Hadronization of the QGP

- some historical comments: the QGP in ALICE phase 1 and 2
- the statistical hadronization model and ALICE data
- remarks on the importance of low transverse momentum coverage
- charm and multi-charm hadrons, deconfinement and universal hadronization
- outlook

pbm
talk on behalf of the ALICE collaboration
workshop on
Discovery Physics at the LHC
Kruger Park, South Africa
Thursday, Dec. 8, 2022

hadronization of the QGP- the title of this talk
the title of one of Jean Cleymans' transformational papers
Z.Phys.C 58 (1993) 347-356

- the early years: 1970 – 1990 Aachen, CERN, SLAC, Bielefeld
- 1986 - 2021 Professor in Capetown
- 1991 – 1996 the beginning of work on the QCD phase diagram and hadron production
- 1992 the development of the statistical hadronization model
- 2004 – 2021 Jean in the ALICE collaboration

see my detailed remarks at the special session
in memory of Jean Cleymans

Kruger 2022 – Discovery Physics at the LHC
Thursday, Dec. 8, 2022

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

EMMI

GSI

Jean Cleymans
1944 born in Turnhout, Belgium
1970 doctorate in physics Louvain, Belgium
1970 – 1975 fellow positions in Aachen, SLAC, CERN

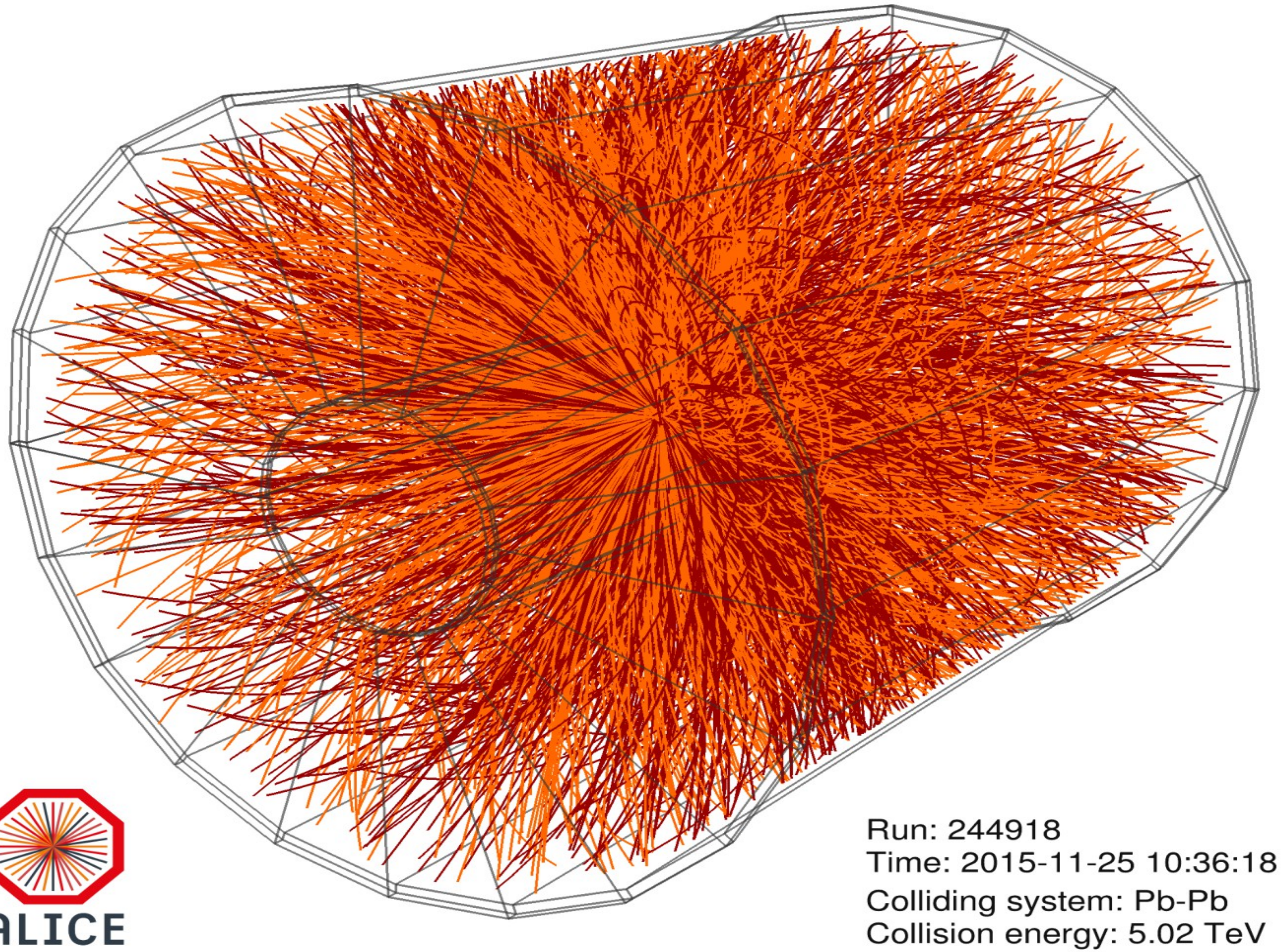
see also:
Satz, H. The Abundance of the Species Physics 2022, 4, 912–919. https://doi.org/10.3390/physics4030059

acknowledgement:

long time collaborators on:
statistical hadronization and deconfinement: Anton Andronic, Krzysztof Redlich, Johanna Stachel

in addition I acknowledge in the work on
multicharm production:
Bengt Friman, Pok Man Lo, Aleksas Mazeliauskas, Vytautas Vislavicius

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



Run 1: 3 data taking campaigns
pp, pPb, Pb-Pb

Run 2 with 13 TeV pp
Pb-Pb run 5 TeV/u
pPb Run at 5 and 8 TeV

Snapshot taken with the ALICE TPC

March 2022: Run 1 and Run 2 combined: 418 publications

as of March 24, 2022, LHC Run 3 has started!

central Pb-Pb collisions:
more than 32000
particles produced per collision
at top LHC energy
fireball size > 10 fm

ALICE plans for the coming decade 2022 – 2030
LHC Run 3 and Run 4

ALICE has just been 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

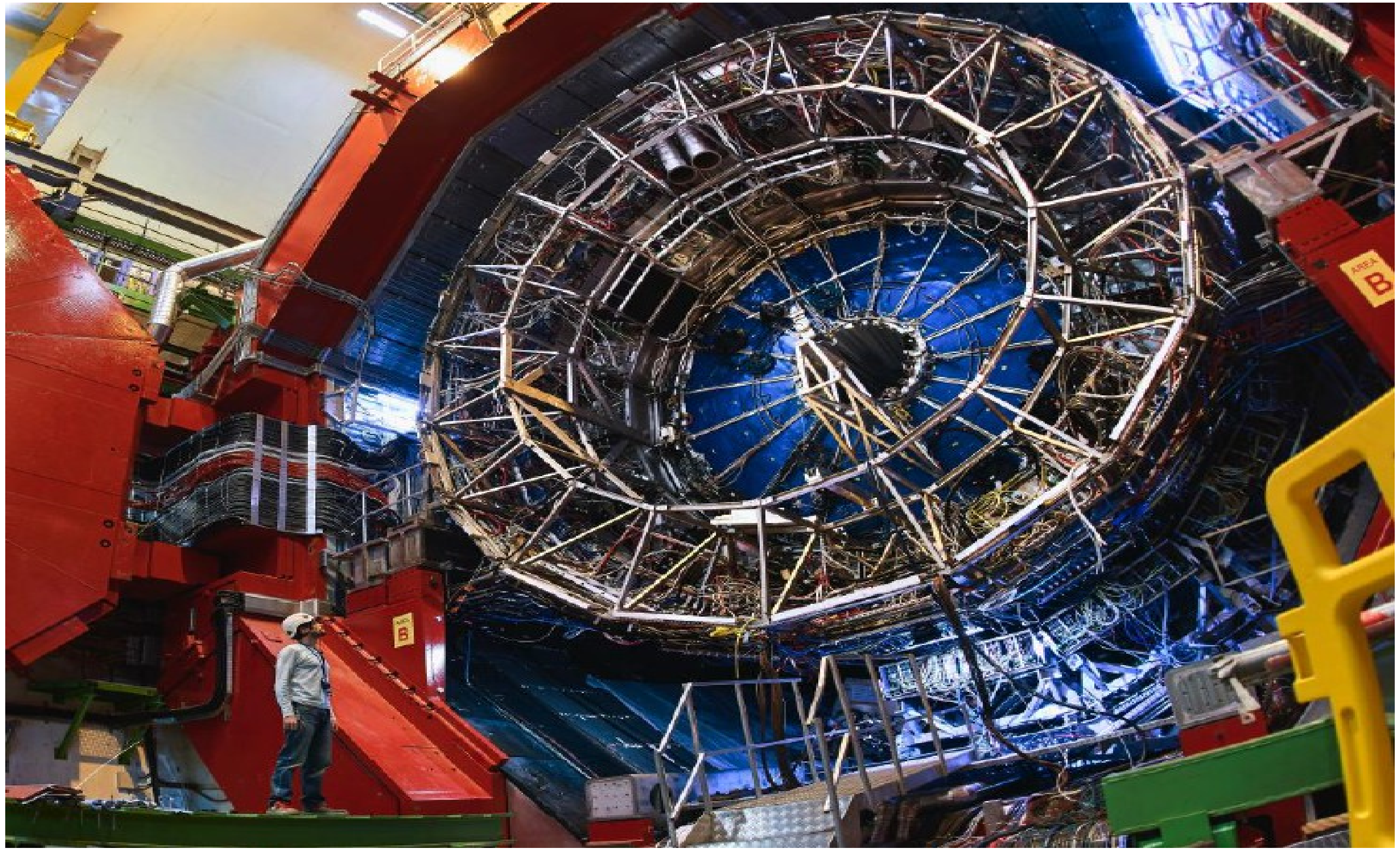
focus on rare objects, exotic quarkonia, single (and possibly double) charm hadrons to address a number of fundamental questions and issues such as:

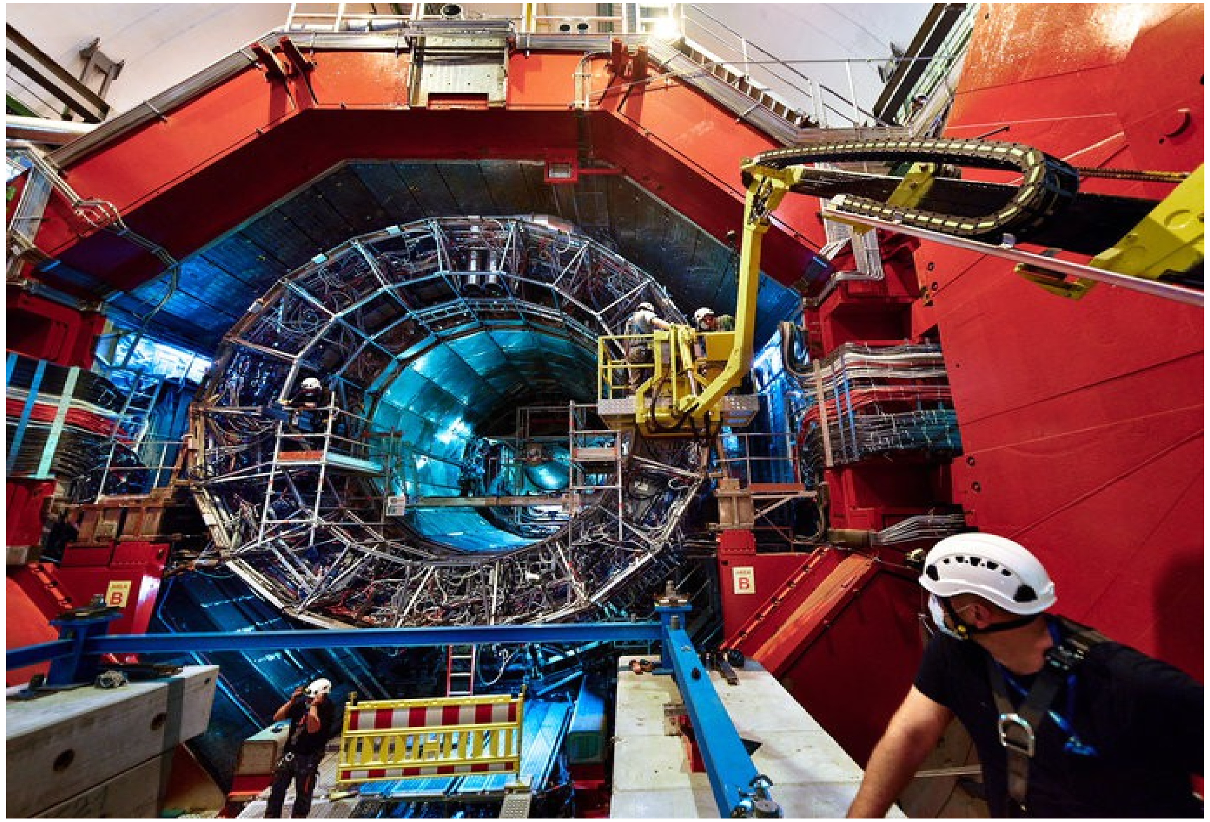
- what is the deconfinement radius for charm quarks
- are there colorless bound states in a deconfined medium?

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

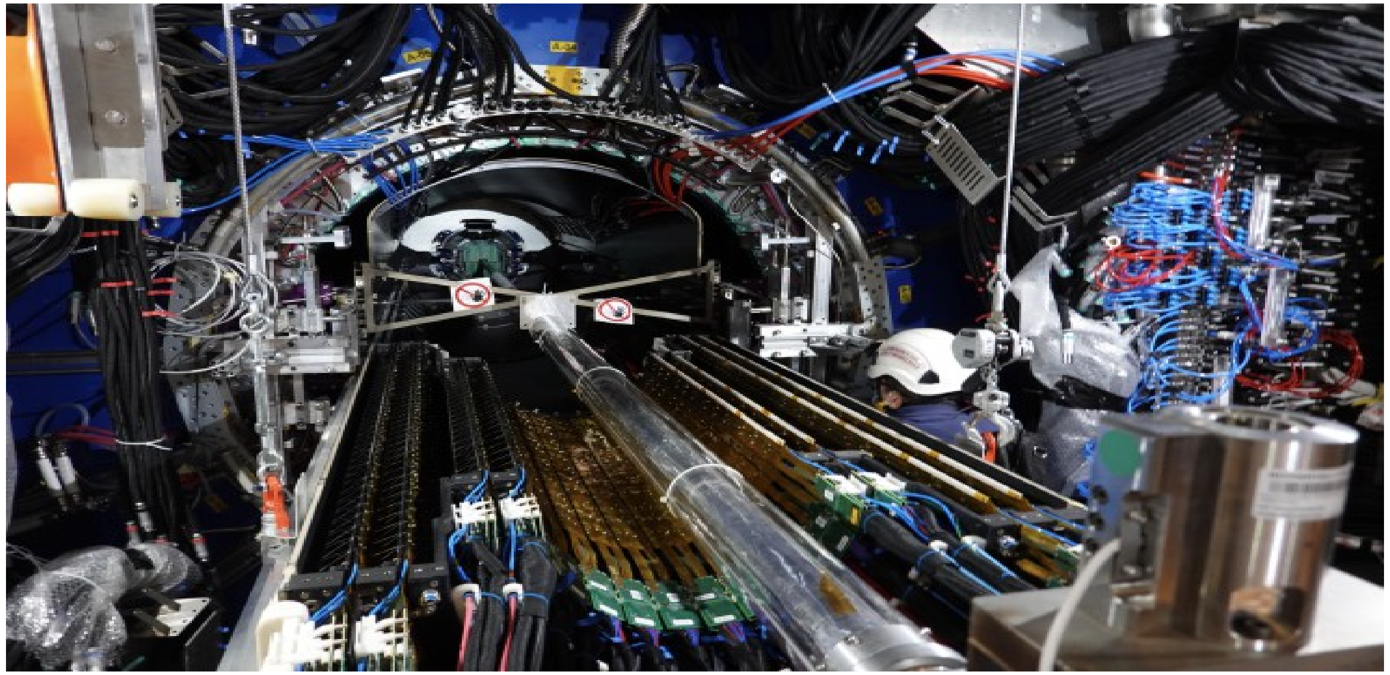
- can fluctuation measurements shed light on the mechanism of baryon production and critical behavior near the phase boundary?

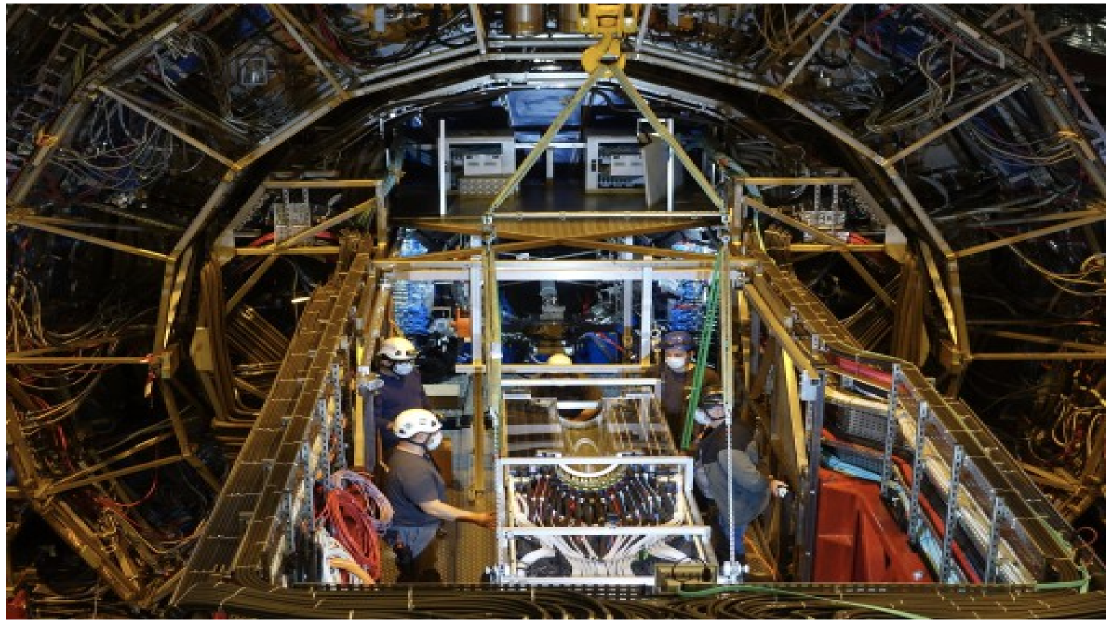
deciphering QCD in the strongly coupled regime





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

a summary of all ALICE data including original references from LHC Run 1 and Run 2 is found at the very recent ALICE review paper:

``The ALICE experiment - A journey through QCD,"
[arXiv:2211.04384 [nucl-ex]].

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:

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

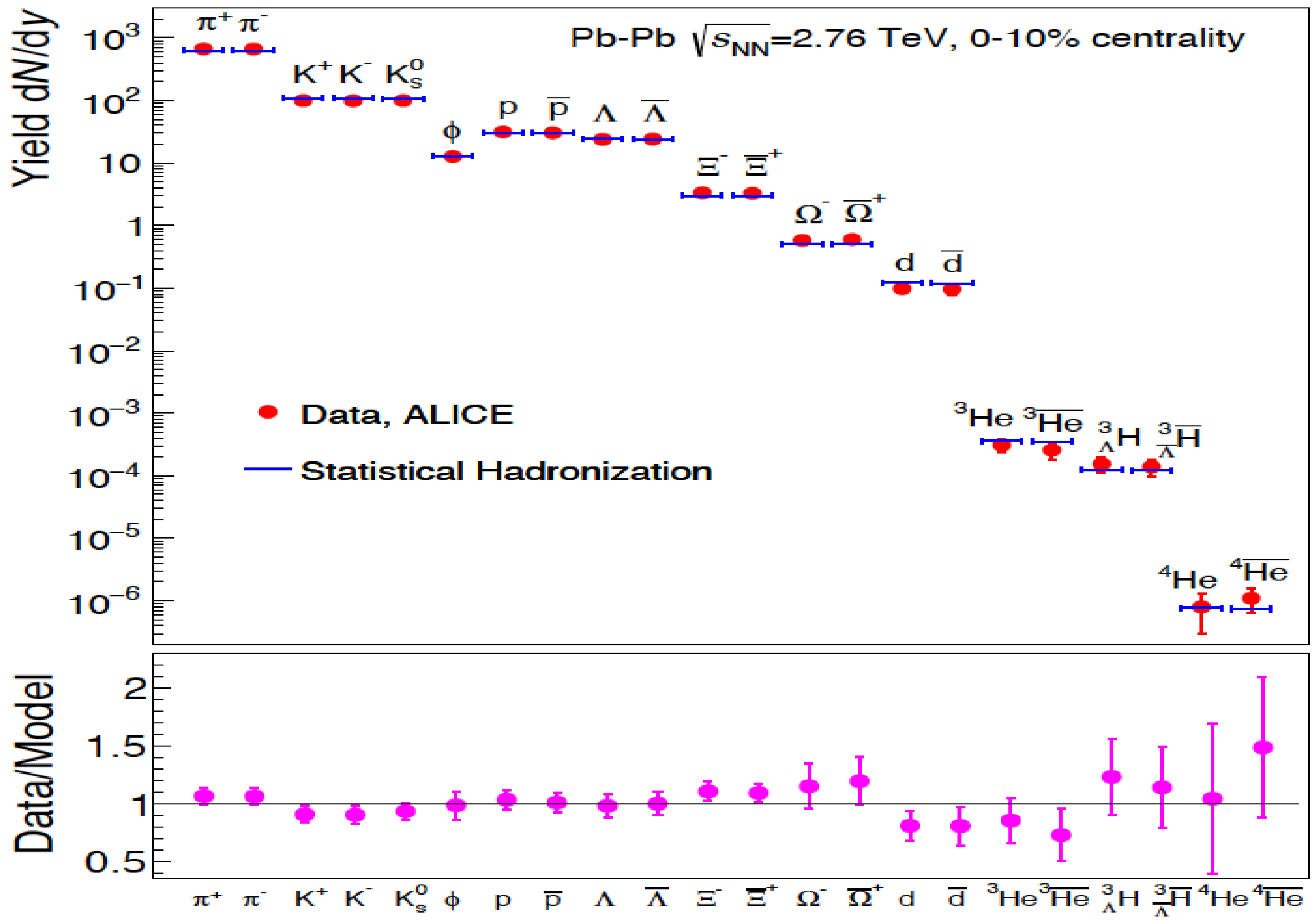
from
parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

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 inter-actions (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

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

Production of hadrons and (anti-)nuclei at LHC

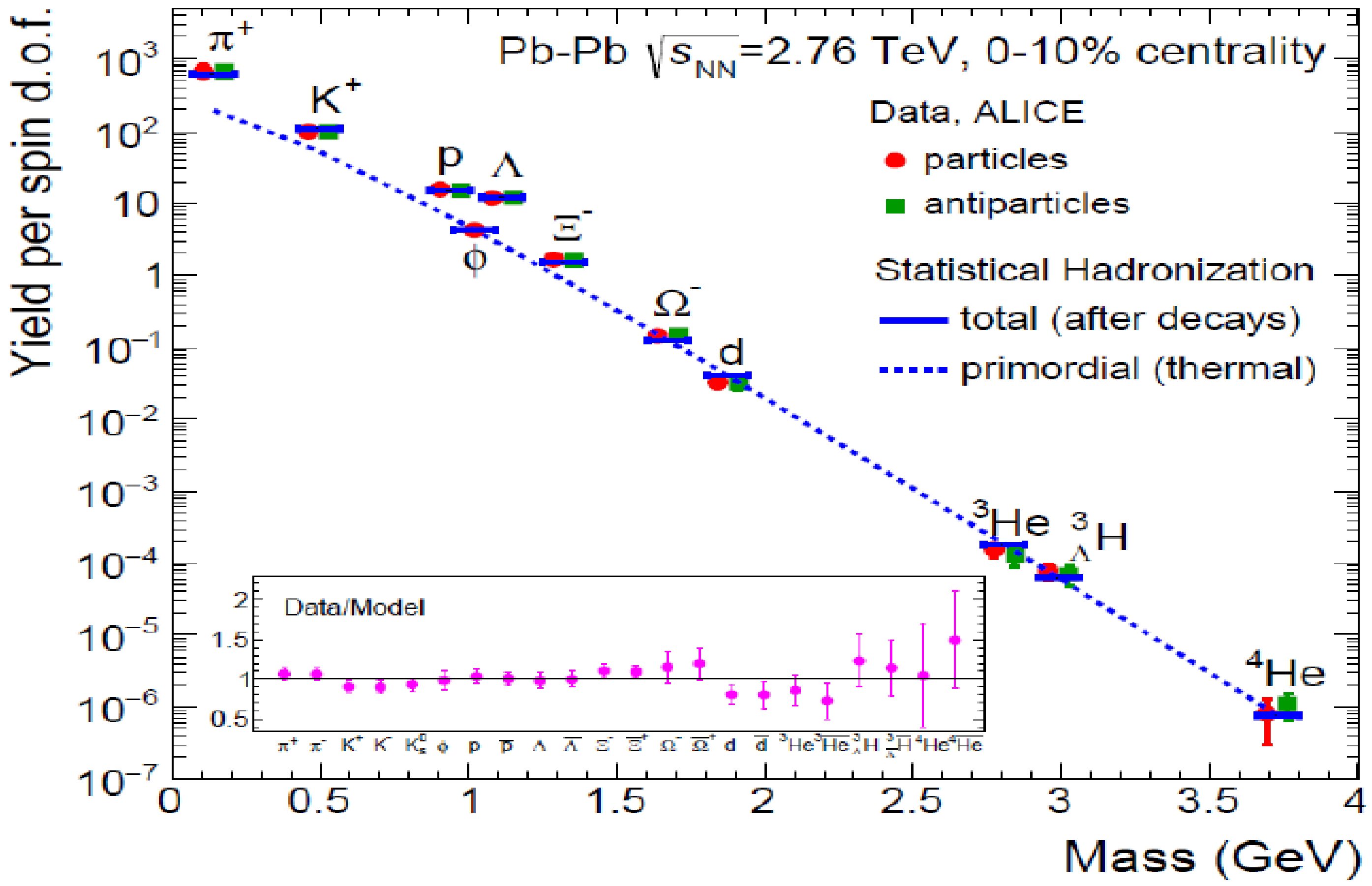
1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

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

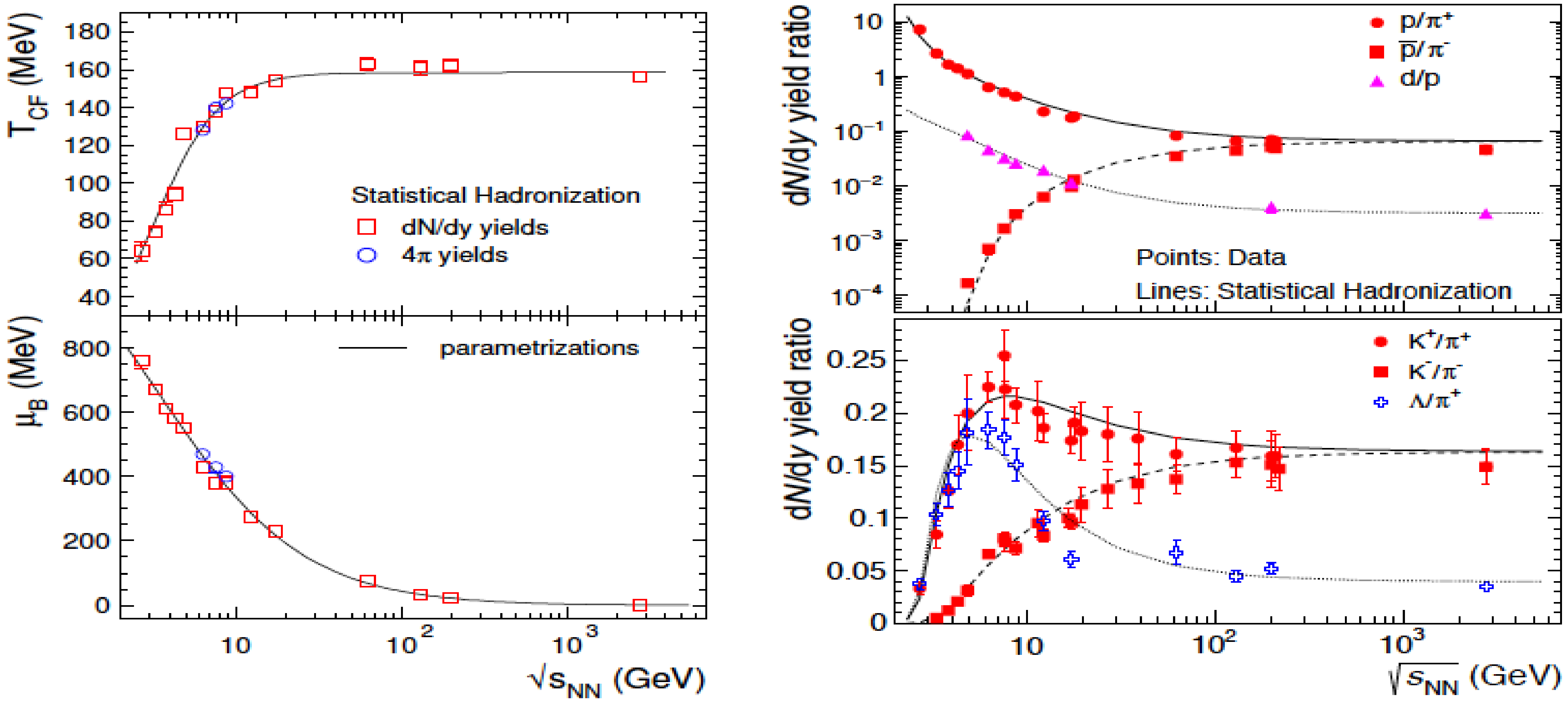
- matter and antimatter are formed in equal portions at LHC
- even large very fragile hypernuclei follow the same systematics

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



at LHC energy, all chemical potentials vanish, so strangeness is immaterial for particle production, particle yields ~ $M^{3/2}\exp(-M/T)$
(no 'strangeness enhancement')

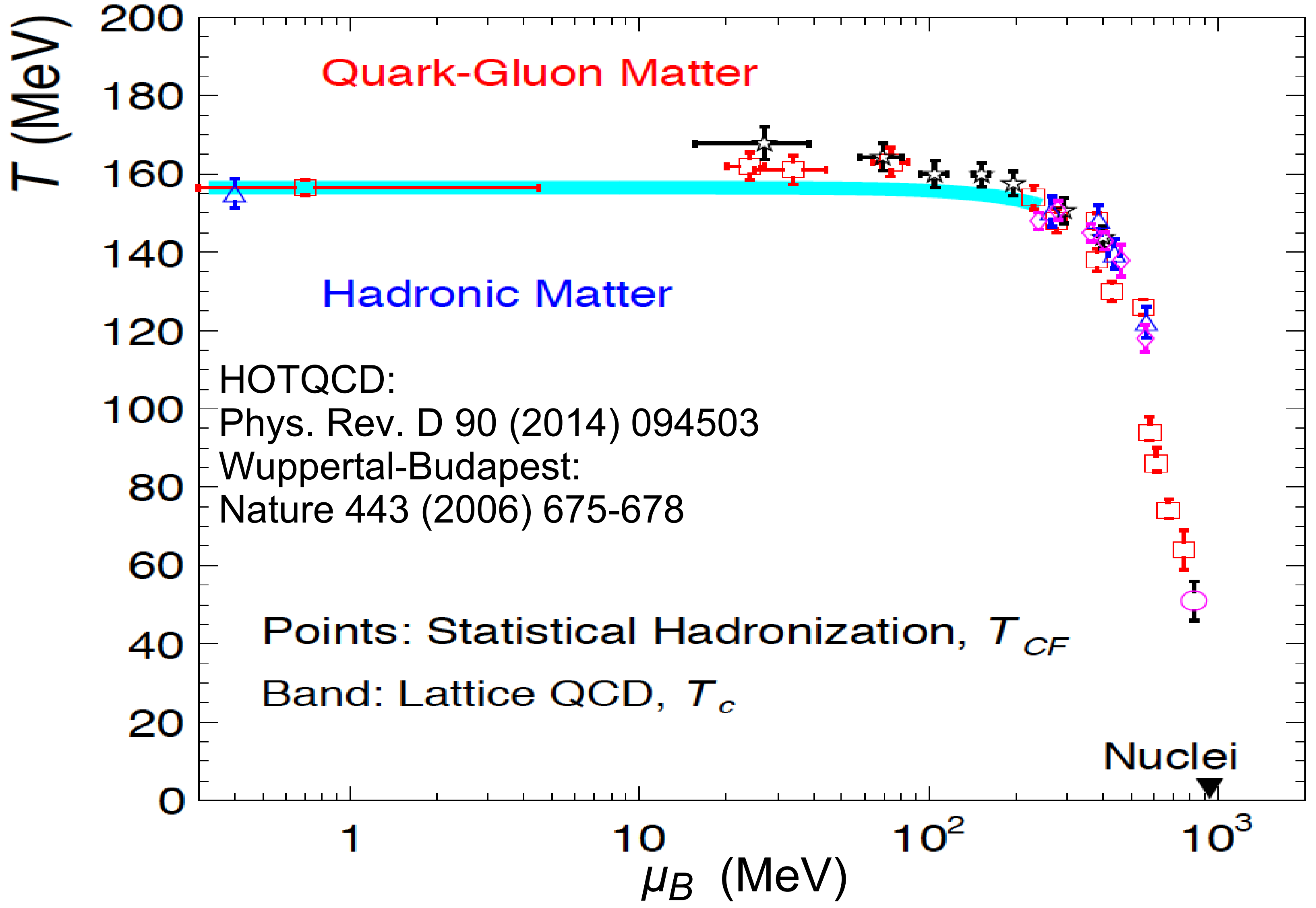
energy dependence of hadron production described quantitatively



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



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

ALICE data: J.~Adam et al. [ALICE],
``Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions,''
Nature Phys. {13} (2017), 535-539

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

arXiv:2009.04484, Phys.Rev.C 103 (2021) 1, 01490
arXiv:2010.02714, CPOD

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

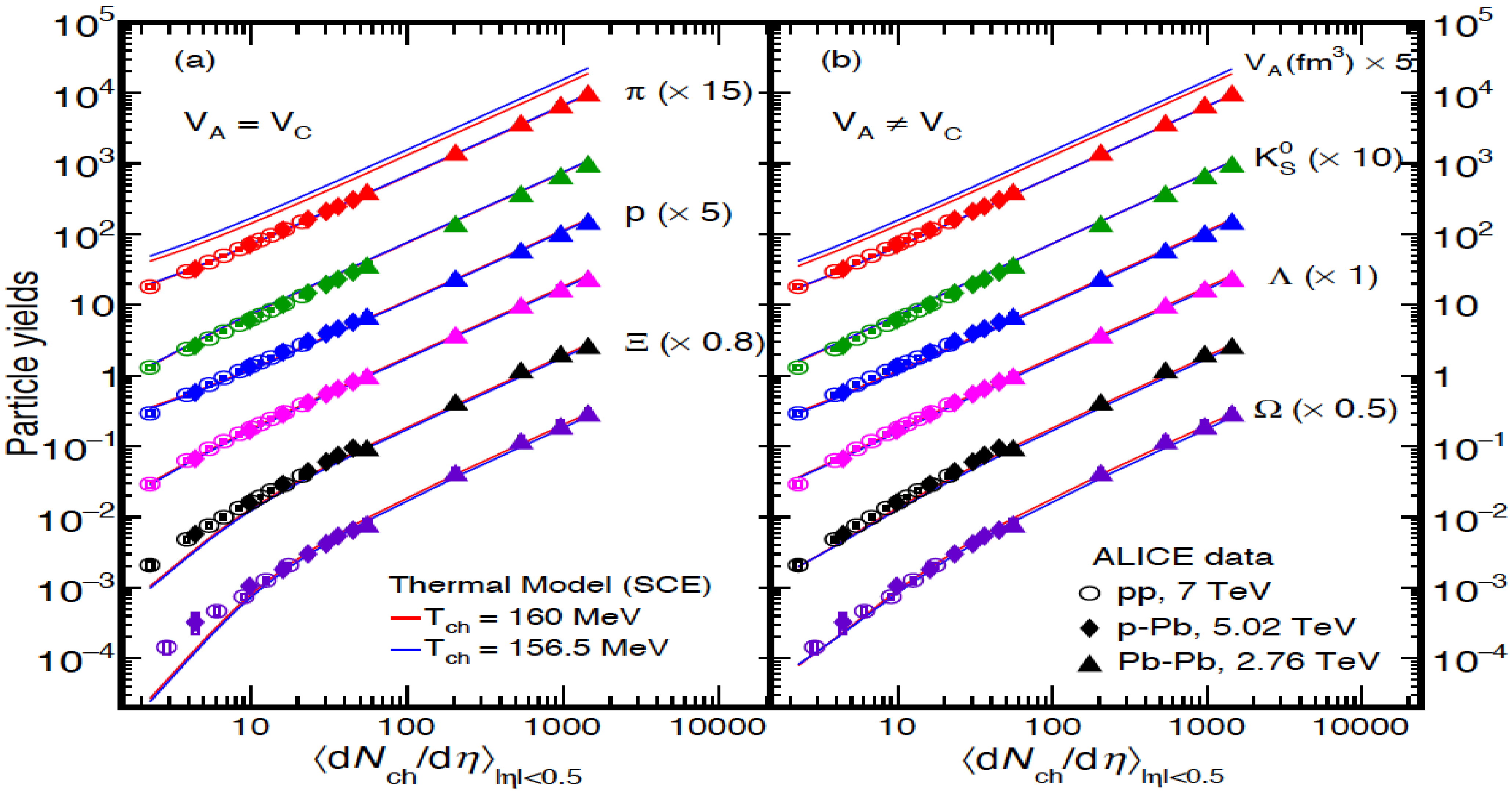


FIG. 5. Left-hand figure: Yields for $V_A = V_C$. Right-hand figure: Yields for $V_A \neq V_C$, Top line is the volume (x5) in fm^3. The particle yields are indicated in the right panel together with the multiplicative factor used to separate the yields. The solid blue lines have been calculated for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

summary so far (2022) – production of (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
- first measurements from ALICE at the 5% accuracy level showed 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, see below

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

why emphasis on low transverse momenta p_T?

- the bulk of particles produced in hadronic and nuclear collisions takes place at $p_T < 1$ GeV
- typical sizes of the interaction region range from 1 fm (pp collisions) to > 10 fm (Pb—Pb collisions)
- our main emphasis is to create matter (such as the quark-gluon plasma) in such collisions and study its properties
- matter (in contrast to a weakly or non-interacting gas of hadrons) implies some degree of thermalization; thermalization takes place predominantly where the bulk of particles is
- larger systems emit particles at low transverse momenta: $p_T < 1$ GeV implies spatial size $r_T > 0.2$ fm, $p_T < 100$ MeV implies $r_T > 2$ fm, $p_T < 20$ MeV implies $r_T > 10$ fm (note that $\hbar c = 197$ MeV fm)
- all produced particles are accompanied by photons with characteristic $1/p_T$ spectrum, the majority of these photons is at very low p_T (see below)

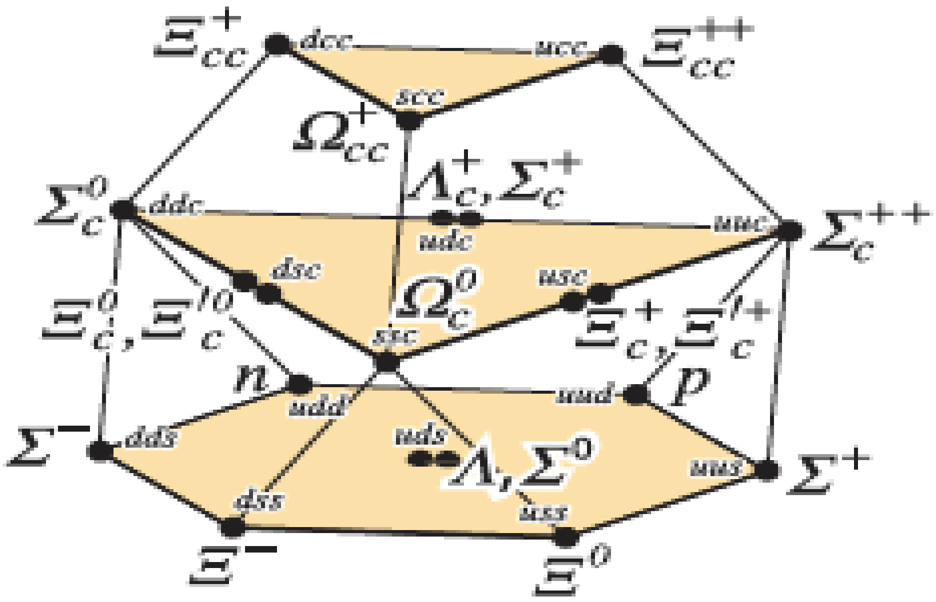
relativistic nuclear collisions and the charm sector

- production of hadrons with charm in relativistic nuclear collisions
- brief review of quark model of baryons and mesons
- focus on baryons containing charm quarks
- the multiple charm hierarchy
- deconfinement and hadronization of a fireball containing charm quarks

the charm baryons in the quark model

(a)

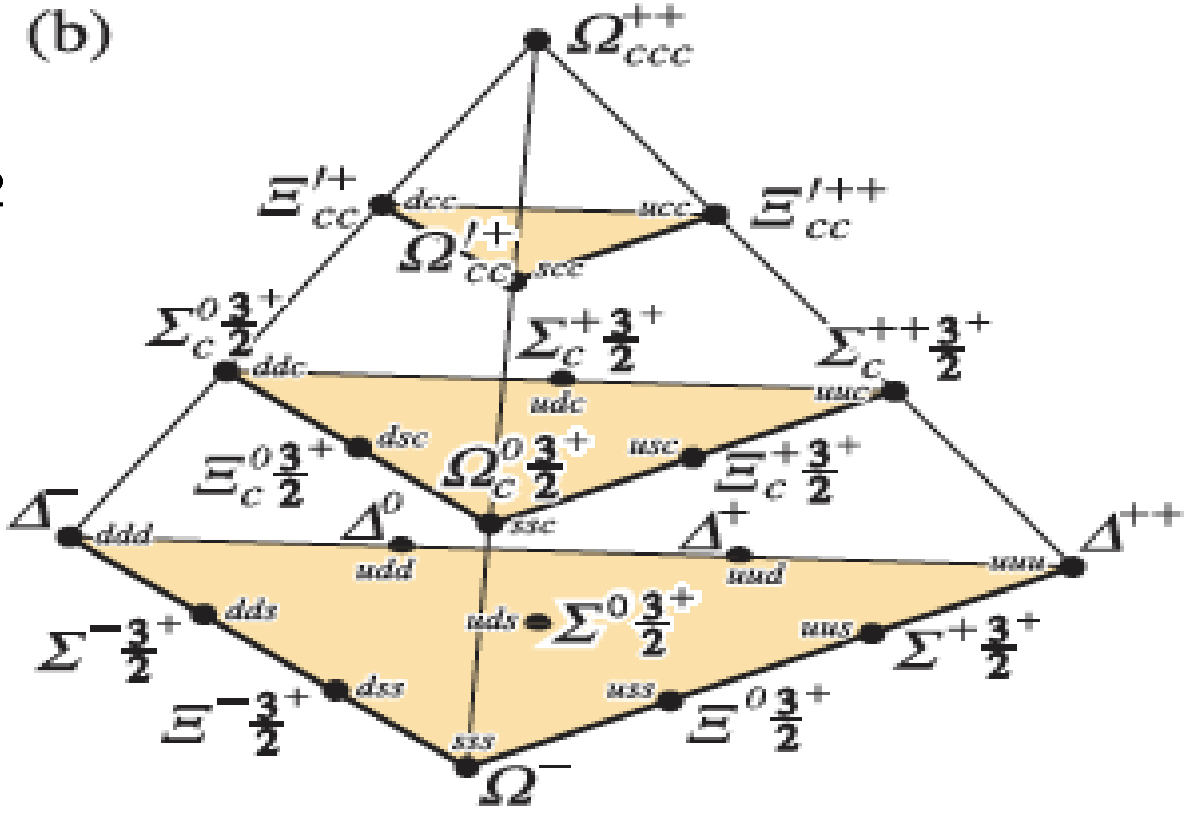
J = 1/2



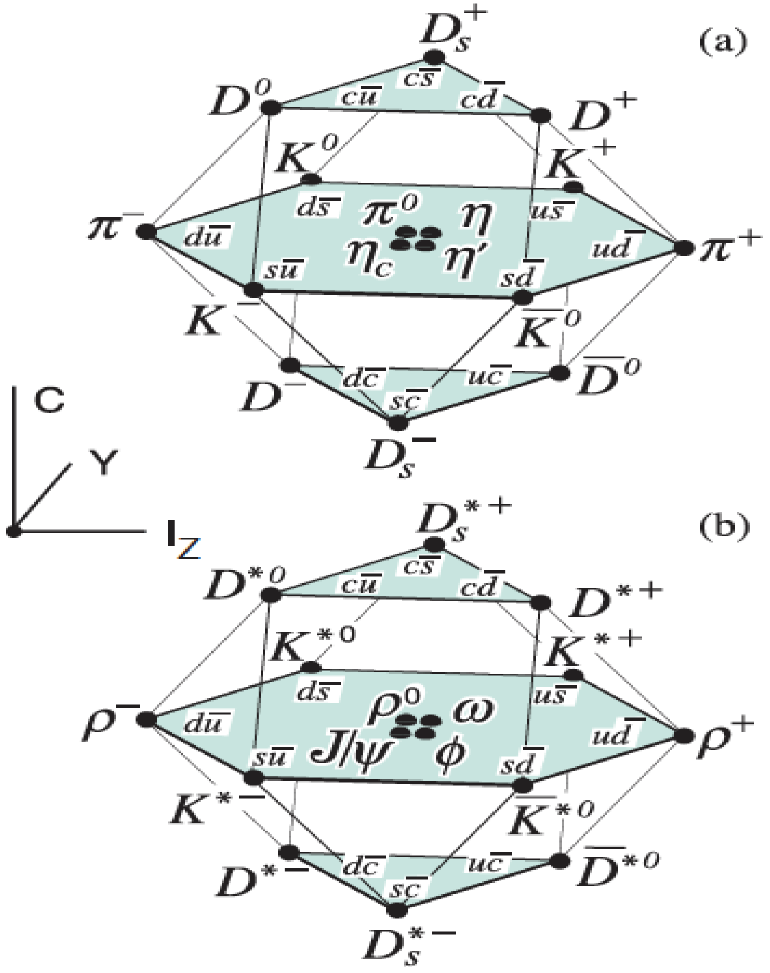
note: baryons with 2 or 3 charm quarks cannot be produced in a single (hard) collision

(b)

J = 3/2



charm mesons in the quark model



the mechanism for statistical hadronization with charm (SHMc)

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

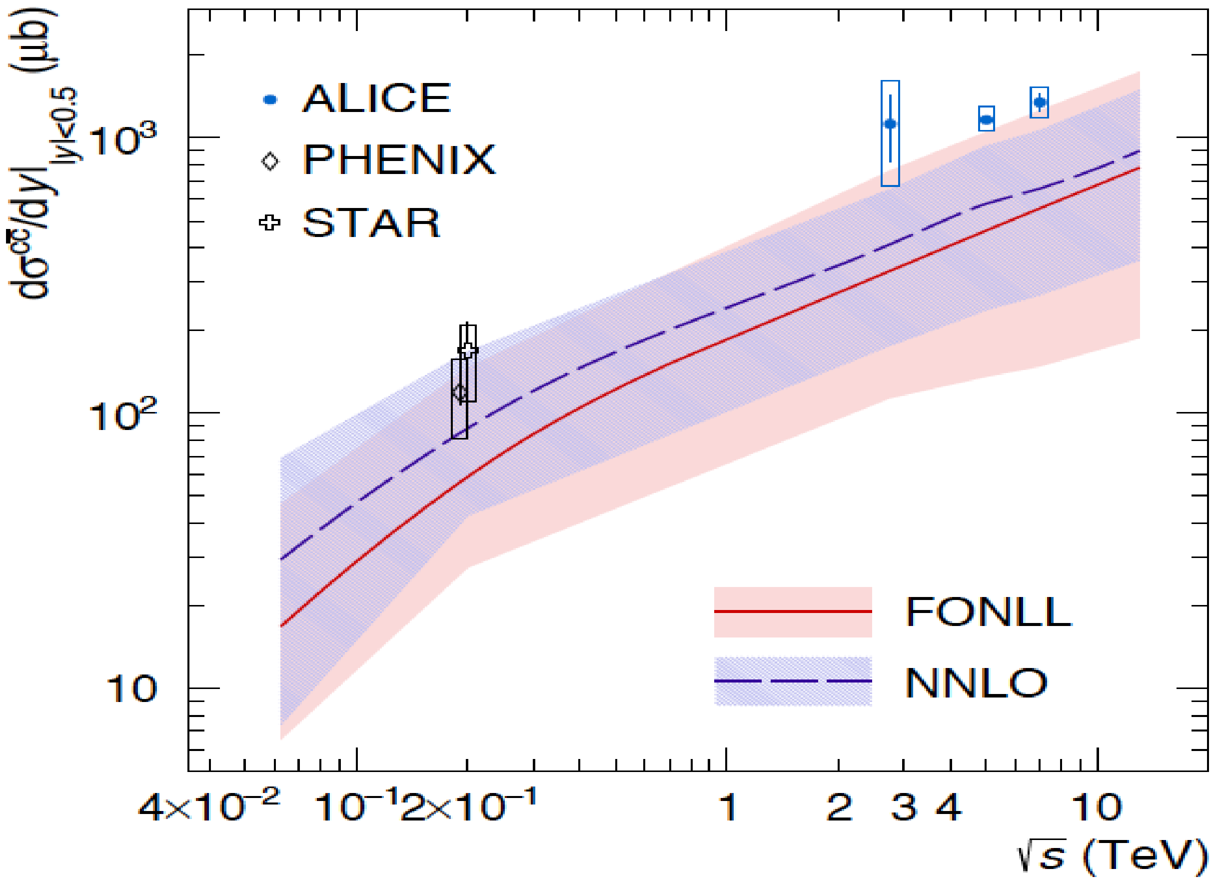
- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_c$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{QCD}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together with other hadrons)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

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

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

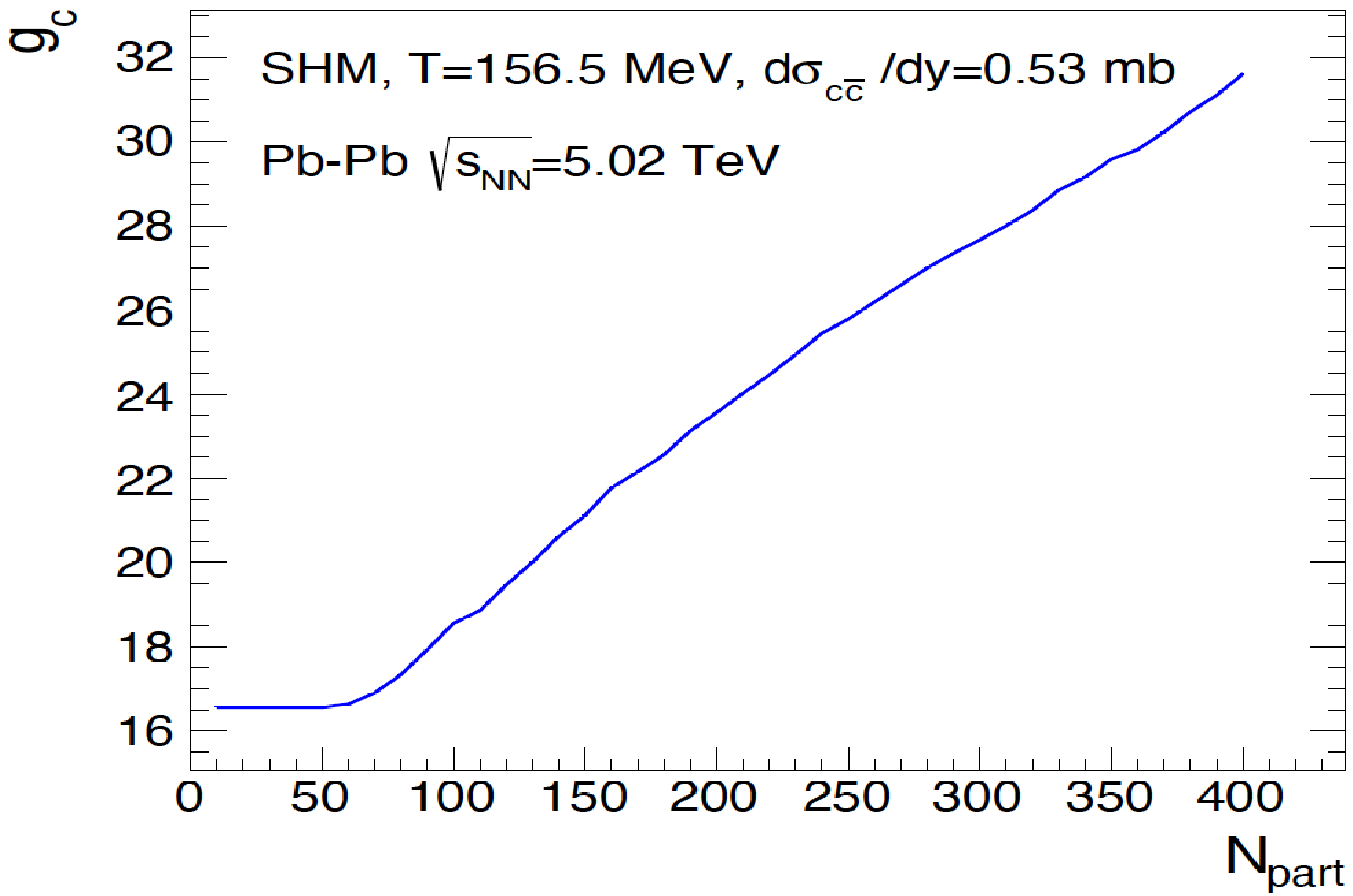
core-corona picture: treat low density part of nuclear overlap region, where a nucleon undergoes 1 or less collisions as pp collisions, use measured pp cross section scaled by $T_{AA} = N_{coll}/\sigma_{inel}^{pp}$ with N_{coll} the number of (hard) collisions as obtained in the Glauber approach

energy dependence of charm production cross section at mid-rapidity



ALICE collaboration, arXiv:2105.06335

centrality dependence of charm fugacity g_c at LHC energy



now SHMc predictions for charmed hadrons compared with spectra and yields as measured in ALICE

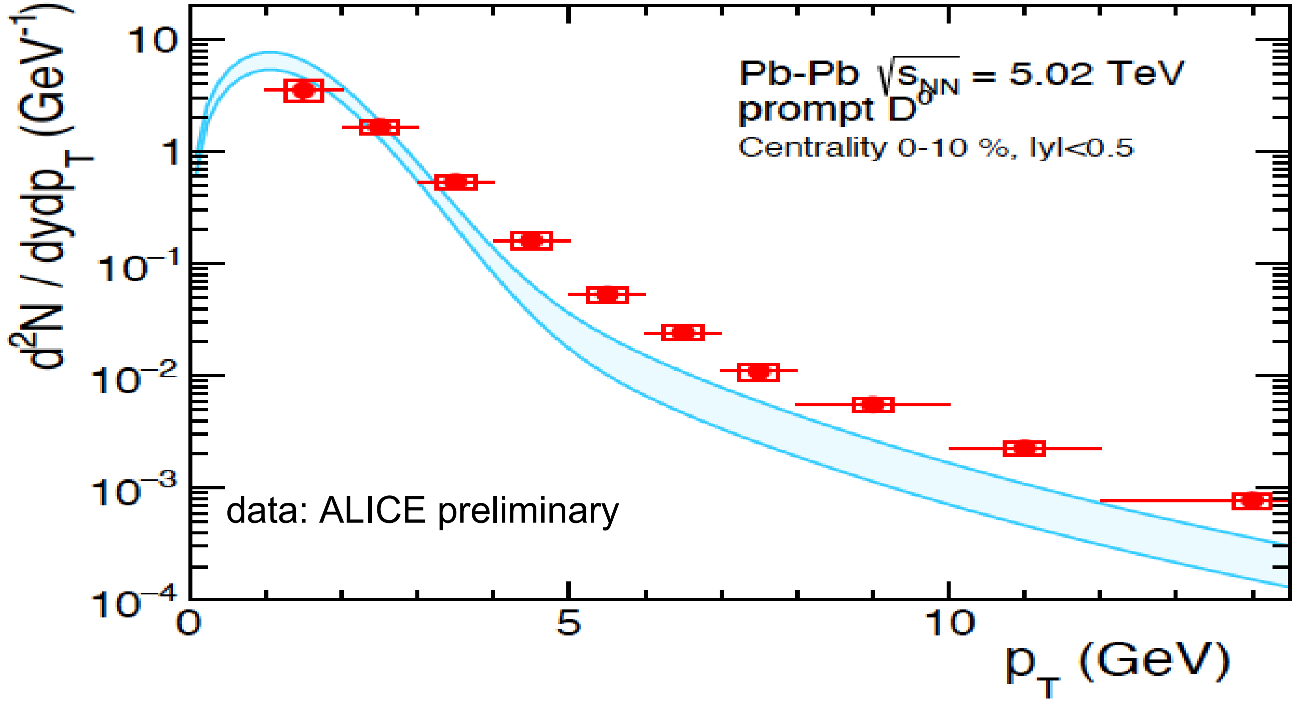
importantly, in the SHMc approach, all charmed hadrons are treated uniformly
the yields of charmonia, (multi-)charm baryons, (multi-)charm mesons etc are predicted without any new parameter
T and μ_B are obtained from (u,d,s) analysis, the only additional input is total open charm cross section, now obtained from inclusive measurement of D^0 production in Pb-Pb collisions

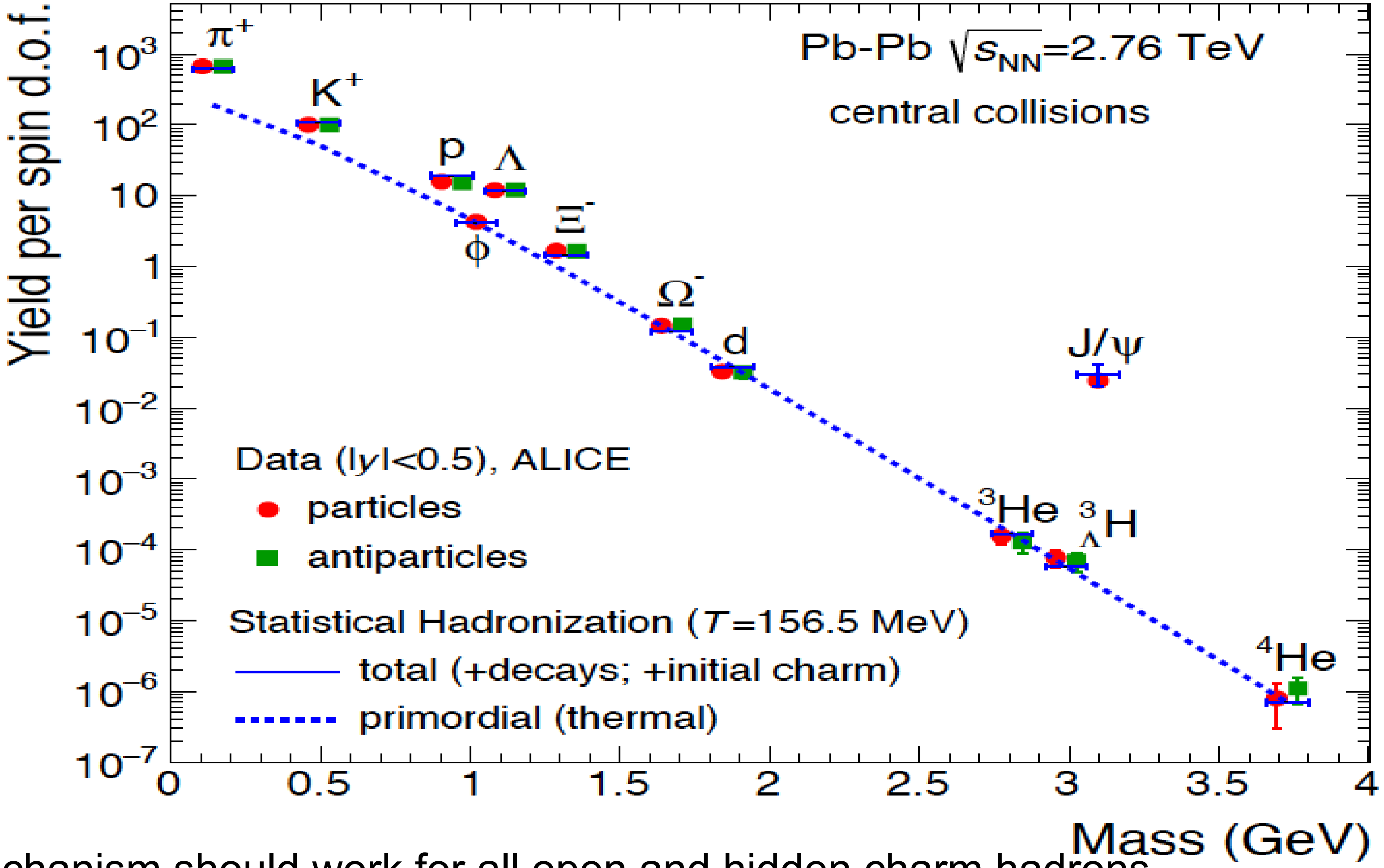
statistical hadronization for hidden and open charm

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, JHEP 07 (2021) 035

quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons, universal hadronization mechanism

even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000

quantitative tests in LHC Run3/Run4 and mainly ALICE 3

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

first we summarize results for hidden charm mesons (J/ψ)

- quarkonia are heavy quark antiquark bound states, i.e. cc_{bar} and bb_{bar}
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV non-relativistic Schrödinger equation can be used to find bound states

$$\left(-\frac{\nabla^2}{2(m_Q/2)} + V(r)\right)\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1\cdot\vec{s}_2}{m_Q^2}\delta(\vec{r}) + \ldots$$

confinement

color Coulomb int.

spin-spin int.

tensor, spin-orbit, higher order rel. corr.

note: the pre-factor of the 'QCD Coulomb term' results from 1 gluon exchange and contains the Casimir factor $C_F = (N_c^2 - 1)/2N_c$ with which all 2-body amplitudes in QCD are multiplied. Here, N_c is the number of colors $N_c = 3$.

and

- with the string tension **σ** ~ 0.9 GeV/fm, the strong coupling constant $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for m_c=1.5 and m_b=4.6 GeV, respectively to obtain the spectrum of quarkonia

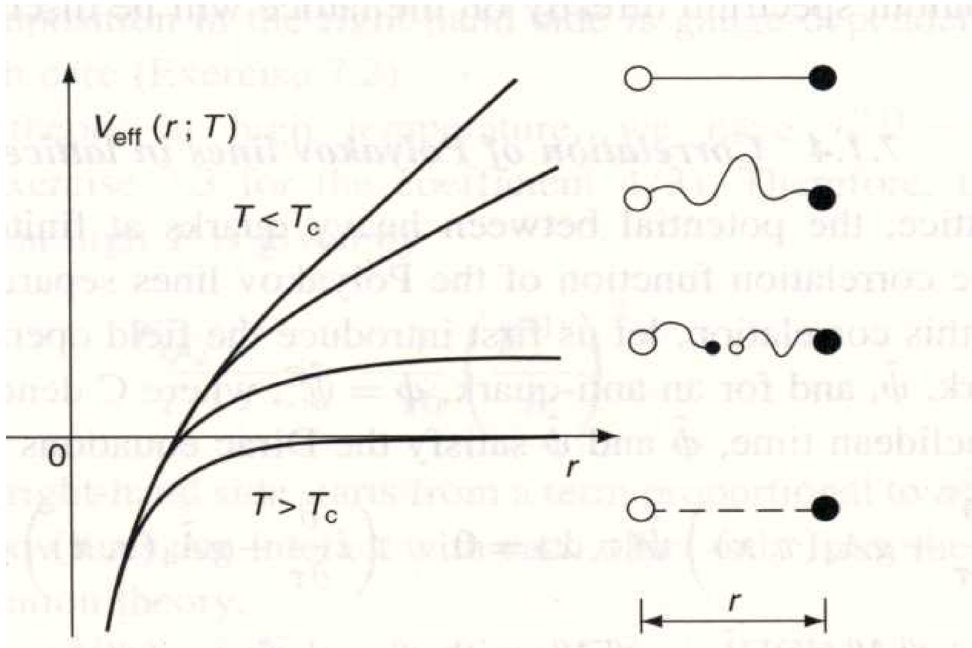
charmonia at finite temperature

consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

consider cc_{bar} in thermal environment of gluons and light quarks

$$V(r) \to V_{eff}(r,T) \quad \text{and} \quad m_Q \to m_Q(T)$$

in QGP color singlet and color octet cc_{bar} states can mix by absorption or emission of a soft gluon
$\rightarrow$ modification of V_{eff}



- reduced string tension as T approaches T_c
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for $T>T_c$ confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r,T) \to -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/\lambda_D}$$

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

note: charmonia are apparently not special, see discussion about T_{cc}+ below

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

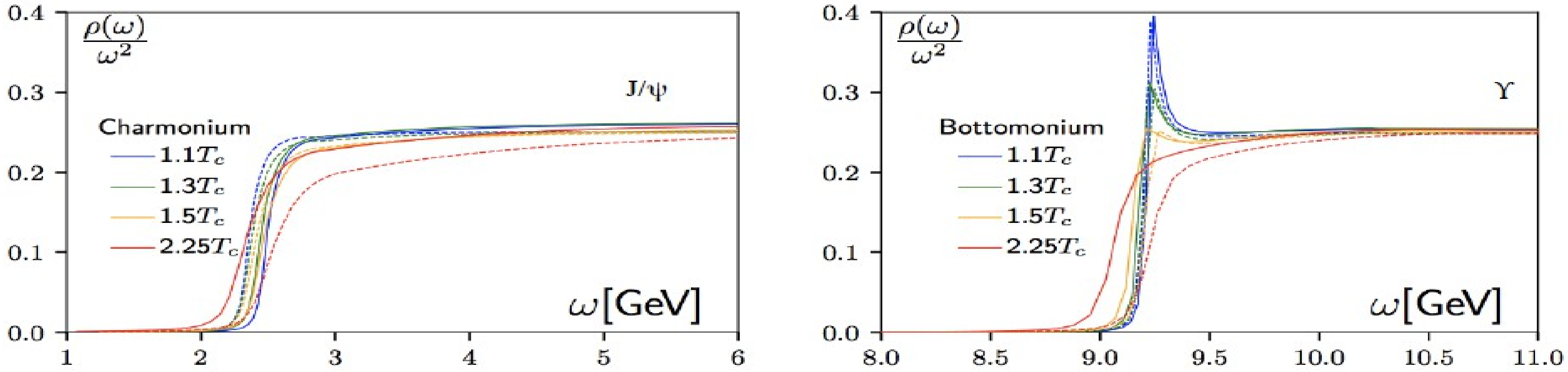
this issue was already anticipated by Blaizot and Ollitrault in 1988

also charm quark production increases strongly with collision energy

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

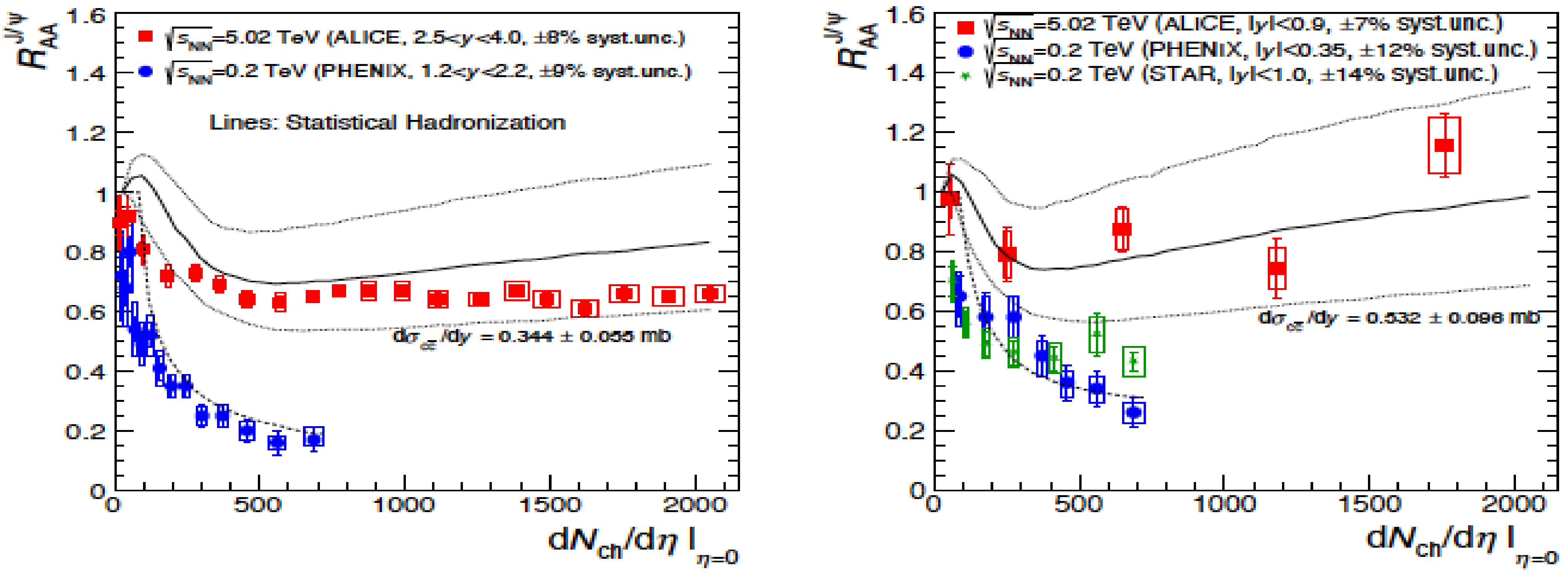
No evidence of survival of
charmonium bound states above T_c

Survival of bottomonium
significantly above T_c

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

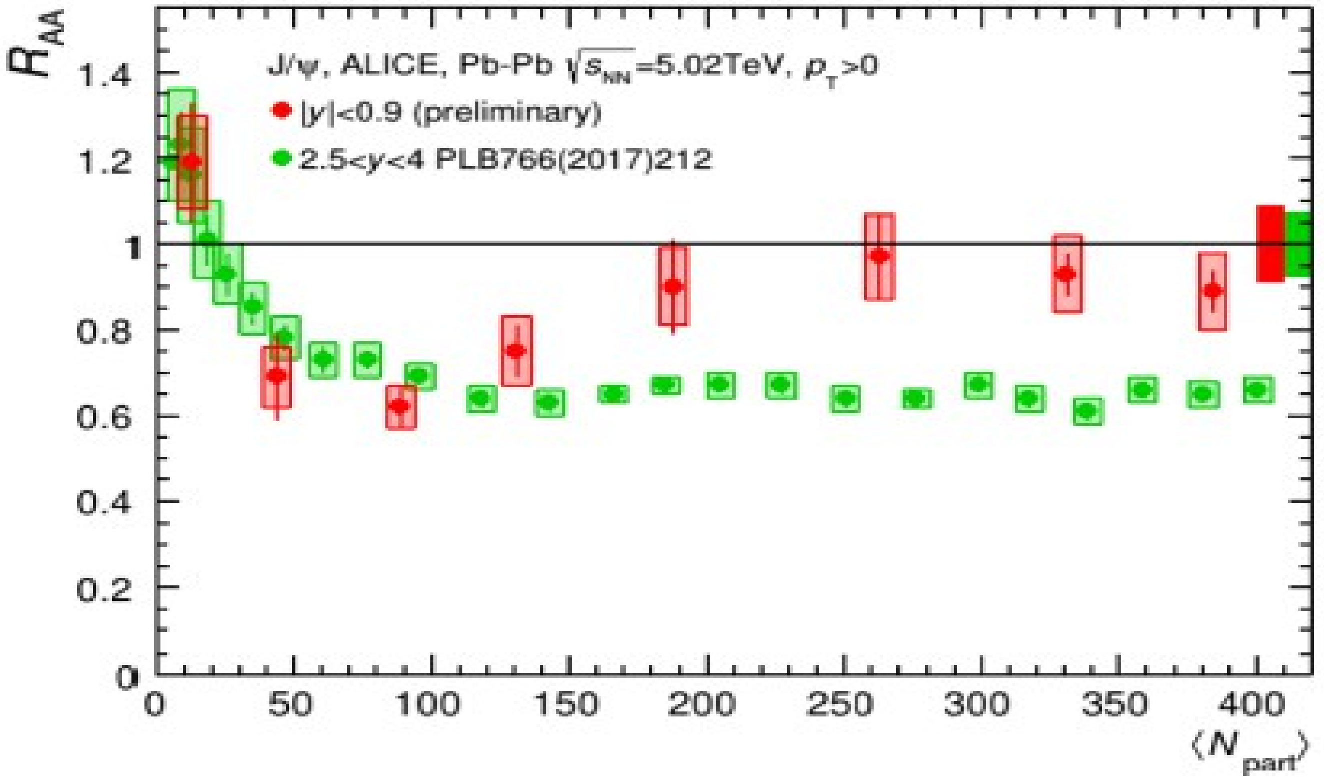
RHIC and LHC data compared to SHM predictions

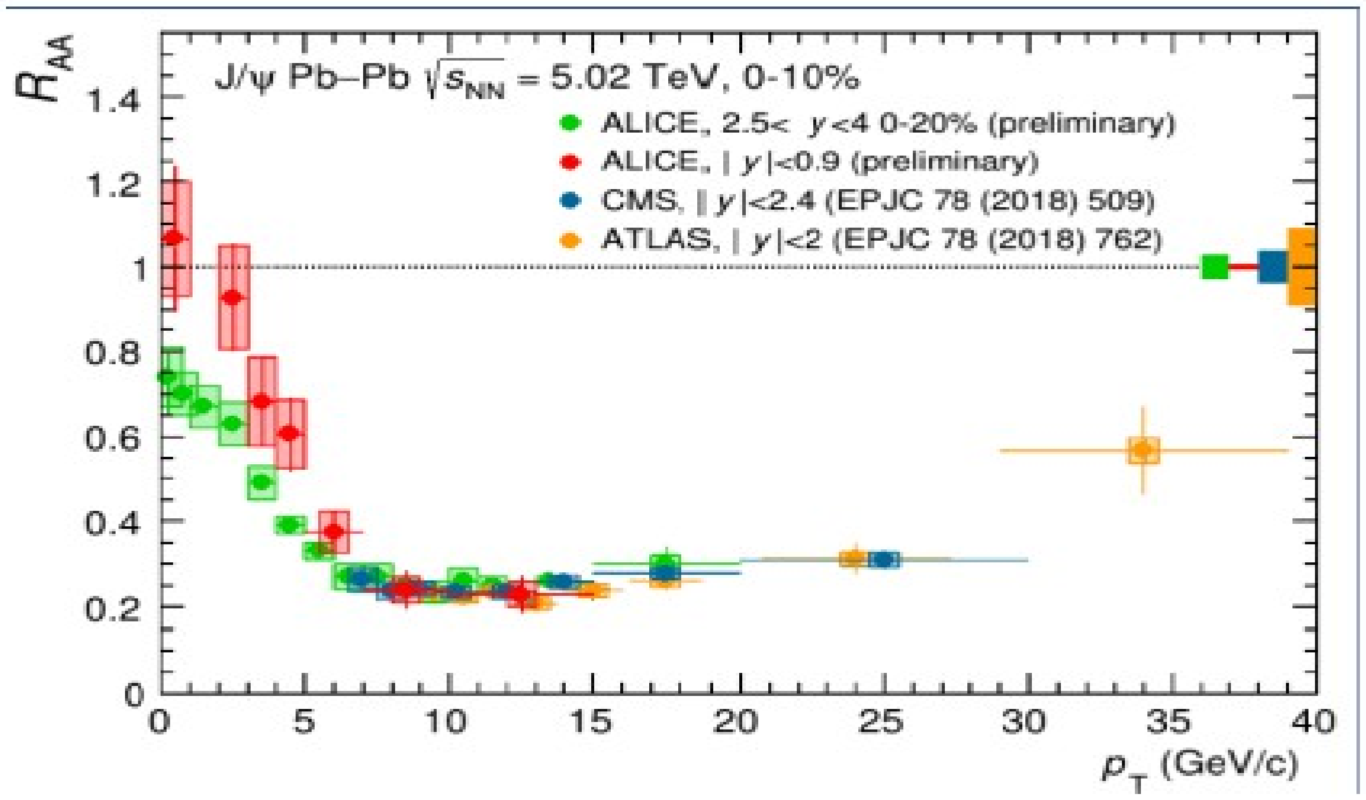
note the energy dependence of the nuclear modification factor R_{AA}



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

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

now open charm hadrons and the SHMc

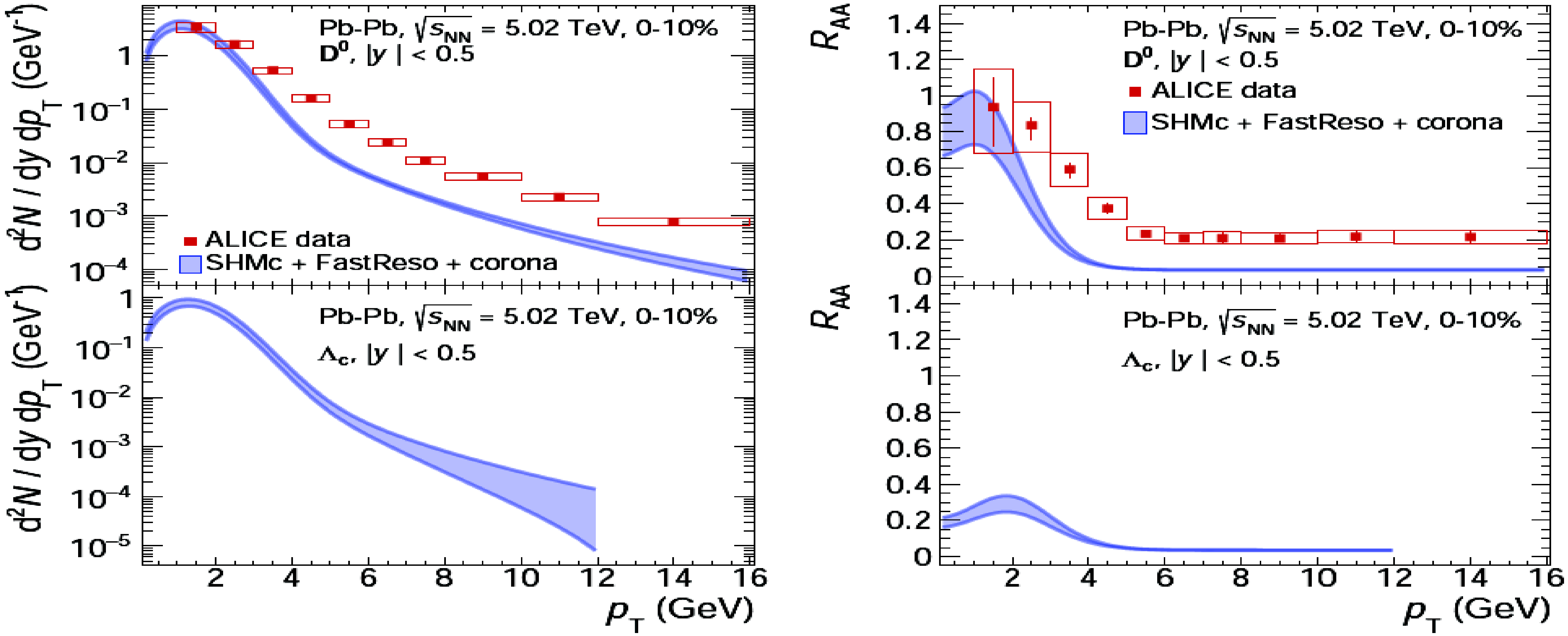
a summary of all ALICE data including original references from LHC Run1 and Run2 is found at the very recent ALICE review paper:

``The ALICE experiment - A journey through QCD,"
[arXiv:2211.04384 [nucl-ex]].

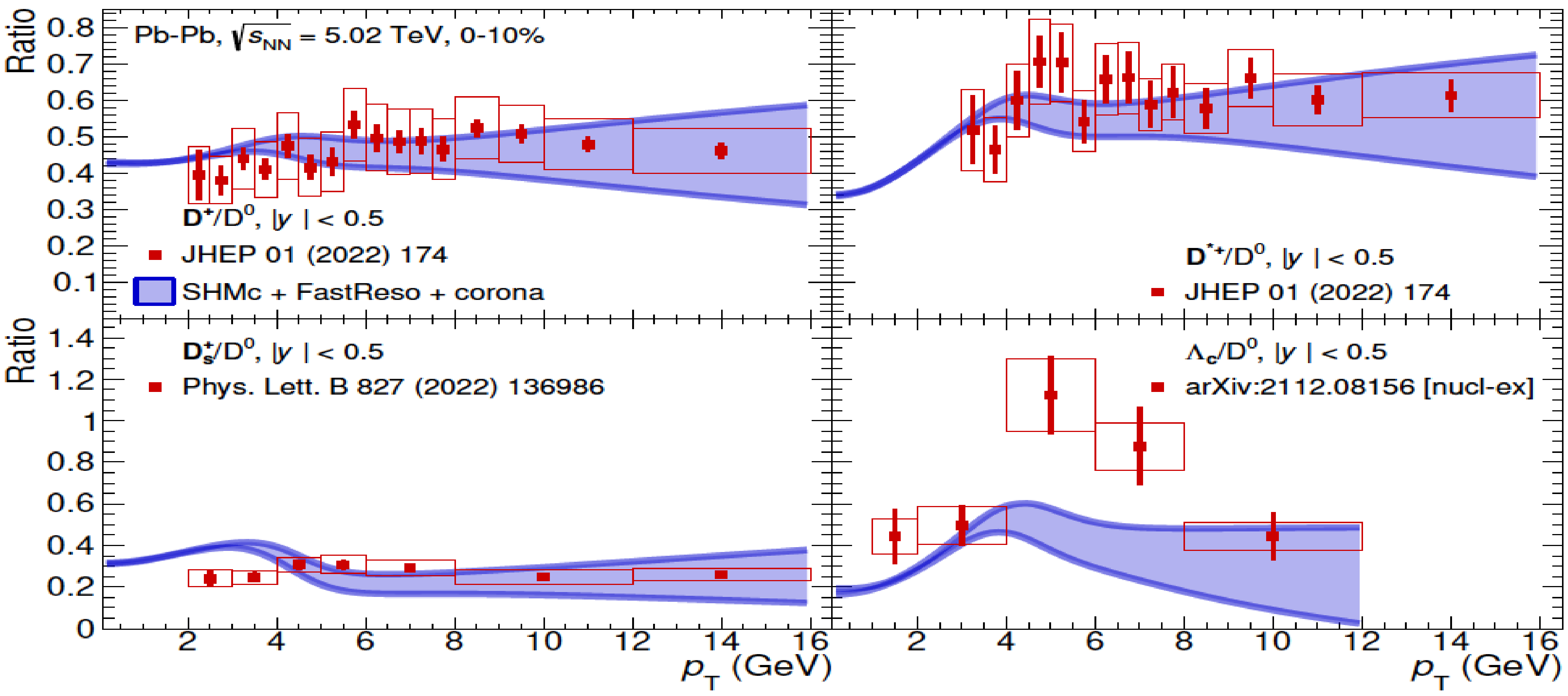
see in particular arXiv:2112.08156

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

for open heavy flavor hadrons strong contribution from resonance decays
- include all known charm hadron states as of PDG2020 in SHMc
- compute decay spectra with FastReso: 76 2-body and 10 3-body decays
  (A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284 arXiv: 1809.11049)



ratios of charm hadrons to D^0 spectra

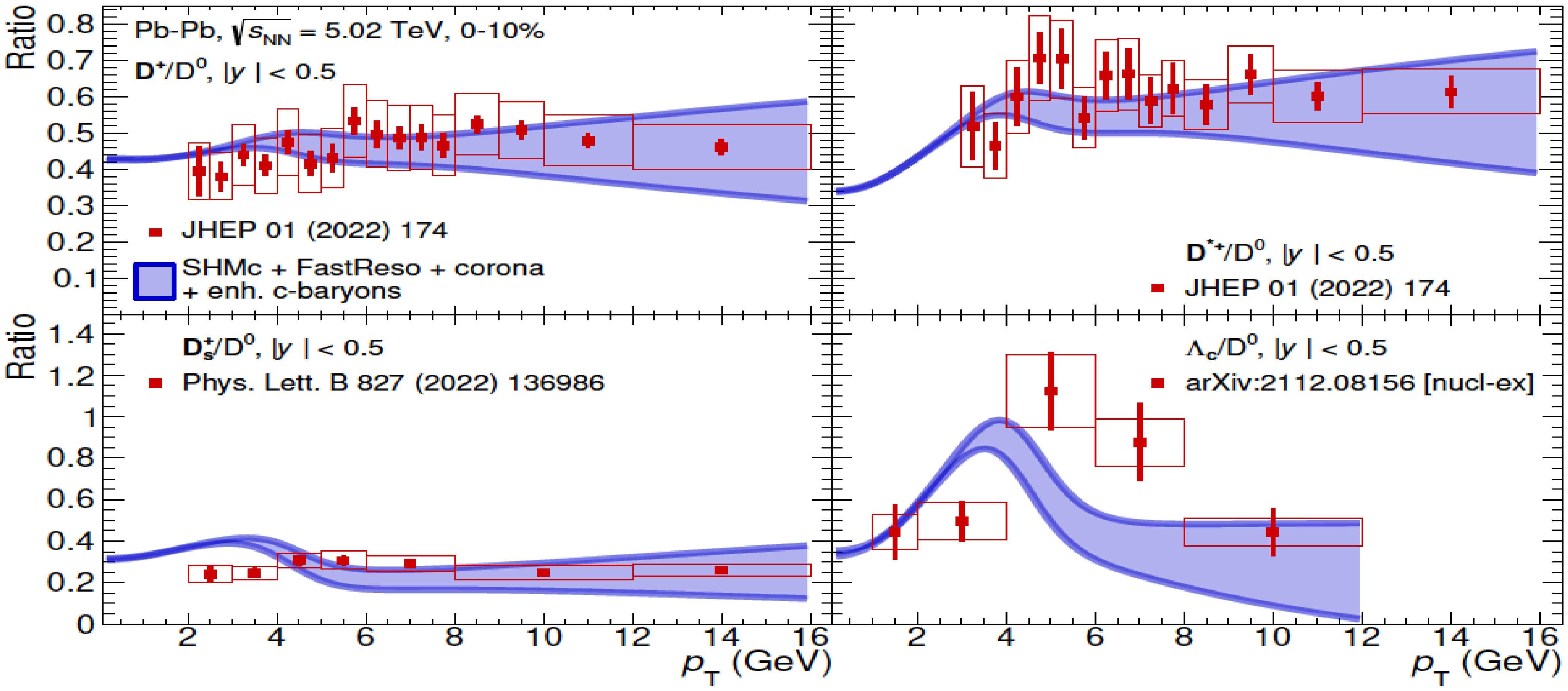


Charm-hadron spectrum: PDG

excellent agreement for meson ratios, NO free parameters, Λ_c/D^0 missed

indication of charm quark deconfinement
to further reduce uncertainties, need improved measurments of total open charm cross section

ratios of charm hadrons to D^0 spectra

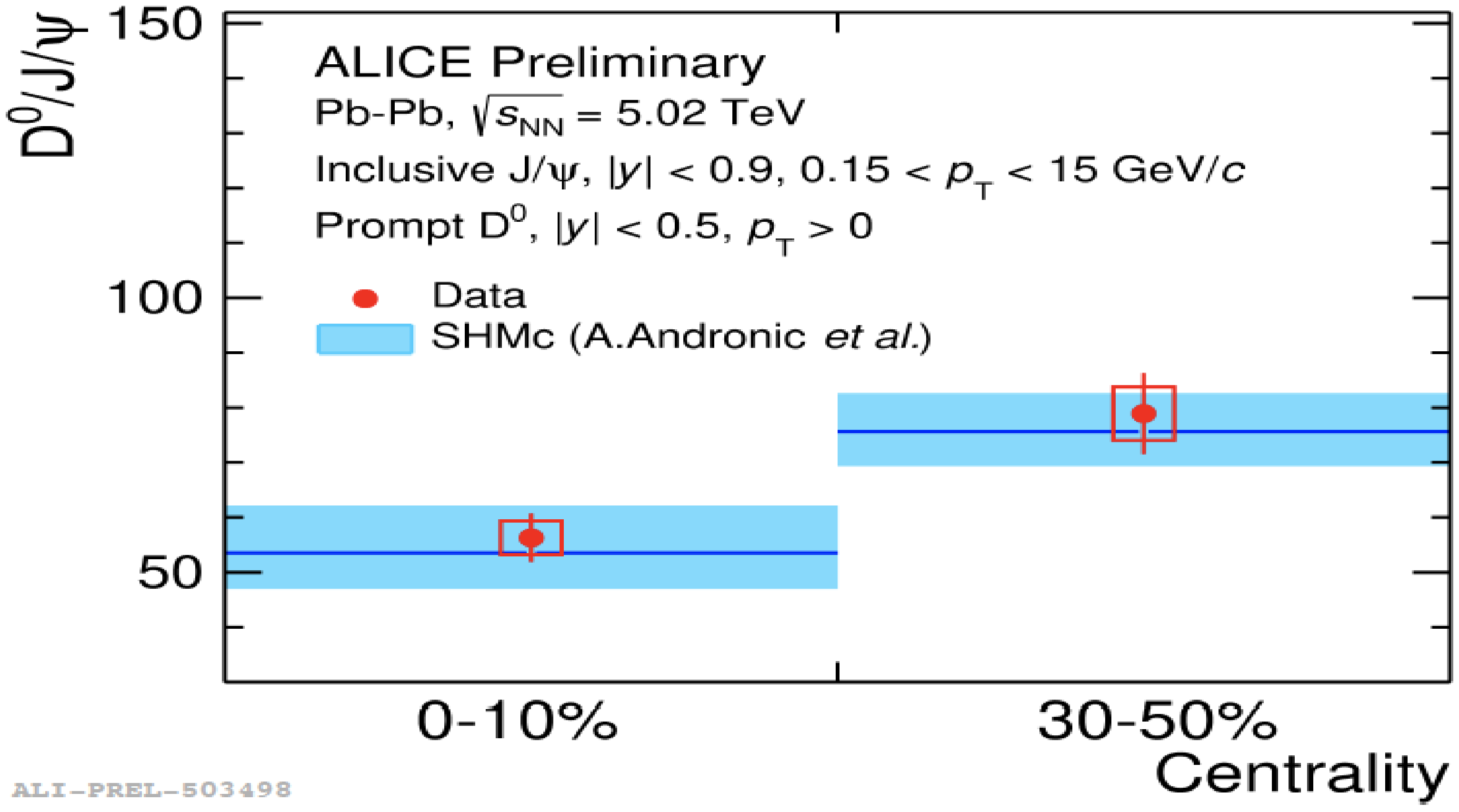


Charm-hadron spectrum: enhanced c-baryons (tripled excited states)

excellent agreement, NO free parameters

indication of charm quark deconfinement
to further reduce uncertainties, need improved measurements of total open charm cross section, important measurement for LHC Run3

comparison of D0/(J/ψ) ratio with statistical hadronization model prediction



A. Andronic et al., JHEP07 (2021) 035

D^0 and J/ψ simultaneously reproduced, no free parameter

at the phase boundary, all processes producing J/ψ included,
even including D Dbar* --> J/ψ π with resonance feeding
no additional contribution to J/ψ production from confined hadronic phase

multi-charm hadrons, deconfinement and universal hadronization

why are multi-charm baryons important to measure?

these complex baryons are assembled at the QCD phase transition from the quarks in the fireball

in the SHMc the production probability scales as $g_c n^c$ if charm quarks are deconfined over the volume of the fireball formed in the Pb-Pb collision, see below

it follows that the yield of the doubly charmed Ξ_{cc}^{++} should be strongly (by a factor 900, see below) enhanced

measurement of this enhancement is hence a clear proof of deconfinement of charm quarks over distances determined by the volume of the fireball

in central Pb-Pb collisions this volume is of order 5000 fm^3

this implies deconfinement over linear dimensions of order 10 fm
much larger than the size of a (confined) nucleon (size of order 0.8 fm)

the multiple-charm hierarchy in the statistical hadronization model

results shown in this lecture are based in part on the recent paper:
A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler,
A. Mazeliauskas, K. Redlich, V. Vislavicius, JHEP 07 (2021) 035,
2104.12754 [hep-ph]

focus on production of open (multi)-charm hadrons at LHC energy
collision systems: Pb-Pb, Xe-Xe, Kr-Kr, Ar-Ar, O-O
production yields, rapidity and transverse momentum distributions

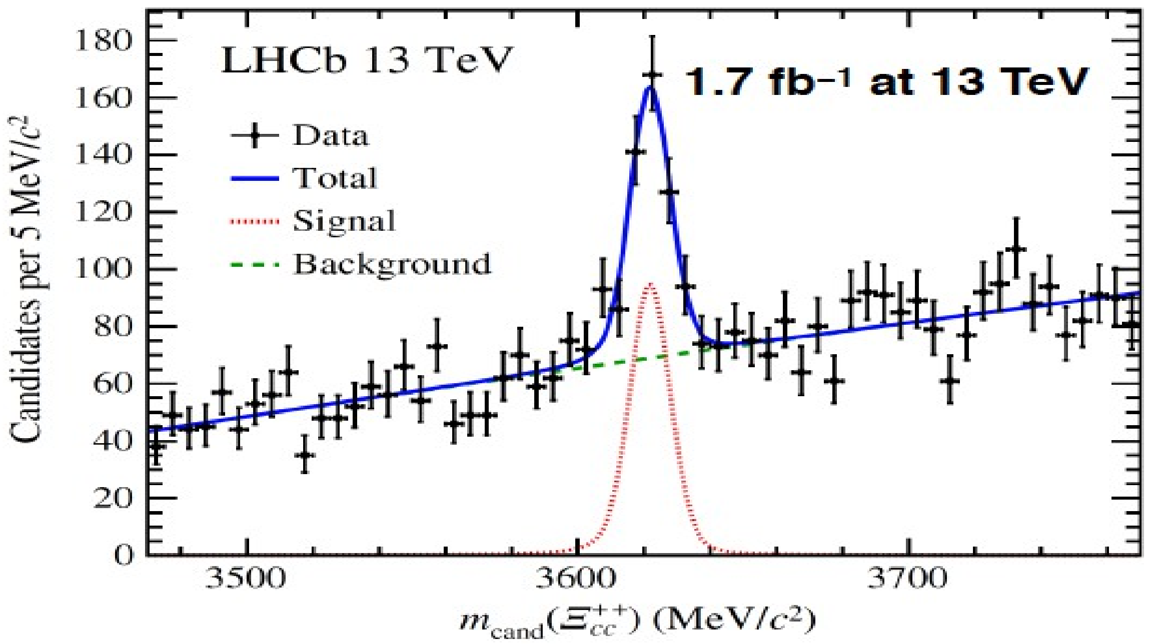
how to measure multi-charm baryons?

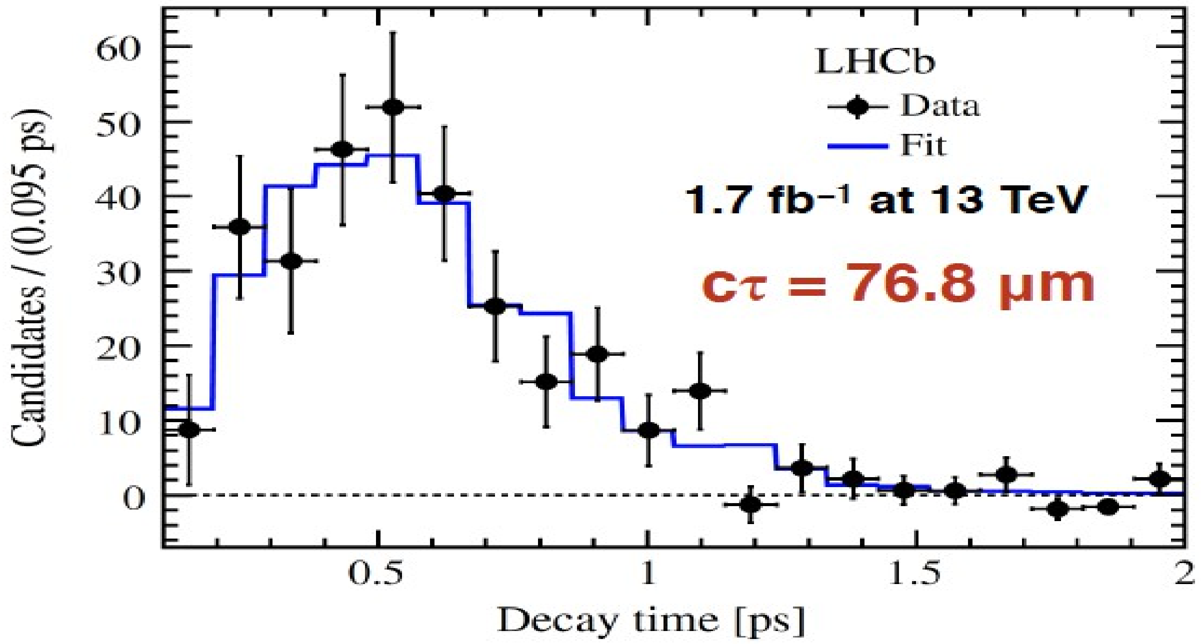
measurements are generally done via invariant mass analysis

but: such measurements need very sophisticated detectors since the decay chains can be very complicated

example:

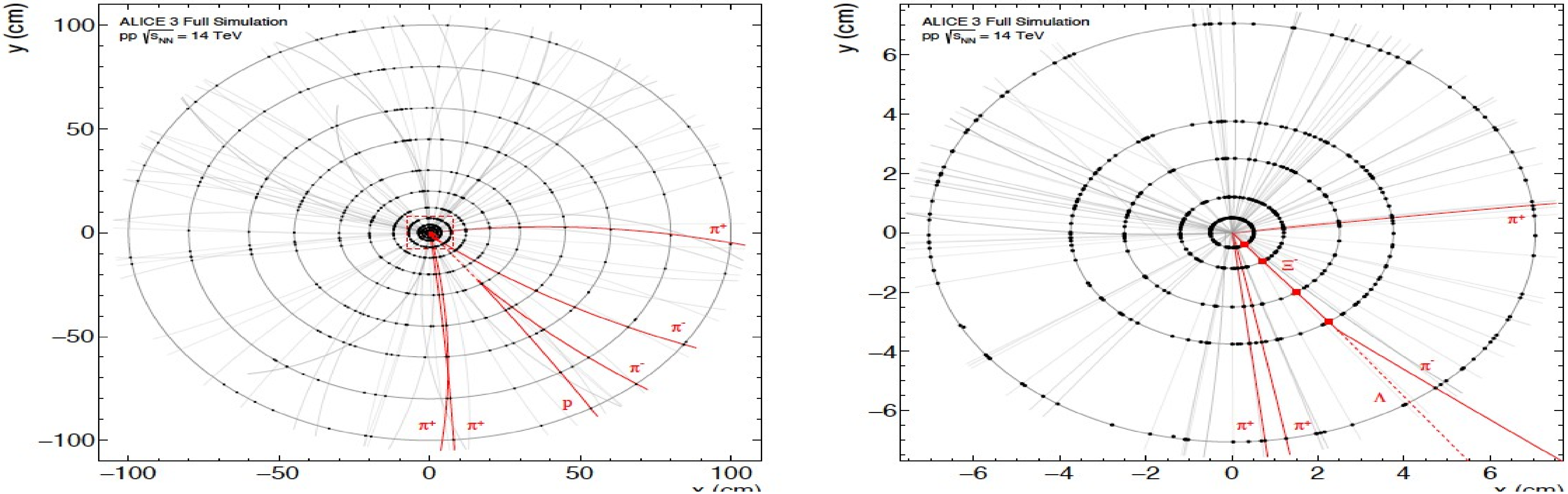
$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$
$$\Lambda_c^+ \to p K^- \pi^+$$





LHCb collaboration, arXiv:1910.11316, pp collisions

new ALICE development: strangeness tracking

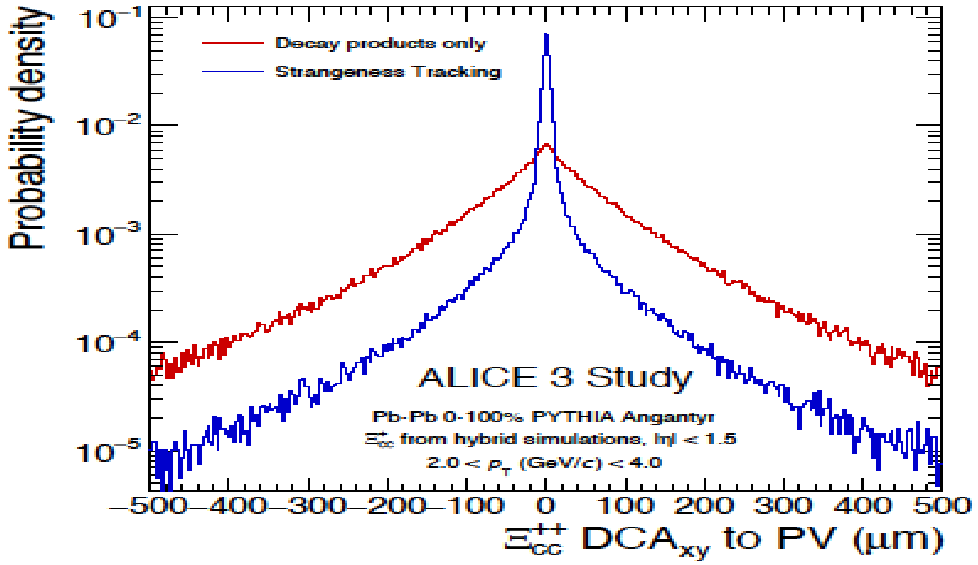


(left) Illustration of strangeness tracking from full detector simulation of the Ξ_{cc}^{++} decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \to \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing the five innermost layers of ALICE 3 and the hits that were added to the Ξ^- trajectory (red squares).

Ξ^{++}_{cc} mass spectrum without (red) and with (blue) strangeness tracking

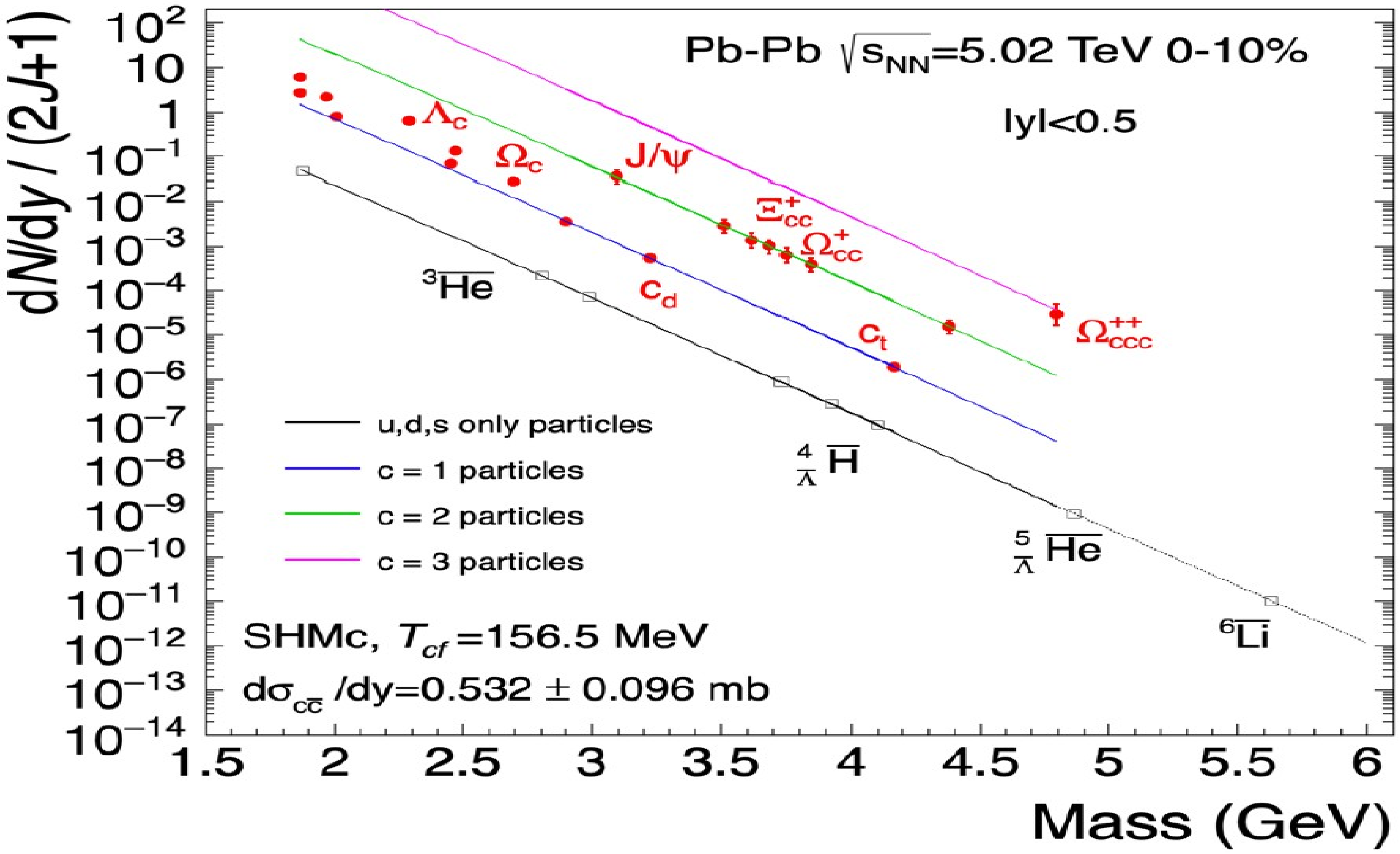
the power of ultra-thin, ultra-precise MAPS detectors for ALICE 3

[arXiv:2211.02491 [physics.ins-det]]



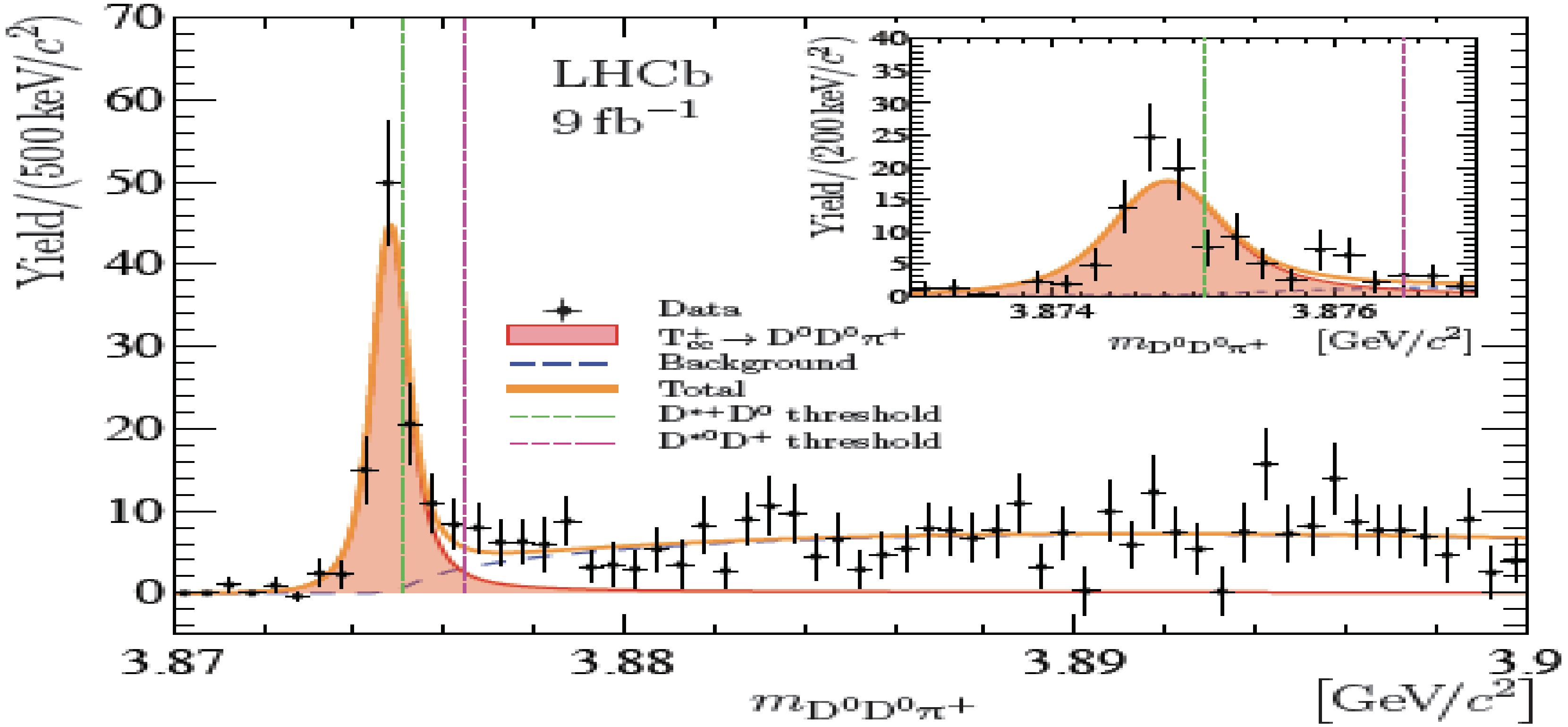
the multi-charm hierarchy

open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, pentaquark, Ω_{ccc}



emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Run 3 and beyond

what about T_{cc}^+ very recently discovered by LHC_b 2109.01038 [hep-ex]



if statistical hadronization is universal, its production cross section will fall on the 2 charm quark line at the measured mass, can be tested experimentally

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
- charm quark hadronization follows the statistical hadronization pattern established for (u,d,s) hadrons with, at LHC energy, only the hadronization (phase transition) temperature as 'parameter'

- 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 confinement, deconfinement and hadronization

the near future at the high lumi LHC

LHC program

RUN 1 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032

RUN 1	RUN 2	RUN 3	RUN 4
pp, pPb, Pb-Pb	pp, pPb, Xe-Xe Pb-Pb	pp, pO, O-O, pPb,Pb-Pb	pp, pPb, Pb-Pb

- **Pb-Pb luminosity limited** by LHC $\sim 1\text{-}2 \cdot 10^{27}$ cm^{-2} s^{-1} (beam losses)
- Several fills lost on beam dumps due to 10 Hz beam oscillation events; collimation efficiency

RUN 3

- **High Luminosity for ions** ($\sim 7 \cdot 10^{27}$ cm^{-2} s^{-1})
- **Oxygen** (small to large system bridge, cosmic ray)
- Improved collimation systems
  → lifted limitation in the LHC from bound-free pair production
  → ion luminosities now limited by bunch intensities from injectors

next 4 slides taken from Sarah Porteboeuf, ALICE

LHC program

RUN 1 2009-2013	LS1	RUN 2 2015-2018	LS2	RUN 3 2022-2025	LS3	RUN 4 2029-2032
pp, pPb, Pb-Pb		pp, pPb, Xe-Xe Pb-Pb		pp, pO, O-O, pPb,Pb-Pb		pp, pPb, Pb-Pb

Total integrated Luminosity RUN 1+2
Pb-Pb: 1.5 nb^{-1} in ALICE, 2.54 nb^{-1} in ATLAS/CMS, 0.26 nb^{-1} in LHCb
p-Pb: 75 nb^{-1} in ALICE, ~220 nb^{-1} in ATLAS/CMS, 36 nb^{-1} in LHCb

Target Luminosity RUN 3+4
Pb-Pb: 13 nb^{-1} in ALICE/ATLAS/CMS, 2 nb^{-1} in LHCb
p-Pb: 0,5 pb^{-1} in ALICE, 1pb^{-1} in ATLAS/CMS, 0.2 pb^{-1} in LHCb
To be continued in RUN 5, see talk by R. Bailhache

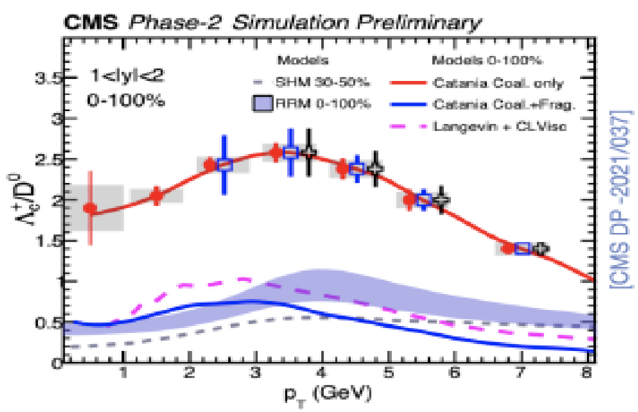
PHYSICS Outlook* – RUN 3+4

* Not an exhaustive overview

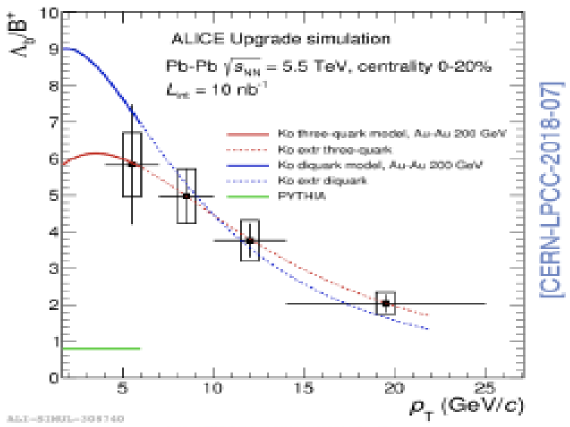
- **Upgraded machine:**
  - increase in energy and luminosity
  - Intermediate systems with Oxygen
- **Upgraded experiments**
  - To cope with the machine upgrade and collect more statistics
  - All experiments developed upgrade for HI physics

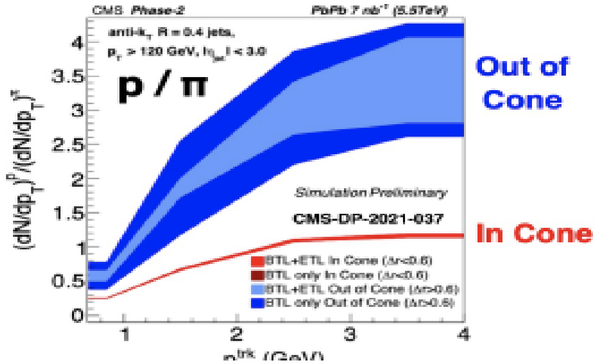
- **Initial State:**
  - Nuclear PDF and Nucleon structure, low-*x*
  - Reference systems (UPC, pA, pp), event characterization
  - Total c cross section
- **In-medium dynamics: thermalization and transport propertie**
  - Thermal radiation with photon and dielectron
  - Susceptibilities and net baryon fluctuations
  - Quenching mass and time dependance
  - Heavy flavor transport, precision measurement for R_{AA} and v_2, bottomonia
- **Onset of collective behavior from small to large systems**
  - Systematic measurements of QGP legacy probes vs. mult, vs. systems, vs. energy
  - Onset of energy loss and thermal radiation
  - High mult pp sample and new collision systems
- **Hadronisation**
  - Baryon/meson ratios, flow
  - Multi-charm baryons
  - Jets

Λ_c/D^0

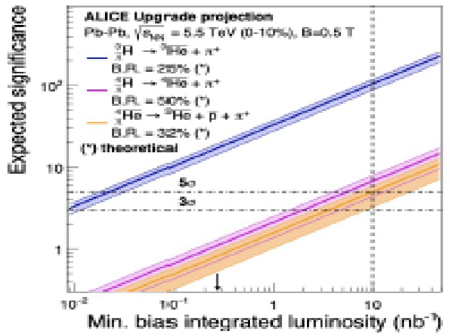


Λ_b/B^+





anti-hyper-nuclei

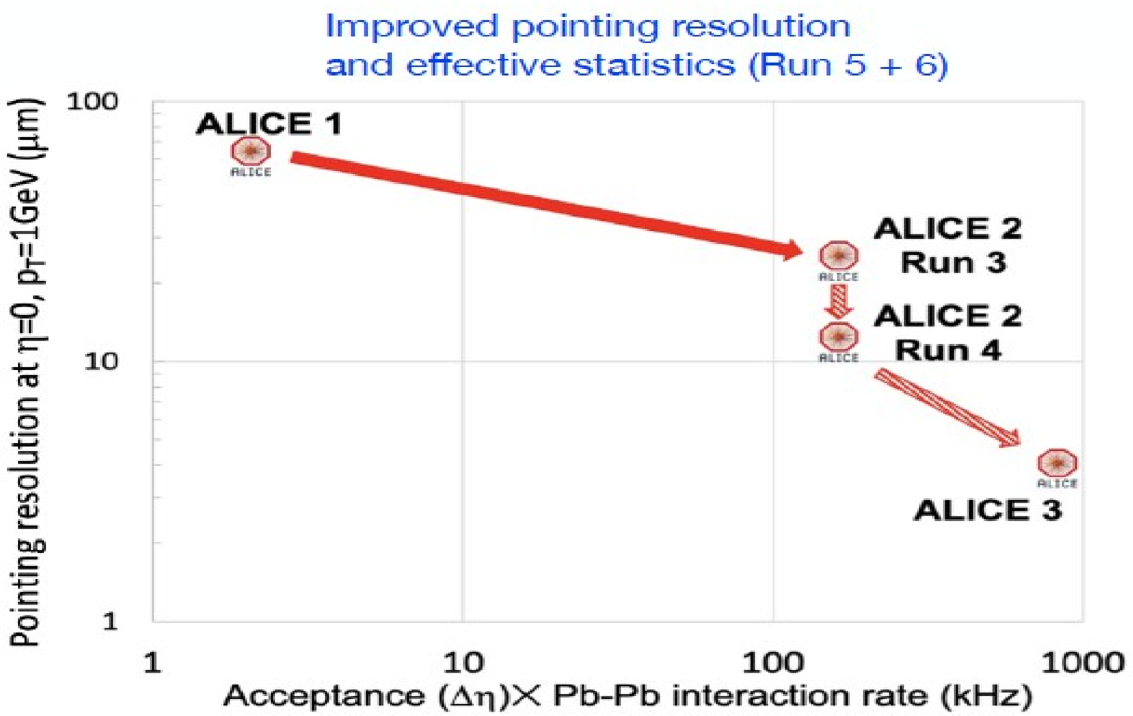


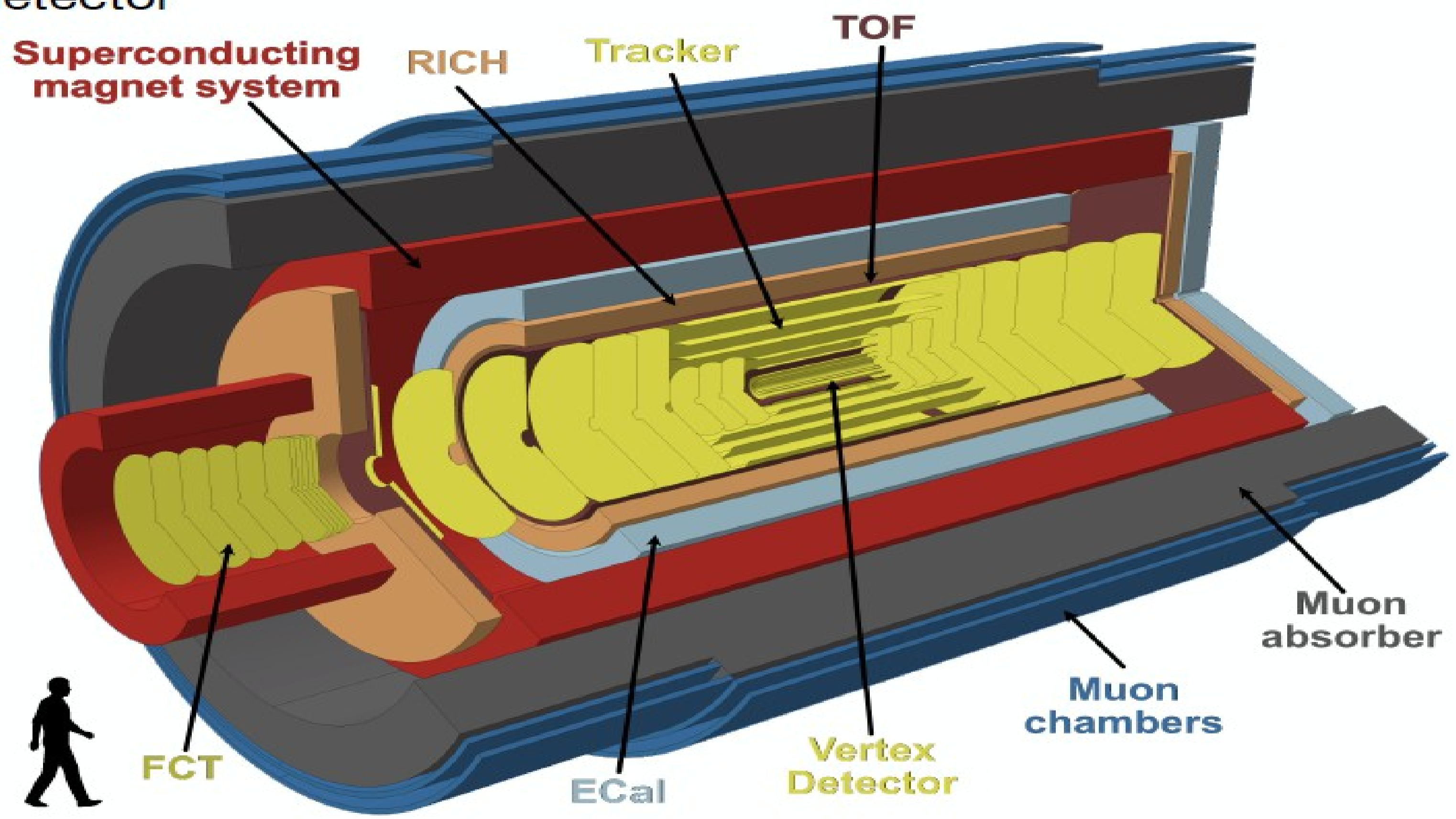
the far future (not so far for a new detector)

ALICE collaboration
``Letter of intent for ALICE 3:
A next-generation heavy-ion experiment at the LHC,"
[arXiv:2211.02491 [physics.ins-det]].

ALICE 3 detector concept

- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification $\gamma, e^{\pm}, \mu^{\pm}, K^{\pm}, \pi^{\pm}$
  - Over large acceptance $(-4 < \eta < 4)$
  - Down to very low p_T





D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

Observables and detector requirements

- **Heavy-flavour hadrons** ($p_{\rm T} \rightarrow 0$, wide η range)
  → Vertexing, tracking, hadron identification
- **Quarkonia and Exotica** ($p_{\rm T} \rightarrow 0$)
  → Muon and γ identification
- **Nuclei**
  → Identification of $z > 1$ particles
- **Dielectrons** ($p_{\rm T} \sim 0.05 - 3$ GeV/c, $m_{\rm ee} \sim$ 0.1 - 4 GeV/c^2)
  → Vertexing, tracking, electron identification
- **Photons** ($E_\gamma \sim$ 0.1 - 50 GeV/c, wide η range)
  → Photon conversion, electromagnetic calorimeter
- **Ultra-soft photons** ($1 \leq p_{\rm T} \leq 10$ MeV/c)
  → Dedicated Forward Conversion Tracker detector (FCT)

Use Time-of-flight detectors, Ring-imaging Cherenkov detectors, Calorimeters, muon chambers, FCT