Charmonia, open charm states, exotica, and deconfinement

new developments in the framework of the SHMc

(SHMc = statistical hadronization model with charm)

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Heavy Flavor Transport in QCD Matter
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the multiple-charm hierarchy in the statistical hadronization model

results shown in this talk: A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler, A. Mazeliauskas, K. Redlich, V. Vislavicius, arXiv:2104.12754

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 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 ($m_{c\bar{c}} \gg \Lambda_{\mathrm{QCD}}$)
- 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 ($T_{\mathrm{CF}}, \mu_{\mathrm{b}} \to n_X^{\mathrm{th}}$)

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

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

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}

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

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

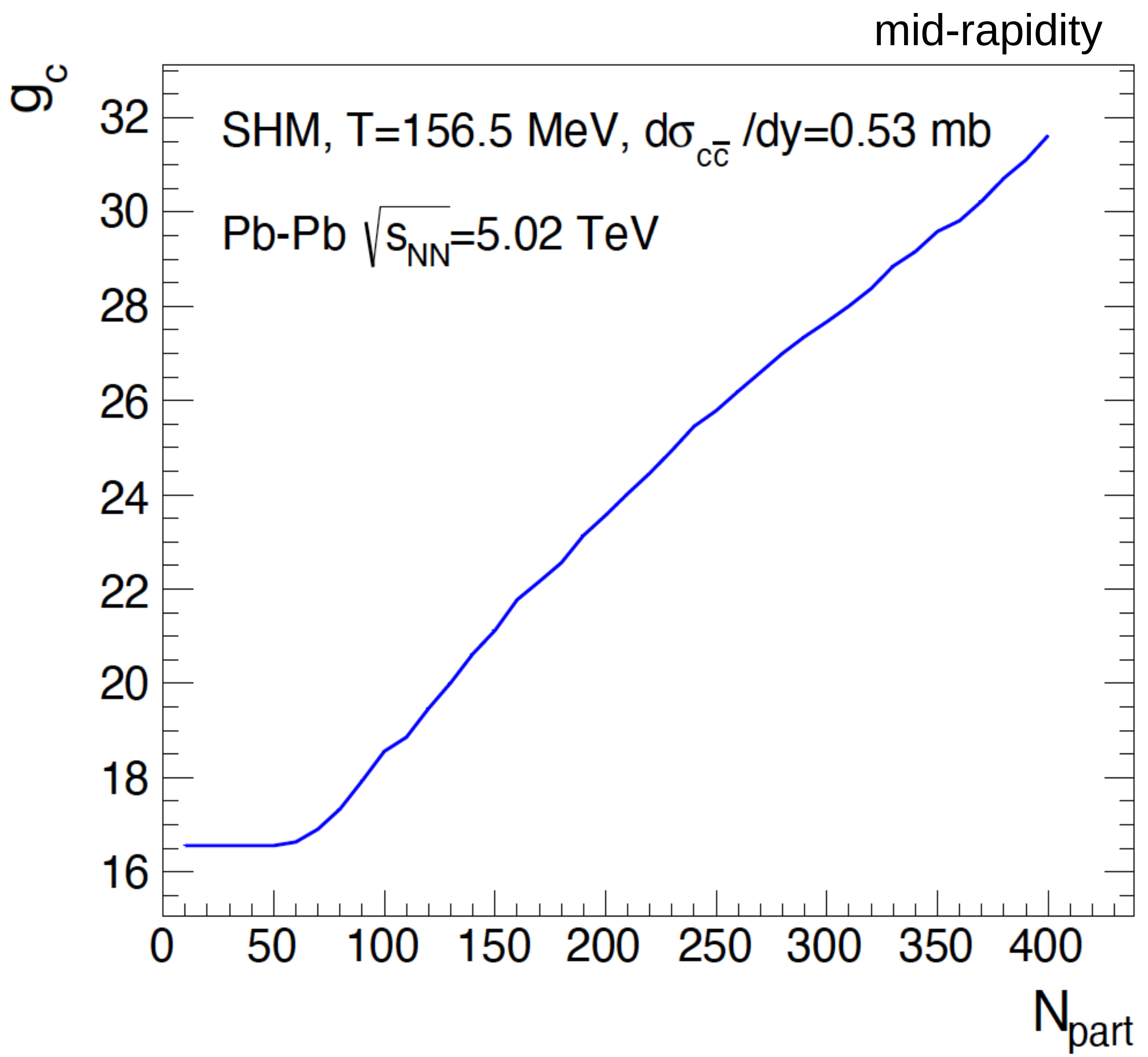
obtained from measured open charm cross section

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

- balance equation with canonical suppression needs to be solved numerically to obtain g_c

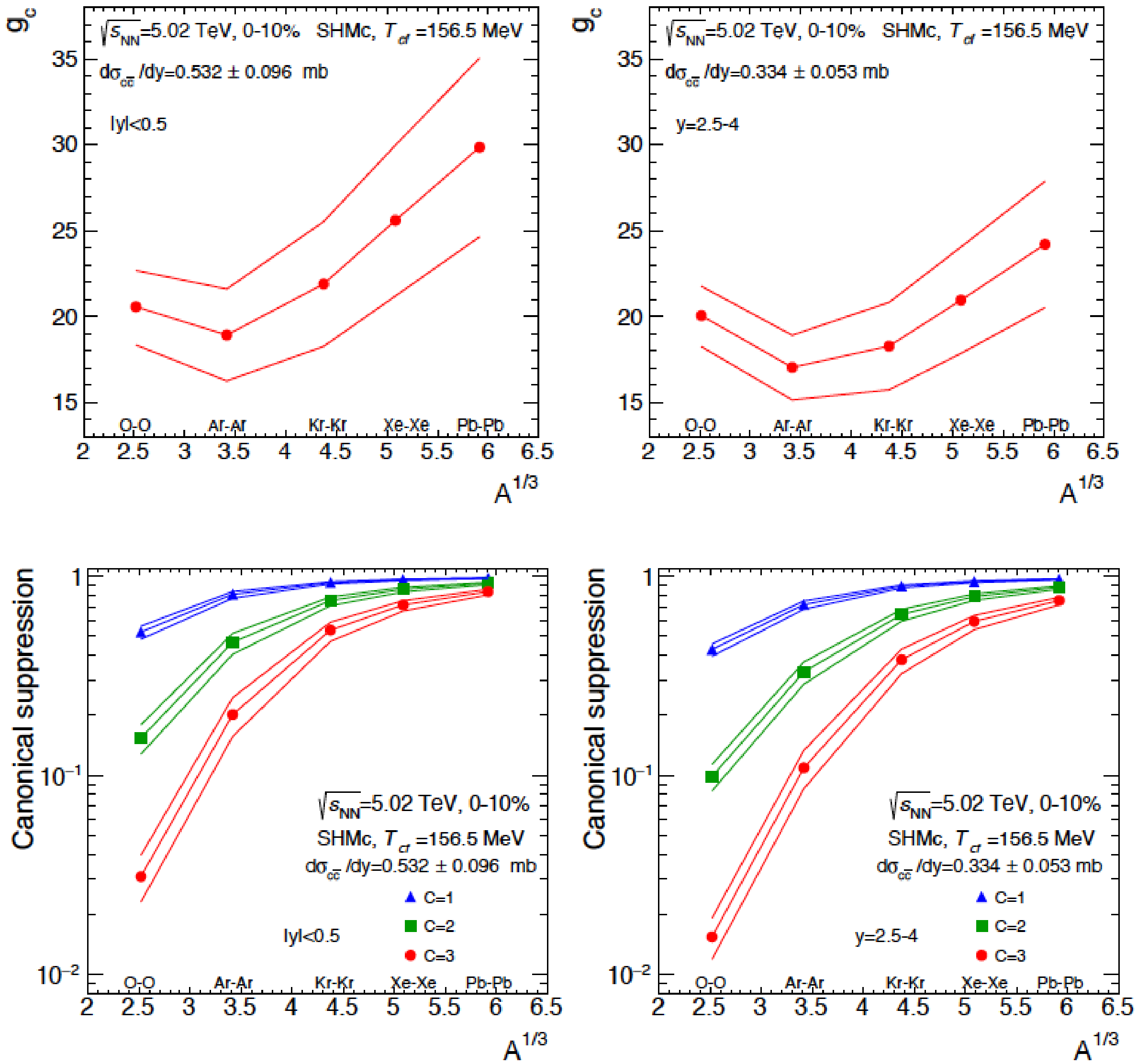
- for yields of charm hadron i with n_c charm quarks $N_{n_c}(i) = g_c^{n_c} N_{n_c}(i)^{th} \frac{I_{n_c}(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})}$

centrality dependence of charm fugacity g_c at LHC energy



charm fugacities and canonical suppression factors

different collision systems:



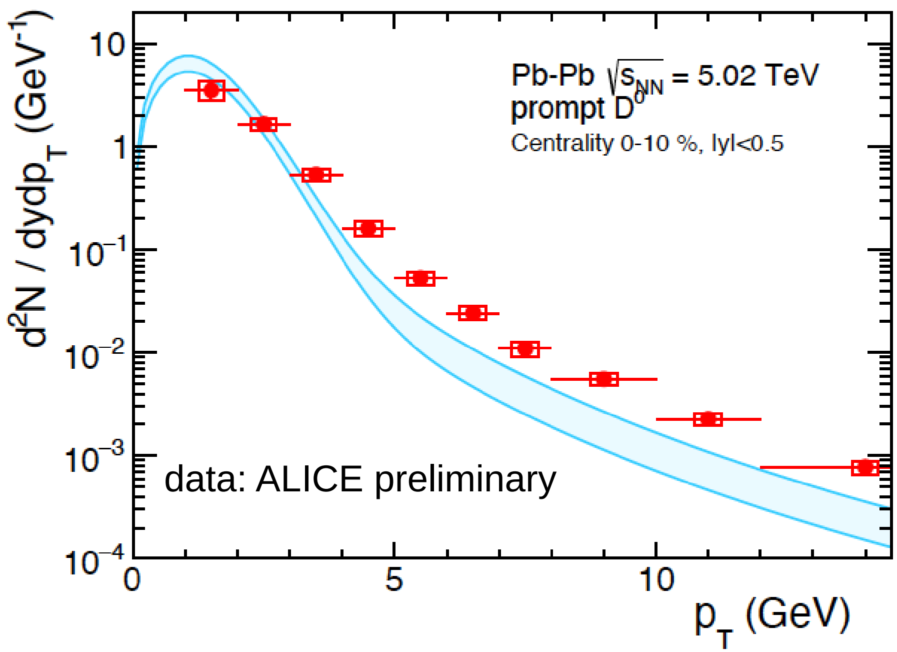
statistical hadronization for hidden and open charm

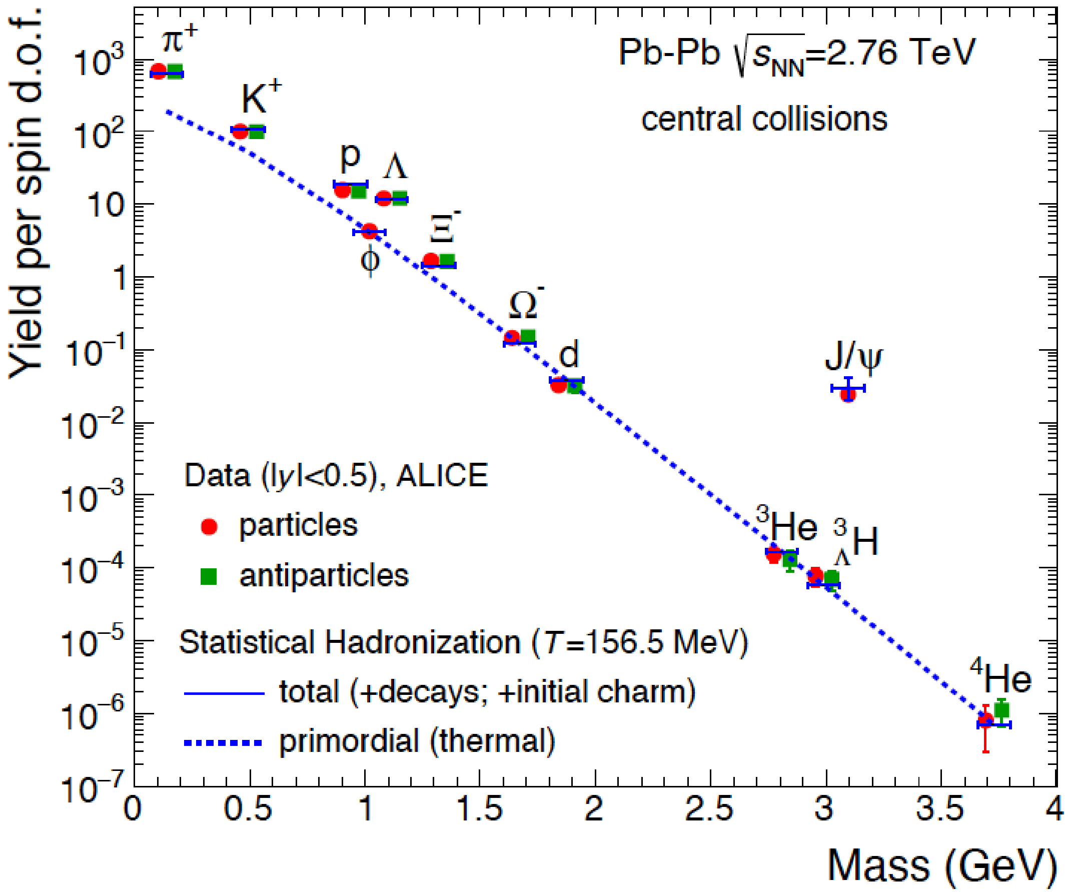
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0





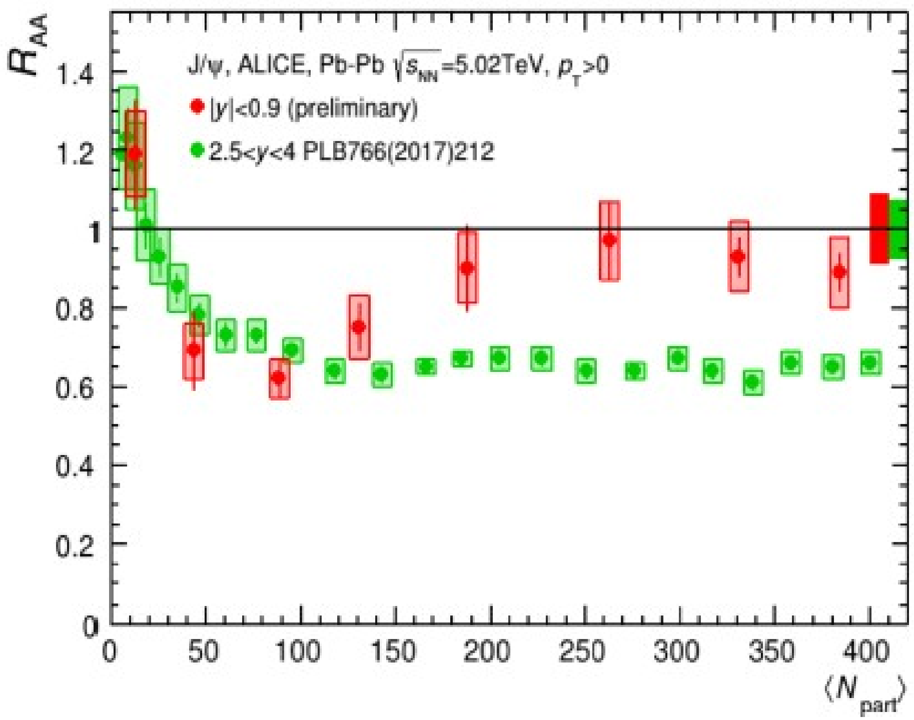
Andronic, Braun-Munzinger, Koehler, Redlich, JS PLB 792 (2019) 304
Andronic, Braun-Munzinger, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius arXiv:2104.12754

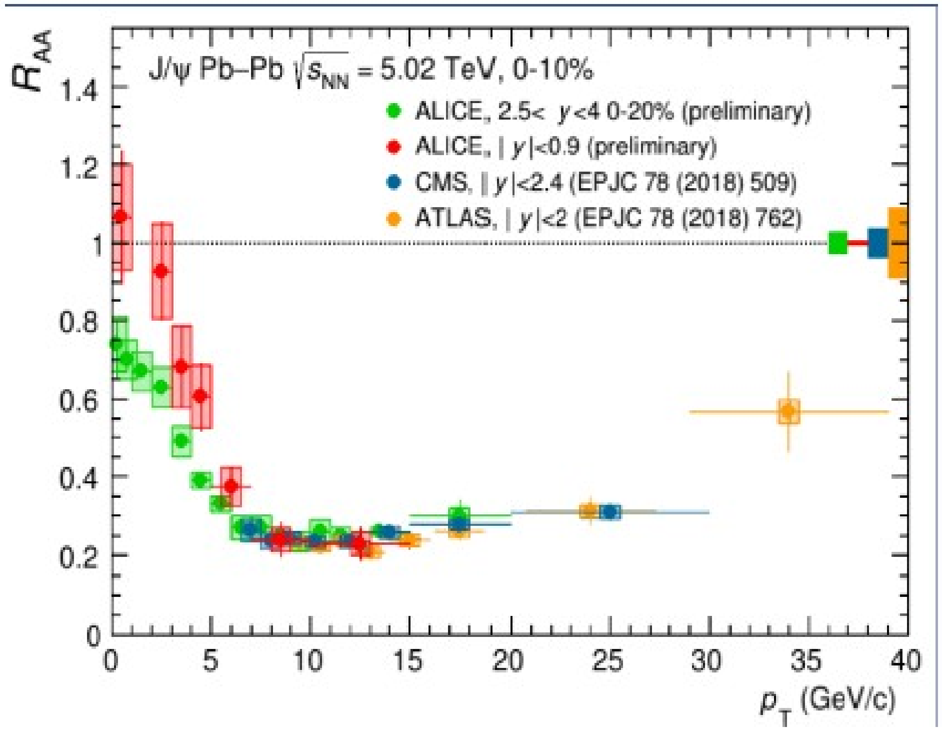
quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons,
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

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

charmonium at LHC: peaks at mid-y and strong enhancement at low transverse momentum

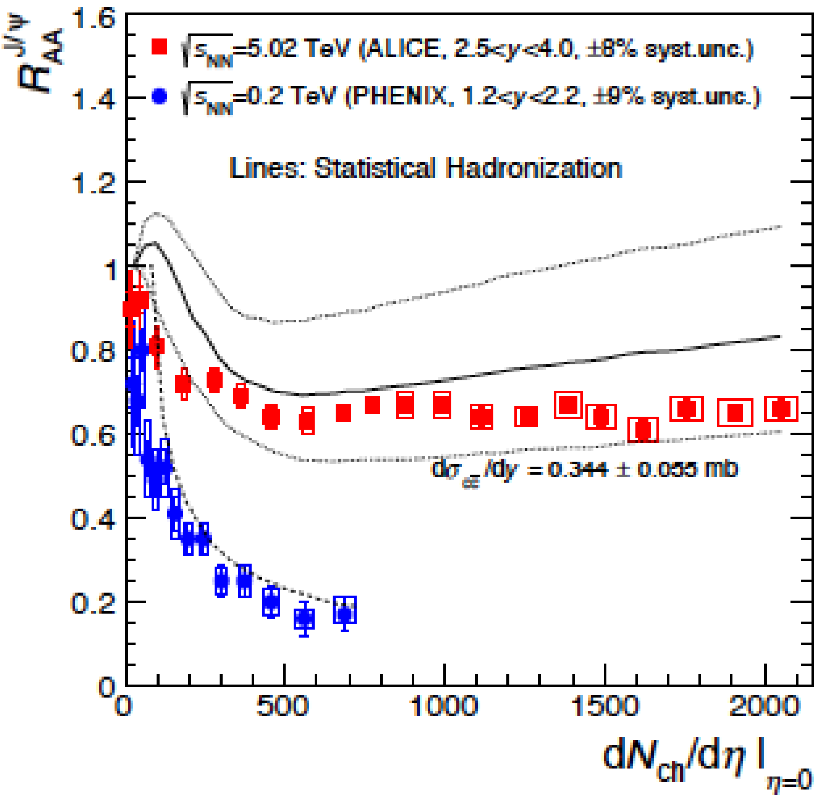
nuclear modification factor: $R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T}$

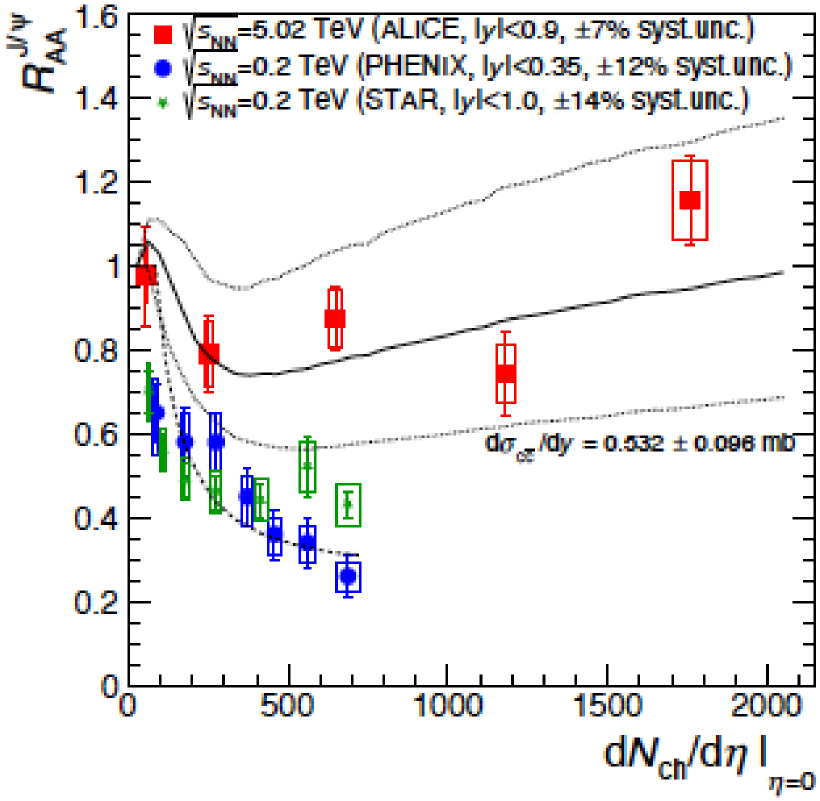




RHIC and LHC data compared to SHMc predictions

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

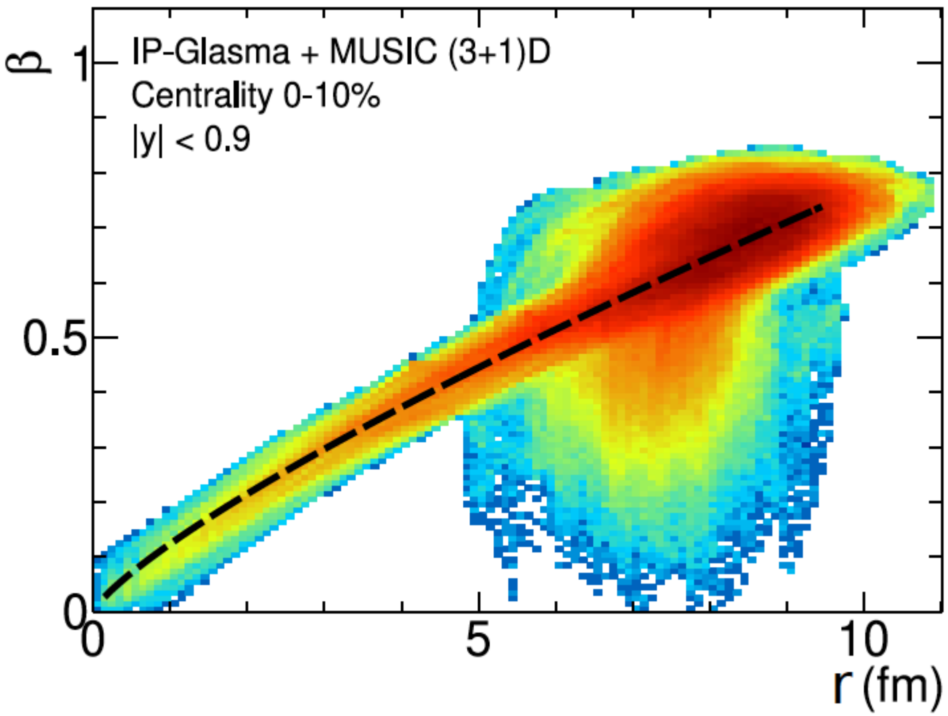




the band with the model predictions at LHC energy is due to the uncertainties in the pp open charm cross section and the necessary shadowing corrections

beyond yields: transverse momentum distributions

assume thermalization of charm quarks in QGP, charm quarks follow collective flow
use hydro velocity profile at pseudocritical temperature from MUSIC (3+1) D
tuned to light flavor observables



$$\beta(r) = \beta_{\max}\frac{r^n}{r^n_{\max}}$$

$$\beta_{\max} = 0.62$$

$$n = 0.85$$

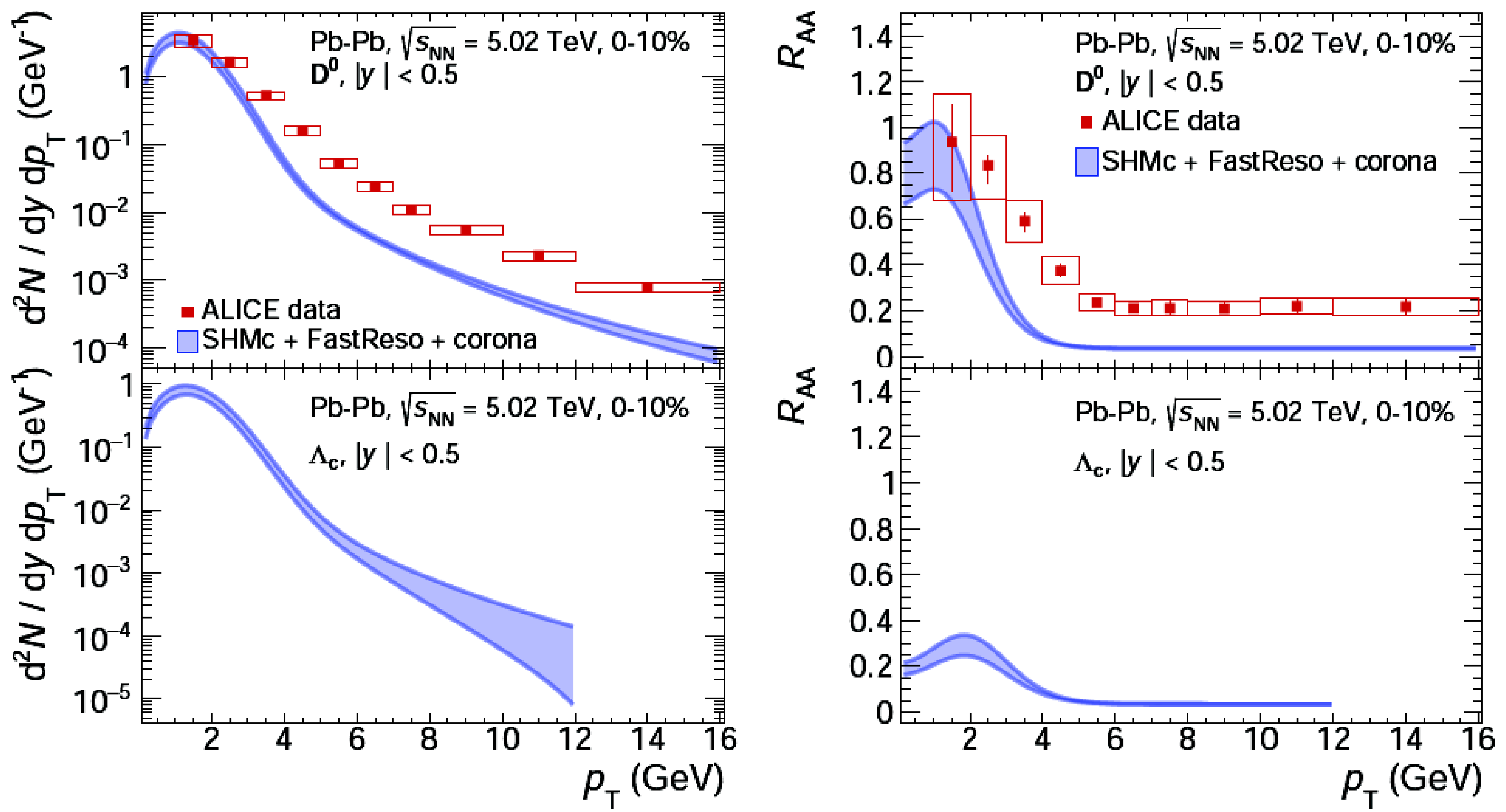
$$V = 2\pi\int_0^{r_{\max}} \mathrm{d}r \; r\tau(r)u^\tau \left[1-\beta(r)\frac{\partial\tau}{\partial r}\right]$$

$$V = 4997\,\mathrm{fm}^3$$

and blast wave parametrization of spectral shape with T = 156.5 MeV and
a fireball volume per unit rapidity for central PbPb collisions V = 4997 fm^3
sensitivity to shape of freeze-out surface: backup

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)

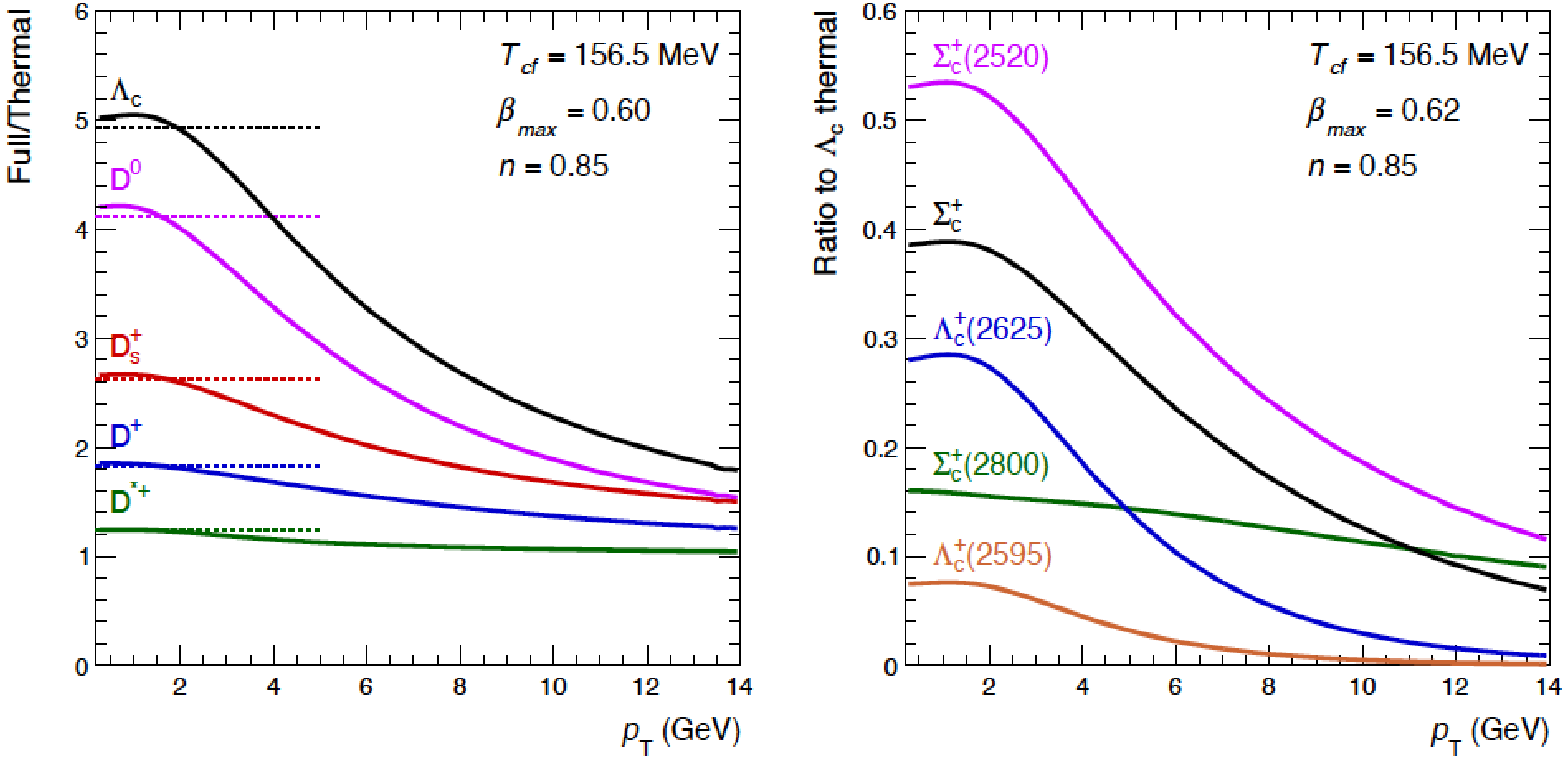


Λ_c data exist but are not (yet) cleared by ALICE

impact of resonance decays

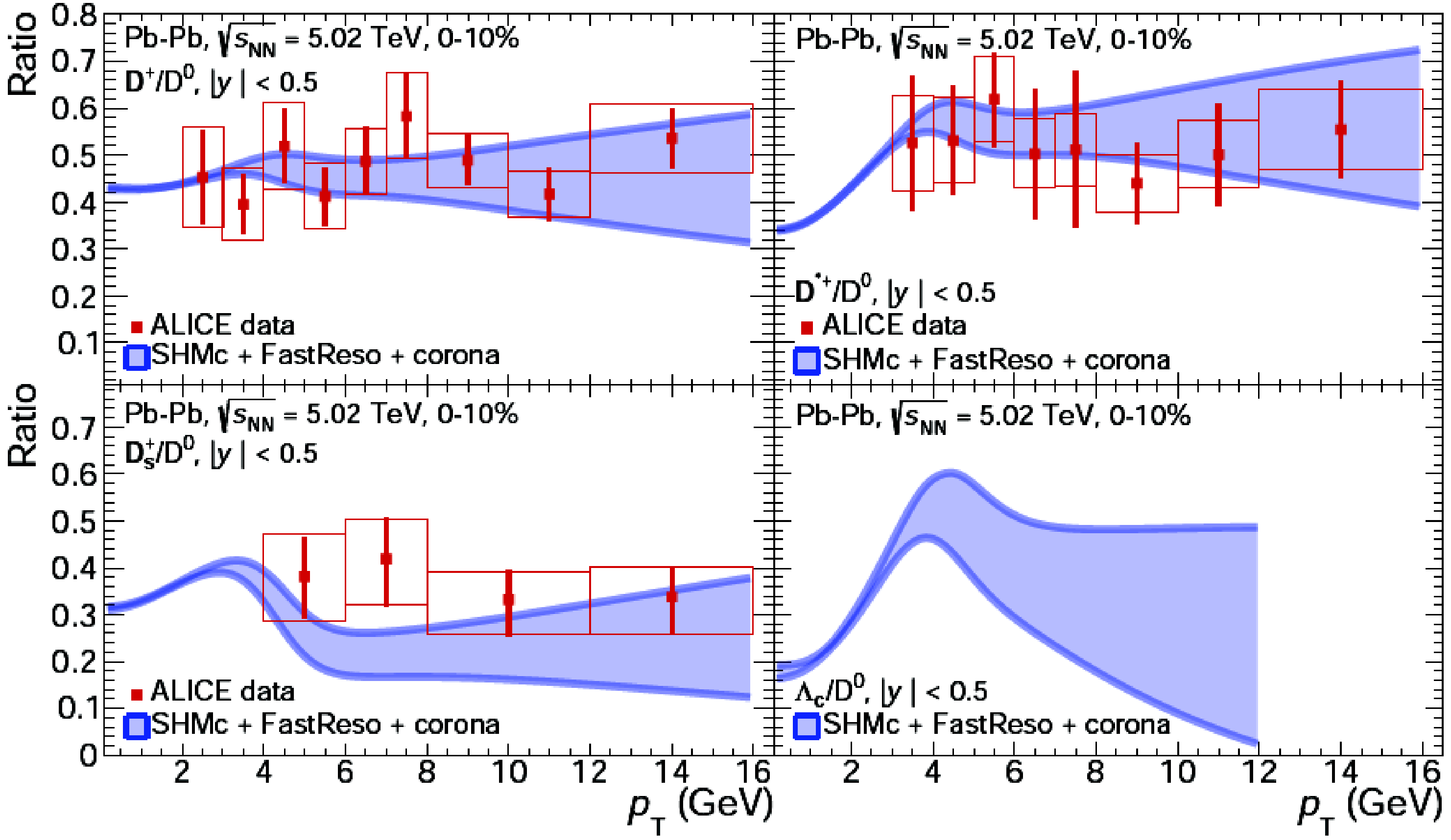
D_0 quadrupled by strong decays
Λ_c 5 times as many after strong decays

feed-down to Λ_c



but: beyond 4 GeV corona dominates, hence change in shape not very visible

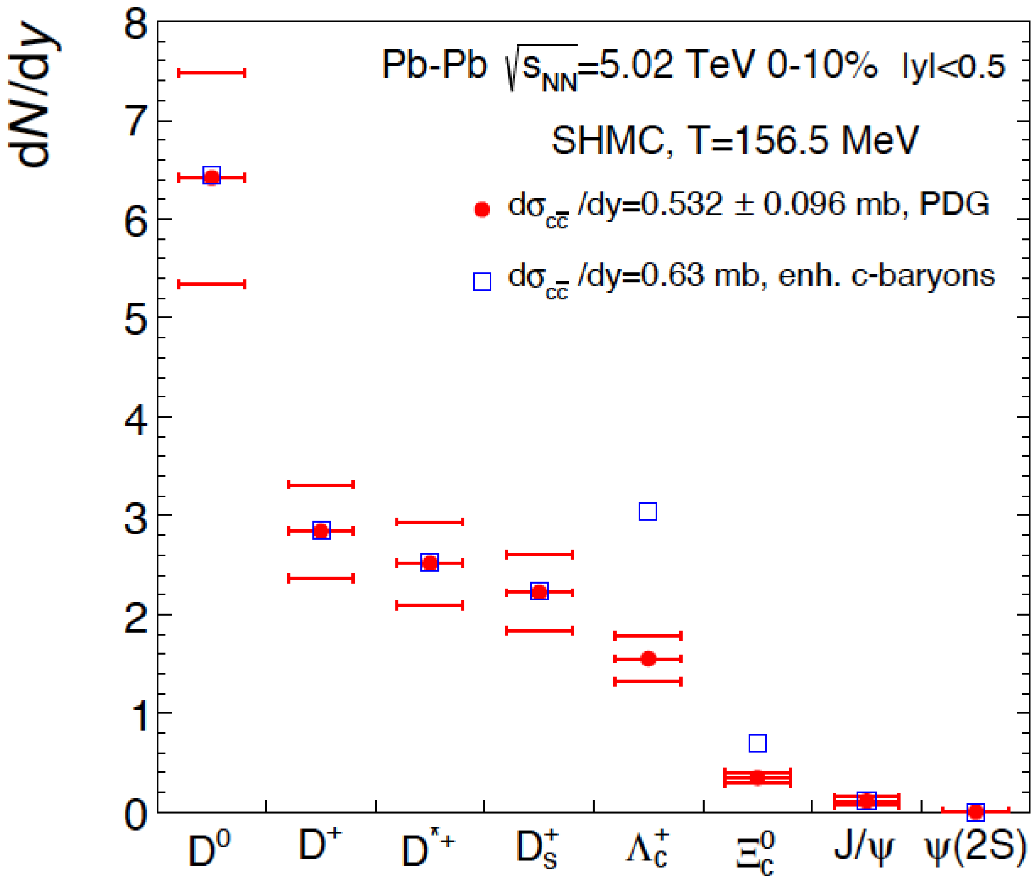
ratios of charm hadron to D^0 spectra



excellent agreement considering that there are NO free parameters

charm hadron yields with modified charm resonance spectrum

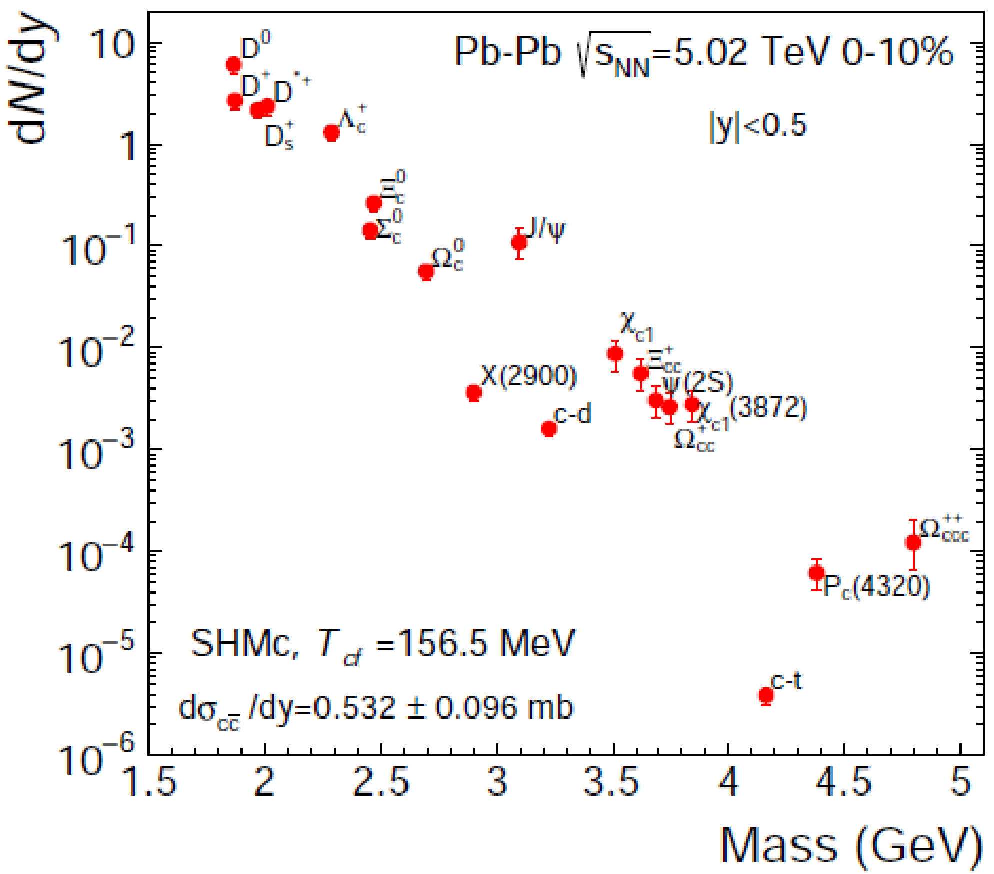
recently a lot of speculation about possibly incomplete charm baryon spectrum
to test impact, tripled statistical weights of excited charm baryons

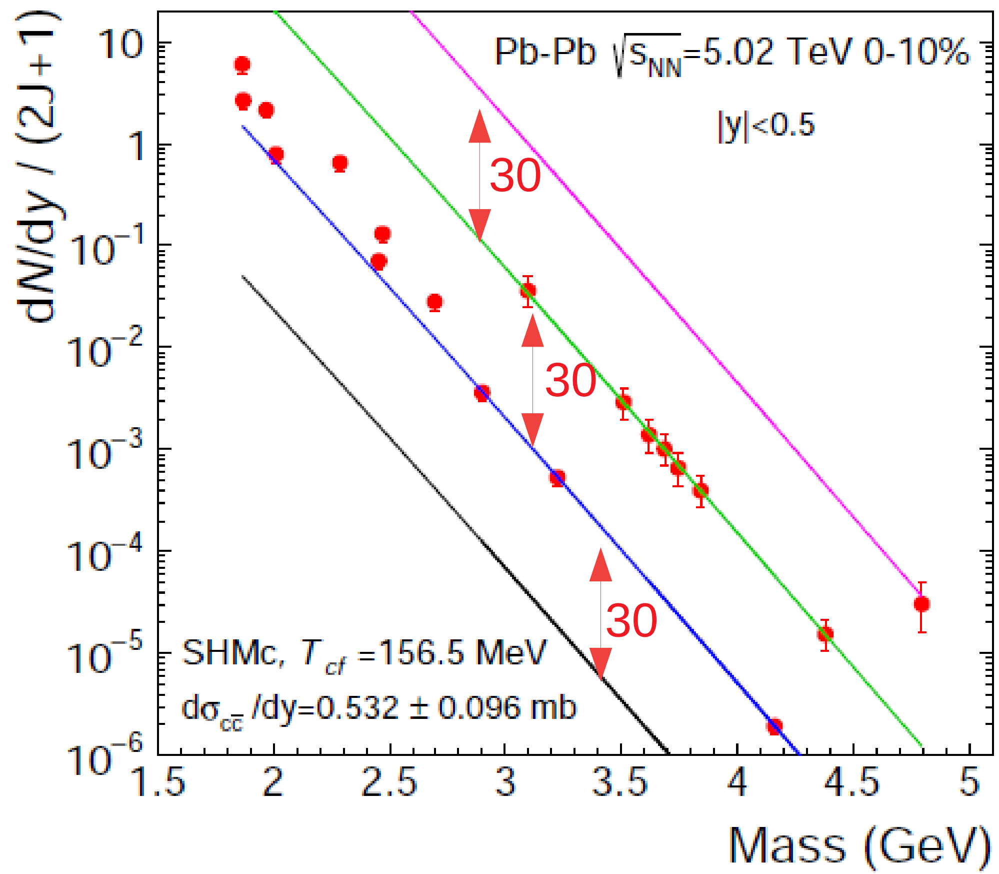


charm cross section increases 20%
yield of charm baryons nearly doubles
mesons practically unaffected

the multi-charm hierarchy

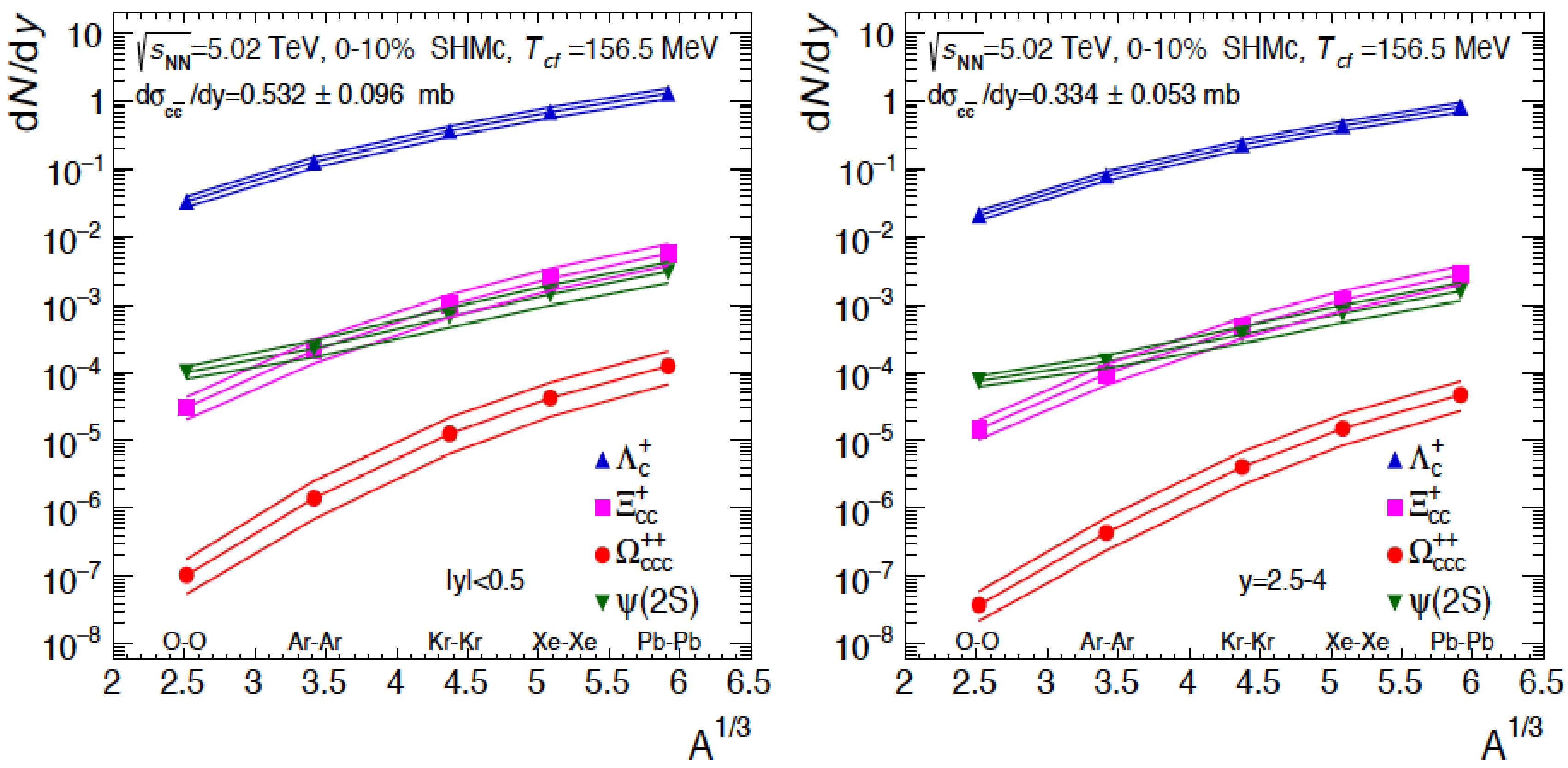
open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, ctriton, pentaquark, Ω_{ccc}





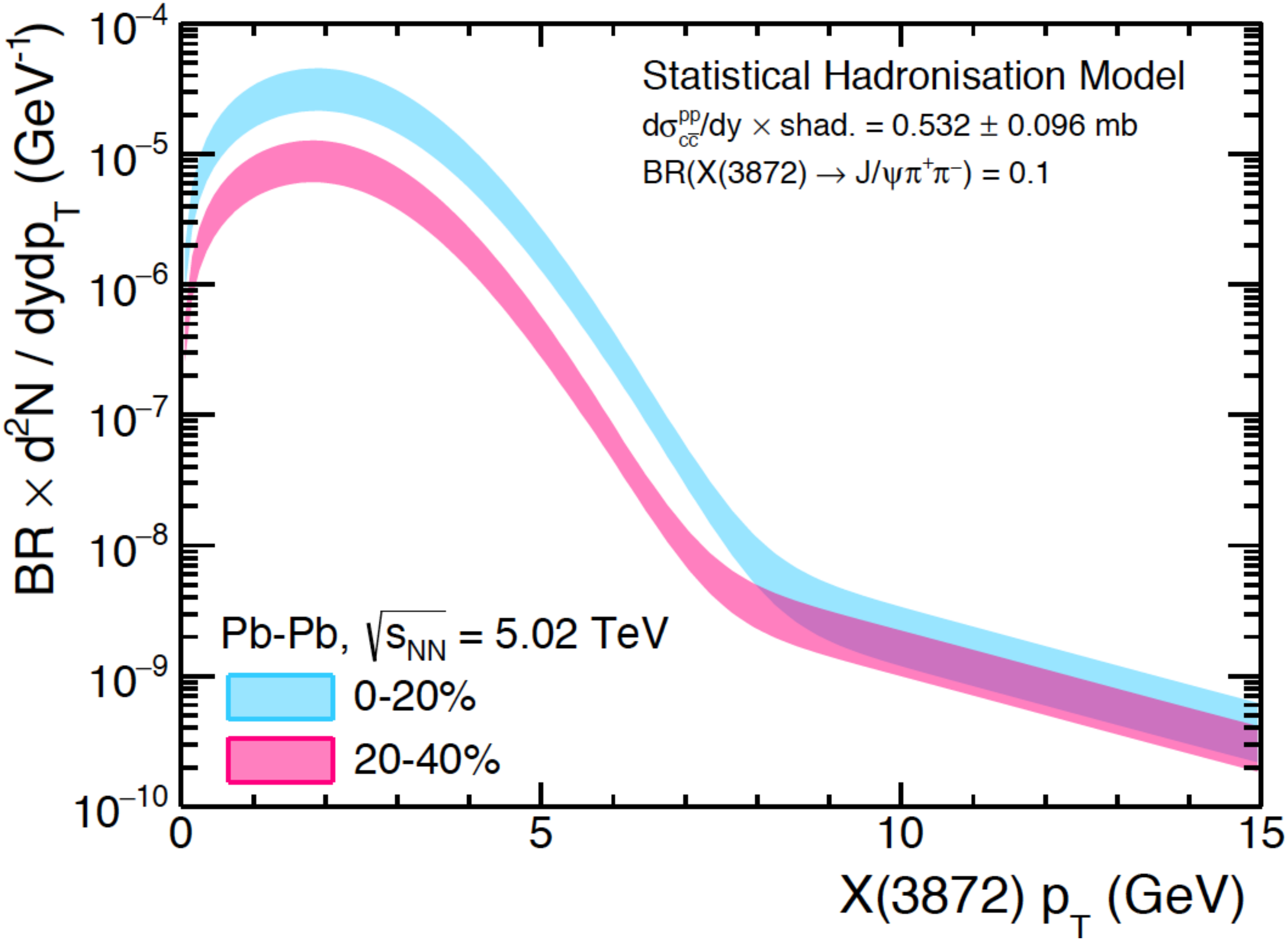
emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Runs3 and beyond

system size dependence of yields



due to different charm quark content different canonical suppression
for multicharm very light collision systems not favored

transverse momentum spectrum for $\chi_{c1}(3872)$ in the SHMc



note: dramatic enhancement at low p_t predicted

summary – charm production
probing the QCD phase boundary with heavy quarks

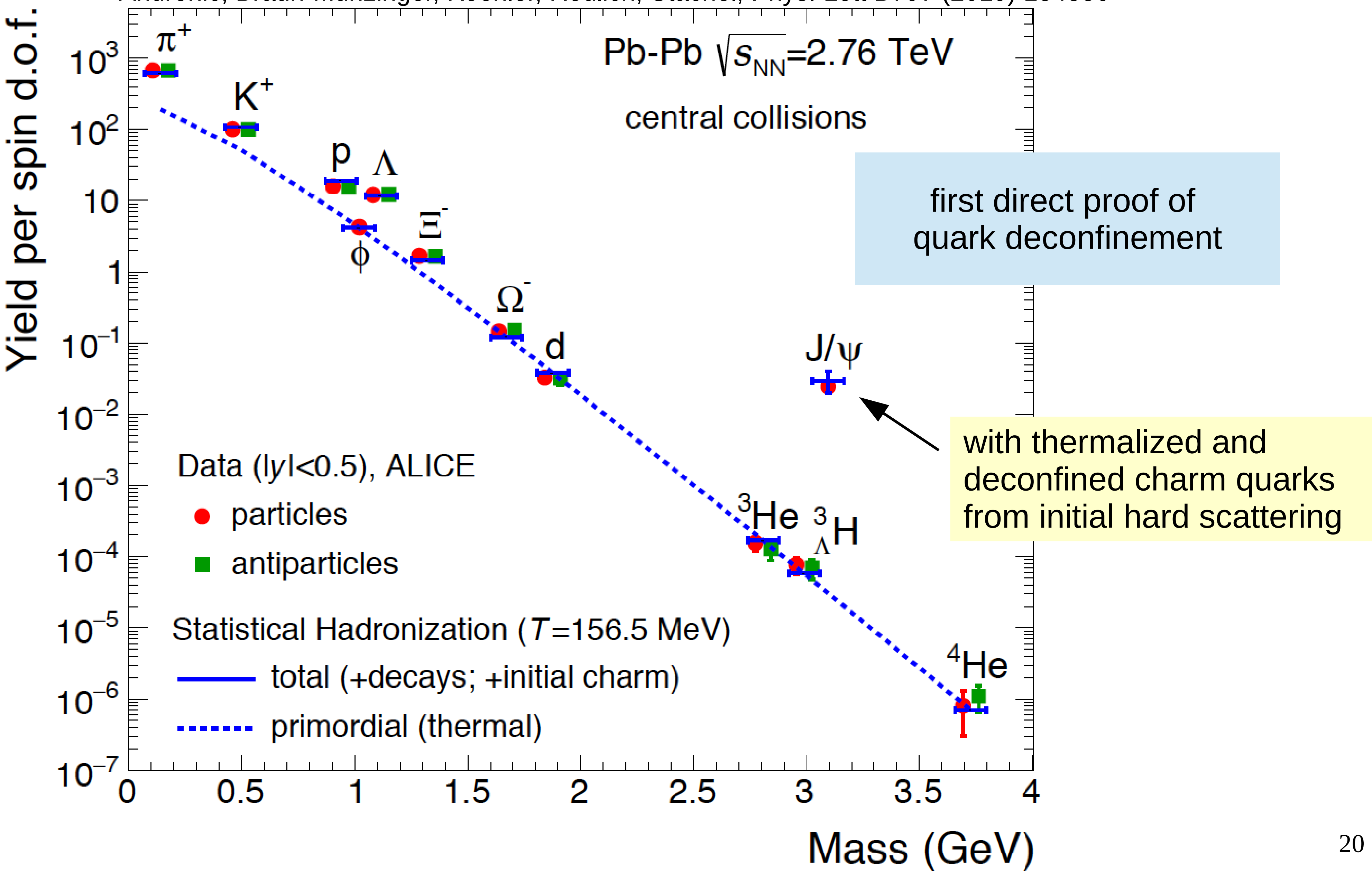
- statistical hadronization works quantitatively also for hadrons with charm quarks
- parameter free, only external input: charm production cross section
- treatment of open and hidden charm on an equal footing, same mechanism
- low momentum part of spectra characterized by hydro expansion + temperature
  no fit parameter

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

backup

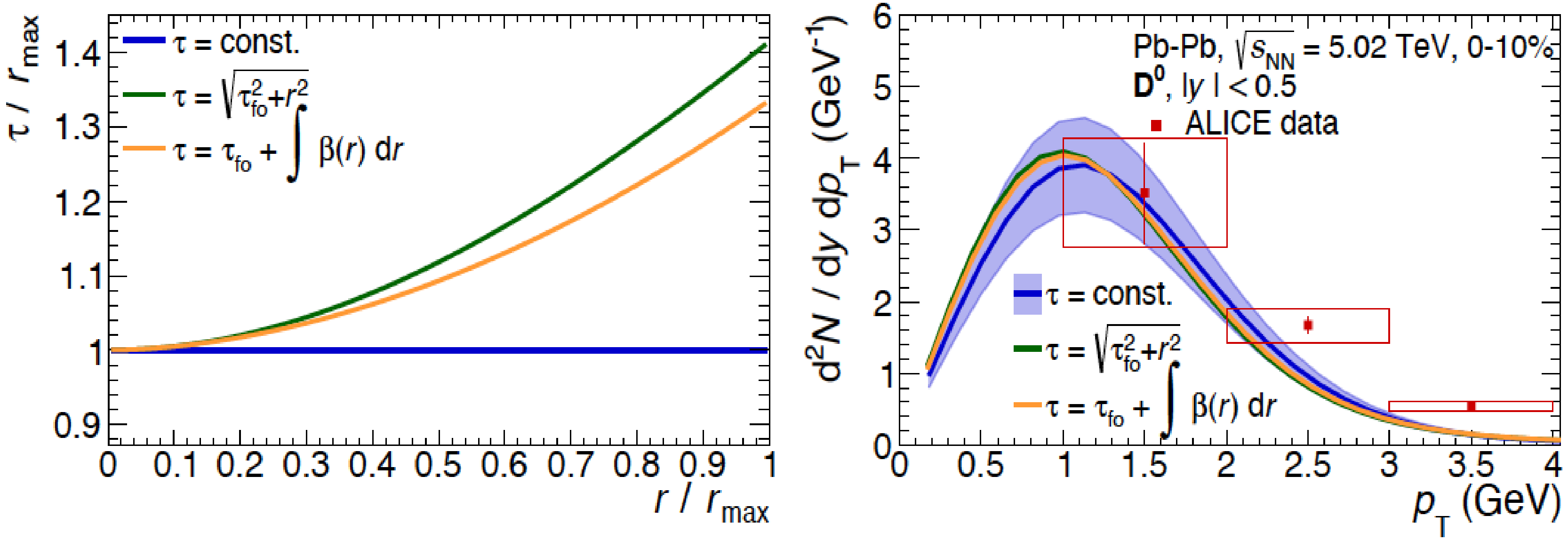
J/ψ enhancement relative to uds hadrons is prediction by SHMc
for quadratic scaling in number of charm quarks, they have to travel freely over
the size of the fireball of 10 fm, about 10 times the radius of a proton

Andronic, Braun-Munzinger, Koehler, Redlich, Stachel, Phys. Lett B797 (2019) 134836



blast wave parametrization of transverse momentum spectrum

$$\frac{\mathrm{d}^2N}{2\pi p_\mathrm{T} dp_\mathrm{T} dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p)$$
$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_\mathrm{max}} \mathrm{d}r\ \tau(r) r \left[K_1^\mathrm{eq}(p_\mathrm{T},u^r) - \frac{\partial\tau}{\partial r}K_2^\mathrm{eq}(p_\mathrm{T},u^r)\right]$$
$$K_1^\mathrm{eq}(p_\mathrm{T},u^r) = 4\pi m_\mathrm{T} I_0\left(\frac{p_\mathrm{T}u^r}{T}\right)K_1\left(\frac{m_\mathrm{T}u^\tau}{T}\right)$$
$$K_2^\mathrm{eq}(p_\mathrm{T},u^r) = 4\pi p_\mathrm{T} I_1\left(\frac{p_\mathrm{T}u^r}{T}\right)K_0\left(\frac{m_\mathrm{T}u^\tau}{T}\right)$$



mid-rapidity yields for Pb-Pb collisions

Particle	dN/dy core (SHMc)	dN/dy corona	dN/dy total
	0-10%		
D^0	6.02 ± 1.07	0.396 ± 0.032	6.42 ± 1.07
D^+	2.67 ± 0.47	0.175 ± 0.026	2.84 ± 0.47
D^{*+}	2.36 ± 0.42	$0.160\ {+0.048}{-0.022}$	2.52 ± 0.42
D_s^+	2.15 ± 0.38	$0.074\ {+0.024}{-0.015}$	2.22 ± 0.38
Λ_c^+	1.30 ± 0.23	0.250 ± 0.028	1.55 ± 0.23
Ξ_c^0	0.263 ± 0.047	0.090 ± 0.035	0.353 ± 0.058
J/ψ	$0.108\ {+0.041}{-0.035}$	$(5.08 \pm 0.37) \cdot 10^{-3}$	$0.113\ {+0.041}{-0.035}$
$\psi(2S)$	$(3.04\ {+1.2}{-1.0}) \cdot 10^{-3}$	$(7.61 \pm 0.55) \cdot 10^{-4}$	$(3.80\ {+1.2}{-1.0}) \cdot 10^{-3}$
	30-50%		
D^0	0.857 ± 0.153	0.207 ± 0.017	1.06 ± 0.154
D^+	0.379 ± 0.068	0.092 ± 0.014	0.471 ± 0.069
D^{*+}	0.335 ± 0.060	$0.084\ {+0.025}{-0.011}$	$0.419\ {+0.065}{-0.061}$
D_s^+	0.306 ± 0.055	$0.039\ {+0.013}{-0.008}$	0.344 ± 0.056
Λ_c^+	0.185 ± 0.033	0.131 ± 0.015	0.316 ± 0.036
Ξ_c^0	0.038 ± 0.007	0.047 ± 0.018	0.084 ± 0.020
J/ψ	$(1.12\ {+0.37}{-0.32}) \cdot 10^{-2}$	$(2.65 \pm 0.19) \cdot 10^{-3}$	$(1.39\ {+0.37}{-0.32}) \cdot 10^{-2}$
$\psi(2S)$	$(3.16\ {+1.04}{-0.89}) \cdot 10^{-4}$	$(3.98 \pm 0.29) \cdot 10^{-4}$	$(7.14\ {+1.08}{-0.94}) \cdot 10^{-4}$

dependence of Ω_{ccc} production yields on system size for a run time of 10^6 s

	O-O	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
$\sigma_{\mathrm{inel}}(10\%)\,\mathrm{mb}$	140	260	420	580	800
$T_{\mathrm{AA}}\,(0-10\%)\,\mathrm{mb}^{-1}$	0.63	2.36	6.80	13.0	24.3
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.5 \cdot 10^{31}$	$2.4 \cdot 10^{30}$	$1.7 \cdot 10^{29}$	$3.0 \cdot 10^{28}$	$3.8 \cdot 10^{27}$
	$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y = 0.53\,\mathrm{mb}$				
$\mathrm{d}N_{\Omega_{ccc}}/\mathrm{d}y$	$8.38 \cdot 10^{-8}$	$1.29 \cdot 10^{-6}$	$1.23 \cdot 10^{-5}$	$4.17 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$
Ω_{ccc} Yield	$5.3 \cdot 10^{5}$	$8.05 \cdot 10^{5}$	$8.78 \cdot 10^{5}$	$7.26 \cdot 10^{5}$	$3.80 \cdot 10^{5}$
	$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y = 0.63\,\mathrm{mb}$				
$\mathrm{d}N_{\Omega_{ccc}}/\mathrm{d}y$	$1.44 \cdot 10^{-7}$	$2.33 \cdot 10^{-6}$	$2.14 \cdot 10^{-5}$	$7.03 \cdot 10^{-5}$	$2.07 \cdot 10^{-4}$
Ω_{ccc} Yield	$9.2 \cdot 10^{5}$	$1.45 \cdot 10^{6}$	$1.53 \cdot 10^{6}$	$1.22 \cdot 10^{6}$	$6.29 \cdot 10^{5}$

example: X(3872)

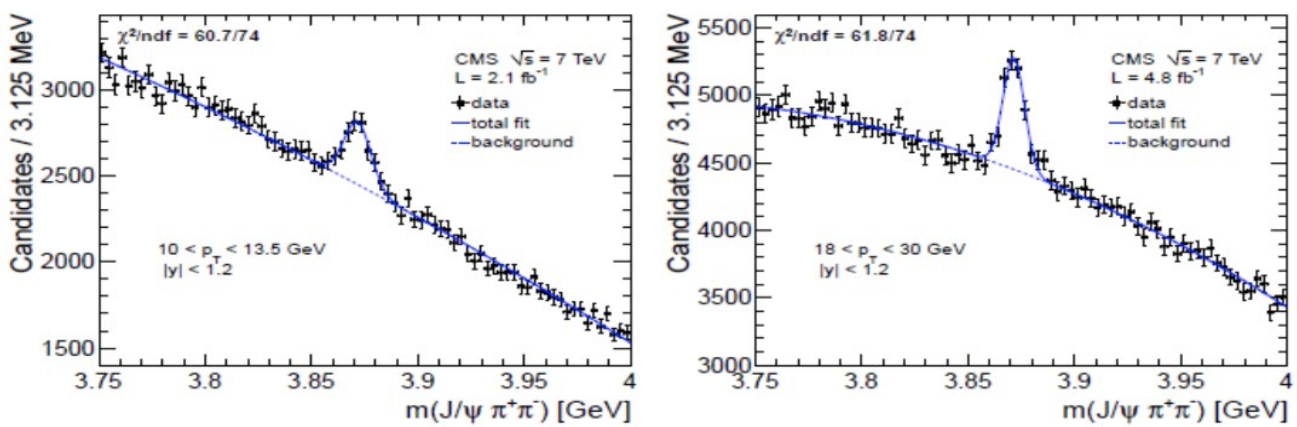
X(3872)

- 2003 -

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

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

- 2013 -



X(3872)

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

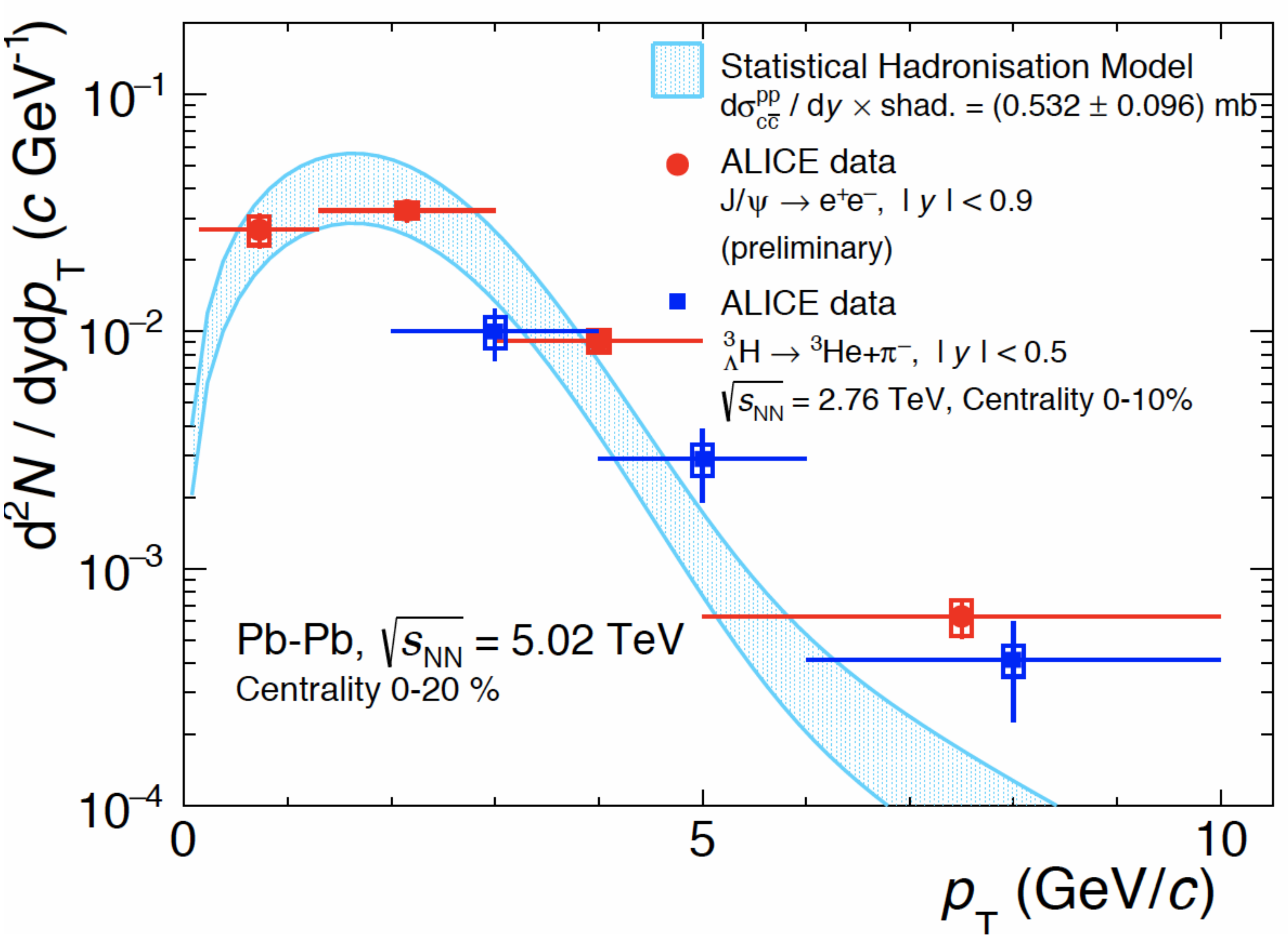
Mass $m = 3871.69 \pm 0.17$ MeV

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

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

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

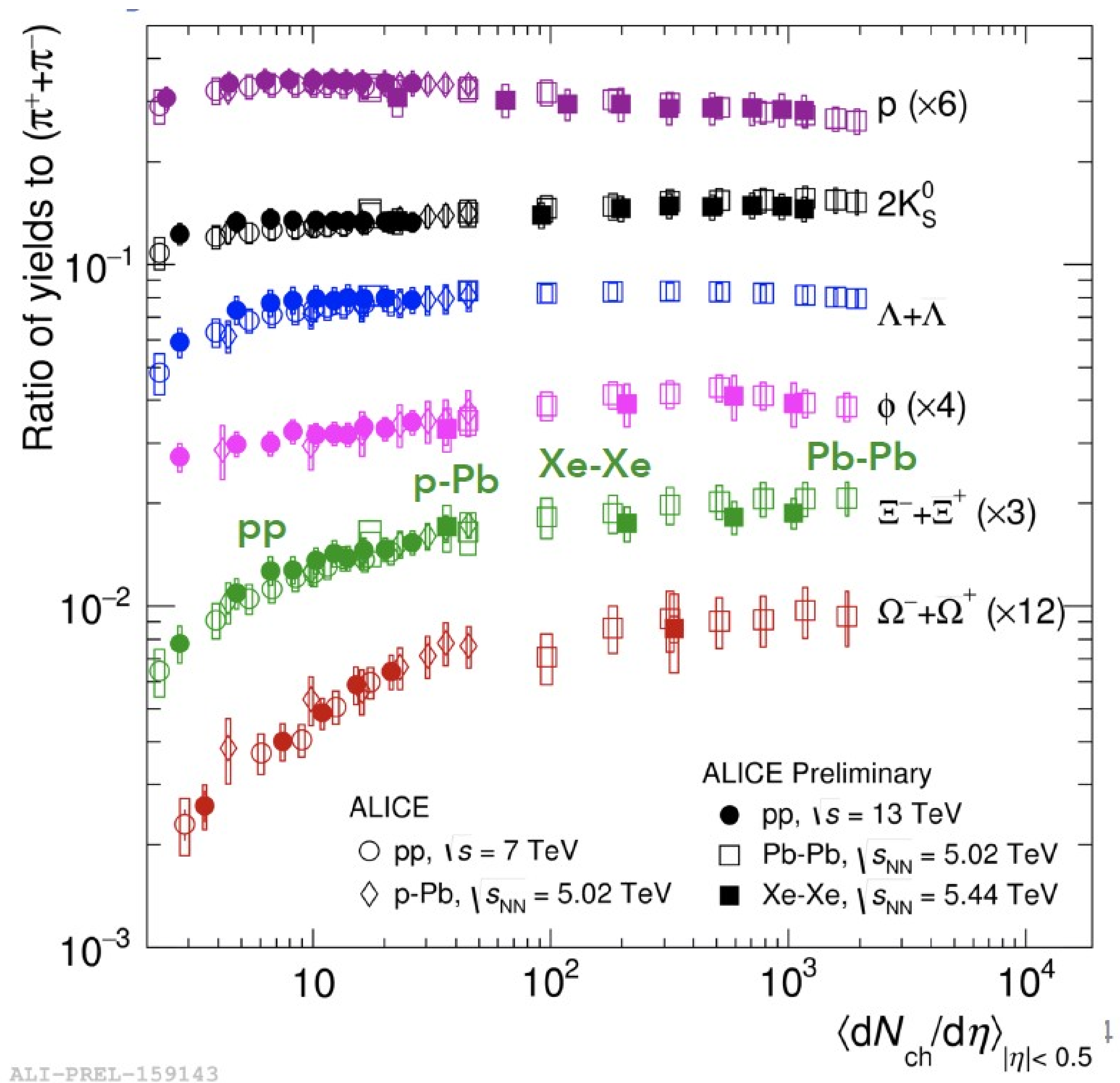
J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



binding energies:
J/psi 600 MeV
hypertriton 2.2 MeV
Lambda S.E. 0.2 MeV

from review: hypernuclei and other loosely bound objects produced in nuclear collisions at the LHC,
pbm and Benjamin Doenigus,
Nucl. Phys. A987 (2019) 144, arXiv:1809.04681

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



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

transition from canonical to grand-canonical thermodynamics

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