SHMc - charm statistical hadronization

jointly with A. Andronic, P. Braun-Munzinger, K. Redlich and recently, in addition, H. Brunßen, J. Crkovska, M. Völkl

Johanna Stachel, Phys. Inst. Universität Heidelberg
GSI, April 8-12 2024

Formation and Hadronization of heavy quarks

formation of ccbar: in hard initial scattering on time scale $1/2m_c$
with m_c = 1.3 GeV $\rightarrow$ t_{ccbar} = 0.08 fm/c
- comparable or shorter than formation of a thermalized QGP
- significantly shorter than formation time of hadrons (1-several fm/c)

can consider deconfined quarm quarks as impurities inside the QGP
thermal production at LHC energy still negligible
annihilation of charm quarks in QGP negligible

there is strong experimental evidence that charm quarks thermalize inside the QGP
- supported by transport coefficients computed in lattice QCD

justifies application of statistical concept of hadronization of heavy quarks and in particular also to quarkonia

Relevant time scales

formation of ccbar: in hard initial scattering on time scale $1/2m_c$
with m_c = 1.3 GeV -> τ_{ccbar} = 0.08 fm/c

typical hadron formation time: τ_{hadron} order 1 fm/c
(Blaizot/Ollitrault 1989 Hüfner, Ivanov, Kopeliovich, and Tarasov 2000)
W. Brooks, QM09: description of recent JLAB and HERMES hadron production data in color dipole model - > time scale 5 fm/c

comparable to or longer than QGP formation time:
$\tau_{QGP} \cong$ 1 fm/c at SPS, < 0.5 fm/c at RHIC, $\cong$ 0.1 fm/c at LHC

at LHC even color octet state not formed before QGP (H.Satz 2006)

$$\tau_8 = 1/\sqrt{2\mathrm{m_c}\Lambda_{\mathrm{QCD}}} \approx 0.25\,\mathrm{fm}$$

collision time: $\mathrm{t_{coll}} = 2\mathrm{R}/\gamma_{\mathrm{cm}}$ at RHIC 0.1 fm/c, at LHC < 5 10^{-3} fm/c

Time scales continued

hard	0.05 fm	pre–resonance	0.25 fm	resonance
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$	

ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS $t_{coll} = \tau_{ccbar} \cong \tau_{QGP} \cong \tau_{hadron}$

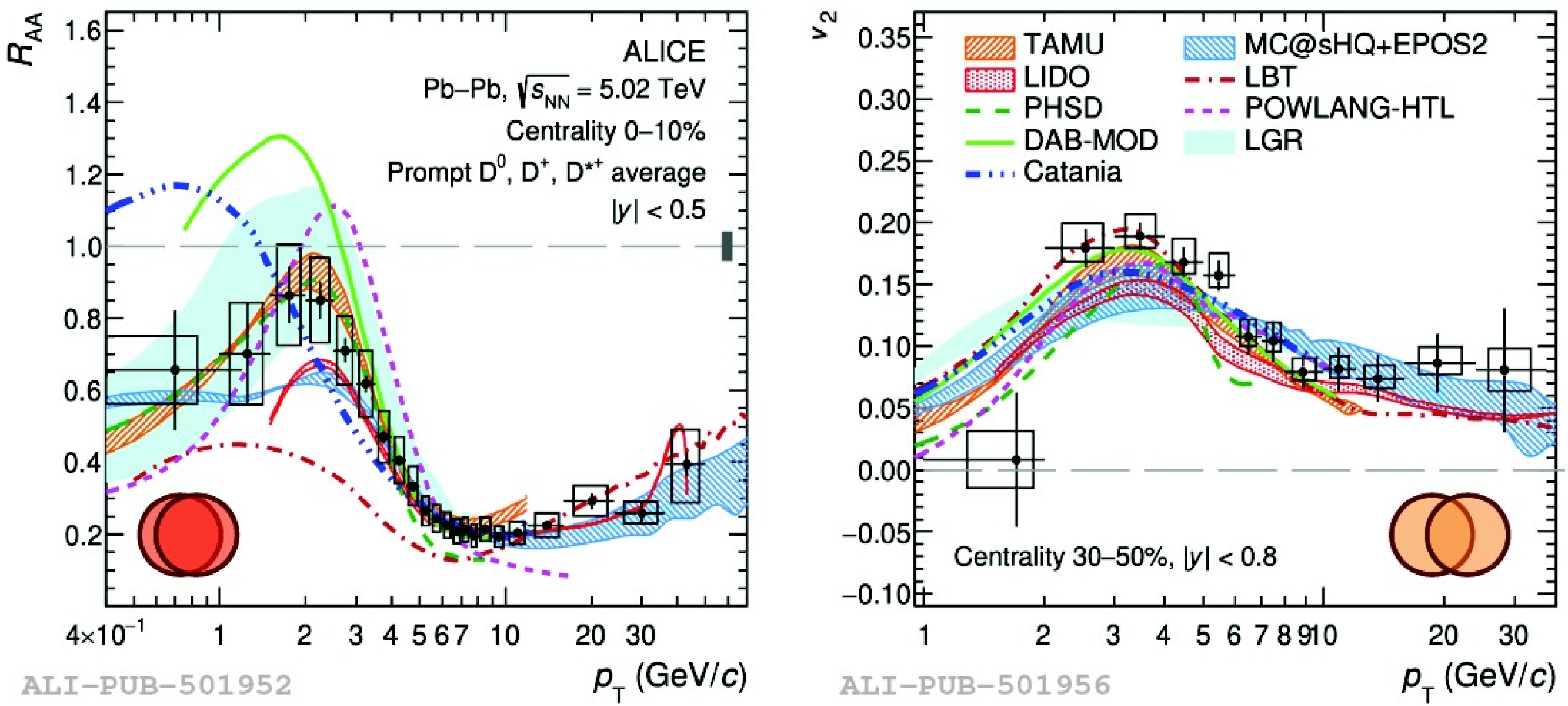
but at RHIC and much more pronounced at LHC there is the following hierarchy: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

Charm quark thermalization

LHC data: strong charmed hadron elliptic flow and energy loss (R_{AA}) point to large degree of charm quark thermalization in QGP
modeling in terms of heavy quark diffusion in hot and dense medium leads to spatial diffusion coefficients $1.5 < 2\pi TD < 4.5$ at T_c $\rightarrow$ τ_{kin} = 2.5 – 7.6 fm/c

JHEP01 (2022) 174 arXiv:2110.09420



Charm quark thermalization

LHC data: strong charmed hadron elliptic flow and energy loss (R_{AA}) point to large degree of charm quark thermalization in QGP

modeling in terms of heavy quark diffusion in hot and dense medium leads to spatial diffusion coefficients: $1.5 < 2\pi TD < 4.5$ at T_c $\rightarrow$ τ_{kin} = 2.5 – 7.6 fm/c

lQCD:

D from gradient flow on color-electric two-point function

(leading order in 1/M expansion)

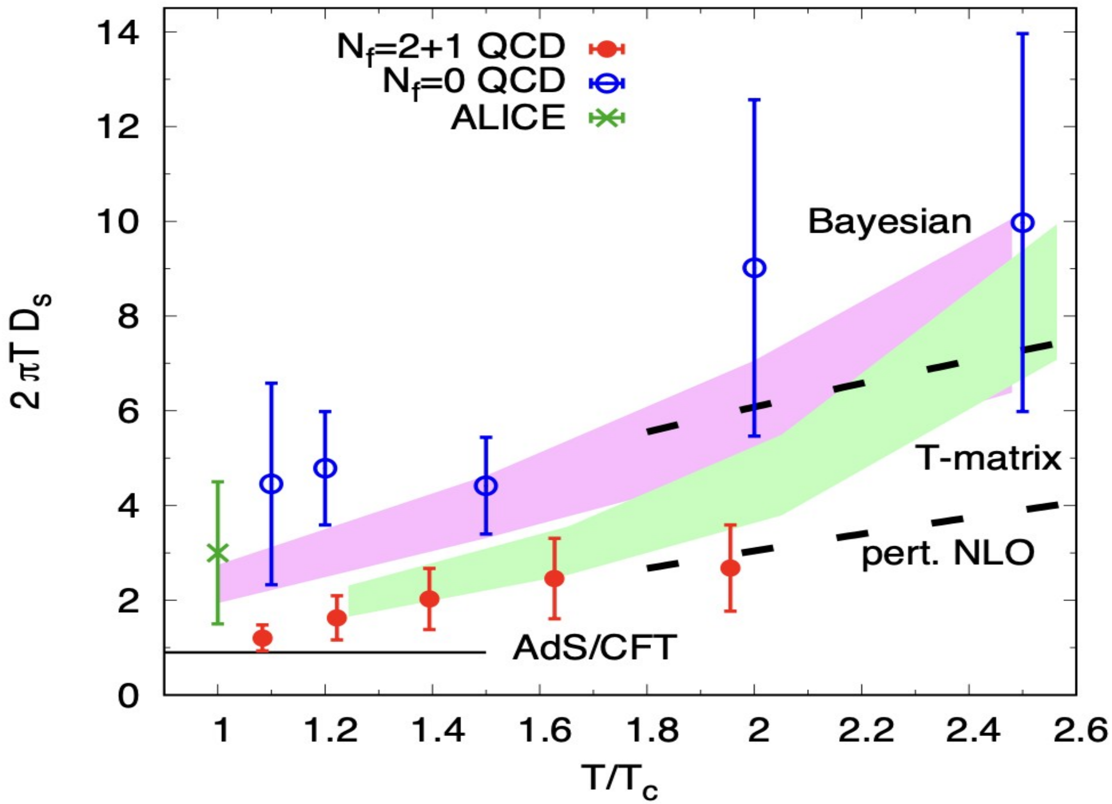
$$2\pi TD = \frac{4\pi}{\kappa/T^3} \propto \tau_{\rm kin}\frac{T^2}{M}$$

first results in full QCD

for charm τ_{kin} = 1 – 2 fm/c

consistent picture:
thermalization in QGP

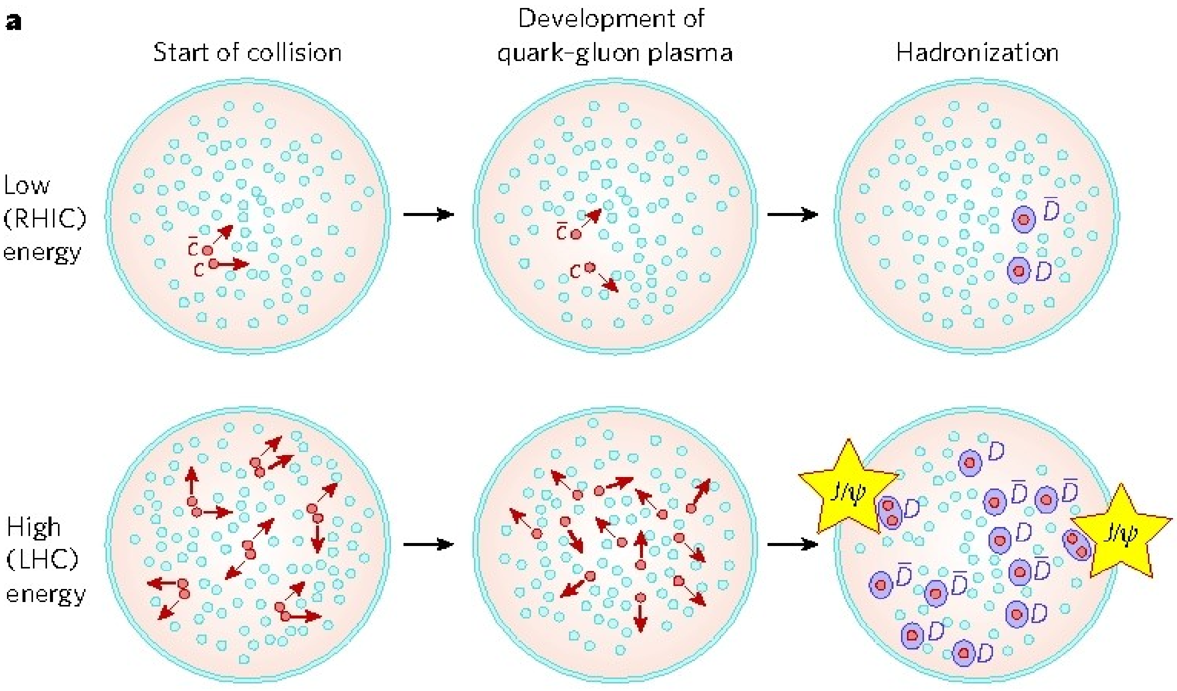
L. Altenkort et al. arXiv: 2302.08501



Hadronization of charm quarks

all charm quarks have to appear in charmed hadrons
at hadronization of QGP also J/ψ can form from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^2$
(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)
also applies to b-quarks and bottomonia
(A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel NPA 789 (2007) 334)

expect J/ψ **suppression** at low beam energies (SPS, RHIC) and J/ψ **enhancement** at high energies (LHC)



Statistical hadronization model for charm (SHMc) including canonical thermodynamics

- the charm balance equation determines the fugacity g_c

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}} + g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}} + \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}$$

obtained from measured open charm cross section

$n_{i,j,k}^{th}$: # of thermal charm hadrons

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

$$N_{c\bar{c}} = \sum_{\alpha=1,2} N_{oc,\alpha} \frac{I_\alpha(N_c^{\mathrm{tot}})}{I_0(N_c^{\mathrm{tot}})} + N_{hc}$$

defining:

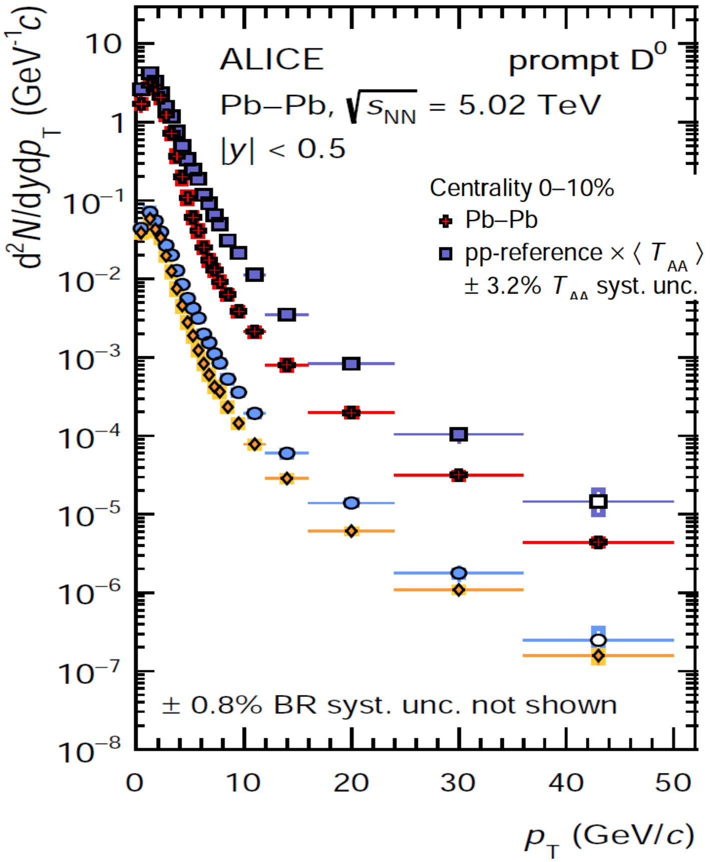
$$N_{oc,1} = \frac{1}{2} g_c V \sum_{h^i_{oc,1}} n_i^{\mathrm{th}}$$

$$N_{oc,2} = \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\mathrm{th}}$$

$$N_{hc} = g_c^2 V \sum_{h^j_{hc}} n_j^{\mathrm{th}}$$

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

$$dN_{ccbar}/dy = 13.7 \pm 2.1$$

corresponding 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

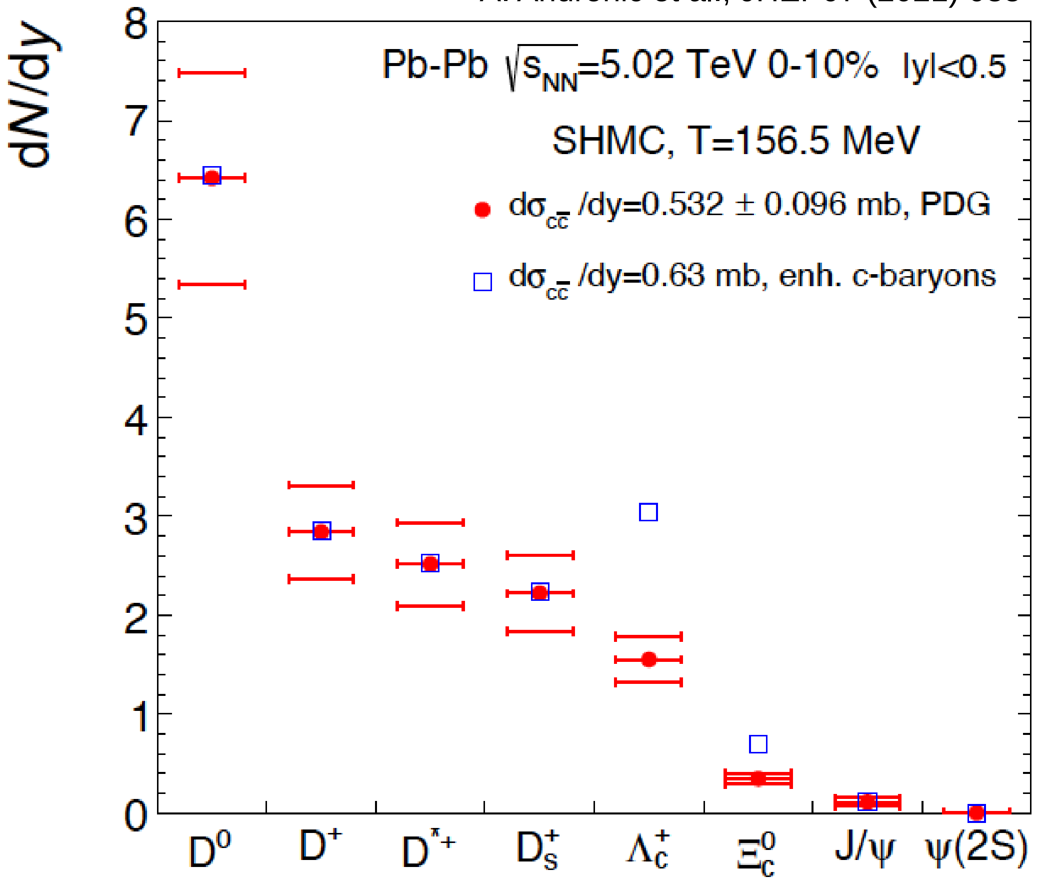
uncertainty reduced by 15%

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

Charm hadron yields with modified charm resonance spectrum

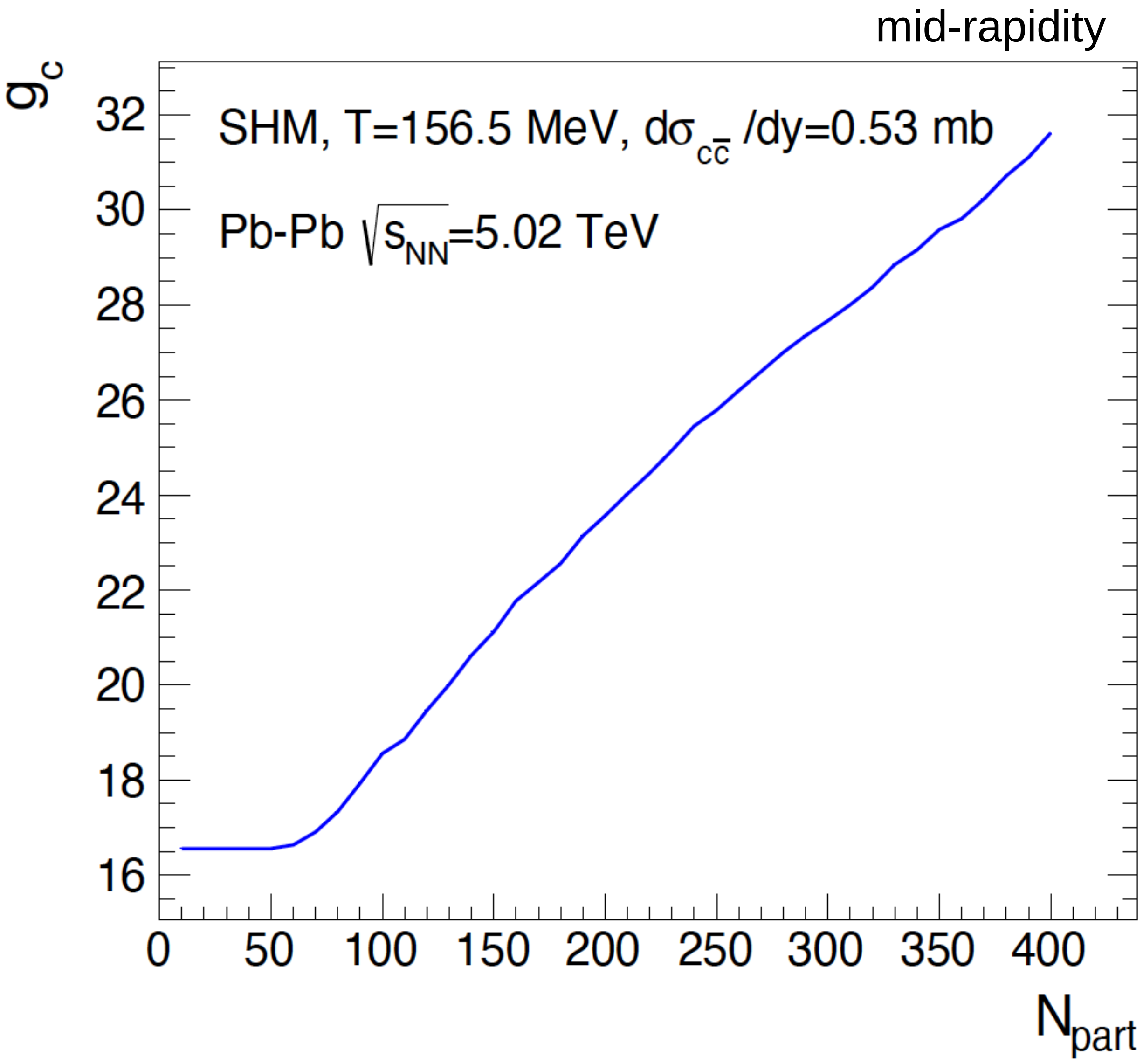
recently a lot of speculation about possibly incomplete charm baryon spectrum
to test impact, tripled statistical weights of excited charm baryons

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



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

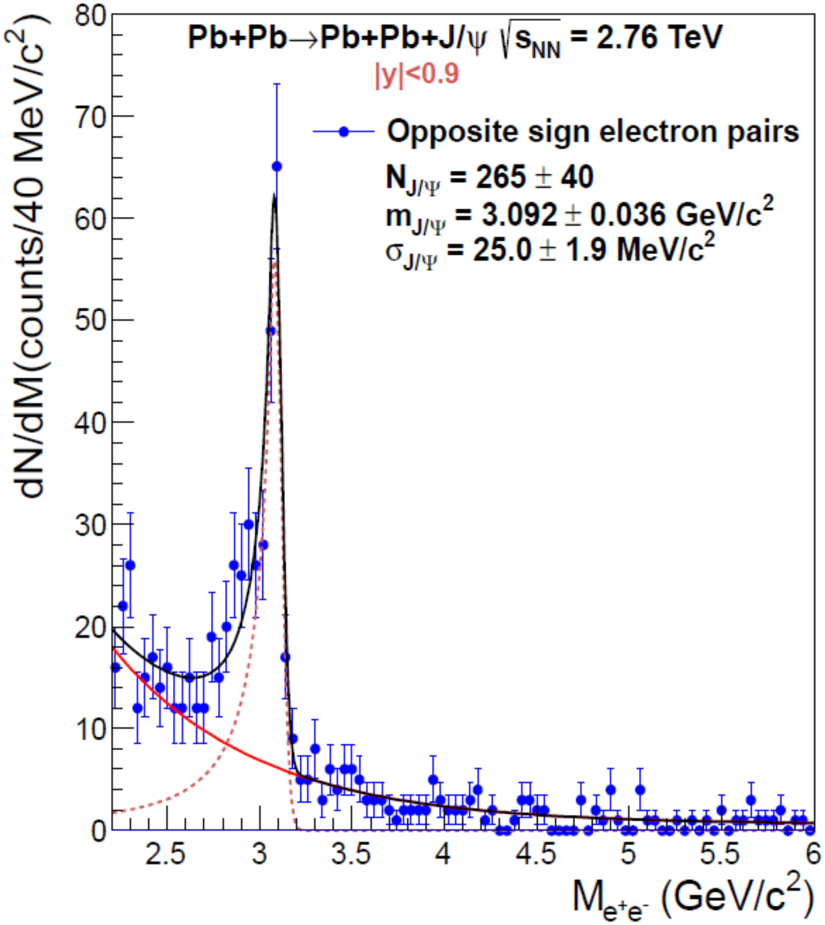
Centrality dependence of charm fugacity g_c at LHC energy



Reconstruction of J/ψ in PbPb collisions at LHC

$J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$ with 6%

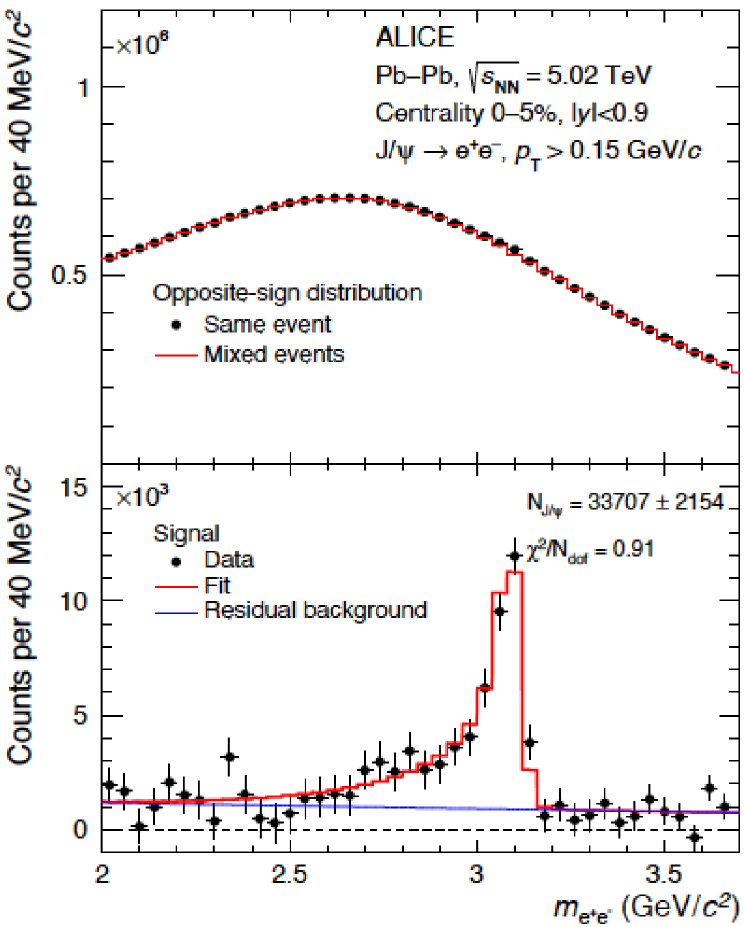
ALICE EPJ C73 arXiv:1305.1467



photoproduction in ultra-peripheral PbPb collisions – excellent signal to background
very good understanding of line shape

most challenging: central PbPb collisions
in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

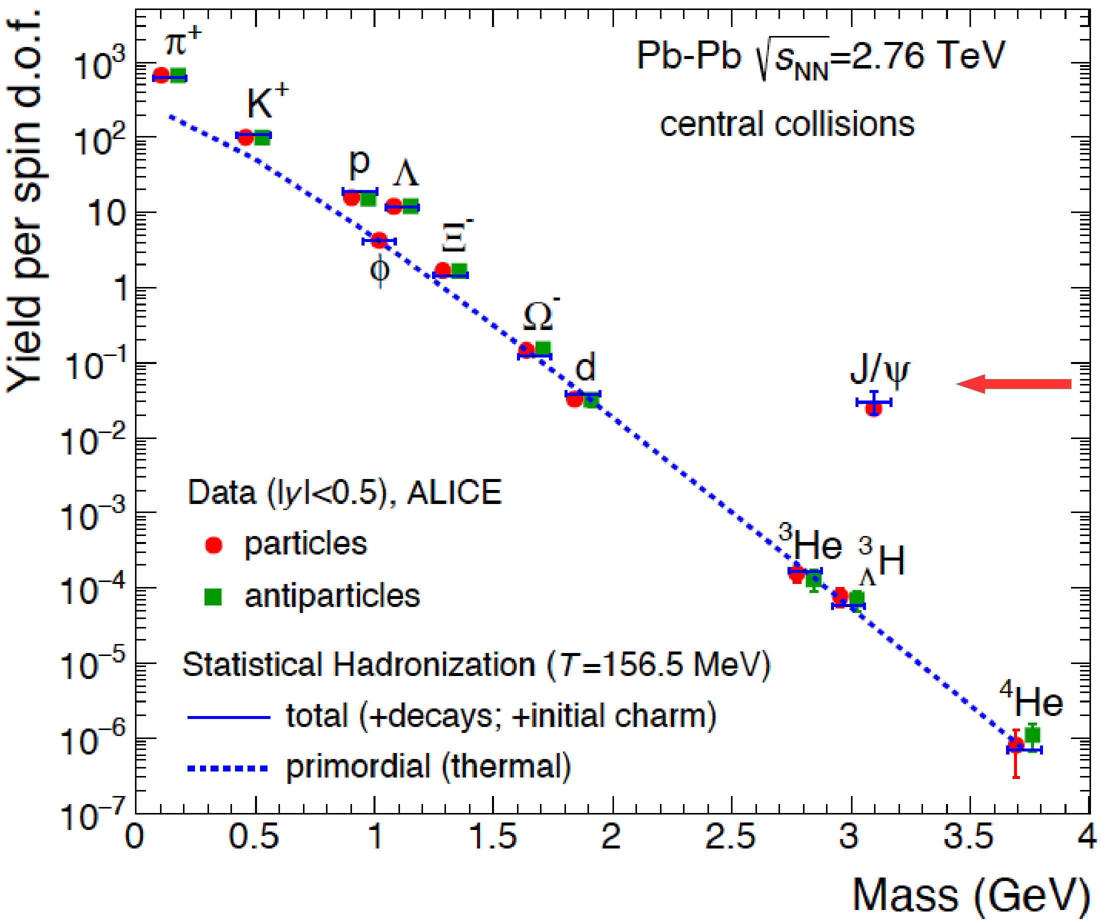
mid |y| < 0.8



arXiv:2303.13361

Systematics of hadron production in SHMc

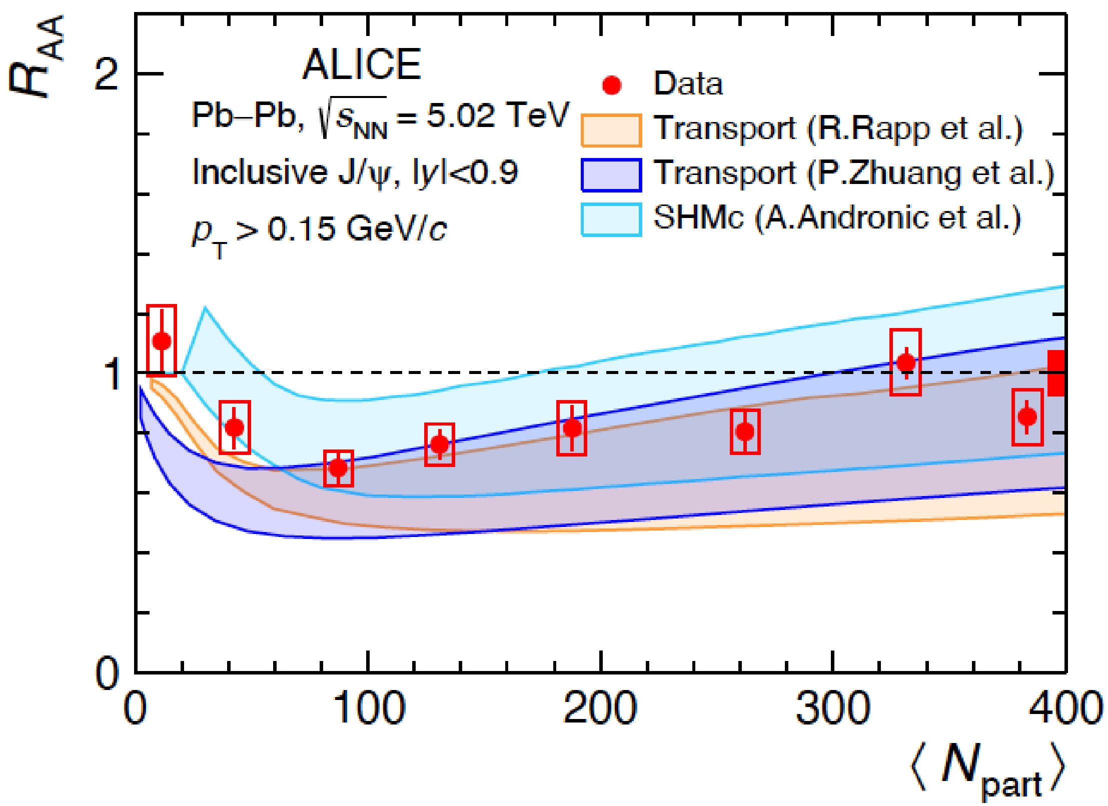
A.Andronic et al., PLB 797 (2019) 134836

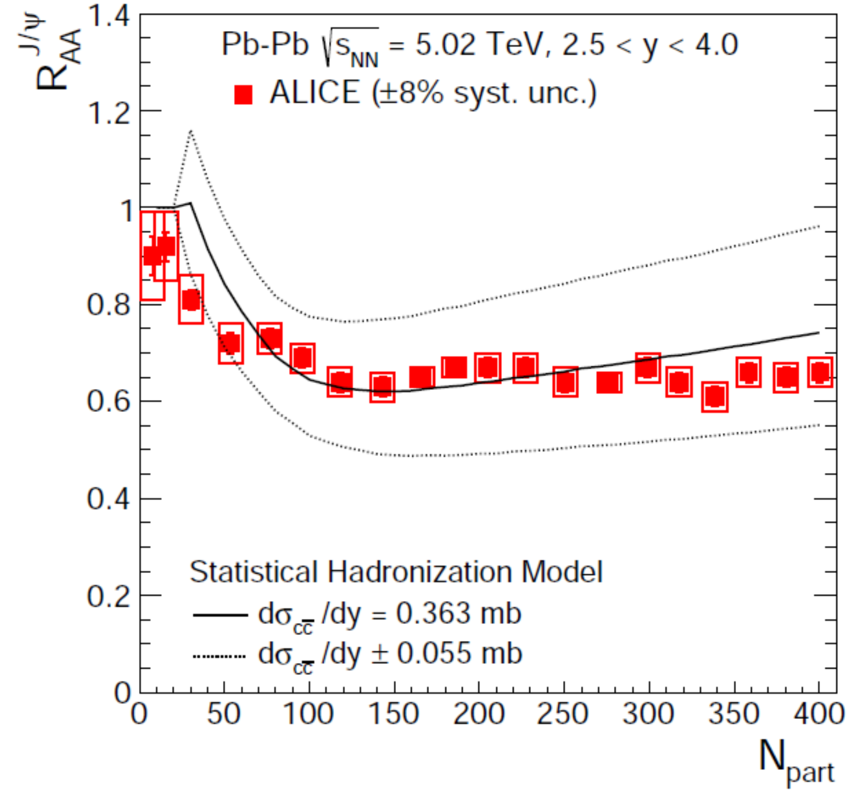


enhancement factor is 900 for J/ψ

J/ψ and statistical hadronization

arXiv: 2303.13361



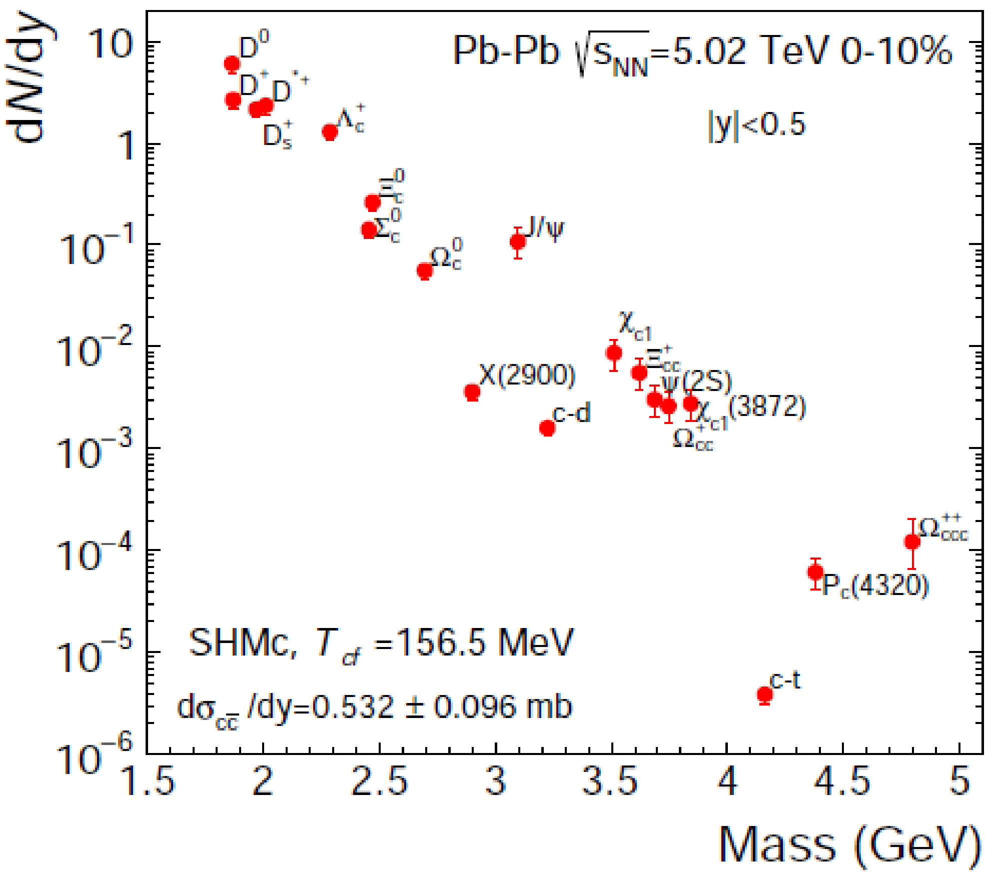


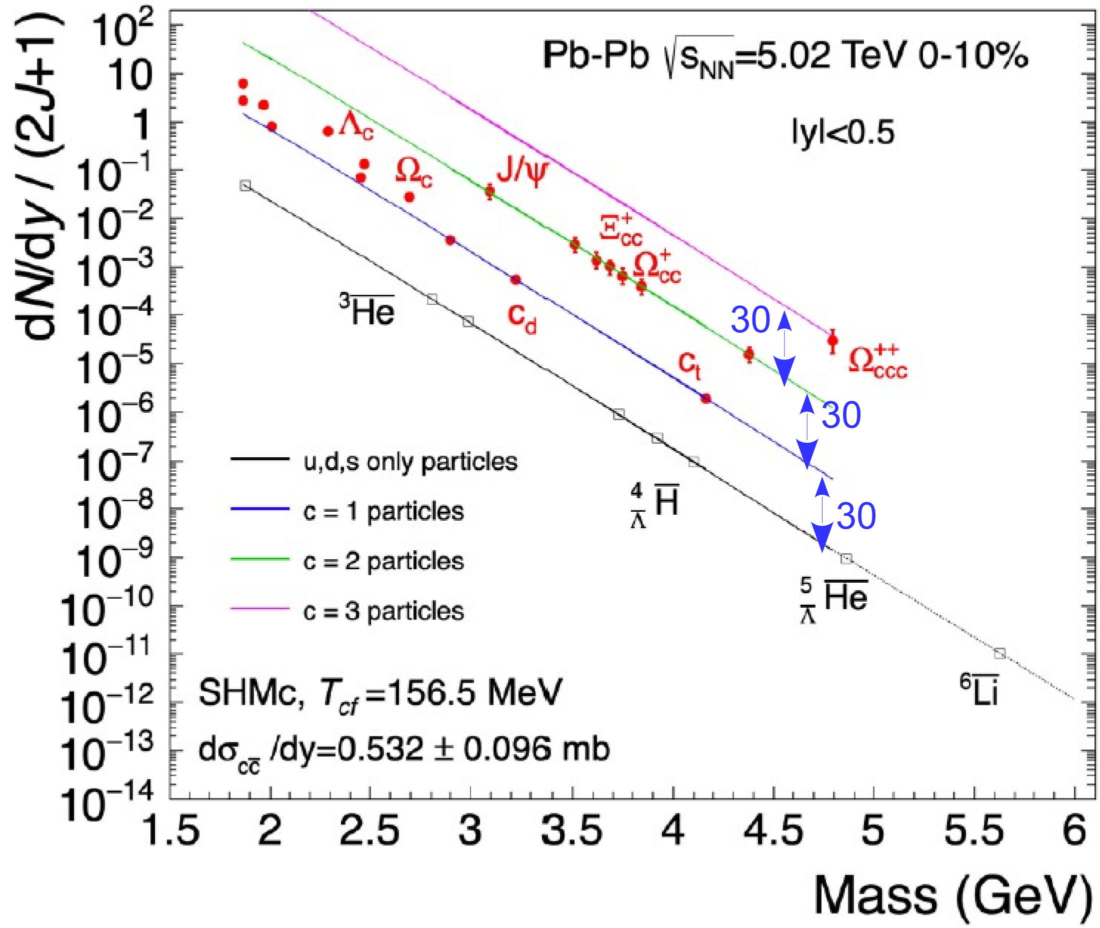
production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

the multi-charm hierarchy

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

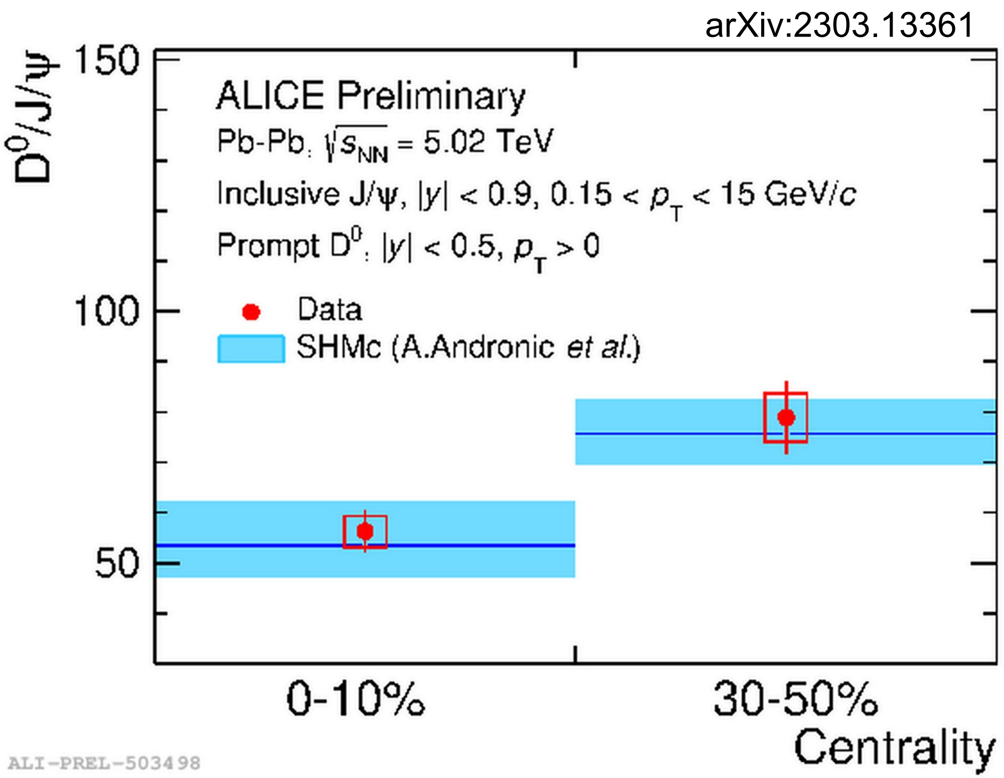
A. Andronic et al.. JHEP07 (2021) 035





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

Unique prediction of SHMc – open charm/charmonium



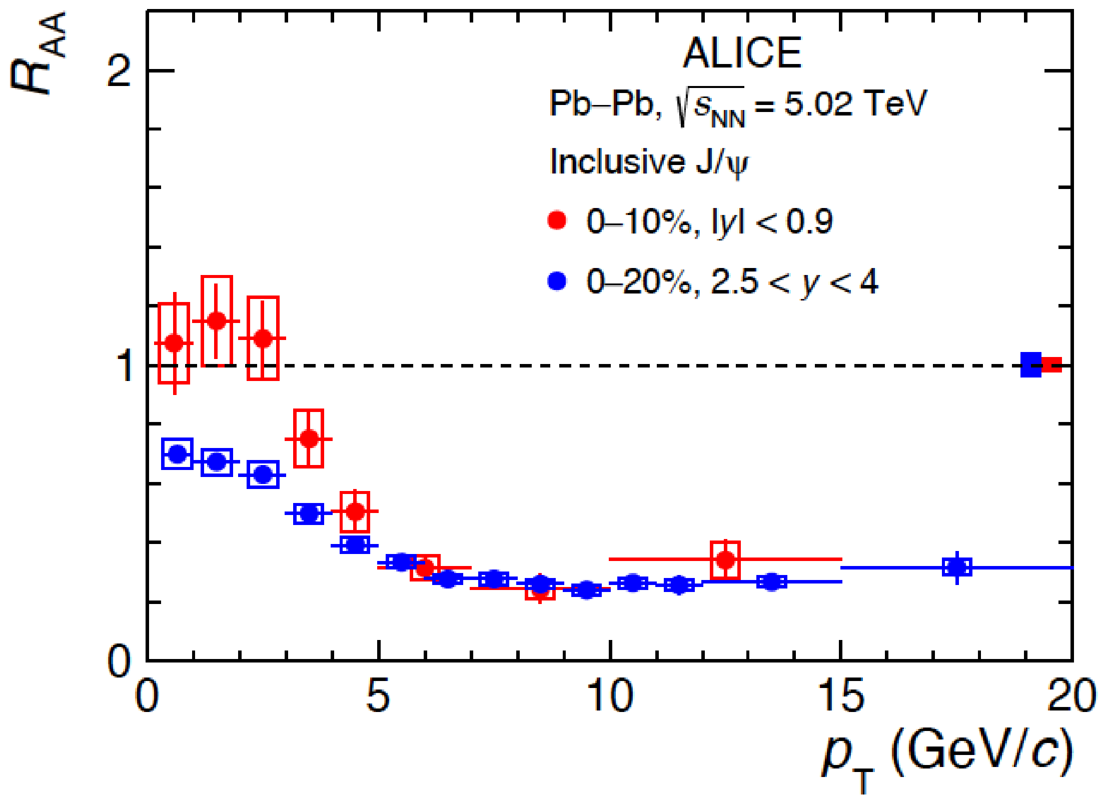
for the first time ratio of fully p_t integrated D^0 to J/ψ available from ALICE

D^0: cubar, m = 1.9 GeV, J=0
J/ψ: ccbar, m = 3.1 GeV, J = 1
in SHMc yield ratio governed by masses, degeneracy, strong feeding, and g_c

→ J/ψ relative to D^0 falls into place naturally

Beyond yields: transverse momentum distributions

arXiv:2303.13361

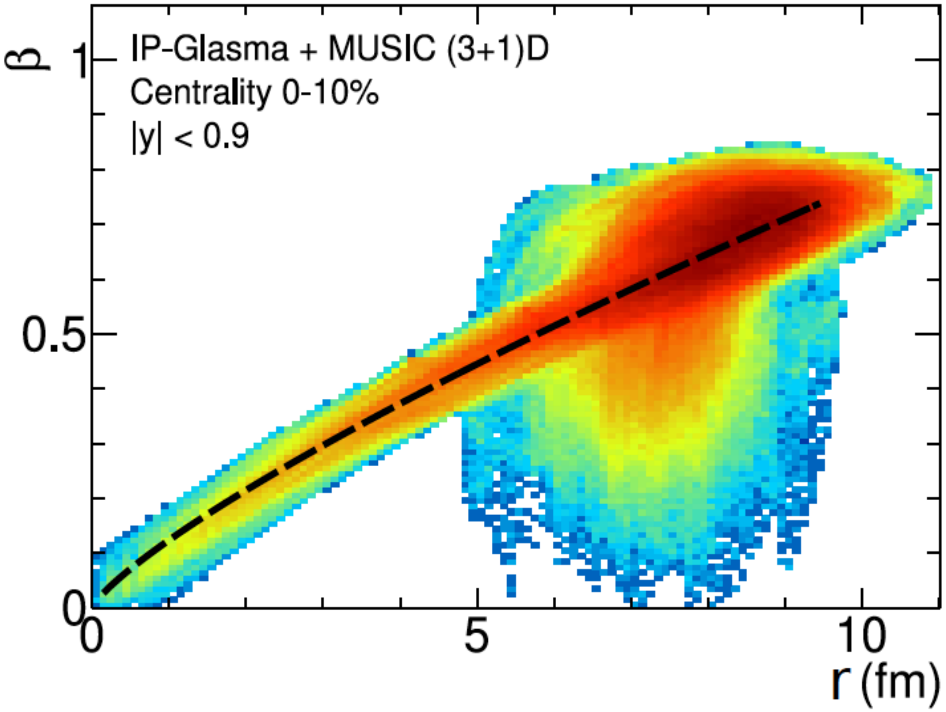


enhancement strongly rising towards lower p_t
for mid-rapidity even beyond pp
(not even considering shadowing)

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:1901.09200



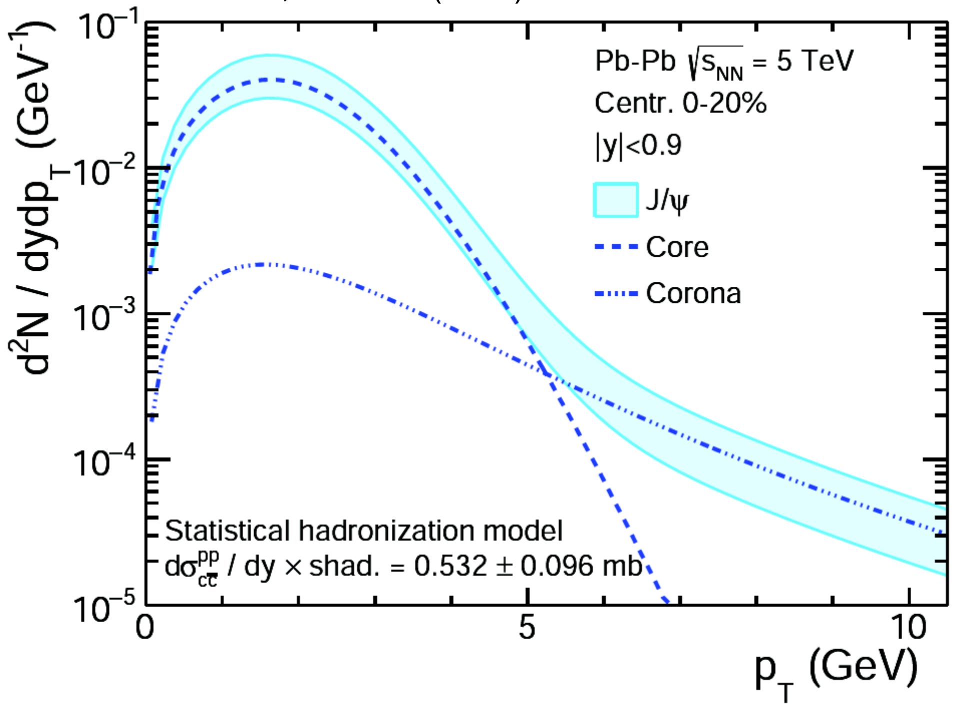
$$\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y} \propto \int_0^R r\mathrm{d}r \Big\{ m_\mathrm{T}\cosh\rho\, K_1\left(\frac{m_\mathrm{T}\cosh\rho}{T}\right) I_0\left(\frac{p_\mathrm{T}\sinh\rho}{T}\right) - p_\mathrm{T}\sinh\rho\, K_0\left(\frac{m_\mathrm{T}\cosh\rho}{T}\right) I_1\left(\frac{p_\mathrm{T}\sinh\rho}{T}\right)\Big\}$$

$$\rho = \mathrm{atanh}(\beta_\mathrm{T}^\mathrm{s}(r/R)^n)$$

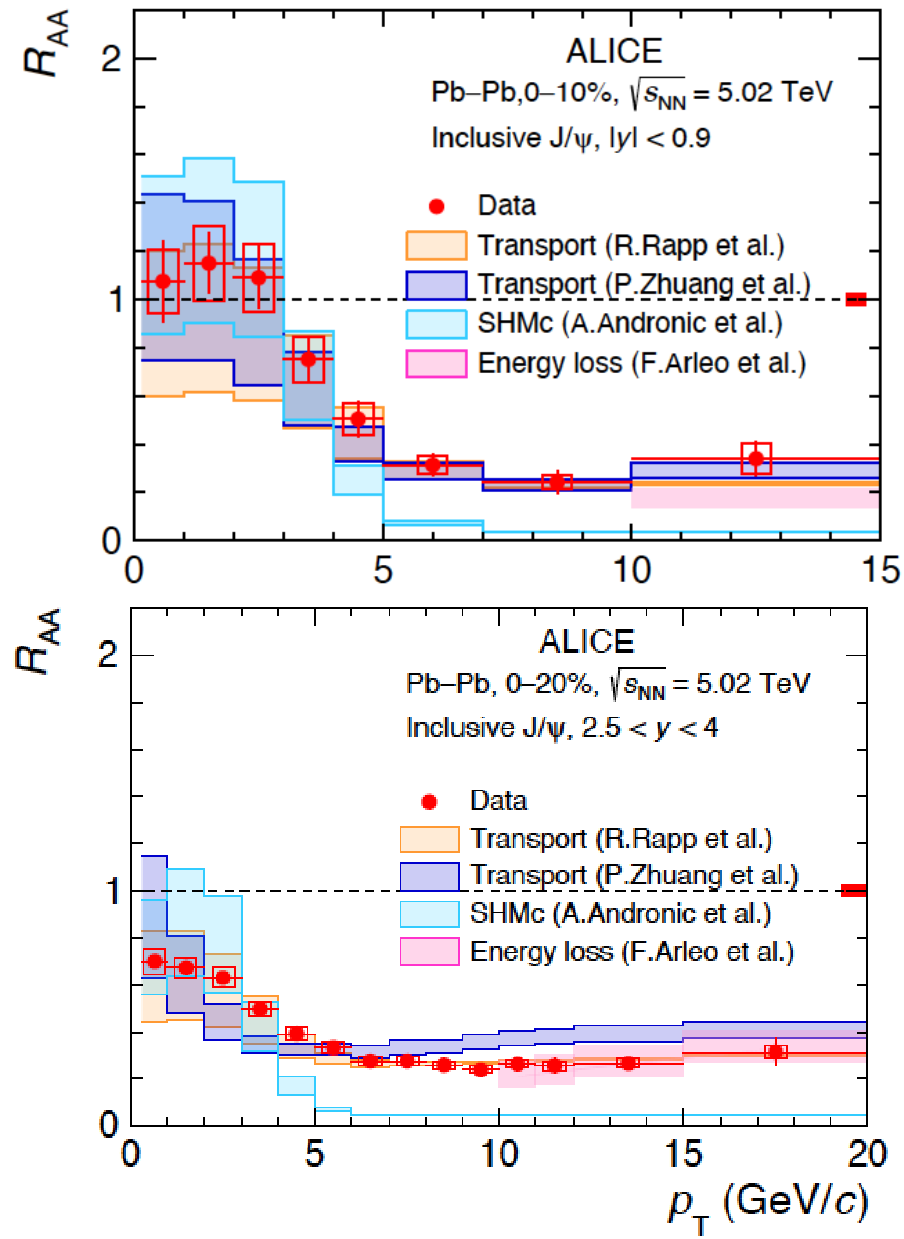
'blast wave parametrization' of spectral shape with T = 156.5 MeV and parameters from MUSIC: n = 0.85 and $\beta_{max} = \beta^s{}_T = 0.62$

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:1901.09200



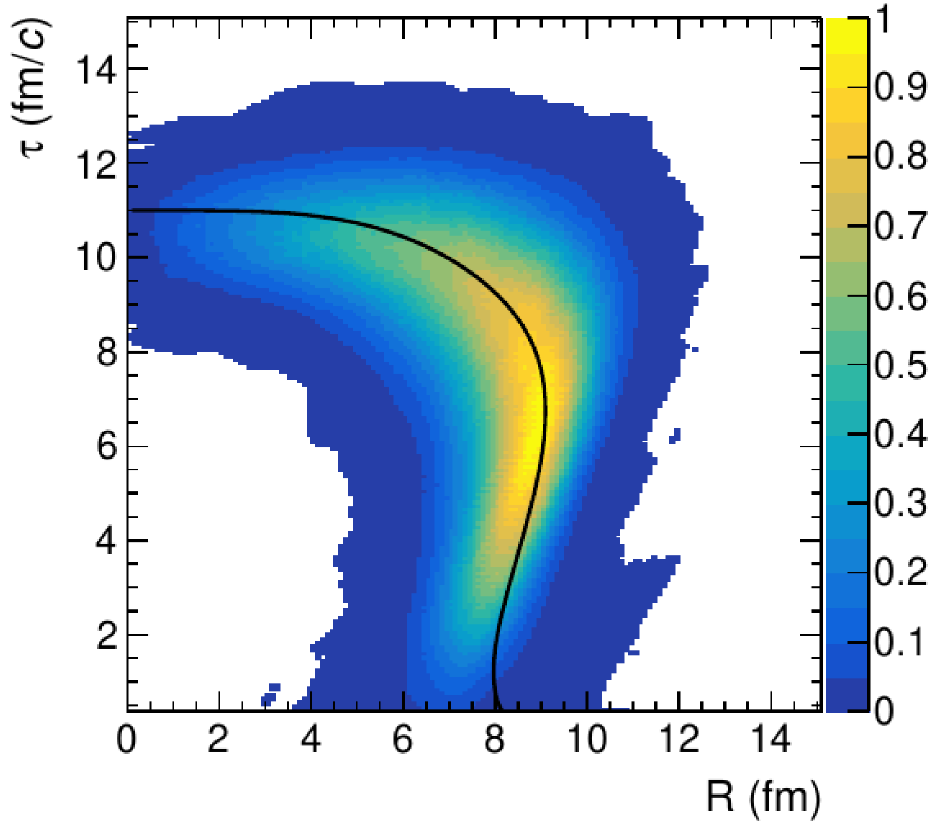
arXiv:2303.13361



- at low and intermediate p_t very good description of data
- beyond 5 GeV there is additional source beyond statistical hadronization e.g. nonthermalized component

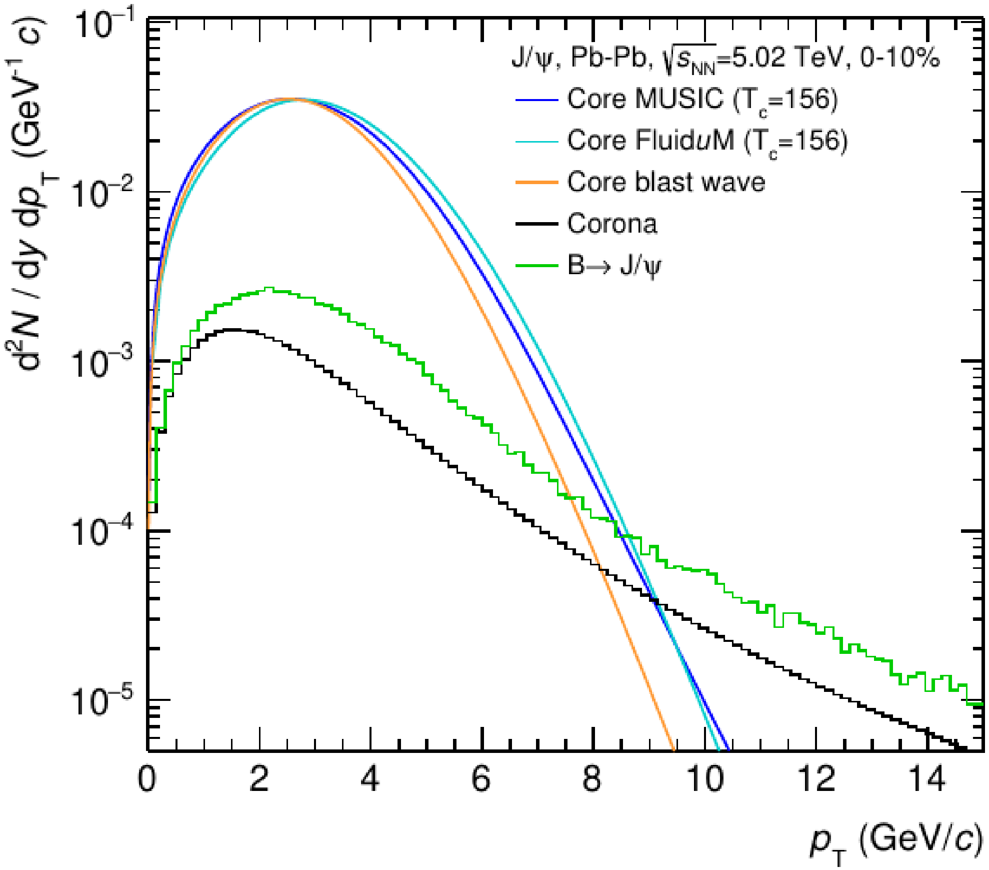
new approach to spectra and v_2: use Cooper-Frye freeze-out of hydrodynamics codes directly

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



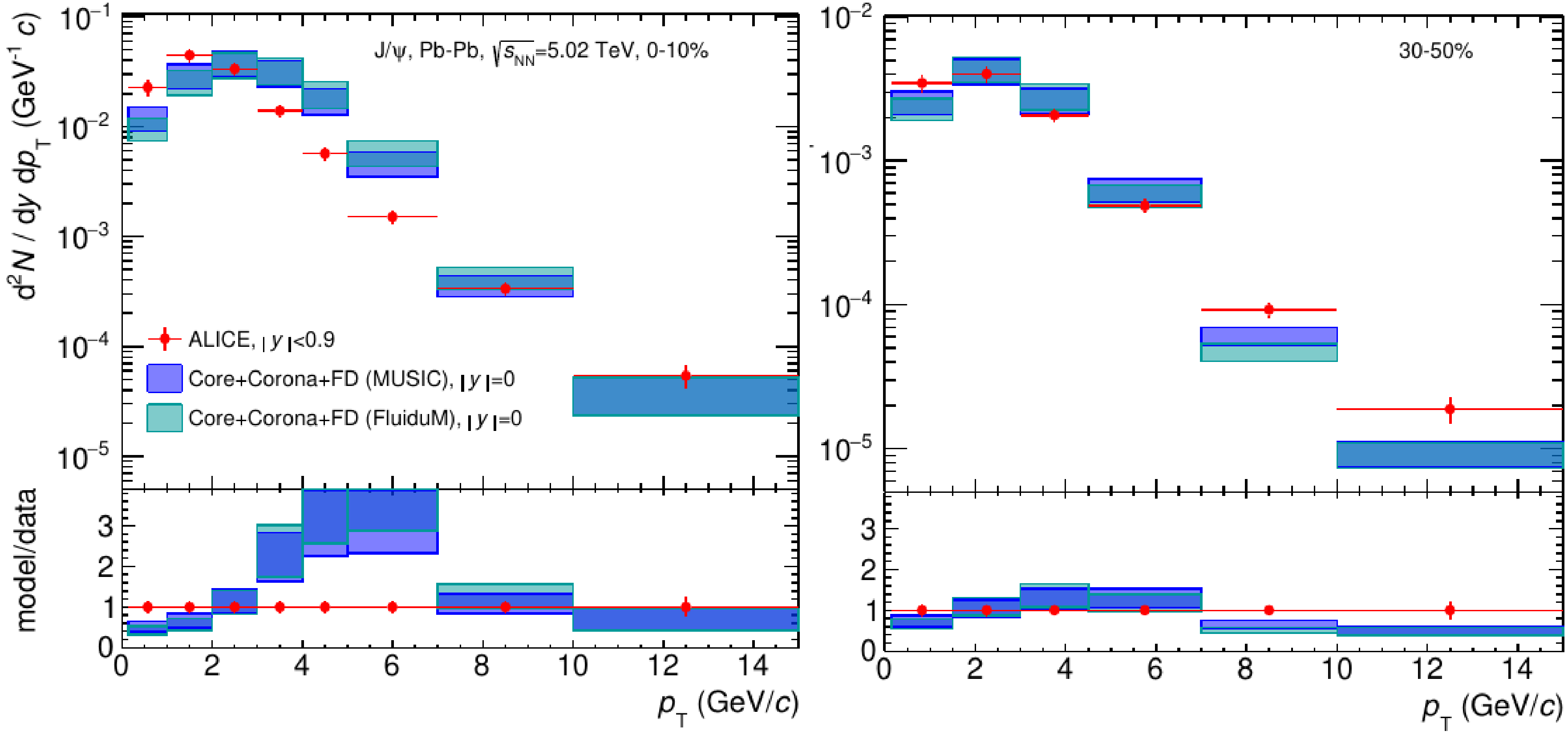
freeze-out hyper surface elements
at T=156.5 MeV from MUSIC
solid line: FluiduM

resulting J/ψ spectra including corona contribution and feed-down from B



J/ψ spectra new approach

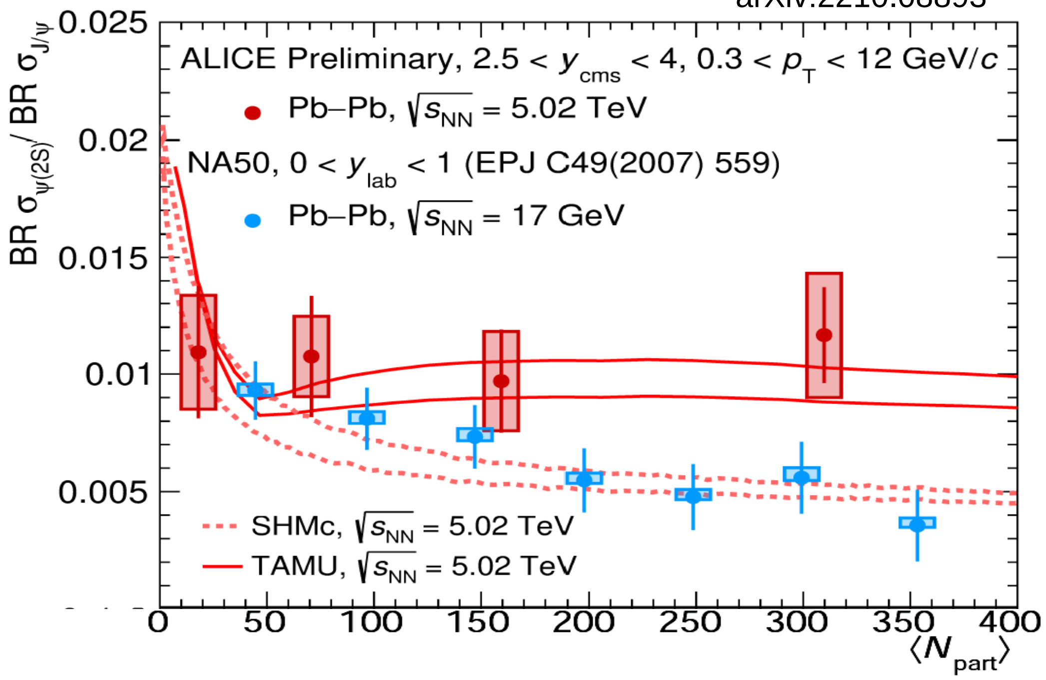
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



- spectra harder by about 1 GeV, in hydro many fluid cells at large velocities not accounted for by simple blast wave parametrization
- for central collisions somewhat too much flow – are charm quarks reaching the very outer front of the expanding fireball?

What about ψ(2S)?

arXiv:2210.08893



inclusive ψ(2S)
- first measurement in PbPb down to p_t=0
- factor 2 suppressed relative to J/ψ

in SHMc excited state population suppressed by Boltzmann factor
- data 1.8 σ above SHMc for most central bin

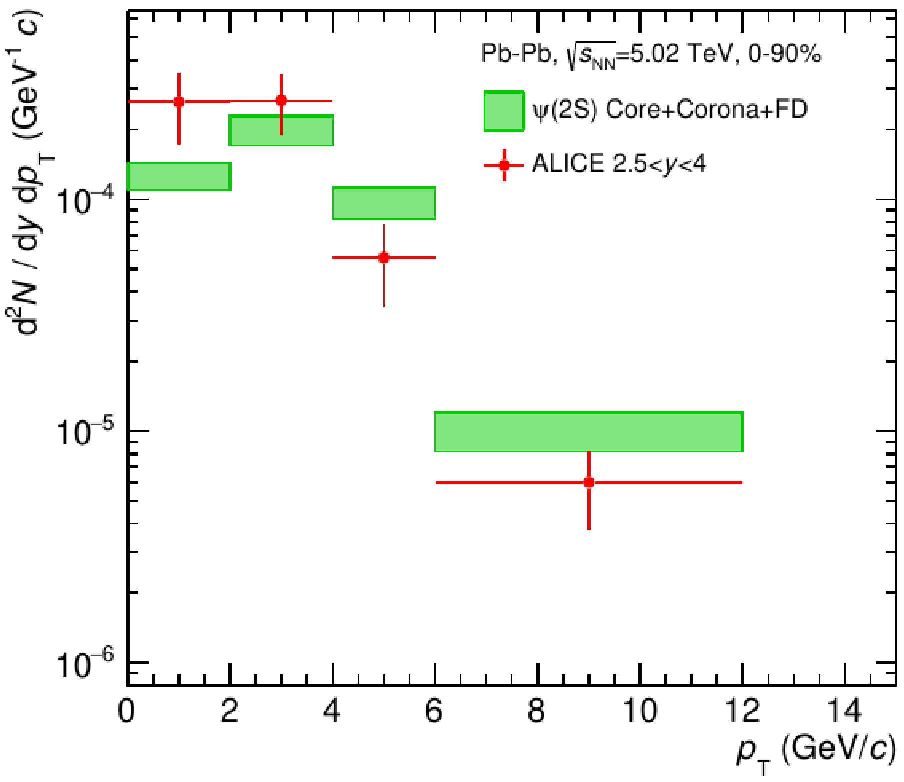
within stat. hadronization approach, an unexpected result
→ little room to accommodate in a likely physical scenario
but: feeding from b is not subtracted in data, expected to be substantial!

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

} deconfinement temperature from charmonium spectrum

ψ(2S) spectrum

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821

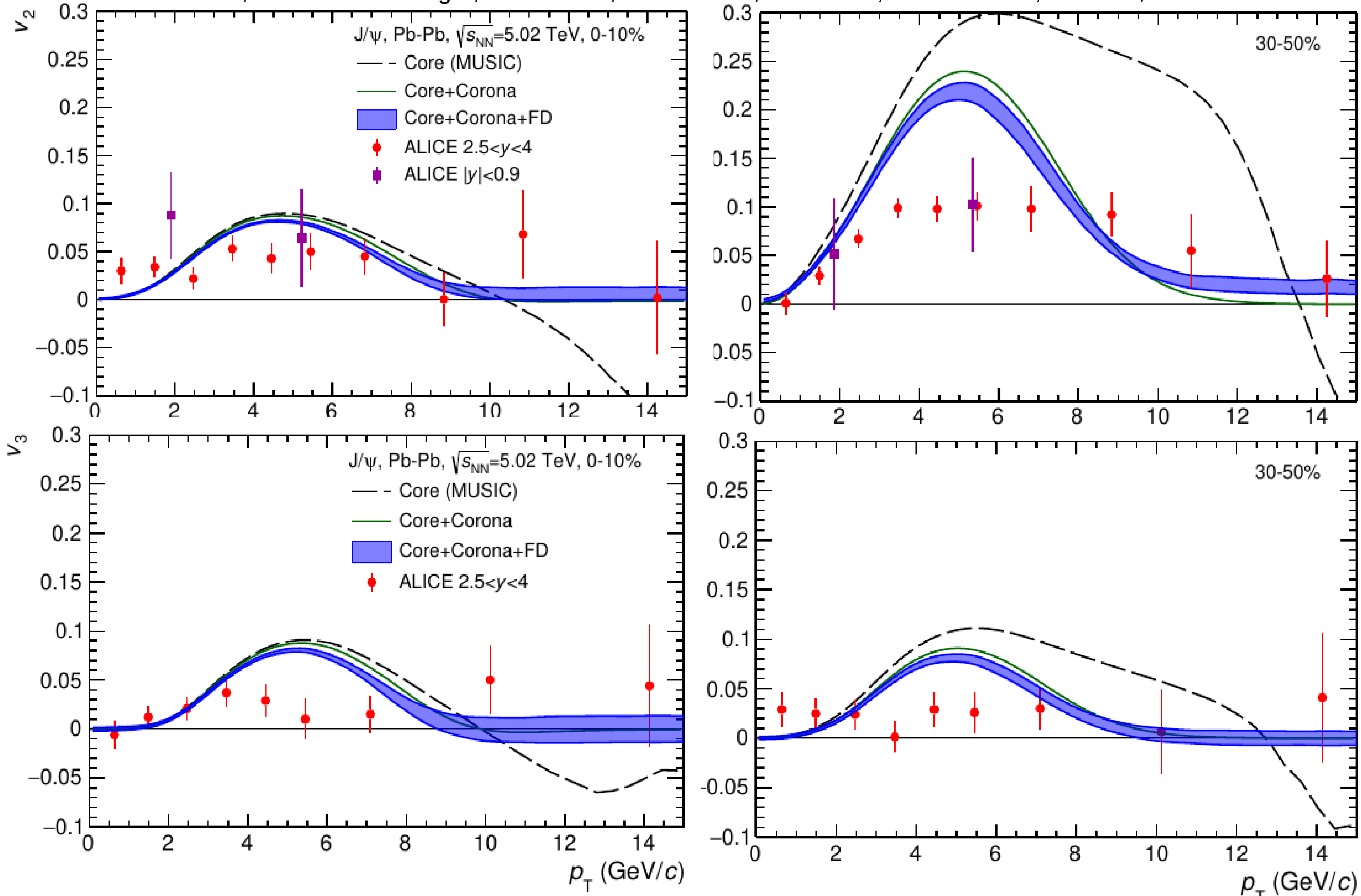


- for parameter free calculation pretty good agreement
- tendency towards somewhat too hard spectrum from model

-> needs more data

first calculation of J/ψ flow in SHMc plus hydro approach

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



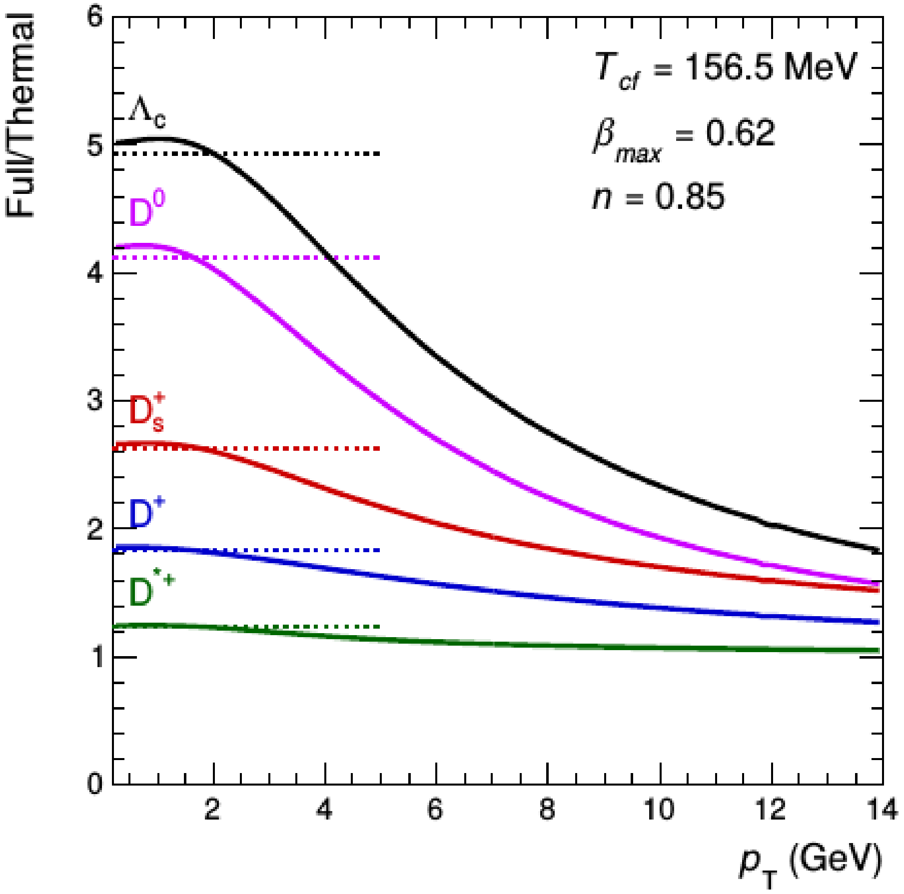
- significant flow arises over large pt range, difficult for other models
- for semi central collisions magnitude of flow over predicted

Spectra of D 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

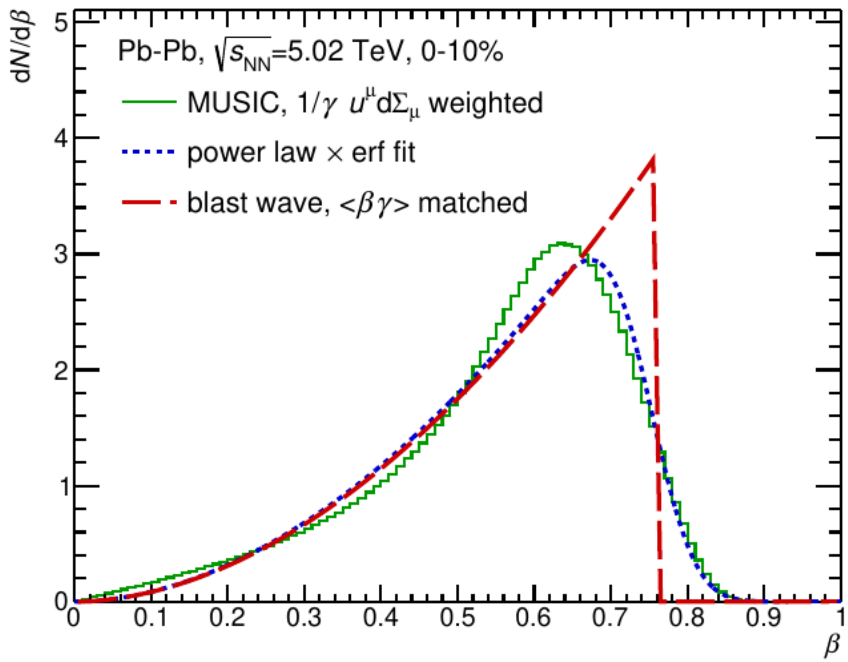
(A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284)

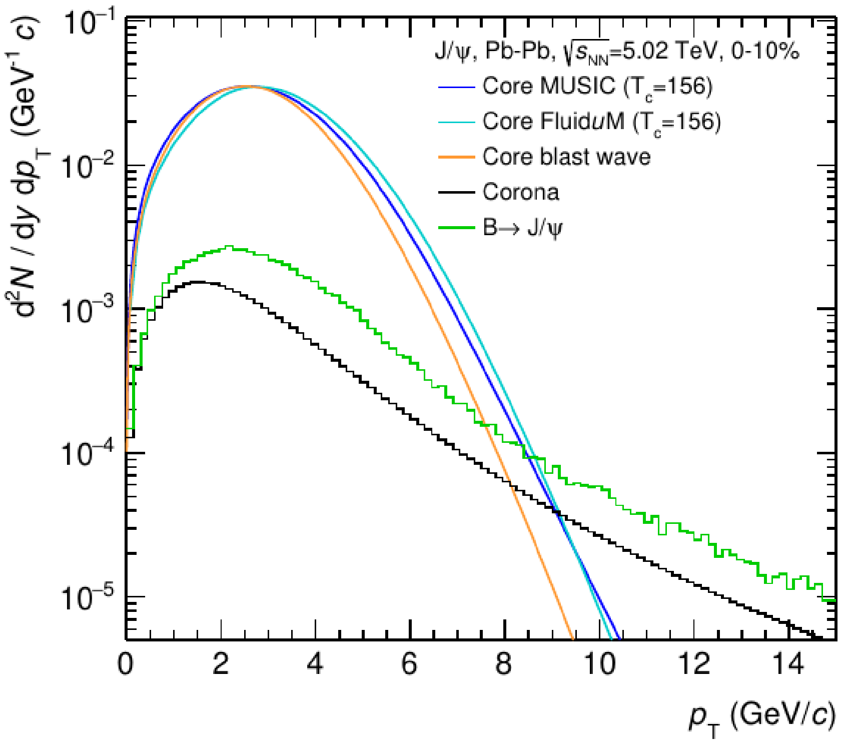
A.Andronic, P.Braun-Munzinger, M.Köhler, A.Mazeliauskas, K.Redlich, JS,V.Vislavicius JHEP 07 (2021) 035



Optimally matched blast wave parameters

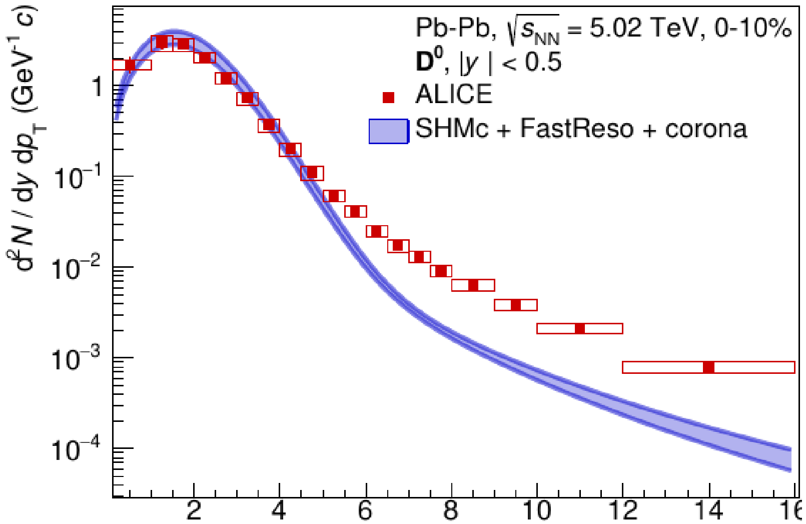
instead of inserting dozens of charmed hadrons into MUSIC, resort to blast wave parametrization again
but now we have advantage to be able to compare to 'true' hydro J/ψ spectrum
→ blastwave parameters modeled such that mean βγ of hydrodynamics is matched

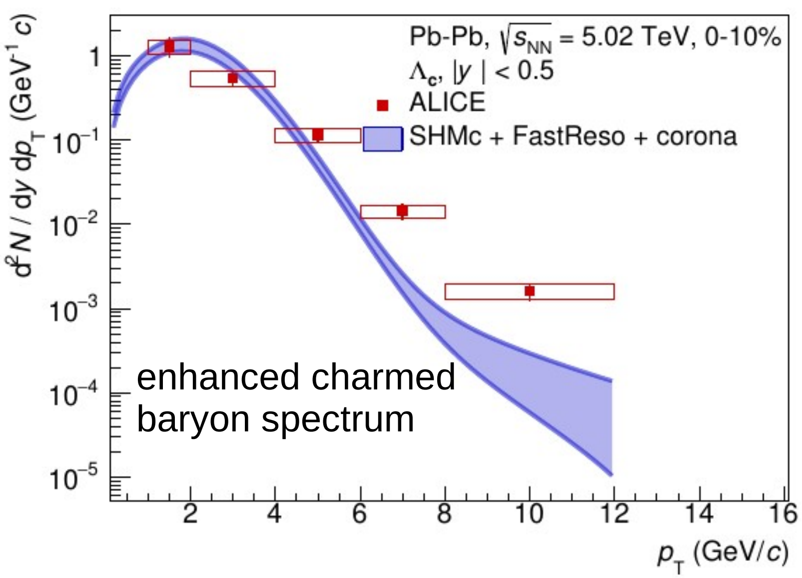




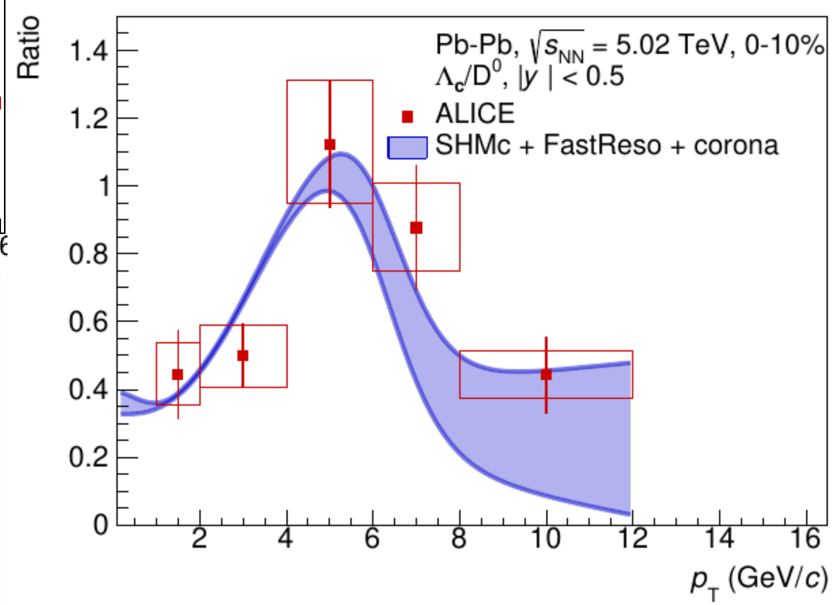
with β_{max} = 0.76 good matching can be achieved (red vs blue curves for core)

Open charm spectra – examples D^0 and Λ_c





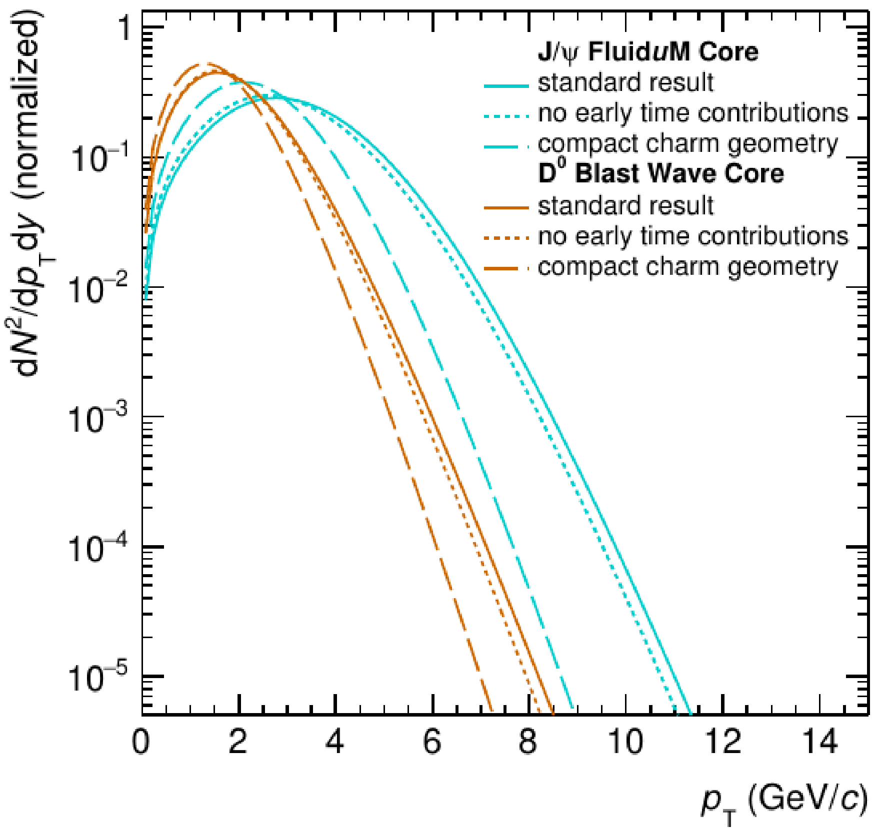
A. Andronic, P. Braun-Munzinger, J. Brunßen,
J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl,
arXiv: 2308.14821



very good description of low and intermediate p_t data
maximum in ratio arises naturally from expansion

Charm quark spatial distribution at hadronization

A. Andronic, P. Braun-Munzinger, H. Brunßen,
J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl,
arXiv: 2308.14821



strong indication that charm quarks are largely thermalized in terms of momenta

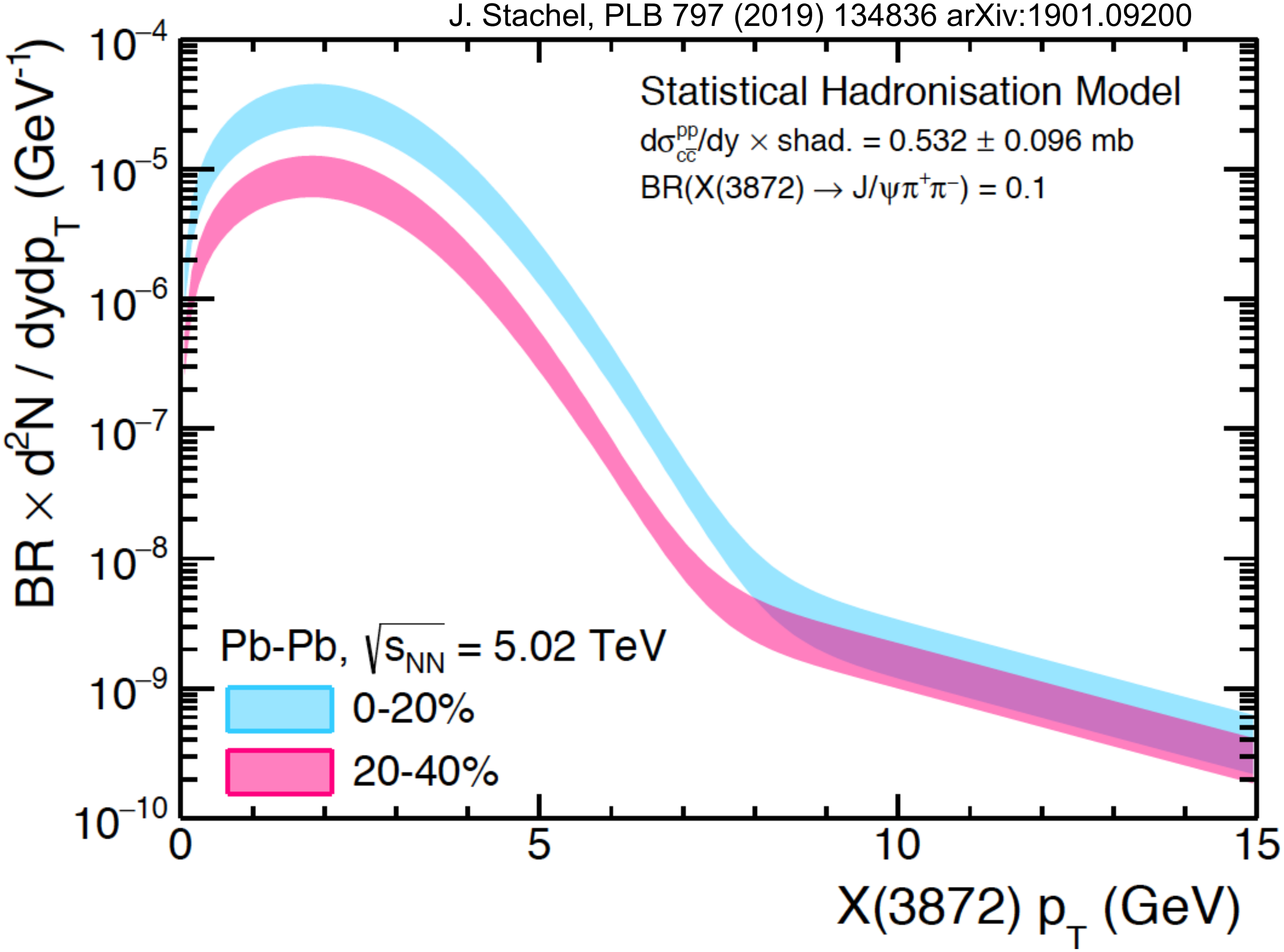
but since thermalization takes time, spatial distribution could lag behind front of expanding fireball

no experimental input
production of charm quarks very compact (N_{coll})

test: cut off outermost 1 fm in spatial distribution (dashed line)
→ this goes in direction of matching exp. data

Future opportunities: $\chi_{c1}(3872)$

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich, J. Stachel, PLB 797 (2019) 134836 arXiv:1901.09200

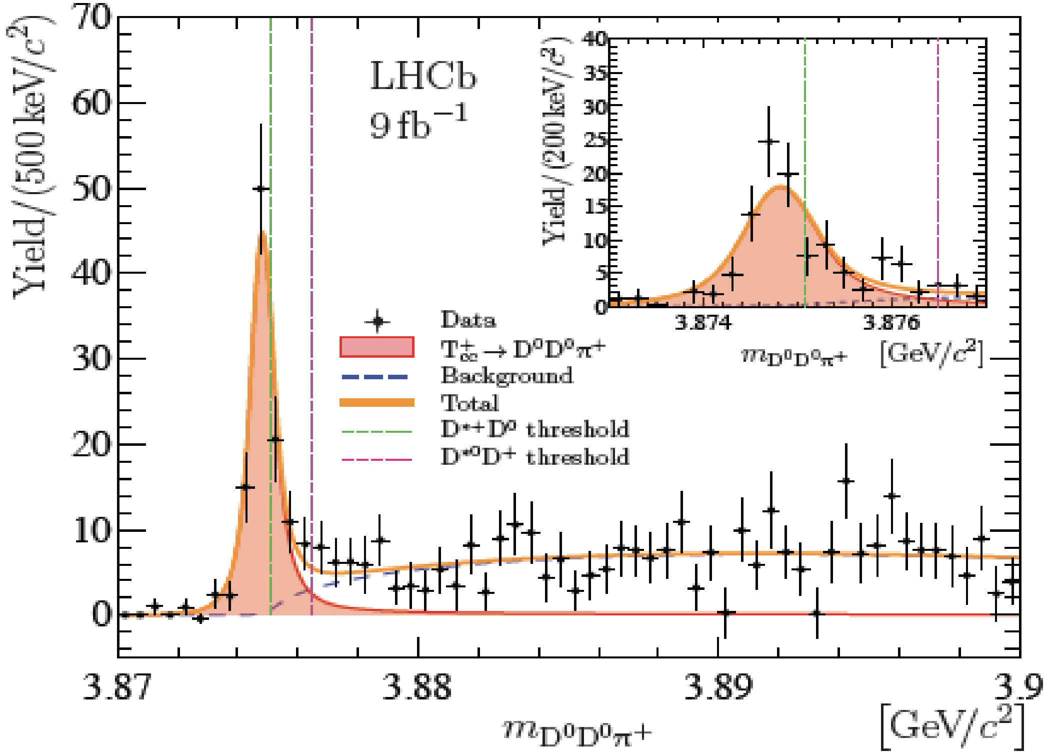


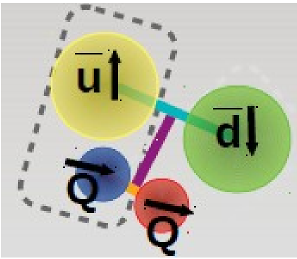
close to D^0D^{0*} threshold
- tetraquark or molecule?
- is it formed like (hyper)nuclei?

- decay into $J/\psi\ \pi^+\pi^-$
- doable in Run3/4?
- otherwise ALICE3

note: dramatic enhancement at low p_t predicted
CMS addresses only very high p_t part

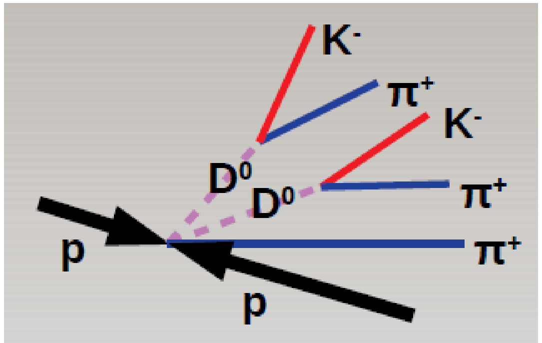
What about T_{cc}^{+} recently discovered by LHCb





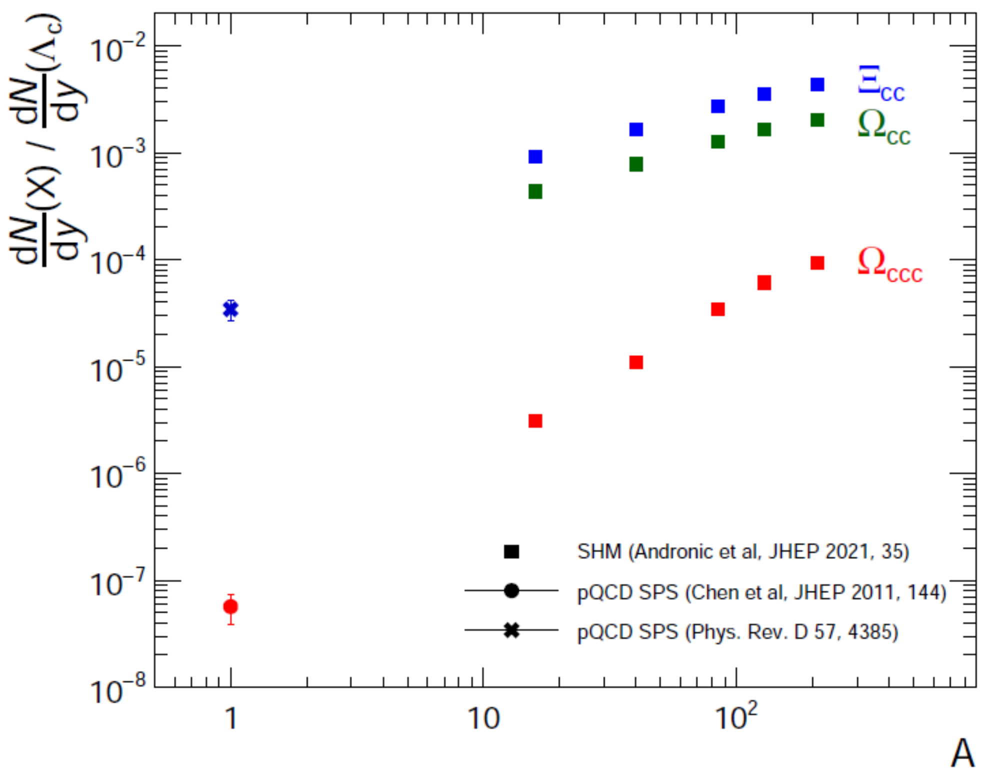
mass = 3874.75 ± 0.11 MeV
width = 48 ± 2 + 0 - 14 keV
d(m) = - 360 ± 40 keV

$T_{cc}^{+} \rightarrow D^0 D^0 \pi^+$



- if statistical hadronization is universal, it’s production cross section will fall on the 2 charm quark line at the measured mass, practically identical to $\chi_{c1}(3872)$ about 1% of J/ψ
- definitely no preformed state at charm production, two c quarks

Multi-charmed baryons



Letter of intent ALICE3 arXiv: 2211.02491

because of powers of g_c → strongly favored in collisions of heavy nuclei

can be addressed by ALICE3
e.g. Ξ_{cc}^{++} recently discovered by LHCb in pp collisions arXiv:1910.11316

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

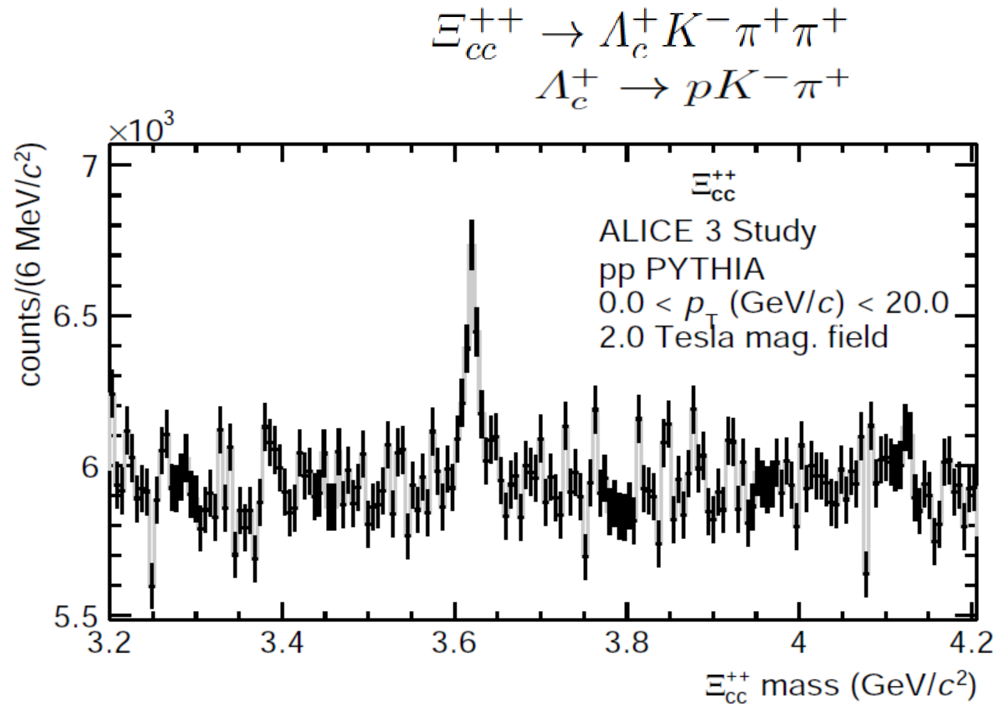


Figure 35: Expected Ξ_{cc}^{++} mass peak and background in pp collisions with $\mathscr{L}_{int} = 18\,\mathrm{fb}^{-1}$

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

arXiv: 2211.02491	O-O	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
$\sigma_{\text{inel}}(10\%)$ mb	140	260	420	580	800
$T_{\text{AA}}(0-10\%)\,\text{mb}^{-1}$	0.63	2.36	6.80	13.0	24.3
$\mathcal{L}(\text{cm}^{-2}\text{s}^{-1})$	$4.5 \cdot 10^{31}$	$2.4 \cdot 10^{30}$	$1.7 \cdot 10^{29}$	$3.0 \cdot 10^{28}$	$3.8 \cdot 10^{27}$
	$\text{d}\sigma_{c\bar{c}}/\text{d}y = 0.53\,\text{mb}$				
$\text{d}N_{\Omega_{ccc}}/\text{d}y$	$8.38 \cdot 10^{-8}$	$1.29 \cdot 10^{-6}$	$1.23 \cdot 10^{-5}$	$4.17 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$
Ω_{ccc} Yield	$5.3 \cdot 10^{5}$	$8.05 \cdot 10^{5}$	$8.78 \cdot 10^{5}$	$7.26 \cdot 10^{5}$	$3.80 \cdot 10^{5}$
	$\text{d}\sigma_{c\bar{c}}/\text{d}y = 0.63\,\text{mb}$				
$\text{d}N_{\Omega_{ccc}}/\text{d}y$	$1.44 \cdot 10^{-7}$	$2.33 \cdot 10^{-6}$	$2.14 \cdot 10^{-5}$	$7.03 \cdot 10^{-5}$	$2.07 \cdot 10^{-4}$
Ω_{ccc} Yield	$9.2 \cdot 10^{5}$	$1.45 \cdot 10^{6}$	$1.53 \cdot 10^{6}$	$1.22 \cdot 10^{6}$	$6.29 \cdot 10^{5}$

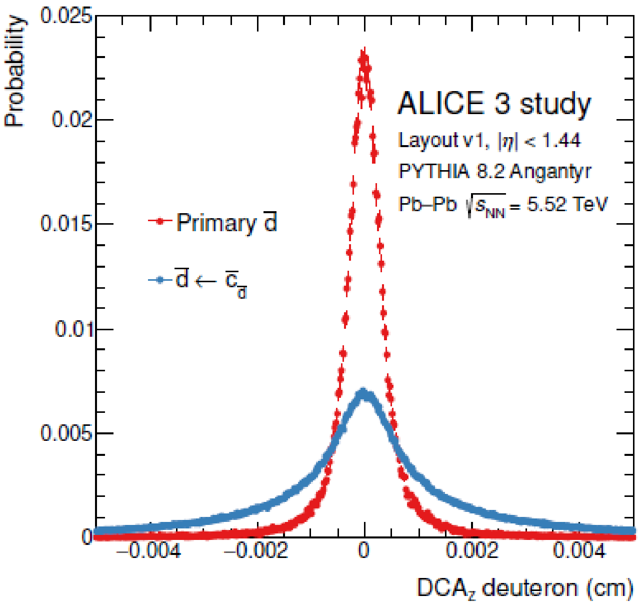
current estimates for luminosities for LHC for lighter nuclei somewhat less optimistic
→ optimum for Xe-Xe with 3.9-6.5 10^5 Ω_{ccc} per year

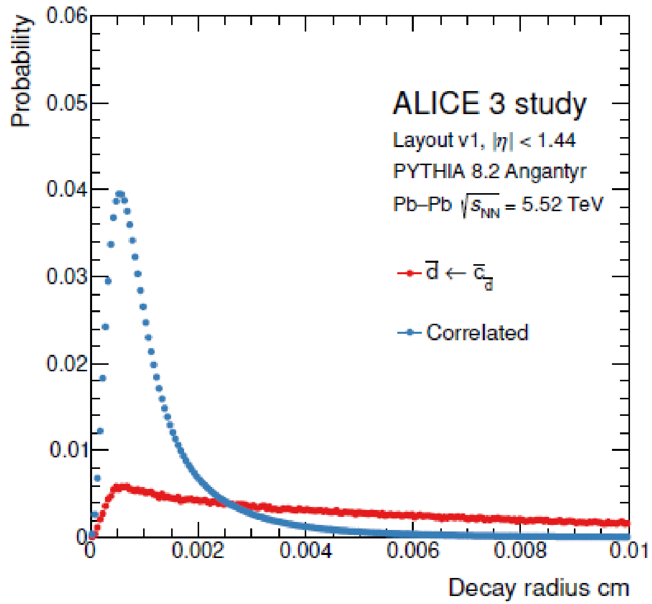
Feasibility for c deuteron in ALICE3

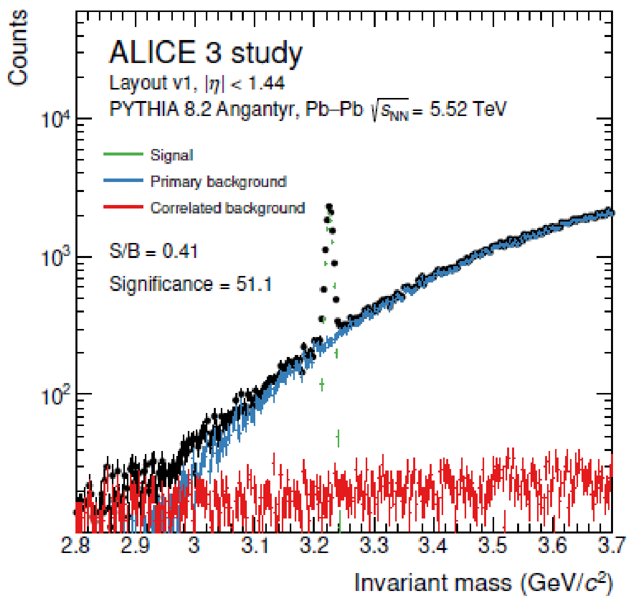
is c-deuteron bound and weakly decaying? discover or put limit

$c_d \rightarrow d + K^- + \pi^+$ using $\Lambda_c \rightarrow p + K^- + \pi^+$ with 6.3 % and binding into d with coalescence model

arXiv: 2211.02491







main combinatorial background from primary deuterons can be effectively suppressed due to superb vertex resolution $\rightarrow$ significance 51

1 month PbPb collisions = 5.6 nb^{-1}

abundance c_t factor 350 less, significance factor 18 less, needs all of Run5+6 (factor 6)

Conclusions

strong experimental evidence for charm quark thermalization in PbPb collisions at LHC suggests statistical treatment of hadronization

extension of SHM to open and hidden charm sector possible, based on presence of deconfined, thermalized charm quarks
- only experimental input needed: total charm production cross section

obtain parameterfree description of charmonium and open charm yields and spectra as well as flow coefficients
caveats:
- still no measured total charm cross section in PbPb collisions
- puzzle of large enhancement of charmed baryons in pp compared to ee or ep how about PbPb?

→ answers will come with much increased luminosity sampled in LHC Run3/4

predictions for complete spectrum of multicharm and exotic charmed hadrons
- some answers in Run3/4, full exploitation with ALICE3

backup

Analysis of yields of produced hadronic species in statistical model – grand canonical

partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

for each hadron species I the grand canonical statistical operator is:

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

leading to particle densities:

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

for every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

but can use conservation laws to constrain V, μ_S, μ_{I_3}

fit at each energy provides values for T and □b

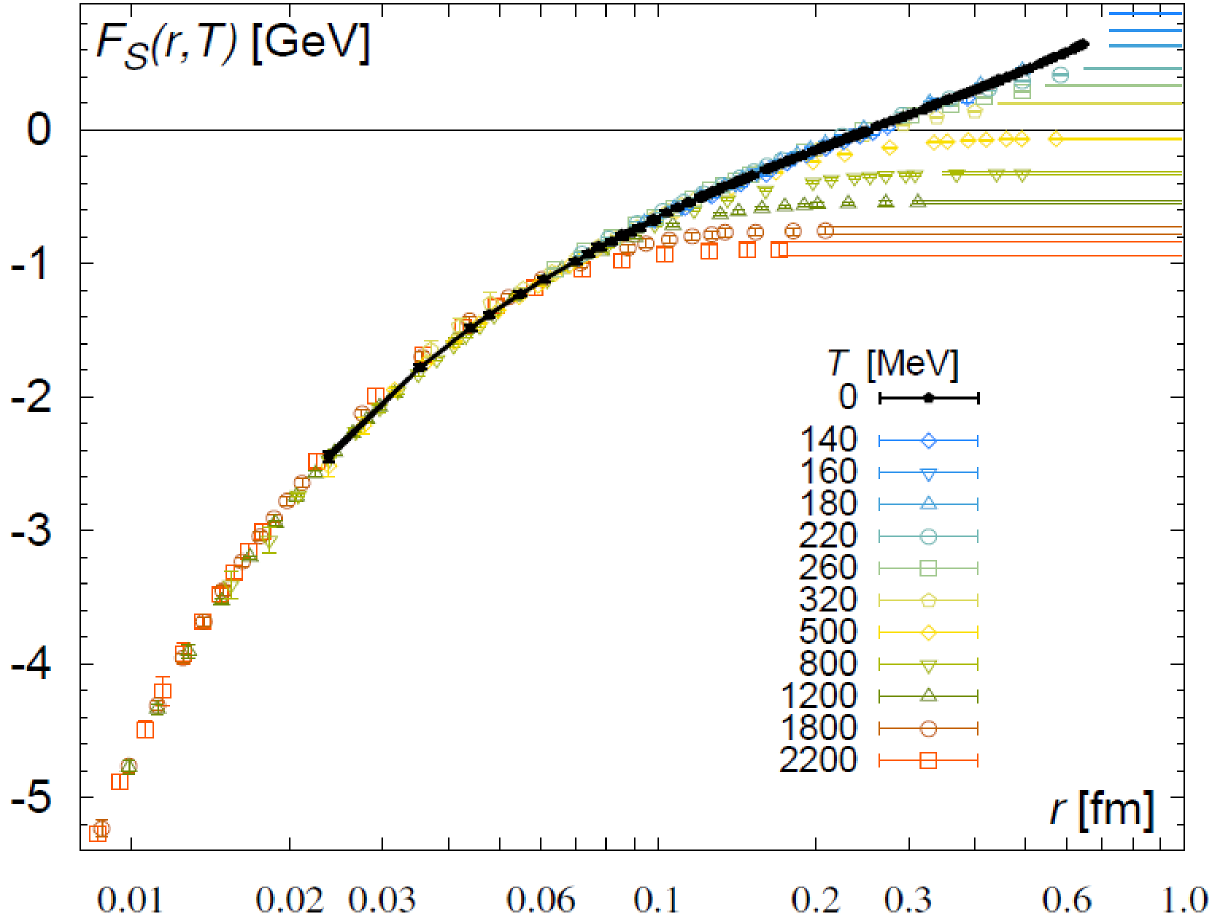
use full hadronic mass spectrum from the PDG to compute 'primordial yields' and feeding from strong decays

Results on Debye screening from lattice QCD

- after a decade of debate, now some agreement how to extract effective heavy quark potential
- starting from: color singlet free energy → general consensus: potential has real and imaginary part

TUMQCD arXiv:1804.10600

- at LHC all quarkonia should be Debye screened
- considering formation time of hadrons, they should not form at high T at all



Relevant time scales

formation of ccbar: in hard initial scattering on time scale $1/2m_c$
with m_c = 1.3 GeV -> τ_{ccbar} = 0.08 fm/c

typical hadron formation time: τ_{hadron} order 1 fm/c
(Blaizot/Ollitrault 1989 Hüfner, Ivanov, Kopeliovich, and Tarasov 2000)
W. Brooks, QM09: description of recent JLAB and HERMES hadron production data in color dipole model - > time scale 5 fm/c

comparable to or longer than QGP formation time:
$\tau_{QGP} \cong$ 1 fm/c at SPS, < 0.5 fm/c at RHIC, $\cong$ 0.1 fm/c at LHC

at LHC even color octet state not formed before QGP (H.Satz 2006)

$$\tau_8 = 1/\sqrt{2\mathrm{m_c}\Lambda_{\mathrm{QCD}}} \approx 0.25\,\mathrm{fm}$$

collision time: $\mathrm{t_{coll}} = 2\mathrm{R}/\gamma_{\mathrm{cm}}$ at RHIC 0.1 fm/c, at LHC < 5 10^{-3} fm/c

Time scales continued

hard	0.05 fm	pre–resonance	0.25 fm	resonance
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$	

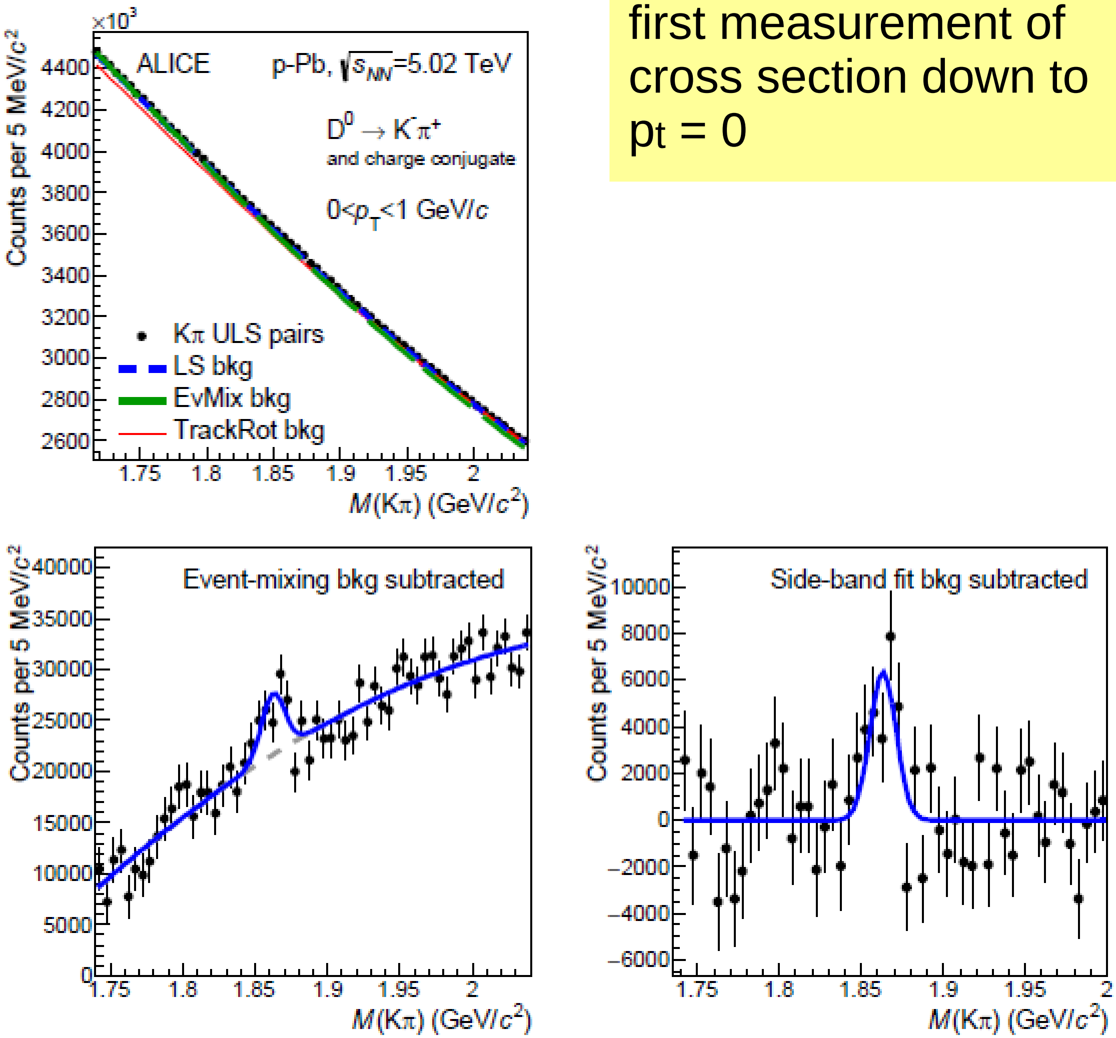
ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS $t_{coll} = \tau_{ccbar} \cong \tau_{QGP} \cong \tau_{hadron}$

but at RHIC and much more pronounced at LHC there is the following hierarchy: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

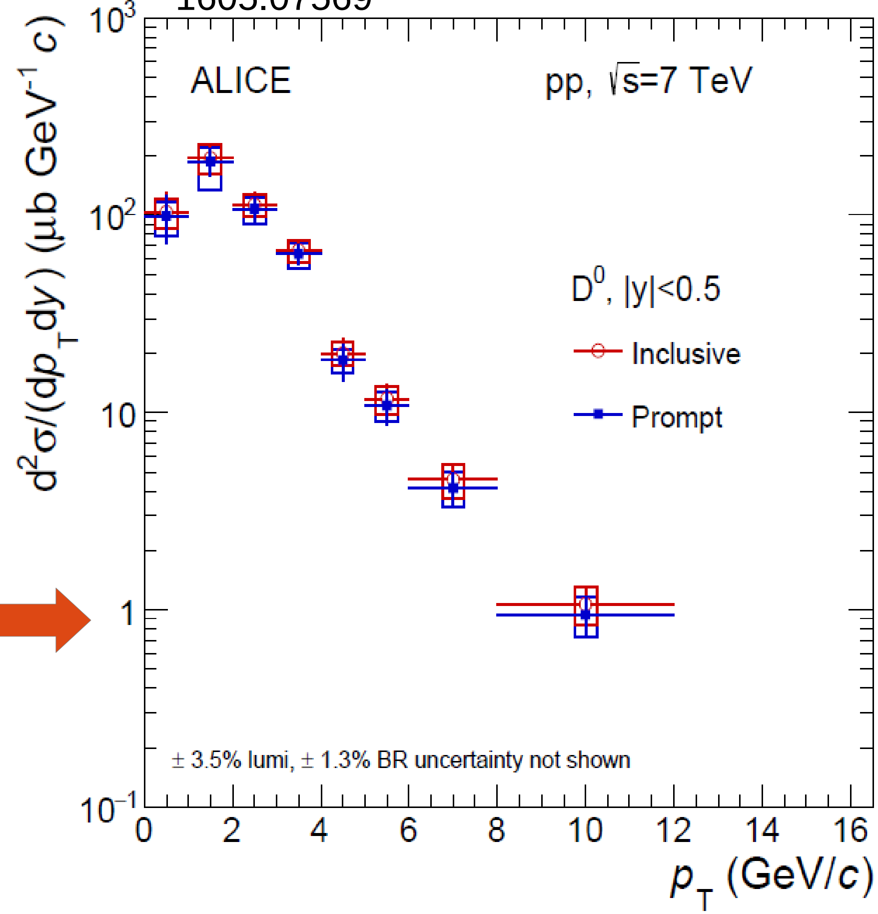
expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

Measurement of charm production cross section



first measurement of cross section down to $p_t = 0$

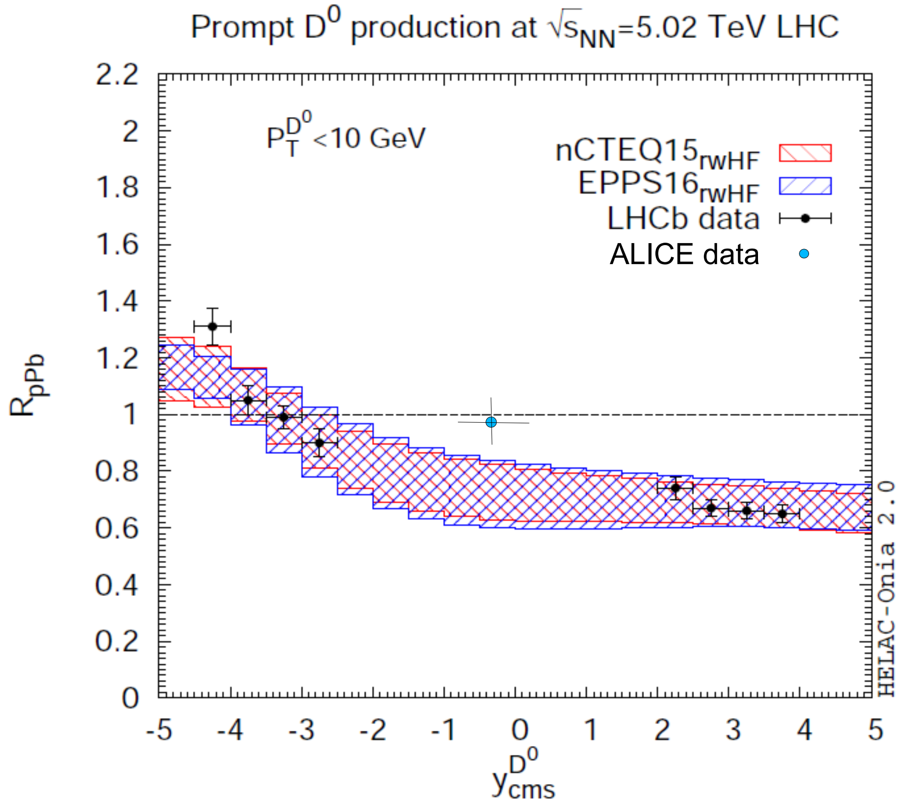
PRC94(2016) 054908 arXiv: 1605.07569



very hard struggle to deal with (irreducible) combinatorial background, successful

Charm cross section – nuclear effects

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



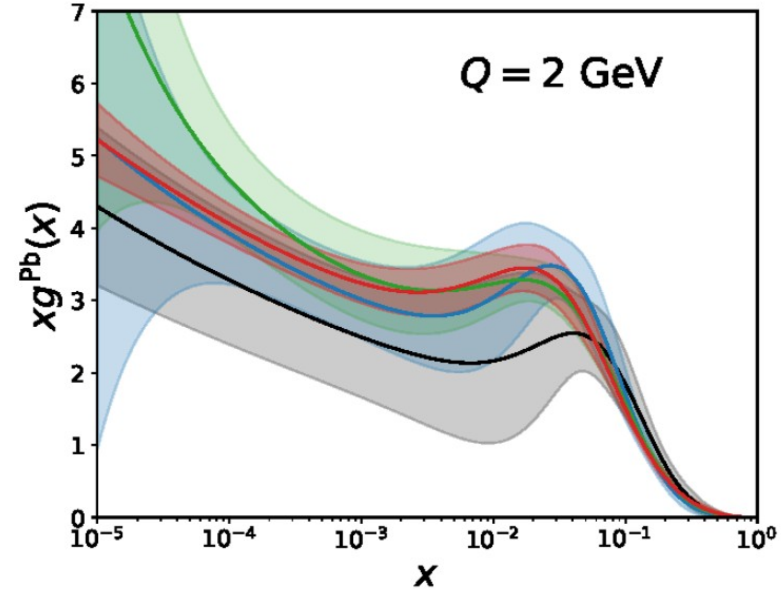
at y=0 R_{pPb} = 0.73 ± 0.067

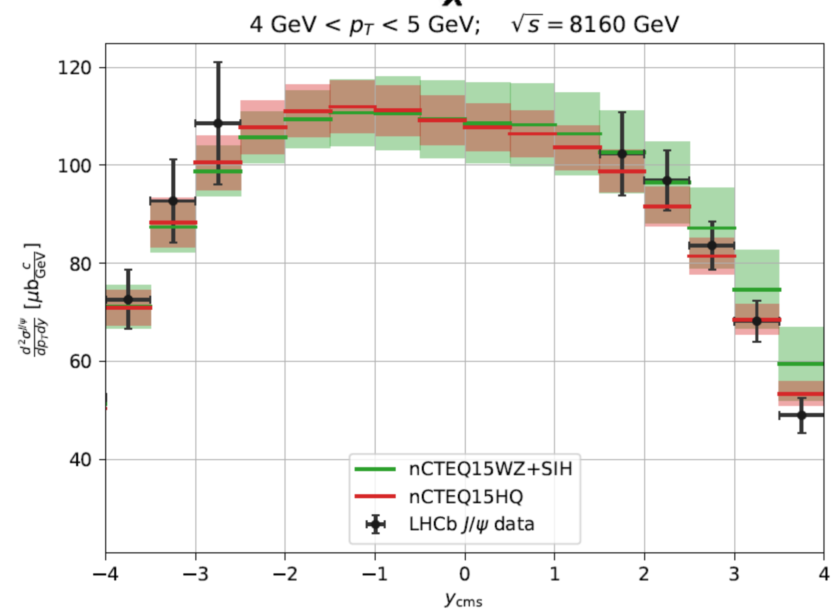
→ S_{PbPb} = 0.53 ± 0.097

supported by J/y yield in photoproduction

in SHMc in the past we used 0.65 ± 0.12

Duwentäster et al. new nCTEQ15HQ fit
2204.09982





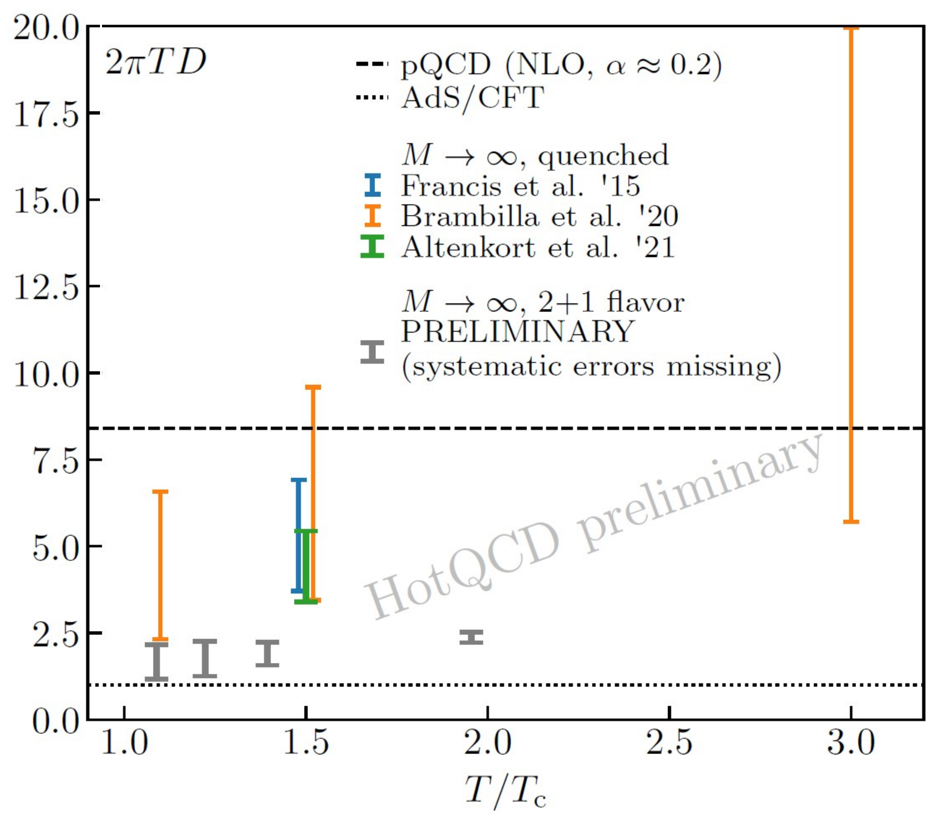
Charm quark thermalization

LHC data: strong charmed hadron elliptic flow and energy loss (R_{AA}) point to large degree of charm quark thermalization in QGP
modelling in terms of heavy quark diffusion in hot and dense medium leads to spatial diffusion coefficients 1.5 < 2pTD < 4.5 at T_c → t_{kin} = 2.5 – 7.6 fm/c

lQCD:
D from gradient flow on color-electric two-point function
(leading order in 1/M expansion)

$$2\pi \mathrm{TD} = \frac{4\pi}{\kappa/\mathrm{T}^3} \propto \tau_{\mathrm{kin}} \frac{\mathrm{T}^2}{\mathrm{M}}$$

quenched QCD, but tendency to go down in full QCD (preliminary, Altenkort QM2022)

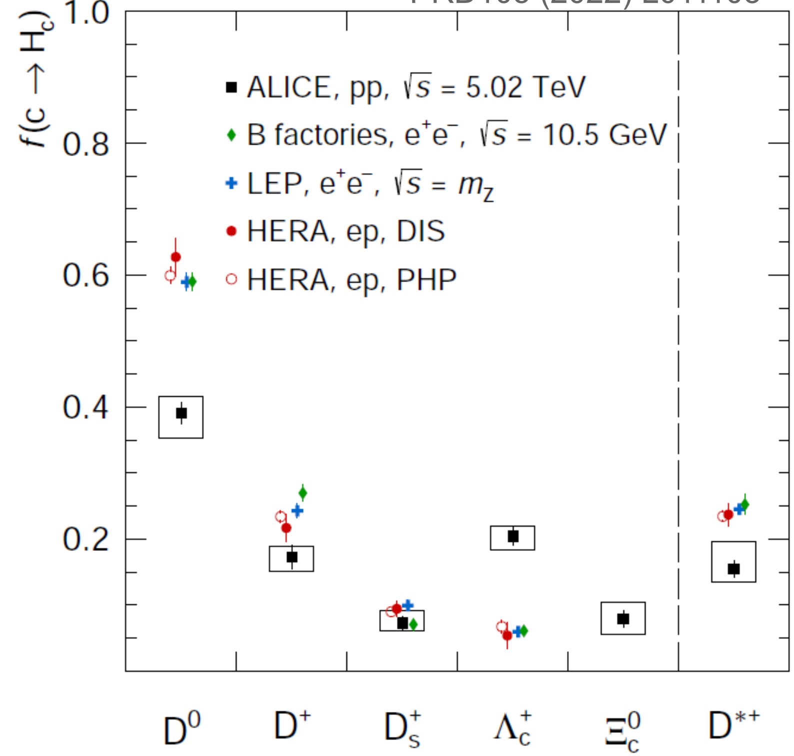


consistent picture:
thermalization in QGP

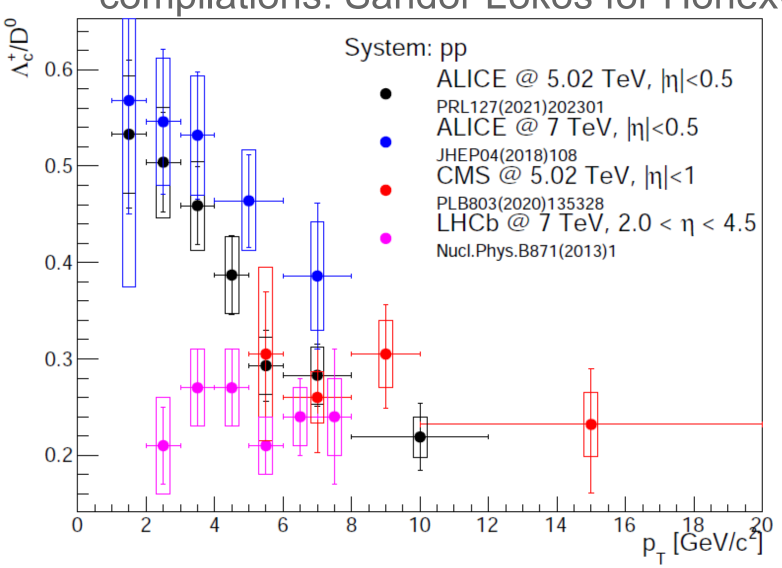
Charm cross section pp collisions

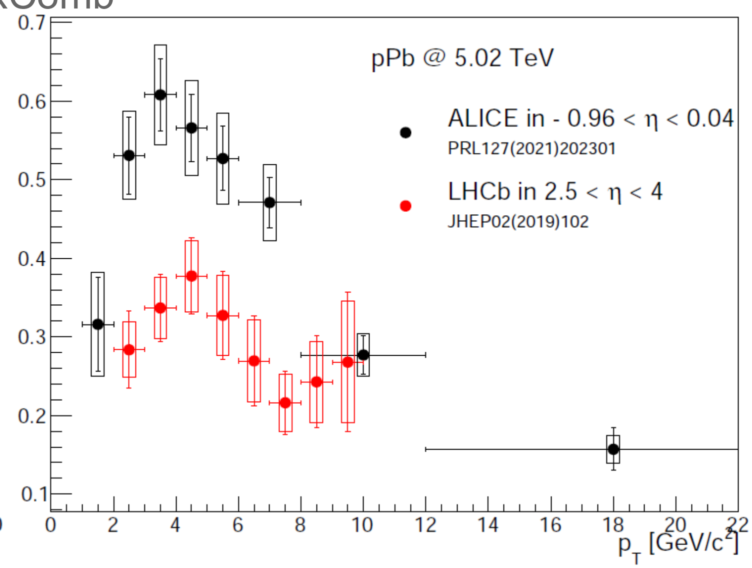
fragmentation into Lc factor 4 increased vs e+e-
can be reproduced by
- some PYTHIA tunes with CR or
- statistical model by about doubling the charmed baryon states as predicted by RQM or lQCD and using T = 170 MeV but at LHC among many newly discovered states only 7 charmed baryons

PRD105 (2022) L011103



compilations: Sandor Lökös for HonexComb

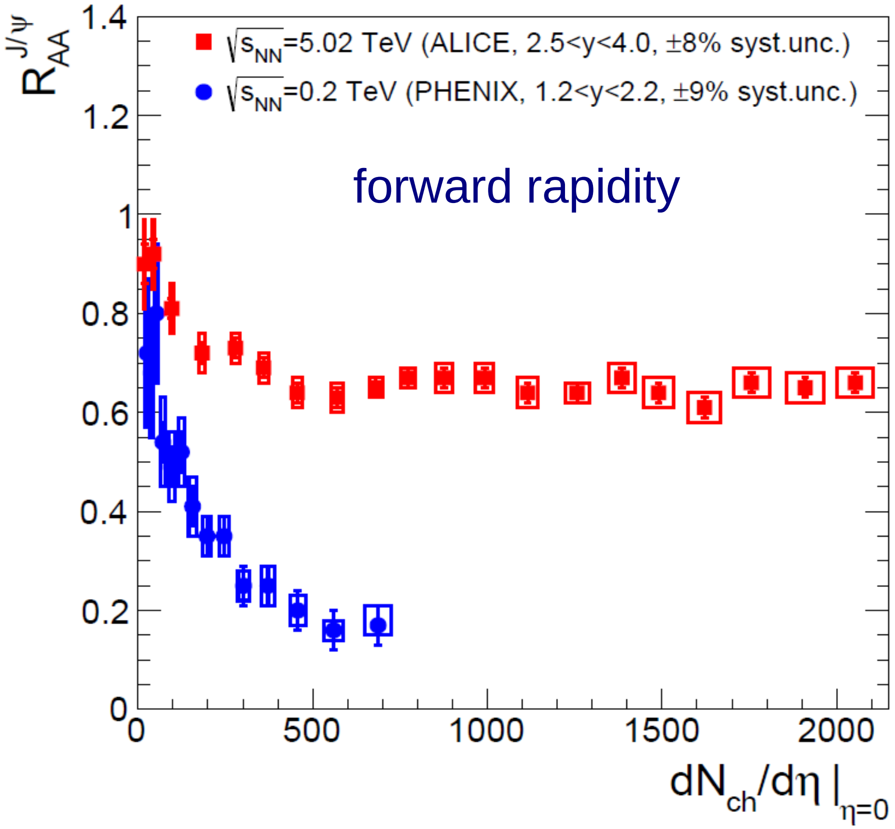


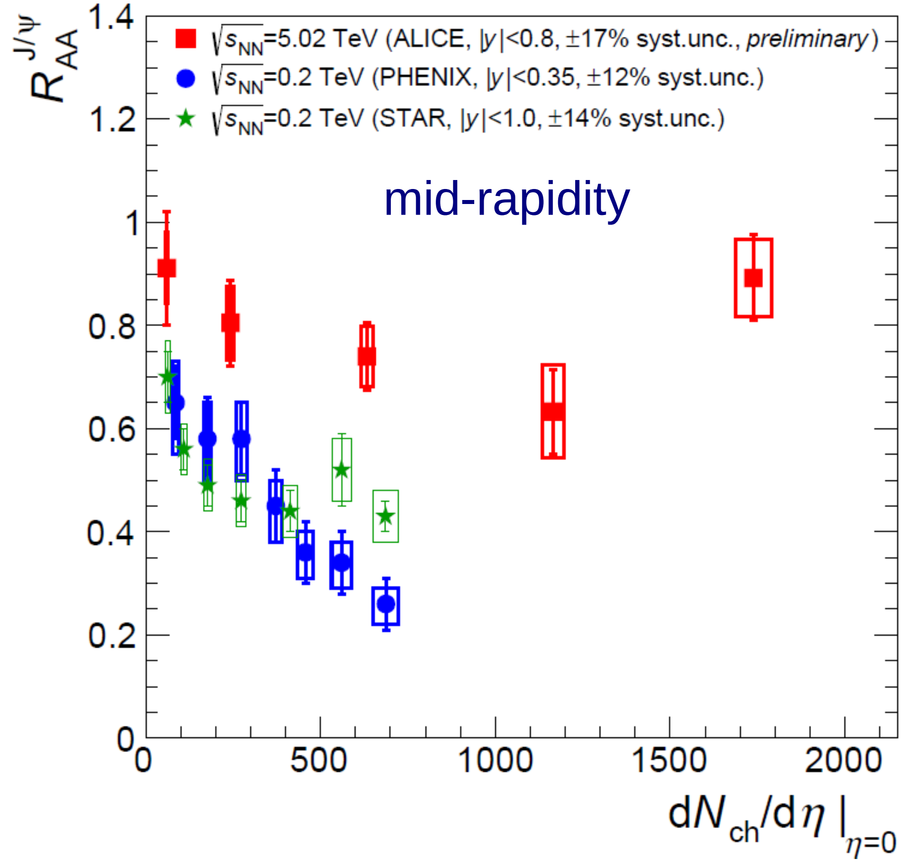


experimental situation needs to be clarified

J/y production in PbPb collisions: LHC relative to RHIC

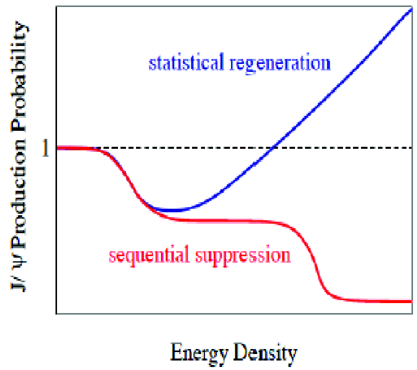
$$R_{AA} = \frac{dN^{AA}/dy}{N_{coll}\, dN^{pp}/dy}$$



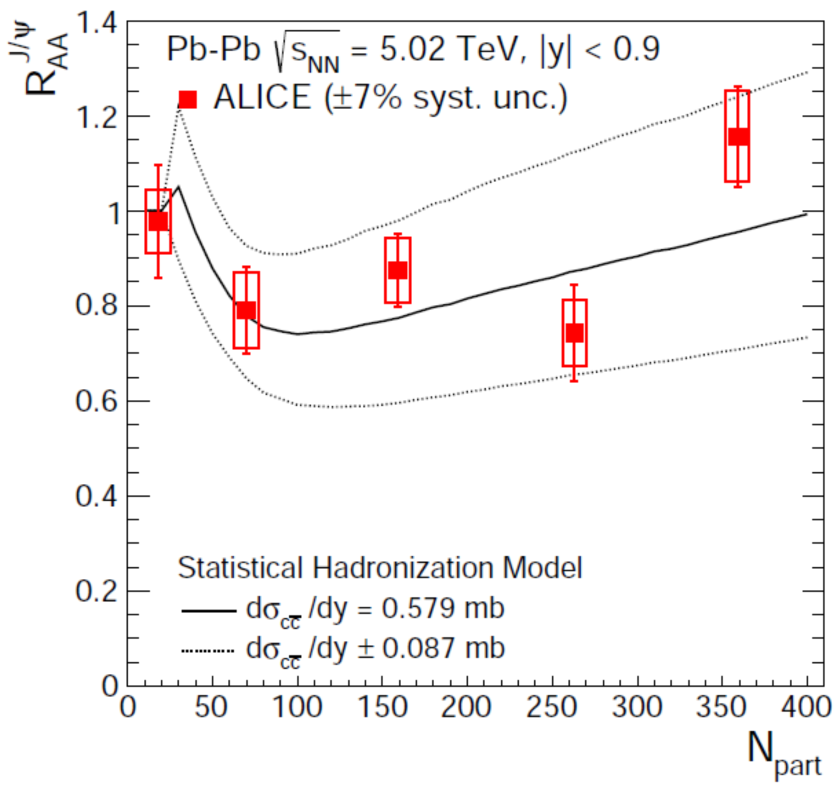


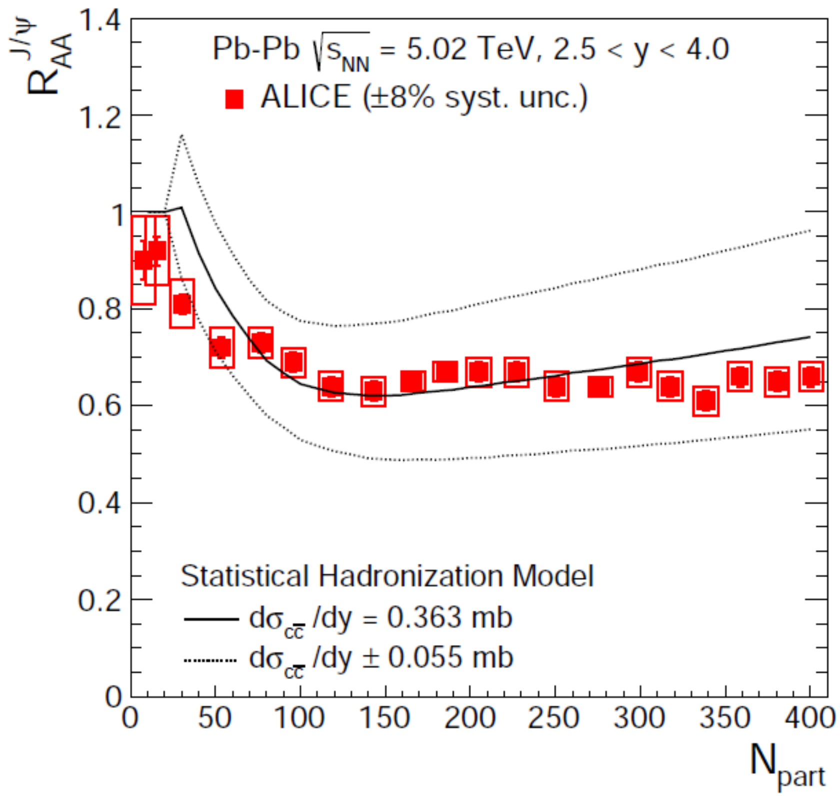
energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



J/ψ and statistical hadronization

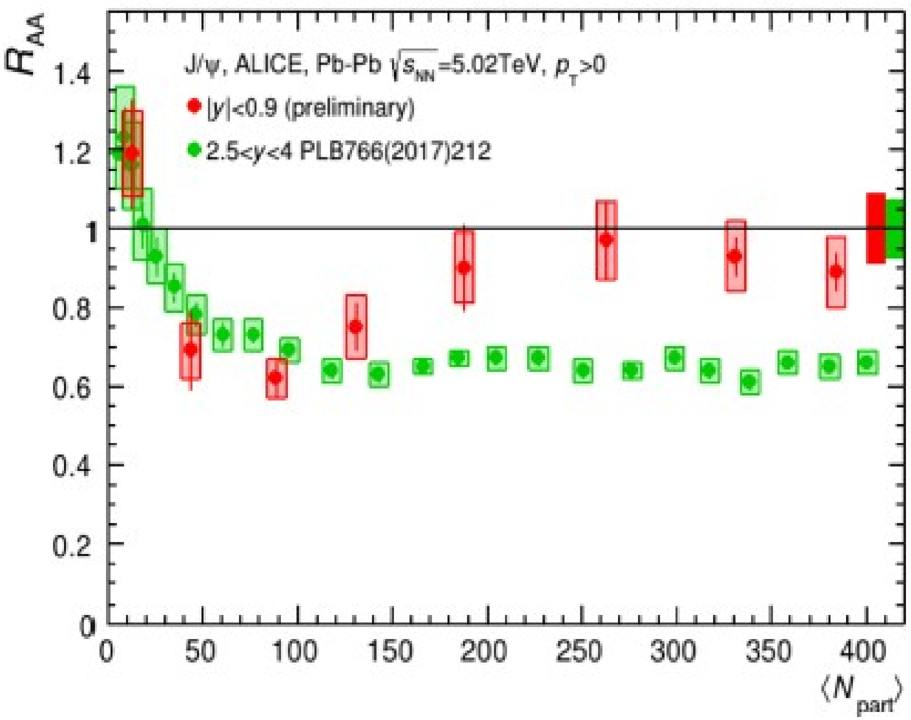


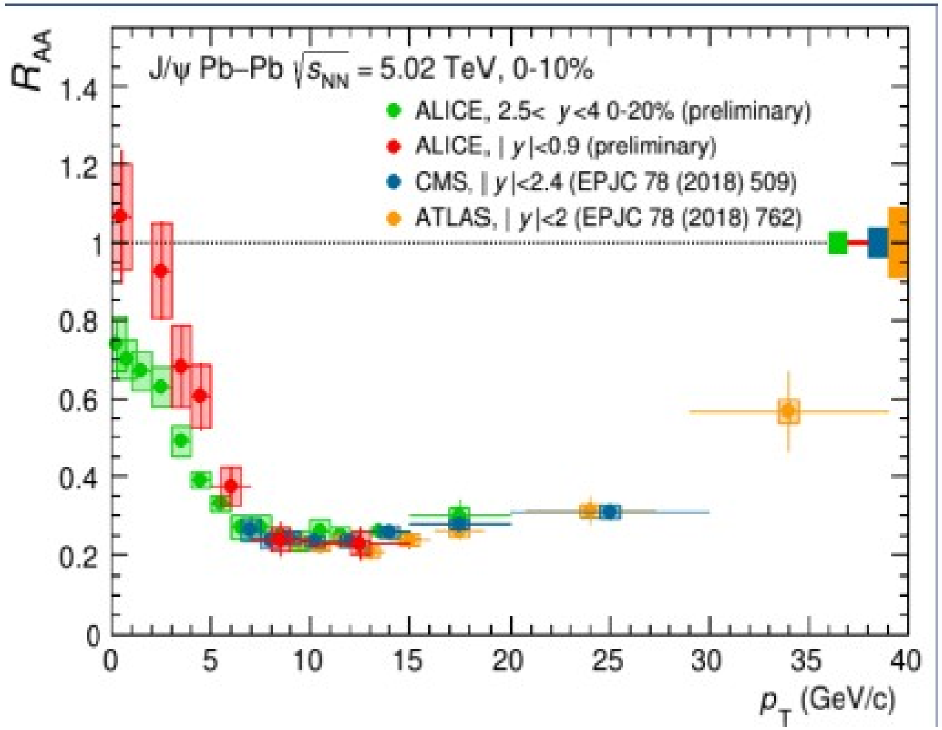


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

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

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

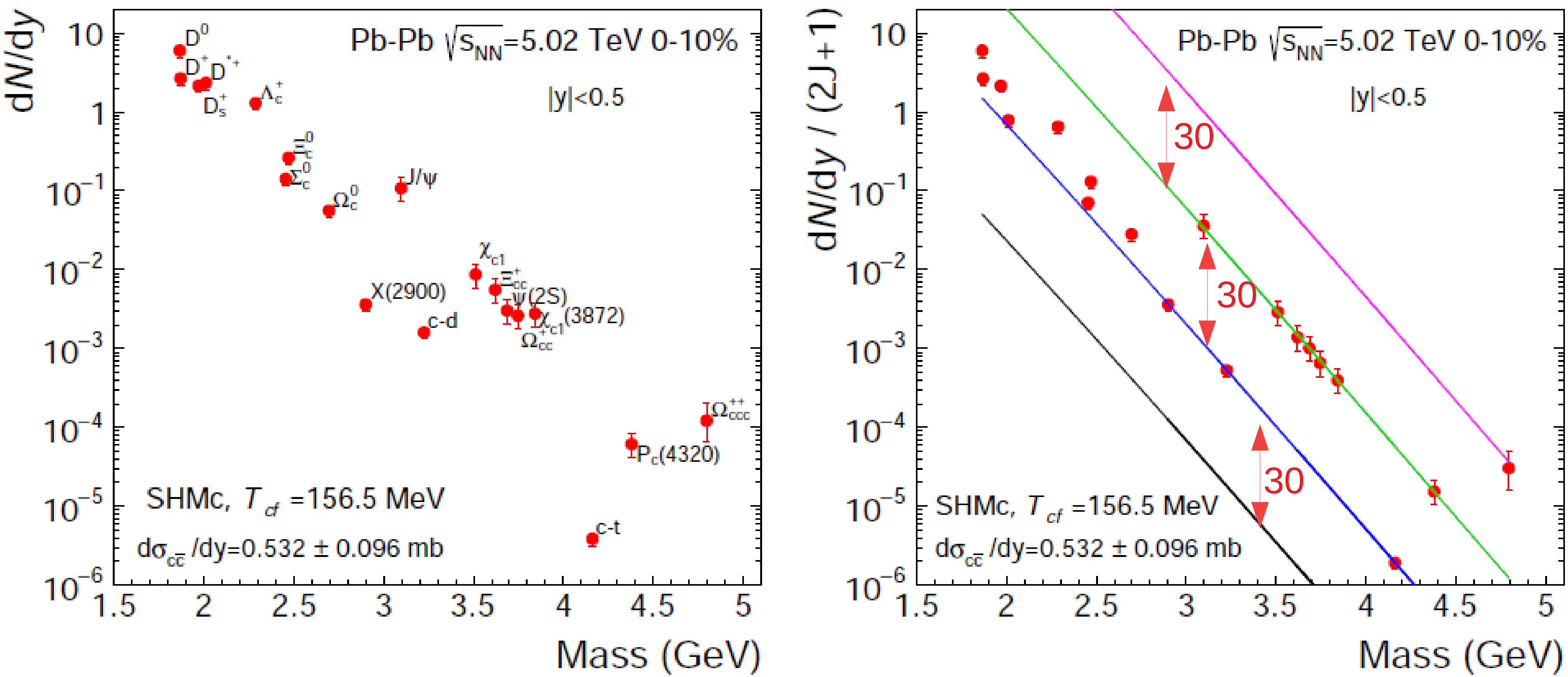




the multi-charm hierarchy

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

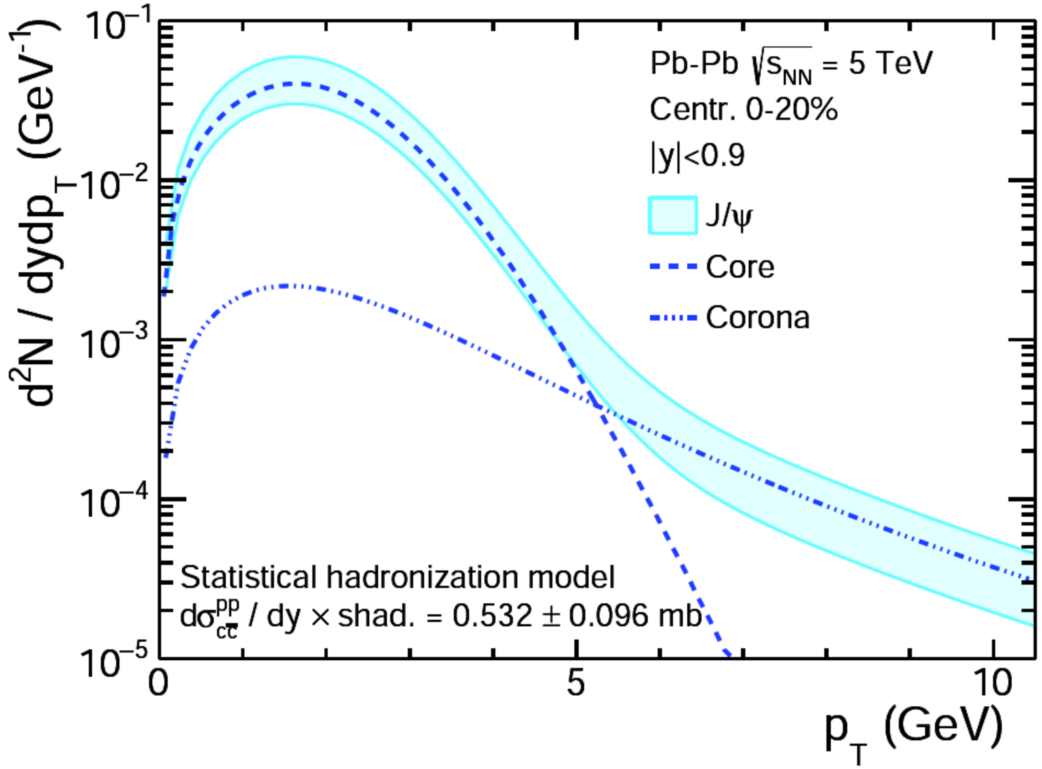
A. Andronic et al.. JHEP07 (2021) 035



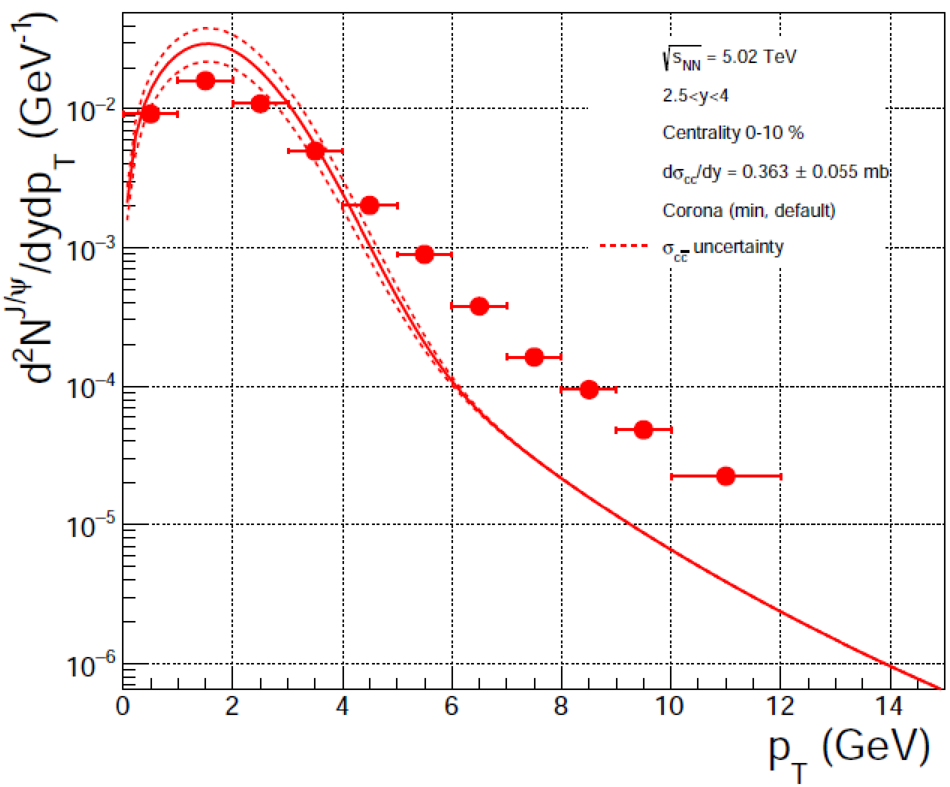
emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Runs3 and beyond

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

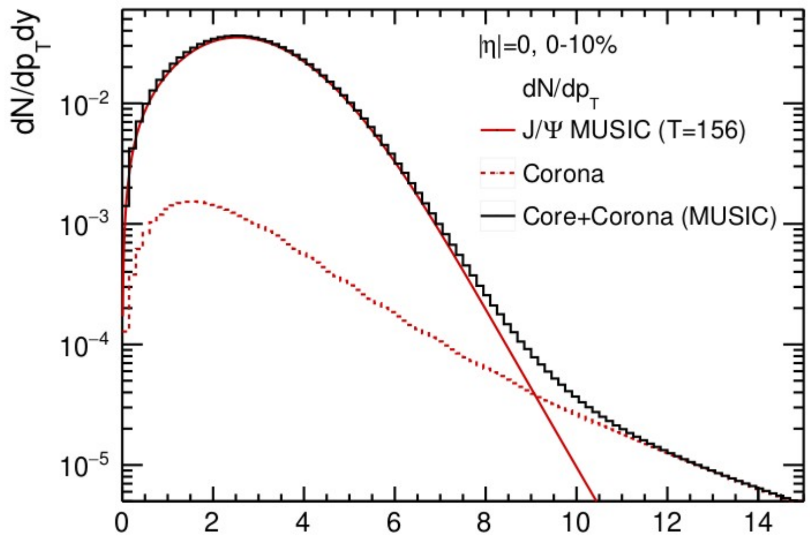


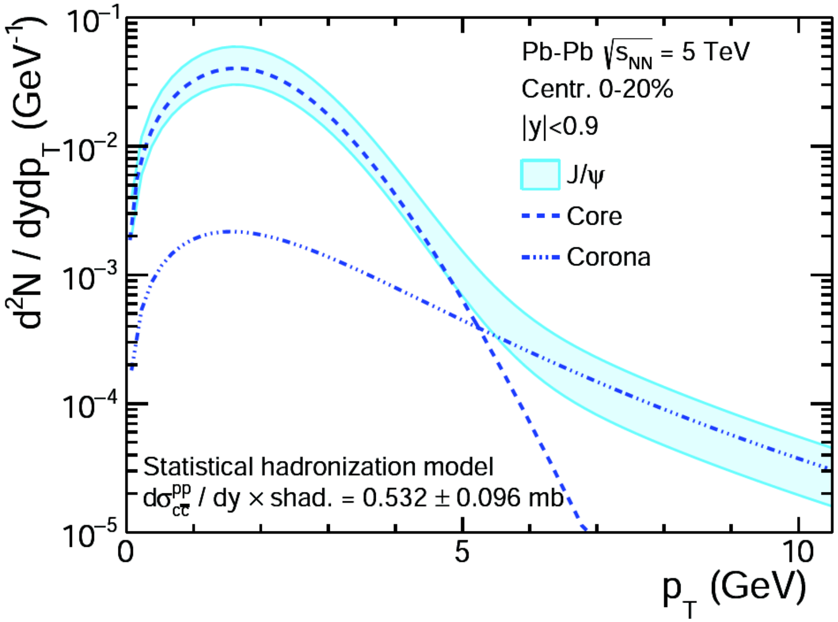
update to A. Andronic et al. 1902.09200



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.

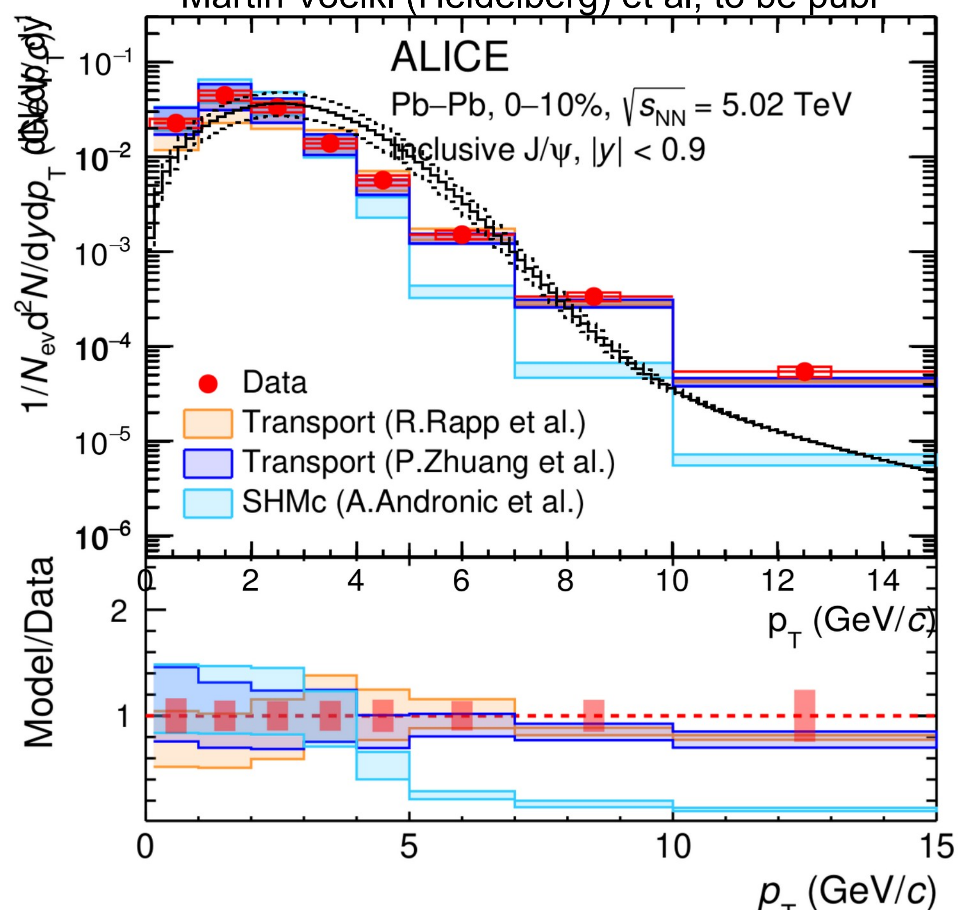




J/y yield MUSIC normalized to SHMc yield
corona unchanged

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

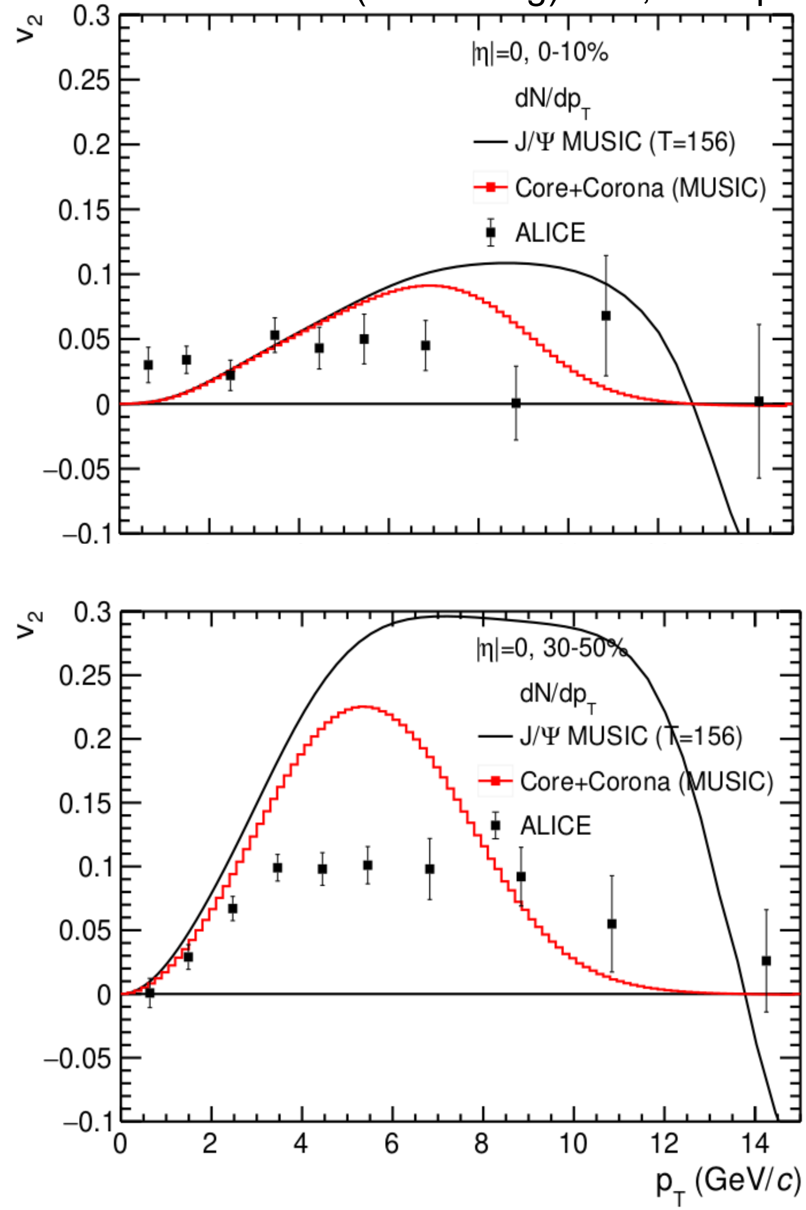
Martin Voelkl (Heidelberg) et al, to be publ



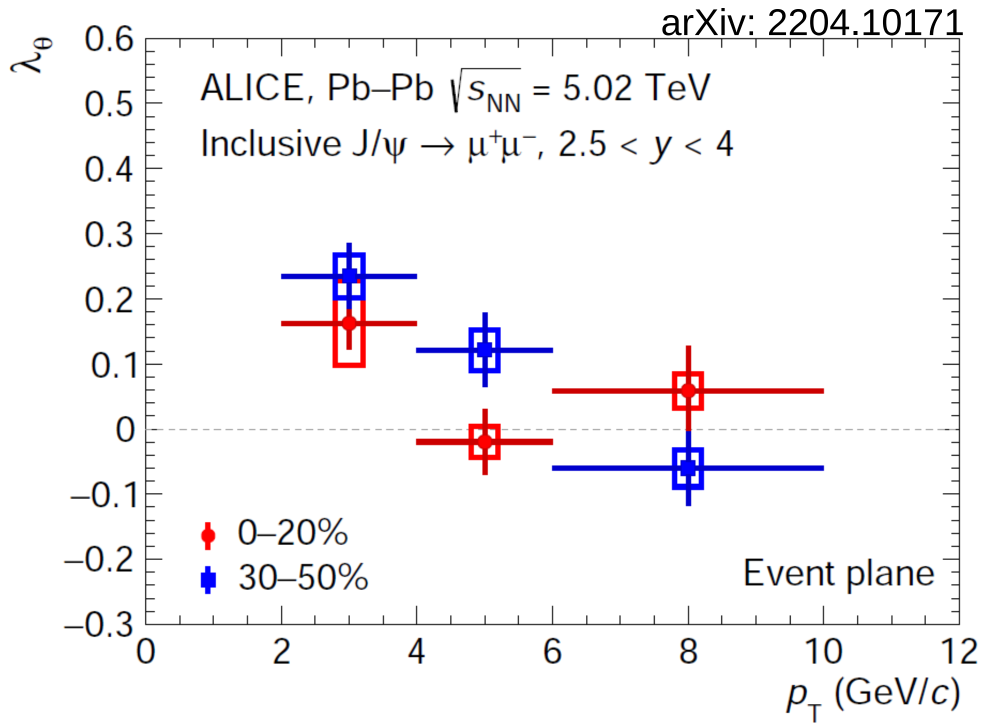
a first look at J/y v2 in this approach

- 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.



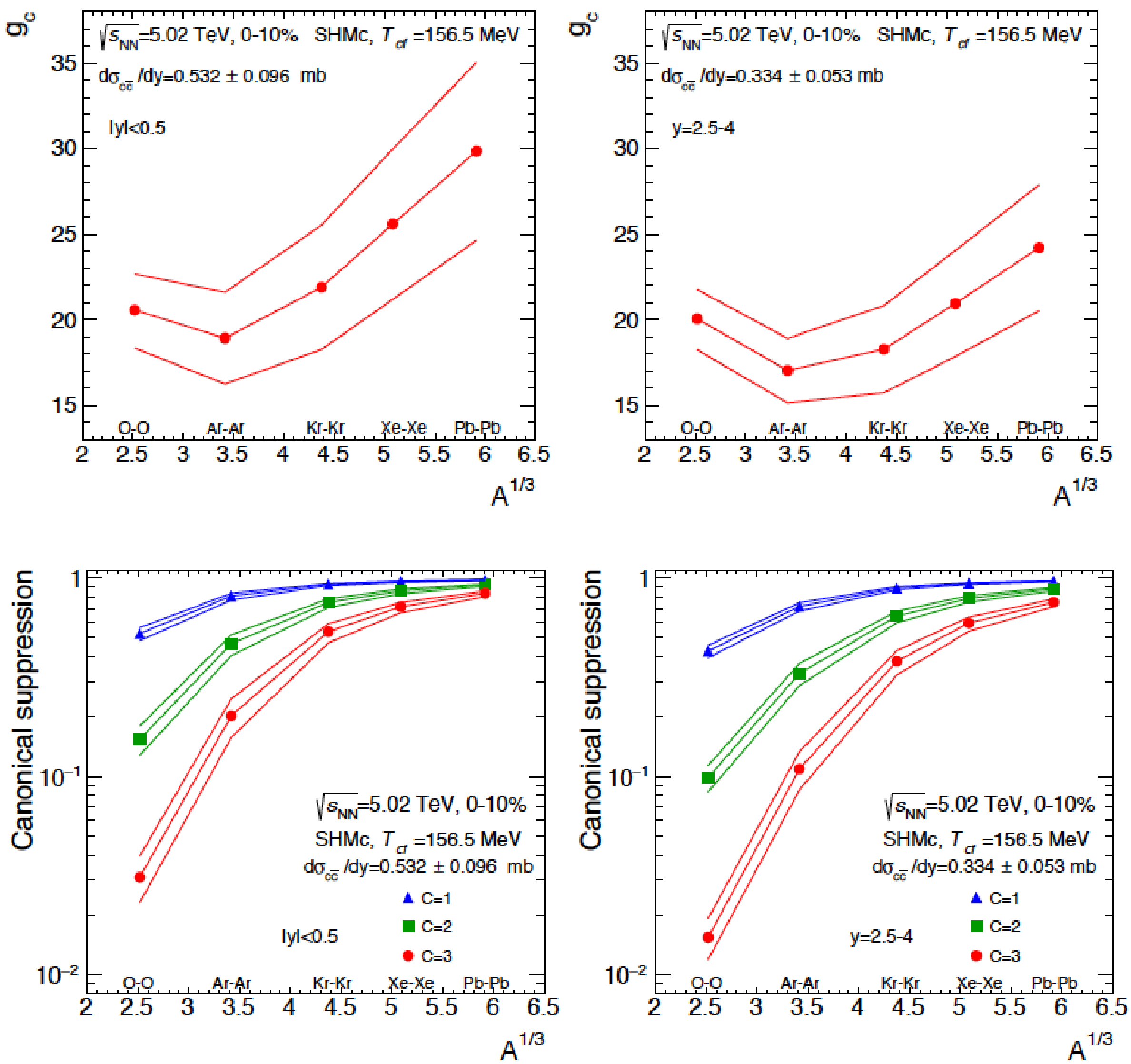
Polarization of J/y relative to event plane



clear signal observed by ALICE,
increase towards lower p_t
reaching 3.9 s
makes early effect due to magnetic field unlikely
link to vorticity and spin-orbit coupl.?

charm fugacities and canonical suppression factors

different collision systems:



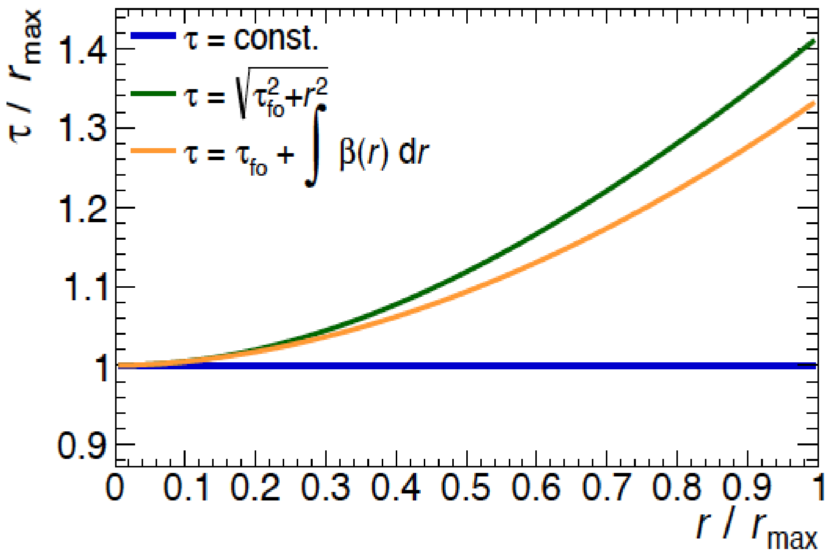
blast wave parametrization of transverse momentum spectrum

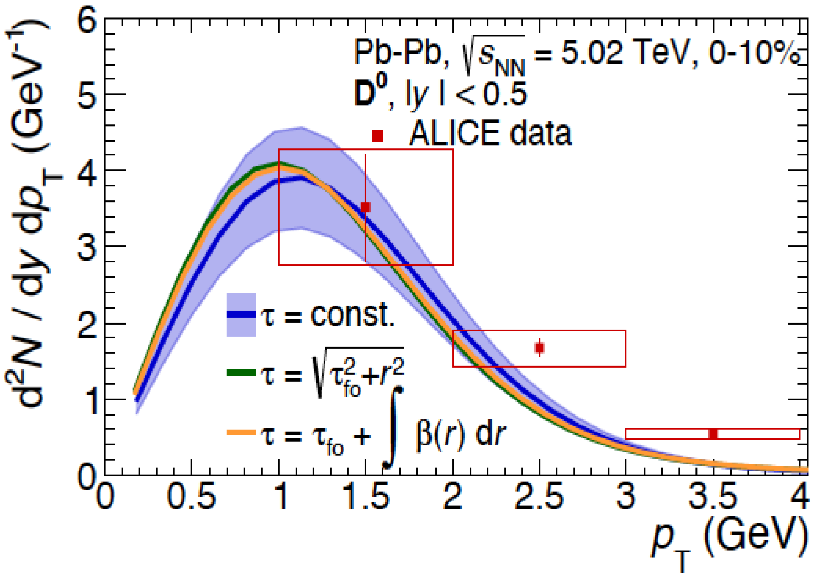
$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{2J+1}{(2\pi)^3}\int d\sigma_\mu p^\mu f(p)$$

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

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

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

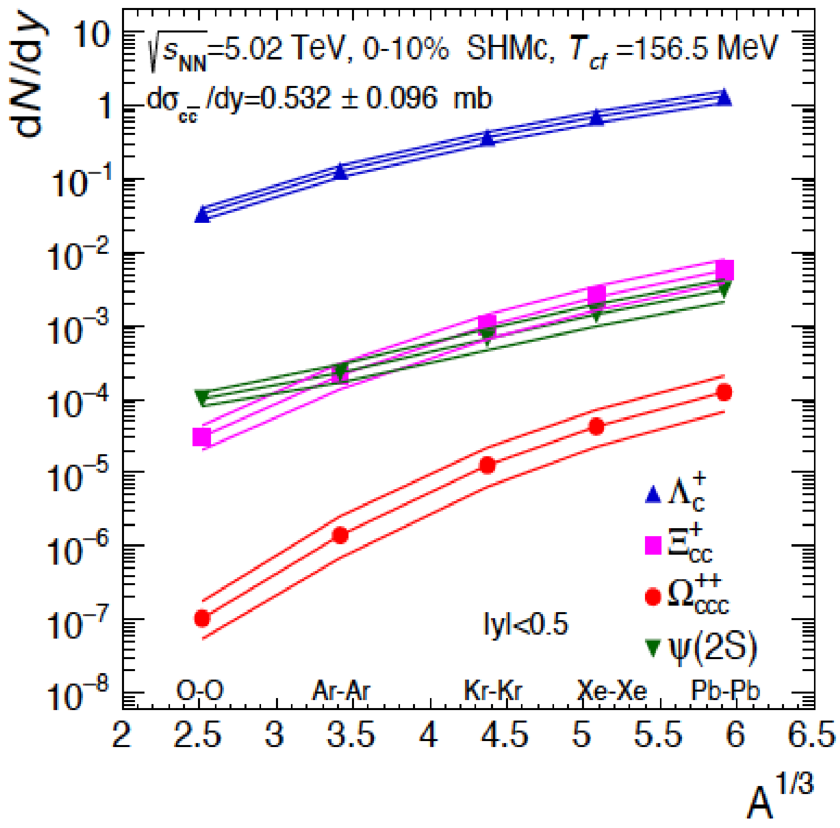


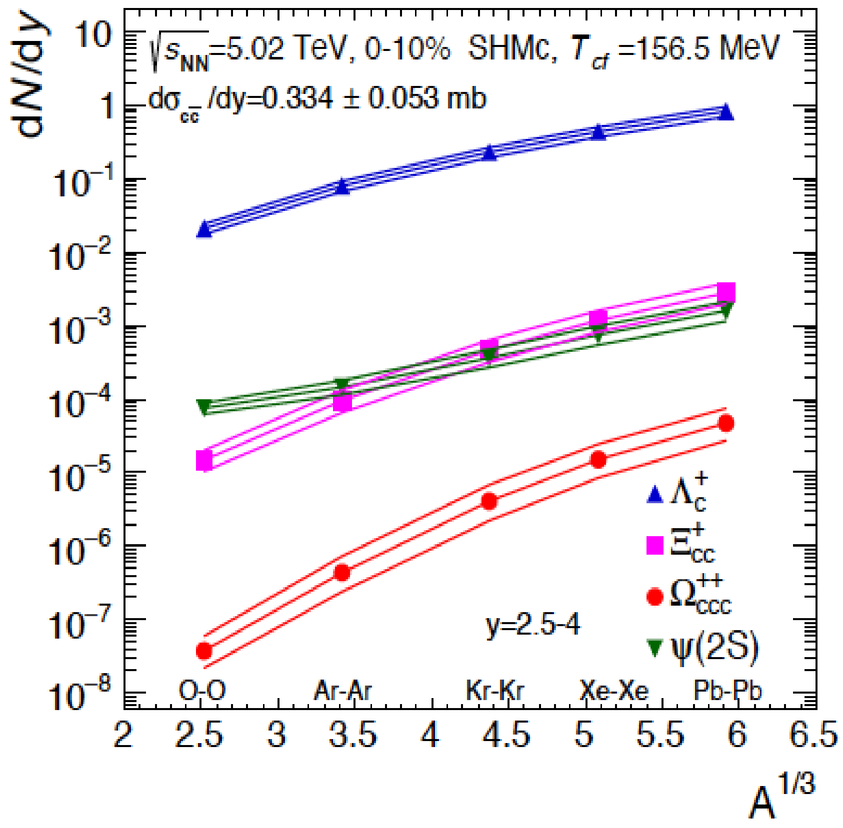


mid-rapidity yields for Pb-Pb collisions

Particle	$\mathrm{d}N/\mathrm{d}y$ 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±0.38)·10^{-3}	0.127 +0.038−0.033
$\psi(2S)$	(3.43 +1.1−0.9)·10^{-3}	(7.87±0.57)·10^{-4}	(4.22 +1.1−0.9)·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)·10^{-2}	(2.59±0.19)·10^{-3}	(1.43 +0.32−0.28)·10^{-2}
$\psi(2S)$	(3.28 +0.90−0.79)·10^{-4}	(3.90±0.28)·10^{-4}	(7.17 +0.94−0.84)·10^{-4}

system size dependence of yields





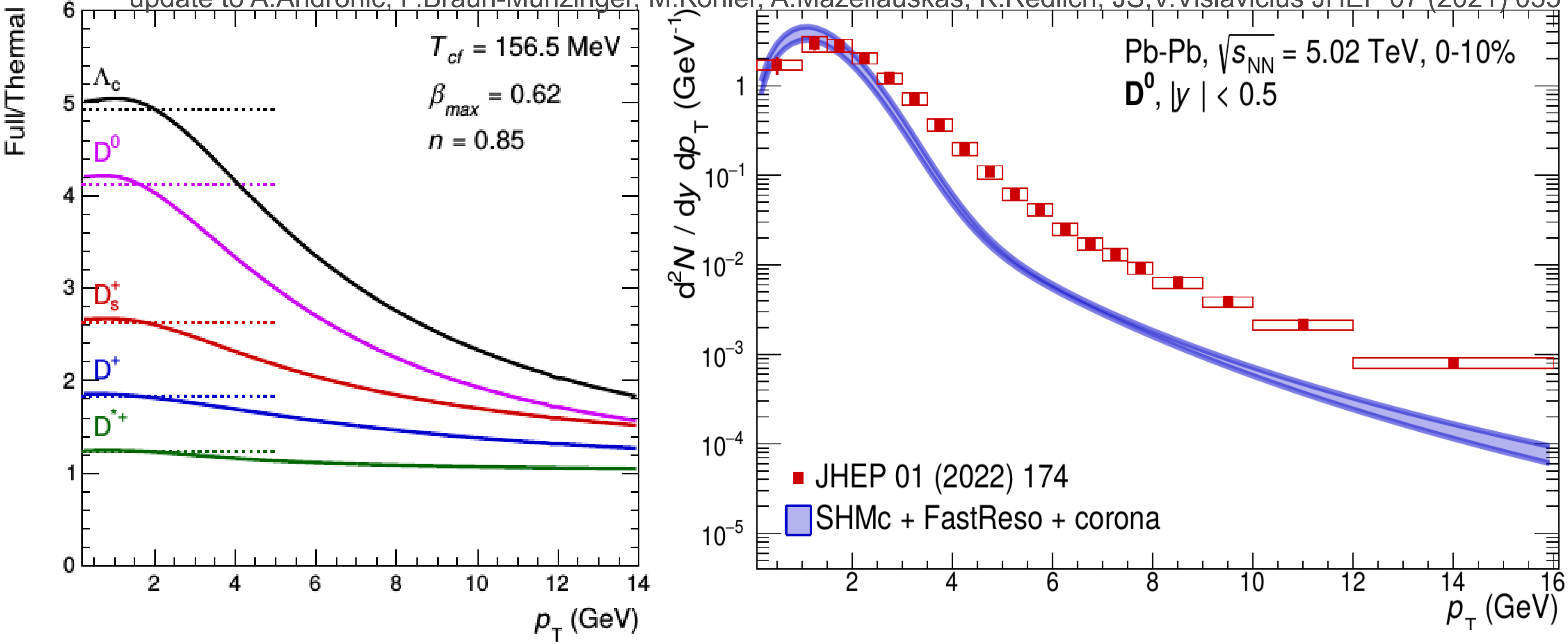
due to different charm quark content different canonical suppression
for multicharm very light collision systems not favored

Spectra of D 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)

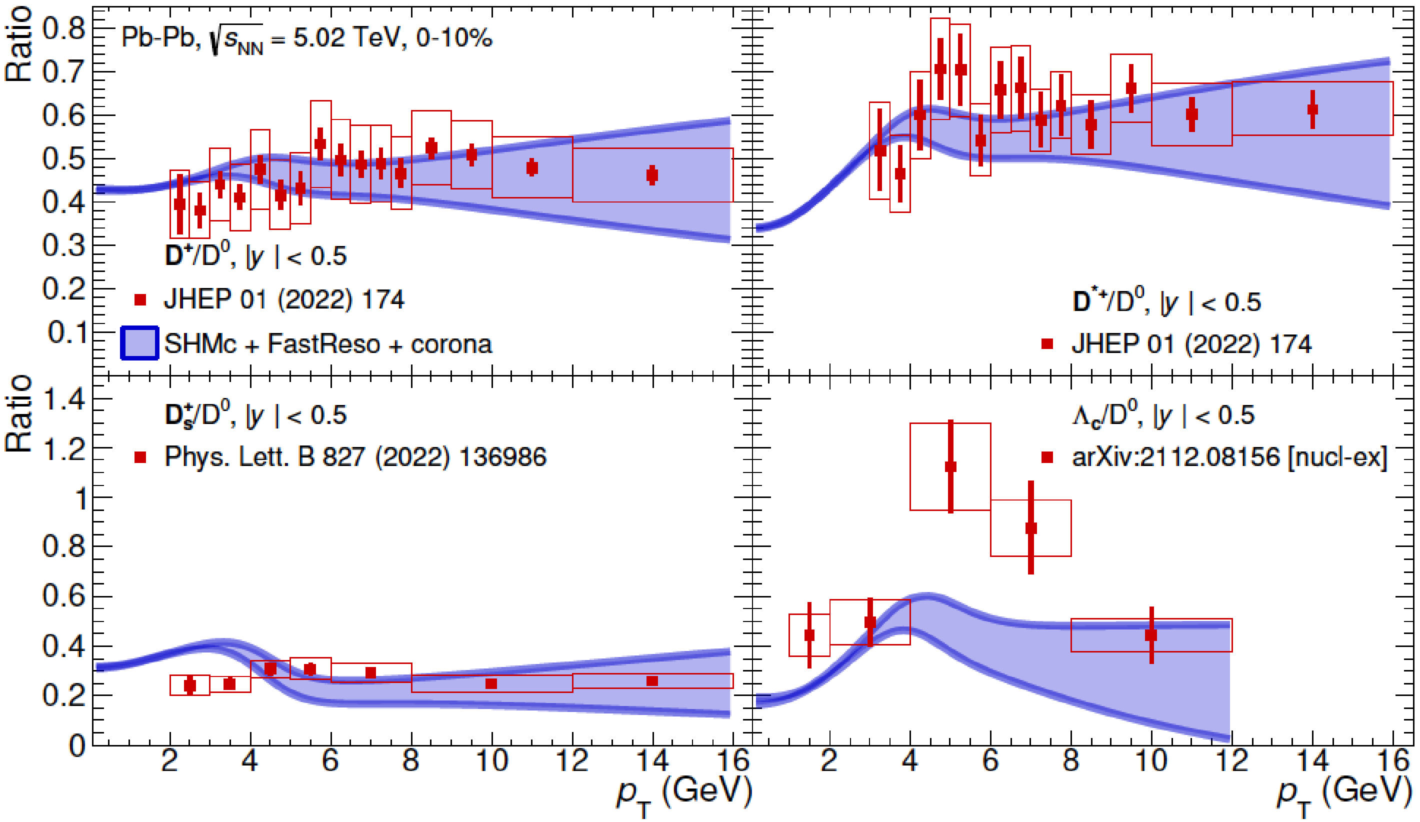
update to A.Andronic, P.Braun-Munzinger, M.Köhler, A.Mazeliauskas, K.Redlich, JS,V.Vislavicius JHEP 07 (2021) 035



thermal part of D^0 spectrum well reproduced by SHMc + hydro flow + decays
as for charmonia, there is need for another source at higher p_t

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

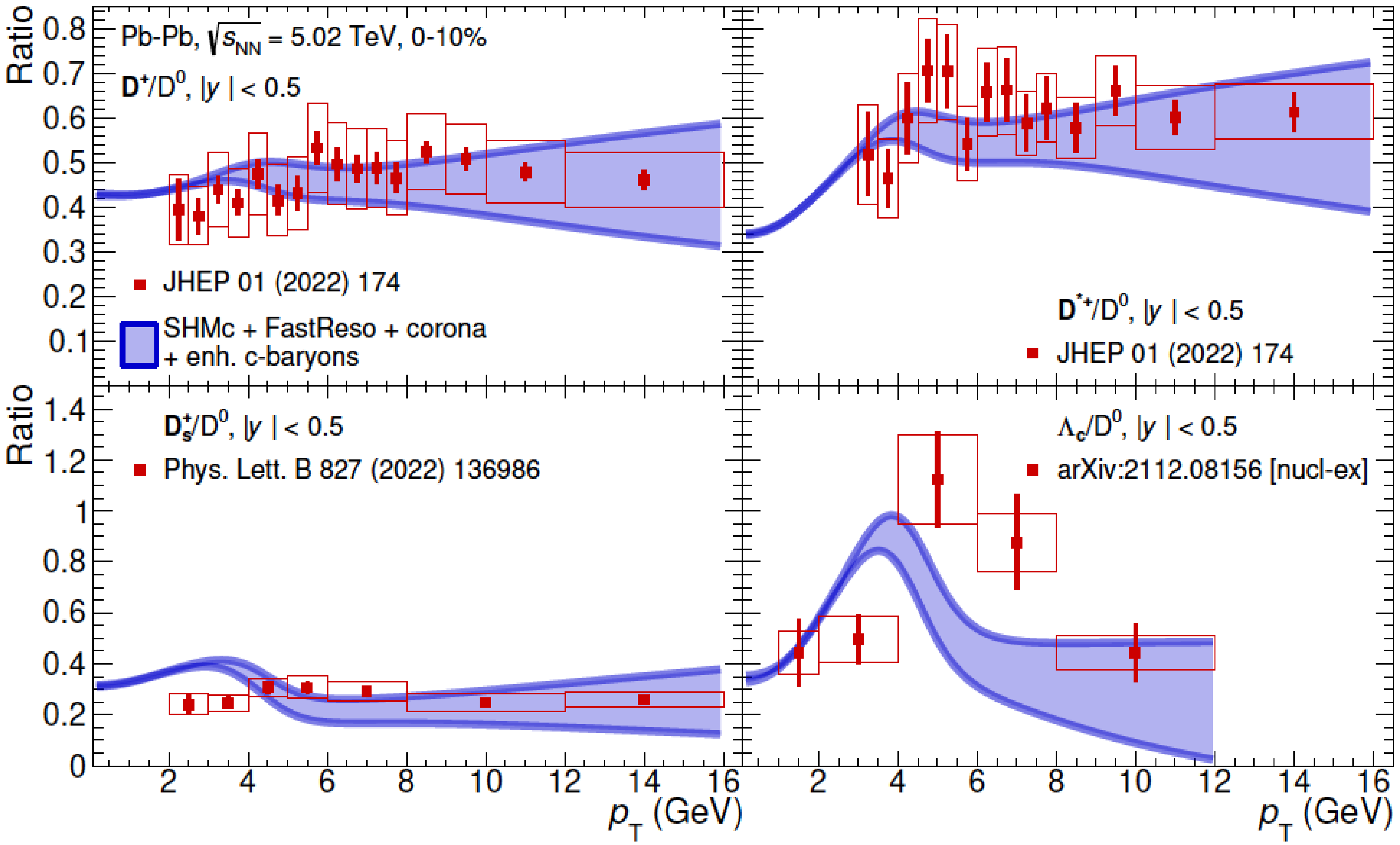


Charm-hadron spectrum: PDG

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

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



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

example: X(3872)

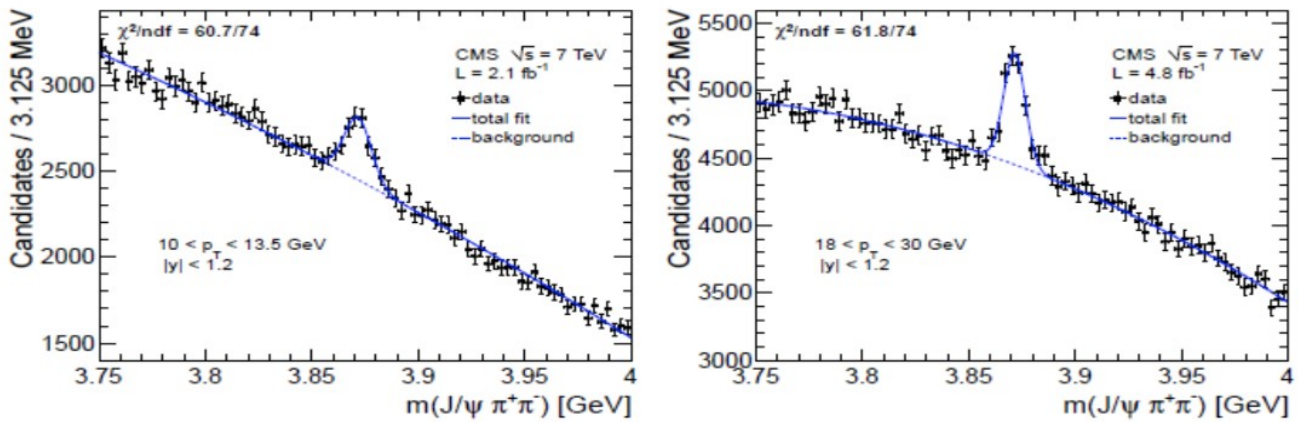
X(3872)

- 2003 -

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

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

- 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

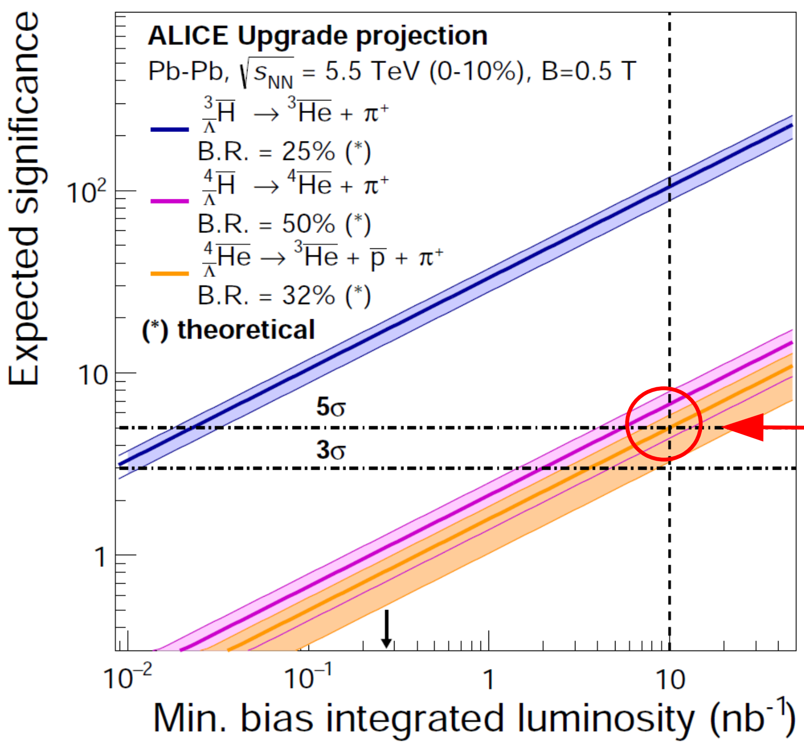
$m_{X(3872)} - m_{\psi(2S)}$

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

22

Opportunities hadronization into nuclei

elucitate mechanism of formation of nuclei:
SHM for QGP hadronizing into compact multiquark states ↔ coalescence

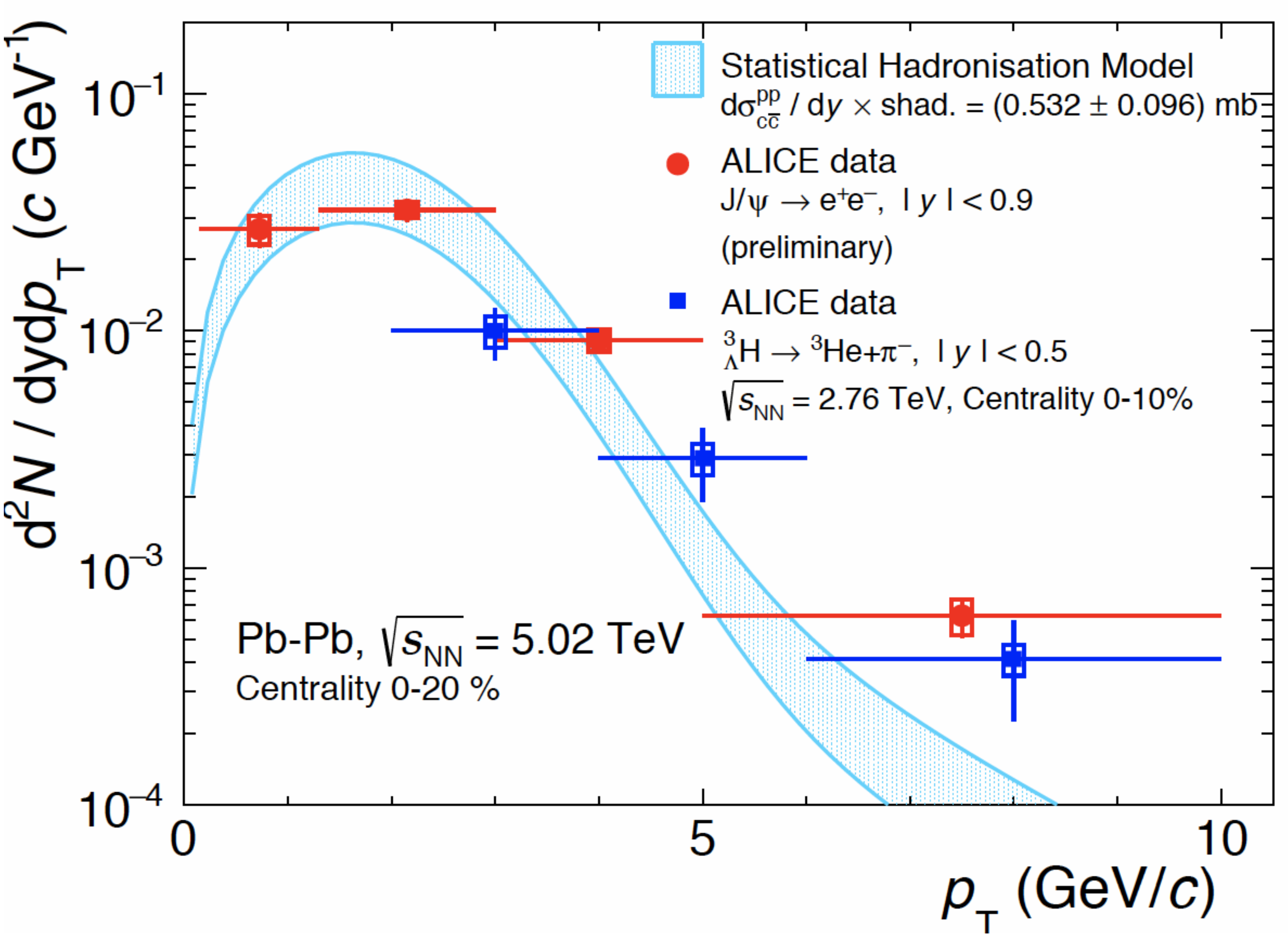


(anti-)(hyper-)nuclei ALICE Run3/4 - 10nb^{-1}
^{3}He, $^{3}_{L}$He, ^{4}He as function of centrality (source size)
spectrum ^{4}He
$^{4}_{L}$H and $^{4}_{L}$He 5s level in reach
S-hyper-nuclei: search for $^{3}_{S}$H
exotic QCD bound states: hexaquark

ALICE3: $^{4}_{L}$He and $^{5}_{L}$He $^{5}_{L}$He not yet discovered (m about as expected W_{ccc})
A = 6 should become accessible ^{6}Li and ^{6}He (lightest halo nucleus)

is hadronization governed by mass and quantum numbers only?

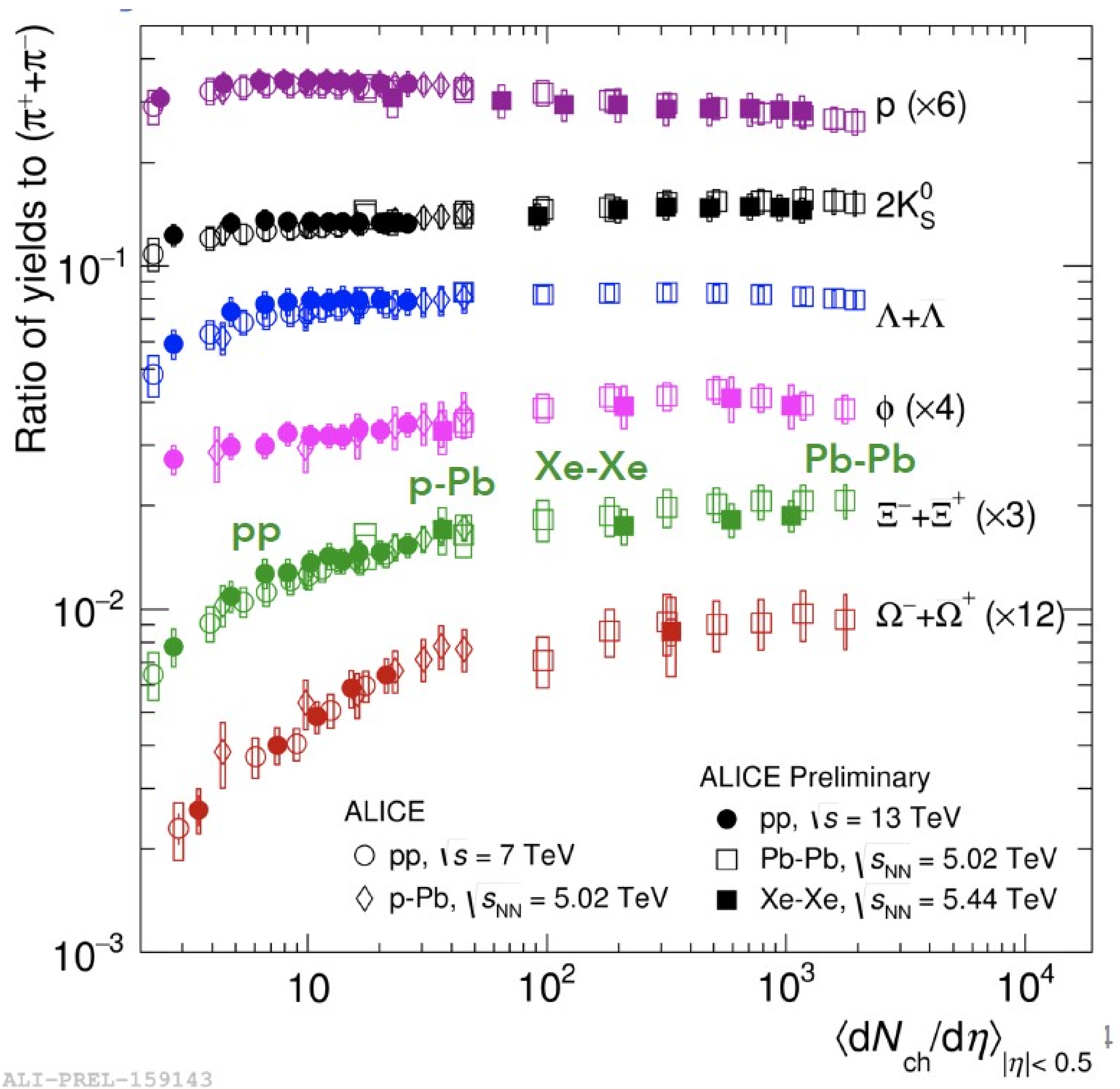
J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



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



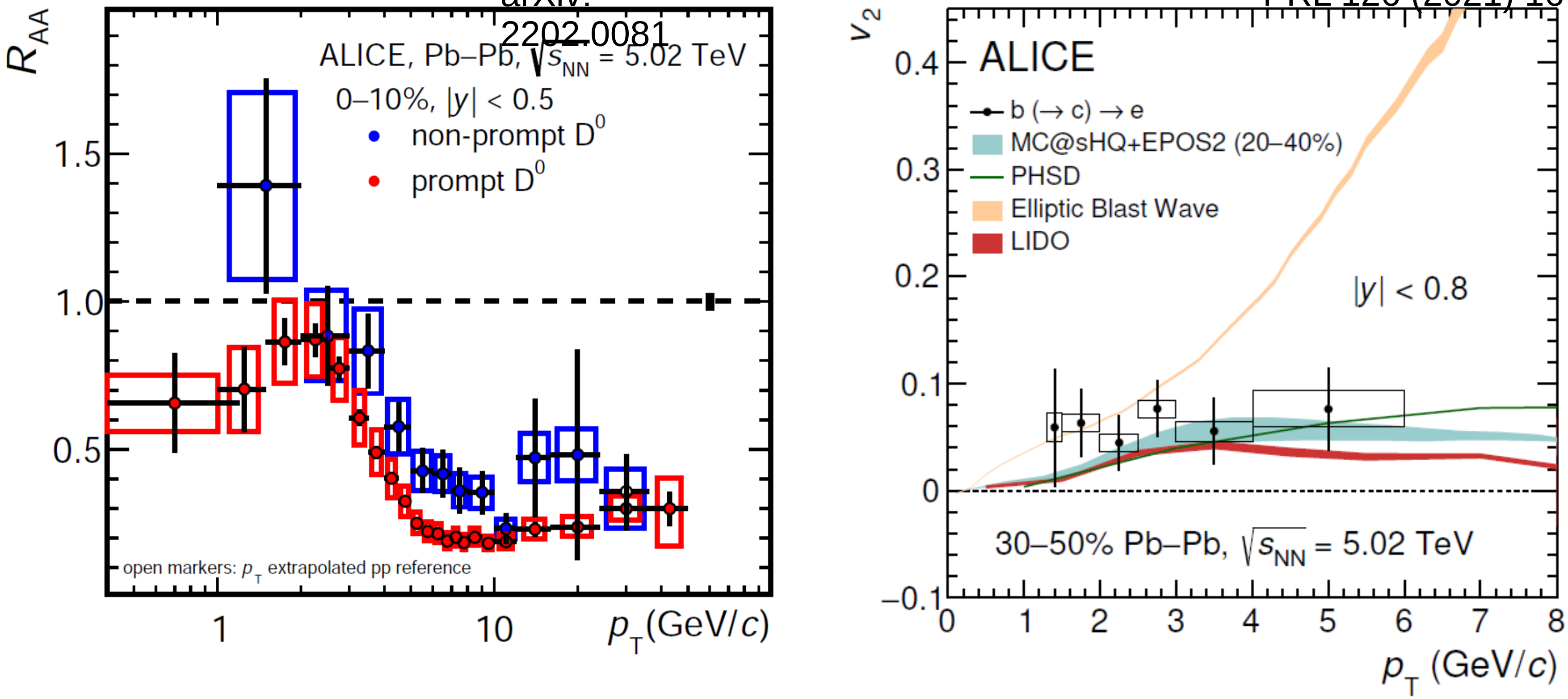
universal hadronization can be described with few parameters in addition to T and μ_B

transition from canonical to grand-canonical thermodynamics

Thermalization of beauty?

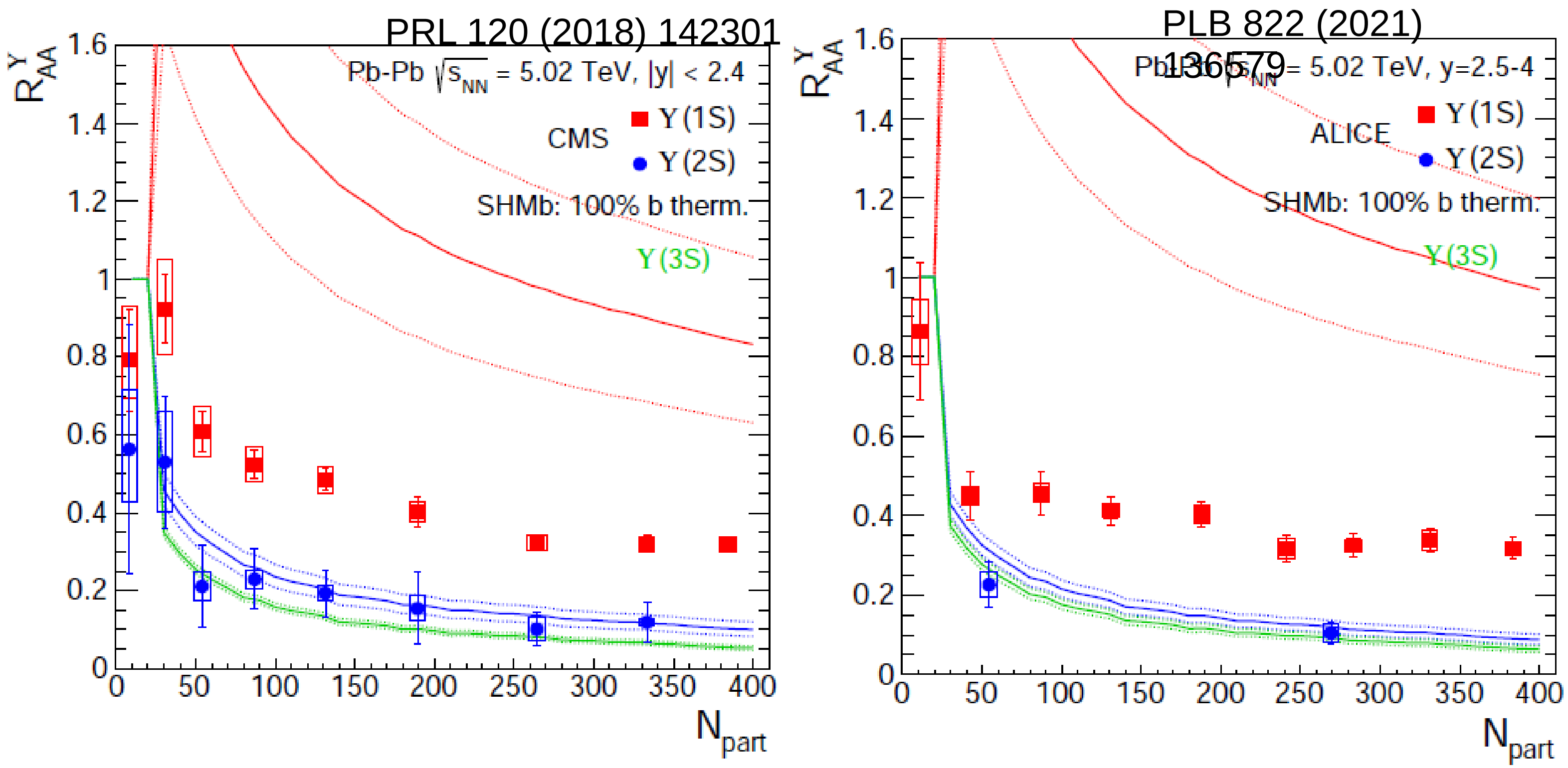
arXiv: 2202.0081

PRL 126 (2021) 16



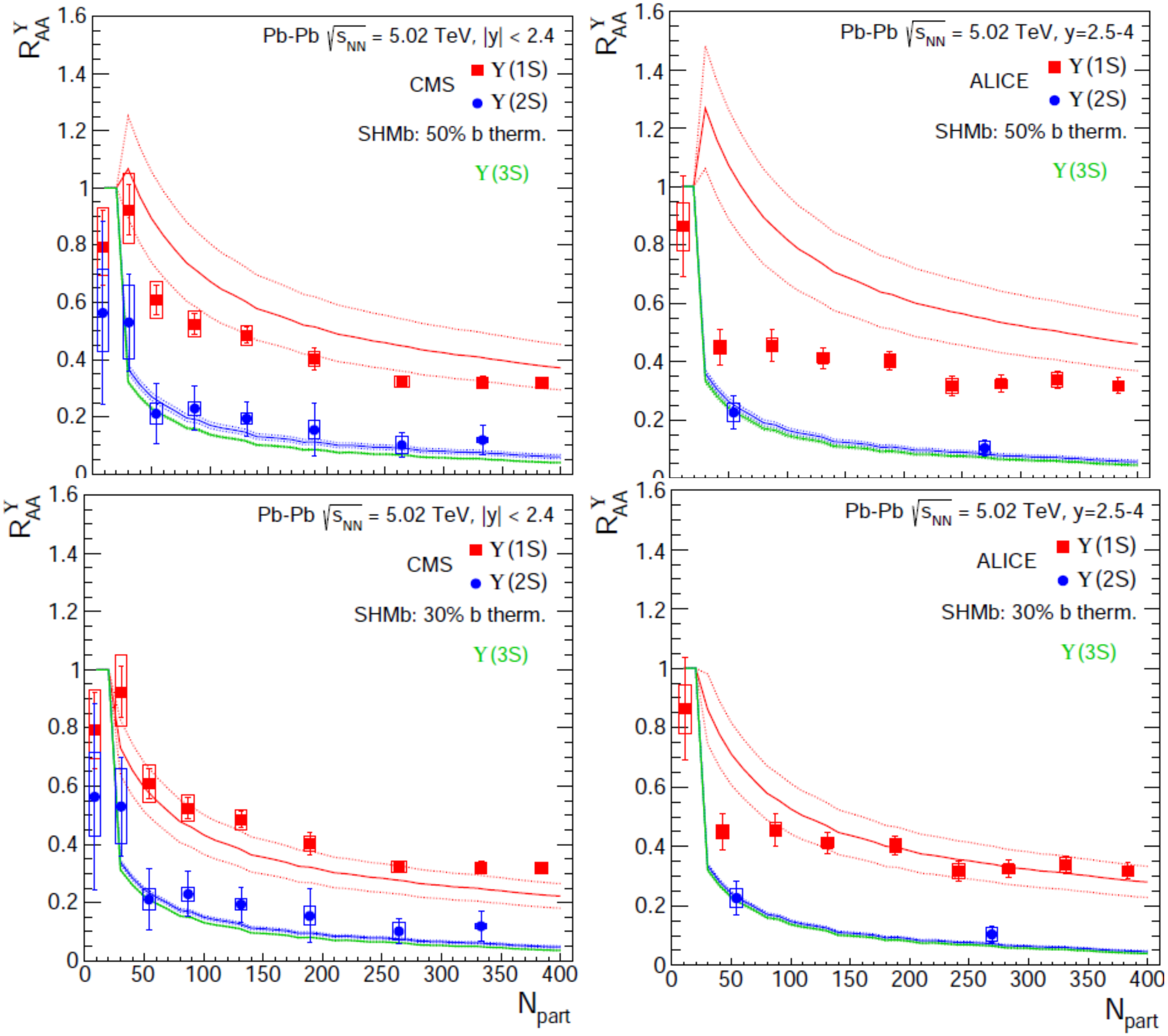
strong reduction of R_{AA} and significant v_2, but both a factor 2 less pronounced than for prompt D0 → indication that beauty quarks thermalize only partly
only the thermalized fraction should hadronize statisticly

Bottomonia in SHMb assuming full thermalization



- indeed, assumption of fully thermalized b-quarks fails to reproduce ϒ(1S) by factor 2-3 for central collisions
  but: $g_b = 10^9$ so ϒ is scaled up from thermal yield by 10^{18}
- so, to come without any free parameter within a factor 2-3 is not a minor feat

Bottomonia assuming partial thermalization



factor 2-3 reproduces Υ yields could be in line with open beauty energy loss and flow