Production of loosely bound objects in ultra-relativistic nuclear collisions

- introduction and perspective
- thermal model and the QCD statistical operator
- hadron data, Hagedorn limiting temperature, and the QCD phase boundary
- production of loosely bound objects
- summary

FIAS-Frankfurt

Seminar
Orsay, Jan. 9, 2015

Peter Braun-Munzinger

General remarks

weakly bound objects: binding energy <<< sqrt{s}

weakly bound objects: binding energy $<< T_{chem}$

production mechanism is of very general interest

MC and coalescence models not even accurate to within order of magnitude without tuning of parameters

can AA collision studies lift the veil?

results important for different communities

Work performed in collaboration with Anton Andronic, Krzysztof Redlich and Johanna Stachel , search for exotica with Nicole Loher and Benjamin Doenigus

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 $T_c = T_{lim}$

Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: an important test of equilibration of quark matter near the phase boundary, **no equilibrium → no QGP matter**
- No (strangeness) equilibration in hadronic phase
- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis
- This implies little energy dependence above RHIC energy
- Analysis of hadron production → determination of T_c

pbm, Stachel, Wetterich,
Phys.Lett. B596 (2004) 61-69

At what energy is phase boundary reached?

Thermal model of particle production and QCD

Partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

For each particle i, the statistical operator is:

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

Particle densities are then calculated according to:

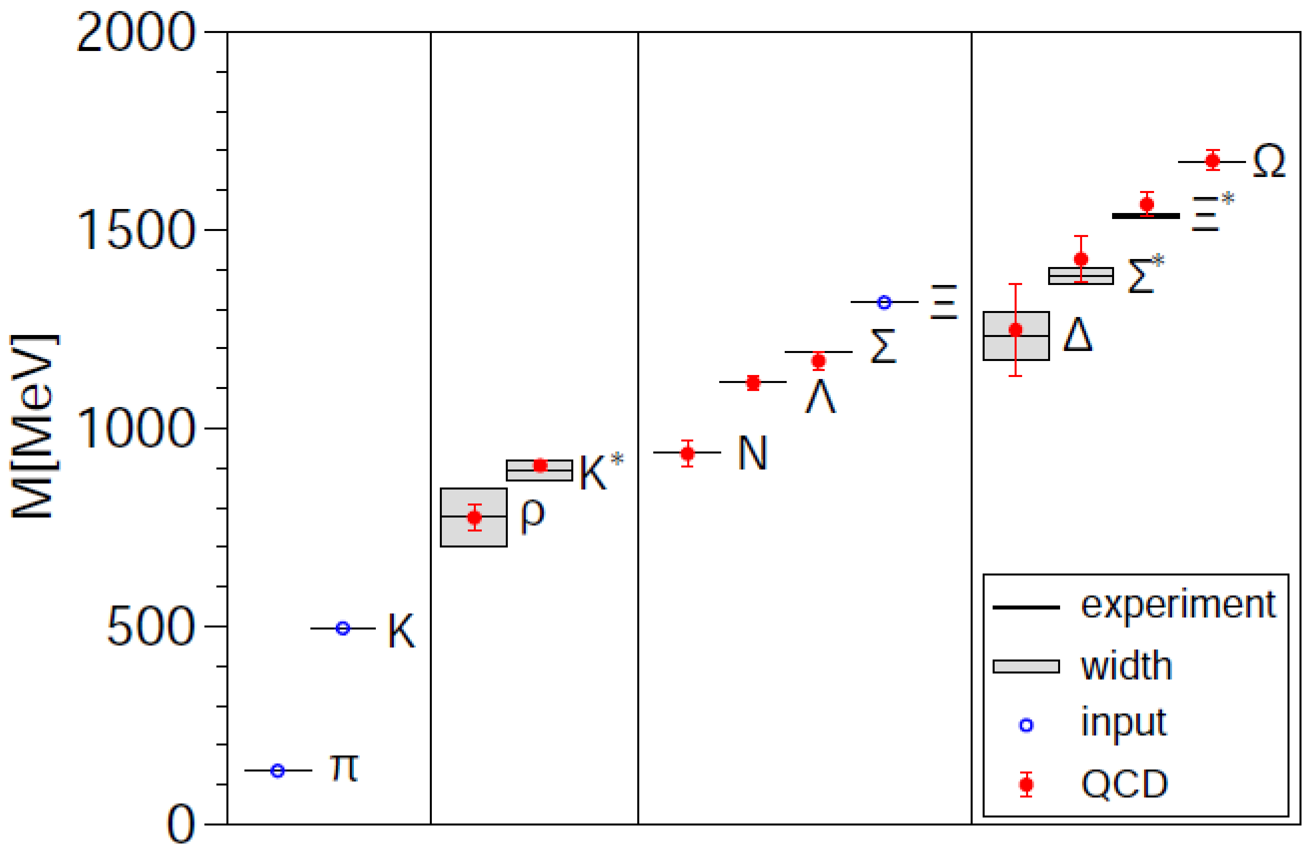
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

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

In practice, we use the full experimental hadronic mass spectrum from the PDG compilation to compute the 'primordial yield'

Comparison with measured hadron yields needs evaluation of all strong decays

The hadron mass spectrum and lattice QCD



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

The QCD statistical operator and the hadron resonance spectrum

At low density, the interacting hadron resonance gas is well approximated by the sum over all resonance states without interactions

R. Dashen, S.-K. Ma, H.J. Bernstein, Phys. Rev. **187** (1969) 345.

R. Dashen, S.-K. Ma, Phys. Rev. A 4 (1971) 700.

Near the (pseudo-)critical temperature T_c interactions are important. Modeling the interaction via excluded volumes leads to significant changes in the volume, but not in T and mu_B

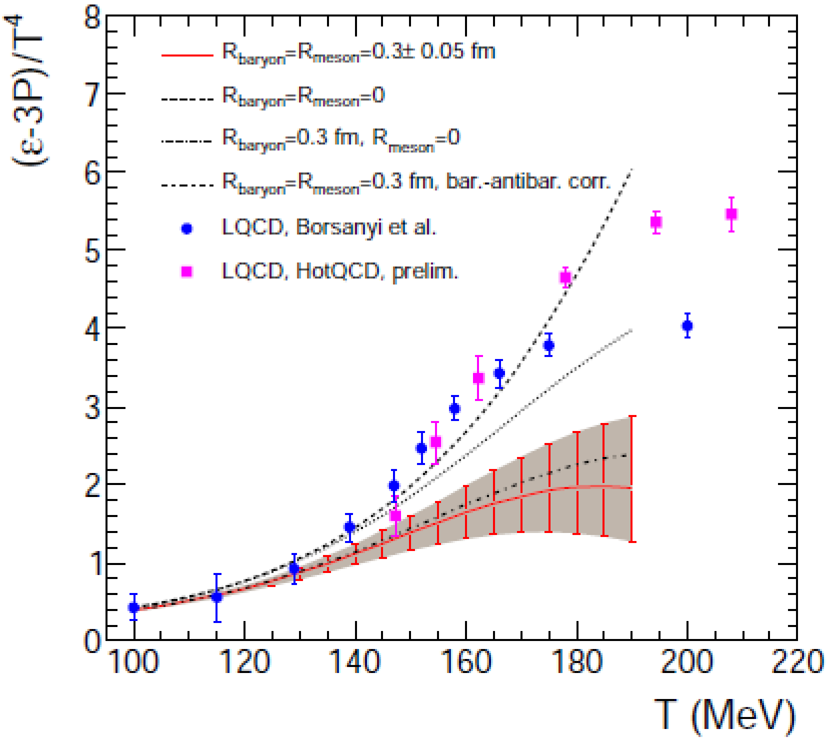
Andronic, pbm, Stachel, Winn, Phys. Lett. B718 (2012) 80

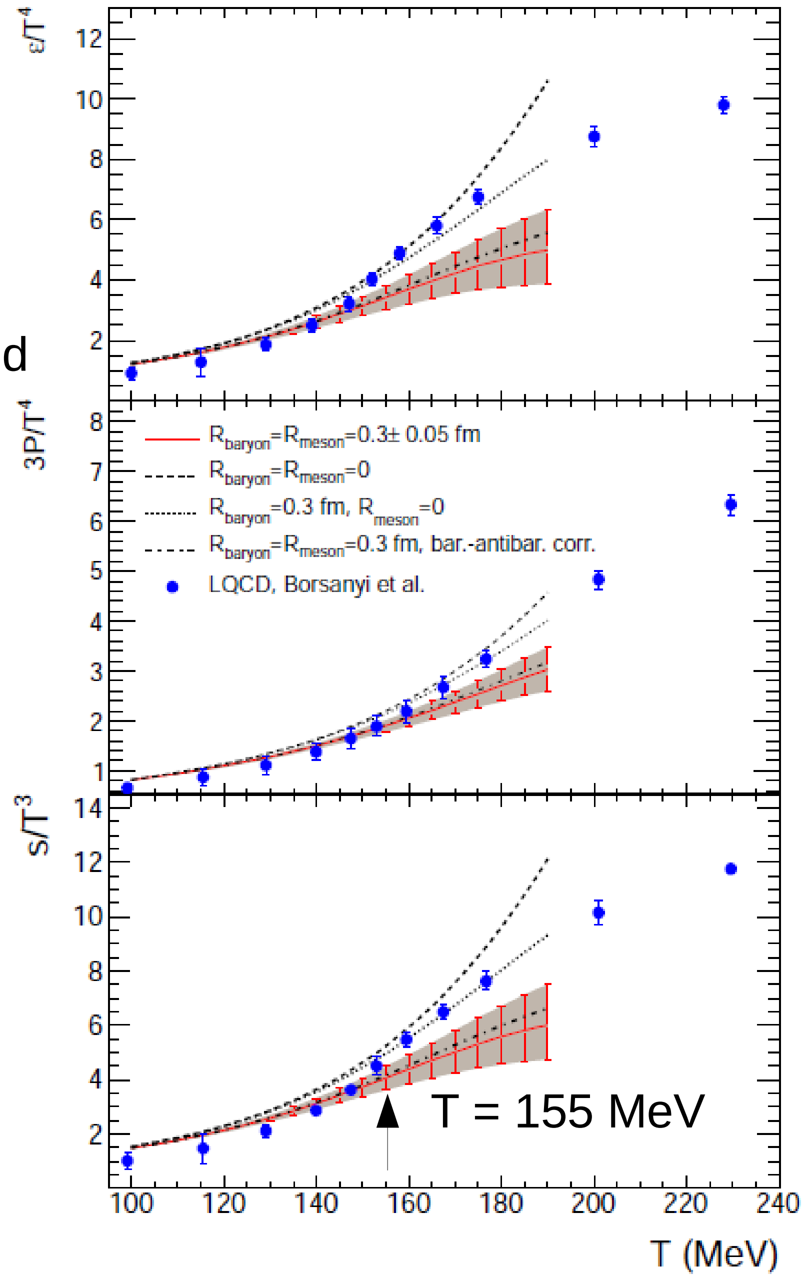
At LHC energy, particle production reflects quantitatively the structure of the QCD statistical operator

Lattice QCD and various hadron resonance gas predictions for thermodynamic quantities

interactions become visible around T = 140 MeV

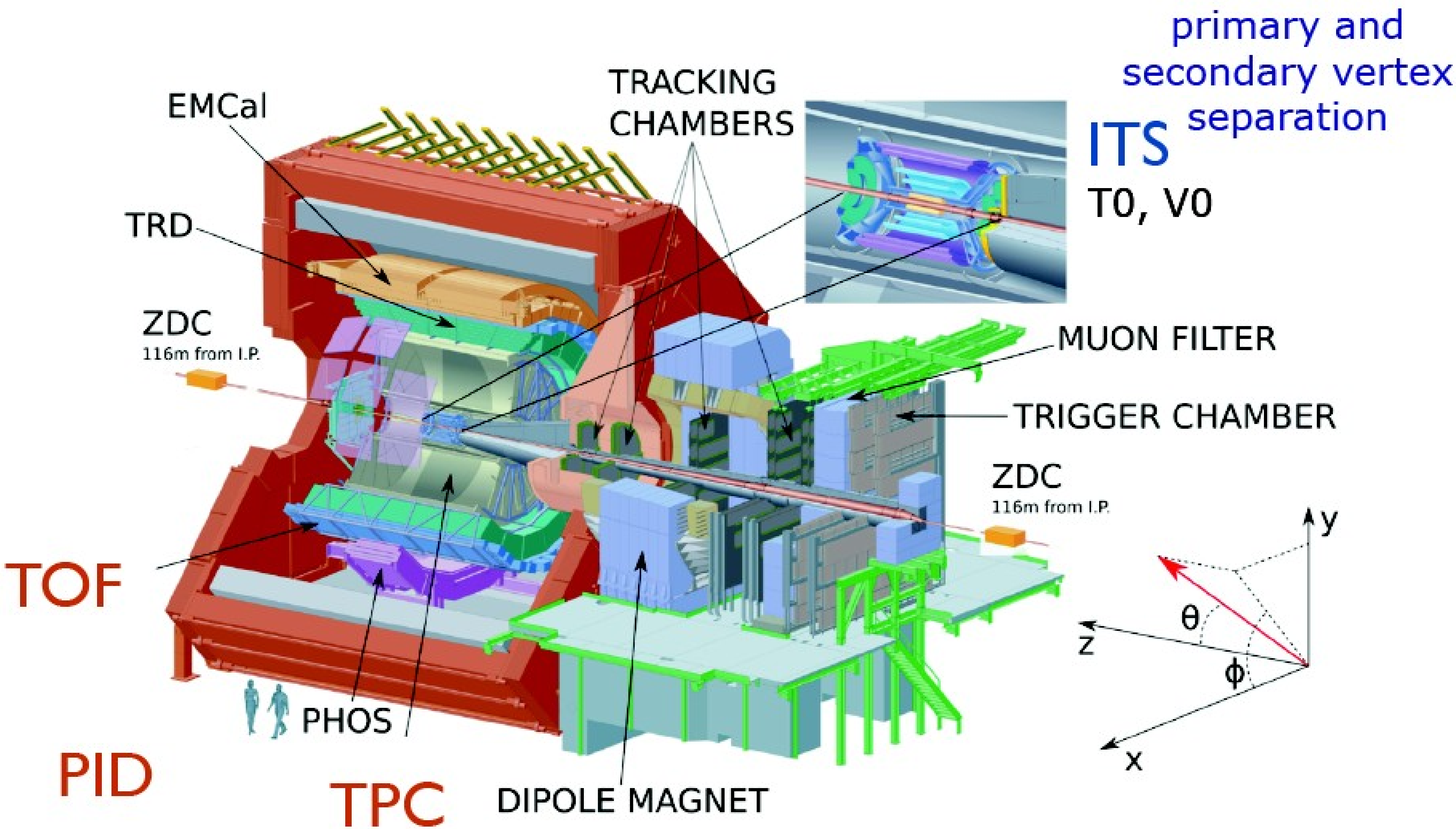
but no well constraint. Modeled here with excluded volumes



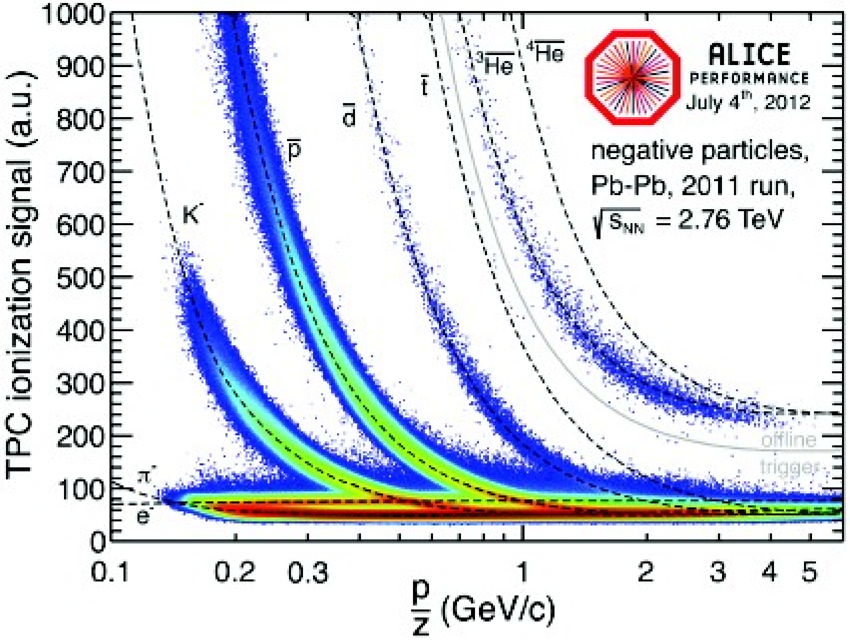


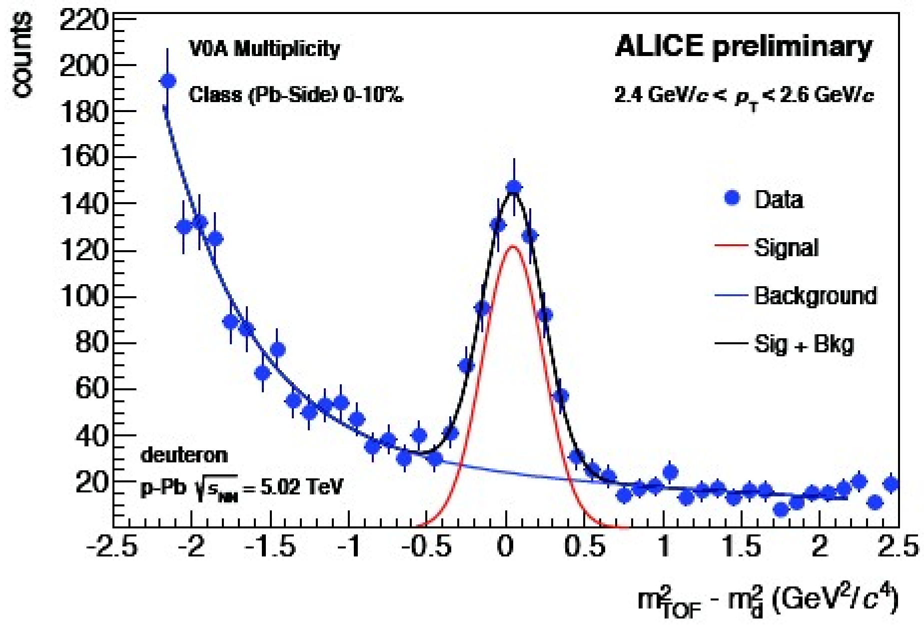
Andronic, pbm, Stachel, Winn, Phys. Lett. B718 (2012) 80

Analysis strategy

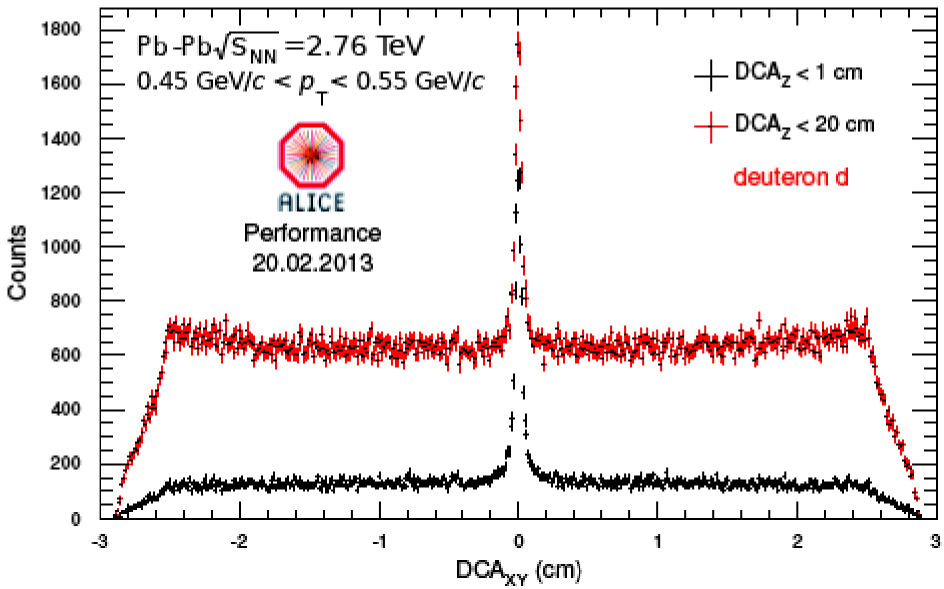


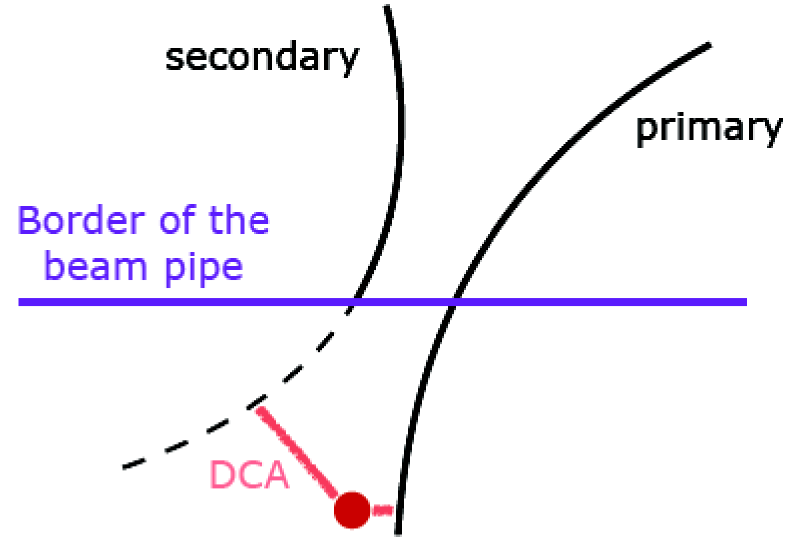
Particle identification via dE/dx and TOF measurements





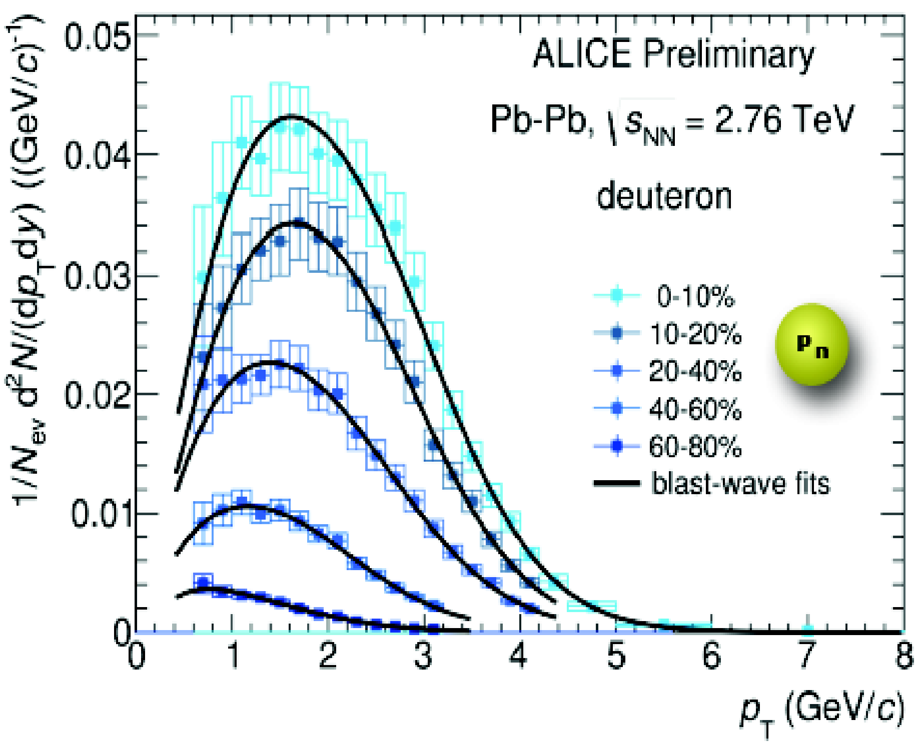
Separation of primaries from secondaries

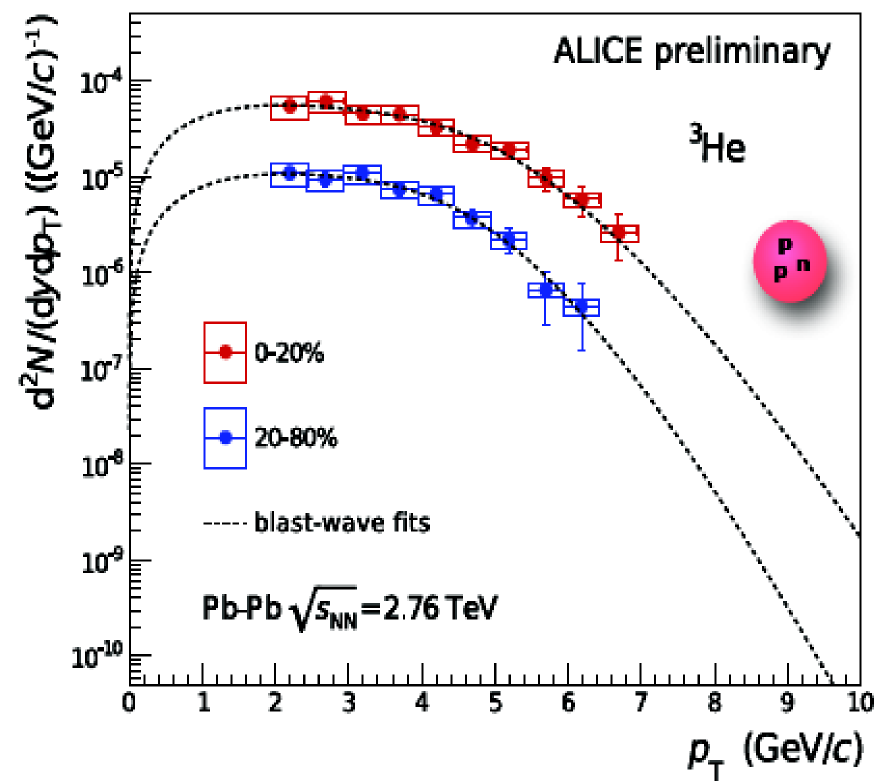




- ➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material e.g. the beam pipe)
- ➜ Knock-out significant problem at low p_T, but only for nuclei not for anti-nuclei

Measurement of transverse momentum spectra





composite objects participate in hydrodynamic flow

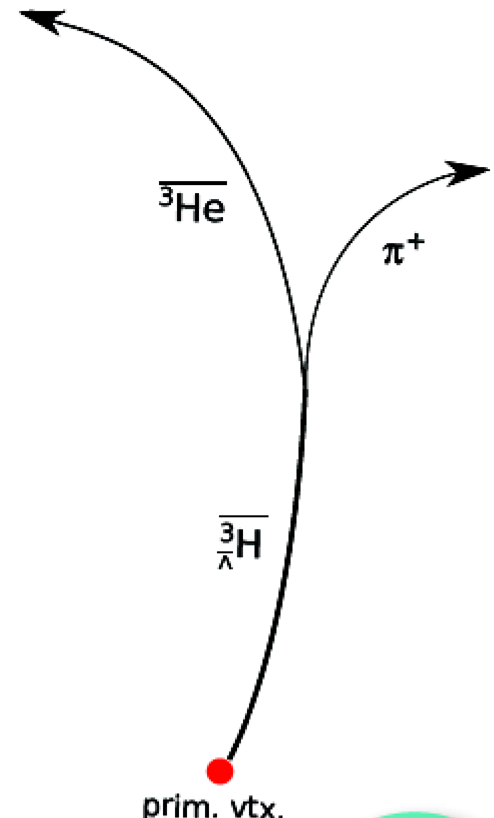
Hypertriton identification via particle ID and vertex measurements

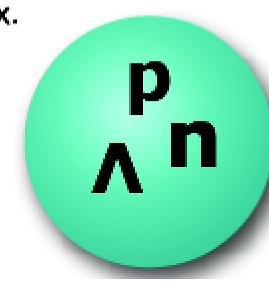
Identification of light nuclei which are daughter tracks originating from decay vertices

Lifetime similar to lifetime of free Λ

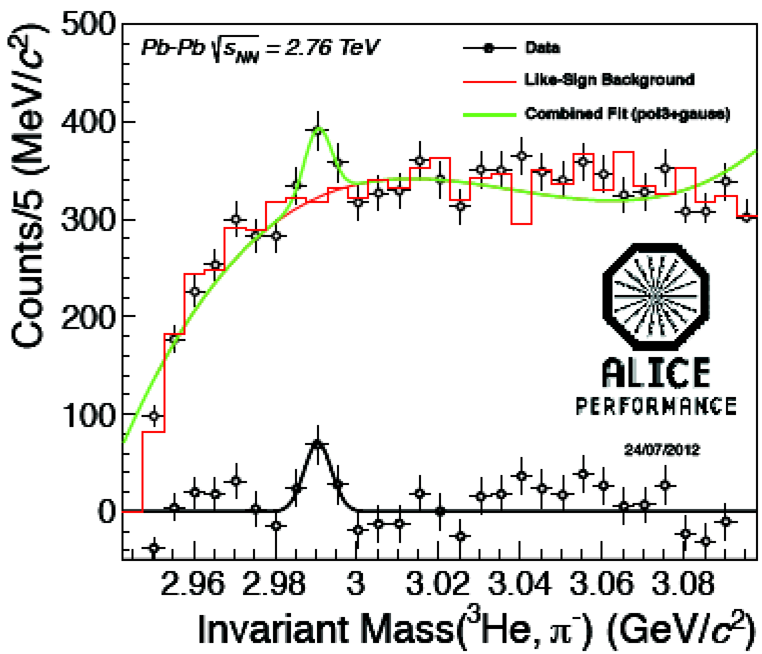
m(Hypertriton) = 2.991 ± 0.002 GeV/c^2

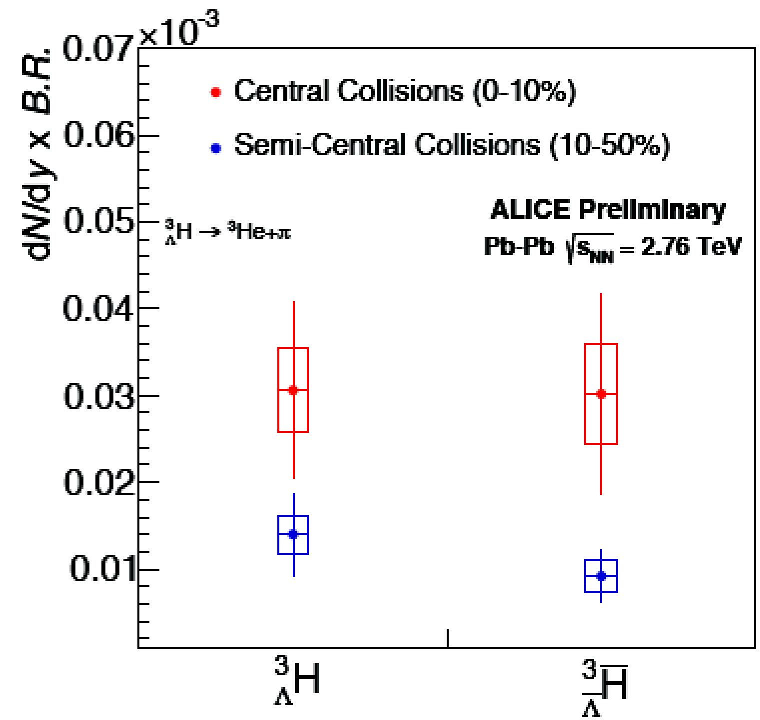
investigated decay channel:
Hypertriton → $^3He + \pi^-$



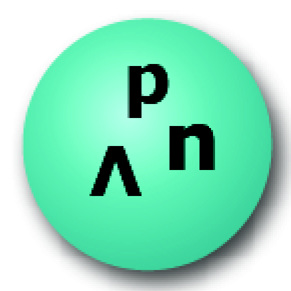


Hypertriton results





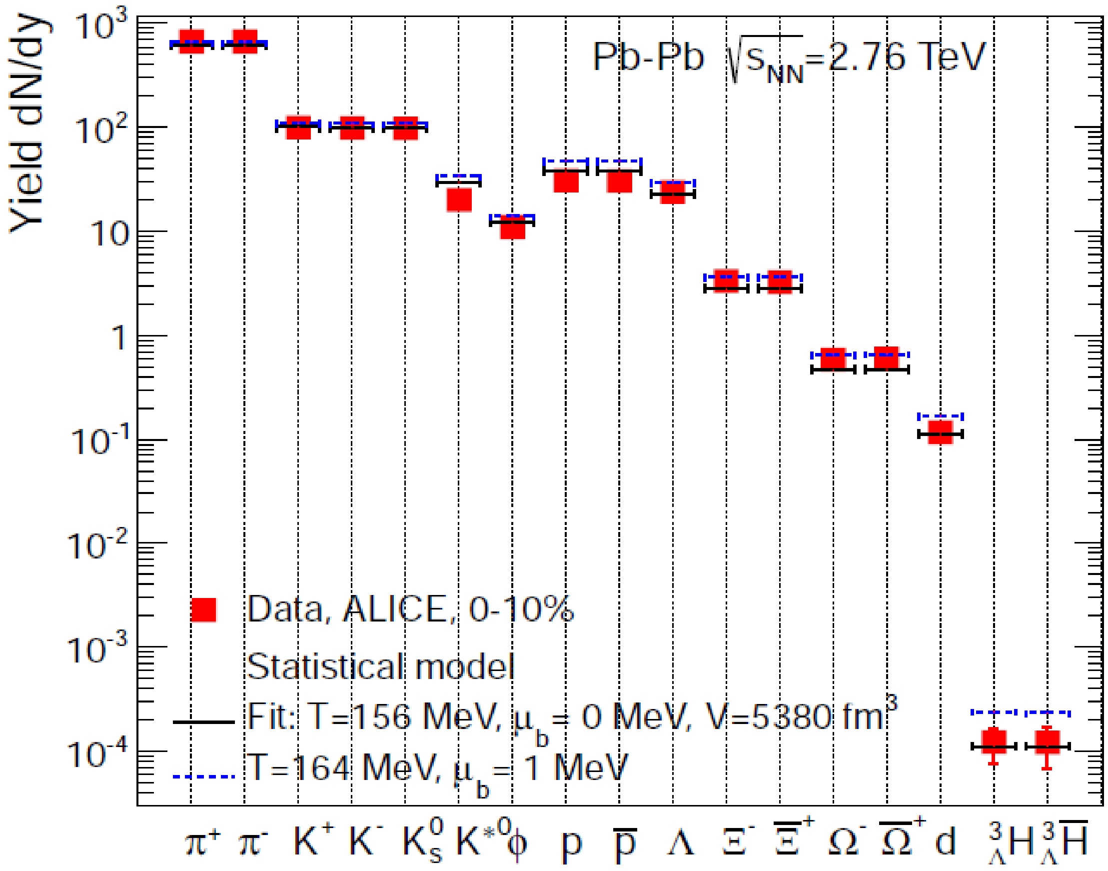
m(Hypertriton) = 2.991 ± 0.002 GeV/c^2

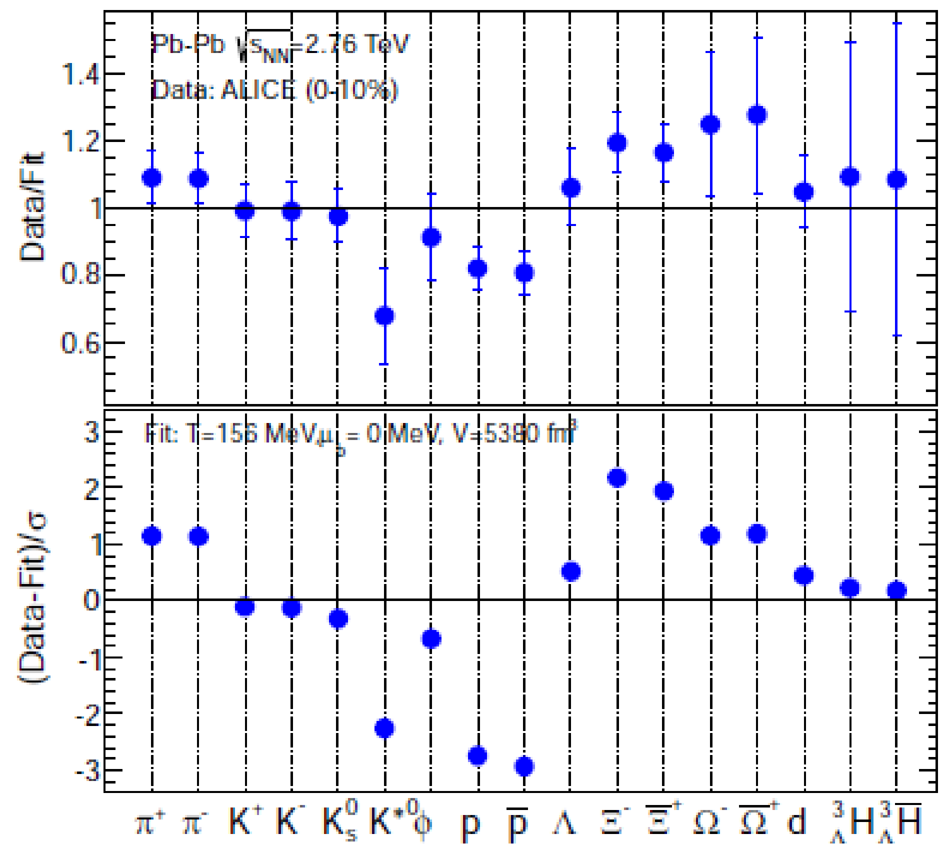


investigated decay channel:
Hypertriton → ^{3}He + π^-

Now comparison of data with thermal model predictions

Excellent description of LHC data

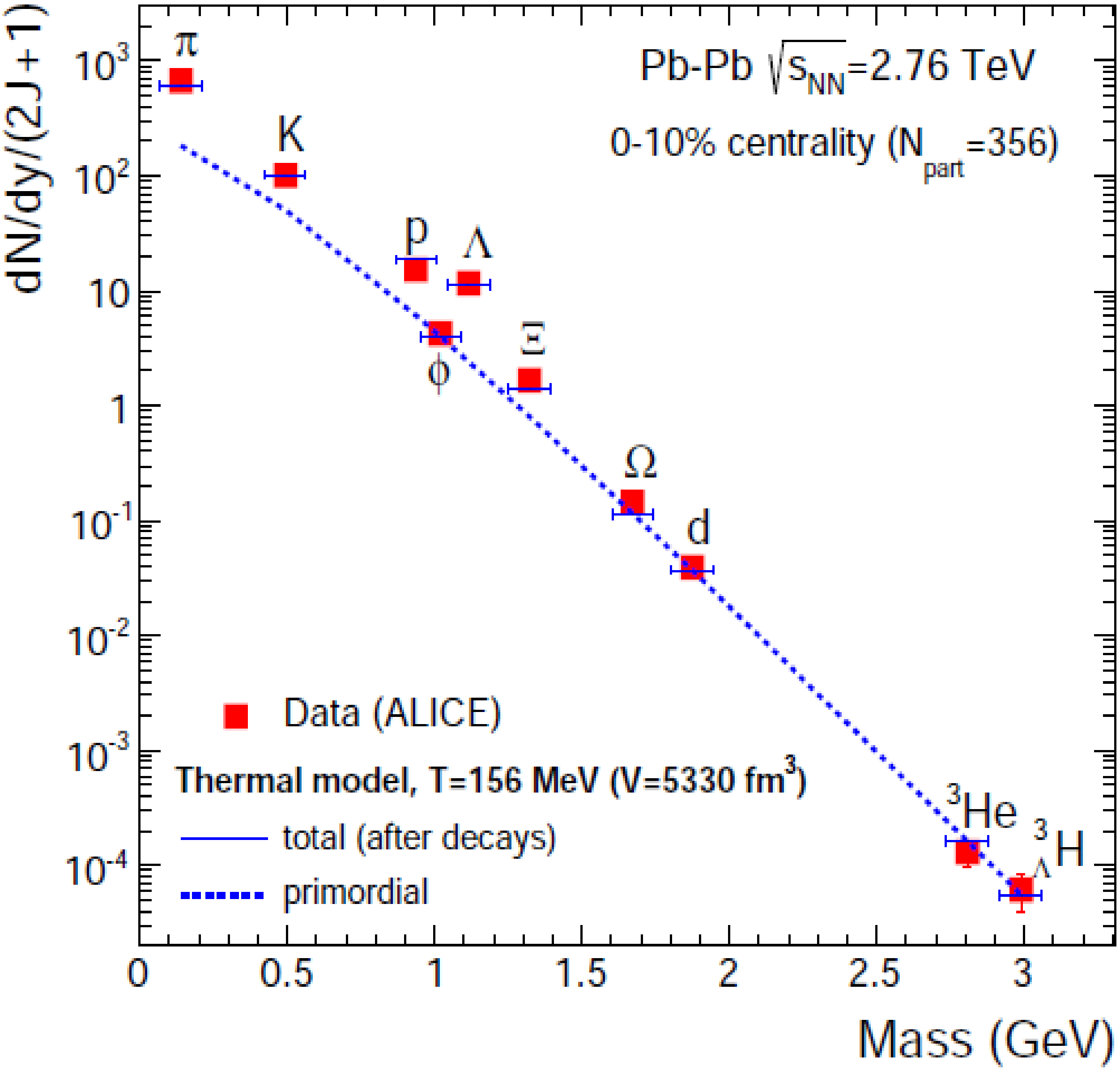




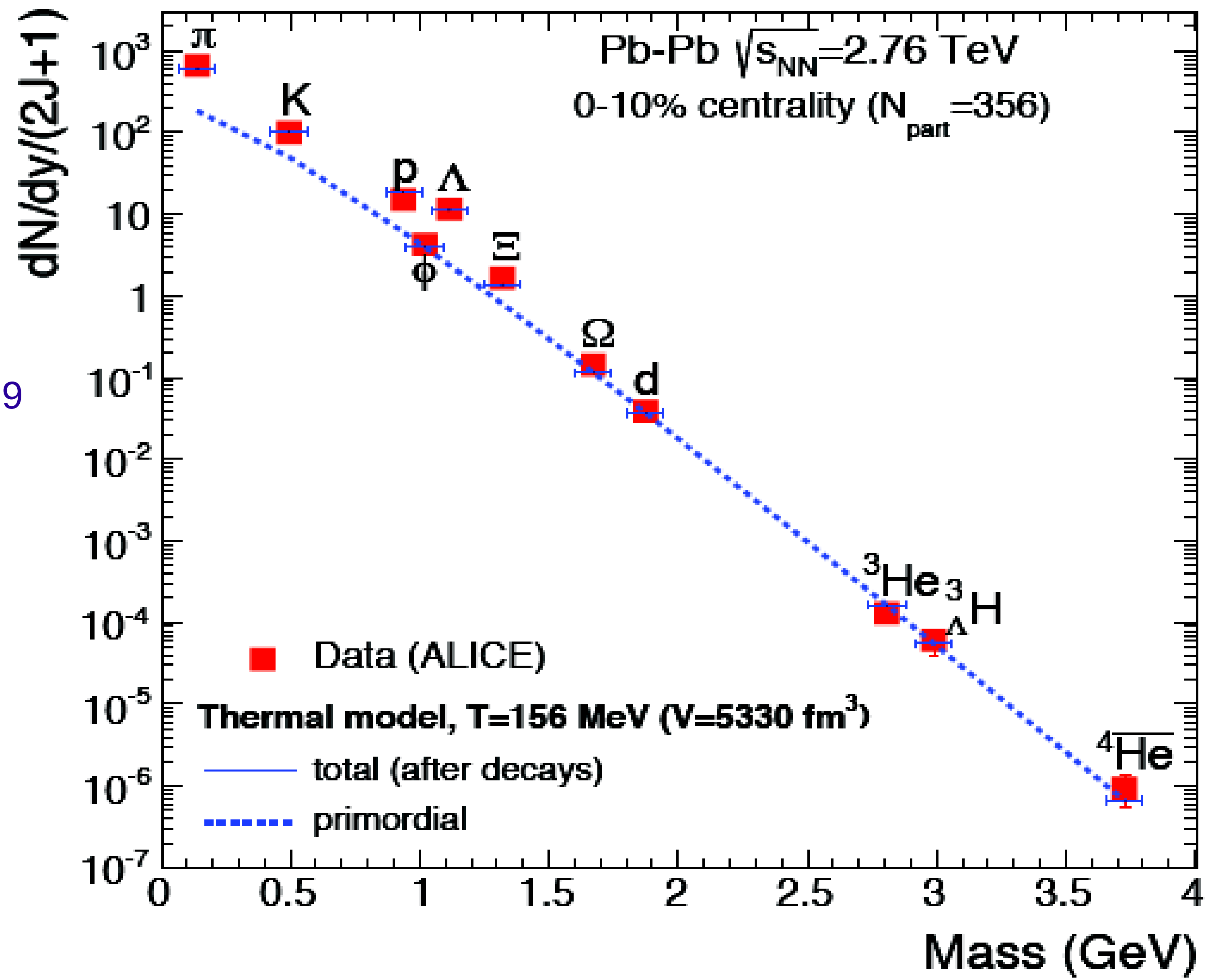
fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound by only 100 keV, it is the **ultimate halo nucleus,**
produced at T=156 MeV.

This result is important for the understanding of the production of exotica, see below.

Mass dependence of primordial and total yield compared to LHC data



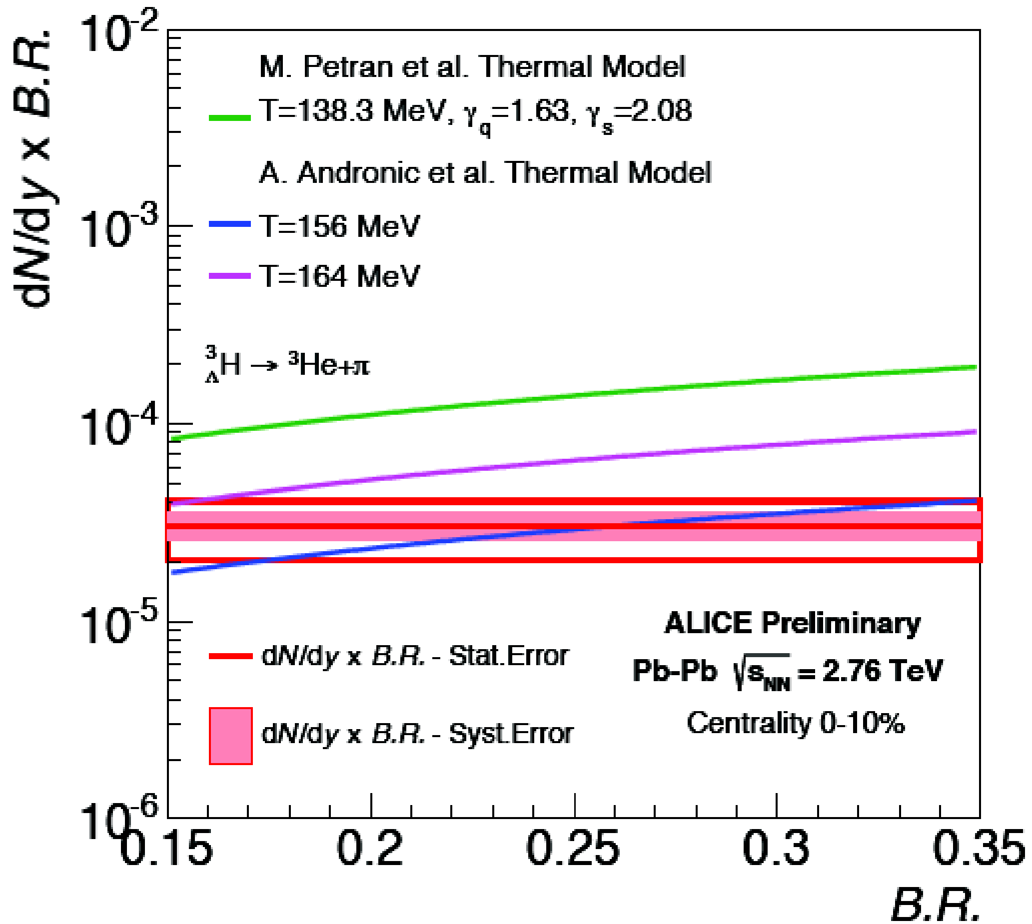
… and also including anti-alphas



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

Hypertriton results vs predictions from different thermal models



d*N*/dy in good agreement with thermal model prediction from Andronic *et al.* for T = 156 MeV

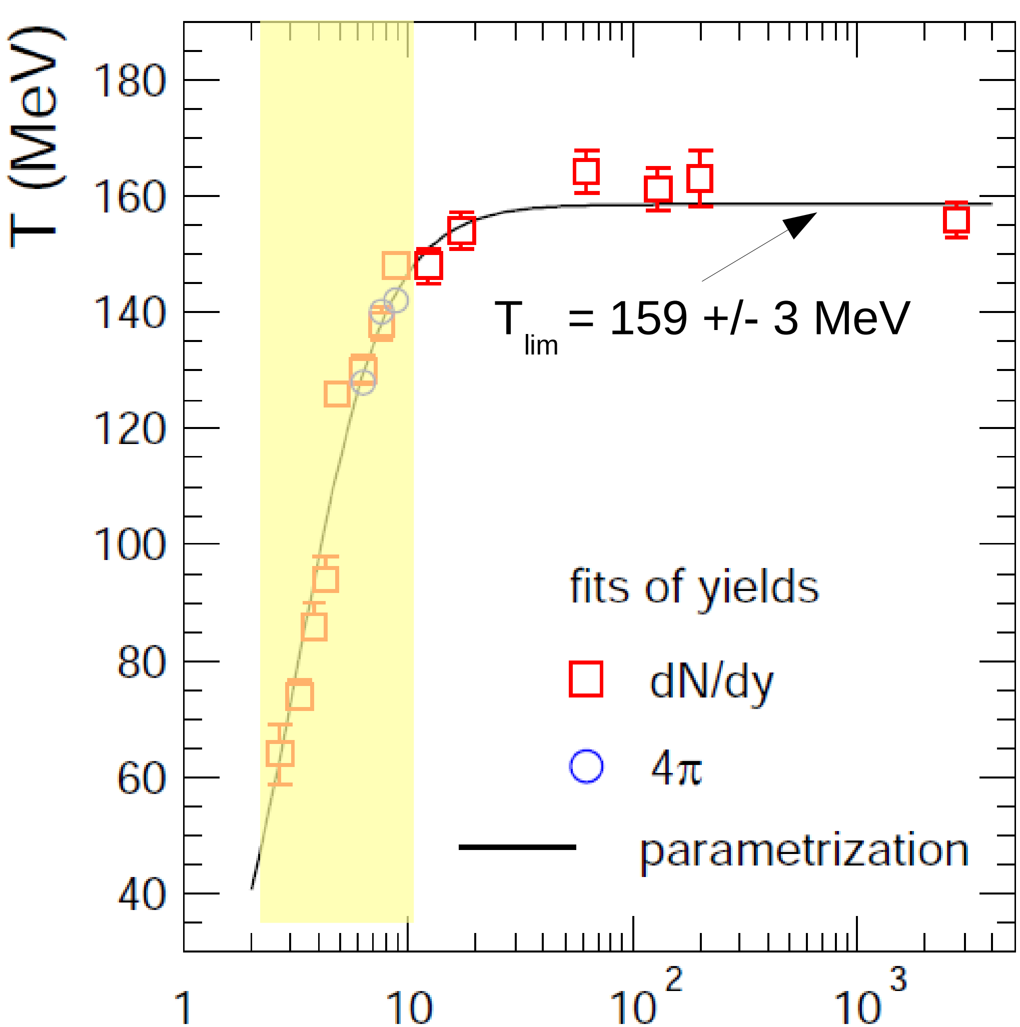
Non-equilibrium model by Rafelski and Petran is off by more than factor of 3

Some systematics of thermal model parameters

Energy dependence of temperature and baryo-chemical potential

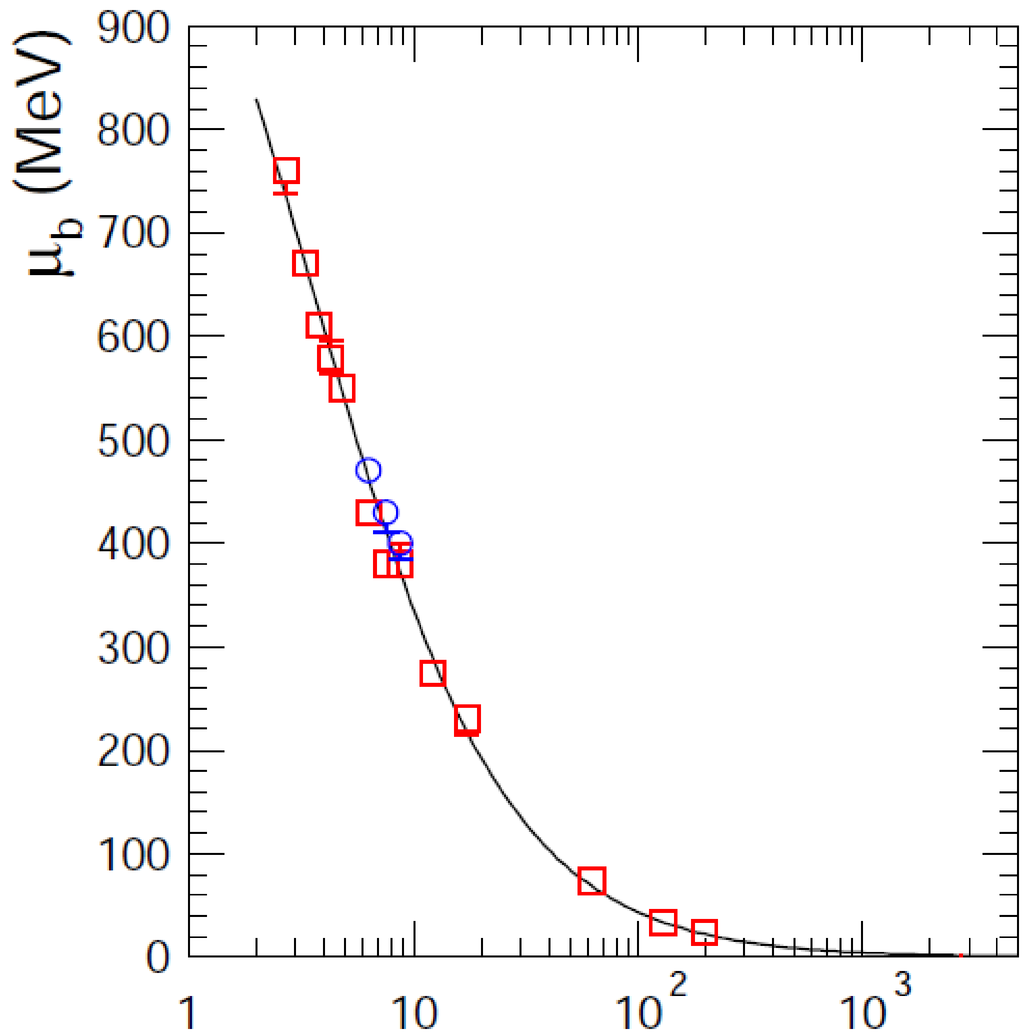
energy range from SPS down to threshold

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



T_{lim} = 159 +/- 3 MeV is lower limit for phase boundary

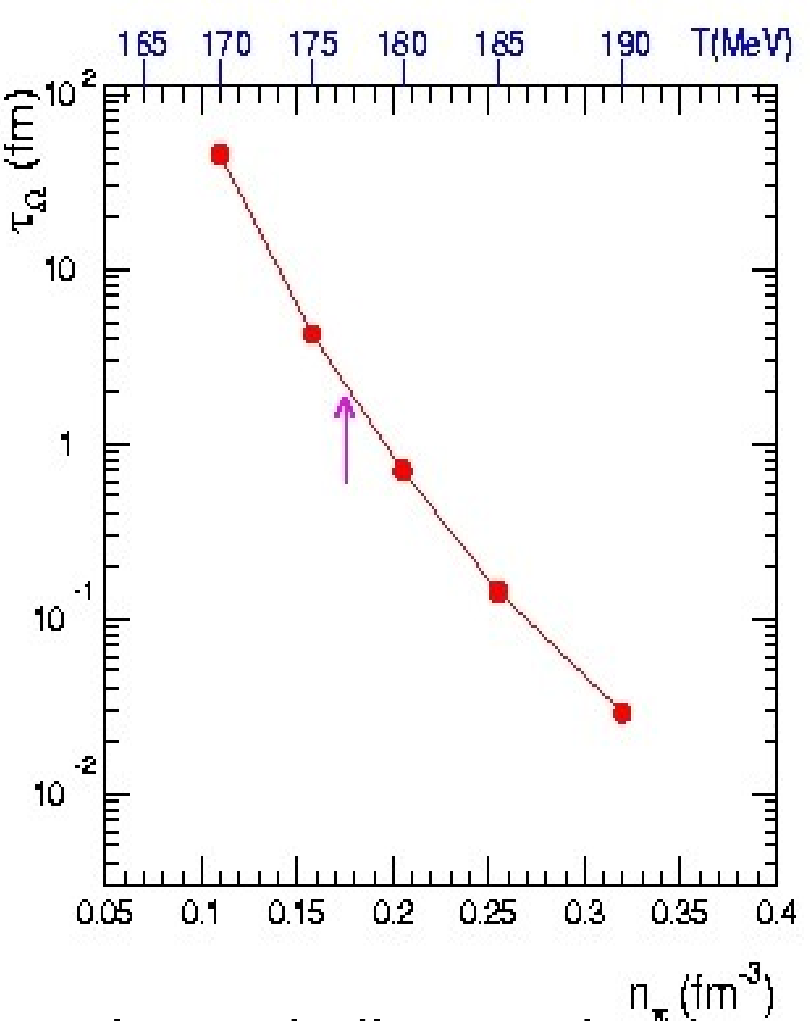
$\sqrt{s_{NN}}$ (GeV)



T_c = 155 +/- 8 MeV from lattice

$\sqrt{s_{NN}}$ (GeV)

The QGP phase transition drives chemical equilibration for small mu_b

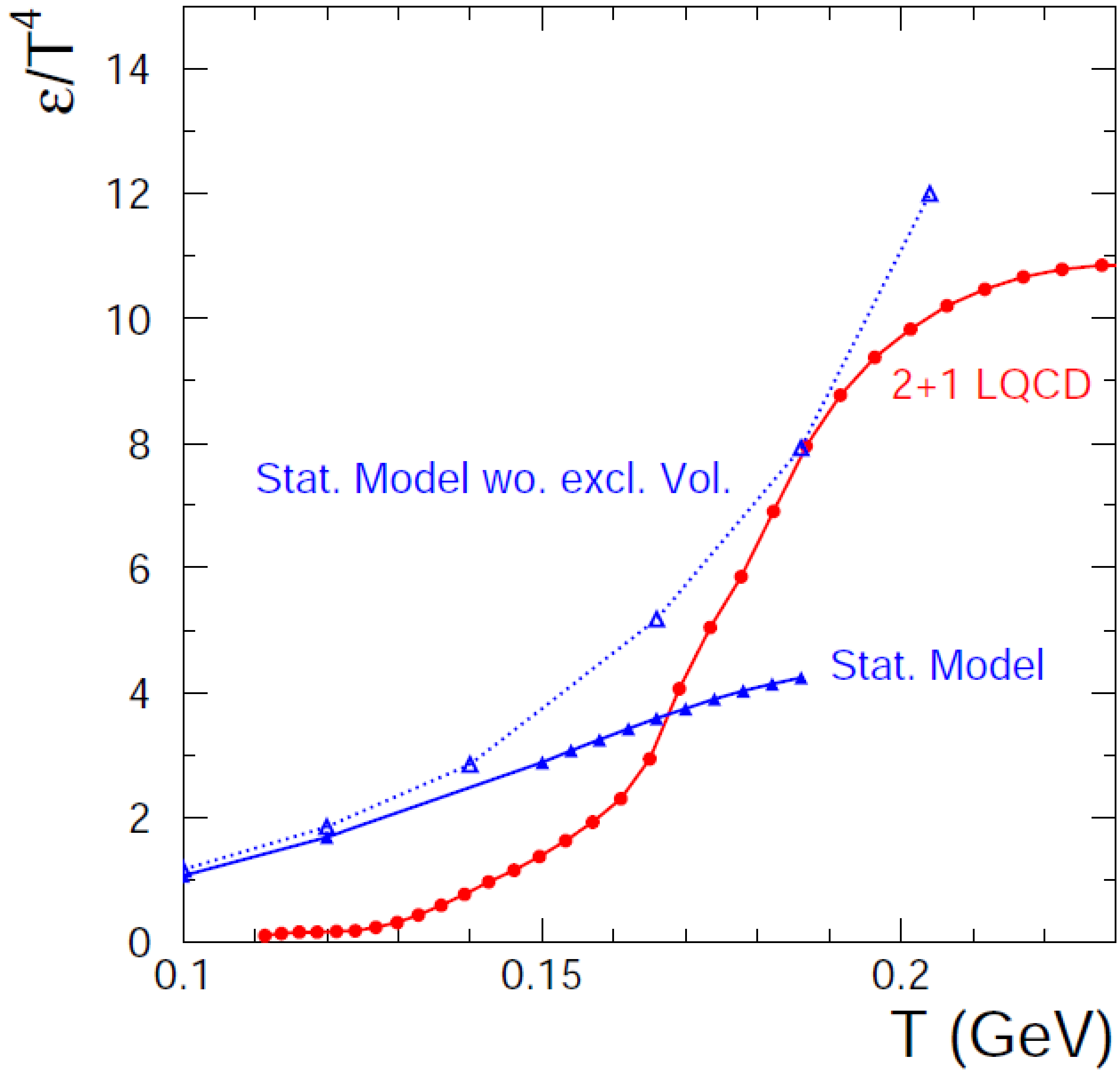


- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window.

are there similar mechanisms for large μ_b?

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

Temperature dependence of energy density near T_c



The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, 3He hypertriton, …
implies no entropy production after chemical freeze-out

hypertriton Lambda separation energy is 130 keV << T_chem = 156 MeV

use relativistic nuclear collision data and thermal model predictions to search for exotic objects

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

Some historical context on cluster production in relativistic nuclear collisions

P.J. Siemens and J.I. Kapusta, Phys. Rev. Lett. 43 (1979) 1486.

here the provocative statement was made that cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. for example:
entropy/baryon is proportional to -ln(d/p)

ENTROPY AND CLUSTER PRODUCTION IN NUCLEAR COLLISIONS

László P. CSERNAI* and Joseph I. KAPUSTA

PHYSICS REPORTS (Review Section of Physics Letters) 131, No. 4 (1986) 223–318.

Very concise summary, including an elucidation of the relation between thermal fireball model and coalescence model

Presented at the Relativistic Heavy-Ion Winter School,
Banff, Alberta, Canada, February 22-26, 1982

I. MECHANISM OF LIGHT PARTICLE EMISSION
II. CURRENT PUZZLES AND FUTURE POSSIBILITIES

Shoji Nagamiya

February 1982

Shoji Nagamiya's derivation

2.1. Entropy Puzzle

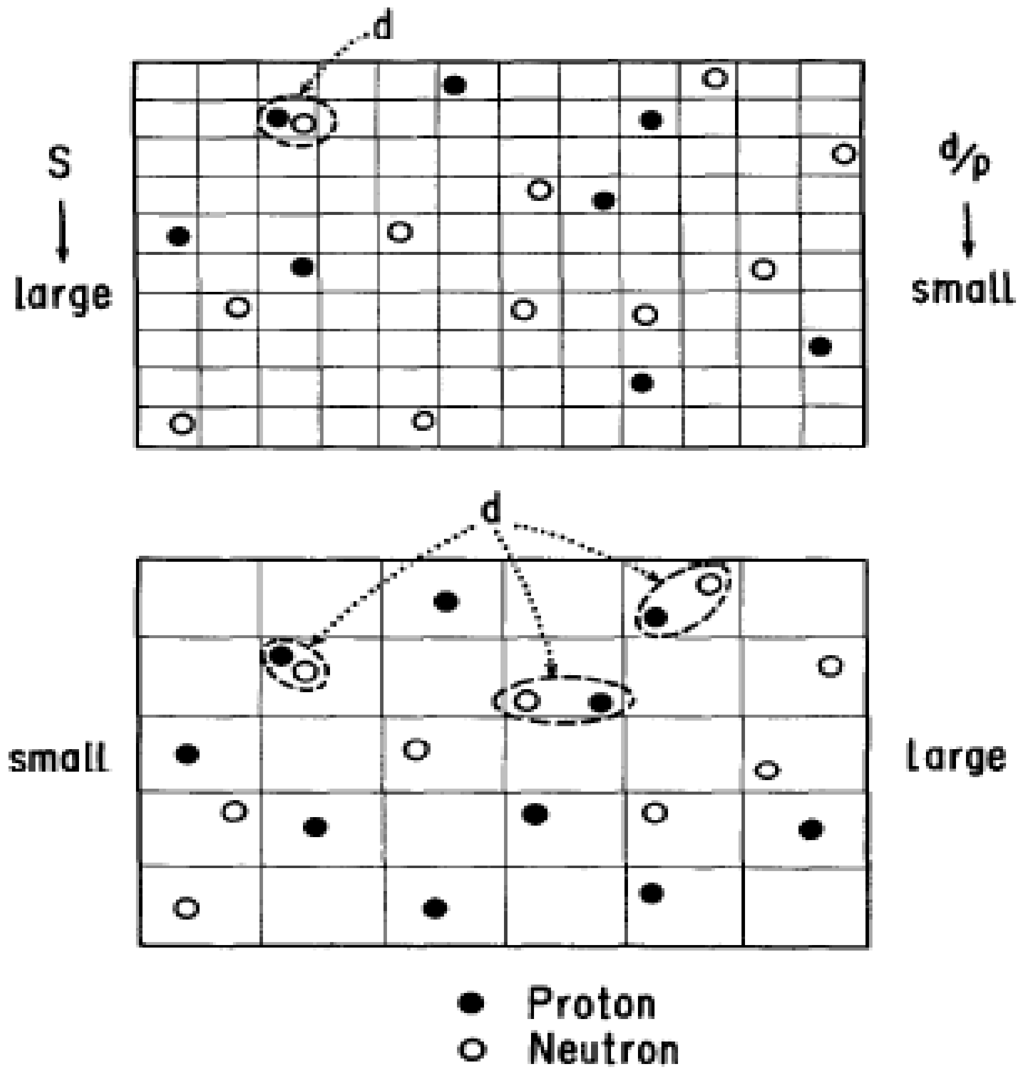
Siemens and Kapusta[1] pointed out that the yield ratios of composite-fragments-to-protons may provide information on "entropy" created in nuclear collisions. Assuming chemical and thermal equilibrium, the entropy S is given by $5/2 - \mu/T$, where μ and T are the chemical potential and the temperature, respectively. Since the d/p ratio is related to the chemical potential by[2]

$$\sigma(d)/\sigma(p) = [(m_d/m_p)^{3/2}(2S_d+1)/(2S_p+1)]\cdot\exp(\mu/T), \quad (1)$$

this ratio is related to S by

$$S = 3.95 - \ln(\sigma_d/\sigma_p), \quad (2)$$

Nagamiya 1982: 'intuitive' explanation of the relation between entropy and formation of composite objects nuclei



changes at high energy:

- no feeding from higher mass states

- entropy is mostly in pions

- conserved quantity: $S/(N_B - N_{Bbar})$

The 'snowball in hell' story

Production of strange clusters and strange matter in nucleus-nucleus collisions at the A

P. Braun-Munzinger, J. Stachel (SUNY, Stony Brook). Dec 1994. 9 pp.

Published in J.Phys. G21 (1995) L17-L20

In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, α ...) and for for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.

Thermal vs coalescence model predictions for the production of loosely bound objects in central Au—Au collisions

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	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}$St^{-8}	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}$St^{-9}	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}$St^{-11}	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}$St^{-13}	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}$St^{-16}	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

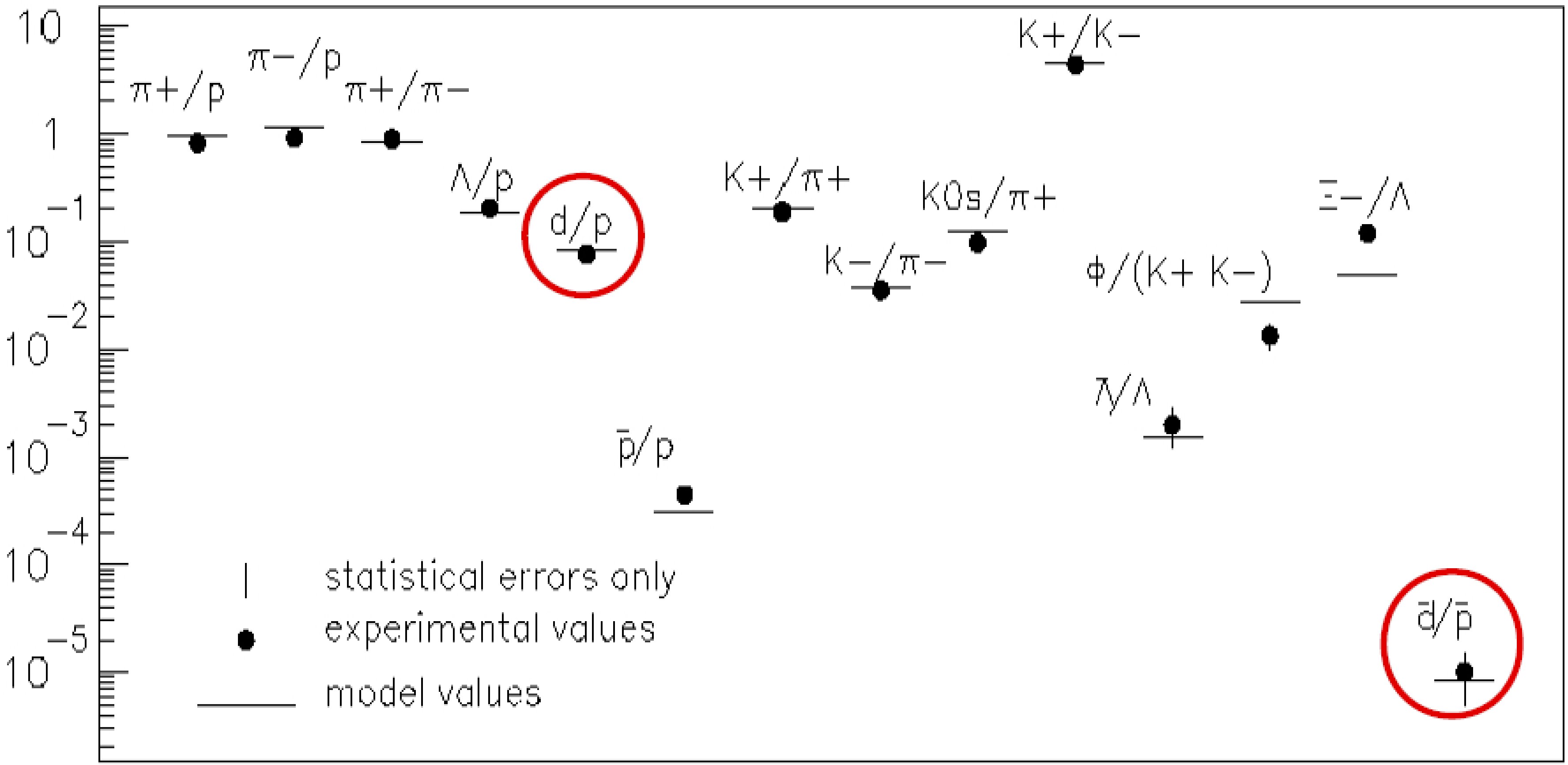
P. Braun-Munzinger, J. Stachel, J. Phys. G **28** (2002) 1971 [arXiv:nucl-th/0112051]

J.Phys. G21 (1995)
L17-L20

deuterons and anti-deuterons also well described at AGS energy

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

Thermal model and production of light nuclei at AGS energy

<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

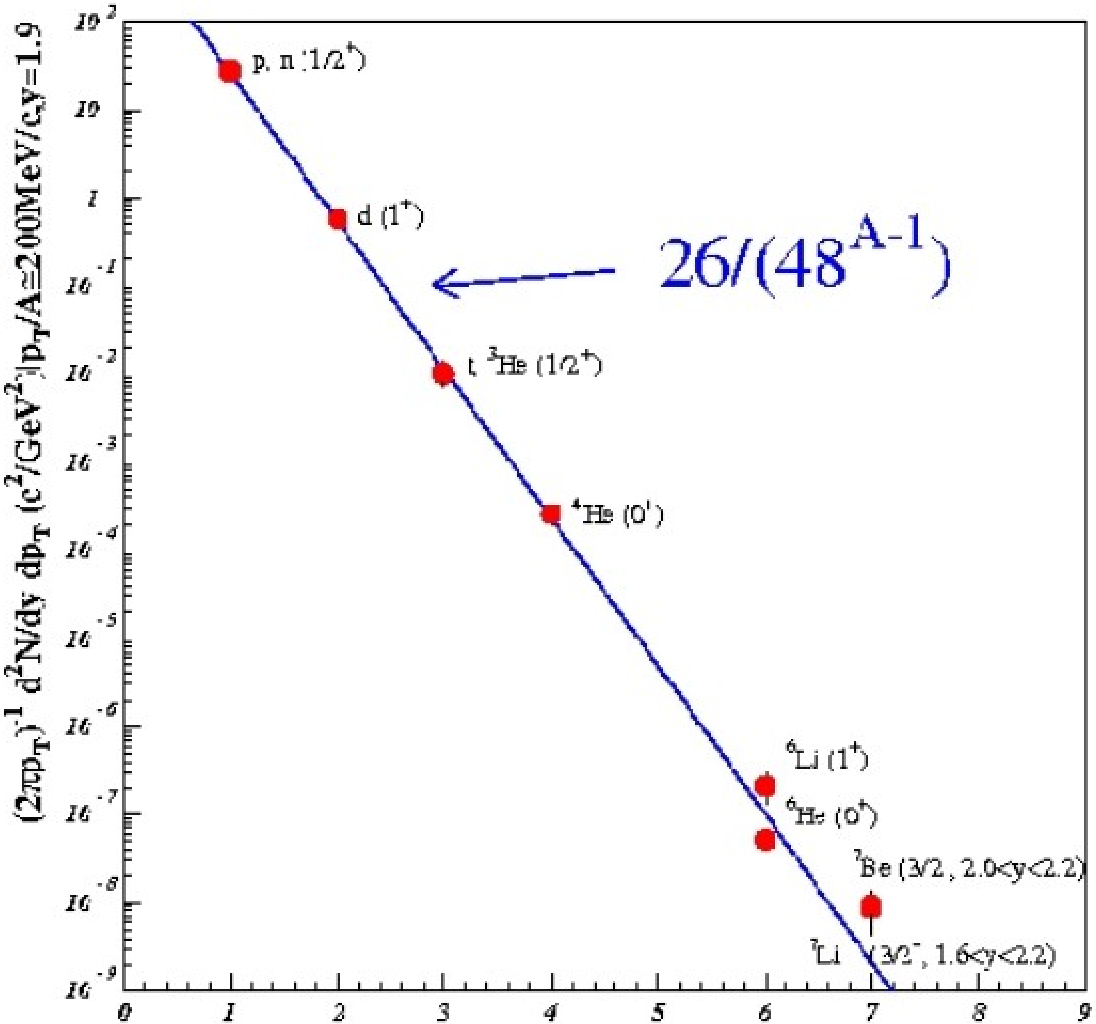
$R_p = 24$ good agreement

also good for **antideuterons**:

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

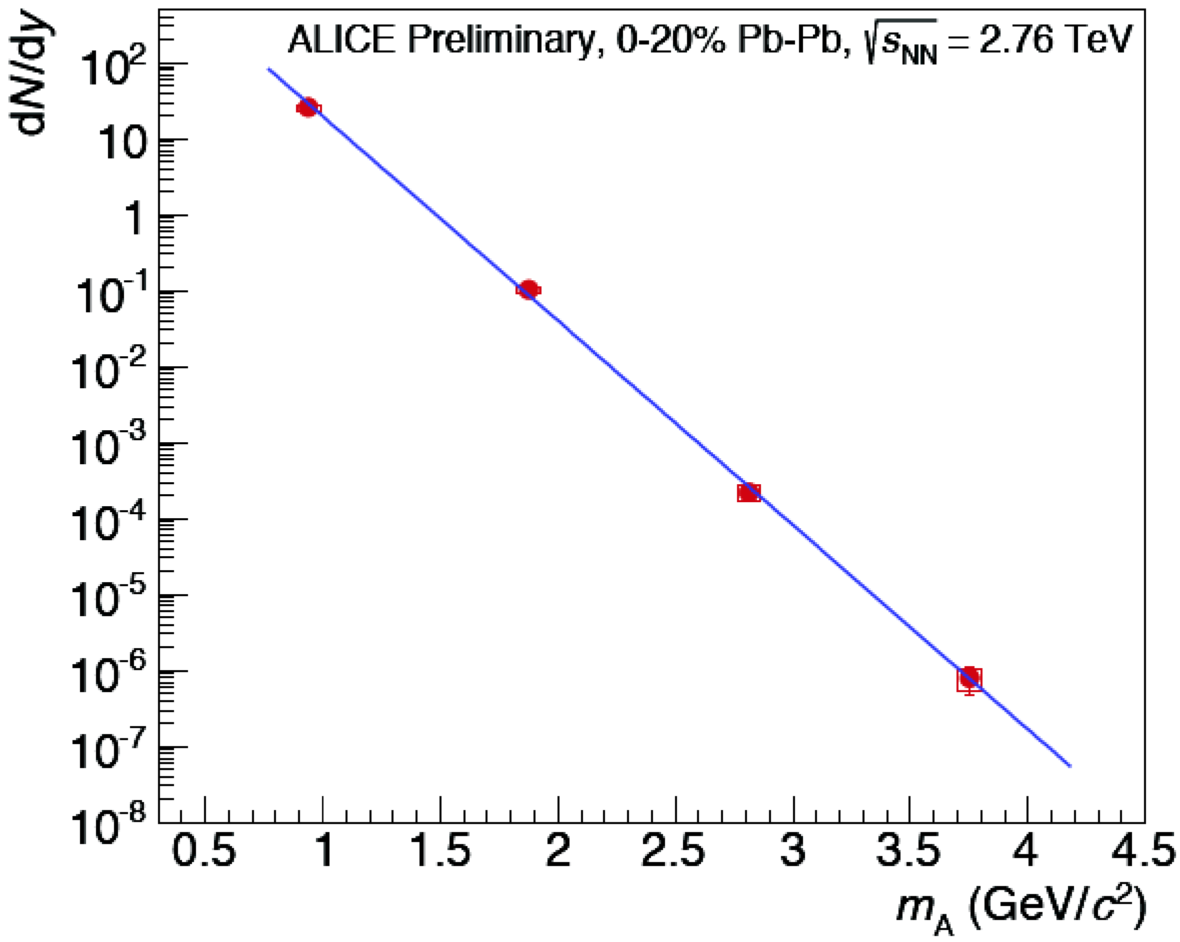
P. Braun-Munzinger, J. Stachel, J. Phys. G28 (2002) 1971

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



mass number A

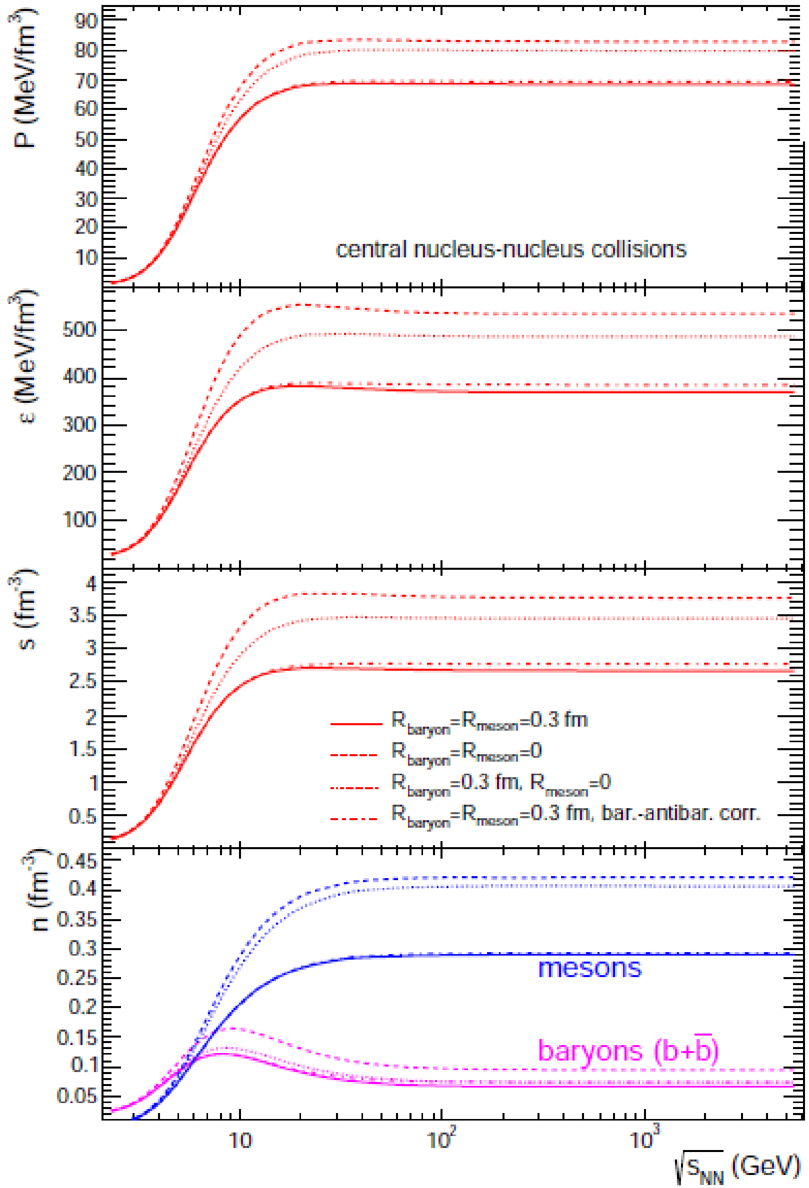
Production of light anti-nuclei at LHC energy



penalty factor exp{-m/T} ≈ 300

Cluster production and entropy

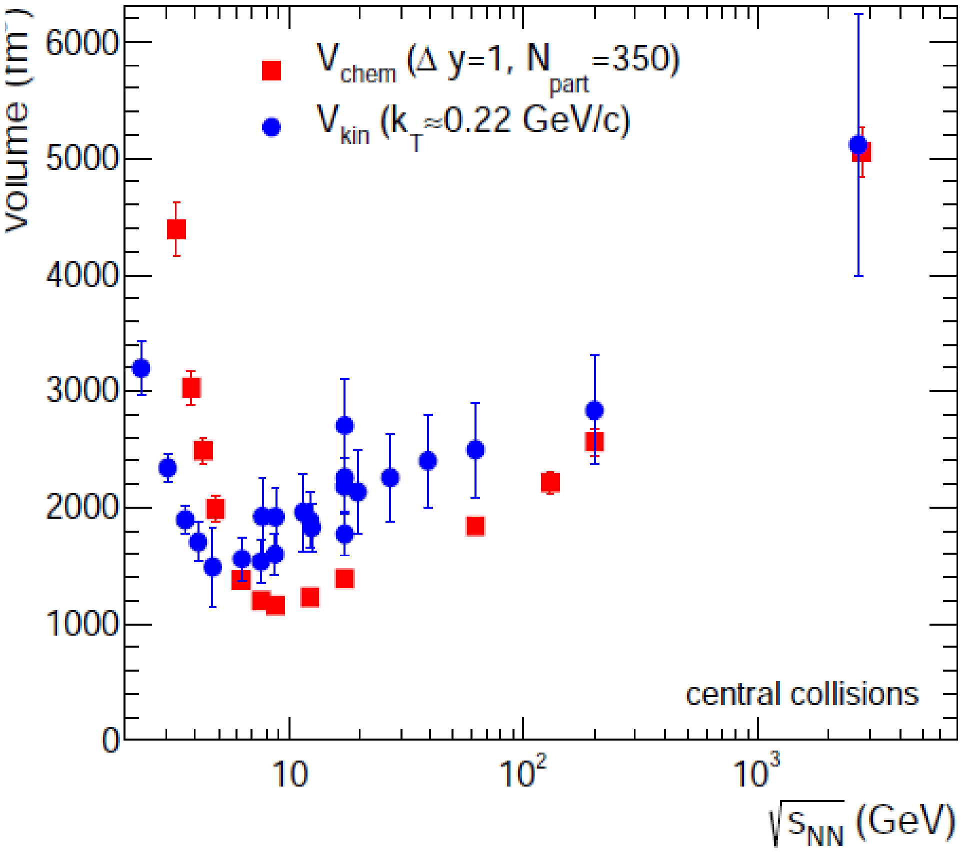
S = s V = -const ln(d/p)



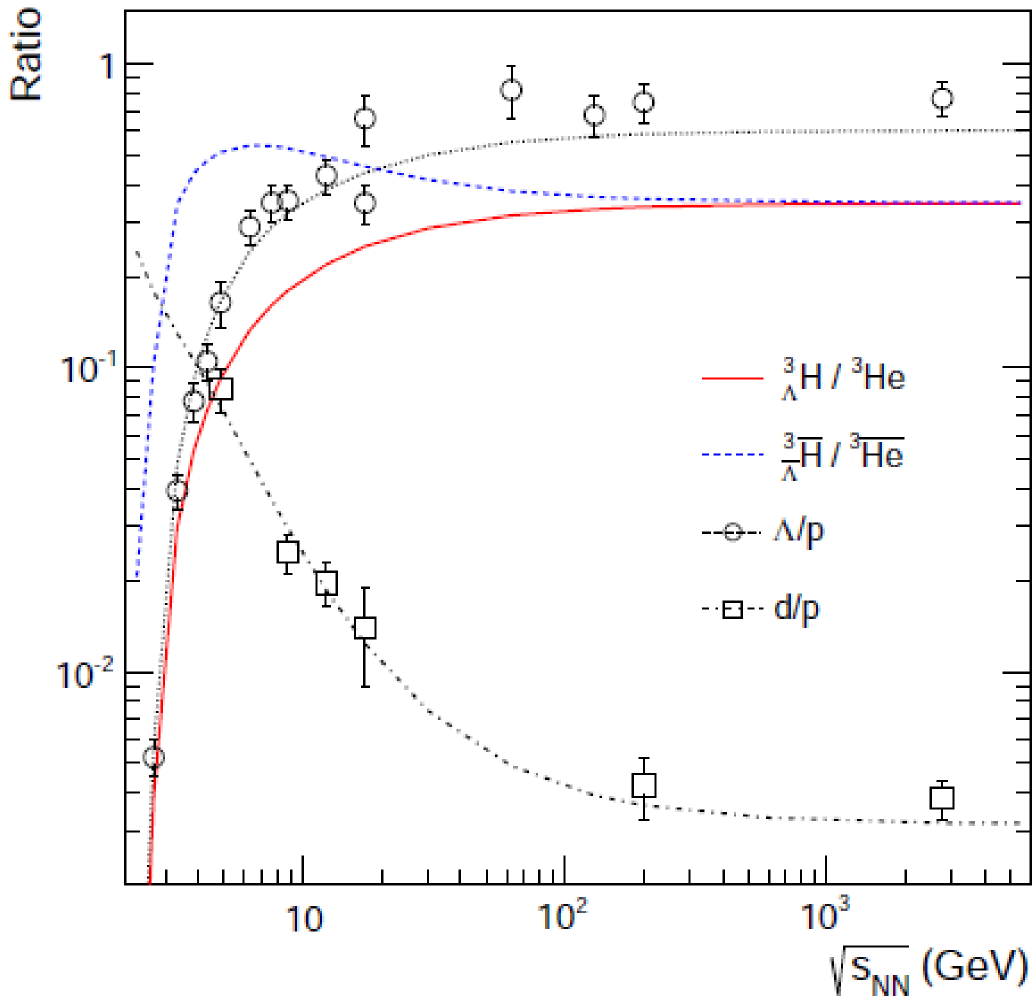
Interacting hadron resonance gas meets lattice QCD

arXiv:1201.0693

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



energy dependence of d/p ratio and thermal model prediction



agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase

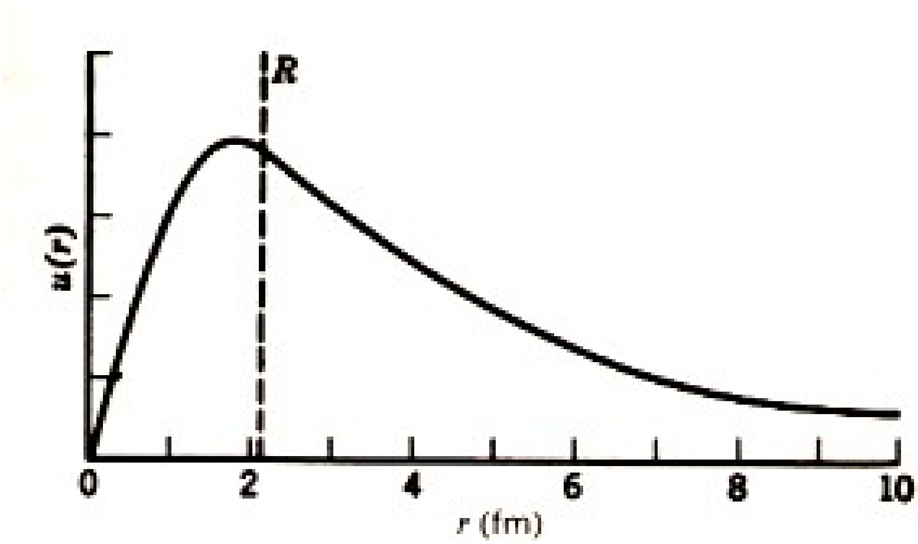
The size of loosely bound molecular objects

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

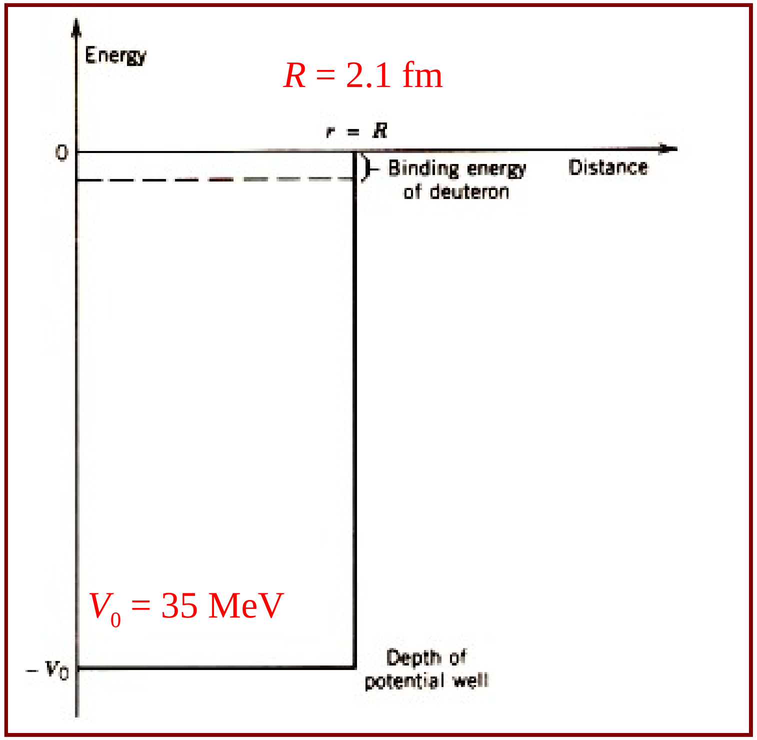
Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which the constituents are almost always separated by more than the range. One of the universal predictions is that the root-mean-square (rms) separation of the constituents is $(4\mu E_X)^{-1/2}$, where E_X is the binding energy of the resonance and μ is the reduced mass of the two constituents. As the binding energy is tuned to zero, the size of the molecule increases without bound. A classic example of a loosely-bound S-wave molecule is the deuteron, which is a bound state of the proton and neutron with binding energy 2.2 MeV. The proton and neutron are correctly predicted to have a large rms separation of about 3.1 fm.

Artoisenet and Braaten,
arXiv:1007.2868

The deuteron as a loosely bound object



Mass = 1875 MeV
B.E. = 2.23 MeV
rms radius = 3 fm > range of potential



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 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 X(3872)

mass is below threshold of (D^{*0} D^0_{bar}) by (0.42 +/- 0.39) MeV

rms separation = 3.5 – 18.3 fm structure: $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$

should be able to predict the X(3872) production probability in pp collisions at LHC energy with an accuracy of about 30%, uncertainty is due to not very precisely known number of charm quarks

result ready shortly

deuteron and anti-deuteron production in pp collisions at high energy

an important background for dark matter searches

Heavy dark matter states DM can decay via

$DM \rightarrow d\ d_{bar} + X$

Major experiments such as AMS-02 and GAPS search for anti-deuterons in cosmic rays

General Analysis of Antideuteron Searches for Dark Matter

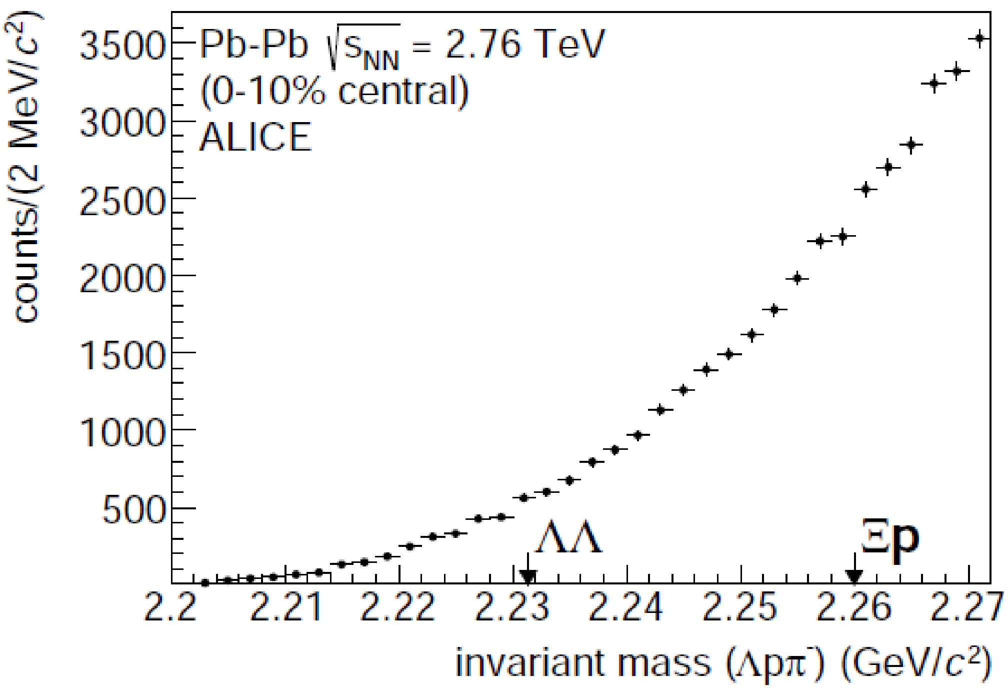
Yanou Cui,[a,1] John D. Mason,[a,2] and Lisa Randall[a,3]

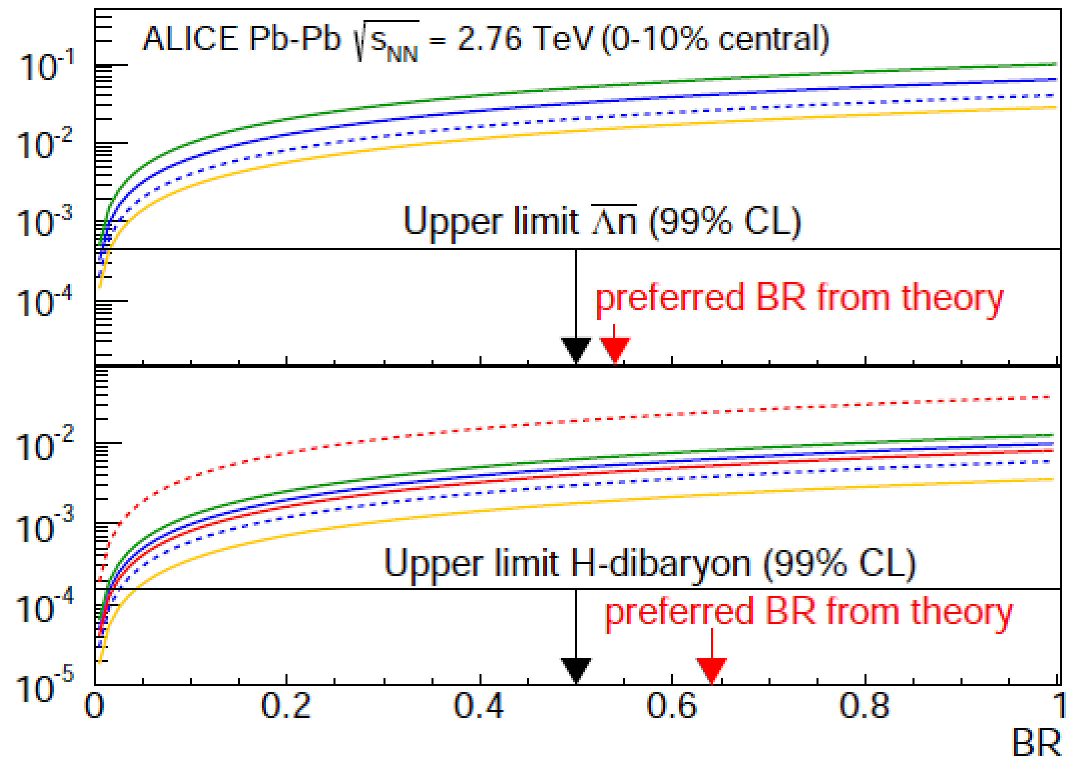
arXiv:1006.0983

background yield from $p + H \rightarrow d_{bar} + X$ and $p + He \rightarrow d_{bar} + X$ should also be well described (better than 50 % accuracy, much better than current coalescence estimates) within thermal model

searches for exotic bound states

Nicole Martin and Benjamin Doenigus, ALICE





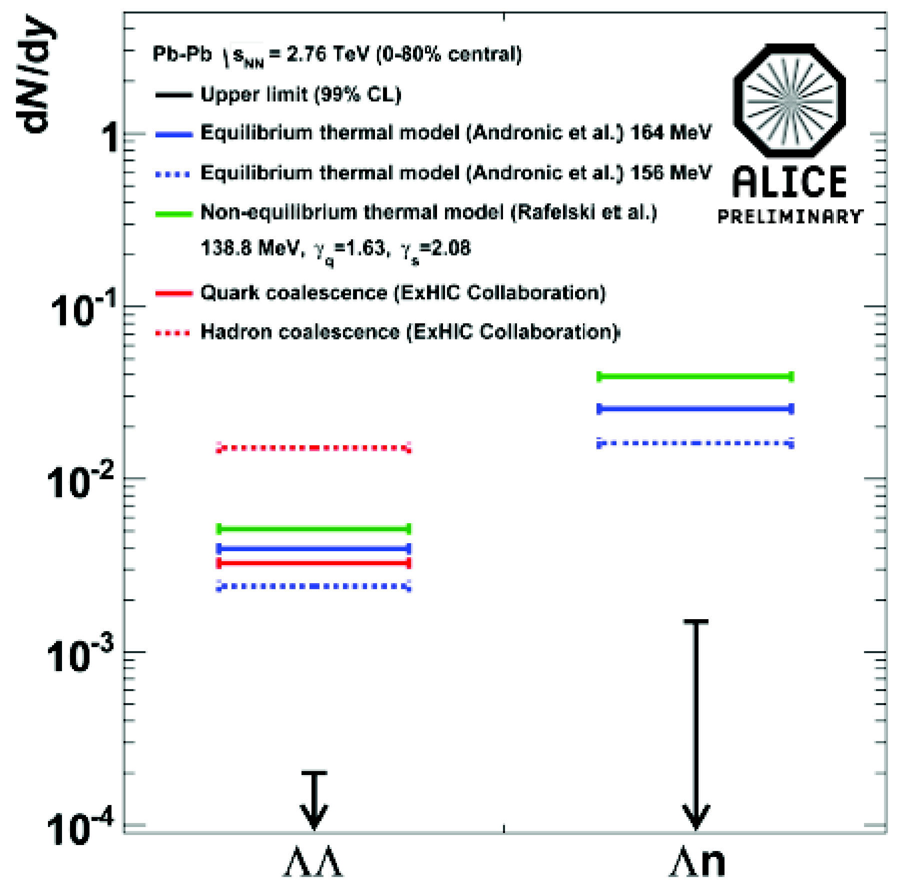
no H, Lambda-n bound states

ALICE upper limits on H and (Lambda-n) production in central Pb-Pb collisions and thermal model predictions

The $\overline{\Lambda n}$ bound state and the H-dibaryon are not observed

Different model predictions are of the same order

Upper limits for the two particles are set, at least a factor 10 below model predictions



Hypertriton yields well reproduced but H and (Lambda-n) yields are overpredicted by at least a factor of 10 --- casting serious doubts on the existence of these states

Summary

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

the full QCD statistical operator is encoded in the nuclear collision data on hadron multiplicities

energy dependence of hadron yields provides strong connection to fundamental QCD prediction of hadronic and quark-gluon matter at high temperature

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

these results should be very useful also for dark matter searches and exotica searches

Additional slides

where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slighty higher T = 158 MeV, driven by hyperons

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important note: corrections for weak decays

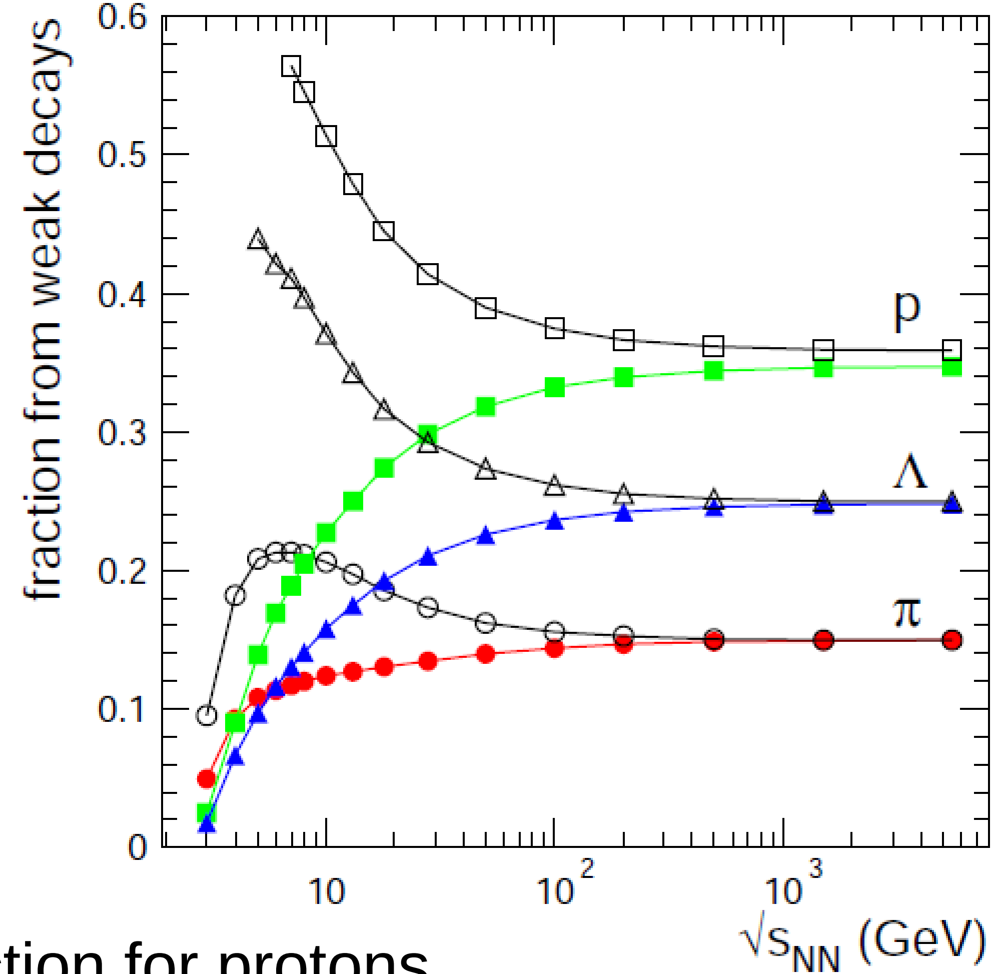
All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

in light of high precision LHC data the corrections done at RHIC may need to be revisited.

treatment of weak decays

fraction of yield from weak decays



biggest correction for protons
done in hardware (vertex cut) at ALICE
software corrections at all lower energies

Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

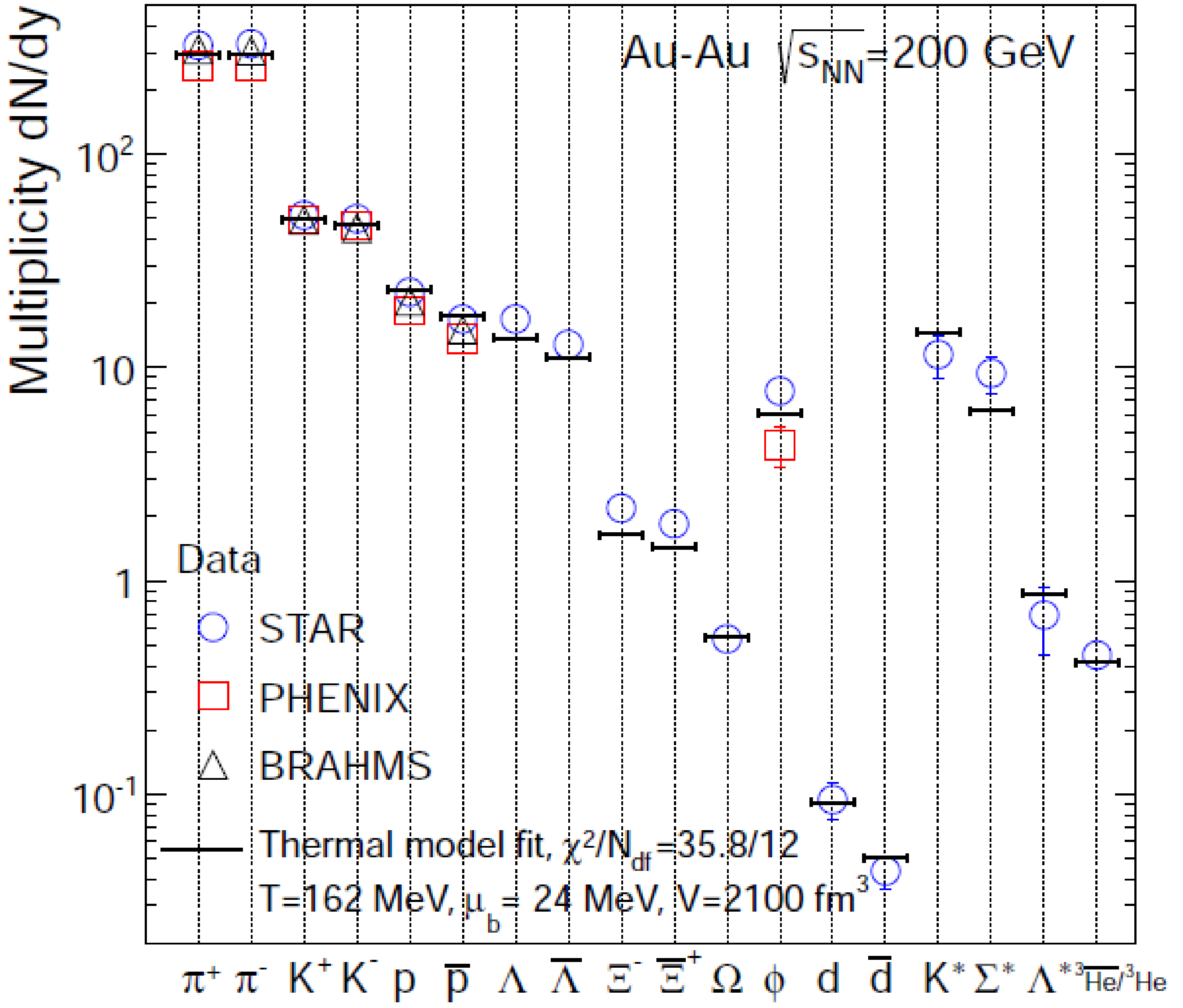
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments

Au+Au central at 200 GeV, all experiments combined

T = 162 Me'



could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation

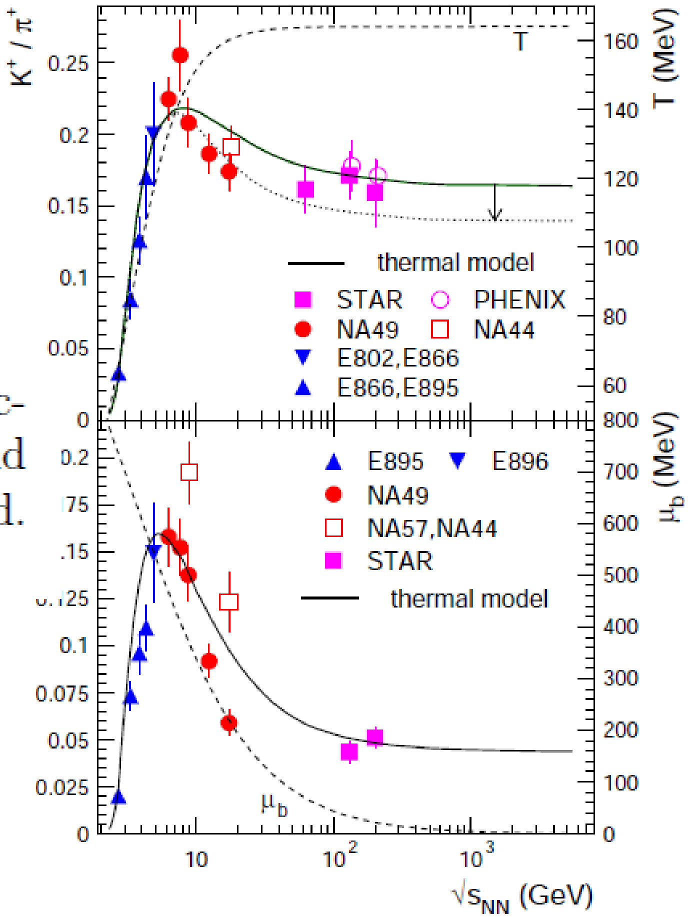
could it be incomplete hadron resonance spectrum?

Note: because of baryon conservation, adding more baryon resonances will decrease in the model the p/pi ratio

An N* will decay dominantly into 1 N + a number (depending on the N* mass) of pions

Same effect seen in
K/pi ratio because of strangeness conservation

A. Andronic, P. Braun-Munzinger, J. Stachel, Thermal hadron production in relativistic nuclear collisions: the sigma meson, the horn, and the QCD phase transition, Phys. Lett. **B673** (2009) 142, erratum ibid. **B678** (2009) 516, arXiv:0812.1186.



could it be proton annihilation in the hadronic

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

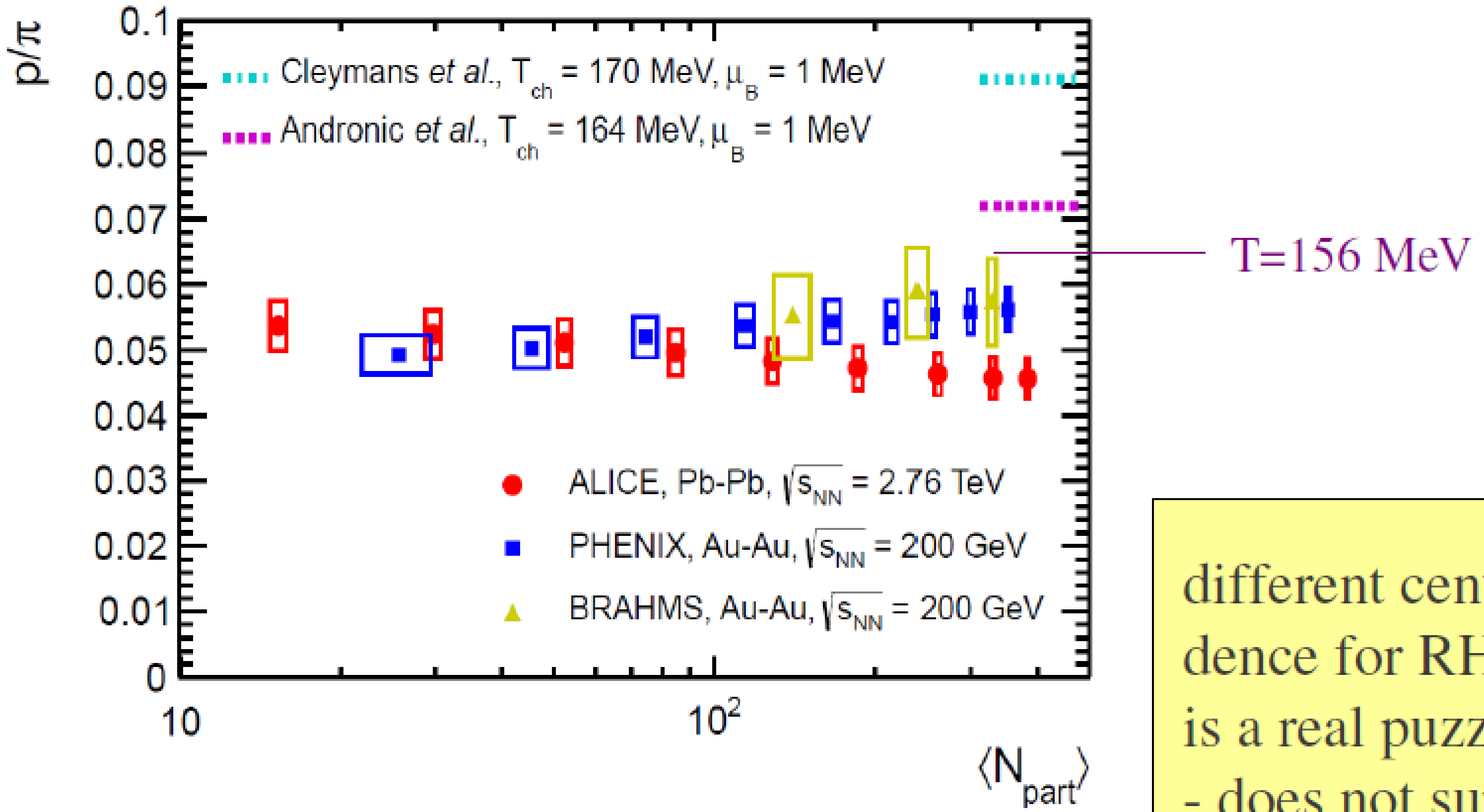
• need to incorporate detailed balance, 5pi → p p_bar
not included in current Monte Carlo codes (RQMD)

• taking detailed balance into account reduces effect strongly, see Rapp and Shuryak 1998

• see also W. Cassing, Nucl. Phys. A700 (2002) 618
and recent reanalysis, by Pan and Pratt, arXiv:

• agreement with hyperon data would imply strongly reduced hyperon annihilation cross section with anti-baryons → no evidence for that

centrality dependence of proton/pion ratio



different centrality dependence for RHIC and LHC is a real puzzle
- does not support annihilation picture
- is it real? physics origin?

the 'proton anomaly' and production of light nuclei

can the measurement of d, t, 3He and 4He settle the issue?
what about hypertriton?

important to realize: production yield of deuterons is fixed at $T = T_{chem} = 156$ MeV even if $E_B(d) = 2.23$ MeV!

entropy/baryon is proportional to $-\ln(d/p)$ and is conserved after T_{chem}

good agreement with LHC d and hyper-triton yield implies: there is no shortage of protons and neutrons at chemical freeze-out, inconsistent with annihilation scenario

Nuclear collisions, open and hidden charm hadrons, and QCD

Hadrons containing charm quarks can also be described provided open charm cross section is known

Recent ALICE data imply Debye screening near T_c for charmonium and deconfined heavy quarks, see talk by Johanna Stachel

Could it be that increasing number of charm quarks changes (lowers) T_c? An issue for the FCC!

Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at T_c

- Debye screening length < 0.4 fm near T_c

- Combination of uncorrelated charm quarks into J/psi → deconfinement

statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP

Debye mass, LQCD, and J/psi data

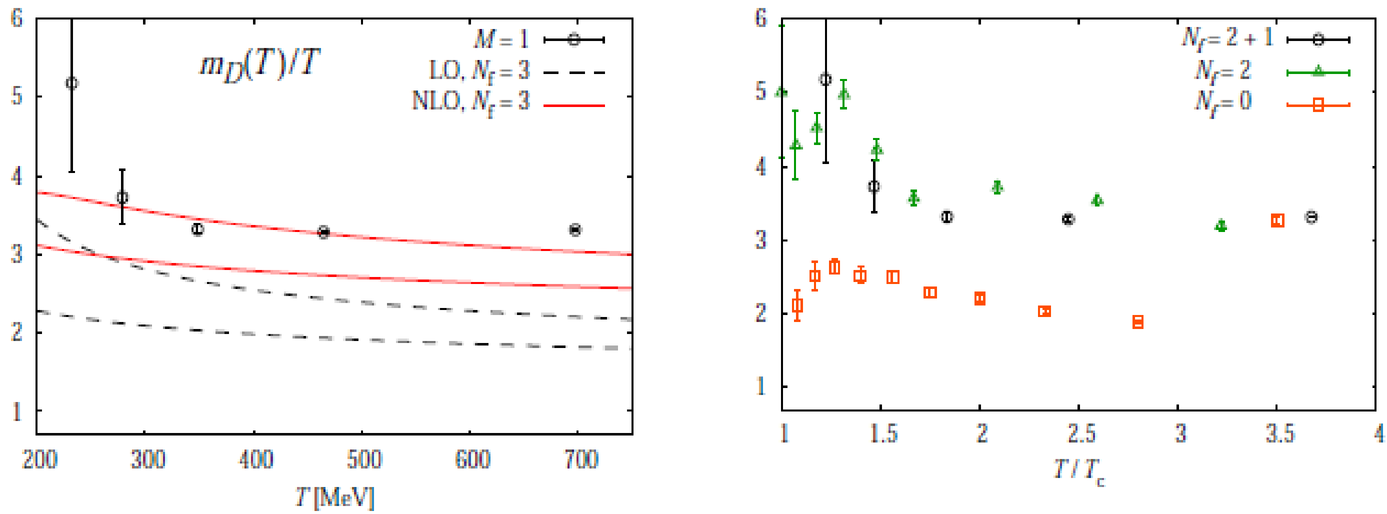


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi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

from J/psi data and statistical hadronization analysis:

$m_{Debye}/T > 3.3$

at T = 0.15 GeV