deconfined charm quarks, multi-charm hadrons and the QCD phase boundary

- ALICE and charm
- relativistic nuclear collisions, loosely bound states, and charmonia
- statistical hadronization of heavy quarks at the QGP phase boundary
- the multi-charm hierarchy in the statistical hadronization model
- interaction among hadrons with charm
- deconfinement and universal hadronization
- outlook

pbm
symposium on
double-charm tetra-quarks and other exotics

Lyon, Nov. 22-23, 2021

ISOQUANT SFB1225
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
EMMI
GSI

ALICE plans for the coming decade 2022 – 2030
LHC Run3 and Run4

ALICE is currently being 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

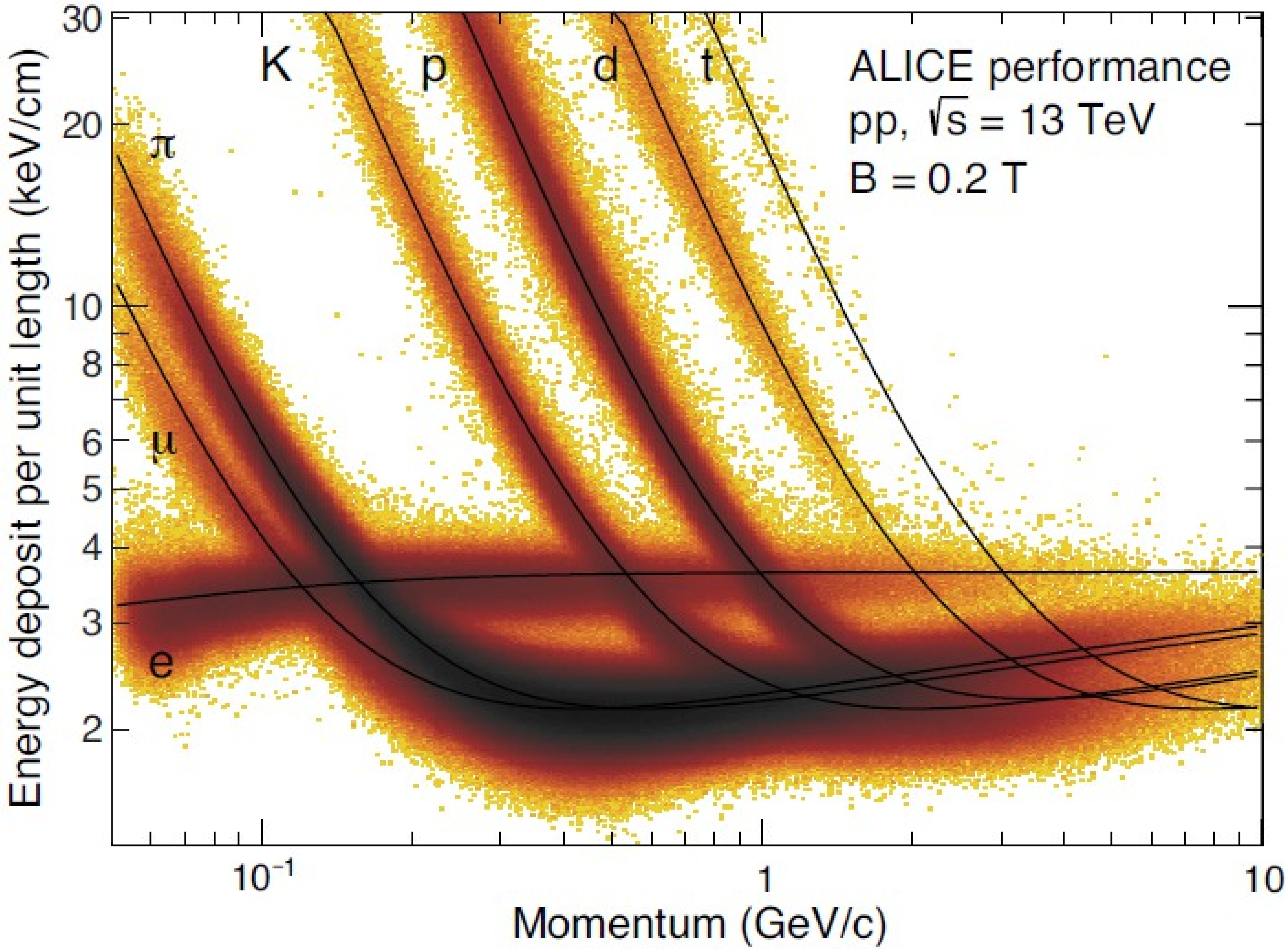
focus on rare objects, exotic quarkonia, single (and possibly double) charm hadrons to address a number of fundamental questions and issues such as:

- 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?

- low mass dileptons and low-p_T thermal photons
- collectivity from pp to AA collisions
- nuclear and hadronic physics
  - structure of light hyper-nuclei
  - hadron-hadron interaction from particle correlations
- ultra-peripheral and diffractive collisions

deciphering QCD in the strongly coupled regime

main advantage of ALICE: particle identification with the ALICE TPC is preserved



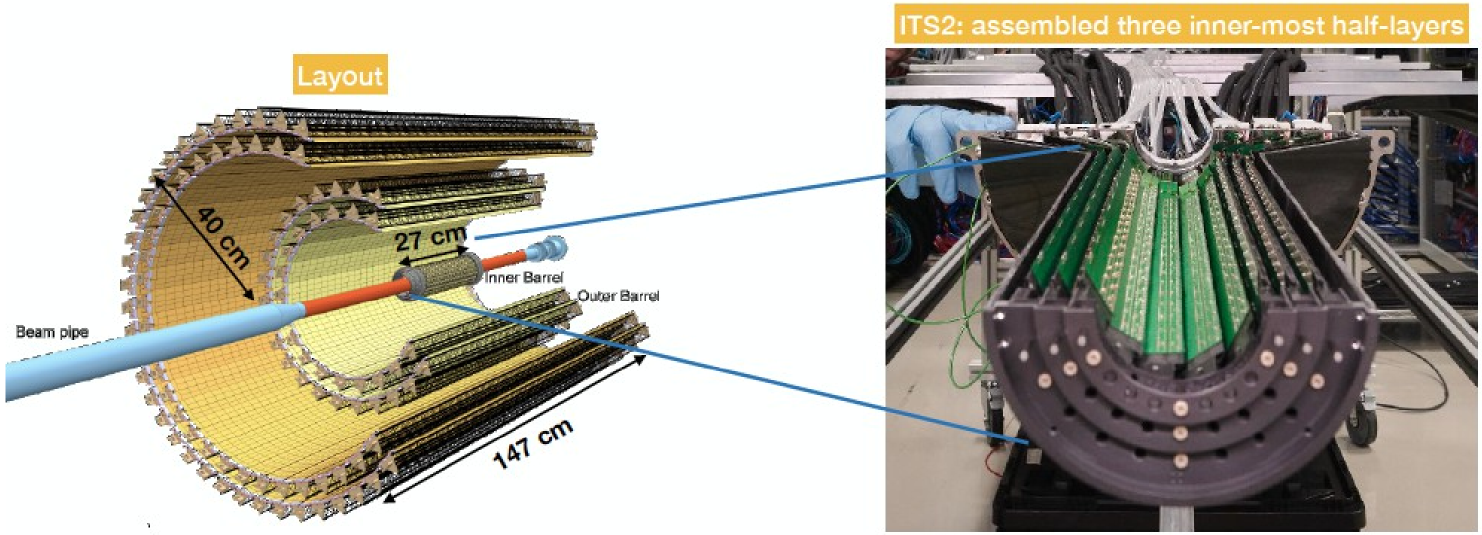
now PDG standard

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

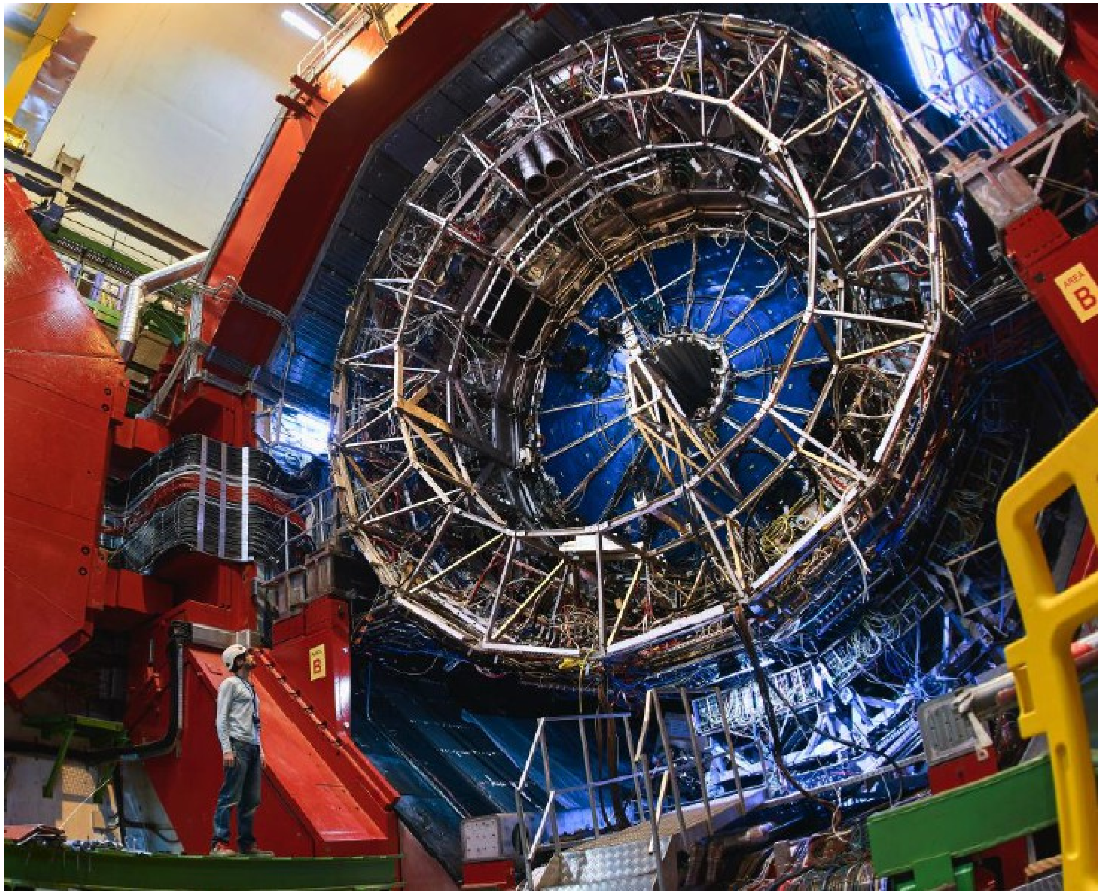
improved tracking and vertexing with all-Si Inner Tracking Systems

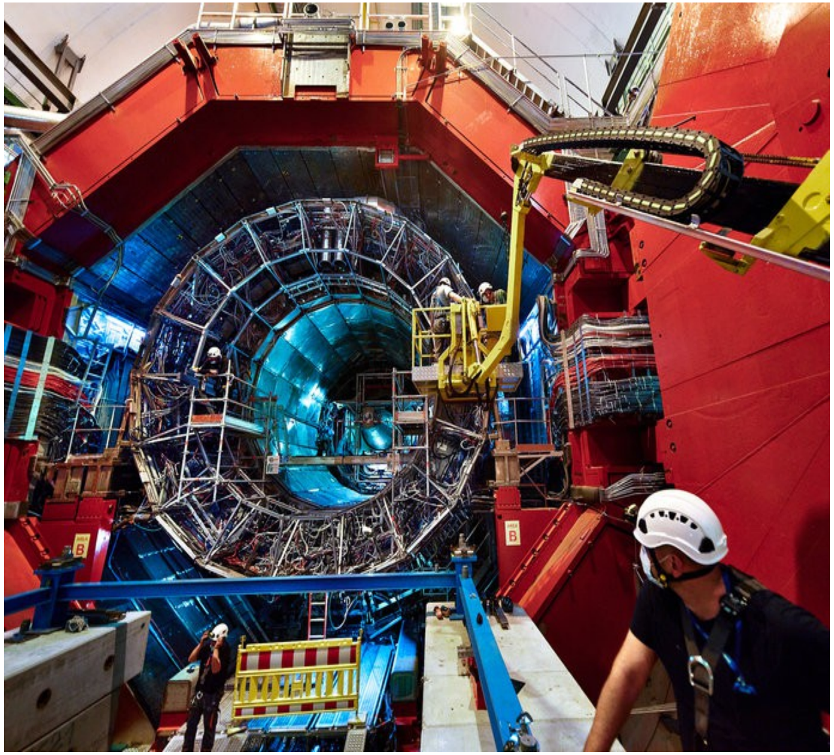
part of current upgrade for LHC Run3

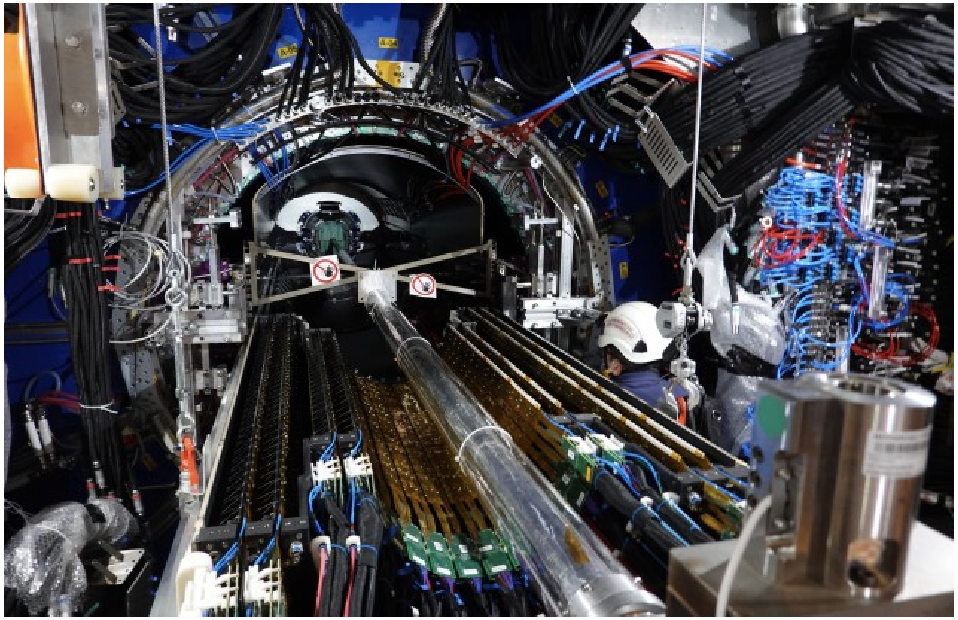
ITS2 inner barrel



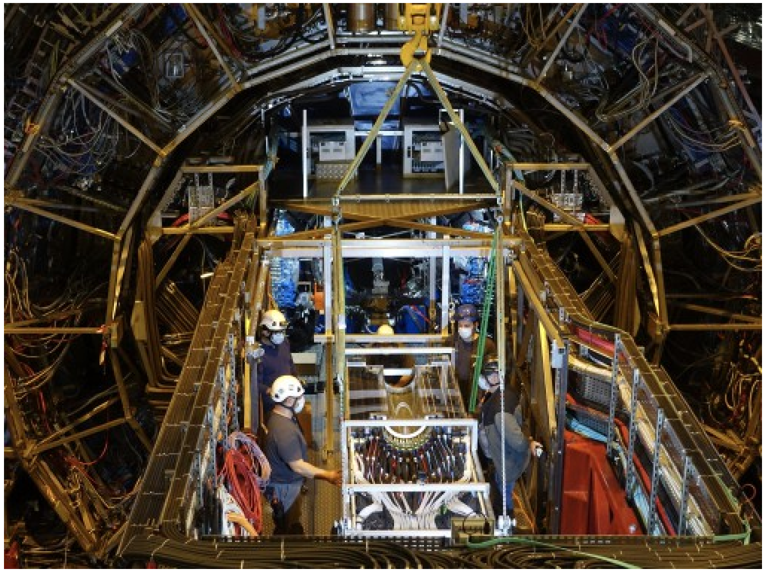
- ITS2 is expected to perform according to specifications or even better
- The Inner Barrel is ultra-light but rather packed → further improvements seem possible
- **Key questions: Can we get closer to the IP? Can we reduce the material further?**







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



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

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

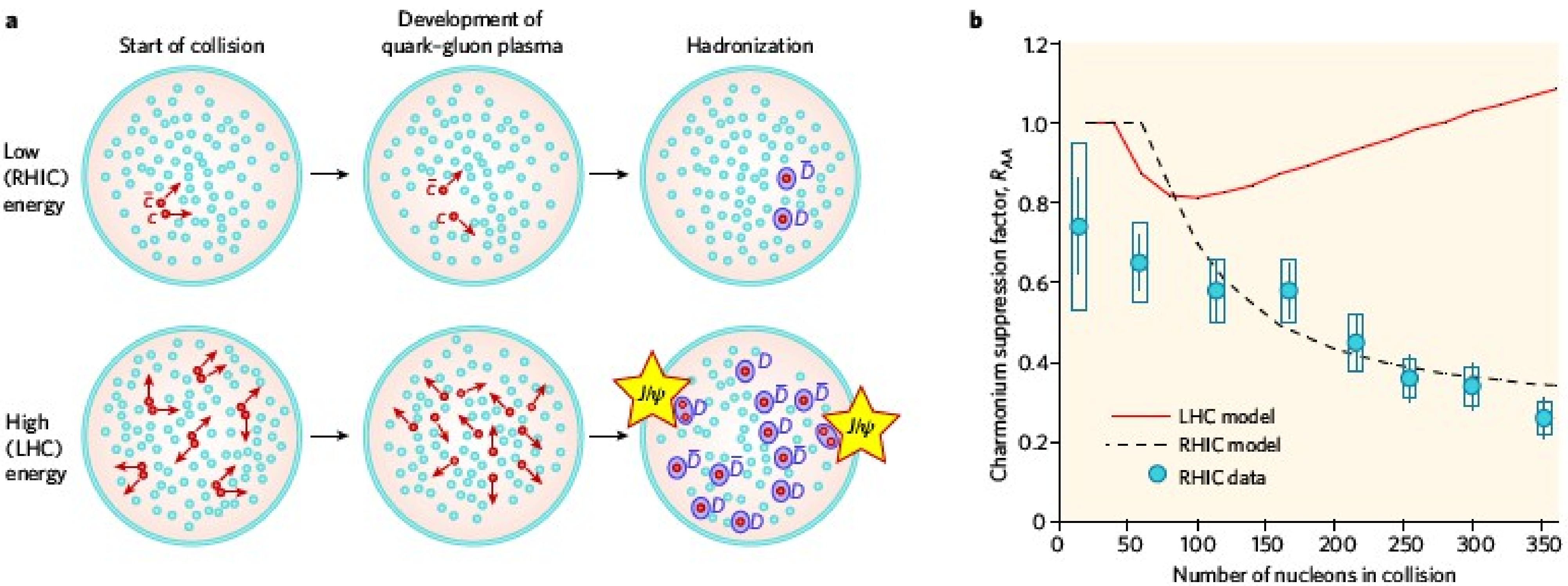
implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

also charm quark production increases strongly with collision energy

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

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

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

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

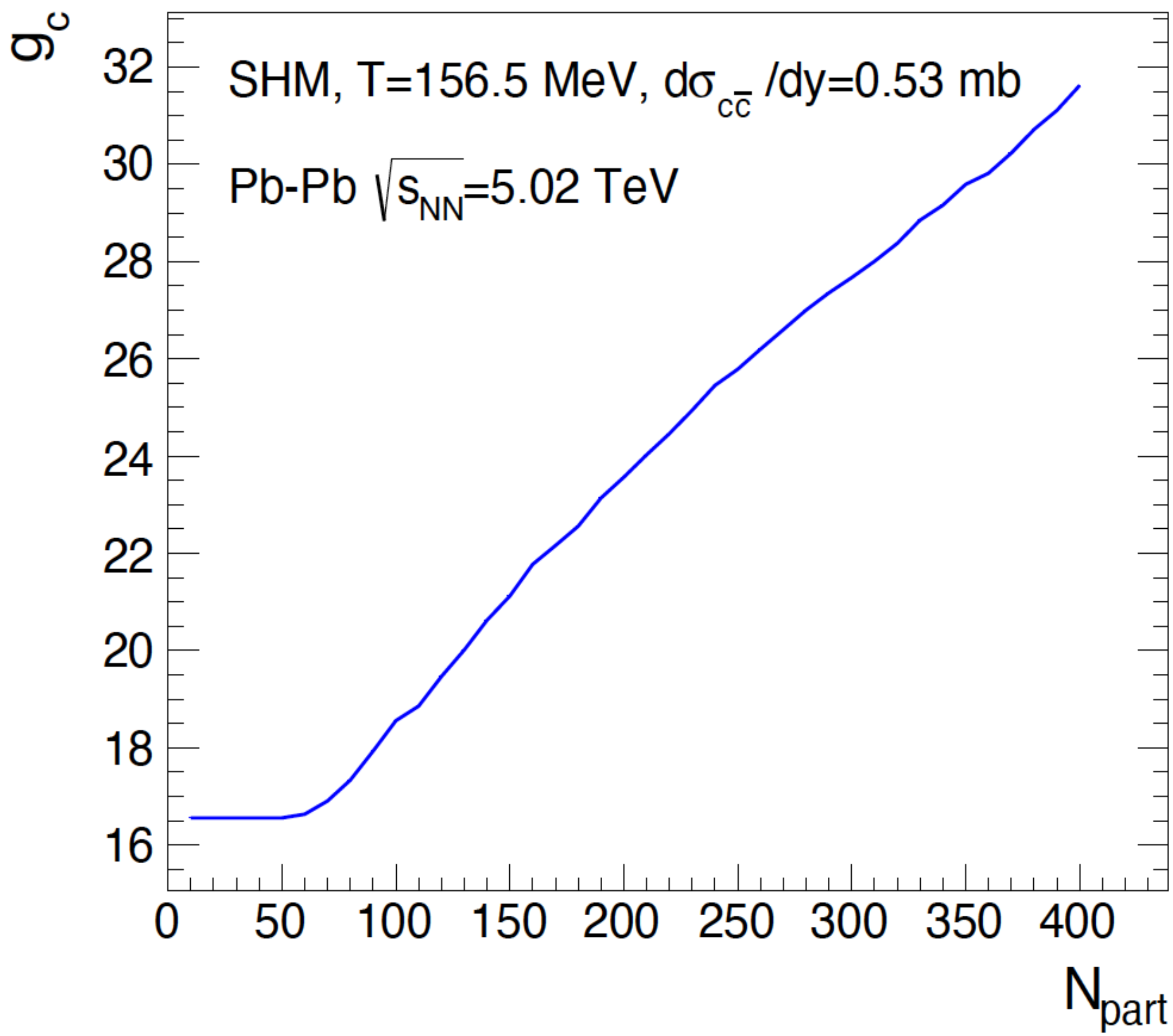
obtained from measured open charm cross section

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

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



why are multi-charm hadrons important to measure?

$c c_{bar}$ quarks are produced in pairs, hadrons with 2 or 3 charm quarks imply exotic production mechanism

in our view, these complex particles are assembled at the QCD phase border from the deconfined charm and (u,d,s) 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 proof of deconfinement of charm quarks over distances determined by the volume of the fireball

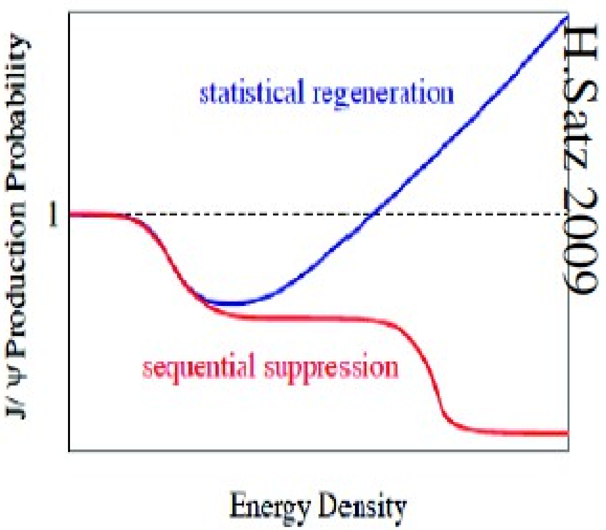
in central Pb-Pb collisions this volume is of order 5000 fm^3

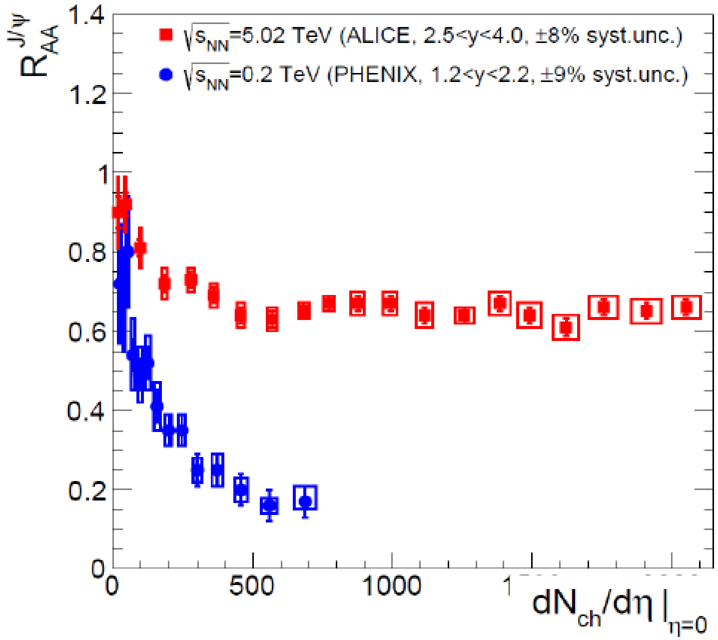
this implies deconfinement over linear dimensions of order 10 fm
much larger than the size of a (confined) nucleon (size of order 0.8 fm)

results on statistical hadronization of charmonia, mesons and baryons with charm in relativistic nuclear collisions

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

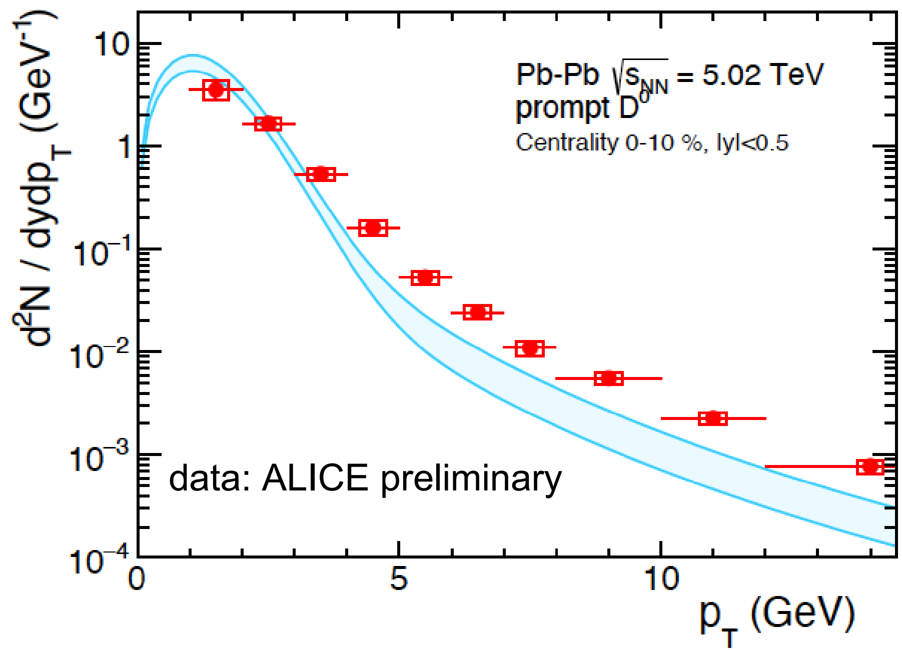
statistical hadronization for hidden and open charm

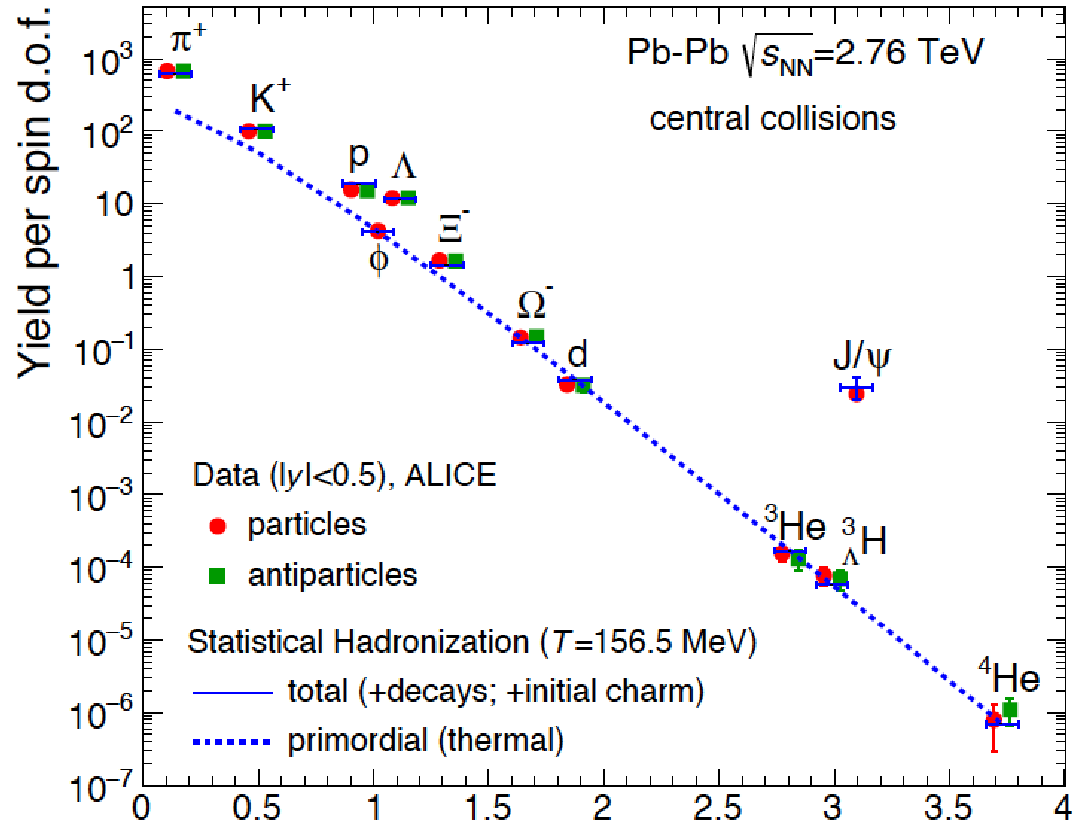
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0



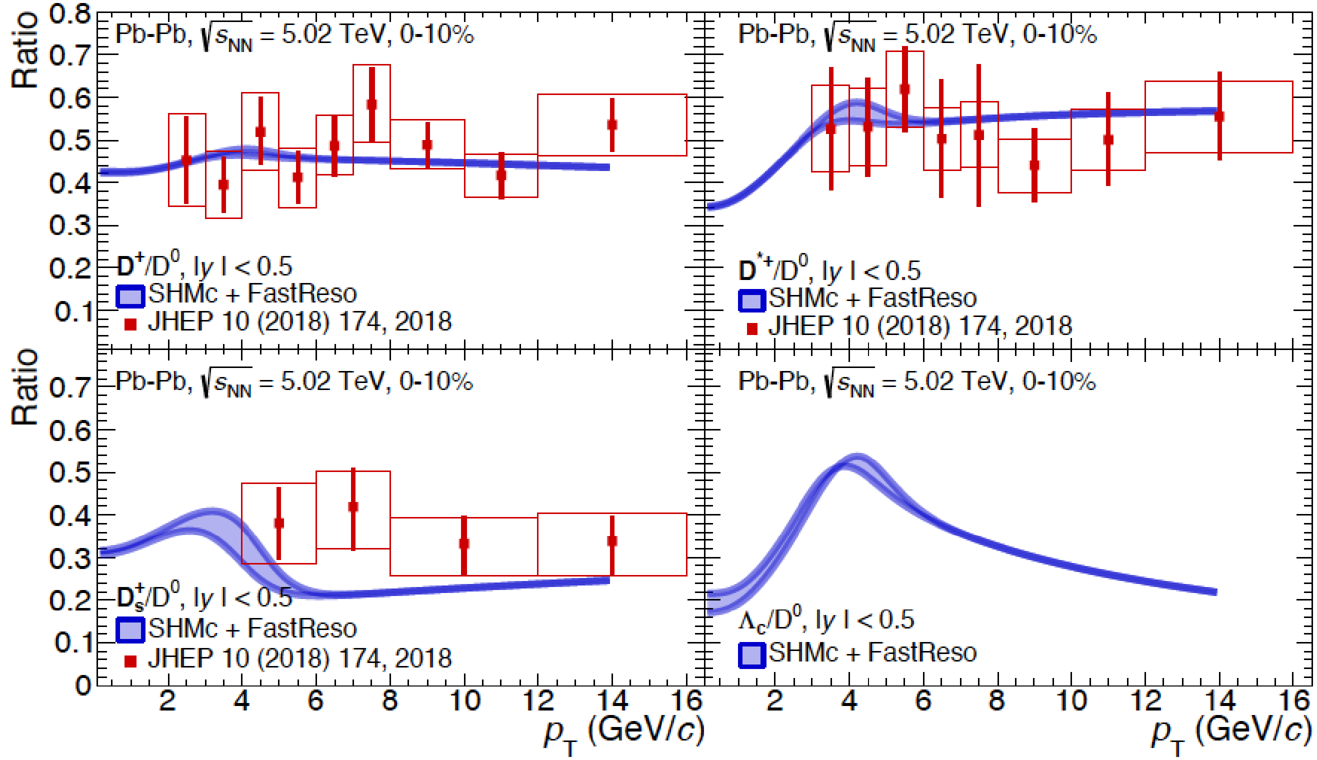


Andronic, pbm, Koehler, Redlich, Stachel PLB 792 (2019) 304 and
Andronic, pbm, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, in preparation

quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons, no Debye screening needed
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

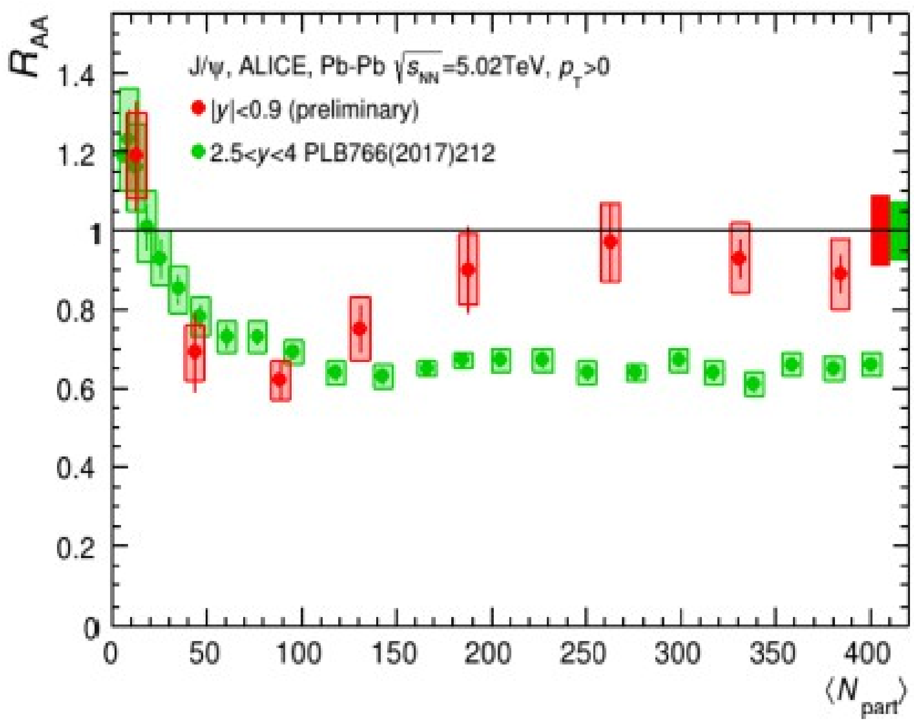
enhancement is defined relative to purely thermal value, not to pp yield

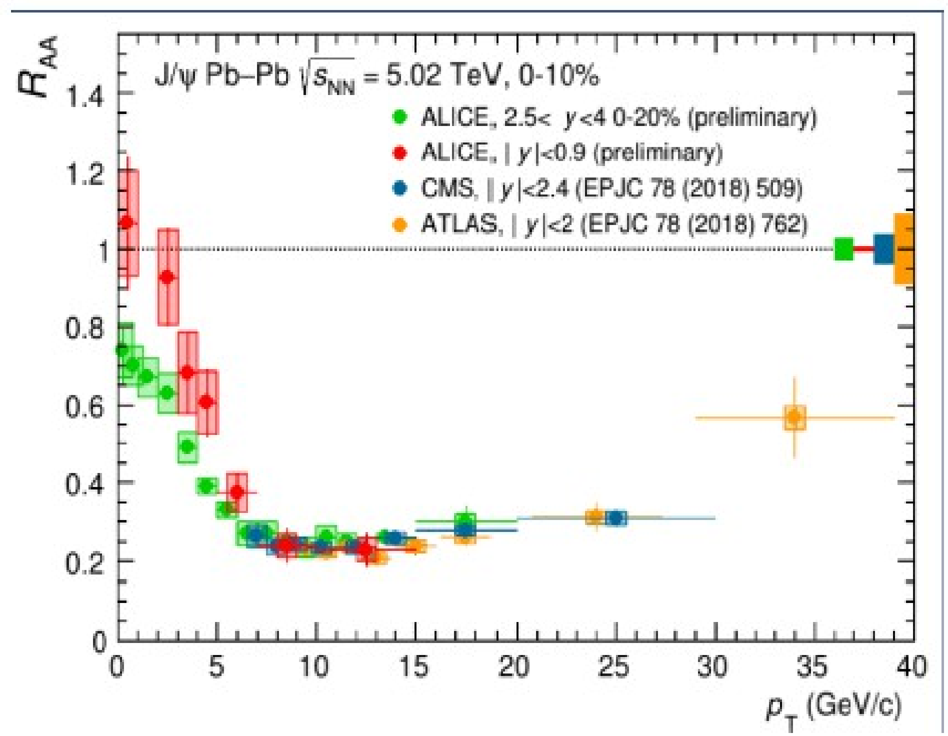
ratios to D^0



excellent agreement considering that there are NO free parameters

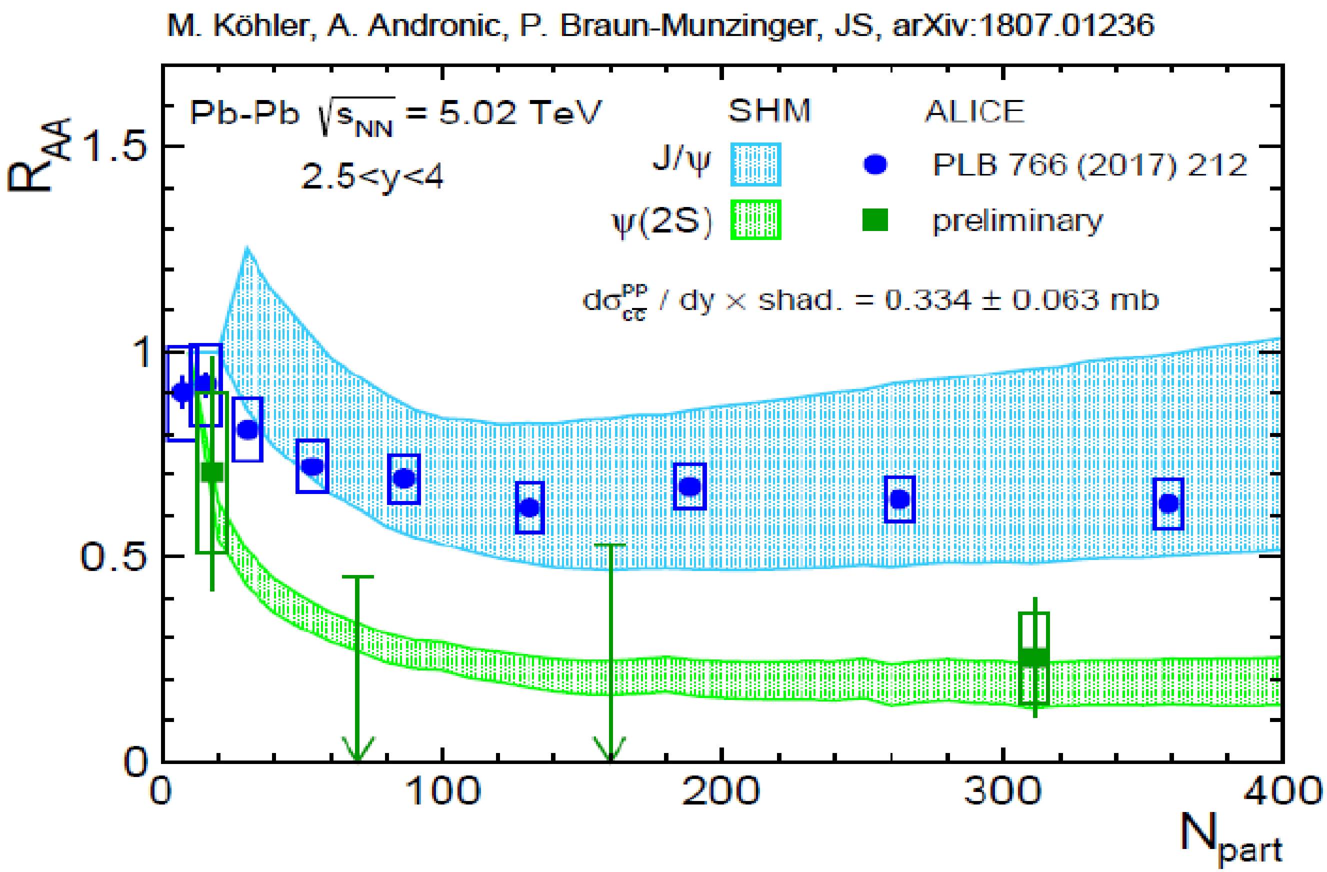
enhancement is at low (transverse) momentum and at angles perpendicular to the beam direction, as expected for a thermal, nearly isotropic source





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

excited state population



note: ψ'/(J/ψ) = f(T) here: T is hadronization temperature of charmonia

measurement of ψ'/(J/ψ) determines at which temperature the ψ' hadronizes

SHMc: both J/ψ and ψ' hadronize at the QGP phase boundary

need precision measurement of ψ'
one of the main ALICE aims for LHC Run3

the multiple-charm hierarchy in the statistical hadronization model

results shown 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]

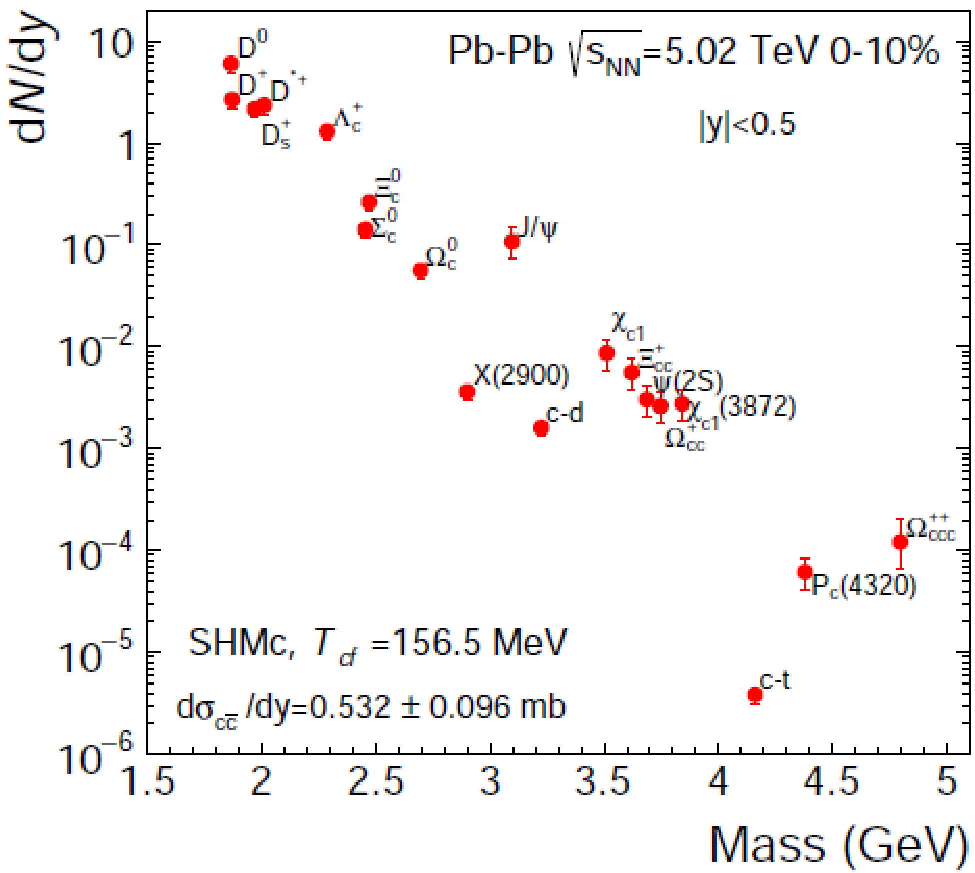
focus on production of open (multi)-charm hadrons at LHC energy
collision systems: Pb-Pb, Xe-Xe, Kr-Kr, Ar-Ar, O-O
production yields, rapidity and transverse momentum distributions

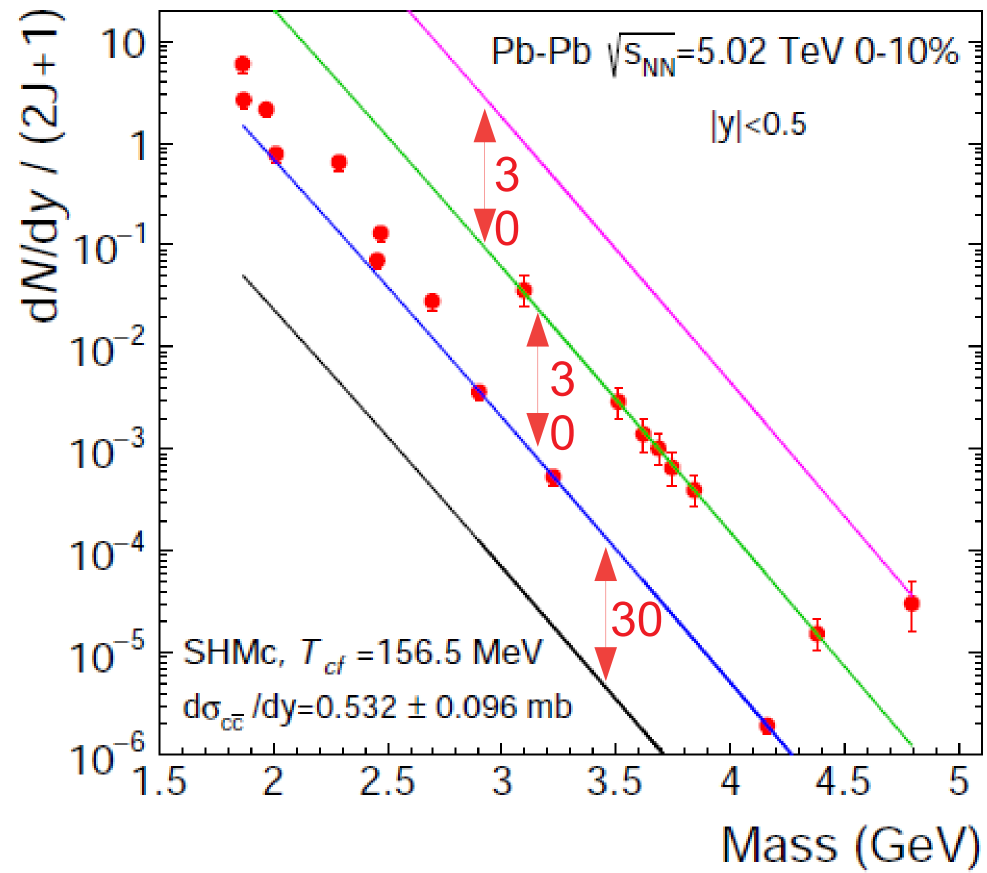
the only new input is the (hopefully soon measured) open charm cross section
in Pb-Pb collisions
for now, use pp and pPb data from ALICE and LHCb
rapidity dependence is important

no free parameter to adjust

the multi-charm hierarchy

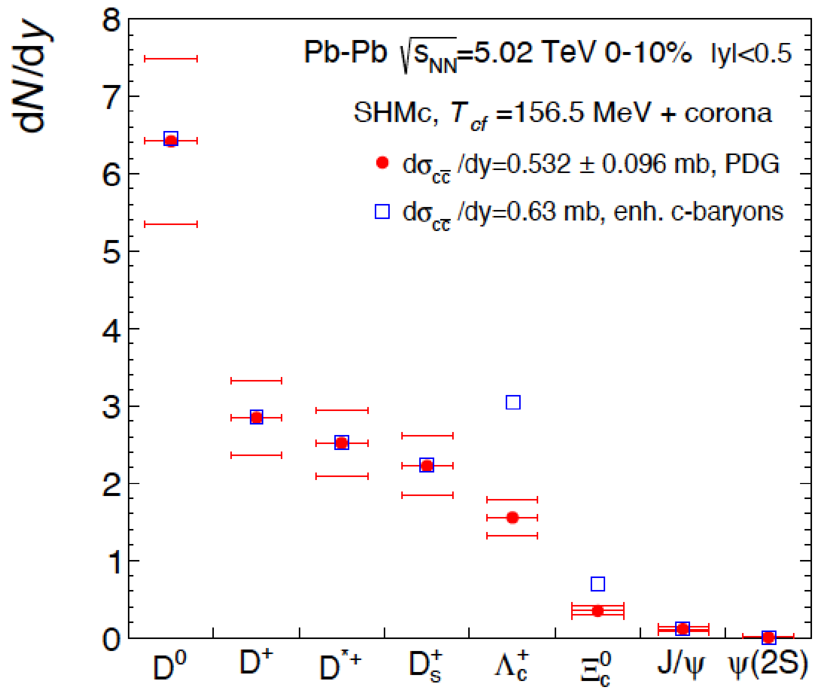
open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, pentaquark, Ω_{ccc}





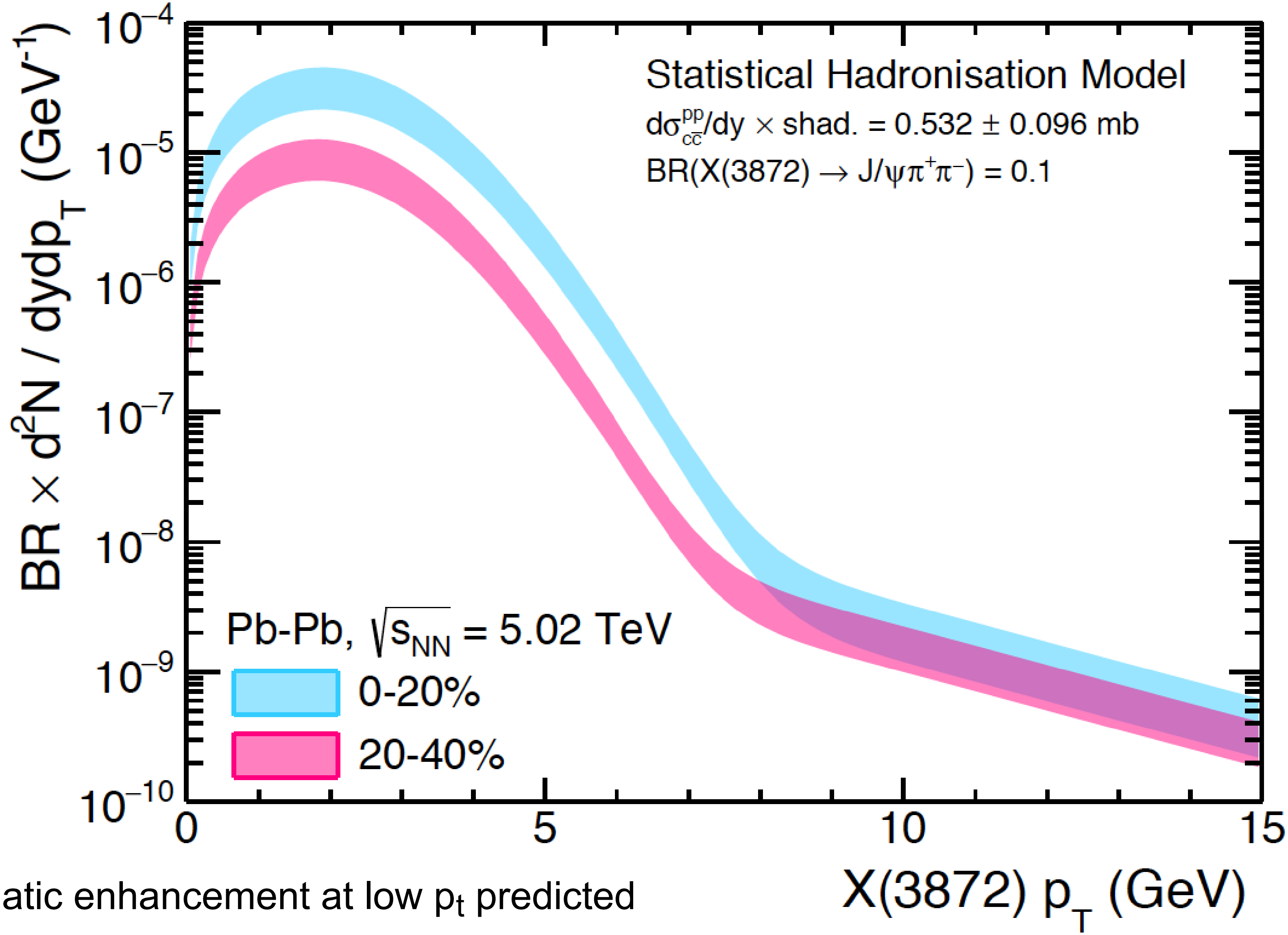
emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Run 3 and beyond

SHMc predictions for charm hadrons without and with modified resonance spectrum



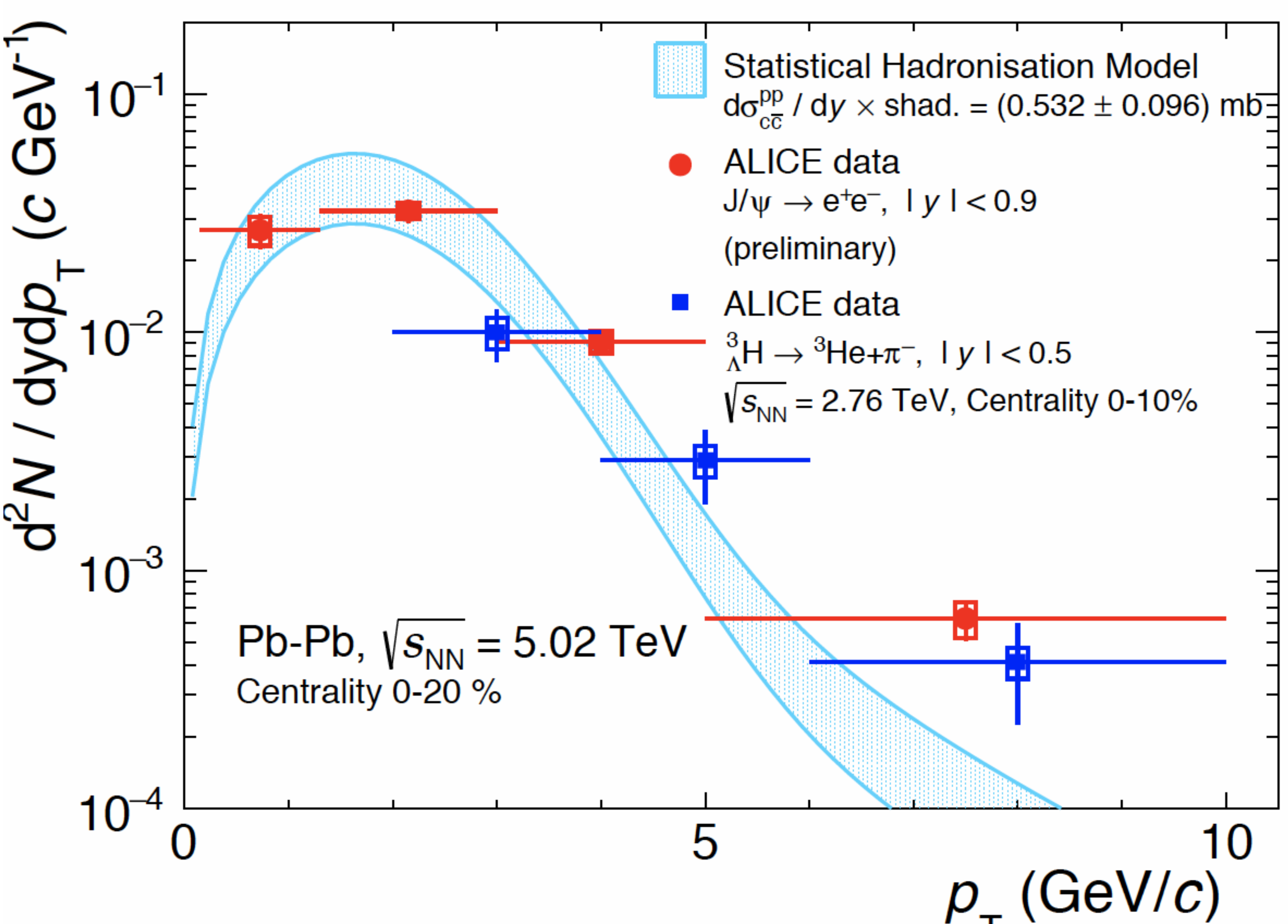
red points correspond to the standard mass spectrum
open points were obtained with an enhanced total open charm cross section implemented via tripled statistical weights for excited charmed baryons

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

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

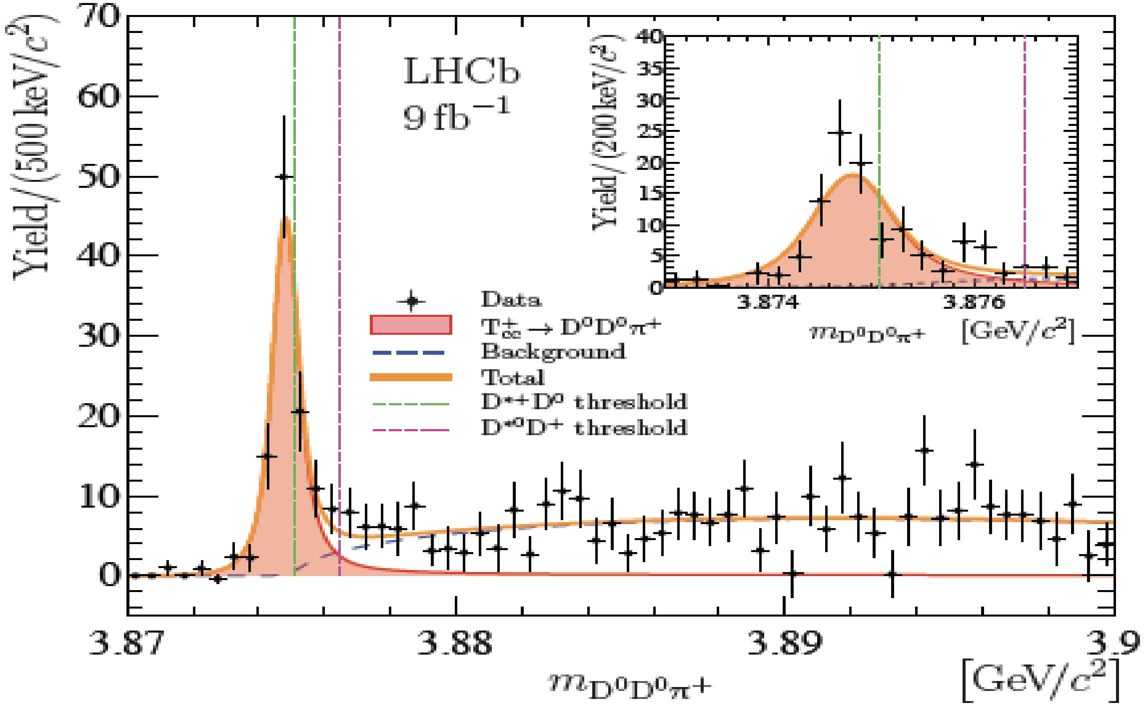


binding energies:
J/ψ 600 MeV
hypertriton 2.2 MeV
Λ sep.energy 0.13 MeV

binding energy does not seem to matter for production

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

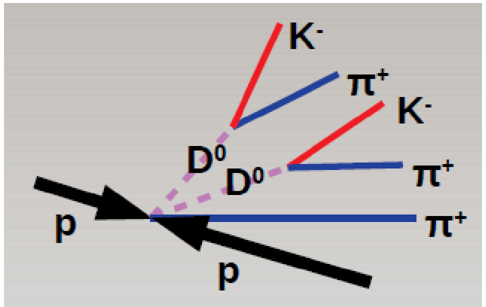
what about T_{cc}^+ very recently discovered by LHC_b
2109.01038 [hep-ex]

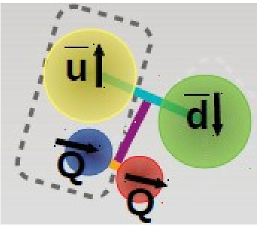


if statistical hadronization is universal, its production cross section will fall on the 2 charm quark line at the measured mass, can be tested experimentally this loosely bound state has net charm 2, very different from charmonia

there is no Debye screening, but we assume that it will be formed at the phase boundary just like the other charmed hadrons

fits naturally into SHMc



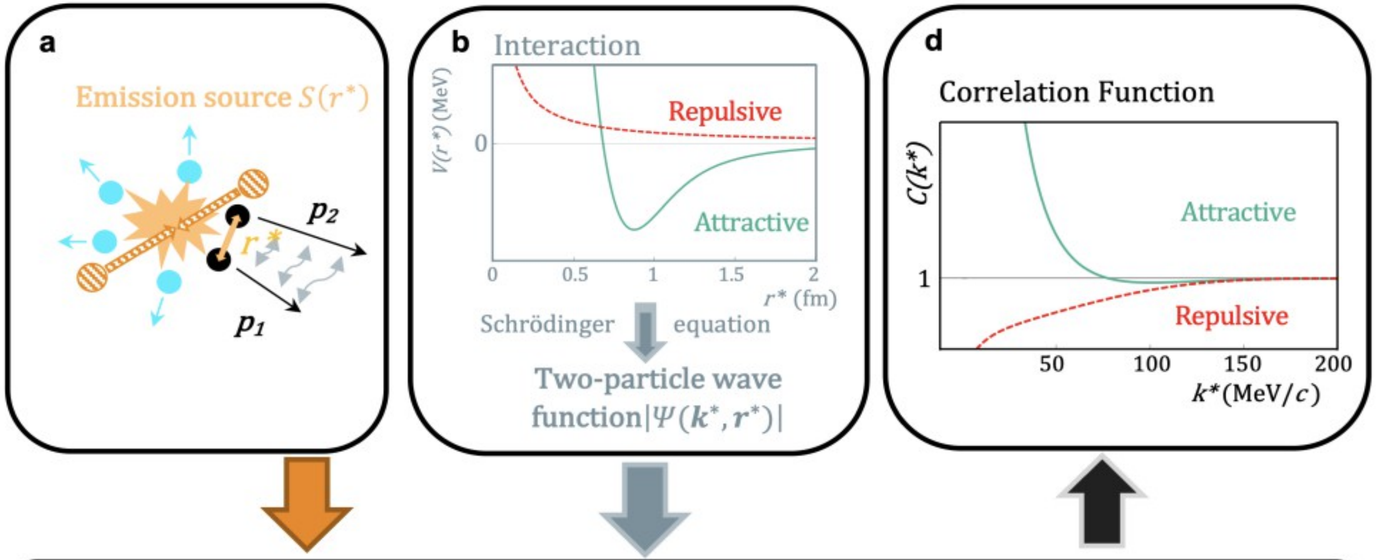


mass = 3874.75 ± 0.11 MeV
mass is very close to that of D^0*D^+_{bar}
width = 48 ± 2 + 0 - 14 keV
d(m) = - 360 ± 40 keV
binding energy: 360 ± 40 keV
T_{cc}+ → D0 D0 π+
angular momentum: J=1, isospin I = 0

see LHCb papers
2109.01038 [hep-ex]
2109.01056 [hep-ex]

Hadron-hadron interactions studied with femtoscopy at the LHC

ALICE coll., Nature 588 (2020) 232–238



c

$$C(k^*) = \int S(r^*) \; |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \otimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

Estimates for the measurement of D^0D^{*+} momentum correlations with ALICE3

Correlation functions and bound states

Correlation functions can be used to study the existence of bound states
Interplay between system size and scattering length can lead to a size-dependent modification of the correlation function in presence of a bound state

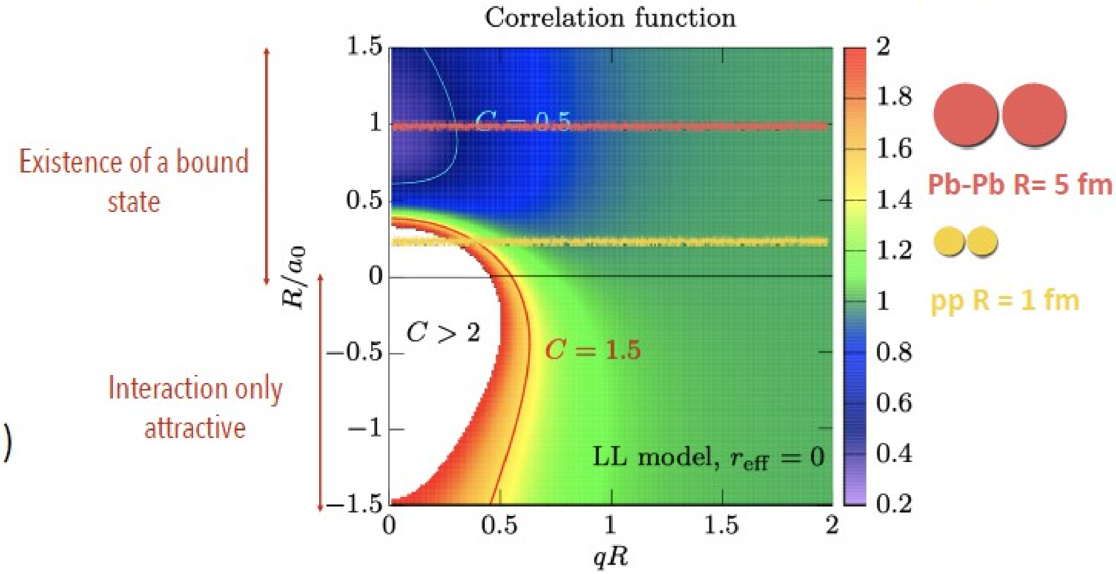
$$x = qR \quad y = \frac{R}{a_0} \qquad\qquad C(q) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}\int_0^{2x} dt\,\frac{e^{t^2-4x^2}}{x} - \frac{(1-e^{-4x^2})}{2}\right]$$

R= source size
q= invariant relative momentum
a_0= scattering length

A single measurement at fixed R does not suffice
A systematic measurements of different sizes is necessary :

- pp (R= 1 fm), p-Pb(R= 1. 5 fm), Pb-Pb (R= 2-6 fm)

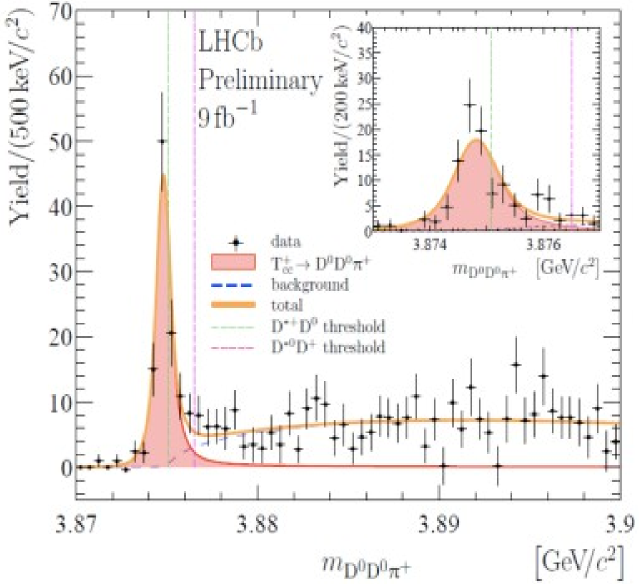
Example: a_0 = 5 fm



Y. Kamiya et al. arXiv:2108.09644v1

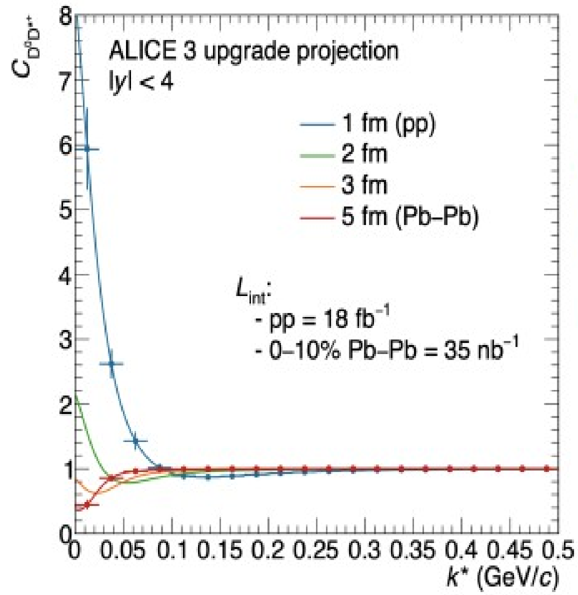
The T_{cc}^{+} example

- Recent measurement of tetraquark-like state by LHCb
  - Just below D^0D^{*+} and D^+D^{*0} thresholds $\longrightarrow$ candidate to be a molecular state
  - Correlation functions evaluated by means of a Gaussian potential that reproduces the T+cc 'binding energy' (T. Hyodo, Y. Kamiya)



E. S. Swanson, Phys. Rept. 429 (2006) 243-305

In case of a bound state (T_{cc}^+) the correlation function is expected to change from smaller to larger than unity for different source sizes



Scan from pp to AA collisions needed
ALICE3 is the ideal detector for acceptance

summary

- 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 is firmly 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
- the expected cross section for T_{cc}+ production in Pb-Pb colisions is very close to that predicted and published for X(3872) production
- precision study of such hadrons → further insight into confinement, deconfinement and hadronization of multi-charm hadrons

additional slides

a note on the total charm cross section

see also: JHEP 07 (2021) 035, arXiv:2104.12754 [hep-ph]

The charm production cross section at the LHC

A. Andronic

June 25, 2021

- LHCb $p_T < 8\,GeV/c$, $2.0 < y < 4.5$ (after Erratum, May 10, 2017)

pp 5 TeV, JHEP 06 (2017) 147

$\sigma(c\bar{c}) = 1193 \pm 3(stat) \pm 67(syst) \pm 58(frag)\,\mu\text{b}, \quad \rightarrow \frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 0.477 \pm 0.036$ mb

pp 7 TeV, NPB 871 (2013) 1

$\sigma(c\bar{c}) = 1419 \pm 12(stat) \pm 116(syst) \pm 65(frag)\,\mu$b

$$\Lambda_c/D^0 = 0.140 \pm 0.045$$

- ALICE, $|y| < 0.5$, $p_T > 0\,GeV/c$

pp 5 TeV, arXiv:2105.06335, arXiv:2102.13601 :

$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 1.165 \pm 0.044(stat) \pm 0.065(syst)^{+.098}_{-.038}(extr) \pm 0.043(BR) \pm 0.042(RS) \pm 0.024(lumi)$ mb

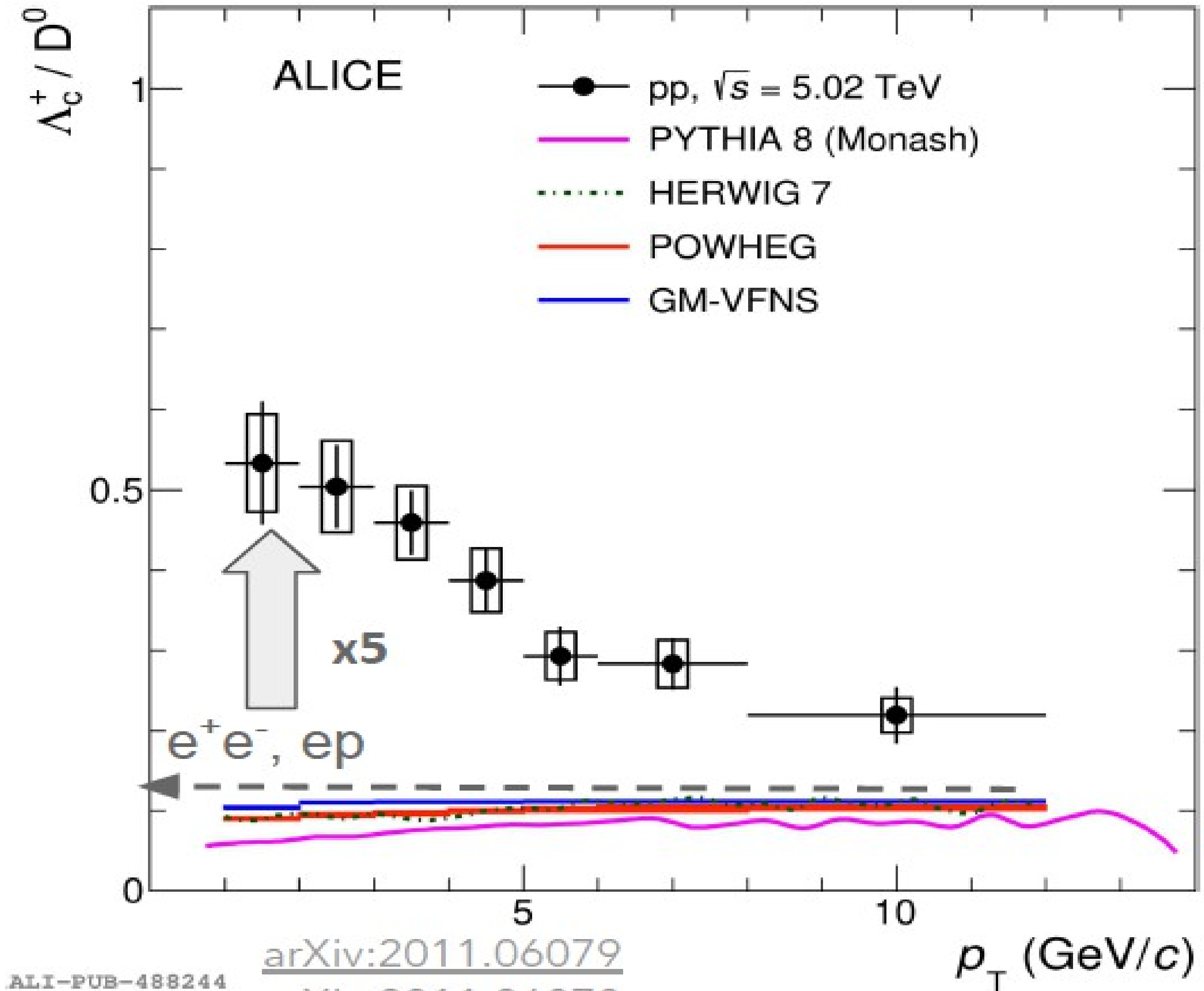
$$\Lambda_c/D^0 = 0.51 \pm 0.06$$

pp 7 TeV, JHEP 04 (2018) 108

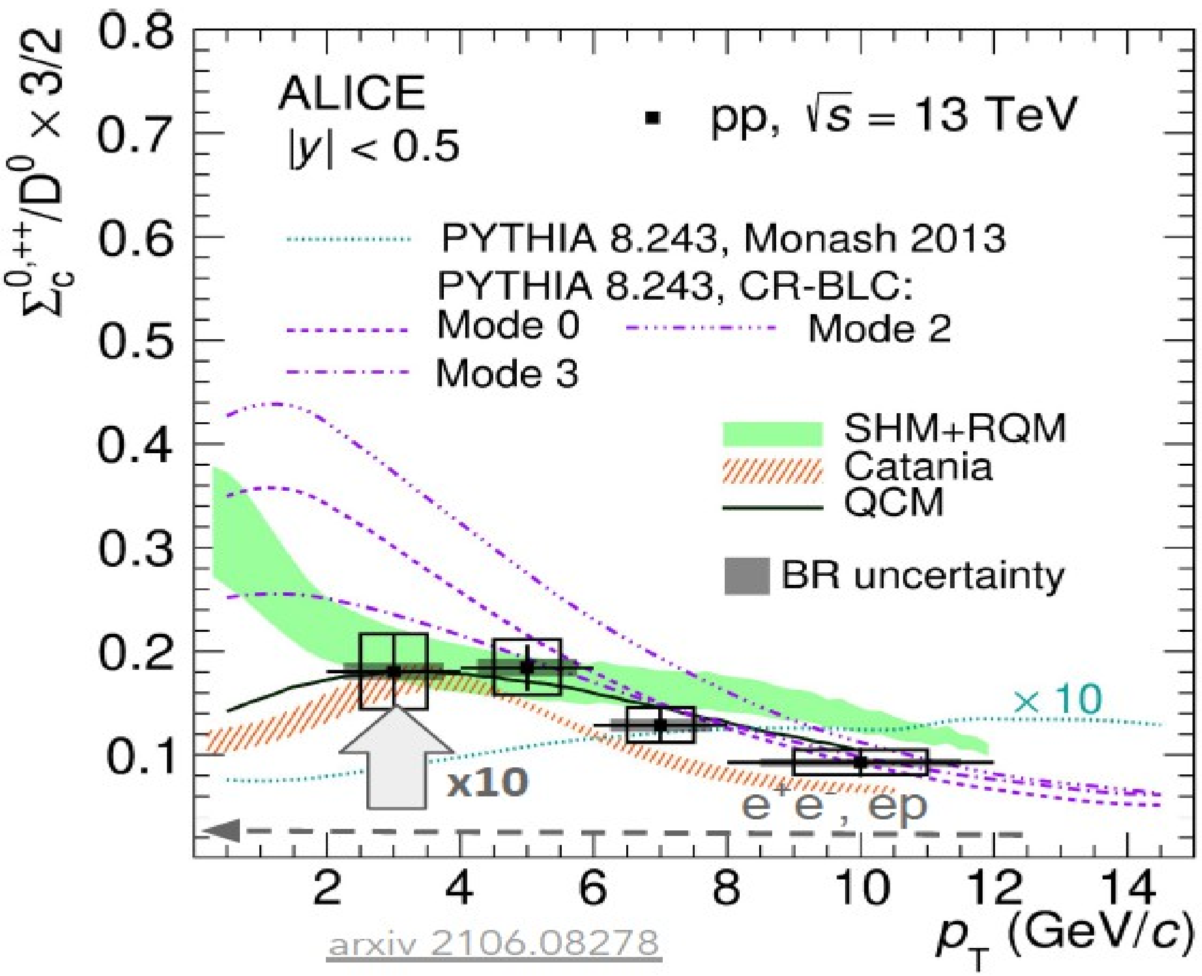
$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 1.347 \pm 0.097(stat) \pm 0.104(syst)^{+.142}_{-.105}(FF) \pm 0.011(BR) \pm .044(RS) \pm 0.047(lumi)$ mb

brief summary of latest LHC results on charm production in pp and pPb collisions

fragmentation of charm quarks not universal?



arXiv:2011.06079
arXiv:2011.06078



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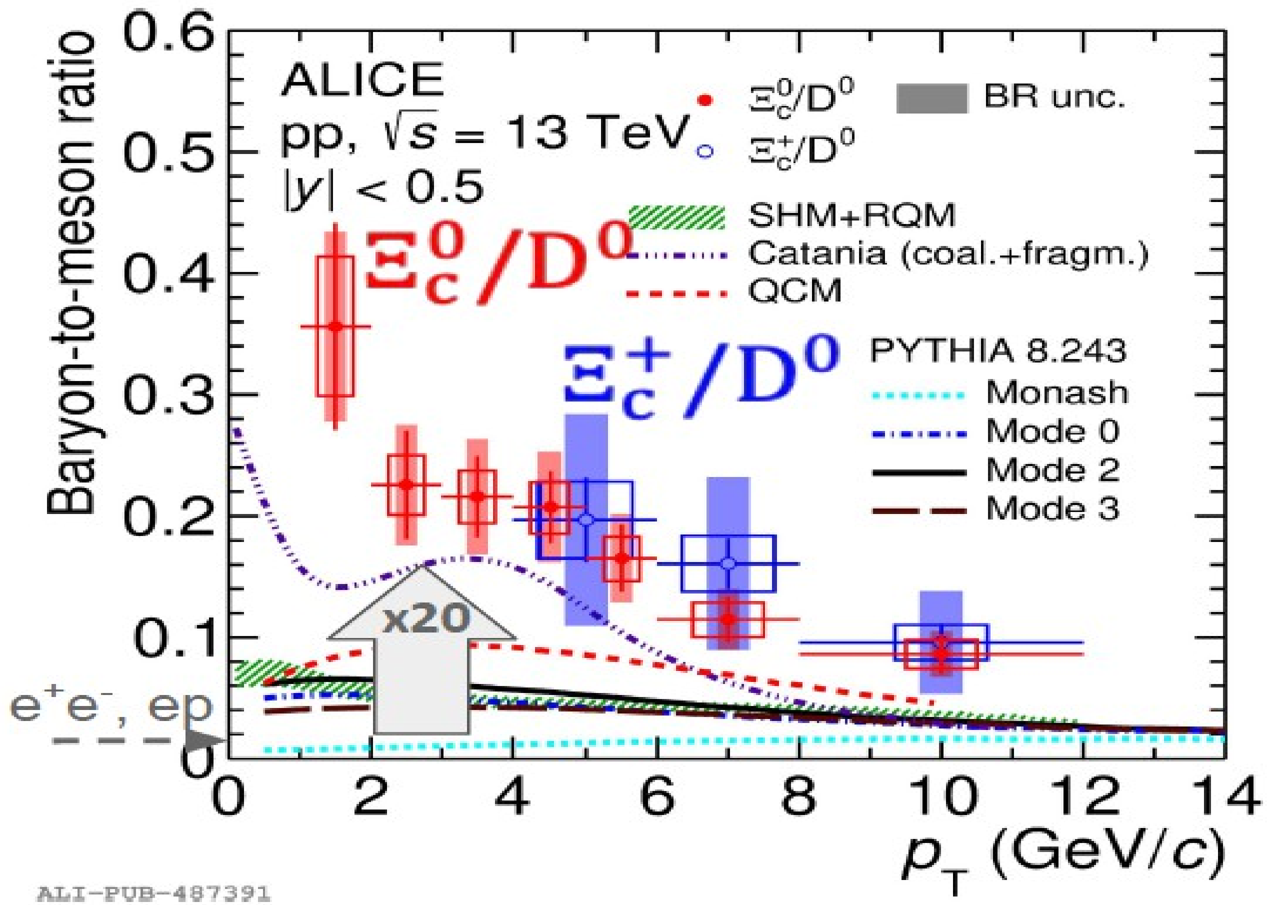
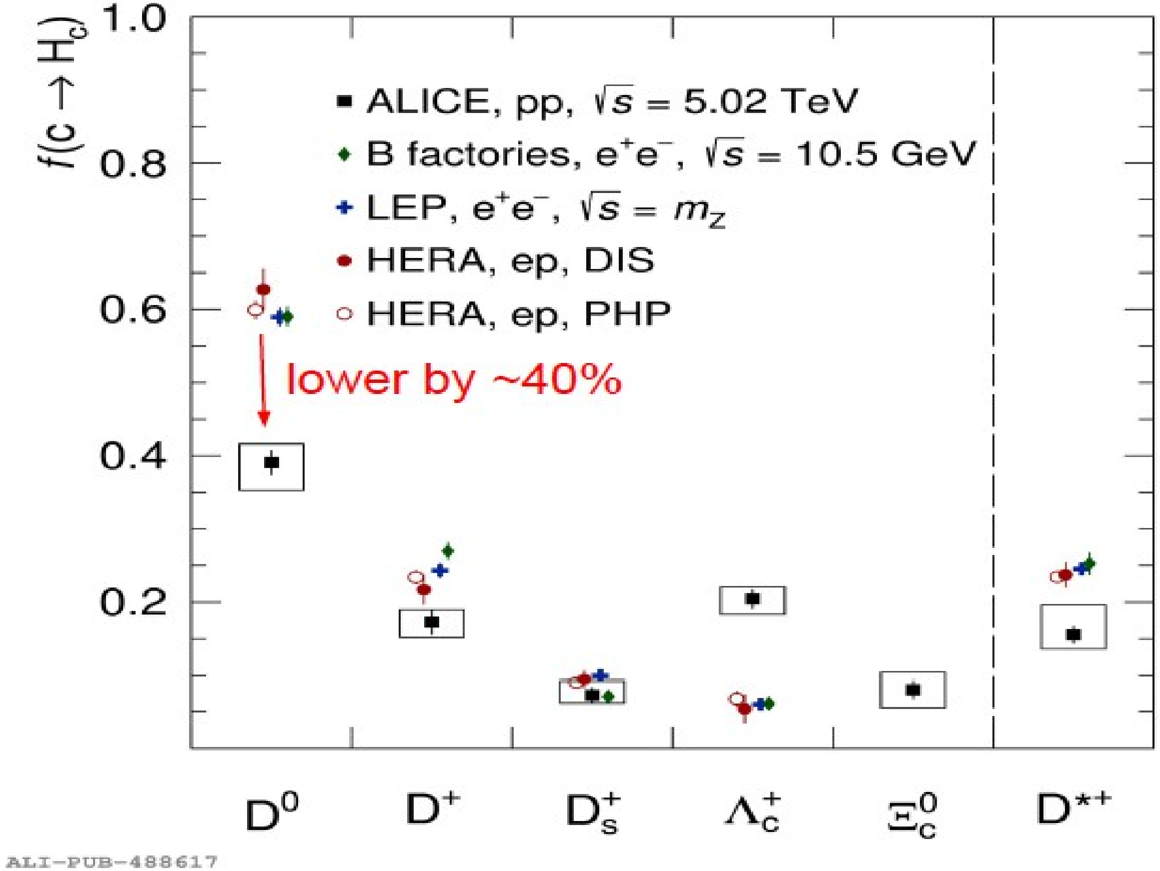


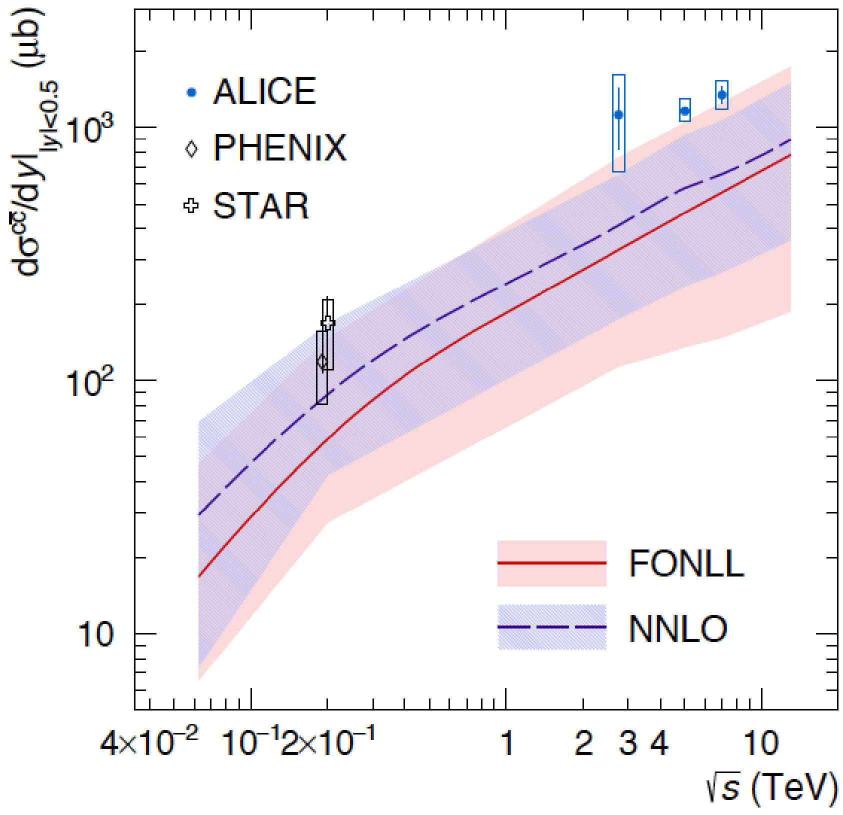
arxiv 2105.05187

fragmentation of charm quarks into hadrons with charm



arxiv 2105.06335

energy dependence of charm production cross section at mid-rapidity

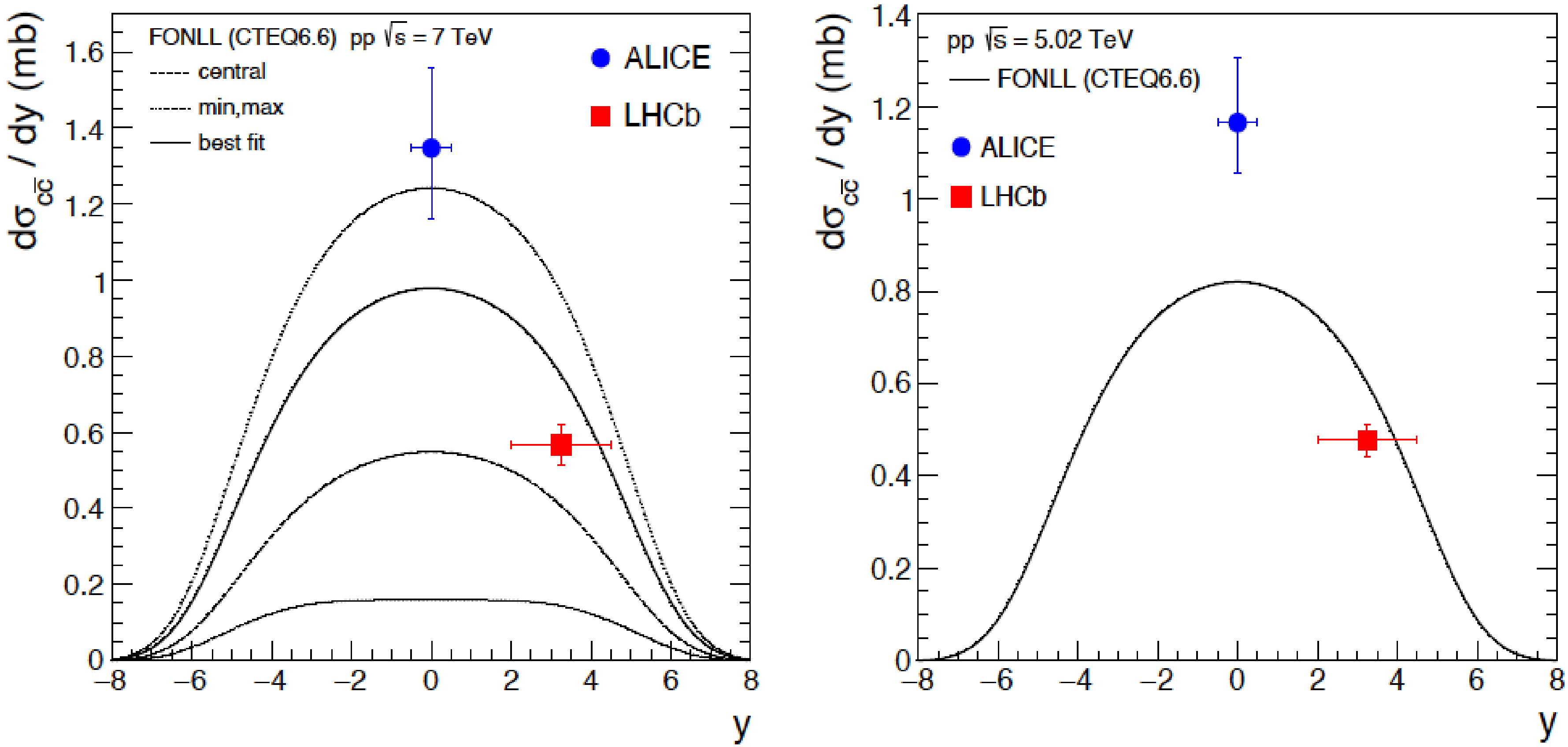


ALICE collaboration, arXiv:2105.06335

Data in comparison to FONLL

A. Andronic

...p_T-integrated ($p_T > 0$); FONLL web interface



estimate of shadowing S

JHEP 07 (2021) 035, arXiv:2104.12754 [hep-ph]

JHEP 07 (2021) 035

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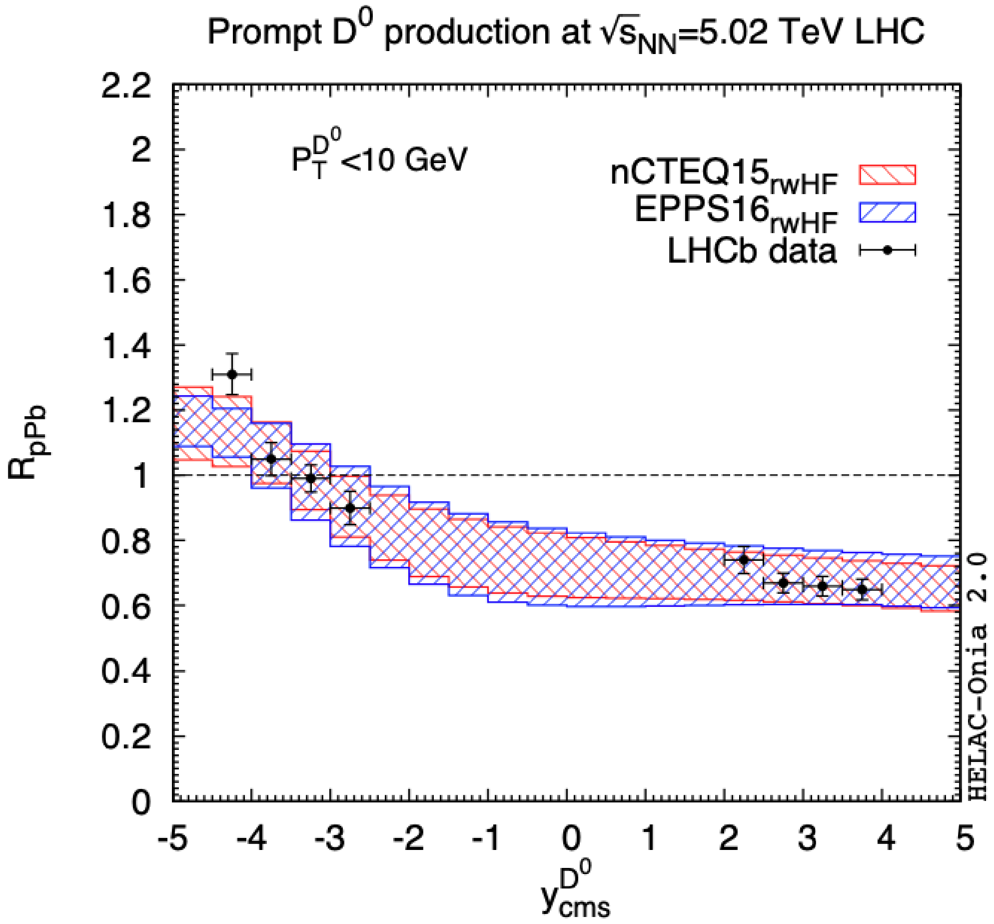
e-Print:

2104.12754 [hep-ph]



assume $S = R_{pPb}(y)\, R_{pPb}(-y)$

transverse momentum distributions
hydrodynamic approach based on MUSIC hydro code
over normalization fixed by SHMc results
charmed hadron production at T = 156.5 MeV

$$\frac{\mathrm{d}^2N}{2\pi p_\mathrm{T} dp_\mathrm{T} dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p)$$

$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_\mathrm{max}} \mathrm{d}r\, \tau(r) r \left[K_1^\mathrm{eq}(p_\mathrm{T}, u^r) - \frac{\partial\tau}{\partial r} K_2^\mathrm{eq}(p_\mathrm{T}, u^r)\right]$$

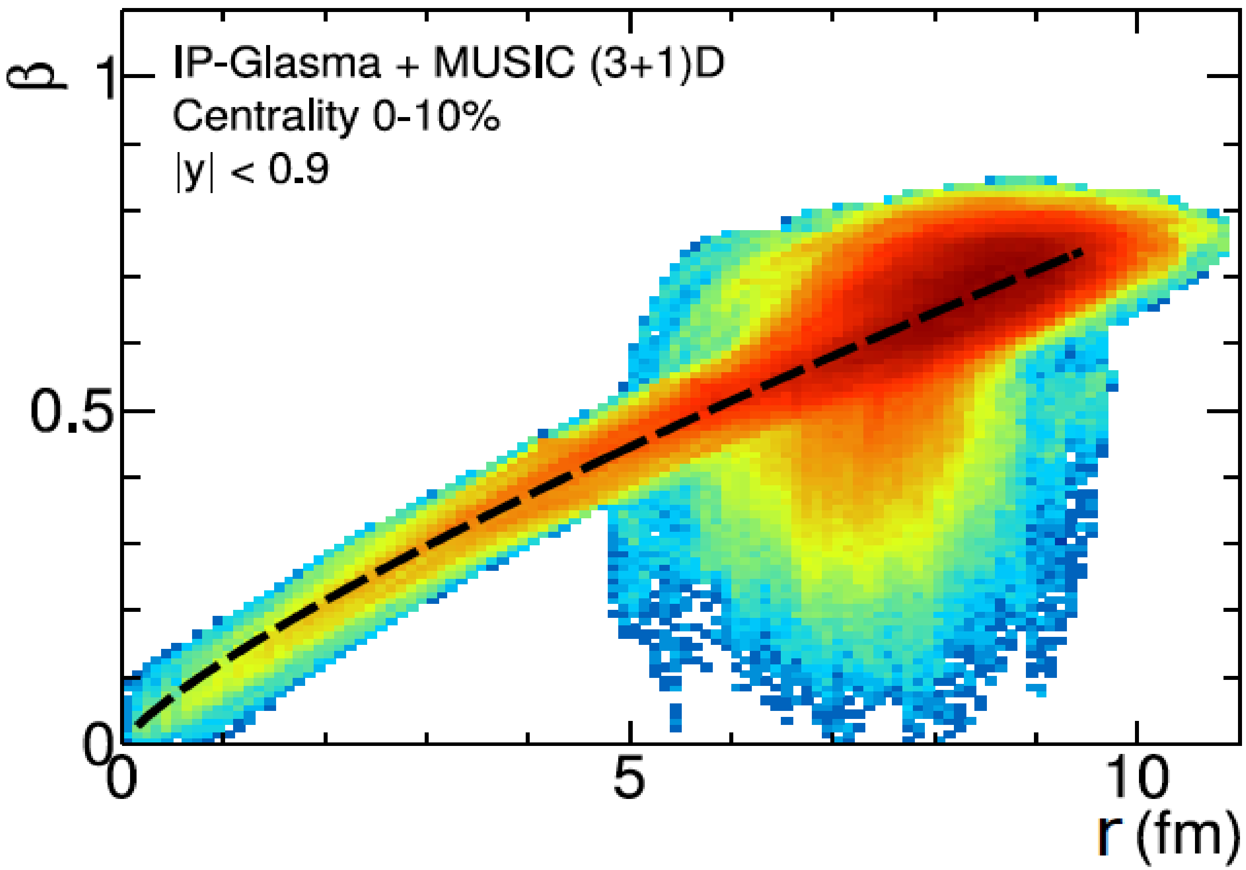
$$f(p) = \exp(-\sqrt{m^2+p^2}/T) \qquad u^r = \beta/\sqrt{1-\beta^2}$$

$$K_1^\mathrm{eq}(p_\mathrm{T}, u^r) = 4\pi m_\mathrm{T} I_0\left(\frac{p_\mathrm{T}u^r}{T}\right) K_1\left(\frac{m_\mathrm{T}u^\tau}{T}\right)$$

$$K_2^\mathrm{eq}(p_\mathrm{T}, u^r) = 4\pi p_\mathrm{T} I_1\left(\frac{p_\mathrm{T}u^r}{T}\right) K_0\left(\frac{m_\mathrm{T}u^\tau}{T}\right)$$

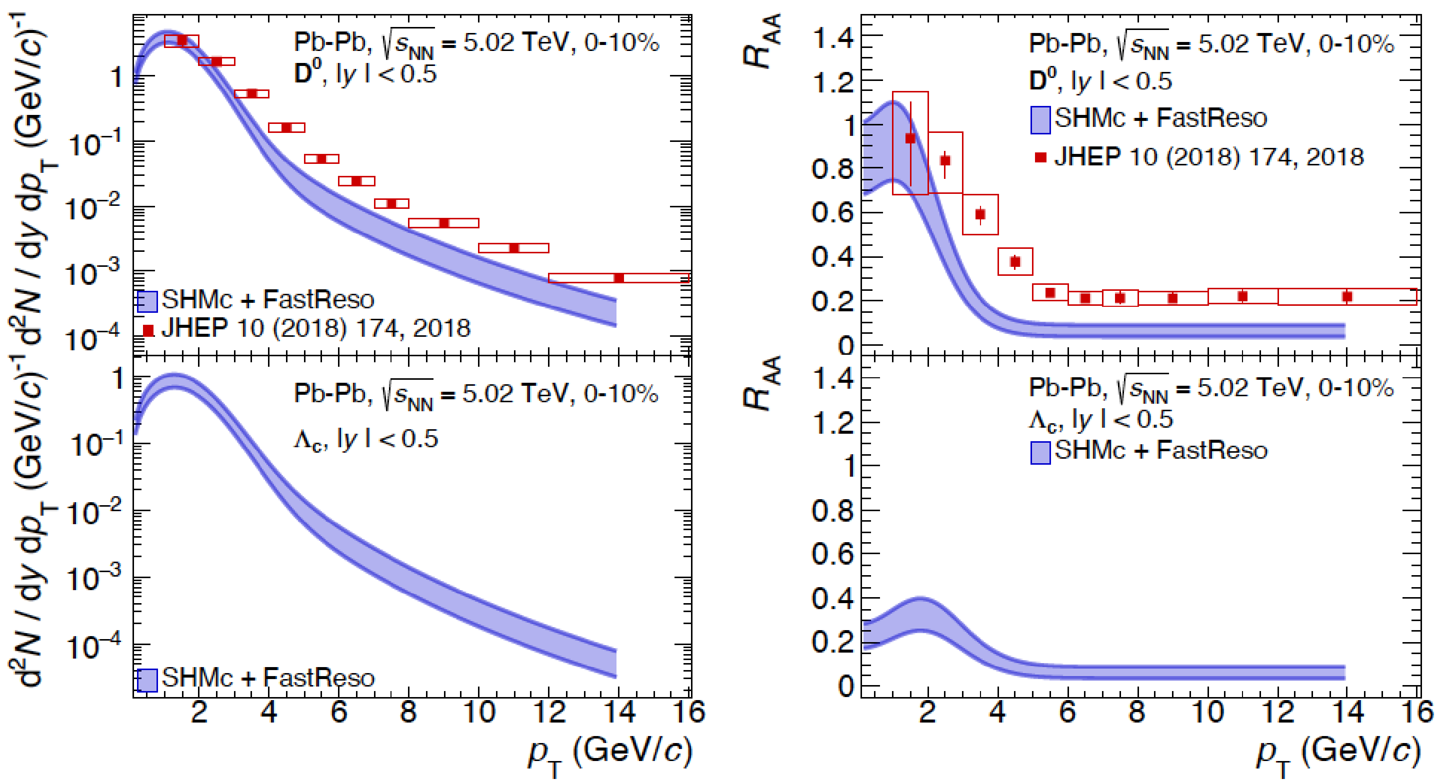
$$\beta(r) = \beta_\mathrm{max}\frac{r^n}{r_\mathrm{max}^n}.$$

velocity profile for central Pb-Pb collisions



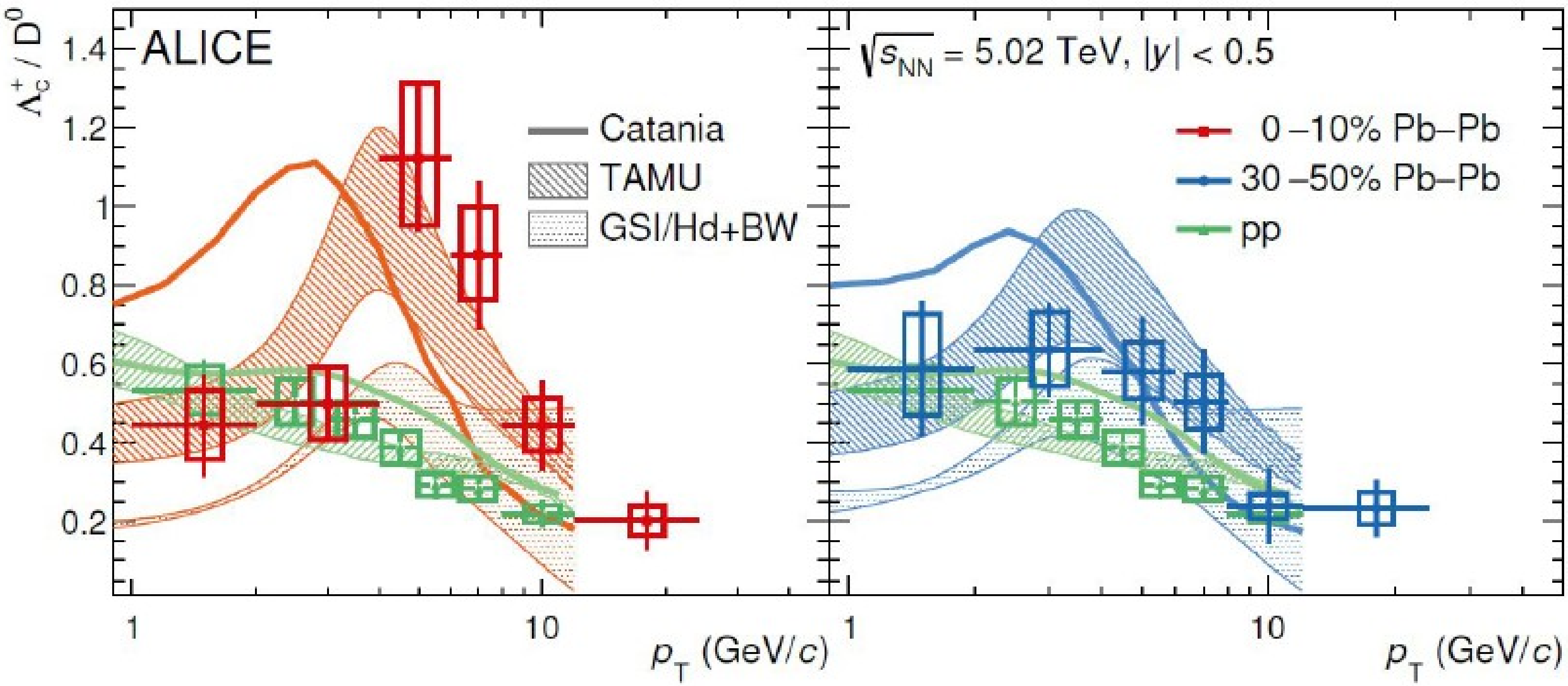
velocity profile from MUSIC
best fit with β_{max} = 0.62 and n = 0.85 for 0-10% centrality

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

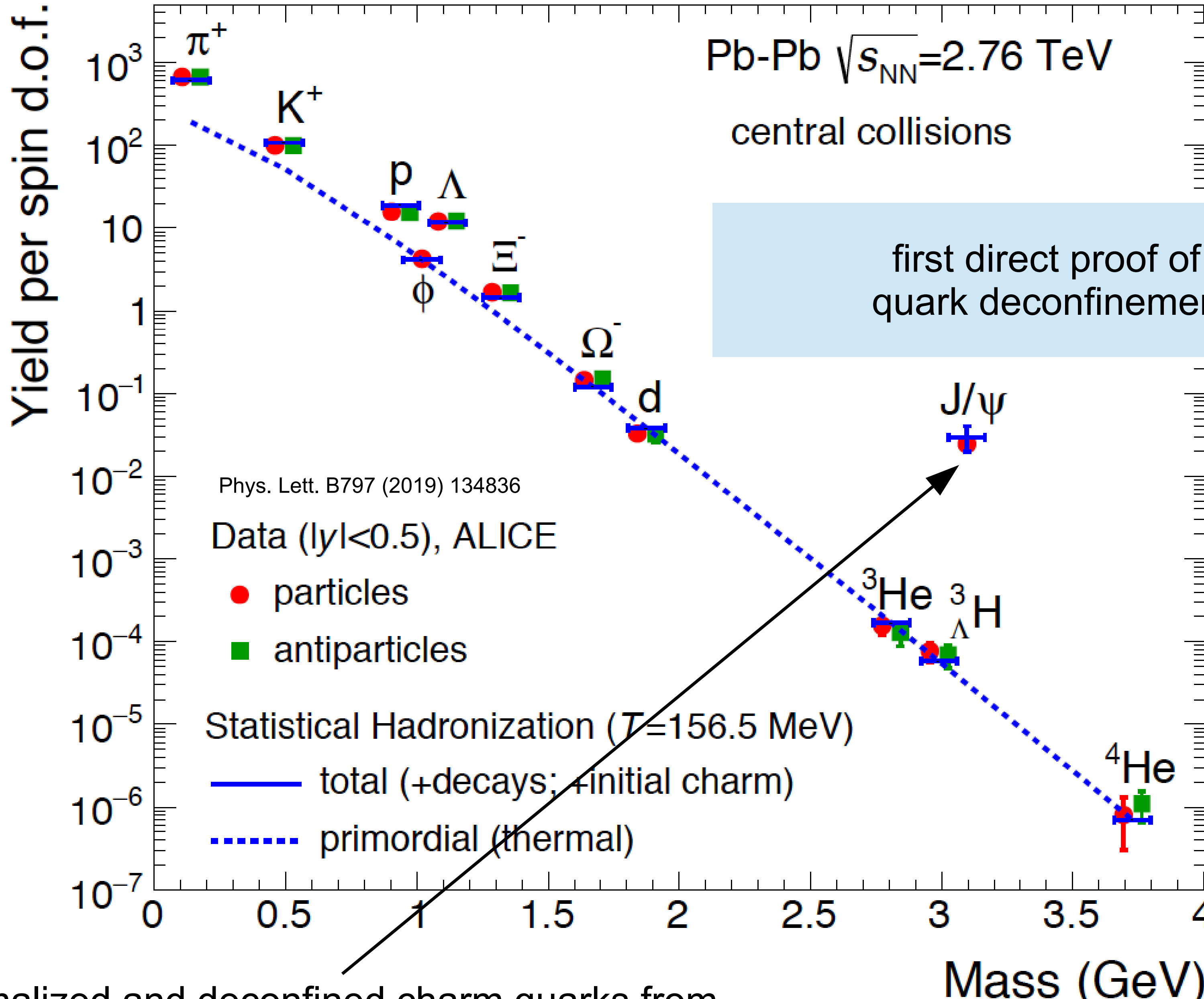


Λ_c data exist but are not (yet) cleared by ALICE

not quite preliminary but nearly final data



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



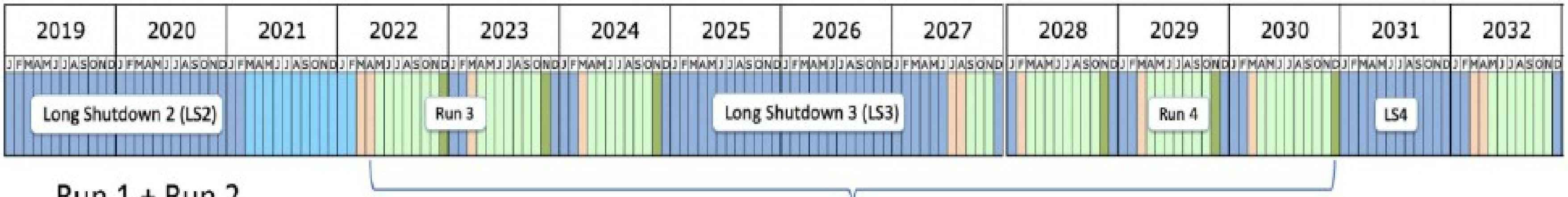
first direct proof of
quark deconfinement

with thermalized and deconfined charm quarks from
initial hard scattering

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

ALICE plans for Run 3 and 4

Long-term LHC schedule



Run 1 + Run 2

$\mathcal{L}_{int}(Pb-Pb) \approx 1nb^{-1}$

$\mathcal{L}_{int}(Pb-Pb) \approx 13\, nb^{-1}$

Run 3 luminosity targets

Pb-Pb (**13 nb^{-1}**): x 10 increase wrt Run 1 + Run2 (max interaction rate 50 kHz)

⇨ ALICE continous detector readout (no trigger) and recording

⇨ **x 50 increase in statistics** for most observables (minimum-bias rate limited to 1 kHz in Runs 1 and 2)

not only Pb-Pb, but also pp (**200/pb**), p-Pb (**~0.6/pb**) and O-O (**~1/nb**)

ALICE detector upgrade for LHC Run3: a 3 year effort
> 300 scientists and technicians involved

Which correlations could be of interest ?

State	Mass [MeV]	Width [MeV]	S-wave threshold [MeV]	Coupled Channels
X(3872) [14]	3872 ± 0.17	1.19 ± 0.21	$D^{*0}\bar{D}^0(-0.04)$, $D^{*+}\bar{D}^-(-8.11)$	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$
X(3940) [14]	3942 ± 9	37	$D^*\bar{D}^*$ (-75 ± 9)	$D^*\bar{D}$
X(4140) [14]	4147 ± 4.5	83 ± 21	$D_s\bar{D}_s^*$ ($-66^{+4.9}_{-3.2}$)	$\phi J/\psi$
X(4274) [14]	4273 ± 8.3	56 ± 11	$D_s\bar{D}_s^*$ ($-49.1^{+19.1}_{-9.1}$)	$\phi J/\psi$
Z_b(10610) [14]	10607 ± 2.0	18.4 ± 2.4	$B\bar{B}^*$(4 ± 3.2)	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$Z_b^\pm$(10650) [14]	10652.2 ± 1.5	11.5 ± 2.2	$B^*\bar{B}^*(+2.9)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
P_c^+(4312) [15]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Sigma_c\bar{D}(-9.7)$	pJ/ψ
P_c^+(4440) [15]	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c\bar{D}^*(-21.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
P_c^+(4457) [15]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c\bar{D}^*(-4.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
T_{cc}^+ [16]	3874.827	0.410	$D^{*+}\bar{D}^0(-0.273)$, $D^{*0}\bar{D}^+(-1.523)$	$D^0D^0\pi^+$

Tetraquarks with $c\bar{c}$?

Tetraquarks with $b\bar{b}$?

Pentaquarks with $\bar{c}c$?

Tetraquarks with cc ?

Or all molecular states ?