Hadronization and the QCD Phase Boundary

- brief introduction – hadron production from LEP to the LHC era
- the hadron resonance gas and (u,d,s) hadron production
- Dashen-Ma-Bernstein taken seriously
- charmed hadrons
- loosely bound objects
- summary and outlook

pbm

Symposium on Contemporary QCD Physics and Relativistic Nuclear Collisions
College of Physical Science and Technology
Central China Normal University, Wuhan, China
November 9 – 11, 2019

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

EMMI

GSI

HUAZHONG UNIVERSITY

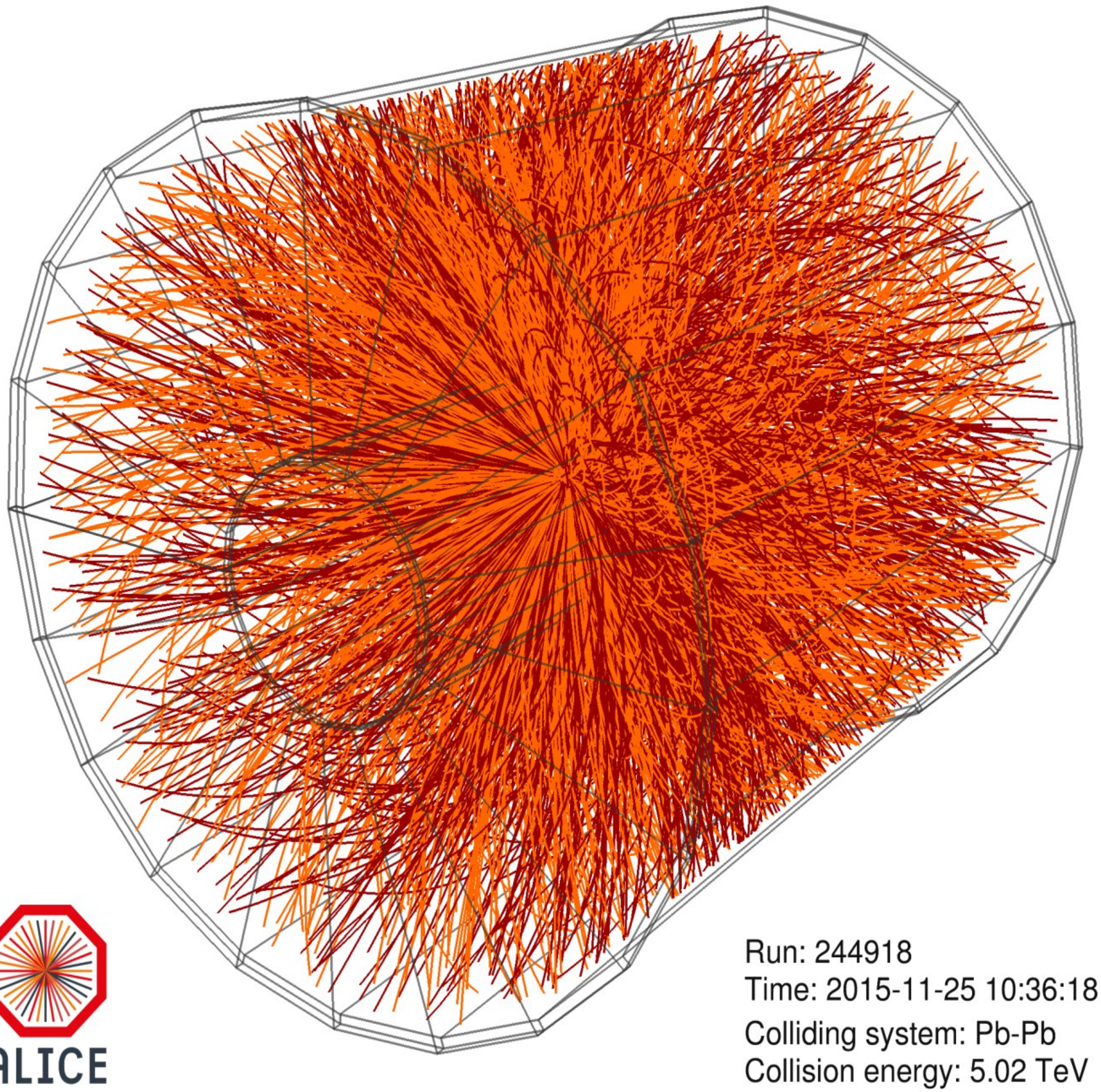
phenomenology results obtained in collaboration with
Anton Andronic, Krzysztof Redlich, and Johanna Stachel
arXiv:1710.09425,
Nature 561 (2018) 321

most of the new data are from the ALICE collaboration
at the CERN LHC

newest results including pion-nucleon phase shifts
from arXiv:1808.03102
Andronic, pbm, Friman, Lo, Redlich, Stachel
Phys.Lett. B792 (2019) 304

statistical hadronization model and particle spectra
Andronic, pbm, Koehler, Redlich, Stachel
Phys.Lett. B797 (2019) 134836

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



Run1: 3 data taking campaigns
pp, pPb, Pb—Pb
> 170 publications

Run2   with 13 TeV pp
Pb—Pb run 5 TeV/u
p-Pb Run at 5 and 8 TeV
> 50 publications

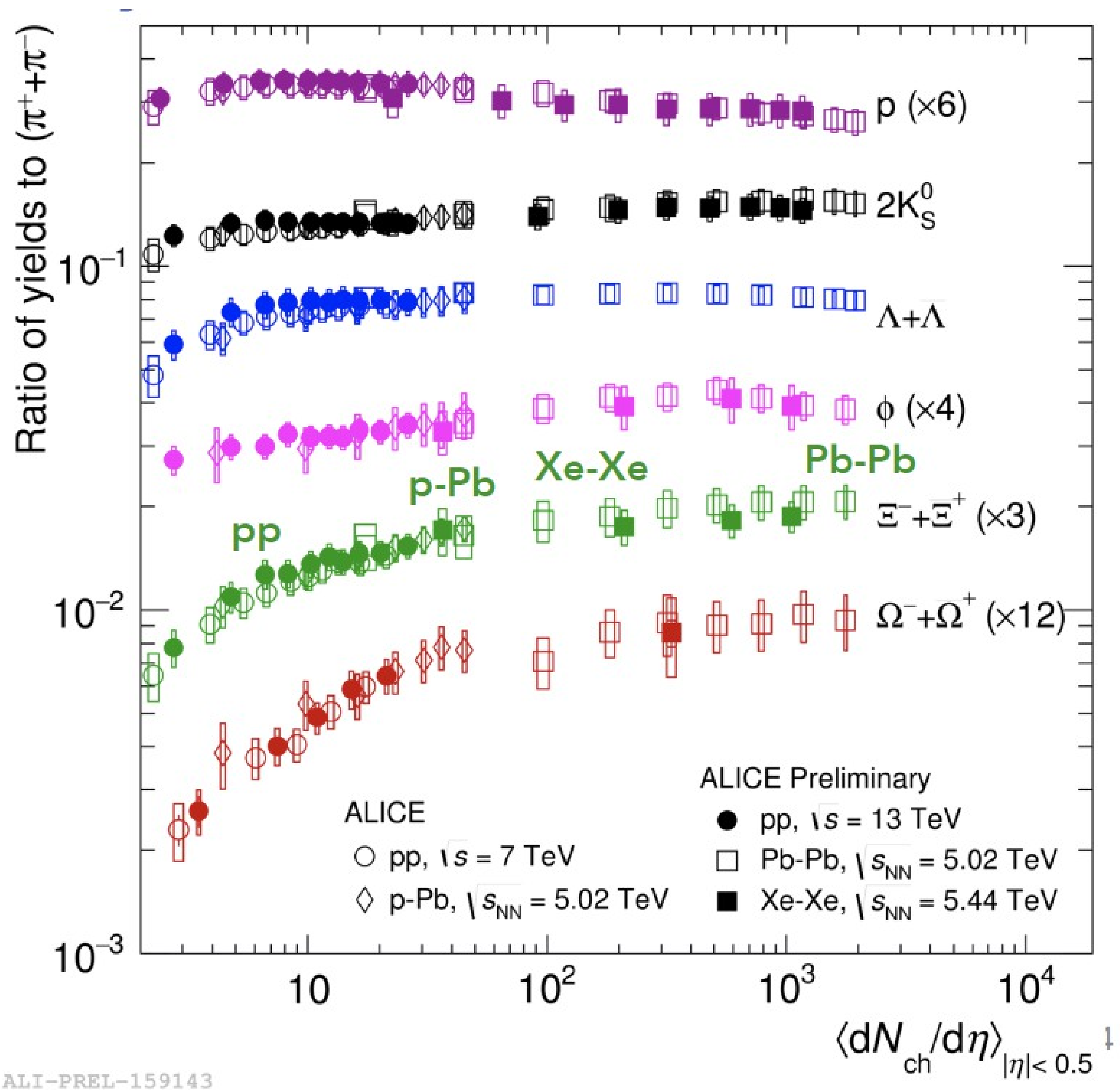
Nov. 2018: PbPb 5 TeV/u

Snapshot taken with the ALICE TPC

central Pb-Pb collisions
more than 32000
particles produced per collision

ALICE

particle production from small to large systems: from strangeness suppression to grand-canonical thermodynamics



J. Adam *et al.* [ALICE Collaboration], Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, Nature Phys. **13**, 535 (2017), doi:10.1038/nphys4111 [arXiv:1606.07424 [nucl-ex]]

hadron multiplicities in e+e- collisions at the Z resonance

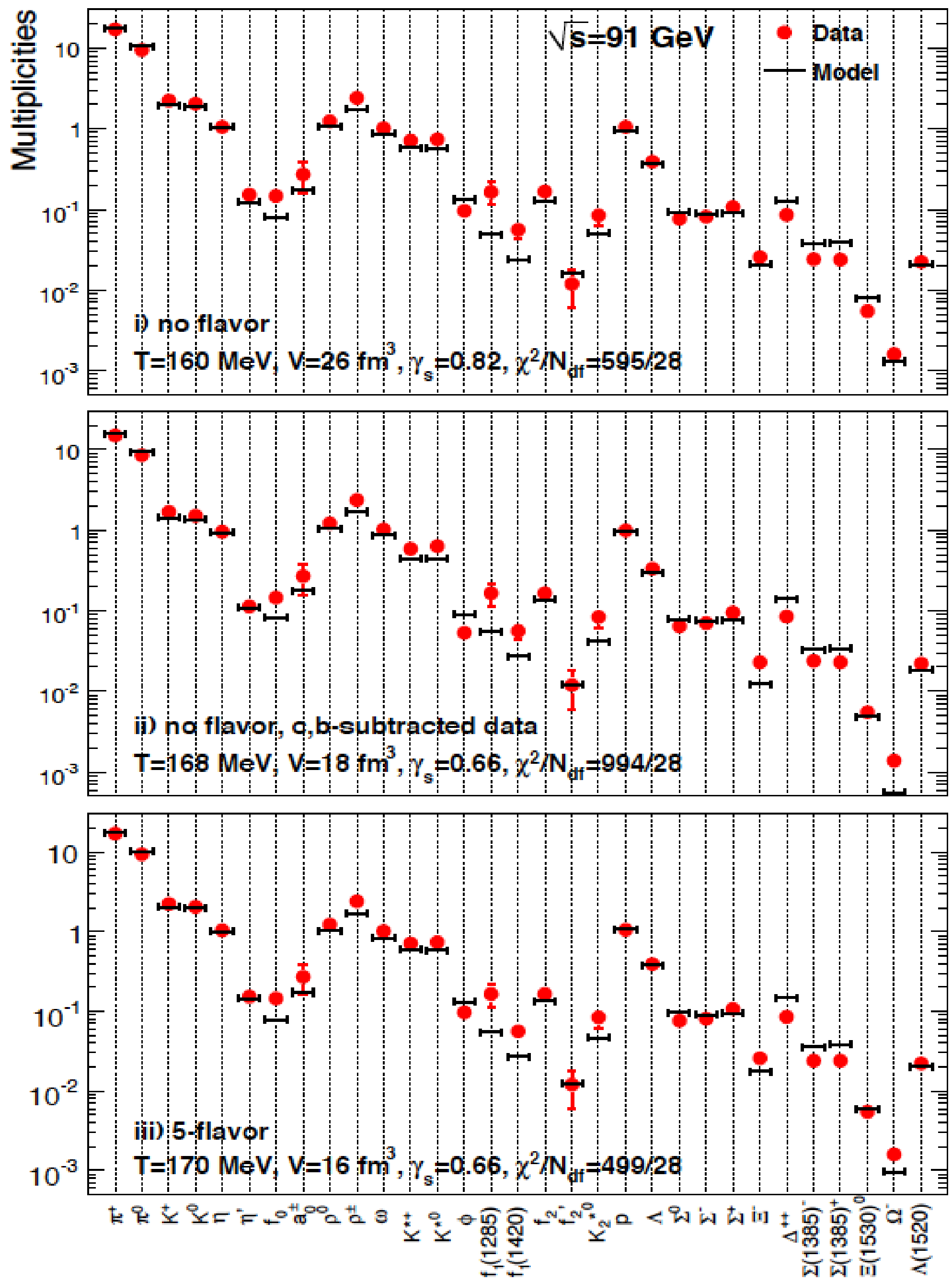
thermal analysis pioneered by F. Becattini, Z.Phys. C69 (1996) no.3, 485-492

results identify thermal features in data with effective temperature
T around 160 – 170 MeV

this analysis is for 2 jet events, note that heavy quarks are not thermally produced but their relative abundances are (due to electroweak effects)
b = 22% and c = 17%

analysis needs strangeness suppression fugacity gamma_s

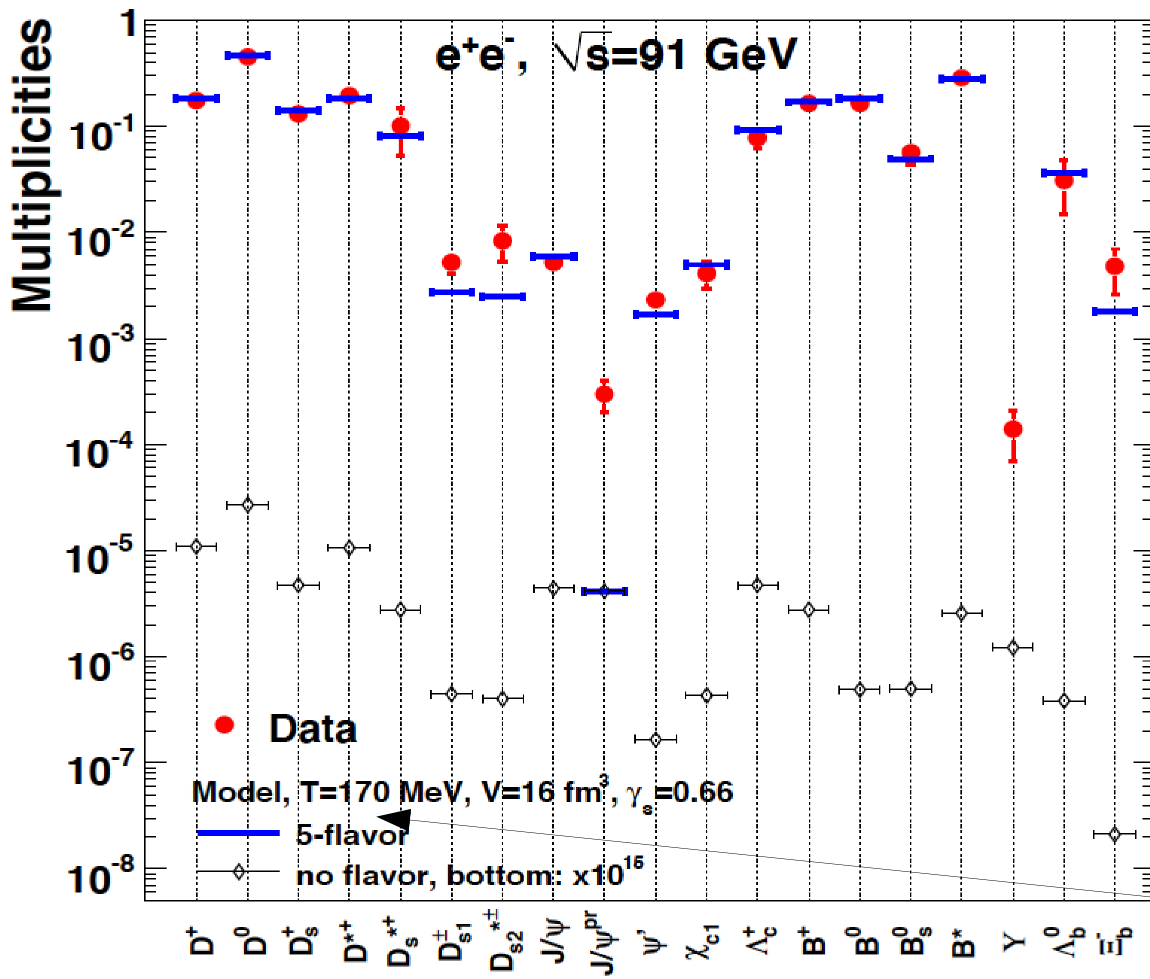
reanalysis in Phys.Lett. B675 (2009) 312-318,
Andronic, Beutler, pbm, Redlich Stachel



earlier analysis substantiated, relatively poor chi^2

thermal features clearly visible in light flavor spectrum

open heavy flavor hadrons and quarkonia



only some aspects of hadronization correctly described

on to grand-canonical limit of QCD

T = 170 MeV
gamma_s = 0.66
V=16 fm^3

open heavy flavor hadrons well described, quarkonia many orders of magnitude off

hadron production and the QCD phase boundary

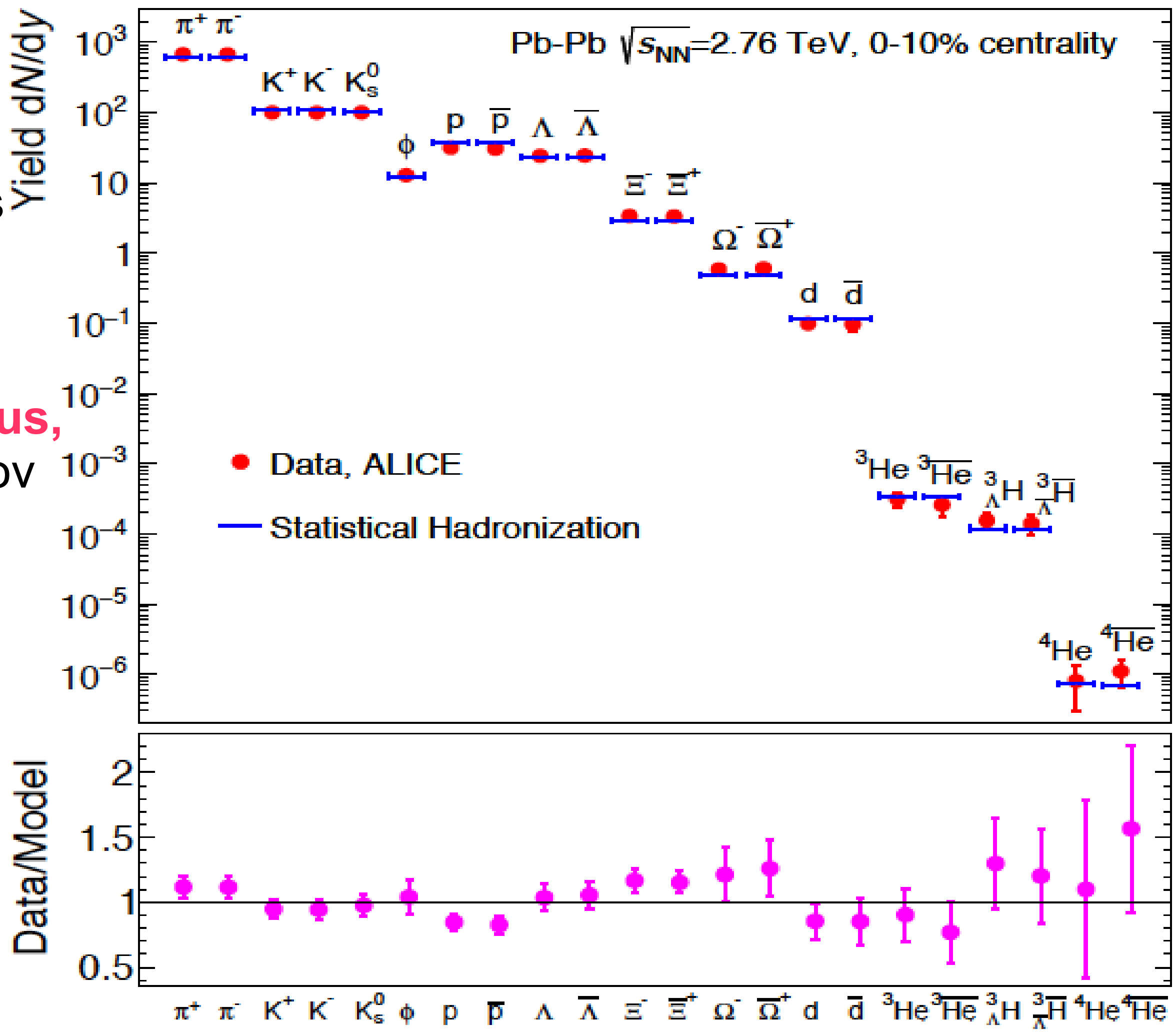
measure the momenta and identity of all produced particles at all energies and look for signs of equilibration, phase transitions, regularities, etc

at the phase boundary, all quarks and gluons are 'hadronized' into hadrons which we measure in our detectors

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,
Nature 561 (2018) 321

the proton anomaly and the Dashen, Ma, Bernstein S-matrix approach

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

The S-matrix formalism [20–24] is a systematic framework for incorporating interactions into the description of the thermal properties of a dilute medium. In this scheme, two-body interactions are, via the scattering phase shifts, included in the leading term of the S-matrix expansion of the grand canonical potential. The resulting interacting density of states is then folded into an integral over thermodynamic distribution functions, which, in turn, yields the interaction contribution to a particular thermodynamic observable.

thermal yield of an (interacting) resonance with mass M, spin J, and isospin I

$$\langle R_{I,J}\rangle = d_J \int_{m_{th}}^{\infty} dM \int \frac{d^3p}{(2\pi)^3}\,\frac{1}{2\pi}\,B_{I,J}(M) \times \frac{1}{e^{(\sqrt{p^2+M^2}-\mu)/T}+1},$$

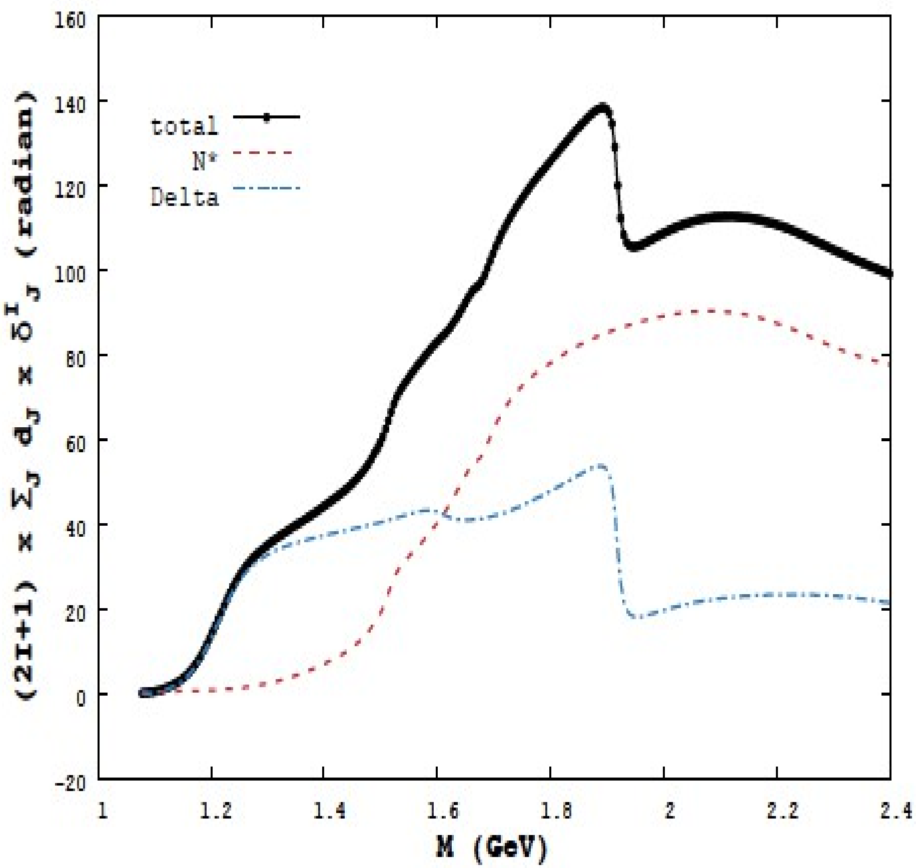
A. Andronic, pbm, B. Friman, P.M. Lo, K. Redlich, J. Stachel, arXiv:1808.03102, Phys.Lett.B792 (2019)304

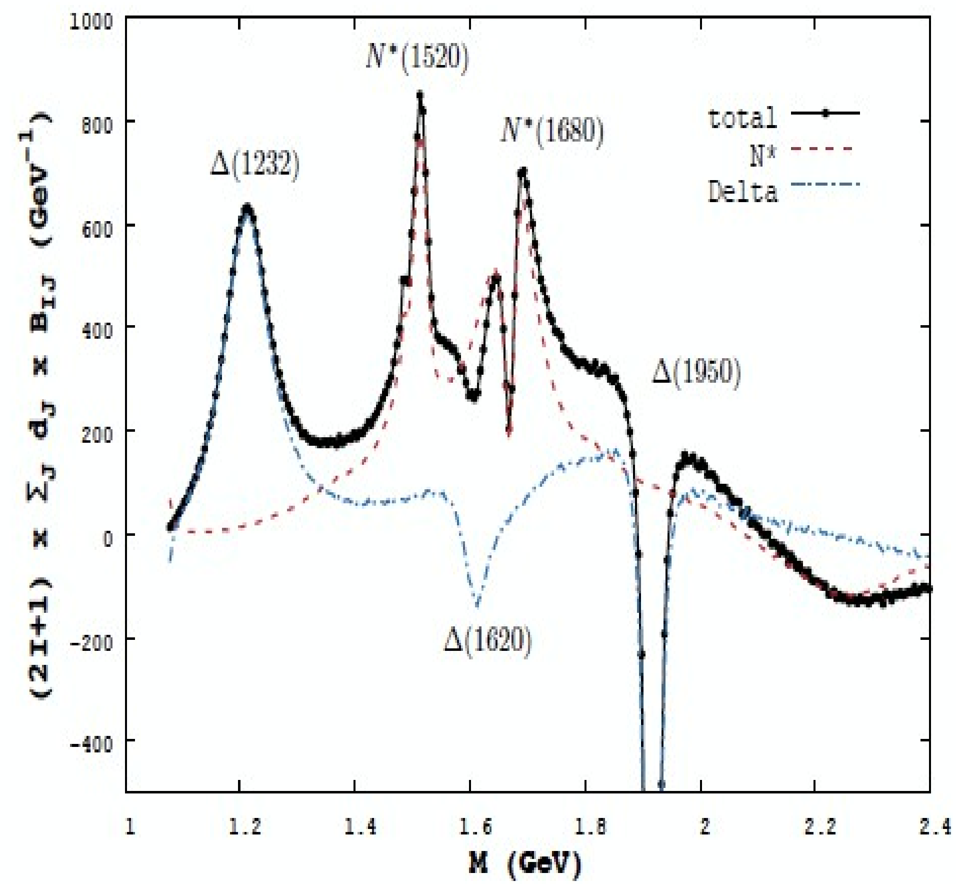
need to know derivatives of phase shifts with respect to invariant mass

$$B_{I,J}(M) = 2\,\frac{d\delta_J^I}{dM}.$$

pion nucleon phase shifts and thermal weights for N* and Δ resonances

GWU/SAID phase shift analysis, 15 partial waves for each isospin channel

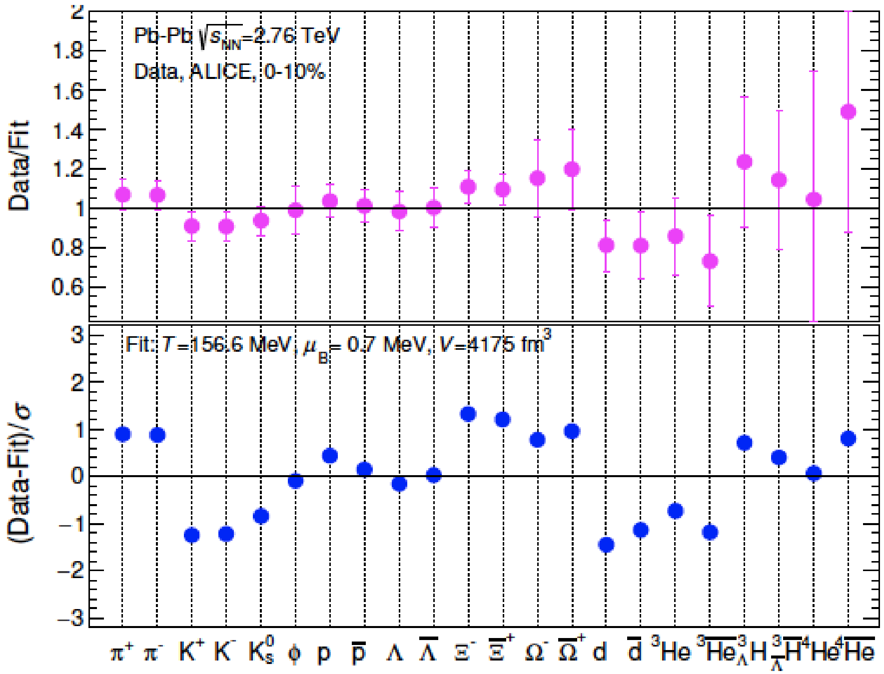




Jan. 2019 update: excellent description of ALICE@LHC data

proton discrepancy of 2.8 sigma is now explained in arXiv:1808.03102
explicit phase shift description of baryon resonance region
(Andronic, pbm, Friman, Lo, Redlich, Stachel Phys.Lett.B792 (2019)304)

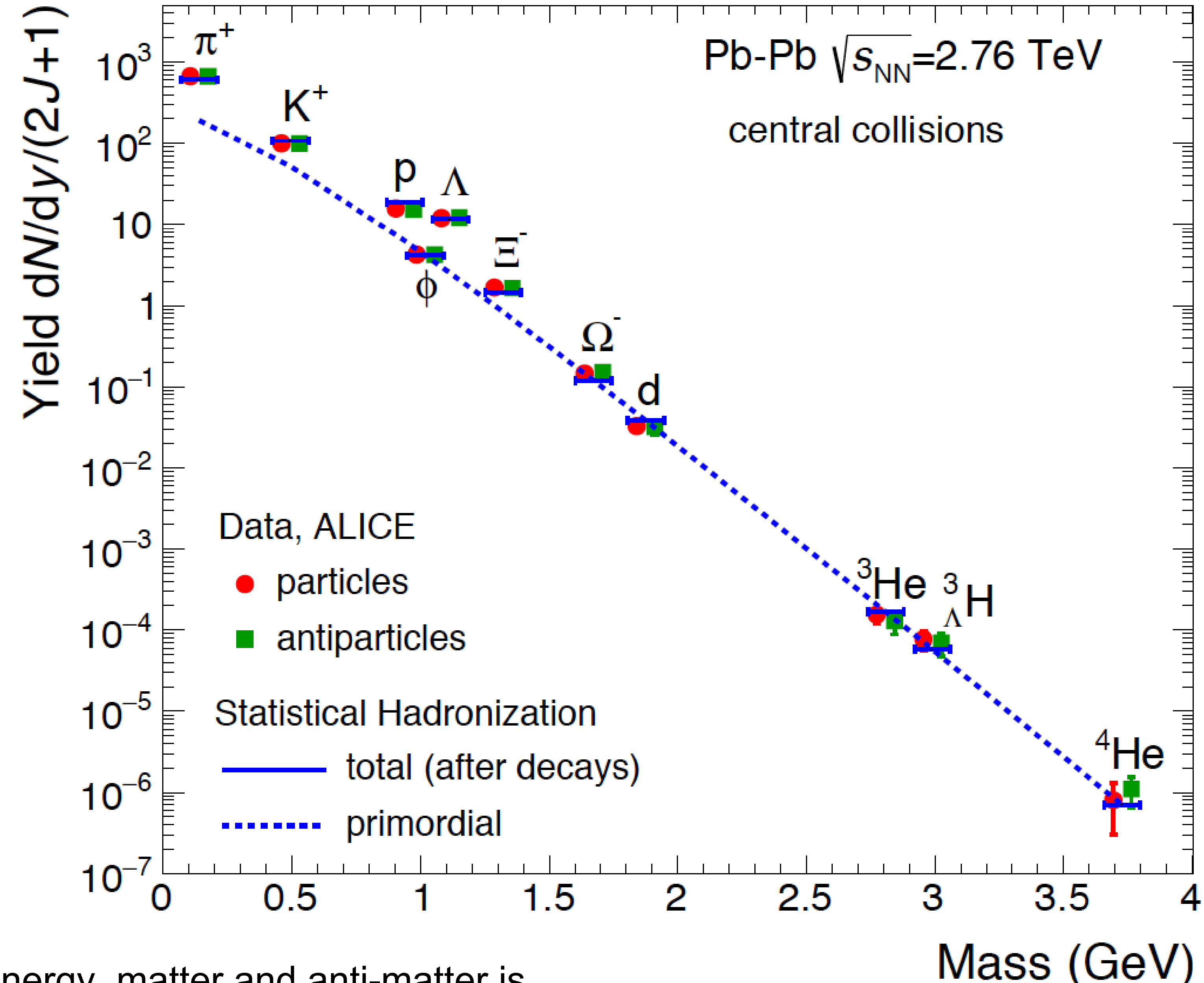
Contributions of three- and higher resonances and inelastic channels are taken into account with normalization with normalization to LQCD susceptibilities



$$\chi^2 = 19.7 \,\text{per}\, 19 \;\; \text{dof}$$

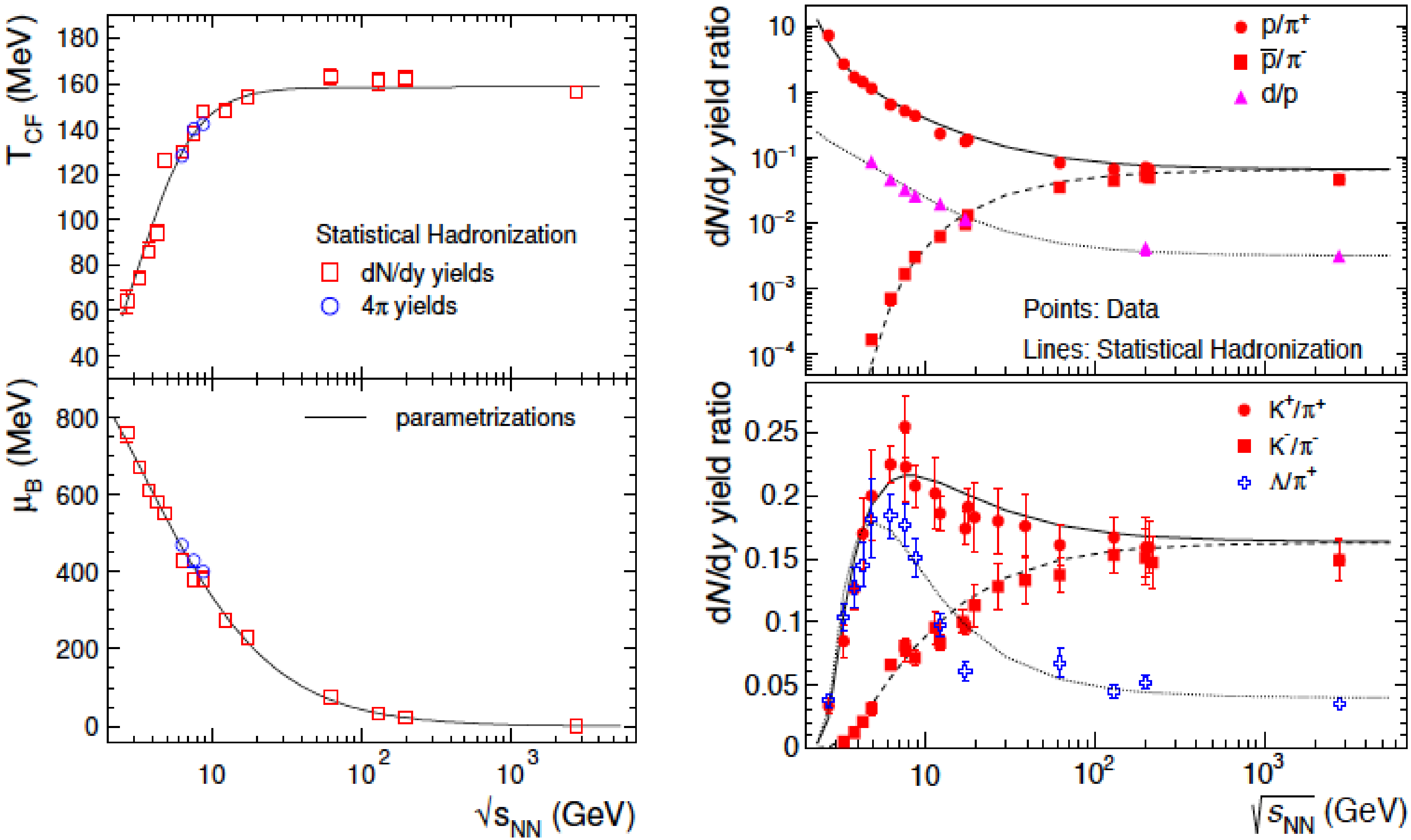
very good fit!

at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



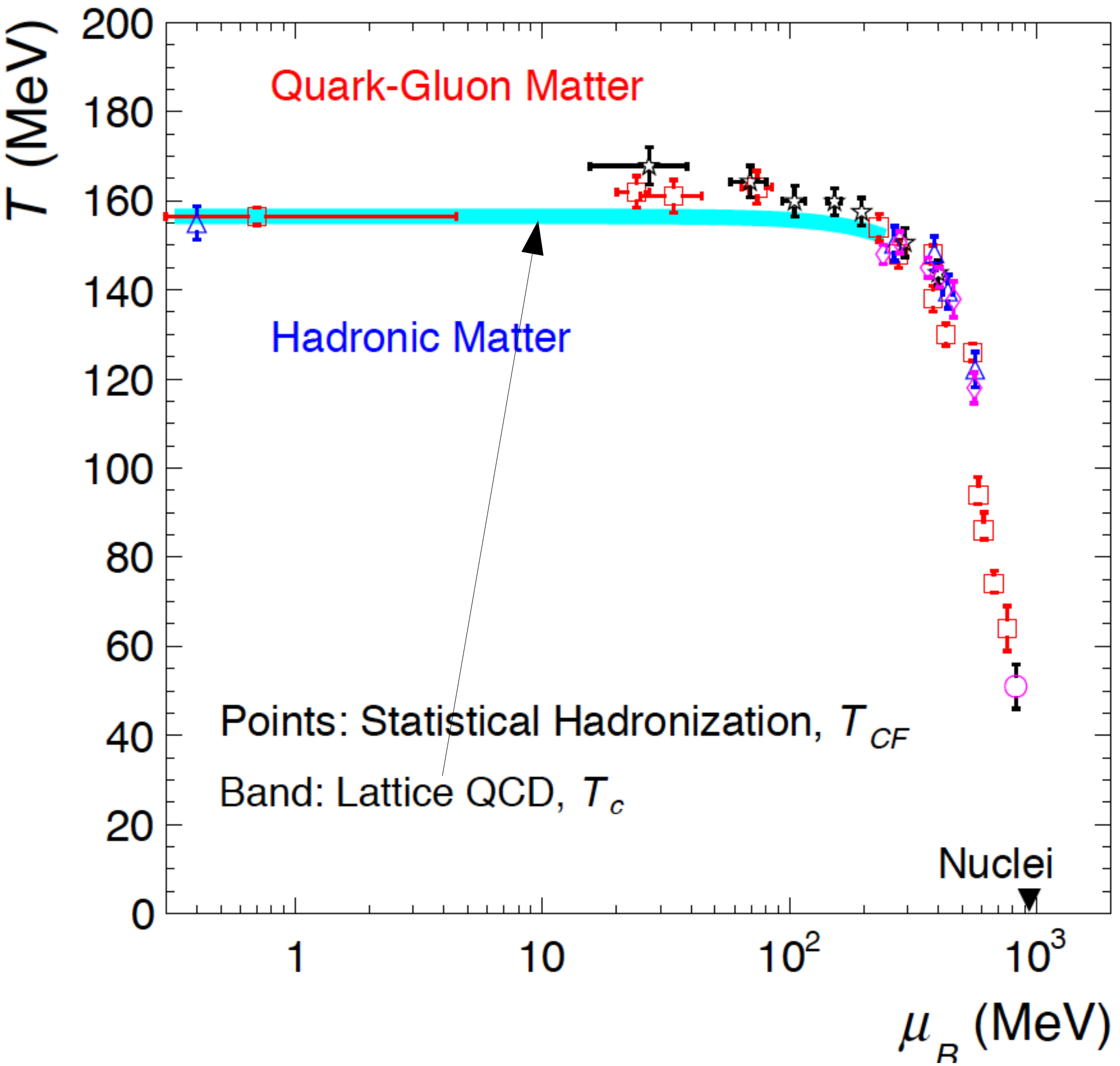
at LHC energy, matter and anti-matter is
produced with equal yields

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

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

cross over transition at μ_B = 0 MeV

open and hidden charm hadrons
universal (thermal) hadronization or:
statistical hadronization with charm (SHMC)

general idea: at high energy (LHC), charm quarks are copiously generated in early hard collisions, then thermalize in the dense partonic medium (QGP)

this leads to strong 'oversaturation' of charm in the medium
→ very large fugacities g_c

in practice, at LHC energies, $g_c > 30$ in central Pb-Pb collisions
→ open charm hadrons are enhanced (compared to thermal production) by factor of 30, no new parameters, sigma_{charm} measured

→ charmonia and hadrons with 2 charm quarks are enhanced by factor of > 900

→ hadrons with 3 charm quarks like Ω_{ccc} are enhanced by factor of 30000. This opens a new and exotic world of charm spectroscopy to be explored in LHC Run 3 and 4 and beyond

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B571 (2003) 36-44, B652 (2007) 659
Becattini, Phys.Rev.Lett. 95 (2005) 022301

at LHC energy, production of (u,d,s) hadrons is governed
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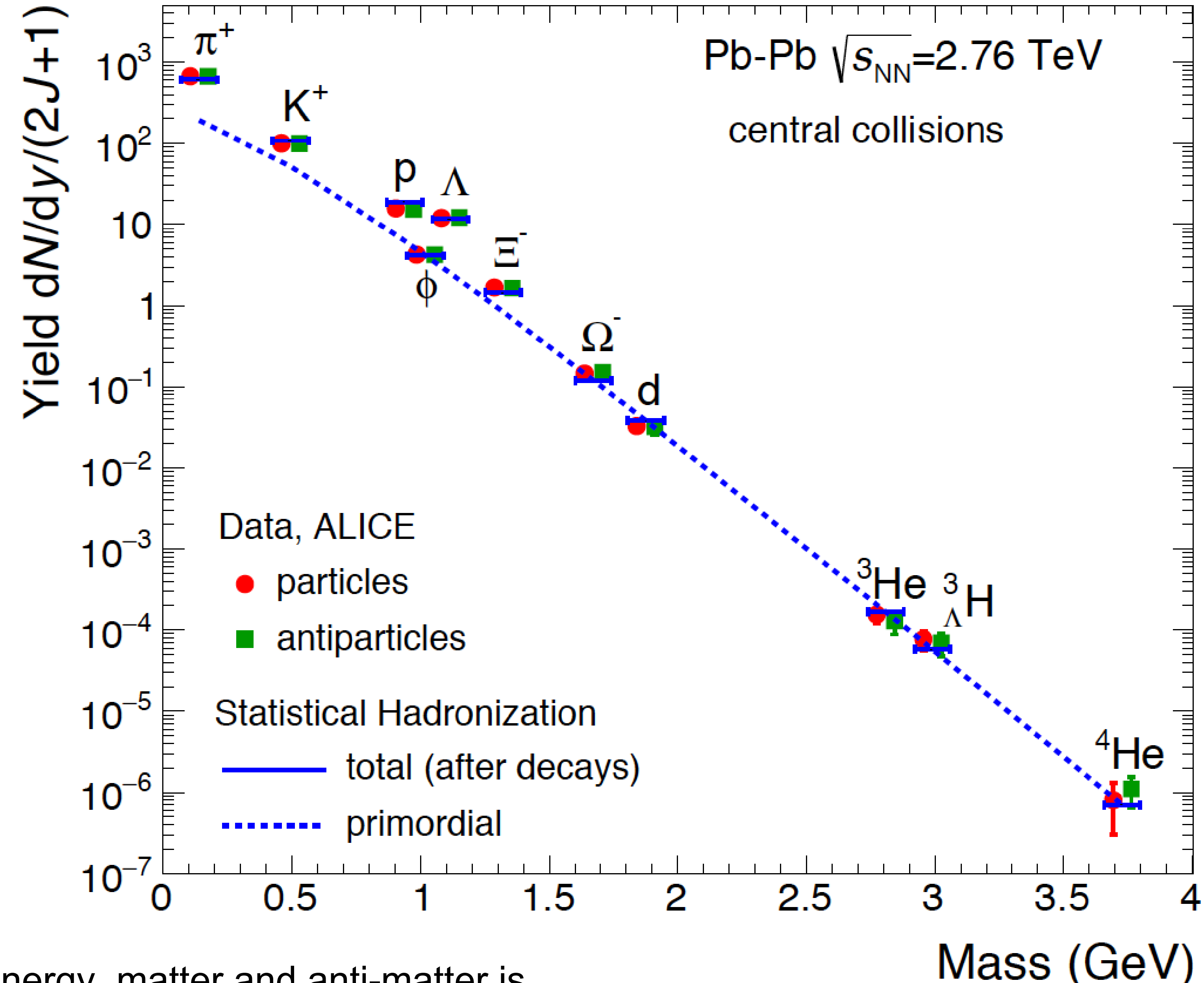
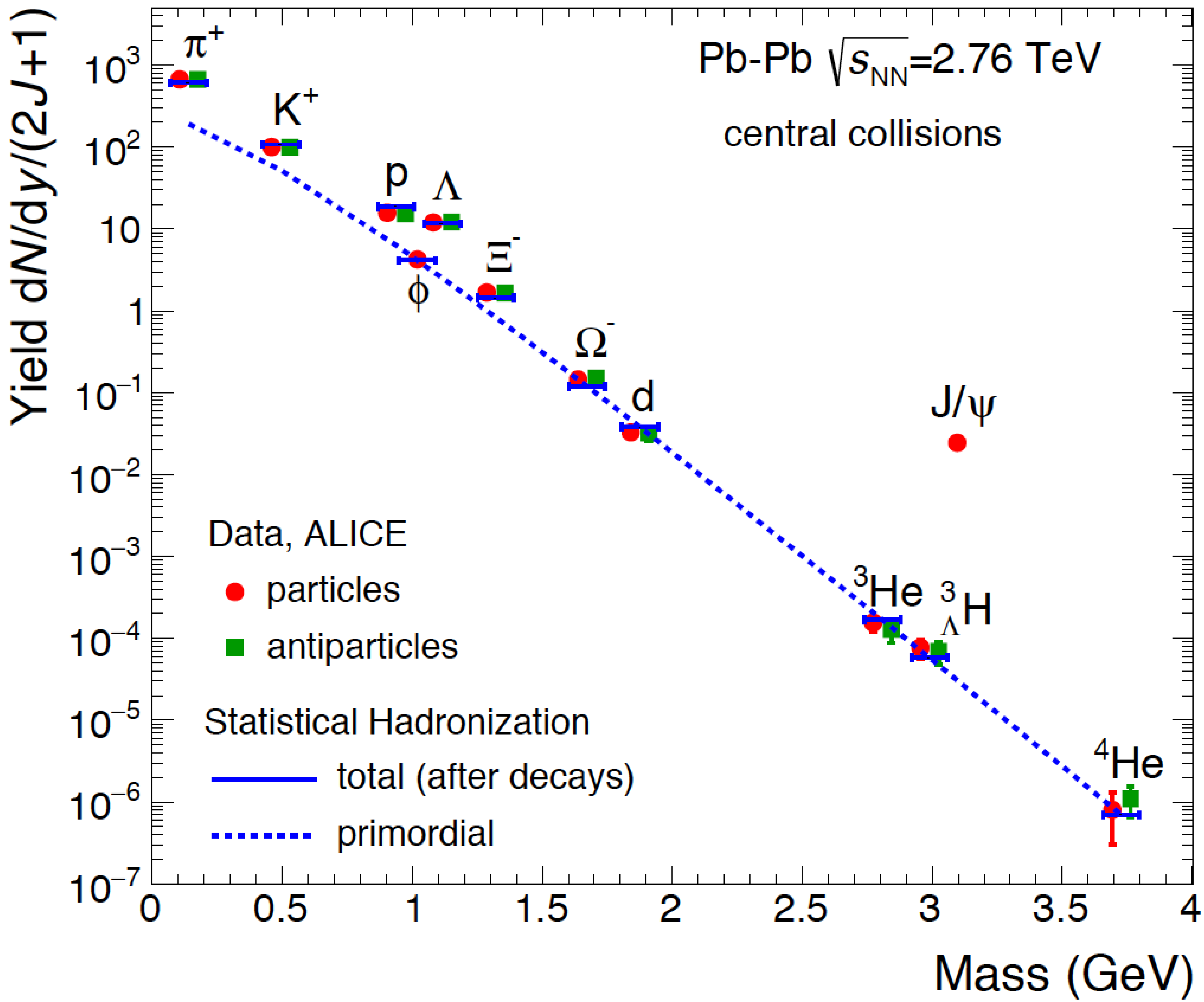
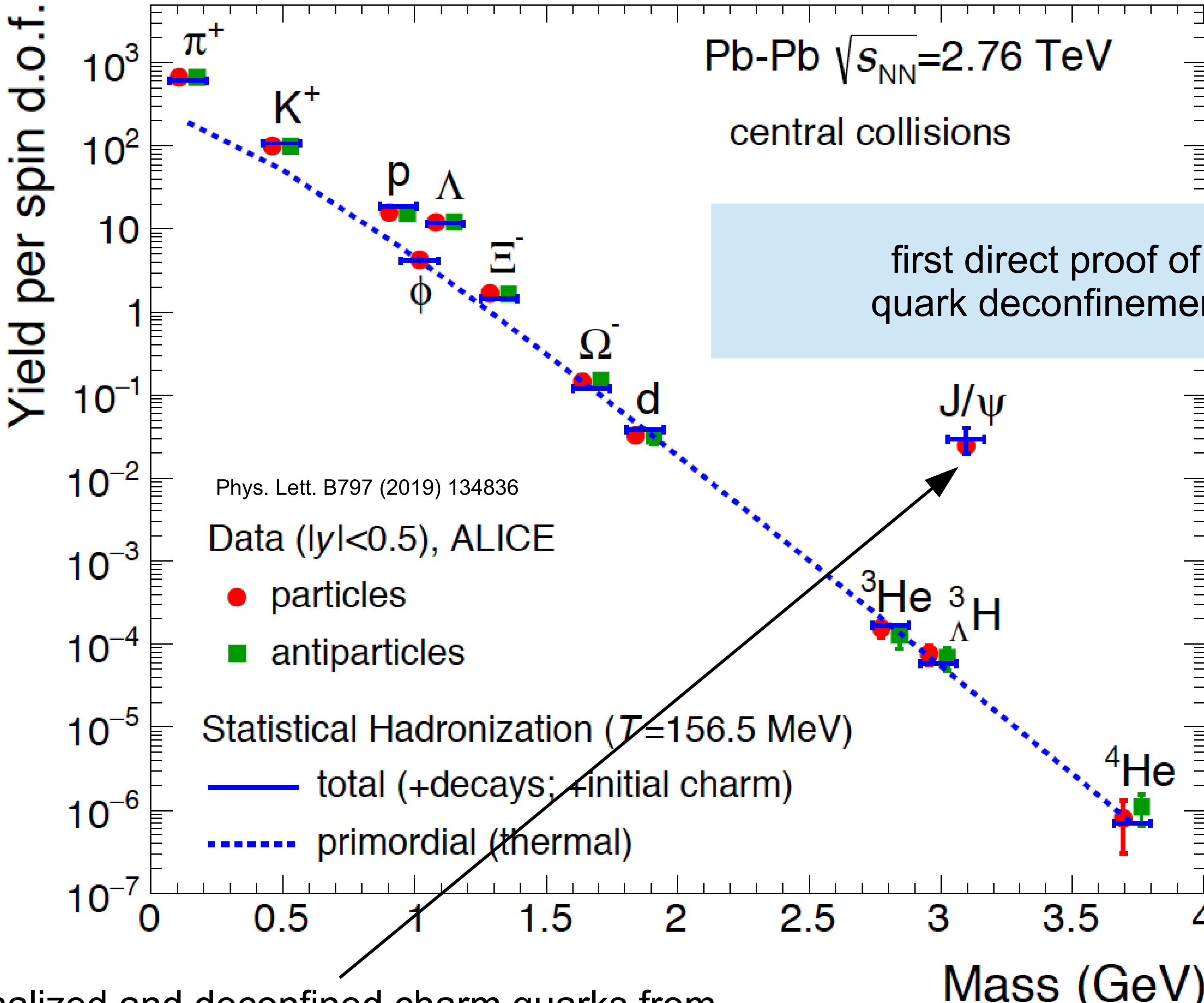


at LHC energy, matter and anti-matter is
produced with equal yields

J/psi mass is close to that of hypertriton, where is enhancement by 3 orders of magnitude from?



enhancement is precisely prediction by Statistical Hadronization Model
for quadratic scaling in number of charm quarks, they have to travel freely over
the size of the fireball of 10 fm, about 10 times the radius of a proton



first direct proof of
quark deconfinement

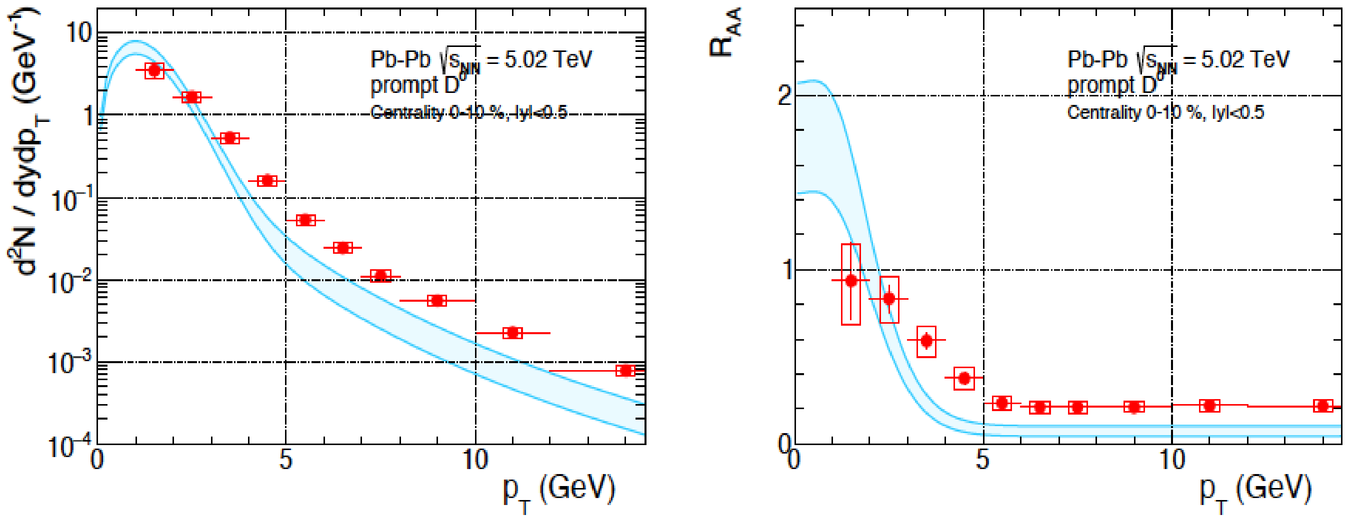
with thermalized and deconfined charm quarks from
initial hard scattering

Andronic, pbm, Koehler, Redlich, Stachel,
Phys. Lett B797 (2019) 134836

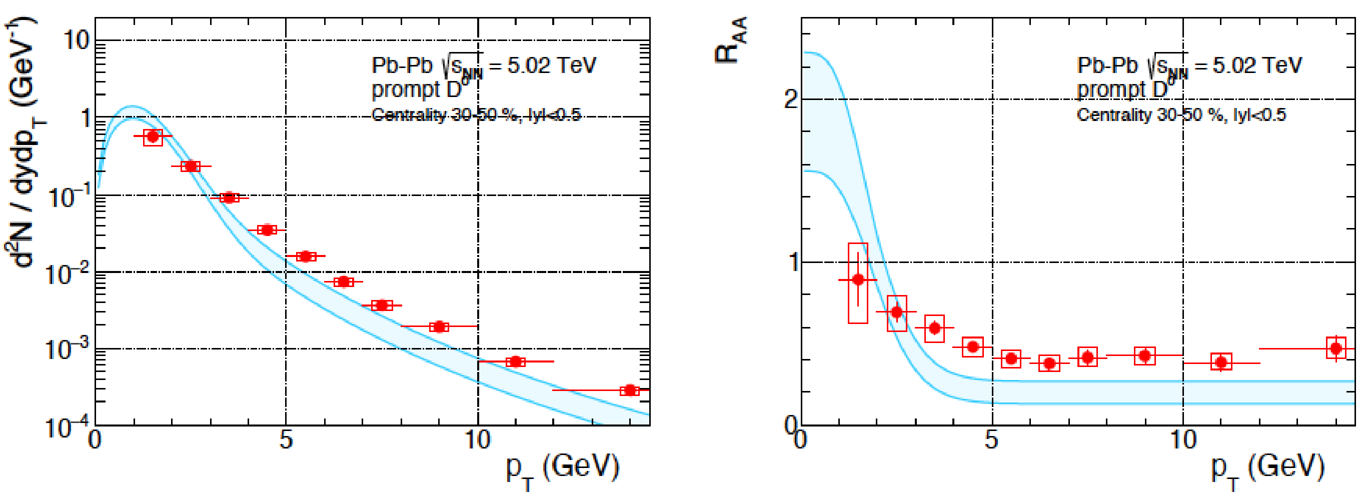
statistical hadronization model and particle spectra

Andronic, pbm, Koehler, Redlich, Stachel
Phys.Lett. B797 (2019) 134836, arXiv:1901.09200

D^0 in 0-10 %

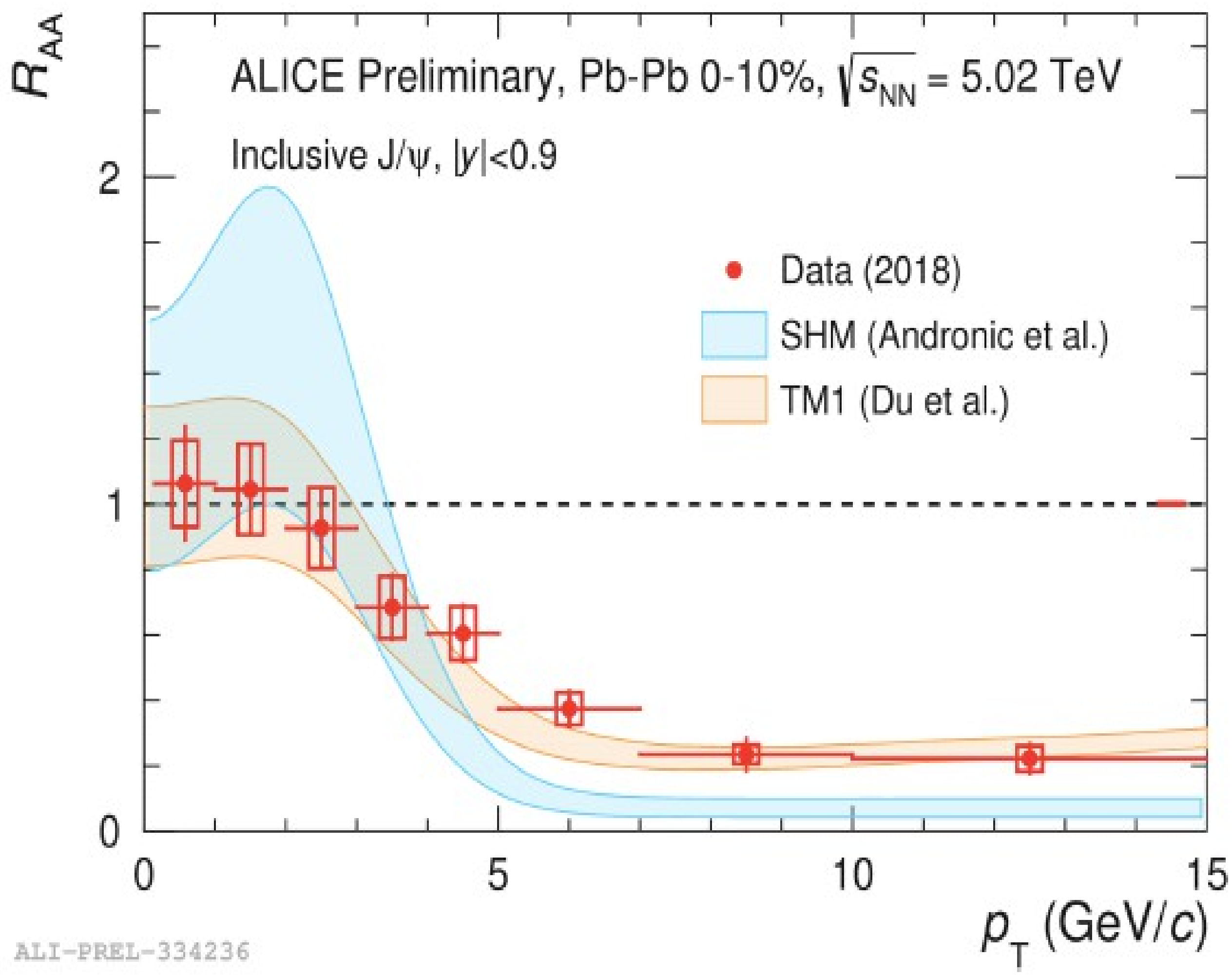


D^0 in 30-50 %



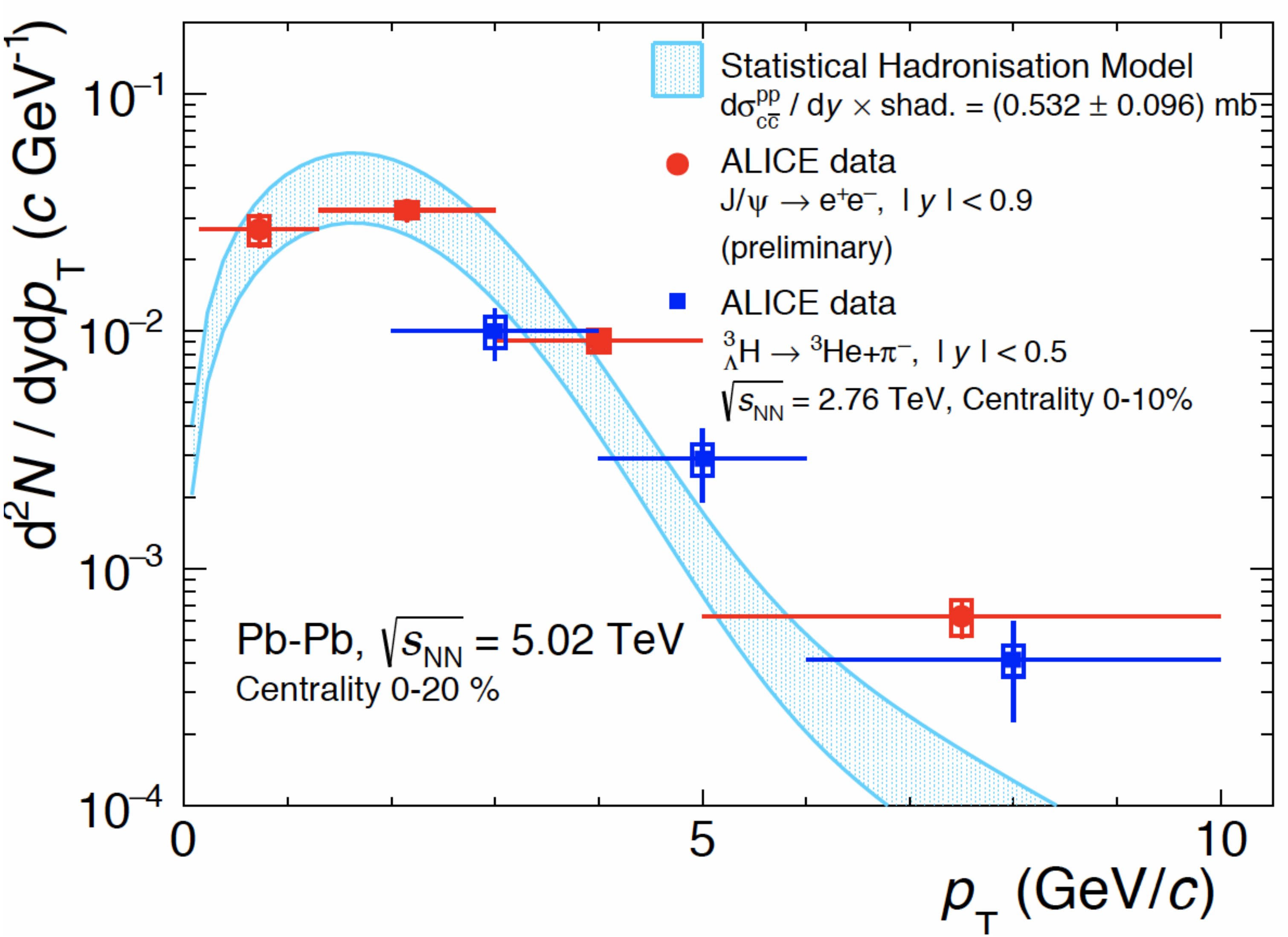
comparison of SHMC predictions with most recent data

precision still limited by uncertainty in open charm cross section for Pb-Pb collisions
but good agreement without any new parameters



Andronic, pbm, Koehler, Redlich, Stachel,
Phys. Lett B797 (2019) 134836, SHMC + hydro (MUSIC)

J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model

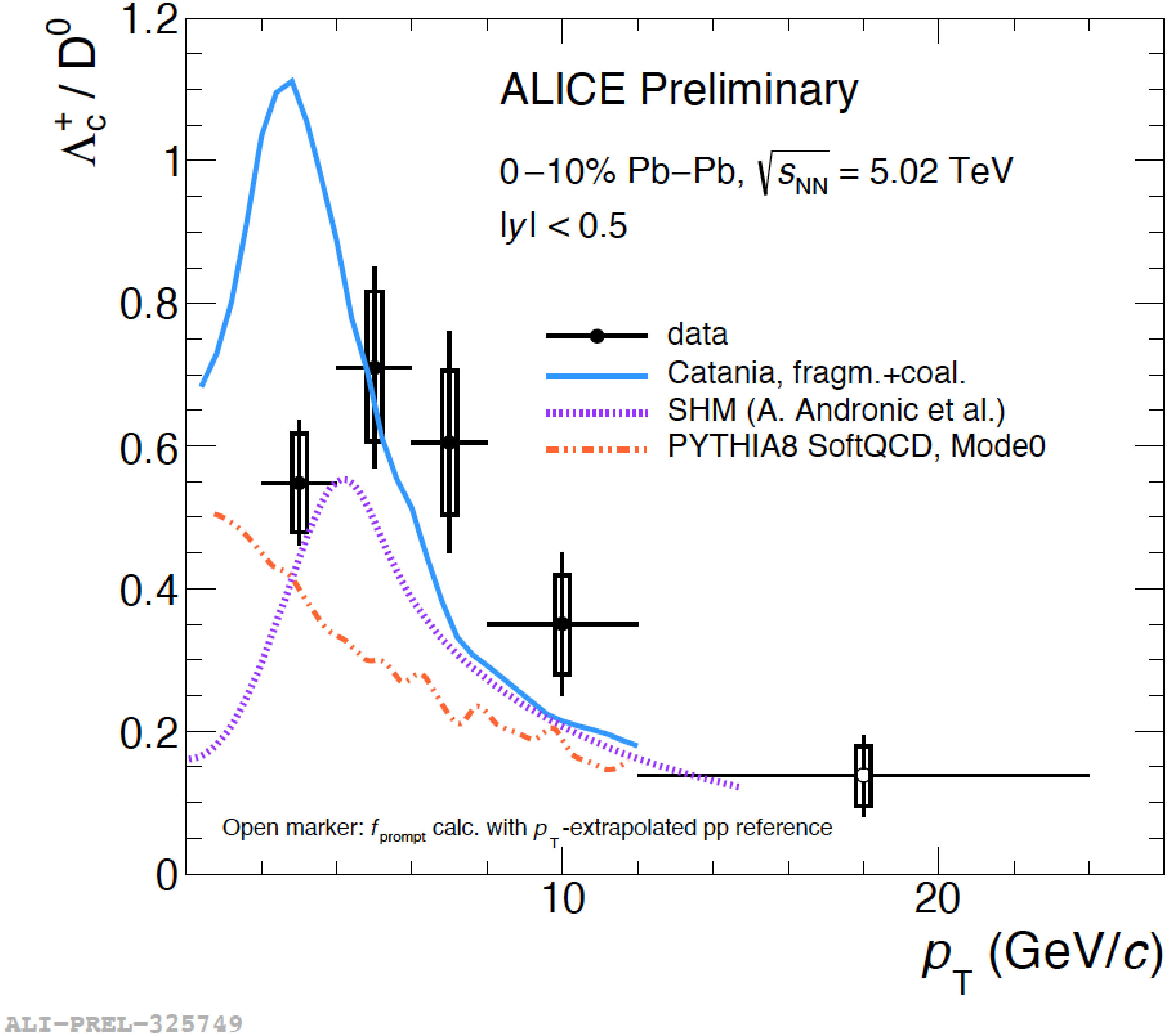


binding energies:
J/psi 600 MeV
hypertriton 2.2 MeV
Lambda S.E. 0.2 MeV

from review: hypernuclei and other loosely bound objects produced in nuclear collisions at the LHC,
pbm and Benjamin Doenigus,
Nucl. Phys. A987 (2019) 144, arXiv:1809.04681

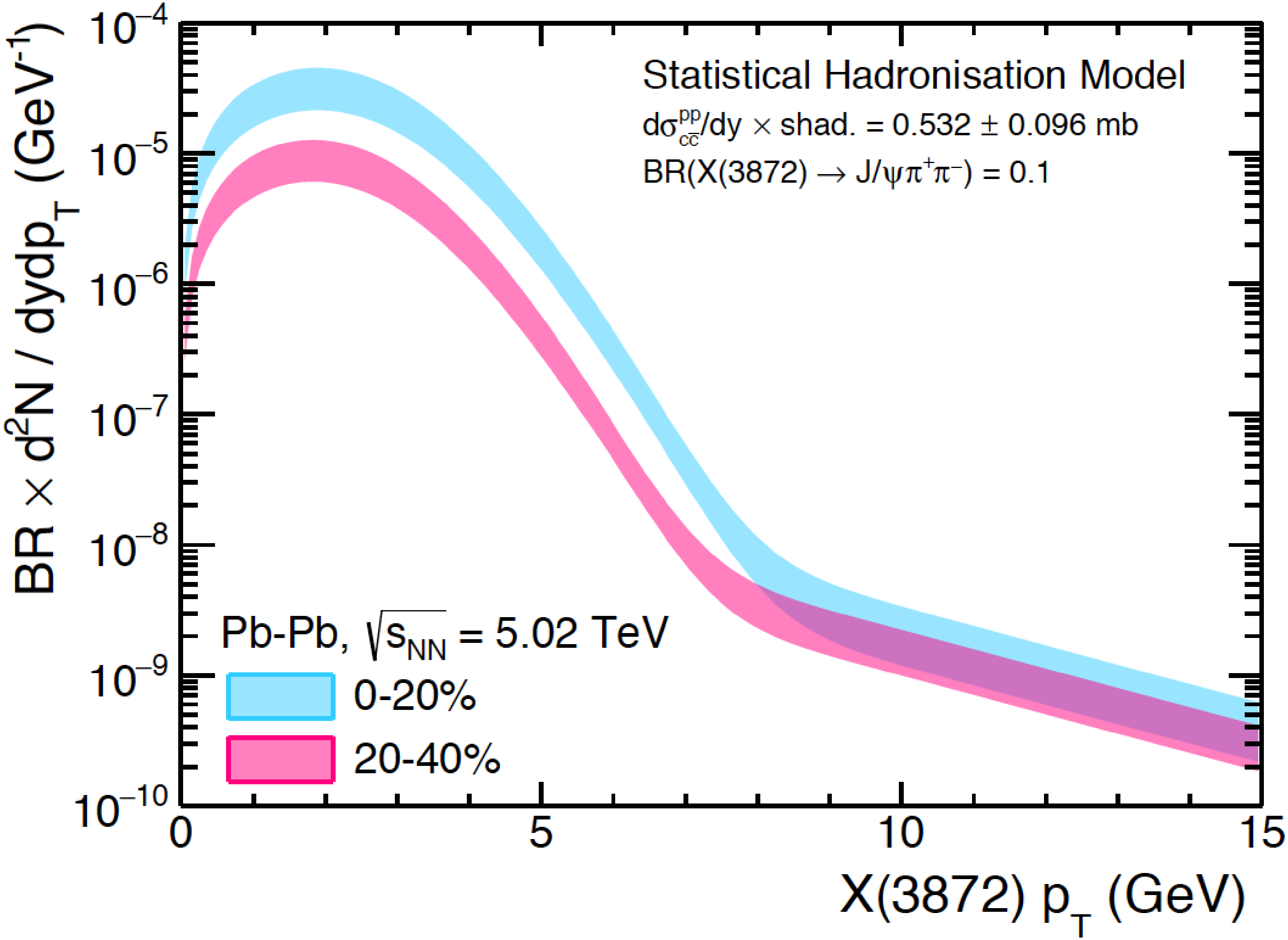
statistical hadronization model and particle spectra

Andronic, pbm, Koehler, Redlich, Stachel
Phys.Lett. B797 (2019) 134836, arXiv:1901.09200



no anomaly for Lambda$_c$

transverse momentum spectrum for X(3872) in the statistical hadronization model
Pb-Pb collisions at 5 TeV/u



doorway state hypothesis:
all nuclei and hyper-nuclei, penta-quark and X,Y,Z states 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, penta-quark and X,Y,Z states from pp via pPb to Pb-Pb

a major new opportunity for ALICE Run3/4
and beyond LS4 for X,Y,Z and penta-quark states

also new opportunities for
GSI/FAIR and JINR/NICA
experiments

summary

- statistical hadronization model is an effective tool to understand the phenomenology of hadron production in relativistic nuclear collisions from SIS to LHC energy with predictive power for future facilities
- deeply rooted in duality 'hadrons – quarks' near QCD phase boundary
- present precision is mostly limited by incomplete knowledge of hadron mass spectrum and related branching ratios for decays
- measurements from ALICE at the 5% accuracy level show deviations for protons, now quantitatively understood by using experimental pion-nucleon phase shifts
- yields of light nuclei and hyper-nuclei successfully predicted → maybe produced as quark bags?
- works also for hadrons with charm quarks → open charm and charmonium enhancement in QGP, direct proof of deconfinement for charm quarks, access to exotic multiply charmed hadrons

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156.5 ± 3 MeV
new insight into universal hadronization for charm

additional comments on hadrons with charm

SHMC predictions for yield of hadrons with multiple charm quarks:
spectacular enhancements of factor > 900 (2 charm quarks)
to > 27000 (3 charm quarks)

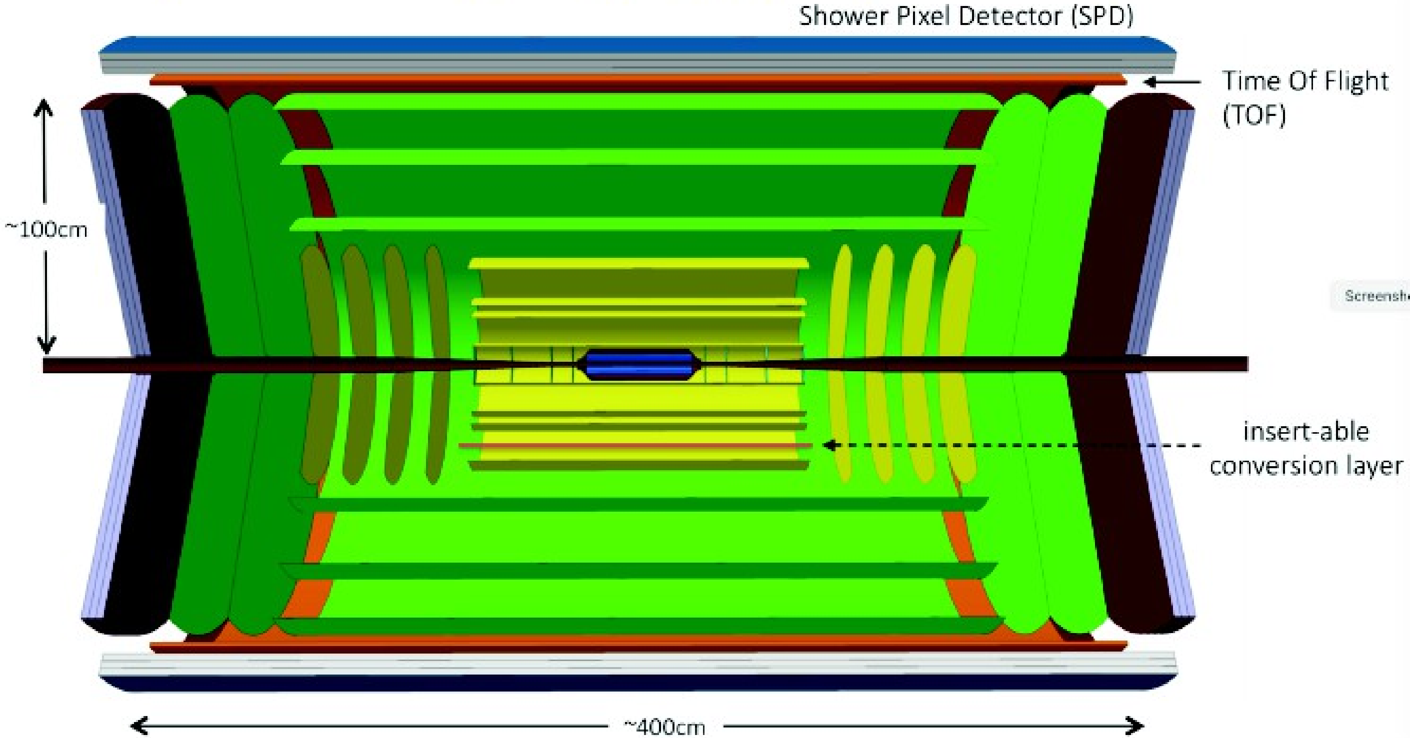
can be detected in ALICE Run3/4 with new Si-tracker based on MAPS technology (ITS2 and ITS3)

many new opportunities with an all Si next generation LHC heavy ion experiment, see 1902.01211

a whole new harvest of exotic hadrons with multiple charm and possibly beauty is in front of us

**in the large volume limit,
hadronization of u,d,s,c quarks is very well described
by a thermal distribution with
T = T(chiral cross over)**

Next generation of AA/pA/pp experiment for installation beyond Run4 @ HL-LHC



proposal to replace ALICE

Ultra-thin chip (<50 um): flexible with good stability

Detector concept is an all Silicon detector:

- Pixel detector with fast and light CMOS MAPS
- High-rate capabilities of MAPS will allow the experiment to run at significantly higher luminosities (a factor 20 to 50), e.g. with lighter ions

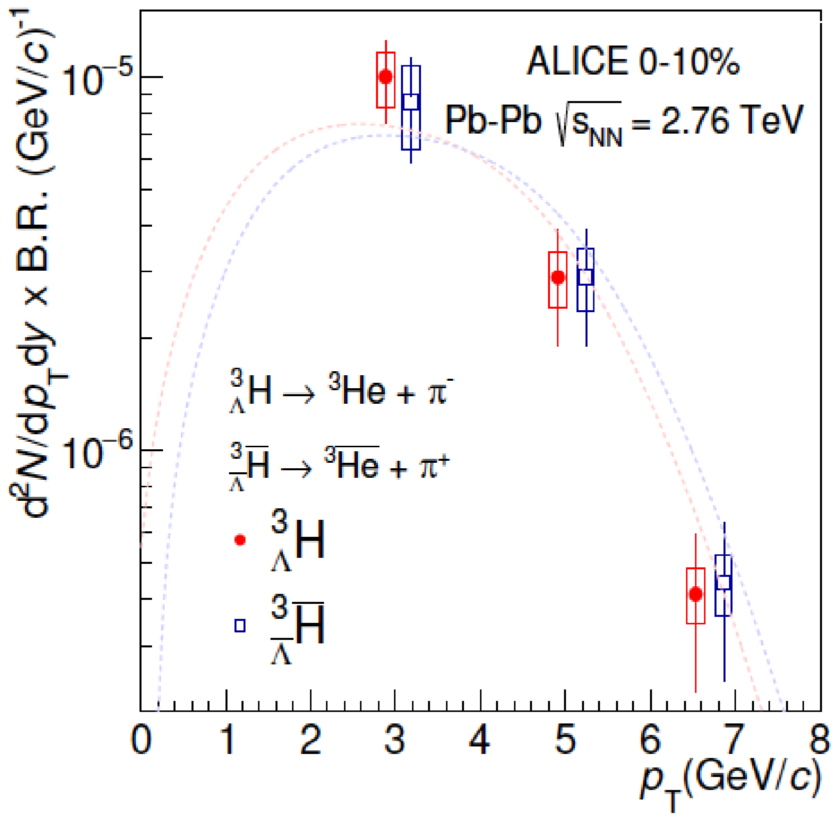
Physics potential:

- QGP properties via precision measurements in heavy flavor sector
- Access to new low-p_T phenomena (γ & hadrons)
- Low mass di-leptons

1902.01211

additional slides

even hyper-triton flows with same common fluid velocity



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-

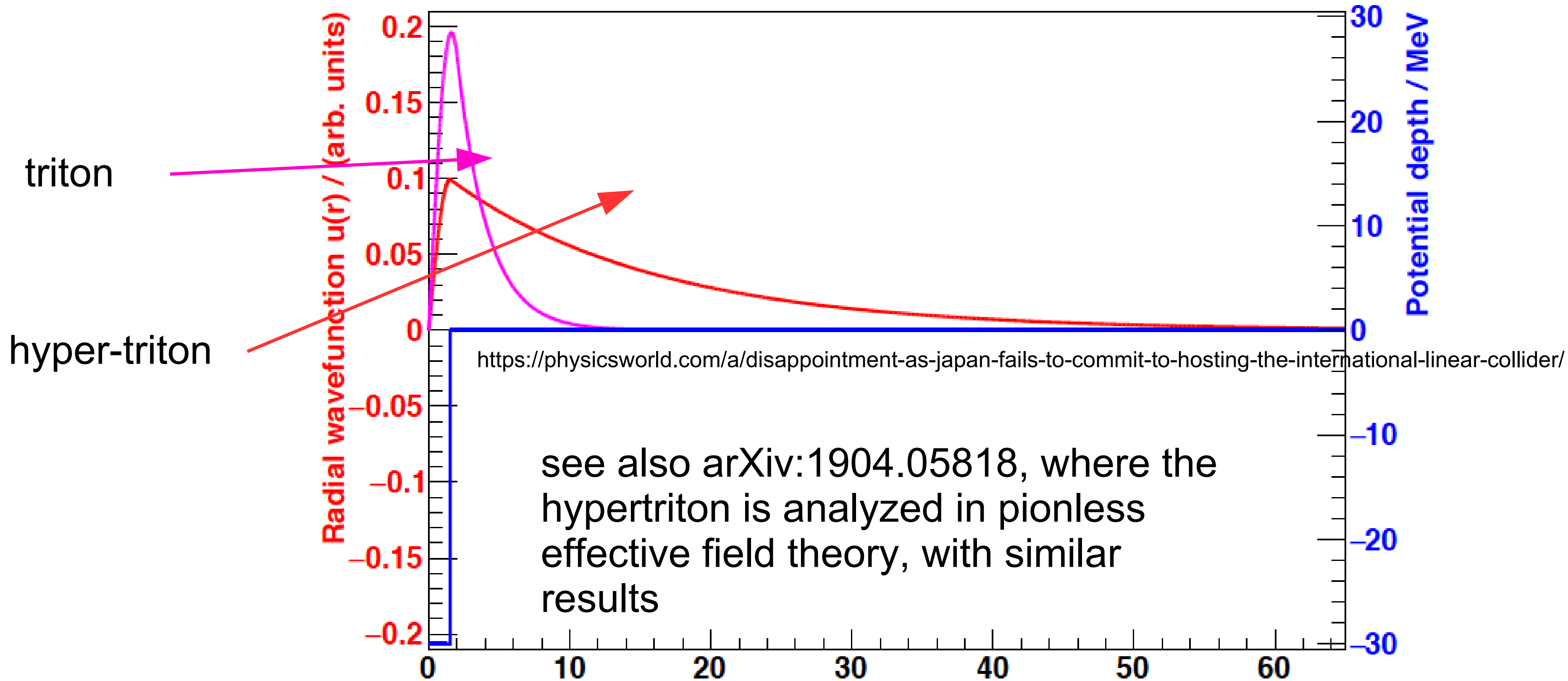
rms radius = $(4 \text{ B.E. } M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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 Lambda separation energy.)

wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017

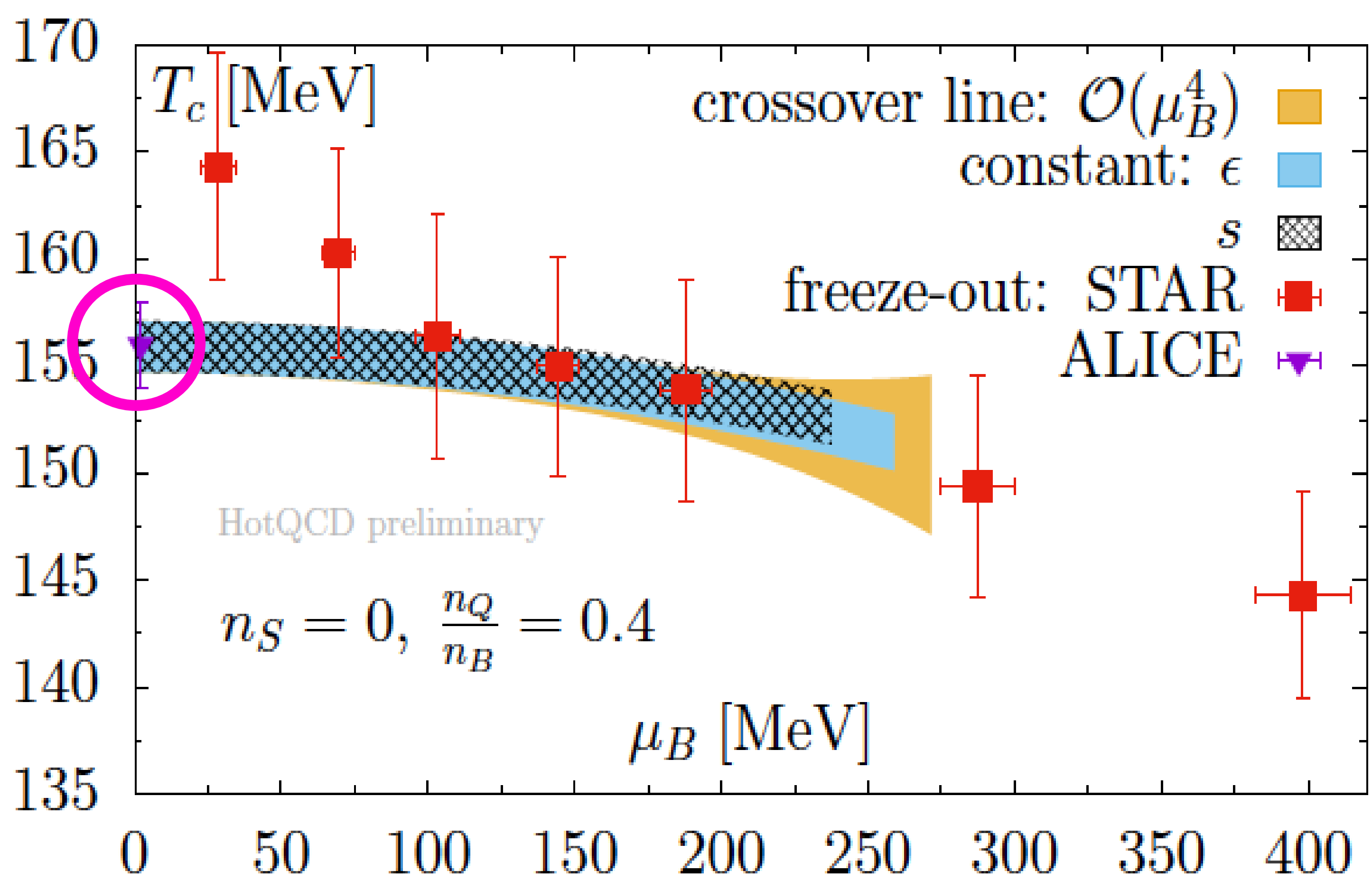


see also arXiv:1904.05818, where the hypertriton is analyzed in pionless effective field theory, with similar results

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.

chemical freeze-out and the chiral crossover line

ALICE point: 156 ± 1.5 ± 3 (sys) MeV, measured with TPC and Si vertex detector
STAR points: measured with TPC only, feeding from weak decays
lattice: 156 ± 1.5 MeV



lattice: BNL-Bielefeld coll. 1807.05607

a note on the chemical freeze-out temperature

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

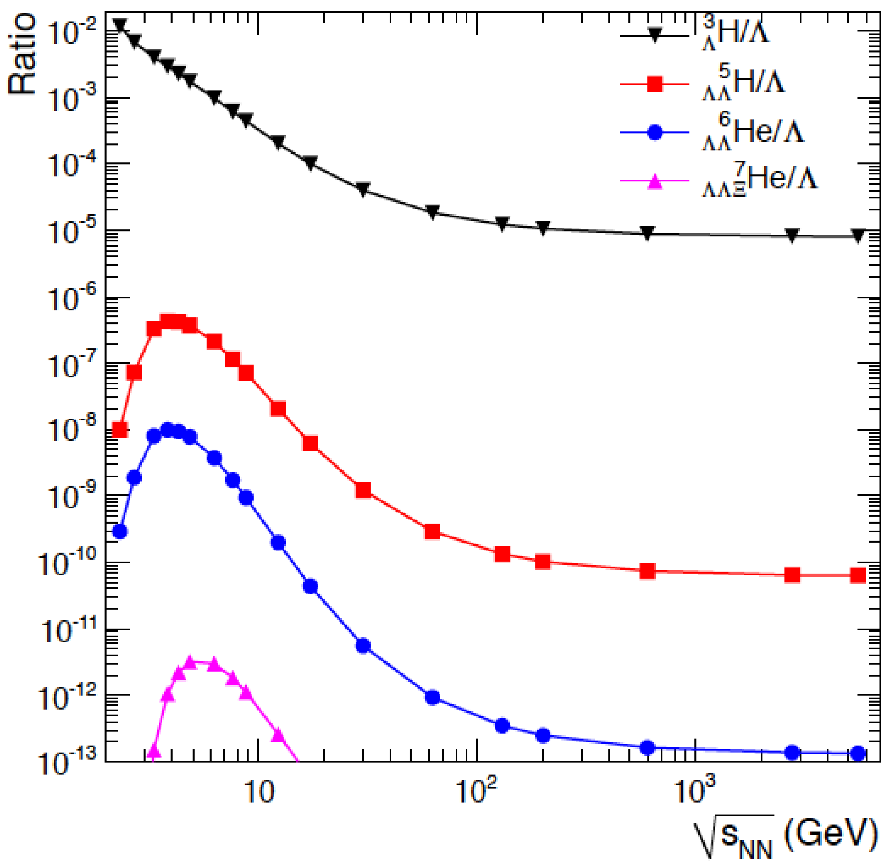
there is an additional uncertainty because of the poorly known hadronic mass spectrum for masses > 2 GeV

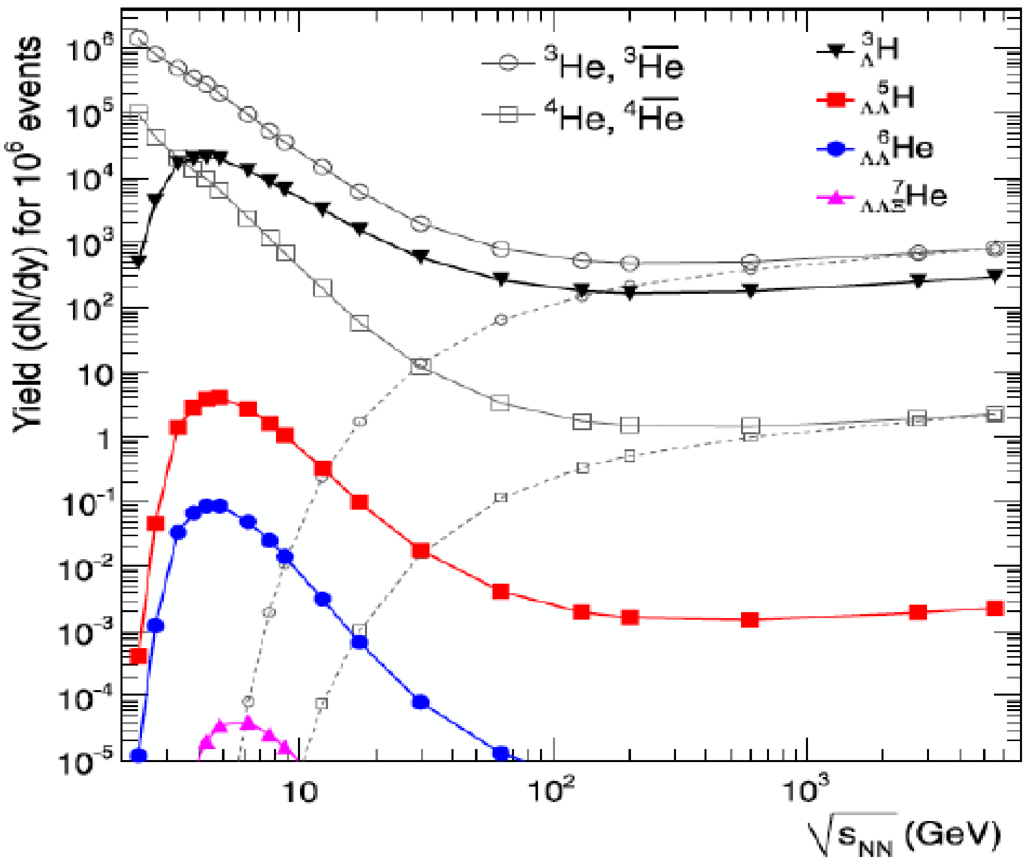
for d, 3He, hypertriton and alpha, there is very little feeding from heavier states and none from high mass states in the hadronic mass spectrum, for these particles the temperature T_{nuc} can be determined 'on the back of an envelope' :

T_{nuc} = 159 ± 5 MeV, independent of hadronic mass spectrum

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

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 light nuclei, 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)

[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 ($T_{CF}, \mu_b \to n_X^{th}$)

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

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

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

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

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

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

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

Effective weight function ↓ *Scattering phase shift* ↓

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

- Interactions driven by narrow resonance of mass M_R

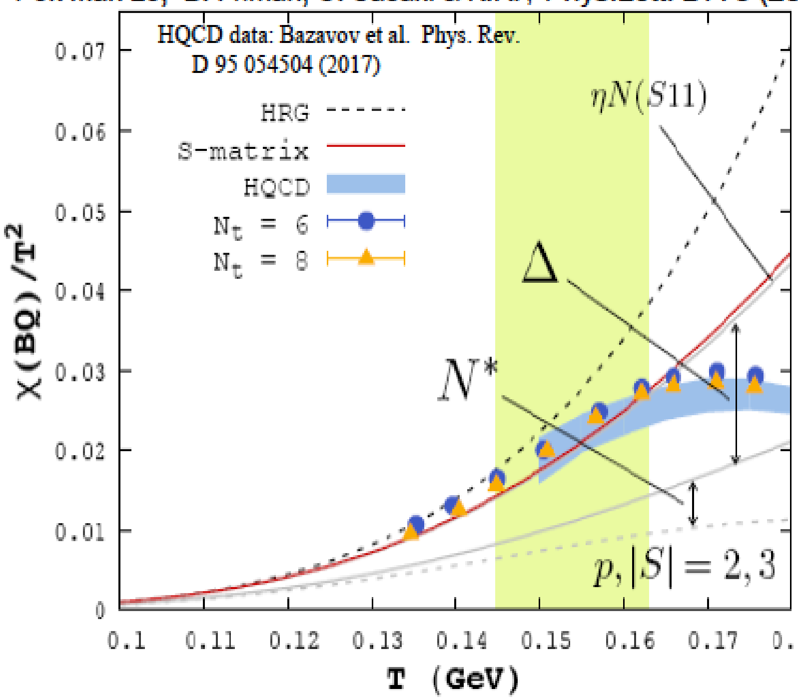
$$B(M) = \delta(M^2 - M_R^2) \;\; \Rightarrow \;\; P^{\text{int}} = P^{id}(T, M_R) \;\; \Rightarrow HRG$$

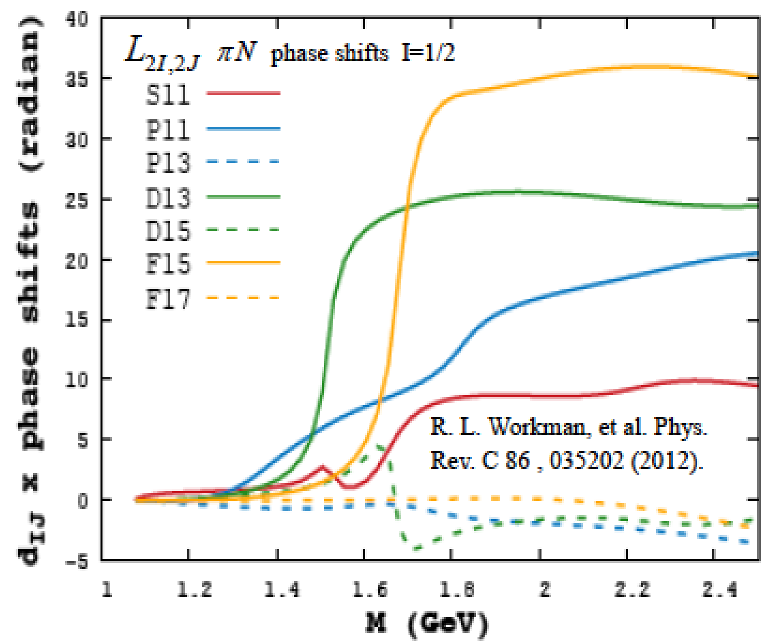
- For non-resonance interactions or for broad resonances the HRG is too crude approximation and $P^{\text{int}}(T)$ should be linked to the phase shifts considering all pion-nucleon phase shifts with isospin 1/2 and 3/2

Probing non-strange baryon sector in πN- system

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

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



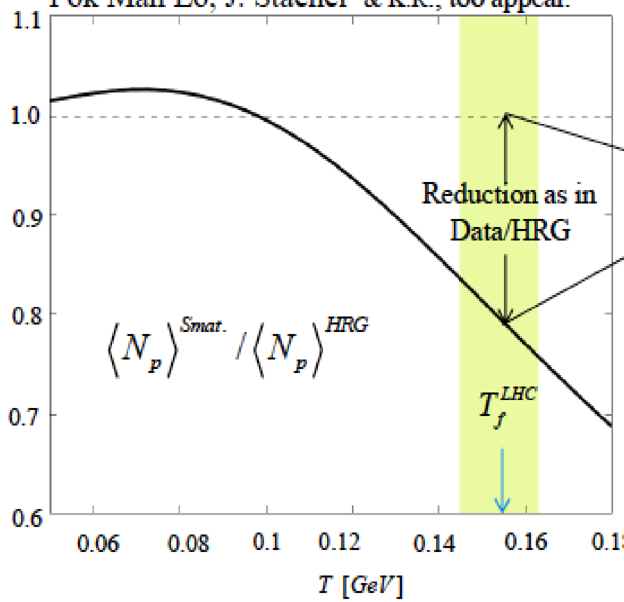


$$\Delta\chi_{BQ} \approx \sum_{I_z, j, B} d_j BQ \int dM \int d^3p \frac{1}{T} \frac{d\delta_j^I}{dM} \times e^{-\beta\sqrt{p^2+M^2}} (1 + e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

- 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

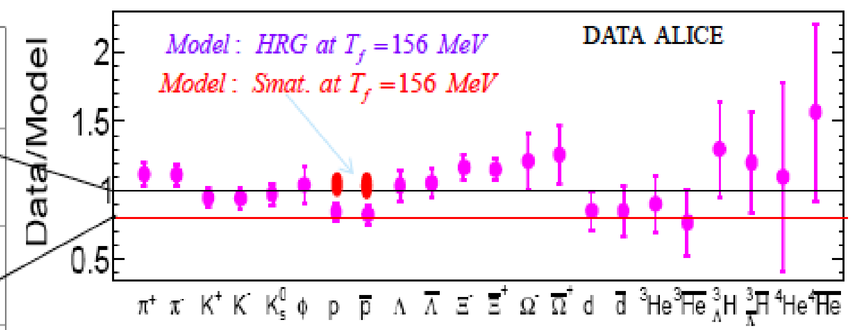
A. Andronic, P. Braun-Munzinger, B. Friman, Pok Man Lo, J. Stachel & K.R., too appear.



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

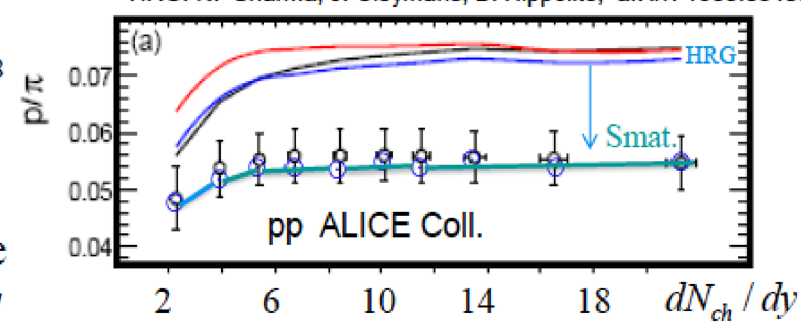
For further consequences of smat. See also: P. Huovinen, P. Petreczky Phys. Lett. B77 (2018) P. Huovinen, poster QM2018

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

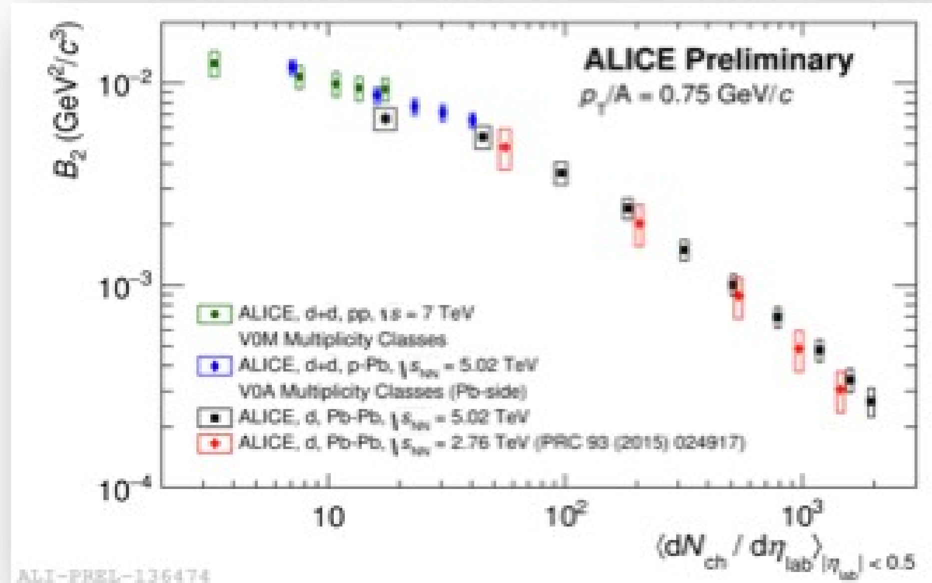


- S-matrix results well consistent with pp data

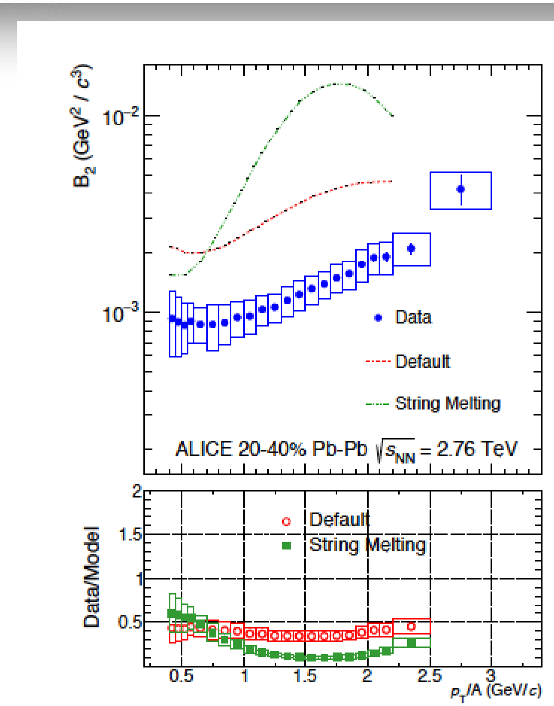
points a way to explain 'proton puzzle',new description to appear soon

is coalescence approach an alternative?

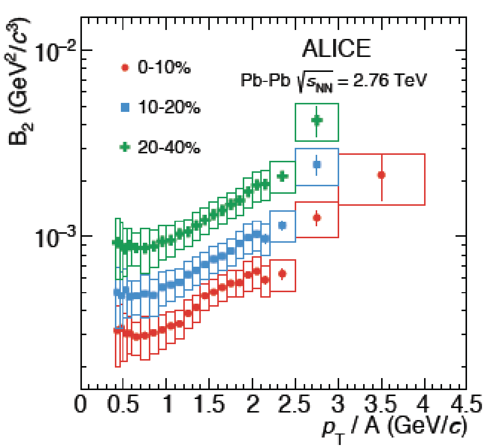
$$E_i \frac{d^3N_i}{dp_i^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \qquad B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{M}{m^A}$$

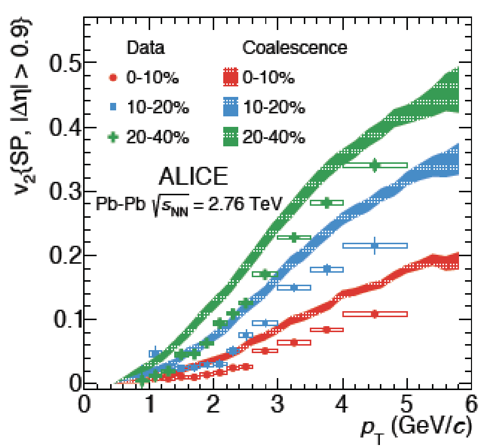


centrality and p_T dependence of coalescence parameter not understood and not well reproduced by models such as AMPT



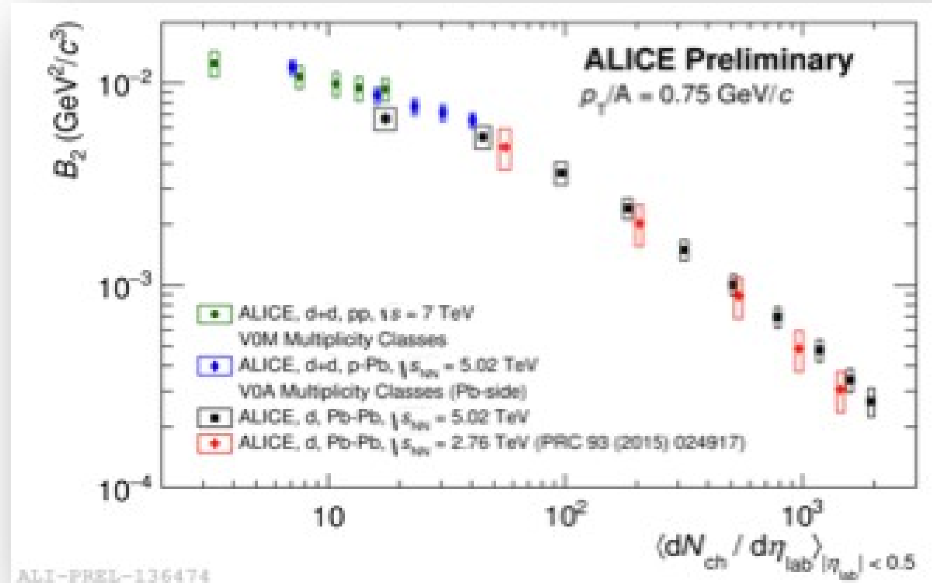
ALICE: arXiv:1707.07304





is coalescence approach an alternative?

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



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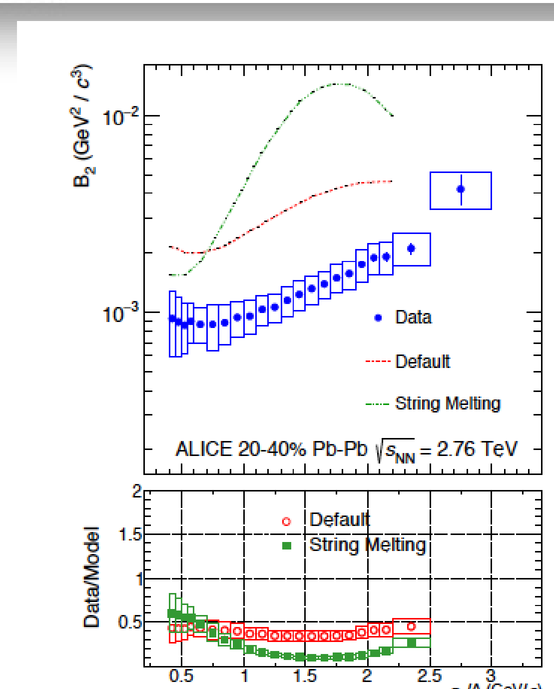
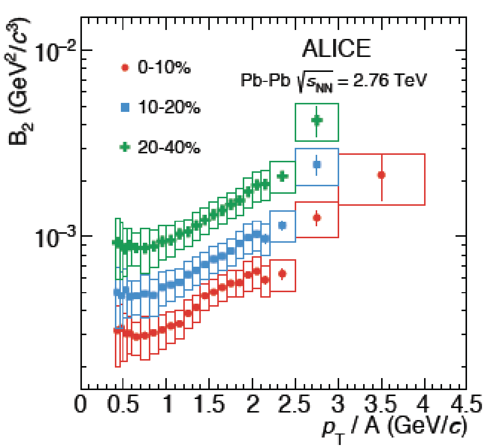
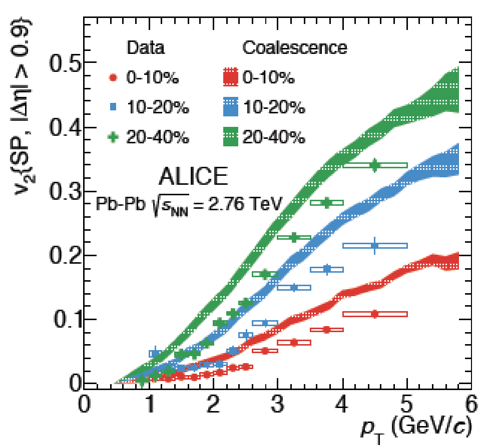






coalescence approach, general considerations for loosely bound states

- 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: 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 $\sigma > 70$ 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 $n < 1/(\lambda\,\sigma) = 0.001/\text{fm}^3$. Inconsistent with formation at kinetic freeze-out, where $n \approx 0.05/\text{fm}^3$.

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

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

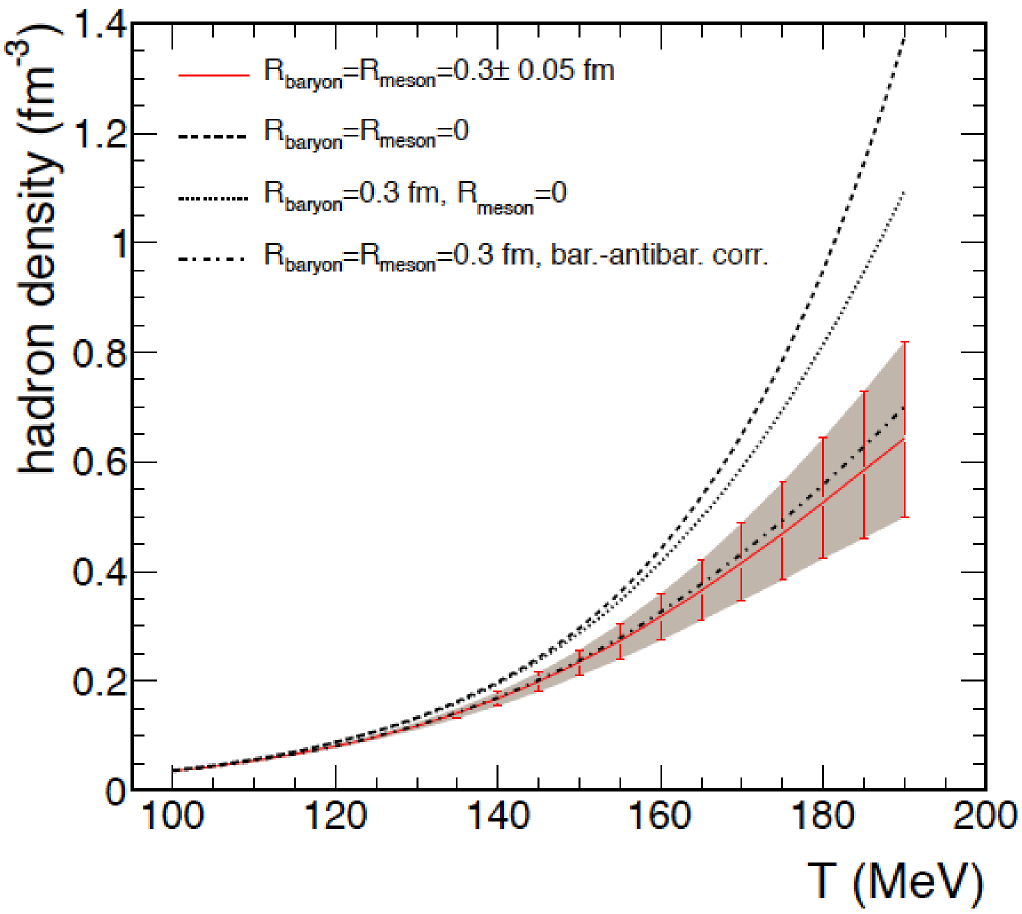
the agreement of the baryon number 3 states is also big problem for coalescence model

see also the detailed analysis by Francesca Bellini and Alexander Kalweit, arXiv:1807.05894,
Benjamin Doenigus and Nicole Loeher, GSI-EMMI meeting, Feb. 2018

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

a possible way out

Hadron resonance gas and interactions



for T < 165 MeV, the details of the interactions don't matter and the 'low density approximation' is a good assumption

Quark Model Spectroscopy

Why does the quark model work so well?

Why do M and B body plans dominate?

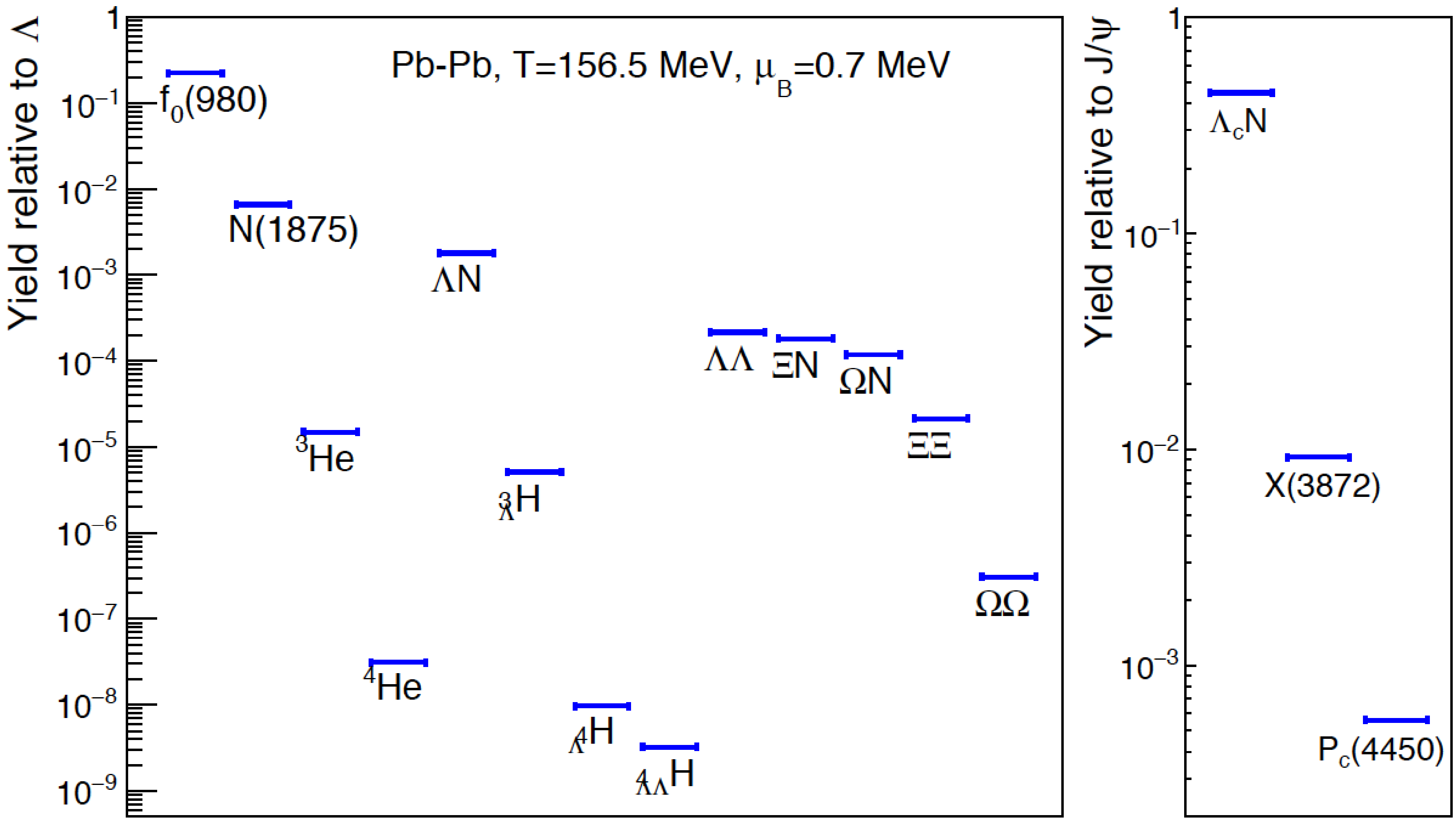
Why don't multibaryons make one big bag?

Frank Wilczek, QM2014 introductory talk

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

thermal production yields of exotic states in central Pb-Pb collisions at 5 TeV/u

Andronic, pbm, Koehler, Redlich, Stachel preprint in preparation



example: X(3872)

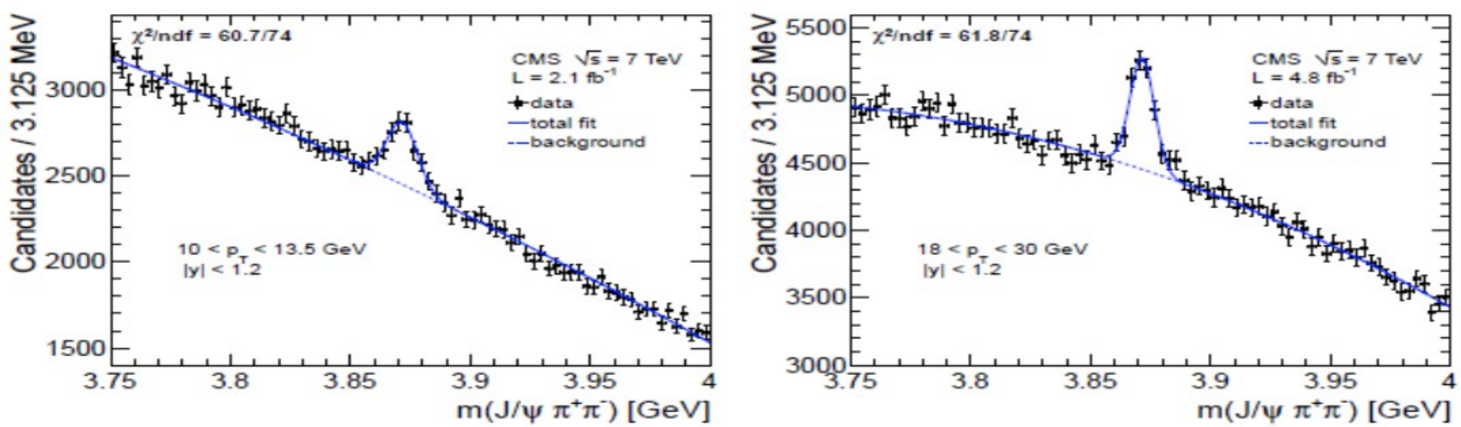
X(3872)

\- 2003 -

$$B^{\pm} \rightarrow K^{\pm} \pi^{+} \pi^{-} J/\psi$$

$$M = 3872.0 \pm 0.6 \pm 0.5\ \text{MeV}$$

\- 2013 -



X(3872)

$I^G(J^{PC}) = 0^+(1^{++})$

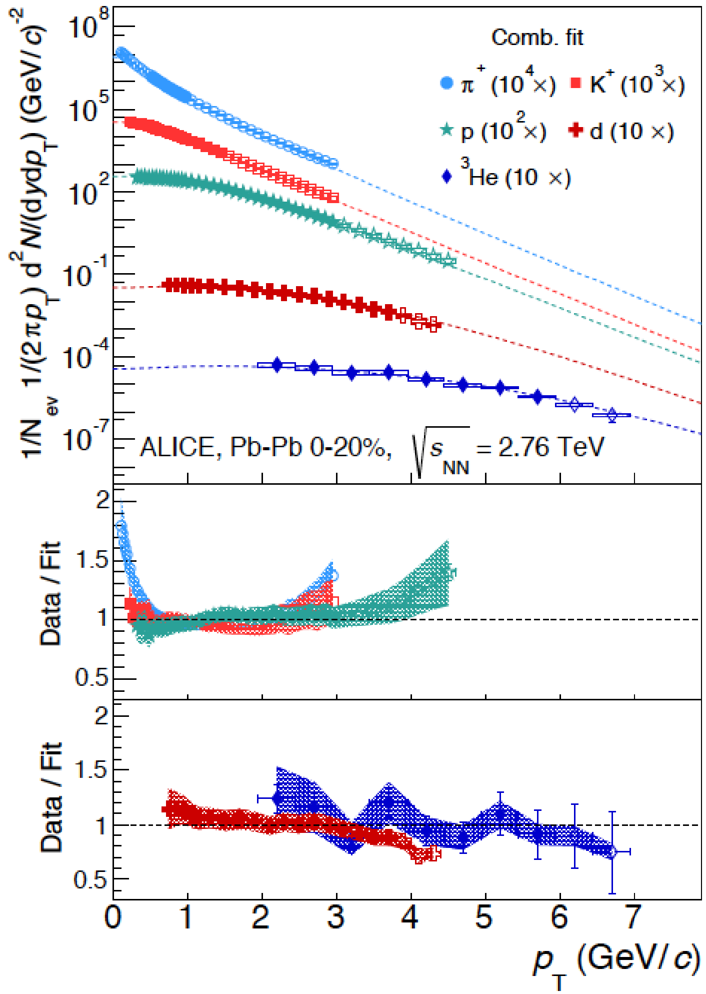
Mass $m = 3871.69 \pm 0.17$ MeV

$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV

$m_{X(3872)} - m_{\psi(2S)}$

Full width $\Gamma < 1.2$ MeV, CL = 90%

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



outlook

ALICE is currently upgraded:

GEM based read-out chambers for the TPC
new inner tracker with ultra-thin Si layers
continuous read of (all) subdetectors

increase of data rates by factor 100

focus on rare objects, exotic quarkonia, low mass lepton pairs and low p_t photons to address a number of fundamental questions and issues such as:

- are there colorless bound states in a deconfined medium?
- are complex, light nuclei and exotic charmonia (X,Y,Z) produced as compact multi-quark bags?
- can fluctuation measurements shed light on critical behavior near the phase boundary?

deciphering QCD in the strongly coupled regime

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

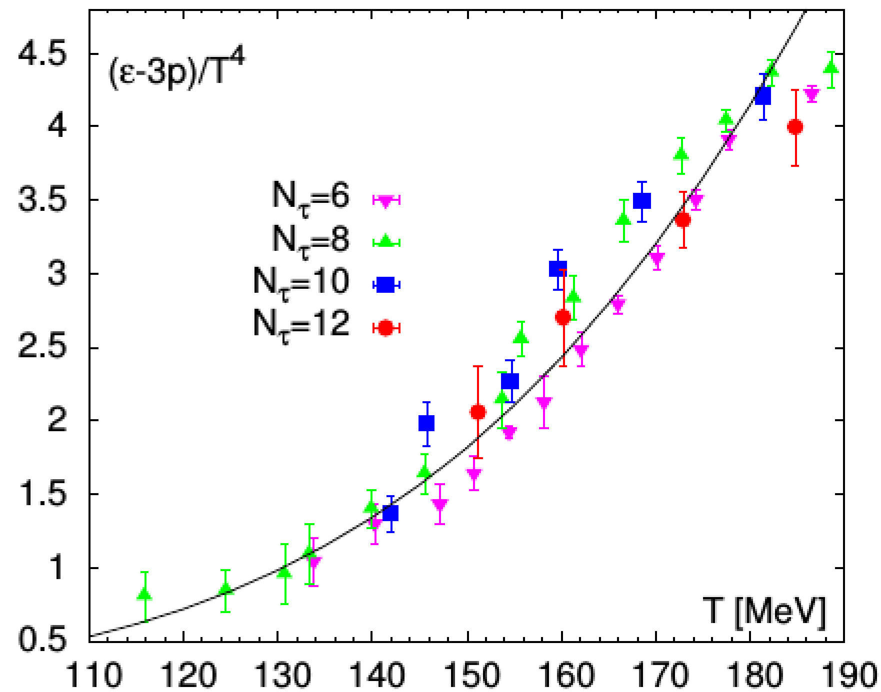
for the pressure we get:

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

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

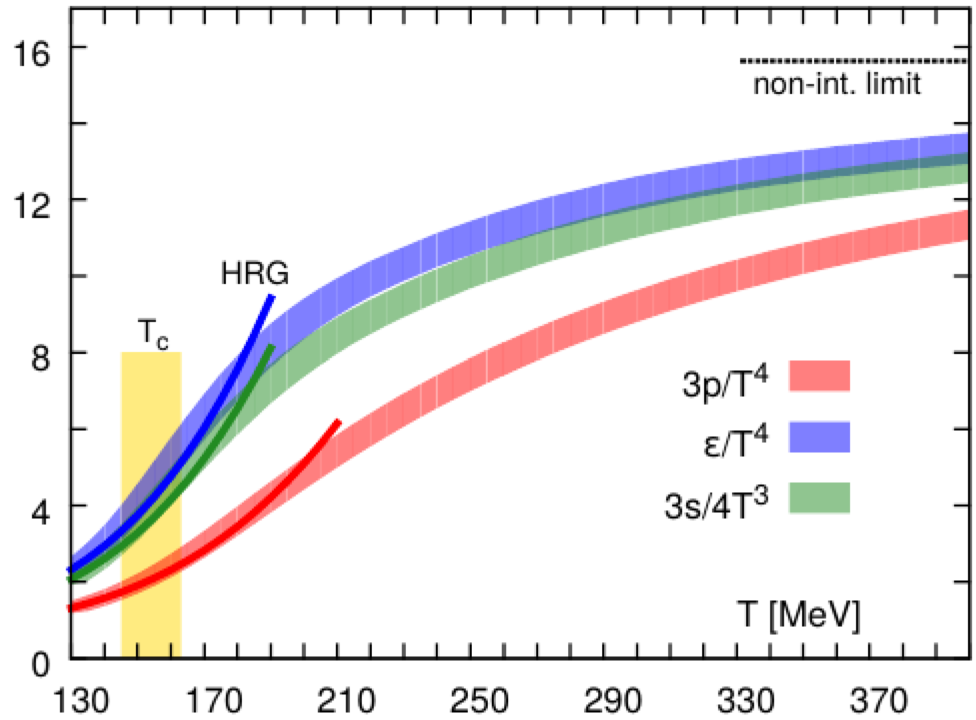


duality between hadrons and quarks/gluons (I)

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

$T_c = 156.5 \pm 1.5$ MeV, arXiv:1807.05607

very new and improved

$\varepsilon_{crit} = 420 \pm 60 \text{ MeV/fm}^3$

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

duality between hadrons and quarks/gluons (II)

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