the QCD phase structure

recent experimental results and future prospects

- introduction
- (u,d,s) hadrons in the large volume limit – Pb-Pb collisions
- a brief disgression to small systems
- some remarks on net baryon number fluctuations and chemical parameters
- extension to hadrons with open and hidden charm
  - brief historical comments
  - charm and beauty in e+e-
  - open charm in Pb-Pb – the multi-charm hierarchy and deconfinement
- outlook

pbm

RHIC-BES seminar 2021

Zoom presentation

Tuesday, Jan. 19, 2021

ISOQUANT
SFB1225

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

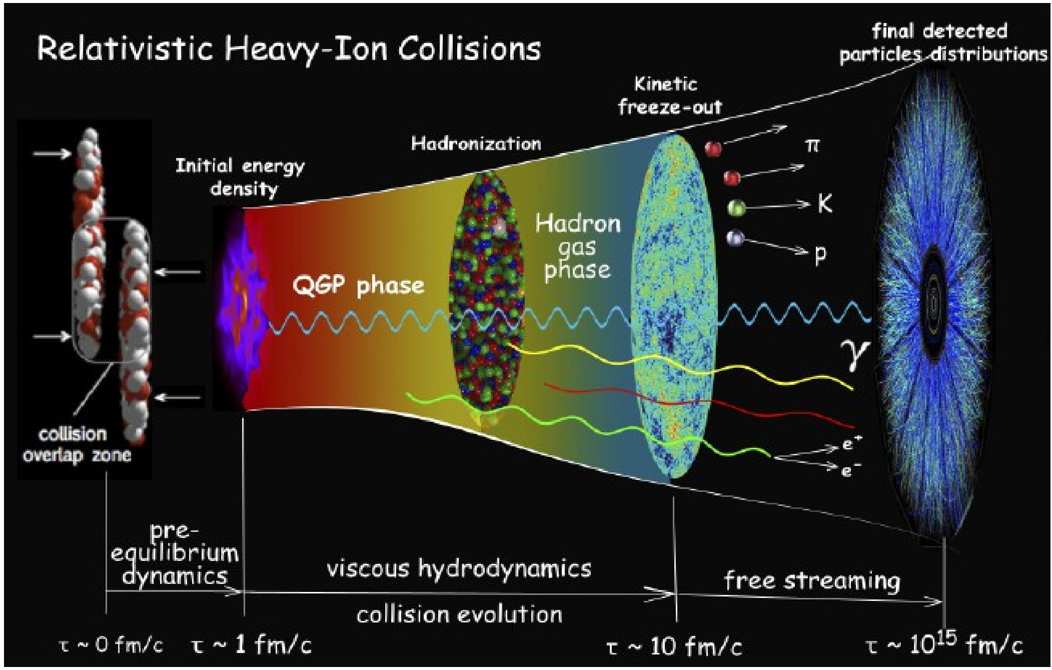
EMMI

GSI

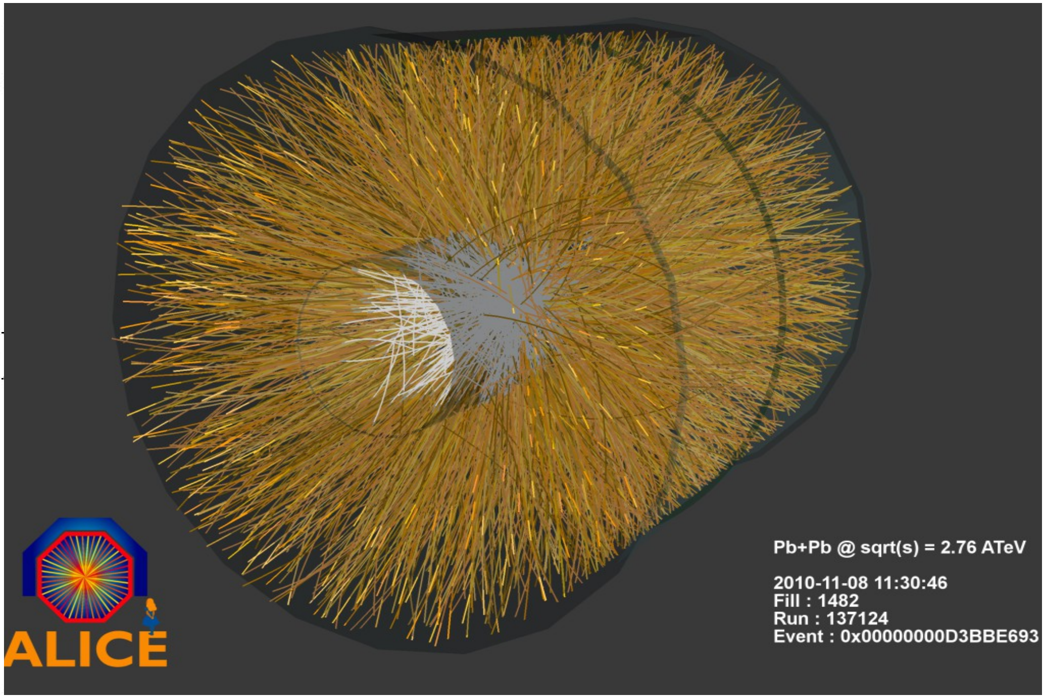
time line and matter in the early universe

- 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: $\overline{q}qg\overline{l}l\gamma ZW^{\pm}H$, 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

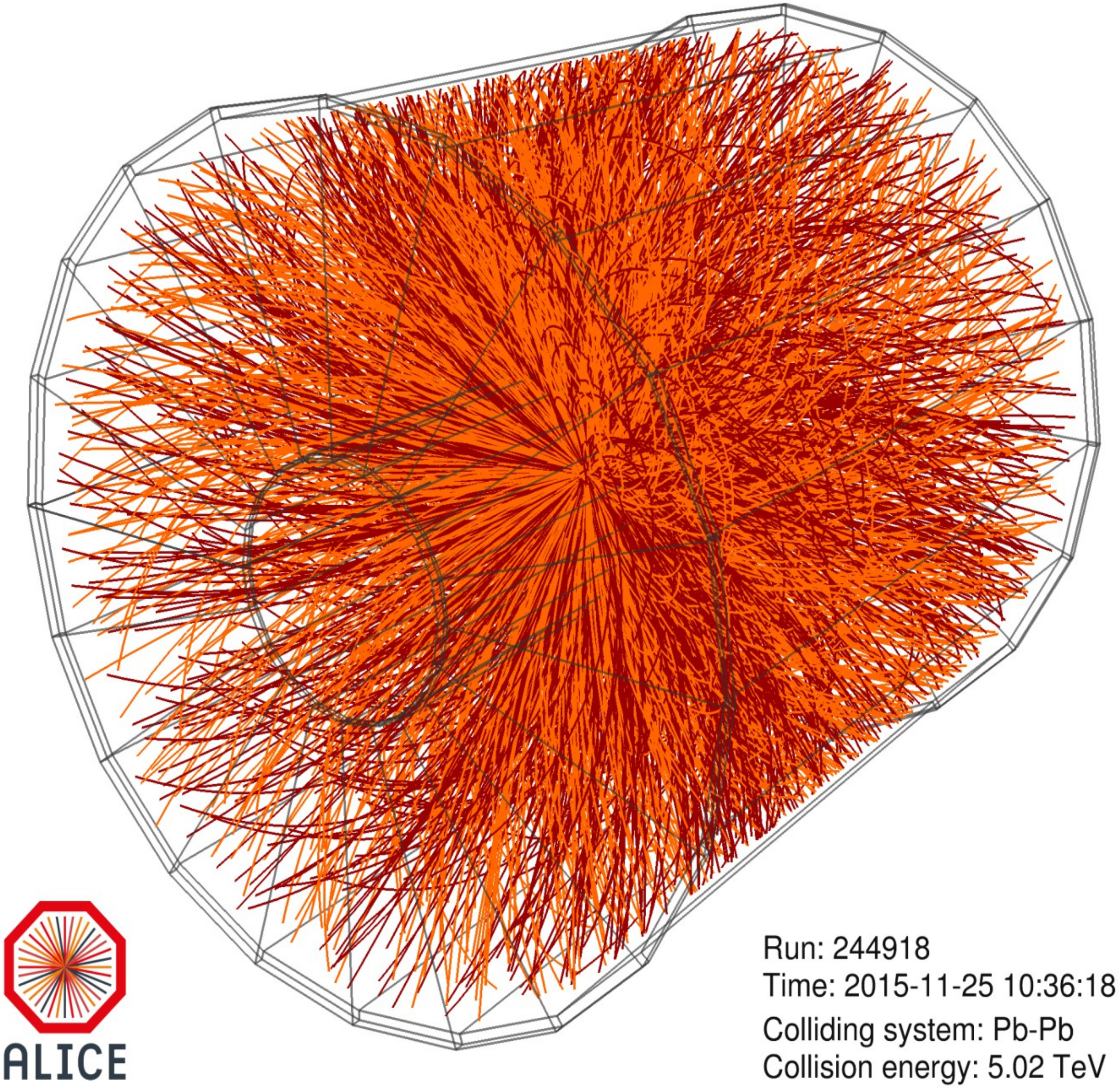
the Quark-Gluon Plasma formed in nuclear collisions at very high energy



Paul Sorensen and Chun Shen



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

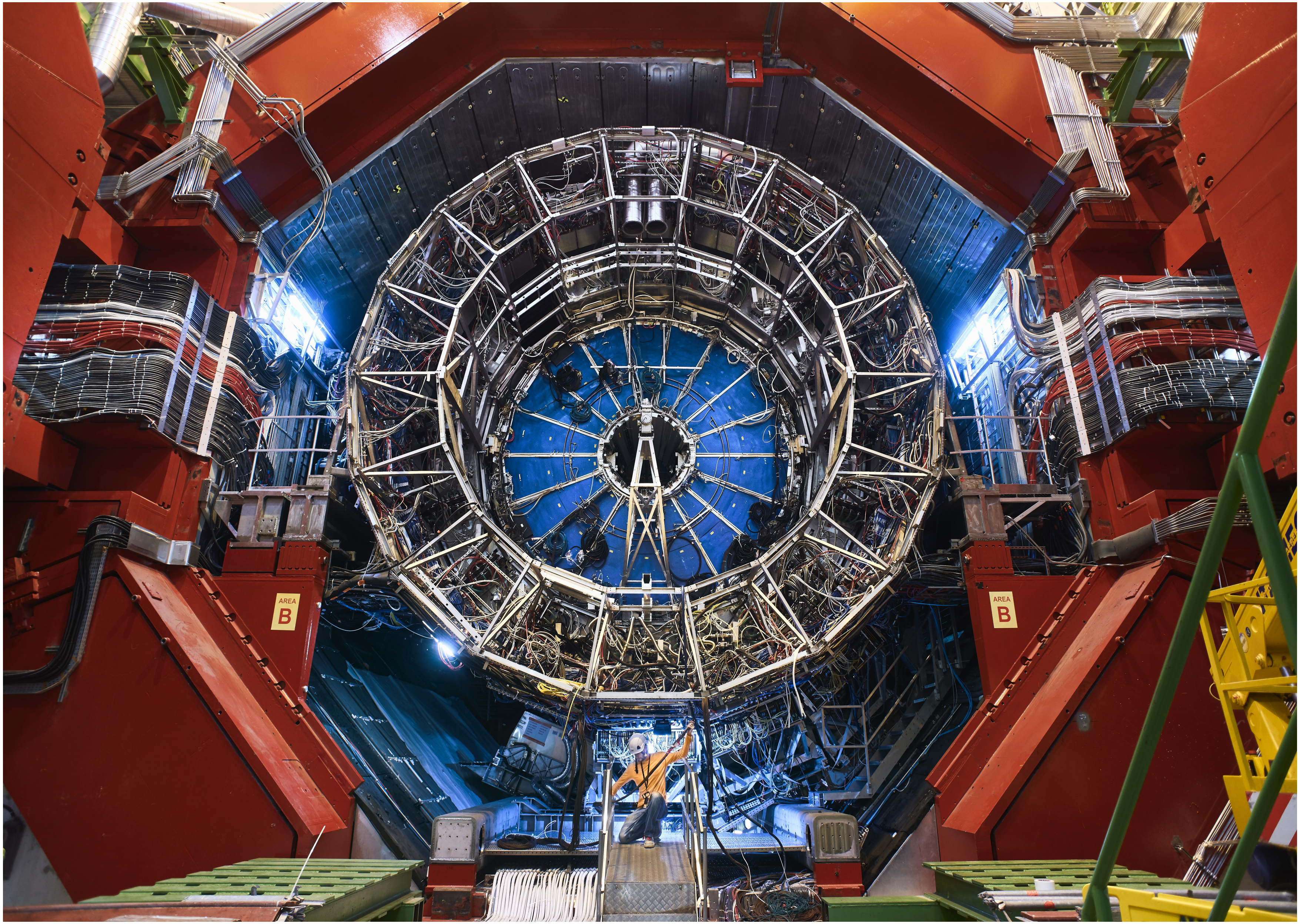
Nov. 2018: PbPb 5 TeV/u

Snapshot taken with the ALICE TPC

Dec. 2020: Run1 and Run2 combined: > 300 publications

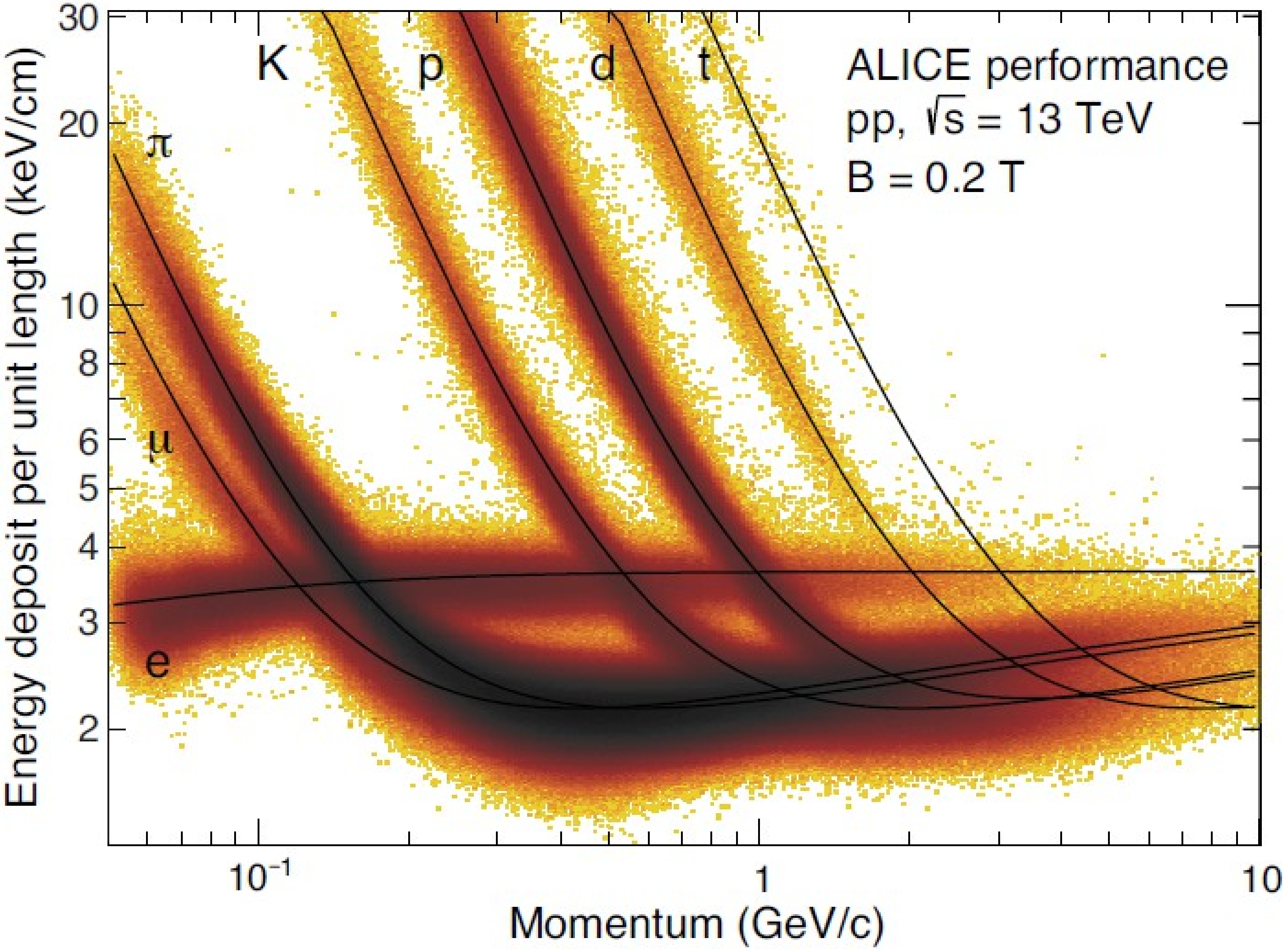
central Pb-Pb collisions:
more than 32000
particles produced per collision
at top LHC energy

the ALICE detector, inside the huge L3 solenoid, after 10 years of running at the LHC, with InnerTracking System and all connections removed, ready for the big upgrade phase in 2019-2020



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

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

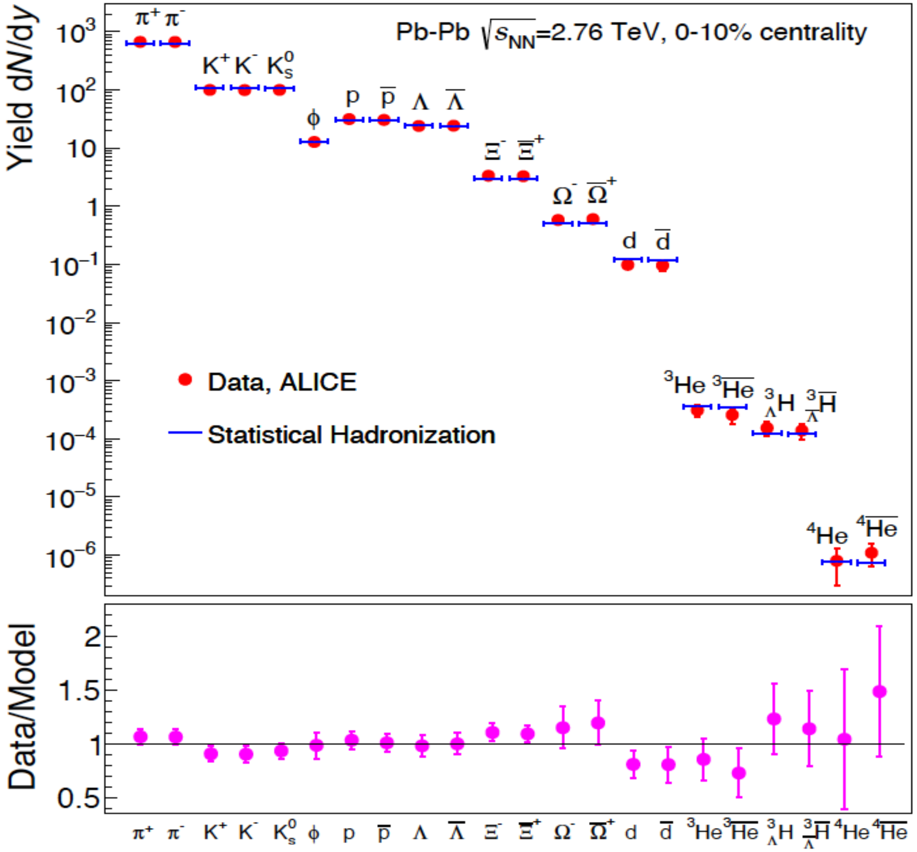
main aim: establish the existence and position of the phase boundary

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

(u,d,s) hadrons and the QGP phase boundary

statistical hadronization of (u,d,s) hadrons

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



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

Best fit:

$$T_{CF} = 156.6 \pm 1.7 \text{ MeV}$$
$$\mu_B = 0.7 \pm 3.8 \text{ MeV}$$
$$V_{\Delta y=1} = 4175 \pm 380 \text{ fm}^3$$

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

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

"proton puzzle" solved

PLB 792 (2019) 304

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

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

connection to QCD (QGP) phase diagram?

a note on the chemical freeze-out temperature

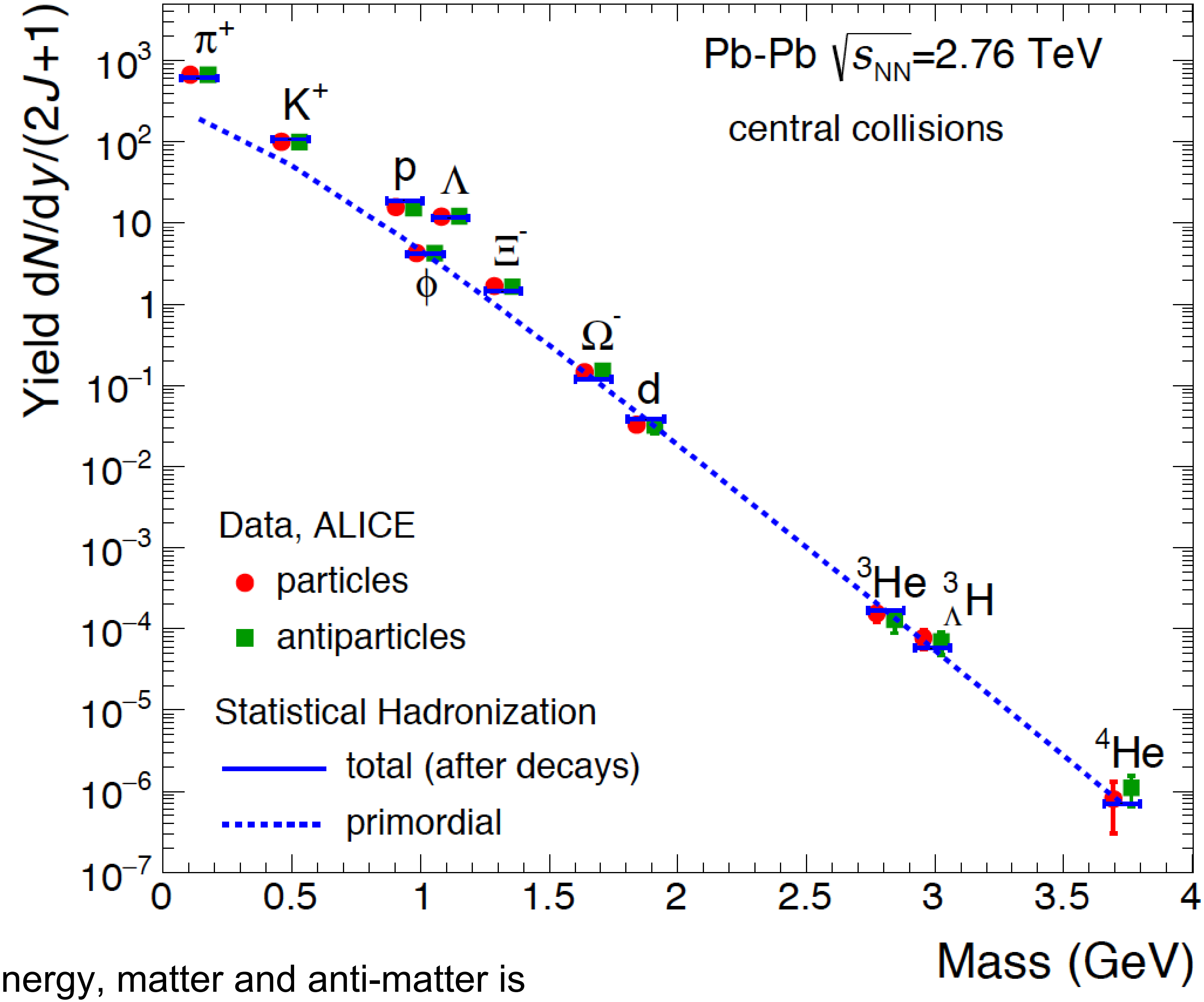
T_{chem} = 156.5 ± 1.5 MeV from fit to all particles

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' :

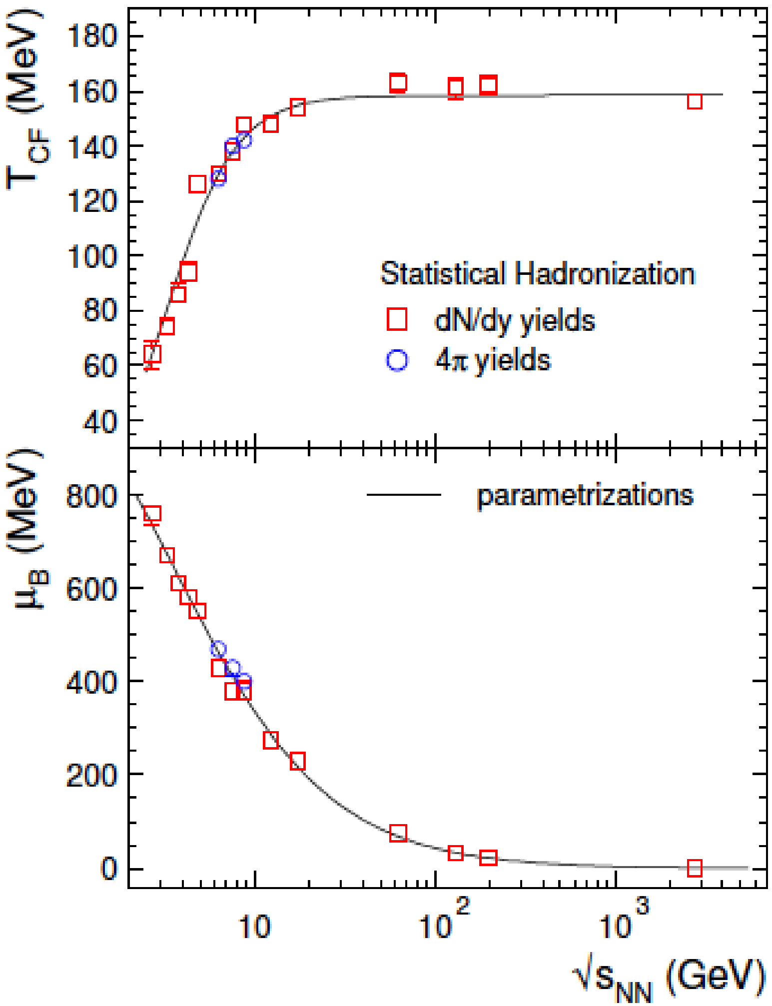
T_{nuc} = 159 ± 5 MeV, independent of hadronic mass spectrum

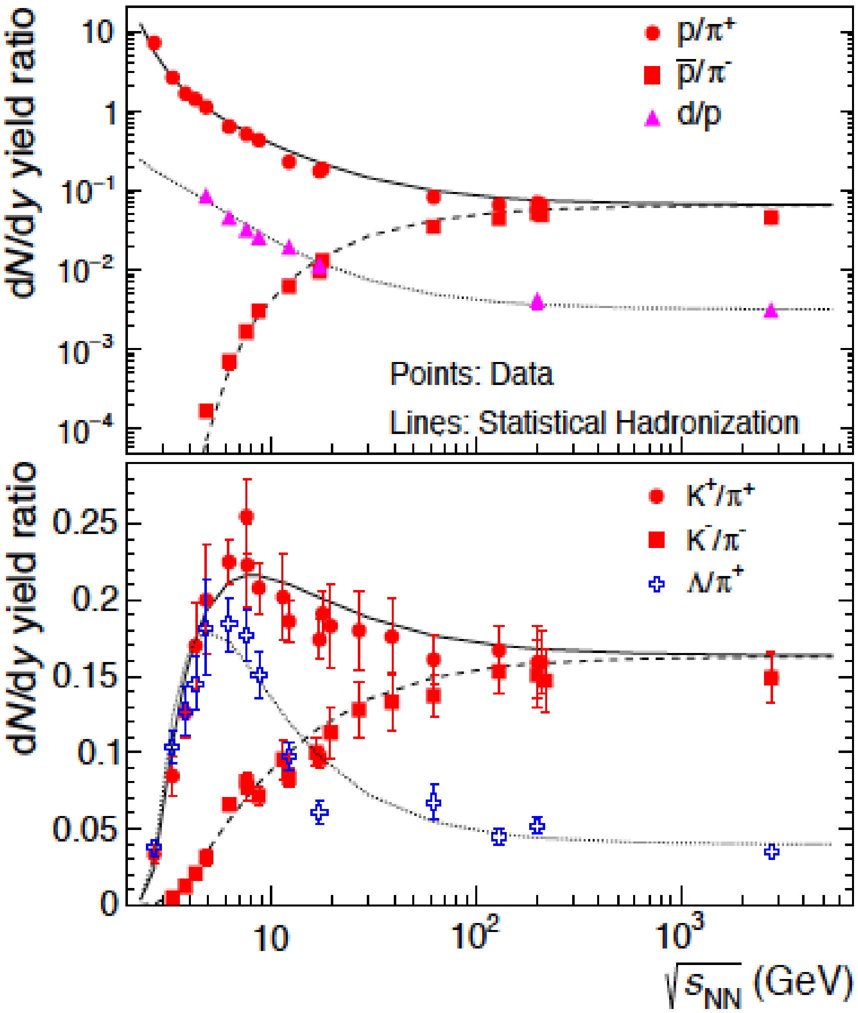
at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



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

energy dependence of hadron production described quantitatively

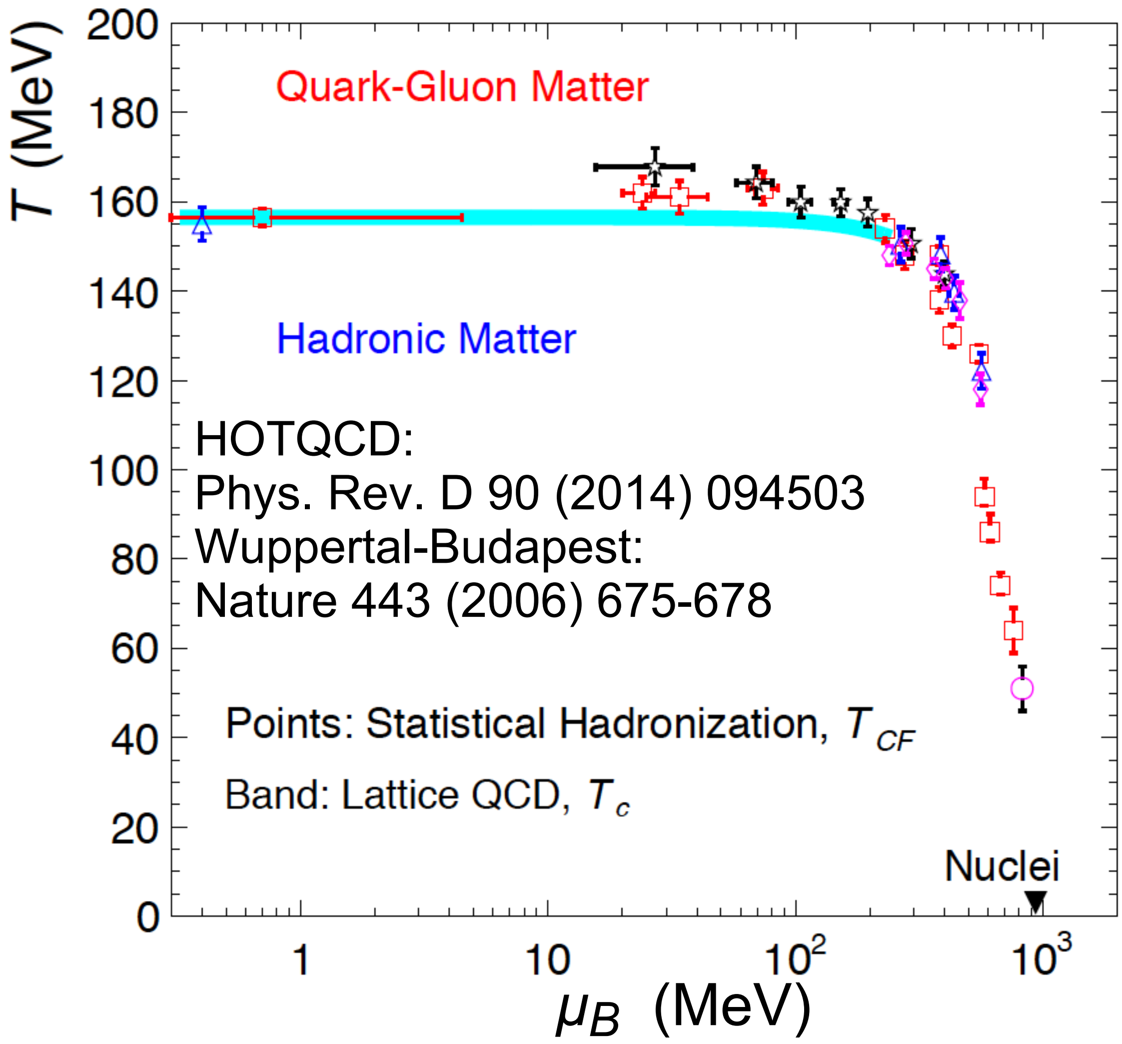




together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

the QGP phase diagram, LatticeQCD, and hadron production data

note: all coll. at SIS, AGS, SPS, RHIC and LHC involved in data taking
each entry is result of several years of experiments, variation of μ_B via variation of cm energy



HOTQCD:
Phys. Rev. D 90 (2014) 094503
Wuppertal-Budapest:
Nature 443 (2006) 675-678

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

cross over transition at $\mu_B = 0$ MeV, no experimental confirmation

should the transition be 1st order for large μ_B (large net baryon density)?

then there must be a critical endpoint in the phase diagram

experimental determination of phase boundary at
$T_c = 156.6 \pm 1.7$ (stat.) ± 3 (syst.) MeV and $\mu_B = 0$ MeV
Nature 561 (2018) 321

statistical hadronization for small systems

Jean Cleymans, Pok Man Lo, Krzysztof Redlich, Natasha Sharma

arXiv:2009.04484 and arXiv:2010.02714

statistical hadronization for small systems

Jean Cleymans, Pok Man Lo, Krzysztof Redlich, Natasha Sharma

arXiv:2009.04484 and arXiv:2010.02714

It is shown that the number of charged hadrons is linearly proportional to the volume of the system. For small multiplicities the canonical ensemble with local strangeness conservation restricted to mid-rapidity leads to a stronger suppression of (multi-)strange baryons than seen in the data. This is compensated by introducing a global conservation of strangeness in the whole phase-space which is parameterized by the canonical correlation volume larger than the fireball volume at the mid-rapidity. The results on comparing the hadron resonance gas model with and without S-matrix corrections, are presented in detail. It is shown that the interactions introduced by the phase shift analysis via the S-matrix formalism are essential for a better description of the yields data.

very good agreement from pp to pPb to central Pb-Pb

arXiv:2009.04484

key new ingredient: strangeness conservation over the volume of the whole fireball, not in the slice at mid-rapidity
this is same as for baryons, see
pbm, Rustamov, Stachel, arXiv:1907.03032
ALICE coll., Phys.Lett.B 807 (2020) 135564

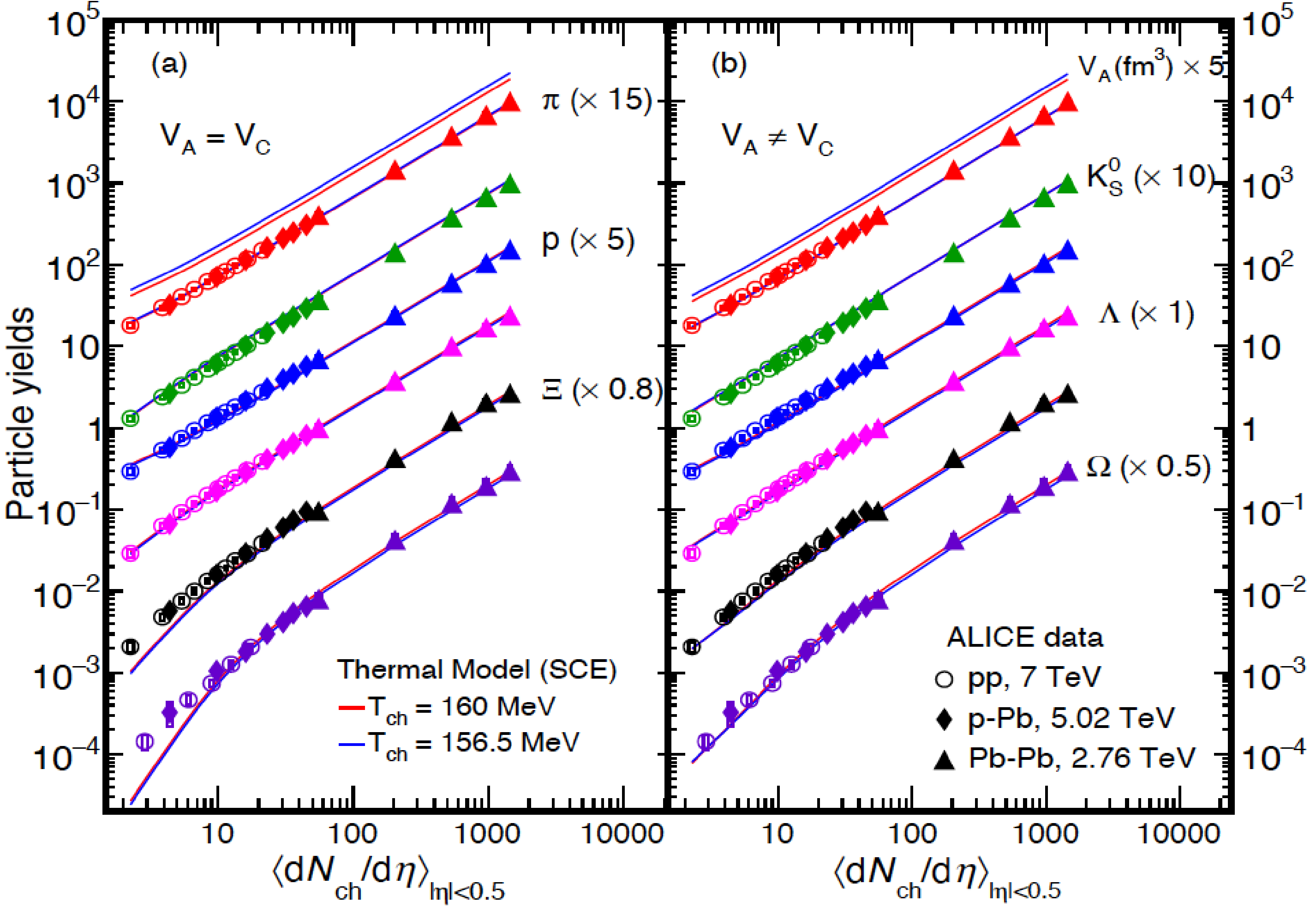
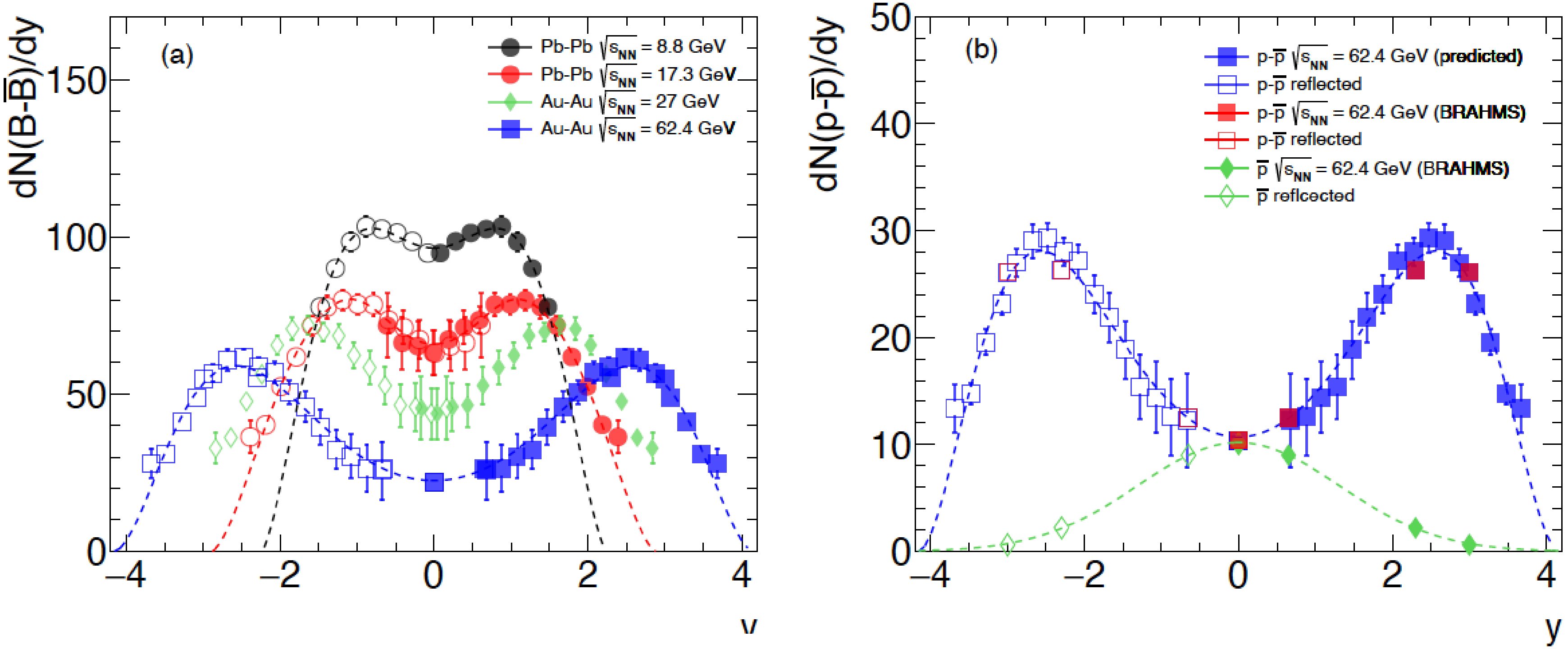


FIG. 5. Left-hand figure: Yields for $V_A = V_C$. Right-hand figure: Yields for $V_A \neq V_C$, Top line is the volume (x5) in fm^3. The particle yields are indicated in the right panel together with the multiplicative factor used to separate the yields. The solid blue lines have been calculated for $T = 156.5$ MeV while the solid red lines have been calculated for $T = 160$ MeV.

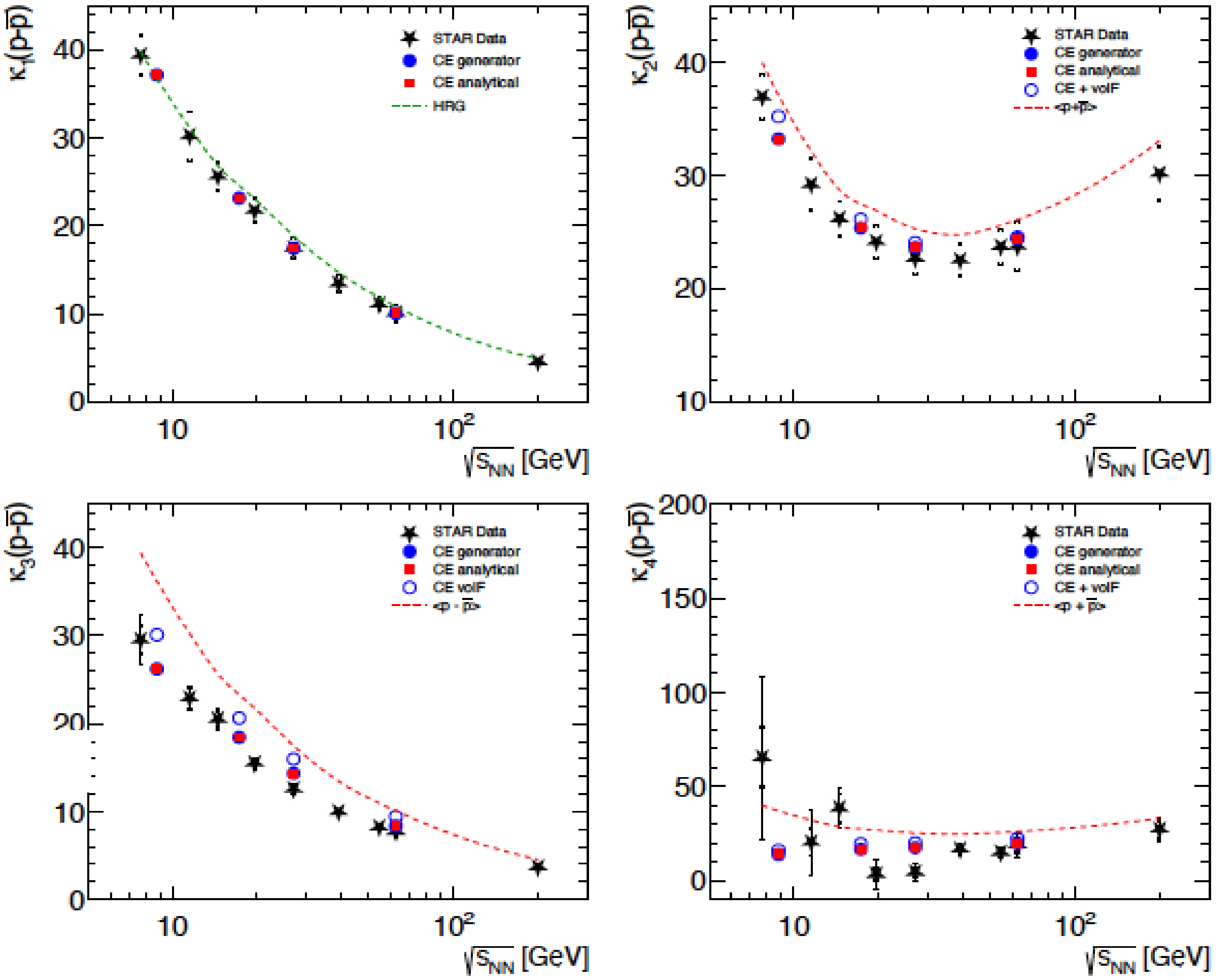
net baryon distributions, event-by-event fluctuations and chemical freeze-out

`P.Braun-Munzinger, B.Friman, K.Redlich, A.Rustamov and J.Stachel,`
`Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements,`
`[arXiv:2007.02463 [nucl-th], Nucl.Phys. A (in print)].`



(a): Rapidity distributions of net baryons at $\sqrt{s_{NN}} = 8.8$ and 17.3 GeV (measured distributions from NA49) and 27 and 62.4 GeV (constructed using the limiting fragmentation concept described in the text). (b): Constructed (blue symbols) and BRAHMS measured (red symbols) rapidity distributions of net-protons at $\sqrt{s_{NN}} = 62.4$ GeV.

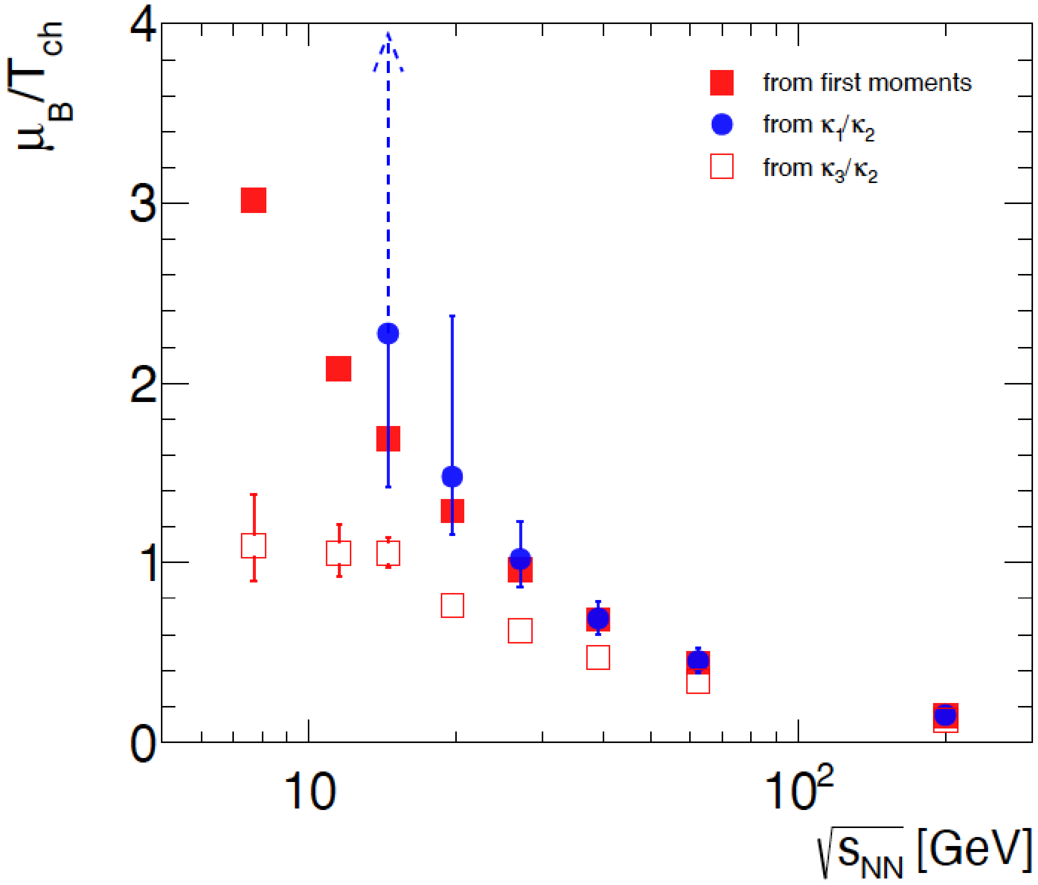
cumulants of net-proton distributions and canonical thermodynamics description



P.Braun-Munzinger, B.Friman, K.Redlich, A.Rustamov and J.Stachel,
Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements,
[arXiv:2007.02463 [nucl-th], Nucl.Phys. A (in print)].

moments of net-baryon distributions and chemical freeze-out analysis

P.Braun-Munzinger, B.Friman, K.Redlich, A.Rustamov and J.Stachel,
Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements,
[arXiv:2007.02463 [nucl-th], Nucl.Phys. A (in print)].



determination of freeze-out parameters μ_B/T_{ch} and from chemical freeze-out analysis and from mean particle multiplicities and cumulant ratios κ1/κ2 and κ3/κ2

discrepancy arises since higher moments are sensitive to correlations due to baryon number conservation, this needs to be incorporated into analysis

summary – (u,d,s) hadrons

- 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 → charmonium enhancement in QGP, direct proof of deconfinement for charm quarks

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156.5 ± 3 MeV for $\mu_b = 0$
new insight into hadronization

how about charm and statistical hadronization?

open and hidden charm and beauty in e+e-

Andronic, Beutler, pbm, Redlich, Stachel, Phys. Lett. B 678 (2009) 350-354

in the 5 flavor scheme
with quantum number conservation,
yields for open charm
and beauty hadrons are very
well described,
charmonia ard Y states are off
by many orders of magnitude

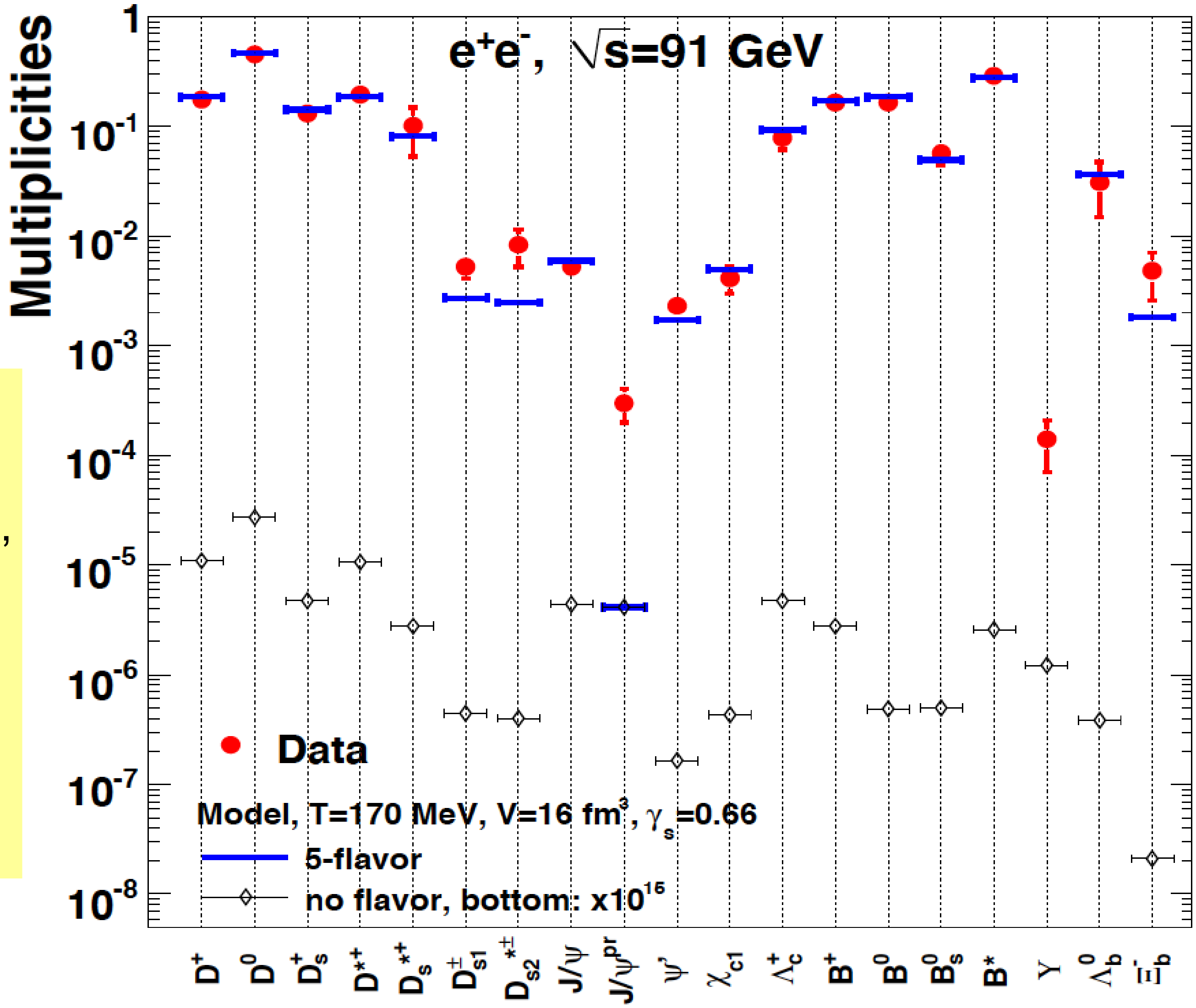


Figure 1. Multiplicities of hadrons with charm and bottom quarks in e^+e^- collisions compared to the thermal model calculations for two cases: i) the 5-flavor jet scheme (thick lines) and ii) no (net) flavor jet scheme (thin lines with diamonds). Note, for case ii) the factor 10^{15} used to scale the model calculations for bottom hadrons to fit in the plotting range. The data are from the compilation published by the Particle Data Group (PDG) [26]. The prompt J/ψ measurement J/ψ^{pr} is from the L3 experiment [27].

explanation of calculational scheme for e+e-

for the present study, we perform calculations for two cases:

i) a 2-jet initial state which carries the quantum numbers of the 5 flavors, with the relative abundance of the five flavors in one jet and corresponding antiflavor in the other jet taken from the measurements at the Z0 resonance quoted in [26]. These relative abundances (17.6% for uu¯ and cc¯ and 21.6% for dd¯, ss¯ and b¯b) are thus external input values, unrelated with the thermal model.

ii) a purely thermal ansatz , i.e. a 2-jet initial state characterized by vanishing quantum numbers in each jet. Then ccbar and bbbar jets are strongly Boltzmann suppressed.

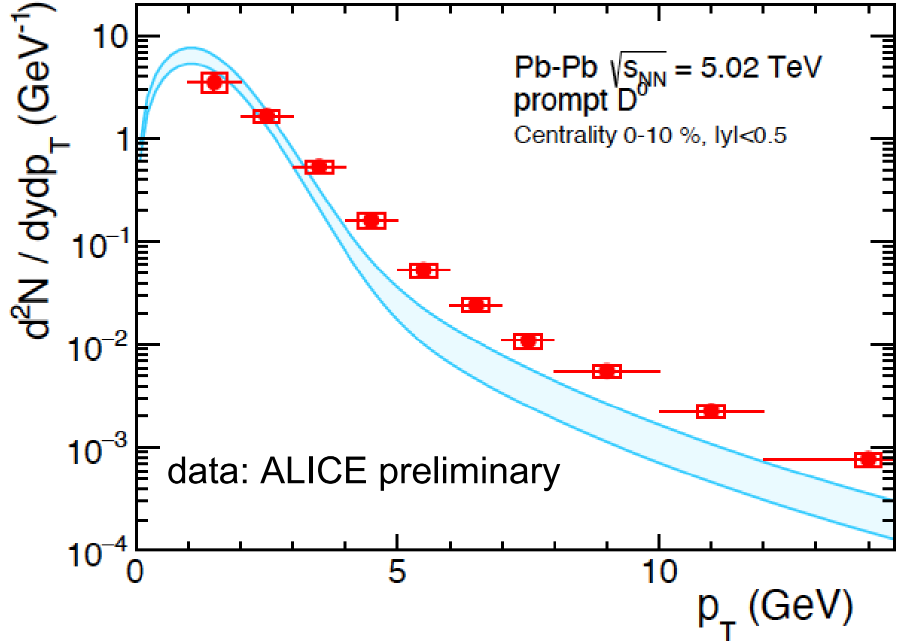
statistical hadronization for hidden and open charm

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.

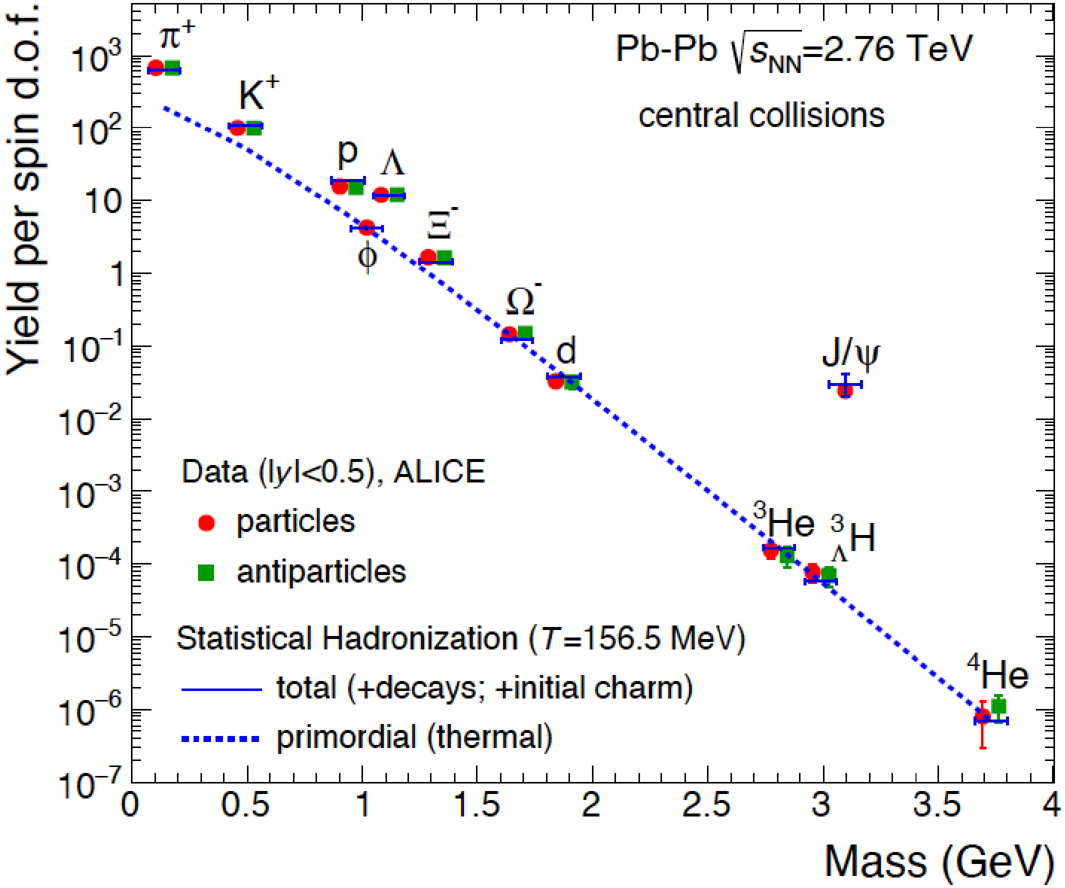
production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0



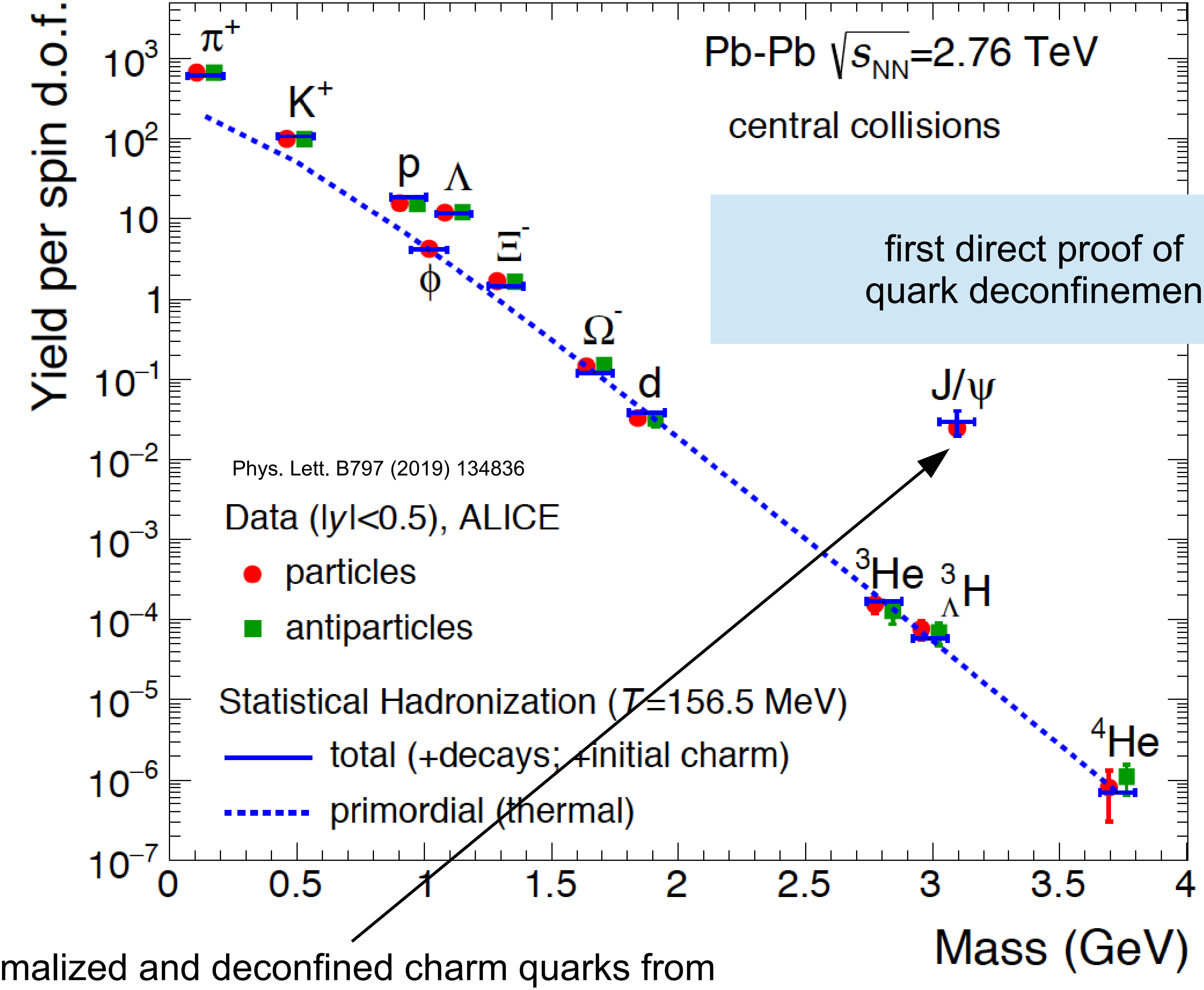
Andronic, pbm, Koehler, Redlich, Stachel PLB 792 (2019) 304 and Andronic, pbm, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, in preparation



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

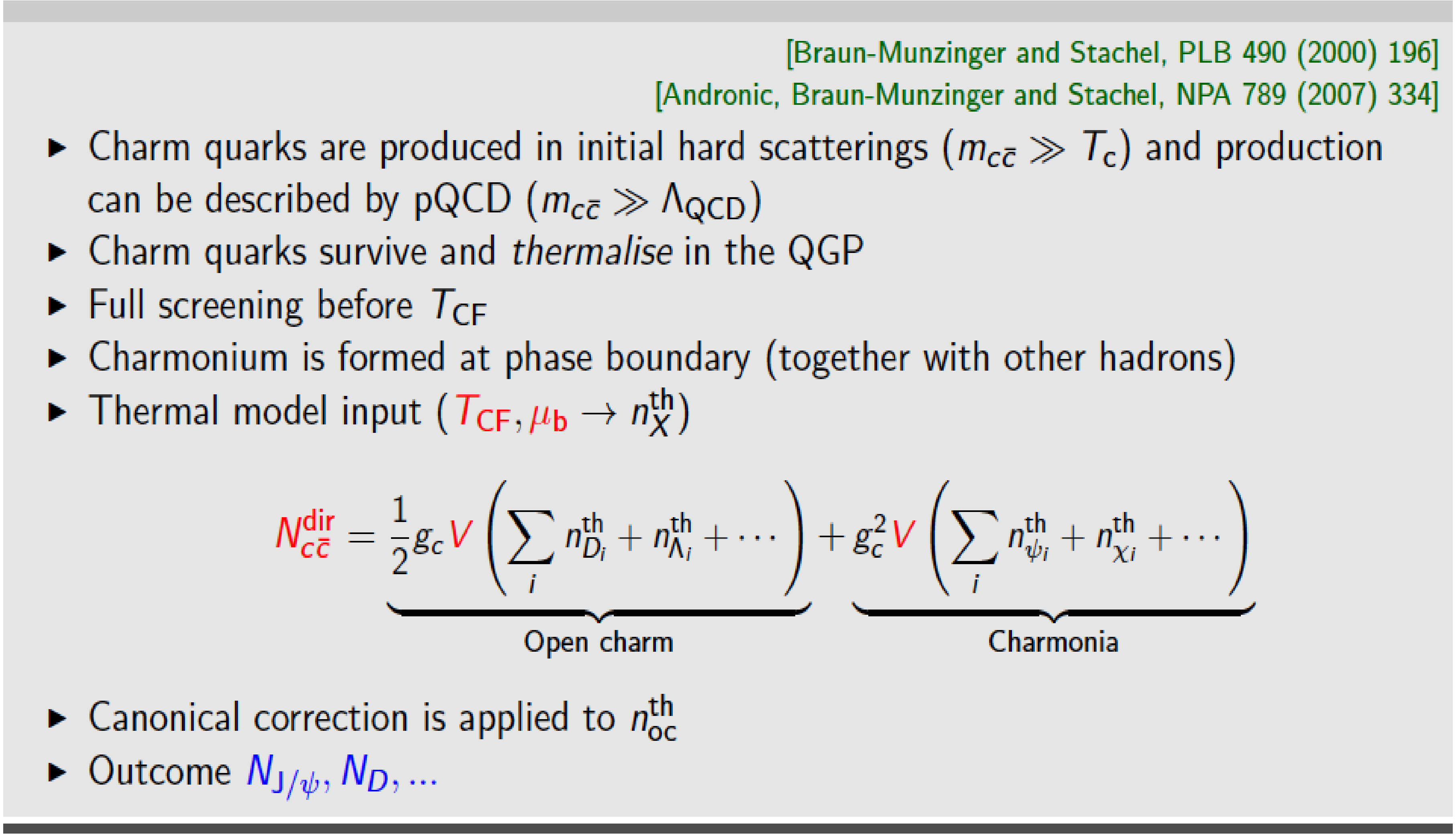


first direct proof of
quark deconfinement

with thermalized and deconfined charm quarks from
initial hard scattering

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

the mechanism for SHM with charm 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 ($m_{c\bar{c}} \gg \Lambda_{\mathrm{QCD}}$)
- 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 ($T_{\mathrm{CF}}, \mu_{\mathrm{b}} \rightarrow n_X^{\mathrm{th}}$)

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

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

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

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

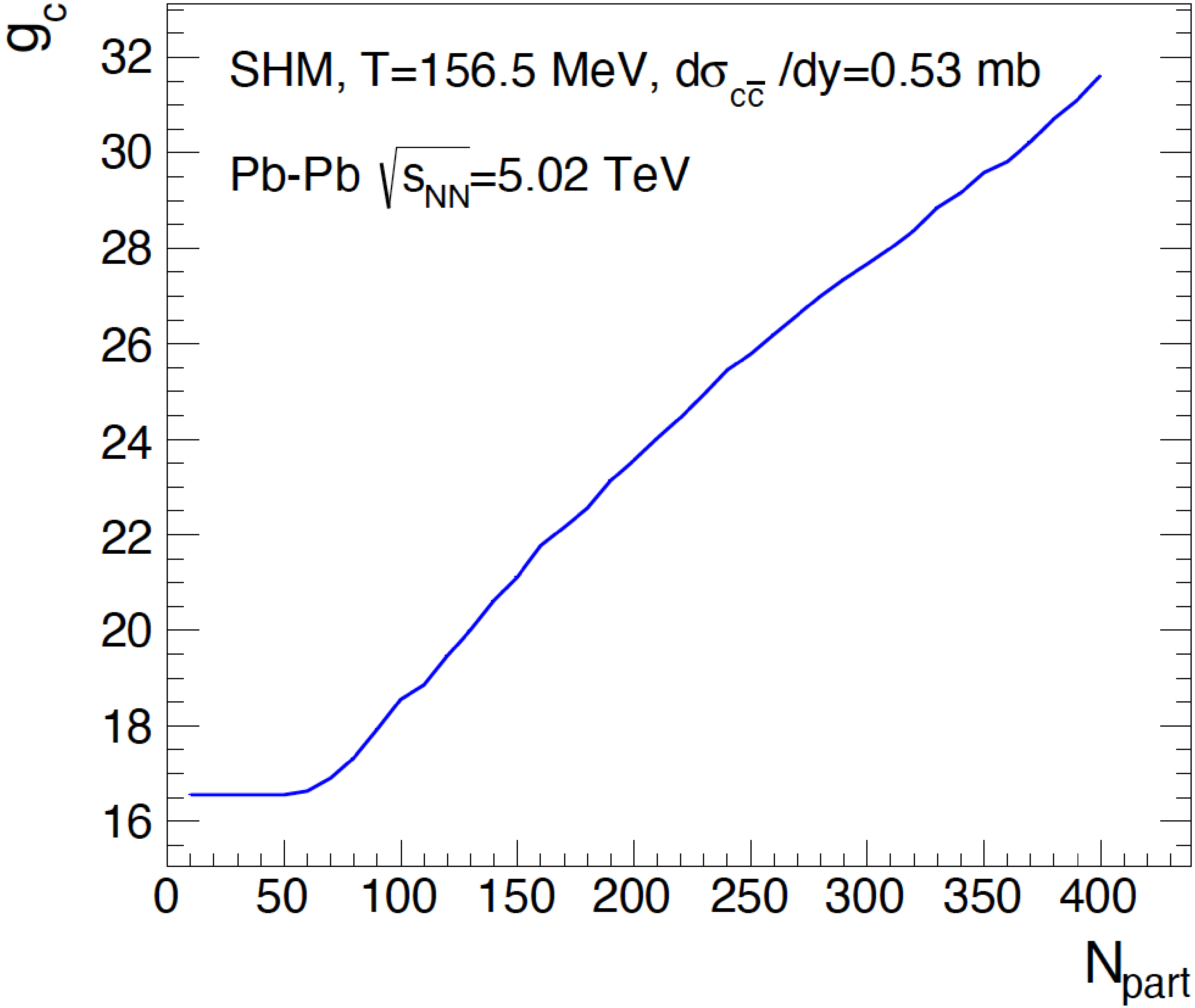
obtained from measured open charm cross section

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

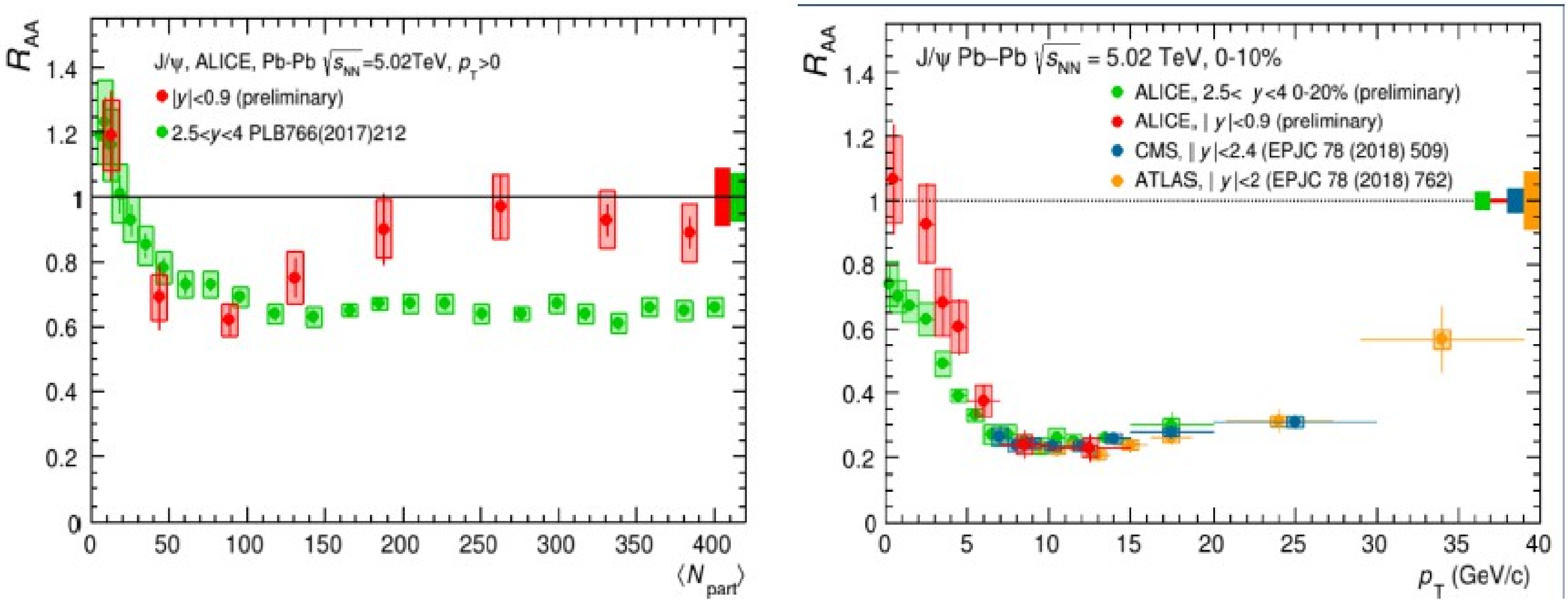
equation for yields of charm hadron i with n_c charm quarks

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

centrality dependence of charm fugacity g_c at LHC energy

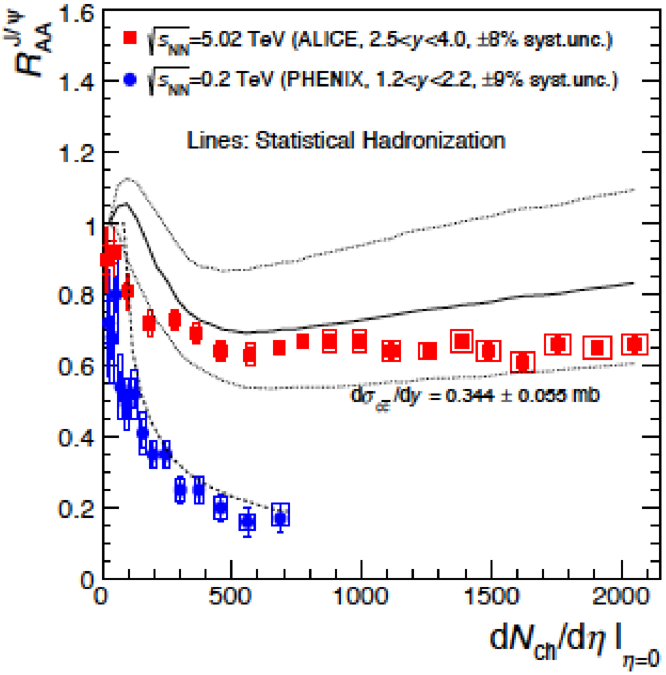


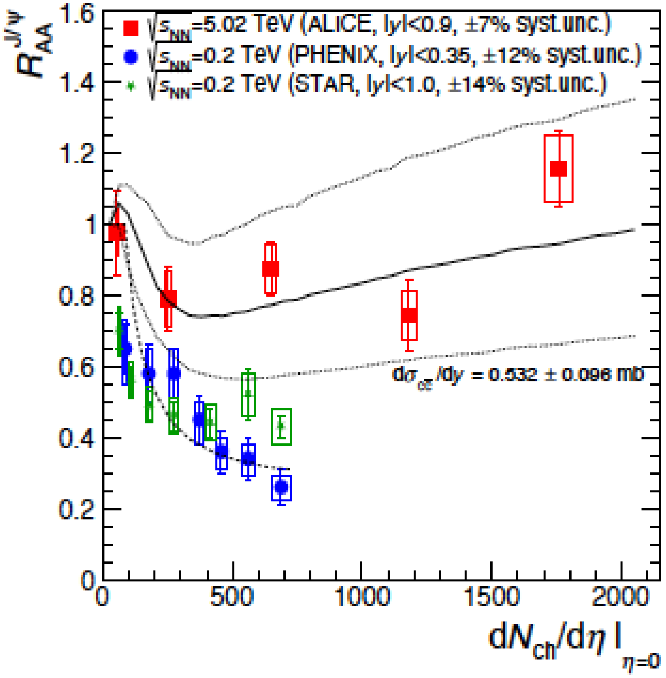
strong enhancement at low transverse momentum



RHIC and LHC data compared to SHM predictions

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





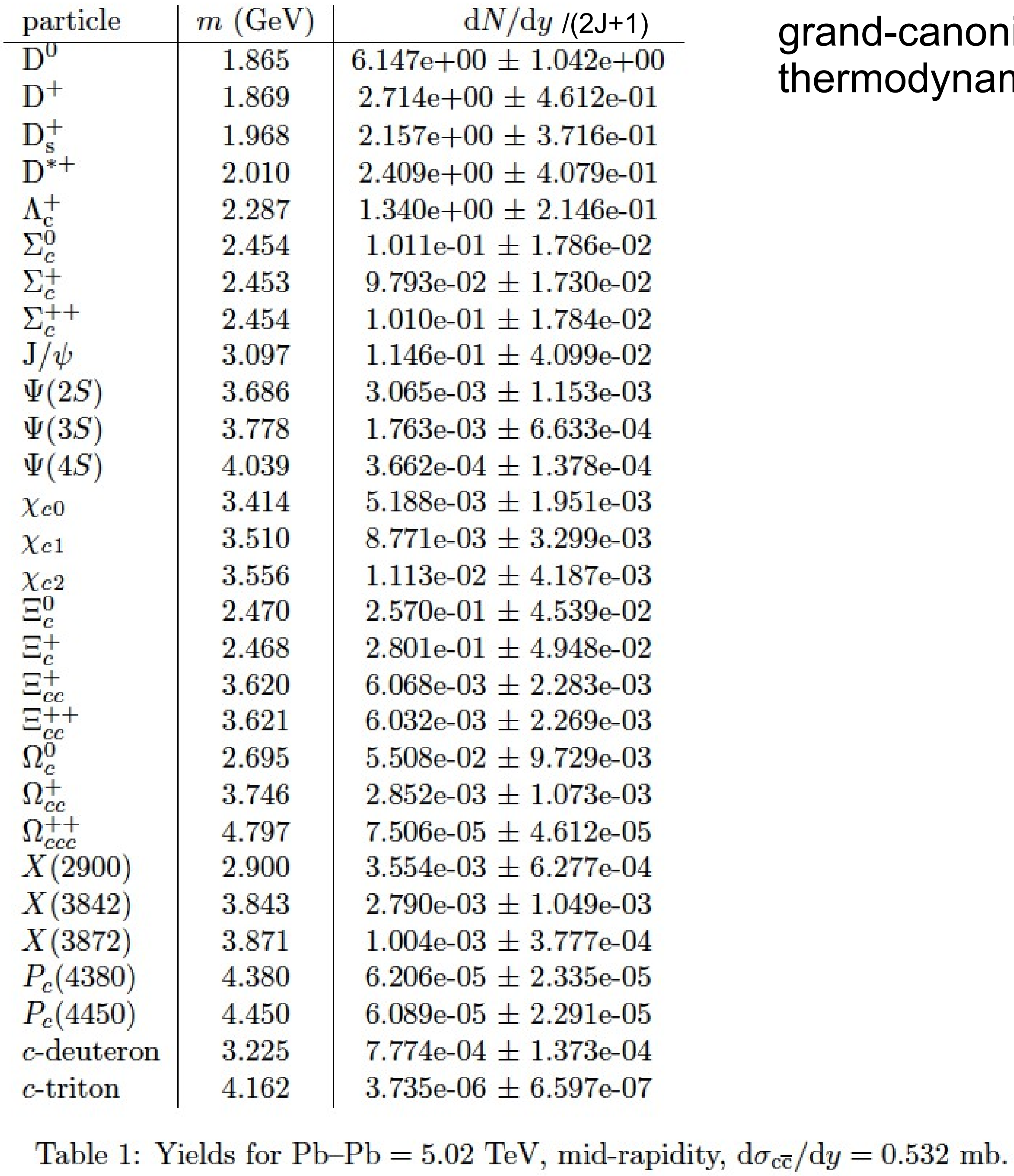
the band with the model predictions at LHC energy is due to the uncertainties in the pp open charm cross section and the necessary shadowing corrections

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

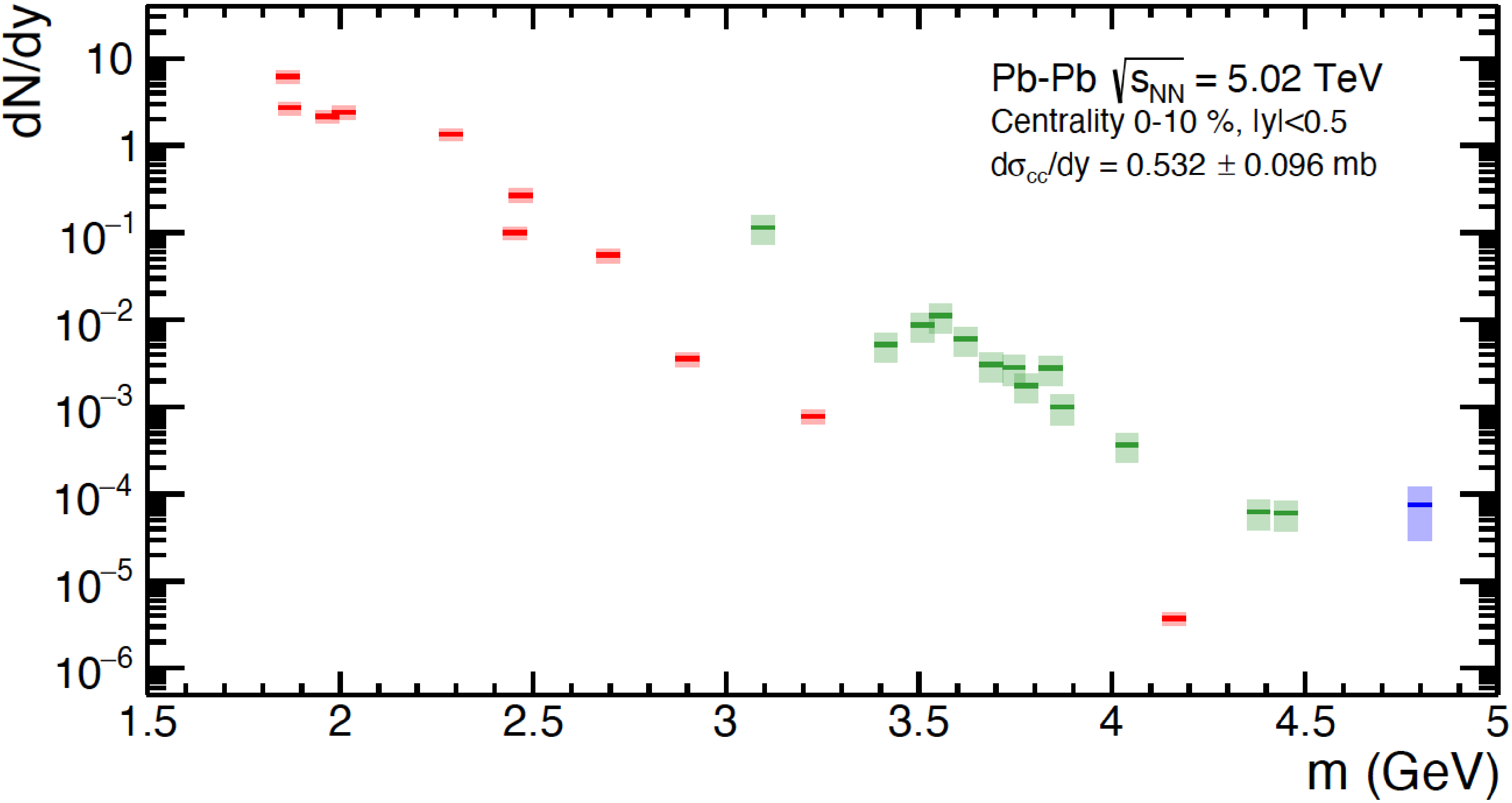


particle	m (GeV)	dN/dy /(2J+1)
D^0	1.865	6.147e+00 ± 1.042e+00
D^+	1.869	2.714e+00 ± 4.612e-01
D_s^+	1.968	2.157e+00 ± 3.716e-01
D^{*+}	2.010	2.409e+00 ± 4.079e-01
Λ_c^+	2.287	1.340e+00 ± 2.146e-01
Σ_c^0	2.454	1.011e-01 ± 1.786e-02
Σ_c^+	2.453	9.793e-02 ± 1.730e-02
Σ_c^{++}	2.454	1.010e-01 ± 1.784e-02
J/ψ	3.097	1.146e-01 ± 4.099e-02
$\Psi(2S)$	3.686	3.065e-03 ± 1.153e-03
$\Psi(3S)$	3.778	1.763e-03 ± 6.633e-04
$\Psi(4S)$	4.039	3.662e-04 ± 1.378e-04
χ_{c0}	3.414	5.188e-03 ± 1.951e-03
χ_{c1}	3.510	8.771e-03 ± 3.299e-03
χ_{c2}	3.556	1.113e-02 ± 4.187e-03
Ξ_c^0	2.470	2.570e-01 ± 4.539e-02
Ξ_c^+	2.468	2.801e-01 ± 4.948e-02
Ξ_{cc}^+	3.620	6.068e-03 ± 2.283e-03
Ξ_{cc}^{++}	3.621	6.032e-03 ± 2.269e-03
Ω_c^0	2.695	5.508e-02 ± 9.729e-03
Ω_{cc}^+	3.746	2.852e-03 ± 1.073e-03
Ω_{ccc}^{++}	4.797	7.506e-05 ± 4.612e-05
$X(2900)$	2.900	3.554e-03 ± 6.277e-04
$X(3842)$	3.843	2.790e-03 ± 1.049e-03
$X(3872)$	3.871	1.004e-03 ± 3.777e-04
$P_c(4380)$	4.380	6.206e-05 ± 2.335e-05
$P_c(4450)$	4.450	6.089e-05 ± 2.291e-05
c-deuteron	3.225	7.774e-04 ± 1.373e-04
c-triton	4.162	3.735e-06 ± 6.597e-07

Table 1: Yields for Pb–Pb = 5.02 TeV, mid-rapidity, $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y = 0.532$ mb.

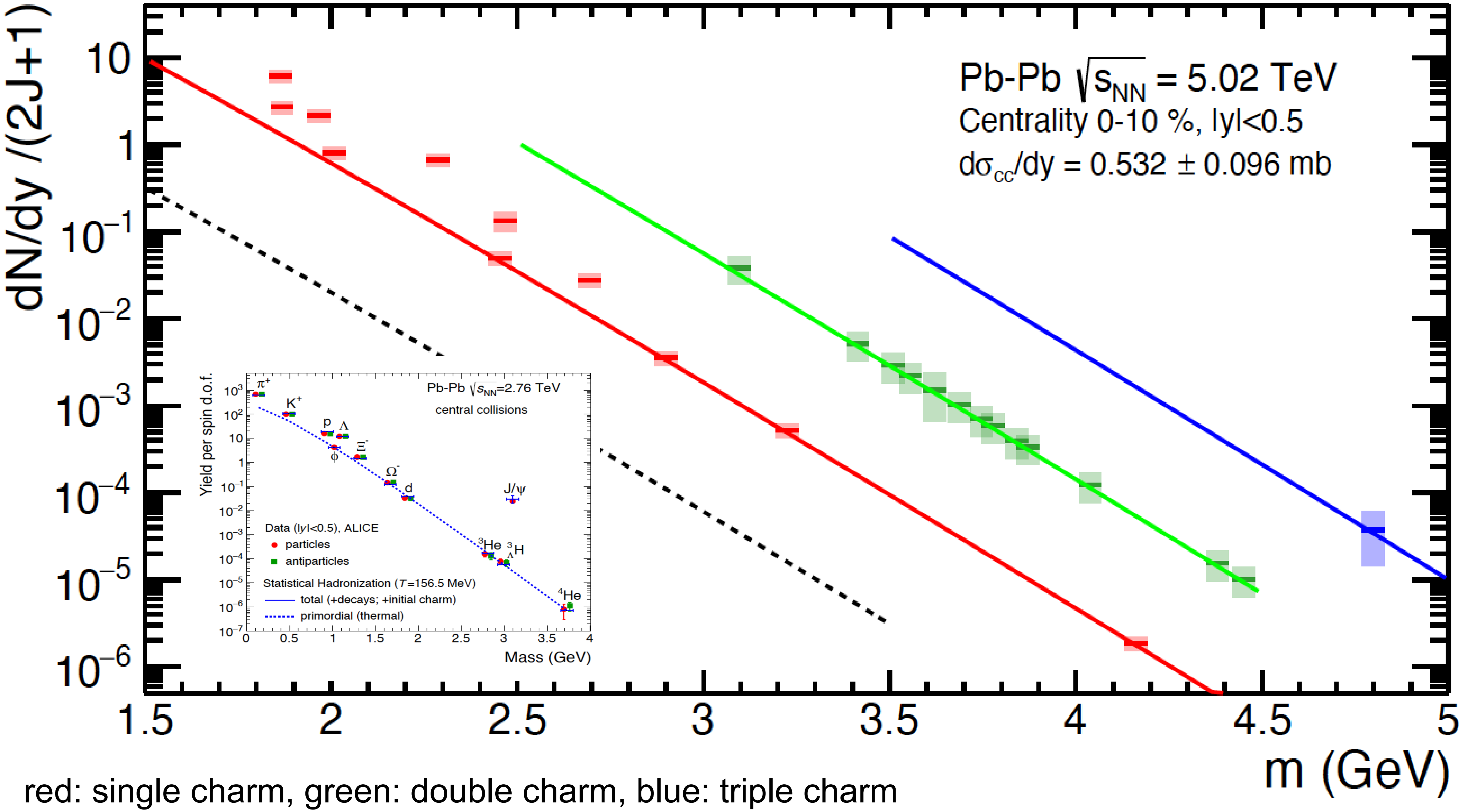
grand-canonical
thermodynamics

yields for production of charm hadrons vs. mass



red: single charm, green: double charm, blue: triple charm

yields/degeneracy for charm hadrons
grand-canonical, correction factor 0.84 for $n_c = 3$



red: single charm, green: double charm, blue: triple charm

lines: primordial SHM predictions

dashed line: SHM (u,d,s), red line: SHMC (1c), green line: SHMC (2c), blue line: SHMC (3c)

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 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?

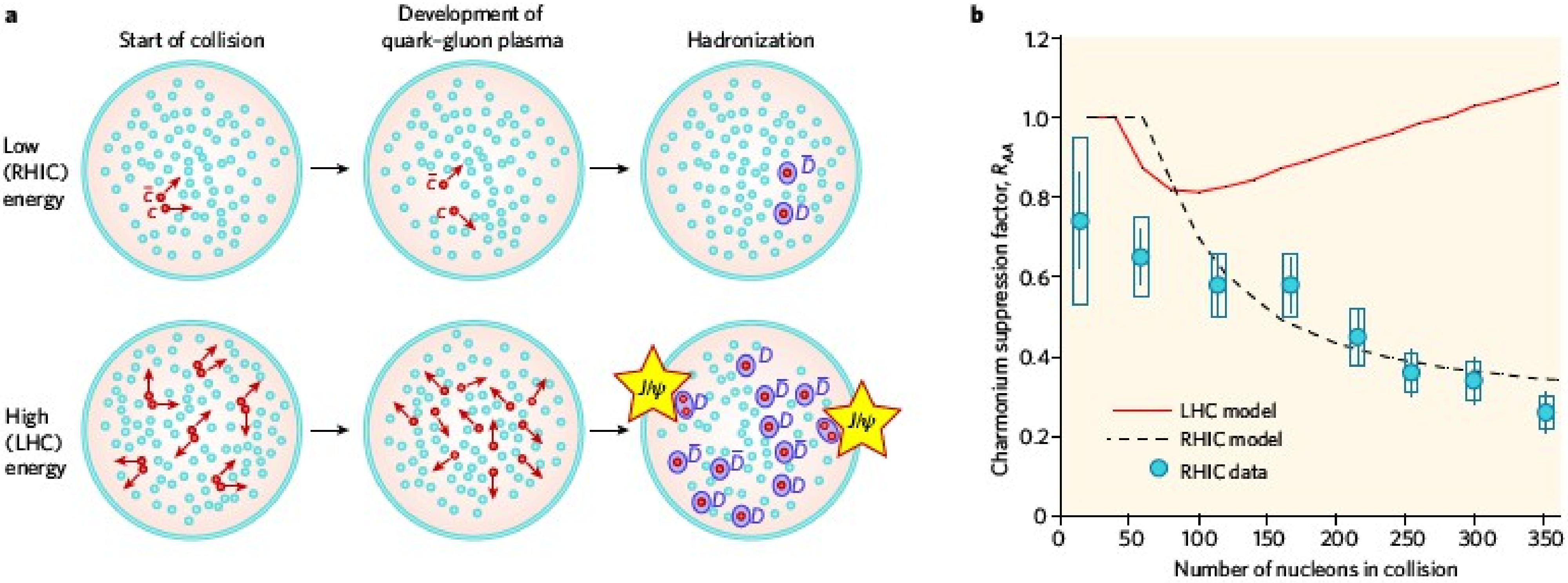
- are complex, light nuclei and exotic charmonia (X,Y,Z) produced as compact multi-quark bags?

- can fluctuation measurements shed light on critical behavior near the phase boundary?

deciphering QCD in the strongly coupled regime additional slides:

charmonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma,
Nature **448** Issue 7151, (2007) 302-309.



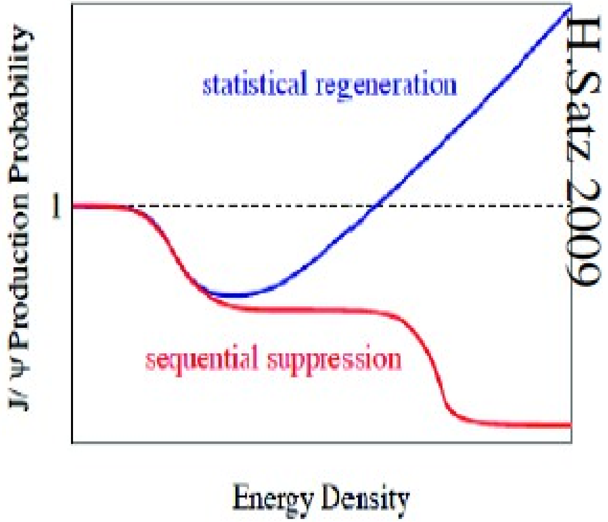
charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

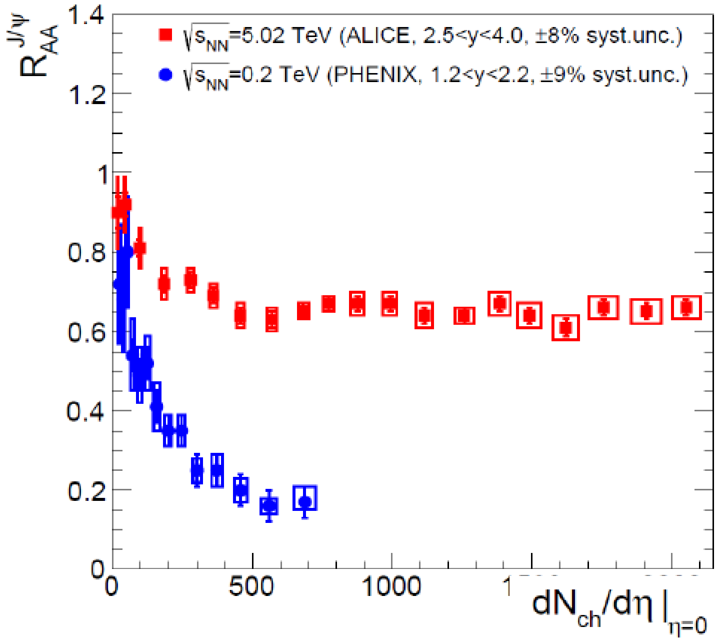
prediction long before the LHC started data taking

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B 571 (2003) 36-44, prediction for open charm
first results from RHIC, Phys. Lett. B652 (2007) 659

sequential suppression vs statistical hadronization

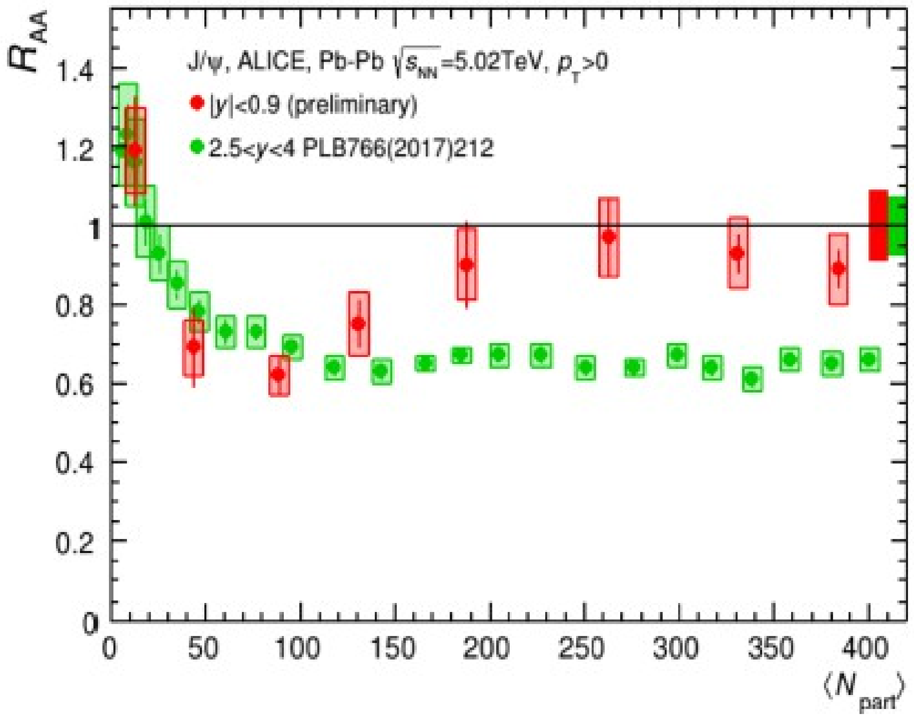
LHC ALICE data settle the issue in favor of statistical hadronization/generation at the phase boundary

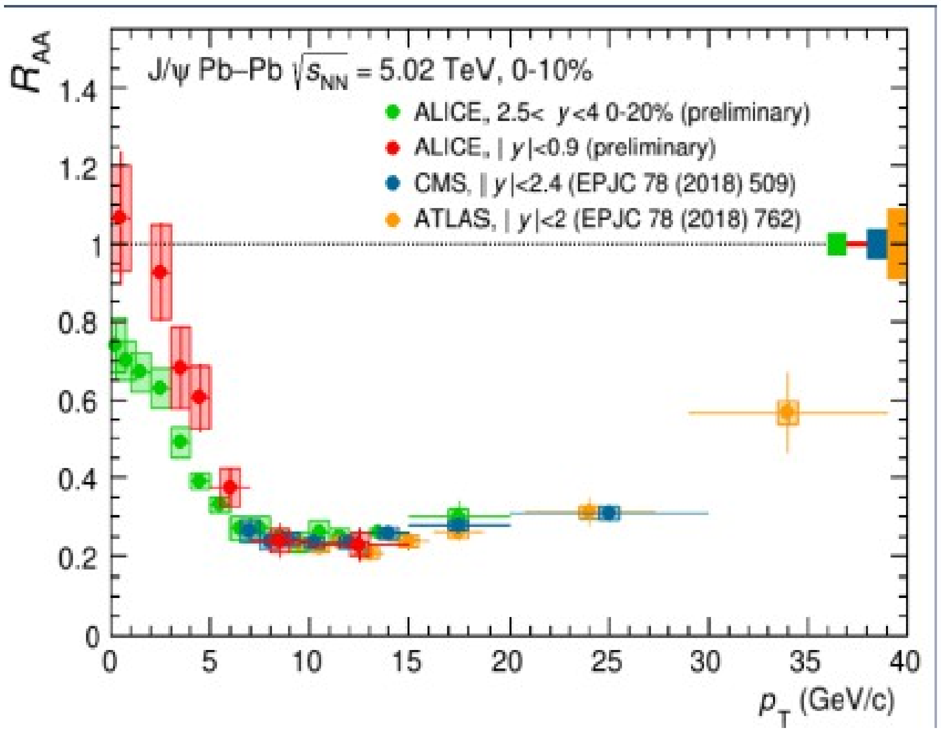




charmonium formation from uncorrelated c quarks at the phase boundary → direct proof of deconfinement for charm quarks, see Nature 561 (2018) 321

enhancement is at low (transverse) momentum and at angles perpendicular to the beam direction, as expected for a thermal, nearly isotropic source



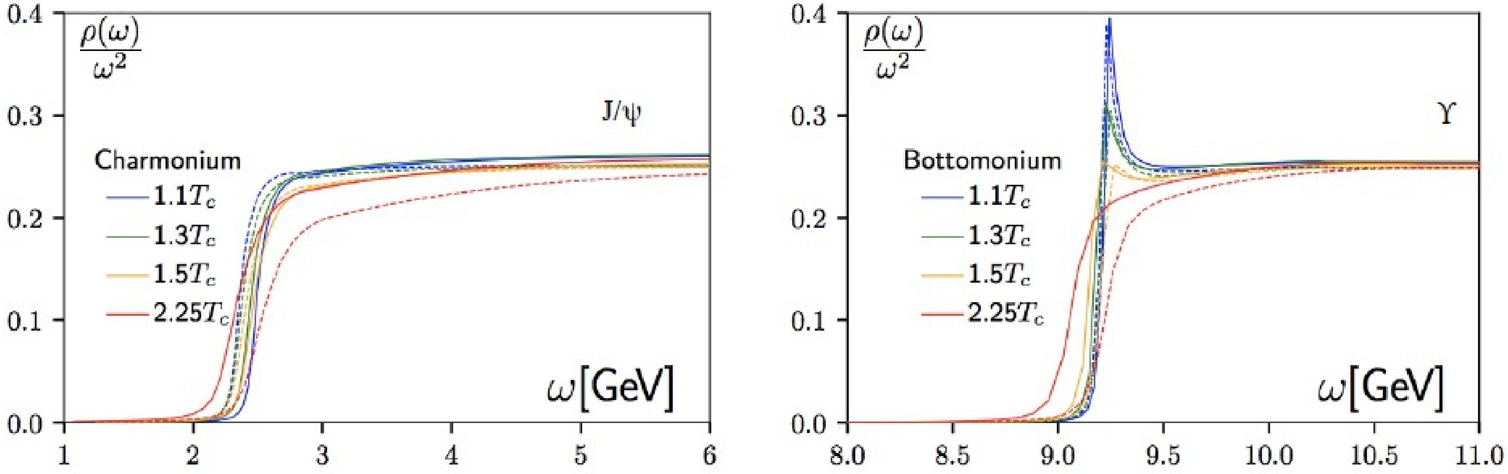


enhancement is due to statistical combination of charm- and anti-charm quarks these heavy quarks have masses O(1 GeV) and are not produced thermally since T_{cf} = 156 MeV << 1 GeV. Interactions in the hot fireball bring the charm quarks close to equilibrium → production probability scales with N_{ccbar}^2

an aside: charmonium melts at T_c
newest result from the Bielefeld/BNL/Wuhan lattice group
arXiv:2002.00681

little modification of quarkonia in QGP:
charmonia and (presumably) all charm hadrons melt at T_c
bottomonia melt at < 1.5 T_c

Thermal modification of spectral functions for
charmonium and bottomonium at high temperature



A.L. Lorenz, H.T. Ding, O. Kacmarek et al., arXiv:2002.00681

No evidence of survival of
charmonium bound states above T_c

Survival of bottomonium
significantly above T_c

-> Consistent with picture of statistical (re-)generation of J/ψ at freeze-out

charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting (suppression)

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{\text{ccbar}})^2$

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$t_{\text{coll}} << t_{\text{QGP}} < t_{\text{Jpsi}}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

also charm quark production increases strongly with collision energy