Quark-Gluon Plasma Physics

6.2 statistical hadronization model and charm, part 2
open charm hadrons, deconfinement, and universal hadronization

the multiple-charm hierarchy in the statistical hadronization model

results shown in this lecture taken mostly from the recent preprint:
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

outline

- production of hadrons with charm in relativistic nuclear collisions
- brief review of quark model of baryons and mesons
- focus on baryons containing charm quarks
- reminder of the statistical hadronization model for (u,d,s) hadrons
- adding charm: the charm balance equation and canonical thermodynamics
- yields and spectra of open charm hadrons
- the multiple charm hierarchy
- deconfinement and hadronization of a fireball containing charm quarks

quarks and their quantum numbers

$$Q = I_z + \frac{\mathcal{B} + S + C + B + T}{2}$$

$\mathcal{B}$ is the baryon number

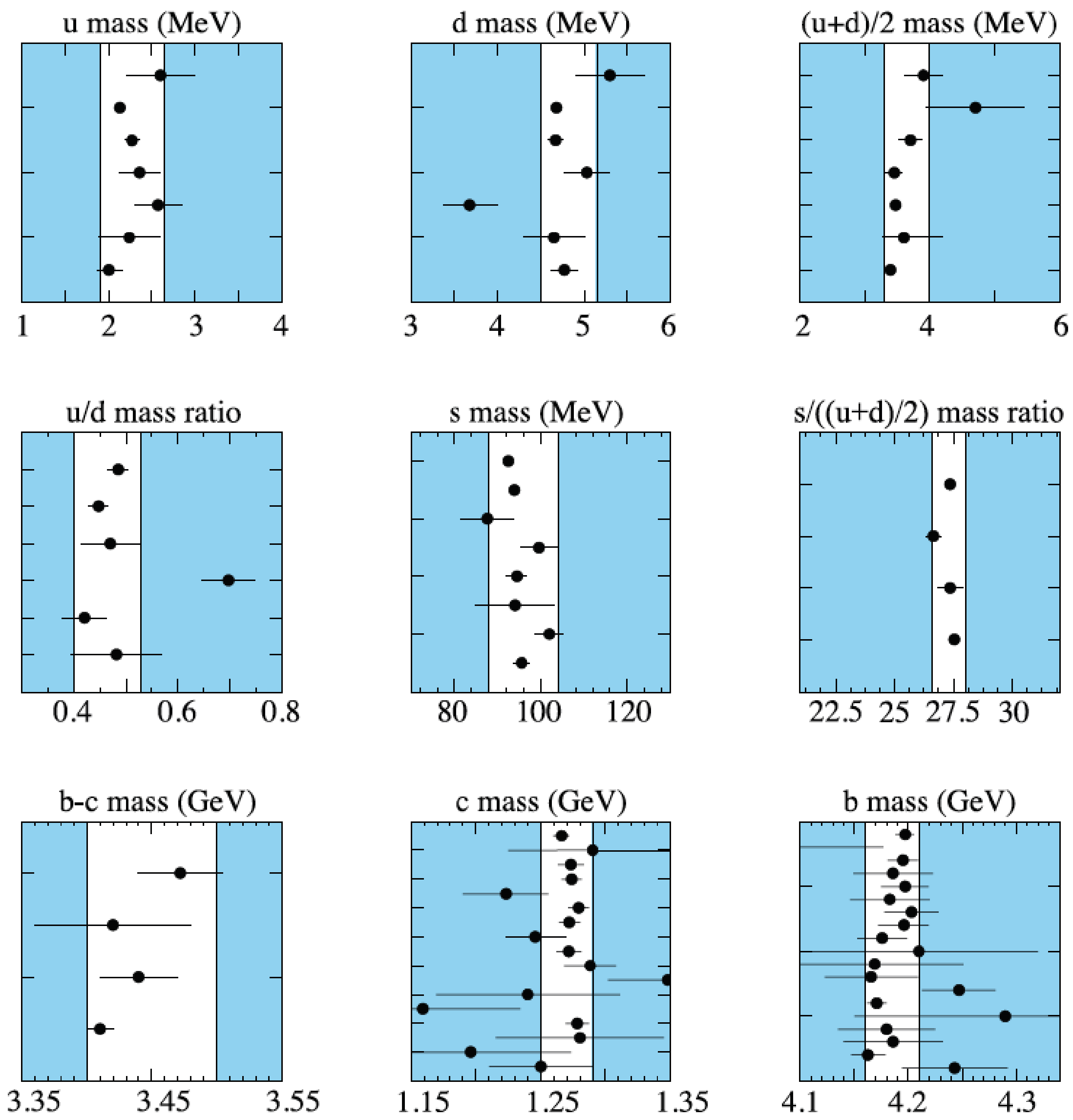
	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

hyper-charge Y

$$Y = \mathcal{B} + S - \frac{C - B + T}{3}$$

all plots on this and the following 6 slides are from the PDG, Particle Data Group, https://pdg.lbl.gov

the masses of the quarks, data points are in chronological order
the latest entry is on top

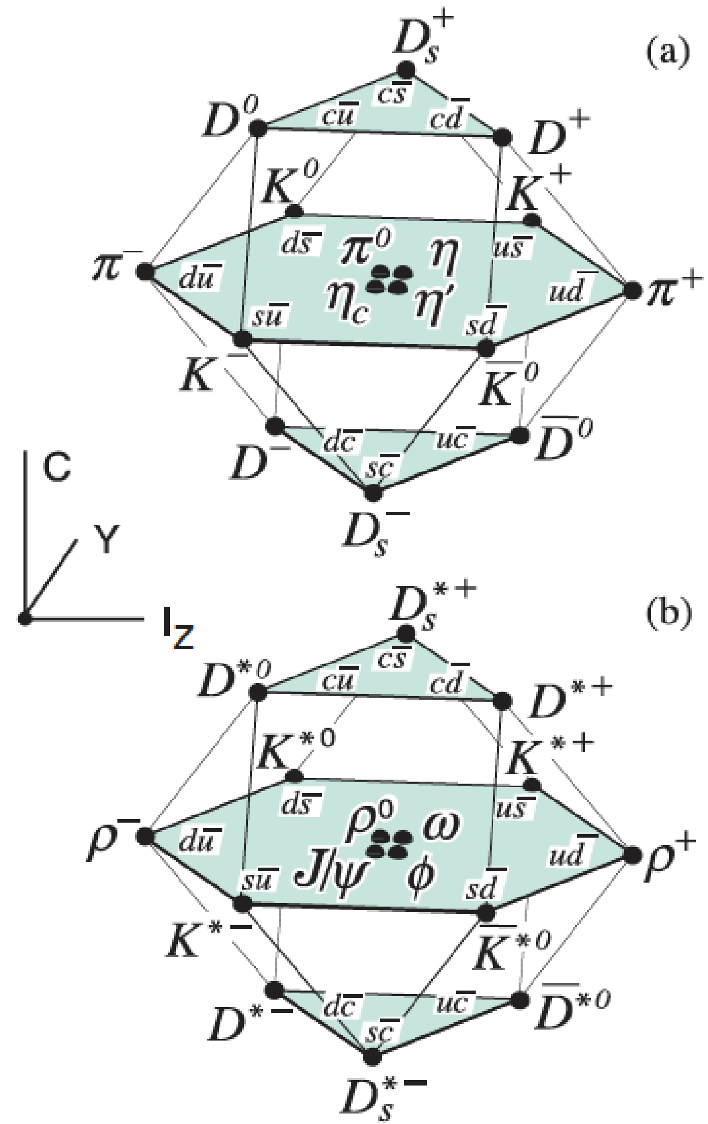


n.b.: quarks are confined and cannot be isolated → a model or theory is needed for mass determination for details see PDG entry

(u,d,s) mesons and the quark model

$n^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
1^1S_0	0^{-+}	π	K	η	$\eta'(958)$	−11.3	−24.5
1^3S_1	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	39.2	36.5
1^1P_1	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1415)$	$h_1(1170)$		
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
1^3P_1	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$		
1^3D_2	2^{--}		$K_2(1820)^\dagger$				
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	31.8	30.8
1^3F_4	4^{++}	$a_4(1970)$	$K_4^*(2045)$	$f_4(2300)$	$f_4(2050)$		
1^3G_5	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$		
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$	$\phi(1680)$	$\omega(1420)$		
2^3P_1	1^{++}	$a_1(1640)$					
2^3P_2	2^{++}	$a_2(1700)$	$K_2^*(1980)$	$f_2(1950)$	$f_2(1640)$		

the quark model and (u,d,s,c) mesons

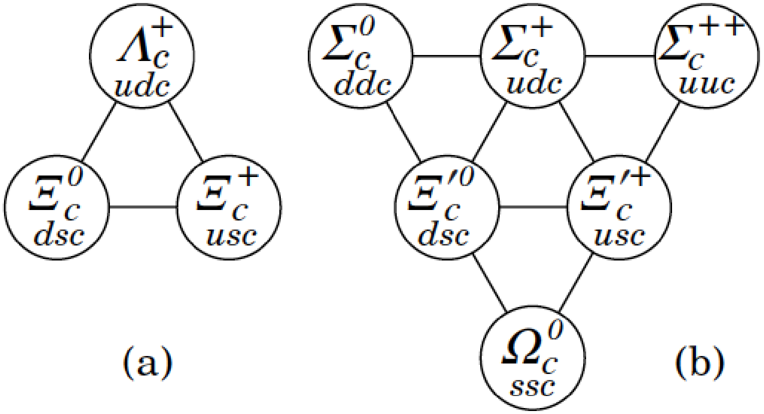


pseudo-scalar, $J = 0^-$

pseudo-vector, $J = 1^-$

$n^{2s+1}\ell_J$	J^{PC}	I = 0 $c\bar{c}$	I = $\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	I = 0 $c\bar{s}$; $\bar{c}s$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	D	$D_s^{\pm}$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	D^*	$D_s^{*\pm}$
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$D_0^*(2300)$	$D_{s0}^*(2317)^{\pm\dagger}$
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$
$1\,^1P_1$	1^{+-}	$h_c(1P)$	$D_1(2420)$	$D_{s1}(2536)^{\pm}$
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$D_2^*(2460)$	$D_{s2}^*(2573)$
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$		
$2\,^3S_1$	1^{--}	$\psi(2S)$		$D_{s1}^*(2700)^{\pm\ddagger}$
$1\,^3D_1$	1^{--}	$\psi(3770)$		$D_{s1}^*(2860)^{\pm\ddagger}$
$1\,^3D_2$	2^{--}	$\psi_2(3823)$		
$2\,^3P_J$	$0, 1^{++}$	$\chi_{c0}(3860)$		
	2^{++}	$\chi_{c2}(3930)$		
$3\,^3S_1$	1^{--}	$\psi(4040)$		
$2\,^3D_1$	1^{--}	$\psi(4160)$		
$4\,^3S_1$	1^{--}	$\psi(4415)$		
$1\,^3D_3$	3^{--}		$D_3^*(2750)$	$D_{s3}^*(2860)^{\pm}$

charm baryons with C = 1

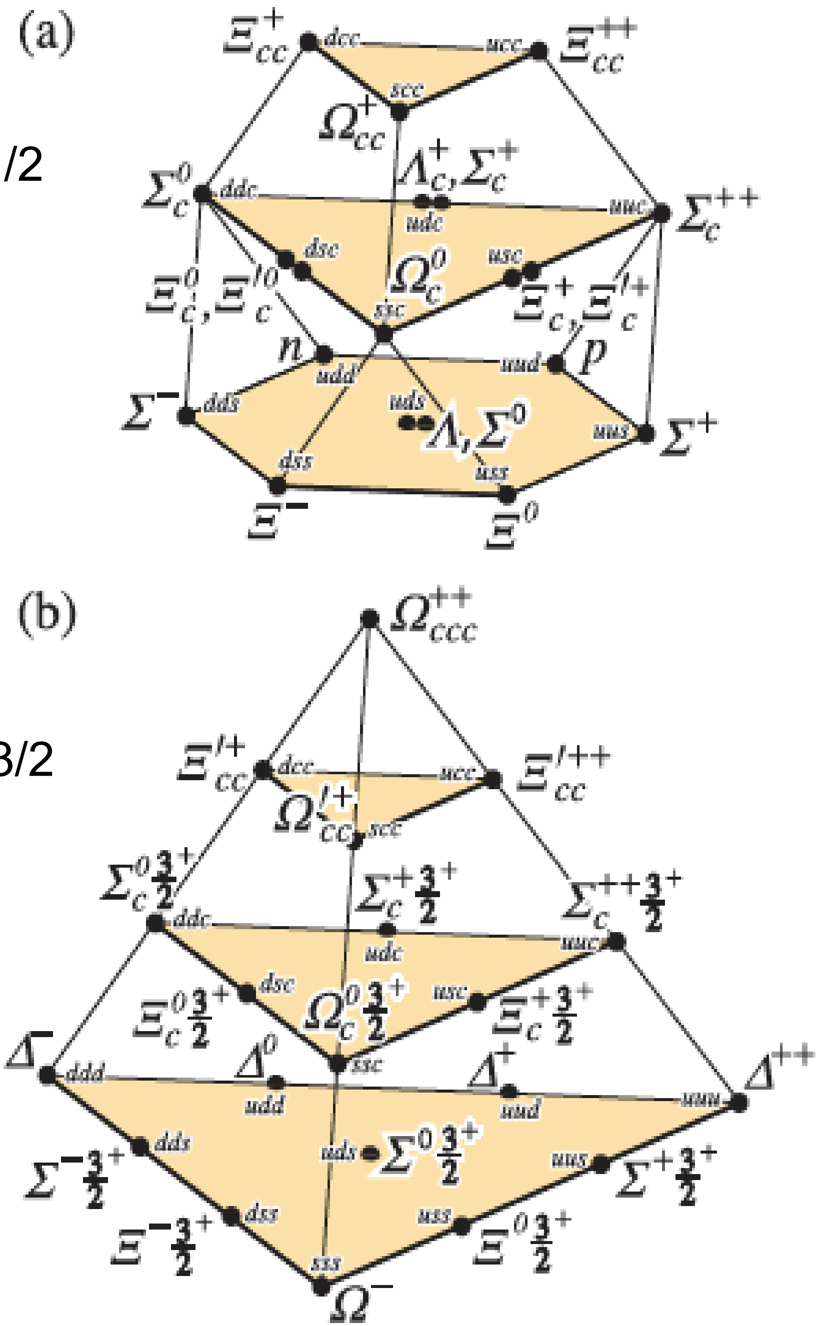


The SU(3) $\bar{\mathbf{3}}$ (a) and $\mathbf{6}$ (b) ground-state $J^P = 1/2^+$ representations. The $\mathbf{6}$ ground-state with $J^P = 3/2^+$ is identical in structure to the right-hand figure.

the charm baryons in the quark model

J = 1/2

J = 3/2



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 N_{ccbar}^2 if charm quarks are deconfined over the volume of the fireball formed in the Pb-Pb collision

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)

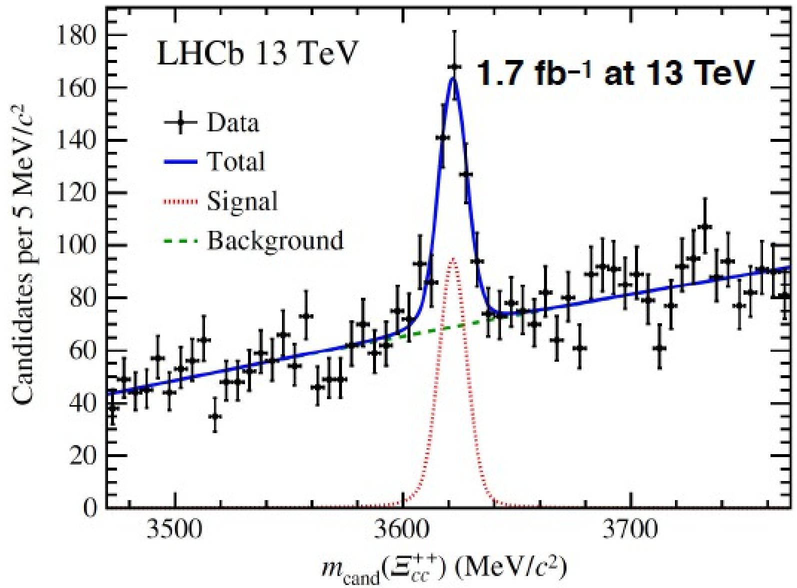
how to measure multi-charm baryons?

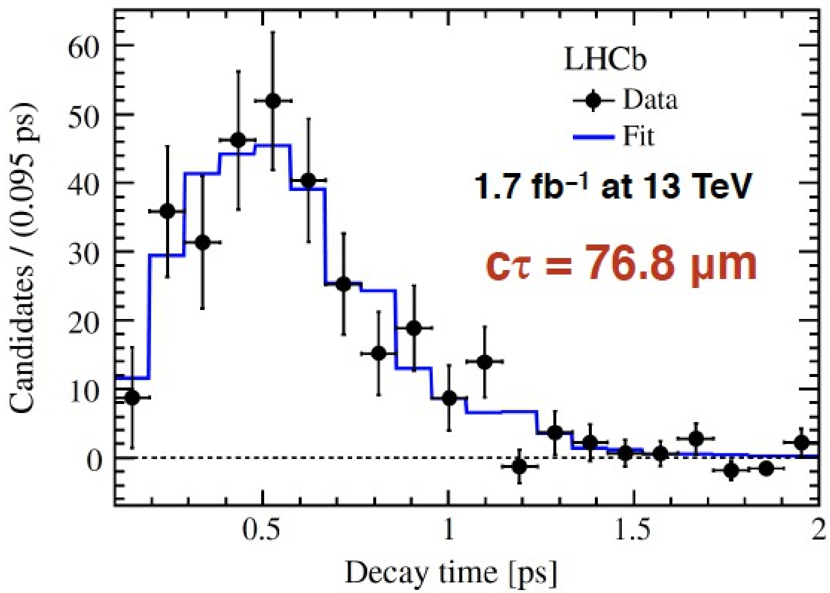
measurements are generally done via invariant mass analysis

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

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

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

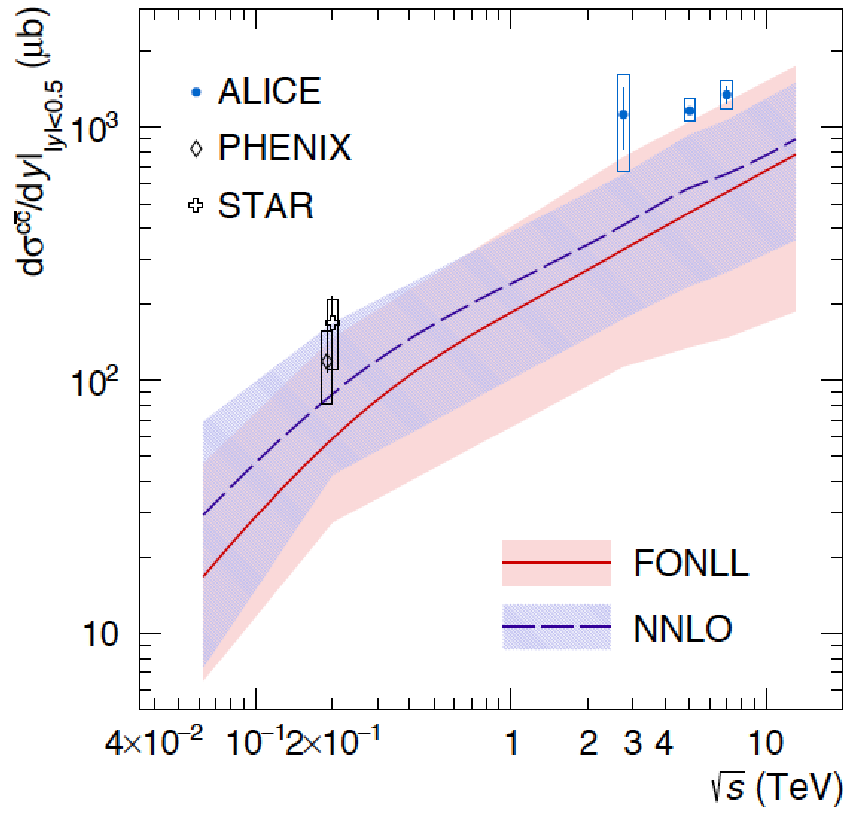
$N_{c\bar{c}}$: obtained from measured open charm cross section

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

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

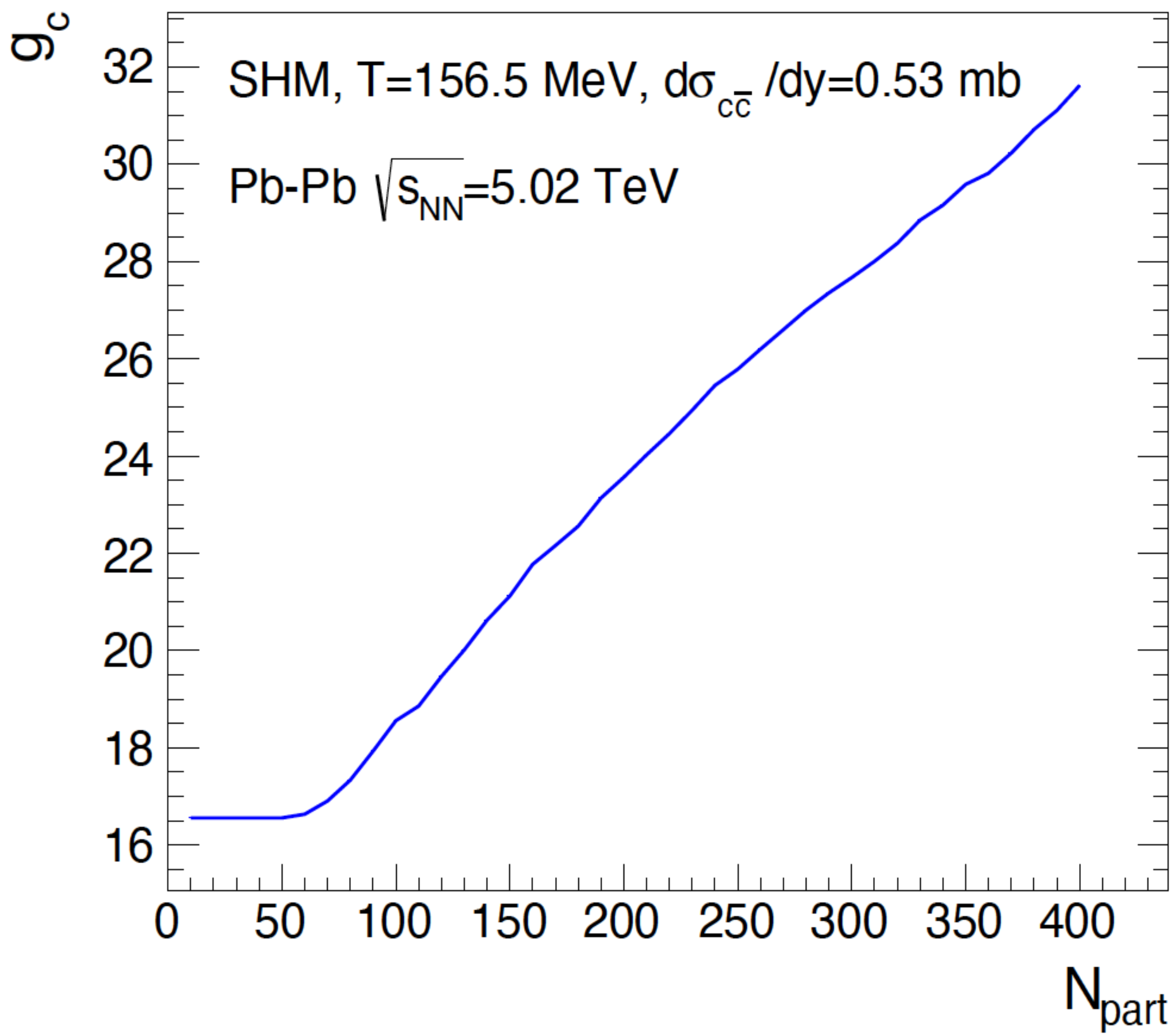
- for yields of charm hadron i with n_c charm quarks $N_{n_c}(i) = g_c^{n_c} N_{n_c}(i)^{th} \frac{I_{n_c}(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})}$

energy dependence of charm production cross section at mid-rapidity



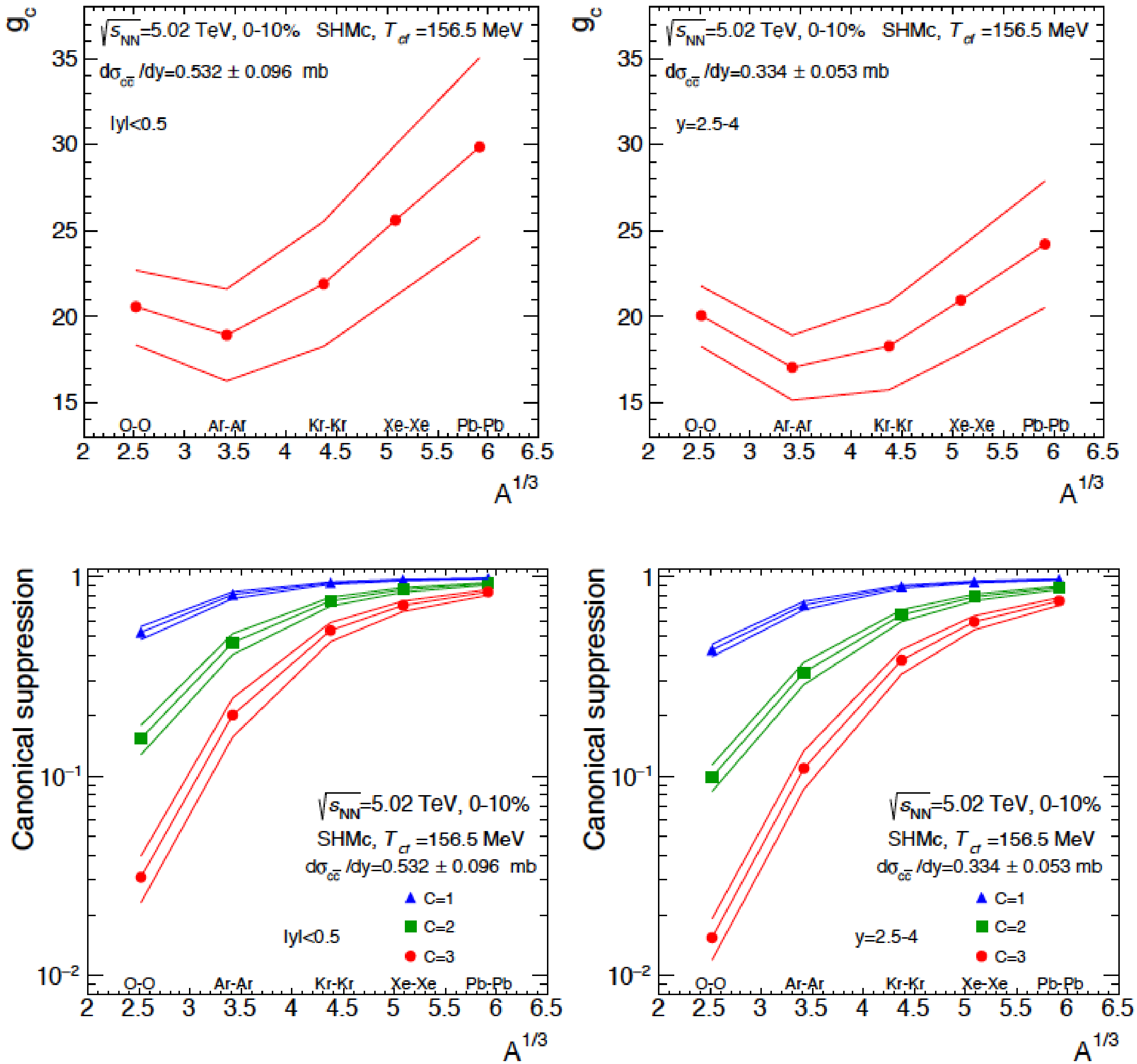
ALICE collaboration, arXiv:2105.06335

centrality dependence of charm fugacity g_c at LHC energy



charm fugacities and canonical suppression factors

different collision systems:



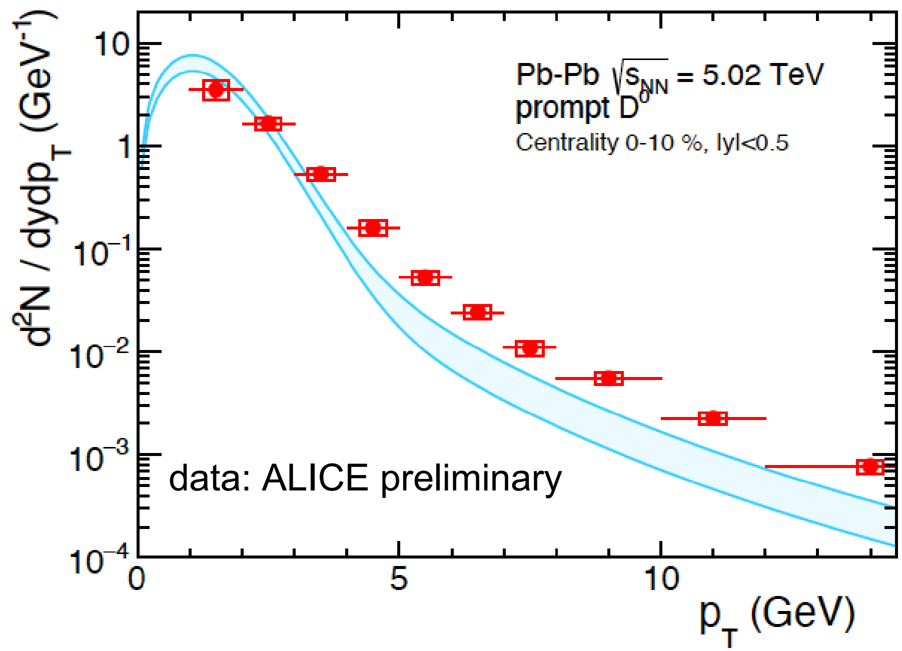
statistical hadronization for hidden and open charm

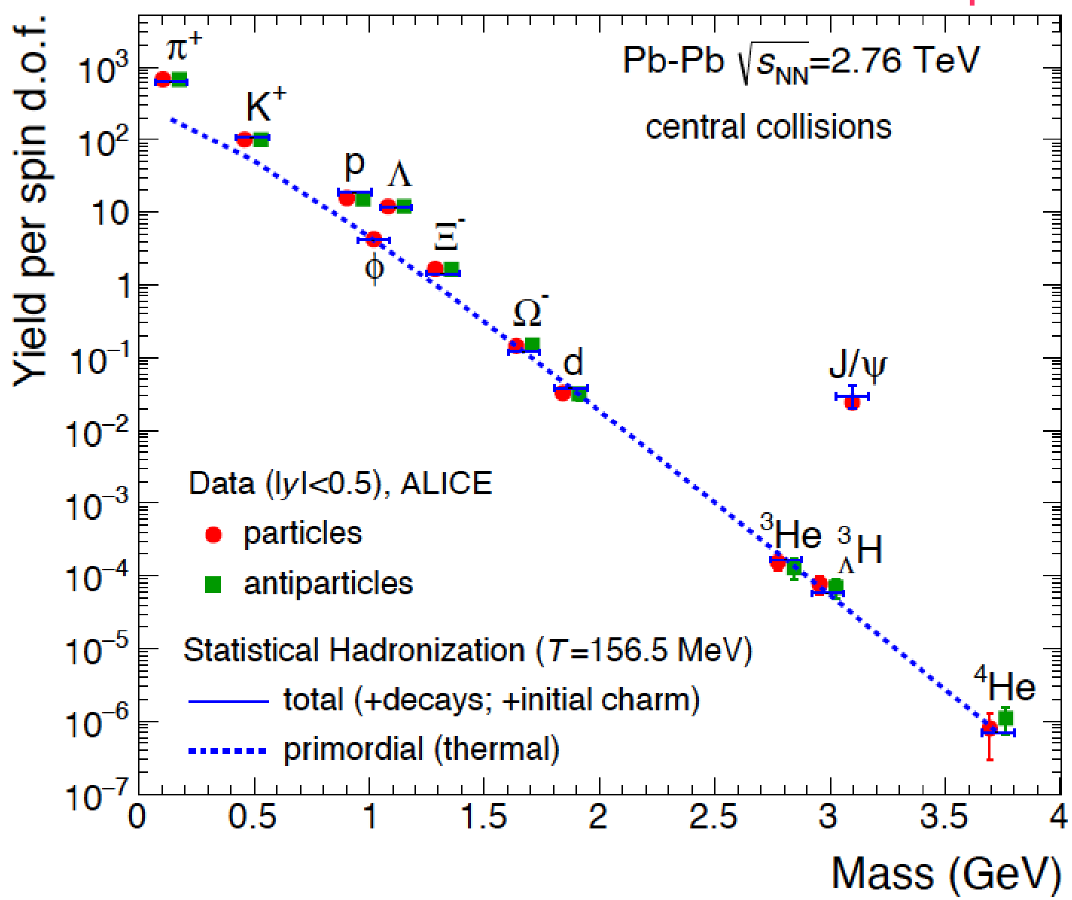
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0





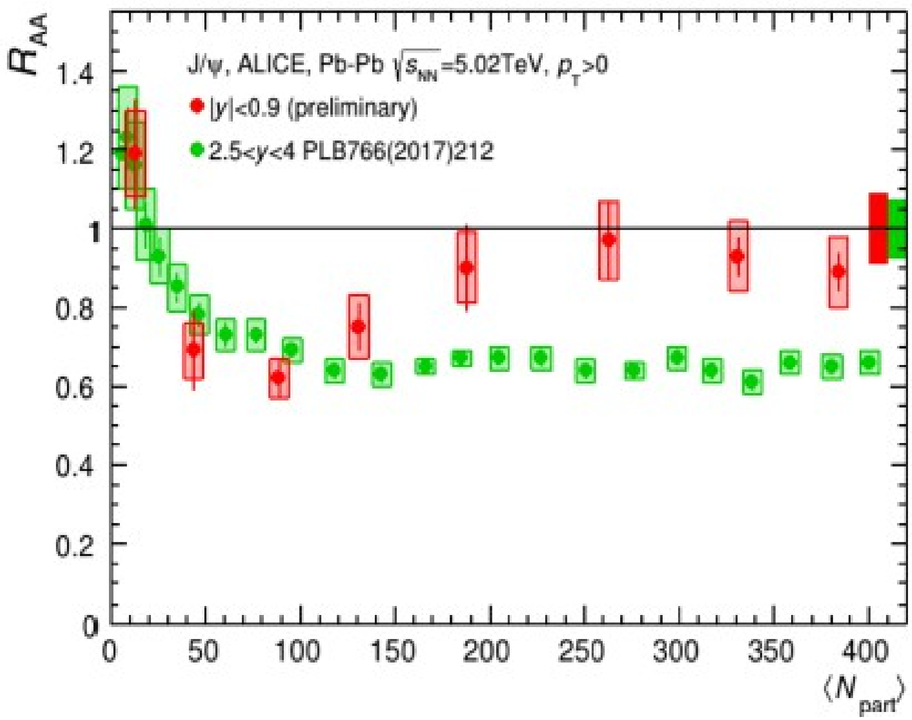
Andronic, Braun-Munzinger, Koehler, Redlich, JS PLB 792 (2019) 304
Andronic, Braun-Munzinger, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius arXiv:2104.12754

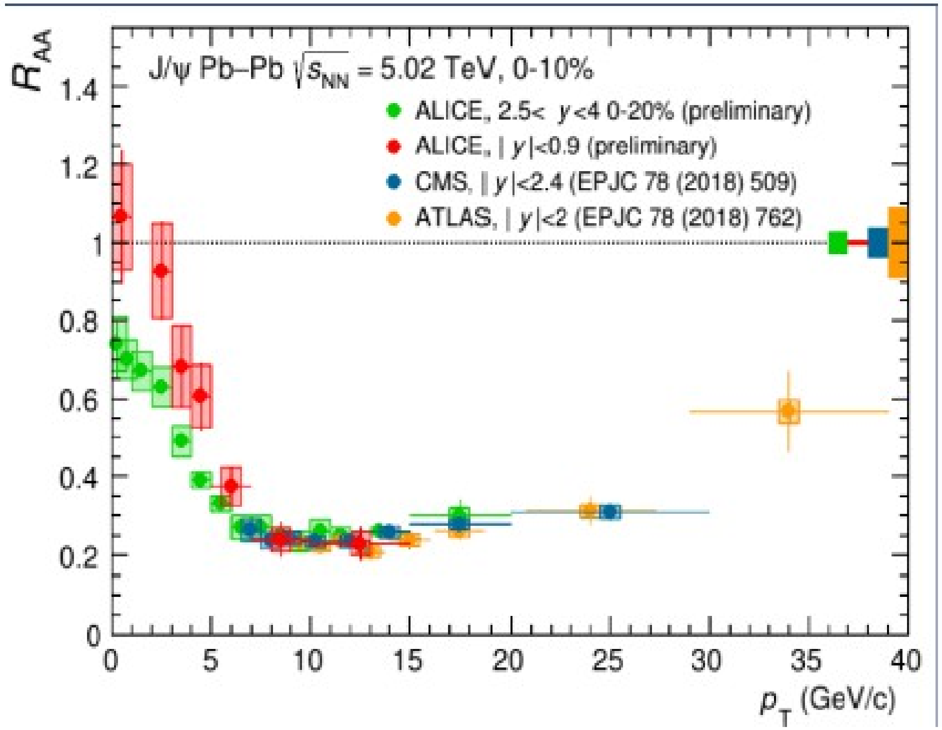
quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons,
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

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

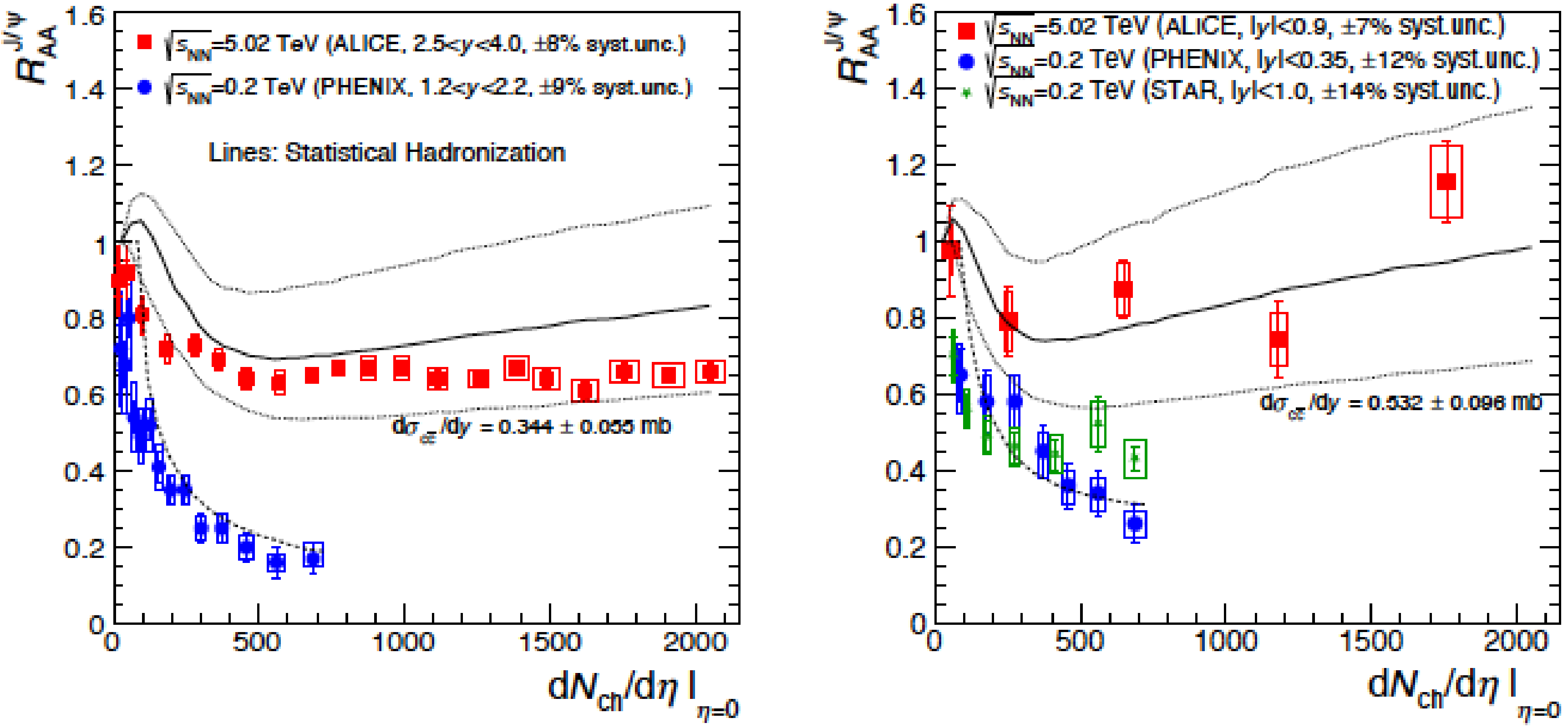
nuclear modification factor: $R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T}$





RHIC and LHC data compared to SHMc predictions

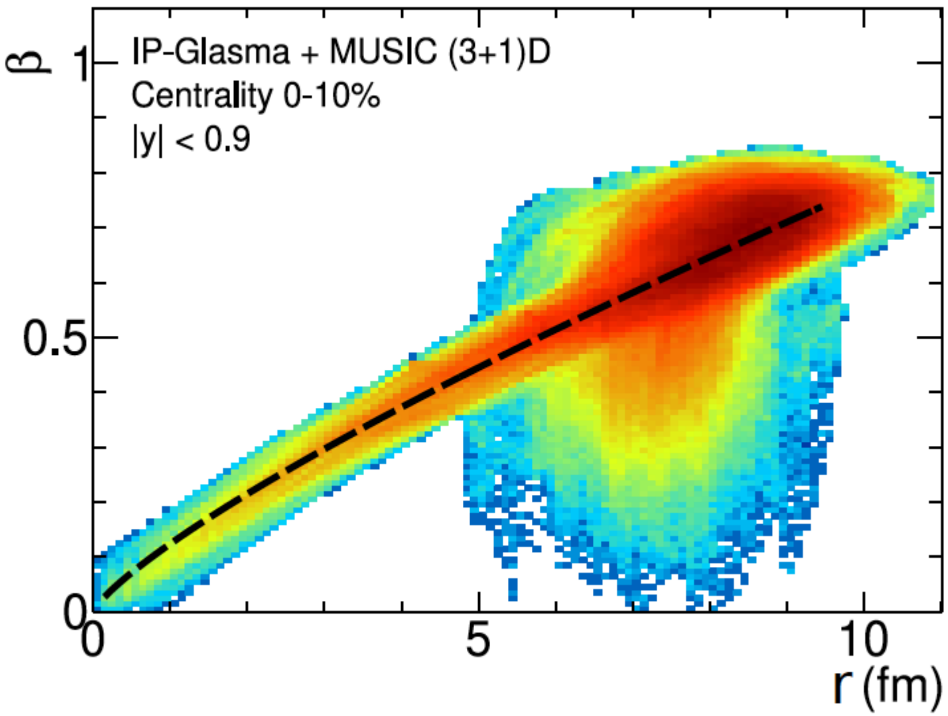
note the energy dependence of the nuclear modification factor R_{AA}



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



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

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

$$n = 0.85$$

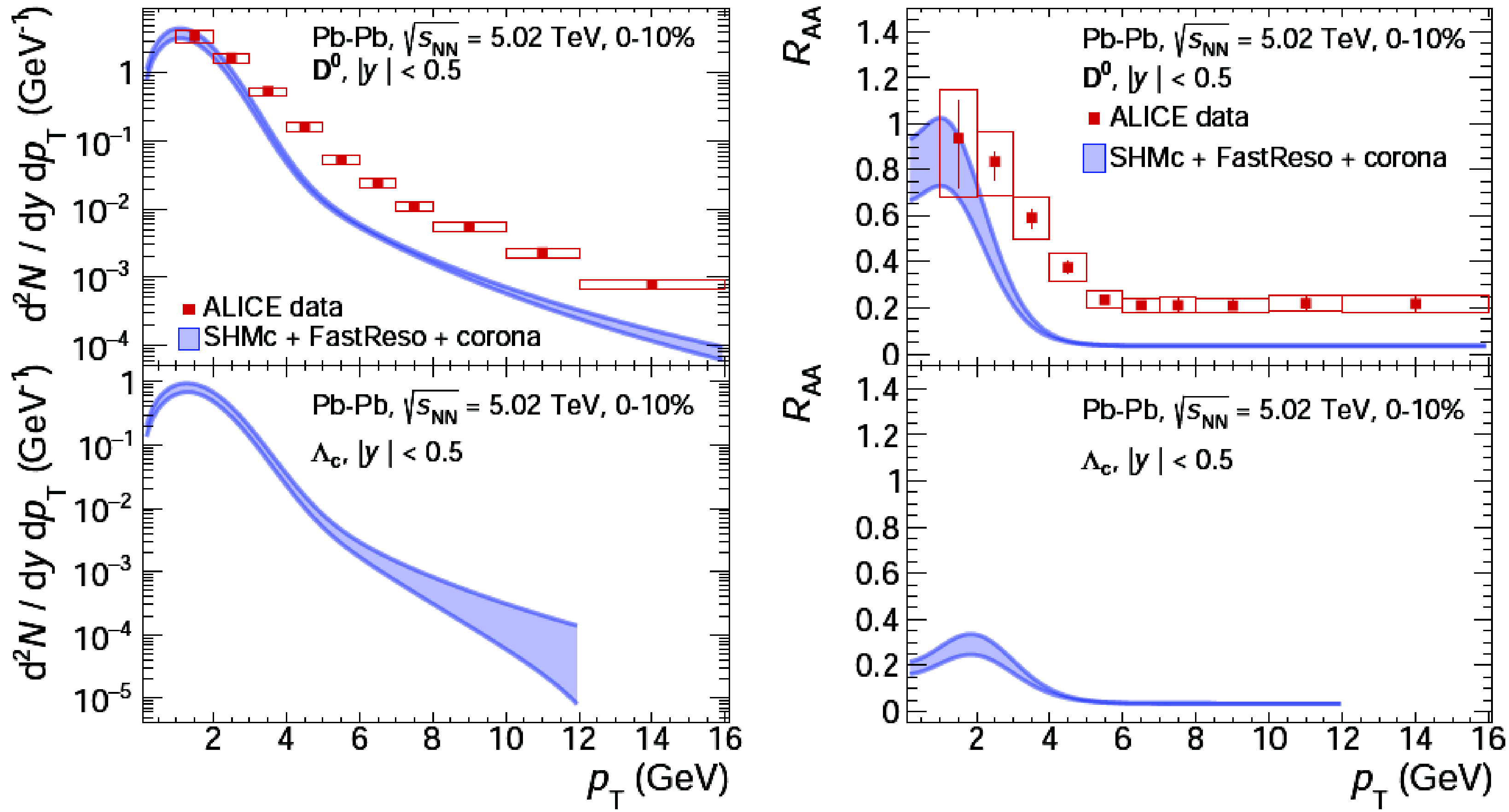
$$V = 2\pi \int_0^{r_{\max}} \mathrm{d}r \; r\tau(r) u^\tau \left[1 - \beta(r)\frac{\partial\tau}{\partial r}\right]$$

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

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

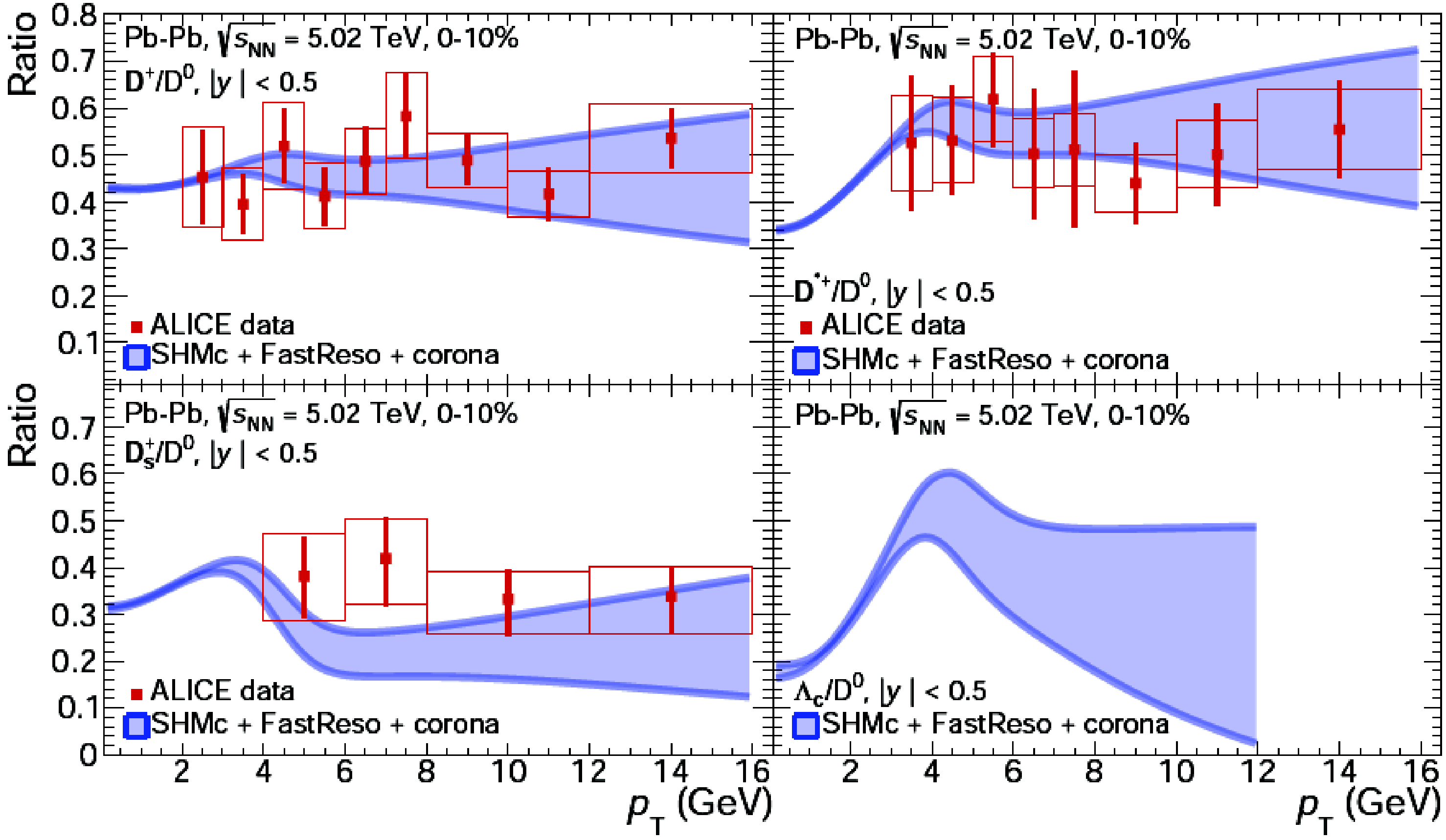
spectra and R_{AA} of D^0 mesons and Λ_c baryons

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, see back-up slides

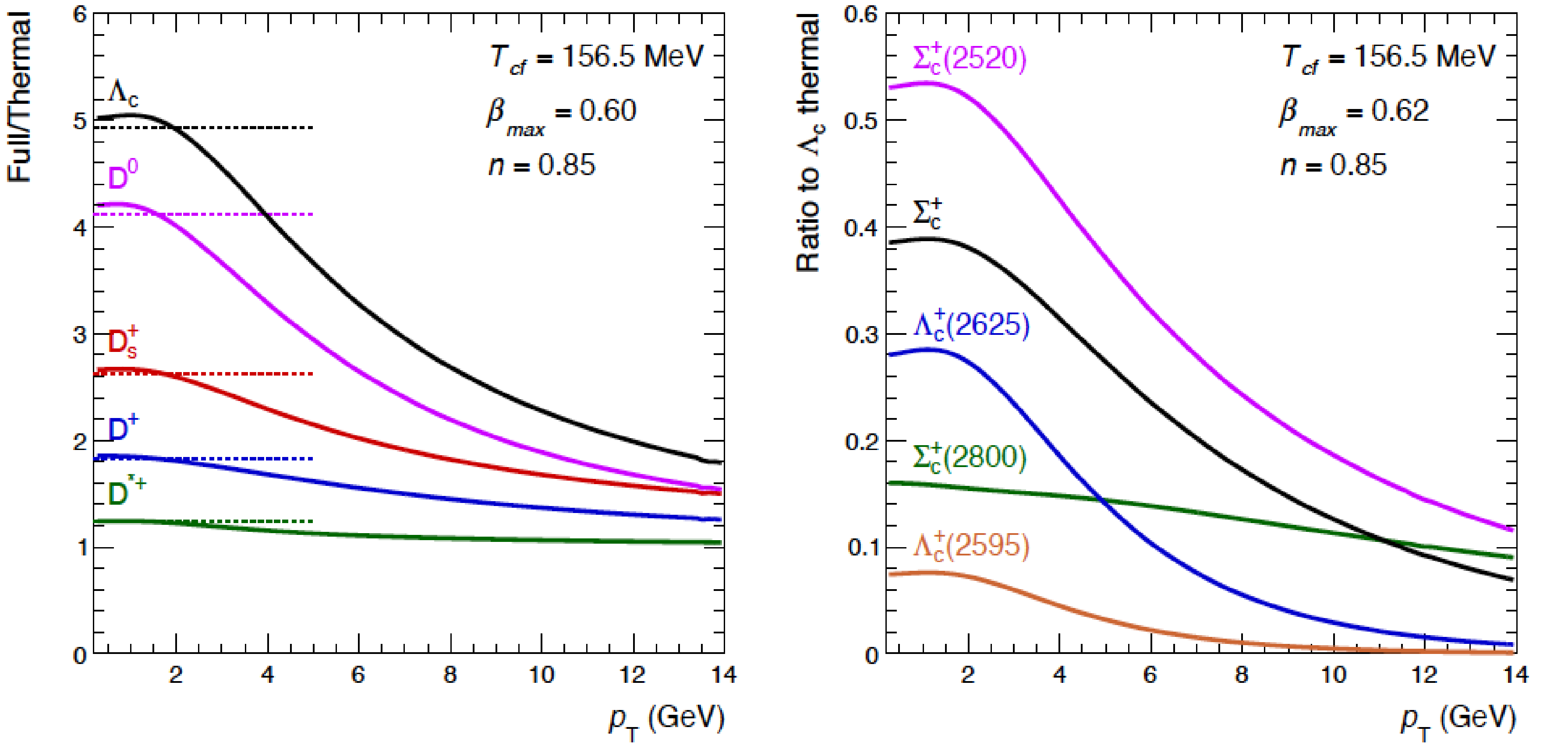
ratios of charm hadron to D^0 spectra



excellent agreement considering that there are NO free parameters

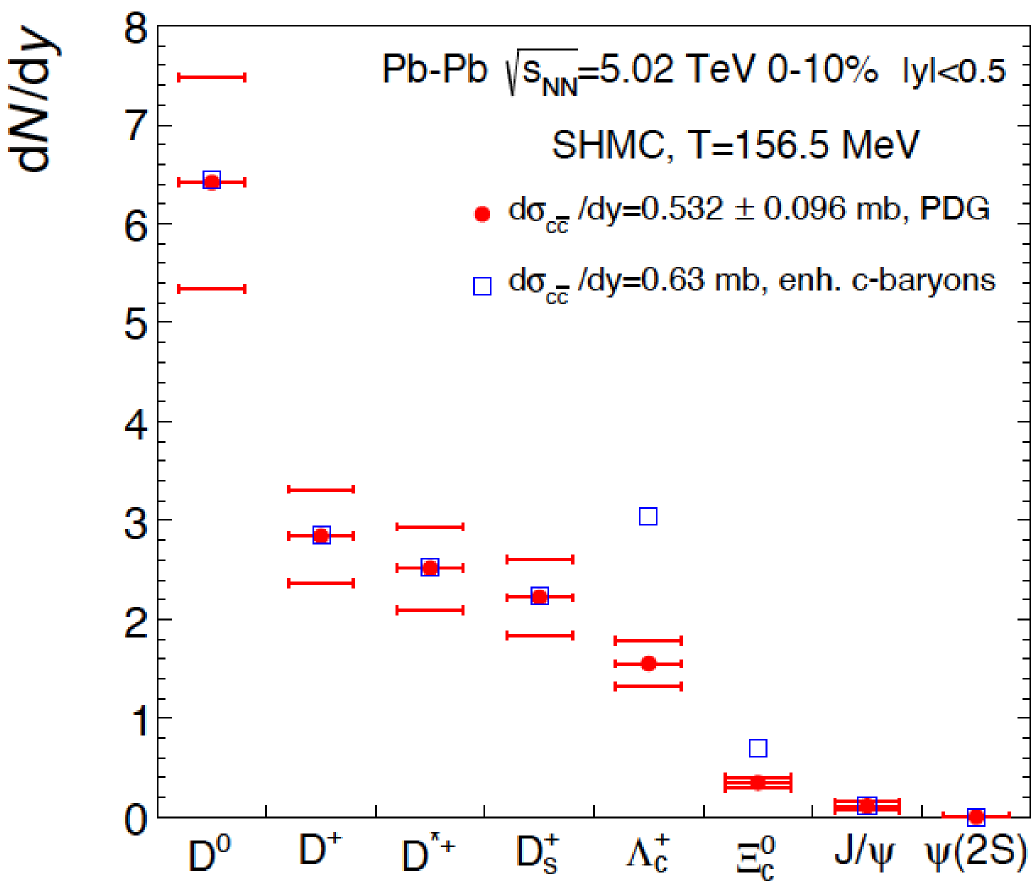
impact of resonance decays

feed-down to Λ_c



charm hadron yields with modified charm resonance spectrum

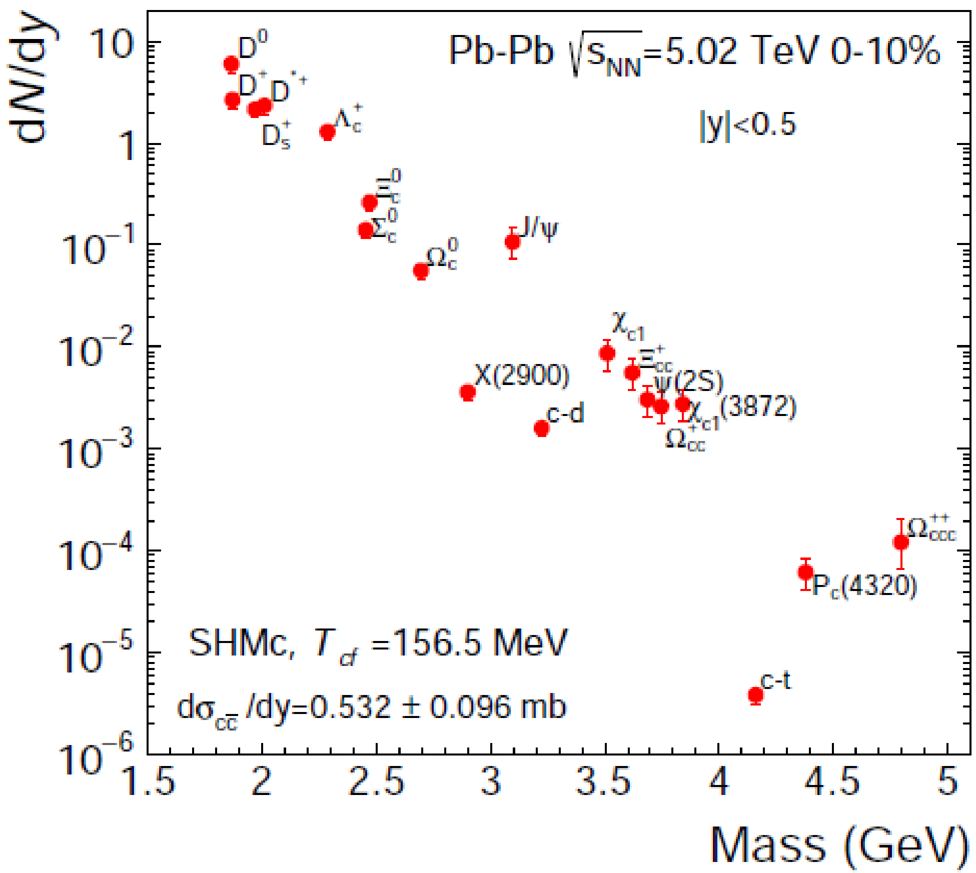
recently a lot of speculation about possibly incomplete charm baryon spectrum
to test impact, tripled statistical weights of excited charm baryons

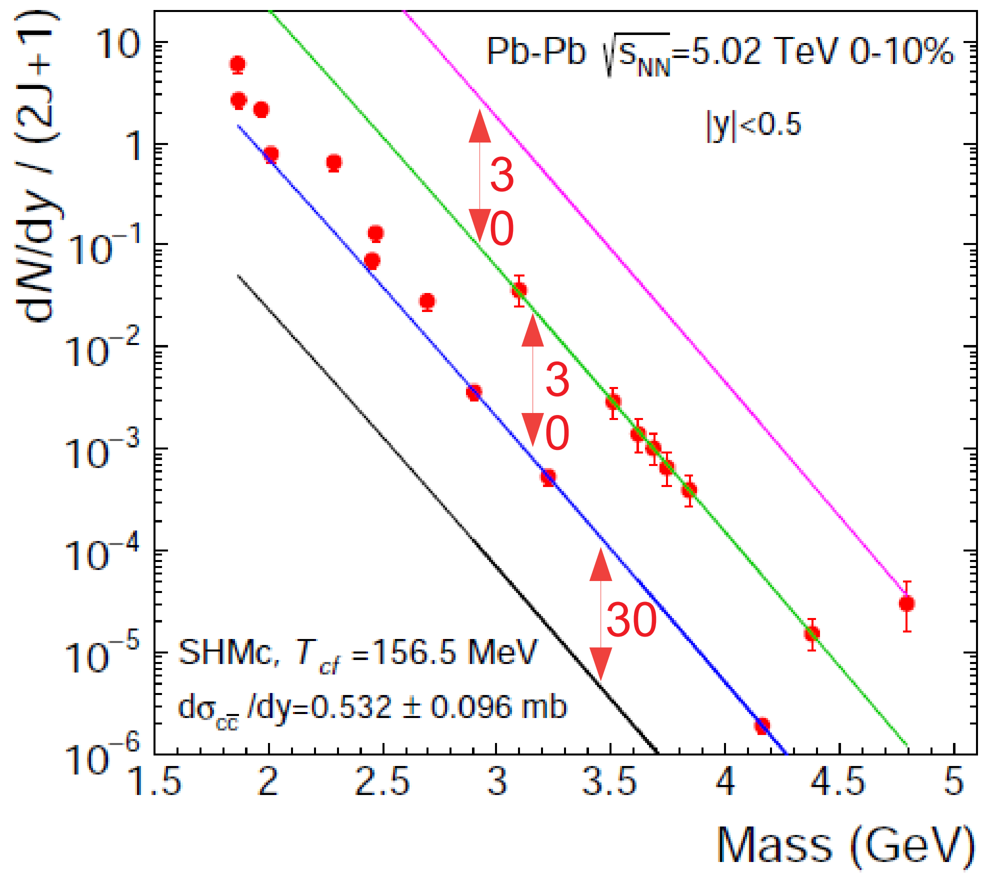


charm cross section increases 20%
yield of charm baryons nearly doubles

the multi-charm hierarchy

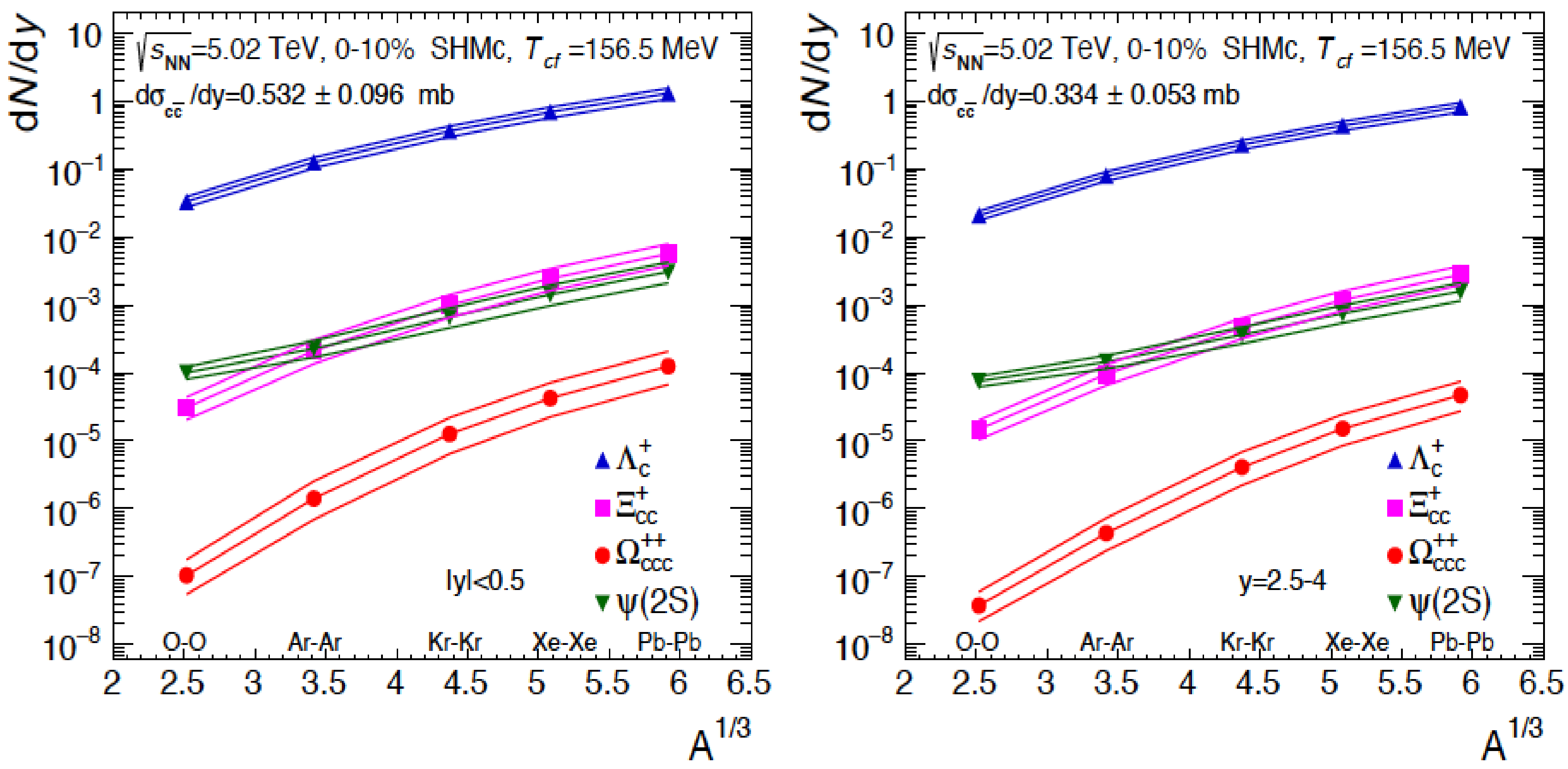
open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, pentaquark, Ω_{ccc}





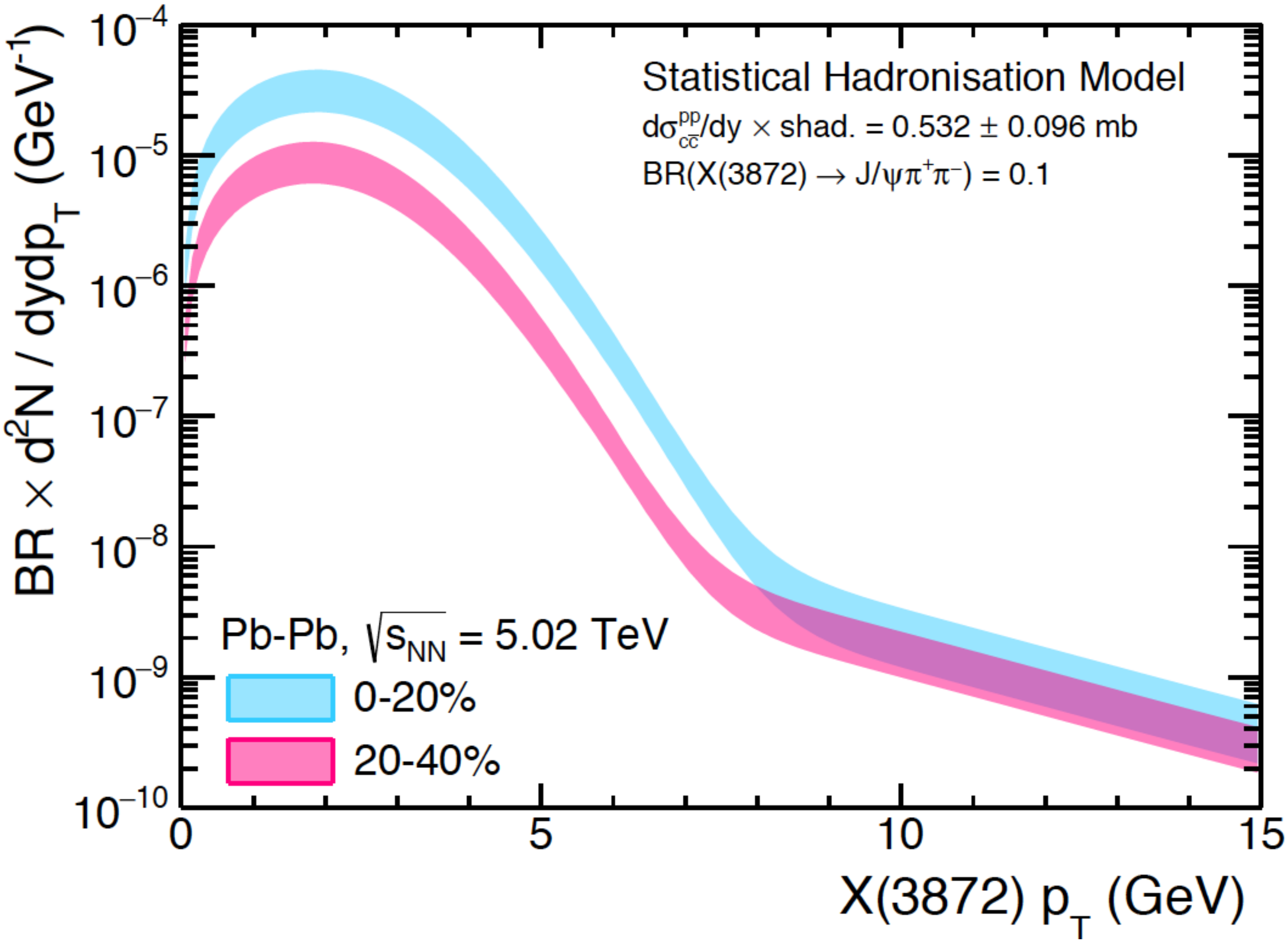
emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Run 3 and beyond

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

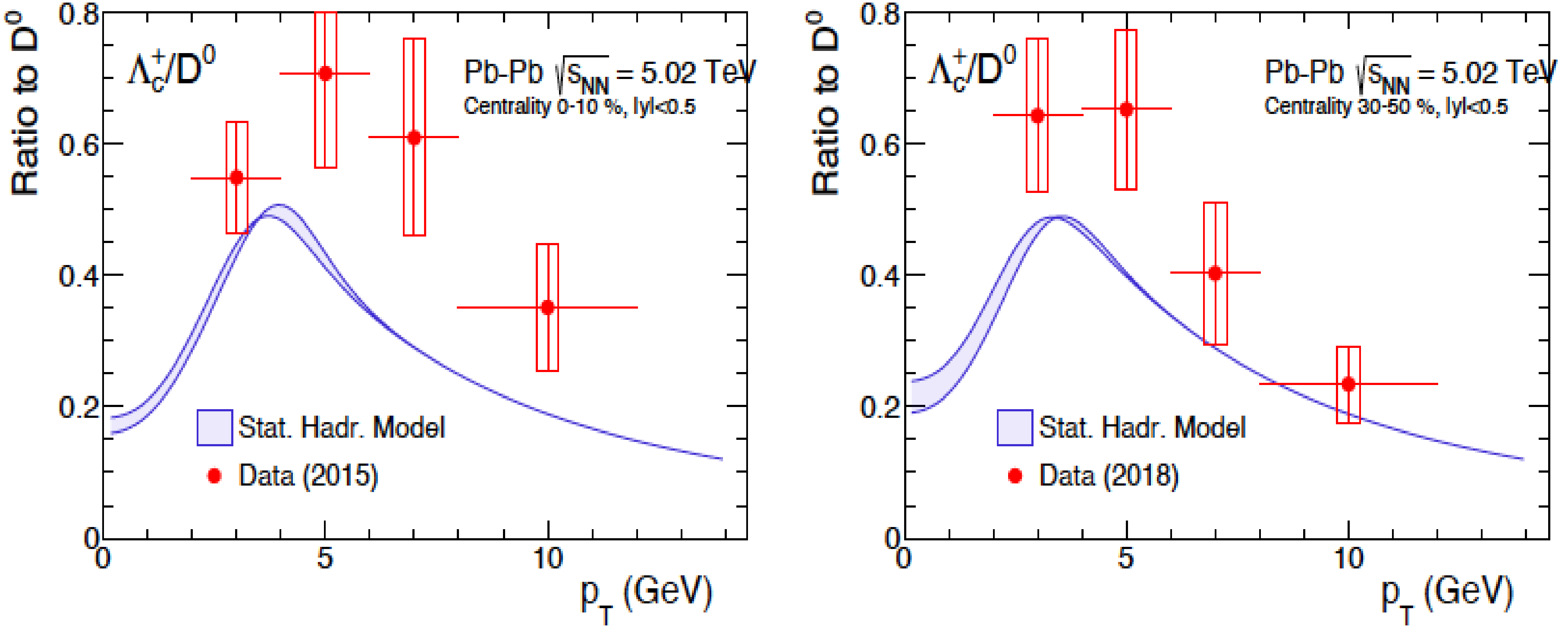
summary – charm production
probing the QCD phase boundary with heavy quarks

- statistical hadronization works quantitatively 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 - 10 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
- precision study of such hadrons → further insight into deconfinement and hadronization
- universal hadronization for hadrons with (u,d,s,c) quarks

backup

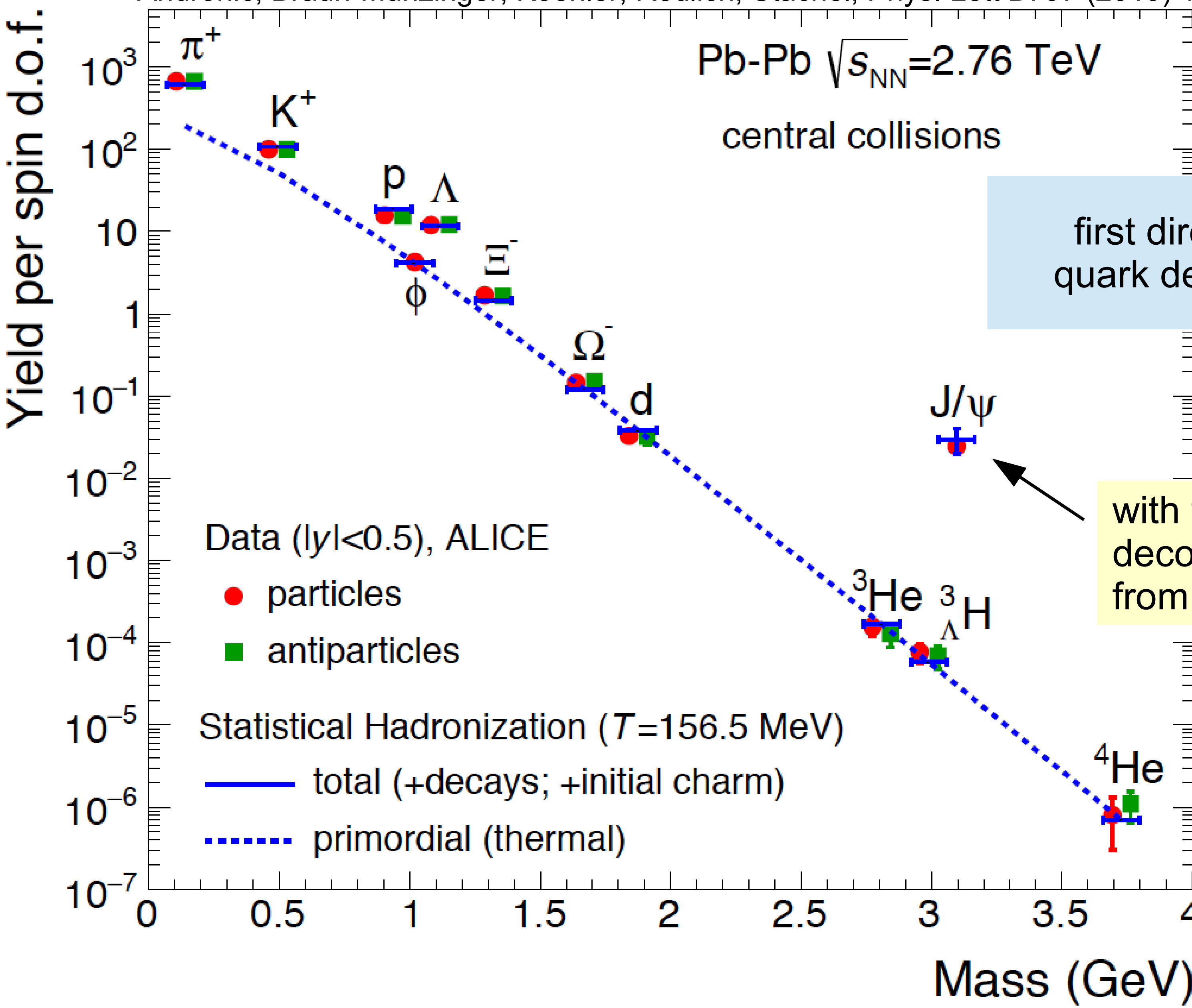
Λ_c/D^0 ratio



data: ALICE preliminary
SHMc predictions: A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler, A. Mazeliauskas, K. Redlich, V. Vislavicius, arXiv:2104.12754

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

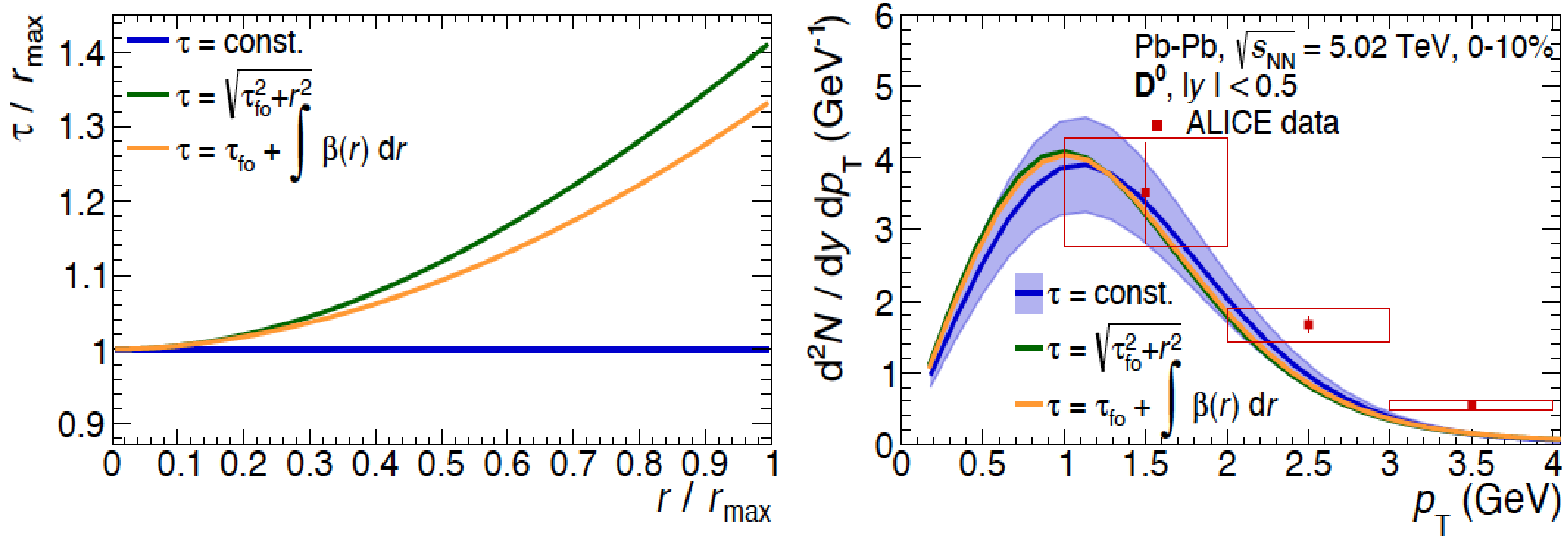


first direct proof of
quark deconfinement

with thermalized and
deconfined charm quarks
from initial hard scattering

blast wave parametrization of transverse momentum spectrum

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



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 -

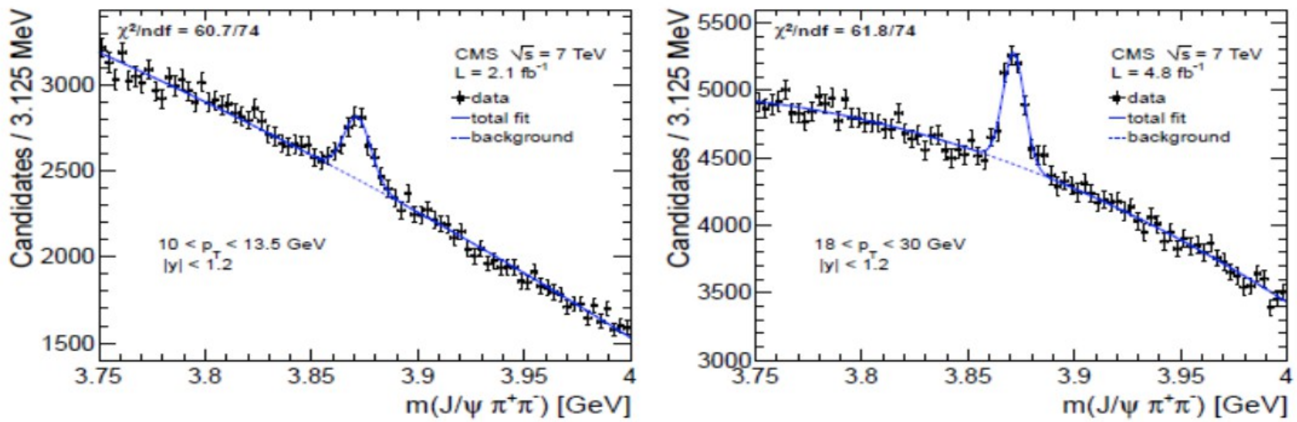
BELLE

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

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

- 2013 -

CMS



PDG particle data group

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%

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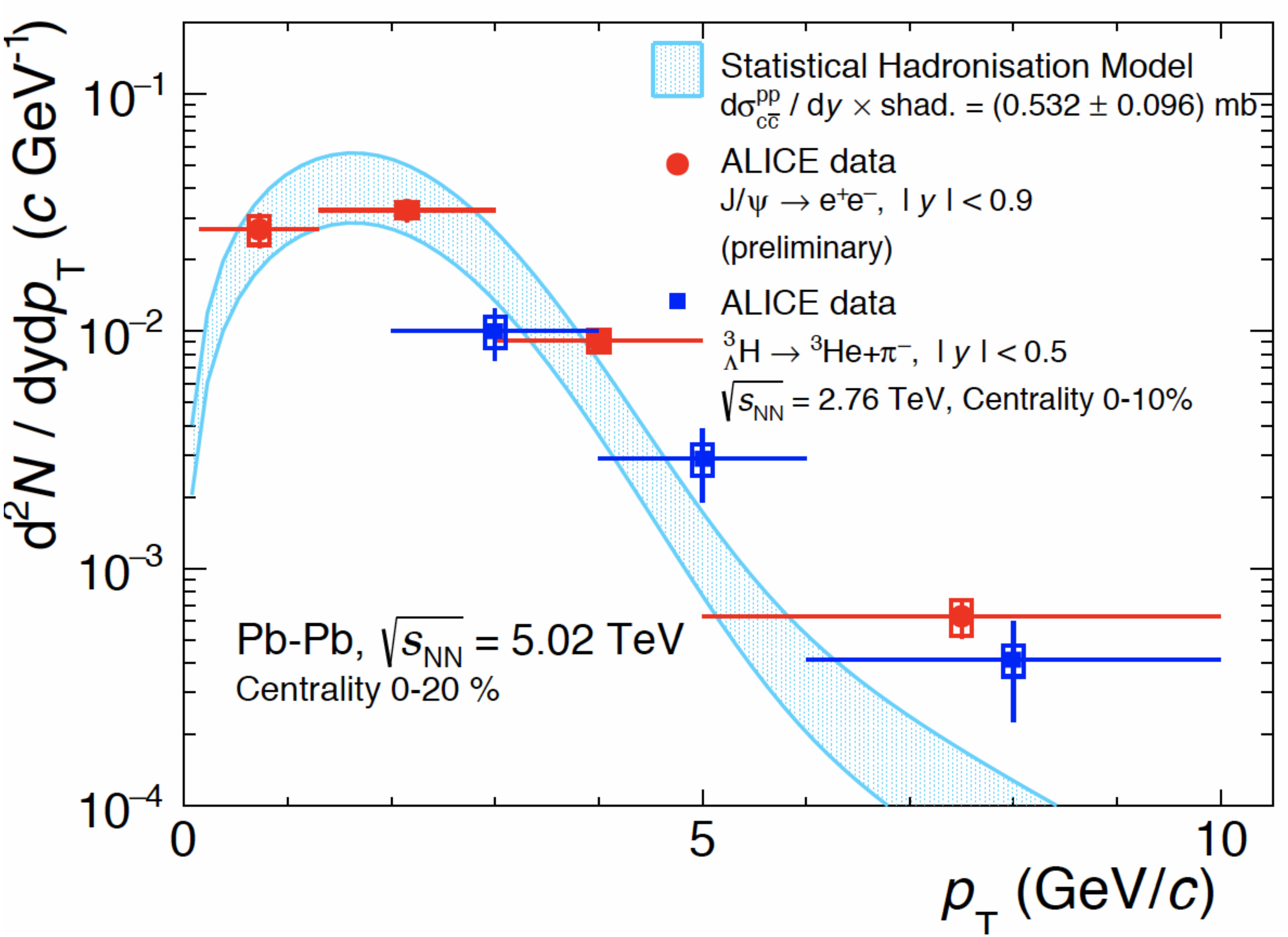
J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



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