charm as probe of deconfinement
status and opportunities

- introduction: the chiral and deconfinement transitions and the phase diagram of strongly interacting matter
- LHC data on open and hidden charm hadrons and relevance for deconfinement
- future opportunities for Runs 3 and 4 and in particular, ALICE3

based on
- published data, mostly ALICE
- work with A. Andronic, P. Braun-Munzinger, K. Redlich and recently, in addition, H. Brunßen, J. Crkovska, M. Völkl
- the ALICE3 LOI and scoping document

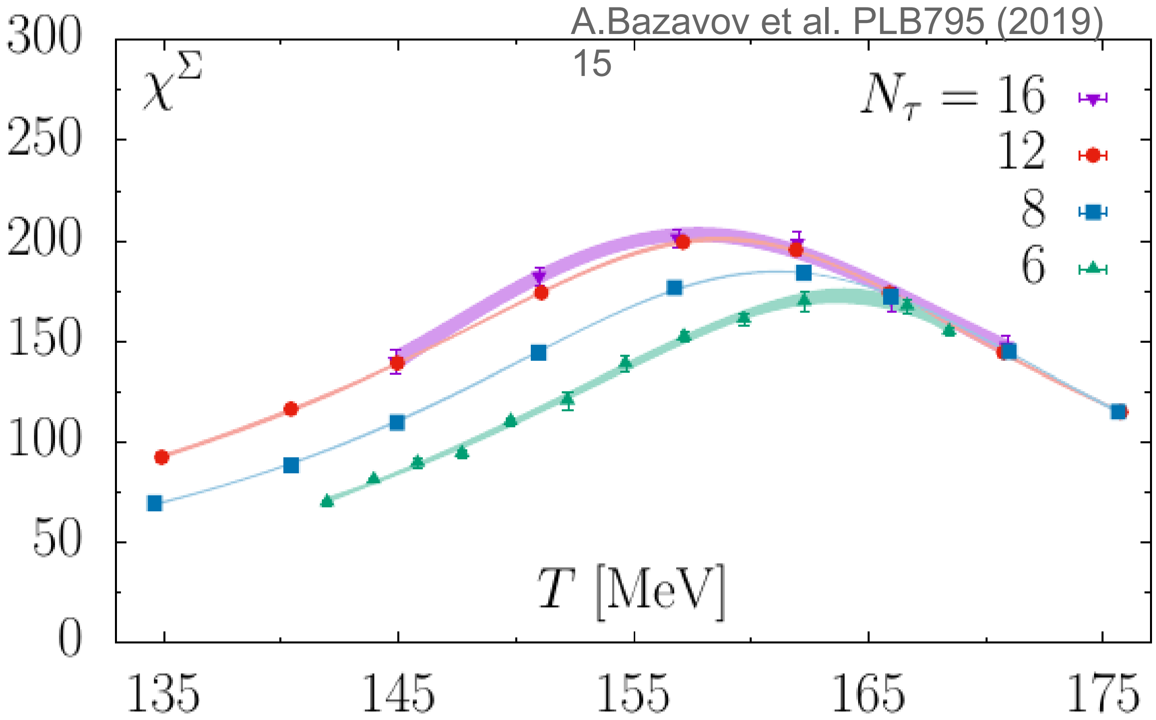
Johanna Stachel, Phys. Inst. Universität Heidelberg
61st Int. Winter Meeting in Nuclear Physics, Bormio, Italy,
January 27-31, 2025

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

$$\langle \bar\Psi \Psi \rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial m} \qquad \chi_{\bar\Psi\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

A.Bazavov et al. PLB795 (2019) 15



most recent results on pseudo-critical temperature for chiral phase transition

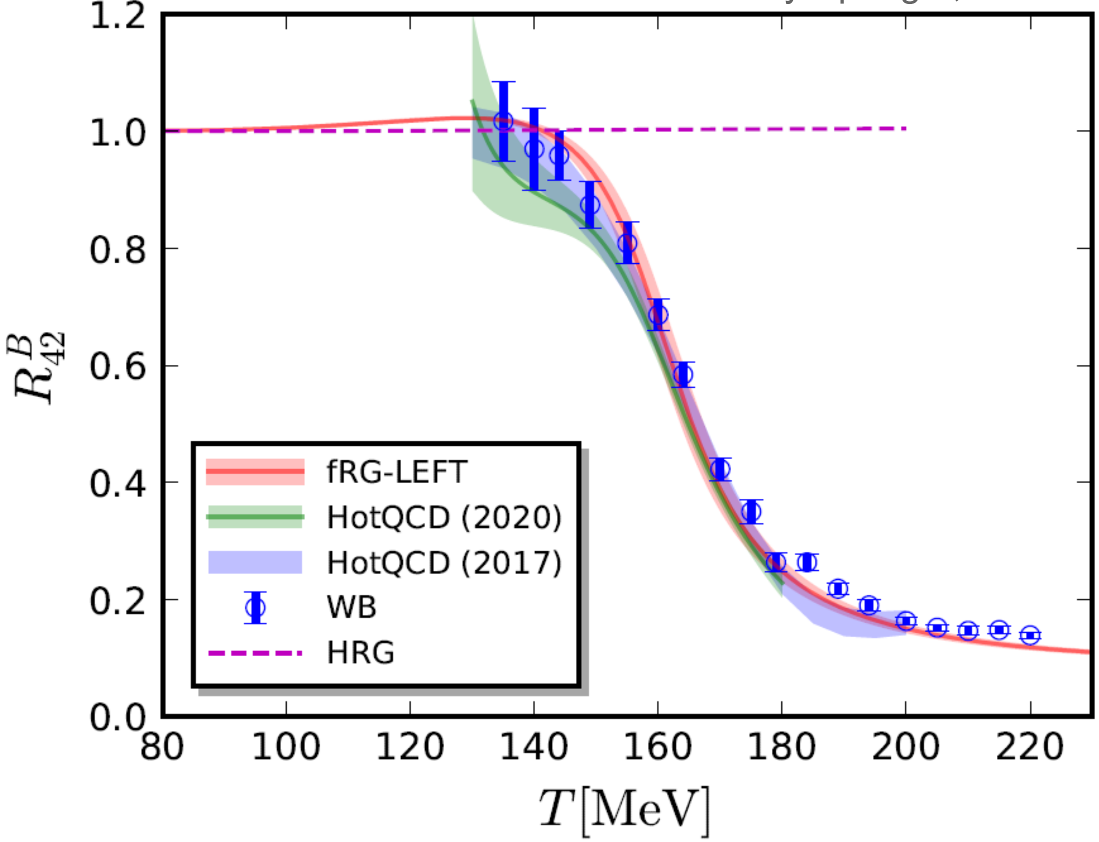
HotQCD Coll. PLB 795 (2019) 15
(comparing diff. measures)
T_{pc} = 156.5 +- 1.5 MeV
Wuppertal-Budapest Coll.
PRL 125 (2020) 052001
T_{pc} = 158.0 +- 0.6 MeV

Measure of deconfinement in lQCD

ratio of quark number susceptibilities

$$R_{42}^{B} = \chi_4^B / \chi_2^B \propto \text{baryon number}^2 \qquad \chi_n^{\mathrm{B}} = \frac{\partial^n (P/T^4)}{\partial \hat{\mu}_B^n}$$

L.W.Chen et al. to be ublished by Springer, 2022



confined: 1

deconfined: $6/9\pi^2$

measure suggested by Ejiri, Karsch, Redlich (2006)

rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

Production of hadrons and (anti-)nuclei at LHC

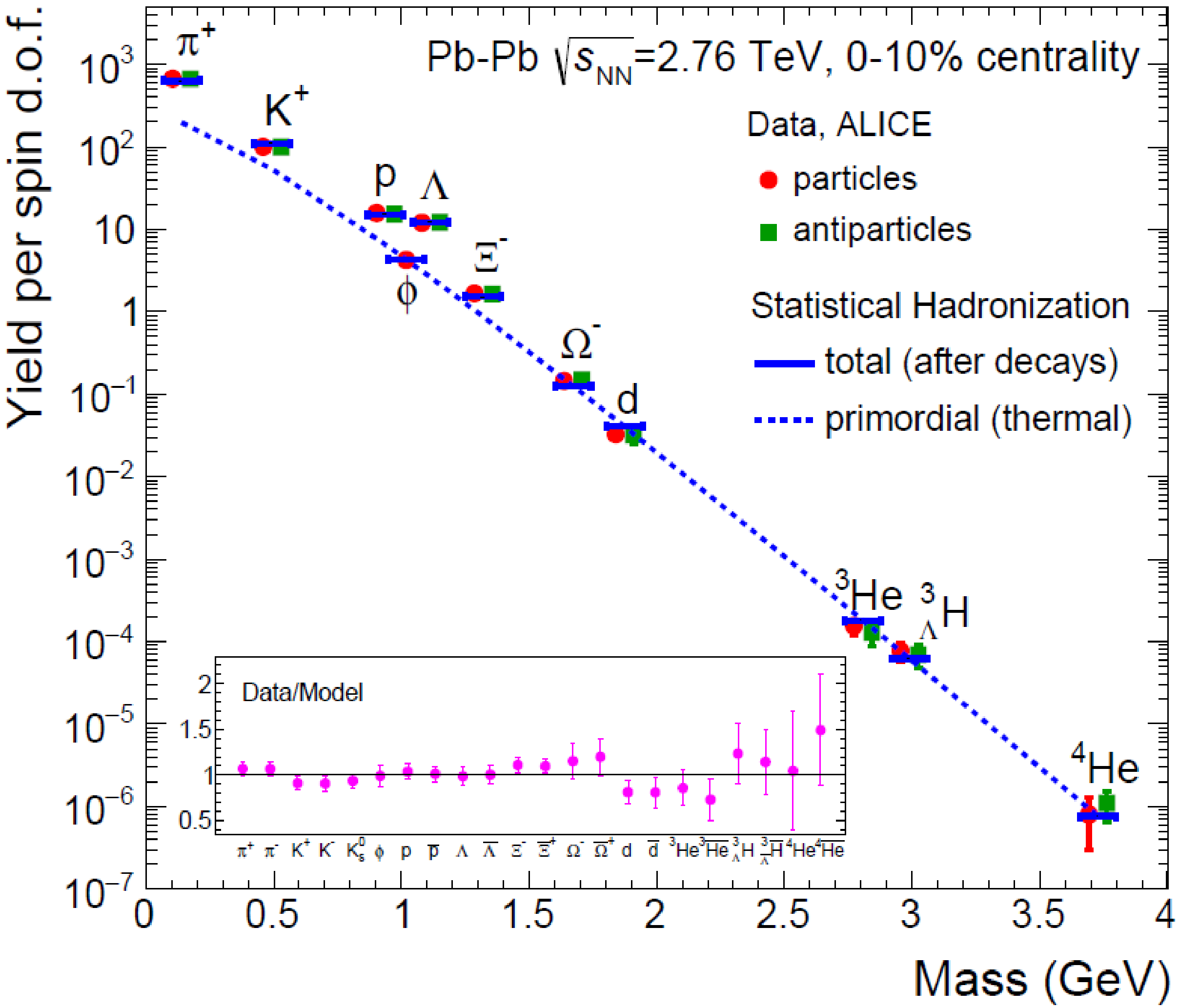
1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

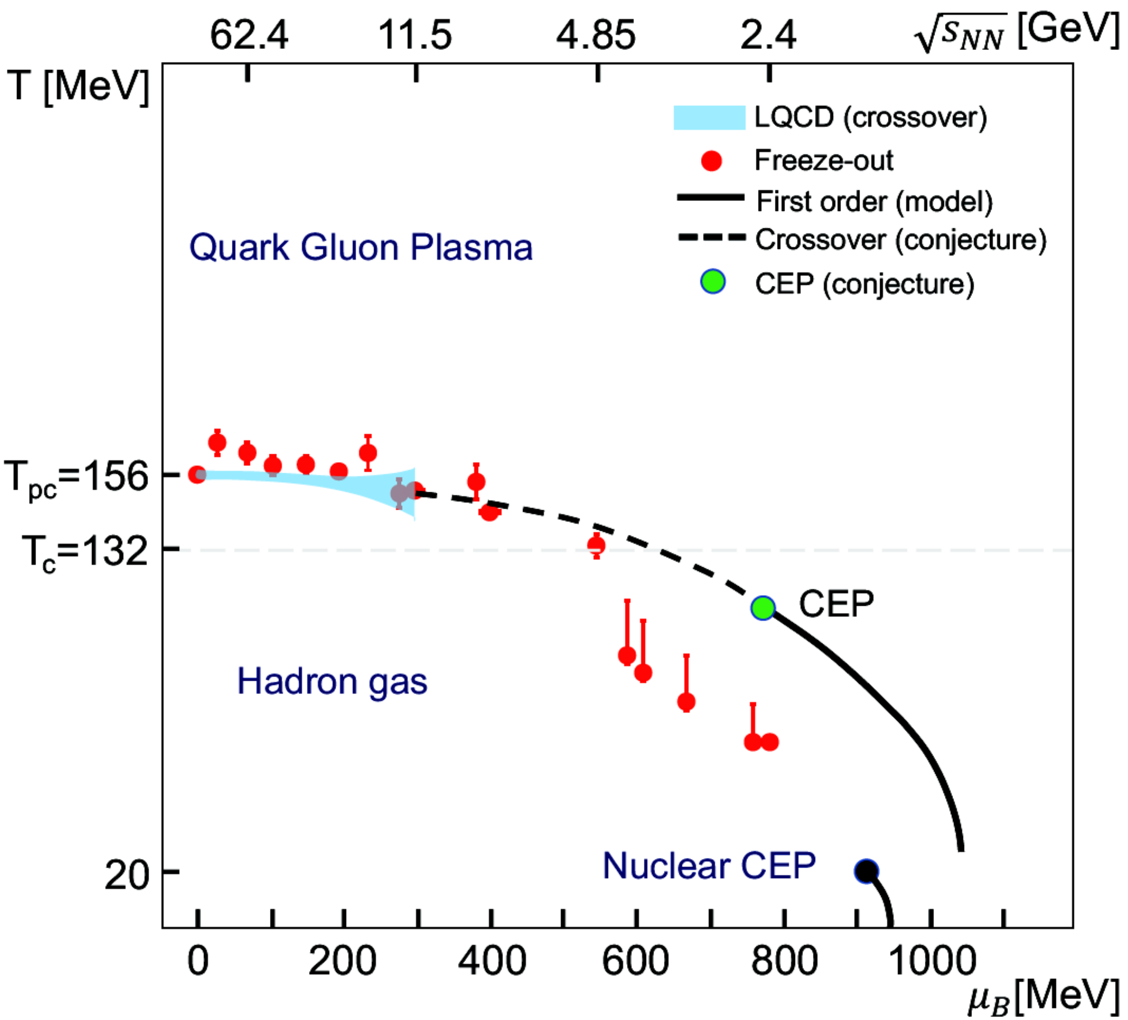
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- matter and antimatter are formed in equal portions at LHC
- even large very fragile hypernuclei follow the same systematics

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321



Freeze-out points and the phase diagram



P. Braun-Munzinger, A. Rustamov, J. Stachel arXiv:2211.08819

hadron yields for Pb-Pb central collisions from LHC down to RHIC, SPS, AGS and even SIS energies well described by a statistical ensemble

- limiting temperature hadronic system, reached for $\sqrt{s_{NN}} \geq 12$ GeV

- T_{CF} at LHC in exact agreement with the pseudo-critical temperature T_{pc} from lQCD

A. Bazavov et al. PLB 795 (2019) 15
S. Borsanyi et al. PRL 125 (2020) 052001

- why chemical freeze-out very close to T_{pc}? close to T_{pc} rate for multi-particle reactions explodes (critical opalescence)

P. Braun-Munzinger, J. Stachel, C. Wetterich (2004)

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)

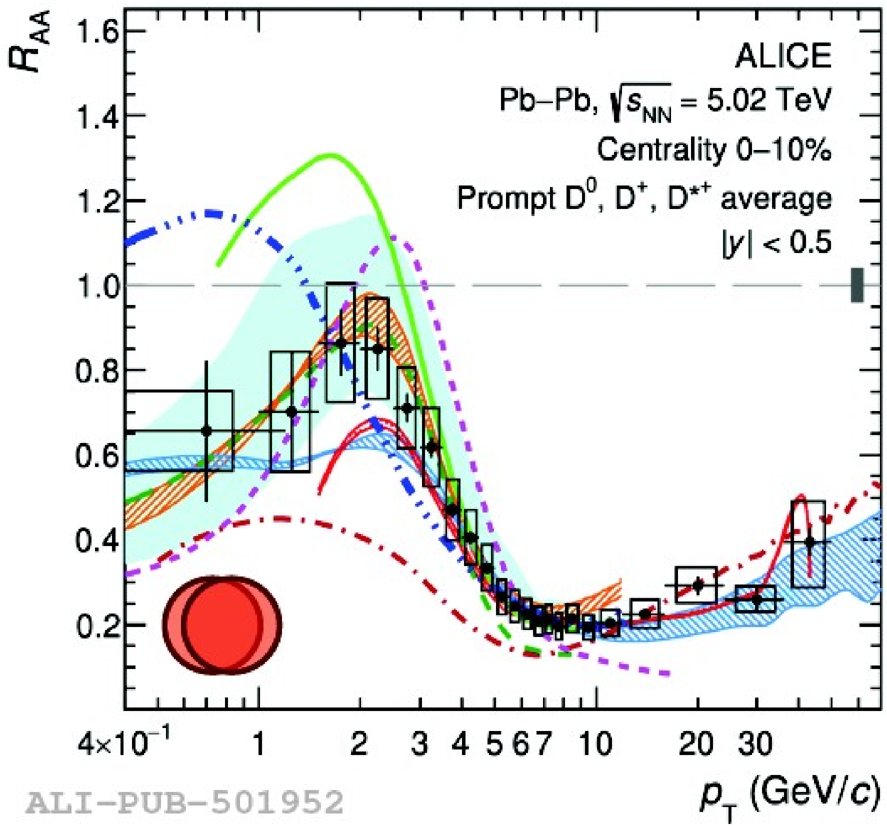
can consider deconfined quarm quarks as impurities inside the QGP
thermal production at LHC energy still negligible
annihilation of charm quarks in QGP negligible

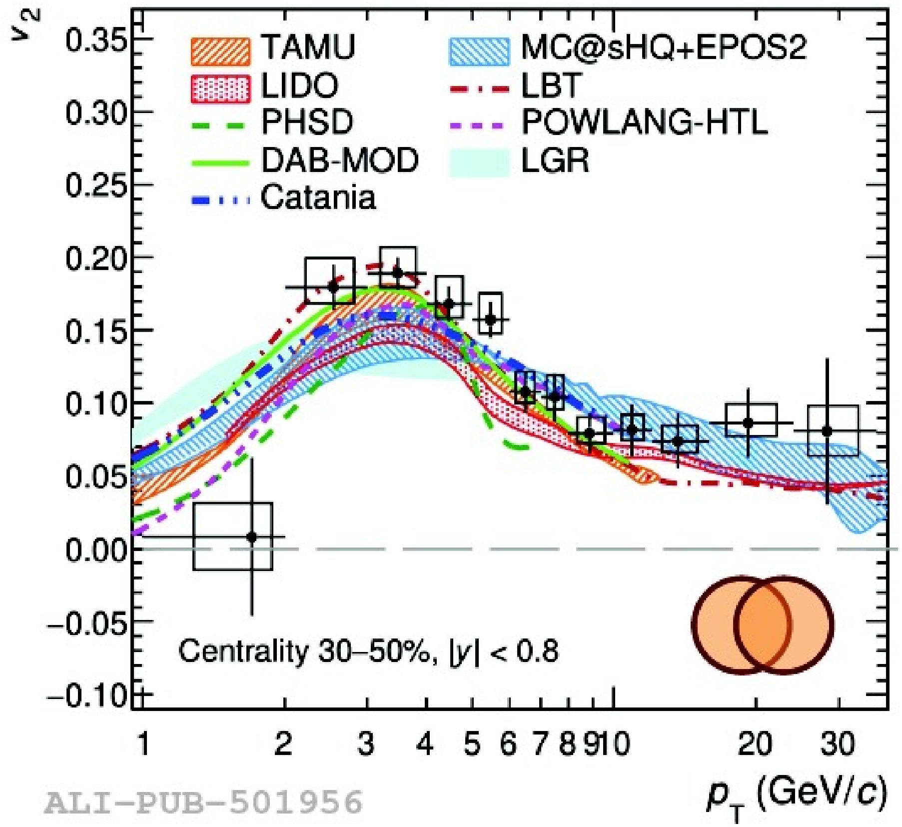
there is strong experimental evidence that charm quarks thermalize inside the QGP
- supported by transport coefficients computed in lattice QCD

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 $1.5 < 2\pi T D_s < 4.5$ at T_c $\rightarrow$ τ_{kin} = 2.5 – 7.6 fm/c

JHEP01 (2022) 174 arXiv:2110.09420





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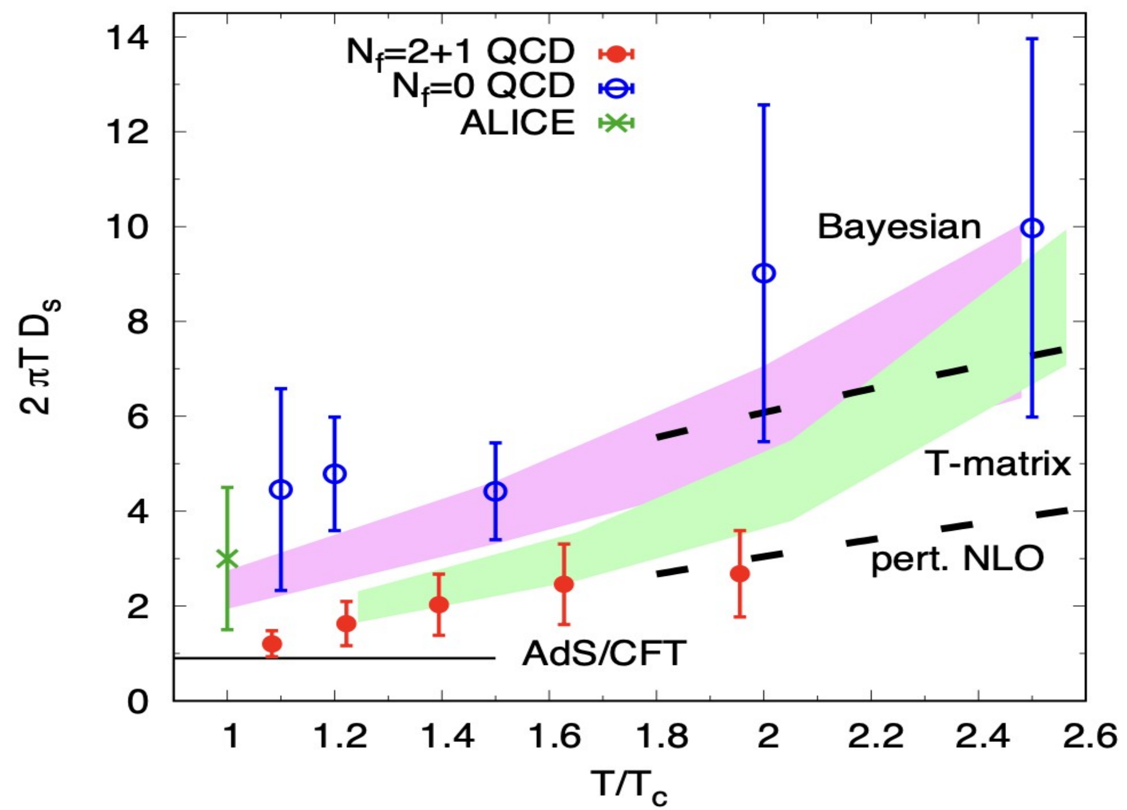
lQCD:
D_s from gradient flow on color-electric two-point function
(leading order in 1/M expansion)

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

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



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

minimal modification of standard statistical model: implant charm as impurity and conserve number of initially produced charm quarks

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

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

Hadronization of charm quarks

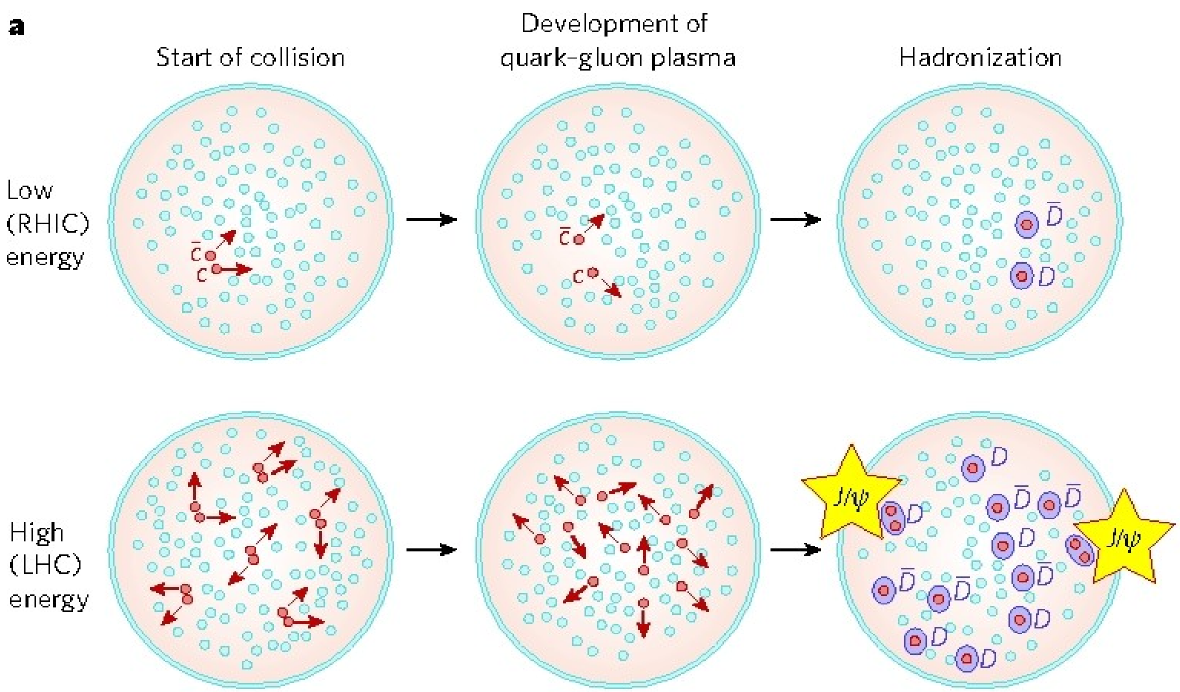
all charm quarks have to appear in charmed hadrons
at hadronization of QGP also J/ψ can form from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^2$

(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)

also applies to b-quarks and bottomonia

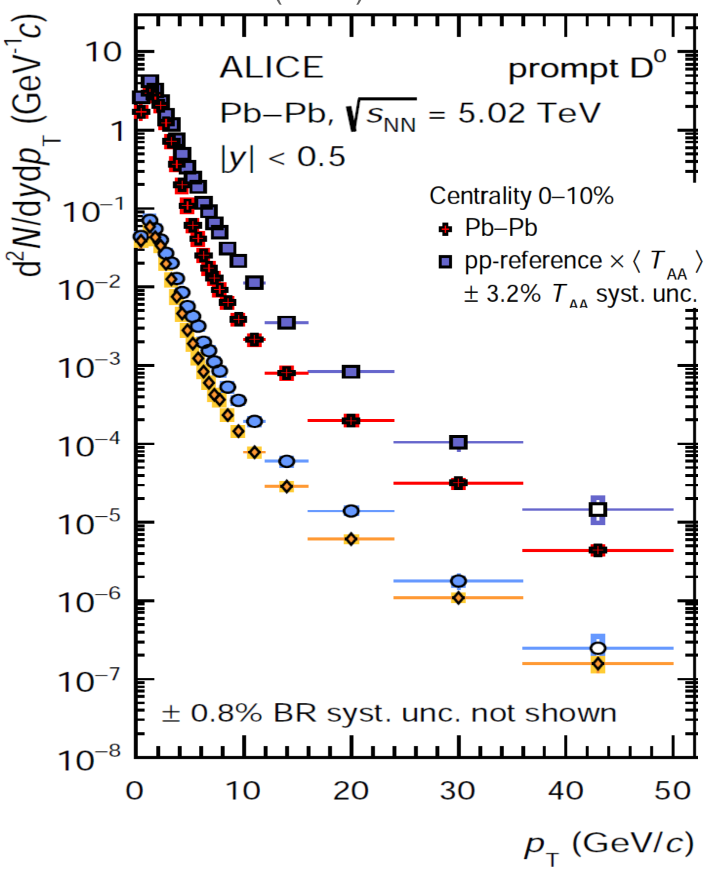
(A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel NPA 789 (2007) 334)

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



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

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

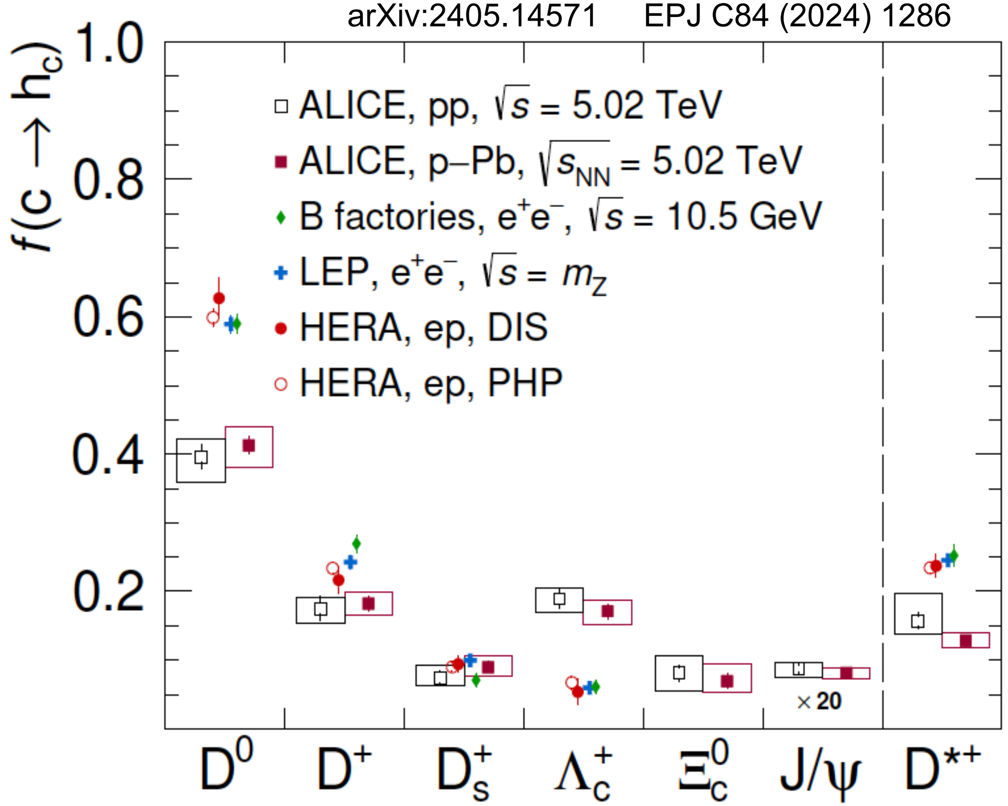
corresponding to $g_c = 31.4 \pm 4.8$

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

Modified charm fragmentation at the LHC

arXiv:2405.14571 EPJ C84 (2024) 1286

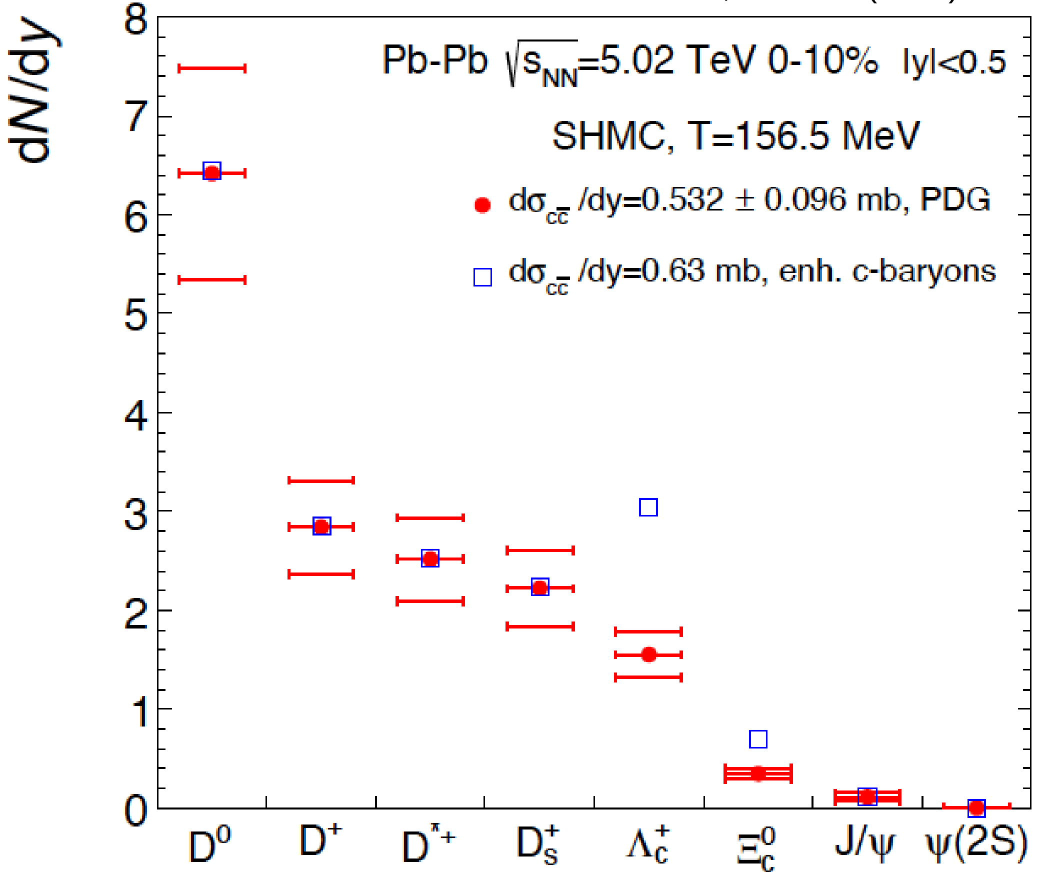


fragmentation into charmed baryons strongly enhanced in pp, pPb and PbPb collisions compared to e^+e^- and ep

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

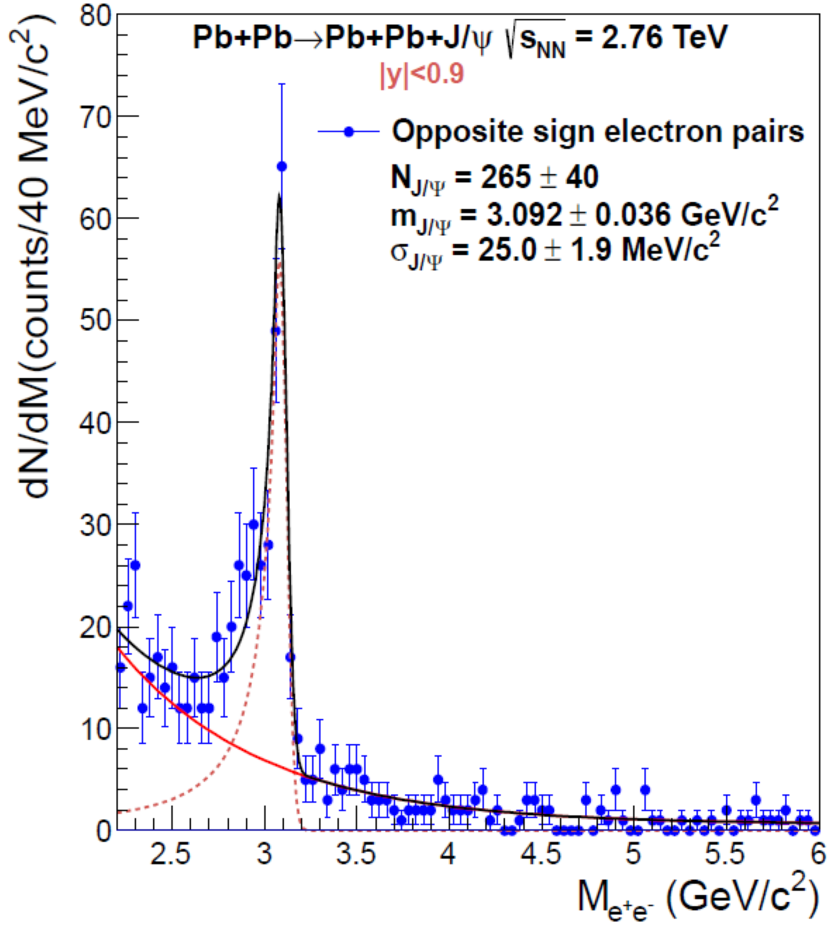


charm cross section increases 20%
yield of charm baryons nearly doubles
mesons practically unaffected

Reconstruction of J/ψ in PbPb collisions at LHC

J/ψ → e^+e^- or $\mu^+\mu^-$ with 6%

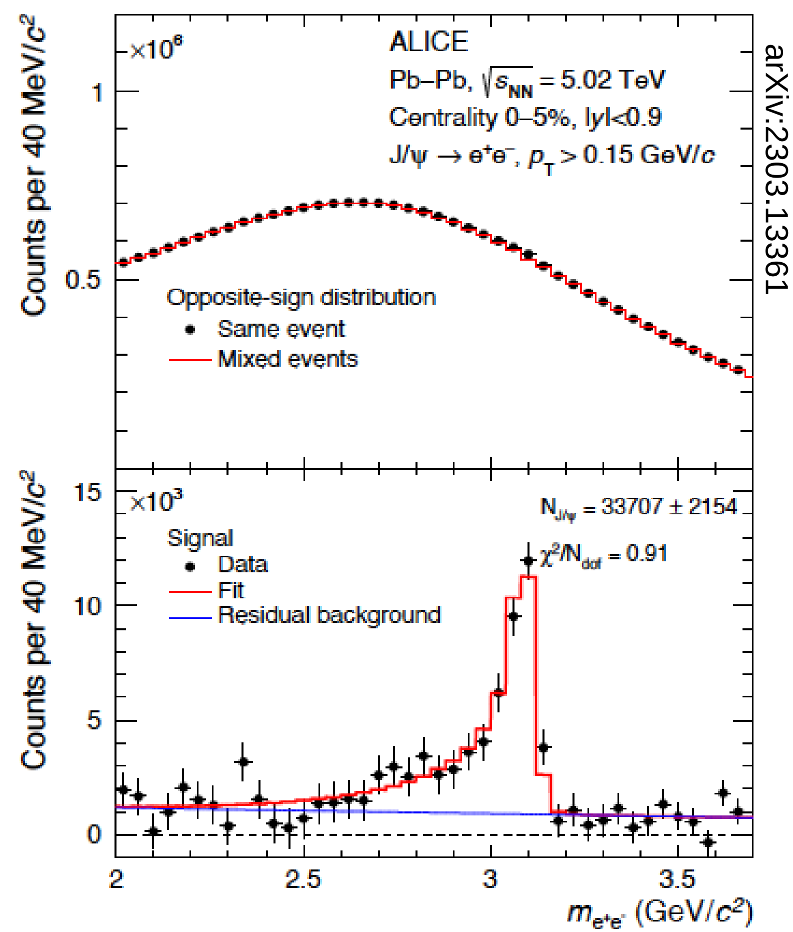
ALICE EPJ C73 arXiv:1305.1467



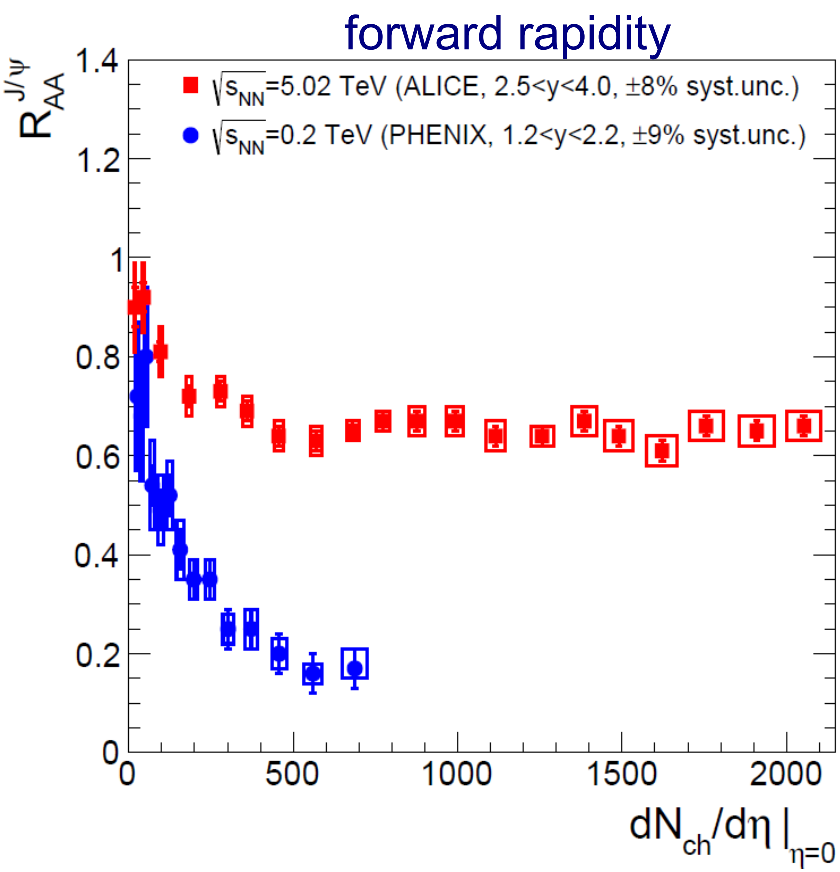
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background very good understanding of line shape

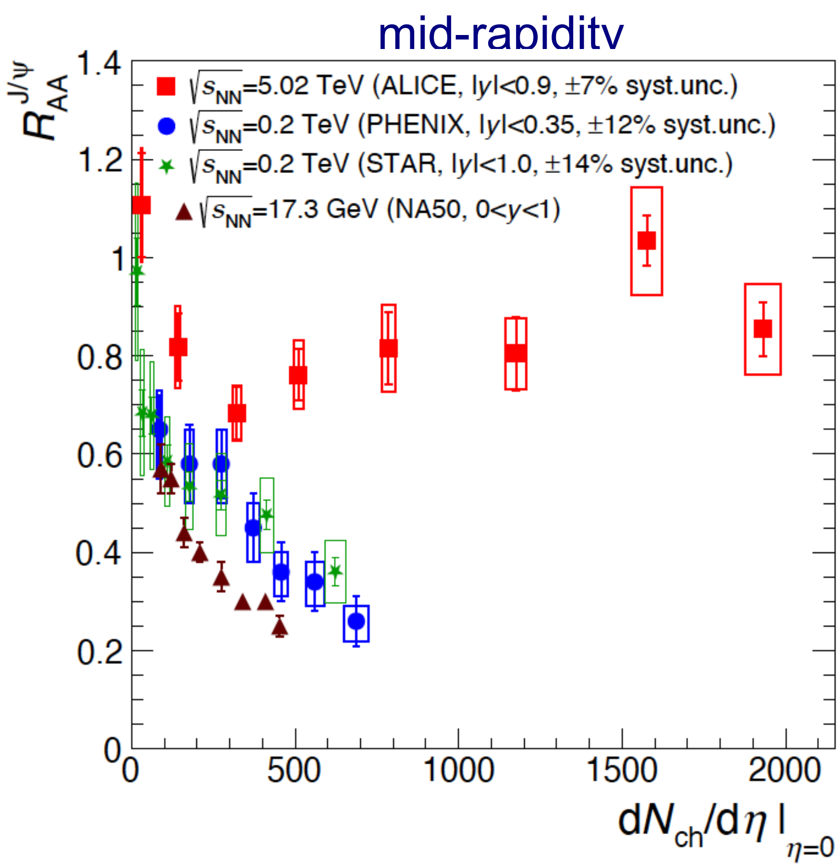
most challenging: central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

mid |y| < 0.8



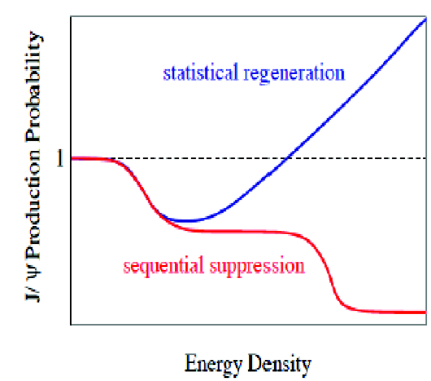
J/ψ production in PbPb collisions: LHC relative to RHIC





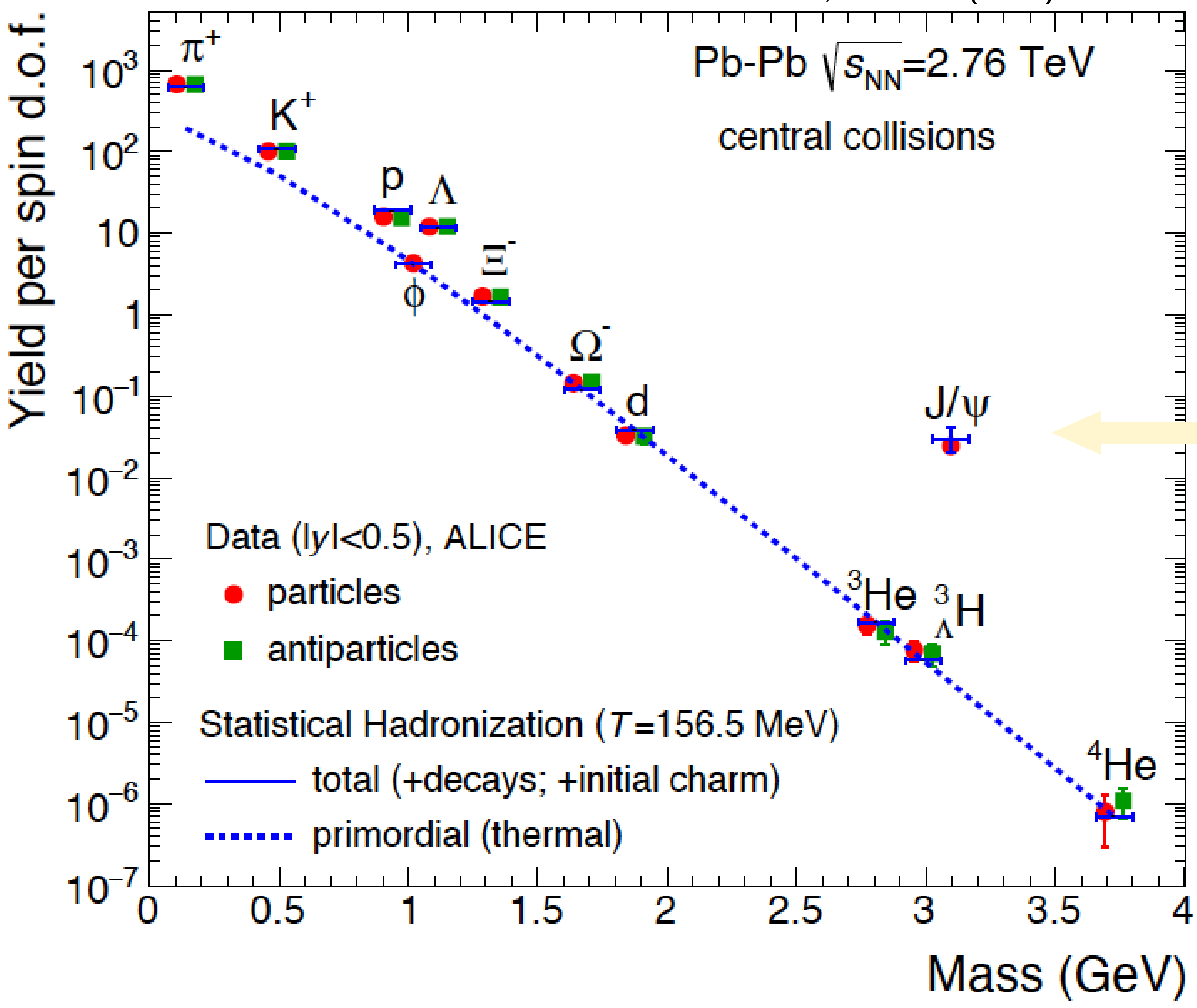
energy density →

the biggest qualitative change from RHIC to LHC:
enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



J/ψ overpopulation due to hard production of charm and statistical hadronization of deconfined quarks

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

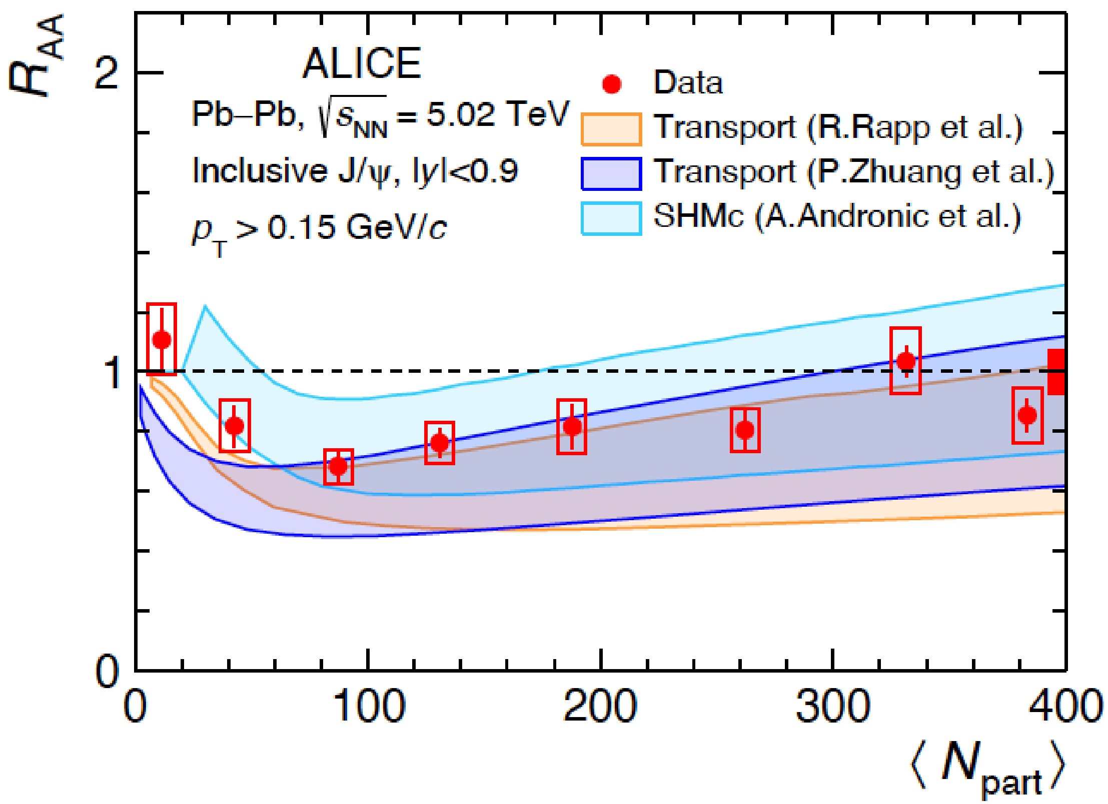


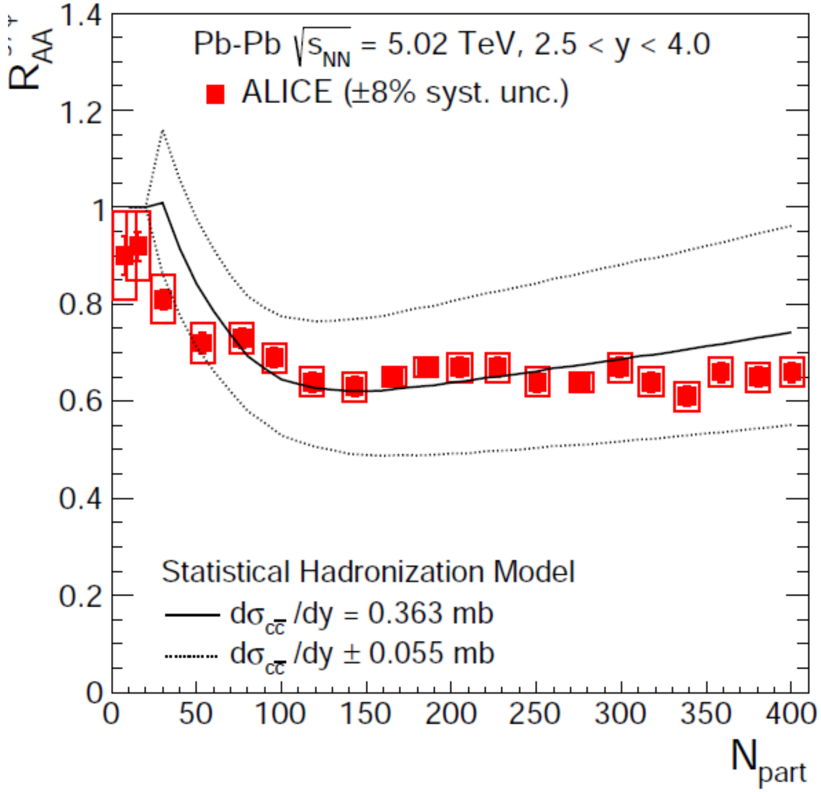
J/ψ enhanced compared to other M = 3 GeV hadrons by factor g_c^2 =900 relative to purely thermal yield

quantitative agreement with hadronization of deconfined thermalized charm quarks

J/ψ and statistical hadronization

arXiv: 2303.13361



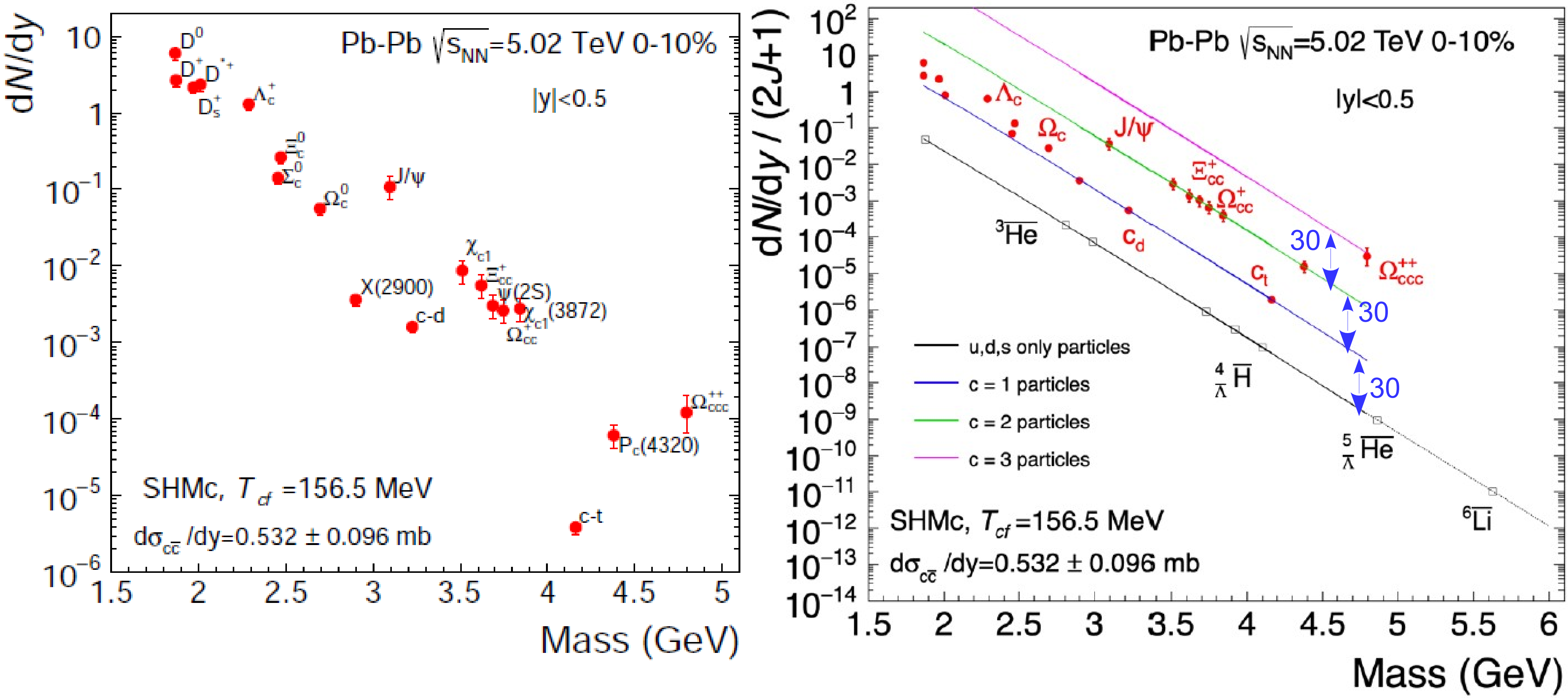


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

the multi-charm hierarchy

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

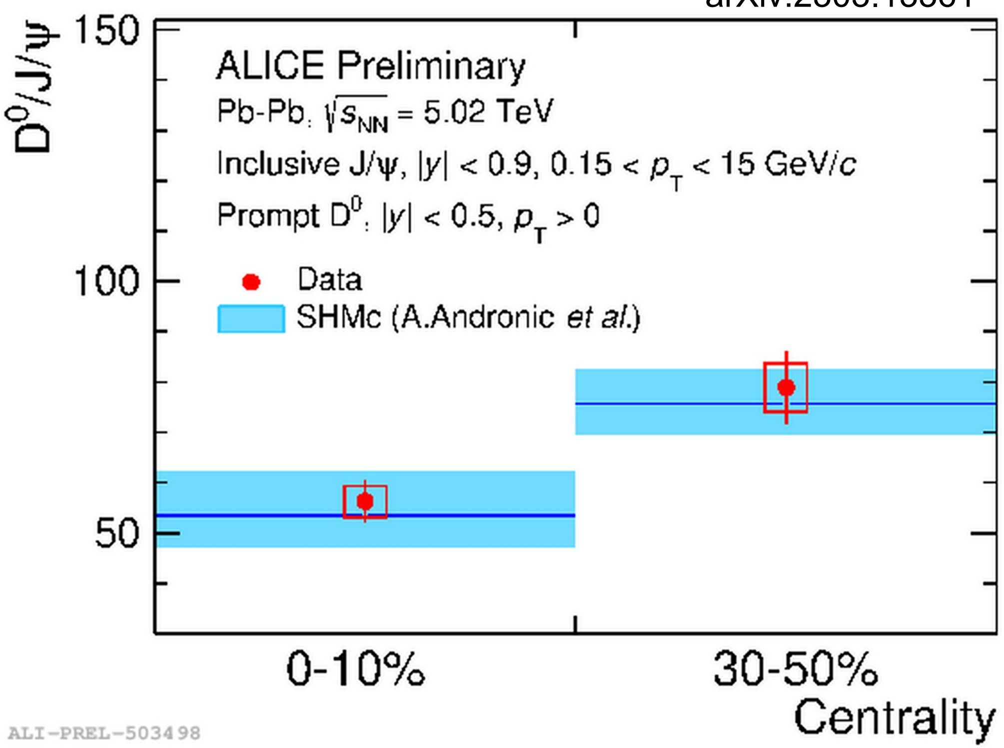
A. Andronic et al.. JHEP07 (2021) 035



emergence of a unique pattern, due to g_c^n and mass hierarchy
perfect testing ground for deconfinement for LHC Runs3,4 and ALICE3

Unique prediction of SHMc – open charm/charmonium

arXiv:2303.13361



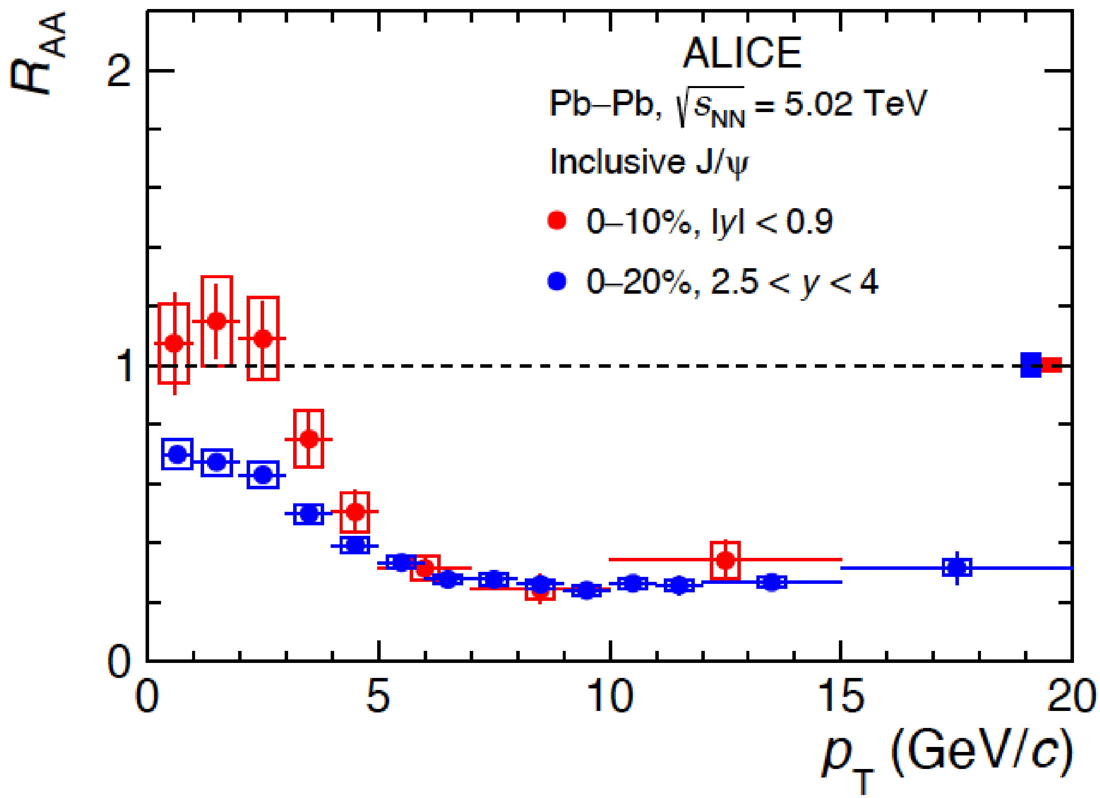
for the first time ratio of fully p_t integrated D^0 to J/ψ available from ALICE

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

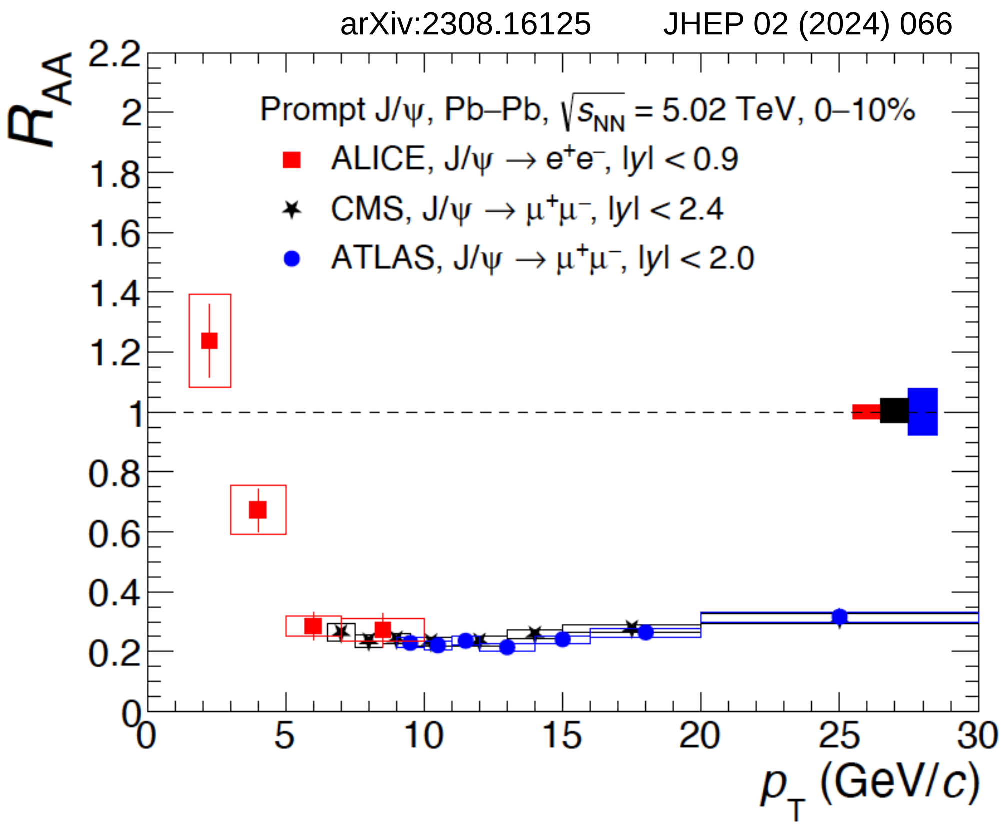
Beyond yields: transverse momentum distributions

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

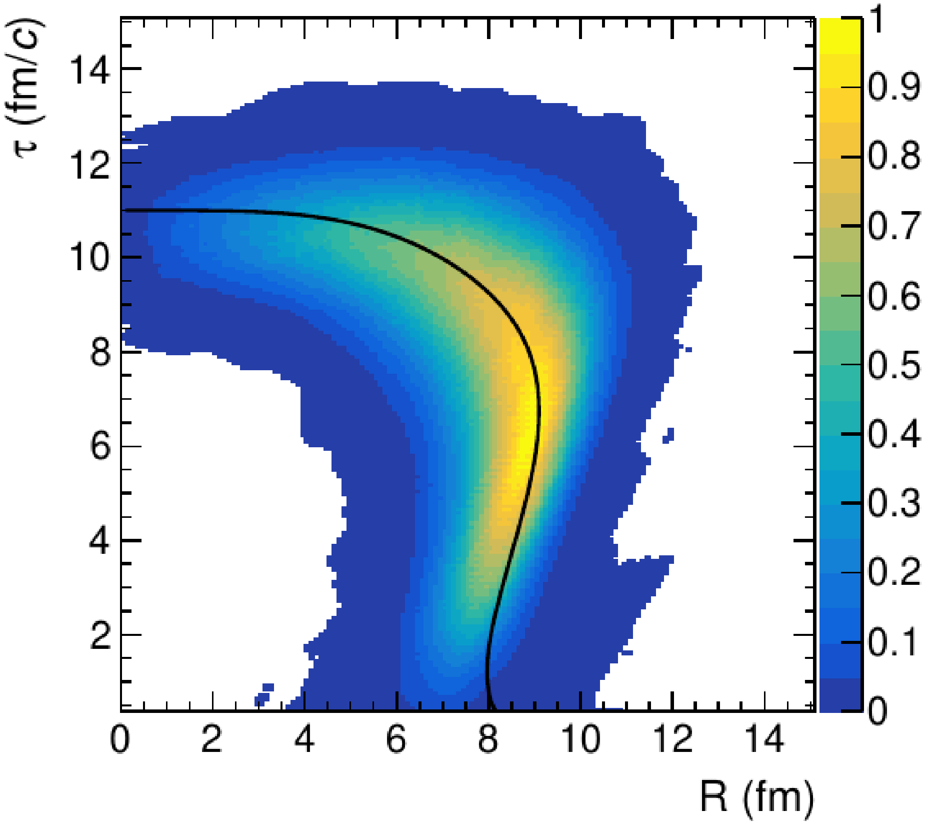


new ALICE: separation of prompt and non-prompt J/y down to 1.3 GeV/c

enhancement strongly rising towards lower p_t even beyond pp
(not even considering shadowing)

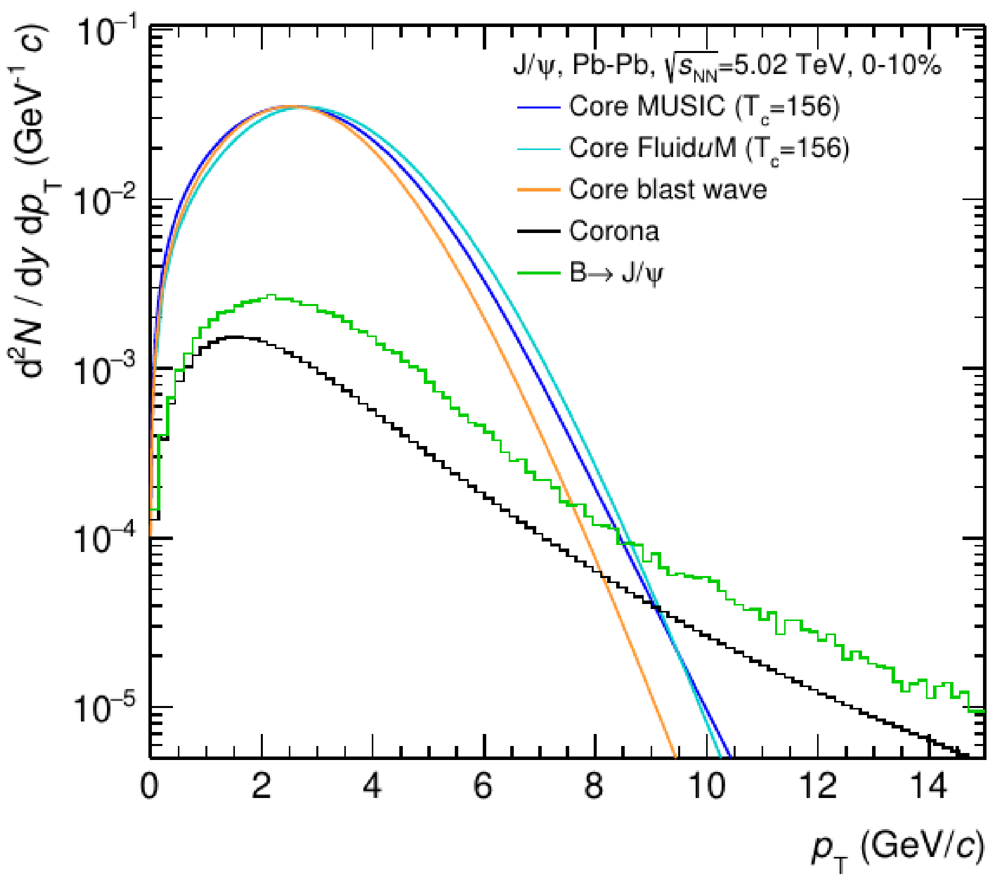
new approach to spectra and v_2: use Cooper-Frye freeze-out of hydrodynamics codes directly

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



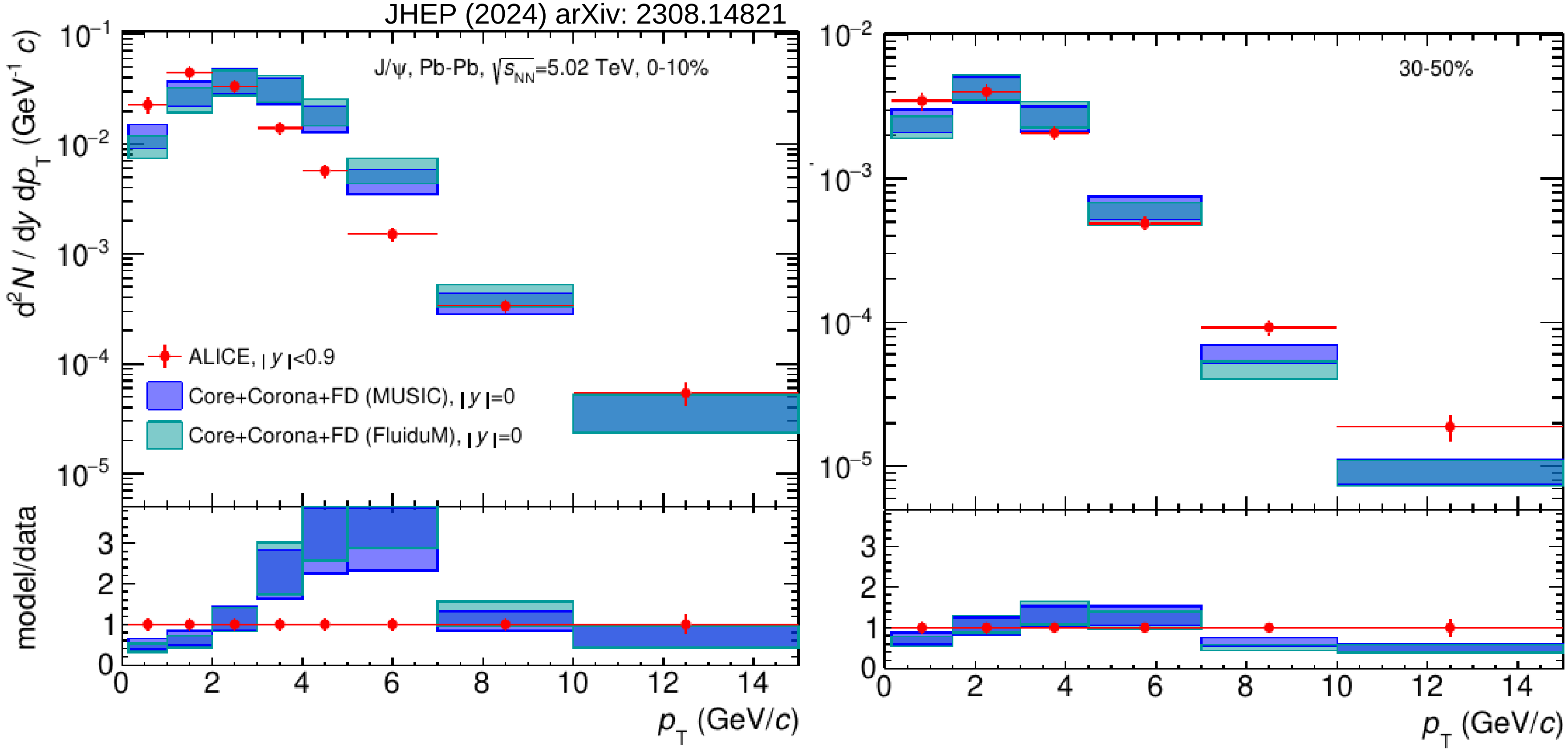
freeze-out hyper surface elements
at T=156.5 MeV from MUSIC
solid line: FluiduM

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



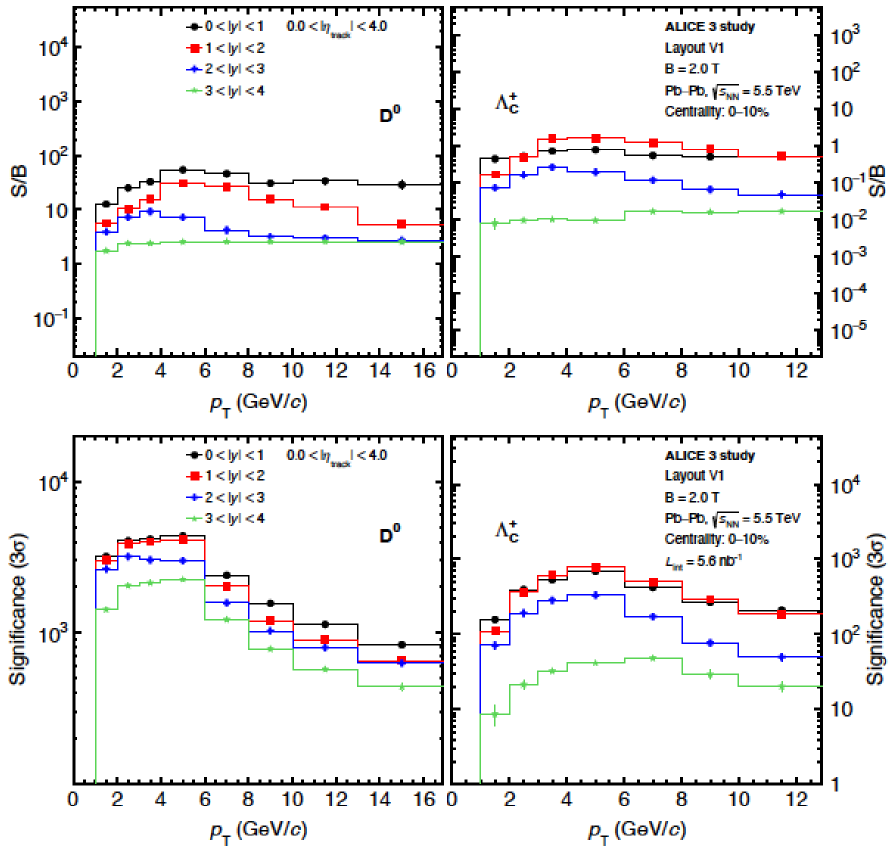
J/ψ spectra

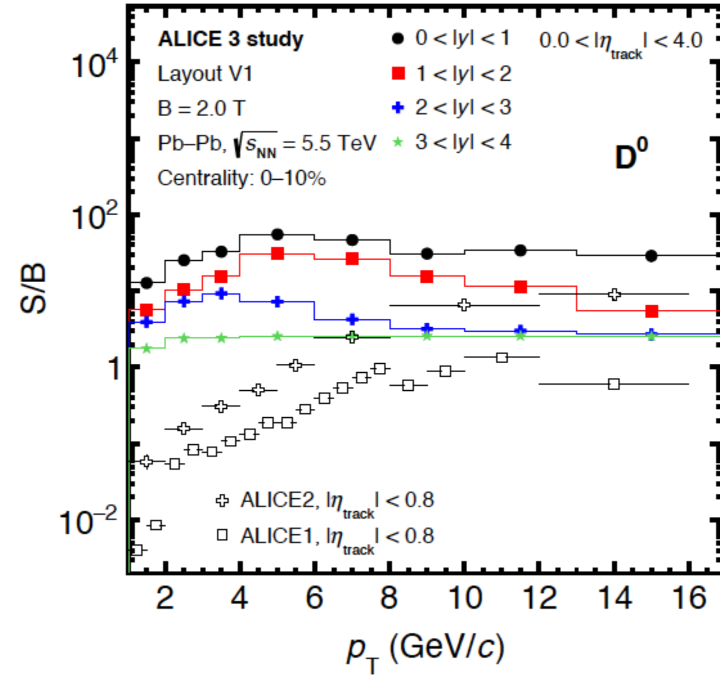
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, JHEP (2024) arXiv: 2308.14821

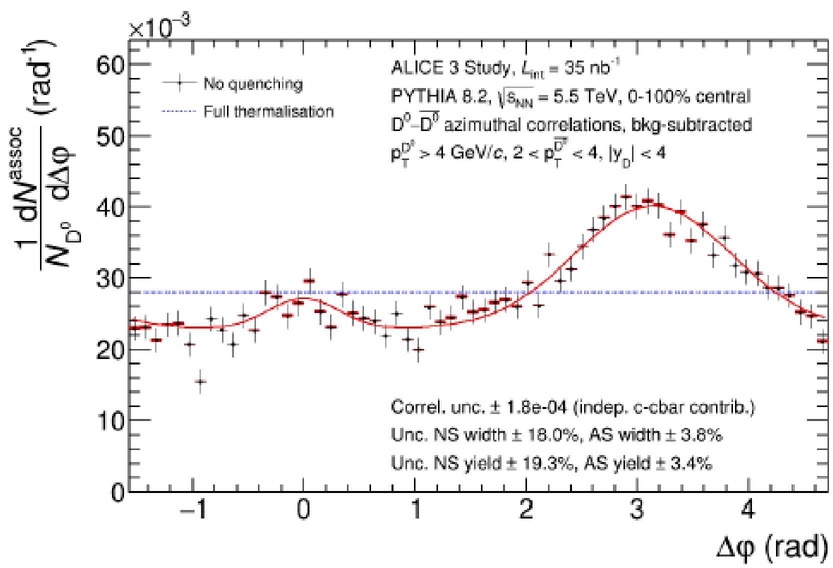


- spectra harder by about 1 GeV, in hydro many fluid cells at large velocities not accounted for by simple blast wave parametrization
- for central collisions somewhat too much flow – are charm quarks reaching the very outer front of the expanding fireball?
- future opportunity: measure source size by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

highly significant D^0 and Λ_c will allow correlation studies



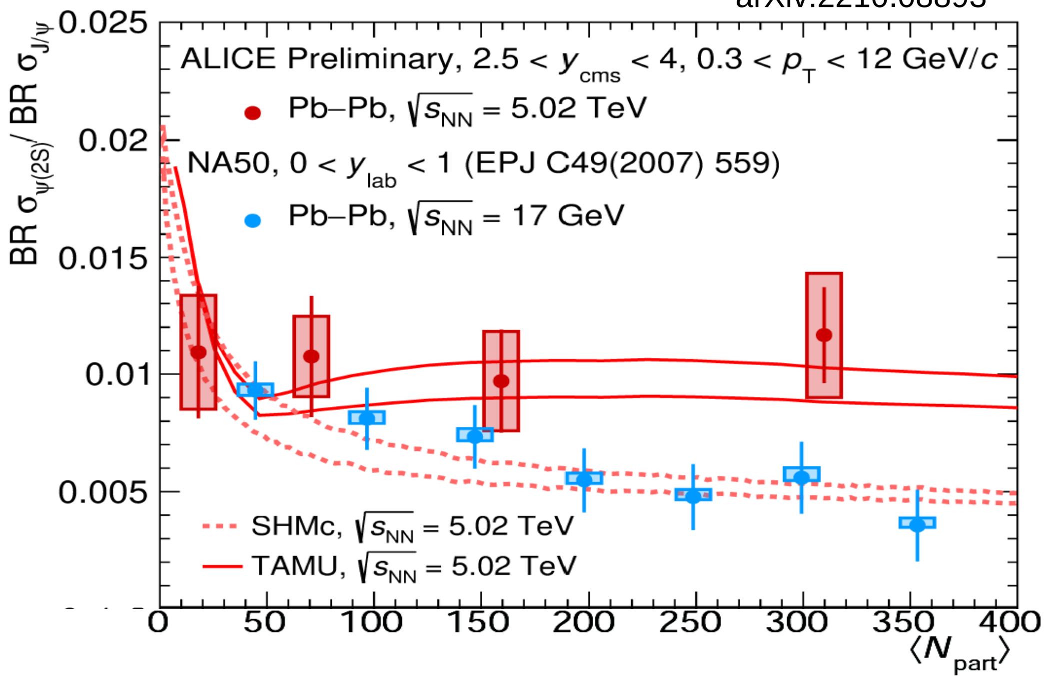




ALICE3: excellent performance in azimuthal correlations
also HBT correlations or net charm fluctuations will be possible

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

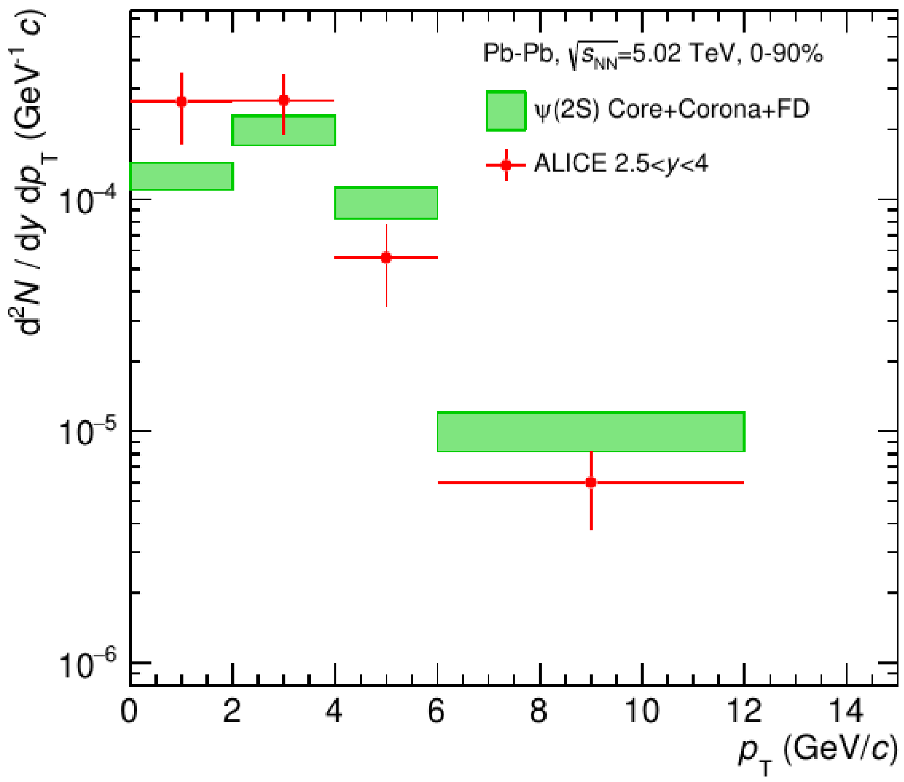
within stat. hadronization approach, an unexpected result
→ little room to accommodate in a likely physical scenario

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

deconfinement temperature from charmonium spectrum

ψ(2S) spectrum

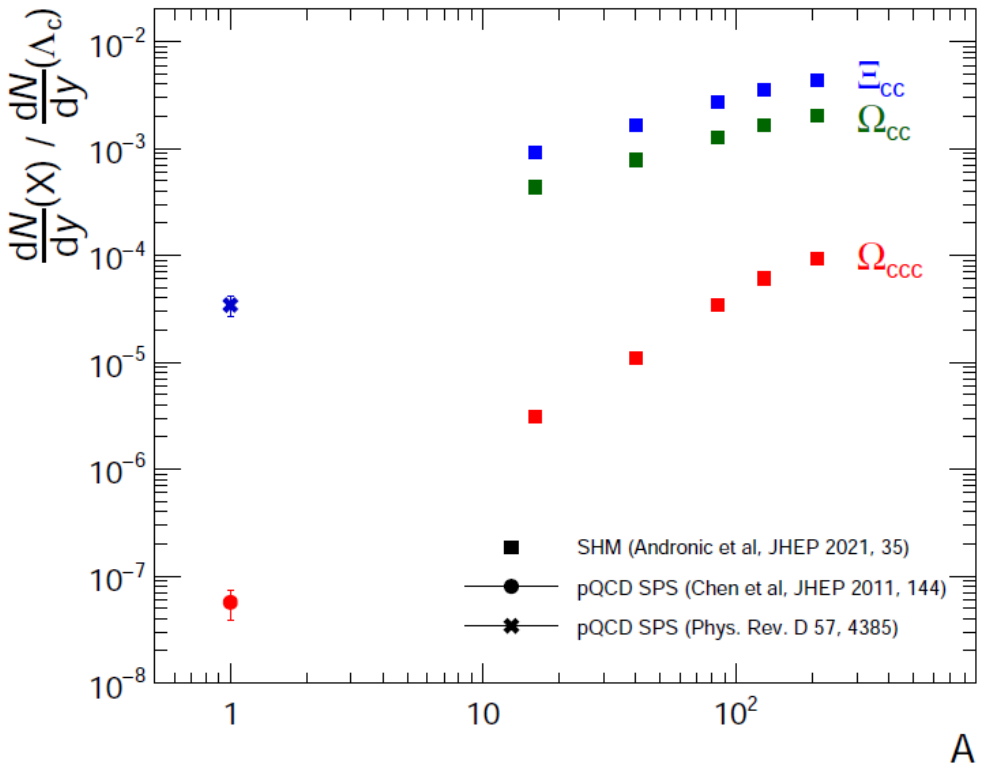
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



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

-> needs more data Runs3,4 and ALICE3

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

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

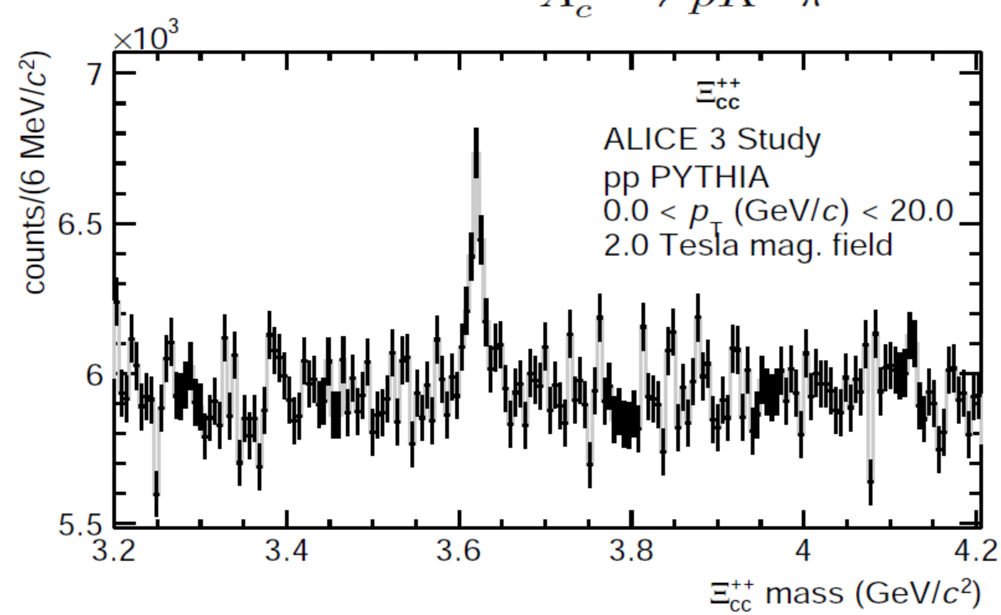
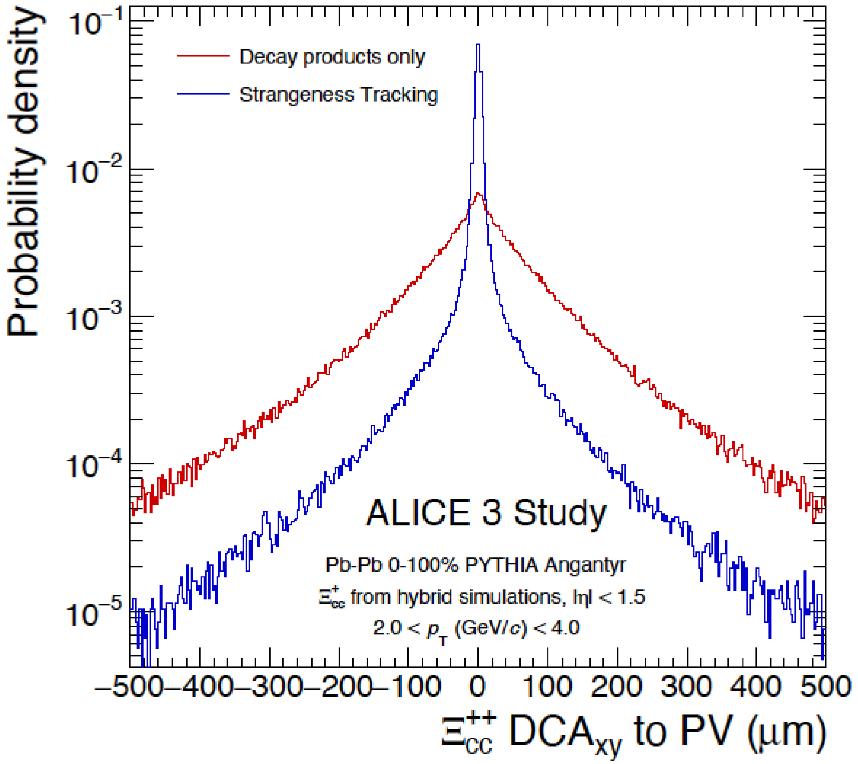
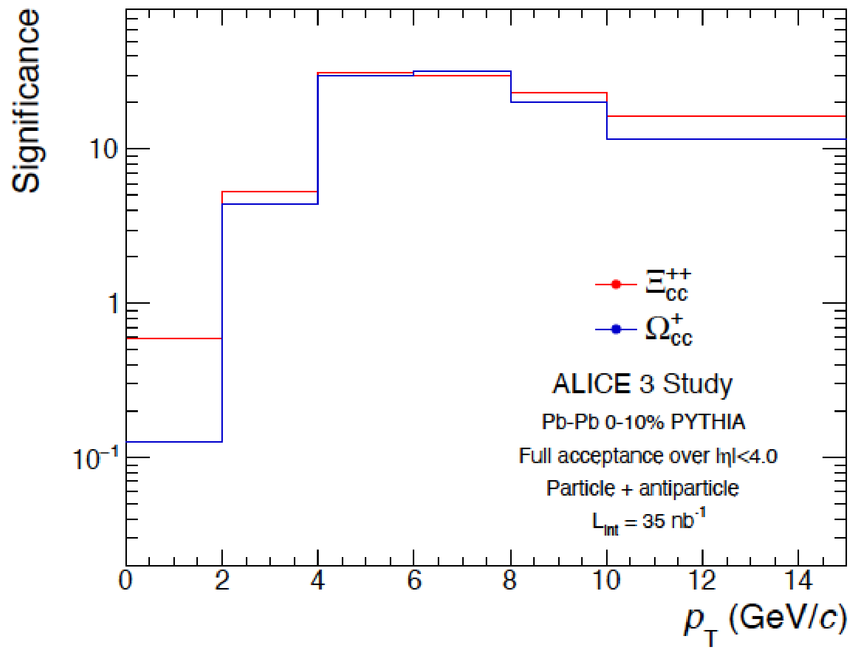


Figure 35: Expected Ξ_{cc}^{++} mass peak and background in pp collisions with $\mathscr{L}_{\text{int}} = 18\,\text{fb}^{-1}$

the power of strangeness tracking in ALICE3

Particle	Mass (GeV/c)	$c\tau$ (μm)	Decay Channel	Branching Ratio (%)
Ω_{cc}^{+}	3.746	50 (assumed)	$\Omega_c^0 + \pi^+$	5.0 (assumed)
Ω_c^0	2.695	80	$\Omega^- + \pi^+$	5.0 (assumed)
Ξ_{cc}^{++}	3.621	76	$\Xi_c^+ + \pi^+$	5.0 (assumed)
Ξ_c^+	2.468	137	$\Xi^- + 2\pi^+$	(2.86 ± 1.27)
Ξ_c^+	2.468	137	$p + K^- + \pi^+$	$(6.2 \pm 3.0)10^{-3}$





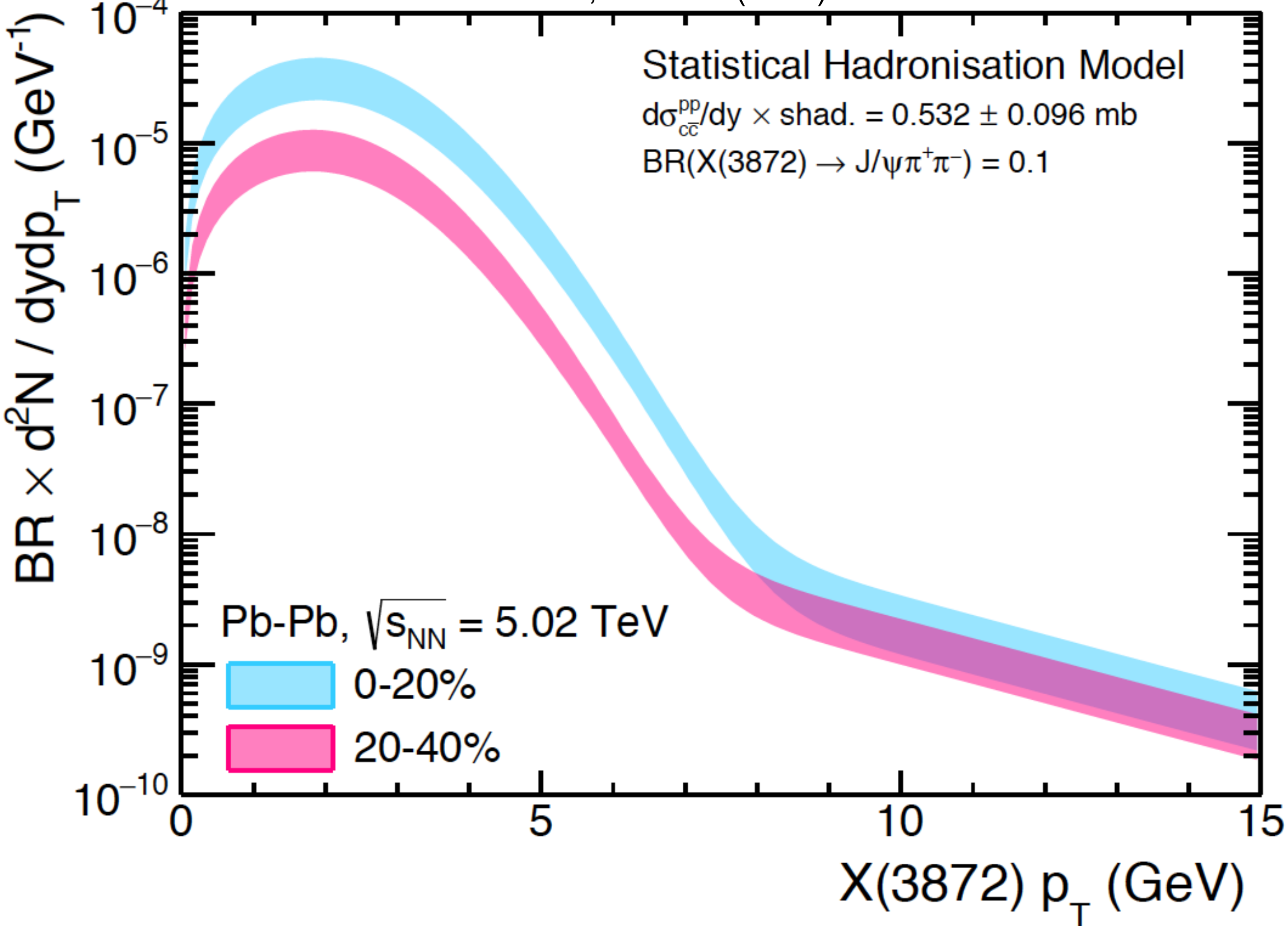
Dependence of Ω_{ccc} production yields on system size for a run time of 10^6 s

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

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

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

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



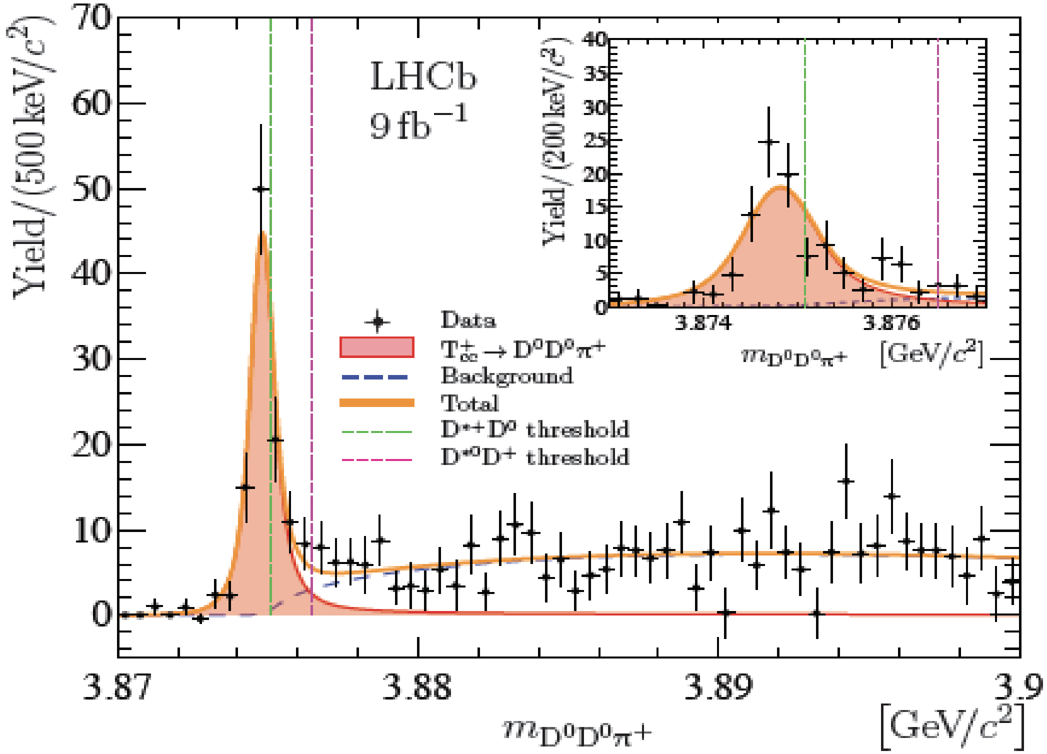
close to D^0D^{0*} threshold
- tetraquark or molecule?
- is it formed like (hyper)nuclei?

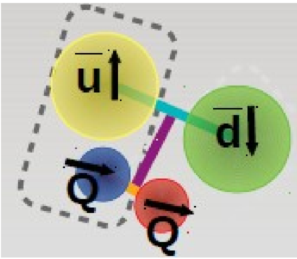
- decay into $J/\psi\ \pi^+\pi^-$
- doable in Run3/4?
- more likely ALICE3

note: dramatic enhancement at low p_t predicted
CMS addresses only very high p_t part
i.e. the tip of the iceberg

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

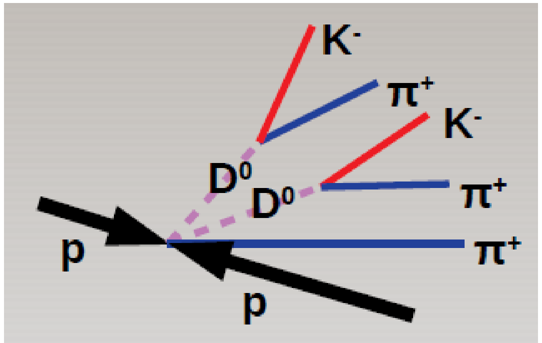
LHCb 2109.01038





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

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



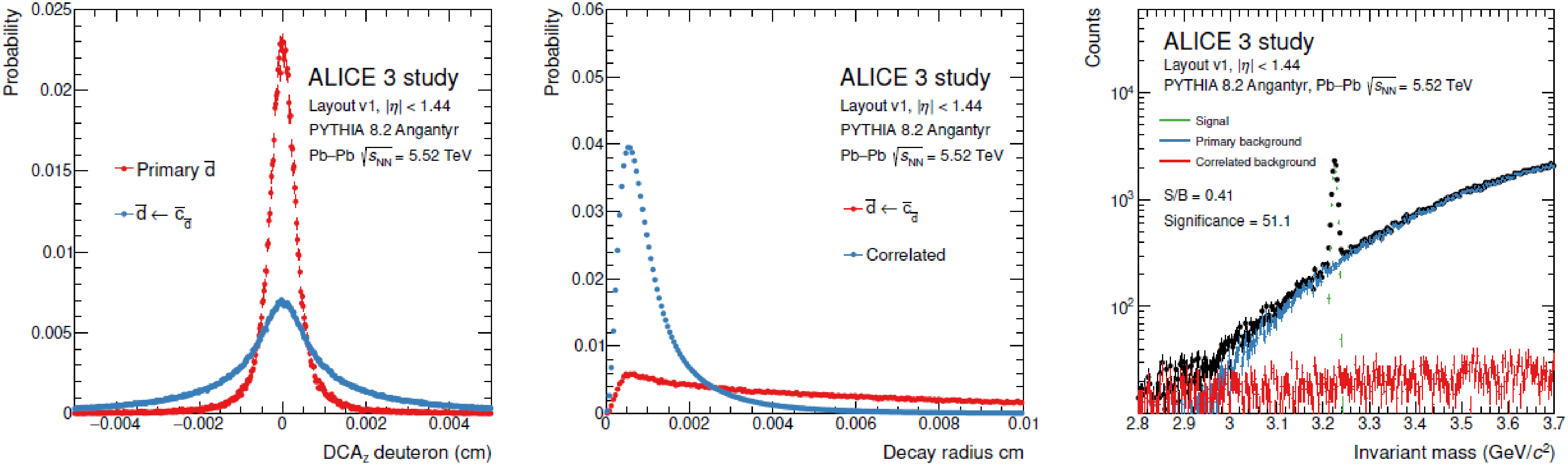
- if statistical hadronization is universal, it's production cross section will fall on the 2 charm quark line at the measured mass, practically identical to $\chi_{c1}(3872)$ about 1% of J/ψ
- definitely no preformed state at charm production, two c quarks

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



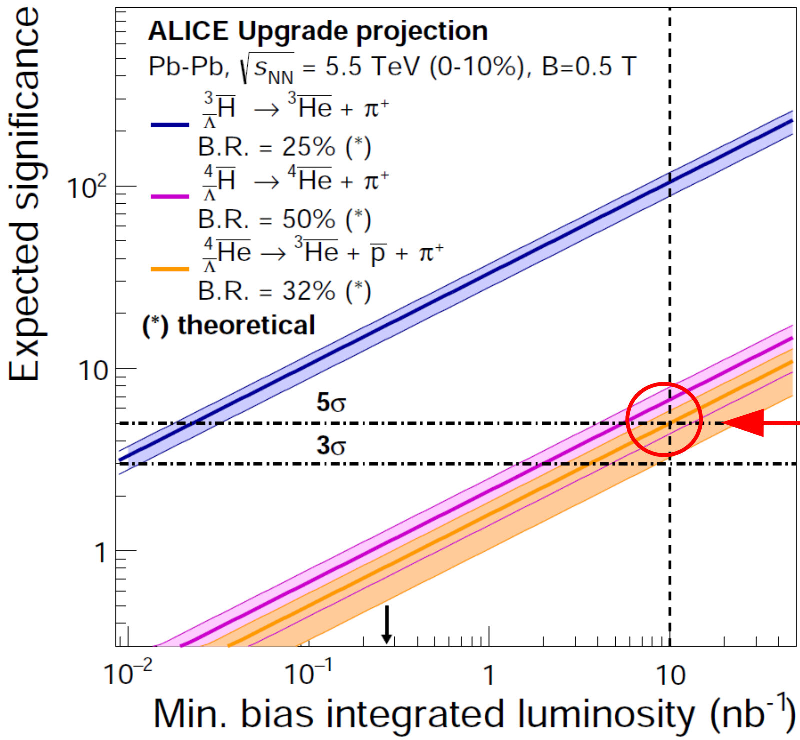
main combinatorial background from primary deuterons can be effectively suppressed due to superb vertex resolution $\rightarrow$ significance 51

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)

Opportunities hadronization into nuclei

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



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

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

is hadronization governed by mass and quantum numbers only?

Conclusions

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

yields of J/psi and several open charm hadrons described by SHMc, points to the presence of deconfined, thermalized charm quarks
- only experimental input needed: total charm production cross section

obtain parameter free description of charmonium and open charm yields and spectra as well as flow coefficients
caveat:
- measured total charm cross section in PbPb collisions in Run3

huge opportunities for the future:
- spectrum of charmonium states → deconfinement temperature
- complete spectrum of multicharm and exotic charmed hadrons
- more massive (anti-)(hyper-)nuclei
- access the beauty sector with similar precision
  degree of equilibration?

- 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:

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

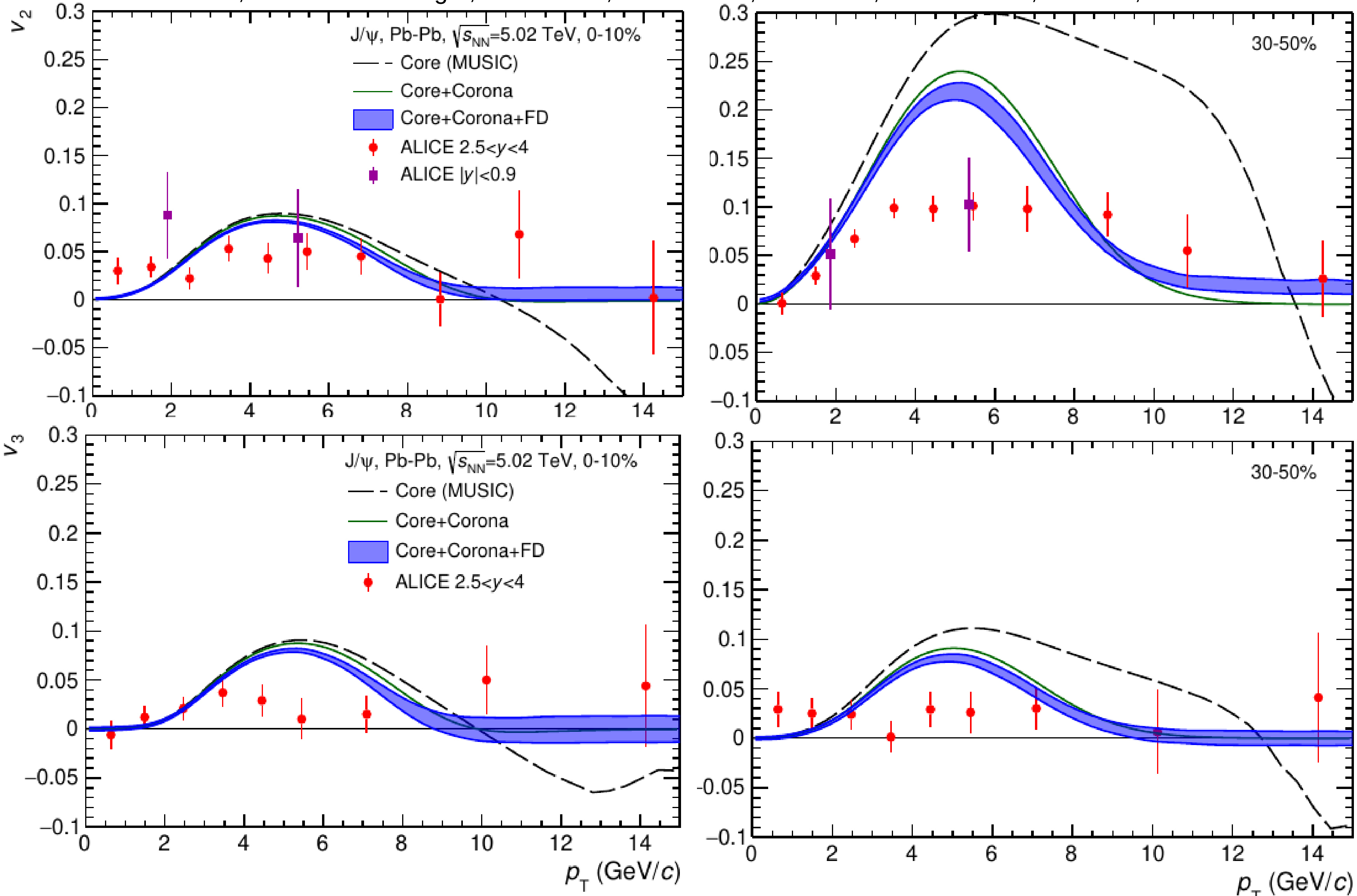
but can use conservation laws to constrain V, μ_S, μ_{I_3}

fit at each energy provides values for T and μ_b

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

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



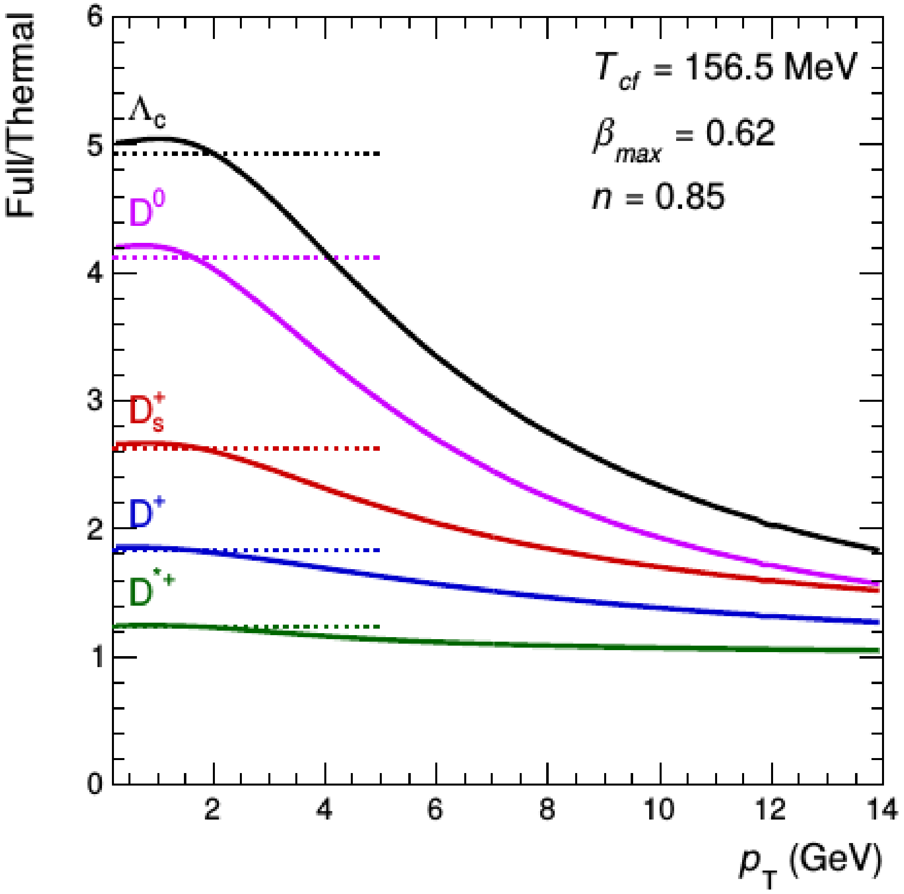
- significant flow arises over large pt range, difficult for other models
- for semi central collisions magnitude of flow over predicted

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

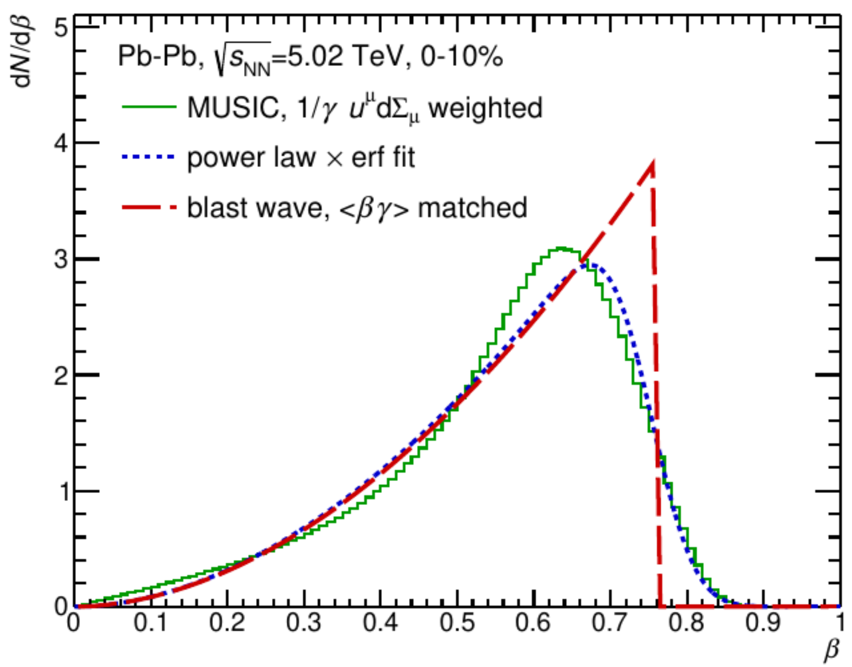
(A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284)

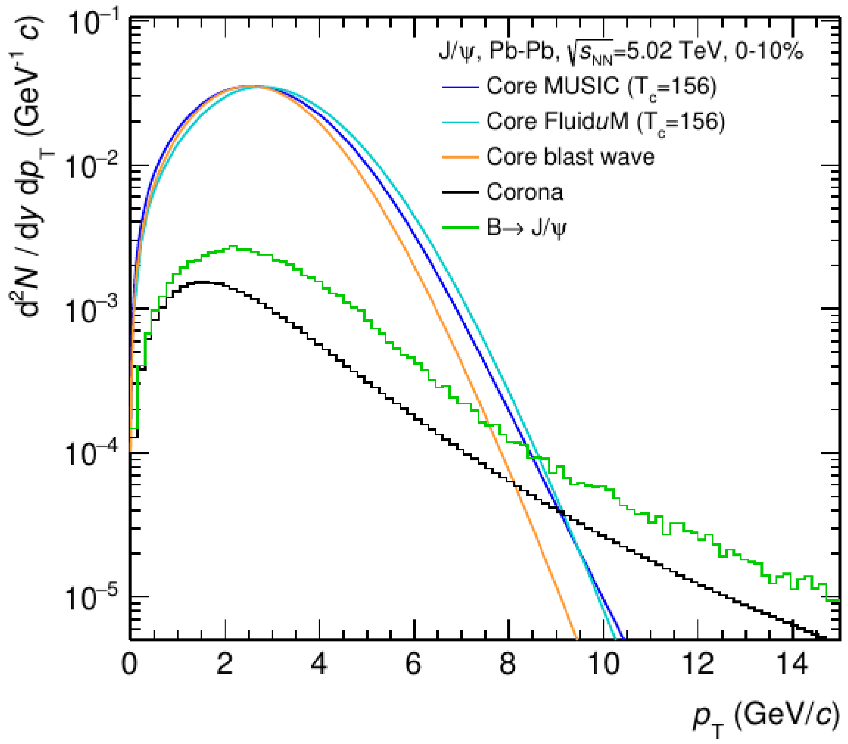
A.Andronic, P.Braun-Munzinger, M.Köhler, A.Mazeliauskas, K.Redlich, JS,V.Vislavicius JHEP 07 (2021) 035



Optimally matched blast wave parameters

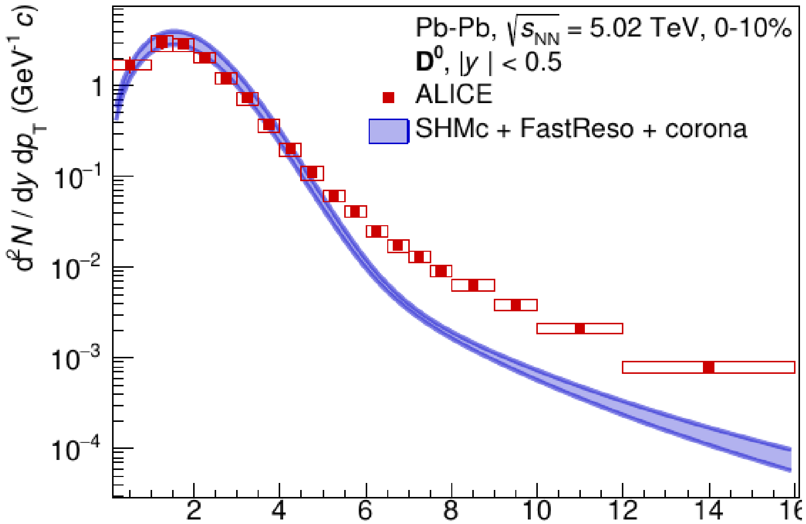
instead of inserting dozens of charmed hadrons into MUSIC, resort to blast wave parametrization again
but now we have advantage to be able to compare to ‘true’ hydro J/ψ spectrum
→ blastwave parameters modeled such that mean $\beta\gamma$ of hydrodynamics is matched

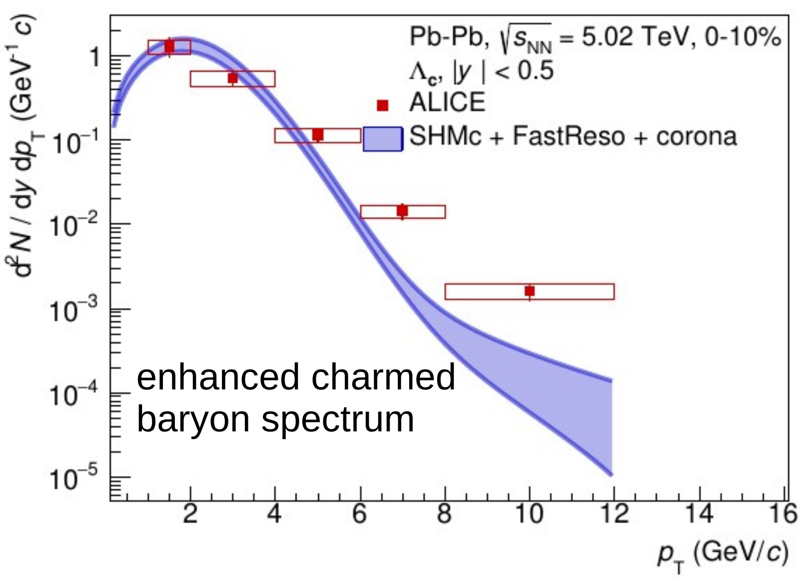




with β_{max} = 0.76 good matching can be achieved (red vs blue curves for core)

Open charm spectra – examples D^0 and Λ_c





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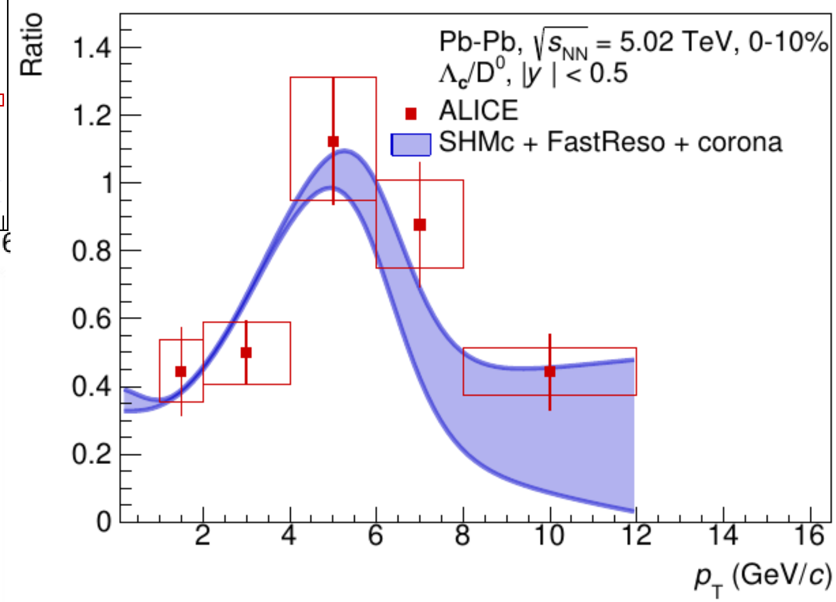
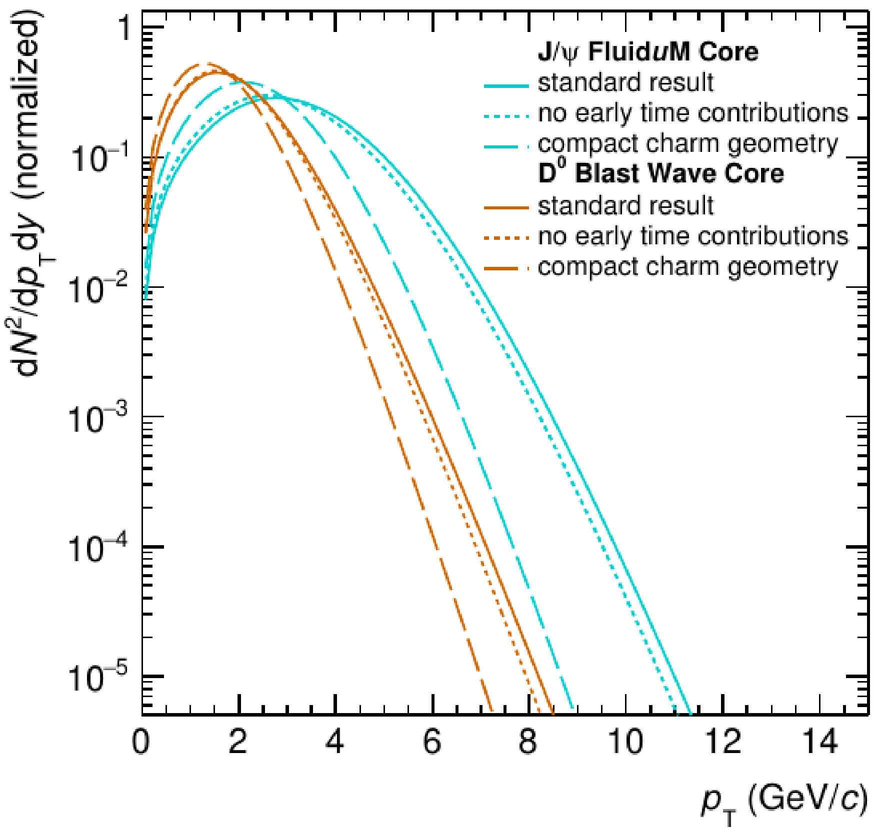


very good description of low and intermediate p_t data

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

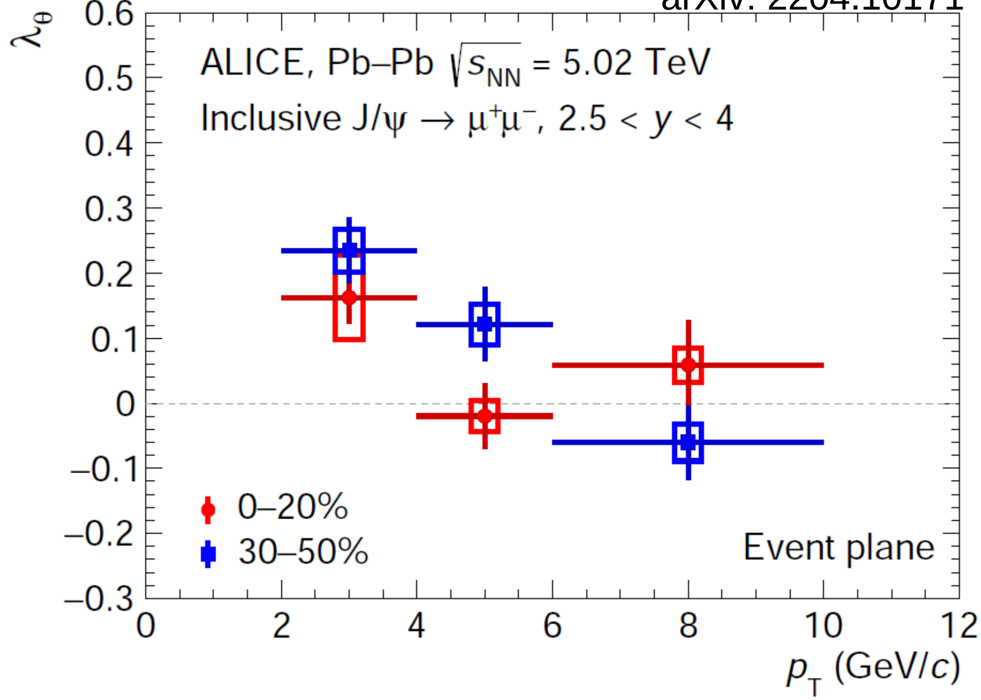
but since thermalization takes time, spatial distribution could lag behind front of expanding fireball

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

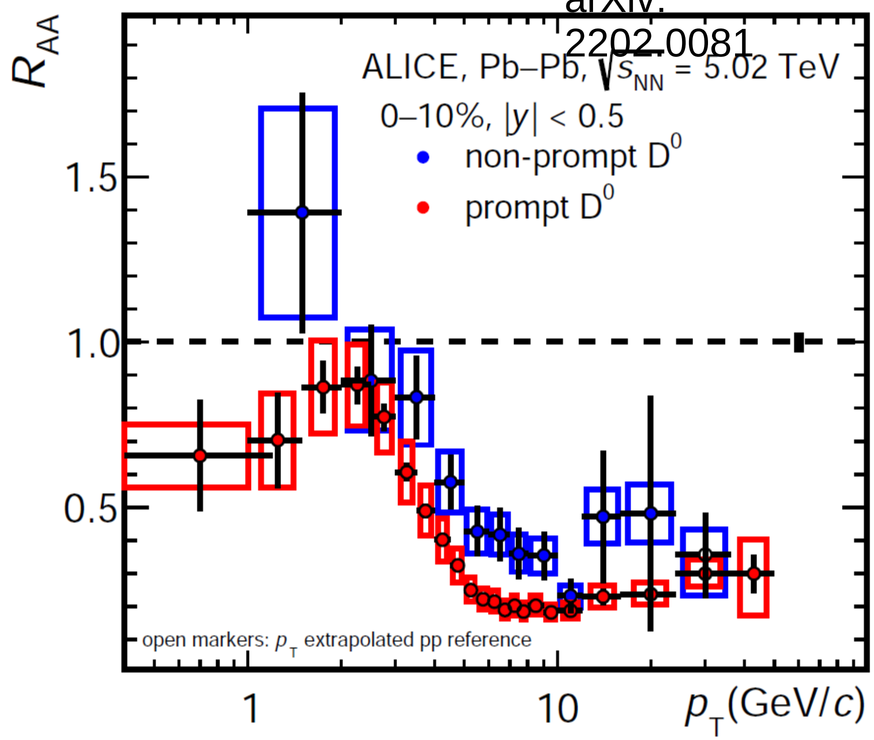
Polarization of J/y relative to event plane

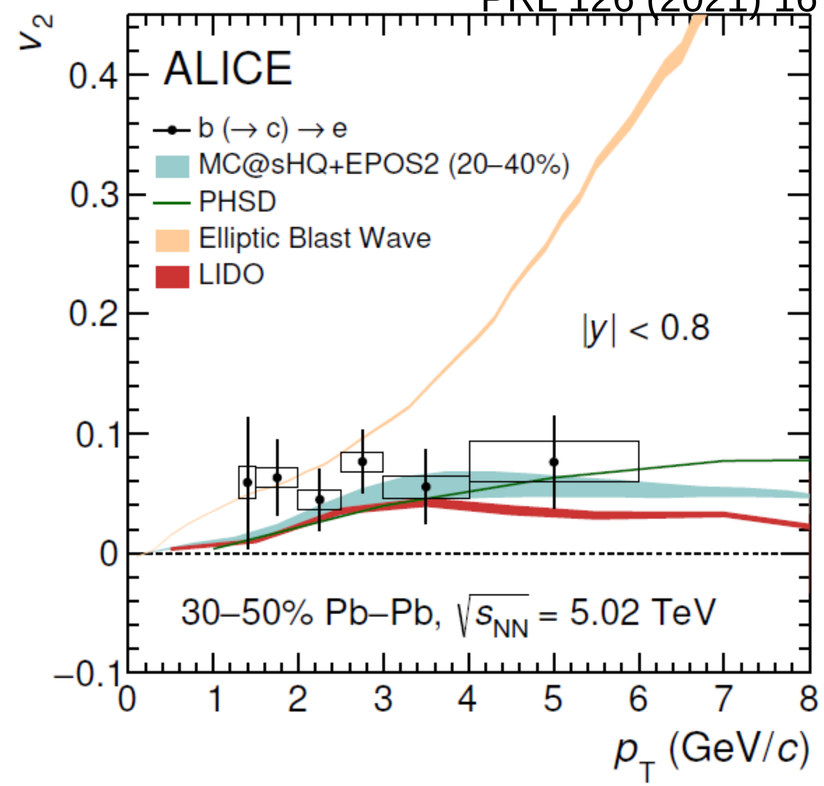
arXiv: 2204.10171



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.?

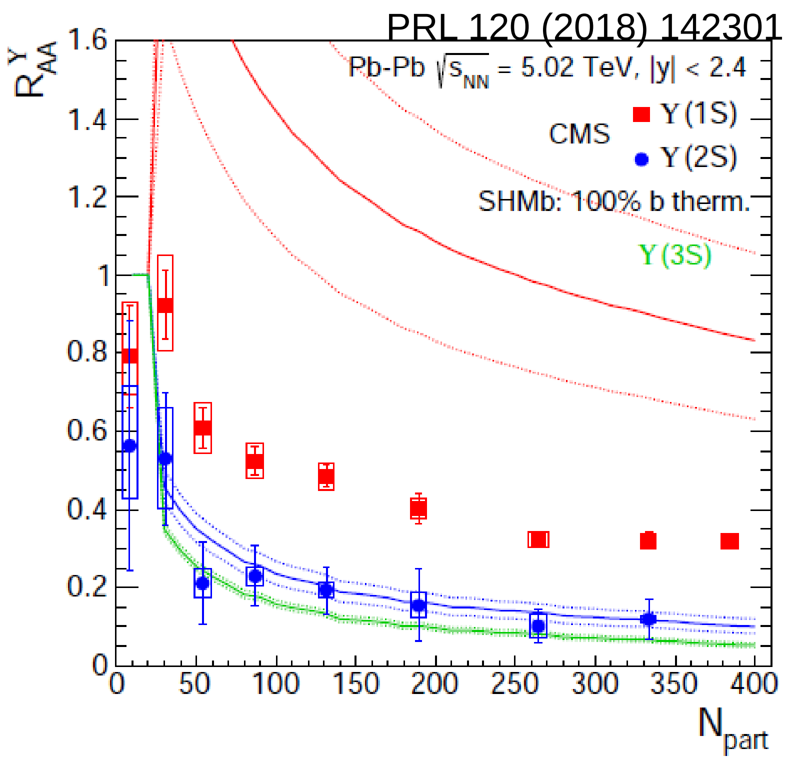
Thermalization of beauty?

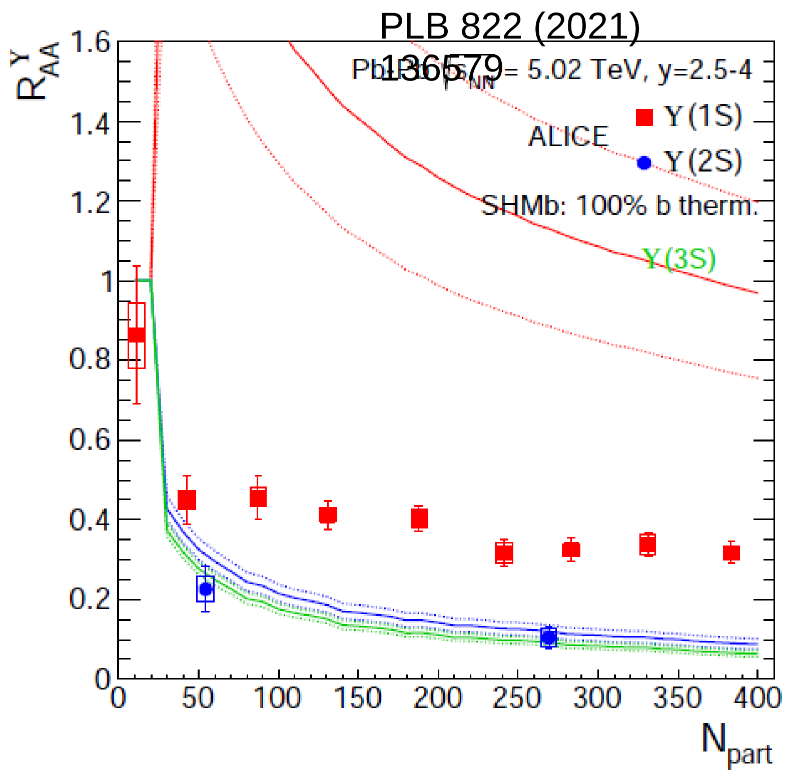




strong reduction of R_{AA} and significant v_2, but both a factor 2 less pronounced than for prompt D0 → indication that beauty quarks thermalize only partly
only the thermalized fraction should hadronize statisticly

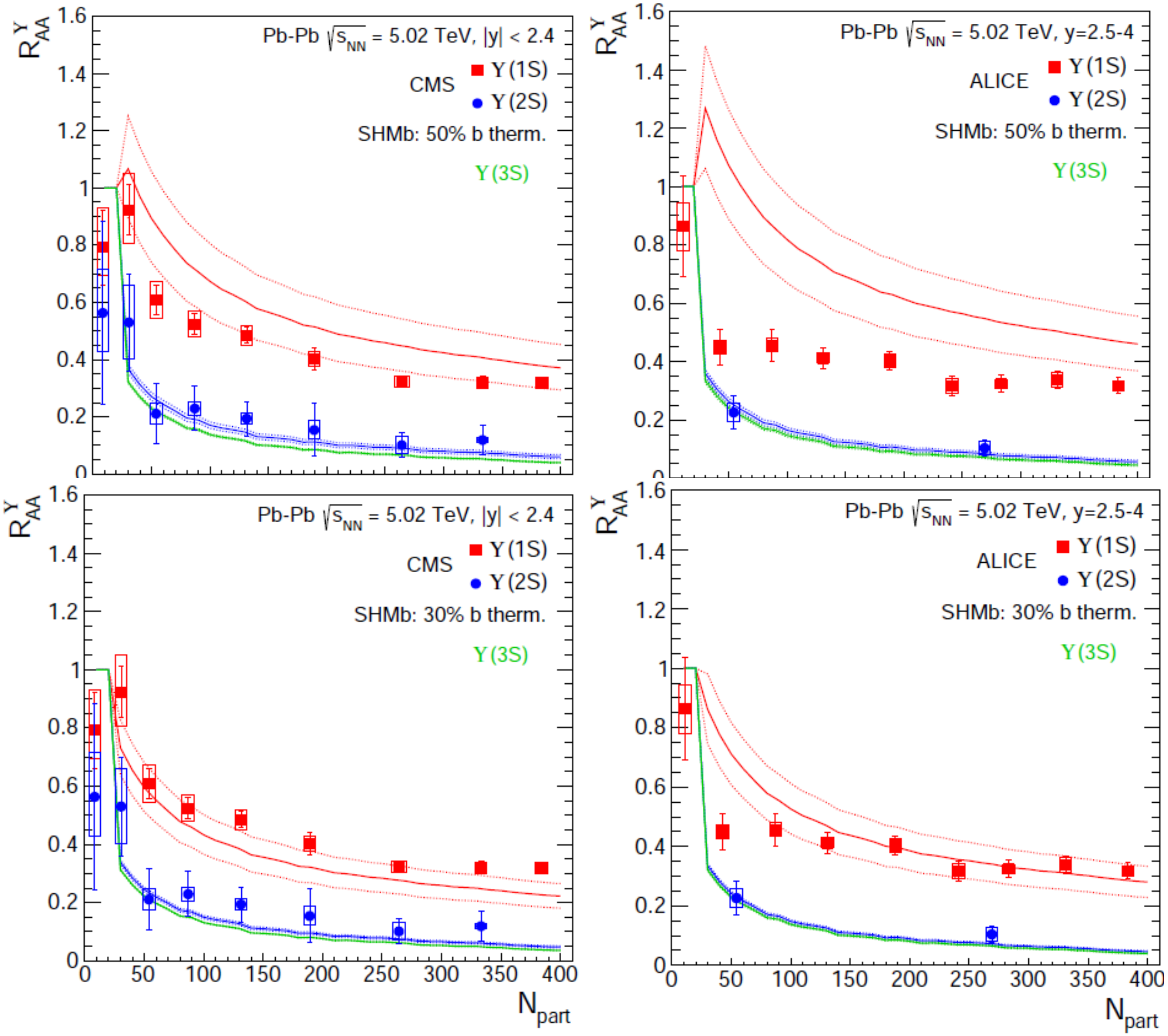
Bottomonia in SHMb assuming full thermalization





- 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