universal hadronization at the QCD phase boundary
the statistical hadronization approach

- (u,d,s) hadrons in the large volume limit – Pb-Pb collisions
- a brief disgression to small systems
- extension to hadrons with open and hidden charm
  - brief historical comments
  - charm and beauty in e+e-
  - open and hidden charm in Pb-Pb
- outlook

pbm

special session replacing the

60-th Cracow School of Theoretical Physics

zoom presentation

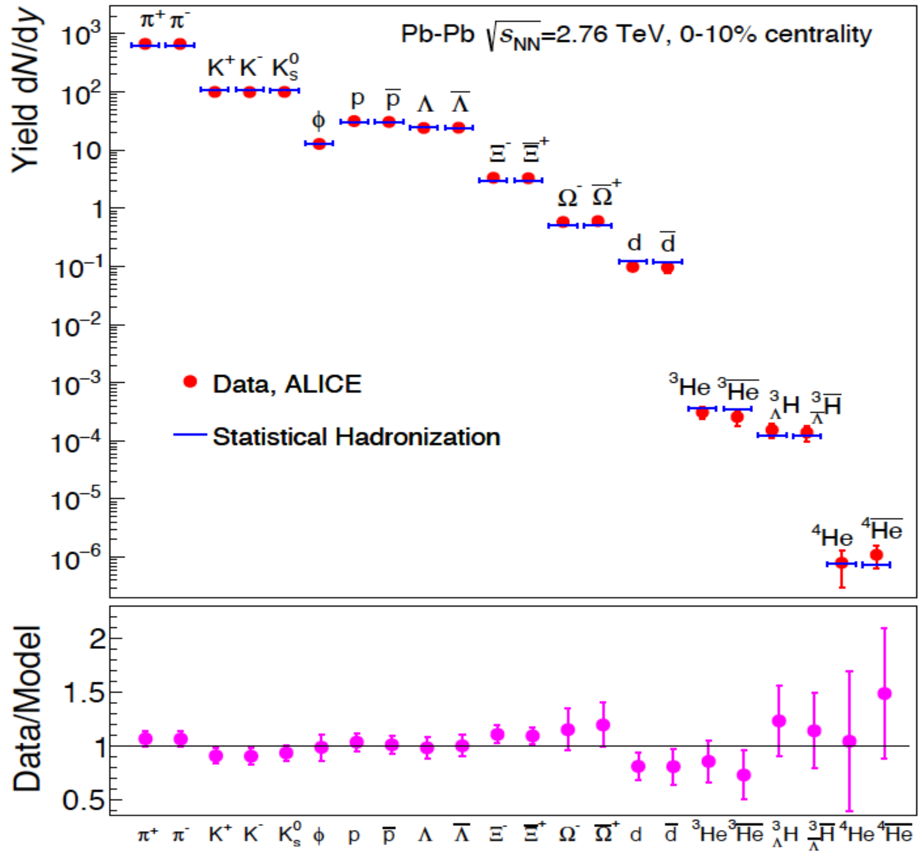
Thursday, Nov. 19, 2020

ISOQUANT SFB1225
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
EMMI
GSI

(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



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)

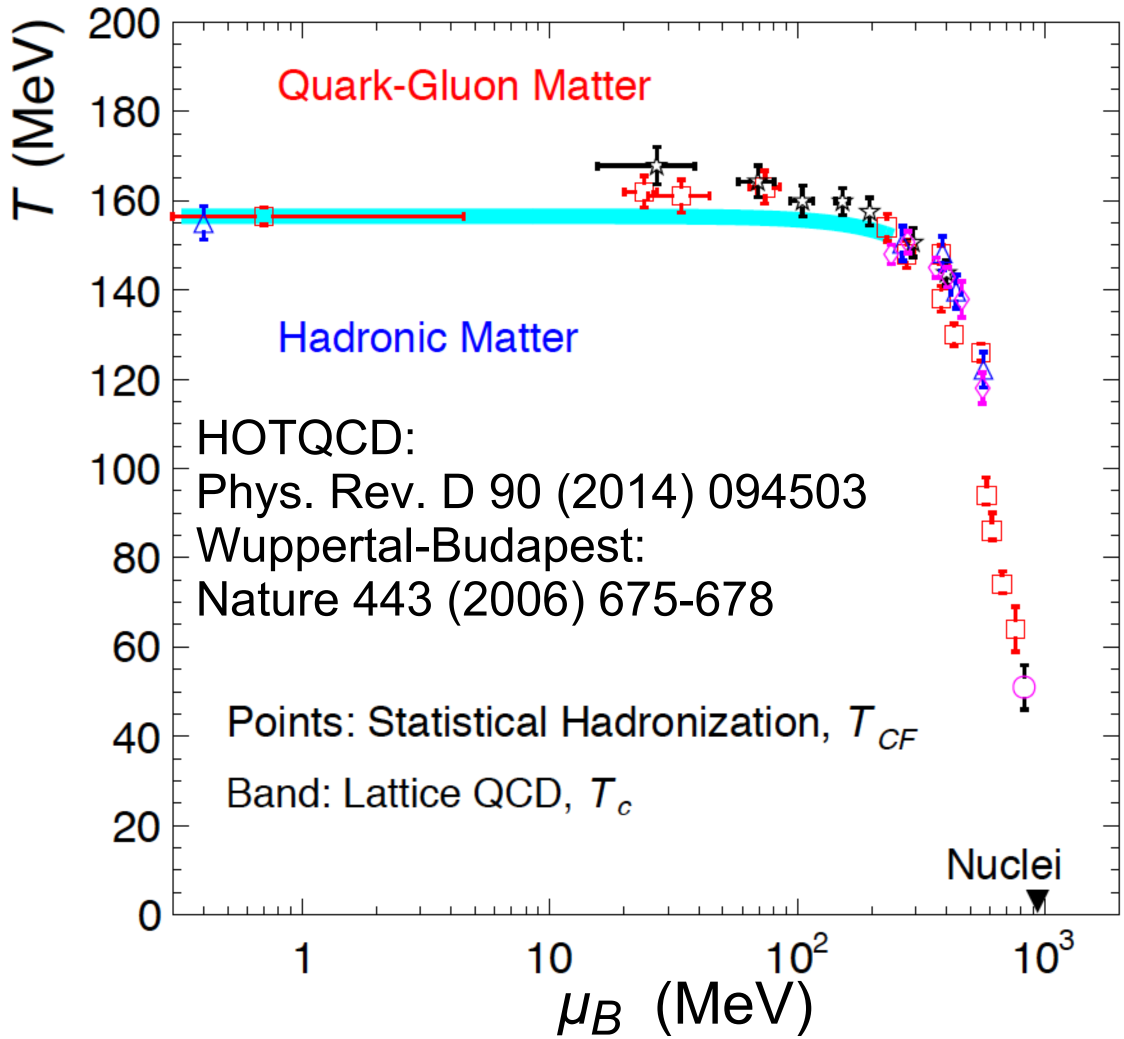
- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

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

connection to QCD (QGP) phase diagram?

the 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



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

cross over transition at μ_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 ± 1.7 (stat.) ± 3 (syst.) MeV and μ_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

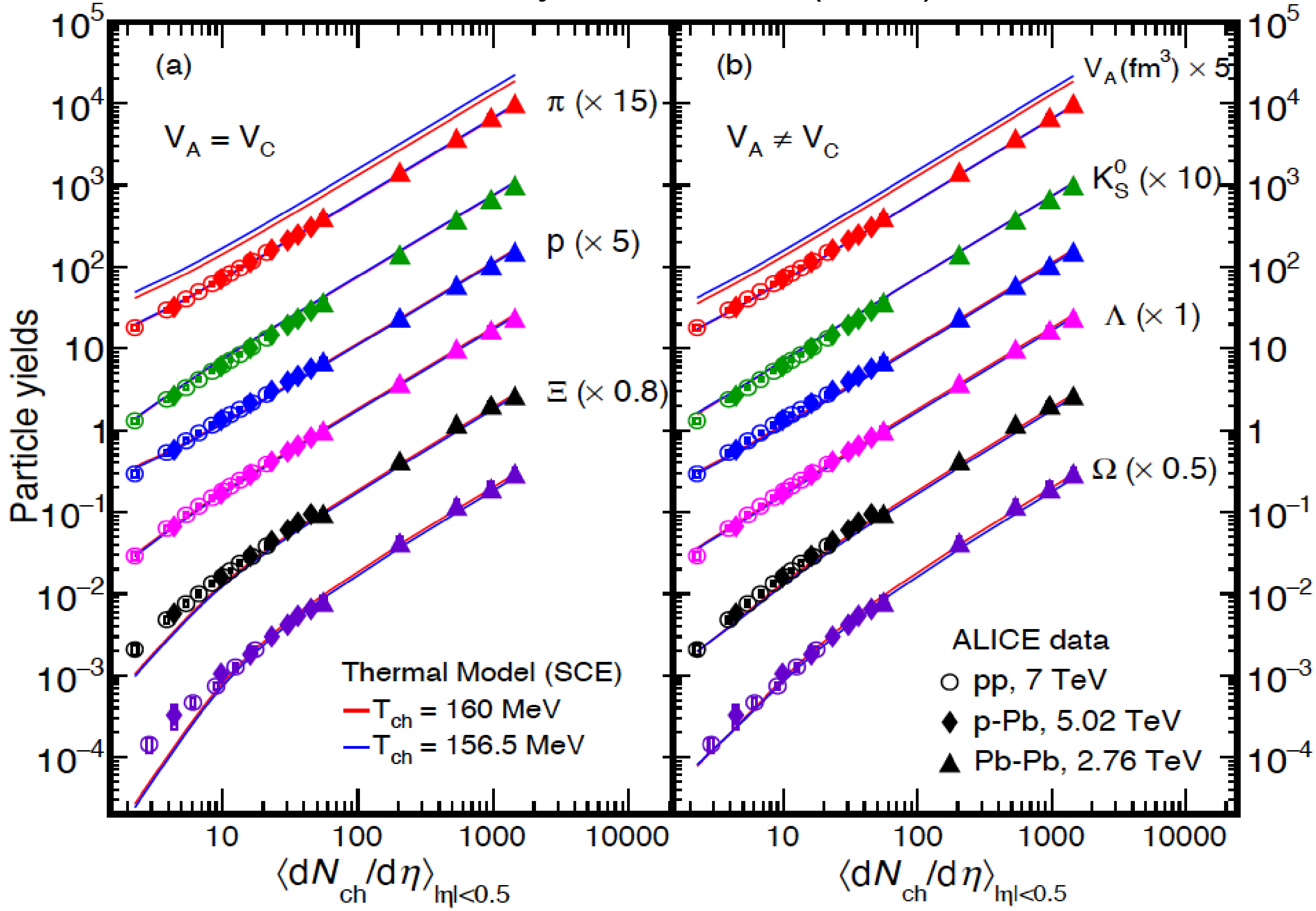


FIG. 5. Left-hand figure: Yields for $V_A = V_C$. Right-hand figure: Yields for $V_A \neq V_C$, Top line is the volume (x5) in fm^3. The particle yields are indicated in the right panel together with the multiplicative factor used to separate the yields. The solid blue lines have been calculated for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

how about charm and statistical hadronization?

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 $N(_{ccbar})^2$

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

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

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

statistical hadronization model for charm (SHMC)

selected early references:

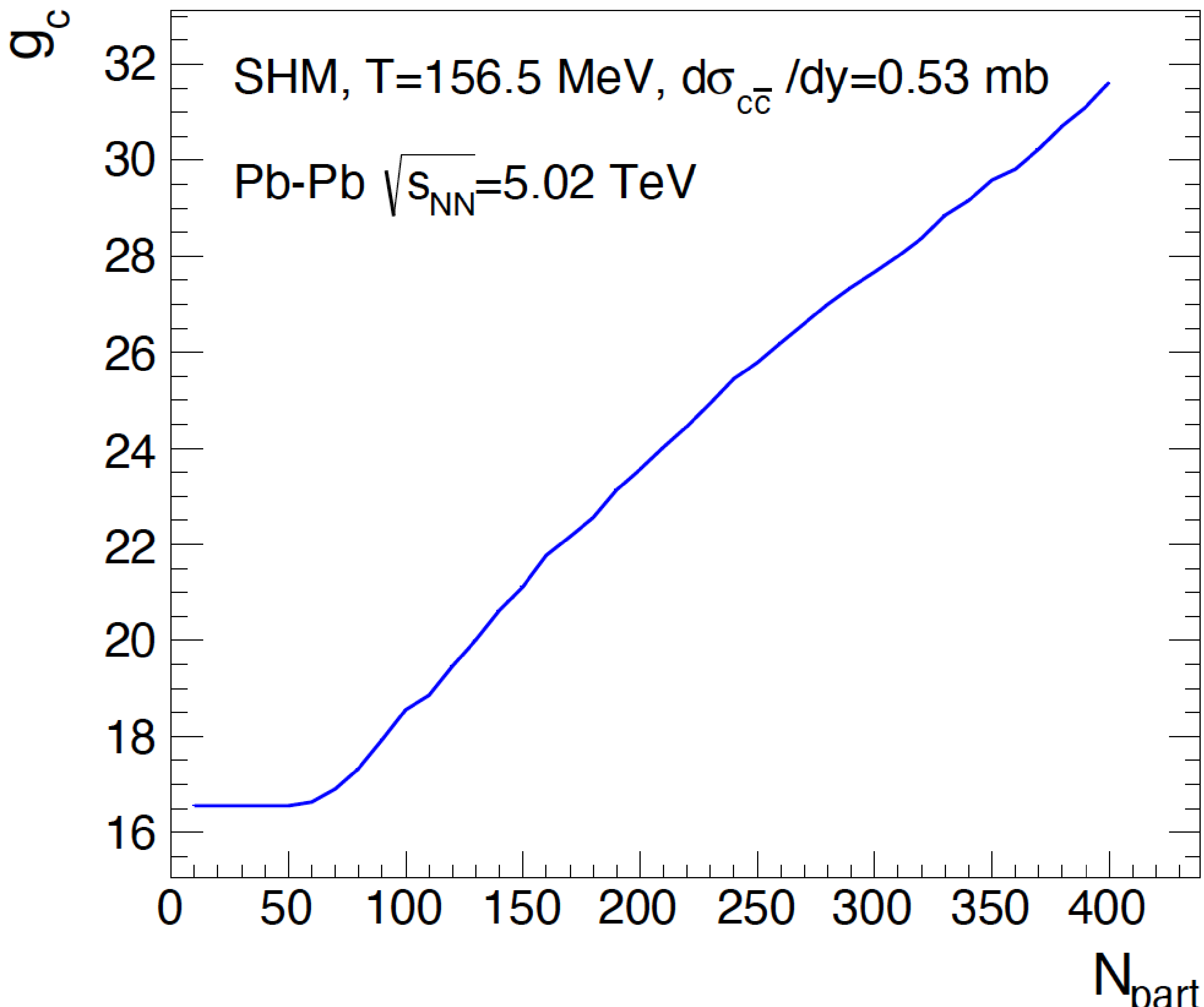
1. P. Braun-Munzinger, J. Stachel: Phys. Lett. B 490 (2000) 196-202, nucl-th/0007059 — the beginning
2. M. Gorenstein, A.P. Kostyuk, H. Stoecker, W. Greiner, Phys.Lett.B 524 (2002) 265-272, hep-ph/0104071 — SPS/RHIC
3. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B 571 (2003) 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. determines the fugacity g_c

$$N_{c\bar{c}} = \frac{1}{2} g_c V \left(\sum_i n^{\rm th}_{D_i} + n^{\rm th}_{\Lambda_i} + \cdots \right) + g_c^2 V \left(\sum_i n^{\rm th}_{\psi_i} + n^{\rm th}_{\chi_i} + \cdots \right) + \cdots$$

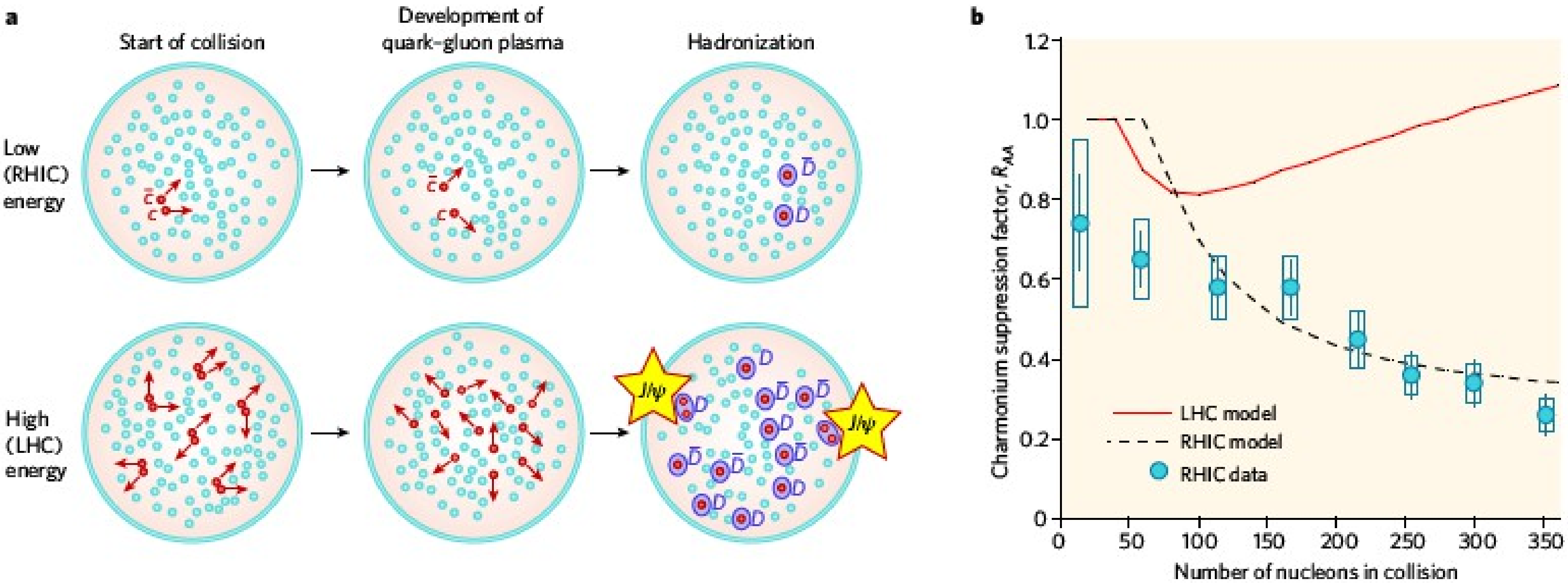
obtained from measured open charm cross section

centrality dependence of charm fugacity g_c at LHC energy



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.



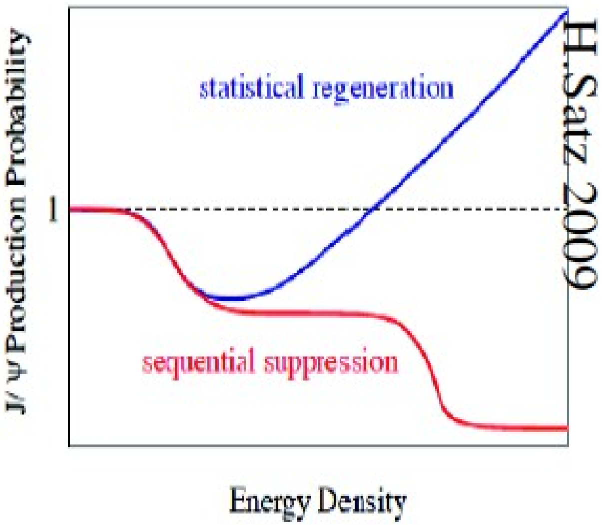
charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

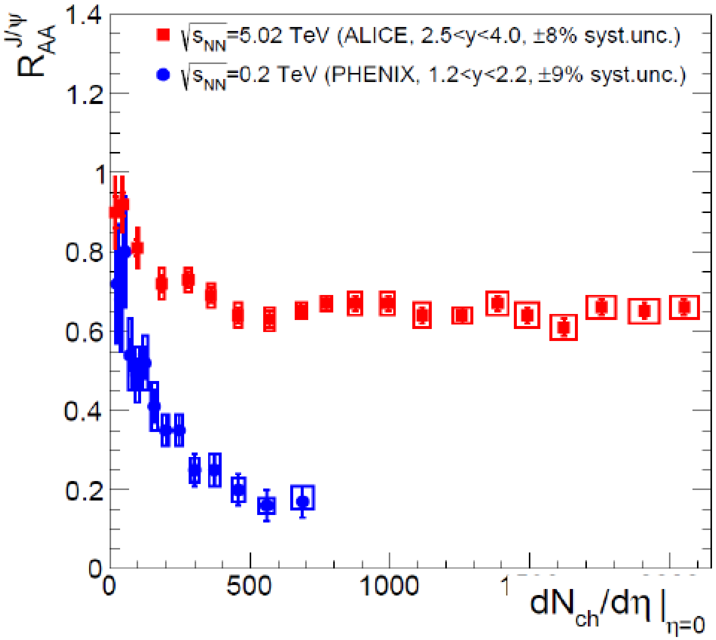
prediction long before the LHC started data taking

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

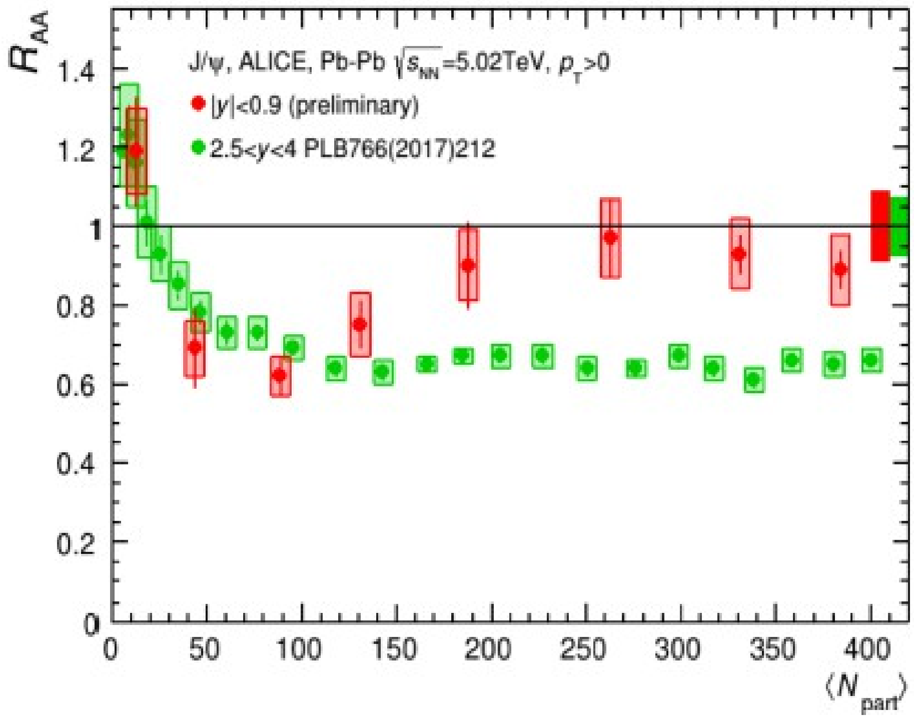
LHC ALICE data settle the issue in favor of statistical hadronization/generation at the phase boundary

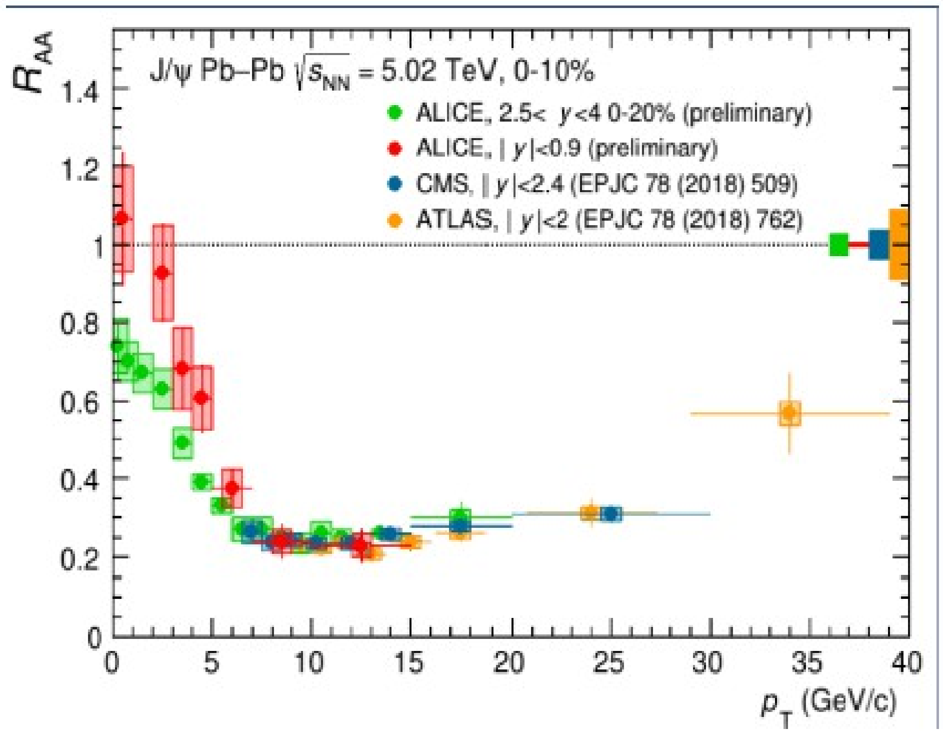




charmonium formation from uncorrelated c quarks at the phase boundary ──► direct proof of deconfinement for charm quarks, see Nature 561 (2018) 321

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

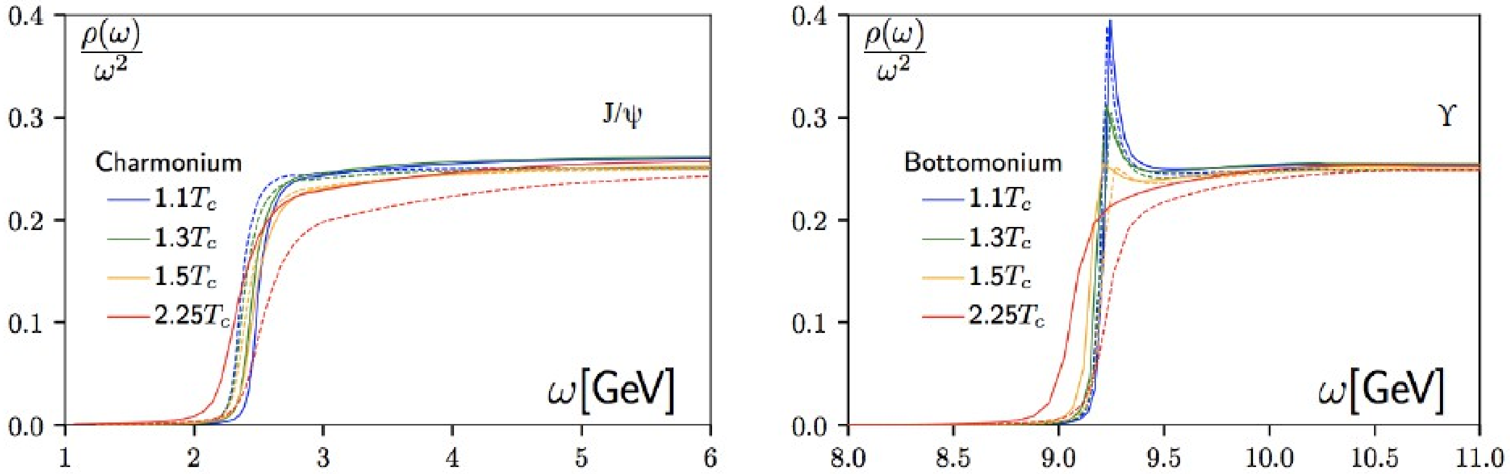
an aside: charmonium melts at T_c

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

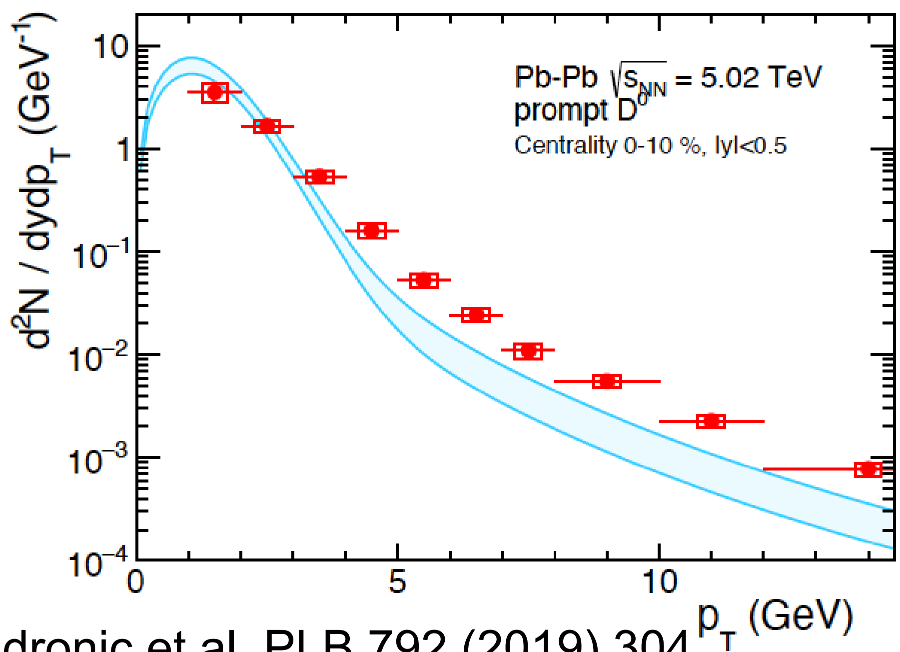
statistical hadronization for hidden and open charm

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.

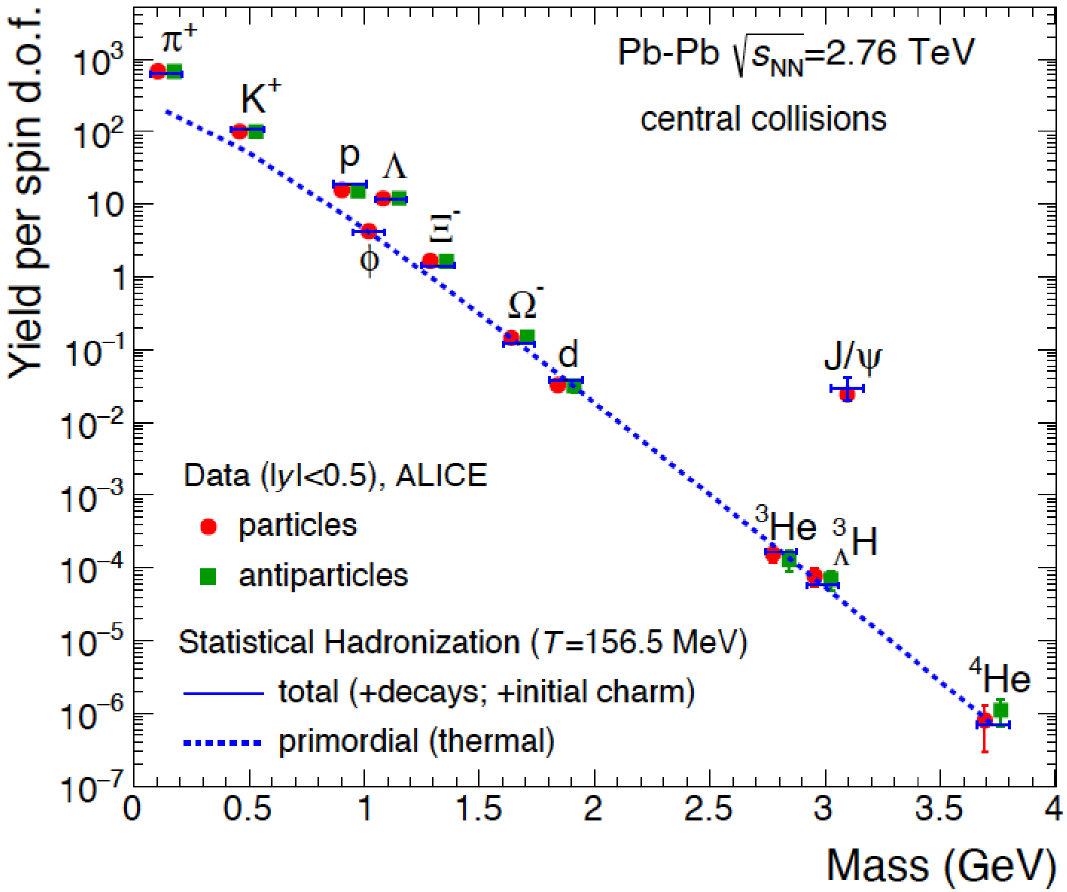
production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0



Andronic et al, PLB 792 (2019) 304 and 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

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

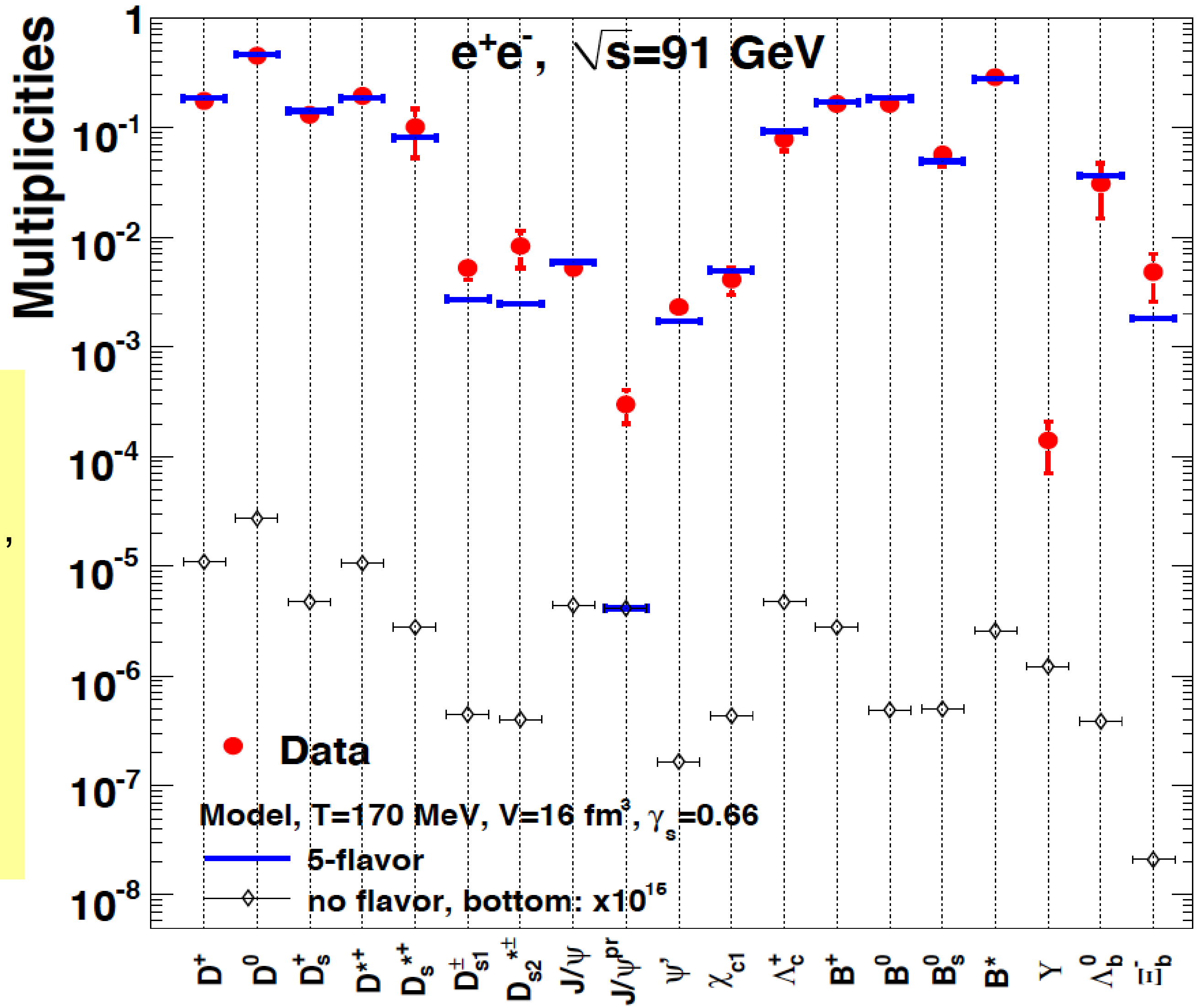


Figure 1. Multiplicities of hadrons with charm and bottom quarks in e^+e^- collisions compared to the thermal model calculations for two cases: i) the 5-flavor jet scheme (thick lines) and ii) no (net) flavor jet scheme (thin lines with diamonds). Note, for case ii) the factor 10^{15} used to scale the 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 $u\bar{u}$ and $c\bar{c}$ and 21.6% for $d\bar{d}$, $s\bar{s}$ and $b\bar{b}$) 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.

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 measured) open charm cross section in Pb-Pb collisions
for now, use pp and pPb data from ALICE and LHCb
rapidity dependence is important

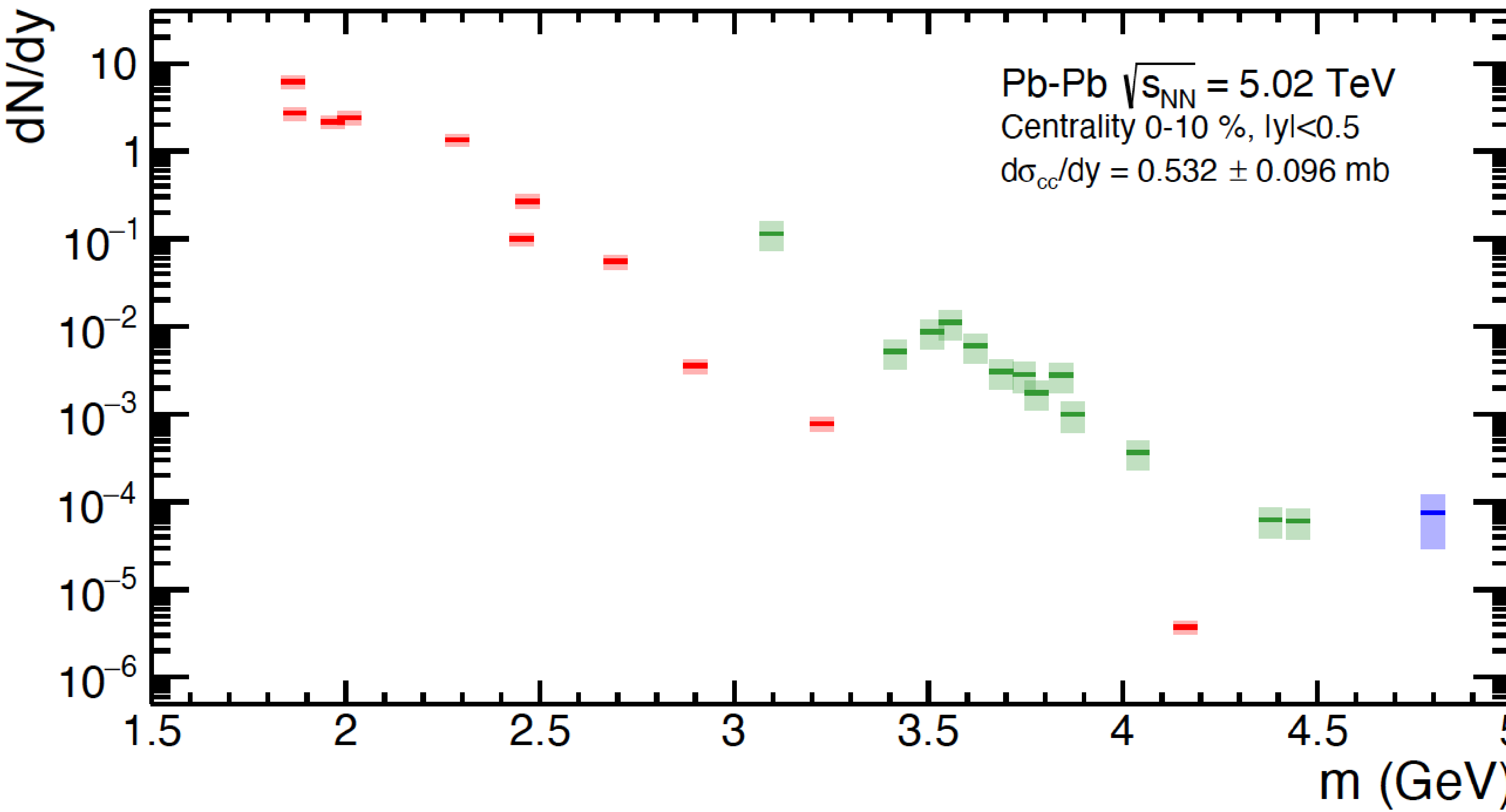
no free parameter to adjust but we realize that the hadronic mass spectrum in the charm and beauty sector is still incomplete

speculations about a large number of additional baryons with charm

particle	m (GeV)	dN/dy
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

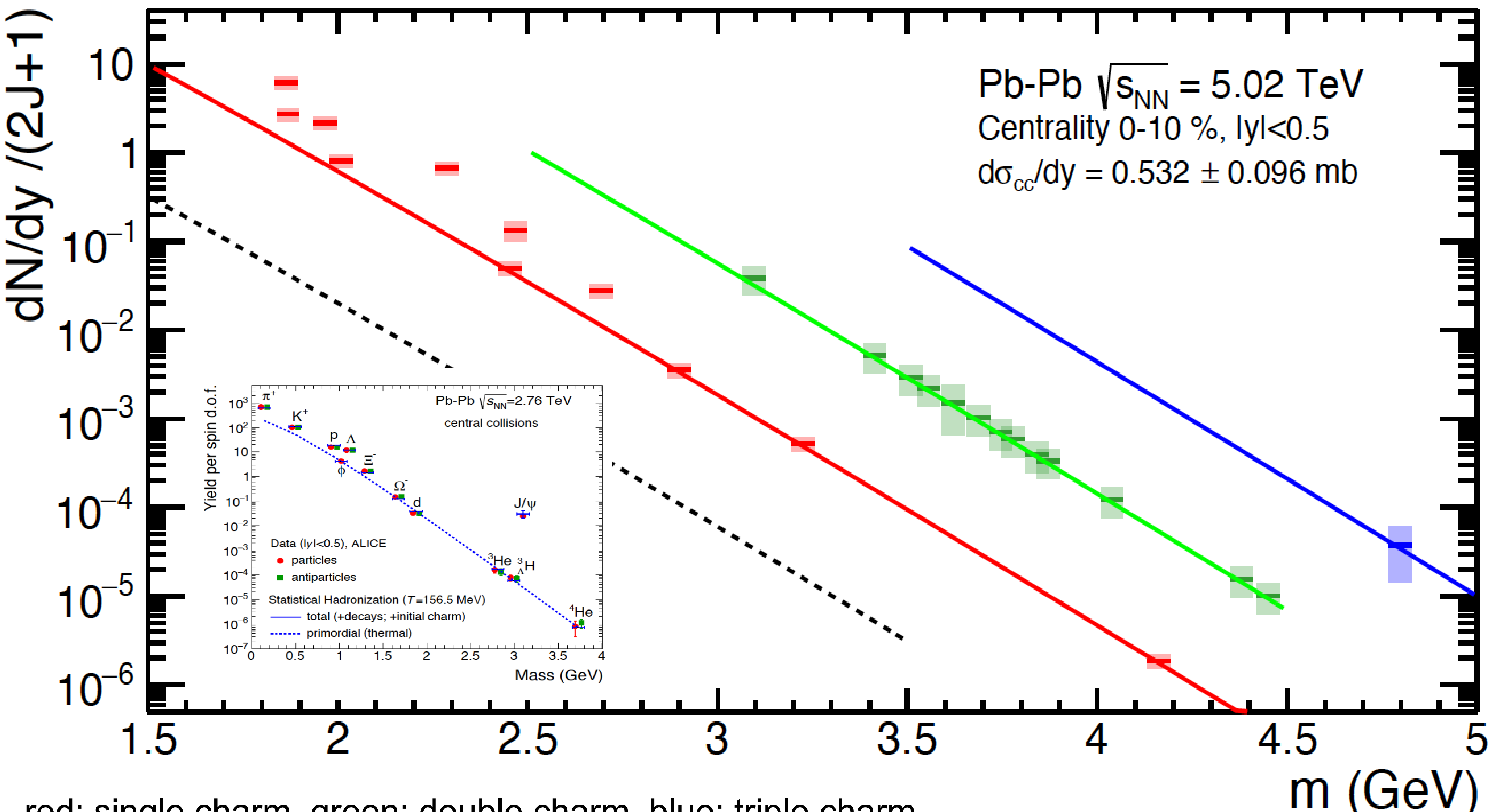
Table 1: Yields for Pb–Pb = 5.02 TeV, mid-rapidity, $d\sigma_{c\bar{c}}/dy = 0.532$ mb.

yields for production of charm hadrons vs. mass



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

yields/degeneracy for charm hadrons

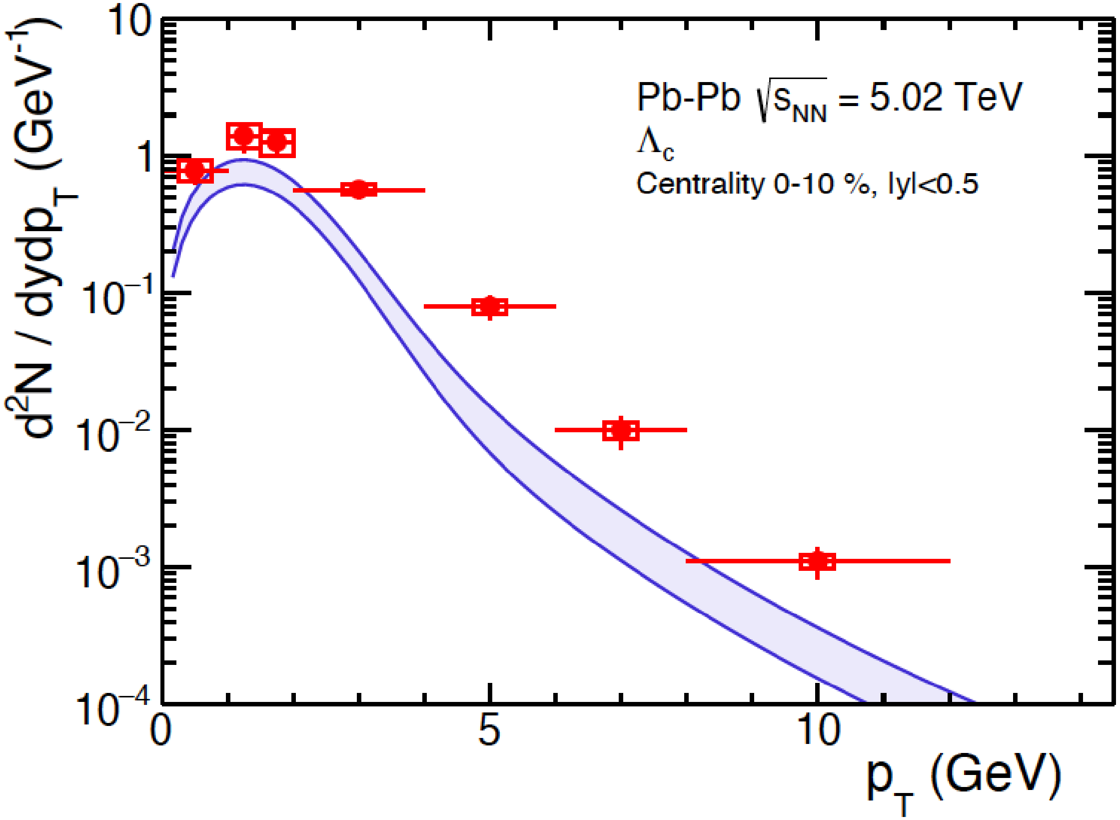


red: single charm, green: double charm, blue: triple charm

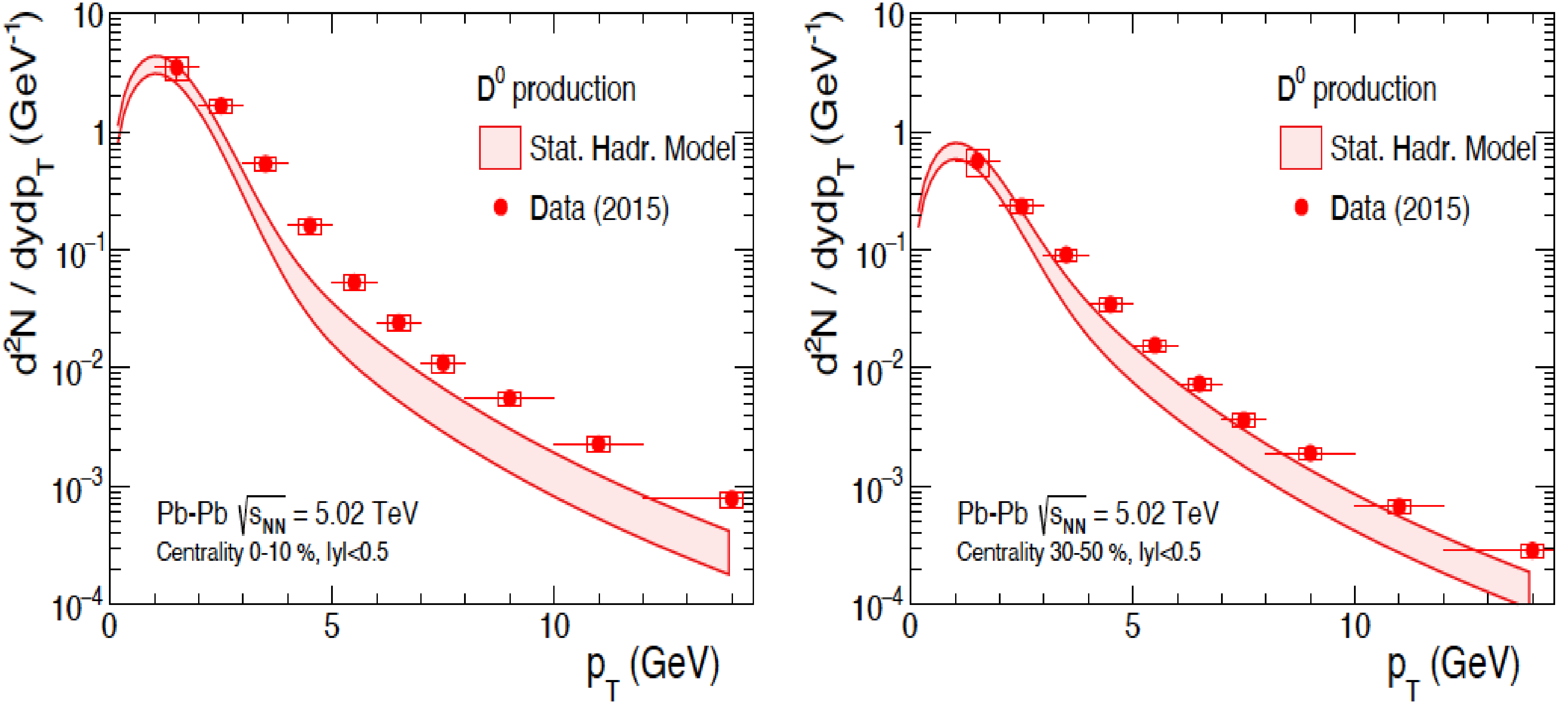
lines: primordial SHM predictions

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

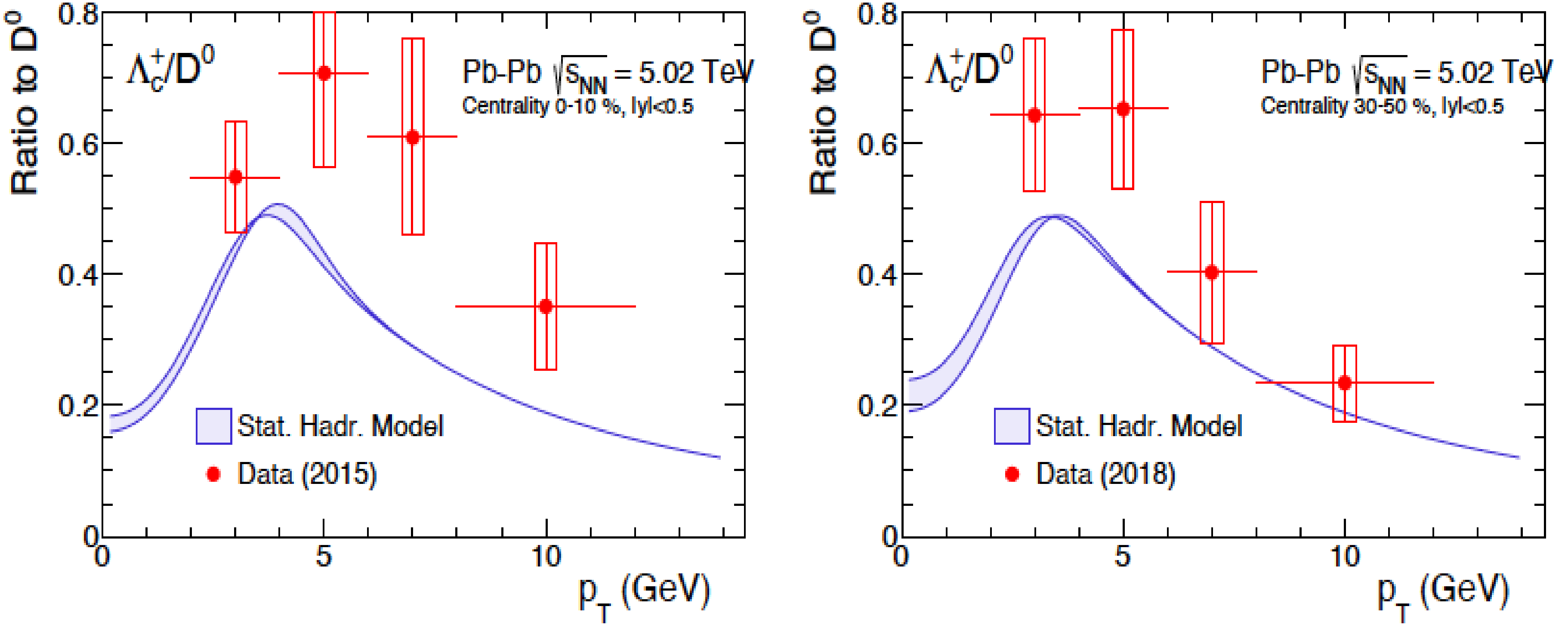
now p_T distributions and data



centrality dependence of D^0

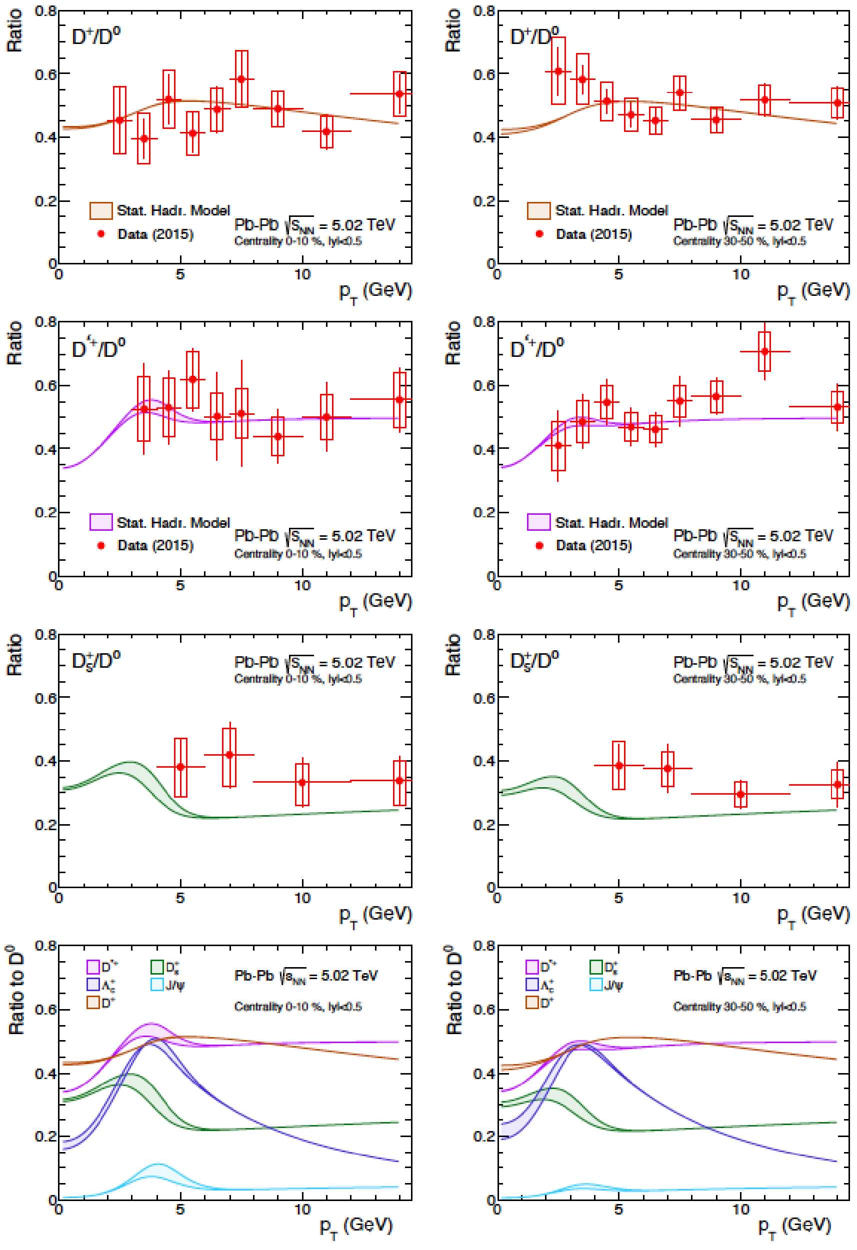


Λ_c/D^0 ratio

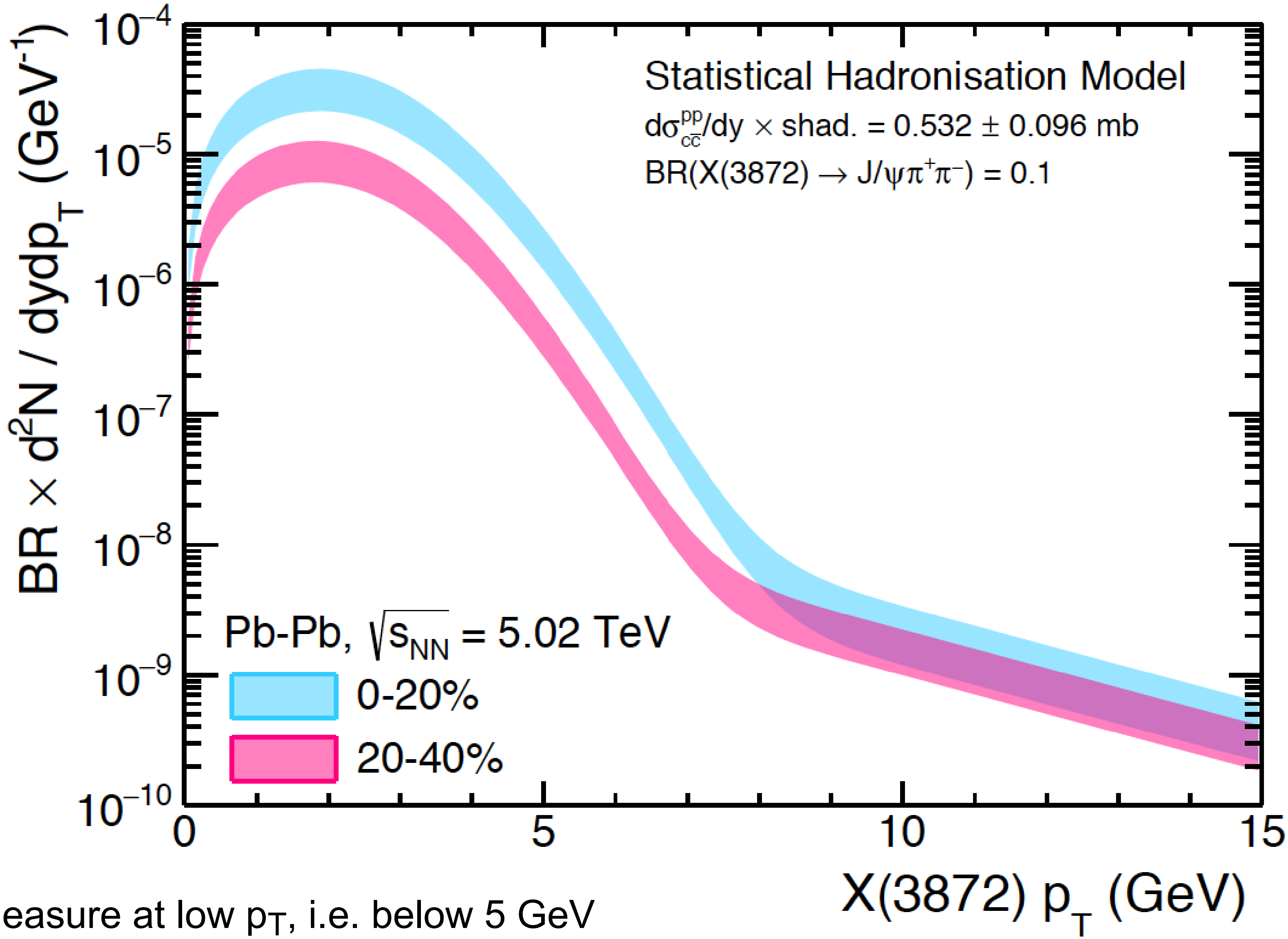


maybe more charmed baryons than listed in the PDG?

ratios continued



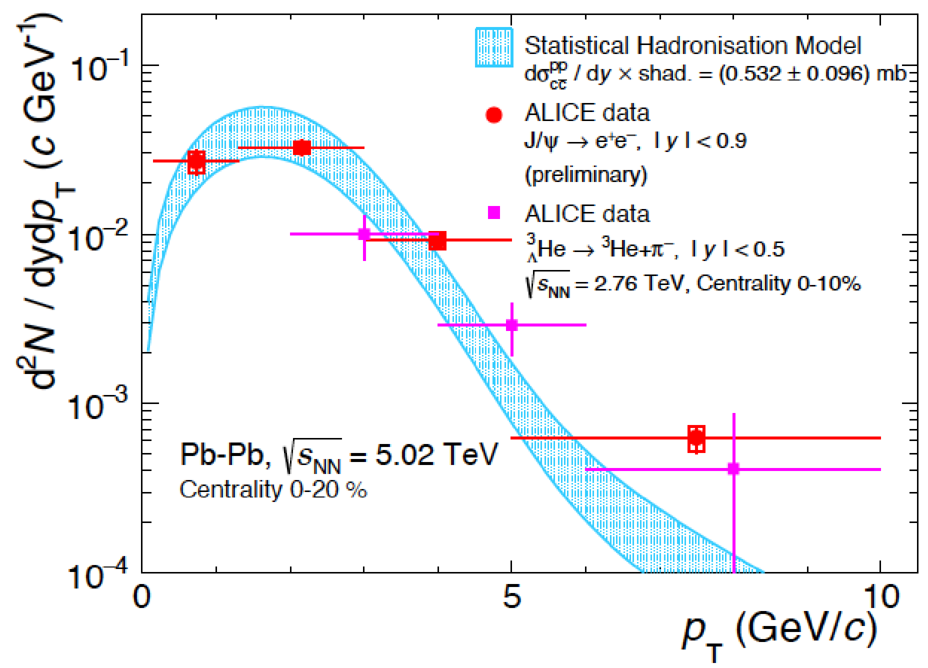
transverse momentum spectrum for X(3872) in the statistical hadronization model
Pb-Pb collisions at 5 TeV/u



need to measure at low p_T, i.e. below 5 GeV

comparison J/ψ and hypertriton

see pbm, Doenigus, Nucl. Phys. A 987 (2019) 144-201



hypertriton distribution scaled by g_c^2

outlook

when precision of open charm cross section improves one can look into higher order corrections such as canonical treatment, correlation width in rapidity, etc.

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?

need to improve knowledge about charmed baryons

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