Charmonia, open charm states, exotica in the framework of the SHMc

(SHMc = statistical hadronization model with charm)

jointly with A. Andronic, P. Braun-Munzinger, K. Redlich

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EMMI Rapid Reaction Task Force on Quarkonia
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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}

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

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

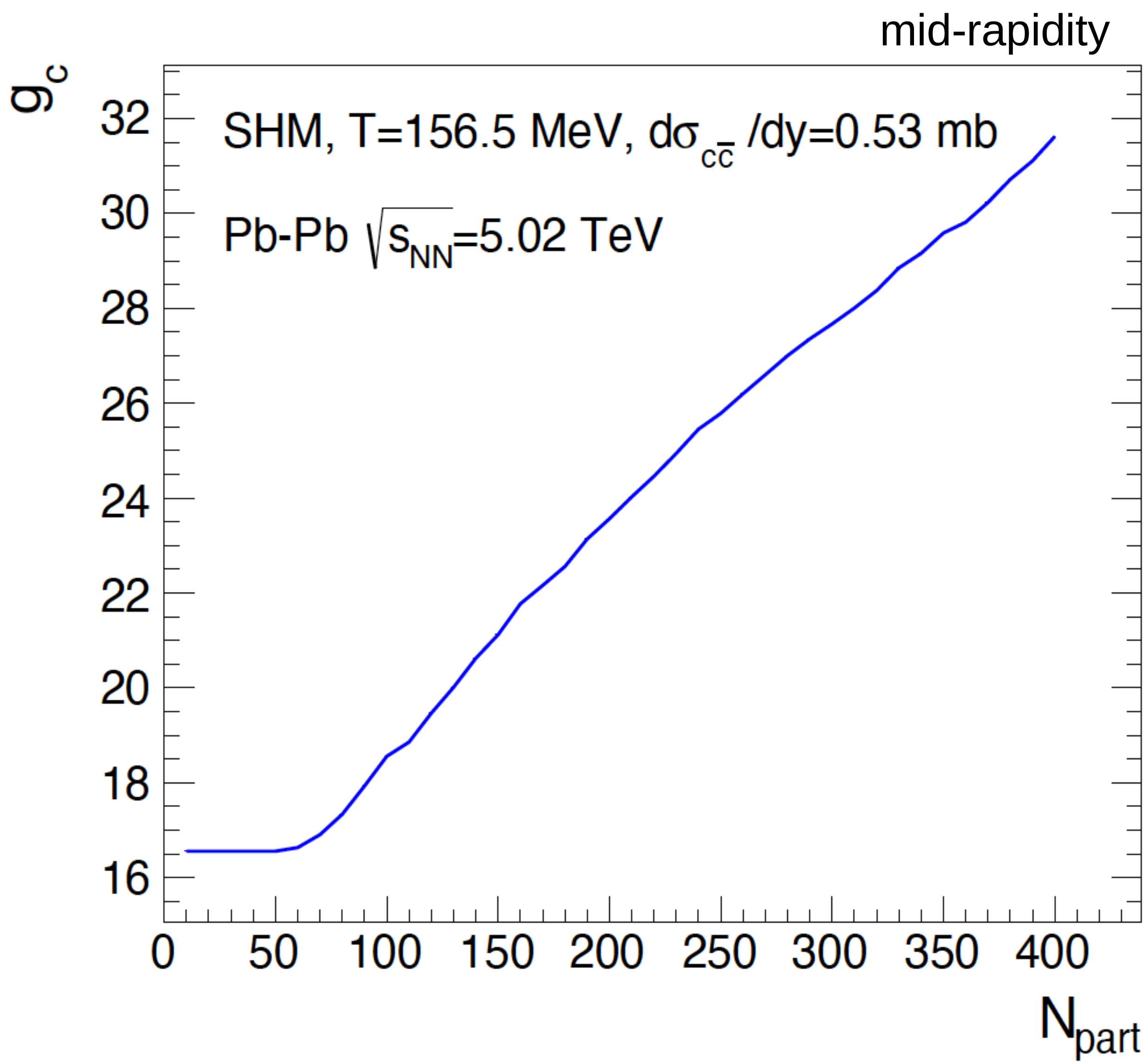
obtained from measured open charm cross section

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

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

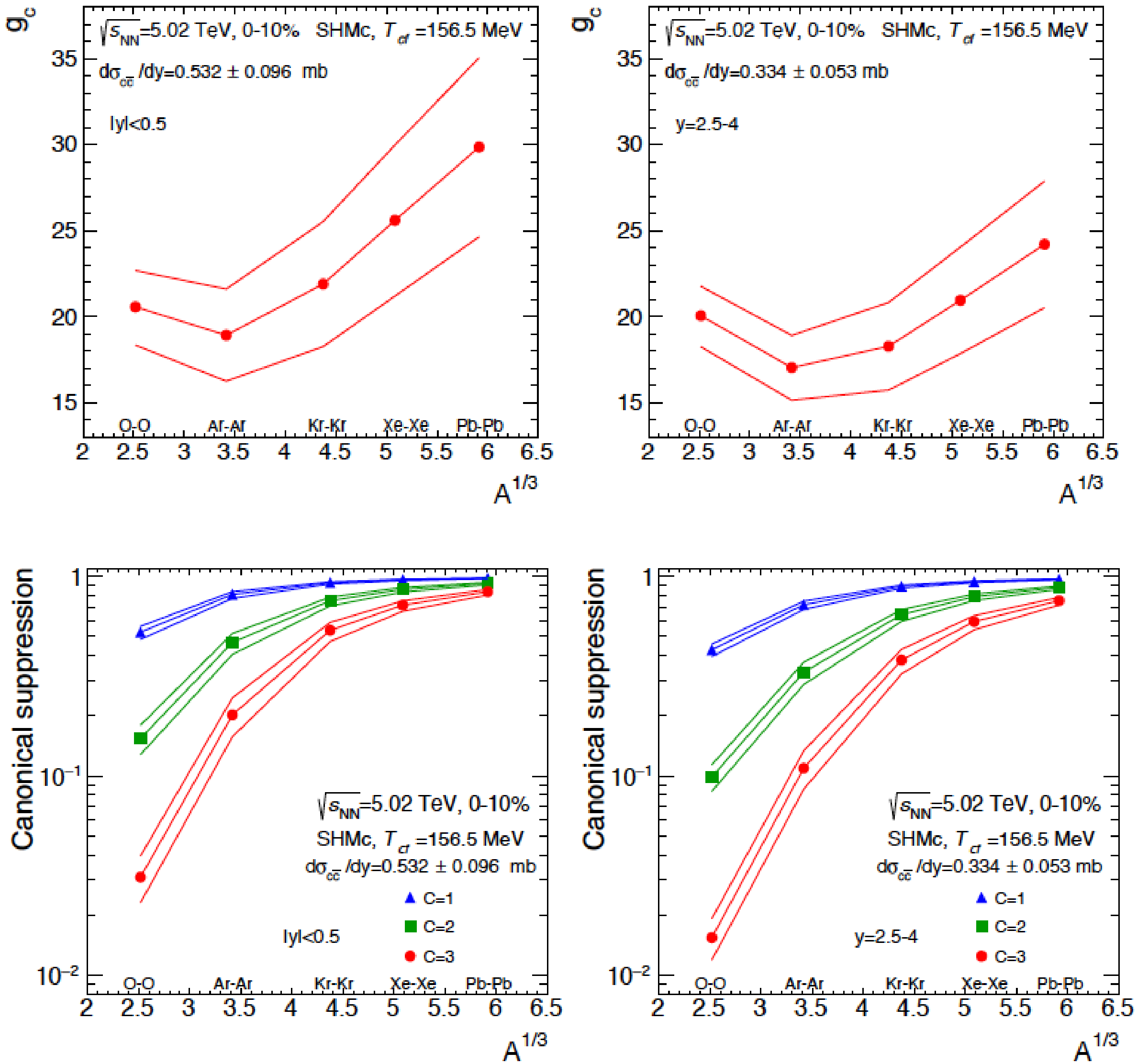
- for yields of charm hadron i with n_c charm quarks $N_{n_c}(i) = g_c^{n_c} N_{n_c}(i)^{th} \frac{I_{n_c}(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})}$

centrality dependence of charm fugacity g_c at LHC energy



charm fugacities and canonical suppression factors

different collision systems:



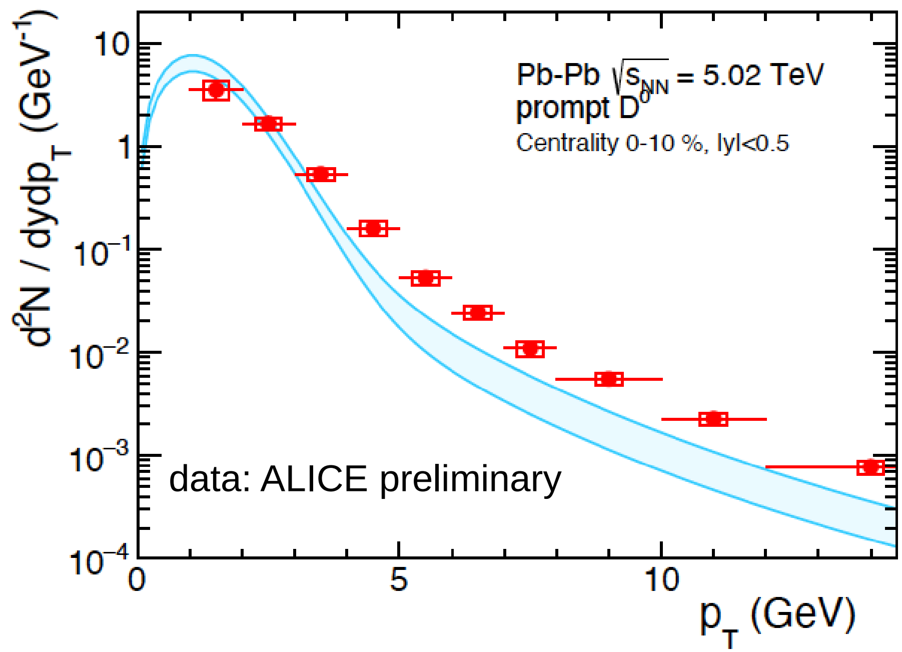
statistical hadronization for hidden and open charm

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.

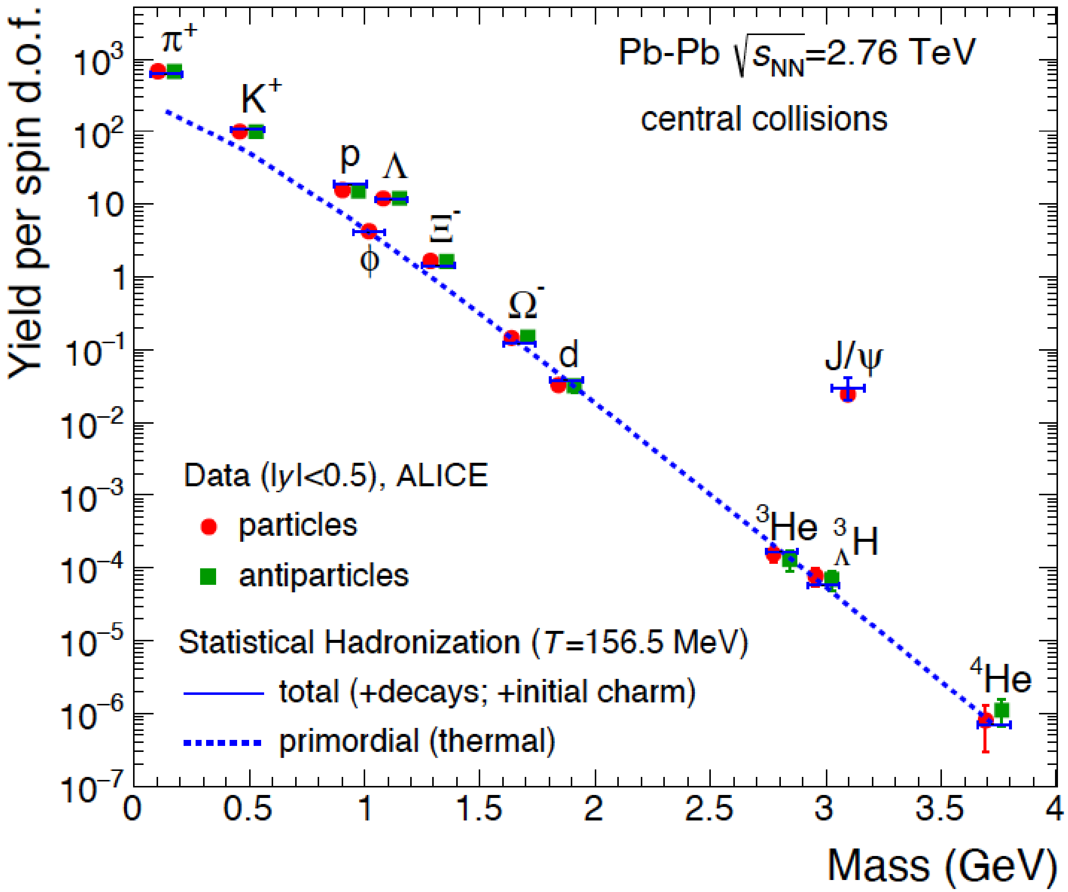
production probability scales with N_{ccbar}^2

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

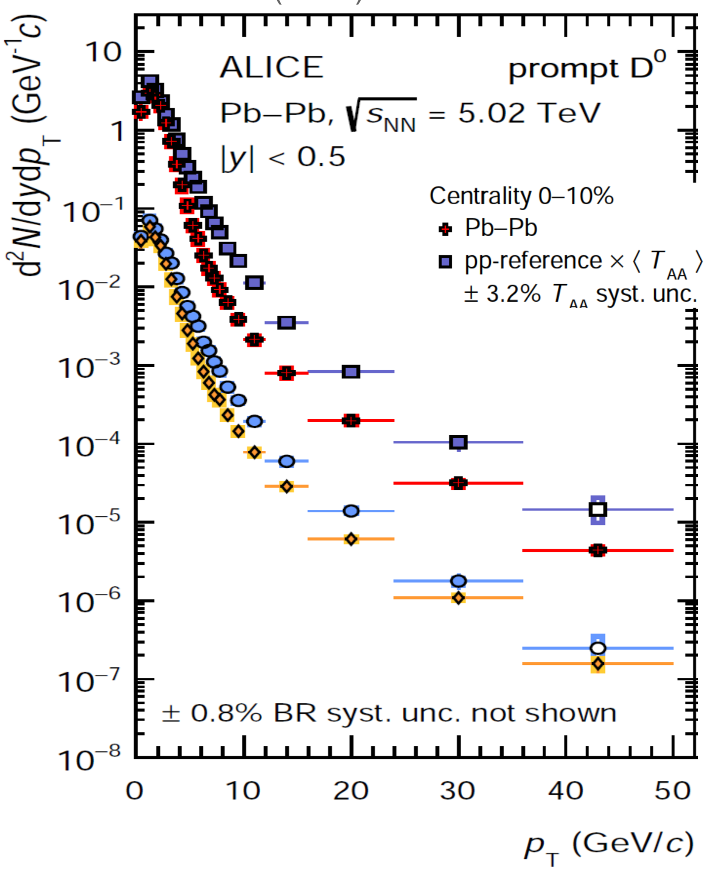


quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons,
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

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

Charm cross section – nuclear effects

JHEP01 (2022) 174 arXiv:2110.09420



first D^0 measurement in central PbPb down to p_t=0

$$dN/dy = 6.819 \pm 0.457\ (\text{stat.})\ ^{+0.912}_{-0.936}\ (\text{syst.}) \pm 0.054\ (\text{BR})$$

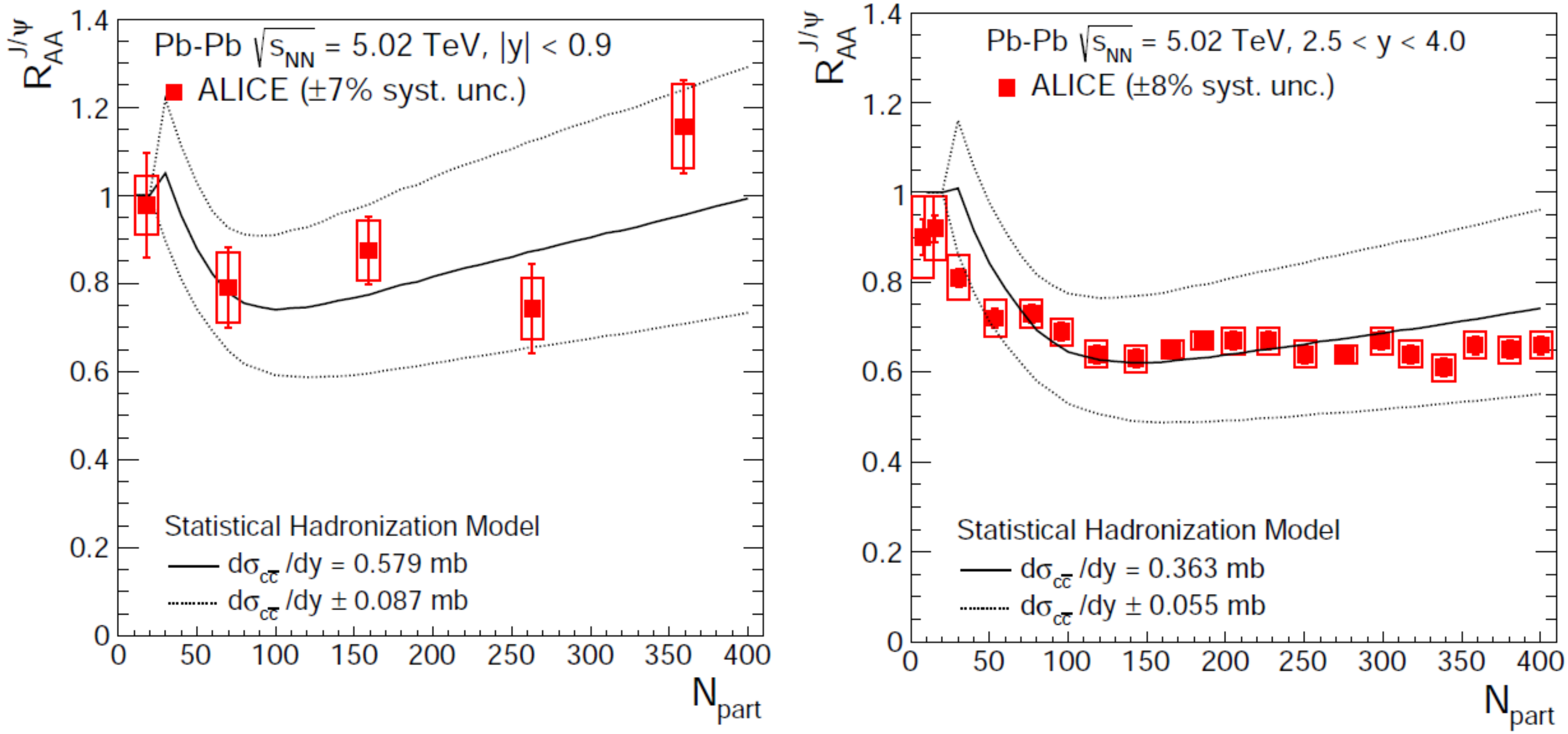
assume fragmentation like in SHMc → charm cross section

$dN_{c\bar{c}}/dy = 13.7 \pm 2.1$ corresponing to $g_c = 31.4 \pm 4.8$

use this as new basis for PbPb predictions from SHMc
8.8% larger than our estimate from pp and nuclear effects
uncertainty reduced by 15%

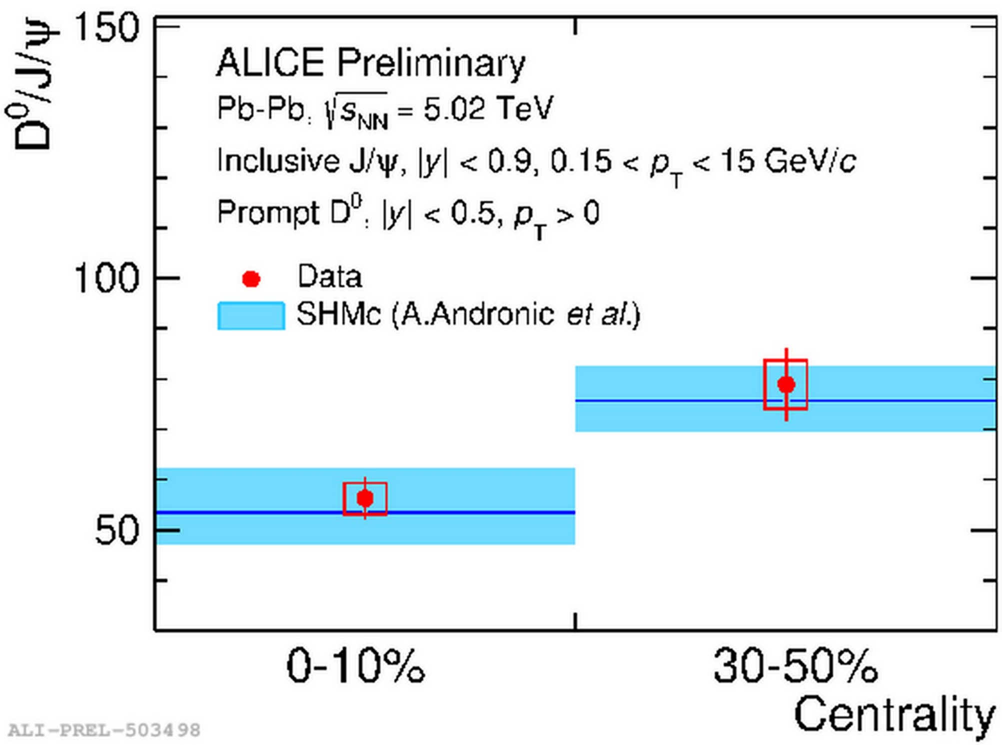
outlook to LHC Run3/4: with upgraded ALICE detector and 50 kHz PbPb collisions → precision measurement of all singly charmed hadrons down to p_t=0

J/ψ and statistical hadronization



production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

towards a meaningful normalization of charmonia



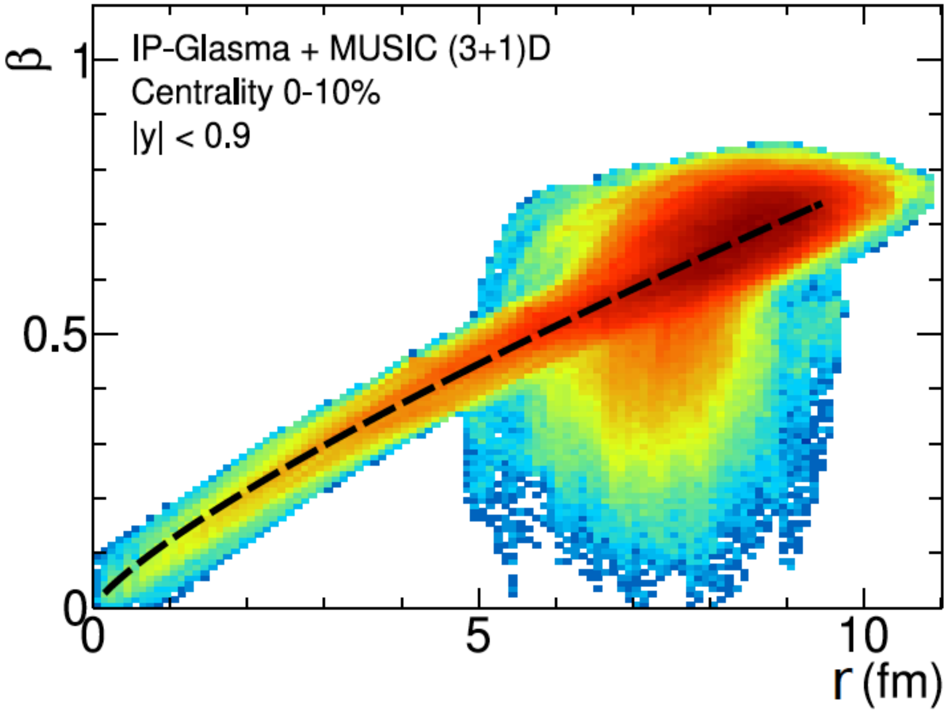
open charm yield would be natural normalization
real breakthrough in data:
can base charm cross section on measured dN/dy of D^0 in PbPb

→ J/ψ relative to D^0 falls into place naturally and with much increased precision

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

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich,
J. Stachel, PLB 797 (2019) 134836 arXiv:1902.09200



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

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

$$n = 0.85$$

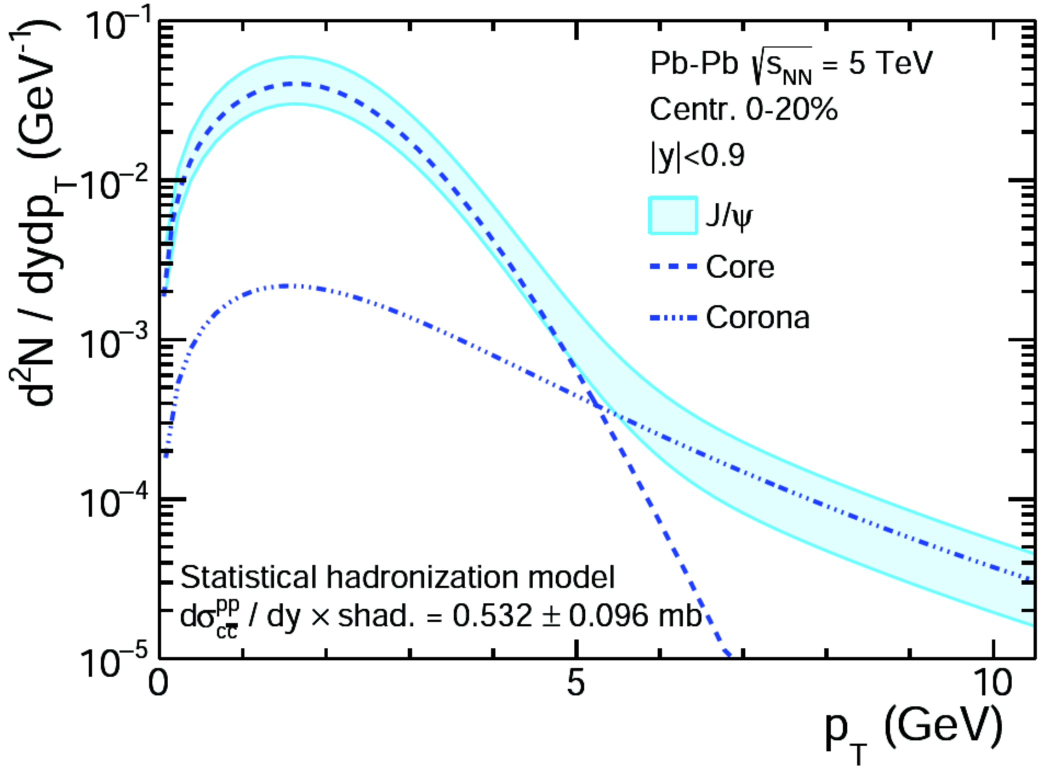
$$V = 2\pi \int_0^{r_{\max}} \mathrm{d}r\, r\tau(r)u^\tau \left[1 - \beta(r)\frac{\partial\tau}{\partial r}\right]$$

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

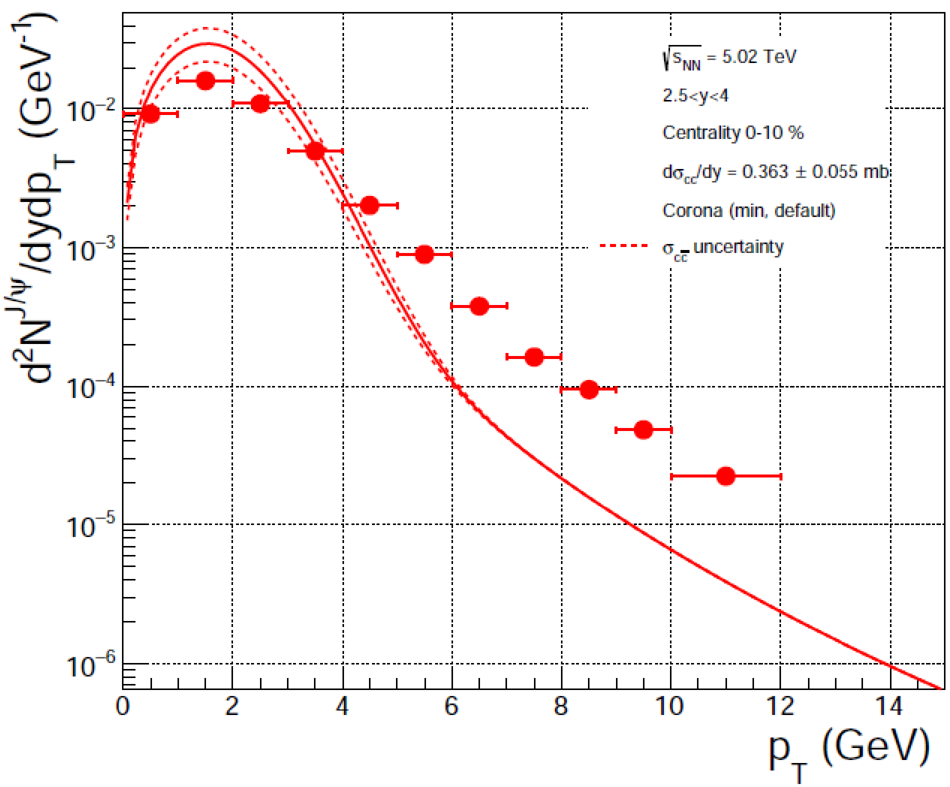
and blast wave parametrization of spectral shape with T = 156.5 MeV and
a fireball volume per unit rapidity for central PbPb collisions V = 4997 fm^3
sensitivity to shape of freeze-out surface: backup

J/ψ spectra from SHMc and parametrization of hydro freeze-out hypersurface

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich, J. Stachel, PLB 797 (2019) 134836 arXiv:1902.09200



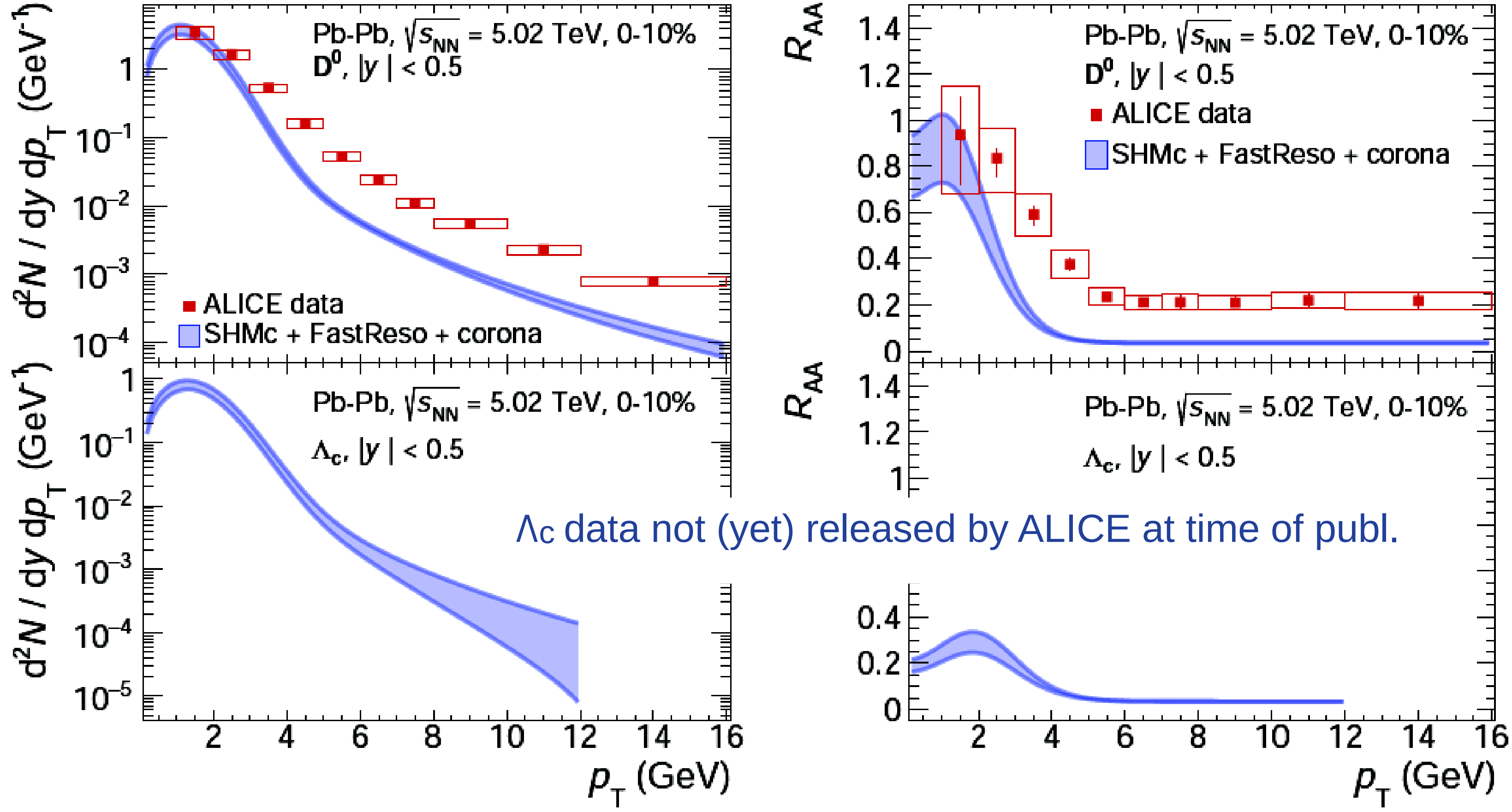
update to A. Andronic et al. 1902.09200



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)

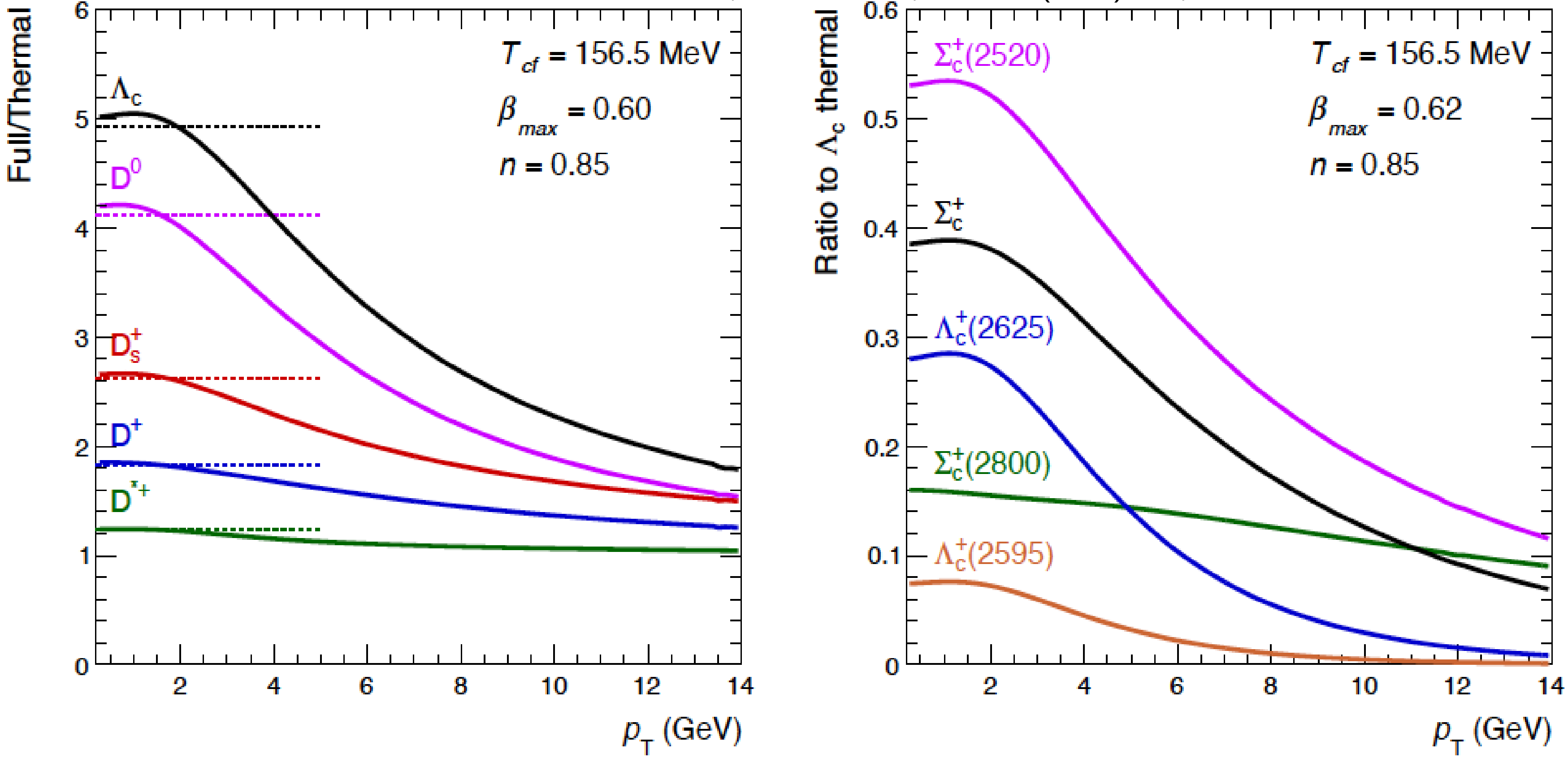
A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler, A. Mazeliauskas, K. Redlich, V. Vislavicius, JHEP07 (2021) 035, arXiv:2104.12754



impact of resonance decays

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

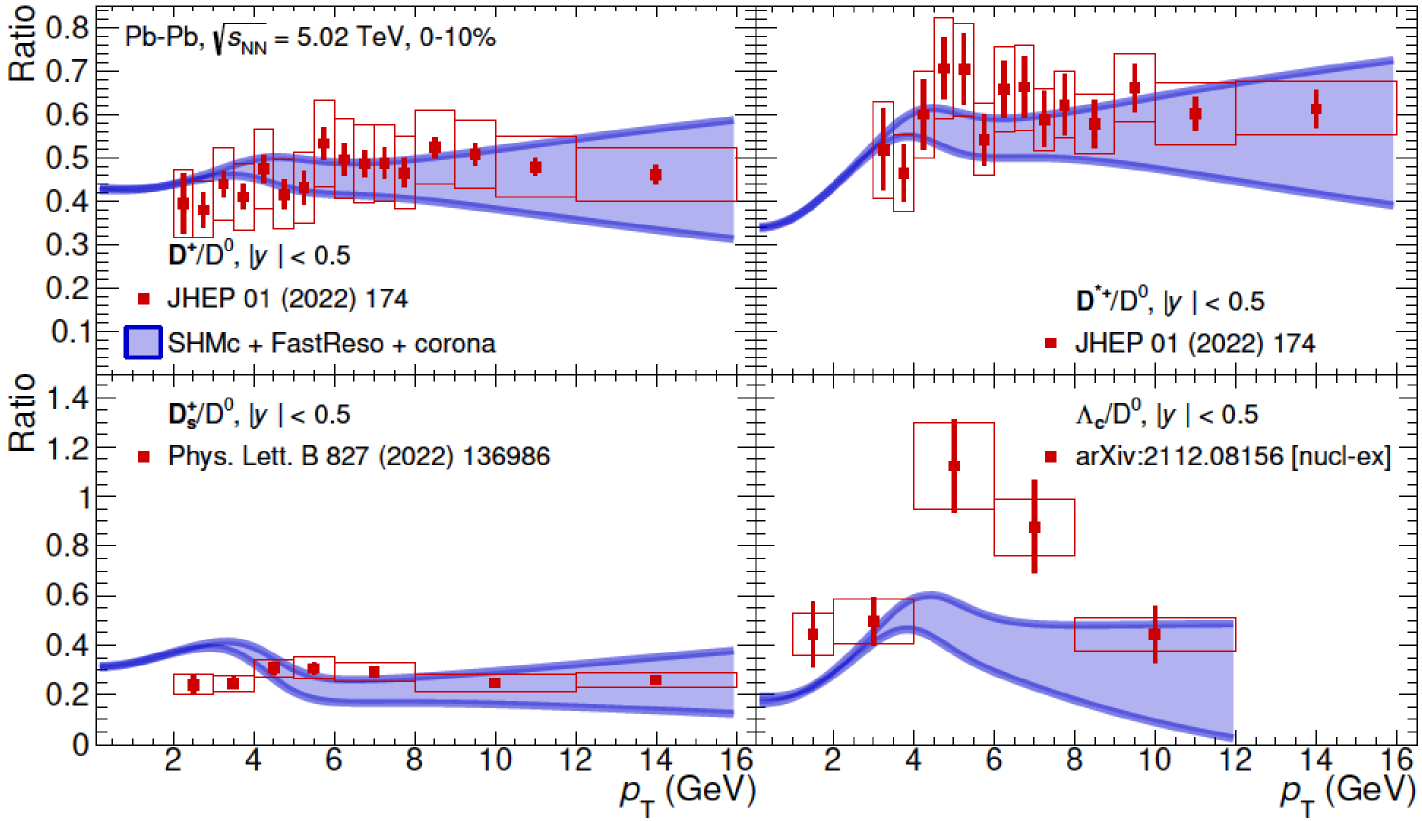
A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler, A. Mazeliauskas, K. Redlich, V. Vislavicius, JHEP07 (2021) 035, arXiv:2104.12754



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

ratios of charm hadron to D^0 spectra

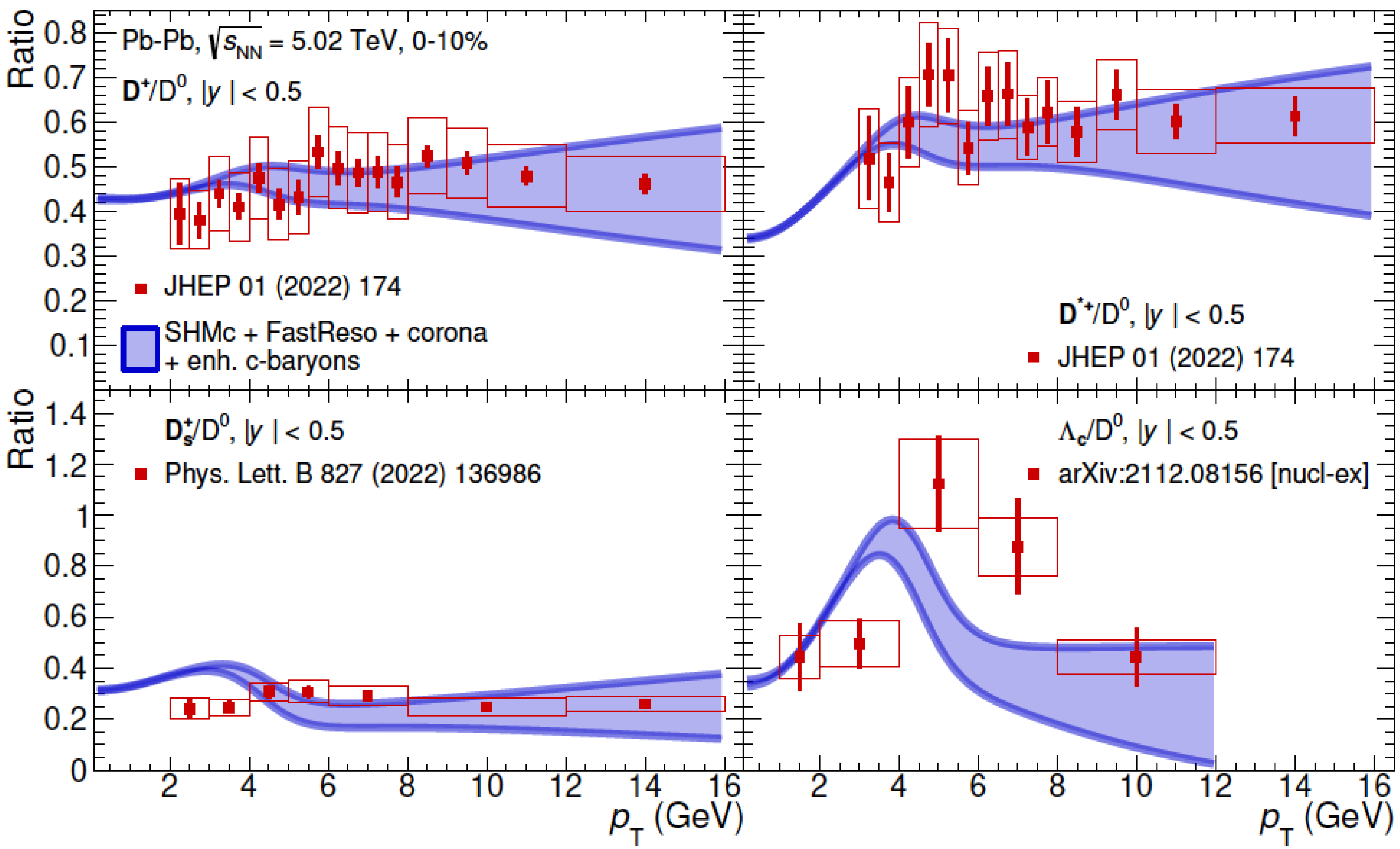
A. Andronic, P. Braun-Munzinger, J. Stachel, M. Koehler, A. Mazeliauskas, K. Redlich, V. Vislavicius, JHEP07 (2021) 035, arXiv:2104.12754



Charm-hadron spectrum: PDG

excellent agreement for D mesons considering there are no free parameters, but too low for Λ_c

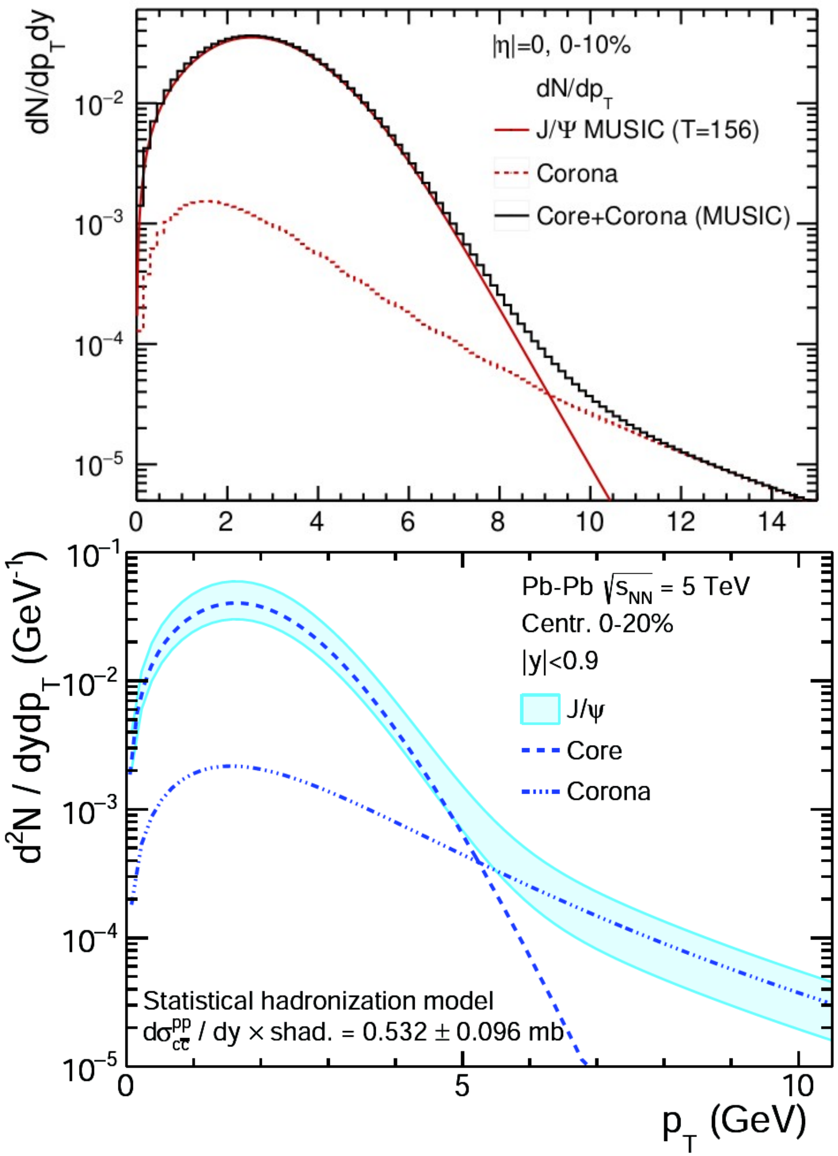
ratios of charm hadron to D^0 spectra



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

new approach to spectra: use Cooper-Frye freeze-out of MUSIC at 156.5 MeV directly instead of blast wave parameterization

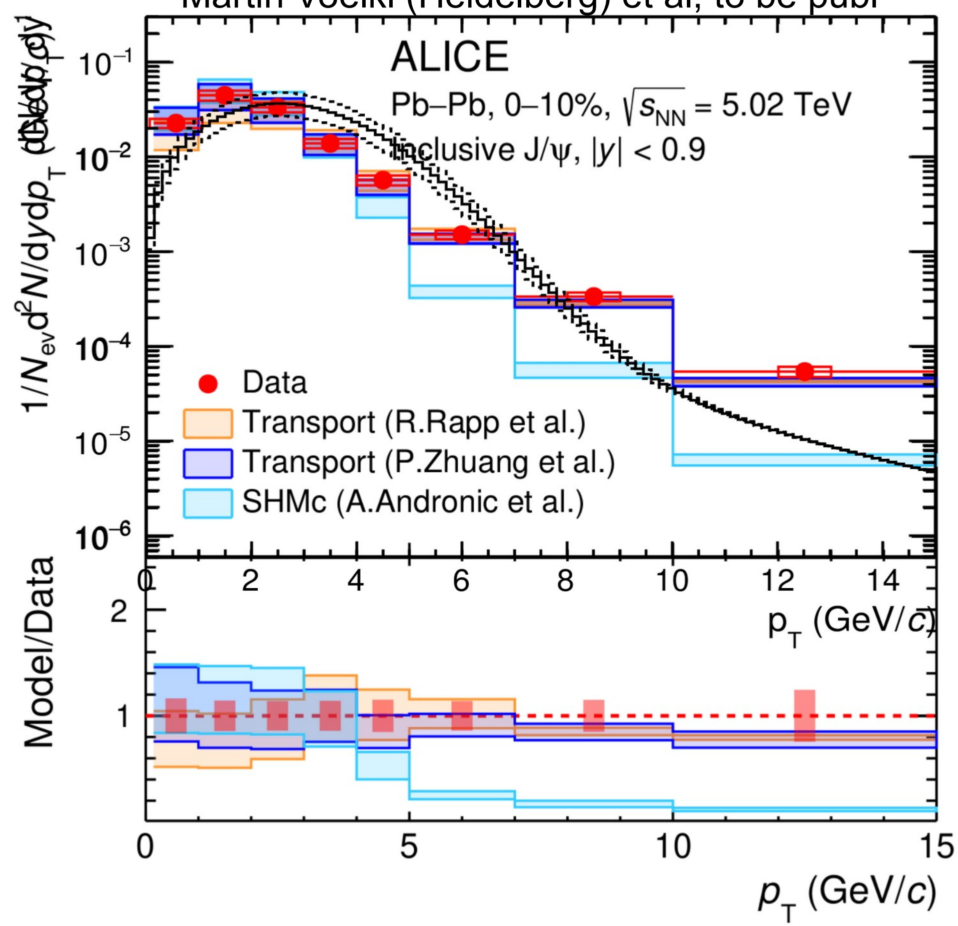
Martin Voelkl (Heidelberg) et al, to be publ.



J/psi yield MUSIC normalized to SHMc yield
corona unchanged

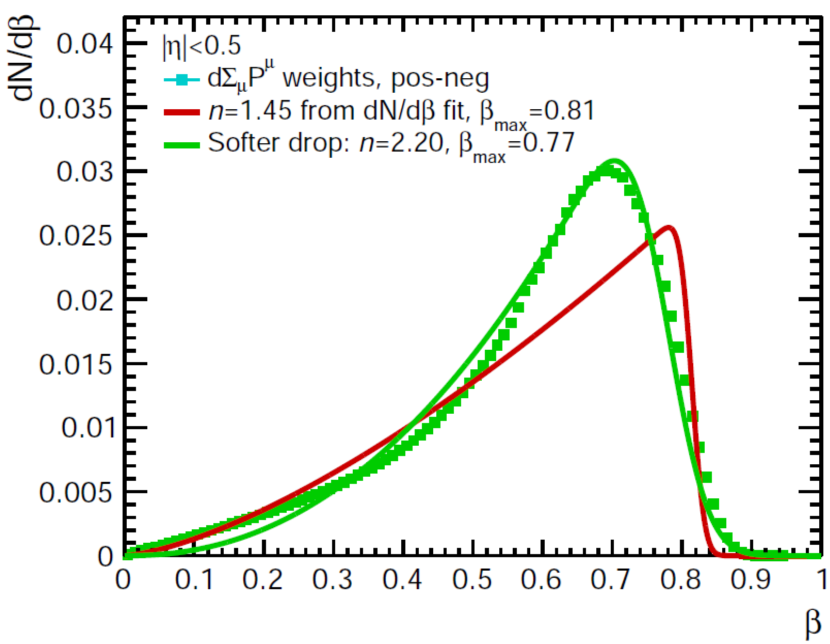
significantly harder spectrum to earlier approach
major influence of thermal contribution out to 9 GeV/c

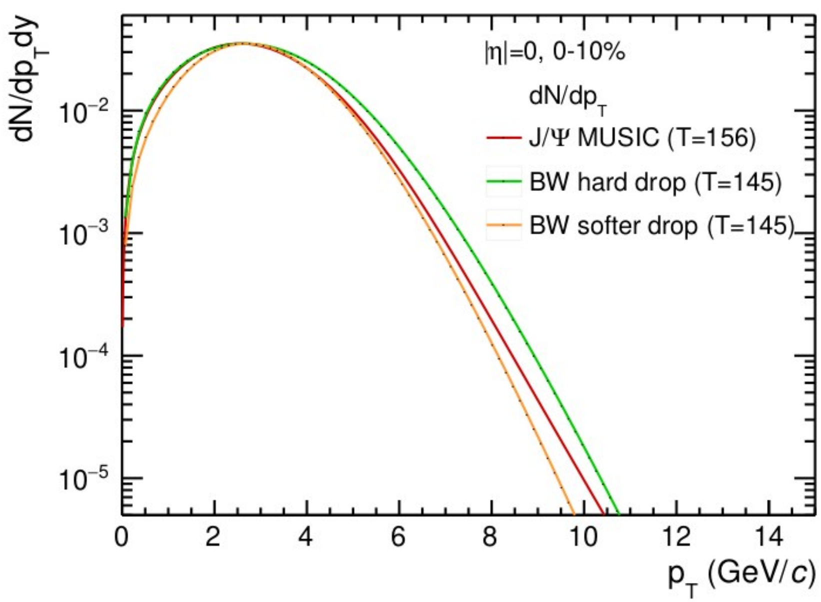
Martin Voelkl (Heidelberg) et al, to be publ



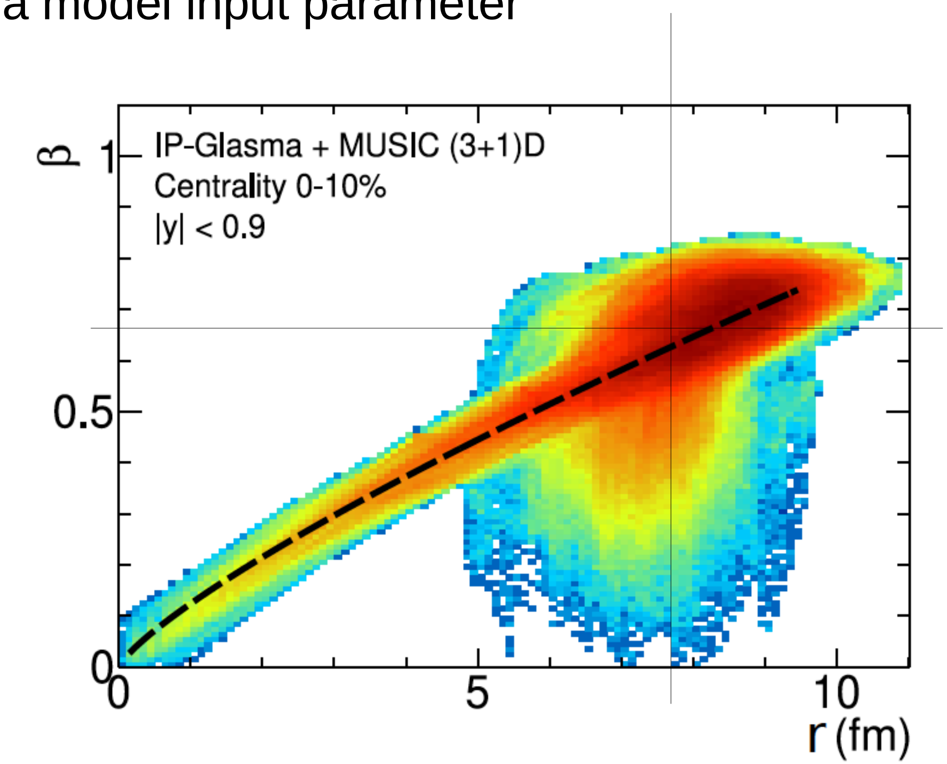
tracing the difference

Martin Voelkl (Heidelberg) et al, to be publ.





- full MUSIC freeze-out hyper surface and blast wave parameteriztion no so different
- but taking r_{max} from thermal freeze-out volume V = 4997 fm³ → r_{max} = 7.9 fm corresponding to β_{max} = 0.62
- a question of spatial distribution of charm quarks, do they experience maximum β of 0.62, 0.77, 0.81? spatial distribution becomes a model input parameter

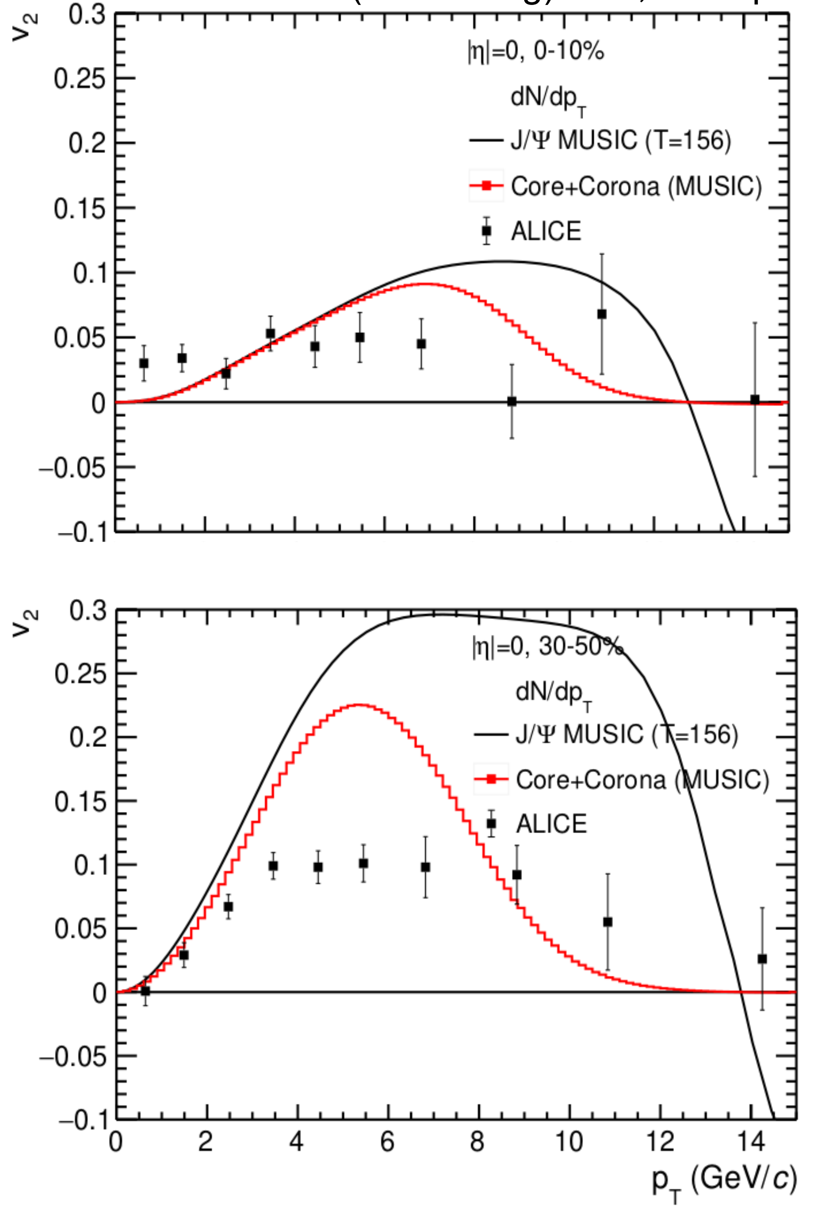


a first look at J/psi v_2 in this approach

- Weight v_2 of thermalized J/ψ with core fraction for full v_2 estimate
- No intuitive explanation why thermalized v_2 changes sign at high p_T, but core fraction is almost 0 there
- v_2 based on reaction plane of event
- For semiperipheral events, smooth peak, while data shows flat plateau
- Rise and p_T-extent of v_2 reproduced, suggesting that v_2 out to 9 GeV/c

  could be due to thermalized contribution
- Same approach can also be used for v_3, but relevant plane needs to be extracted from initial spatial anisotropy instead

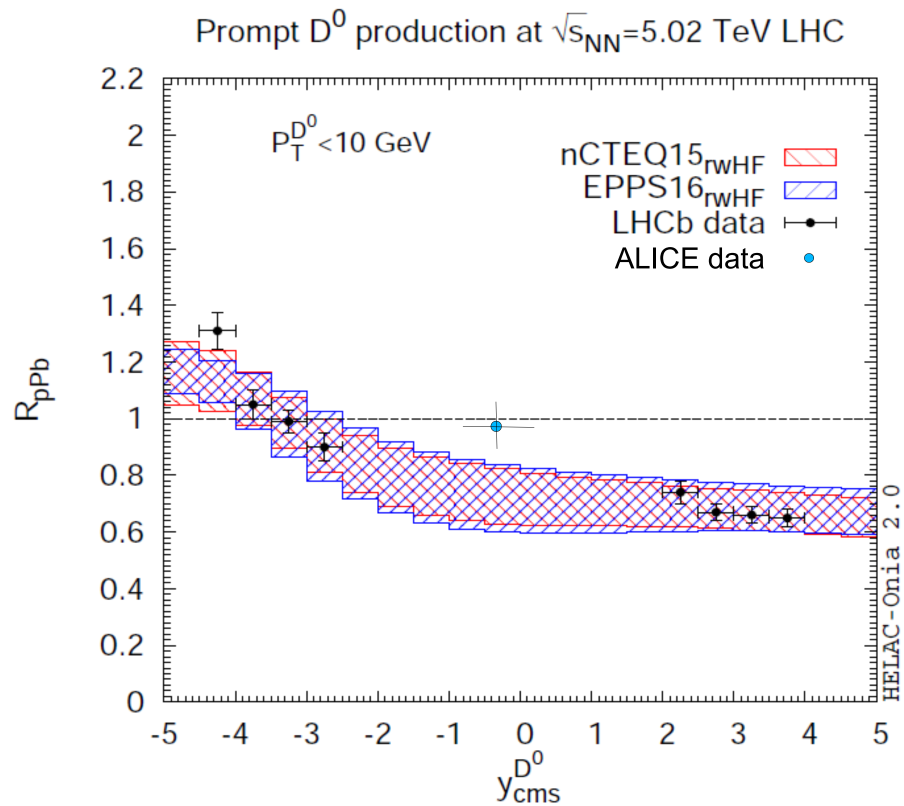
Martin Voelkl (Heidelberg) et al, to be publ.



backup

Charm cross section – nuclear effects

RHIC and LHC data strongly constrain nuclear gluon pdf for $10^{-5} < x < 10^{-1}$



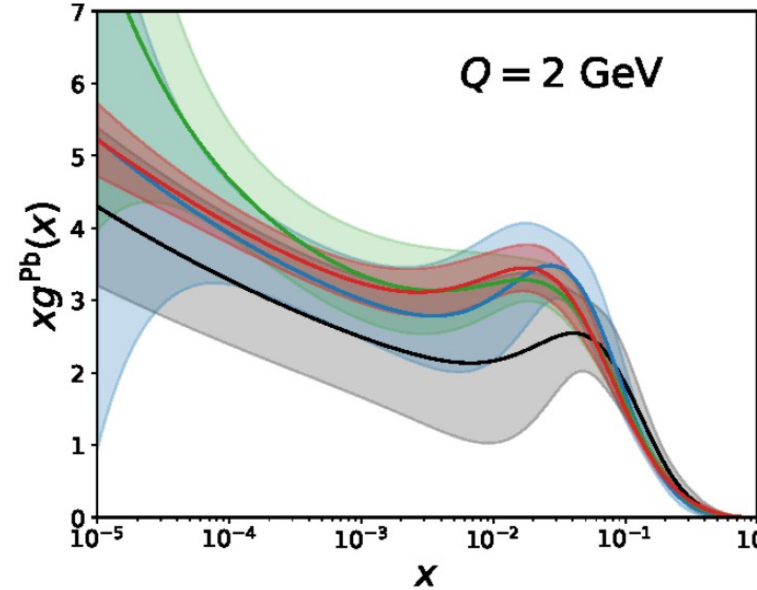
at y=0 R_{pPb} = 0.73 ± 0.067

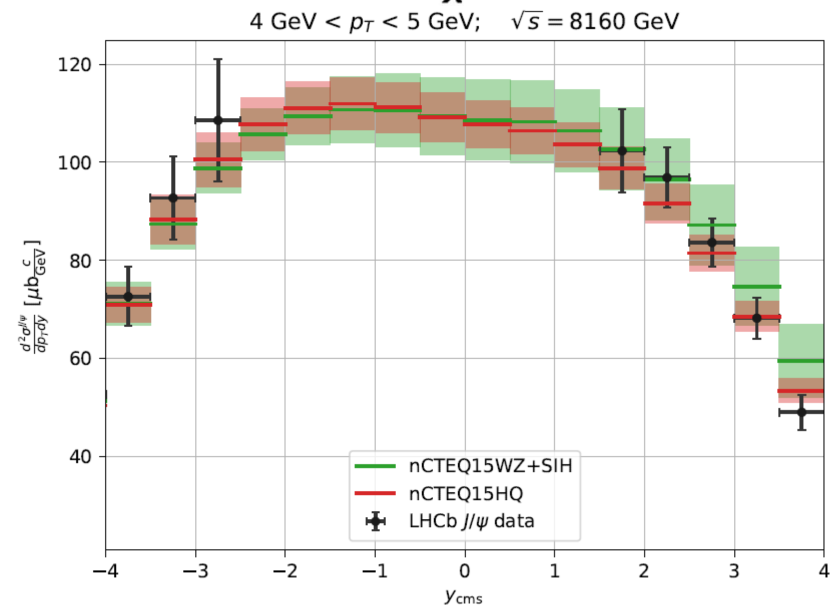
→ S_{PbPb} = 0.53 ± 0.097

supported by J/ψ yield in photoproduction

in SHMc in the past we used 0.65 ± 0.12

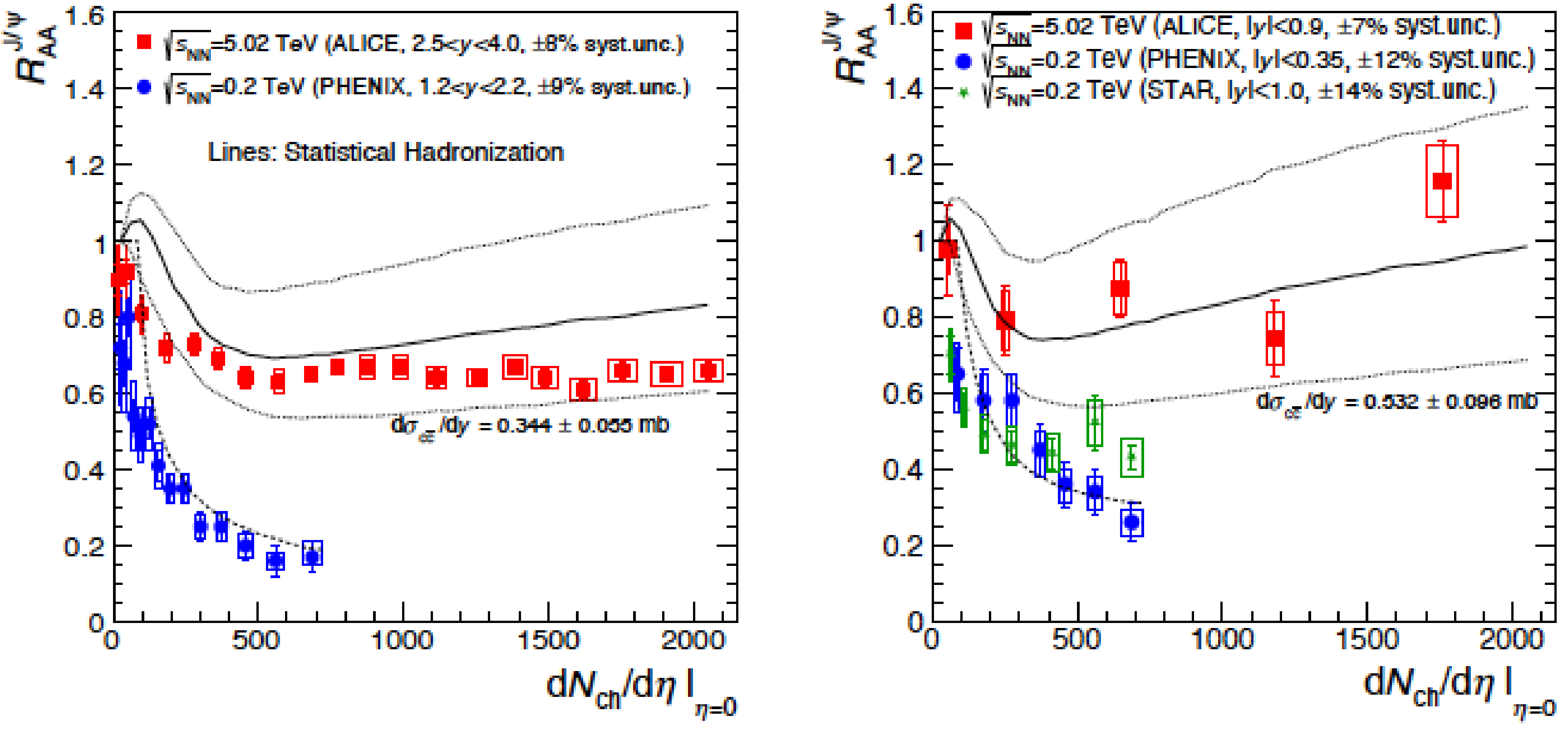
Duwentäster et al. new nCTEQ15HQ fit 2204.09982





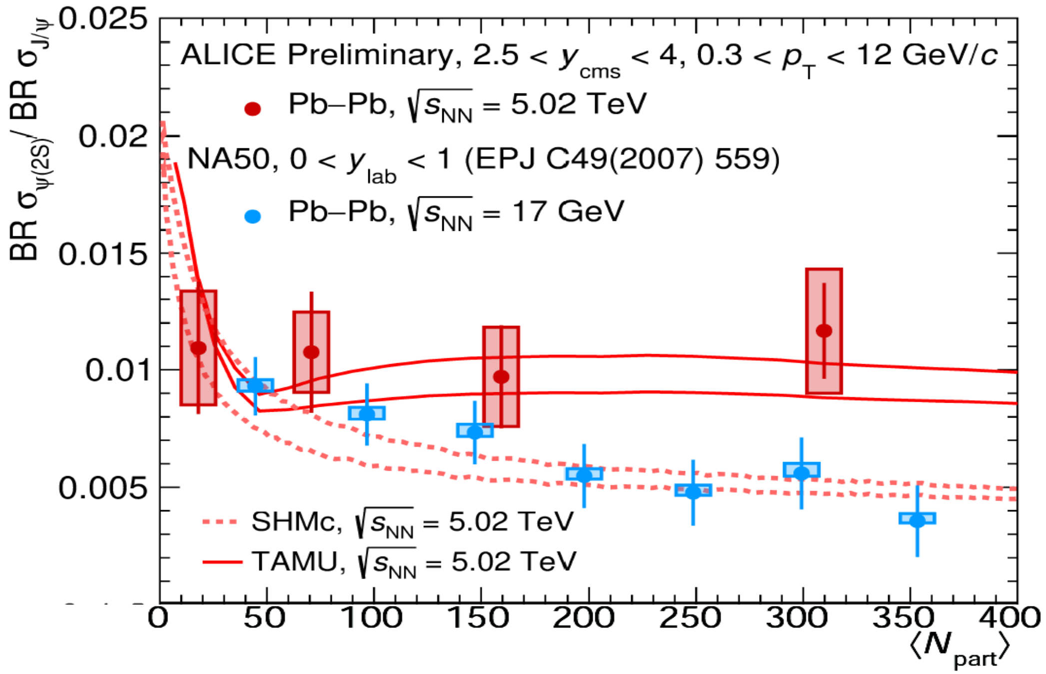
RHIC and LHC data compared to SHMc predictions

note the energy dependence of the nuclear modification factor RAA



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

What about ψ(2S)?



excited state population suppressed by Boltzmann factor
- first measurement in PbPb down to p_t=0
- data 1.8 σ above SHMc for most central bin

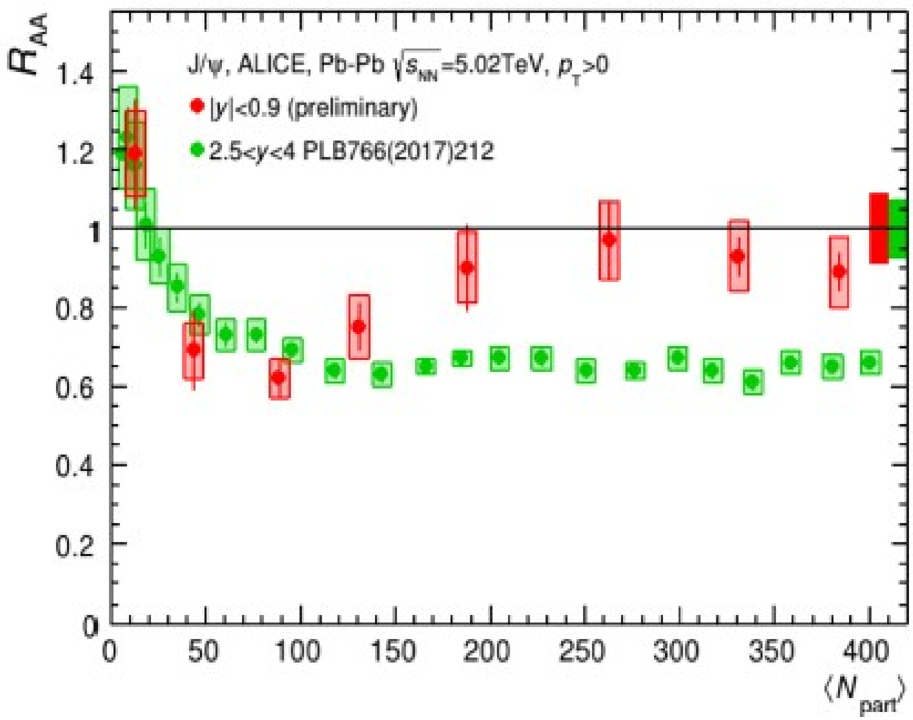
within stat. hadronization approach, an unexpected result
→ little room to accommodate in a likely physical scenario
larger common freeze-out temperature ☹
larger freeze-out temperature for ψ(2S) vs J/ψ ☹

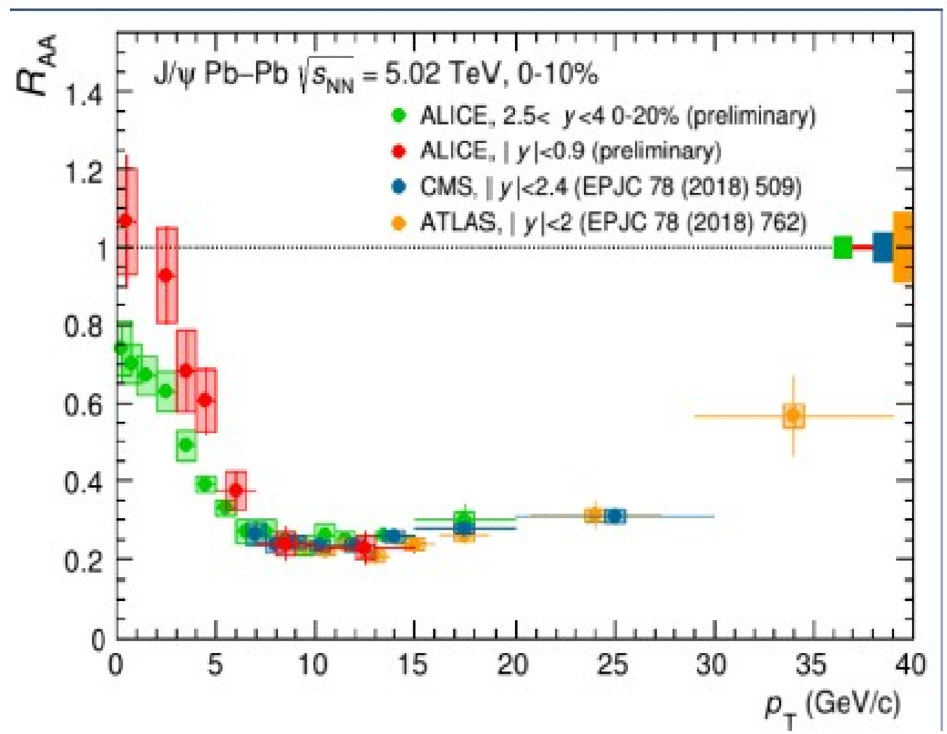
future opportunity:
higher precision ψ(2S), also mid-y
χ_c maybe only in ALICE3?

} deconfinement temperature from charmonium spectrum

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

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





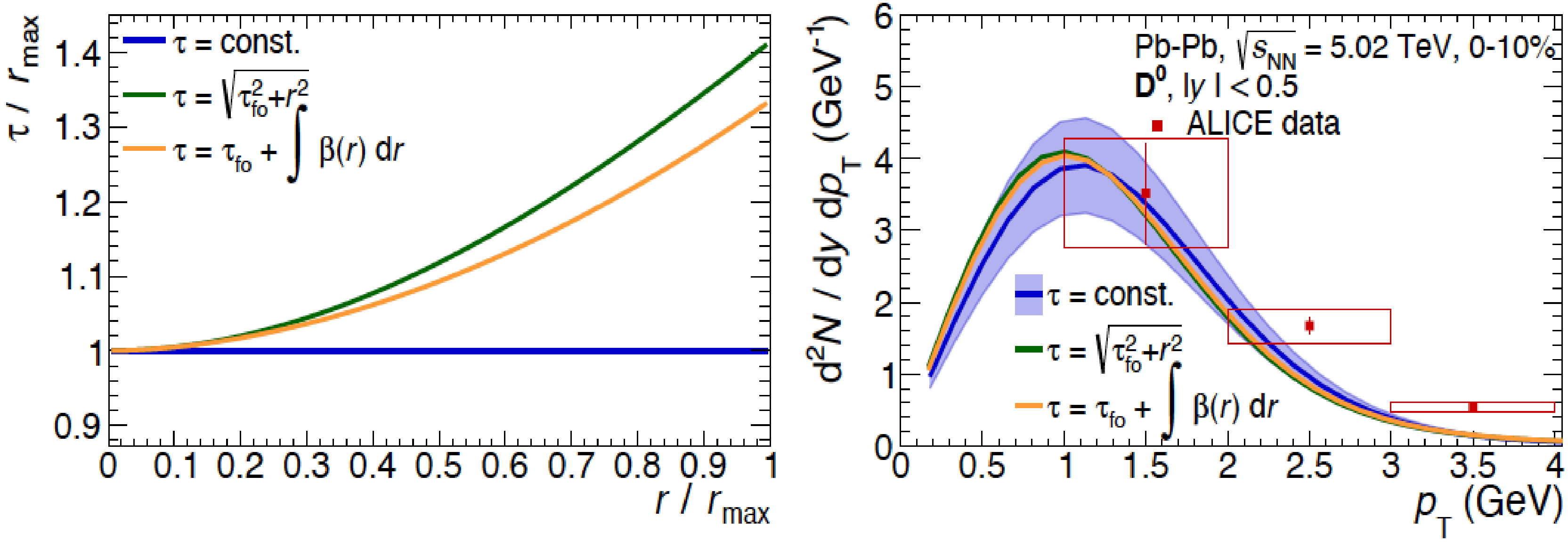
blast wave parametrization of transverse momentum spectrum

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

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

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

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



mid-rapidity yields for Pb-Pb collisions

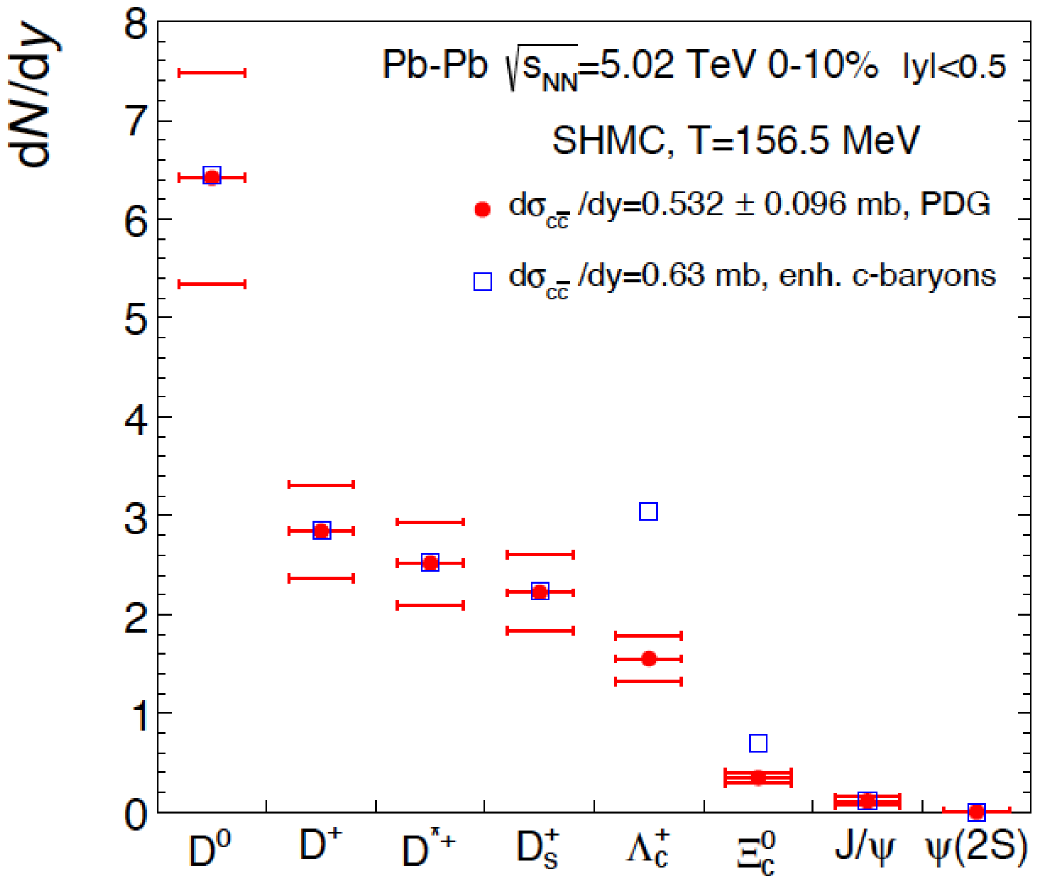
Particle	$\mathrm{d}N/\mathrm{d}y$ core (SHMc)	$\mathrm{d}N/\mathrm{d}y$ corona	$\mathrm{d}N/\mathrm{d}y$ total
		0-10%	
D^0	6.40 ± 0.95	0.409 ± 0.034	6.81 ± 0.95
D^+	2.84 ± 0.42	0.181 ± 0.026	3.02 ± 0.42
D^{*+}	2.51 ± 0.37	0.166 +0.049−0.022	2.67 ± 0.37
D_s^+	2.29 ± 0.34	0.076 +0.025−0.016	2.36 ± 0.34
Λ_c^+	1.39 ± 0.21	0.260 ± 0.029	1.64 ± 0.21
Ξ_c^0	0.280 ± 0.041	0.093 ± 0.036	0.373 ± 0.055
J/ψ	0.122 +0.038−0.033	$(5.25 \pm 0.38) \cdot 10^{-3}$	0.127 +0.038−0.033
$\psi(2S)$	$(3.43 +1.1-0.9) \cdot 10^{-3}$	$(7.87 \pm 0.57) \cdot 10^{-4}$	$(4.22 +1.1-0.9) \cdot 10^{-3}$
		30-50%	
D^0	0.876 ± 0.131	0.202 ± 0.017	1.08 ± 0.132
D^+	0.388 ± 0.058	0.090 ± 0.013	0.477 ± 0.059
D^{*+}	0.343 ± 0.051	0.082 +0.024−0.011	0.425 +0.057−0.052
D_s^+	0.313 ± 0.047	0.038 +0.012−0.008	0.350 ± 0.048
Λ_c^+	0.190 ± 0.028	0.128 ± 0.014	0.317 ± 0.032
Ξ_c^0	0.038 ± 0.006	0.046 ± 0.018	0.084 ± 0.019
J/ψ	$(1.17 +0.32-0.28) \cdot 10^{-2}$	$(2.59 \pm 0.19) \cdot 10^{-3}$	$(1.43 +0.32-0.28) \cdot 10^{-2}$
$\psi(2S)$	$(3.28 +0.90-0.79) \cdot 10^{-4}$	$(3.90 \pm 0.28) \cdot 10^{-4}$	$(7.17 +0.94-0.84) \cdot 10^{-4}$

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
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$4.5\cdot10^{31}$	$2.4\cdot10^{30}$	$1.7\cdot10^{29}$	$3.0\cdot10^{28}$	$3.8\cdot10^{27}$
	$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y = 0.53\,\mathrm{mb}$				
$\mathrm{d}N_{\Omega_{ccc}}/\mathrm{d}y$	$8.38\cdot10^{-8}$	$1.29\cdot10^{-6}$	$1.23\cdot10^{-5}$	$4.17\cdot10^{-5}$	$1.25\cdot10^{-4}$
Ω_{ccc} Yield	$5.3\cdot10^{5}$	$8.05\cdot10^{5}$	$8.78\cdot10^{5}$	$7.26\cdot10^{5}$	$3.80\cdot10^{5}$
	$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y = 0.63\,\mathrm{mb}$				
$\mathrm{d}N_{\Omega_{ccc}}/\mathrm{d}y$	$1.44\cdot10^{-7}$	$2.33\cdot10^{-6}$	$2.14\cdot10^{-5}$	$7.03\cdot10^{-5}$	$2.07\cdot10^{-4}$
Ω_{ccc} Yield	$9.2\cdot10^{5}$	$1.45\cdot10^{6}$	$1.53\cdot10^{6}$	$1.22\cdot10^{6}$	$6.29\cdot10^{5}$

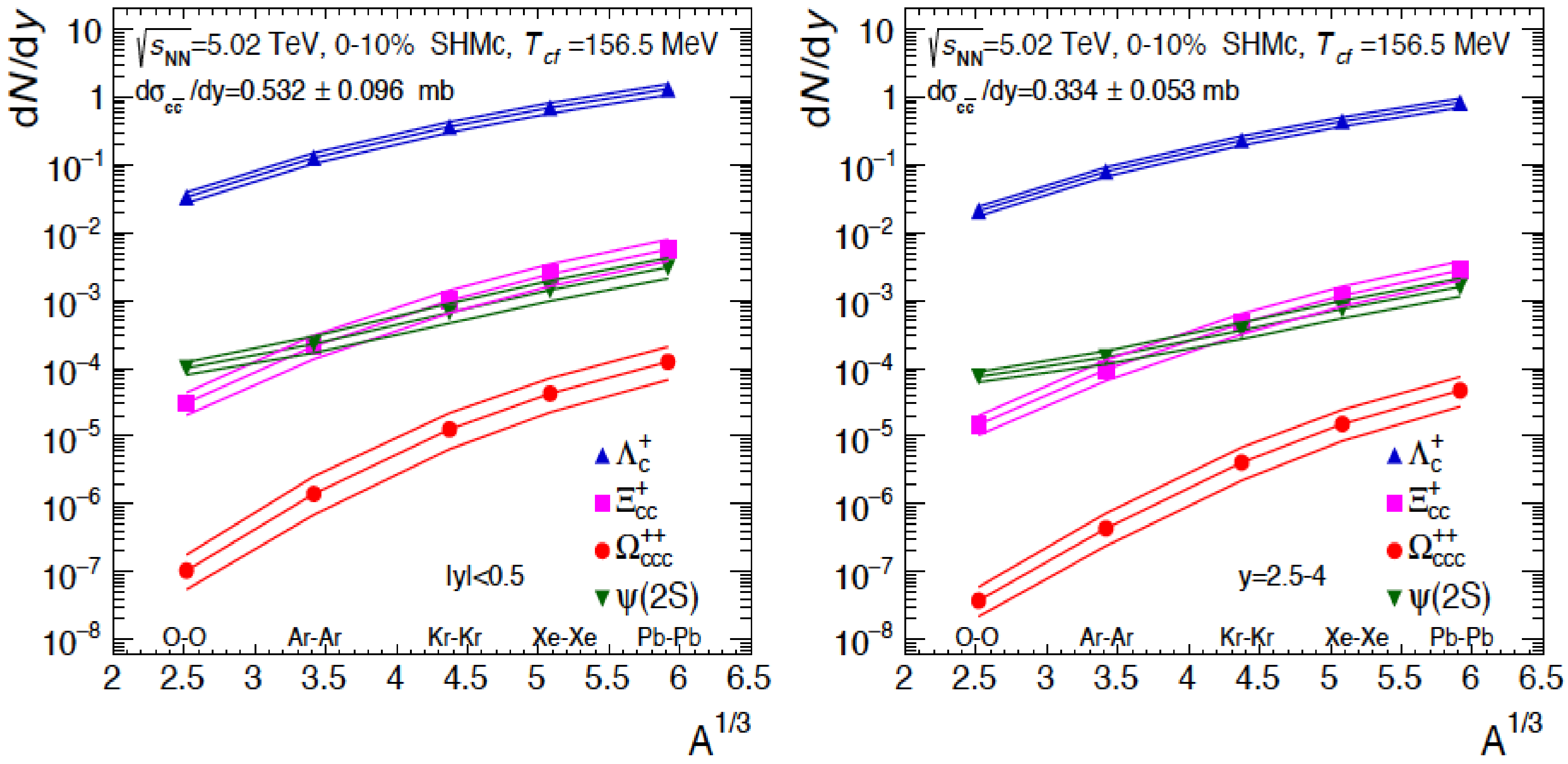
charm hadron yields with modified charm resonance spectrum

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



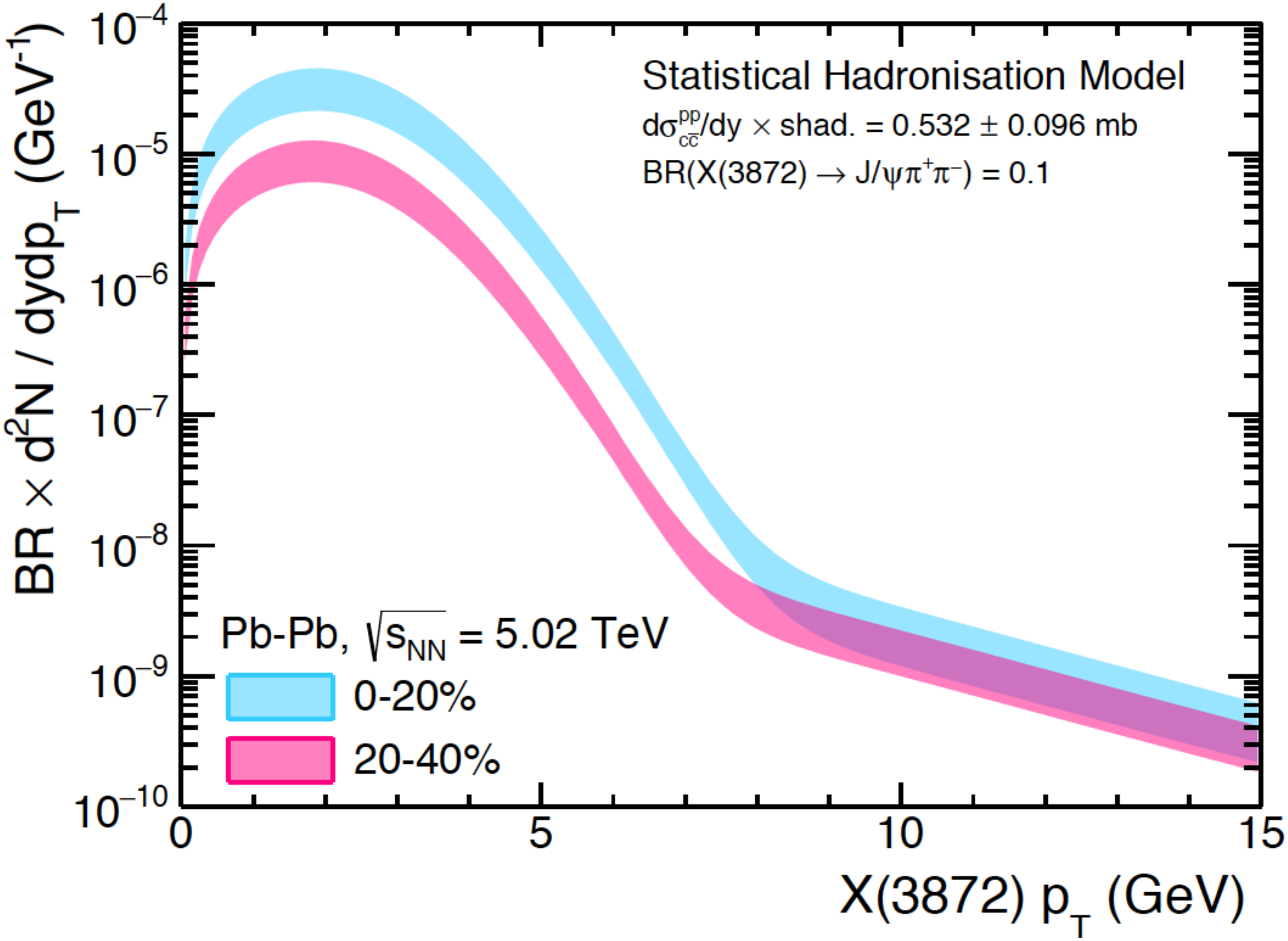
charm cross section increases 20%
yield of charm baryons nearly doubles
mesons practically unaffected

system size dependence of yields



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

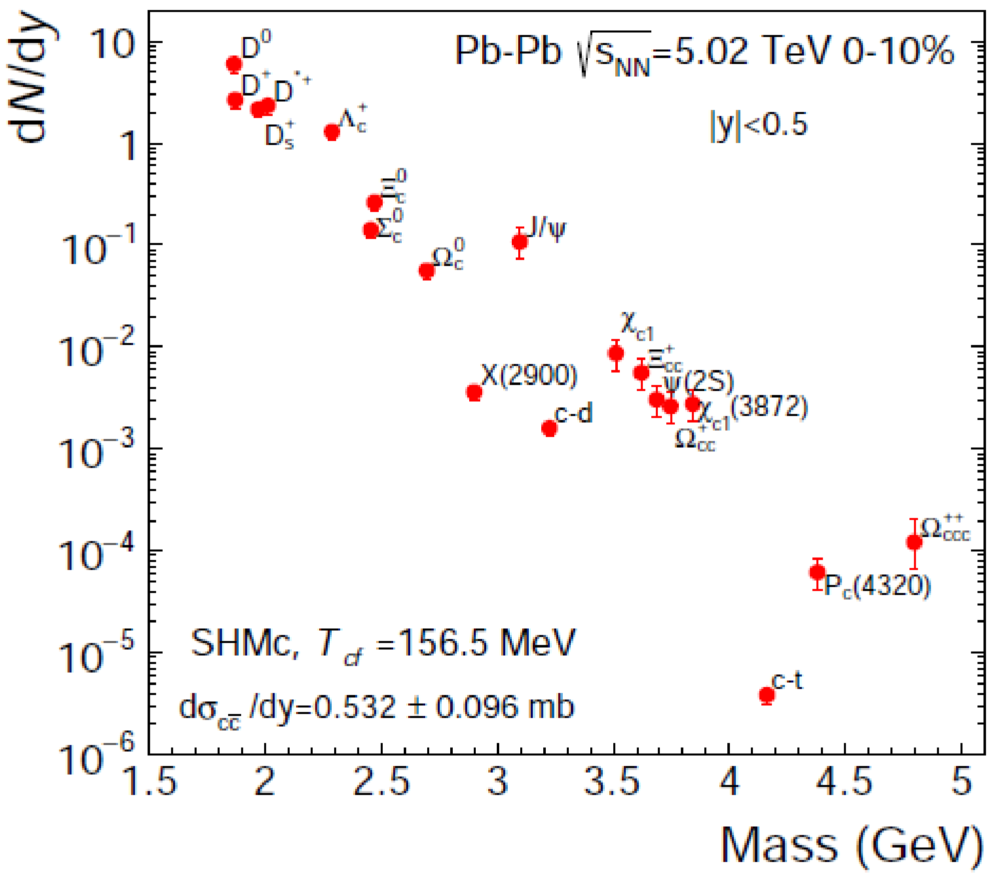
transverse momentum spectrum for $\chi_{c1}(3872)$ in the SHMc

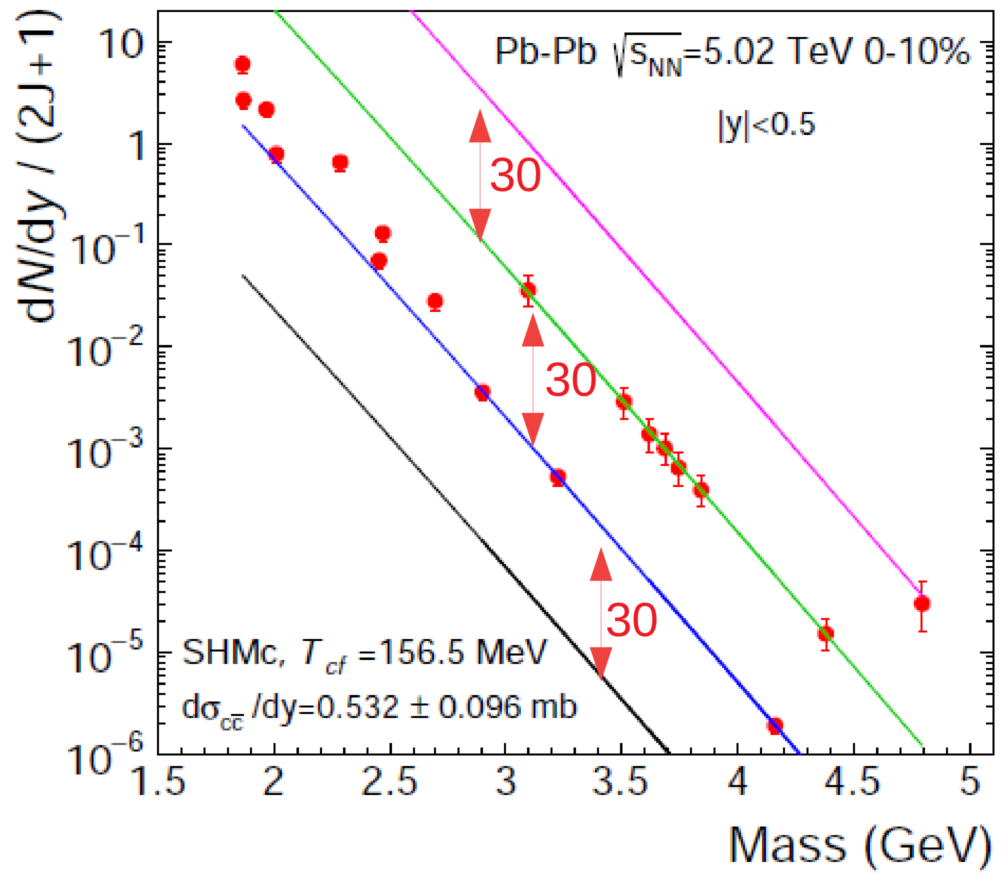


note: dramatic enhancement at low p_t predicted

the multi-charm hierarchy

open and hidden charm hadrons, including exotic objects, such as X-states, c-deuteron, c-triton, 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

example: X(3872)

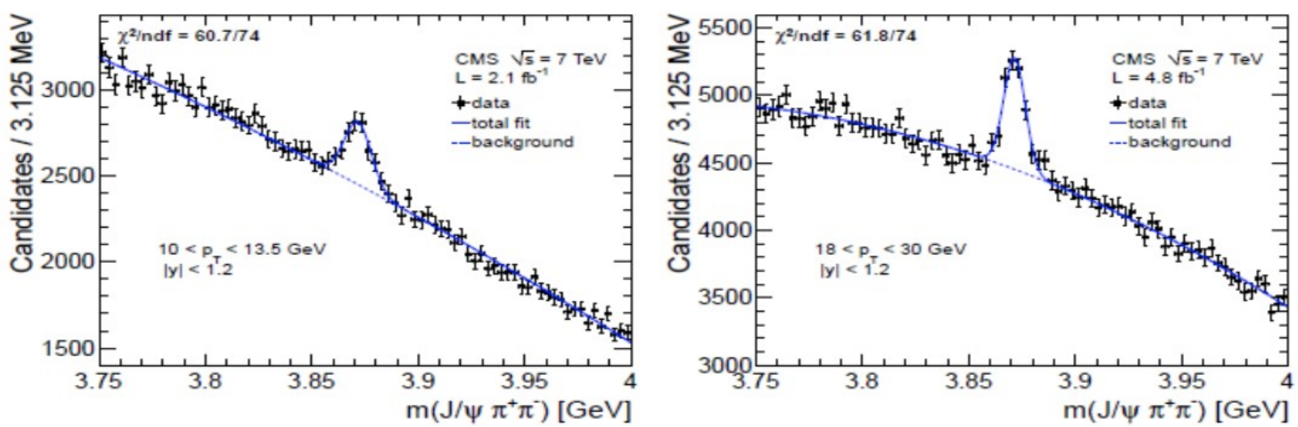
X(3872)

- 2003 -

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

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

- 2013 -



X(3872)

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

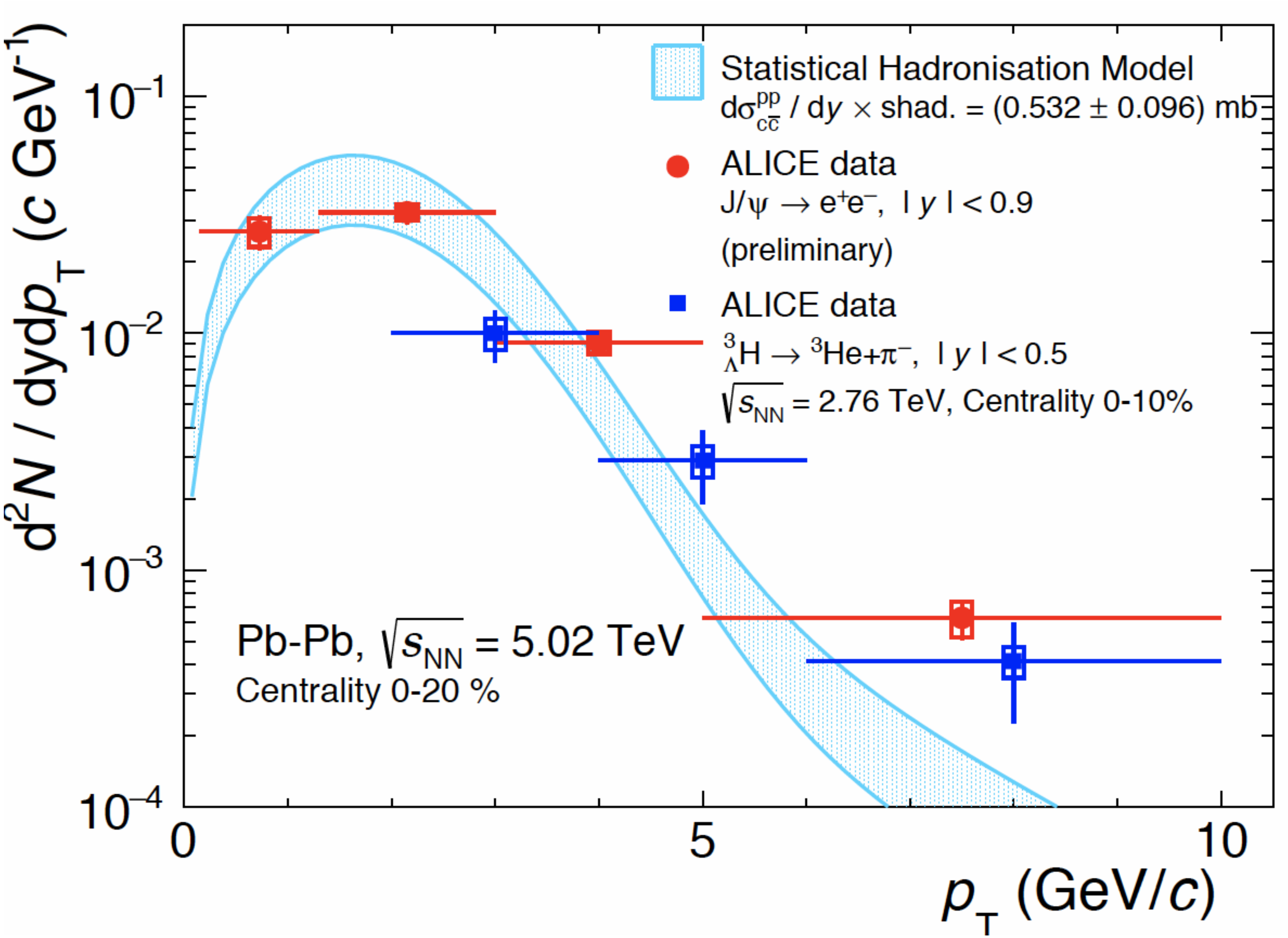
Mass $m = 3871.69 \pm 0.17$ MeV

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

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

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

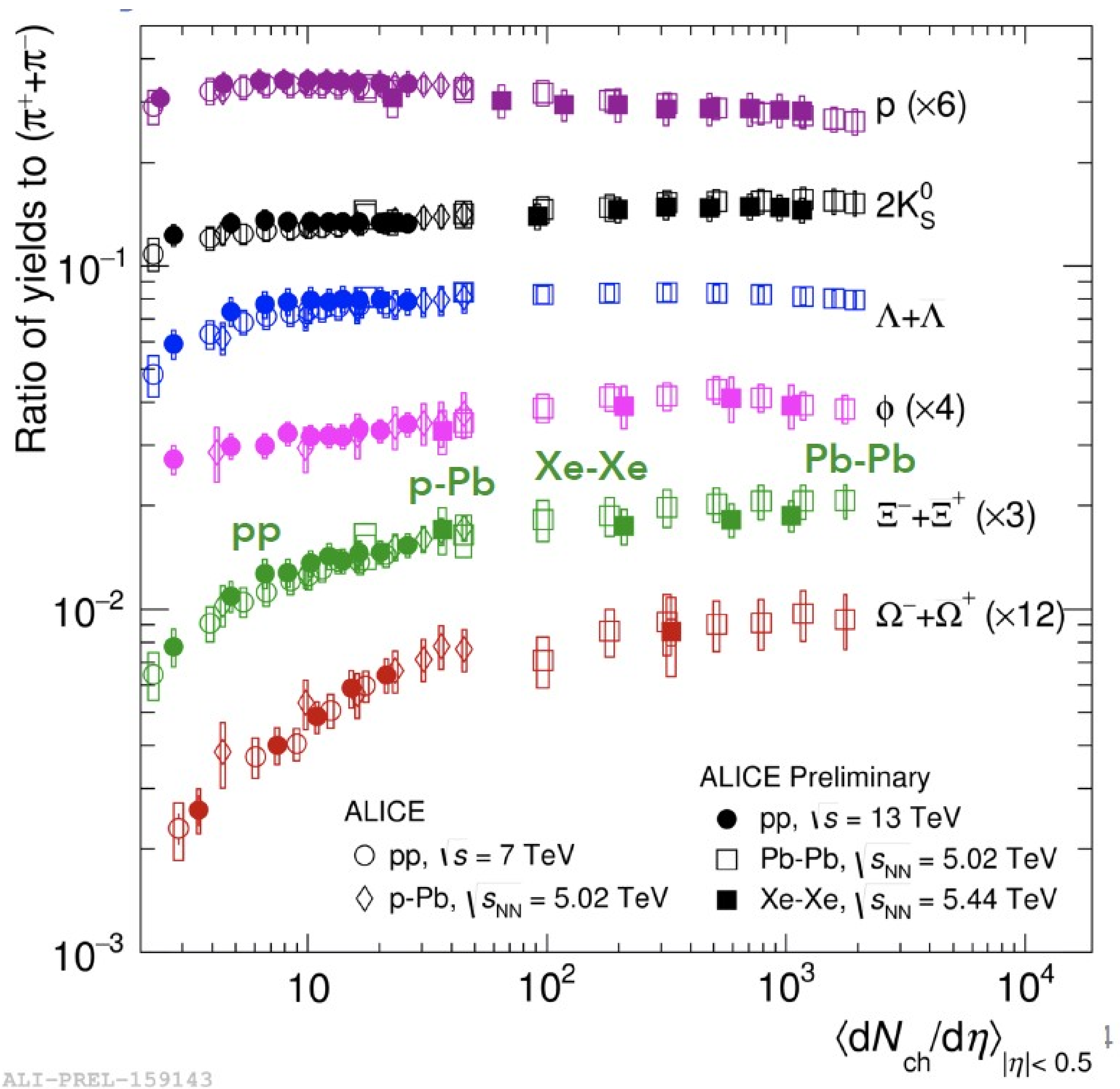
J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



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