012) 80

top AGS energy Au + Au data

GC statistical model applied first time successfully to 10.7 A GeV/c Au + Au collisions P. Braun-Munzinger, J.S., J.P. Wessels, N.Xu, Phys. Lett. B344 (1995) 43

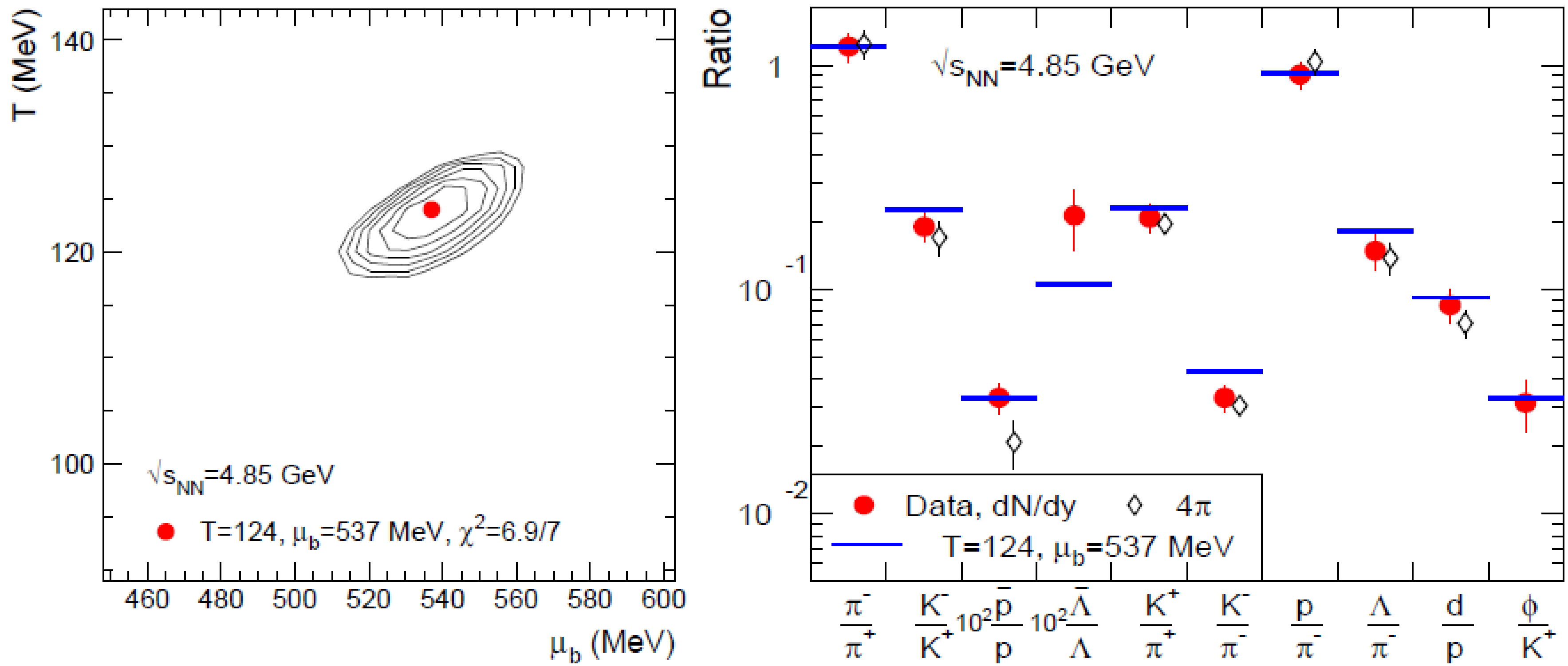
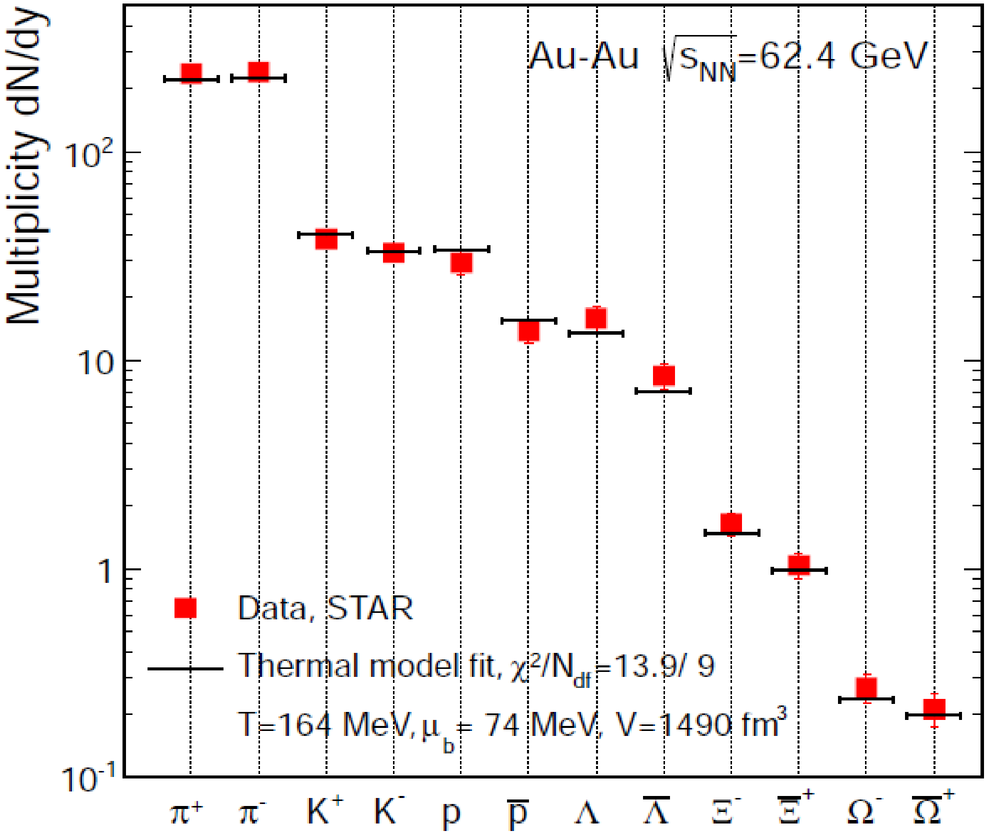
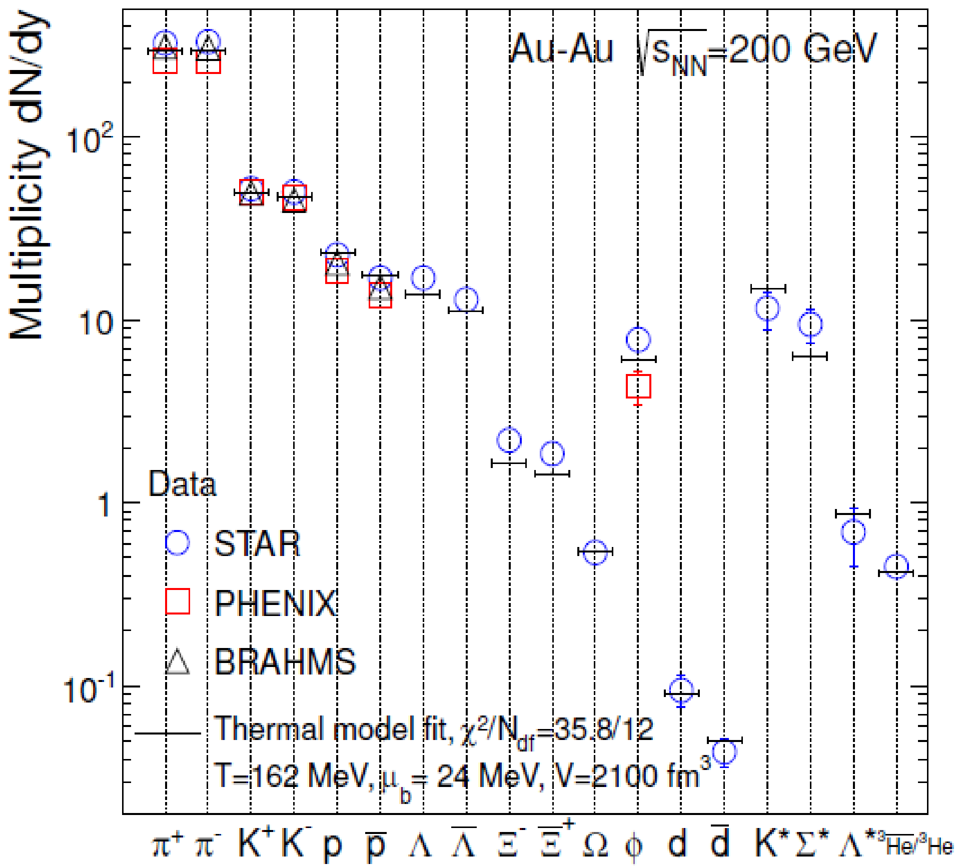


Figure from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

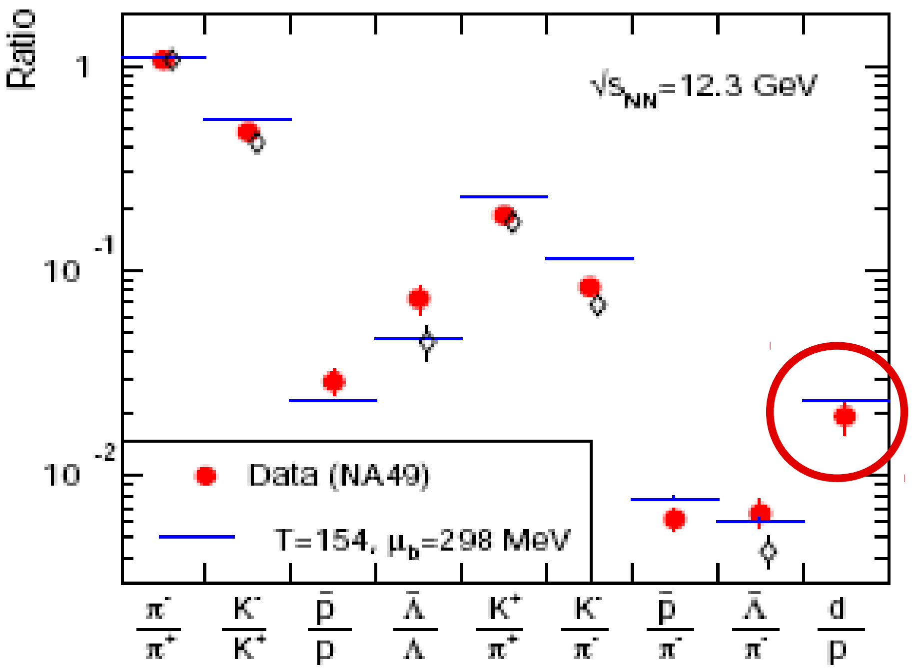
lower RHIC energies, - STAR data only

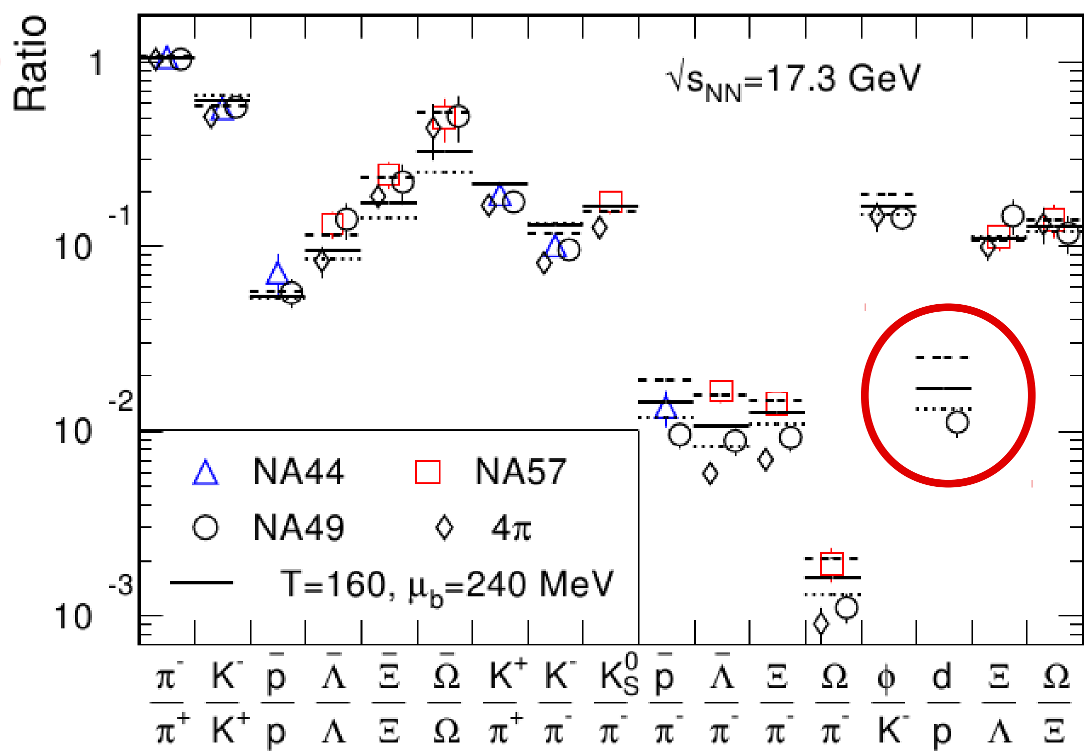


Latest statistical model fit to all RHIC data

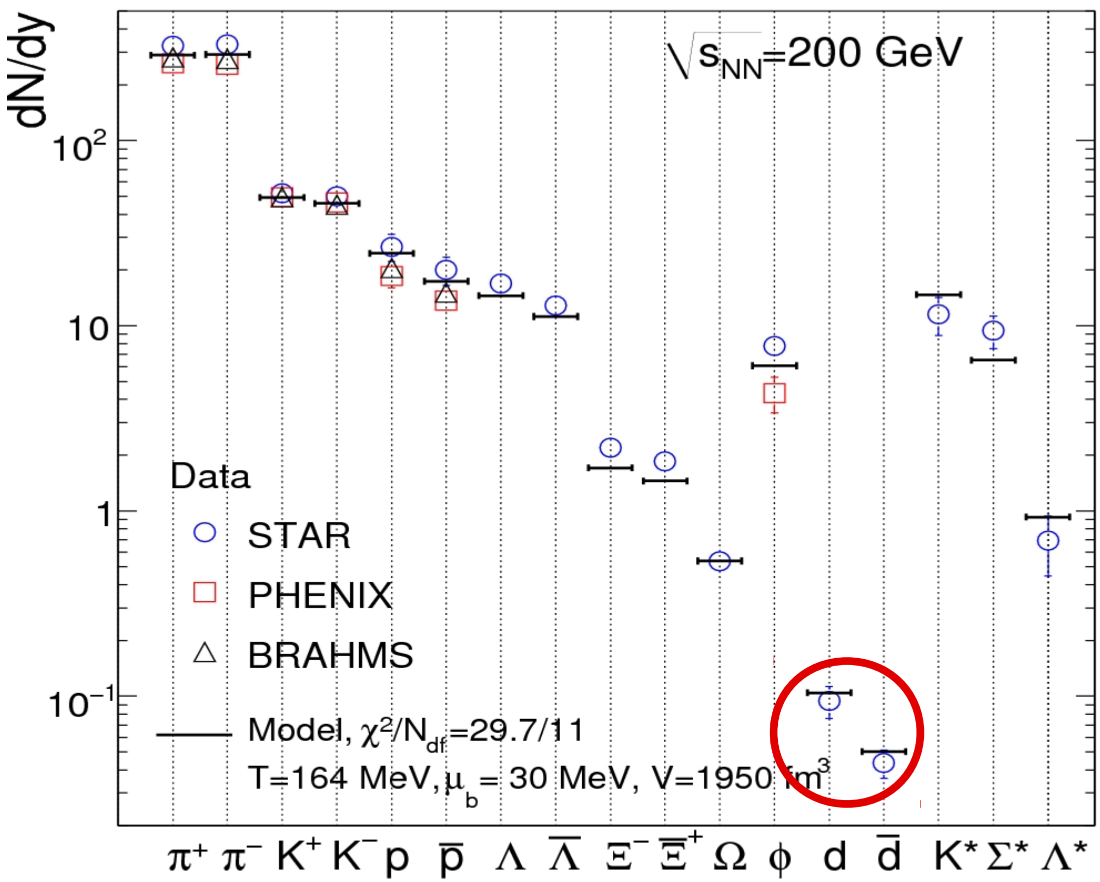


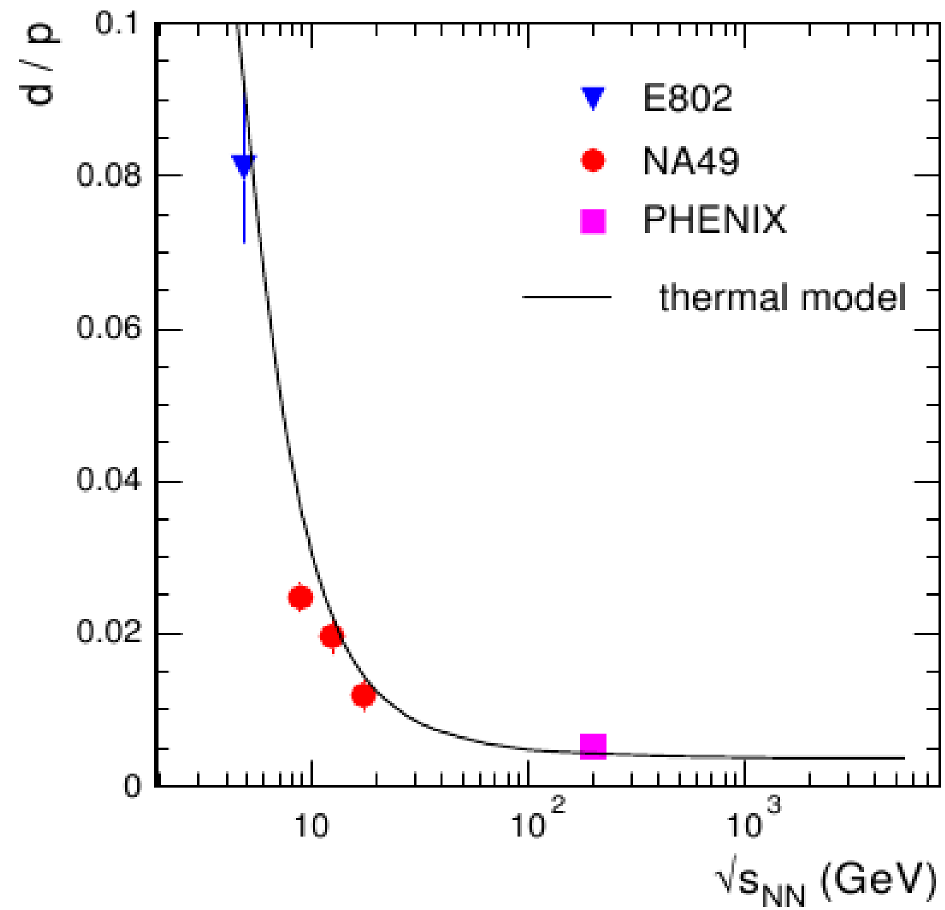
Deuterons at SPS energies reproduced as well





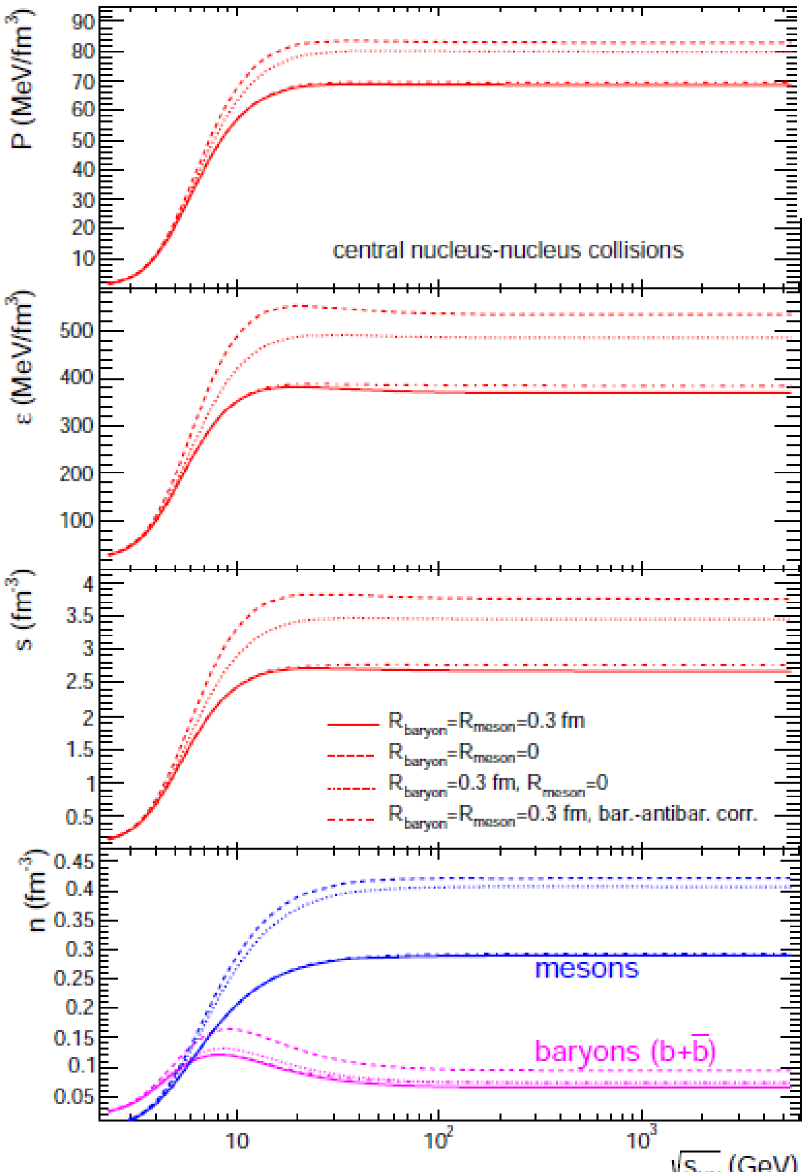
and at RHIC description equally good
- beam energy dependence driven by μ_b





Cluster productio and entropy

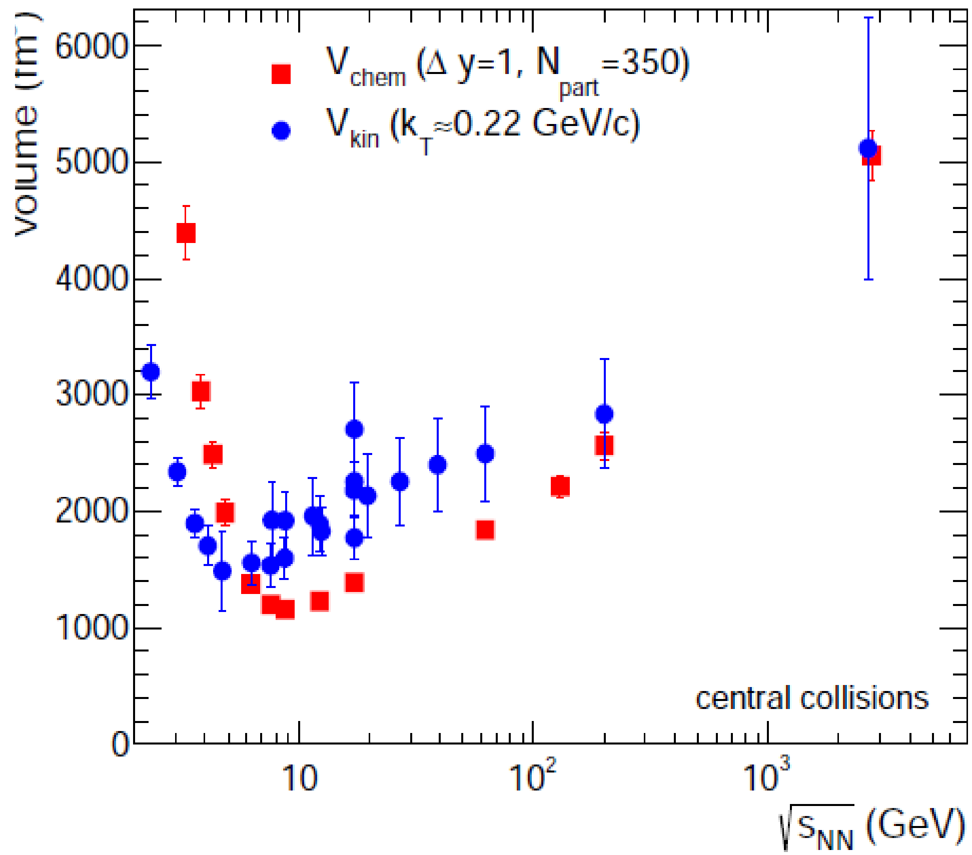
$S = s\,V = -\text{const}\,\ln(d/p)$



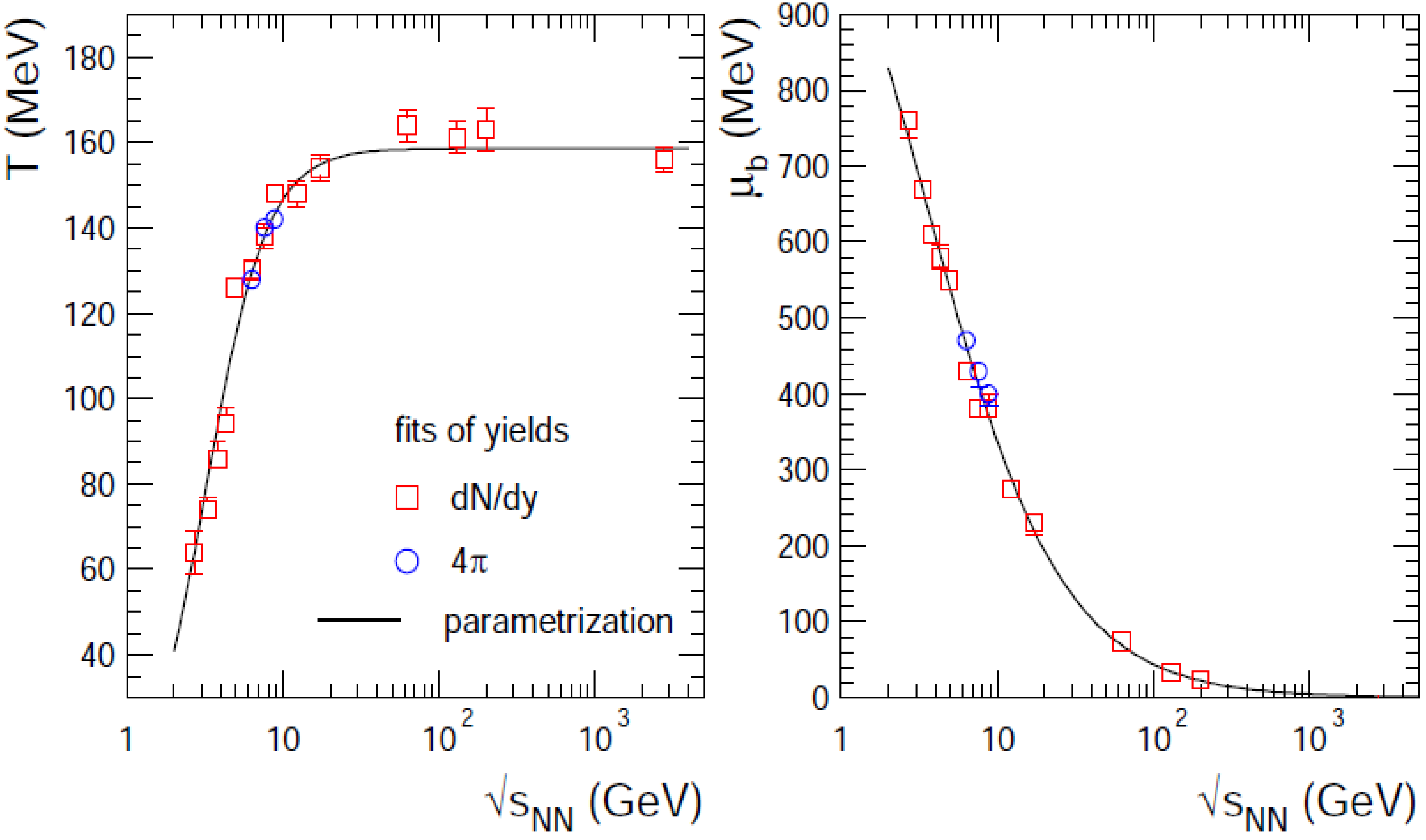
Interacting hadron resonance gas meets lattice QCD

arXiv:1201.0693

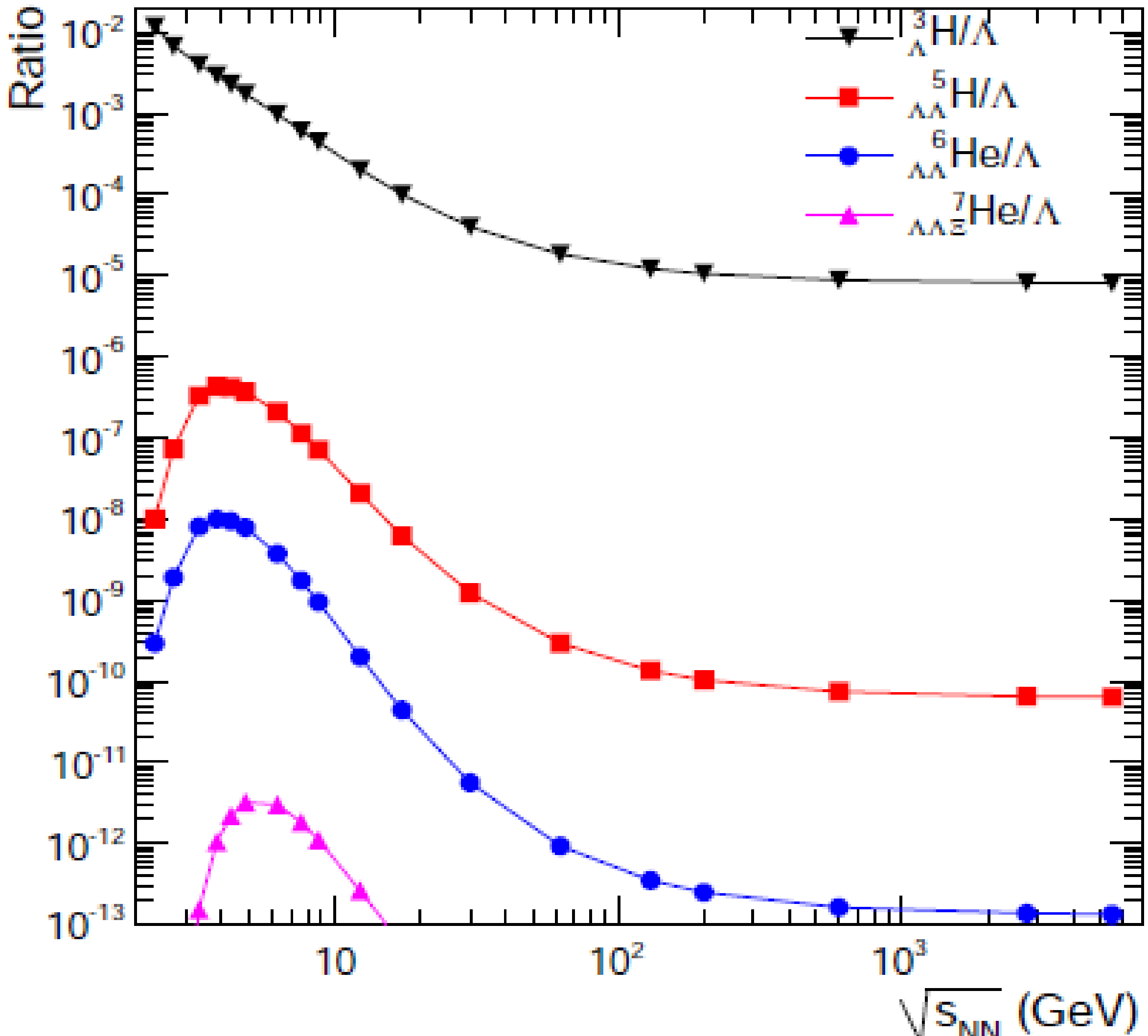
A. Andronic [a,b], P. Braun-Munzinger [a,c,d,e], J. Stachel [f], M. Winn [f]



Latest global fit to T and mub



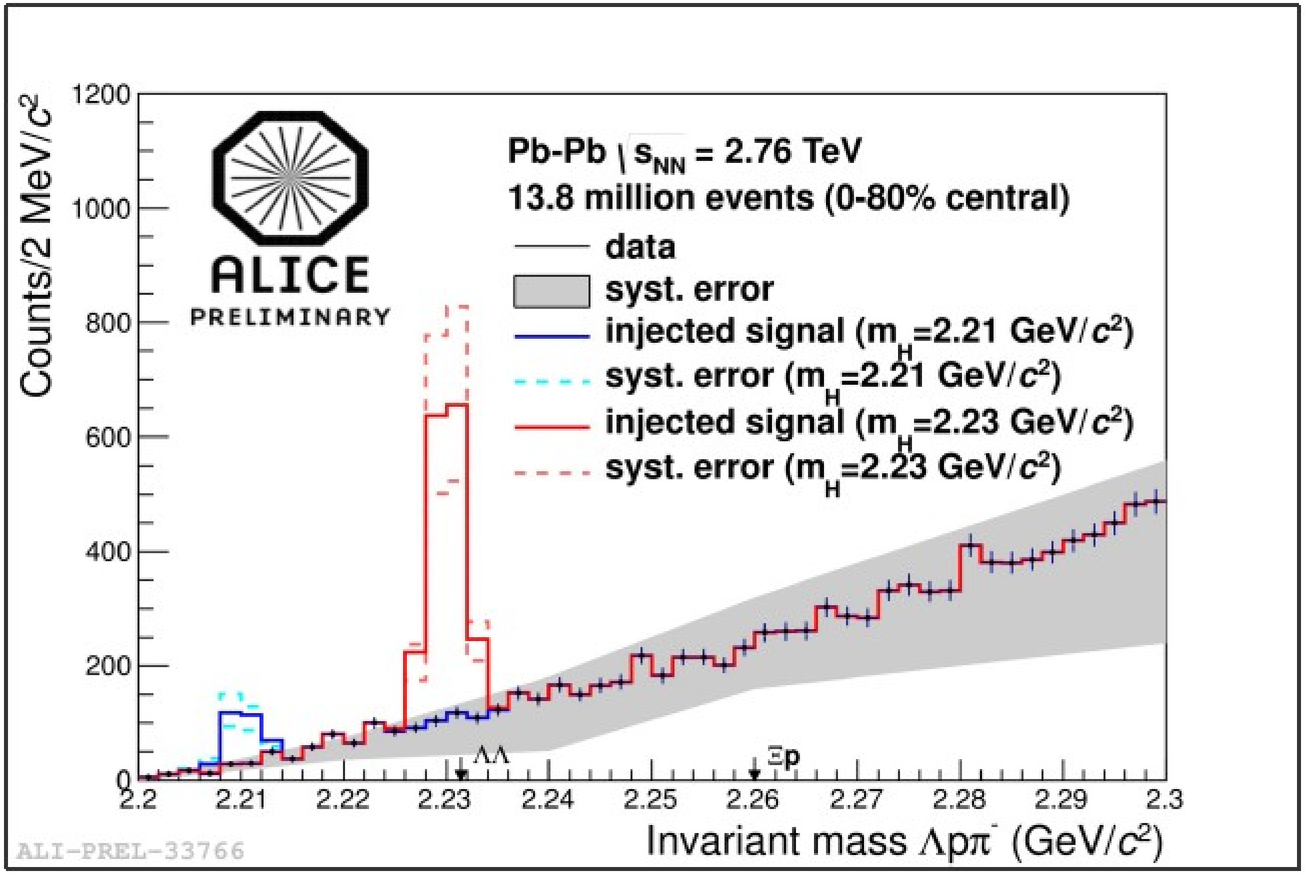
Energy dependence of the yields of exotic objects



note: yield peaks at low (SIS100) energies
an exciting but tough prospect for FAIR

example: search for H-Dibaryon

Ramona Lea, SQM2013

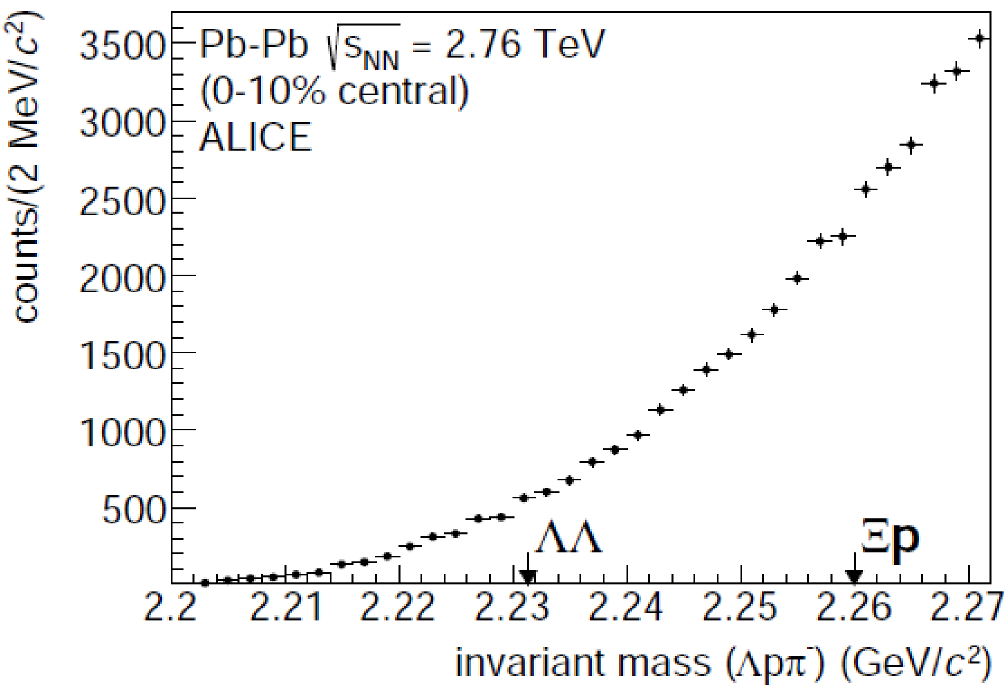


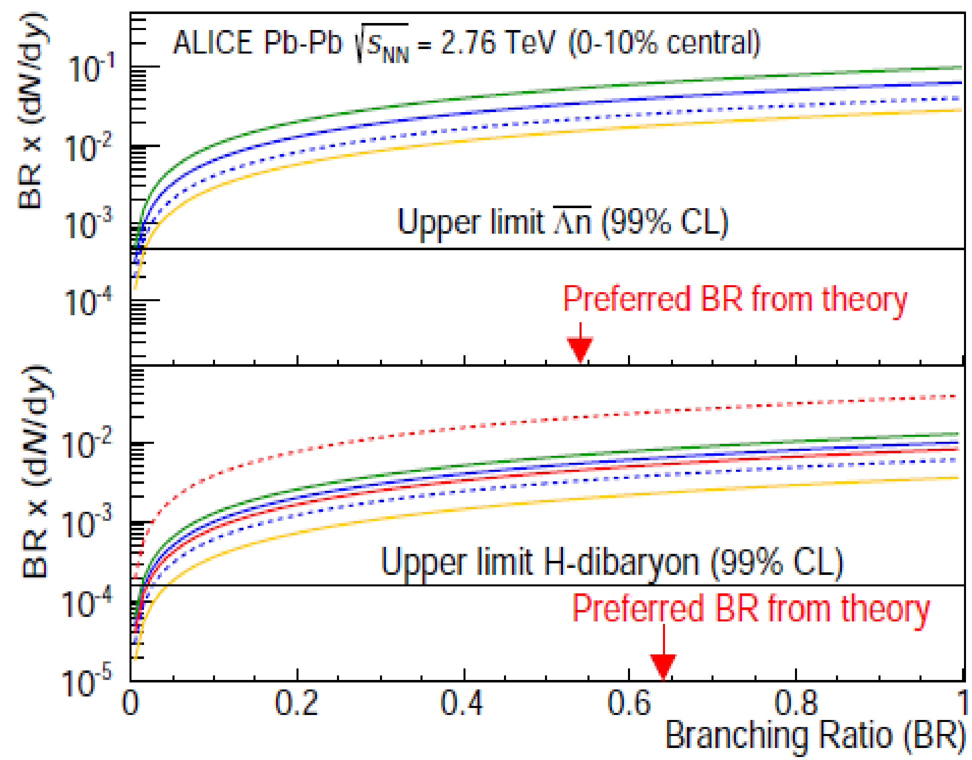
No signal observed, H yield is < 0.1 x (thermal model prediction)

Much more stringent limits to come soon

searches for exotic bound states

Nicole Martin and Benjamin Doenigus, ALICE





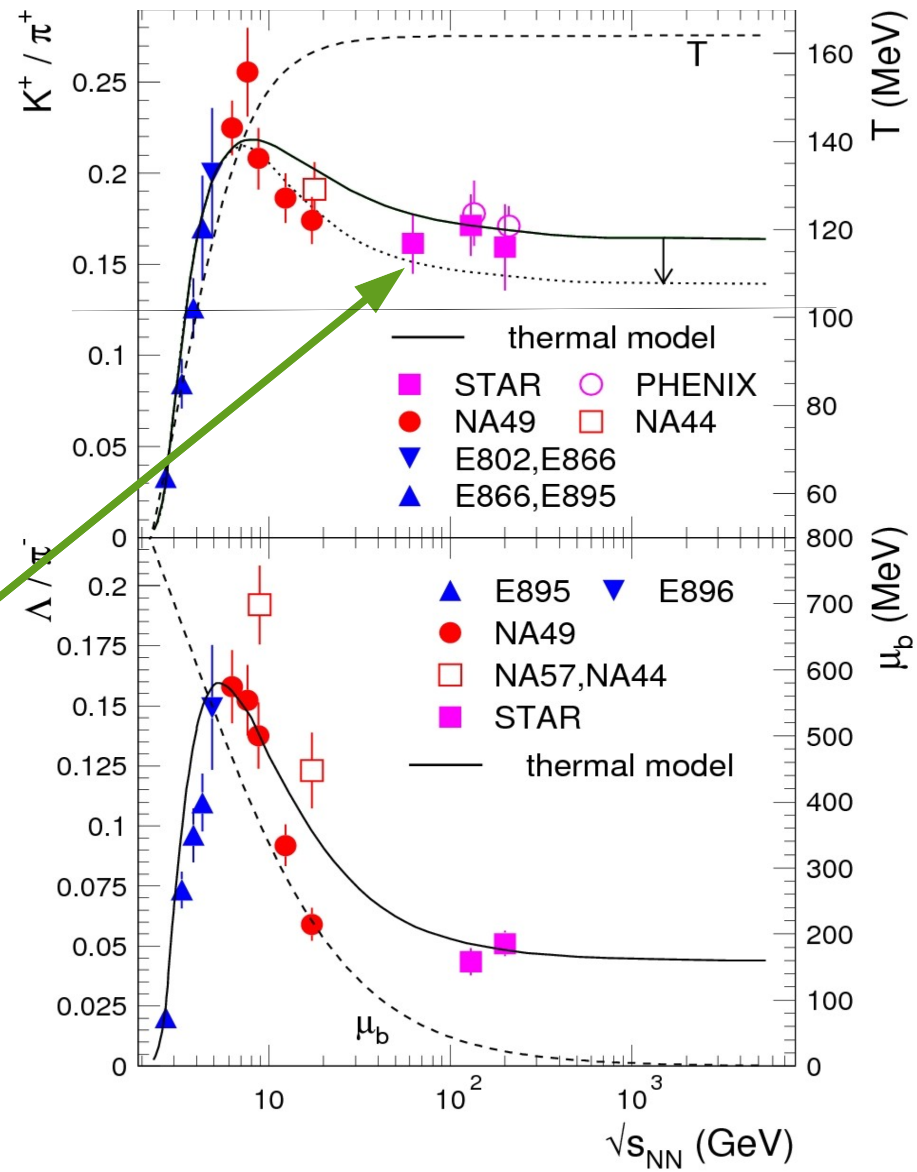
no H, Lambda-n bound states arXiv:1506.07499

possible reasons for low proton yield

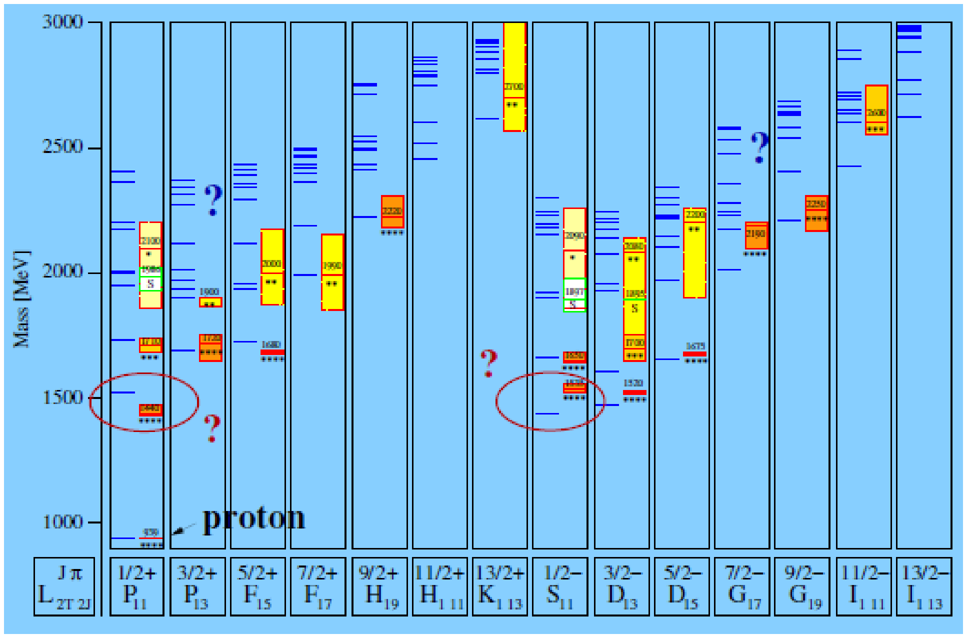
Incomplete hadron spectrum
Annihilation in the hadronic phase
Non-equilibrium scenario with new parameters
other?

Effect of incomplete hadron spectrum

we studied this for K/π ratio:
(Andronic, Braun-Munzinger, JS Phys. Lett. B673 (2009) 142)
estimate effect by extending mass spectrum beyond 3 GeV based on TH = 200 MeV and assumption how states decay
strongest contribution to kaon from K* producing one K
all high mass resonances produce multiple pions
-> further reduction of K^+/π^+



there could be a lot more unfound baryons at low mass and with high spin (degeneracy)



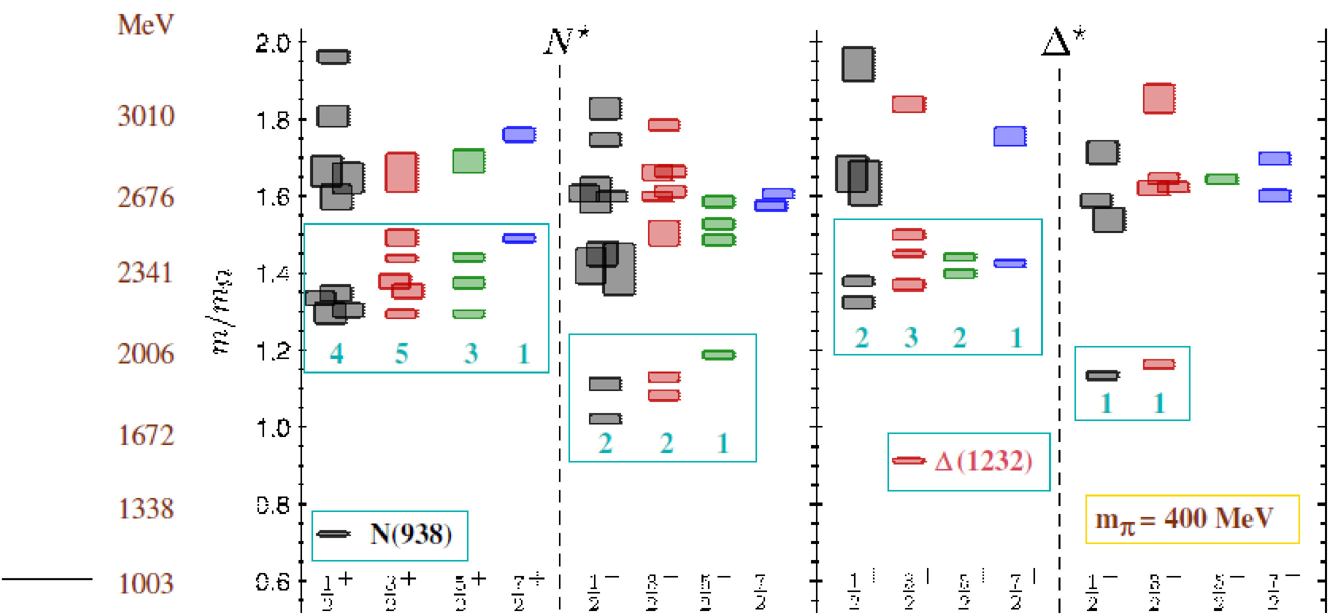
from talk U. Thoma DPG2013

non-strange N* resonances

U. Loering, B. Metsch, H. Petry et al.

relativistic quark model

Constituent quarks, confinement potential
+ residual interaction



Excited baryons from lattice QCD:
R. Edwards et al., Phys. Rev. D84 (2011) 074508

some have been found

annihilation in the hadronic phase?

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

Evaluate hadronic interactions after statistical hadronization using RQMD
find significant effect of apparent cooling due to hadron rescattering

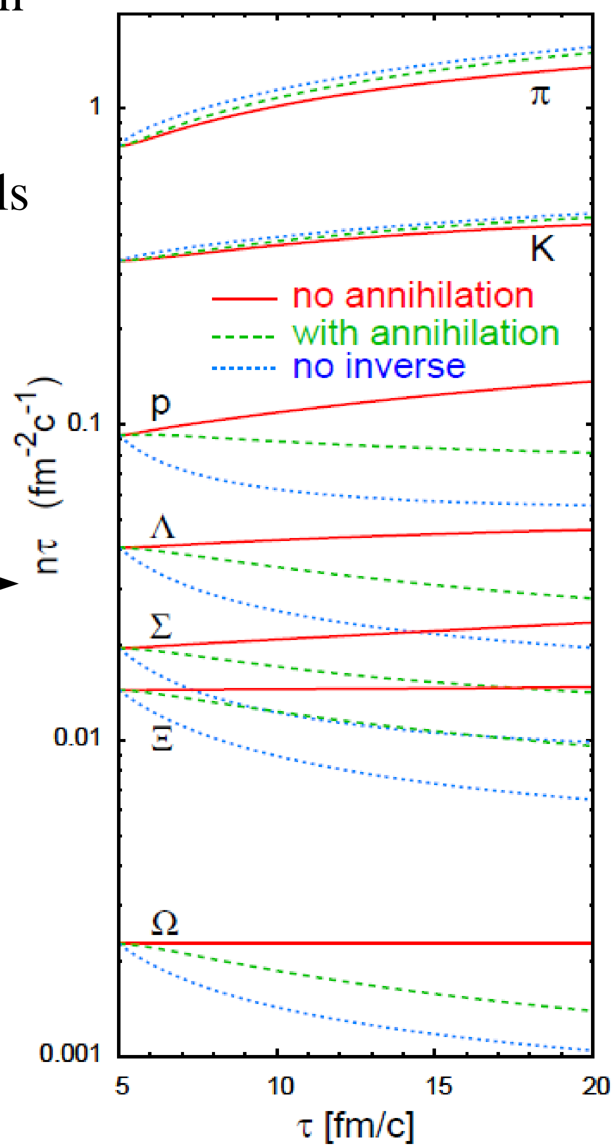
annihilation in the hadronic phase?

- but need to take into account full detailed balance, backreaction like $5\pi \rightarrow$ ppbar (not in RQMD)

analysis by Rapp and Shuryak 2008 for SPS energies: this cancels the annihilation effect,
equilibrium value at T_{chem} is recovered

recent analysis by Pan and Pratt, PRL 110 (2013) 042501:
taking account backreaction cancels half of the effect of annihilation

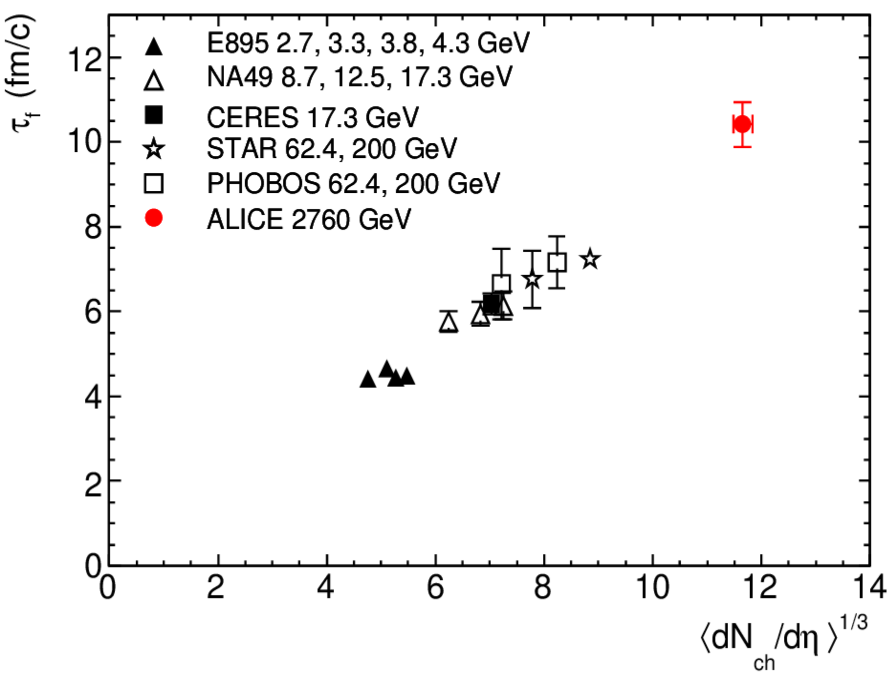
- Why should only proton be affected? and not hyperons? Cross sections should be very similar, e.g. Ω + Nbar $\rightarrow 2\pi + 3$K
evalute 10 mb at threshold Braun-Munzinger, JS, Wetterich, Phys. Lett. B596 (2004) 61
- they show if anything opposite effect
- what about nuclei?? they fit perfectly and their cross sections are larger

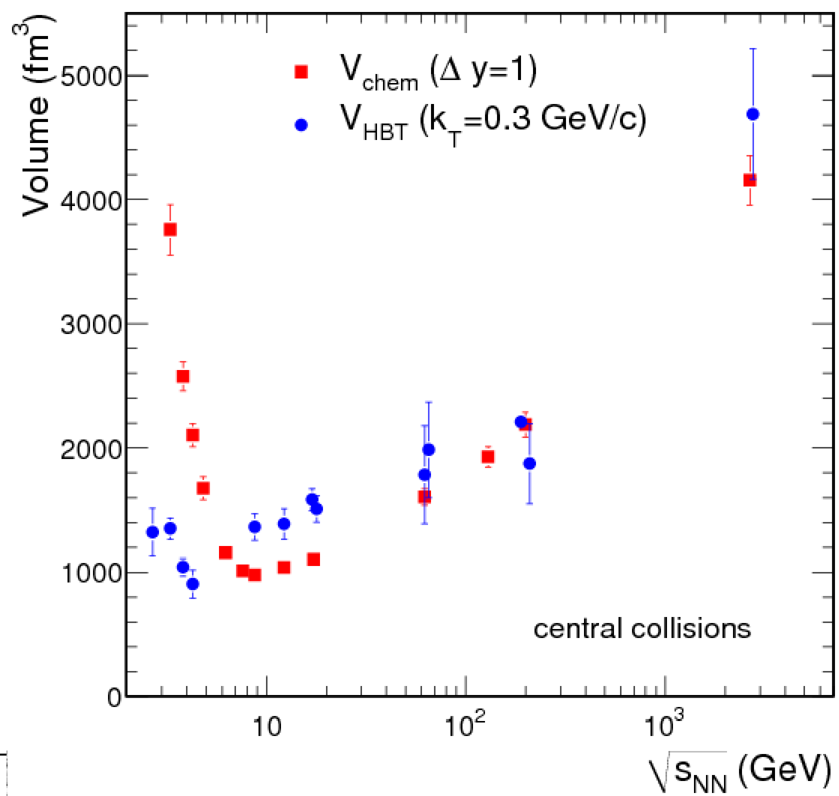


annihilation in hadronic phase

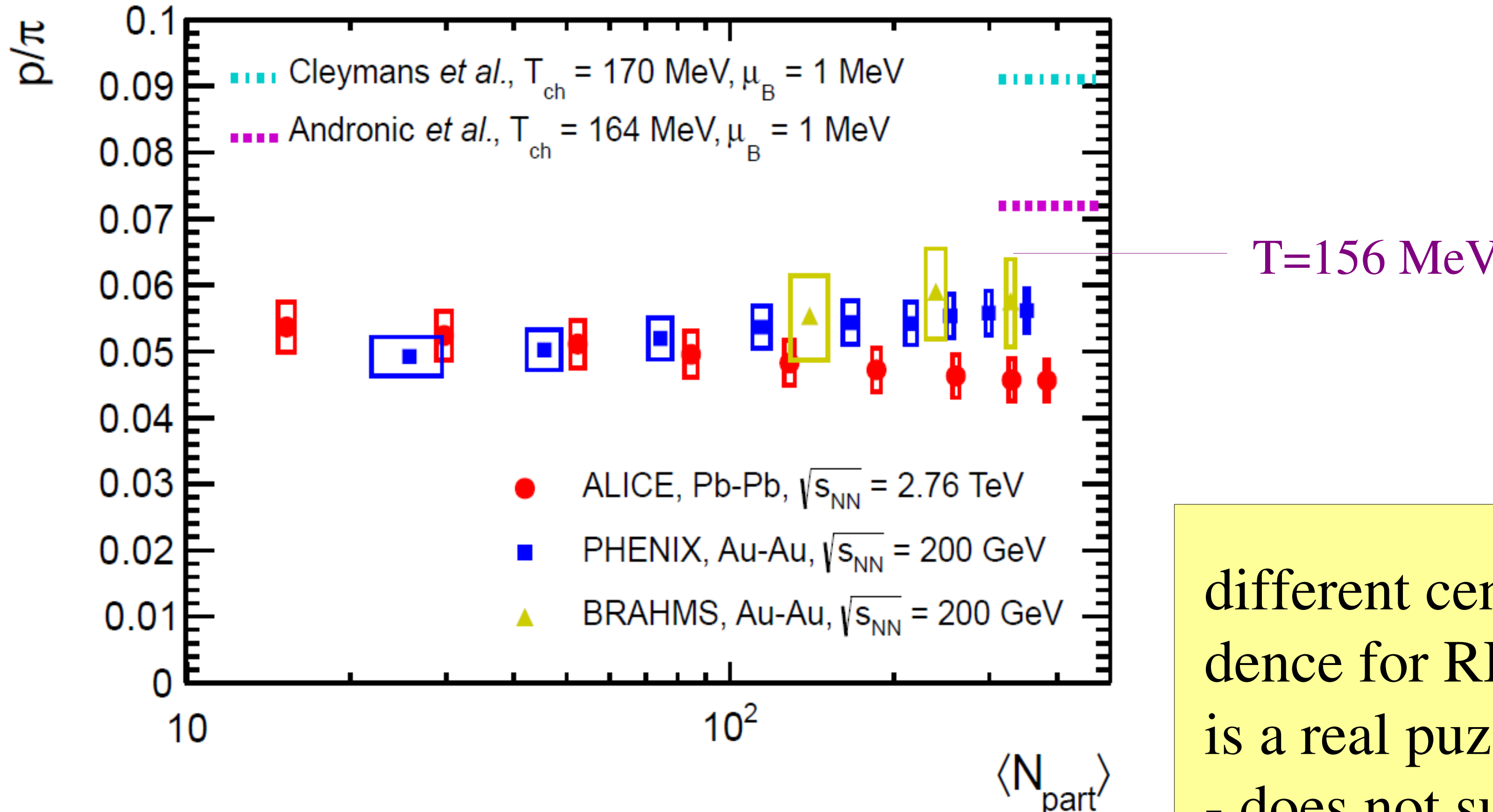
all of this casts serious doubts on the reduction of protons only due to annihilation in hadronic phase

additional argument: in RQMD lifetime of hadronic phase significantly too long (from HBT: total lifetime of system = 10 fm/c – and volume change between chemical and thermal freeze-out does not allow for longlived hadronic phase)
shorter lifetime reduces effect





Centrality dependence of proton to pion ratio



different centrality dependence for RHIC and LHC is a real puzzle

- does not support annihilation picture
- is it real? physics origin?

Out-of-equlibrium model of hadronization

J. Rafelski and collaborators

introduction of additional chemical potentials

- systematic variation of parameters with beam energy?
- yield of deuterons prop to γ_q^6 - comparison to data: strong deviation