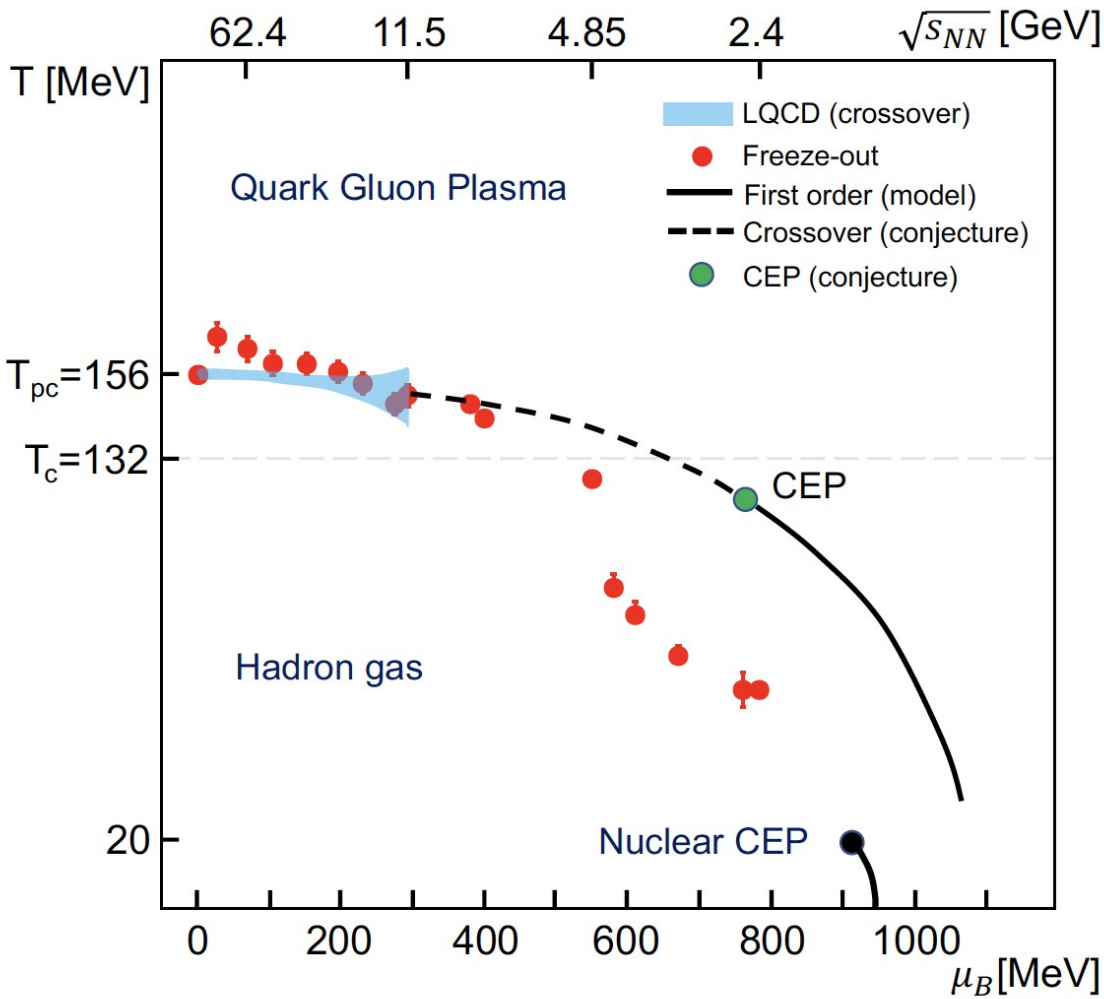
Heavy Quarks and Deconfinement in Relativistic Nuclear Collisions

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

based on
- published data, mostly ALICE
- work of many years with A. Andronic, P. Braun-Munzinger, K. Redlich
- the ALICE3 LOI and scoping document

Johanna Stachel, Phys. Inst. Universität Heidelberg
66th Cracow School of Theoretical Physics
in honor of the 90th birthday of Andrzei Bialas
June 14 - 19, 2026

Freeze-out points and the phase diagram



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

see talk PBM Thursday

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

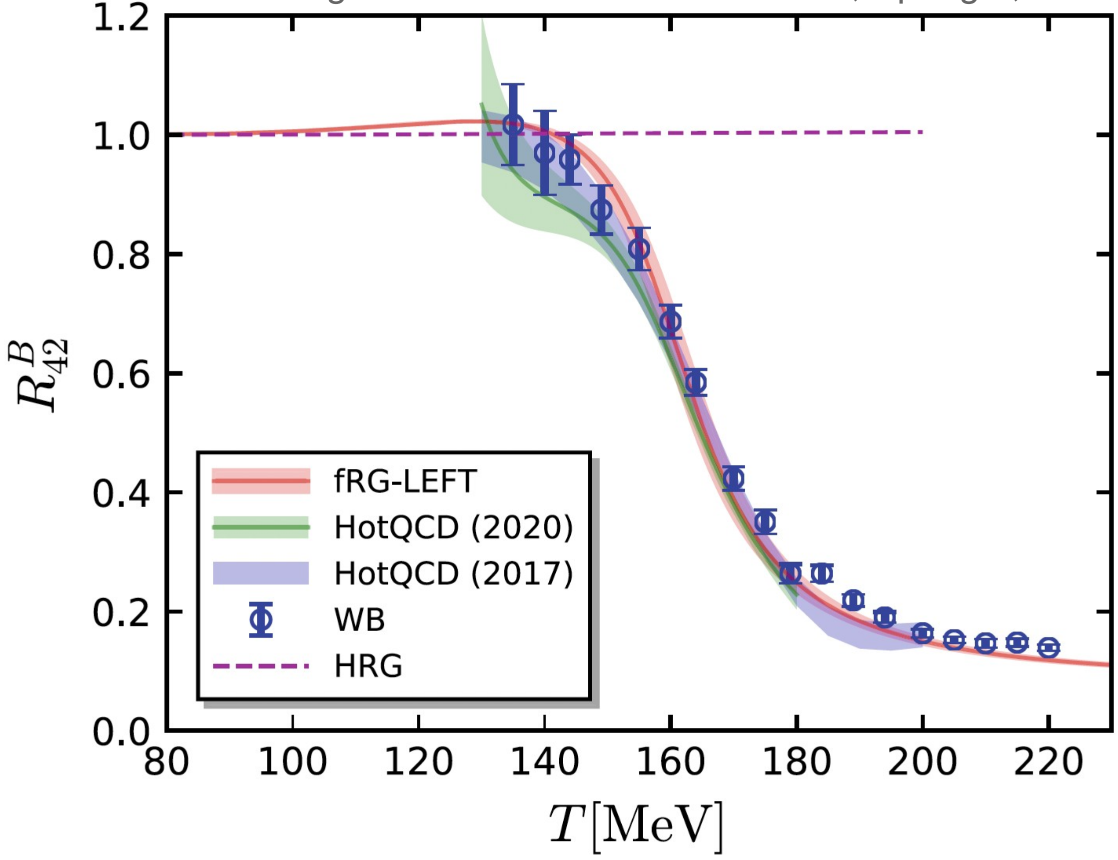
- why chemical freeze-out very close to T_{pc}? close to T_{pc} rate for multi-particle reactions explodes (critical opalescence)
P. Braun-Munzinger, J. Stachel, C. Wetterich (2004)

Measure of deconfinement in lQCD

ratio of quark number susceptibilities

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

H.T. Ding et al. in QCD Phase Structure, Springer, 2022



confined: 1

deconfined: $6/9\pi^2$

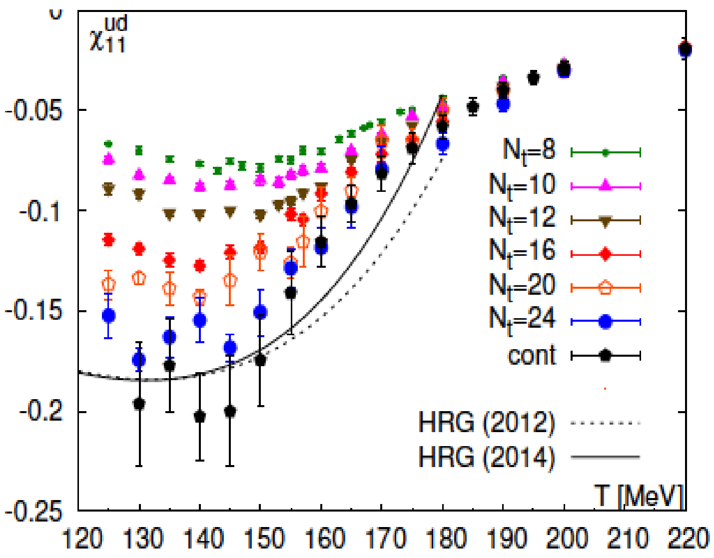
measure suggested by Ejiri, Karsch, Redlich PLB (2006)

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

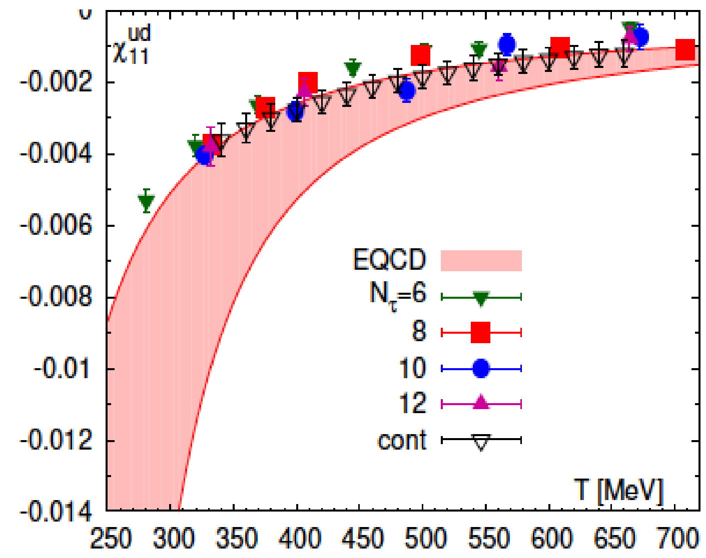
also supported by light quark susceptibilities

Wuppertal-Budapest coll. 1507.04627

$$\chi^{11}_{ud} =$$



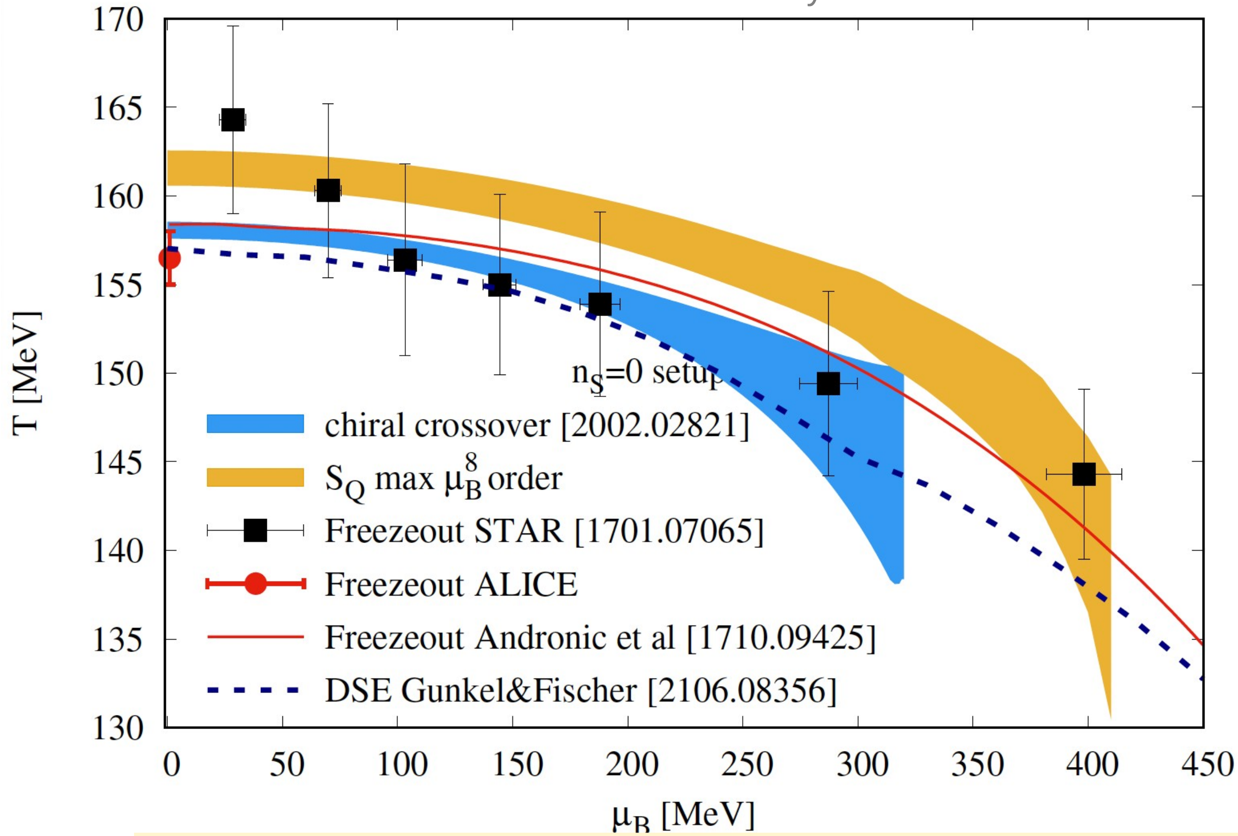
H.T. Ding et al., 1507.06637



correlations between u and d disappear rapidly close to the pseudo-critical temperature for the chiral phase transition

Recent deconfinement line from lQCD

Borsanyi et al. arXiv:2410.06216



static quark entropy $S_Q(T,\mu_B)$ based on renorm. Polyakov loop 16^3x8 lattice

deconfinement band close to chiral crossover band

- hadro-chemical freeze-out points closely follow chiral crossover line (see talk PBM)
  also higher moments, i.e. charge fluctuation observables
- observables for deconfinement?

Charmonia as probe of deconfinement

the original idea: Matsui and Satz, June 1986:

Phys. Lett. B 178 (1986) 416 - 3812 citations

implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with plasma formation (Debye screening of QCD)

in the QGP, the screening length $\lambda_{Debye}(T)$ decreases with increasing T
if $\lambda_{Debye}(T) < r_{quarkonium}$ the system becomes unbound

proposing a Debye screened potential

$$V(r,T) = \frac{\sigma}{\omega_D(T)}(1 - \exp(-\omega_D(T)r)) - \frac{\alpha}{r}\exp(-\omega_D(T)r)$$

scenario of sequential melting appears as **signature of deconfinement**

→ started immediate intense experimental search

and theoretical debate ...

F. Karsch and H. Satz, Z.Physik C51 (1991) 209

	J/ψ	ψ'	χ_c	Υ	Υ'
state	1s	2s	1p	1s	2s
mass(GeV)	3.1	3.7	3.5	9.4	10.0
r (fm)	0.45	0.88	0.70	0.23	0.51
T_D/T_c	1.17	1.0	1.0	2.62	1.12
ϵ_D (GeV/fm^3)	1.92	1.12	1.12	43.3	1.65

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

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: $1.5 < 2\pi TD_s < 4.5$ at T_c → τ_{kin} = 2.5 – 7.6 fm/c
ALICE JHEP 01 (2022) 174

lQCD: mom. diff. coeff. $\kappa_{E,M}$ from gradient flow on color-electric and -magnetic two-point functions
results in full QCD for almost physical quark masses

$$\kappa = \kappa_E + \frac{2}{3}\langle v^2\rangle\kappa_B$$

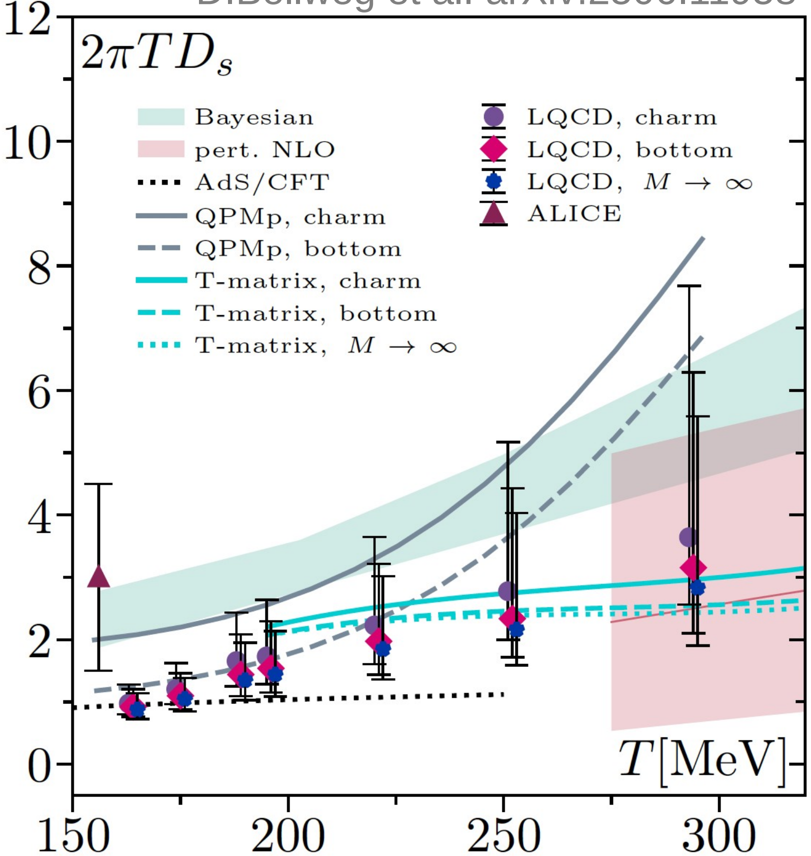
spatial diff. coeff. from Einstein relation

$$2\pi \mathrm{TD_s} \propto \frac{4\pi}{\kappa/\mathrm{T}^3}\frac{\langle \mathrm{p}^2\rangle}{3\mathrm{MT}} \propto \tau_{\mathrm{kin}}\frac{\mathrm{T}^2}{\mathrm{M}}$$

for charm τ_{kin} = 1 – 2 fm/c

consistent picture:
thermalization in QGP

D.Bollweg et al. arXiv:2506.11958



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

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

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

number density of thermal charm hadrons

Hadronization of charm quarks

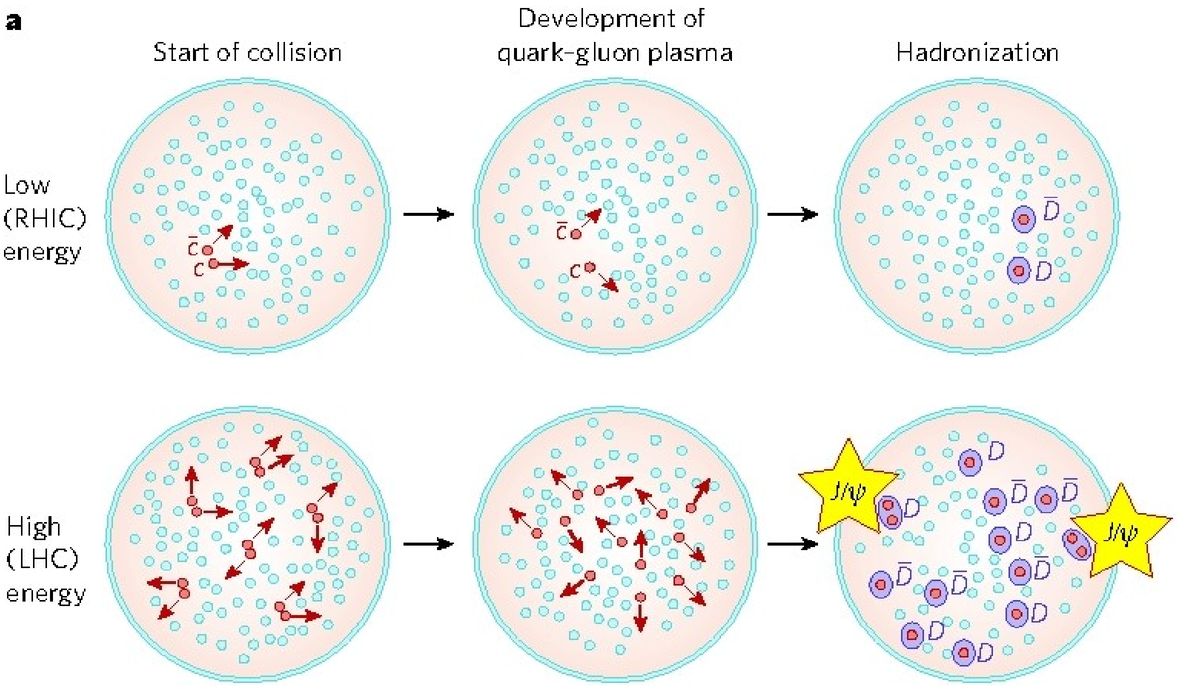
all charm quarks have to appear in charmed hadrons
at hadronization of QGP also J/ψ can form from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^2$

(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)

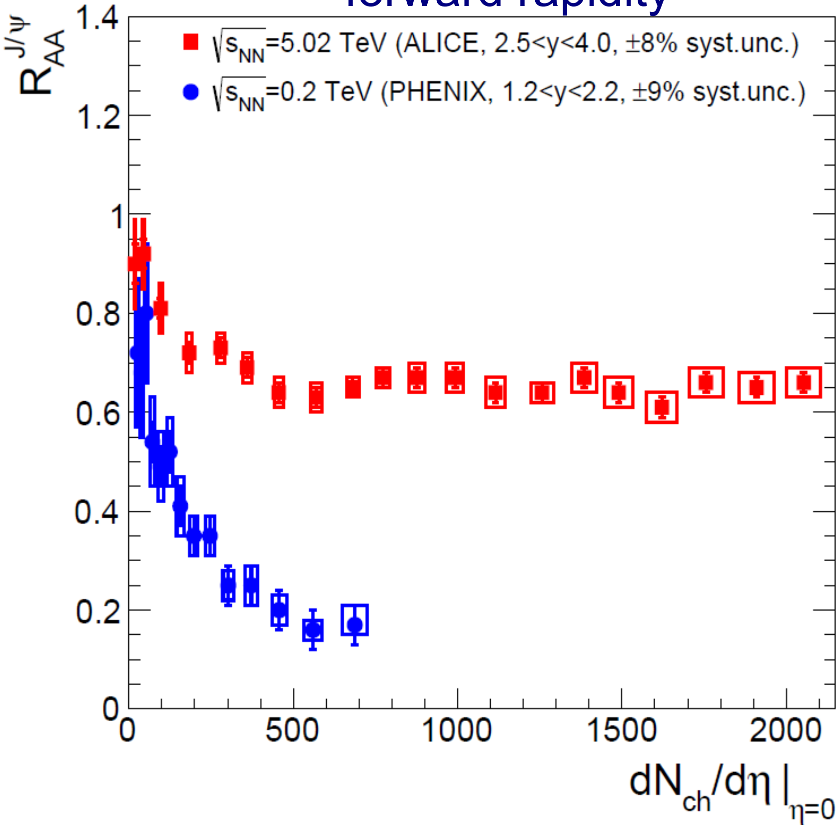
expect J/ψ **suppression** at low beam energies (SPS, RHIC)
and
J/ψ **enhancement** at high energies (LHC)



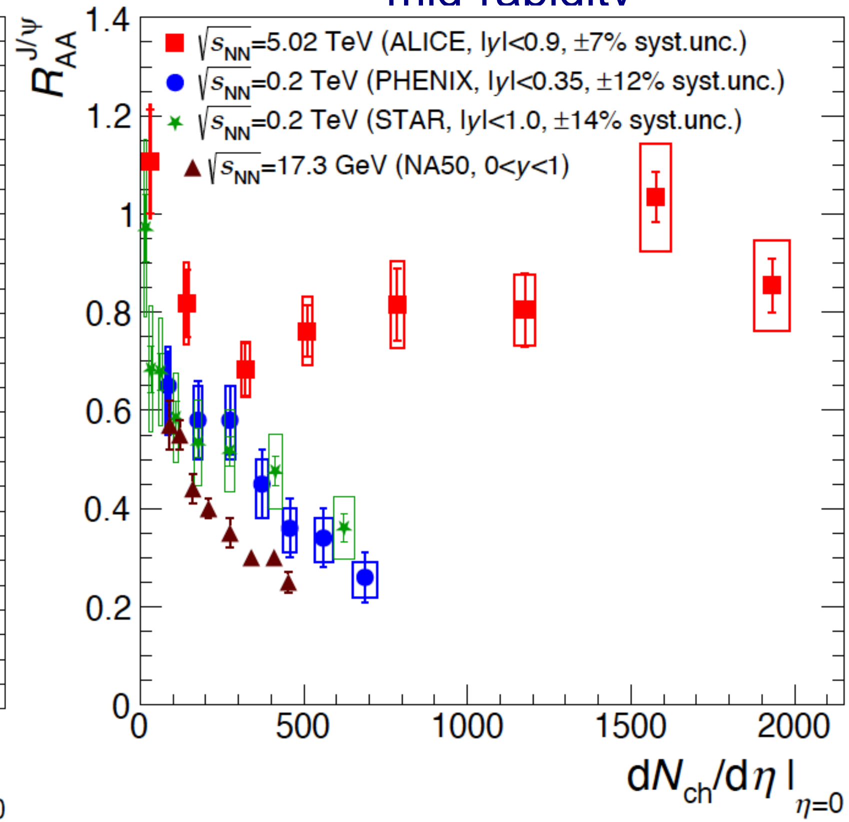
J/ψ production in PbPb collisions: LHC relative to RHIC

see talk Anton Andronic Tuesday

forward rapidity

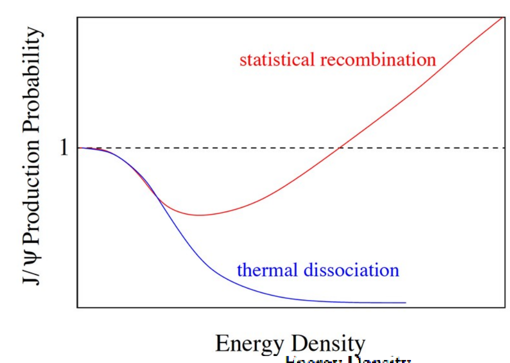


mid-rapidity



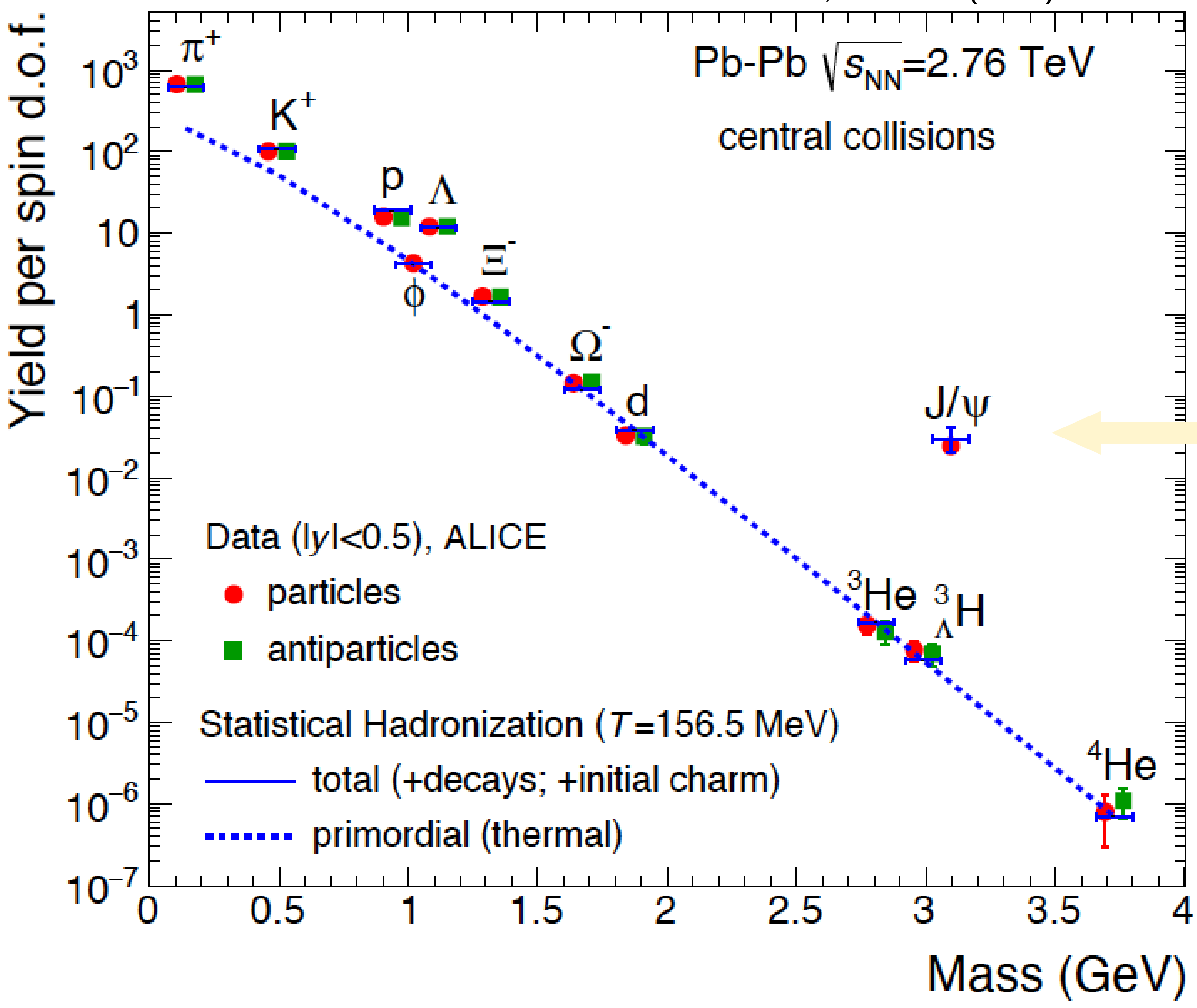
energy density →

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

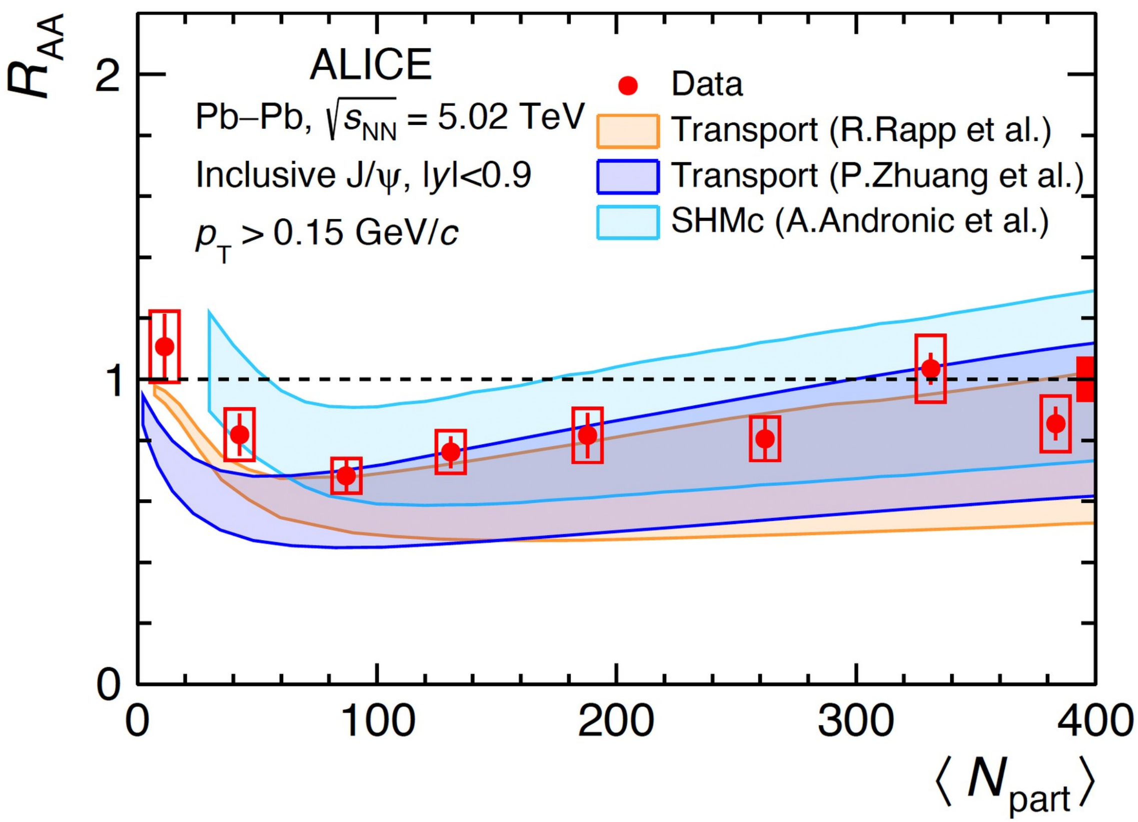
A.Andronic et al., PLB 797 (2019) 134836

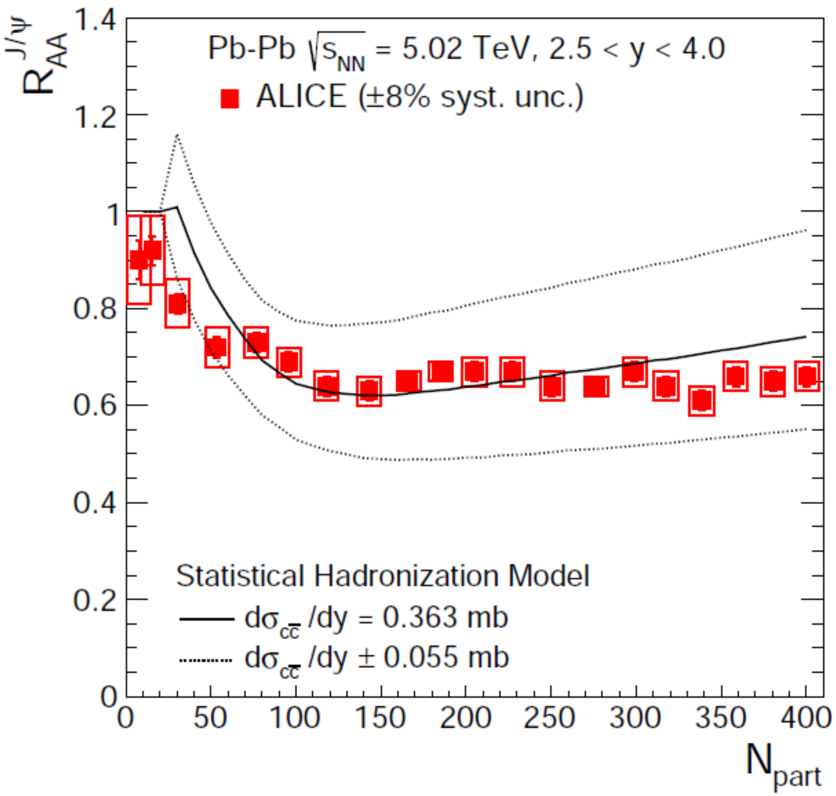


J/ψ enhanced compared to other M = 3 GeV hadrons by factor g_c^2 =900 relative to purely thermal yield
quantitative agreement with hadronization of deconfined thermalized charm quarks

J/ψ and statistical hadronization

arXiv: 2303.13361

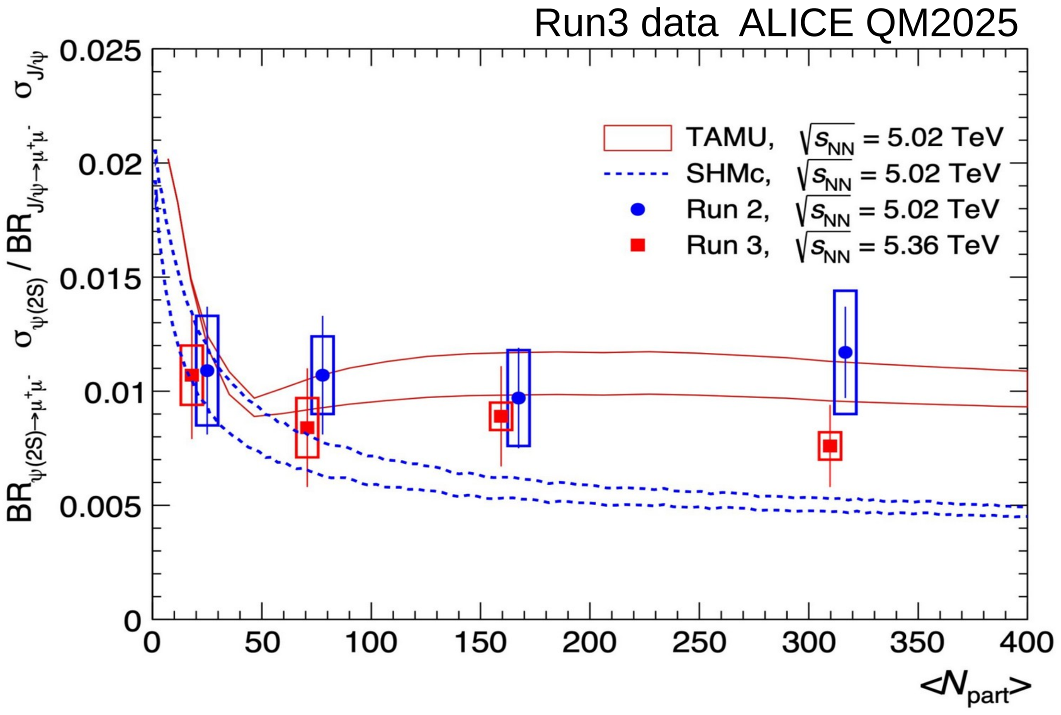




production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

What about ψ(2S)?

see talk Anton Andronic Tuesday



The points of Run 2 are shifted to see better the uncertainties

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

in SHMc excited state population suppressed by Boltzmann factor

- good agreement with data within current uncertainties

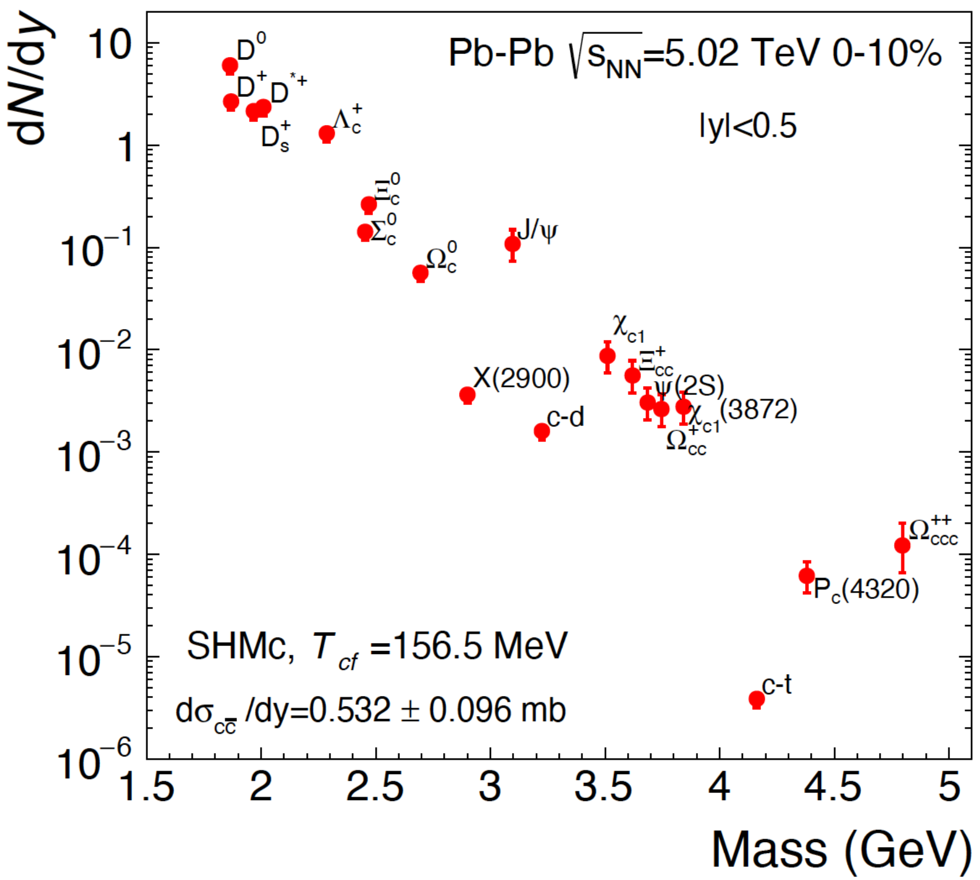
future opportunities:
- higher precision ψ(2S), also mid-y
- χ_c only in ALICE3?

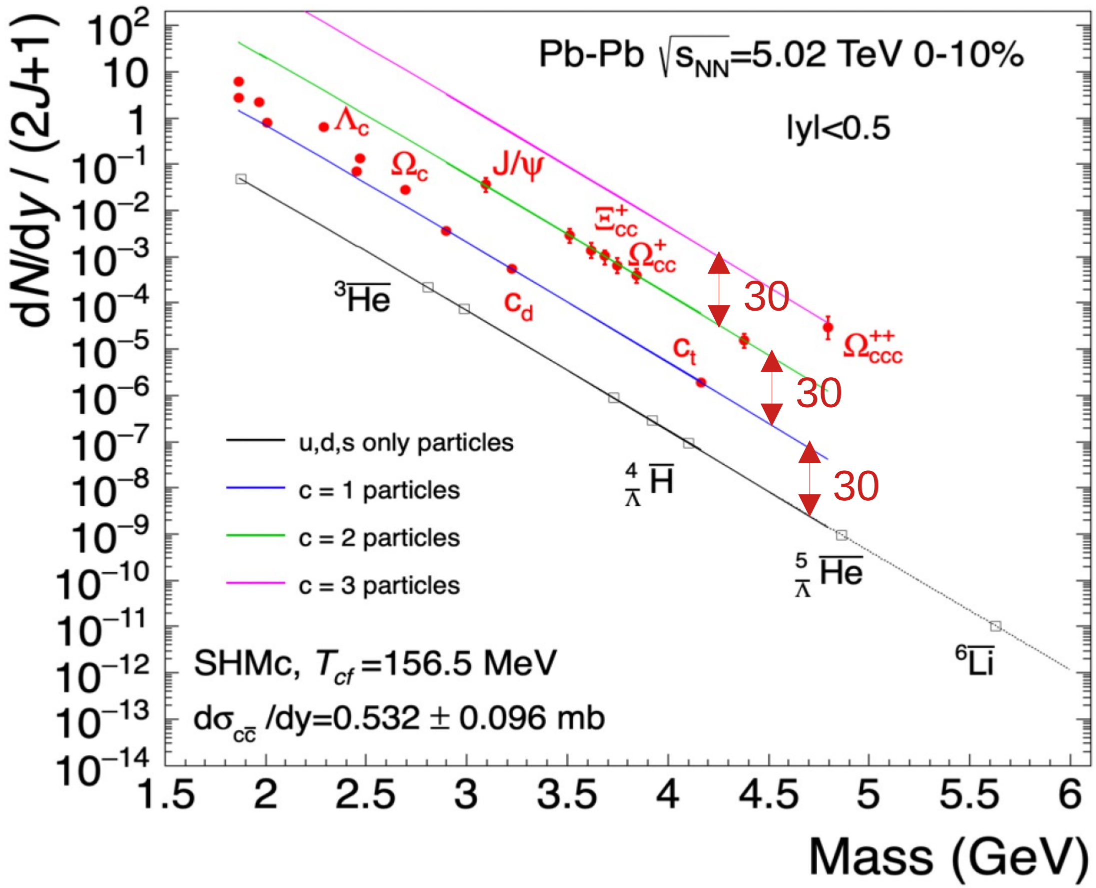
deconfinement temperature from charmonium spectrum
< 5 MeV accuracy for 10 % ψ(2S) measurement

Prediction: the multi-charm hierarchy

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

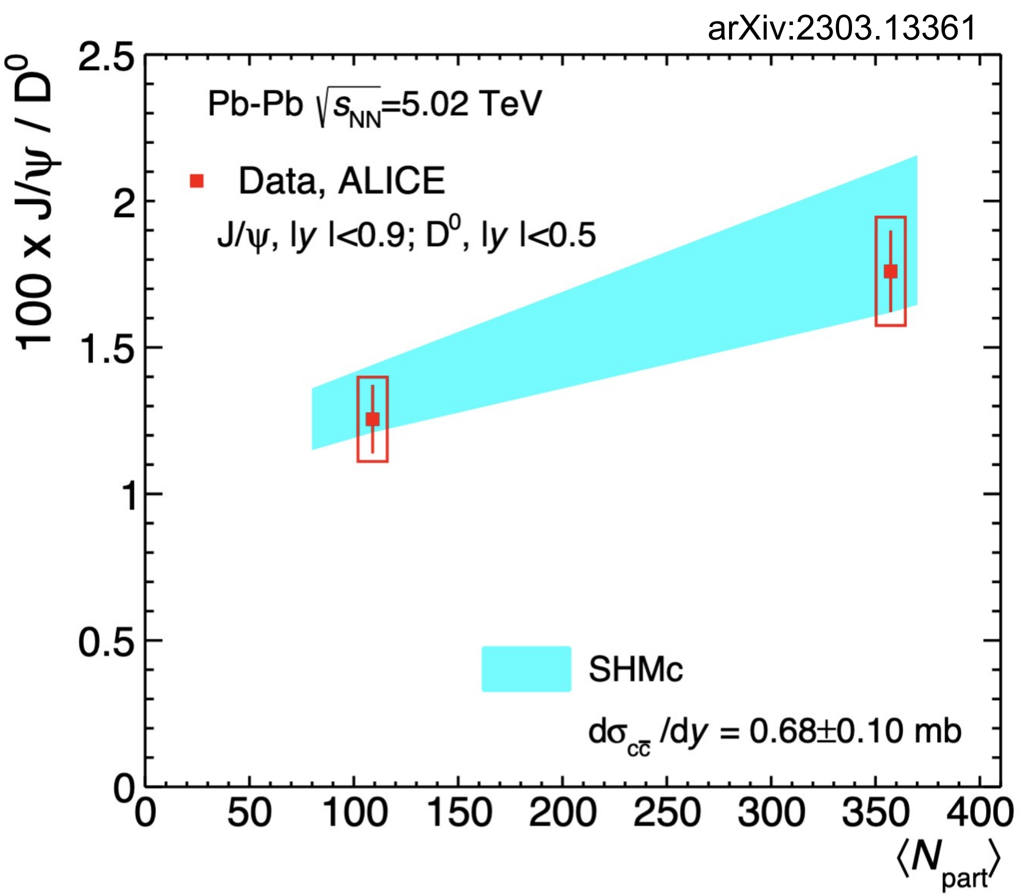
A. Andronic et al., JHEP07 (2021) 035





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

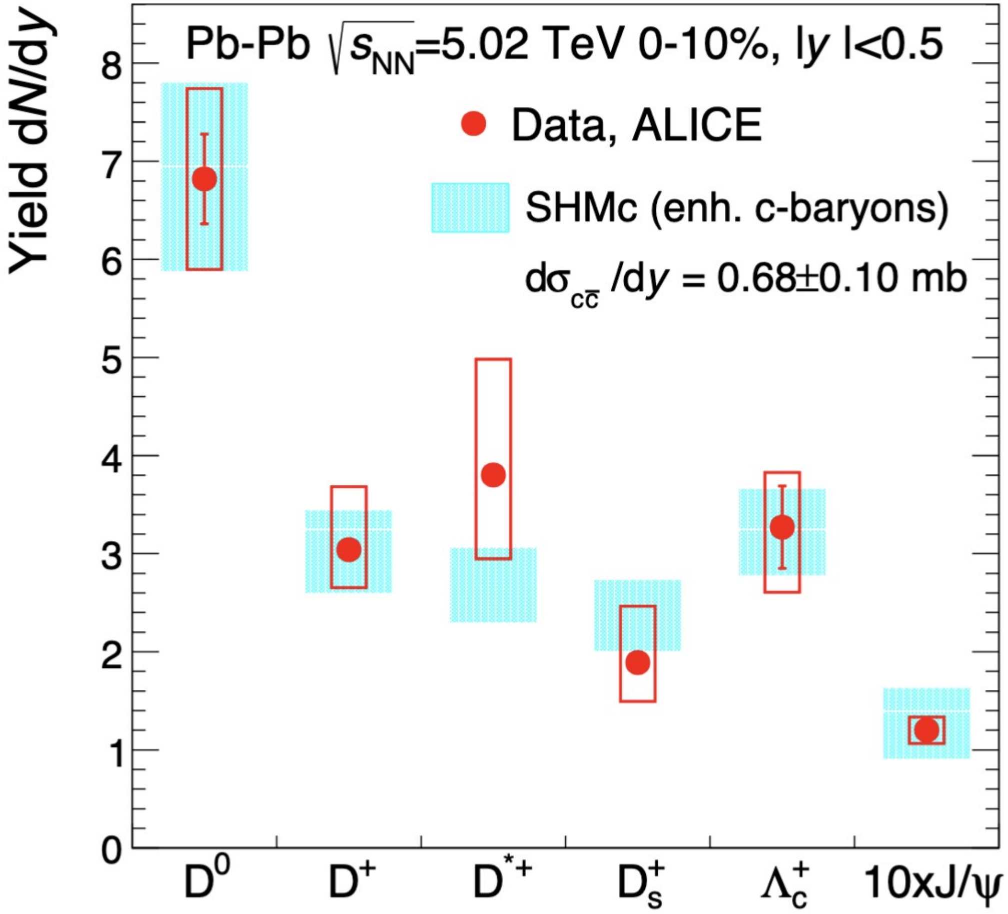


for the first time ratio of fully p_t integrated D^0 to J/ψ available from ALICE

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

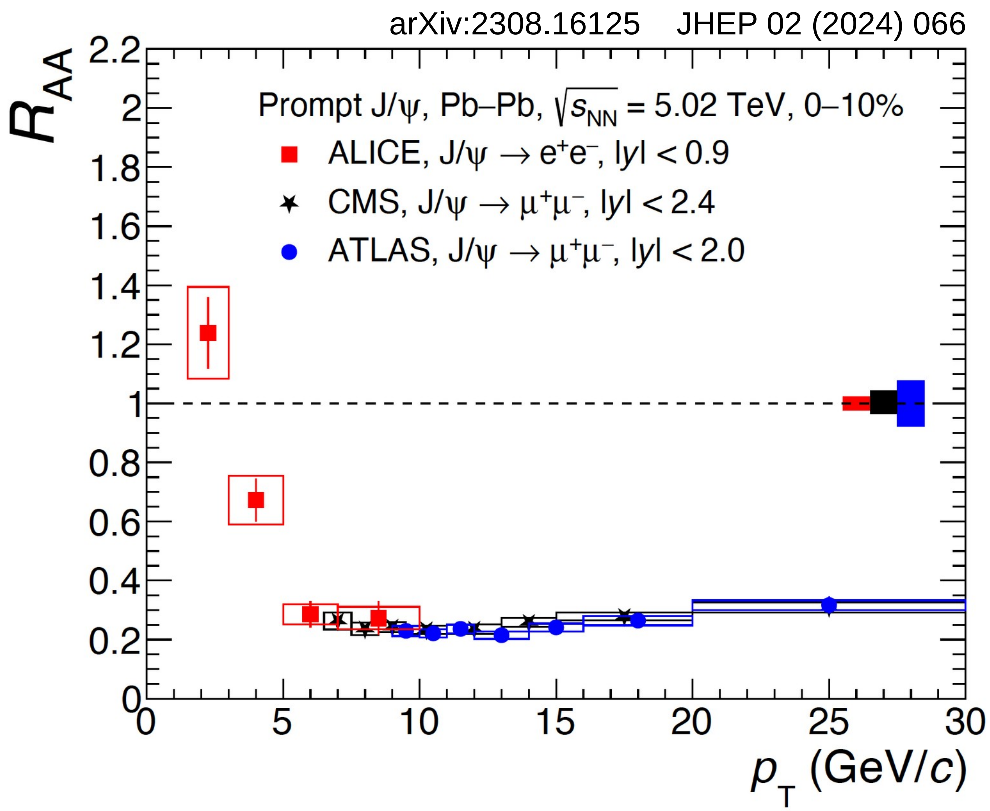
→ J/ψ relative to D^0 falls into place naturally, this is the normalization we aimed for since 30 years to demonstrate concept of deconfinement with charmonia!

Comparison of open charm hadrons to SHMc prediction



- recent ALICE measurements gives dN/dy of different open charm hadrons
- all in agreement with parameterfree SHMc predictions

Beyond yields: transverse momentum distributions

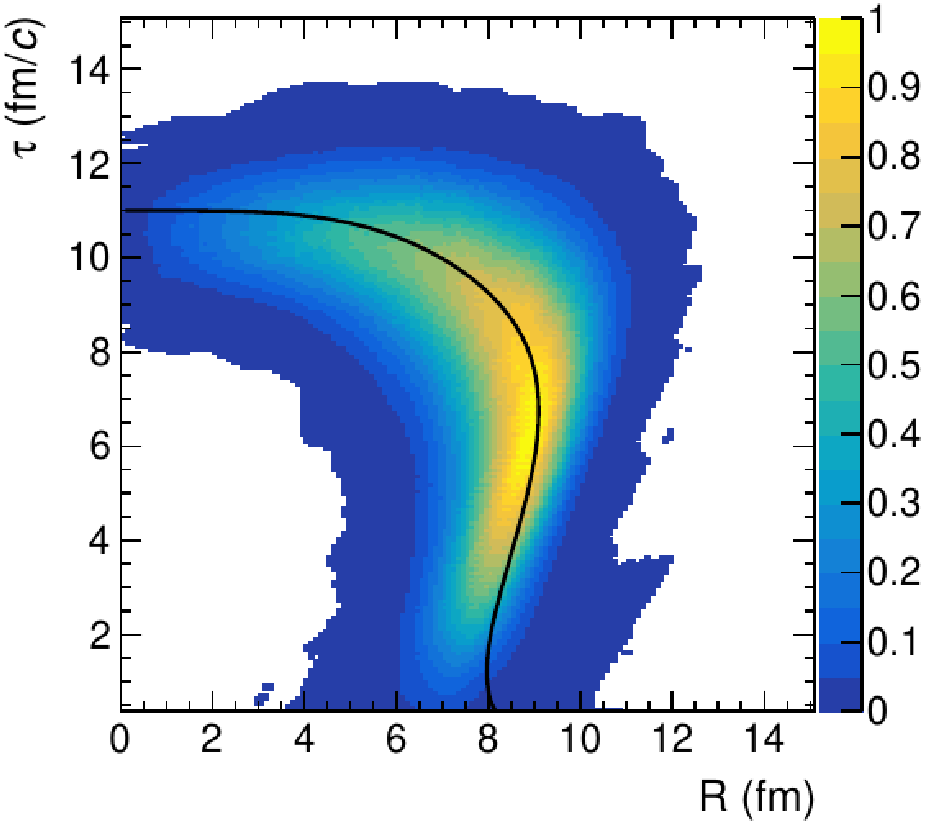


recent ALICE: separation of prompt and non-prompt J/ψ down to 1.3 GeV/c

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

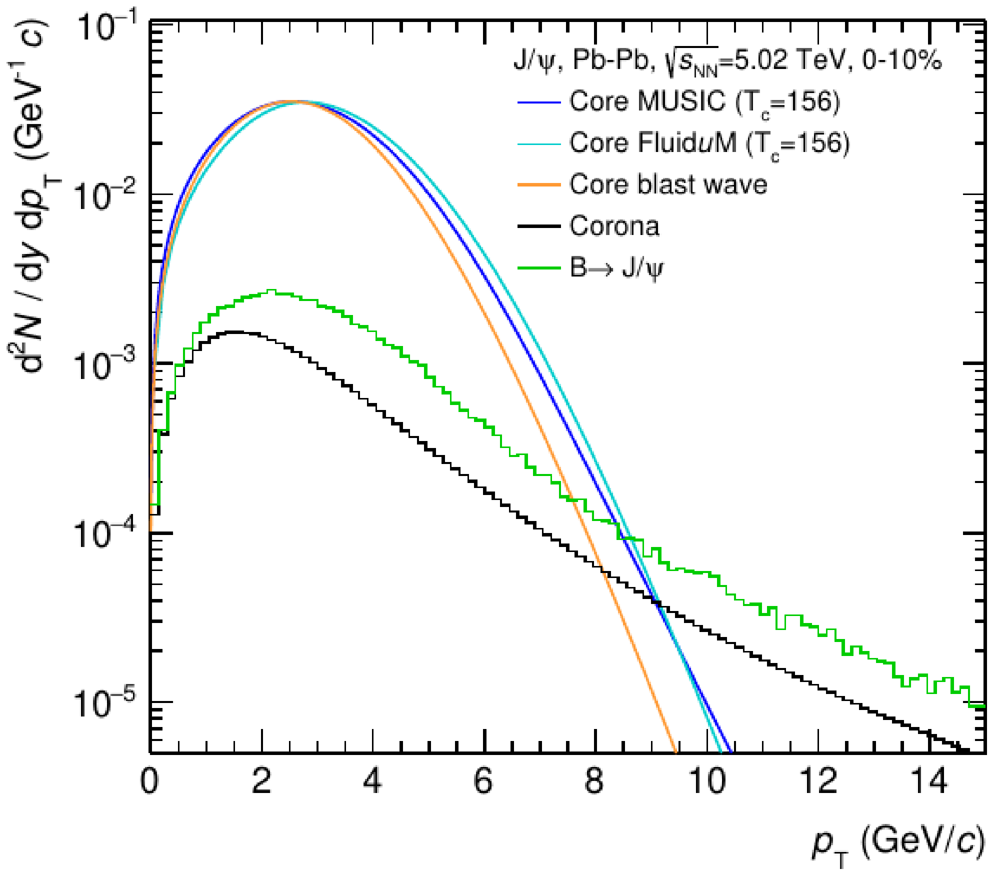
Approach to spectra and v_2: use Cooper-Frye freeze-out of hydrodynamics codes directly

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



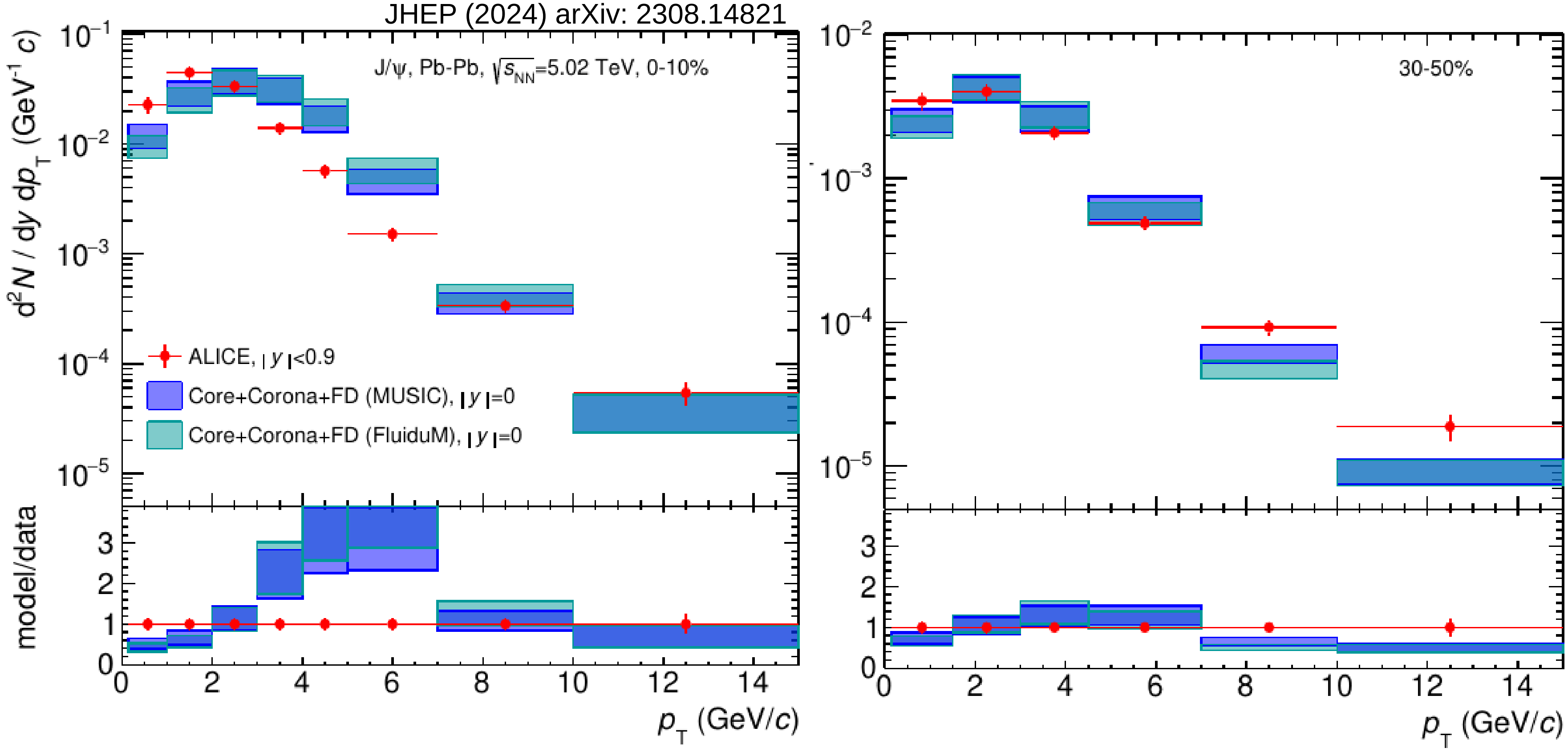
freeze-out hyper surface elements
at T=156.5 MeV from MUSIC
solid line: FluiduM

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



J/ψ spectra

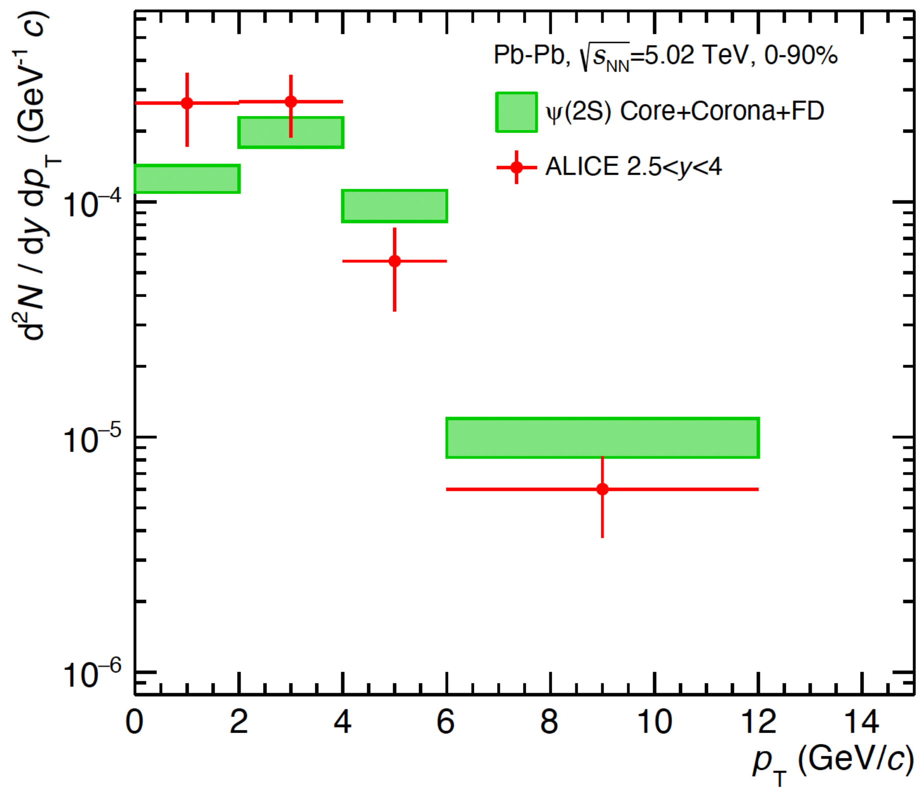
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, JHEP (2024) arXiv: 2308.14821



- spectra harder by about 1 GeV
- are charm quarks reaching the very outer front of the expanding fireball, i.e. fluid cells with the largest velocities?
- future opportunity: measure source size by DD HBT correlations

ψ(2S) spectrum

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



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

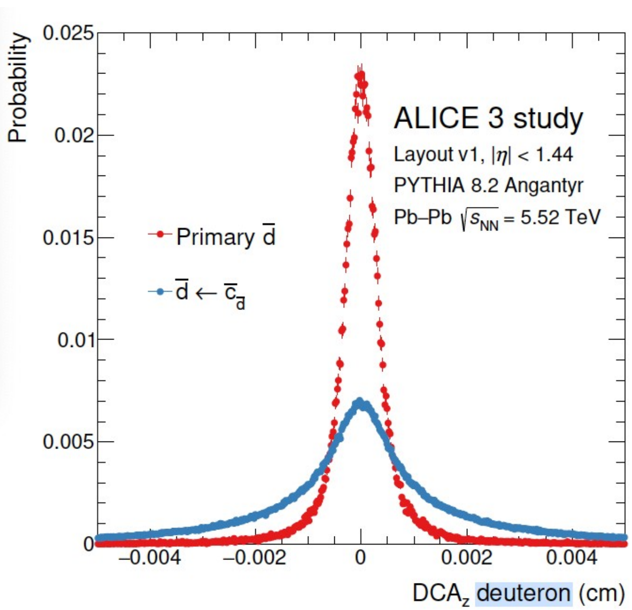
→ needs more data Runs3,4 and ALICE3

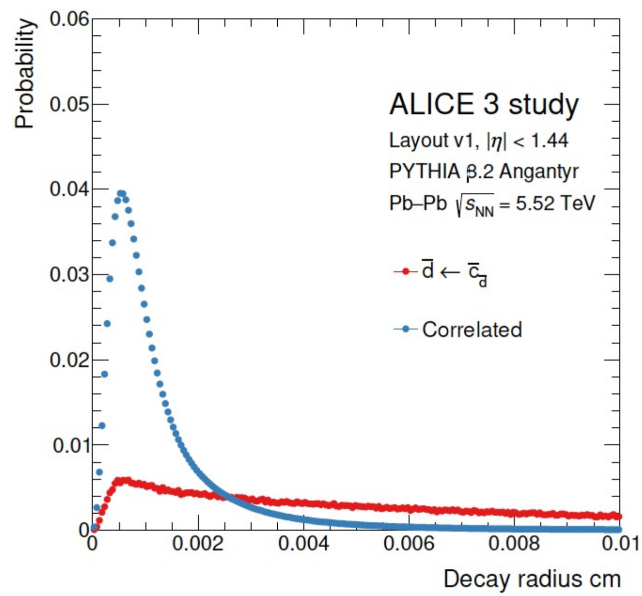
Feasibility for c deuteron in ALICE3

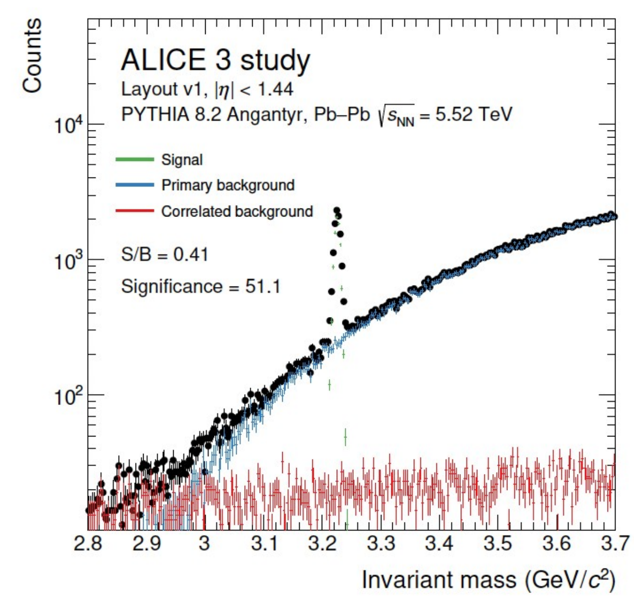
is c-deuteron bound and weakly decaying? discover or put limit

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

arXiv: 2211.02491







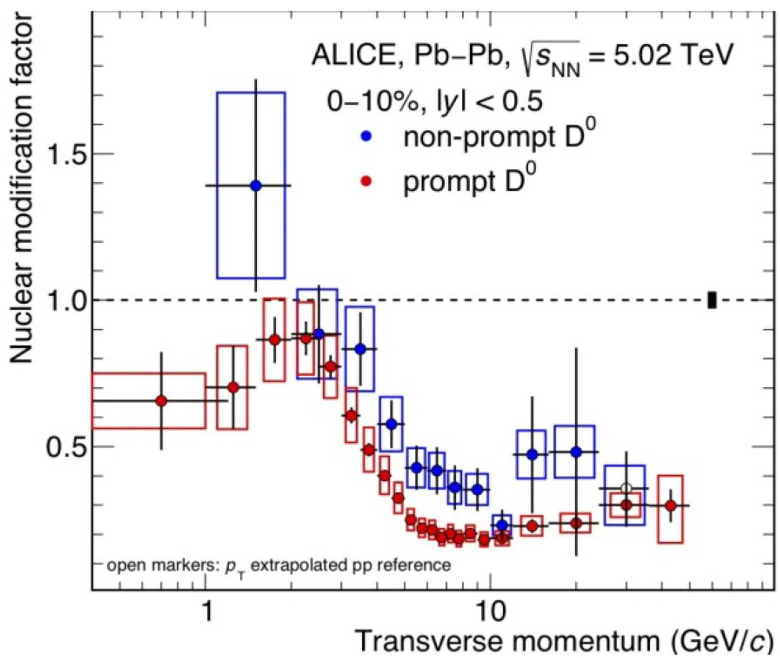
main combinatorial background from primary deuterons can be effectively suppressed due to superb vertex resolution $\rightarrow$ significance 51

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

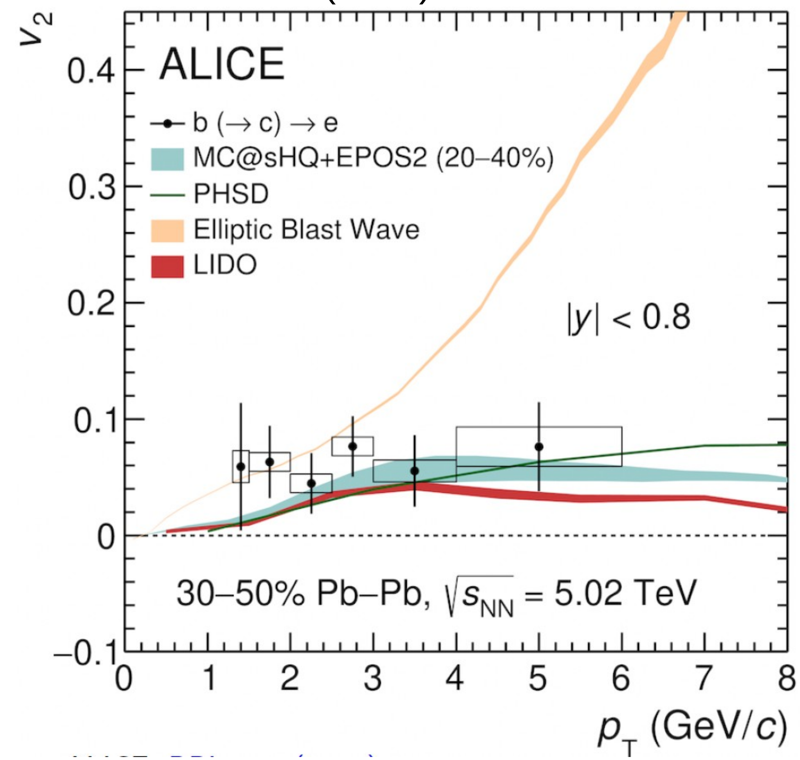
abundance c_t factor 350 less, significance factor 18 less, needs all of Run5+6 (factor 6)

Thermalization of beauty?

JHEP arXiv: 2202.00815

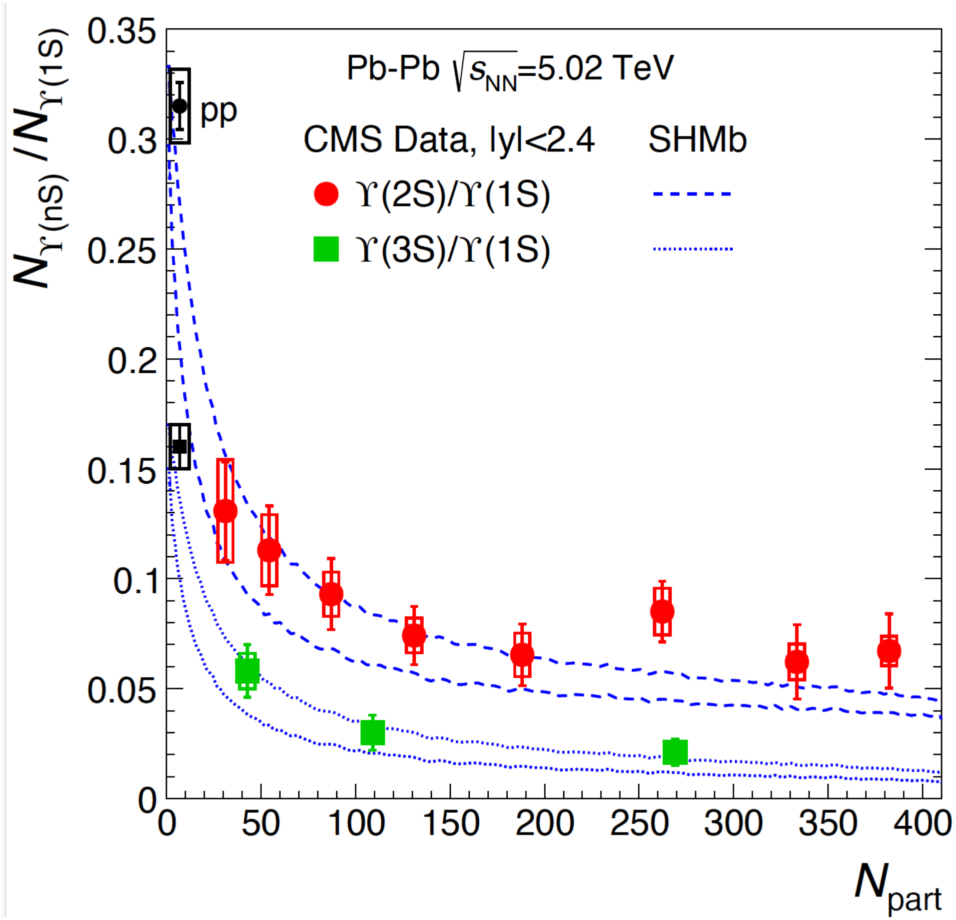


PRL 126 (2021) 16 arXiv: 2005.11130



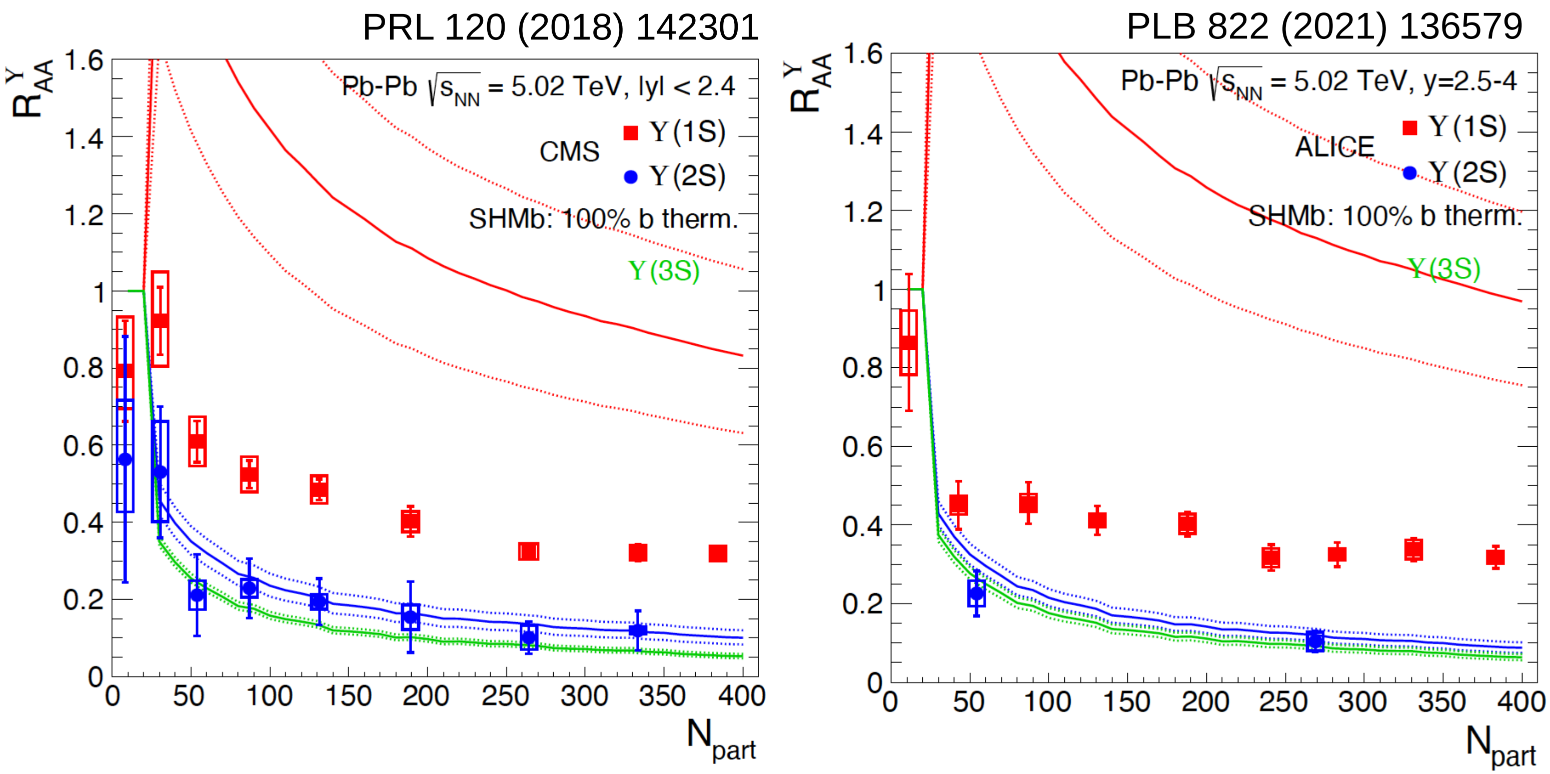
strong reduction of R_{AA} and significant v_2, but both a factor 2 less pronounced than for prompt D^0 → indication that beauty quarks thermalize only partly
only the thermalized fraction should hadronize statisticly

Bottomonia in SHMb assuming full thermalization



ratios of 2S/1S and 3S/1S completely consistent with data over full centrality range for T = 156.5 MeV
no free parameter!

Bottomonia in SHMb assuming full thermalization

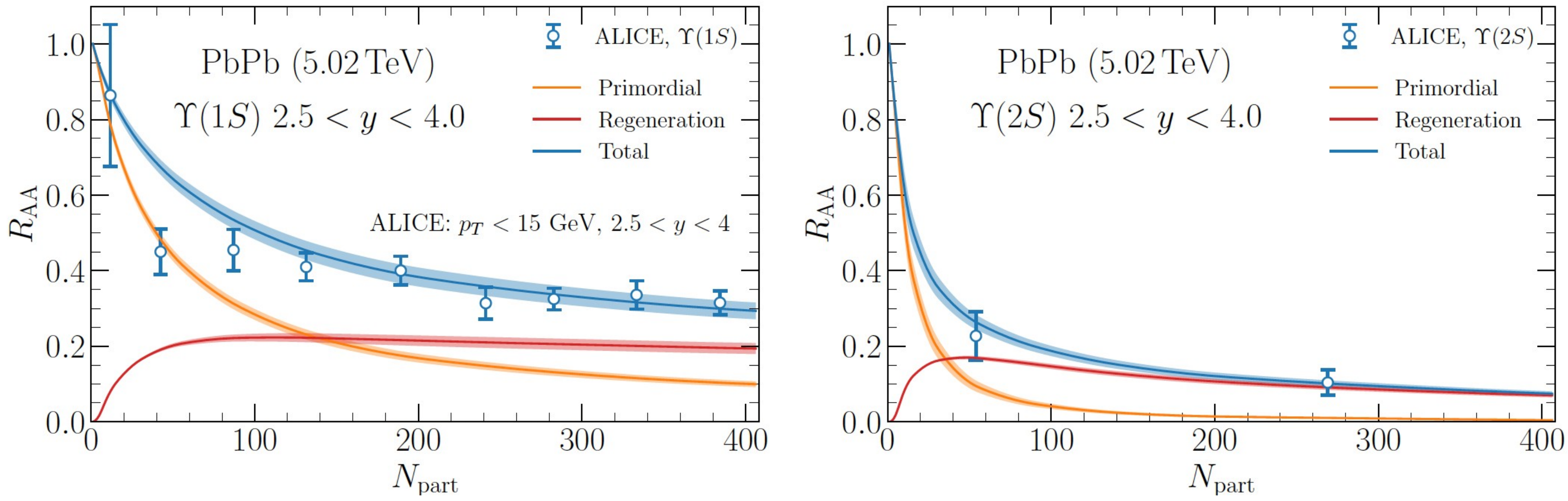


- assumption of fully thermalized b-quarks fails to reproduce Υ(1S) by factor 2-3 for central collisions
  but: $g_b = 10^9$ so Υ is scaled up from thermal yield by 10^{18}
- to come without any free parameter within a factor 2-3 is not a minor feat

Transport approach to beauty quarks in QGP

reaction rates obtained from lQCD constrained T-matrix approach with viscous hydro-dynamics medium evolution

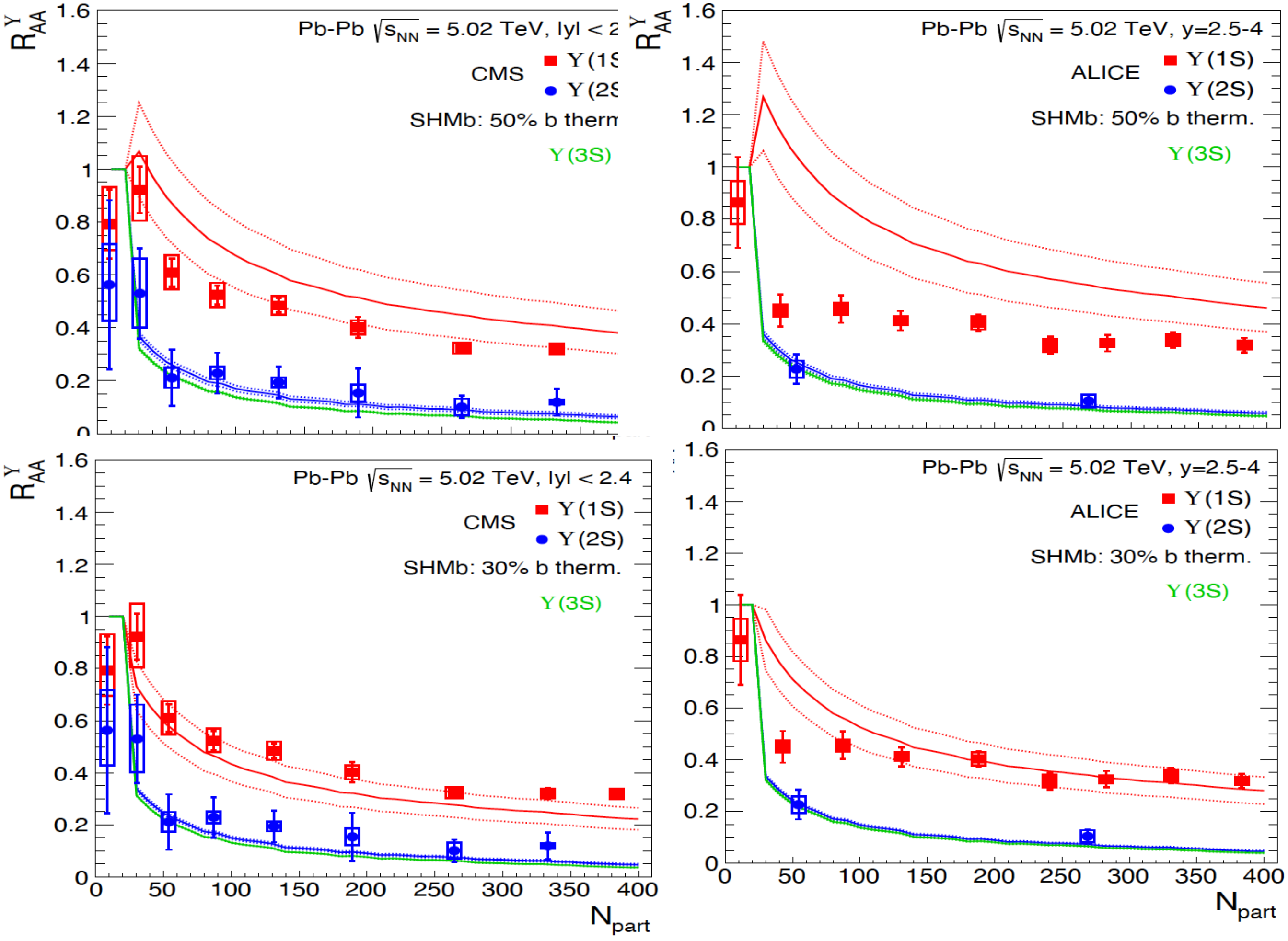
B. Wu and R. Rapp, Phys. Lett. B873 (2026) 140223



in central collisions, regeneration component dominates bottomonium yields

Bottomonia assuming partial thermalization

A. Andronic et al., arXiv: 2209.14562



factor 2-3 reproduces
Υ yields
i.e. 30-50 % thermalized

could be in line with open beauty energy loss and flow

more data are coming

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
- improved total charm cross section PbPb in Run3 coming

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

congratulation and all the best, dear Andrzej!
serdeczne gratulacje!

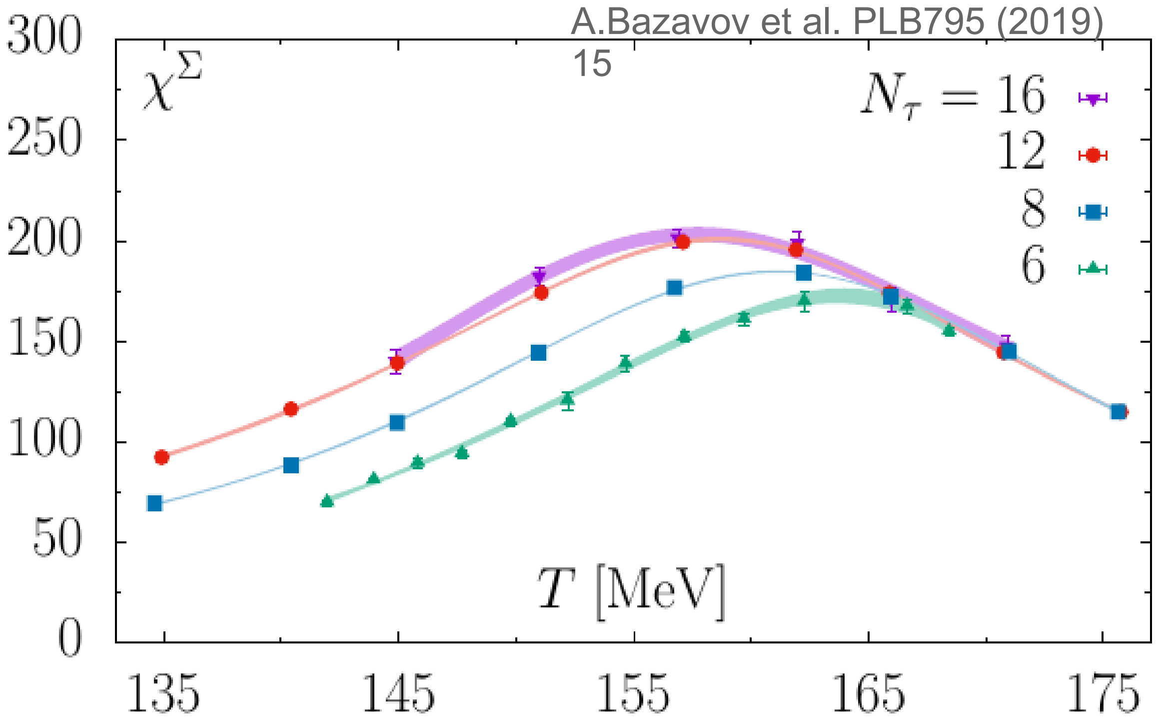
backup

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

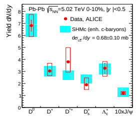


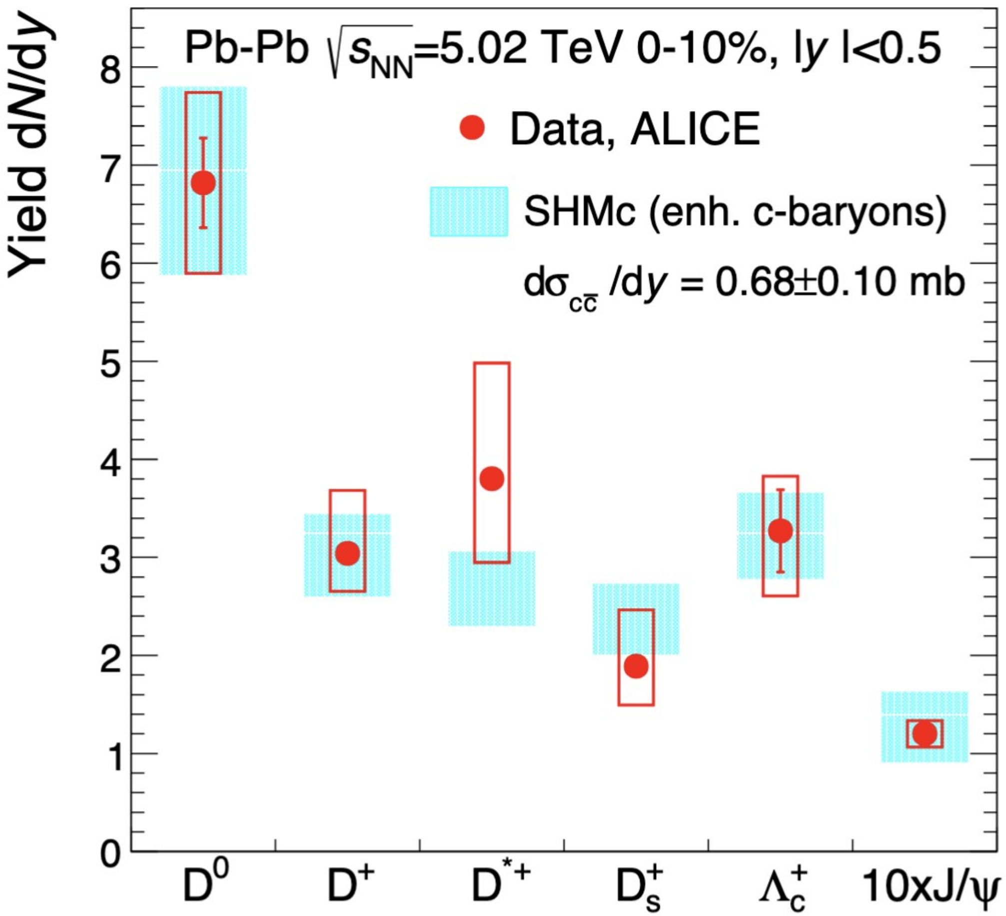
most recent results on pseudo-critical temperature for chiral phase transition

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

comparison of open cham hadrons to SHMc prediction





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

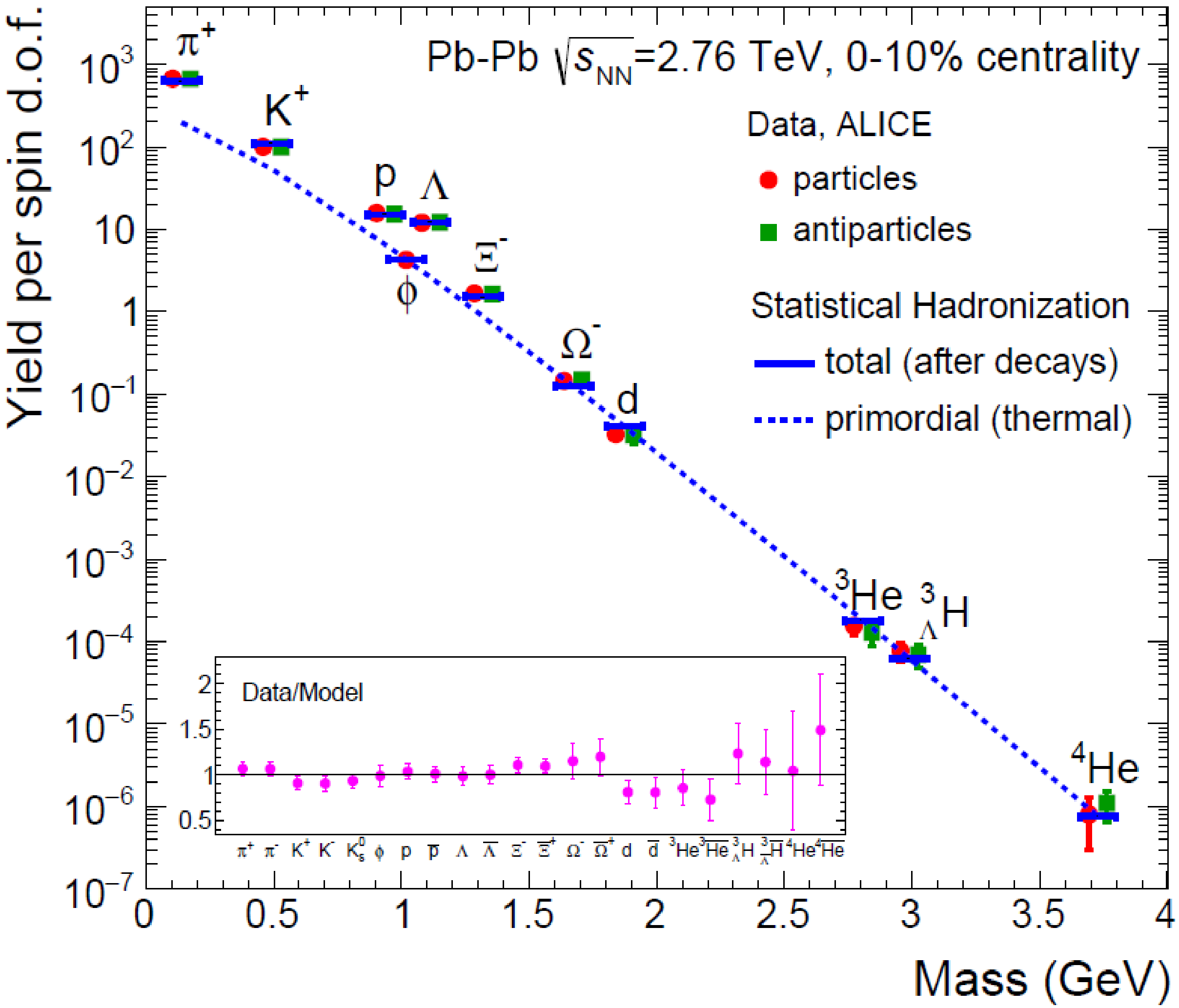
Production of hadrons and (anti-)nuclei at LHC

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)

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



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

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: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

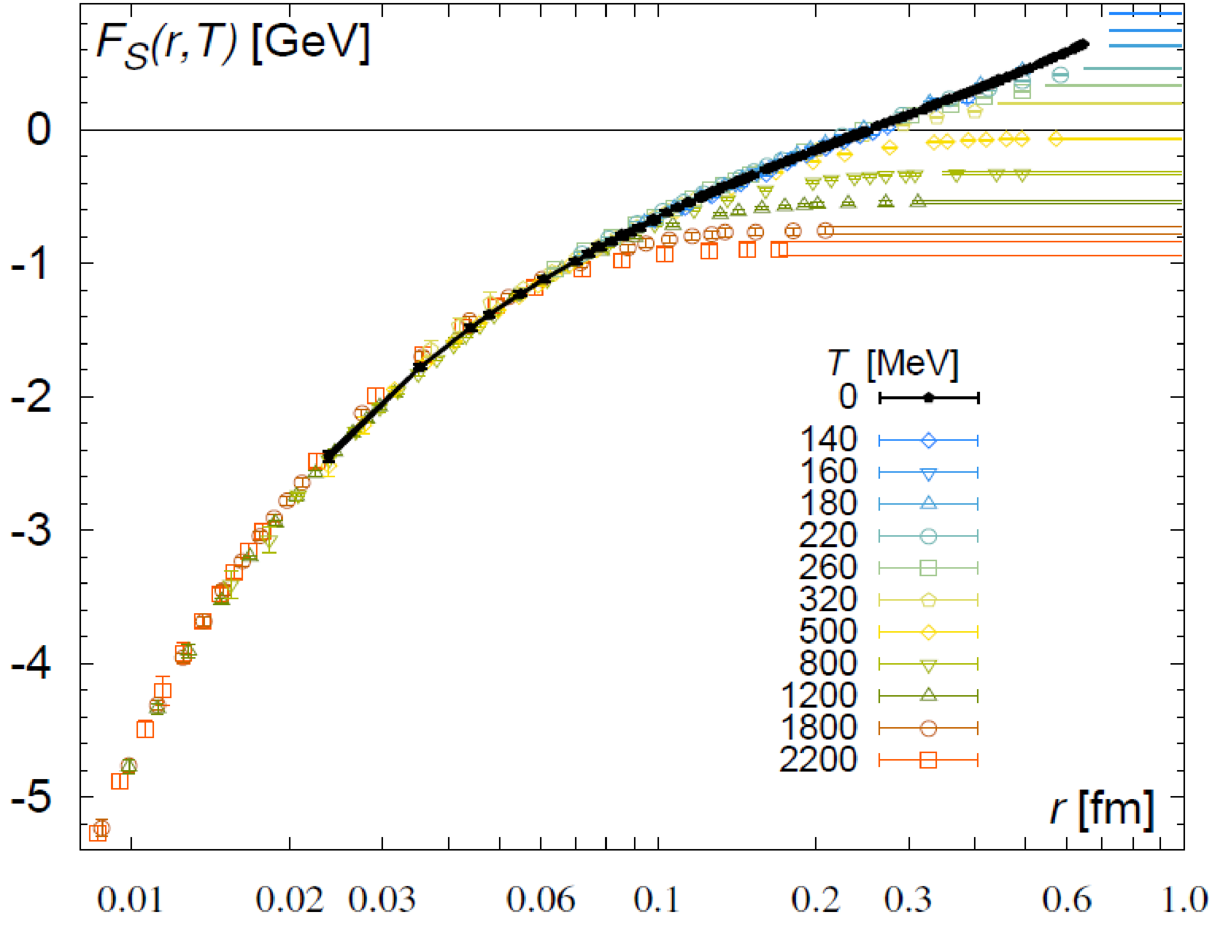
expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

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

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

TUMQCD arXiv:1804.10600



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

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

ccbar pairs are formed at collision time scale tcoll = □ccbar

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS tcoll = □ccbar ≅ □QGP ≅ □hadron

but at RHIC and much more pronounced at LHC there is the following hierarchy: tcoll = □ccbar ≪ □QGP ≪ □hadron

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

Statistical hadronization model for charm (SHMc) including canonical thermodynamics

- the charm balance equation determines the fugacity g_c

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

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

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

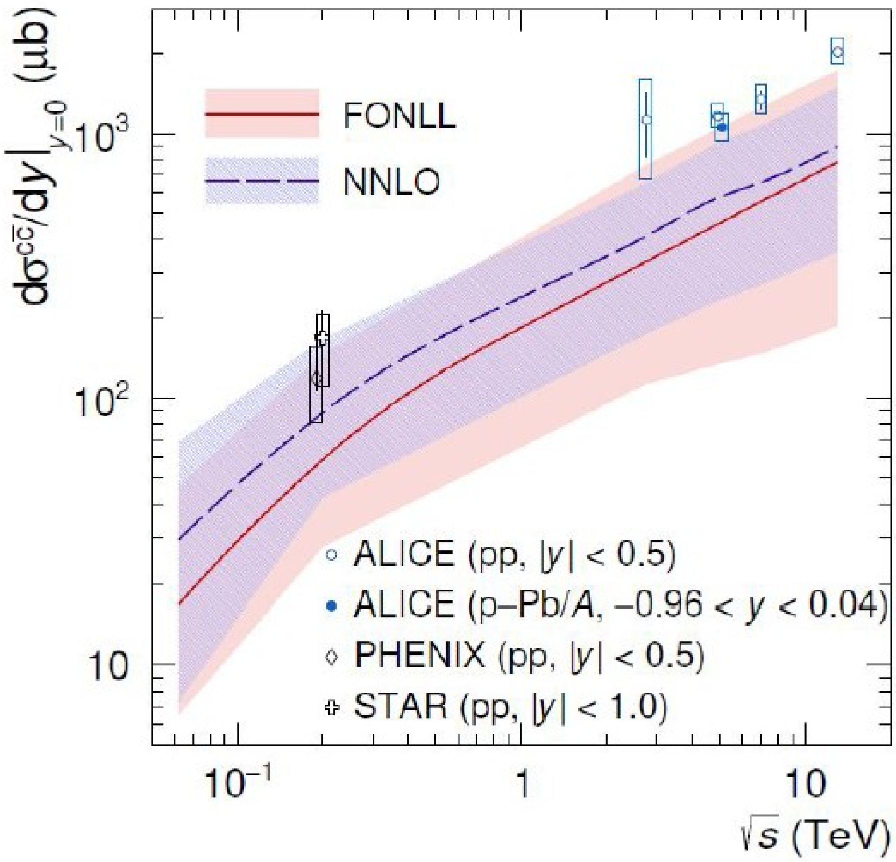
defining:

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

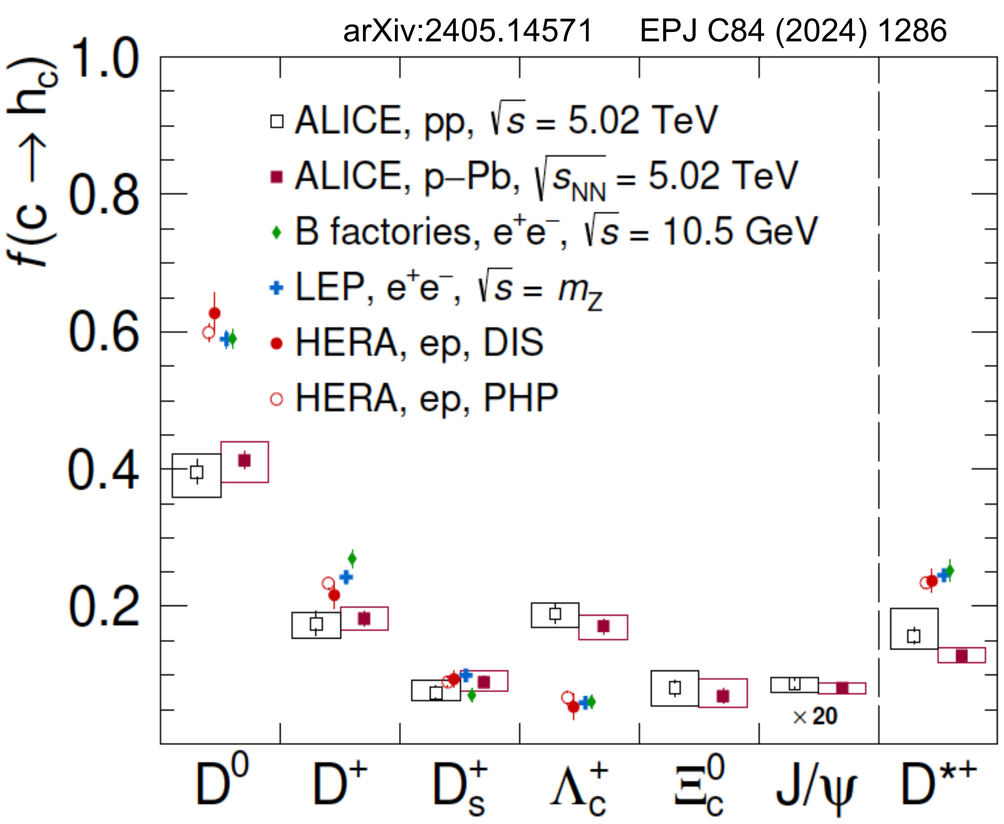
$$N_{oc,2} = \frac{1}{2} g_c^2 V \sum_{h^k_{oc,2}} n_k^{\rm th}$$

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

status charm cross section measurements



Modified charm fragmentation at the LHC

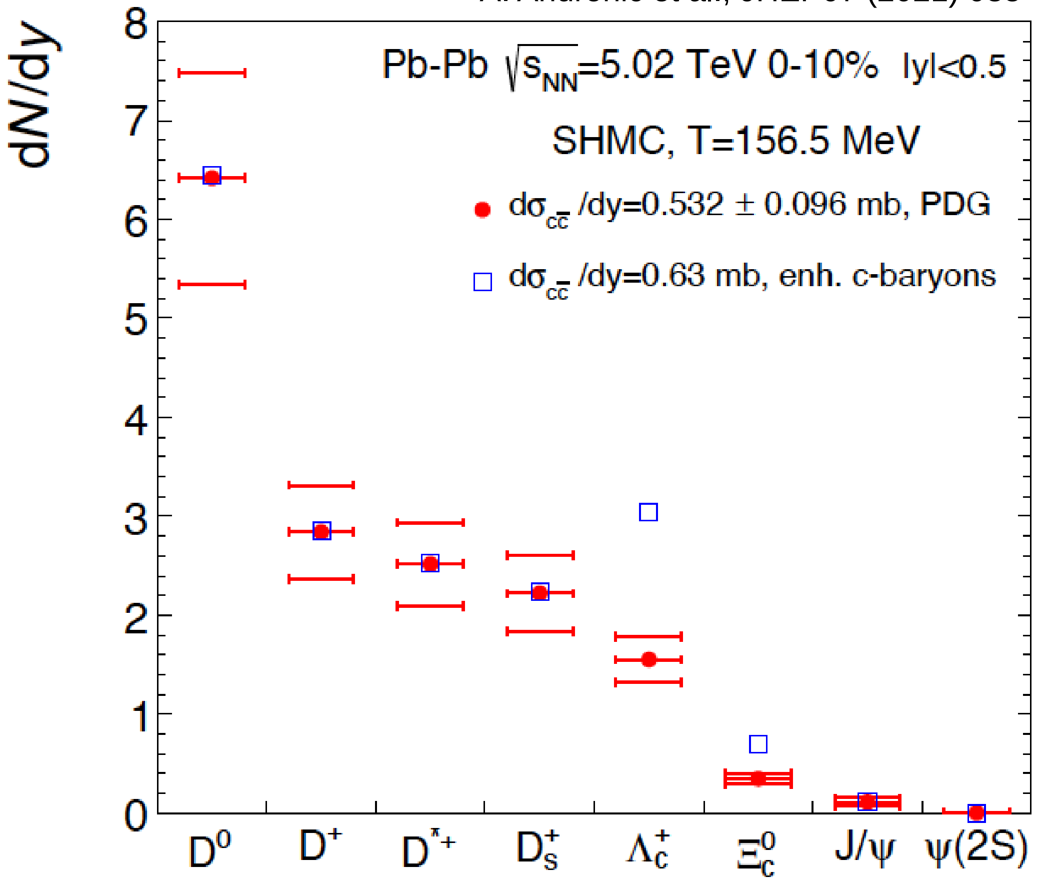


fragmentation into charmed baryons strongly enhanced in pp, pPb and PbPb collisions compared to e^+e^- and ep

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

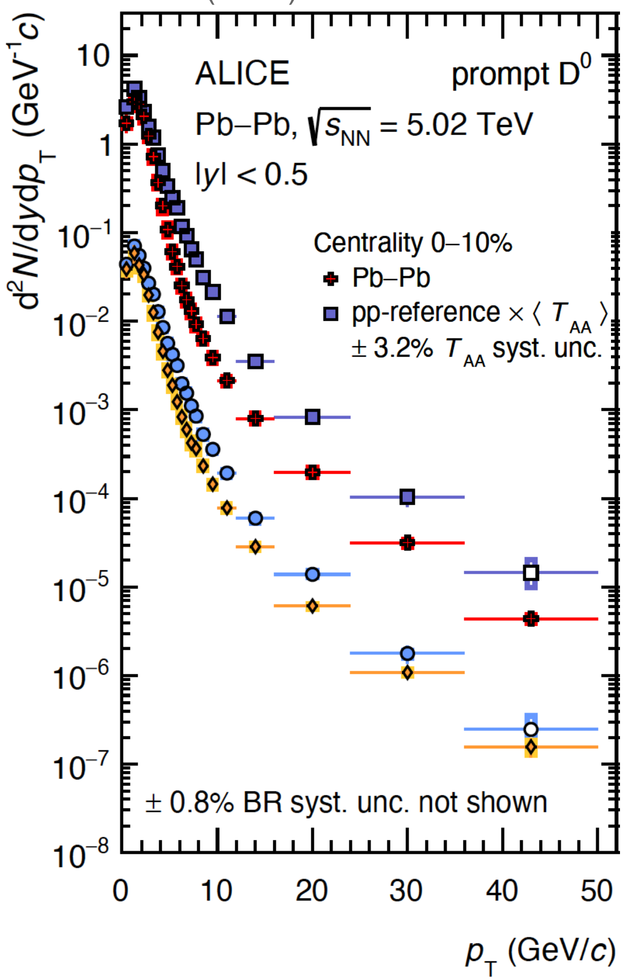
A. Andronic et al., JHEP07 (2021) 035



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

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

$$dN_{c\bar{c}}/dy = 13.7 \pm 2.1$$

corresponding to $g_c = 31.4 \pm 4.8$

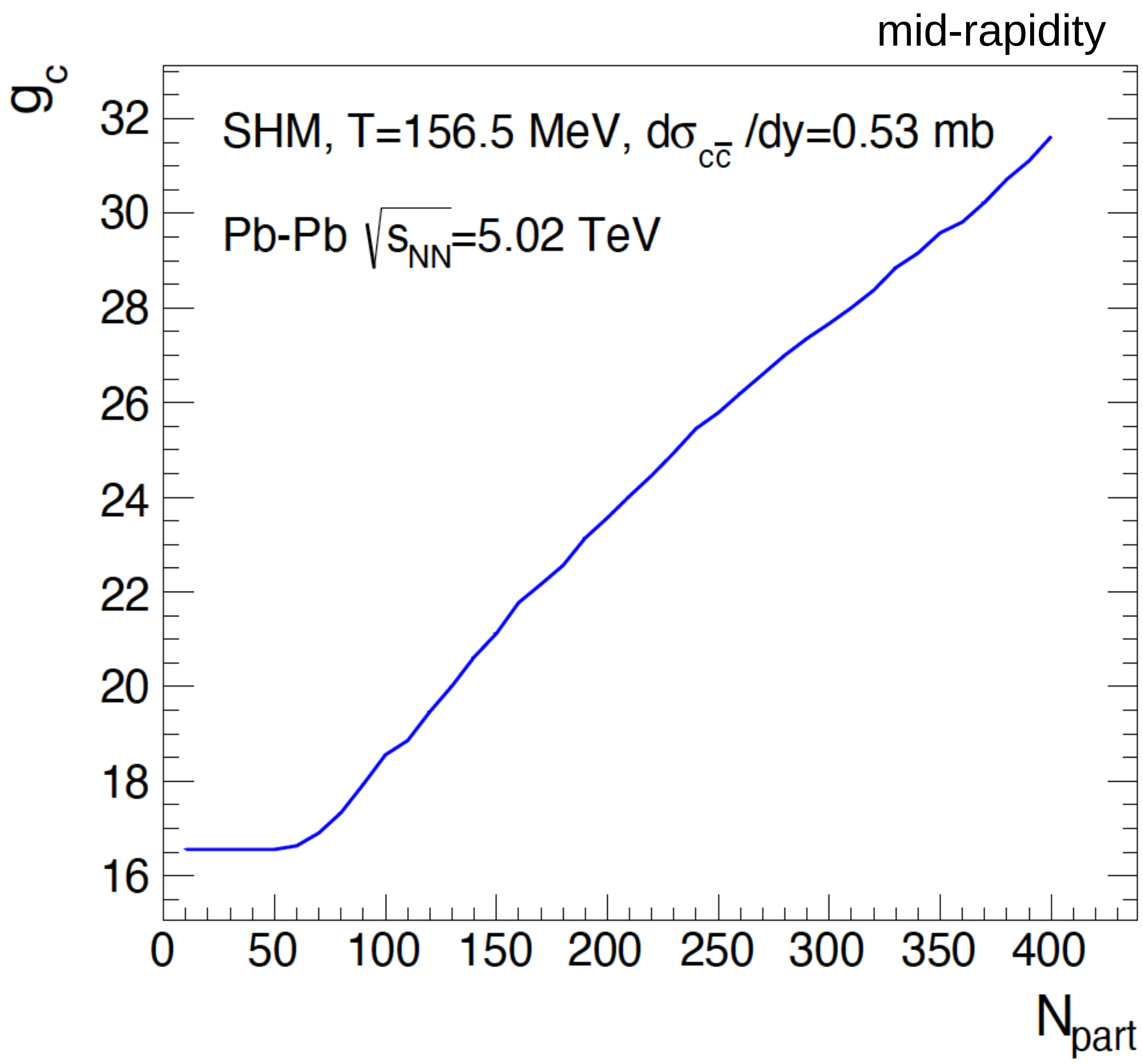
use this as new basis for PbPb predictions from SHMc

8.8% larger than our estimate from pp and nuclear effects

uncertainty reduced by 15%

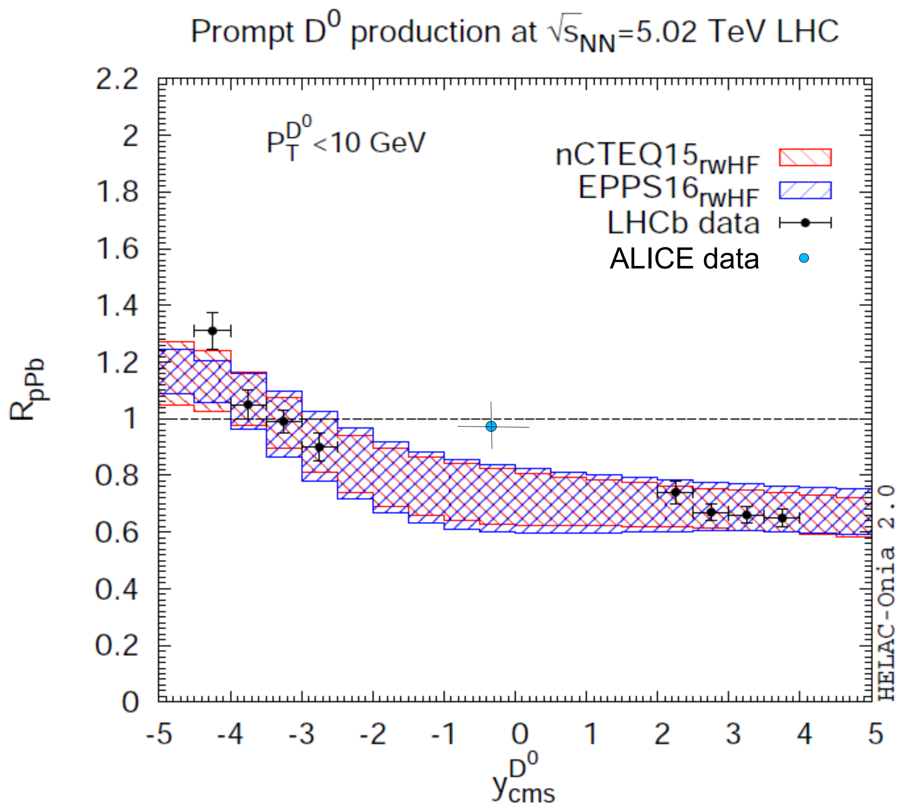
outlook to LHC Run3/4: with upgraded ALICE detector and 50 kHz PbPb collisions → precision measurement of all singly charmed hadrons down to p_t=0

Centrality dependence of charm fugacity g_c at LHC energy

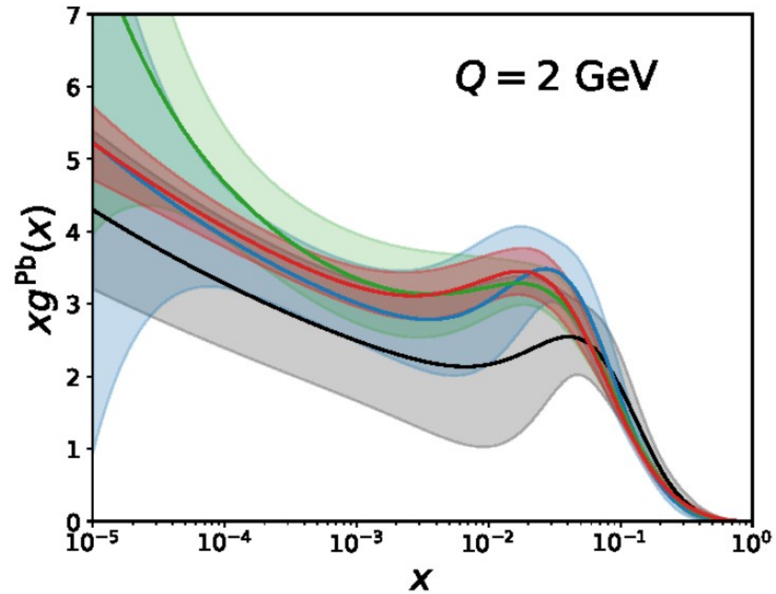


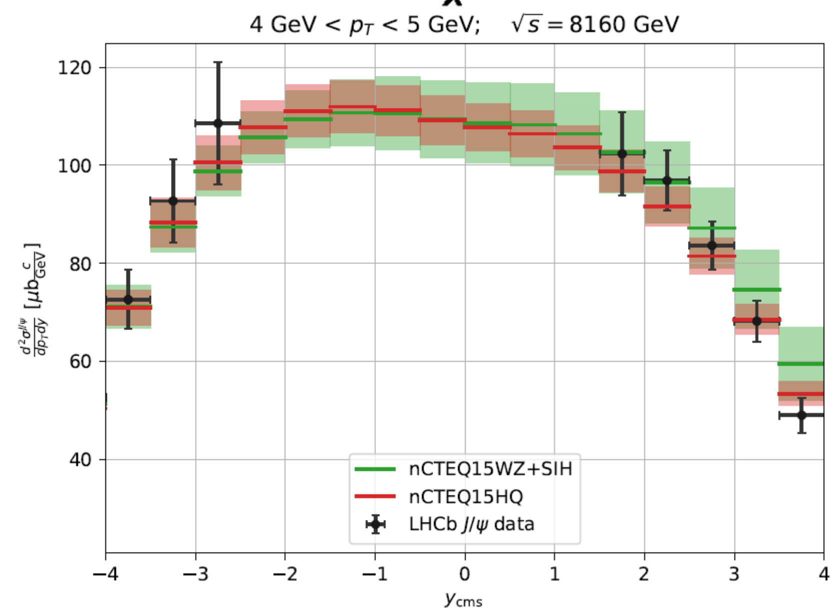
Charm cross section – nuclear effects

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



Duwentäster et al. new nCTEQ15HQ fit
2204.09982





at y=0 $R_{pPb} = 0.73 \pm 0.067$

$\rightarrow$ $S_{PbPb} = 0.53 \pm 0.097$

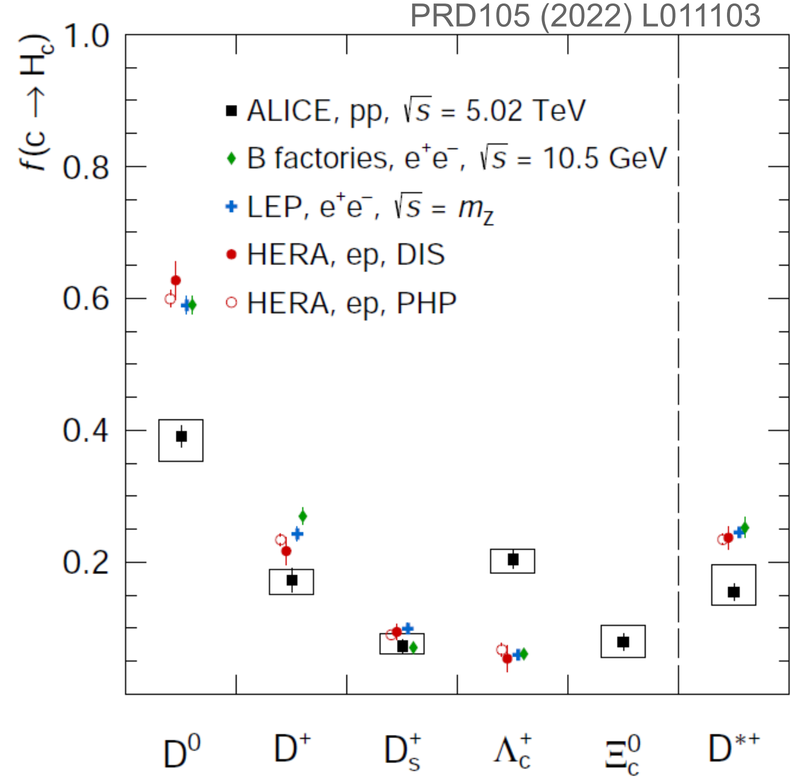
supported by J/y yield in photoproduction

in SHMc in the past we used 0.65 ± 0.12

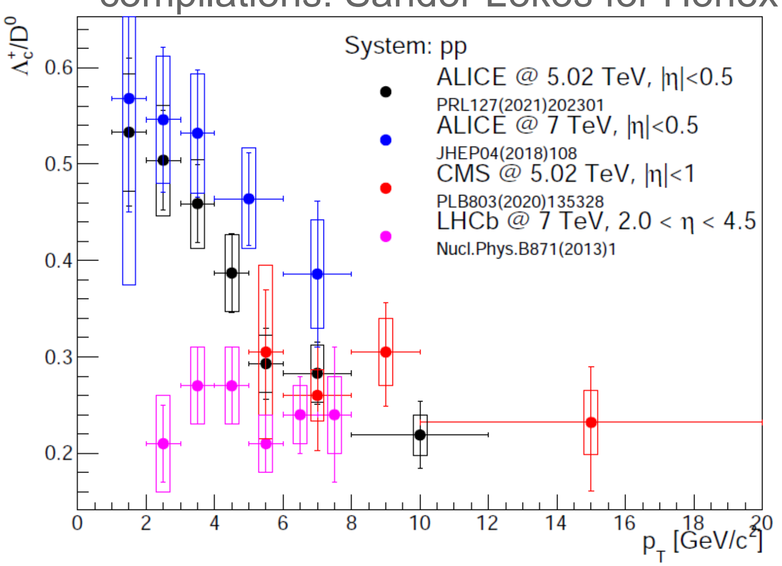
Charm cross section pp collisions

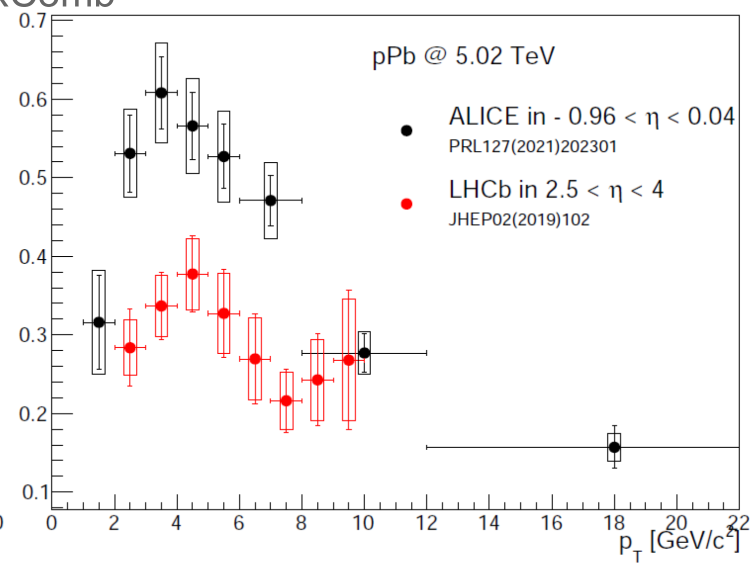
fragmentation into Lc factor 4 increased vs e+e-
can be reproduced by
- some PYTHIA tunes with CR or
- statistical model by about doubling the charmed baryon states as predicted by RQM or lQCD and using T = 170 MeV but at LHC among many newly discovered states only 7 charmed baryons

PRD105 (2022) L011103



compilations: Sandor Lökös for HonexComb



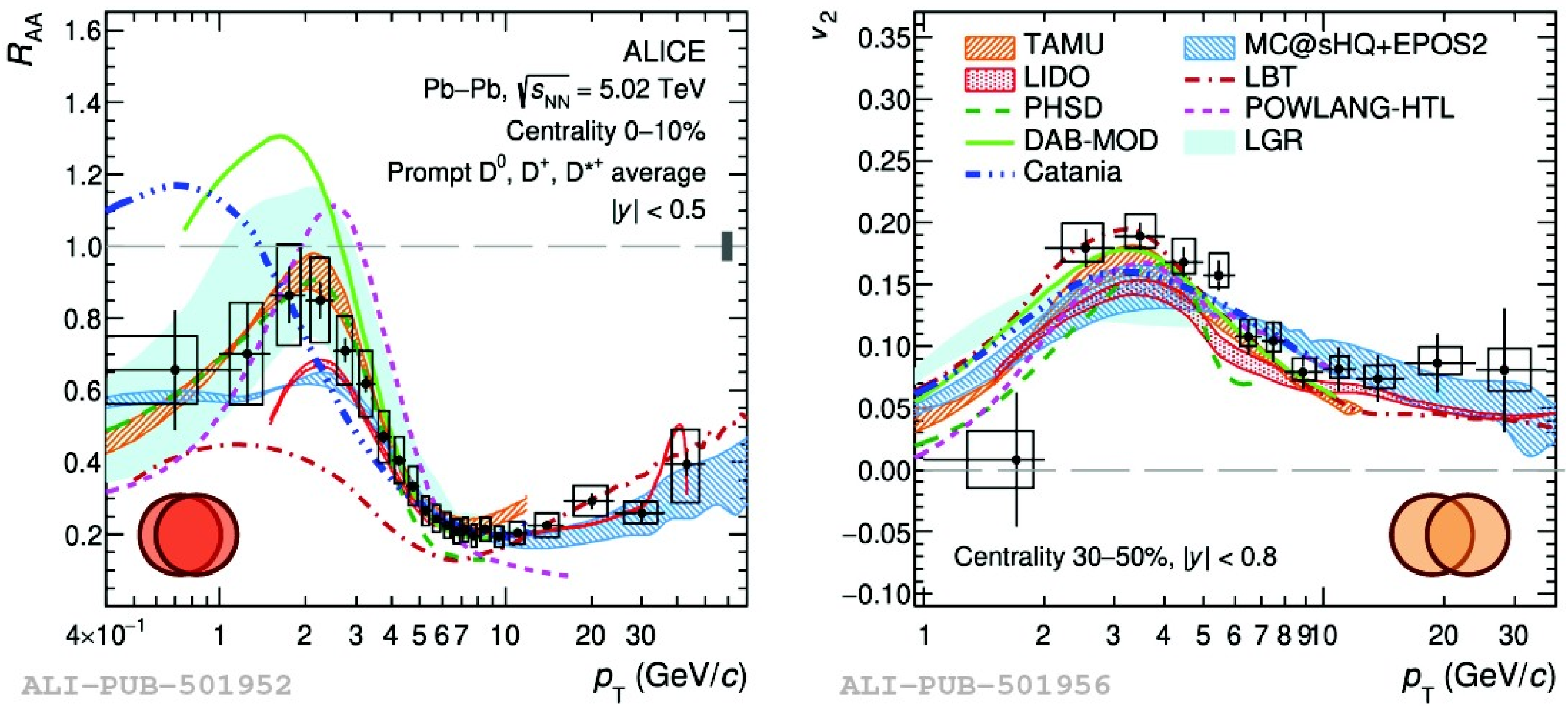


experimental situation needs to be clarified

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

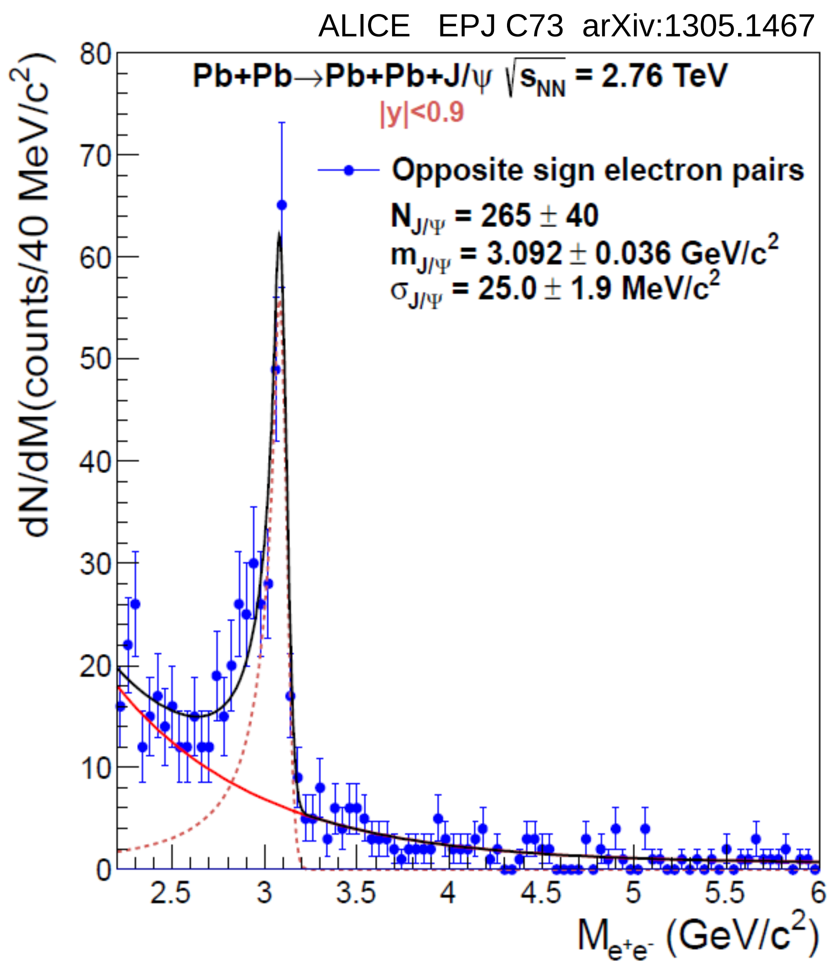
JHEP01 (2022) 174 arXiv:2110.09420



Reconstruction of J/ψ in PbPb collisions at LHC

J/ψ → e^+e^- or $\mu^+\mu^-$ with 6%

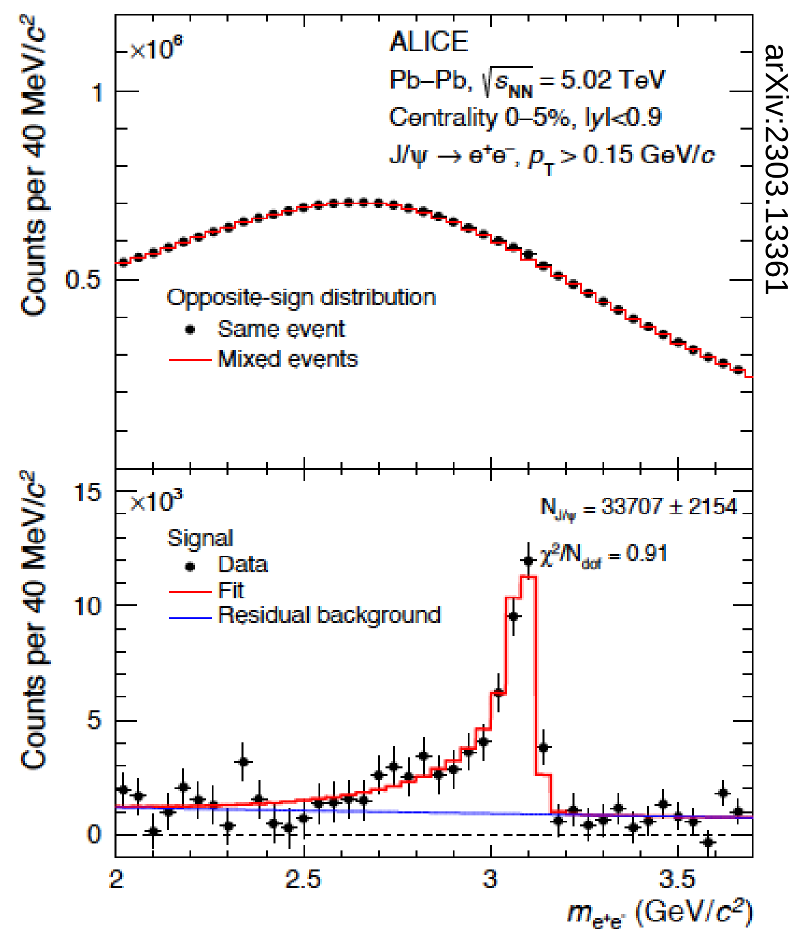
ALICE EPJ C73 arXiv:1305.1467



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

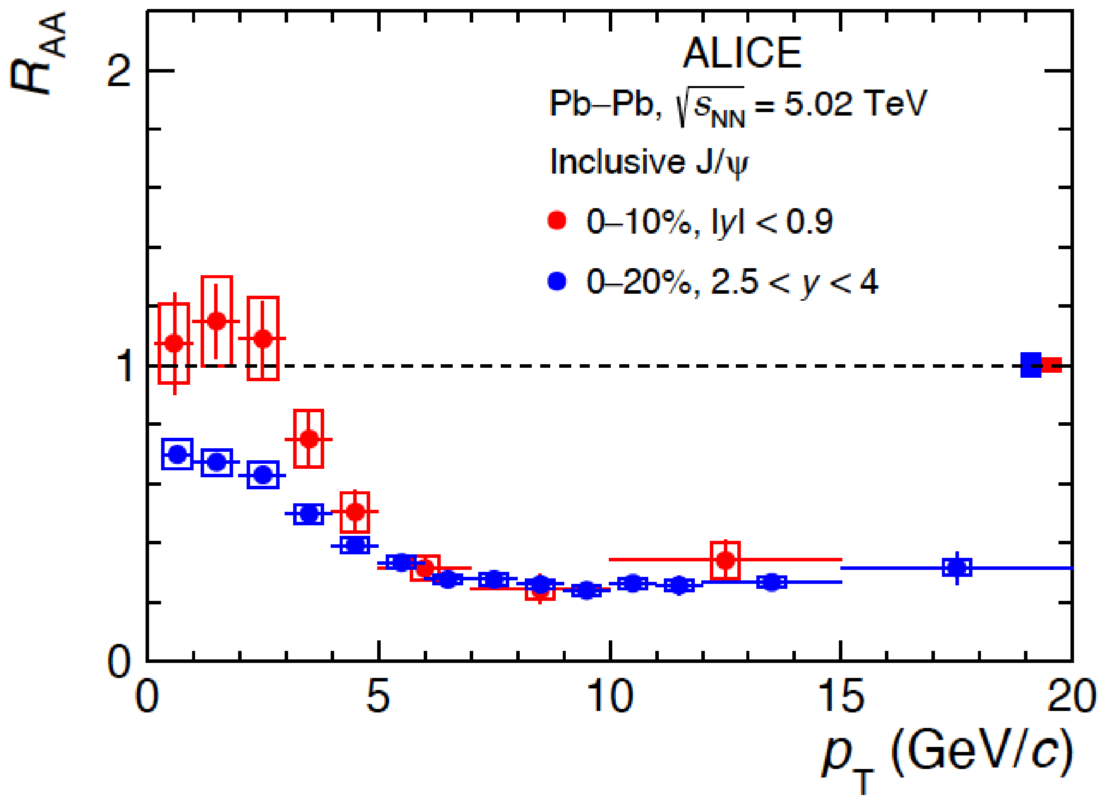
most challenging: central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

mid |y| < 0.8



arXiv:2303.13361

Beyond yields: transverse momentum distributions

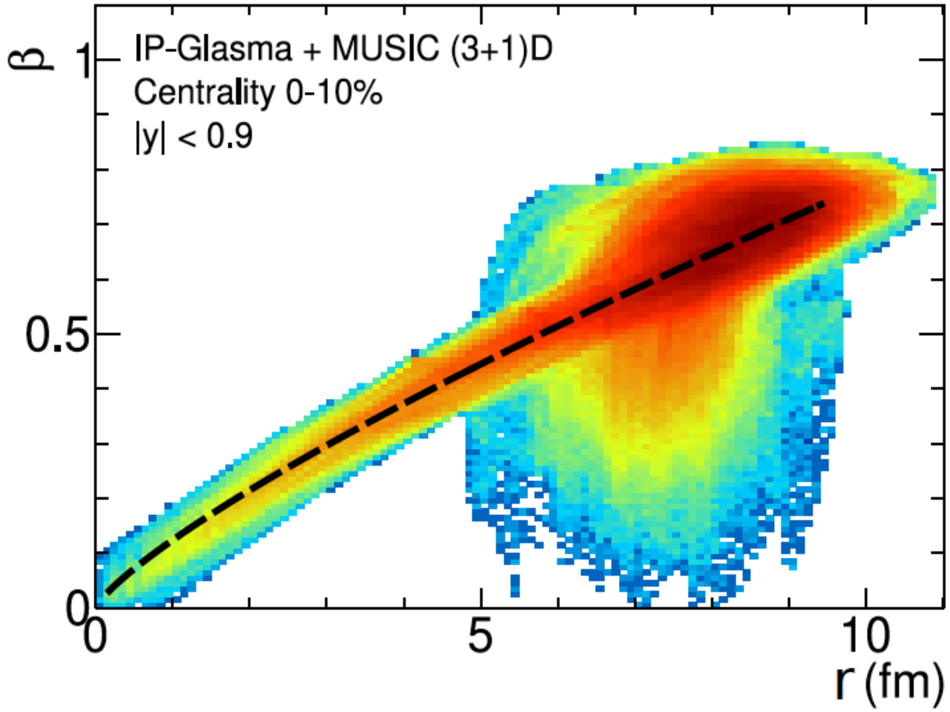


enhancement strongly rising towards lower p_t
for mid-rapidity even beyond pp
(not even considering shadowing)

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



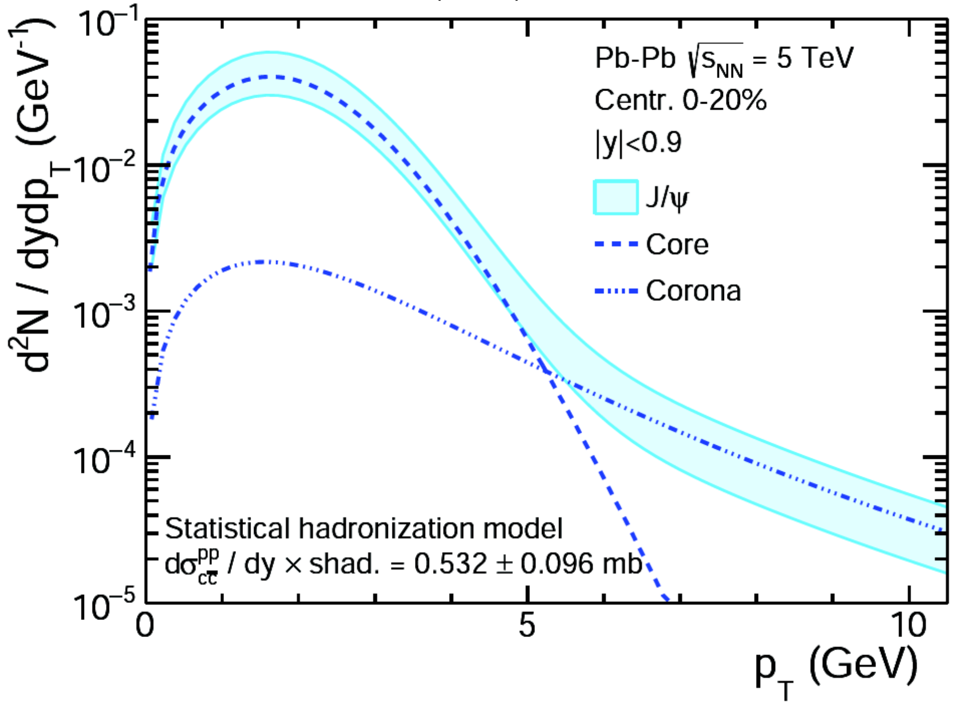
$$\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y} \propto \int_0^R r\mathrm{d}r \left\{ m_T \cosh\rho\, K_1\left(\frac{m_T\cosh\rho}{T}\right) I_0\left(\frac{p_T\sinh\rho}{T}\right) - p_T\sinh\rho\, K_0\left(\frac{m_T\cosh\rho}{T}\right) I_1\left(\frac{p_T\sinh\rho}{T}\right)\right\}$$

$$\rho = \operatorname{atanh}(\beta_T^s (r/R)^n)$$

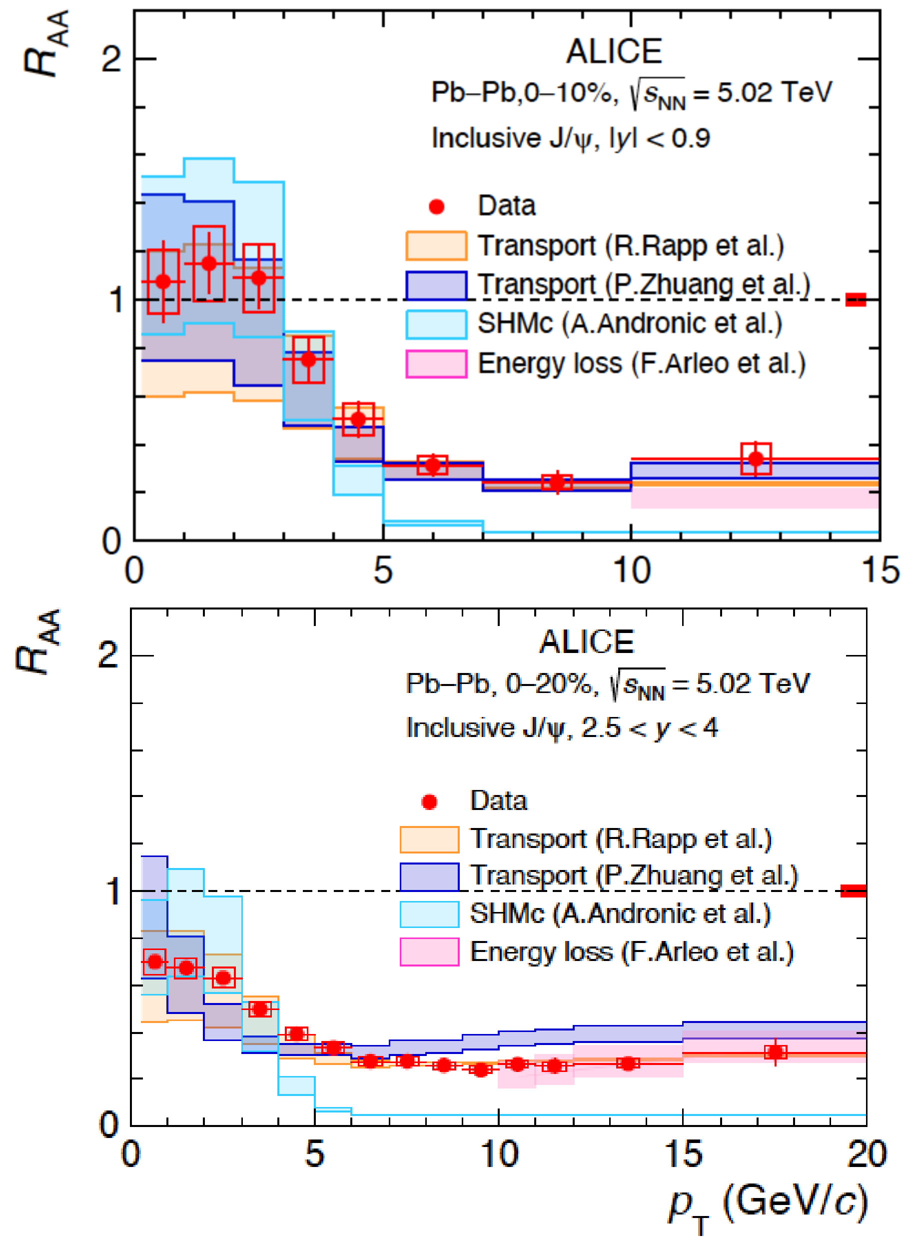
'blast wave parametrization' of spectral shape with T = 156.5 MeV and parameters from MUSIC: n = 0.85 and $\beta_{max} = \beta^s{}_T = 0.62$

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



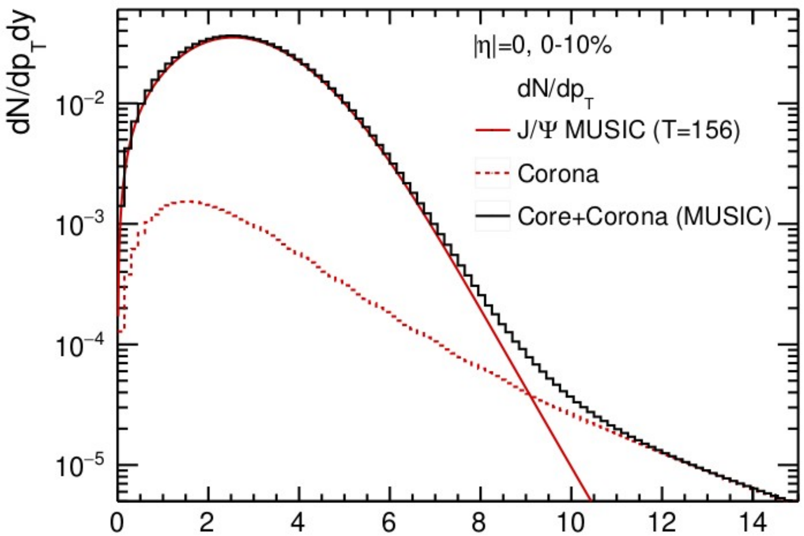
arXiv:2303.13361

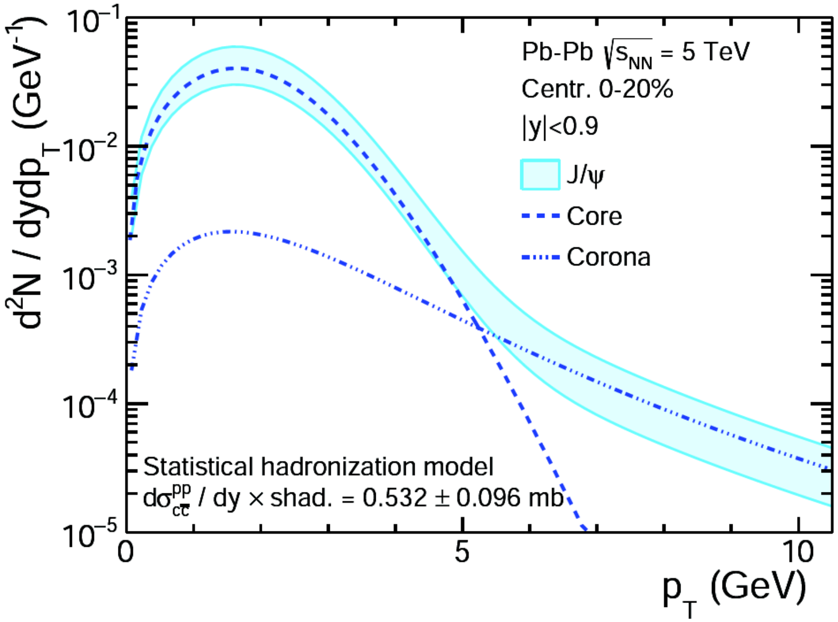


- at low and intermediate p_t very good description of data
- beyond 5 GeV there is additional source beyond statistical hadronization e.g. nonthermalized component

new approach to spectra: 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.

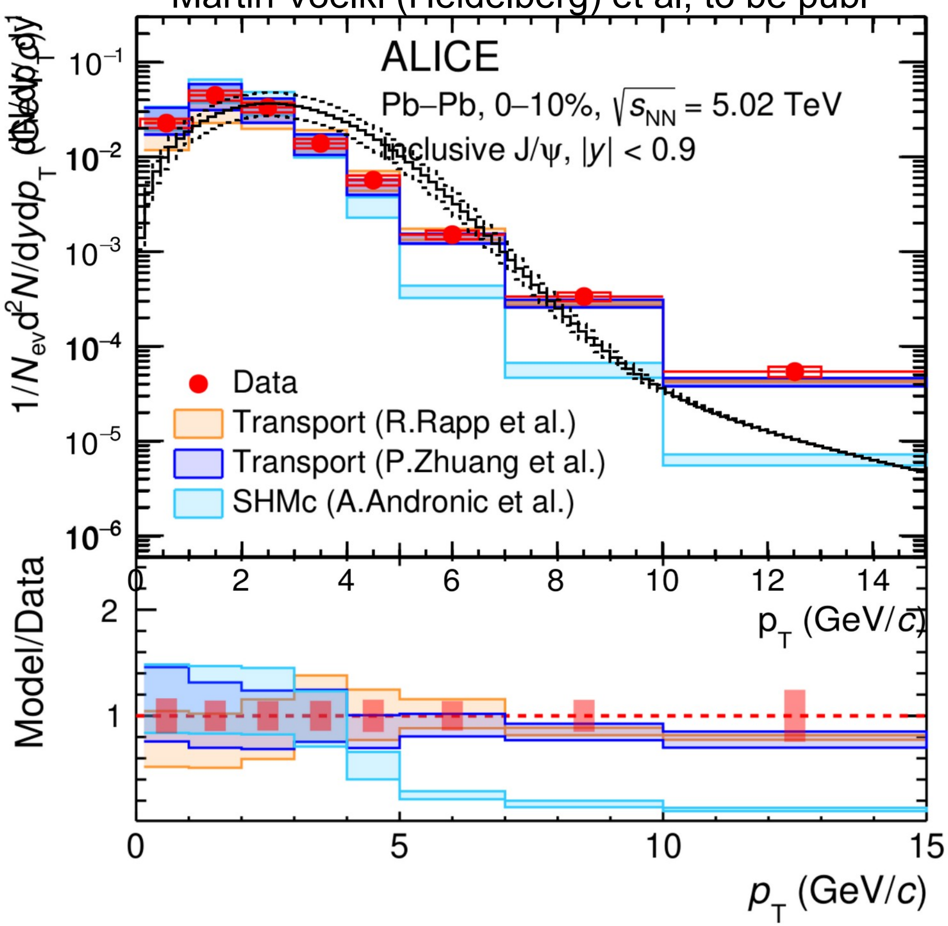




J/y yield MUSIC normalized to SHMc yield
corona unchanged

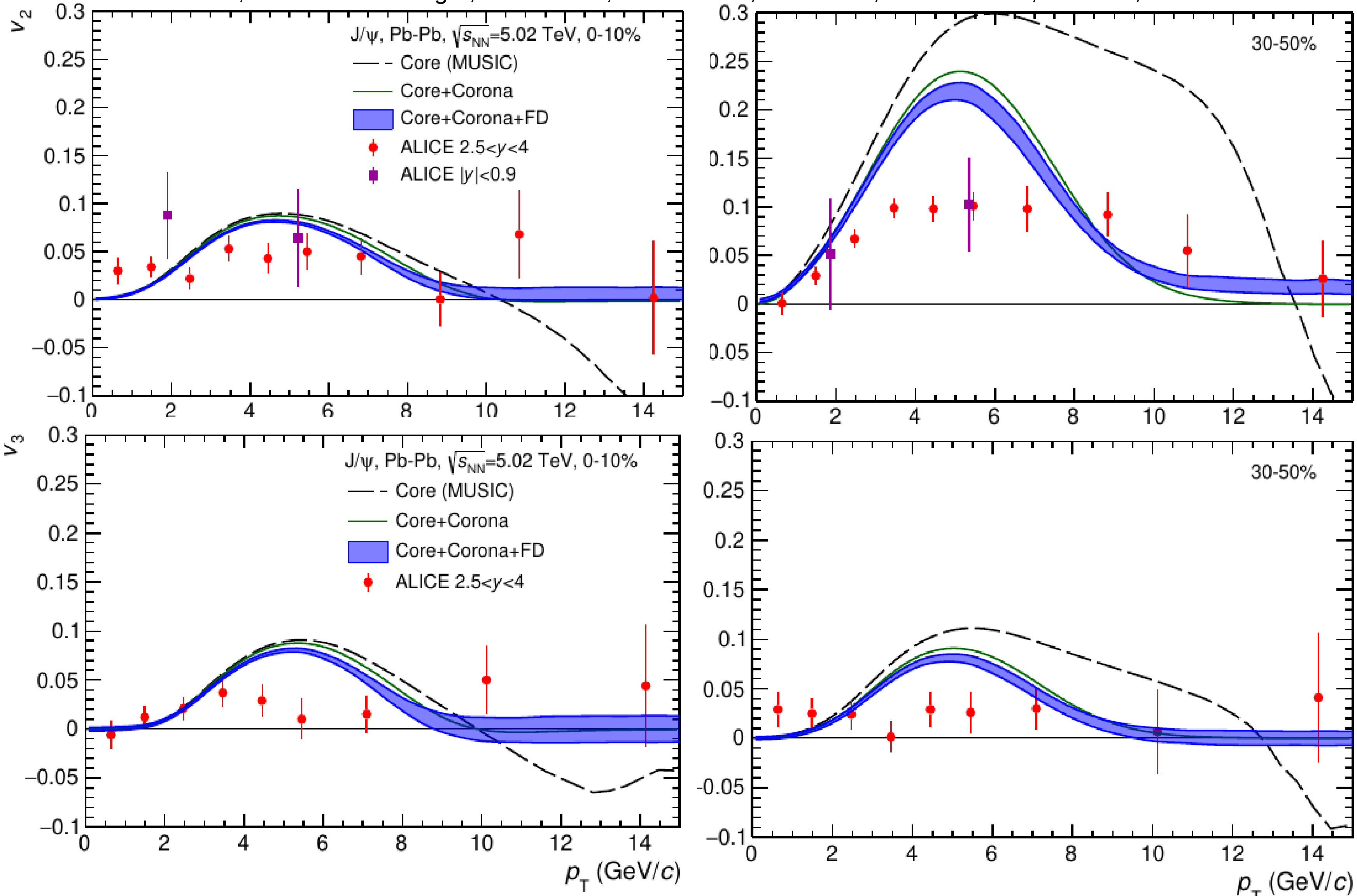
significantly harder spectrum to earlier approach
major influence of thermal contribution out to 9 GeV/c

Martin Voelkl (Heidelberg) et al, to be publ



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



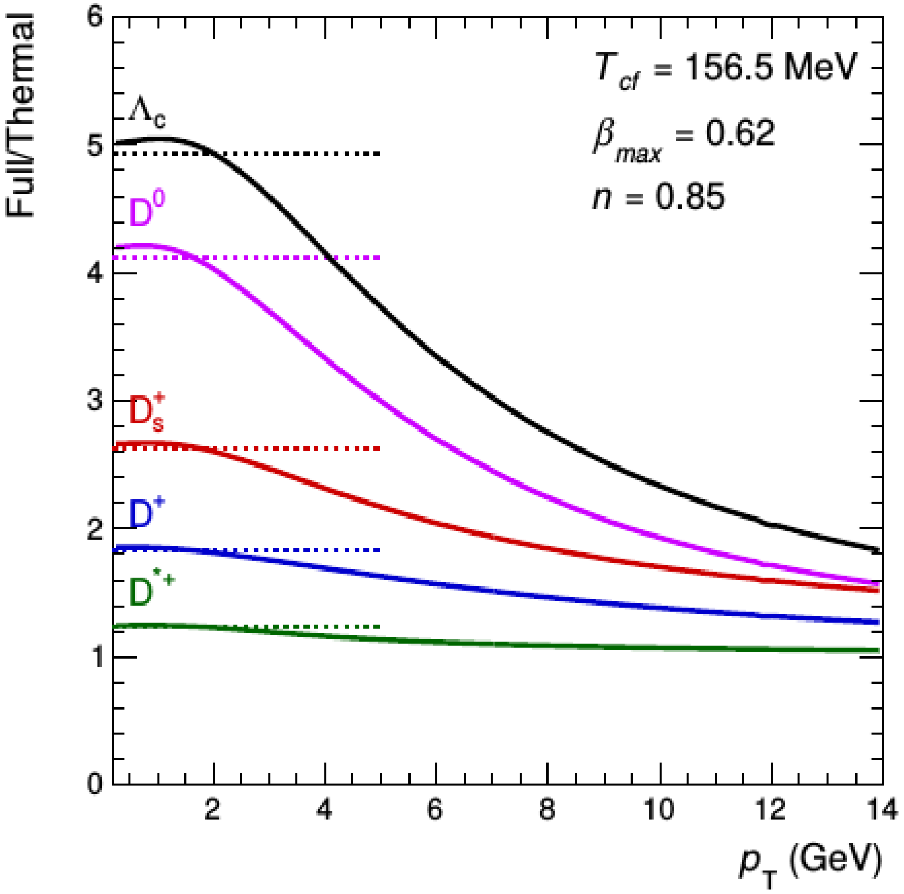
- significant flow arises over large pt range, difficult for other models
- for semi central collisions magnitude of flow over predicted

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

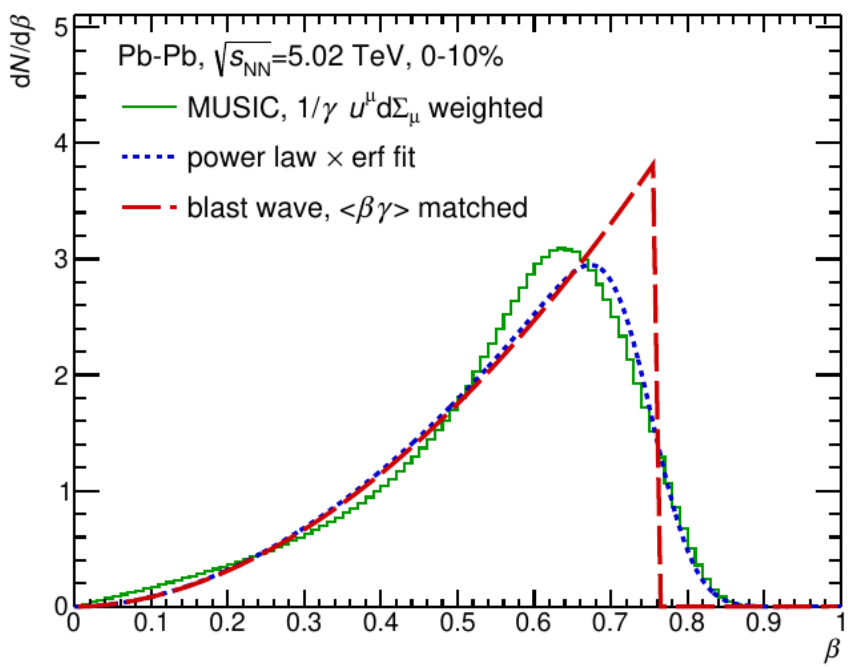
(A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284)

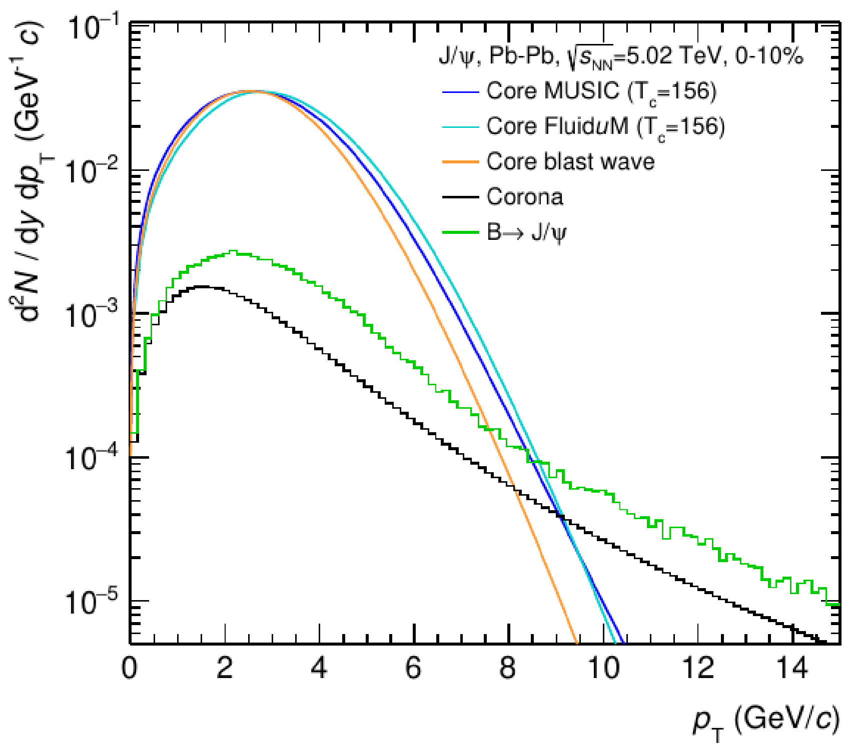
A.Andronic, P.Braun-Munzinger, M.Köhler, A.Mazeliauskas, K.Redlich, JS,V.Vislavicius JHEP 07 (2021) 035



Optimally matched blast wave parameters

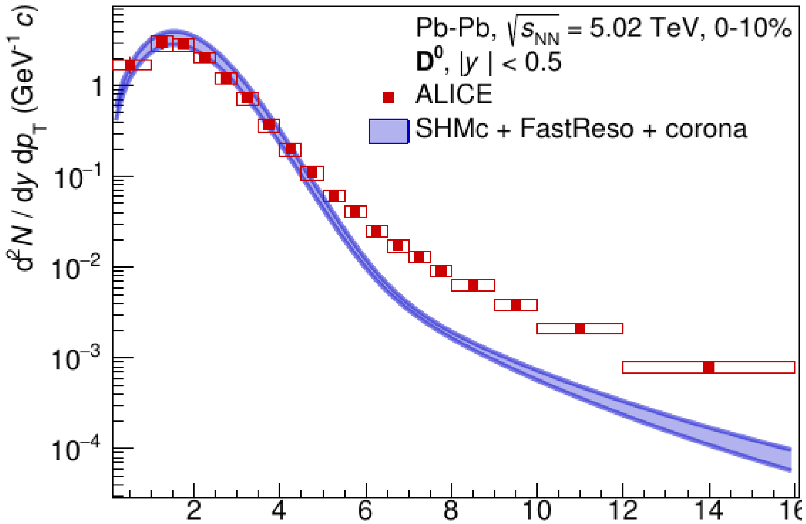
instead of inserting dozens of charmed hadrons into MUSIC, resort to blast wave parametrization again
but now we have advantage to be able to compare to 'true' hydro J/ψ spectrum
→ blastwave parameters modeled such that mean βγ of hydrodynamics is matched



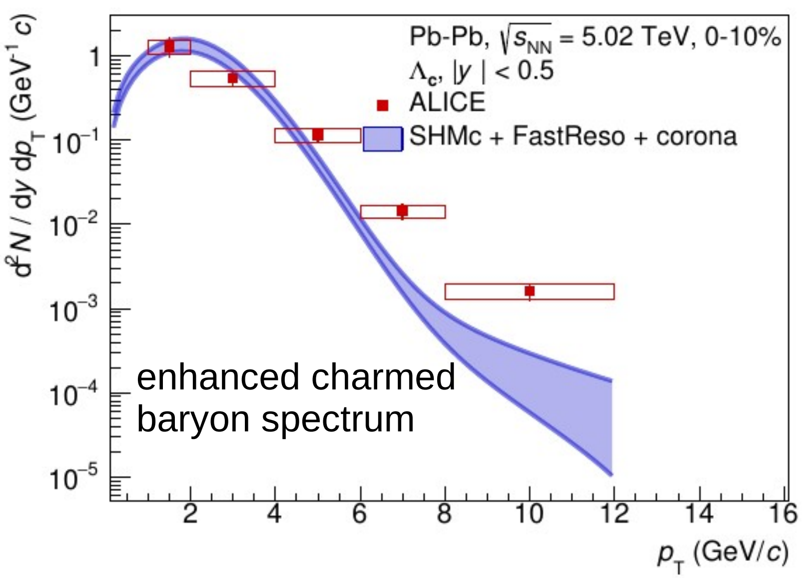


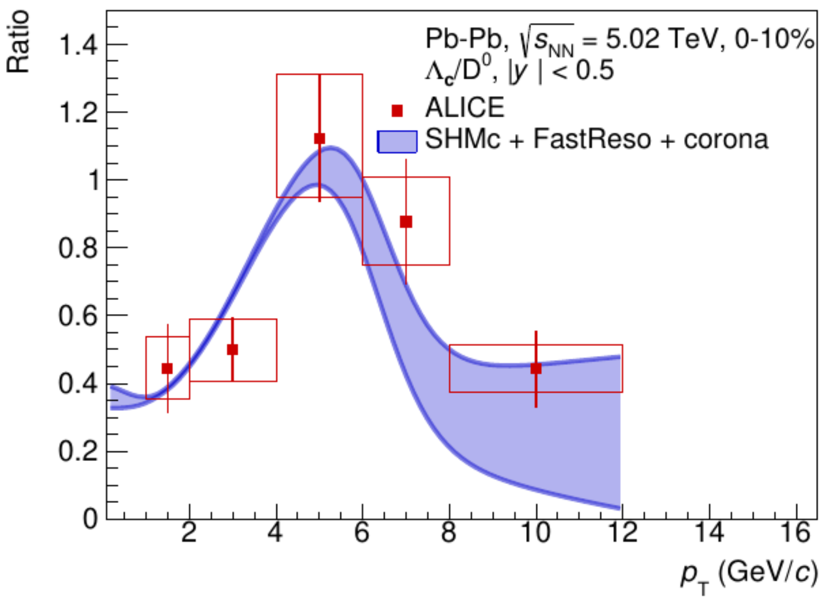
with β_{max} = 0.76 good matching can be achieved (red vs blue curves for core)

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



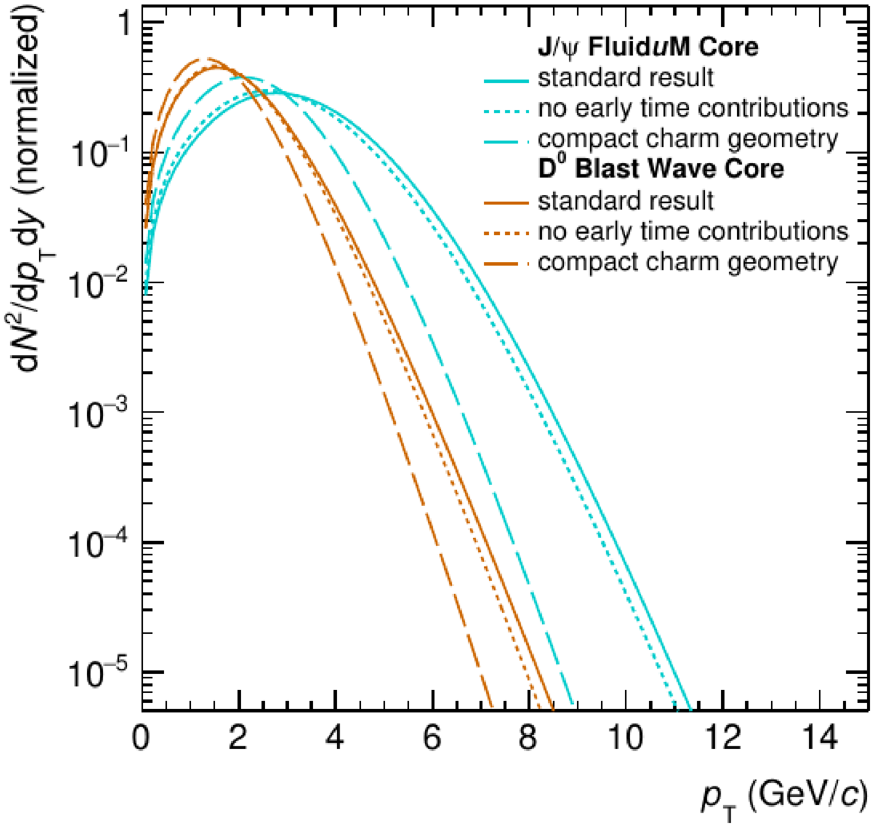


very good description of low and intermediate p_t data

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

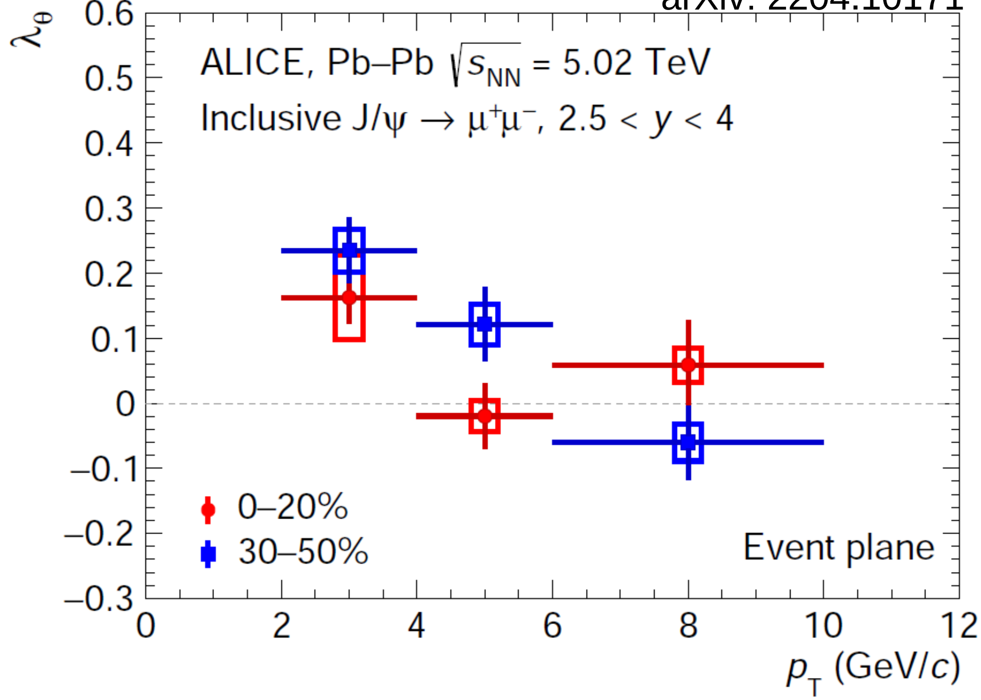
but since thermalization takes time, spatial distribution could lag behind front of expanding fireball

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

Polarization of J/y relative to event plane

arXiv: 2204.10171



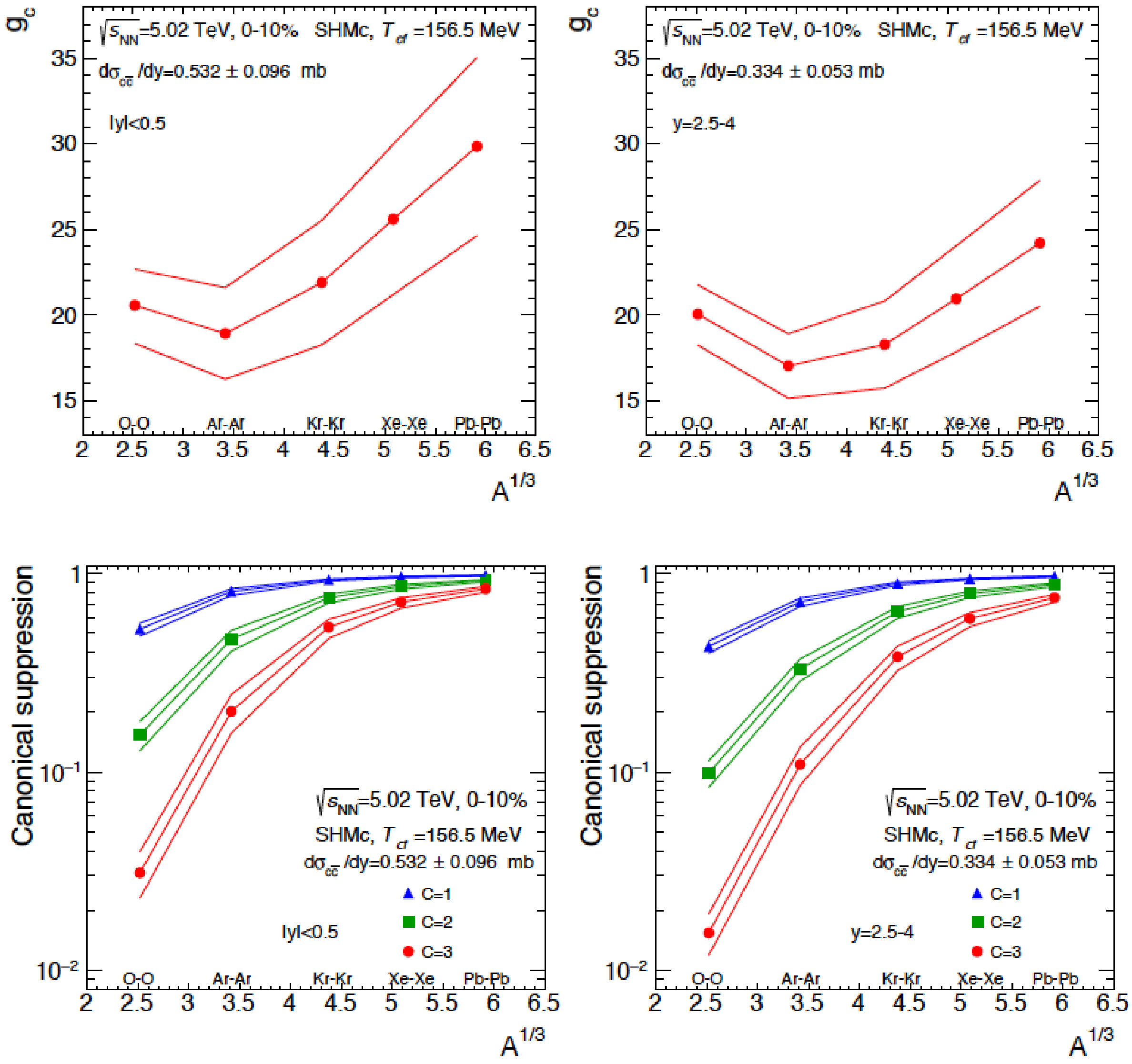
clear signal observed by ALICE,
increase towards lower p_t
reaching 3.9 s

makes early effect due to magnetic field unlikely

link to vorticity and spin-orbit coupl.?

charm fugacities and canonical suppression factors

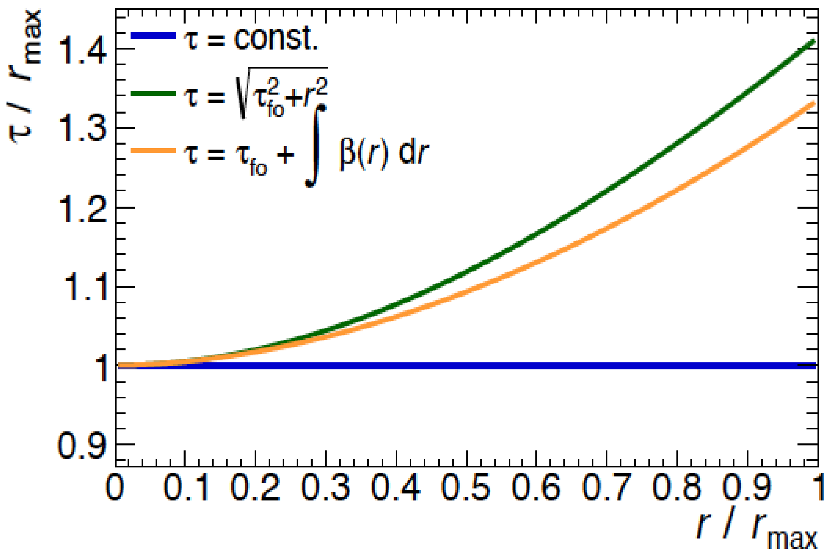
different collision systems:

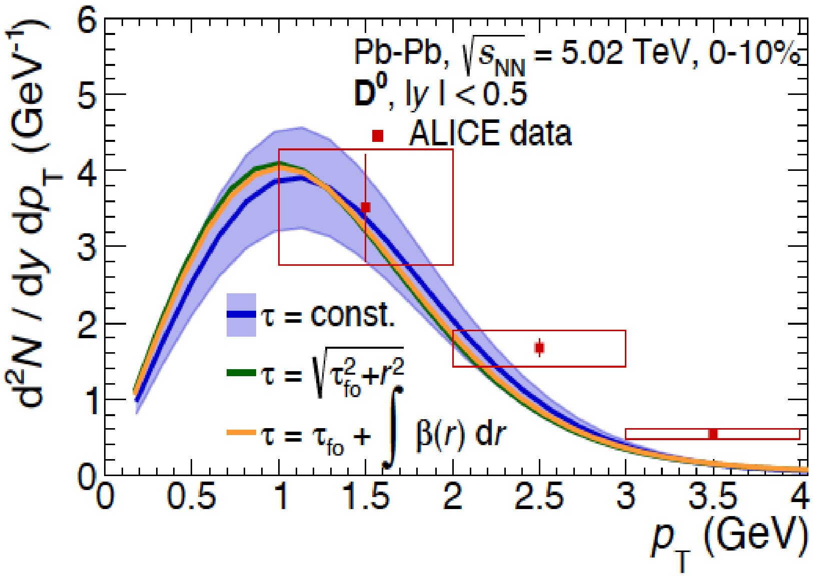


blast wave parametrization of transverse momentum spectrum

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

$$K_1^\mathrm{eq}(p_\mathrm{T}, u^r) = 4\pi m_\mathrm{T} I_0\left(\frac{p_\mathrm{T} u^r}{T}\right) K_1\left(\frac{m_\mathrm{T} u^\tau}{T}\right)$$
$$K_2^\mathrm{eq}(p_\mathrm{T}, u^r) = 4\pi p_\mathrm{T} I_1\left(\frac{p_\mathrm{T} u^r}{T}\right) K_0\left(\frac{m_\mathrm{T} u^\tau}{T}\right)$$

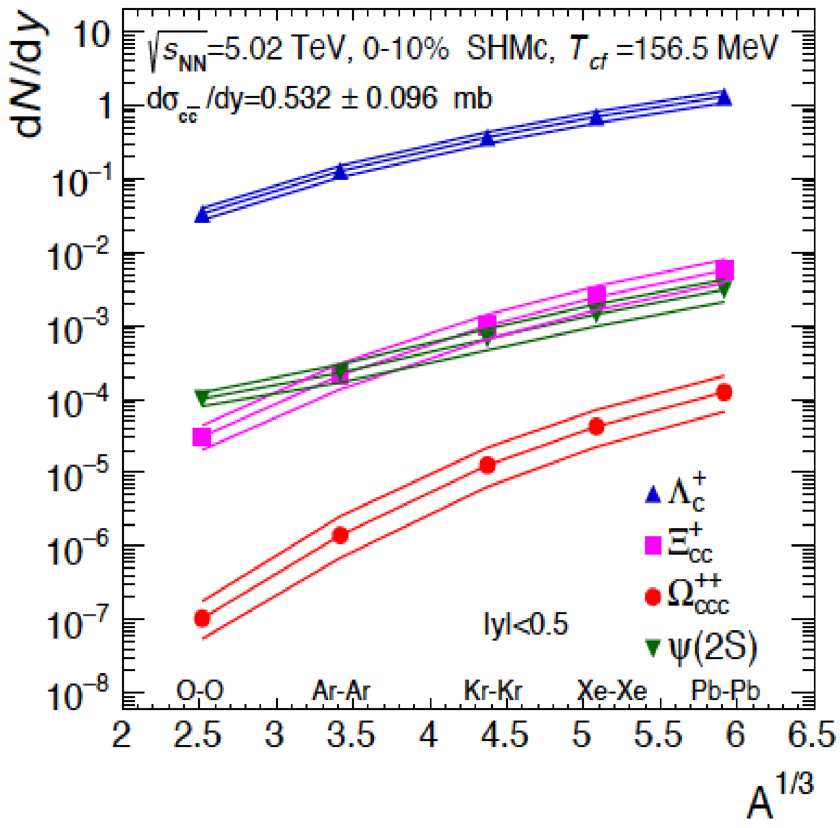


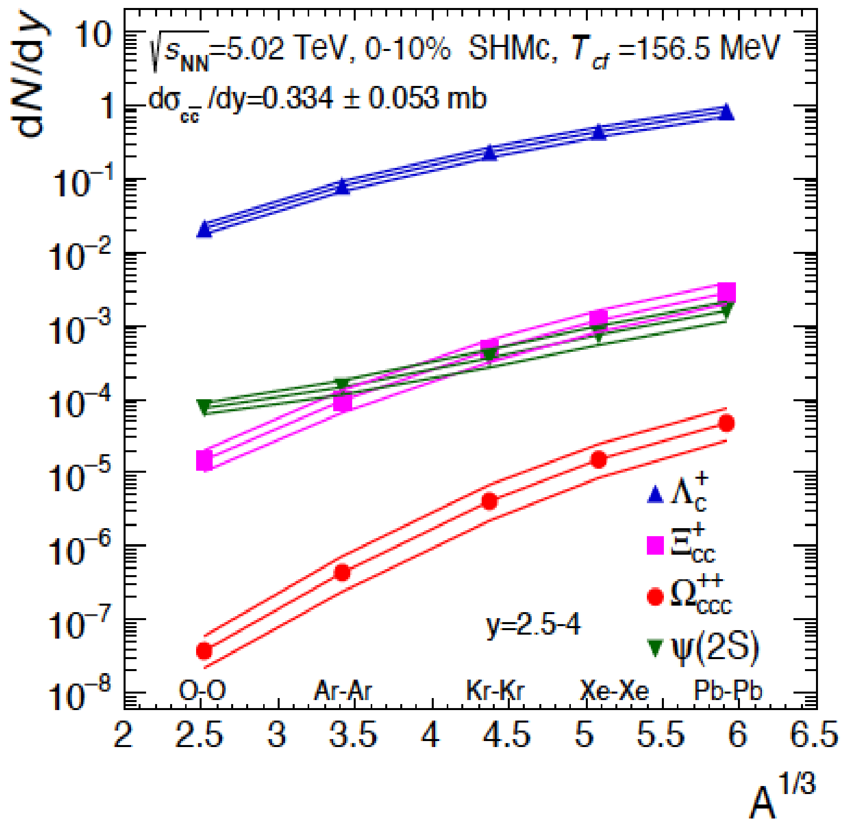


mid-rapidity yields for Pb-Pb collisions

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	$0.122 +0.038-0.033$	$(5.25\pm0.38)\cdot10^{-3}$	$0.127 +0.038-0.033$
$\psi(2S)$	$(3.43 +1.1-0.9)\cdot10^{-3}$	$(7.87\pm0.57)\cdot10^{-4}$	$(4.22 +1.1-0.9)\cdot10^{-3}$
		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	$(1.17 +0.32-0.28)\cdot10^{-2}$	$(2.59\pm0.19)\cdot10^{-3}$	$(1.43 +0.32-0.28)\cdot10^{-2}$
$\psi(2S)$	$(3.28 +0.90-0.79)\cdot10^{-4}$	$(3.90\pm0.28)\cdot10^{-4}$	$(7.17 +0.94-0.84)\cdot10^{-4}$

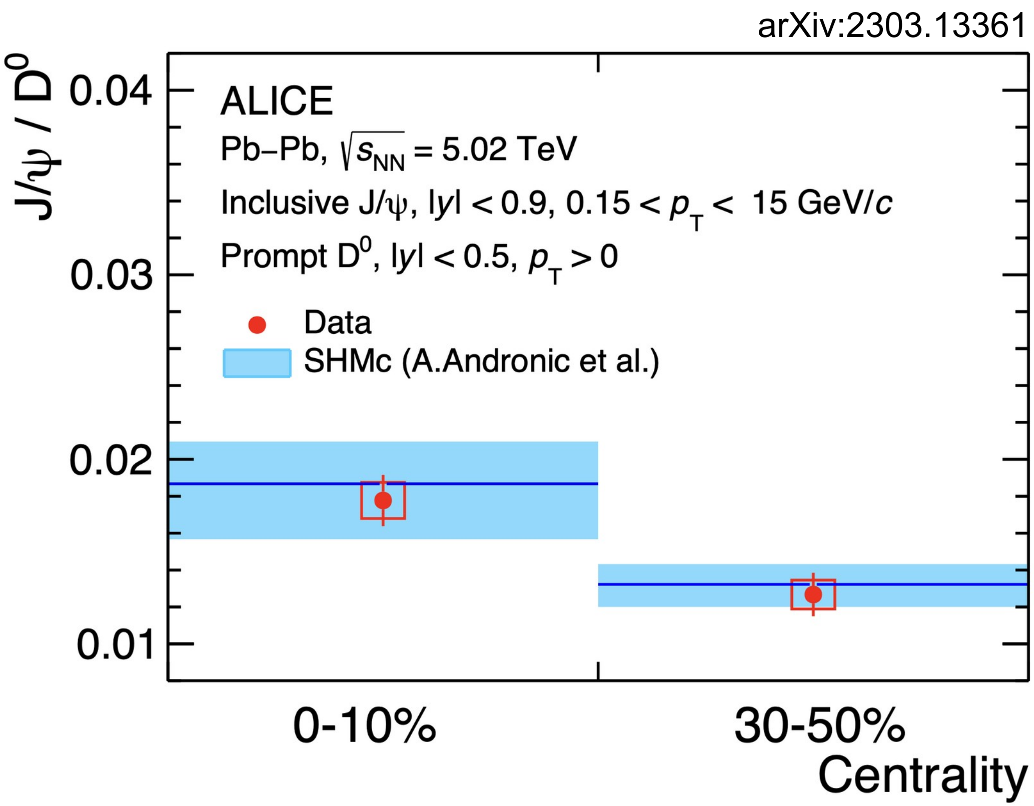
system size dependence of yields





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

Unique prediction of SHMc – open charm/charmonium



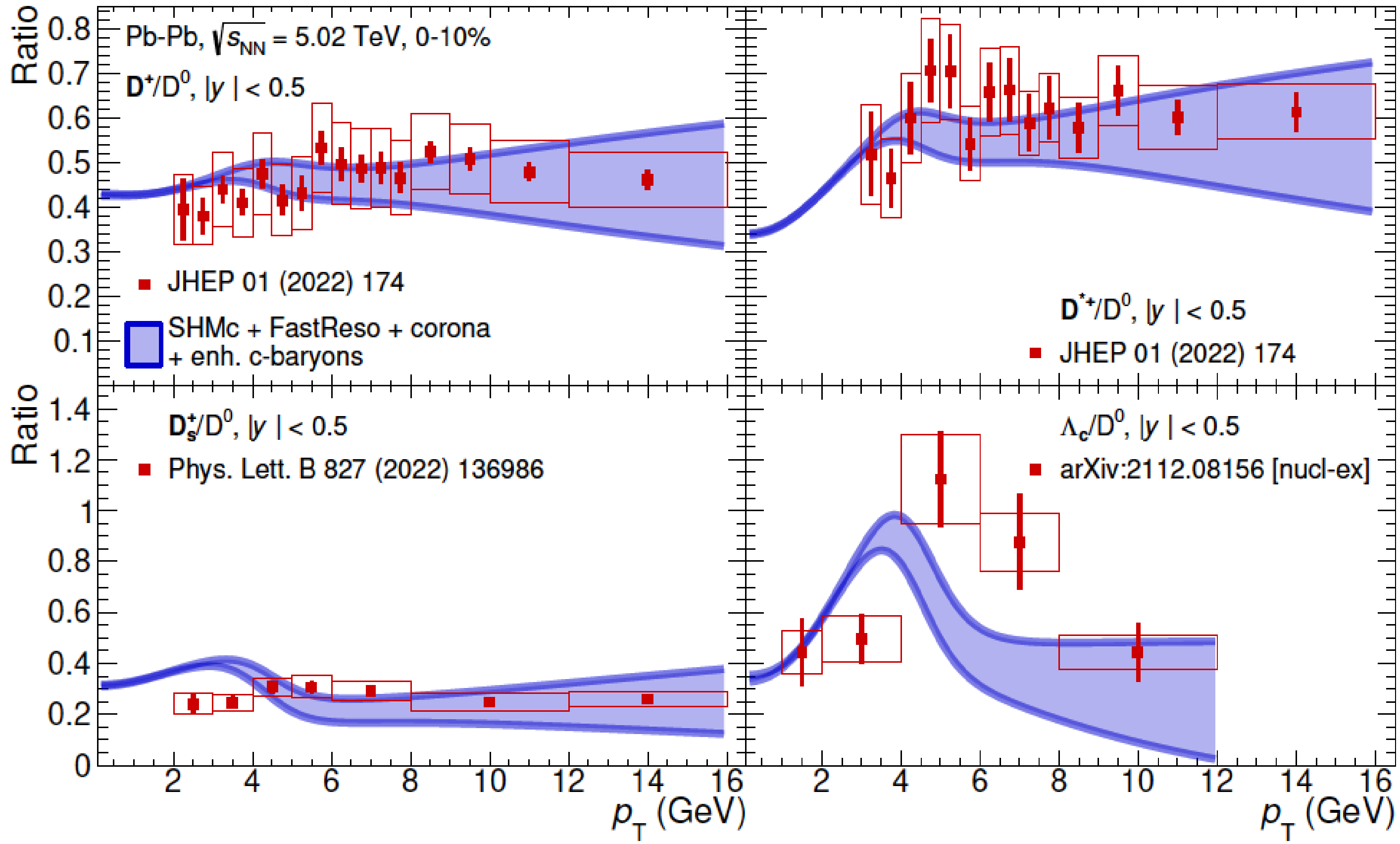
for the first time ratio of fully p_t integrated D^0 to J/ψ available from ALICE

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, this is the normalization we aimed for since 30 years to demonstrate concept of deconfinement with charmonia!

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 -

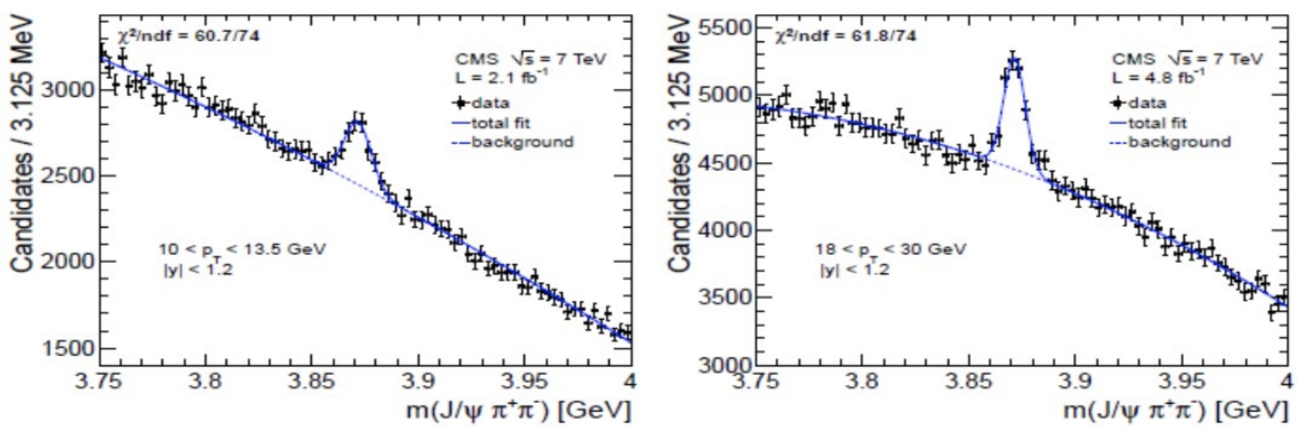
BELLE

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

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

- 2013 -

CMS



PDG particle data group

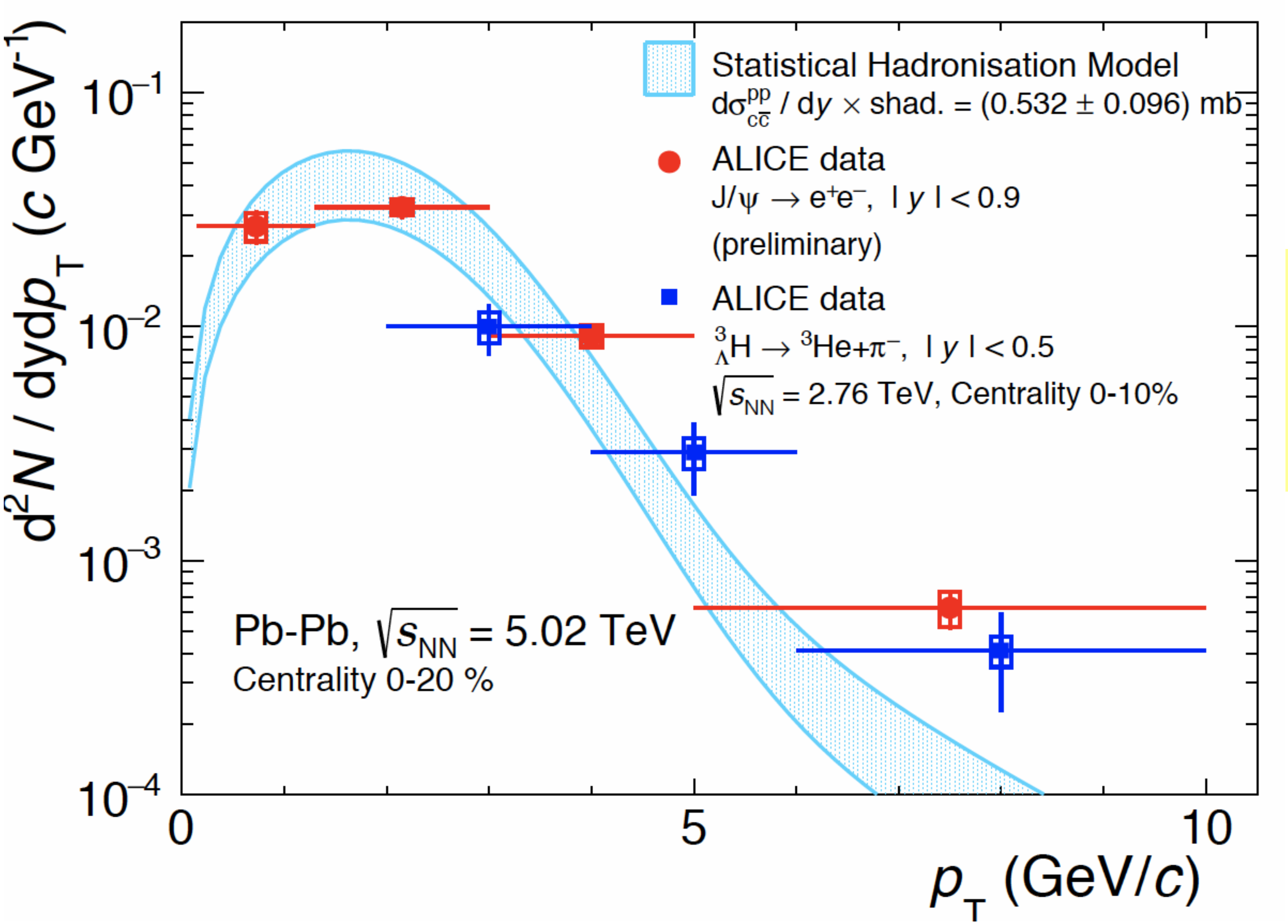
X(3872)

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

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

22

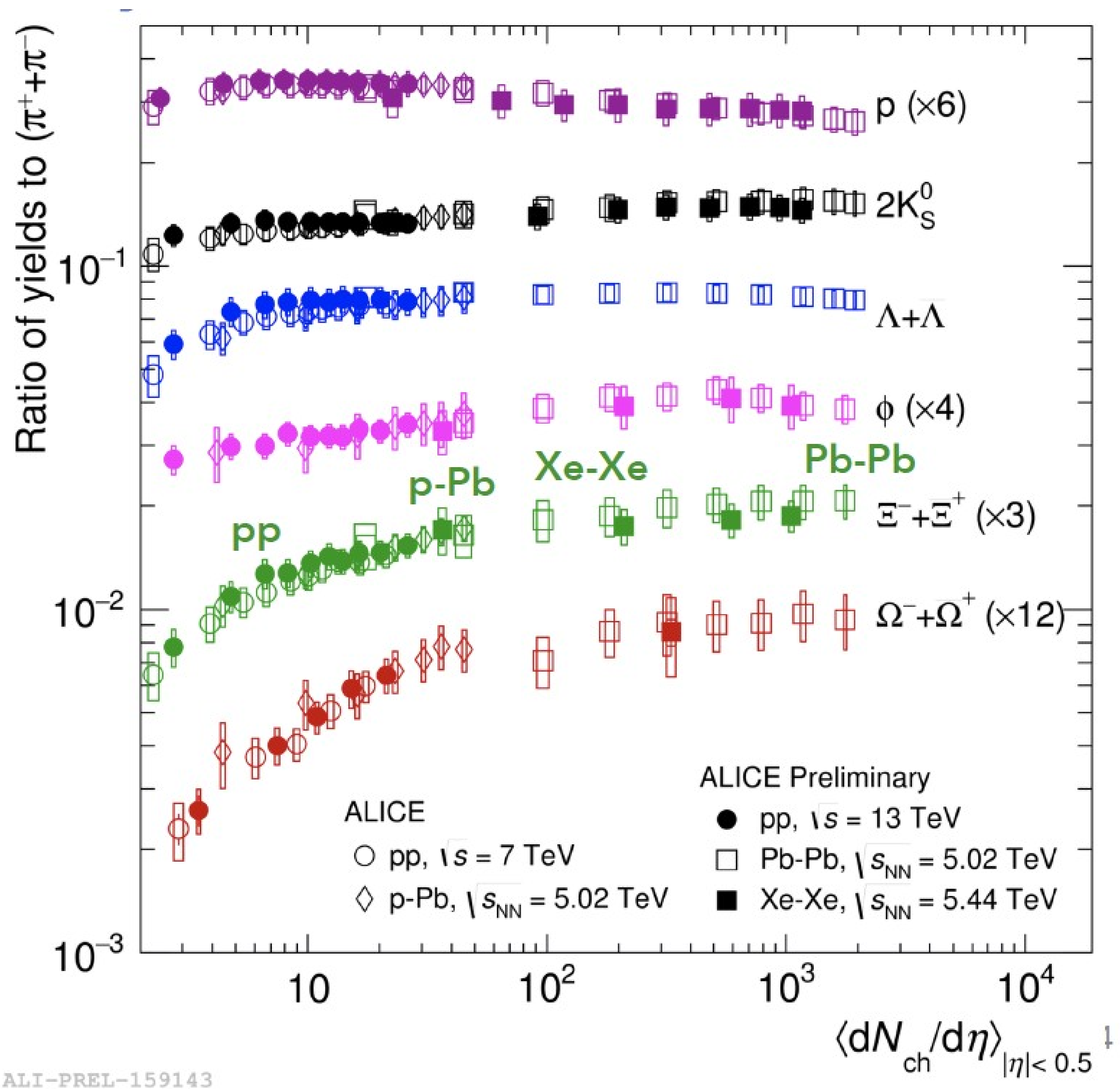
J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



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

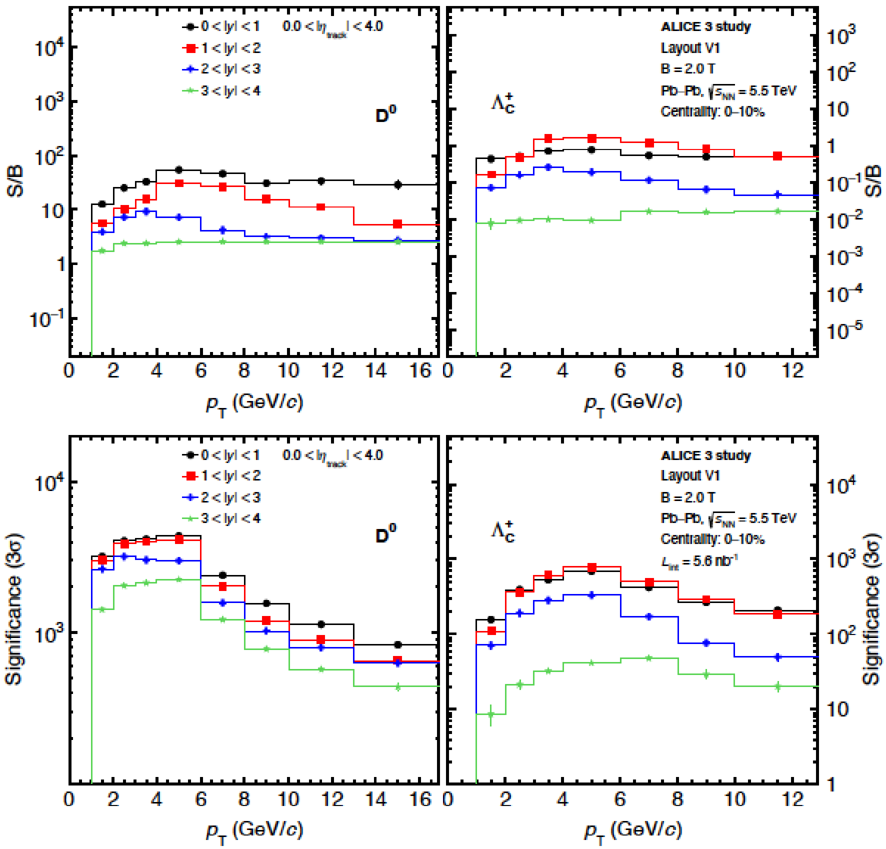
from pp to Pb-Pb collisions: smooth evolution with system size

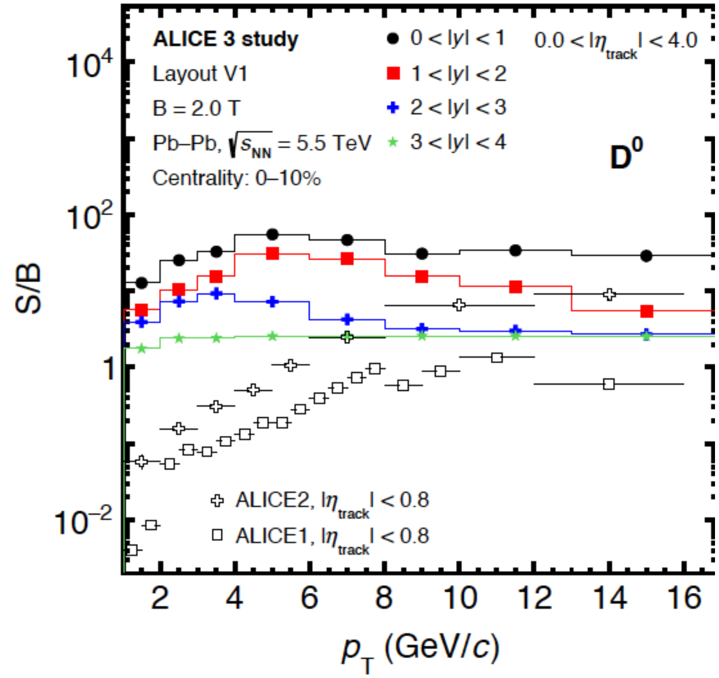


universal hadronization can be described with few parameters in addition to T and μB

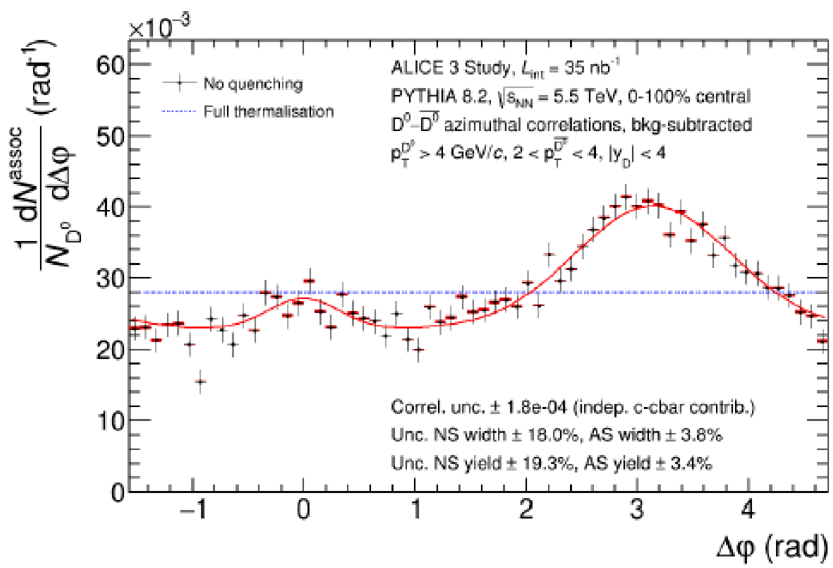
transition from canonical to grand-canonical thermodynamics

highly significant D^0 and Λ_c will allow correlation studies

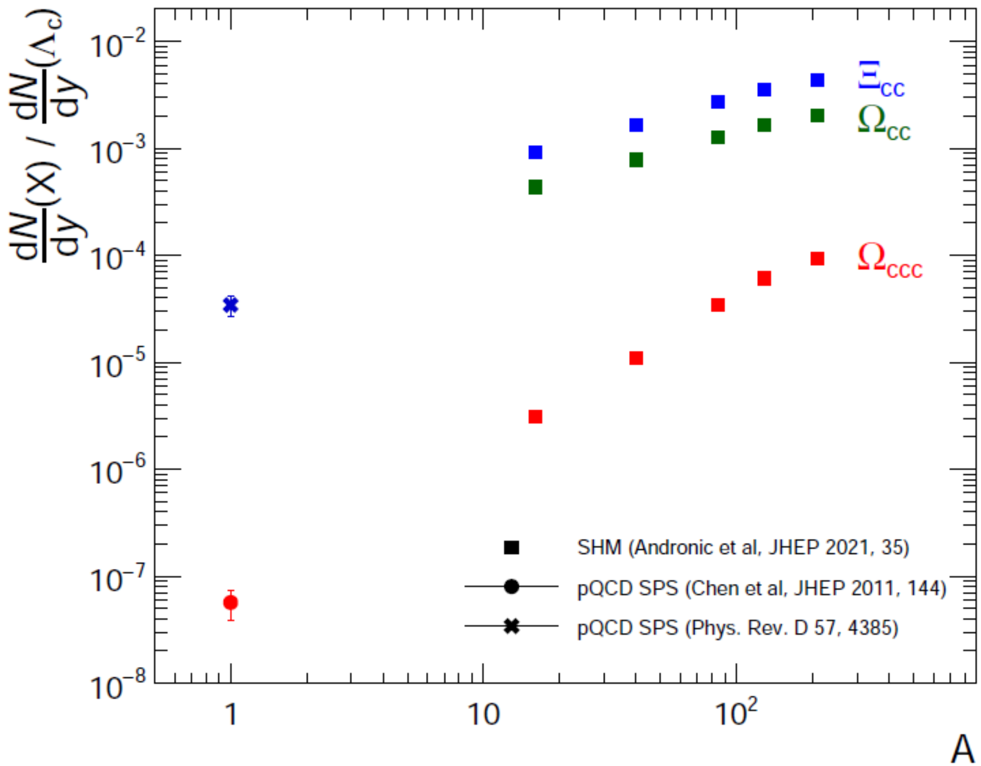




ALICE3: excellent performance in azimuthal correlations
also HBT correlations or net charm fluctuations will be possible



Multi-charmed baryons



Letter of intent ALICE3 arXiv: 2211.02491

because of powers of $g_c \rightarrow$ 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

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

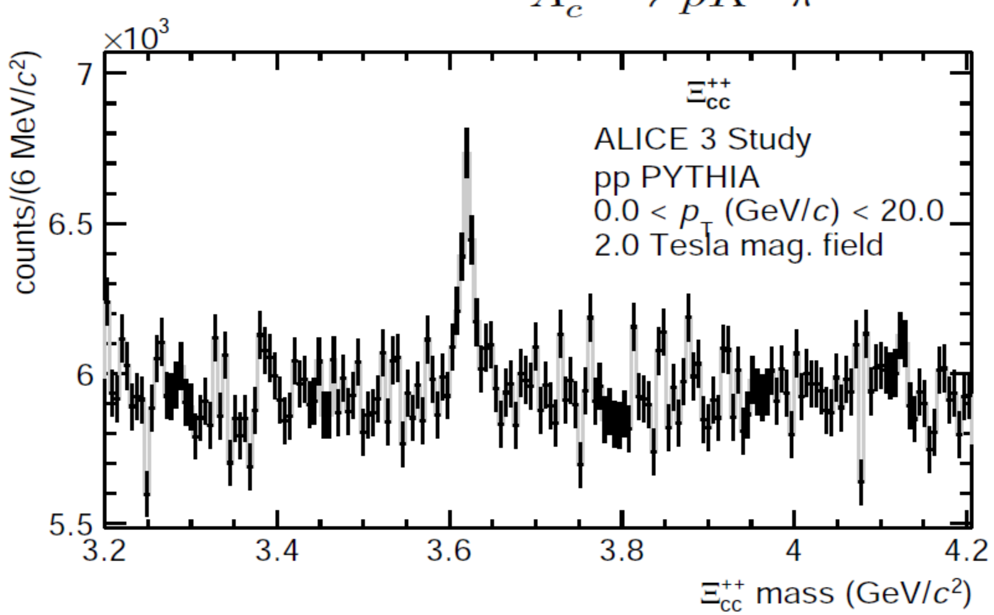
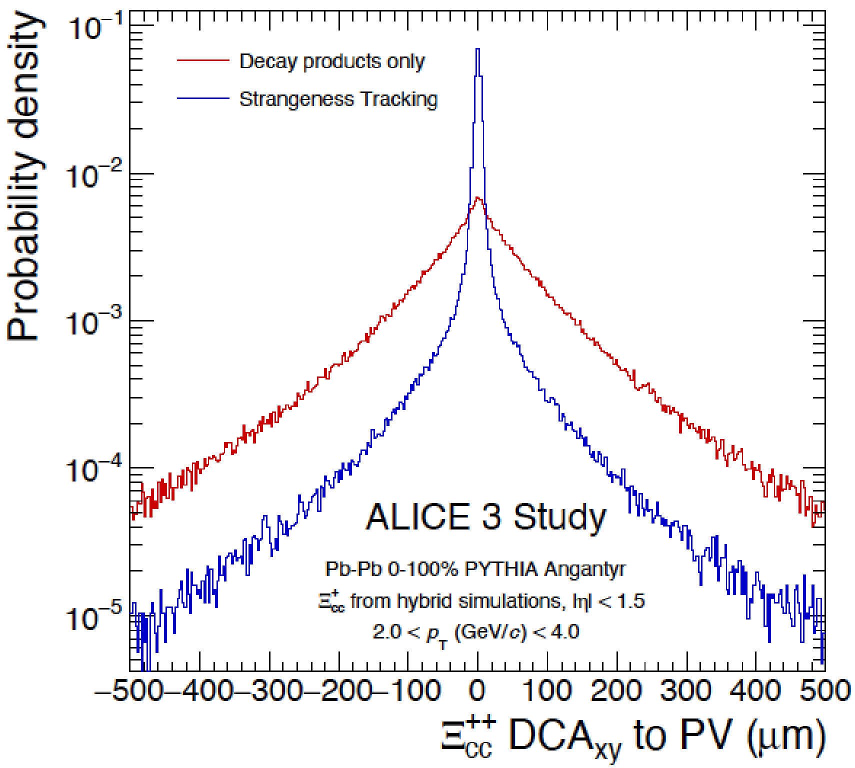
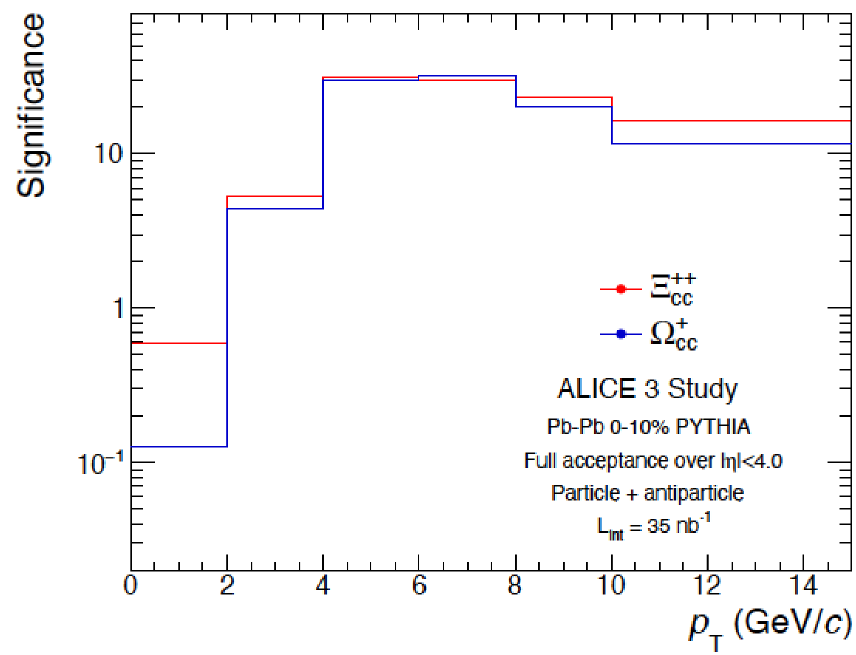


Figure 35: Expected Ξ_{cc}^{++} mass peak and background in pp collisions with $\mathscr{L}_{int} = 18\,\text{fb}^{-1}$

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	$p + K^- + \pi^+$	$(6.2 \pm 3.0)10^{-3}$





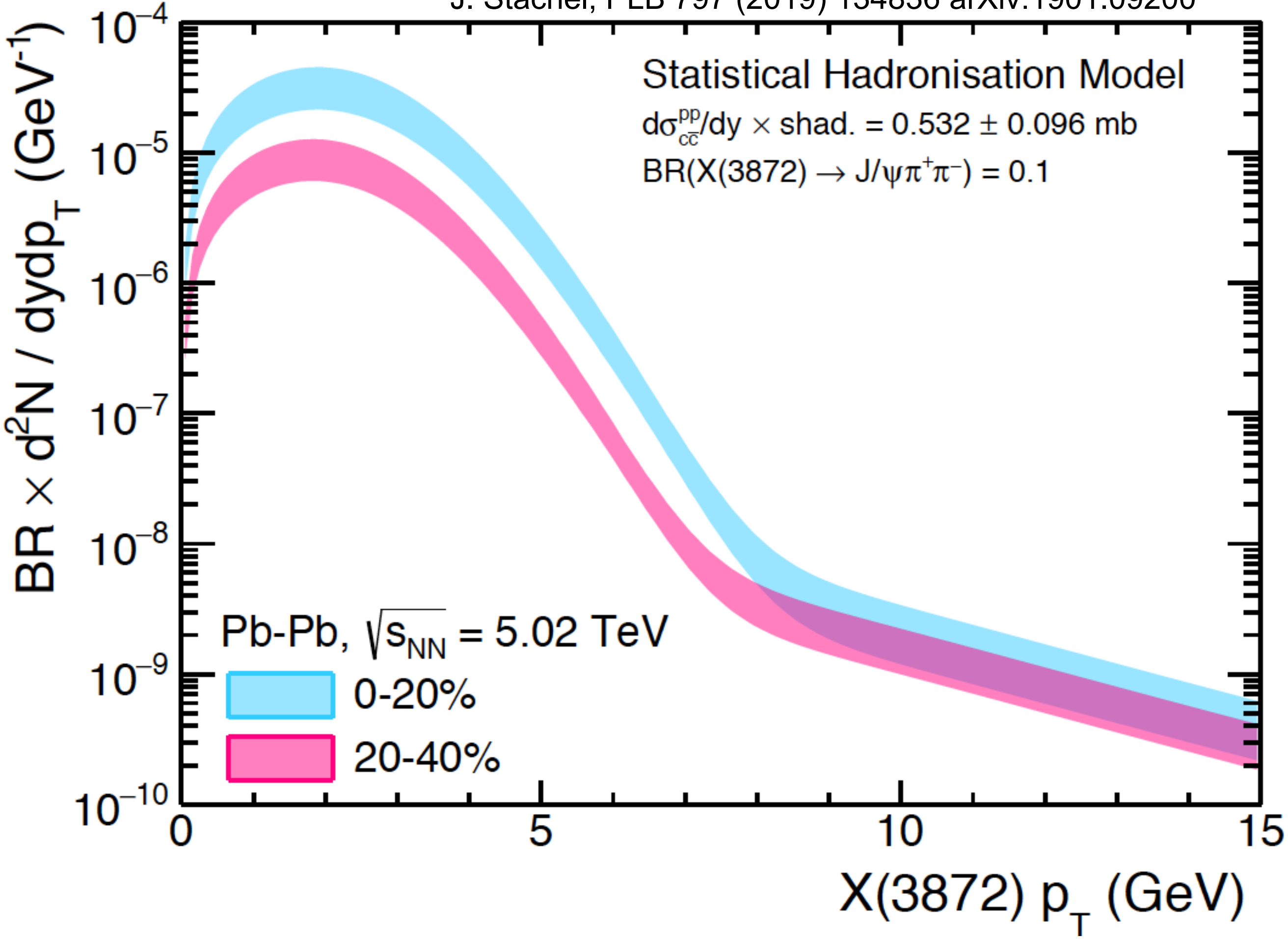
Dependence of Ω_{ccc} production yields on system size for a run time of 10^6 s

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



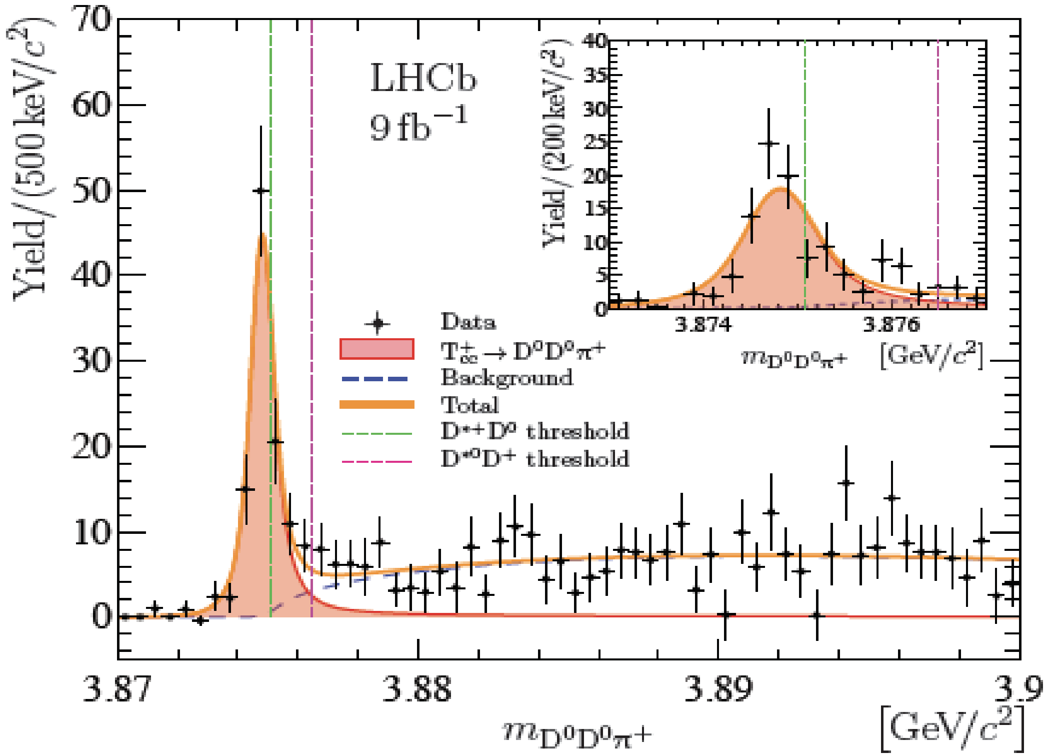
close to D^0D^{0*} threshold
- tetraquark or molecule?
- is it formed like (hyper)nuclei?

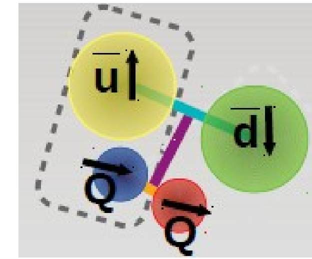
- decay into $J/\psi\ \pi^+\pi^-$
- doable in Run3/4?
- more likely ALICE3

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

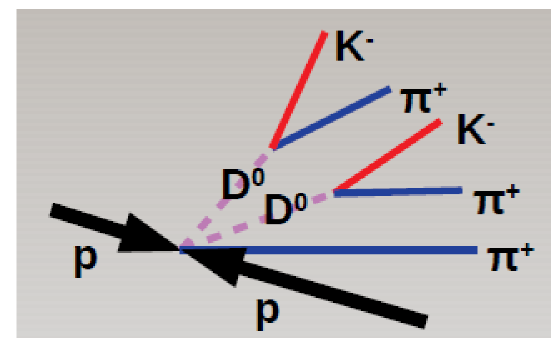
LHCb 2109.01038





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

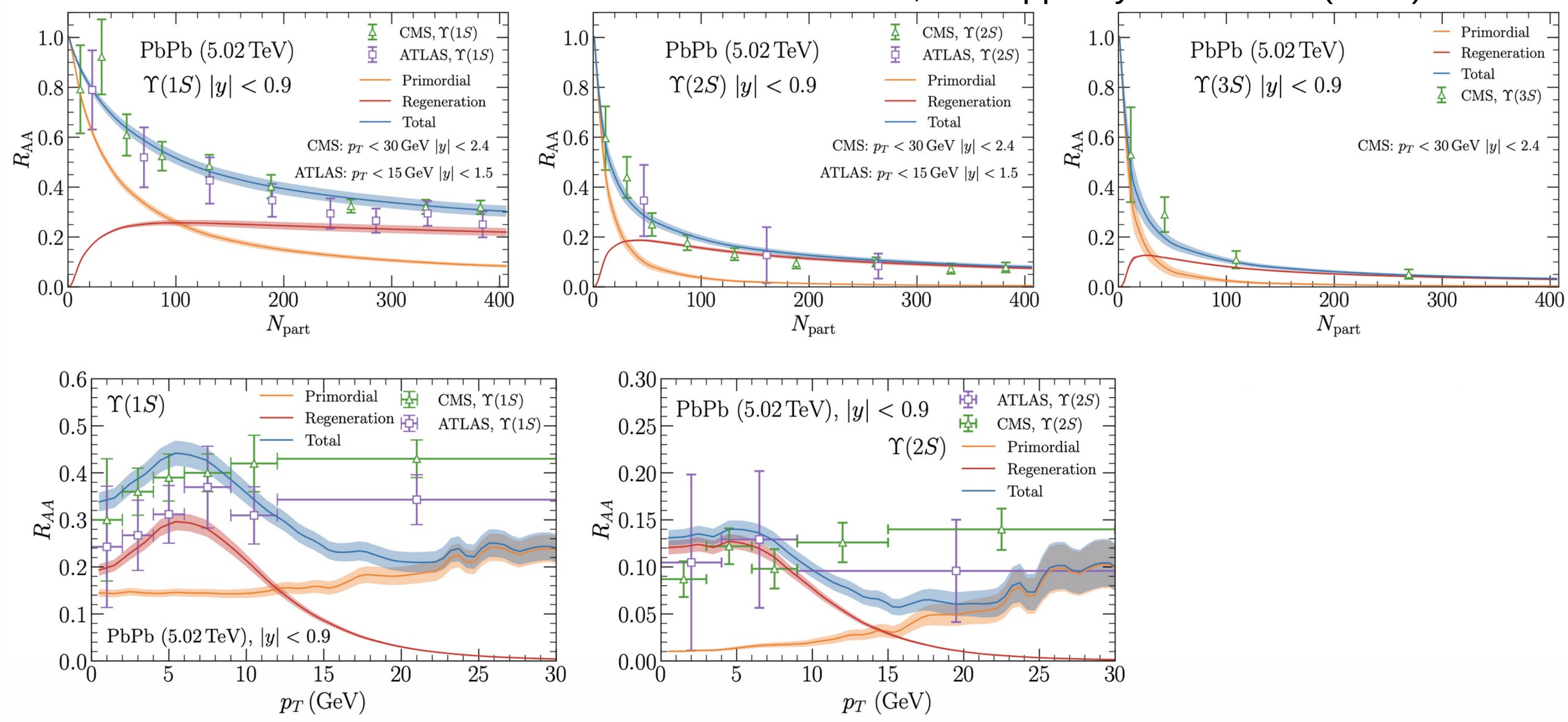
$T_{cc}^+ \to D^0\, D^0\, \pi^+$



- 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

Beauty in transport approach in strongly coupled QGP

B.Wu, R. Rapp Phys Lett B873 (2026) 140223

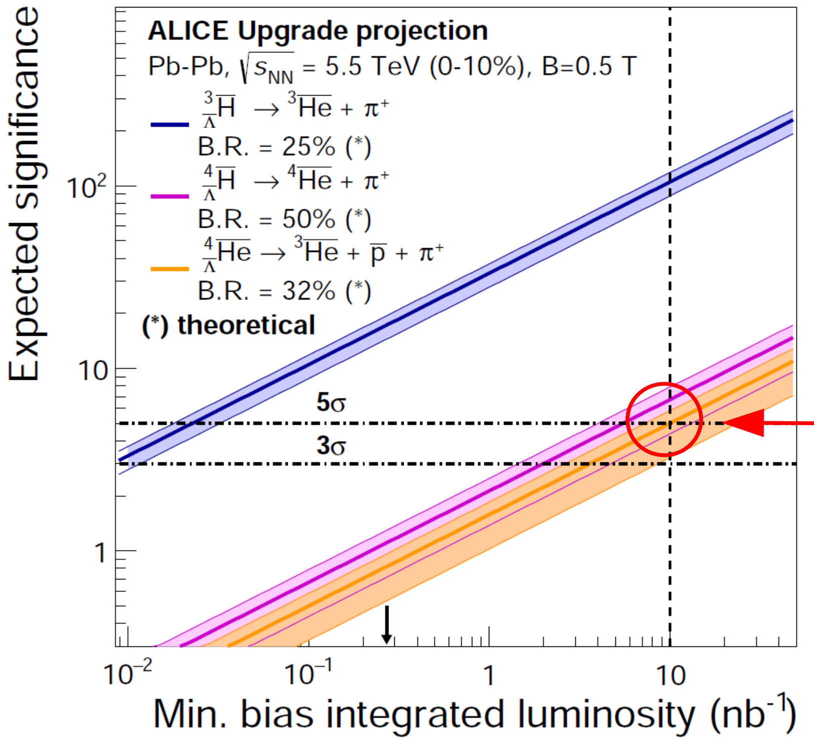


for all but most peripheral collisions ‘regeneration’ component dominates up to p_t = 10 GeV/c

next: precision measurement of dN/dy of bottomonia

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 - $10 nb^{-1}$
^{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 $^{5}{}_{\Lambda}He$ $\overline{^{5}{}_{\Lambda}He}$ 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?