loosely bound states and exotica
in relativistic nuclear collisions at the LHC

- brief introduction – the LHC era and relativistic nuclear collisions
- the hadron resonance gas, QCD phased boundary, and (u,d,s) hadron production
- Dashen-Ma-Bernstein taken seriously
- experimental determination of the QCD phase boundary
- loosely bound objects
- dealing with open and hidden charm hadrons
- summary and outlook

pbm

EMMI workshop on XYZ states

GSI, Apr. 13, 2021

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

EMMI

GSI

HUAZHONG UNIVERSITY

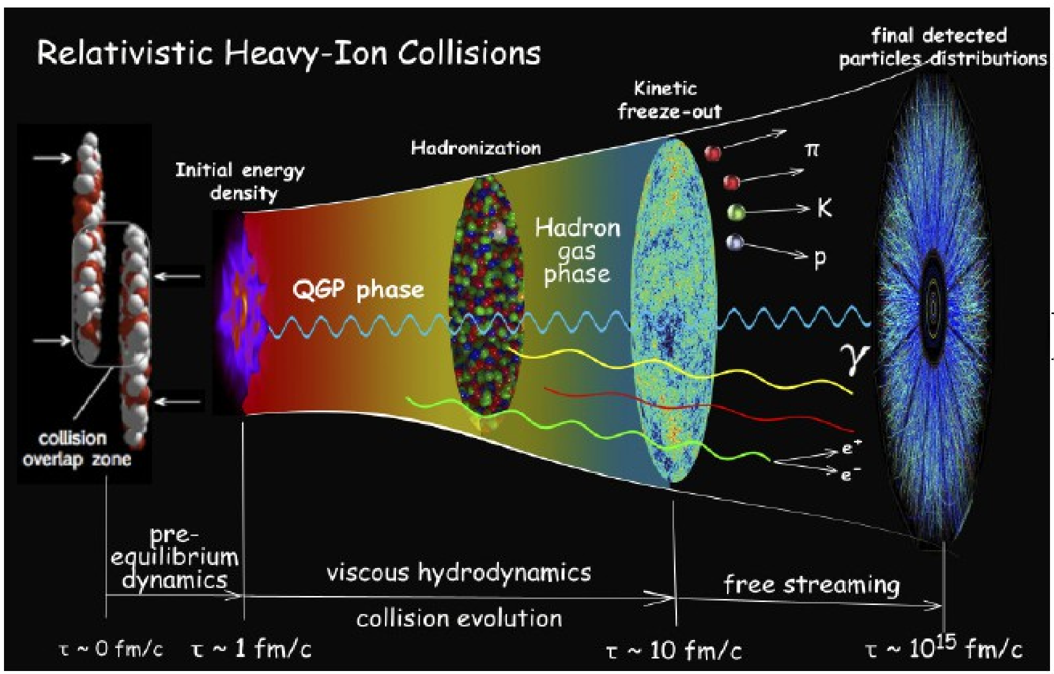
phenomenology results obtained in collaboration with
Anton Andronic, Krzysztof Redlich, and Johanna Stachel
arXiv:1710.09425,
Nature 561 (2018) 321

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

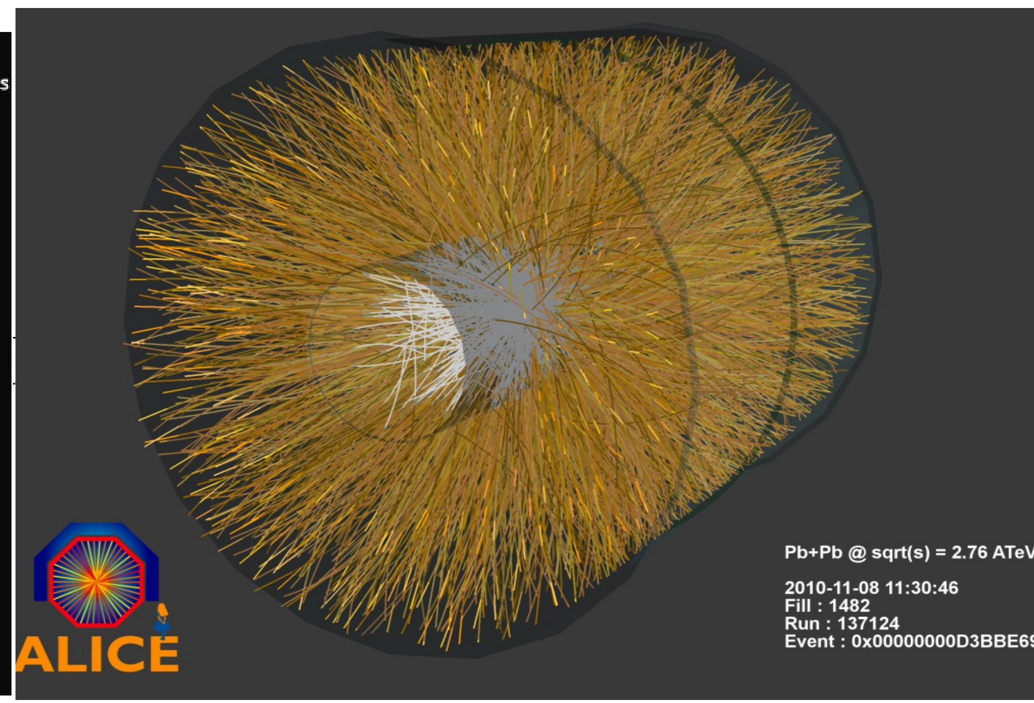
newest results including pion-nucleon phase shifts
from arXiv:1808.03102
Andronic, pbm, Friman, Lo, Redlich, Stachel
Phys.Lett. B792 (2019) 304

open charm results to be published in a few weeks
Andronic, pbm, Kohler, Mazeliauskas, Redlich, Stachel, Vislavicius

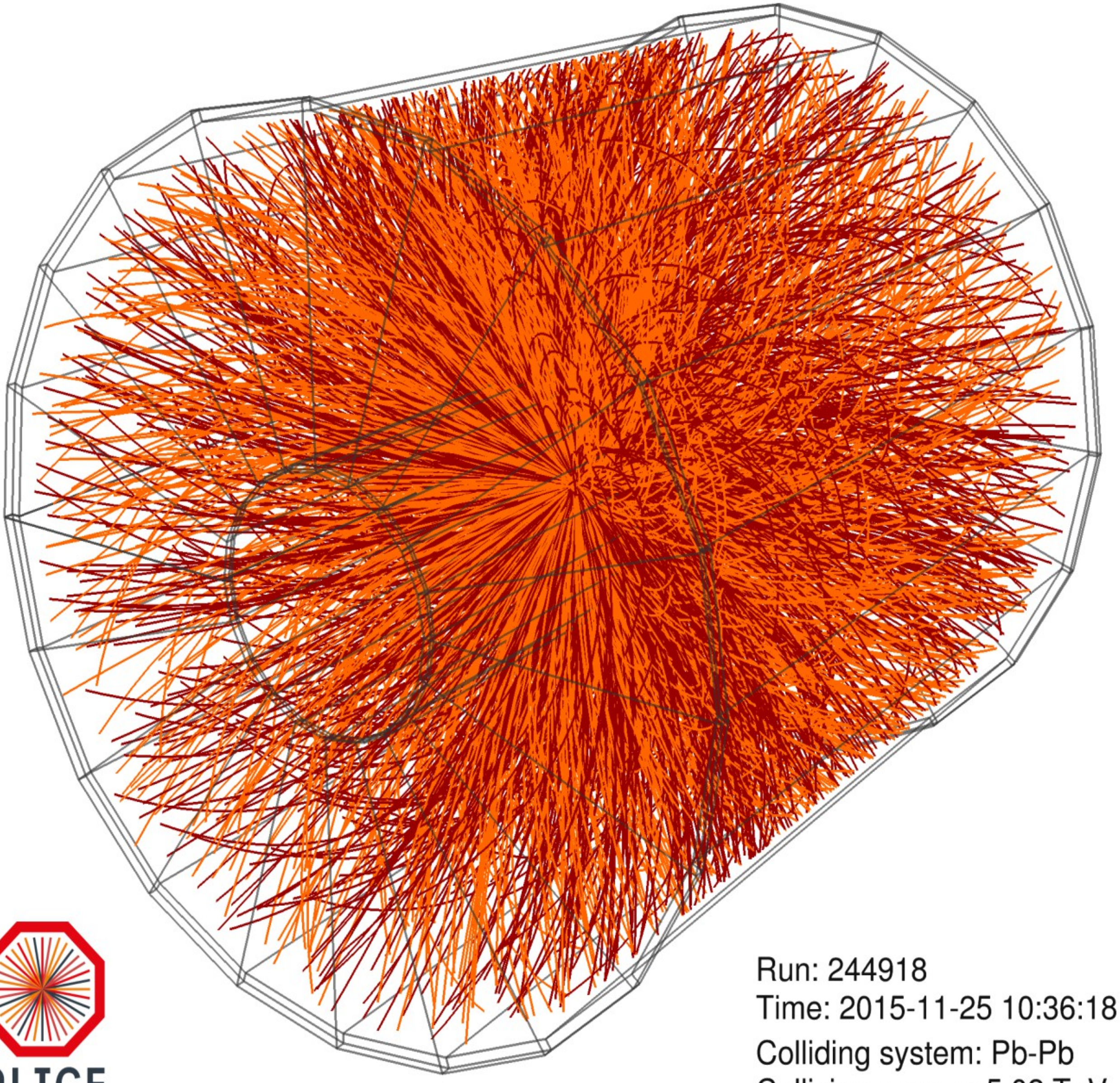
the Quark-Gluon Plasma formed in nuclear collisions at very high energy



Paul Sorensen and Chun Shen



PbPb collisions at LHC at √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

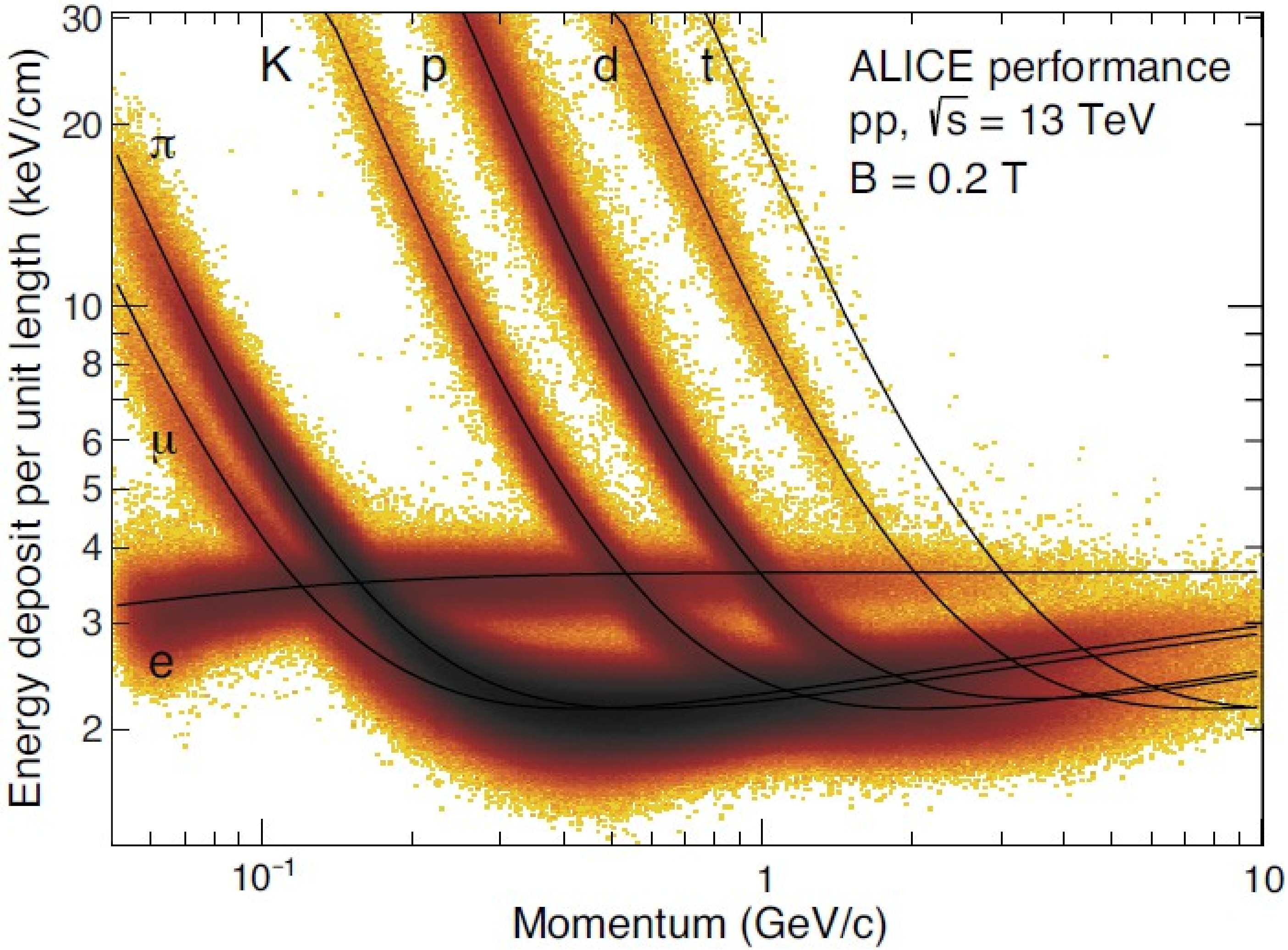
Nov. 2019: Run1 and Run2 combined: > 260 publications

central Pb-Pb collisions:
more than 32000
particles produced per collision
at top LHC energy

ALICE

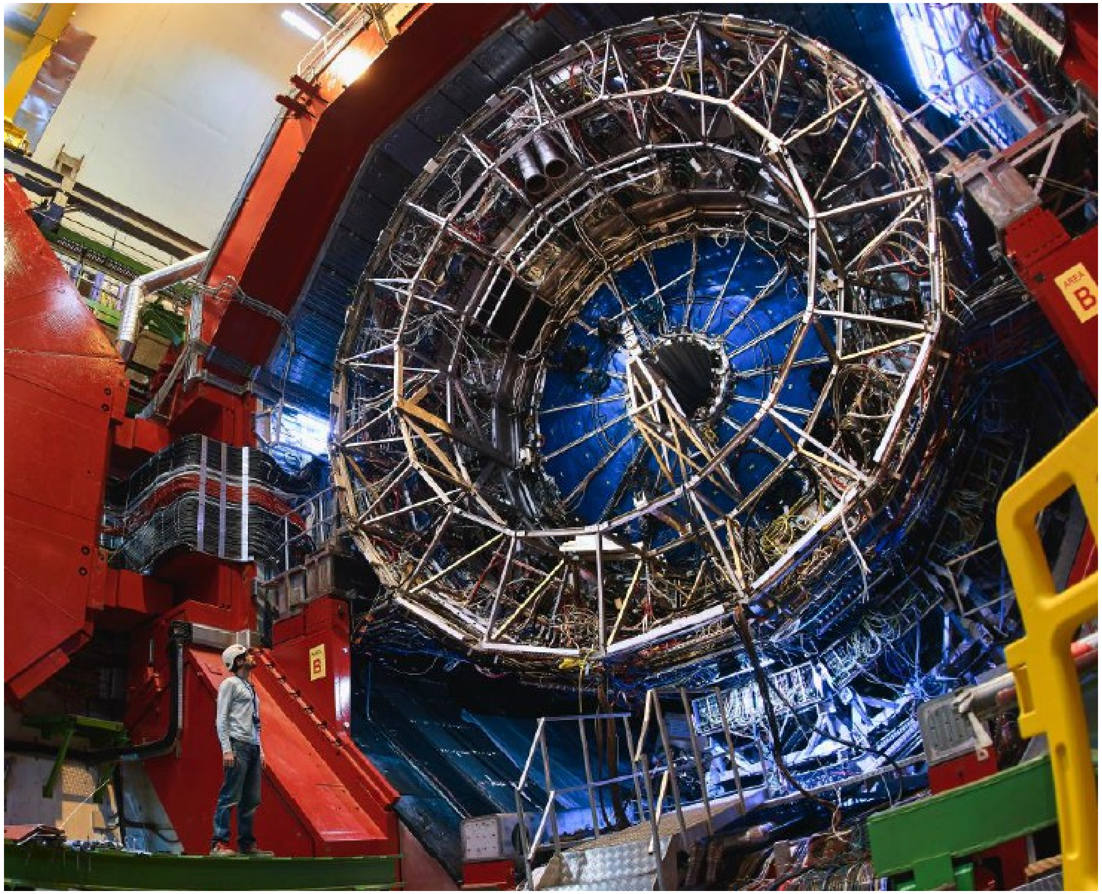
particle identification with the ALICE TPC

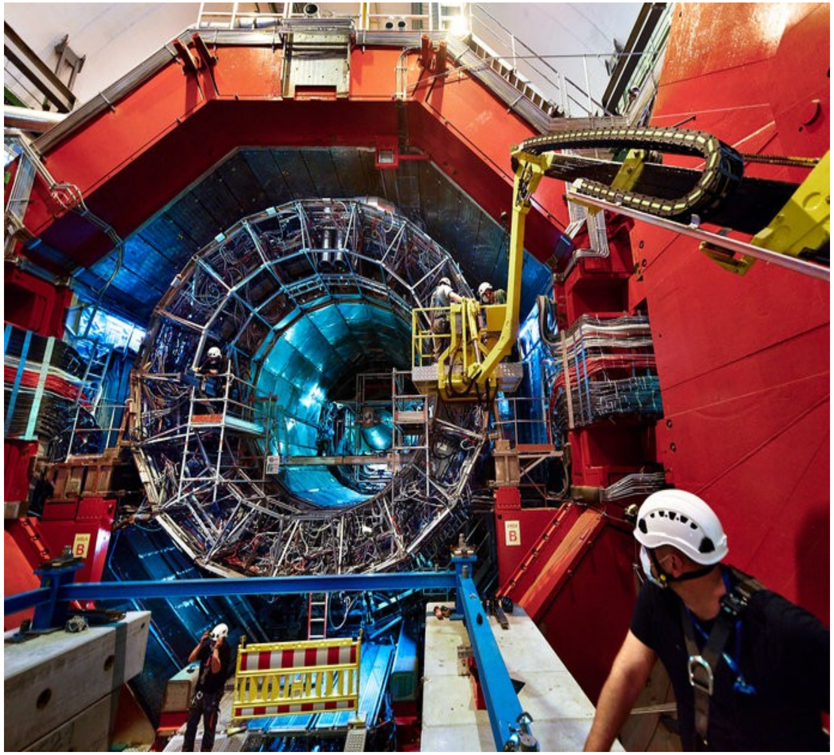
from 50 MeV to 50 GeV

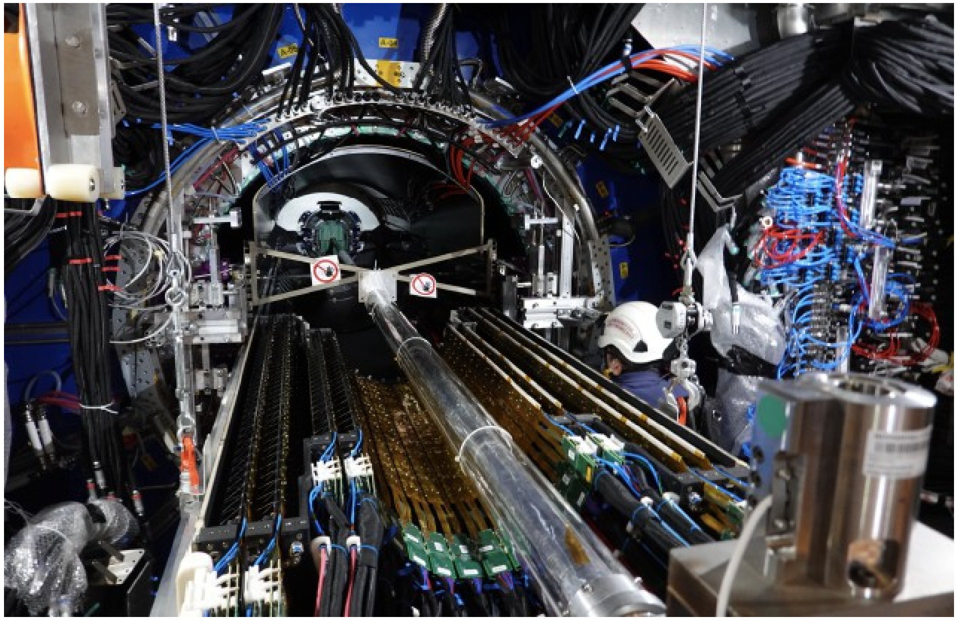


now PDG standard

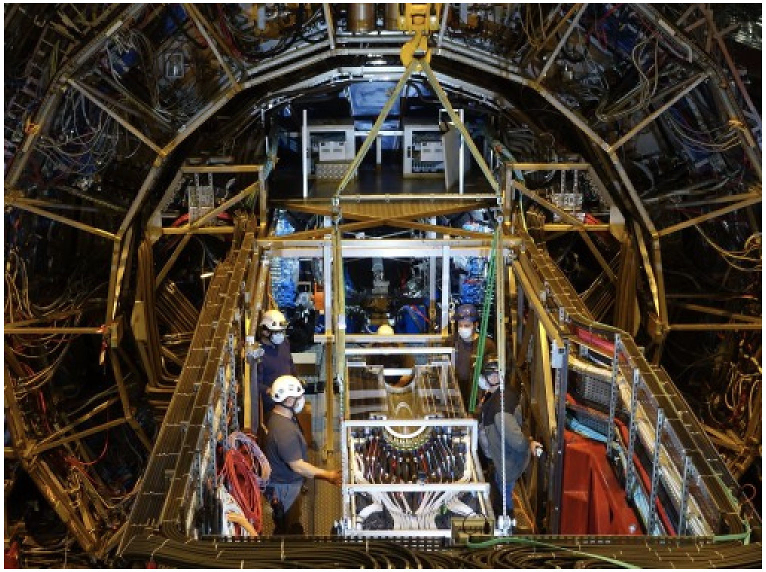
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001, Fig. 34.15







installation of upgraded detectors
TPC and (new) ITS
March 25, 2021



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 converted ('hadronized') into hadrons which we measure in our detectors

main aim: establish the existence and position of the phase boundary

an important milestone also for understanding the evolution of the early universe

statistical hadronization model of particle production

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:

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

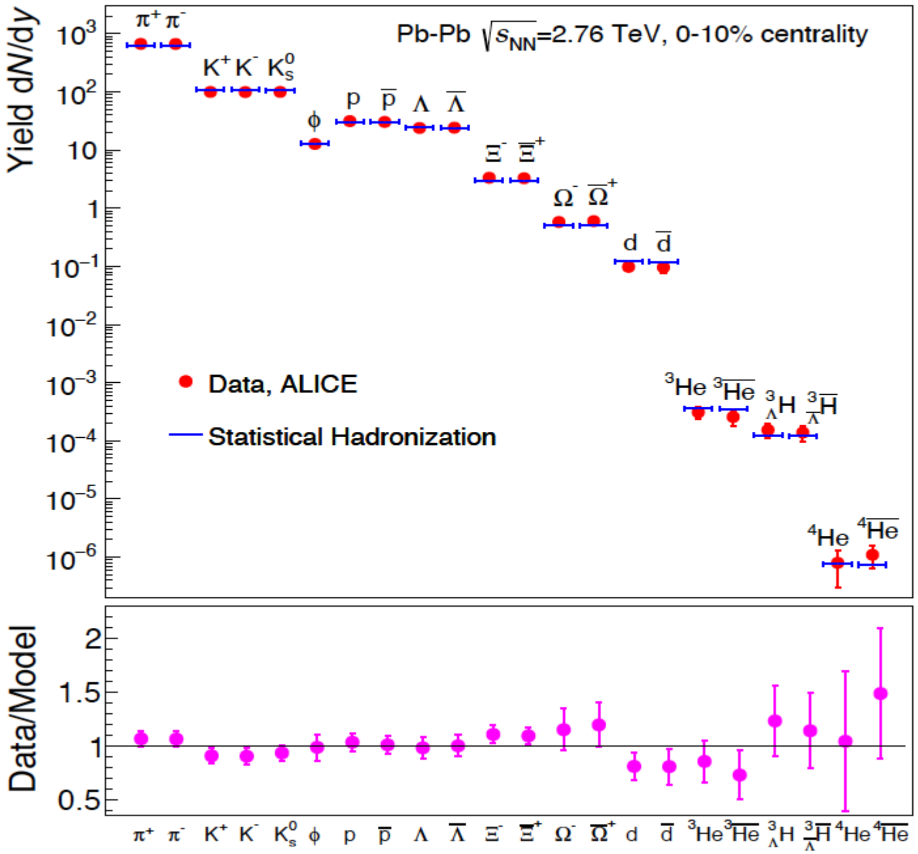
from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

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

statistical hadronization of (u,d,s) hadrons

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321



Best fit:

$T_{CF} = 156.6 \pm 1.7$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V_{\Delta y=1} = 4175 \pm 380$ fm^3

$\chi^2/N_{df} = 16.7/19$

S-matrix treatment of interactions (non-strange sect.)

"proton puzzle" solved

PLB 792 (2019) 304

data: ALICE coll.,
Nucl. Phys. A971 (2018) 1

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

- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

similar results at lower energy, each new energy yields a pair of (T, μ_B) values

connection to QCD (QGP) phase diagram?

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

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

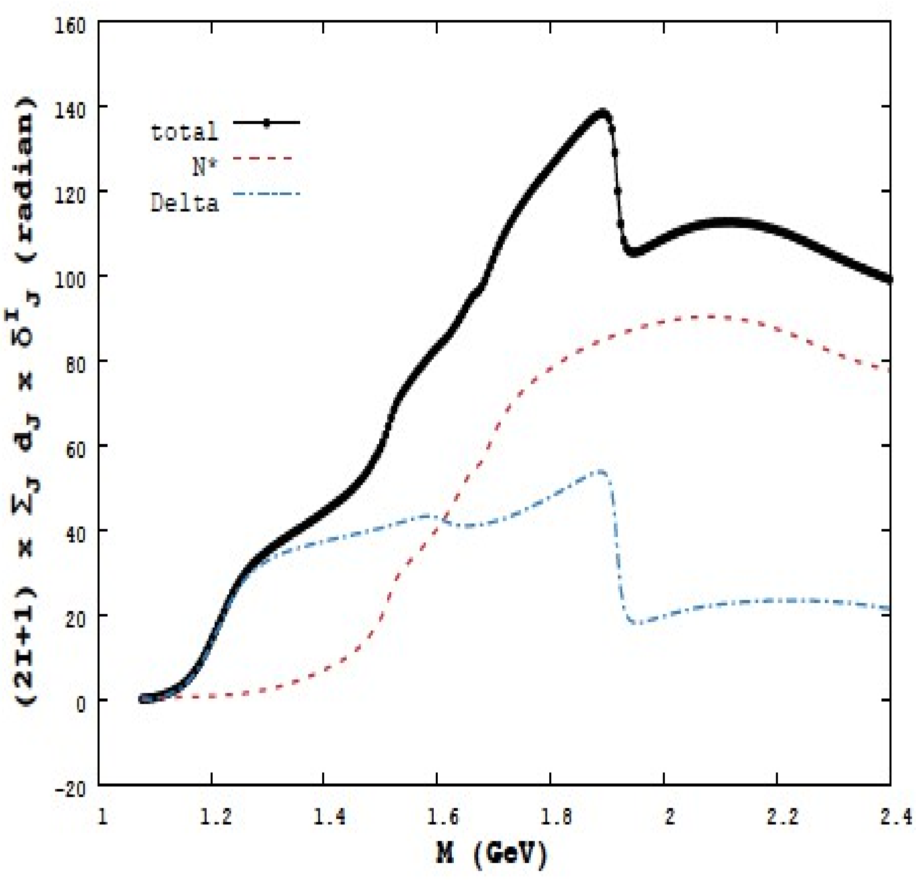
A. Andronic, pbm, B. Friman, P.M. Lo, K. Redlich, J. Stachel, arXiv:1808.03102, Phys.Lett.B792 (2019)304

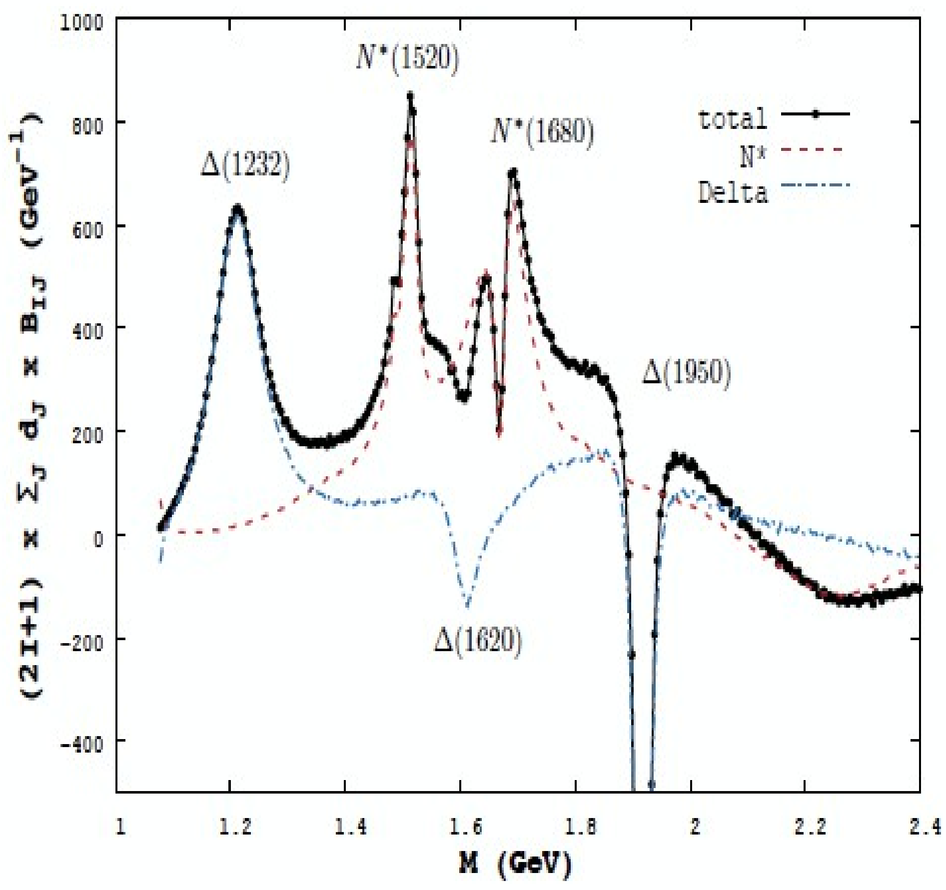
need to know derivatives of phase shifts with respect to invariant mass

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

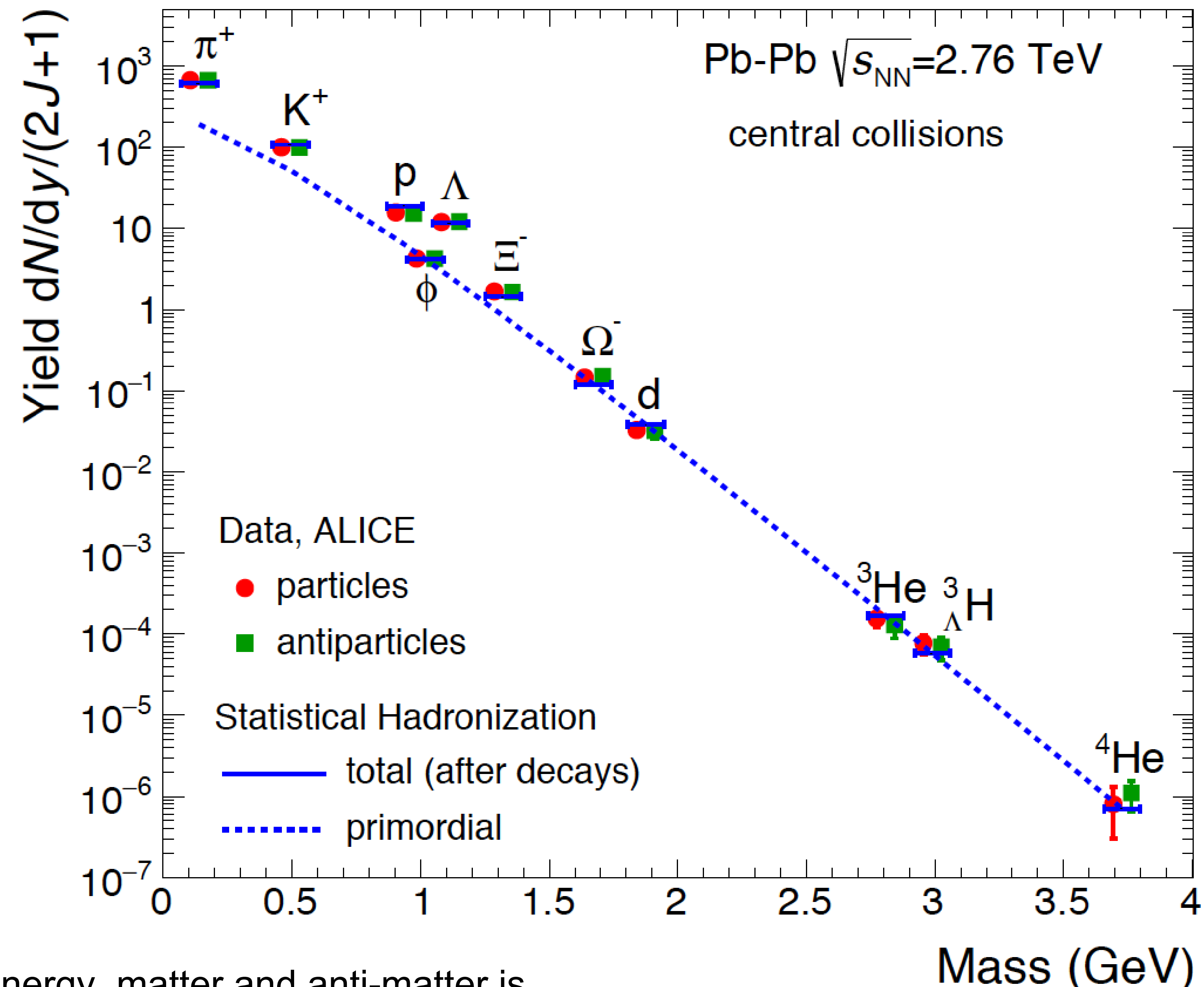
pion nucleon phase shifts and thermal weights for N* and Δ resonances

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



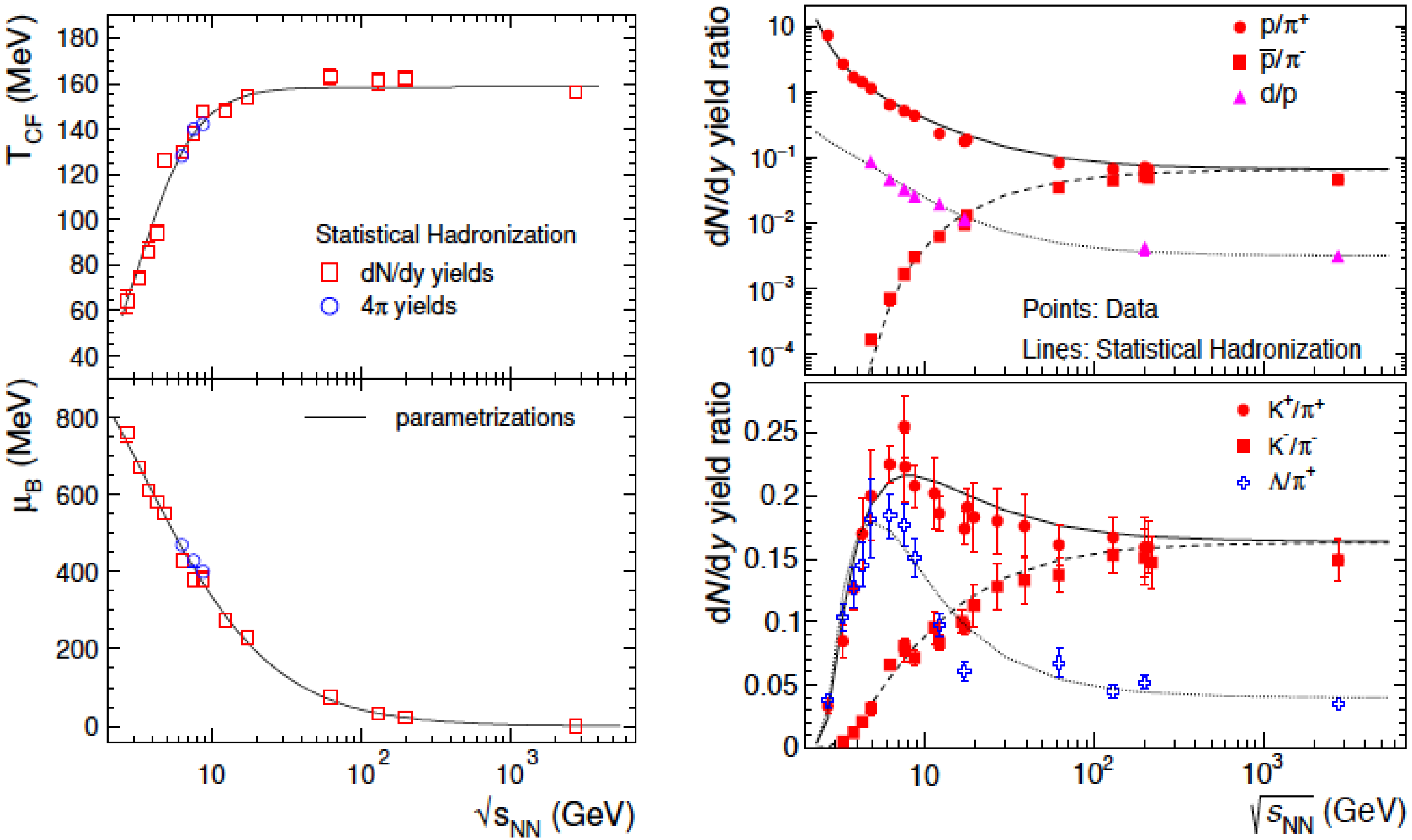


at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



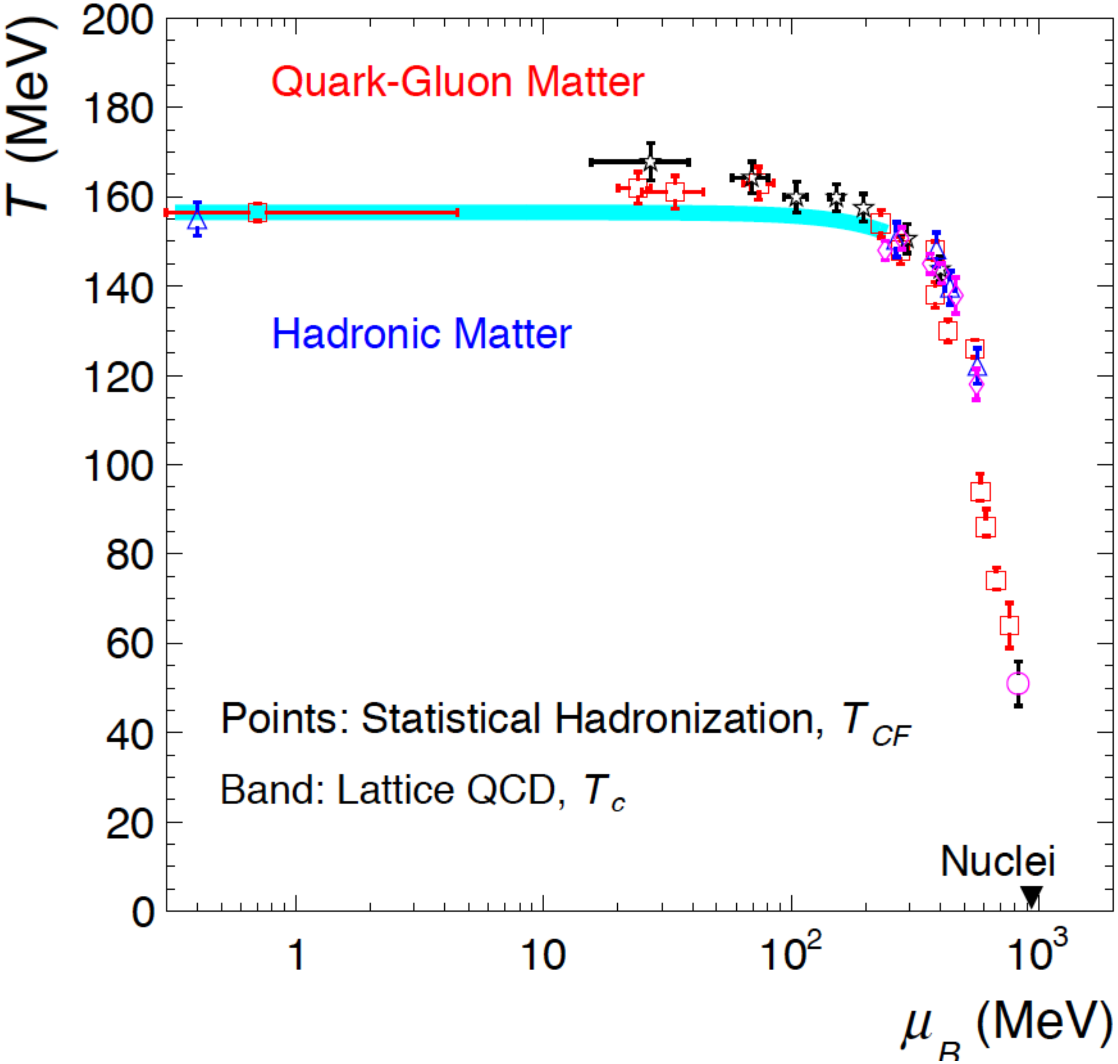
at LHC energy, matter and anti-matter is
produced with equal yields

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

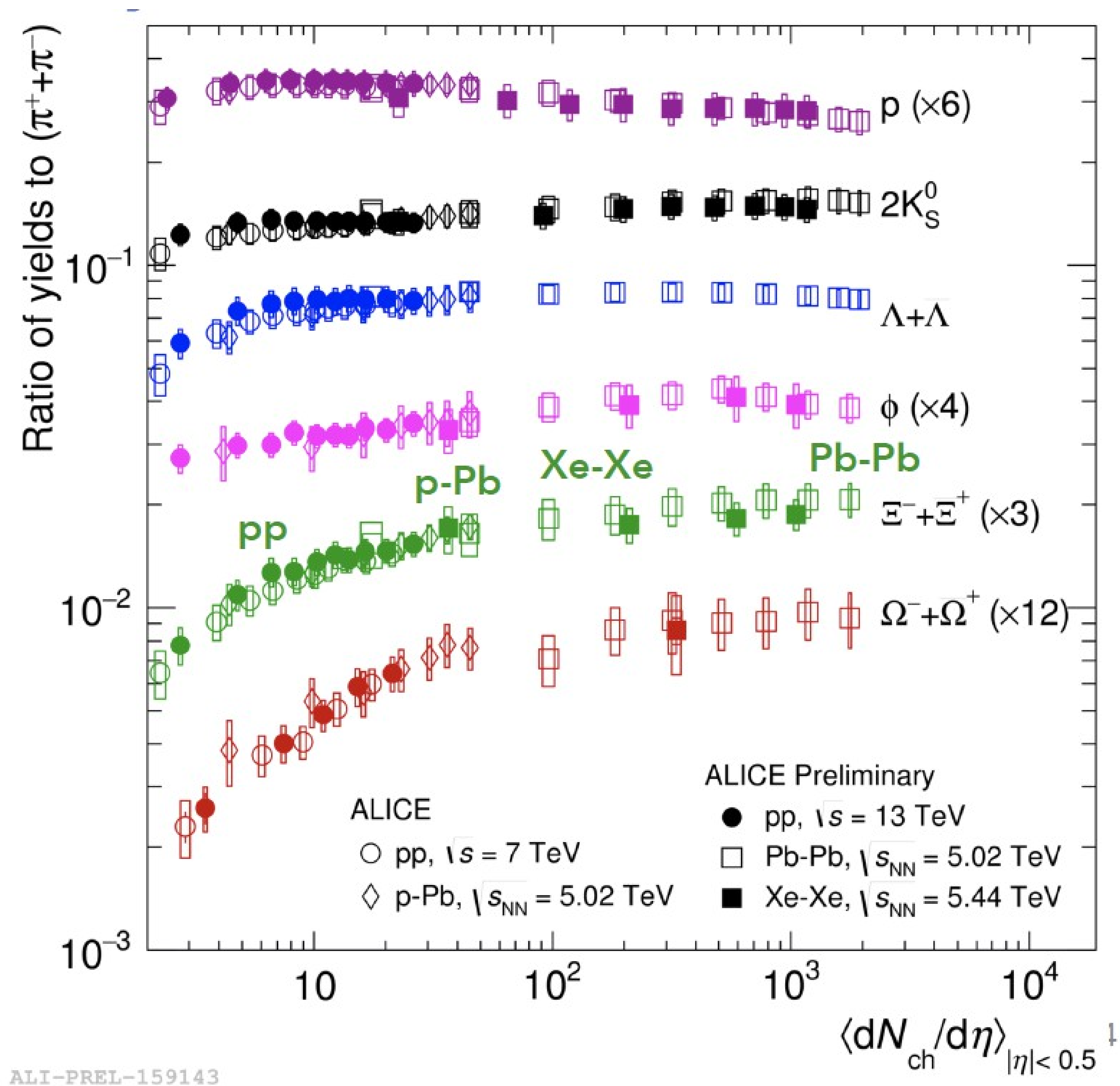
the QGP phase diagram, LQCD, and hadron production data



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

cross over transition at μ_B = 0 MeV

from pp to Pb-Pb collisions: smooth evolution with system size



universal hadronization can be described with few parameters in addition to T and μ_B

transition from canonical to grand-canonical thermodynamics

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-

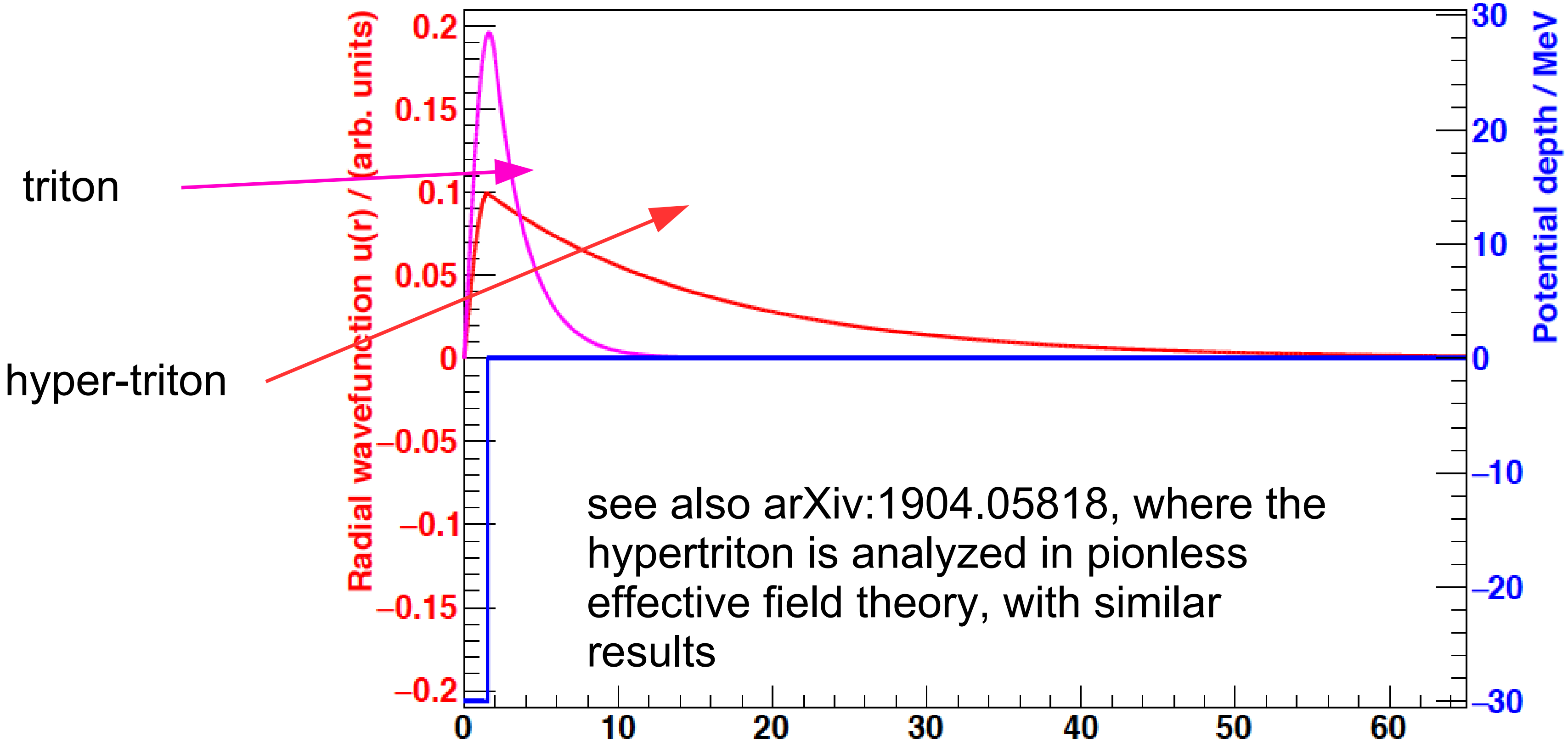
rms radius = (4 B.E. M_{red})$^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

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.)

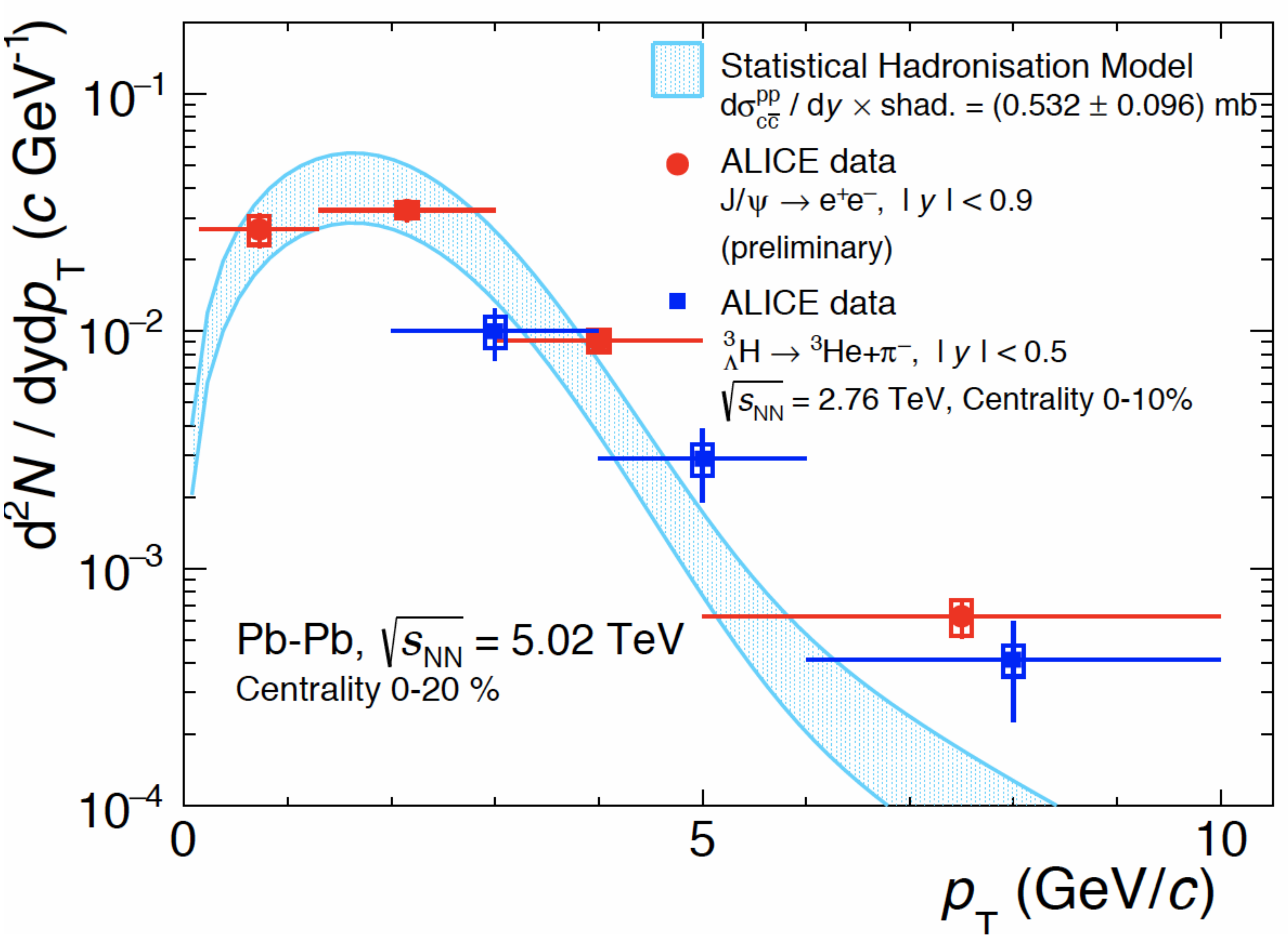
wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017



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.

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

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 2030 for X,Y,Z and penta-quark states

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

charmonia, open charm states, exotica, and deconfinement

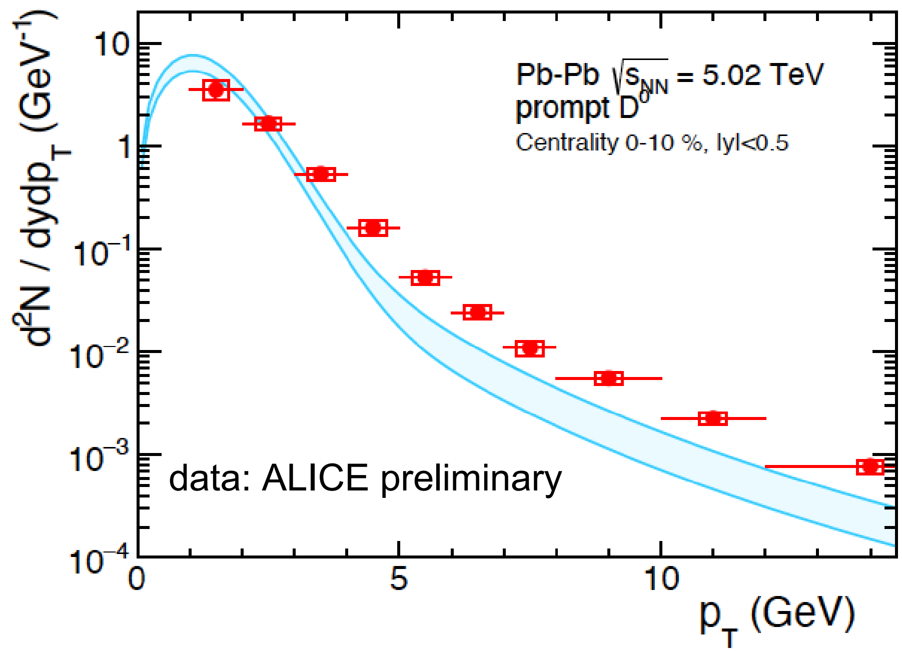
statistical hadronization for hidden and open charm

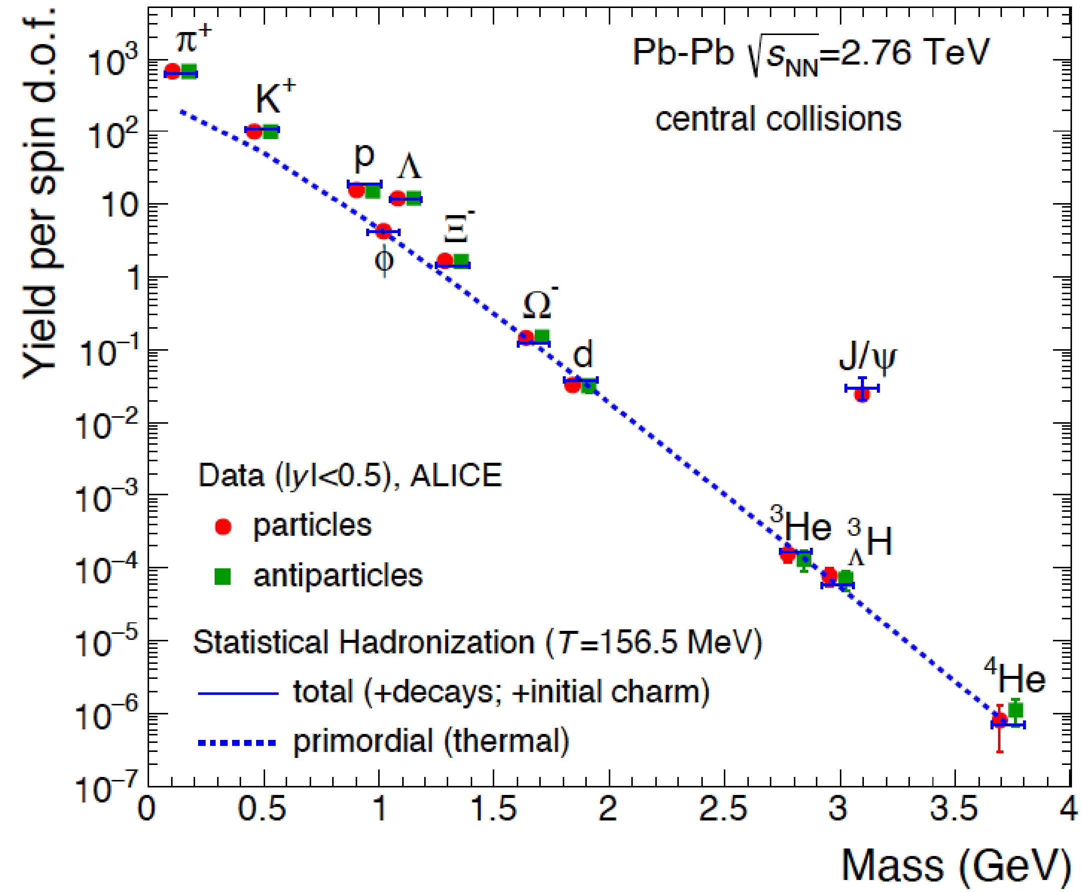
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0



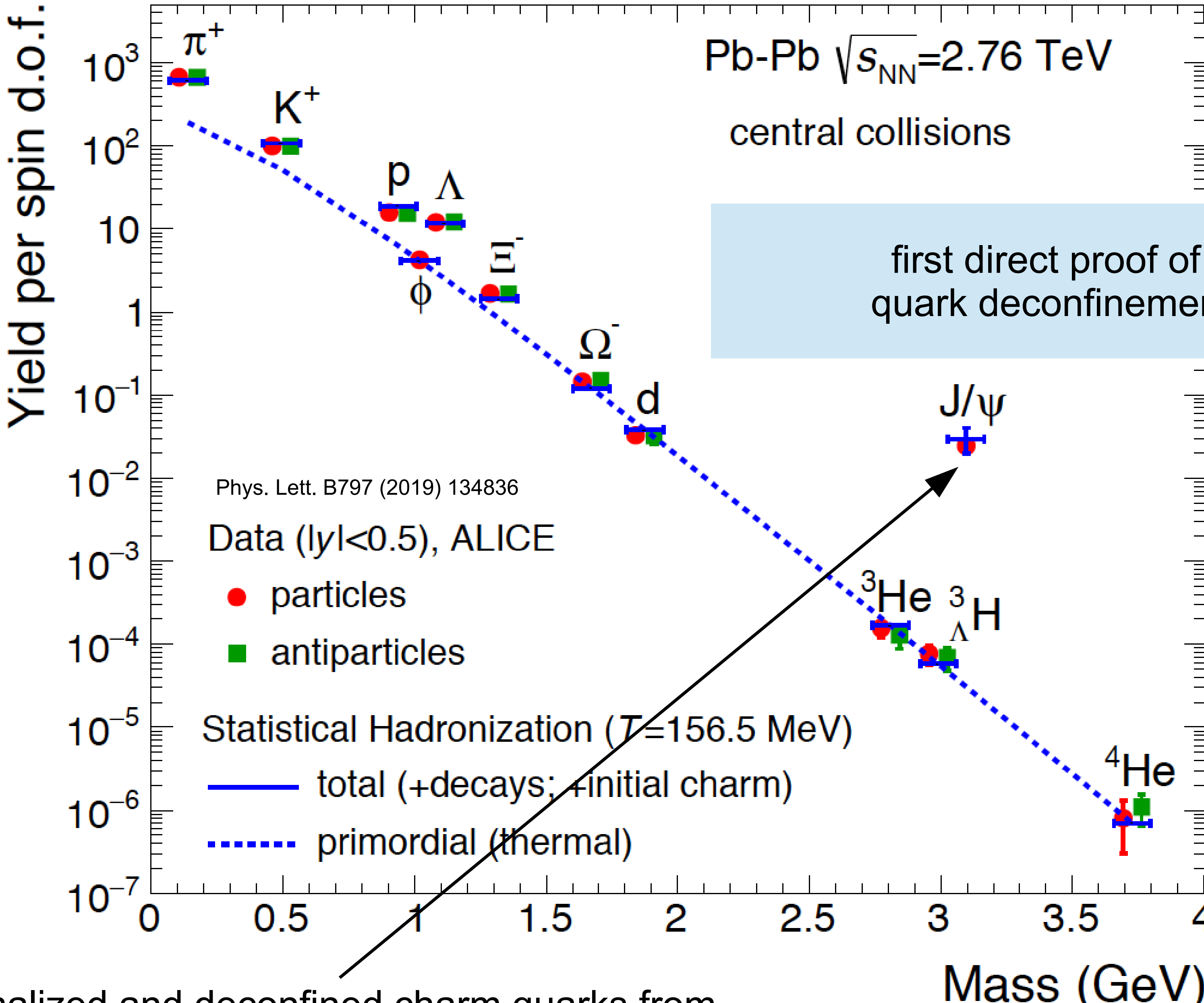


Andronic, pbm, Koehler, Redlich, Stachel PLB 792 (2019) 304 and Andronic, pbm, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, in preparation

quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons,
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

enhancement is defined relative to purely thermal value, not to pp yield

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

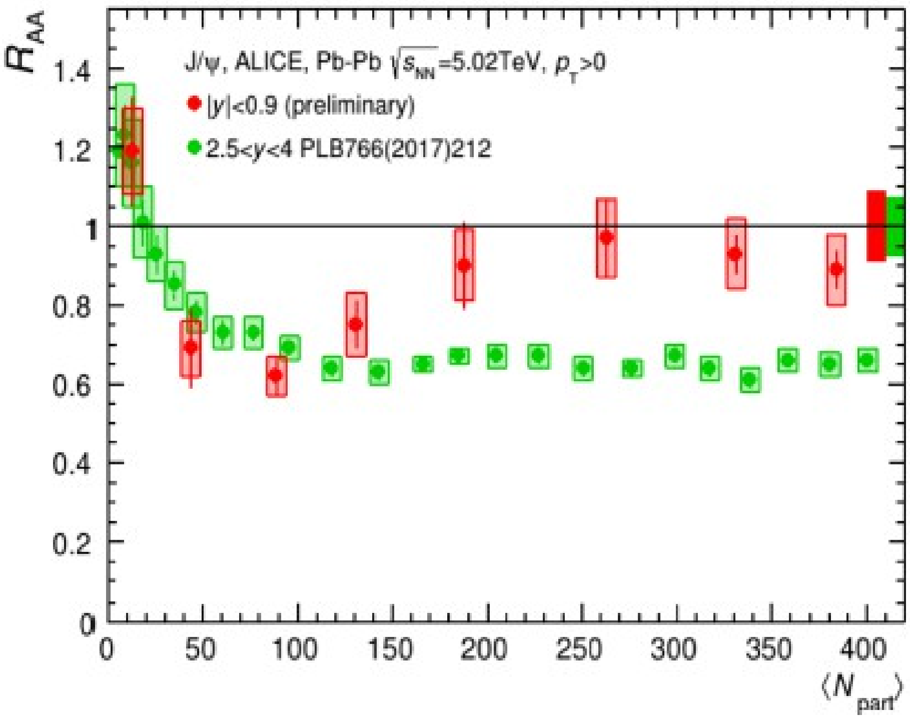


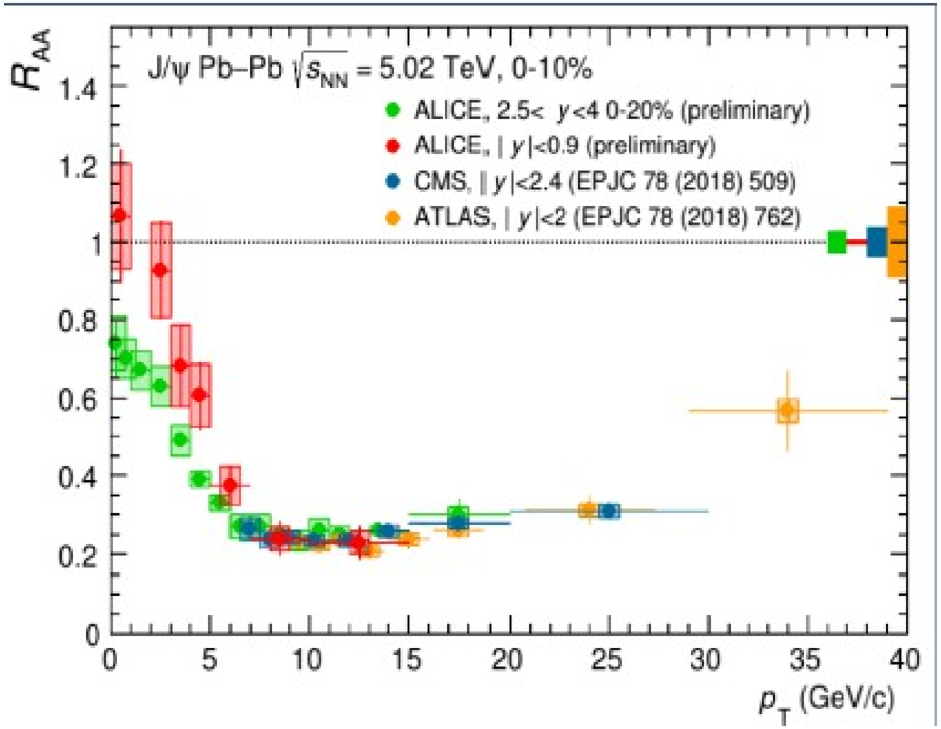
first direct proof of
quark deconfinement

with thermalized and deconfined charm quarks from
initial hard scattering

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

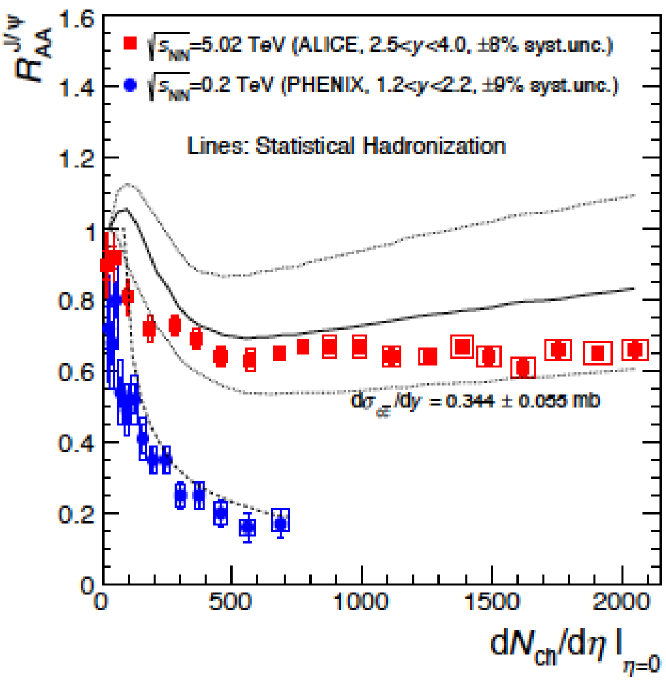
strong enhancement at low transverse momentum

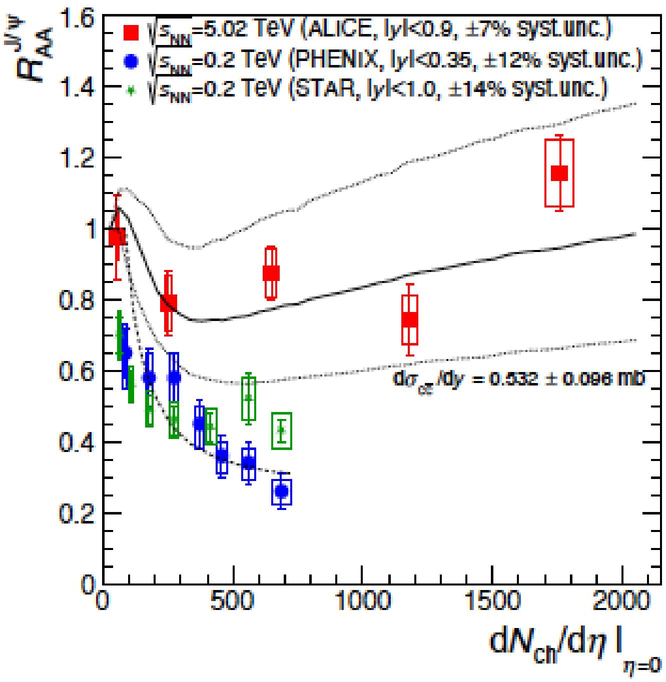




RHIC and LHC data compared to SHM predictions

note the energy dependence of the nuclear modification factor R_{AA}





the band with the model predictions at LHC energy is due to the uncertainties in the pp open charm cross section and the necessary shadowing corrections

predictions for charmed mesons, baryons, and exotic states with open or hidden charm in Pb-Pb collisions as function of p_T, y and centrality

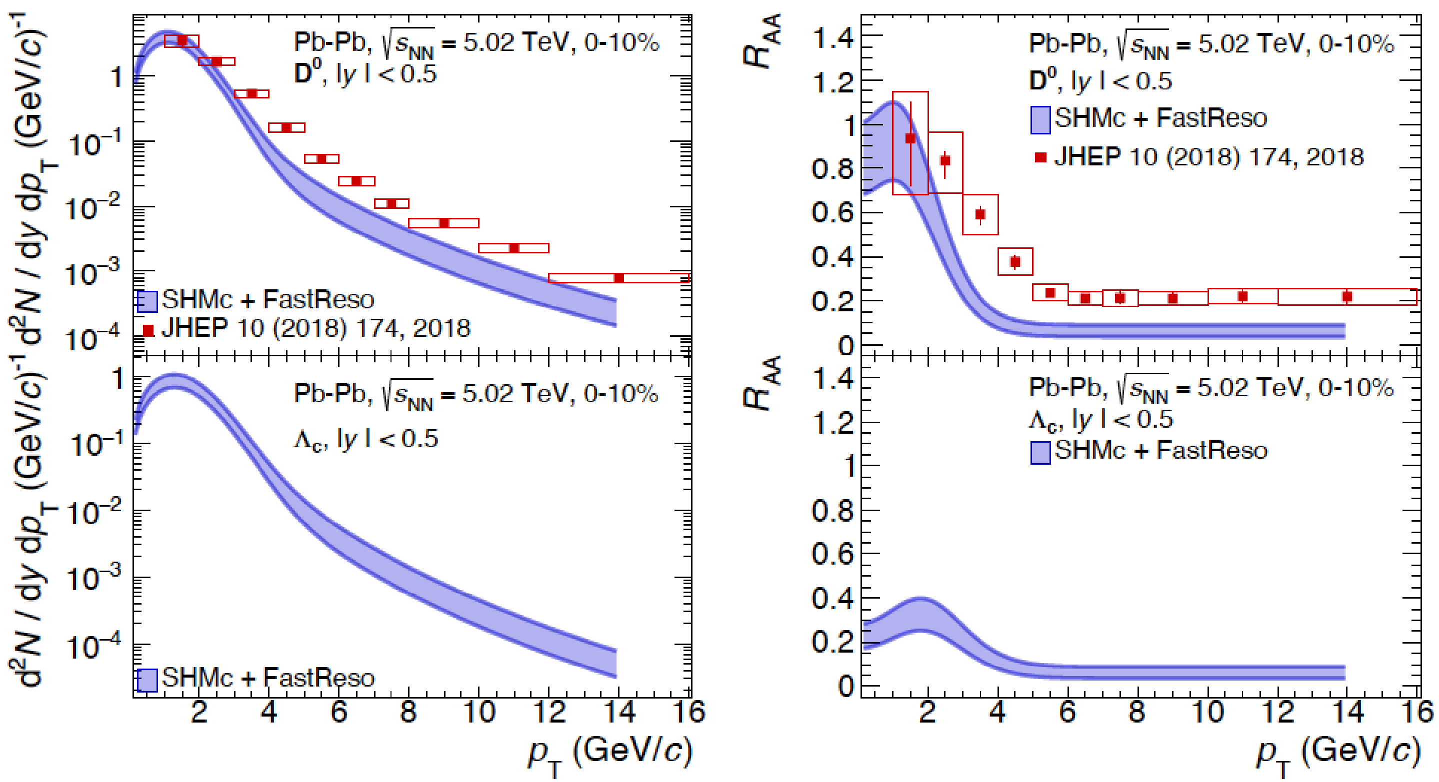
Andronic, pbm, Koehler, Redlich, Stachel, PLB 792 (2019) 304

Andronic, pbm, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, in preparation

the only new input is the (hopefully soon measured) open charm cross section
in Pb-Pb collisions
for now, use pp and pPb data from ALICE and LHCb
rapidity dependence is important

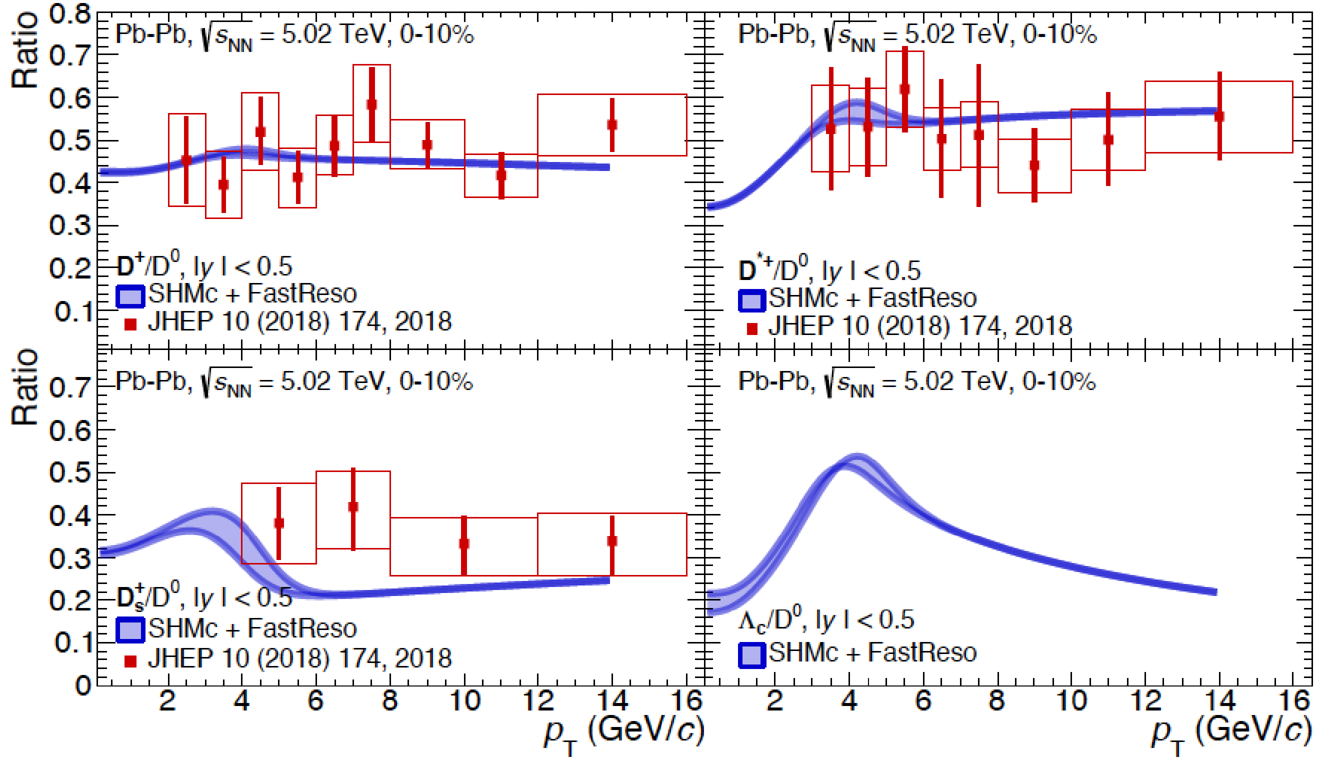
no free parameter to adjust

spectra and R_{AA} of D^0 mesons and Λ_c baryons



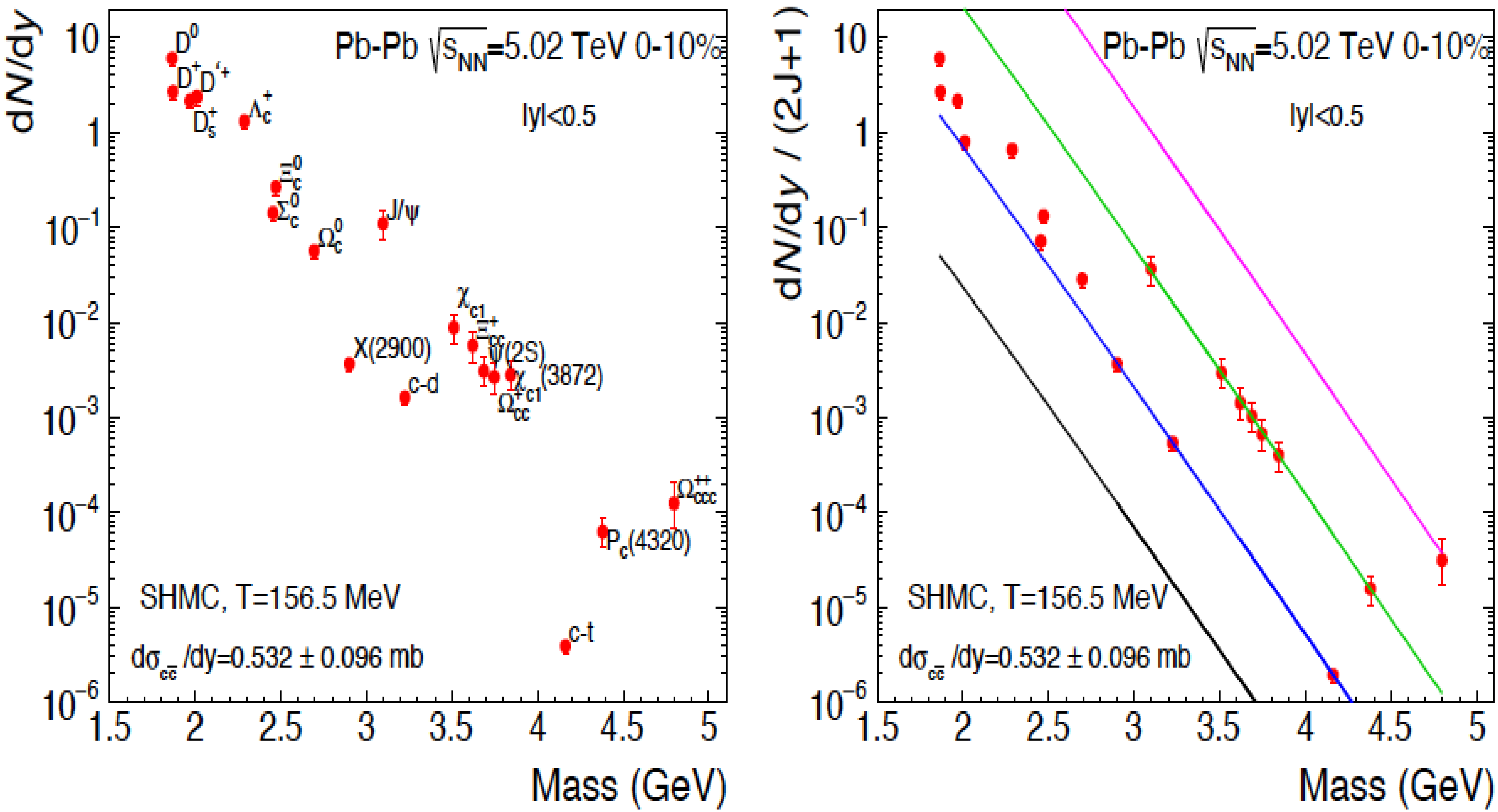
Λ_c data exist but are not (yet) cleared by ALICE

ratios to D^0



excellent agreement considering that there are NO free parameters

the multi-charm hierarchy



example: X(3872)

X(3872)

- 2003 -

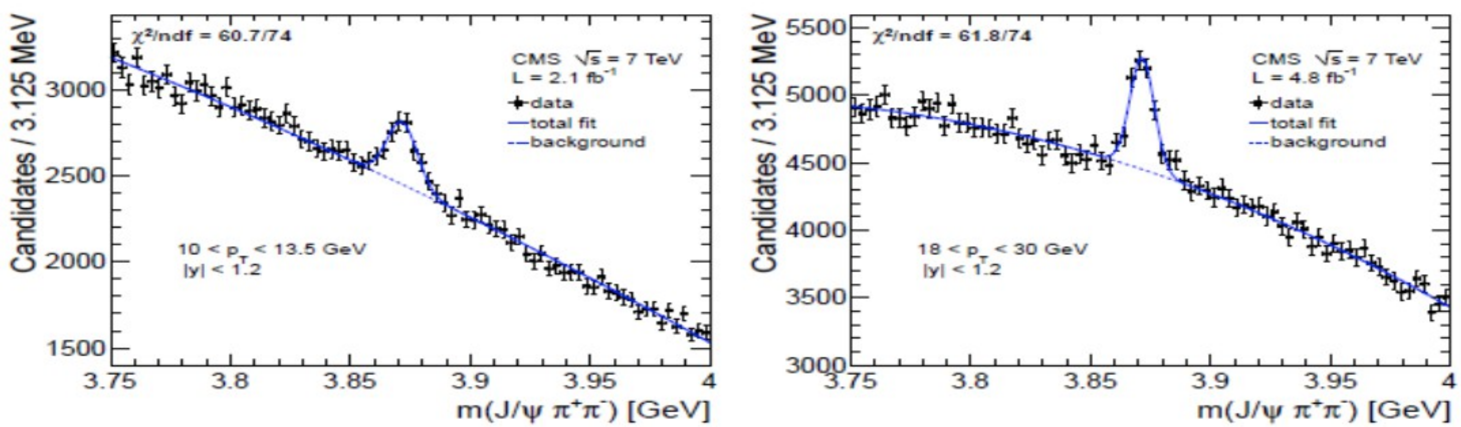
BELLE

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

$$M = 3872.0 \pm 0.6 \pm 0.5\,\mathrm{MeV}$$

- 2013 -

CMS



PDG particle data group

$X(3872)$

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

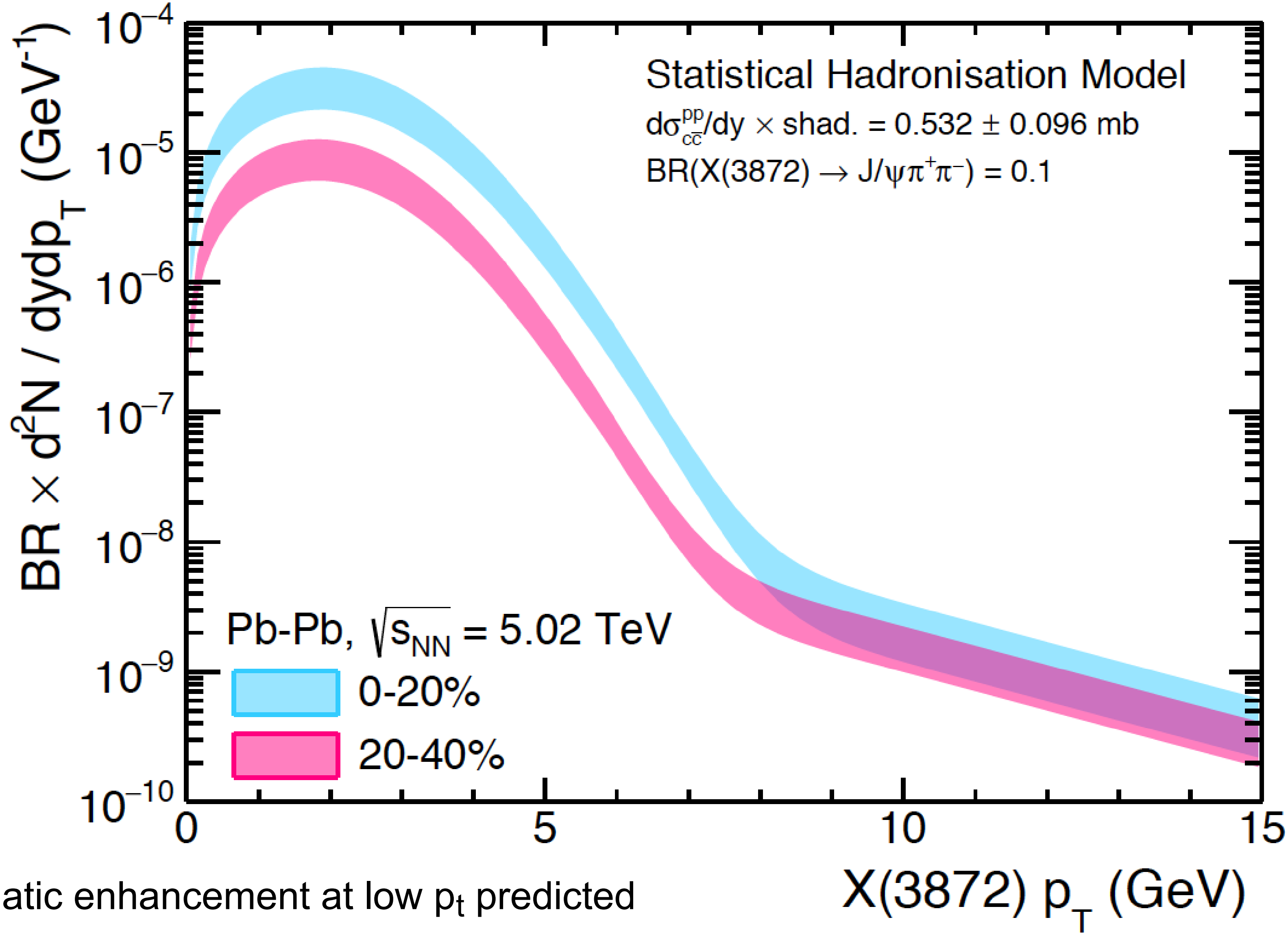
Mass $m = 3871.69 \pm 0.17$ MeV

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

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

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

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



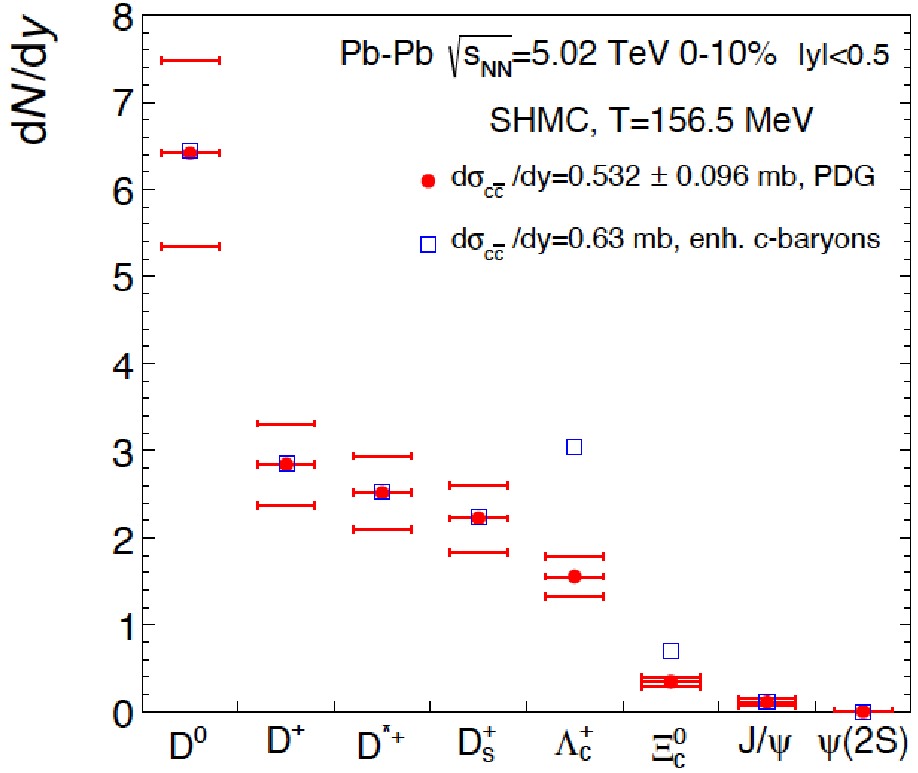
note: dramatic enhancement at low p_t predicted

numerical values for all charm hadrons available selected examples below

Particle	dN/dy core (SHMc)	dN/dy corona	dN/dy total
D^0	6.02 ± 1.07	0.396 ± 0.032	6.42 ± 1.07
D^+	2.67 ± 0.47	0.175 ± 0.026	2.84 ± 0.47
D^{*+}	2.36 ± 0.42	$0.160\ {+0.048}{-0.022}$	2.52 ± 0.42
D_s^+	2.15 ± 0.38	$0.074\ {+0.024}{-0.015}$	2.22 ± 0.38
Λ_c^+	1.30 ± 0.23	0.250 ± 0.028	1.55 ± 0.23
Ξ_c^0	0.263 ± 0.047	0.086 ± 0.035	0.349 ± 0.058
J/ψ	$0.108\ {+0.041}{-0.035}$	$(5.08 \pm 0.37) \cdot 10^{-3}$	$0.113\ {+0.041}{-0.035}$
$\psi(2S)$	$(3.04\ {+1.2}{-1.0}) \cdot 10^{-3}$	$(7.61 \pm 0.55) \cdot 10^{-4}$	$(3.80\ {+1.2}{-1.0}) \cdot 10^{-3}$
D^0	0.857 ± 0.153	0.207 ± 0.017	1.06 ± 0.154
D^+	0.379 ± 0.068	0.092 ± 0.014	0.471 ± 0.069
D^{*+}	0.335 ± 0.060	$0.084\ {+0.025}{-0.011}$	$0.419\ {+0.065}{-0.061}$
D_s^+	0.306 ± 0.055	$0.039\ {+0.013}{-0.008}$	0.344 ± 0.056
Λ_c^+	0.185 ± 0.033	0.131 ± 0.015	0.316 ± 0.036
Ξ_c^0	0.038 ± 0.007	0.045 ± 0.018	0.082 ± 0.020
J/ψ	$(1.12\ {+0.37}{-0.32}) \cdot 10^{-2}$	$(2.65 \pm 0.19) \cdot 10^{-3}$	$(1.39\ {+0.37}{-0.32}) \cdot 10^{-2}$
$\psi(2S)$	$(3.16\ {+1.04}{-0.89}) \cdot 10^{-4}$	$(3.98 \pm 0.29) \cdot 10^{-4}$	$(7.14\ {+1.08}{-0.94}) \cdot 10^{-4}$

TABLE I. Summary of the calculations of yields at midrapidity for open charm and charmonia in Pb–Pb at 5.02 TeV, 0-10% (upper part) and 30-50% (lower part) centralities. For the corona, we used as inputs the production cross sections $d\sigma/dy$ as measured by ALICE in pp collisions and T_{AA}^{corona}=0.90 and 0.47 mb^{-1}, respectively (corresponding to corona assumed for $\rho < 0.1\rho_0$).

rapidity distributions with modified charm resonance spectrum
significant enhancement of charm baryons assumed



summary – charm production

- statistical hadronization works quantitatively for hadrons with charm quarks
- charm quarks are not thermally produced but in initial hard collisions and subsequently thermalize in the hot and dense fireball
- predicted charmonium enhancement at low p_T established at LHC energies
- charmonium enhancement implies that charm quarks are deconfined over distances > 5 fm

- the study of open charm hadron production has just begun
- predict dN/dy for hierarchy of multi-charm states, very large (> 5000) enhancement expected
- precision study of such hadrons → further insight into deconfinement and hadronization

outlook (1)

when statistics and precision of open charm cross section improves
one can look into hadronization of multi-charm states,
correlation width in rapidity

coupling to hydro code determines shape of p_T spectra and flow of
charm hadrons

beauty can be treated in similar way but:
thermalization of b quarks?

it would be interesting to extend the measurements to
charm/beauty hadrons in jets

can one measure net charm correlations and higher moments?

**we look forward to testing the predictions from
SHMc with Run3/Run4 and, of course,
ALICE3 data**

outlook (2)

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 >50

focus on rare objects, exotic quarkonia, double and triple charm hadrons to address a number of fundamental questions and issues such as:

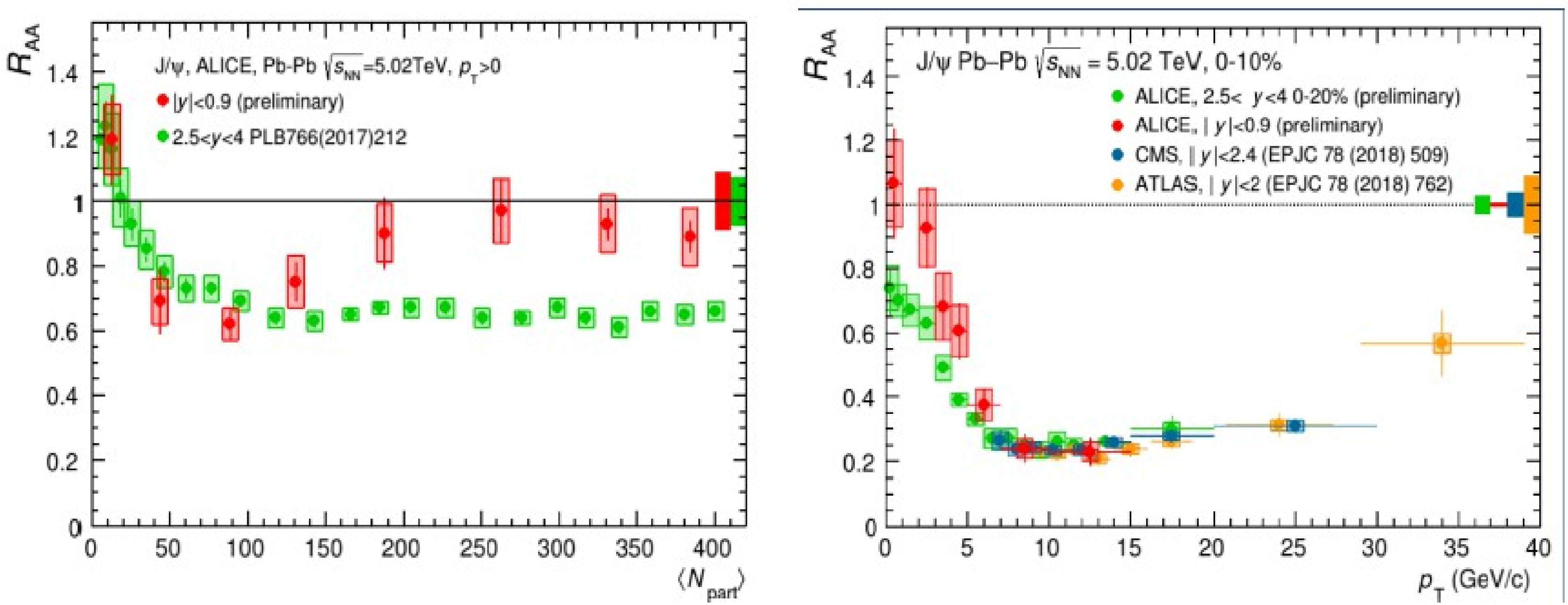
- what is the deconfinement radius for charm quarks
- are there colorless bound states in a deconfined medium?

- 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?

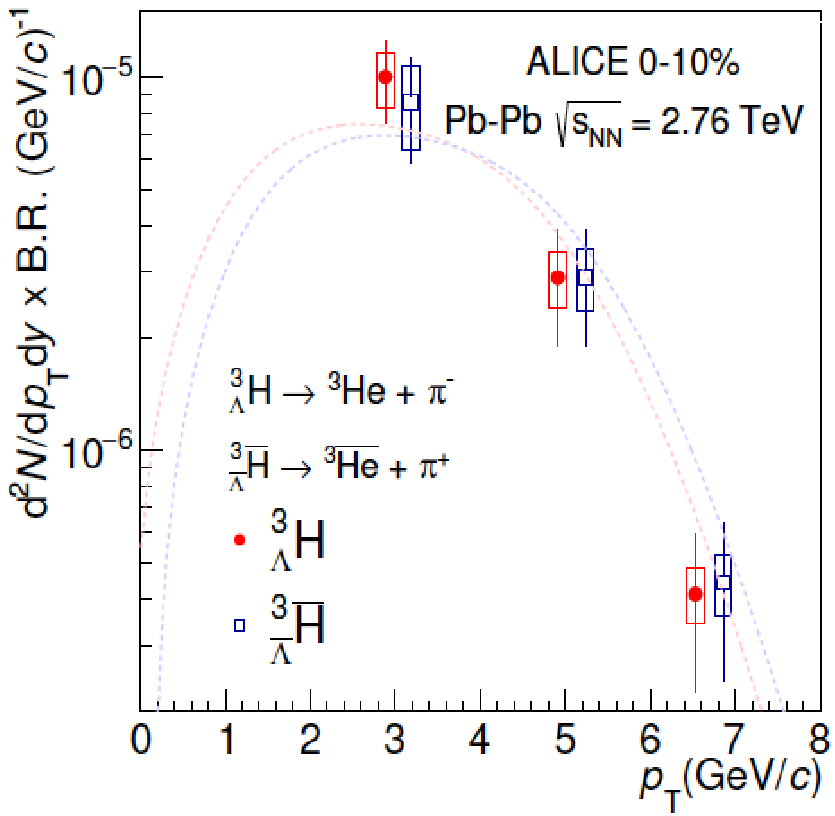
deciphering QCD in the strongly coupled regime

additional slides

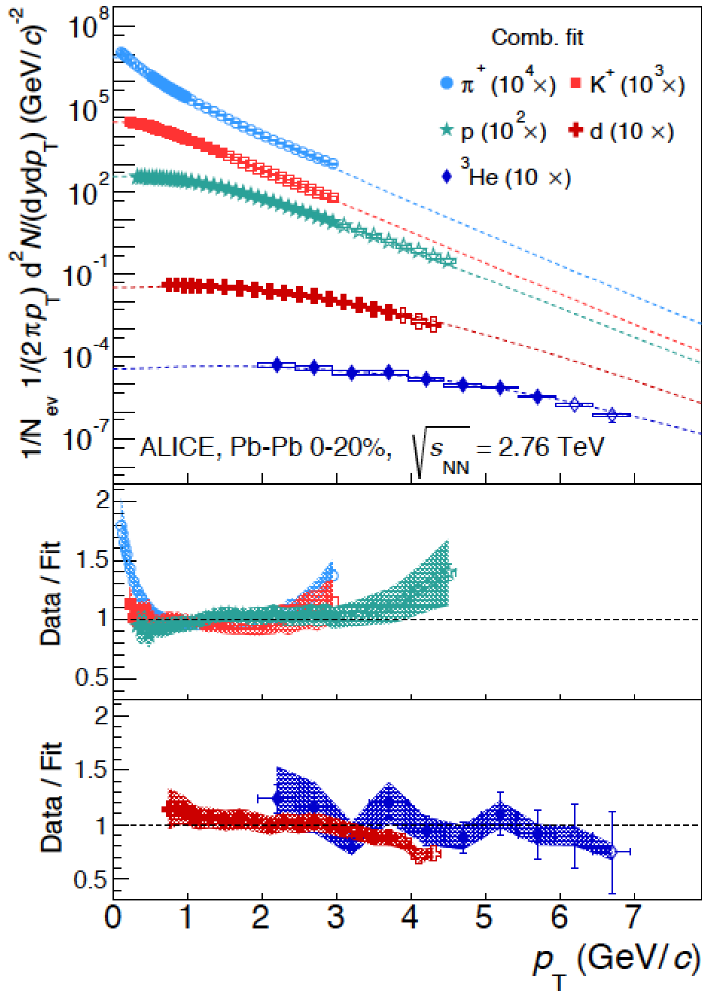


J/ψ, ALICE, Pb-Pb √sNN=5.02TeV, pT>0
|y|<0.9 (preliminary)
2.5<y<4 PLB766(2017)212
RAA
⟨Npart⟩
J/ψ Pb–Pb √sNN = 5.02 TeV, 0-10%
ALICE, 2.5< y<4 0-20% (preliminary)
ALICE, | y|<0.9 (preliminary)
CMS, | y|<2.4 (EPJC 78 (2018) 509)
ATLAS, | y|<2 (EPJC 78 (2018) 762)
pT (GeV/c)

even hyper-triton flows with same common fluid velocity



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

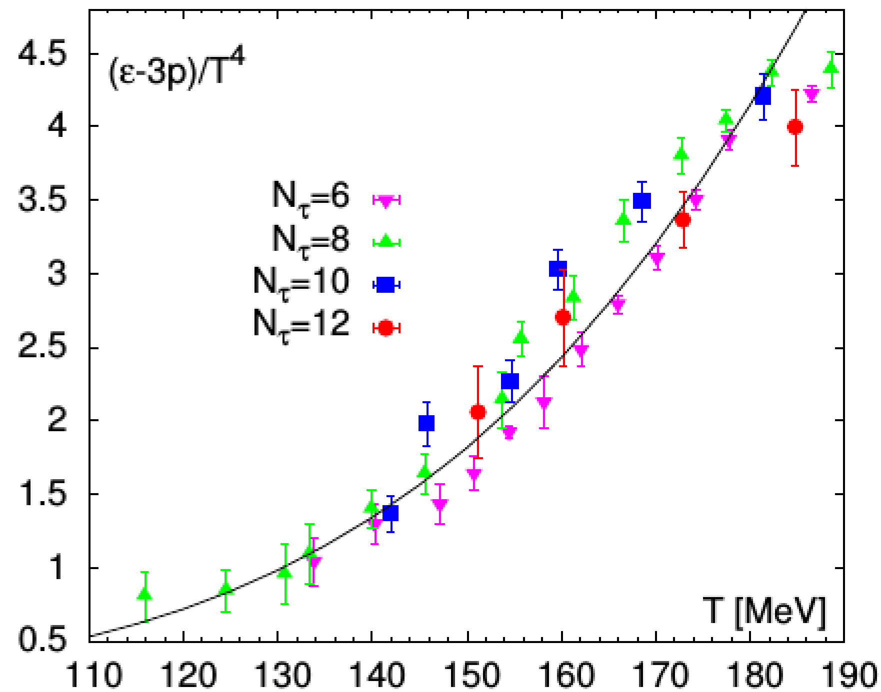
for the pressure we get:

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

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

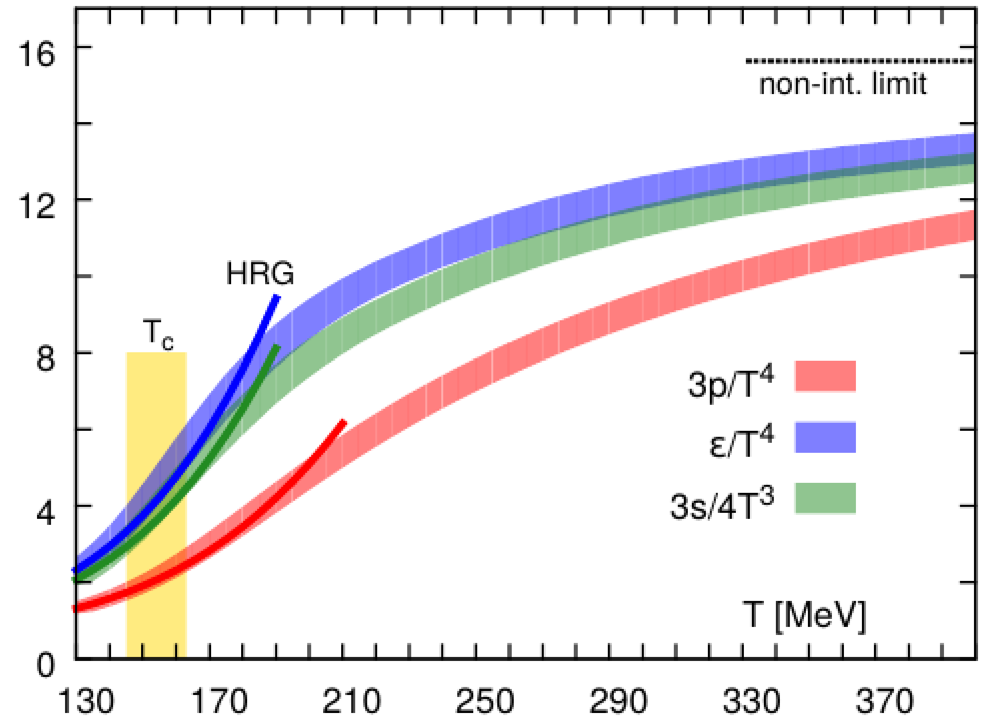


duality between hadrons and quarks/gluons (I)

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

time line and matter in the early universe

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

inside the TPC field cage, 2004

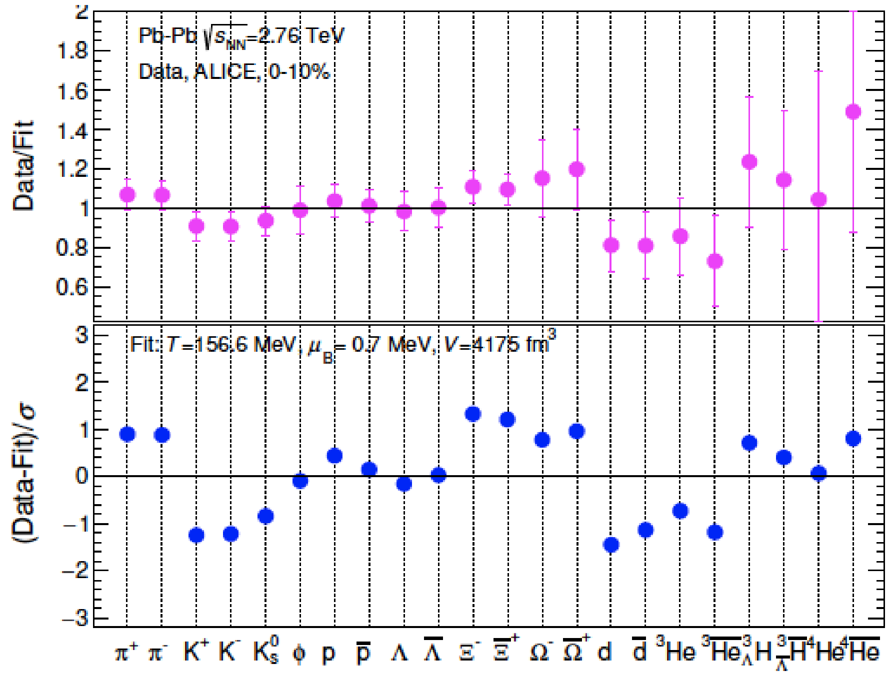
The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events
Nucl.Instrum.Meth. A622 (2010) 316-367

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

hadron physics to the rescue

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 resonance decays and inelastic channels are taken into account with normalization to LQCD susceptibilities

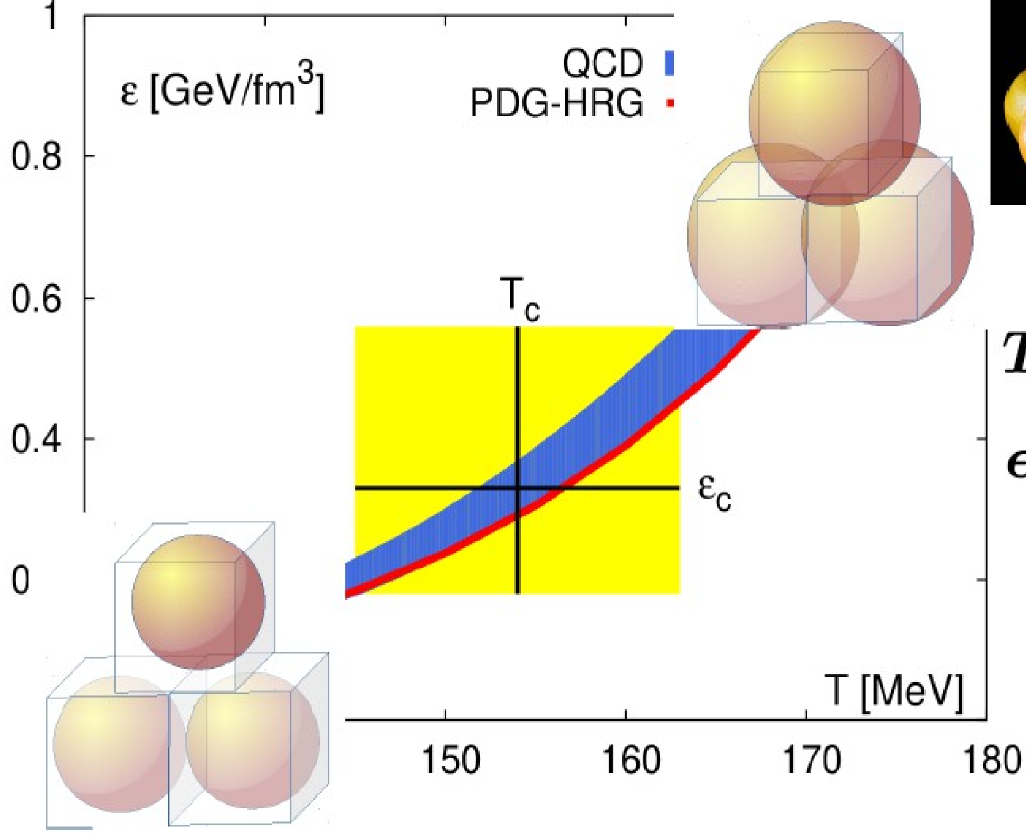


$$\chi^2 = 19.7 \text{ per } 19 \text{ dof}$$

very good fit!

Crossover transition parameters

PDG: Particle Data Group hadron spectrum



dense packing of spheres (DPS)

$$\epsilon^{\mathrm{DPS}} = 0.74\epsilon^{\mathrm{nucleon}}$$
$$\simeq 0.33\ \mathrm{GeV/fm^3}$$
$$(R_p \simeq 0.8\mathrm{fm})$$

overlapping hadrons = QGP ??

$$T_{pc} = (156.5 \pm 1.5)\ \mathrm{MeV}$$
$$\epsilon_{pc} = (0.42 \pm 0.06)\mathrm{GeV/fm^3}$$

compare with:

$$\epsilon^{\mathrm{nucl.\ mat.}} \simeq 150\ \mathrm{MeV/fm^3}$$
$$\epsilon^{\mathrm{nucleon}} \simeq 450\ \mathrm{MeV/fm^3}$$

A. Bazavov et al. (hotQCD) ,
Phys. Rev. D90 (2014) 094503

slide courtesy Frithjof Karsch

statistical hadronization model for charm (SHMC) including canonical thermodynamics

selected early references:

1. P. Braun-Munzinger, J. Stachel: Phys. Lett. B 490 (2000) 196-202, nucl-th/0007059 — the beginning
2. M. Gorenstein, A.P. Kostyuk, H. Stoecker, W. Greiner, Phys.Lett.B 524 (2002) 265-272, hep-ph/0104071 — SPS/RHIC
3. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B 571 (2003) 36-44, nucl-th/0303036 — open/hidden charm
4. F. Becattini, Phys.Rev.Lett. 95 (2005) 022301, hep-ph/0503239 — multi-charm baryons
5. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl.Phys.A 789 (2007) 334-356, nucl-th/0611023 — detailing the model
6. P. Braun-Munzinger, J. Stachel: Nature 448 (2007) 302-309 — LHC predictions
7. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys.Lett.B 652 (2007) 259-261, nucl-th/0701079 — rapidity dependence
8. P. Braun-Munzinger, J. Stachel: Landolt-Bornstein 23 (2010) 424, 0901.2500 — deconfined c quarks

the charm balance eq. developed in 1., 2., and 3. determines the fugacity g_c

$$N_{c\bar{c}} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

obtained from measured open charm cross section

N^{th}_{oc}: # of thermal open charm hadrons

$$N_{n_c}(i) = g_c^{n_c} N_{n_c}(i)^{th} \frac{I_{n_c}(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})}$$

equation for yields of charm hadron i with n_c charm quarks

the mechanism for SHM with charm (SHMc) in more detail

[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 ($m_{c\bar{c}} \gg \Lambda_{\text{QCD}}$)
- 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 ($T_{\text{CF}}, \mu_b \rightarrow n_X^{\text{th}}$)

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

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

centrality dependence of charm fugacity g_c at LHC energy