the QCD phase boundary, deconfinement, and production of rare, loosely bound objects

- the hadron resonance gas and (u,d,s) hadron production
- Dashen-Ma-Bernstein taken at face value
- loosely bound objects
- coalescence vs thermal production
- statistical hadronization of heavy quarks – a window to understand deconfinement

pbm
Light-Up 2018 Workshop
CERN
June 14 - 16, 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

hadron production and the QCD phase boundary

part 1: the hadron resonance gas

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.)

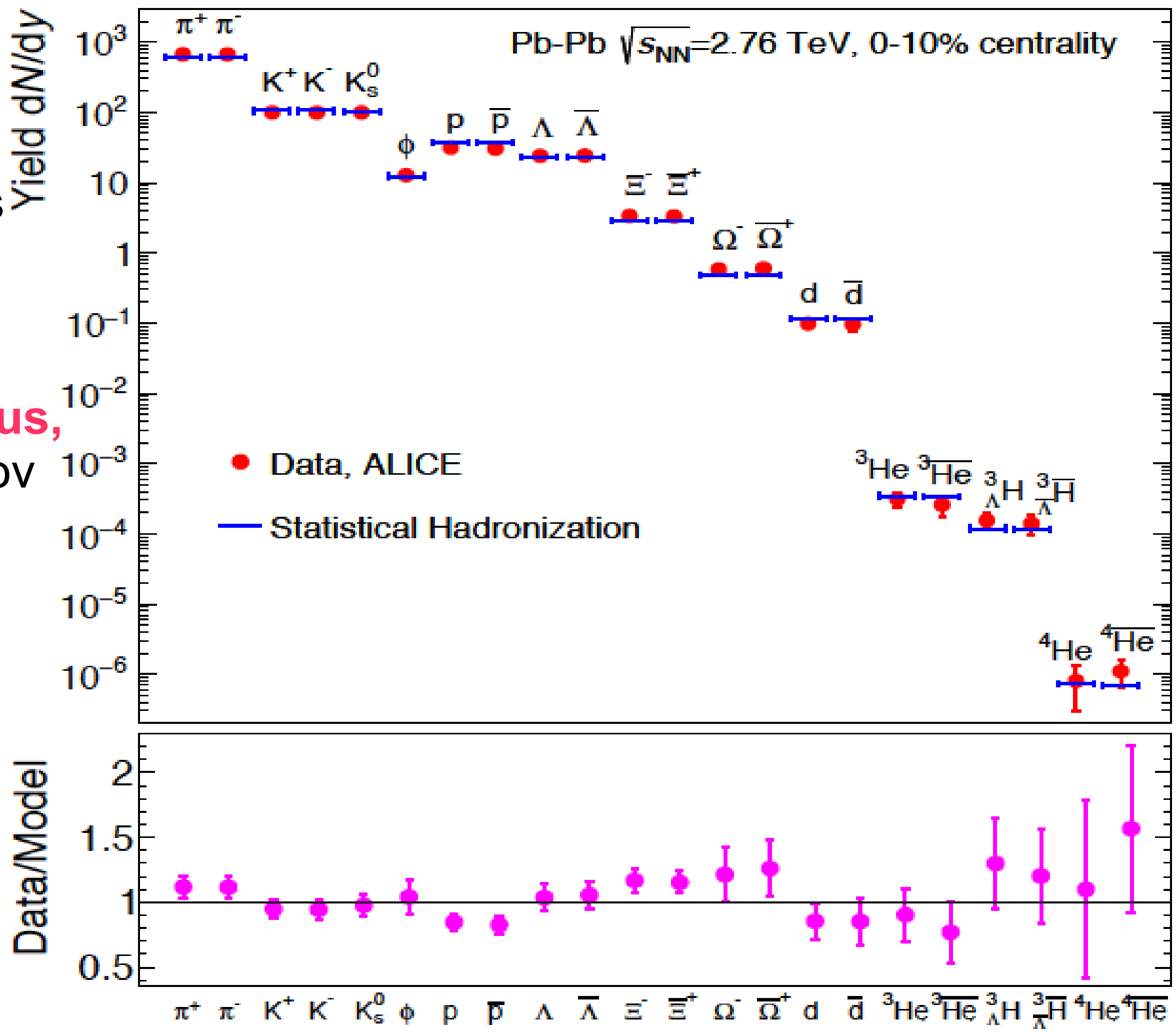
$\Rightarrow (T, \mu_B, V)$

canonical treatment whenever needed (small abundances)

Oct. 2017 update: excellent description of ALICE@LHC data

fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n),
Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156 MeV. close to an Efimov state

proton discrepancy about 2.8 sigma

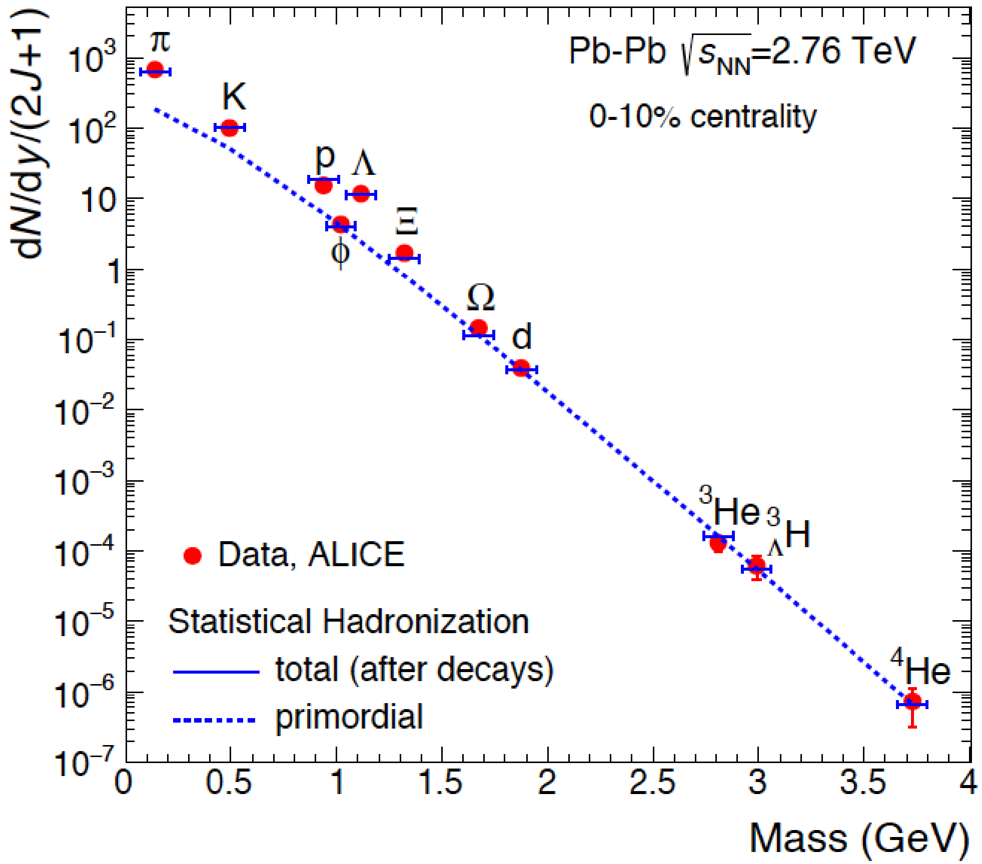


Andronic, pbm, Redlich, Stachel, arXiv:1710.09425

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].

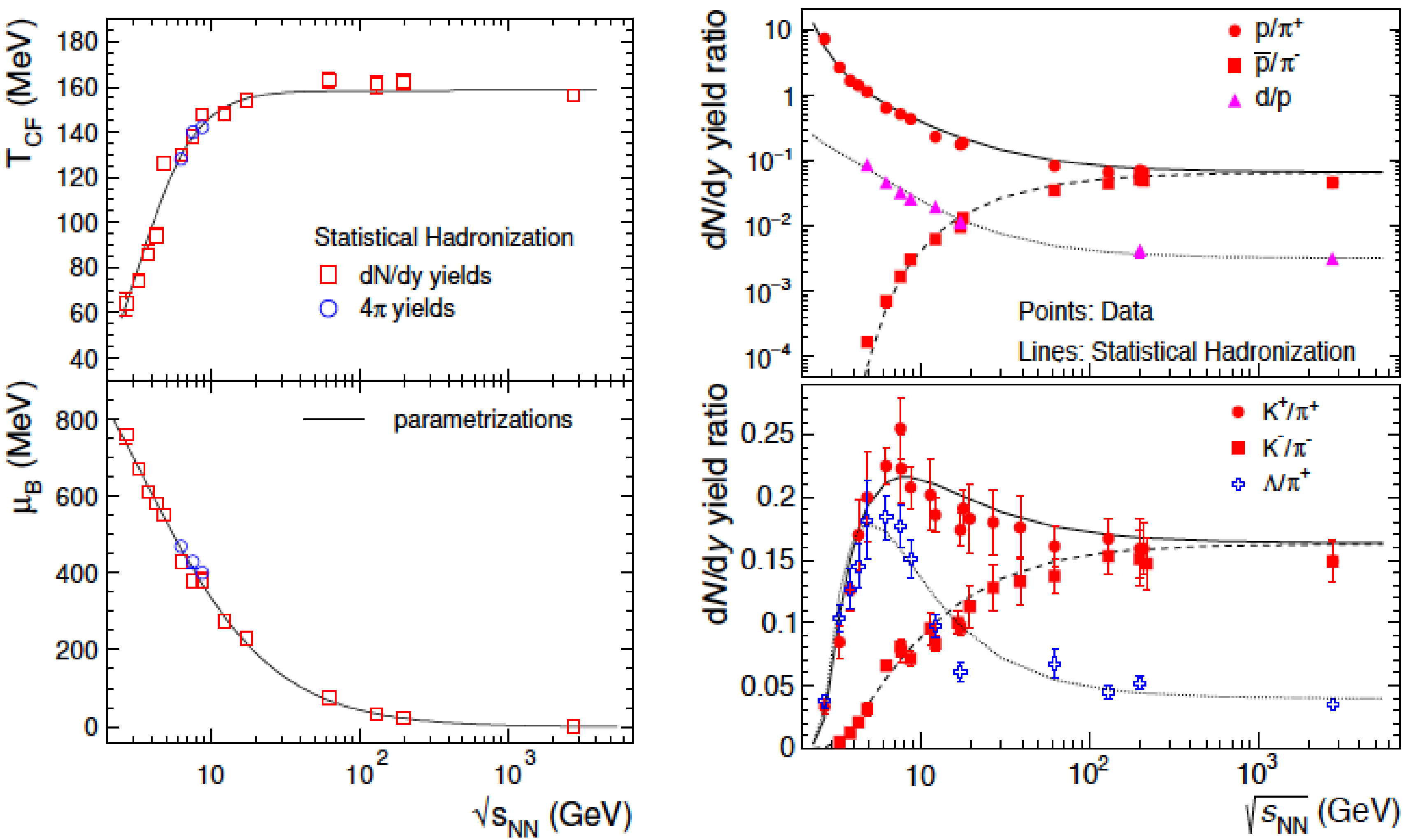
excellent agreement over 9 orders of magnitude

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

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'

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

going beyond the non-interacting HRG – next 3 slides from K. Redlich, QM18

HRG in the S-MATRIX APPROACH

Pressure of an interacting, a+b ⇔ a+b, hadron gas in an equilibrium

$$\boxed{P(T) \approx P_a^{id} + P_b^{id} + P_{ab}^{\text{int}}}$$

The leading order interactions, determined by the two-body scattering phase shift, which is equivalent to the second virial coefficient

$$P^{\text{int}} = \sum_{I,j} \int_{m_{th}}^{\infty} dM \; B_j^I(M) P^{id}(T,M)$$

$$B_j^I(M) = \frac{1}{\pi}\frac{d}{dM}\delta_j^I(M)$$

R. Dashen, S. K. Ma and H. J. Bernstein, Phys. Rev. 187, 345 (1969)
R.Venugopalan, and M. Prakash, Nucl. Phys. A 546 (1992) 718.
W. Weinhold,, and B. Friman, Phys. Lett. B 433, 236 (1998).
Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533

Effective weight function ↓ $B_j^I(M)$ — *Scattering phase shift* ↓ $\delta_j^I(M)$

- Interactions driven by narrow resonance of mass M_R

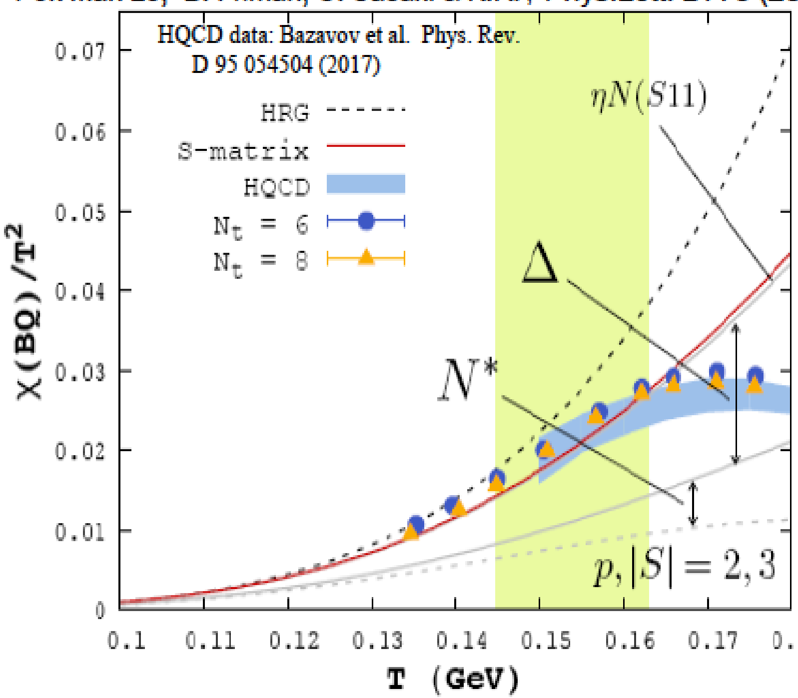
$$B(M) = \delta(M^2 - M_R^2) \quad \Rightarrow \quad P^{\text{int}} = P^{id}(T, M_R) \;\Rightarrow HRG$$

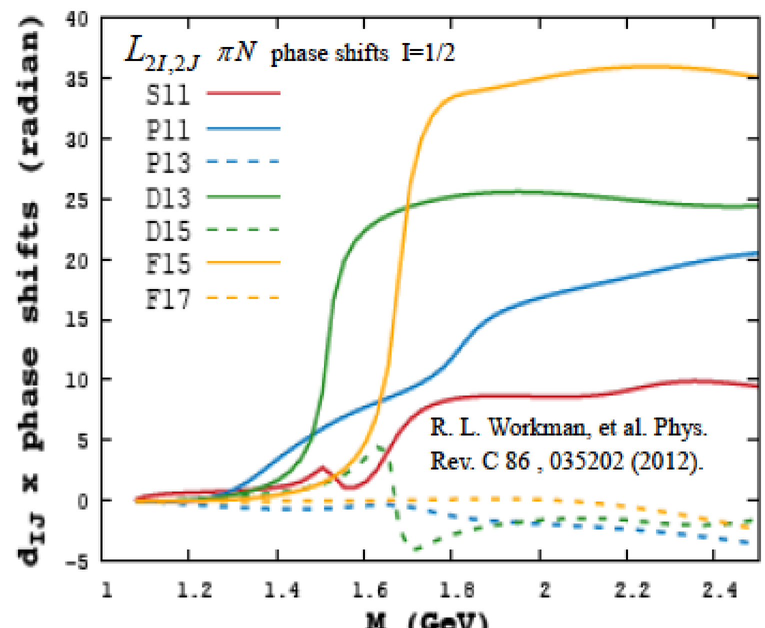
- For non-resonance interactions or for broad resonances the HRG is too crude approximation and $P^{\text{int}}(T)$ should be linked to the phase shifts considering all pion-nucleon phase shifts with isospin 1/2 and 3/2

Probing non-strange baryon sector in πN- system

Pok Man Lo, B. Friman, C. Sasaki & K.R., Phys.Lett. B778 (2018)

$$\chi_{BQ} = (\chi_{BB} - |\chi_{BS}|)/2$$



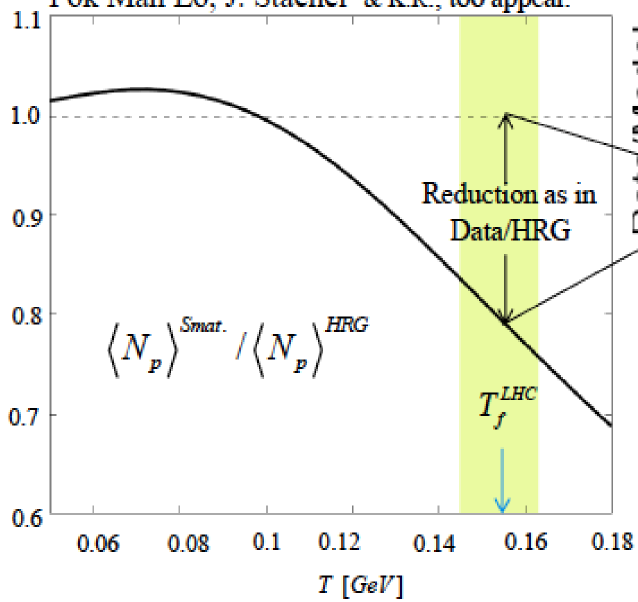


$$\Delta\chi_{BQ} \approx \sum_{I_z,j,B} d_j BQ \int dM \int d^3p \frac{1}{T}\frac{d\delta_j^I}{dM} \times e^{-\beta\sqrt{p^2+M^2}}(1+e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

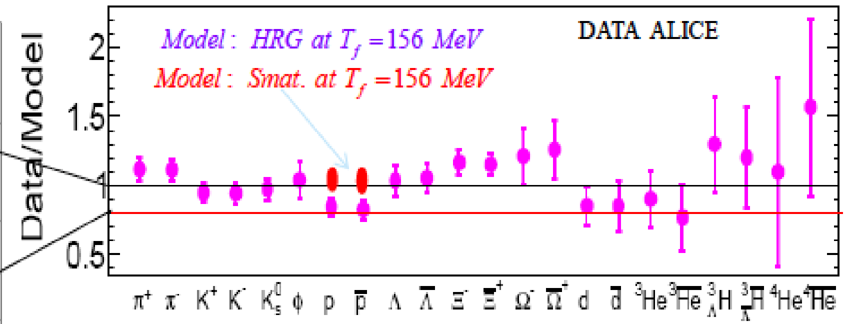
- Considering contributions of all πN $\delta_j^{I=(1/2),\,(3/2)}$ $(N^*, \Delta^*$resonances) to χ_{BQ} within S-matrix approach, reduces the HRG predictions towards the LQCD in the chiral crossover $0.15 < T < 0.16\ GeV$

Phenomenological consequences: proton production yields

A. Andronic, P. Braun-Munzinger, B. Friman, Pok Man Lo, J. Stachel & K.R., too appear.

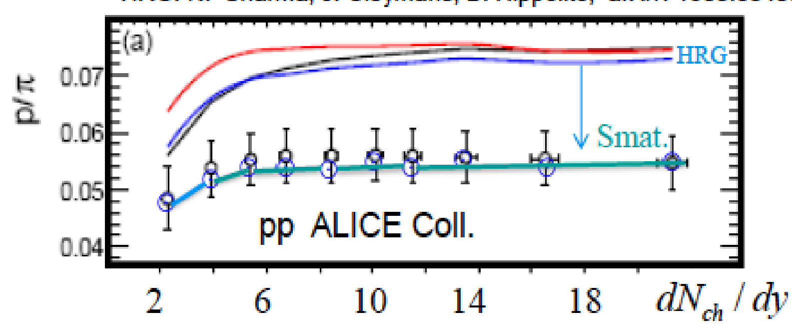


HRG: A. Andronic, P. Braun-Munzinger, J. Stachel & K.R.



- Yields of protons in AA collisions at LHC is consistent with S-matrix result within 1σ

HRG: N. Sharma, J. Cleymans, B. Hippolite, arXiv: 1803.05409



- S-matrix results well consistent with pp data

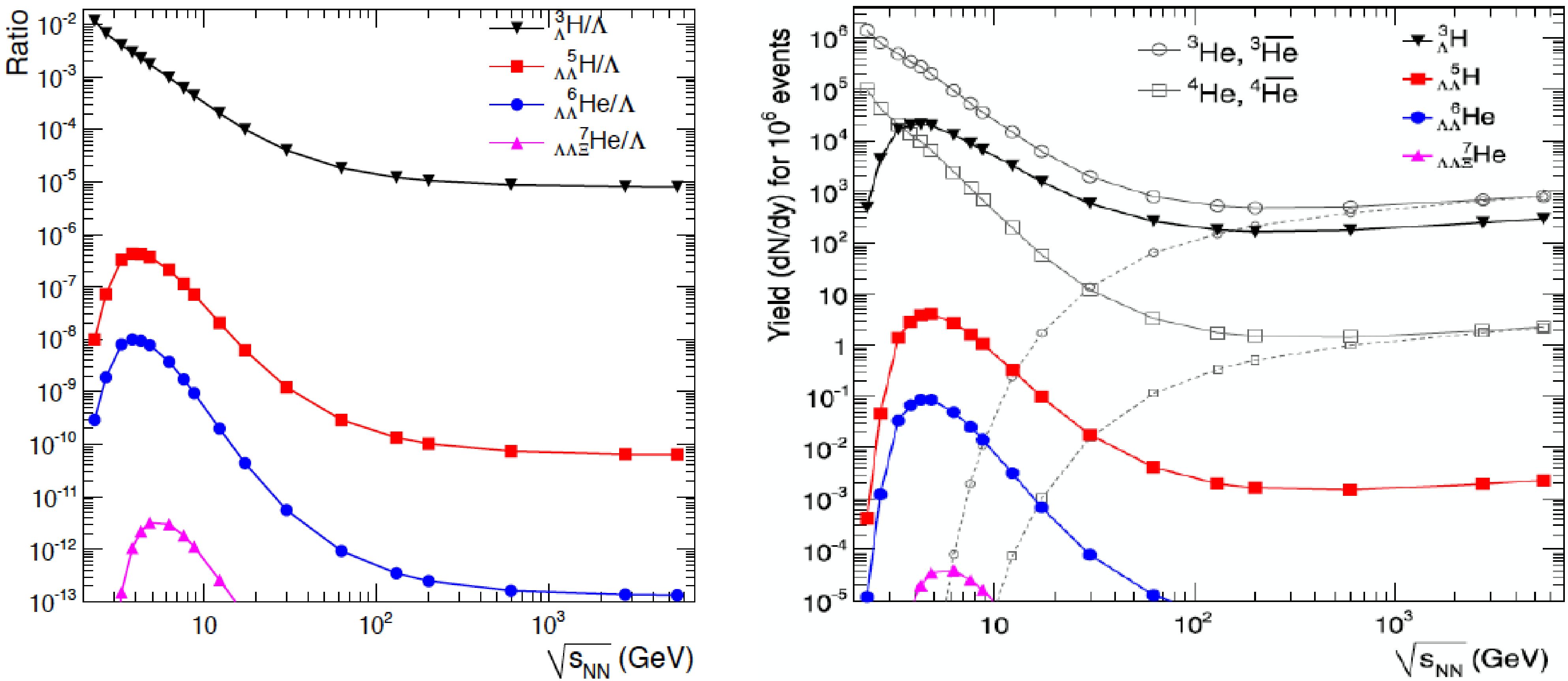
- Yields of protons in the S-matrix is suppressed relative to HRG

For further consequences of smat. See also: P. Huovinen, P. Petreczky Phys. Lett. B77 (2018) P. Huovinen, poster QM2018

points a way to explain 'proton puzzle',new description to appear soon

now 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-

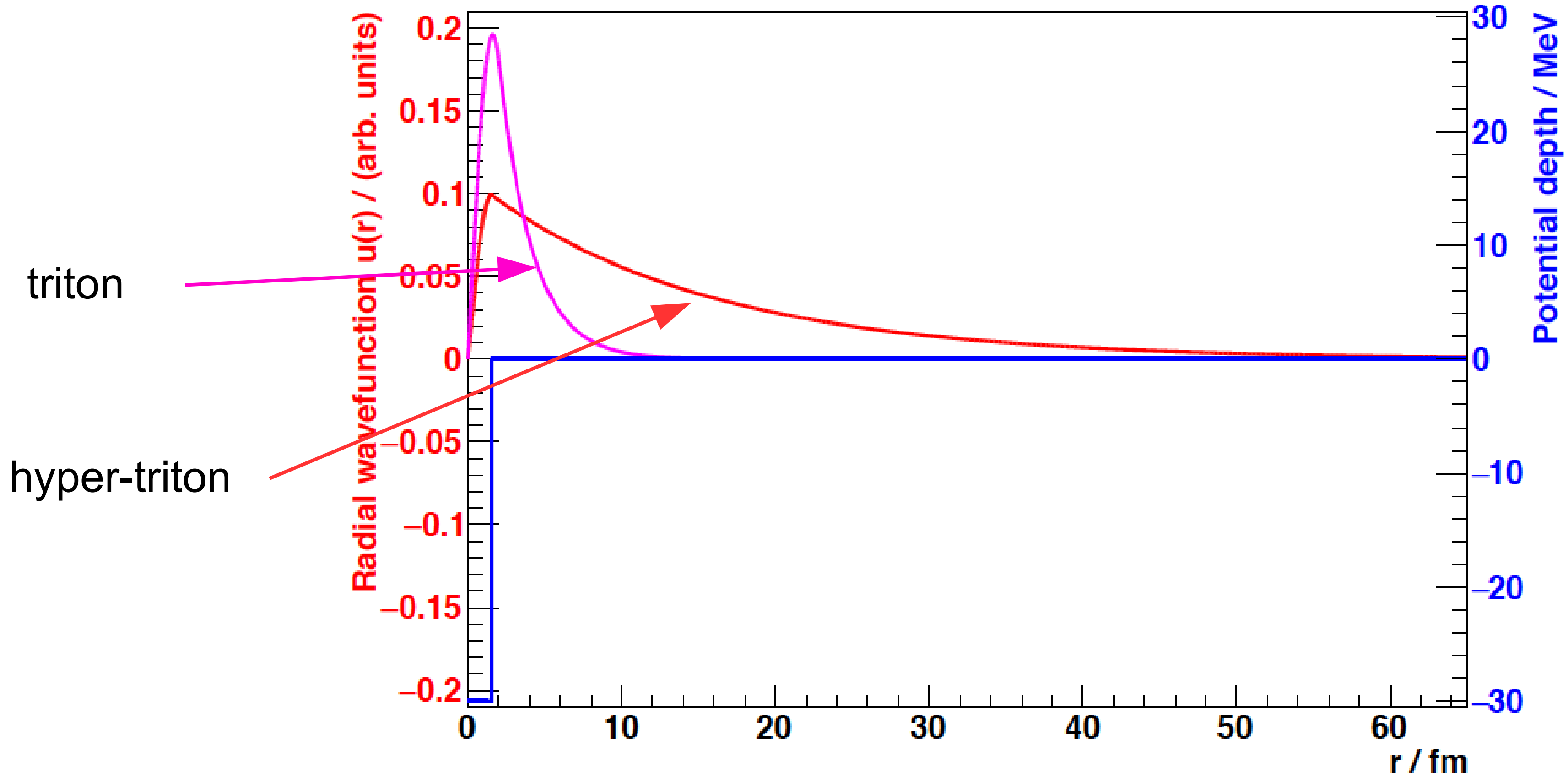
rms radius = $(4\ \mathrm{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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.)

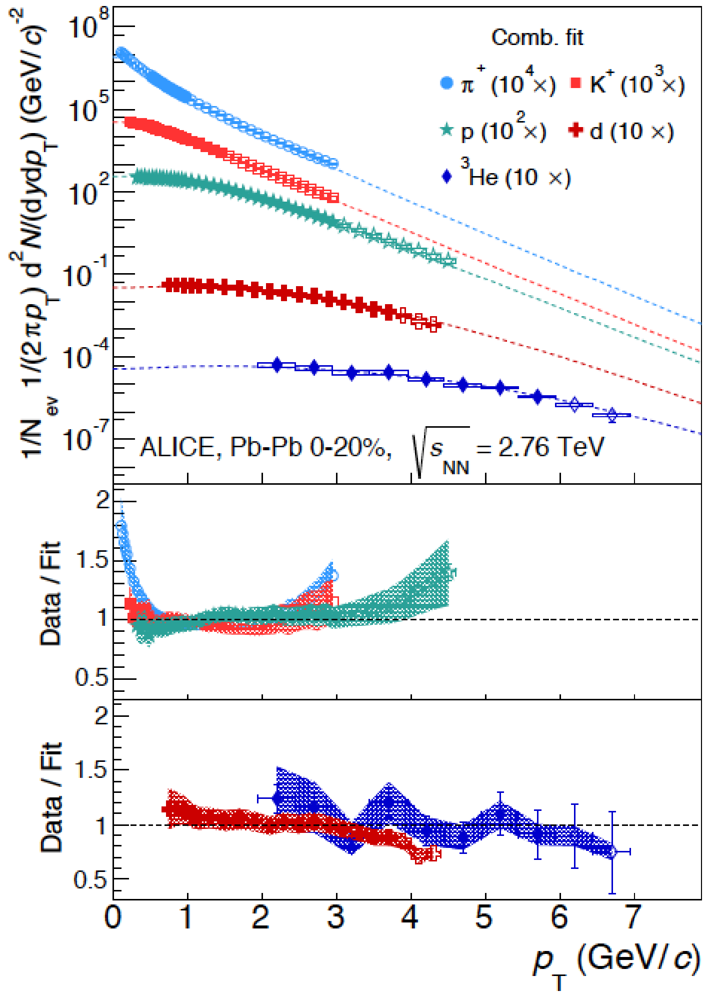
wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017

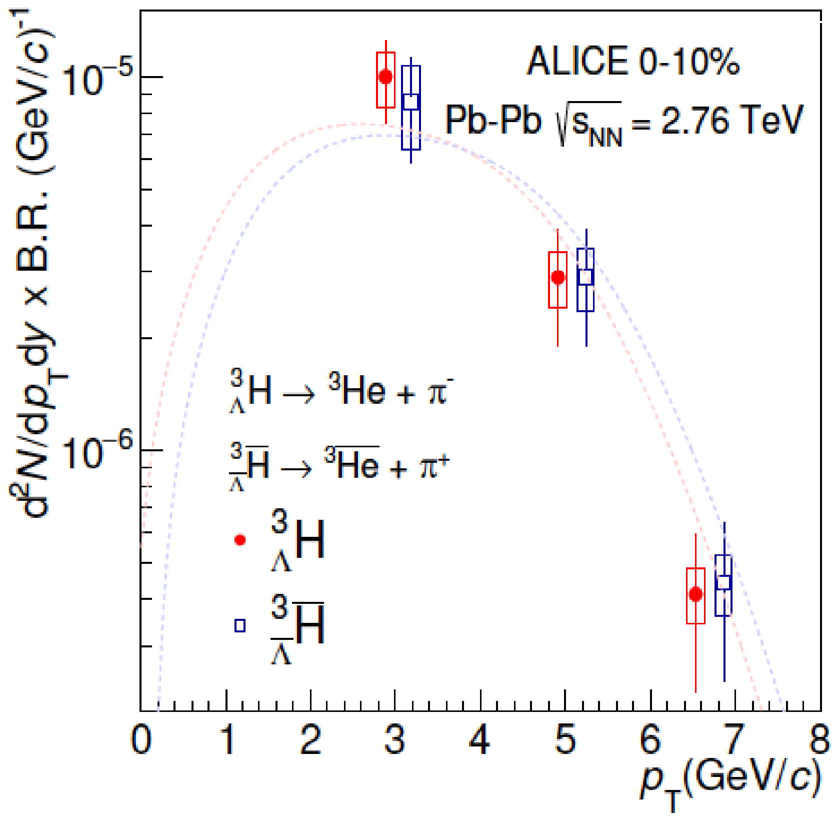


Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve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

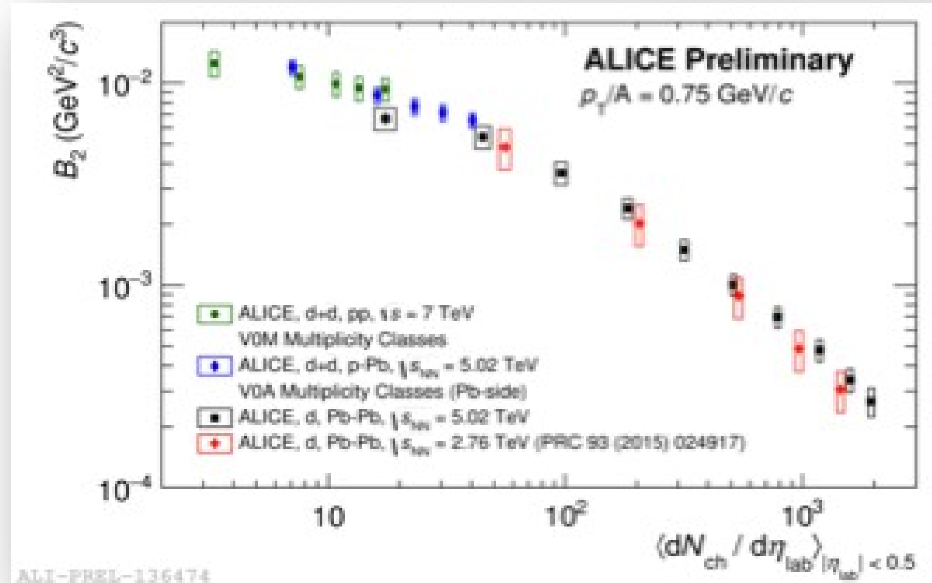


even hyper-triton flows with same common fluid velocity



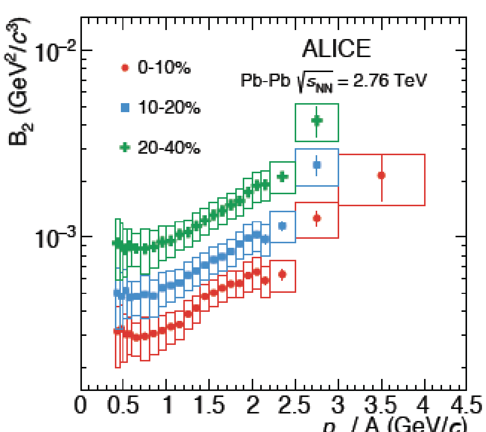
is coalescence approach an alternative?

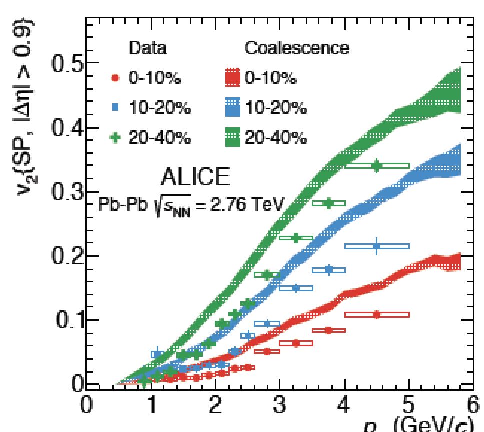
$$E_i \frac{d^3N_i}{dp_i^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \qquad B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{M}{m^A}$$

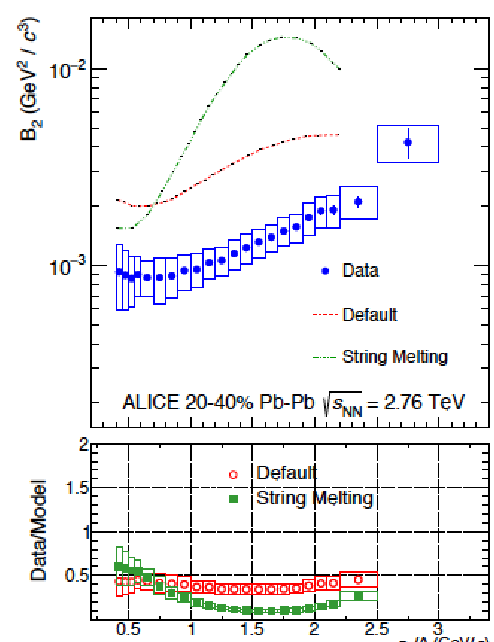


centrality and p_T dependence of coalescence parameter not understood and not well reproduced by models such as AMPT

ALICE: arXiv:1707.07304







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
- coalescence of off-shell nucleons does not help as density must be << nuclear matter density, see below

- delicate balance between formation and destruction; maximum momentum transfer onto hyper-triton before it breaks up: $\Delta Q_{max} < 20$ 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 $\sigma > 70\ \mathrm{fm}^2$. For the majority of hyper-tritons to survive, the mfp λ has to exceed 15 fm → density of fireball at formation of hyper-triton
$n < 1/(\lambda\,\sigma) = 0.001/\mathrm{fm}^3$. Inconsistent with formation at kinetic freeze-out, where
$n \approx 0.05/\mathrm{fm}^3$.

is large size of light nuclei and hypernuclei an issue for statistical hadronization model?

note: in thermal approach, the only scale is temperature T
at LHC energy and below, T < 160 MeV

at such a scale, momentum transfer q=T, form factors of hadrons are sampled at q^2 = T^2
this implies that sizes of hadrons < 2 fm cannot be resolved

since $G(q) \sim 1 - q^2R^2/6$

and since all (rms) radii for nuclei with A = 2, 3, and 4 are smaller than 2 fm, the correction due to the finite size of nuclei will not exceed 35%

the actual change from this on thermal model results should be much less as only the relative change between normal hadrons and light nuclei matters, the overall change only leads to a volume correction, so the correction for nuclei is estimated to be less than 25%

but hyper-triton has much larger radius > 5 fm?
measured yield of hyper-triton and 3He is well compatible with thermal prediction, even though wave function is very different – any wave function correction must be small

the agreement of the baryon number 3 states is also big problem for coalescence model see also the detailed analysis by Francesca Bellini and Alexander Kalweit, ALICE Physics Week, Frascati, Feb. 6-8, 2018 and by Benjamin Doenigus and Nicole Loeher, GSI-EMMI meeting, Feb. 2018

How can 'thermal production near the phase boundary' i.e. at $T \sim 155$ MeV be reconciled with binding energies < 5 MeV and large break-up cross sections?

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

see also the recent review:
Marek Karliner, Jonathan L. Rosner, Tomasz Skwarnicki, arXiv:1711.10626

doorway state hypothesis:
all nuclei and hyper-nuclei are formed as virtual, compact multi-quark states at the phase boundary. Then slow time evolution into hadronic representation. Excitation energy about 20 MeV, time evolution about 10 fm/c

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 from pp via pPb to Pb-Pb

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

statistical hadronization of charmonia as key to understand deconfinement

Andronic, pbm, Redlich, Stachel, arXiv:1710.09425

a major new opportunity for Run3/4

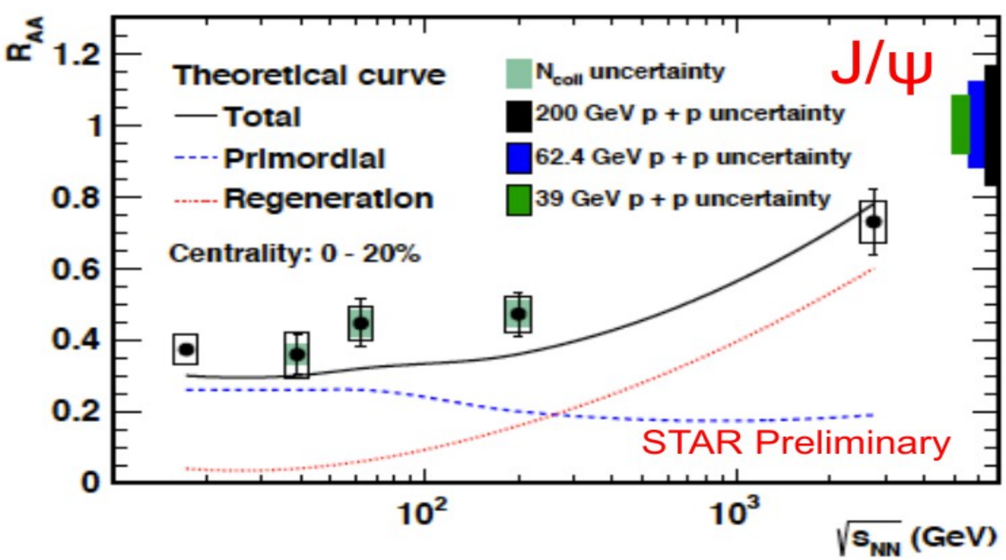
need precise measurement of open charm cross section as well as psi'/psi ratio

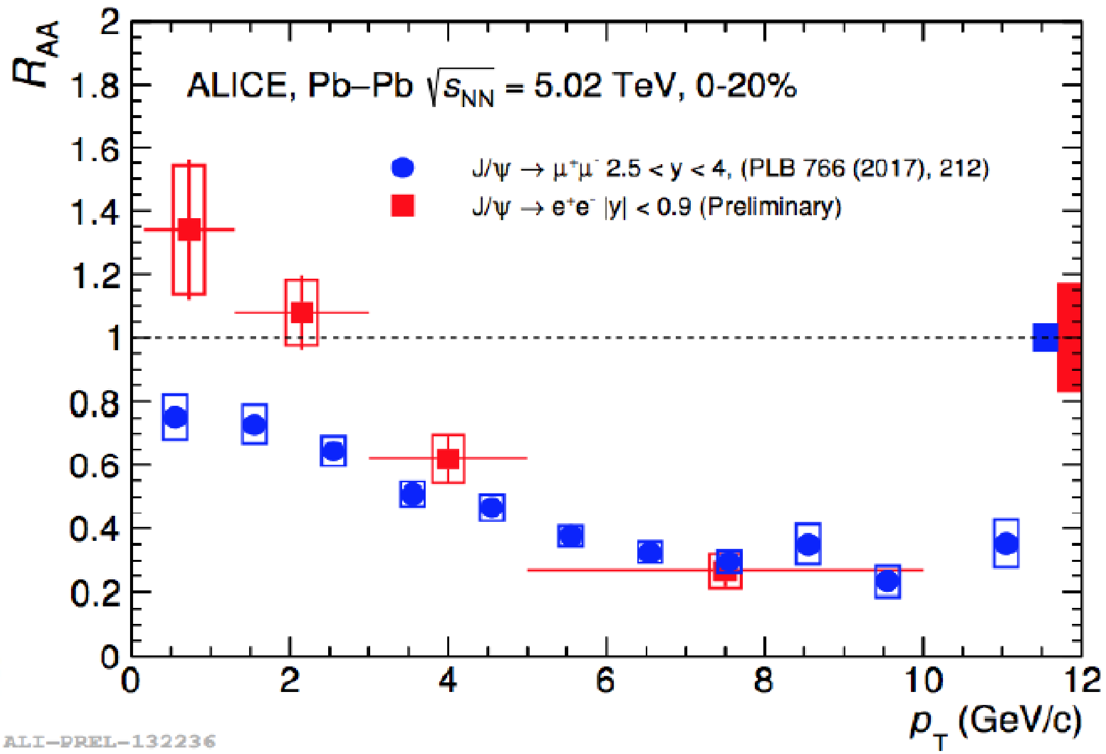
original publications:

pbm,Stachel, Phys. Lett. 490 (2000)196   stat. hadronization

Thews, Schroedter, Rafelski, Phys. Rev. C63 (2001) 054905
formation and destruction in the QGP

charmonium enhancement as signature of deconfinement
dependence of R_AA on transverse momentum
mid-rapidity vs forward rapidity





J/psi enhancement at low p_t near mid-rapidity

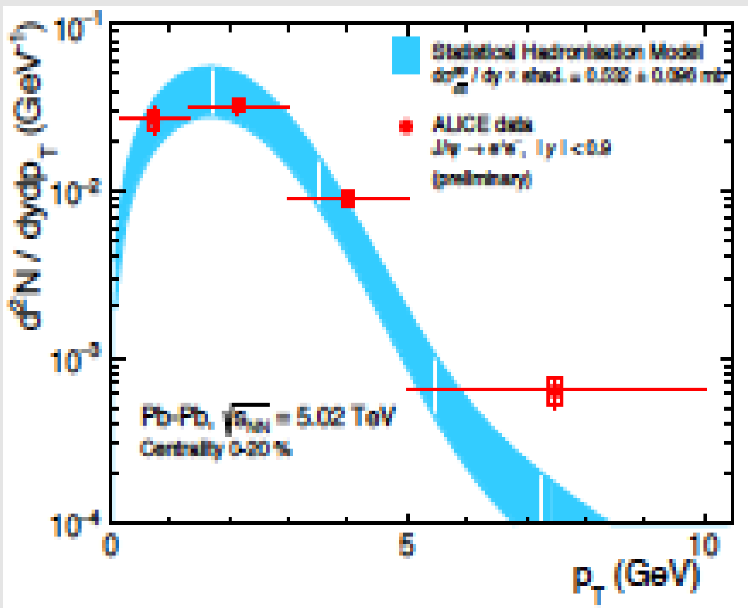
M. Koehler, QM18
Andronic, pbm, Koehler, Stachel, to appear soon

Comparison of the model with data

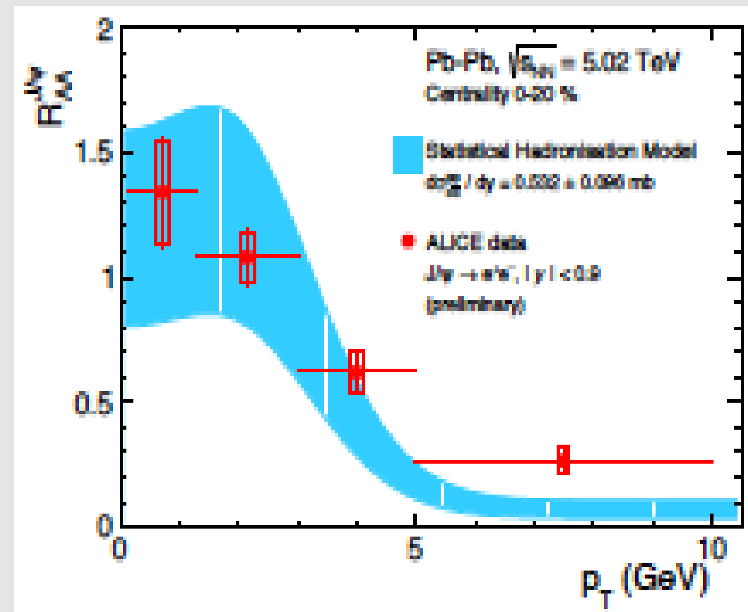
J/psi flows!

$\sqrt{s_{NN}} = 5.02$ TeV, mid-rapidity, 0-20 %

p_T spectrum



R_{AA} versus p_T



- Very good agreement between data and predictions without free parameters

Use collective expansion velocity from MUSIC(3+1)D [Schenke, Jeon & Gale, PRC82 (2010) 014903] with QCD inspired parameters [Dubla *et al.*, arXiv:1805.02985], and IP-Glasma for initial conditions [Schenke, Tribedy & Venugopalan, PRL 108 (2012) 252301] at $T = T_{CF}$

new opportunity: deconfinement from quarkonium measurements

An essential ingredient of the statistical hadronization scenario for heavy quarks is that they can travel, in the QGP, significant distances to combine with other uncorrelated partons. The observed increase of the R_{AA} for J/ψ with increasing collision energy strongly supports the notion that the mobility of the heavy quarks is such that it allows travel distances exceeding that of the typical 1 fm hadronic confinement scale. In fact, for LHC energy, the volume of a slice of one unit of rapidity of the fireball exceeds 5000 fm^3, implying that charm quarks can travel distances of the order of 10 fm. This results in the possibility of bound state formation with all other appropriate partons in the medium with statistical weights quantified by the characteristics of the hadron (mass, quantum numbers) at the phase boundary. The results of the charmonium measurements thereby imply a direct connection to the deconfinement properties of the strongly interacting medium created in ultra-relativistic nuclear collisions.

additional slides

[Braun-Munzinger and Stachel, PLB 490 (2000) 196]
[Andronic, Braun-Munzinger and Stachel, NPA 789 (2007) 334]

- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_c$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{QCD}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_{CF}, \mu_b \rightarrow n_X^{th}$)

$$N_{c\bar{c}}^{dir} = \underbrace{\frac{1}{2} g_c V \left(\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th} + \cdots \right)}_{\text{Open charm}} + \underbrace{g_c^2 V \left(\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th} + \cdots \right)}_{\text{Charmonia}}$$

- Canonical correction is applied to n_{oc}^{th}
- Outcome $N_{J/\psi}, N_D, \ldots$