Heavy flavor hadrons as probes of deconfinement at the LHC

work done over the past 20 years in collaboration with
Peter Braun-Munzinger, Anton Andronic, Krzysztof Redlich
see Nature 561 (2018) 321

breakthrough came with recent ALICE data

Johanna Stachel, Phys. Inst., Univ. Heidelberg
42^{nd} International School of Nuclear Physics
QCD under extreme conditions
– from heavy ion collisions to the phase diagram
Erice, Sept 16-22, 2021

Production of hadrons and (anti-)nuclei at LHC

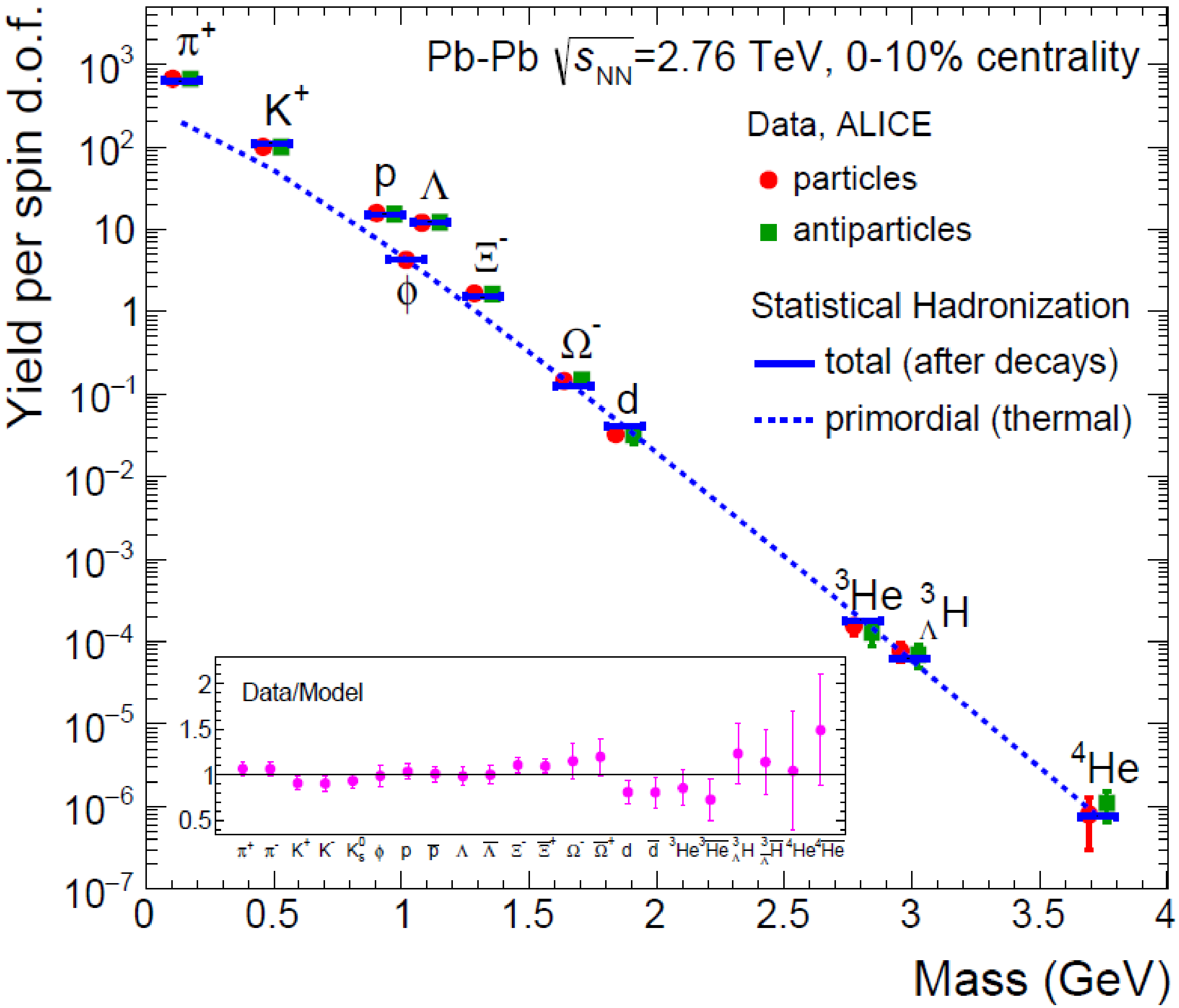
1 free parameter: temperature T

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



Hadronization of heavy quarks

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
- 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 (see talk R. Averbeck) 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

Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV
  non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-antiquark potential of the form

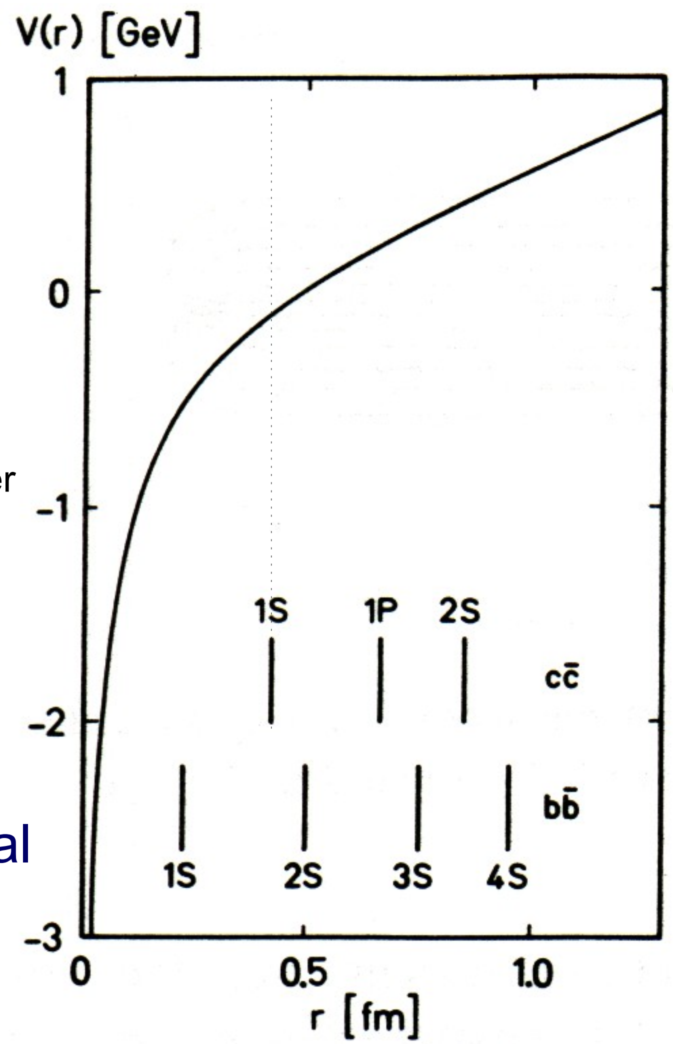
$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1 \cdot \vec{s}_2}{m_Q^2}\delta(\vec{r}) + \ldots$$

confinement

color Coulomb int.

spin-spin int.

tensor, spin-orbit, higher order rel. corr.

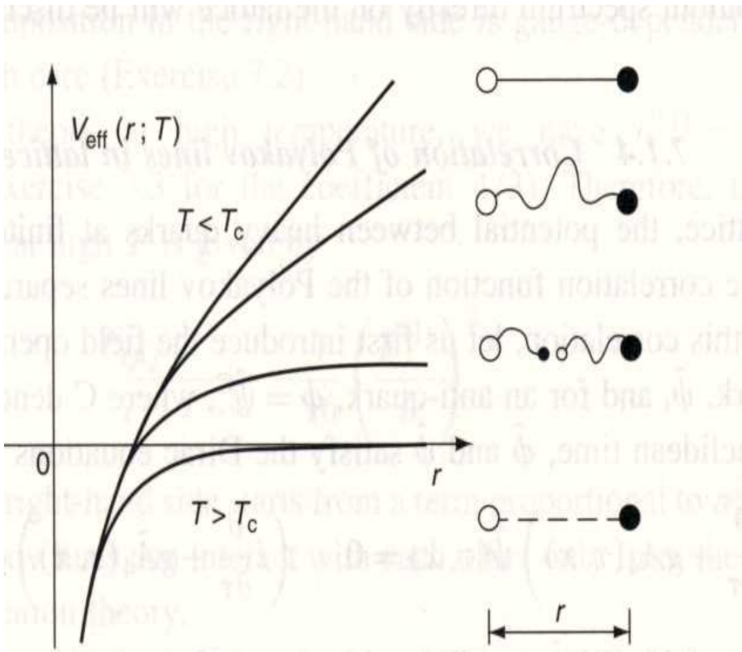


- with σ ~ 0.9 GeV/fm, $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for m_c=1.5 and m_b=4.6 GeV
  obtain spectrum of quarkonia
- all charmonium states sit in confinement part of potential

Charmonia at finite temperature

consider ccbar in thermal environment of gluons and light quarks

in QGP color singlet and color octet ccbar states can mix by absorption or emission of a soft gluon
→ modification of V_{eff} $\quad V(r) \to V_{eff}(r,T) \quad \text{and} \quad m_Q \to m_Q(T)$



- reduced string tension as T approaches T_c
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for $T>T_c$ confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r,T) \to -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/\lambda_D}$$

Debye screening mass and length $\quad \omega_D = 1/\lambda_D$

unlike Coulomb potential, Yukawa potential does not always have bound states → dissociation of quarkonia if ω_D sufficiently large at high T

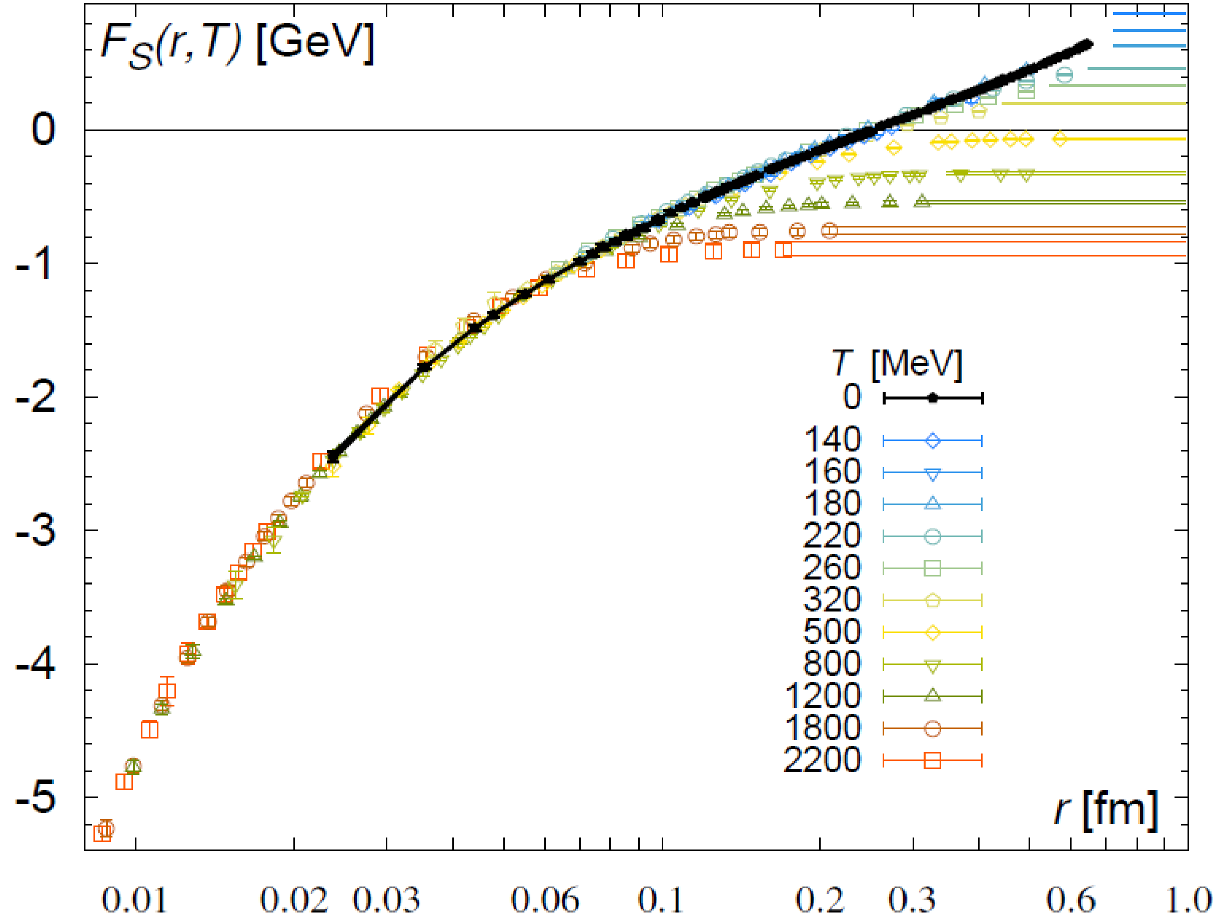
idea: T. Matsui, H. Satz, Phys. Lett. B 178 (1986) 416

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

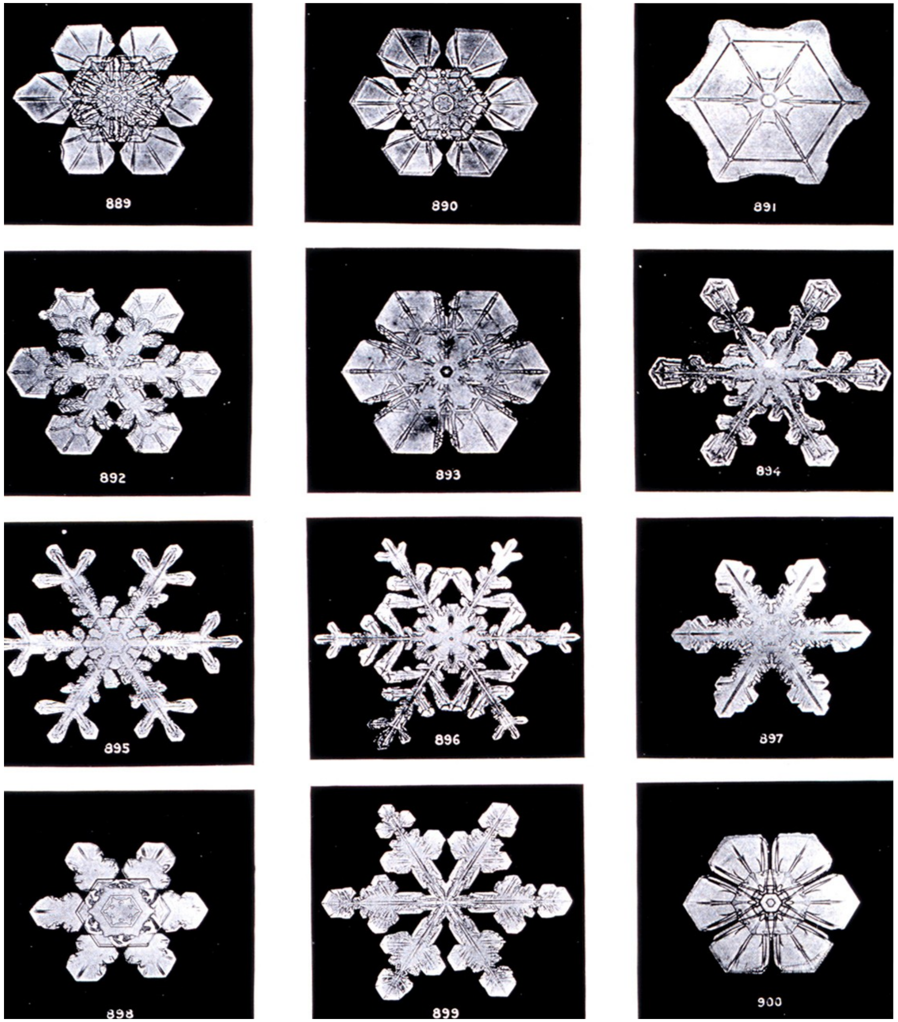
TUMQCD arXiv:1804.10600

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



as charmonia dissolve, charm quarks don't disappear

- QGP cools down
- when critical temperature is reached, quarks and gluons bind to the familiar hadrons 'statistical hadronization'
- why not also charm quarks?

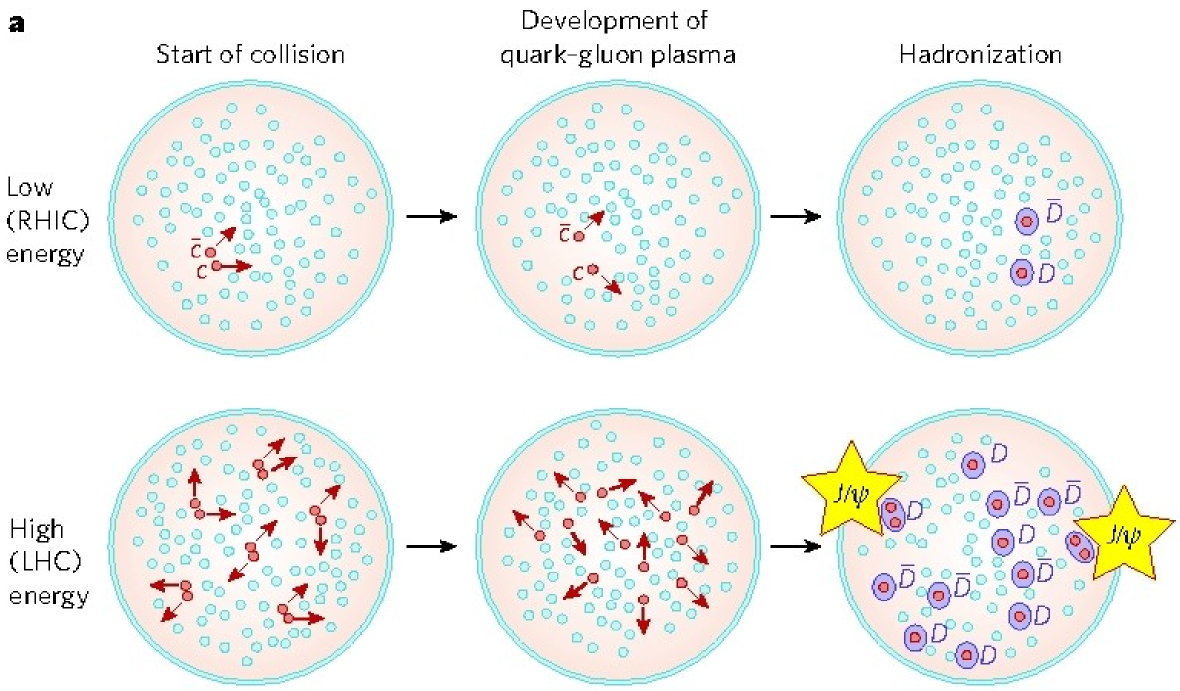


Hadronization of charm quarks

all charm quarks have to appear in charmed hadrons
at hadronization of QGP J/ψ can form again 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)

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



Mechanism for statistical hadronization with charm (SHMc)

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
  $N_{c\bar{c}}^{direct}$ from data (total charm cross section) or from pQCD

- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (canonical corr. if needed)
  technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}) + g_c^2 V (\sum_i n_{\psi_i}^{therm}) + \ldots$$

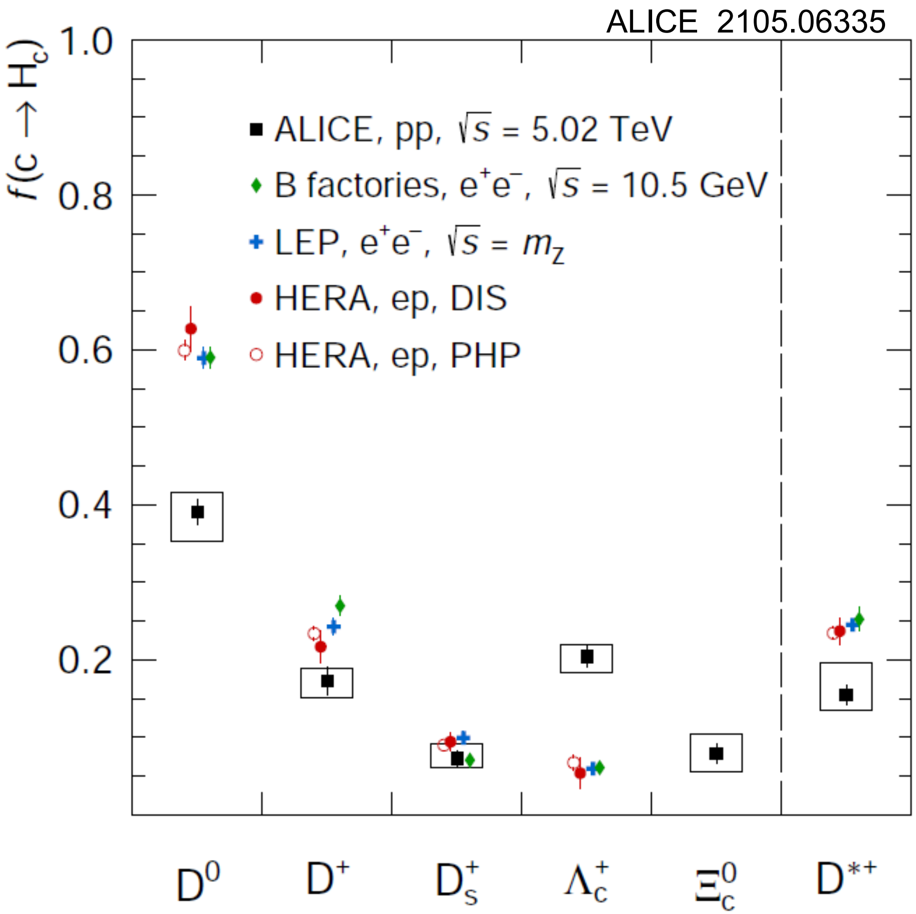
↑

the only additional free parameter

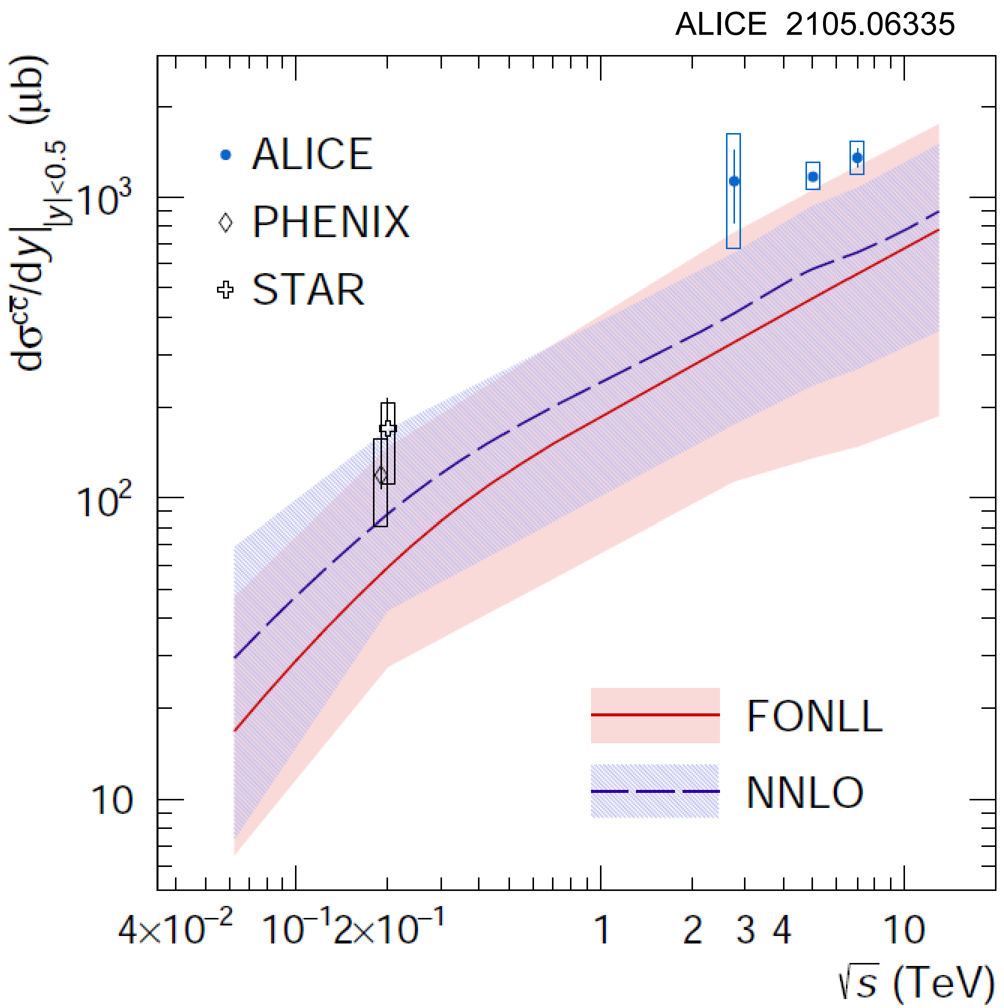
charm production cross section

core-corona picture: treat low density part of nuclear overlap region, where a nucleon undergoes 1 or less collisions as pp collisions, use measured pp cross section scaled by T_{AA}

Charm production cross section in pp at LHC

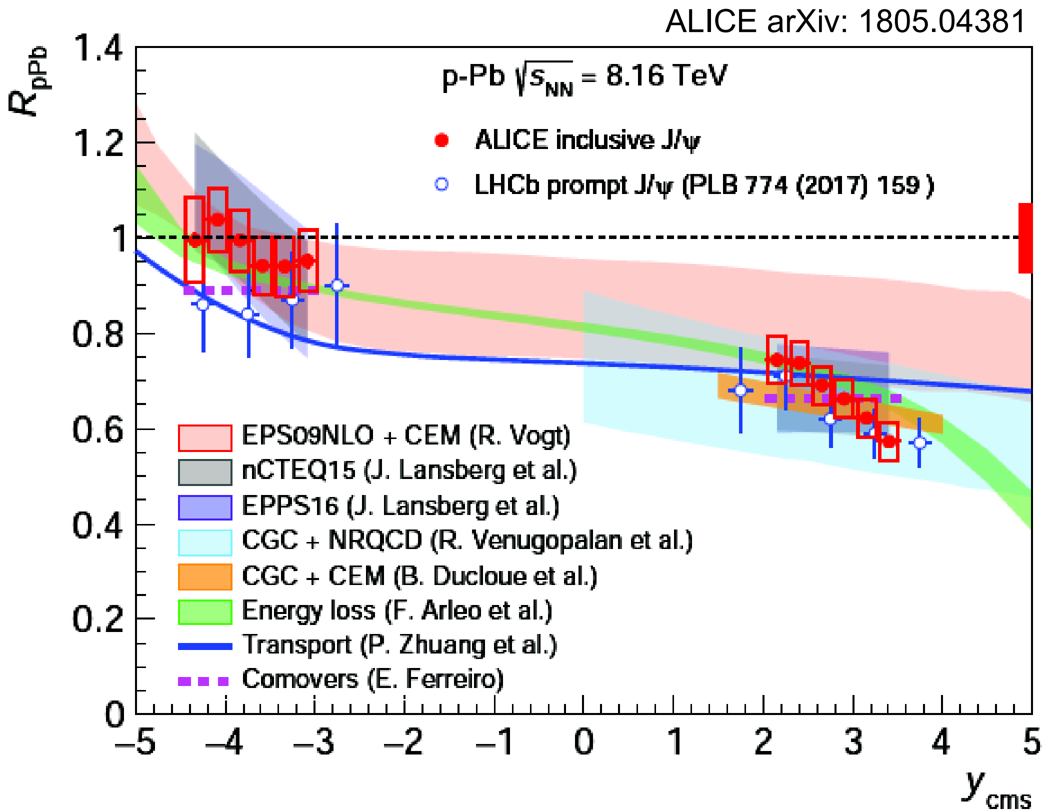


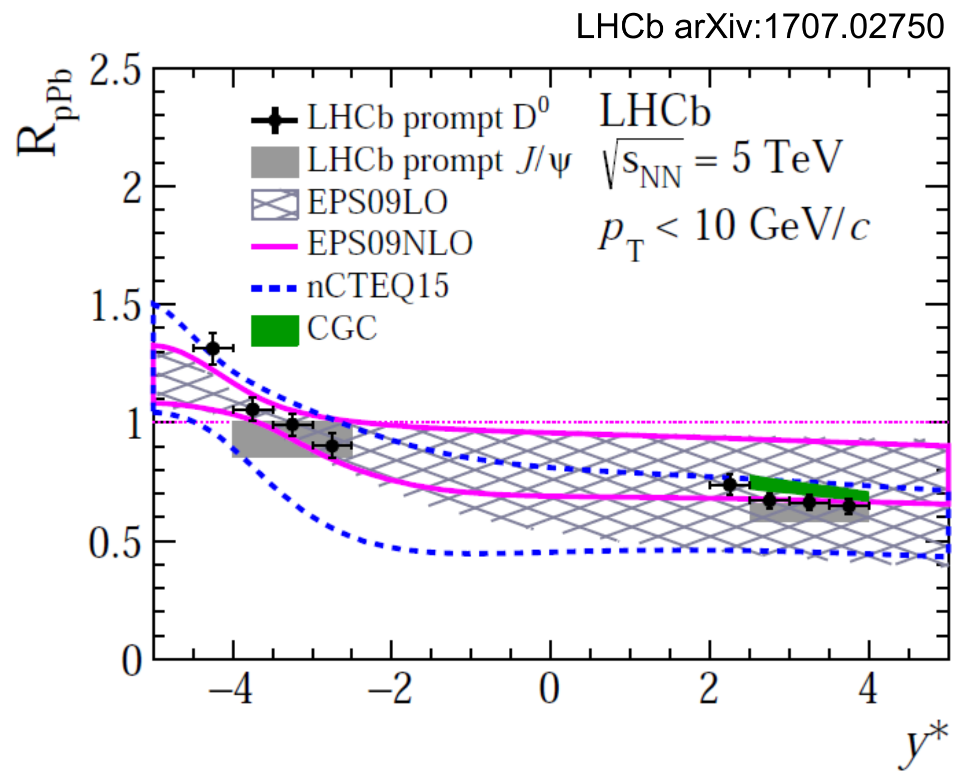
much reduced syst error
40% larger than based on D measurem.
& e^+e^- frag.



new: high statistics ALICE 5 TeV data
- including ML techniques: D^0 and D^+ to p_t=0
- first measurement of charmed baryons at mid-y: much enhanced fragmentation as compared to e^+e^- or ep

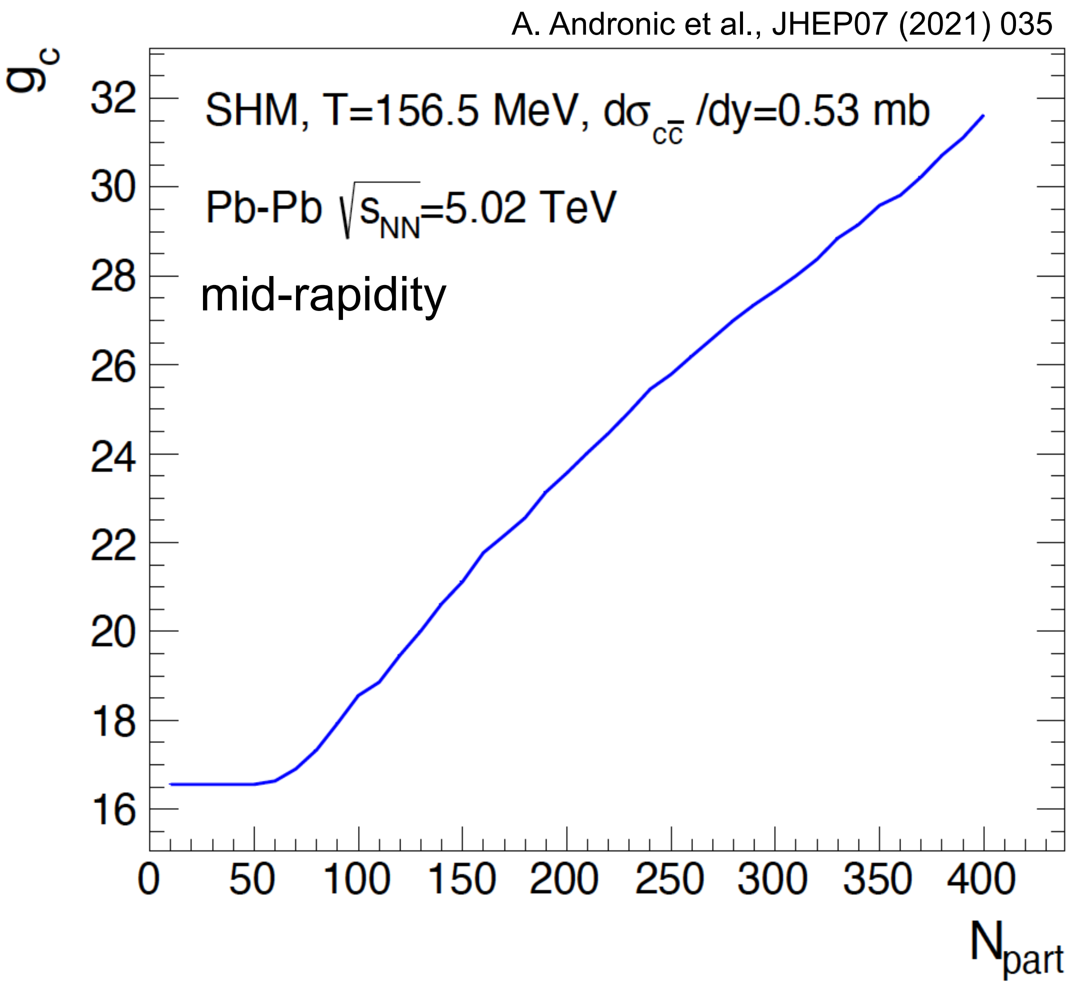
J/psi rapidity distribution in pPb compared to pp





effect of modified gluon distribution in Pb nucleus forms baseline of charm production in PbPb collisions still significant uncertainty

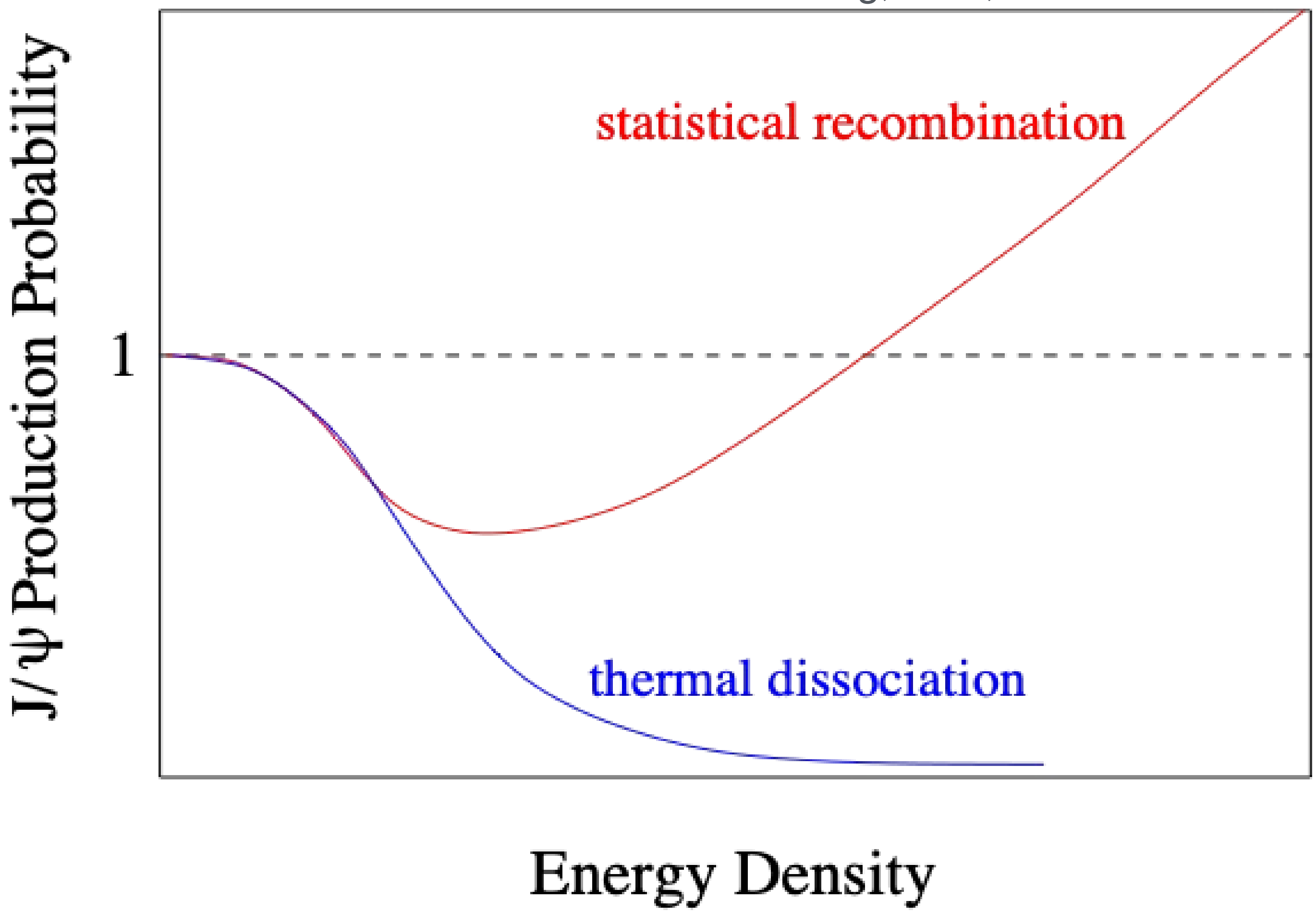
Centrality dependence of charm fugacity g_c at LHC energy



for central PbPb g_c = 30
strong overpopulation vs thermal production of charm

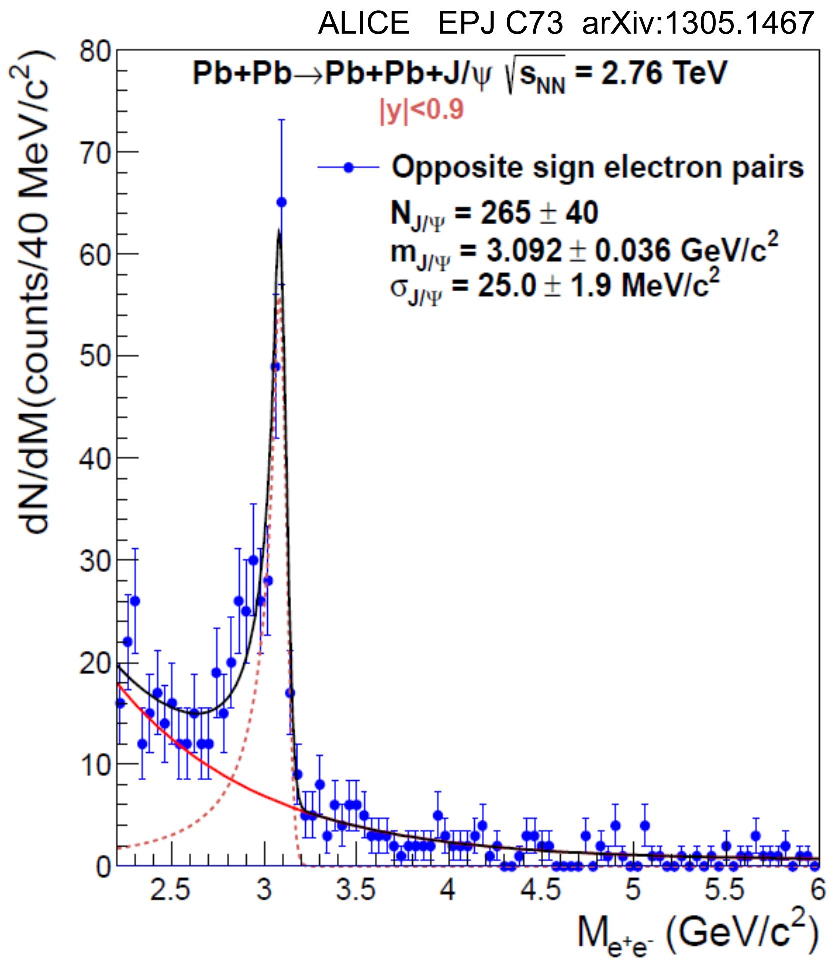
What to expect for J/psi at LHC?

Kluberg, Satz, arXiv:0901.3831



Reconstruction of J/psi in PbPb collisions at LHC

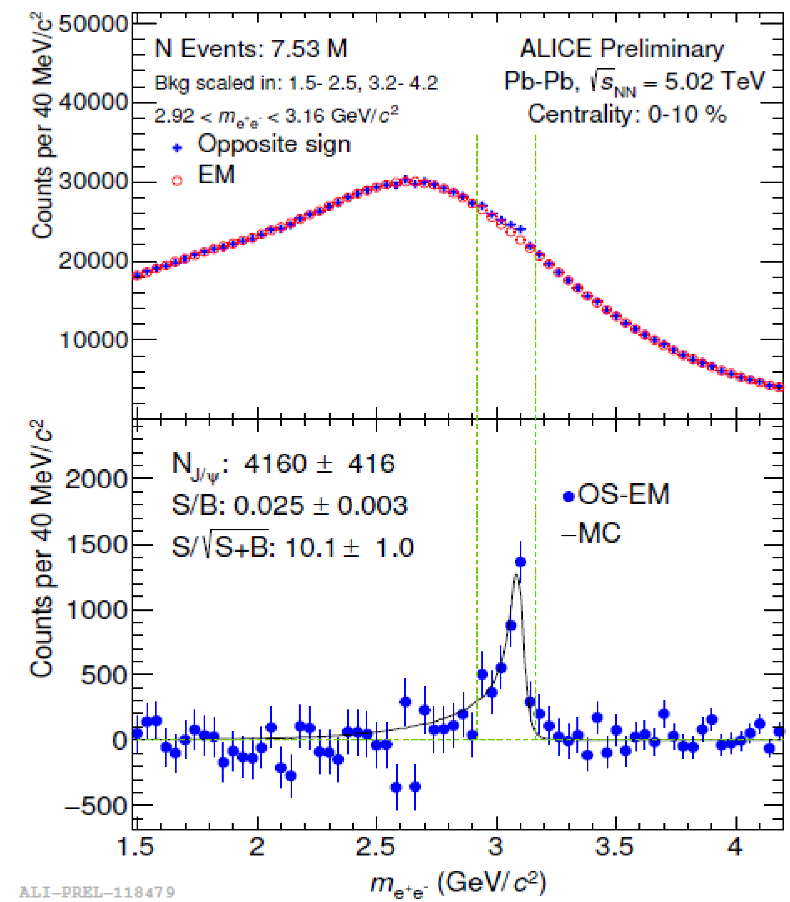
J/psi → e^+e^- or $\mu^+\mu^-$ with 6%



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

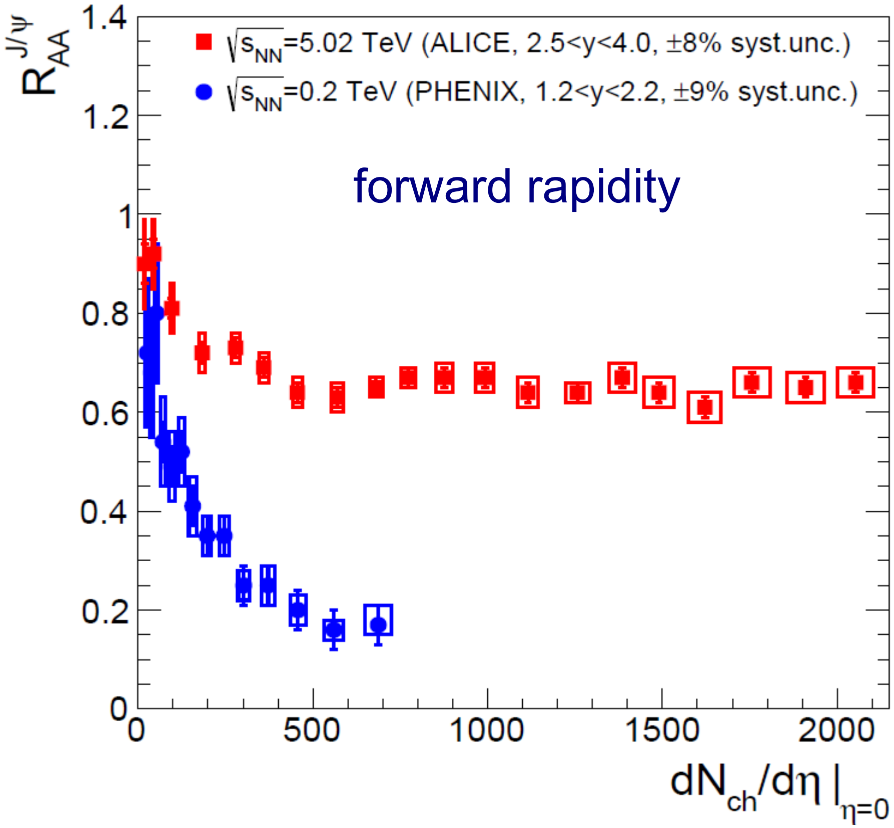
most challenging: central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

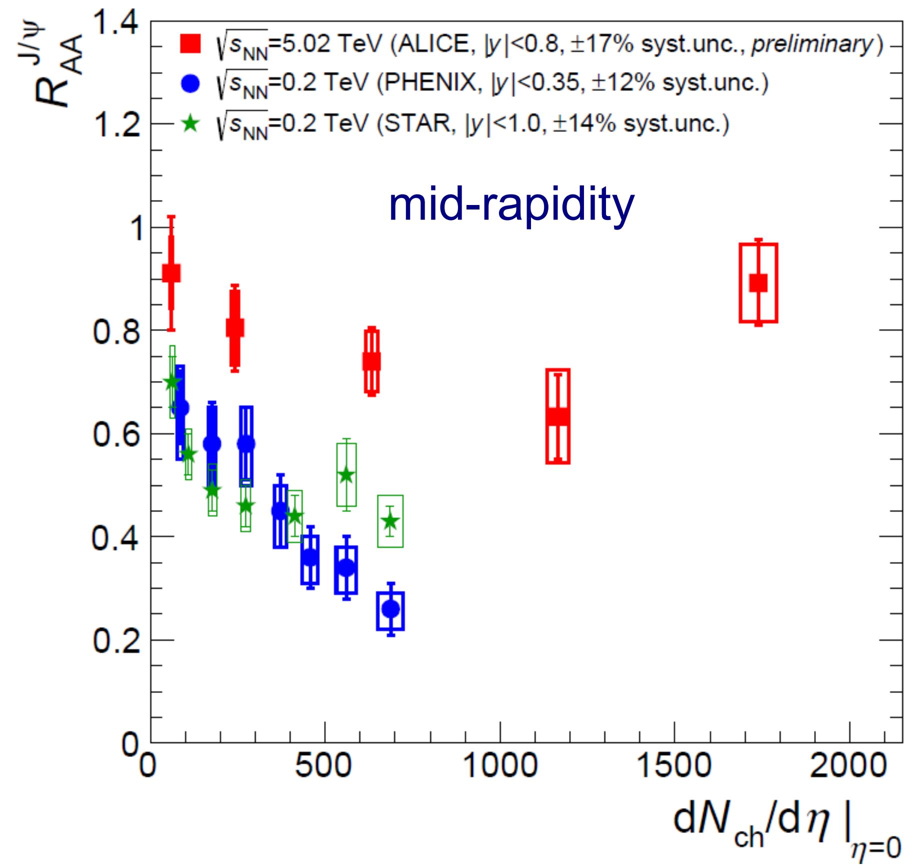
mid |y| < 0.8



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

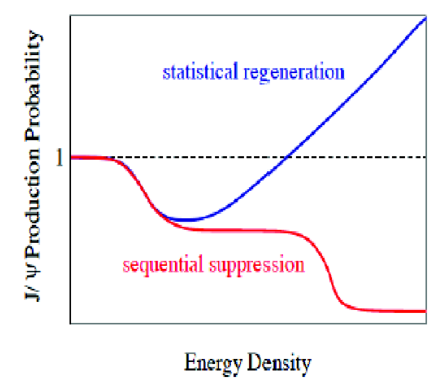
$$R_{AA} = \frac{dN^{AA}/dy}{N_{coll}\, dN^{pp}/dy}$$



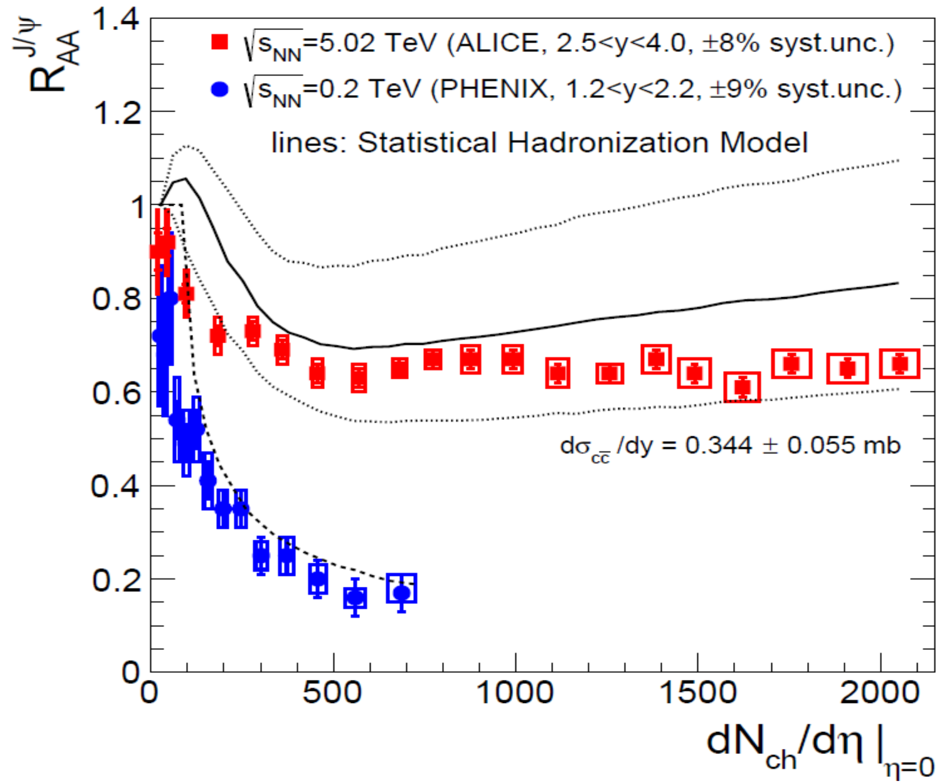


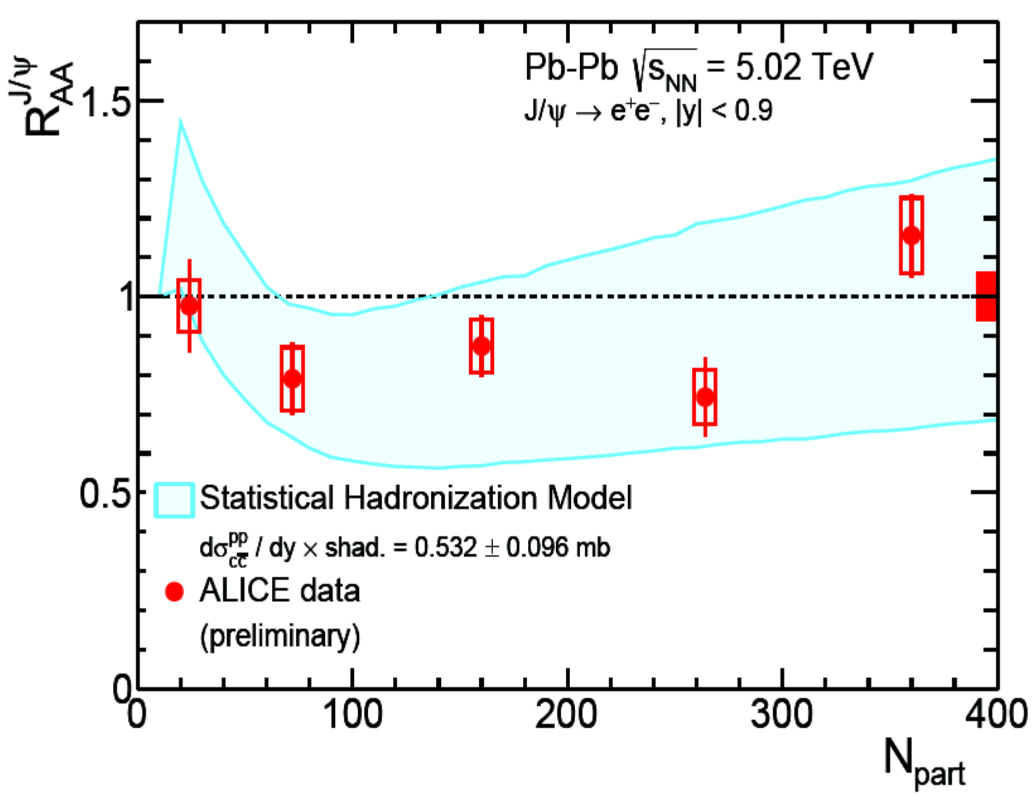
energy density -->

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



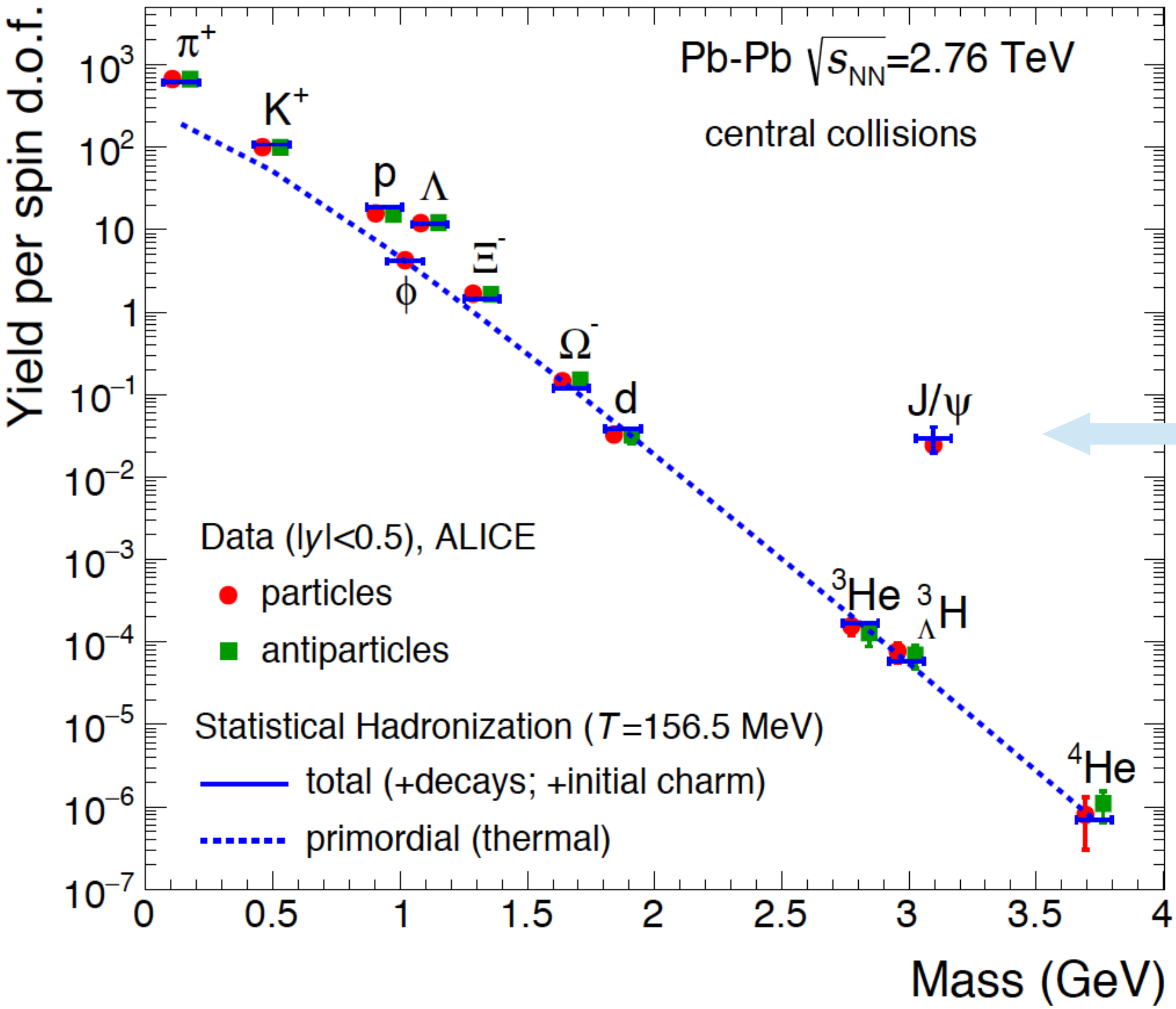


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

main uncertainties for models: open charm cross section due to shadowing in Pb

Systematics of hadron production in SHMc

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

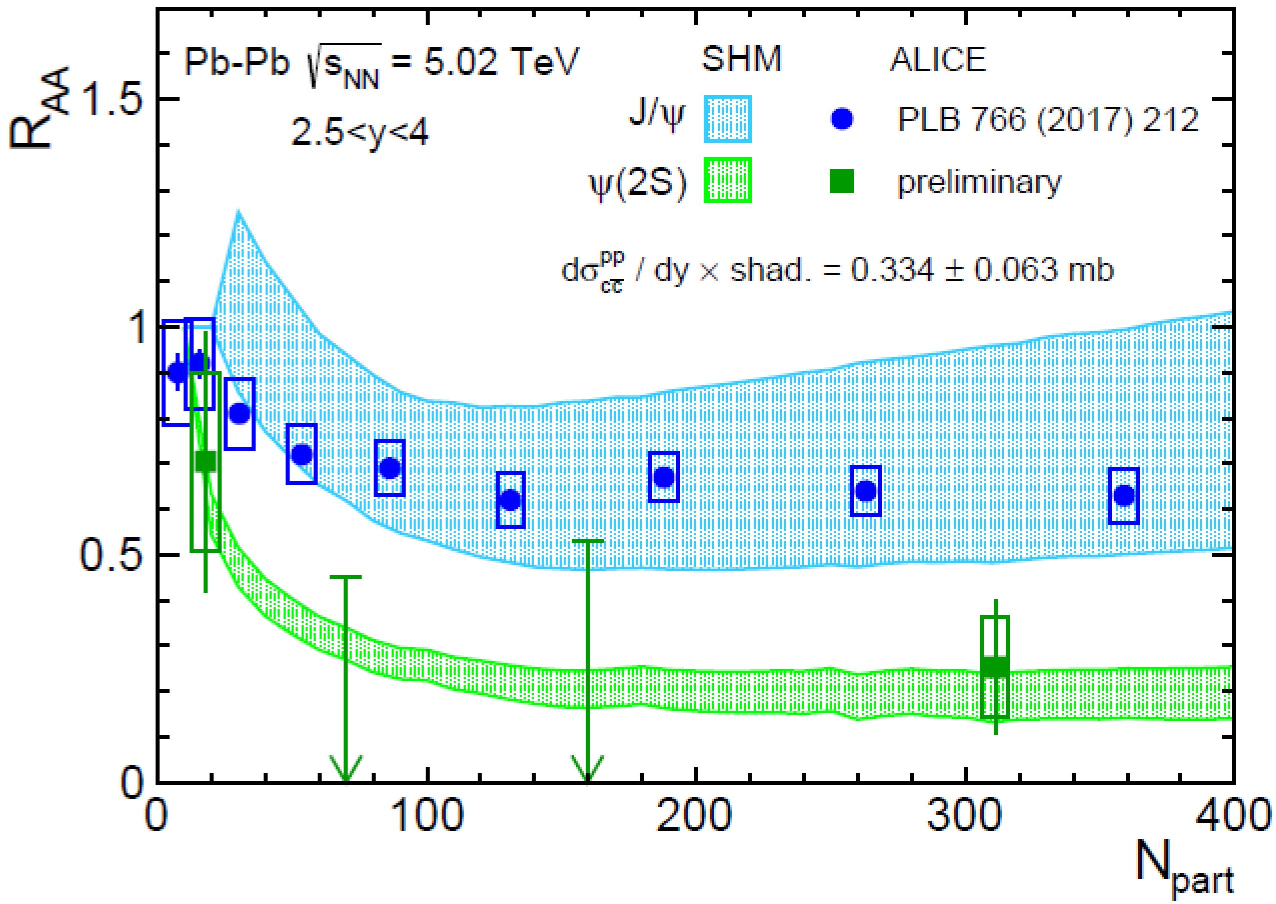


J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

enhancement factor 900 relative to purely thermal yield

What about ψ(2S)?

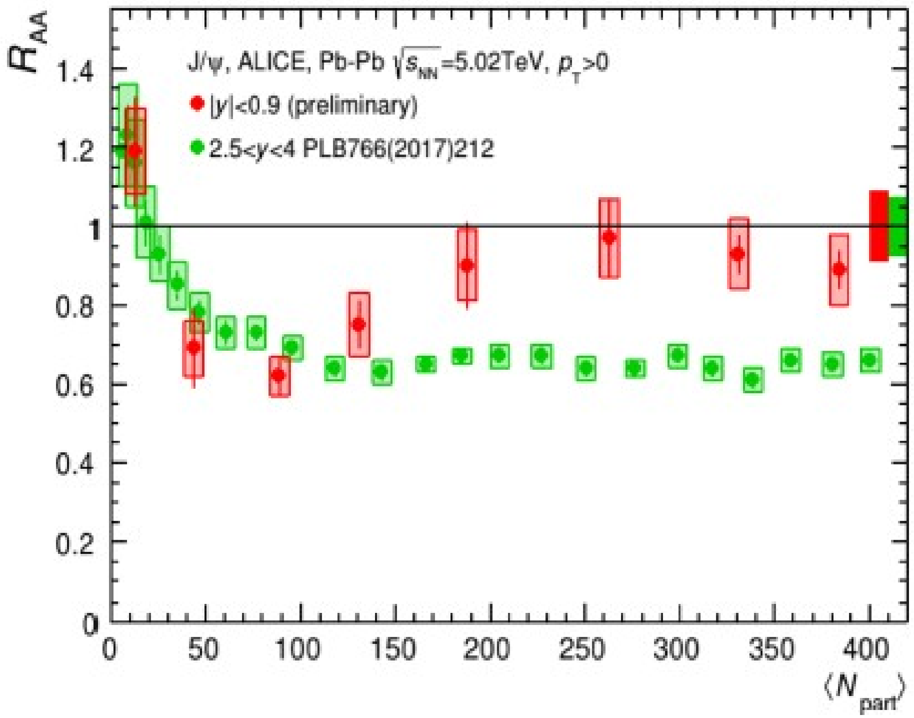
M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236

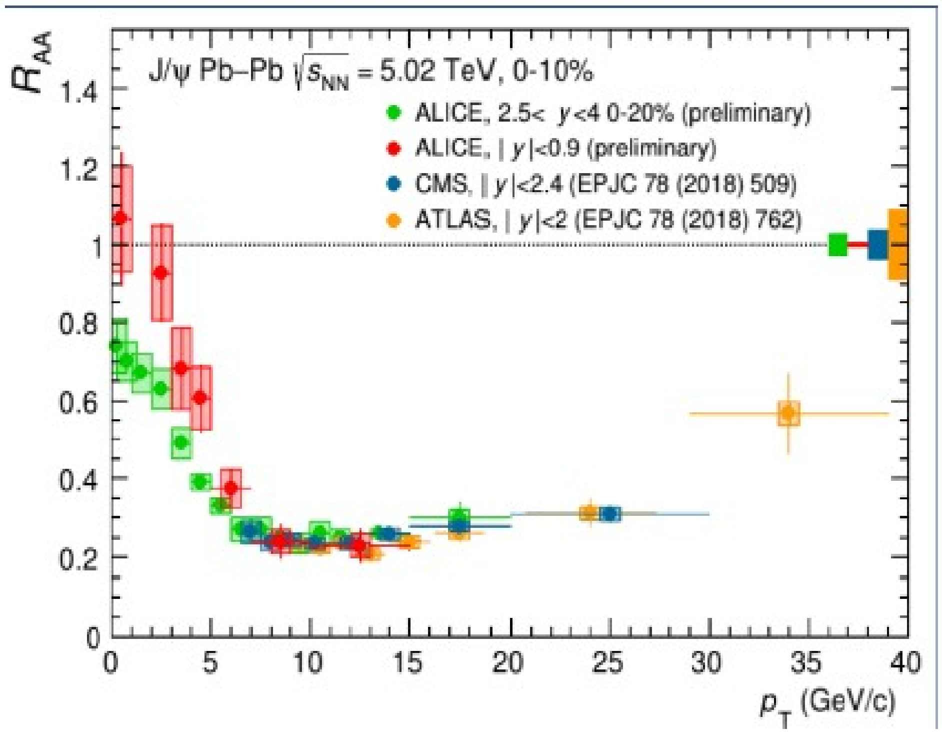


also excited state population completely in line, suppressed by Boltzmann factor
errors will decrease with more data in LHC Run3/4

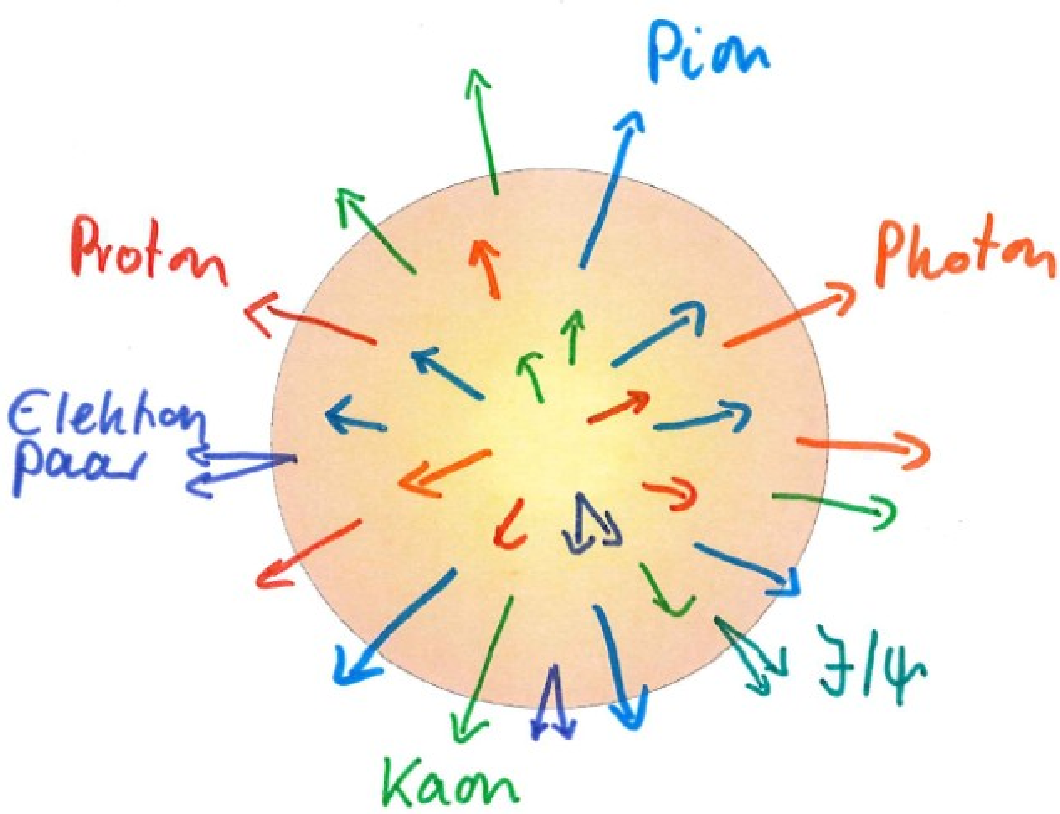
Charmonium at LHC: peaks at mid-y and strong enhancement at low transverse momentum

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





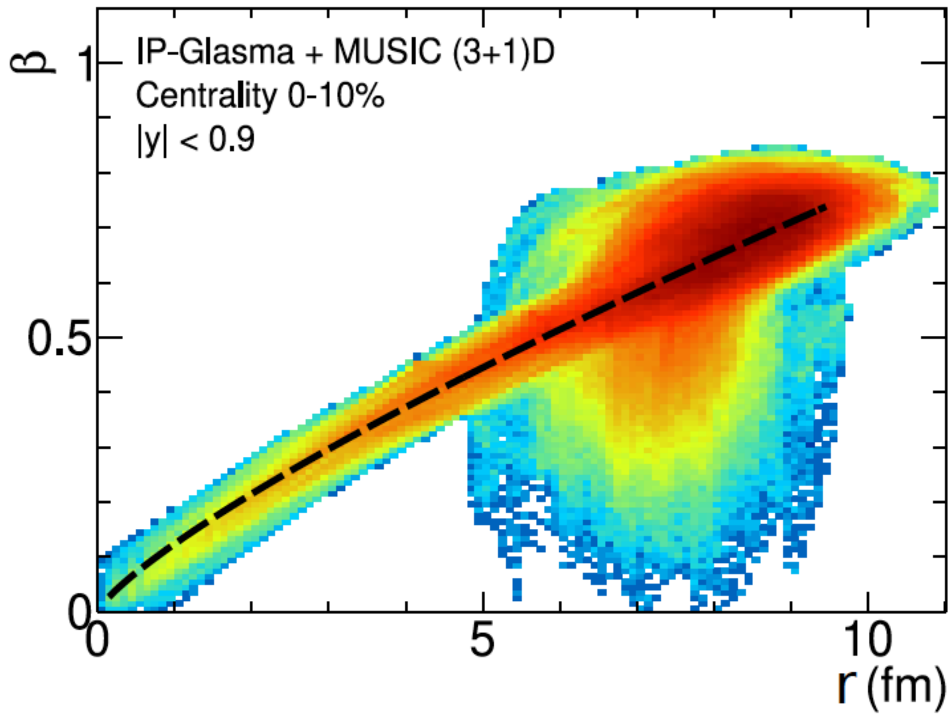
Fireball expands radially - Hubble like expansion



radial expansion modelled by relativistic hydrodynamics
average velocity ≈ 50 % speed of light

Beyond yields: transverse momentum distributions

assume thermalization of charm quarks in QGP, charm quarks follow collective flow
use hydro velocity profile at pseudocritical temperature
from MUSIC (3+1) D tuned to light flavor observables



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

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

$$n = 0.85$$

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

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

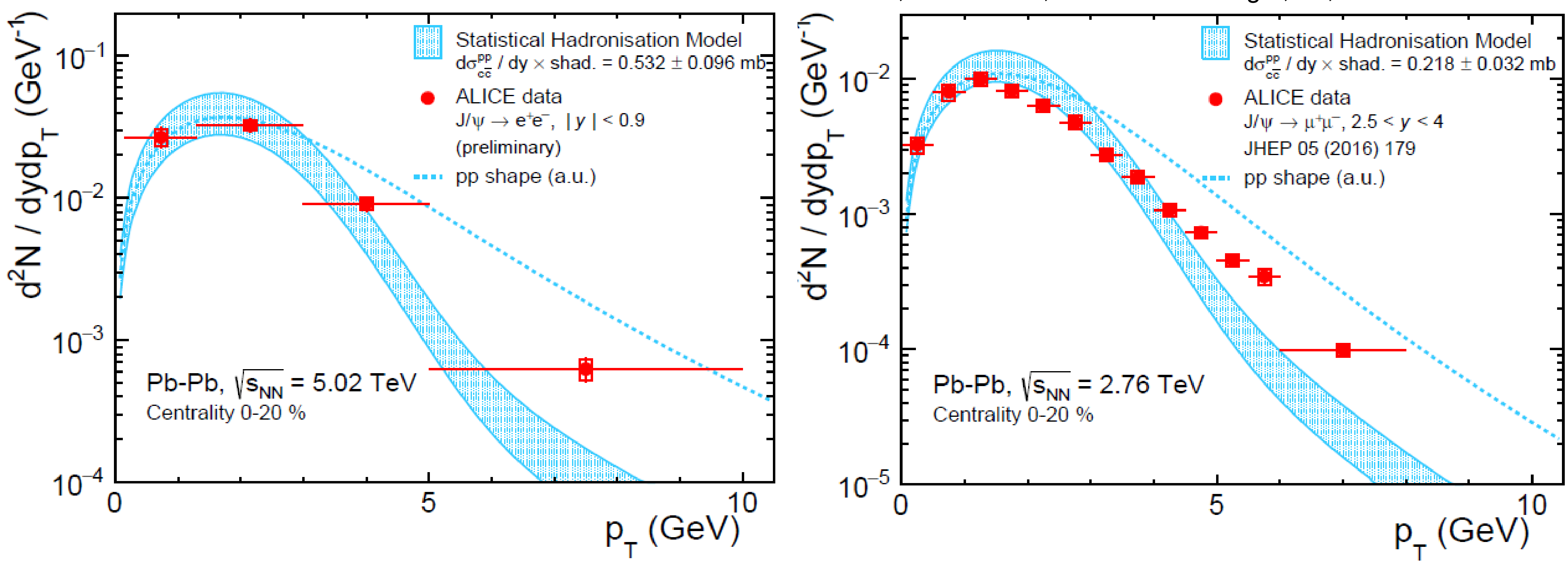
input for blast wave parametrization of spectral shape with T = 156.5 MeV
fireball volume per unit rapidity for central PbPb collisions from measured $dN_{ch}/d\eta \rightarrow$ V = 4997 fm^3

obtain spectra without any free parameter

sensitivity to shape of freeze-out surface: backup

J/ψ transverse momentum spectra from stat. hadr.

M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236



good agreement up to 5 GeV/c without any free parameters
J/ψ formed at hadronization at T_C from thermalized charm quarks flowing with the rest of the medium

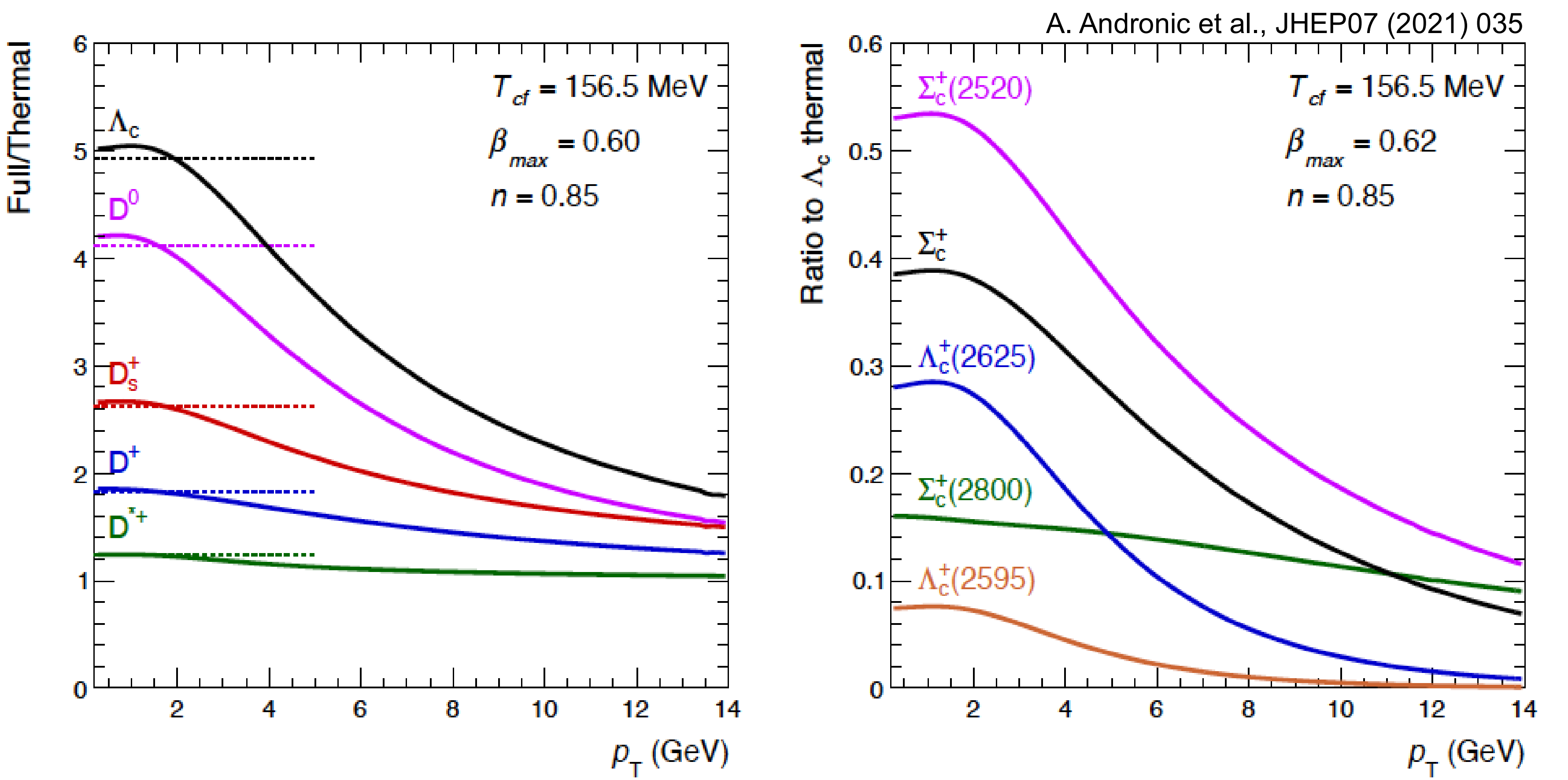
Open charm and SHMc

approach should work as well for open charm hadrons
but:
- strong feeding needs to be taken into account
- only differential spectra, total yields mostly not yet available

Impact of resonance decays for open heavy flavor hadrons

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

feed-down to Λ_c



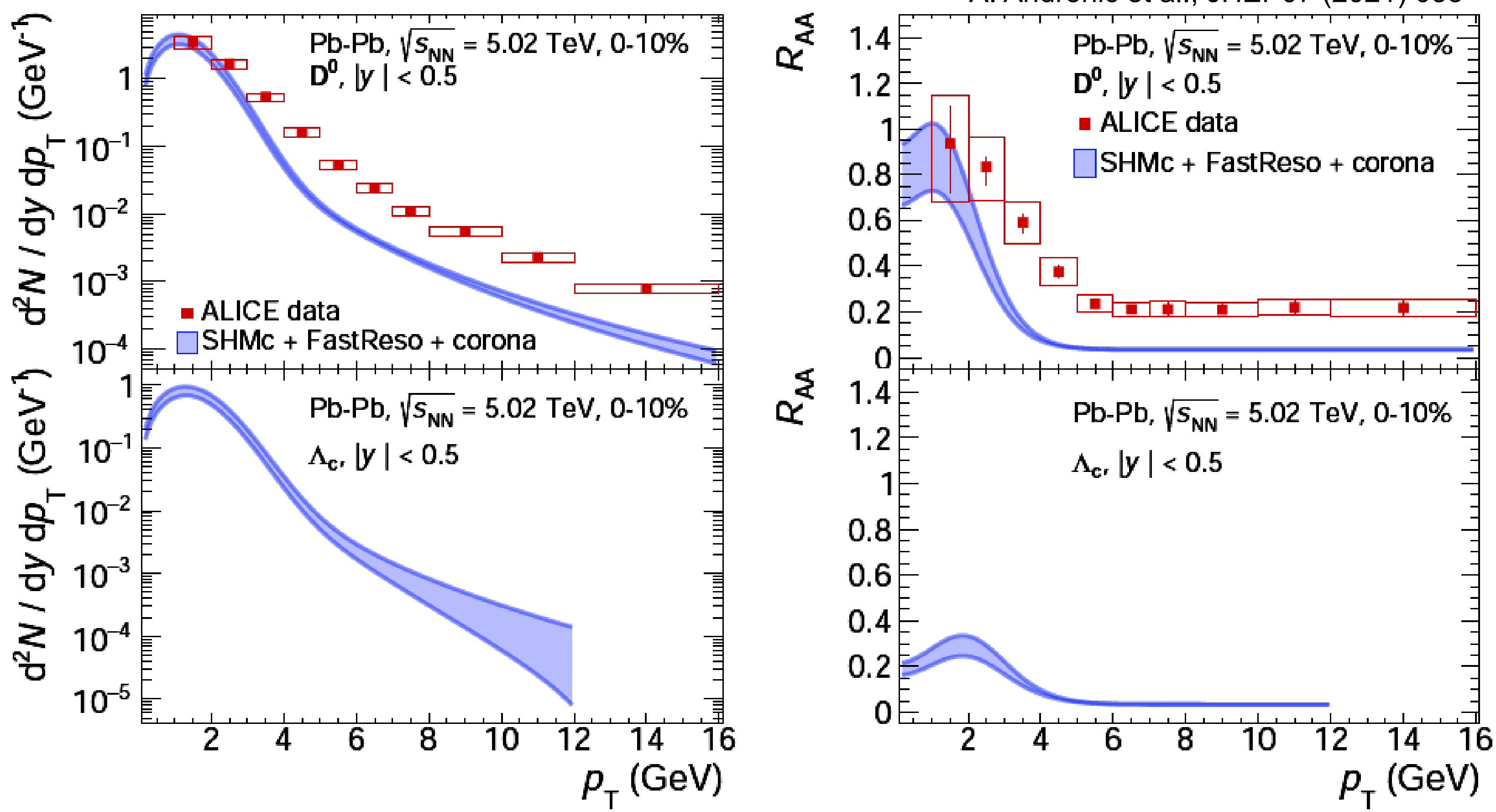
but: beyond 4 GeV corona dominates, hence change in shape not very visible

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

for open heavy flavor hadrons strong contribution from resonance decays
- include all known charm hadron states as of PDG2020 in SHMc
- compute decay spectra with FastReso: 76 2-body and 10 3-body decays

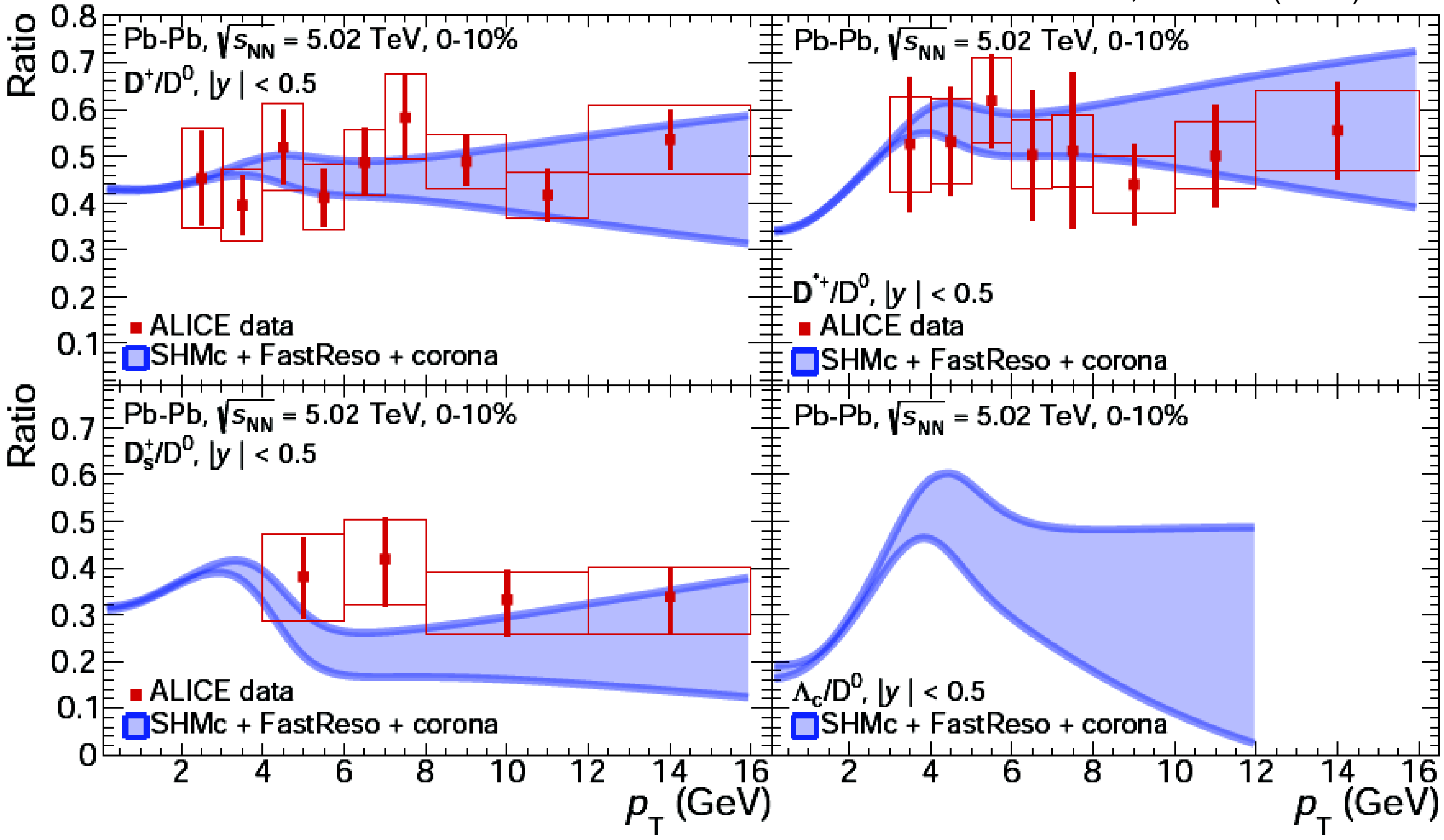
(A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284 arXiv: 1809.11049)

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



Ratios of charm hadron to D^0 spectra

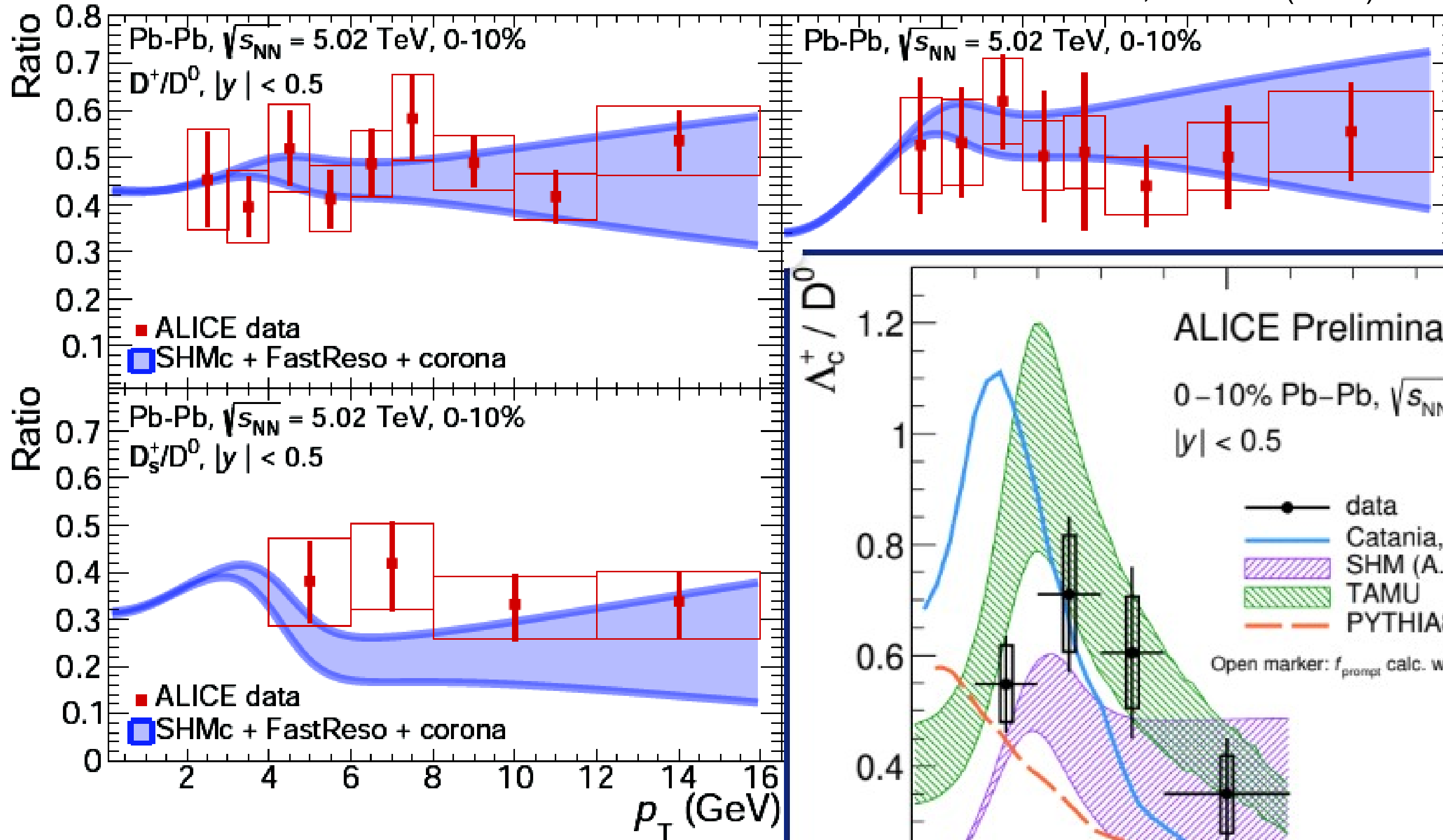
A. Andronic et al., JHEP07 (2021) 035

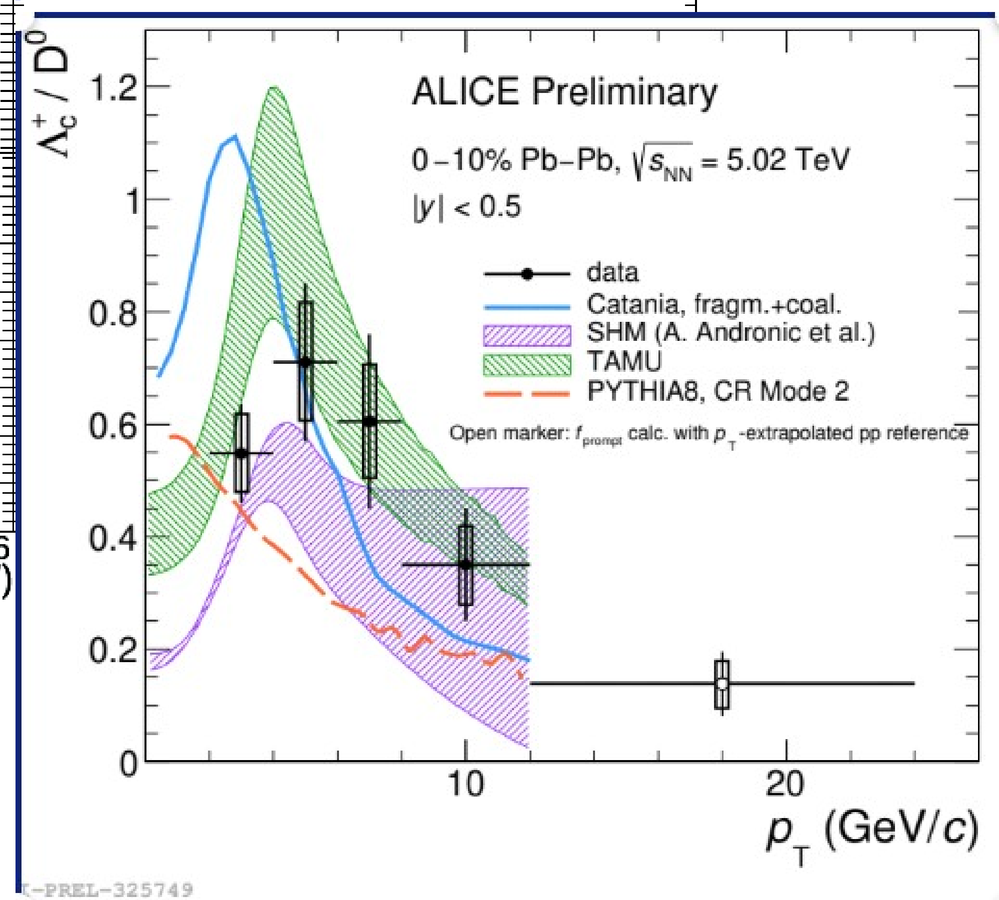


excellent agreement considering that there are NO free parameters

Ratios of charm hadron to D^0 spectra

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



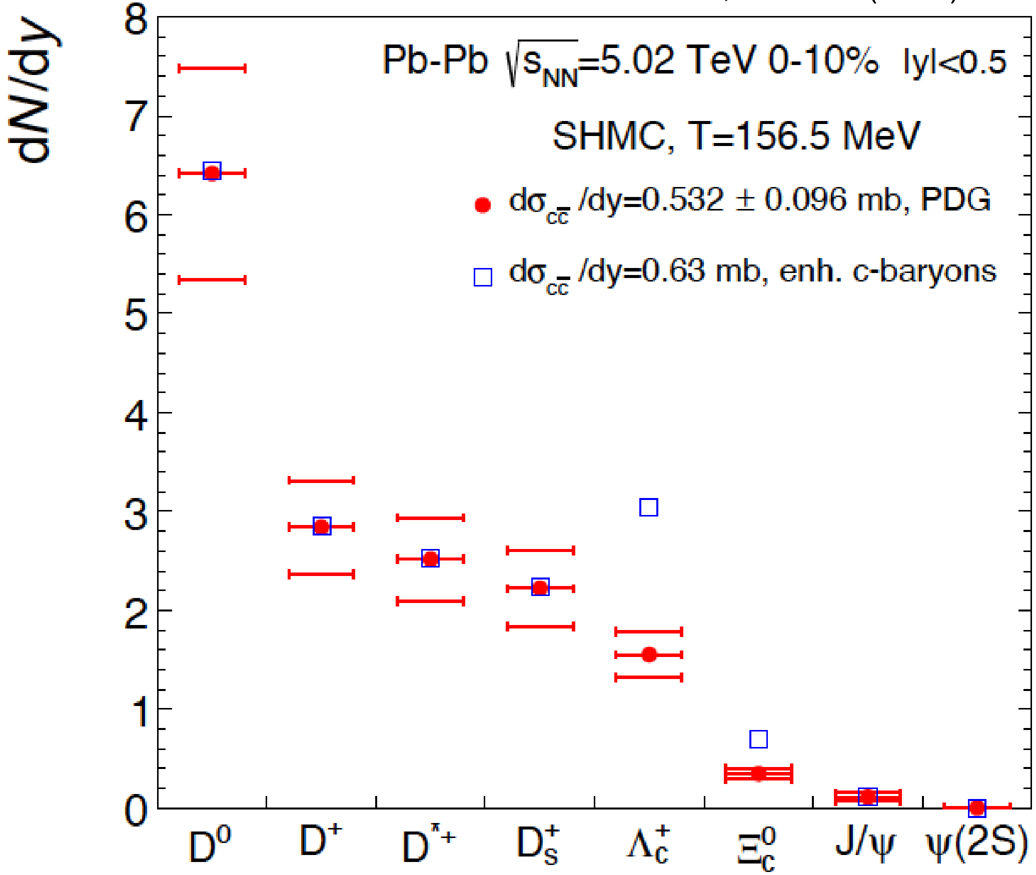


preliminary Lambda_c fits well into picture

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

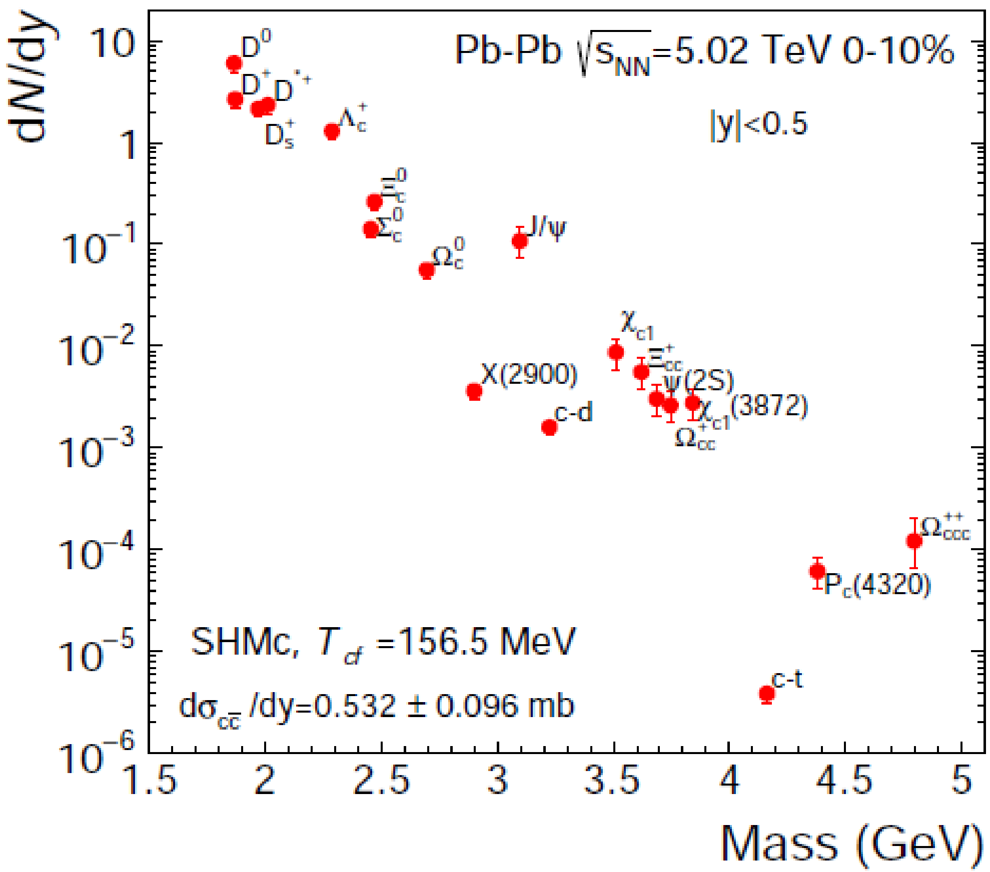


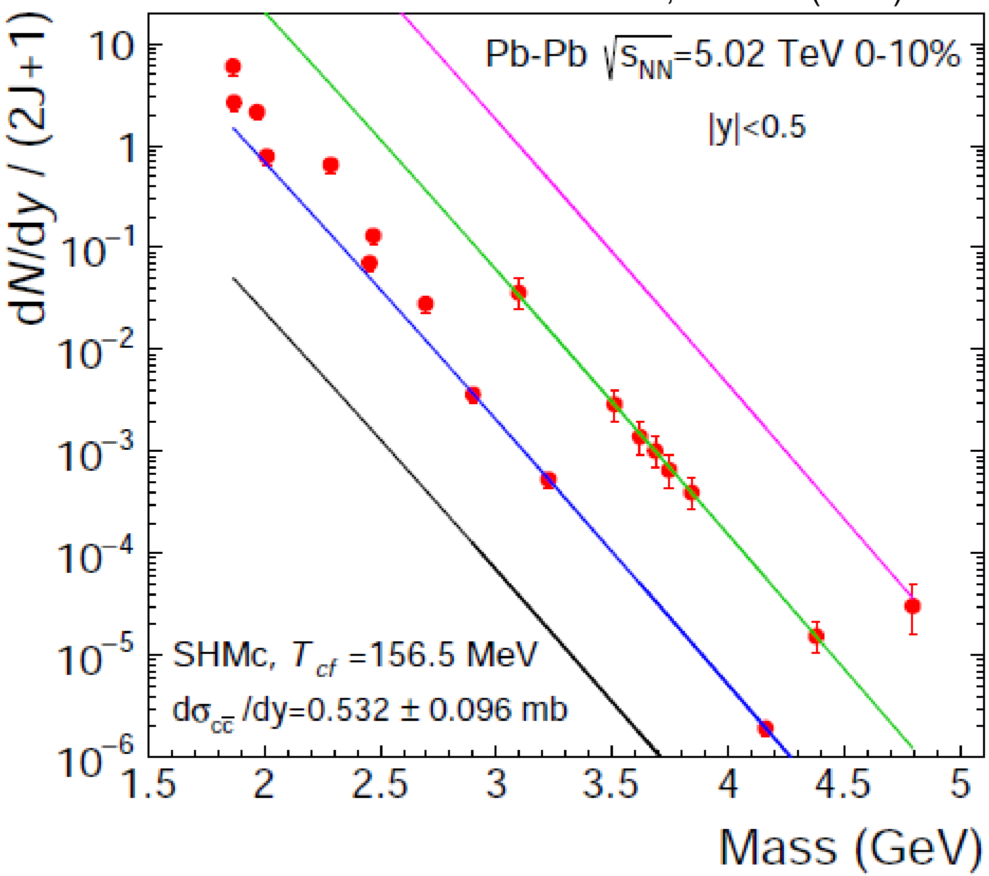
charm cross section increases 20%
yield of charm baryons nearly doubles
mesons practically unaffected

The multi-charm hierarchy

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

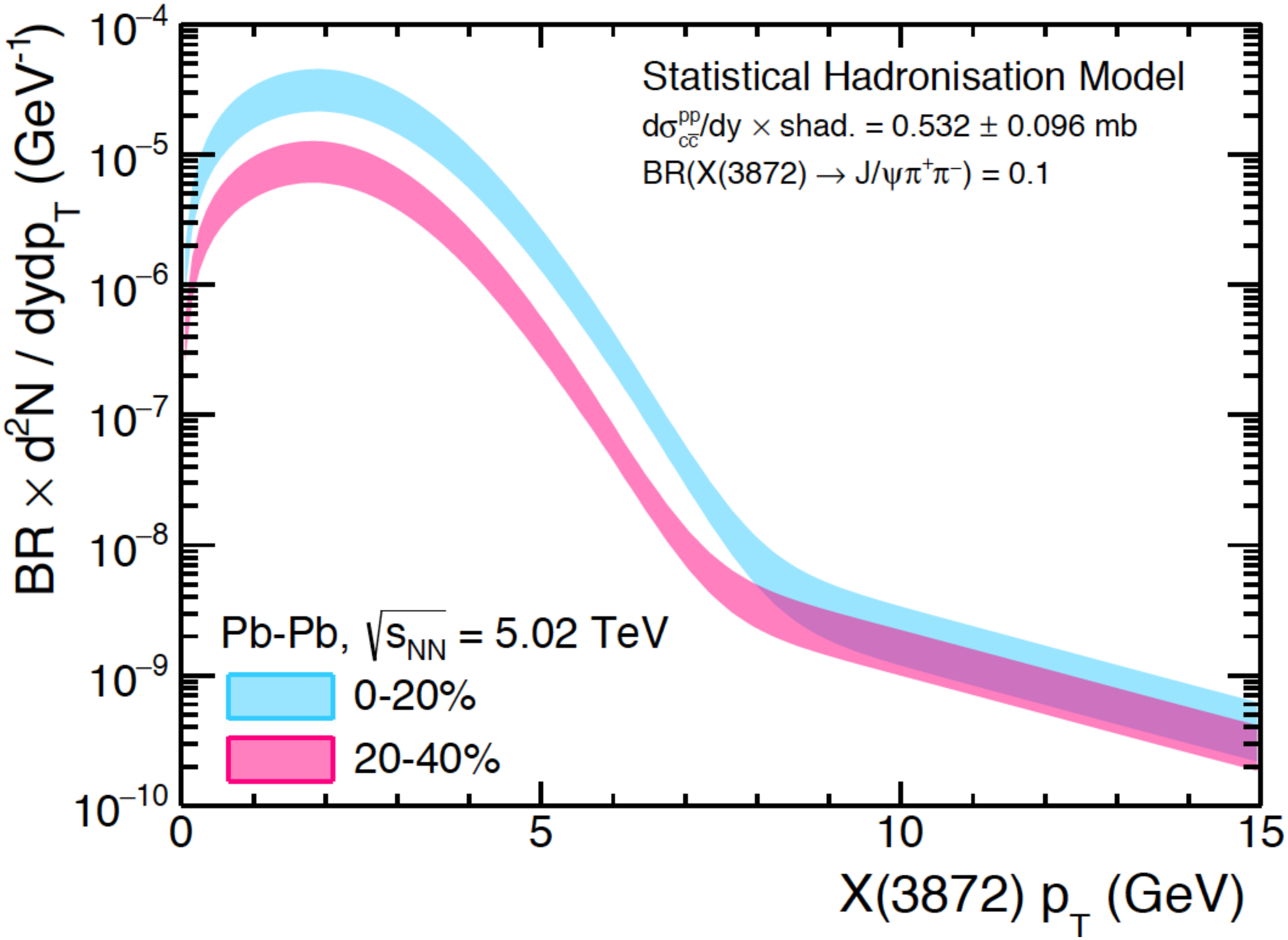
A. Andronic et al., JHEP07 (2021) 035





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

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



close to $D^0 D^{0*}$ threshold
- tetraquark or molecule?

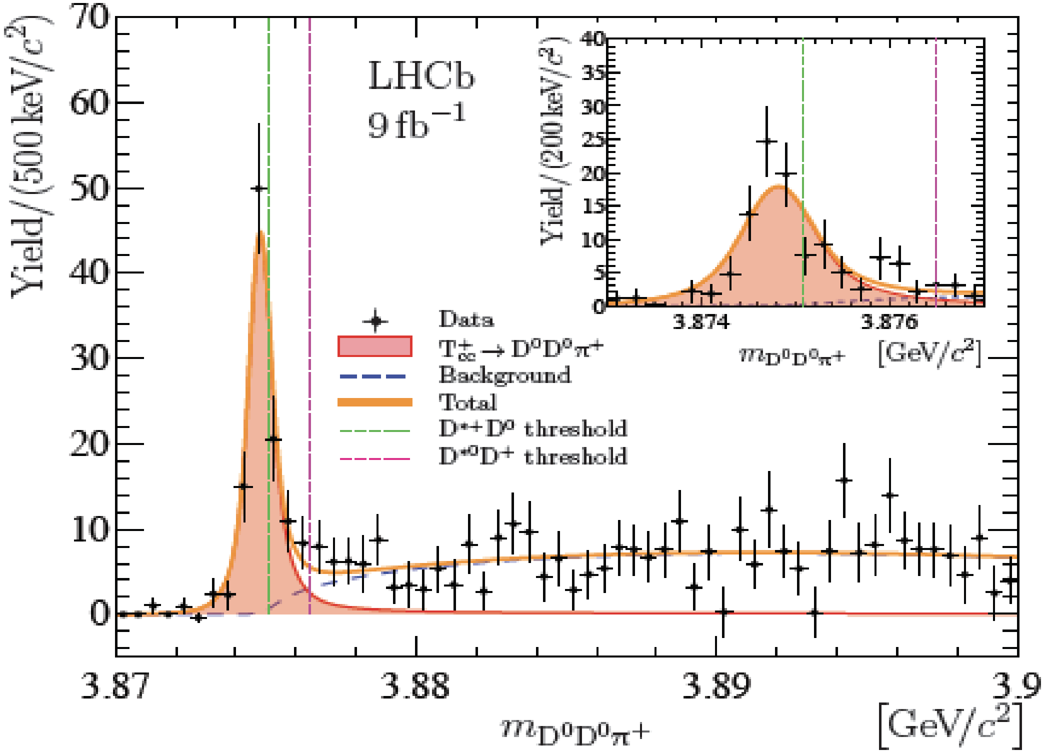
is it formed like (hyper)nuclei?

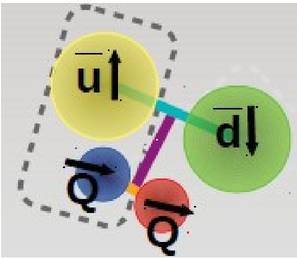
- decay into $J/\psi\ \pi^+\pi^-$
- doable in Run3/4?
- otherwise ALICE3

note: dramatic enhancement at low p_t predicted

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

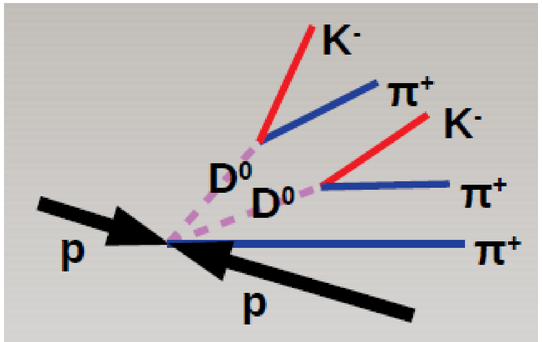
LHCb 2109.01038





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, its production cross section will fall on the 2 charm quark line at the measured mass, pracitally identical to χ_{c1}(3872) about 1% of J/psi
- can be tested experimentally

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
caveats:
- still no measured charm cross section in PbPb colissions → significant uncertainty
- puzzle of large enhancement in production of charmed baryons in pp, how about PbPb?

answers will come with much increased statistics LHC Run3/4 data

predictions for complete spectrum of multicharm and exotic charmed hadrons
- will be tested with ALICE3

Backup

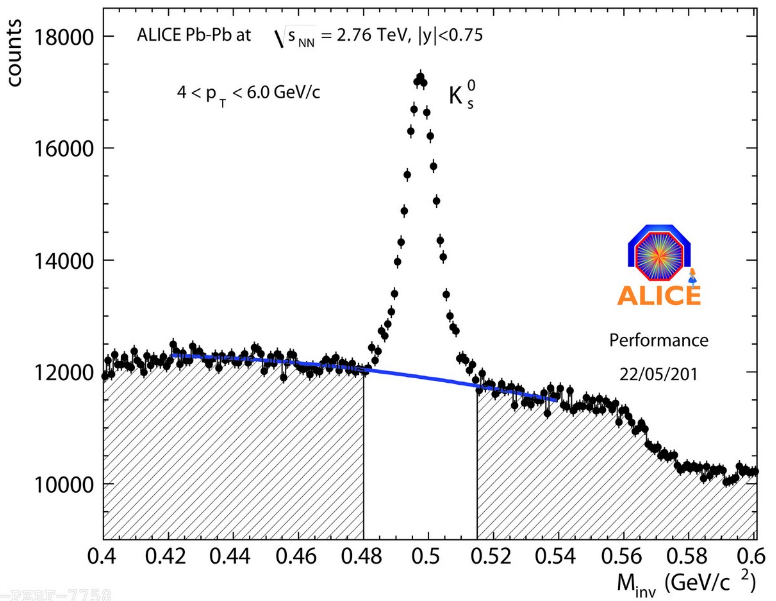
How to measure production yields of identified hadrons

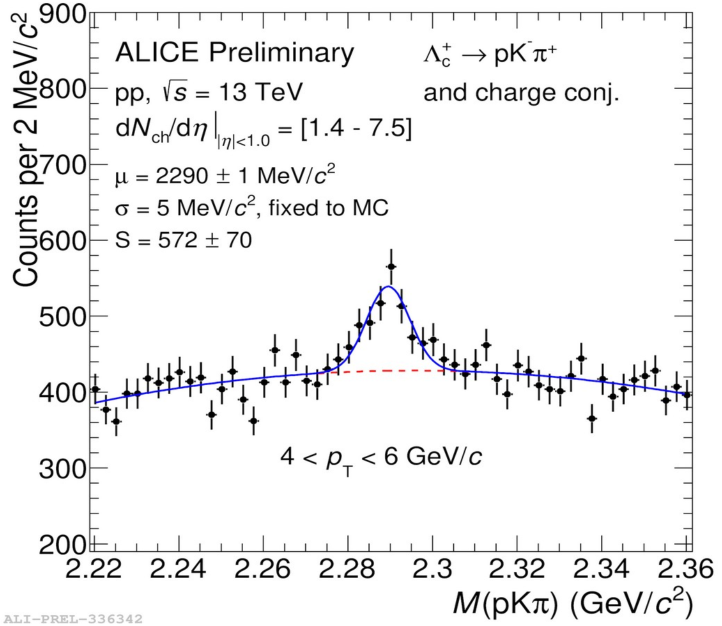
$$K^0_s \rightarrow \pi^+ + \pi^- \quad (\mathrm{B.R.}68\%) \quad c\tau = 2.68\,\mathrm{cm}$$

$$\Lambda_c^+ \rightarrow \mathrm{p}\,\mathrm{K}^-\,\pi^+ \quad (\mathrm{B.R.}\,5\%) \quad c\tau = 60\,\mu\mathrm{m}$$

look for secondary decay vertex away from interaction point

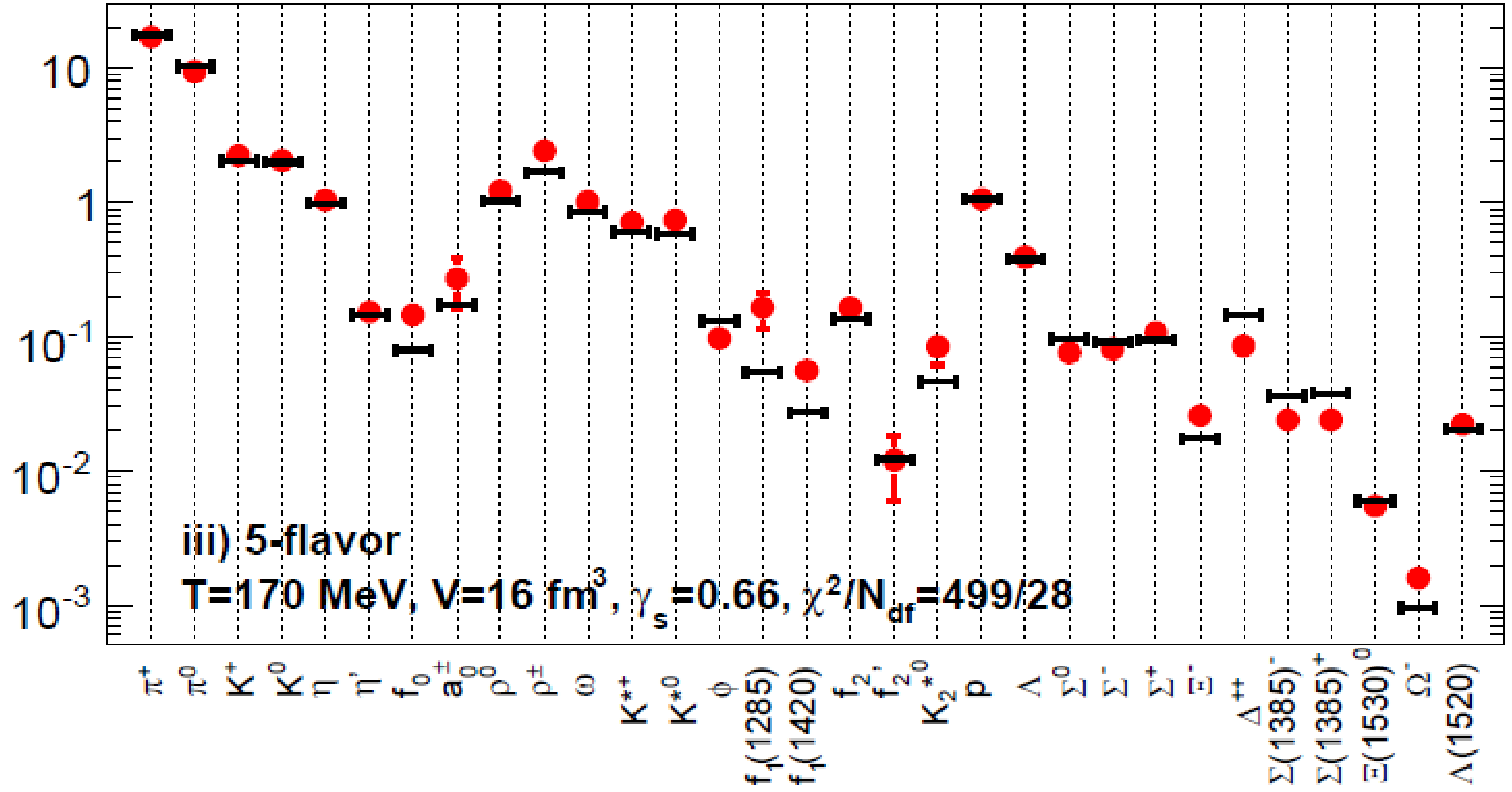
identification via invariant mass of weak decay products works up to very high momentum!





Statistical features in hadronization of jets in e+e- at Z-pole

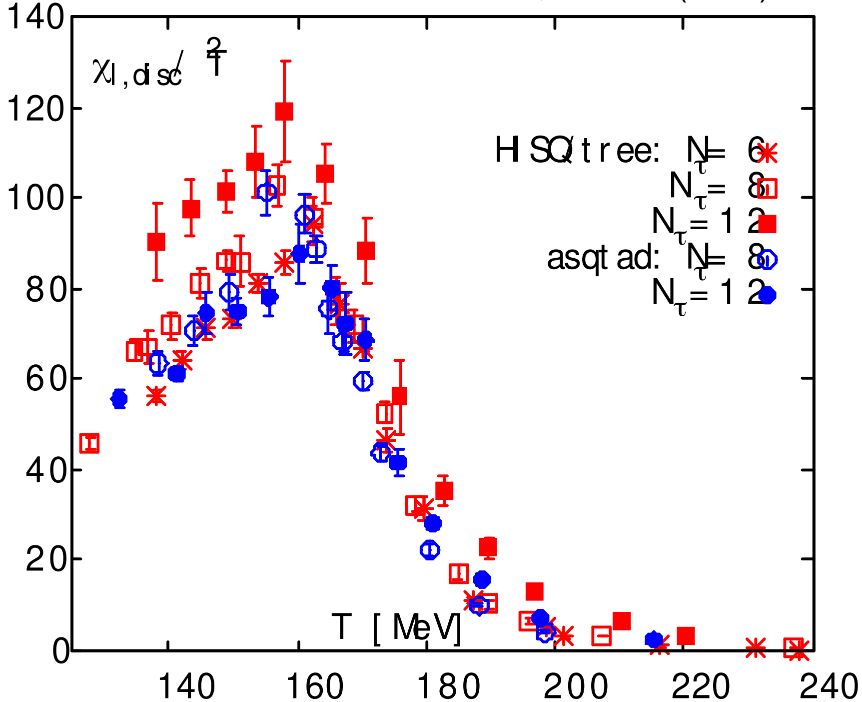
A. Andronic et al., arXiv:0804.4132



Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

S.Borsayi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073
A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



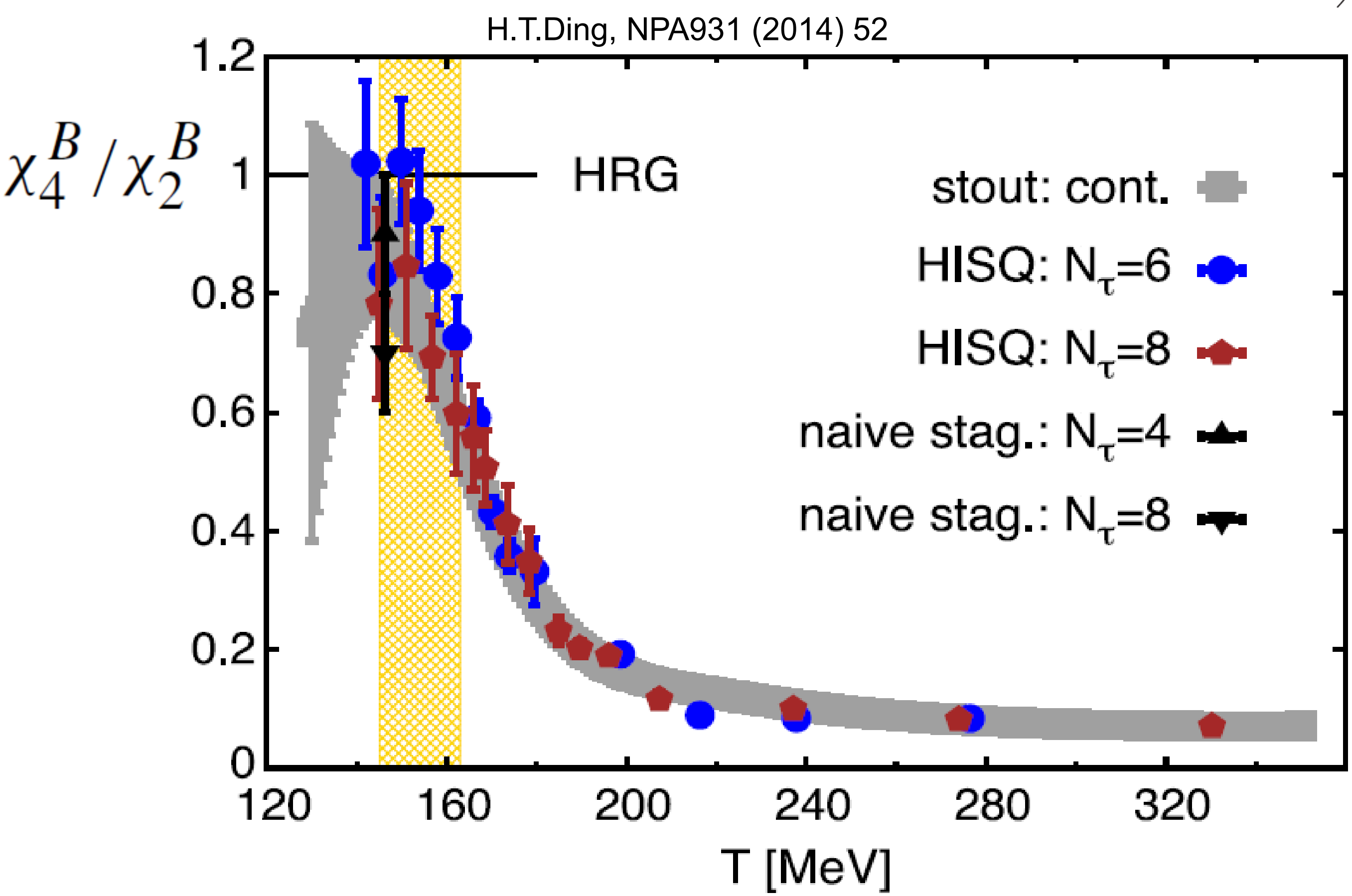
$$\langle\bar{\Psi}\Psi\rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial m}$$

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

comparing different measures and different fermion actions, consensus:
T_c = 150 – 160 MeV for chiral restoration

Measure of deconfinement in lQCD

$\chi_4^B / \chi_2^B \propto \text{baryon number}^2$



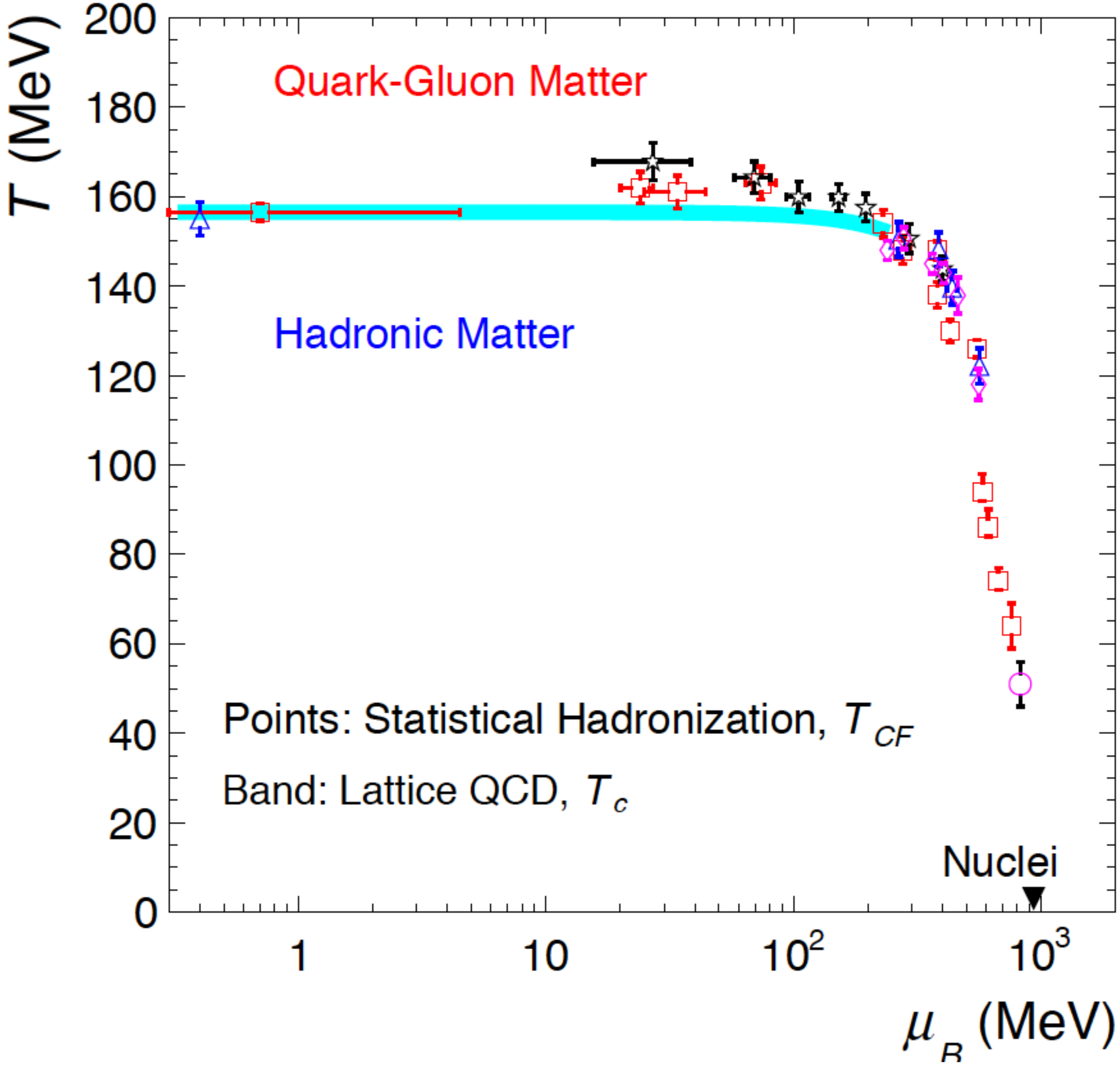
confined: 1

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

The QCD phase diagram – experiment and lattice QCD



quantitative agreement of chemical freeze-out parameters with LQCD predictions for baryo-chemical potential < 300 MeV

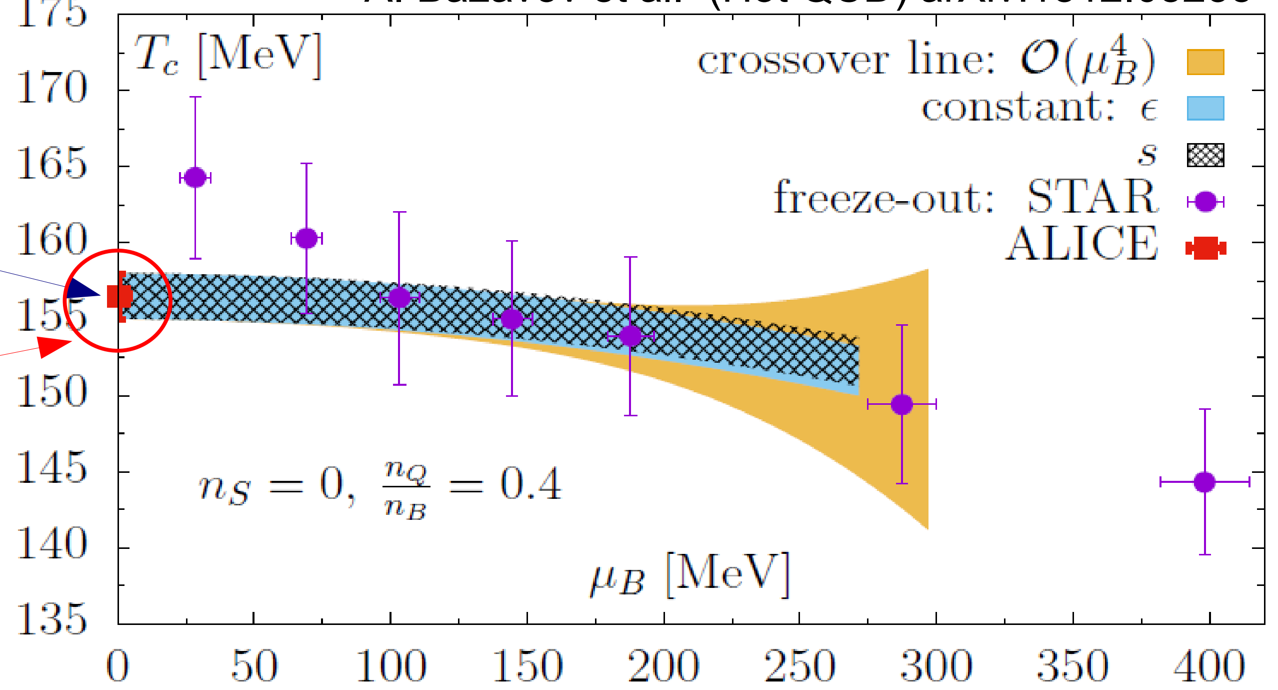
Pseudo-critical temperature from Lattice QCD

recent breakthrough in lQCD: precise determination of pseudo critical temp of chiral cross over

T_{pc} = 156.5 ± 1.5 MeV

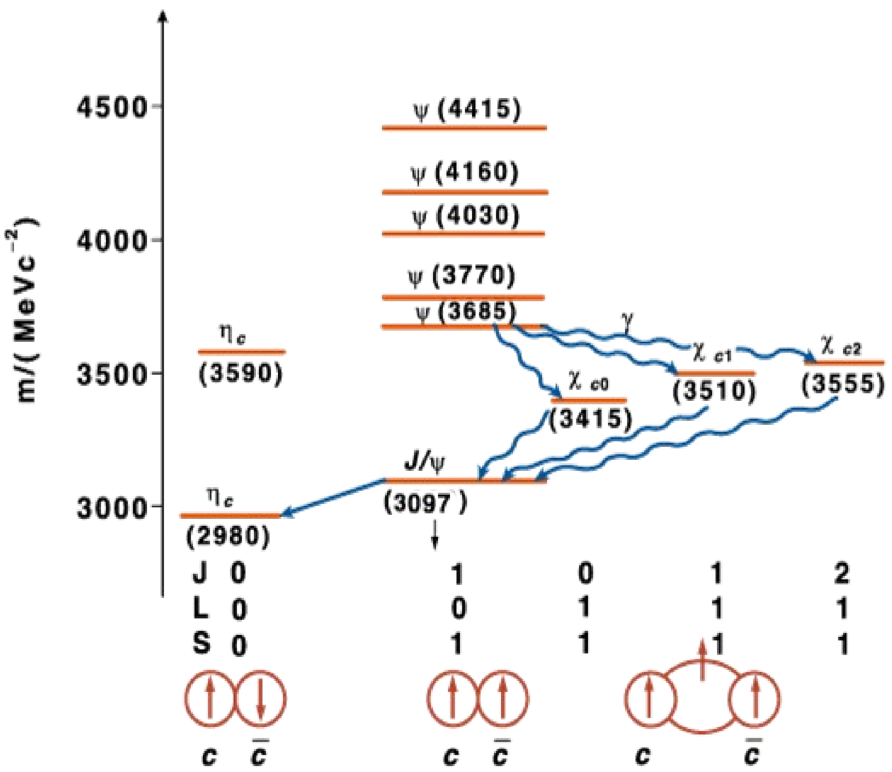
in exact agreement with chemical freeze out temp determined from ALICE data

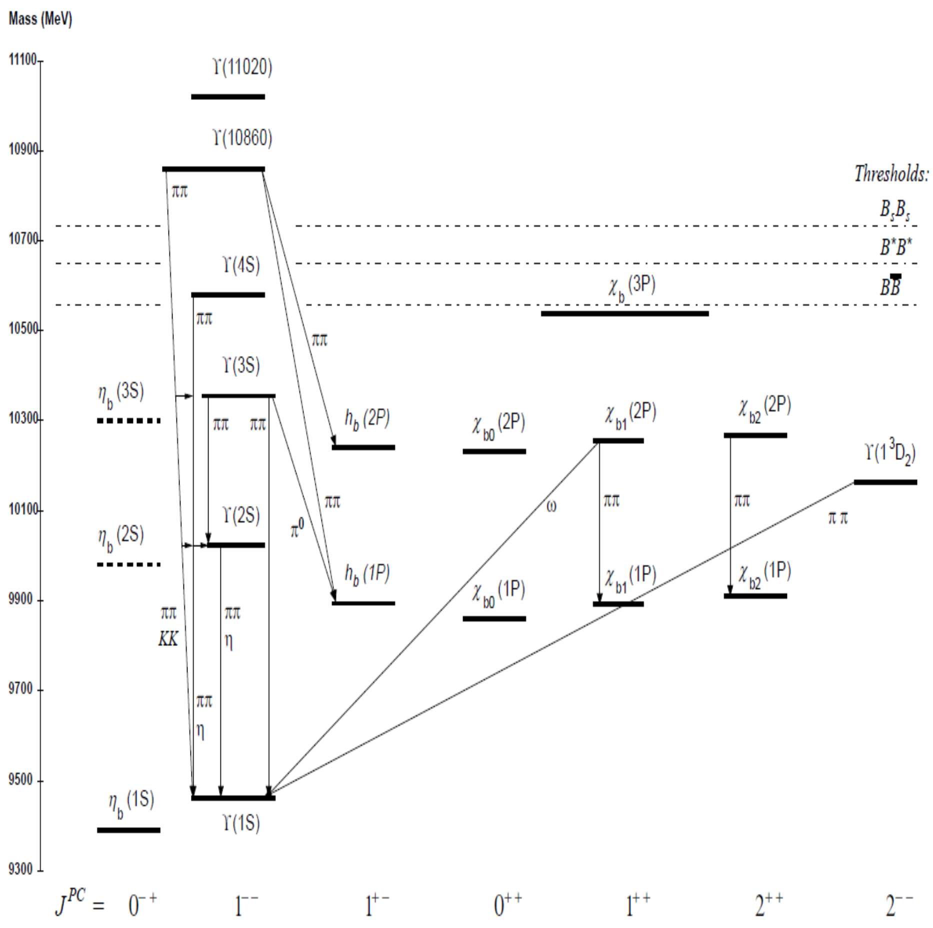
A. Bazavov et al. (Hot QCD) arXiv:1812.08235



hadro-chemical freeze-out happens at the phase conversion from QGP to hadrons

Charmonium and Bottomonium spectra





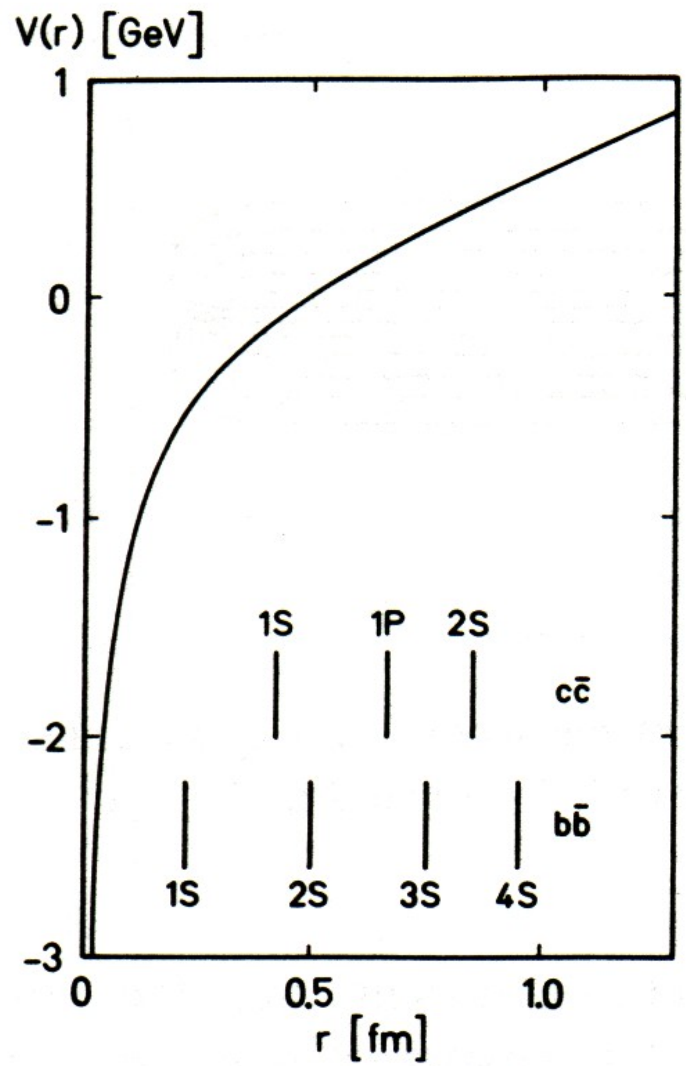
color singlet states

Different quarkonia melt at different temperatures

using $$\mathrm{V(r,T)} = \frac{\sigma}{\omega_\mathrm{D}(\mathrm{T})}(1 - \exp(-\omega_\mathrm{D}(\mathrm{T})\mathrm{r})) - \frac{\alpha}{\mathrm{r}}\exp(-\omega_\mathrm{D}(\mathrm{T})\mathrm{r})$$

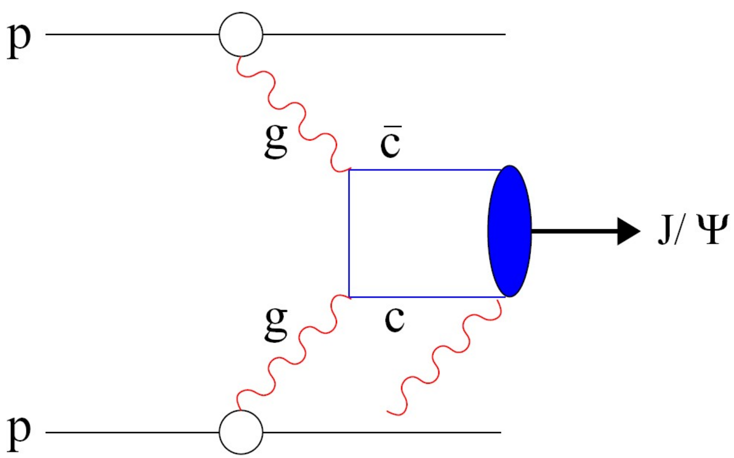
F. Karsch and H. Satz, Z.Physik C51 (1991) 209

	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



exact values very model dependent, but basic feature: J/ψ, ψ', χ_c, Υ' not bound at or little above T_c, Υ survives longer

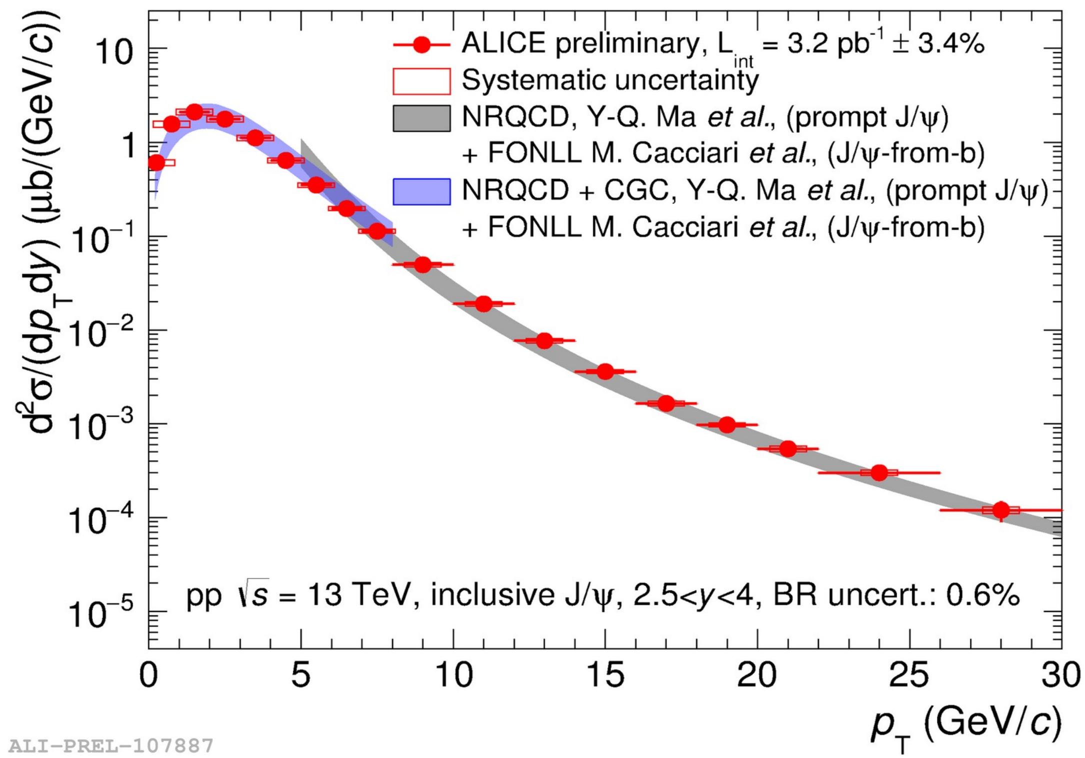
Production of charmonia in hadronic collisions



- charm and beauty quarks are produced in early hard scattering processes
- most important Feynman diagram: gluon fusion
- formation of quarkonia requires transition to a color singlet state

not pure perturbative QCD anymore, some modelling required

by now rather successful



Statistical hadronization model for charm (SHMc) including canonical thermodynamics

- selected early references:

1. P. Braun-Munzinger, J. Stachel: Phys. Lett. B 490 (2000) 196-202, nucl-th/0007059 — the beginning
2. M. Gorenstein, A.P. Kostyuk, H. Stoecker, W. Greiner, Phys.Lett.B 524 (2002) 265-272, hep-ph/0104071 — SPS/RHIC
3. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B 571 (2003) 36-44, nucl-th/0303036 — open/hidden charm
4. F. Becattini, Phys.Rev.Lett. 95 (2005) 022301, hep-ph/0503239 — multi-charm baryons
5. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl.Phys.A 789 (2007) 334-356, nucl-th/0611023 — detailing the model
6. P. Braun-Munzinger, J. Stachel: Nature 448 (2007) 302-309 — LHC predictions
7. A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys.Lett.B 652 (2007) 259-261, nucl-th/0701079 — rapidity dependence
8. P. Braun-Munzinger, J. Stachel: Landolt-Bornstein 23 (2010) 424, 0901.2500 — deconfined c quarks

- the charm balance eq. developed in 1., 2., and 3. determines the fugacity g_c

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

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

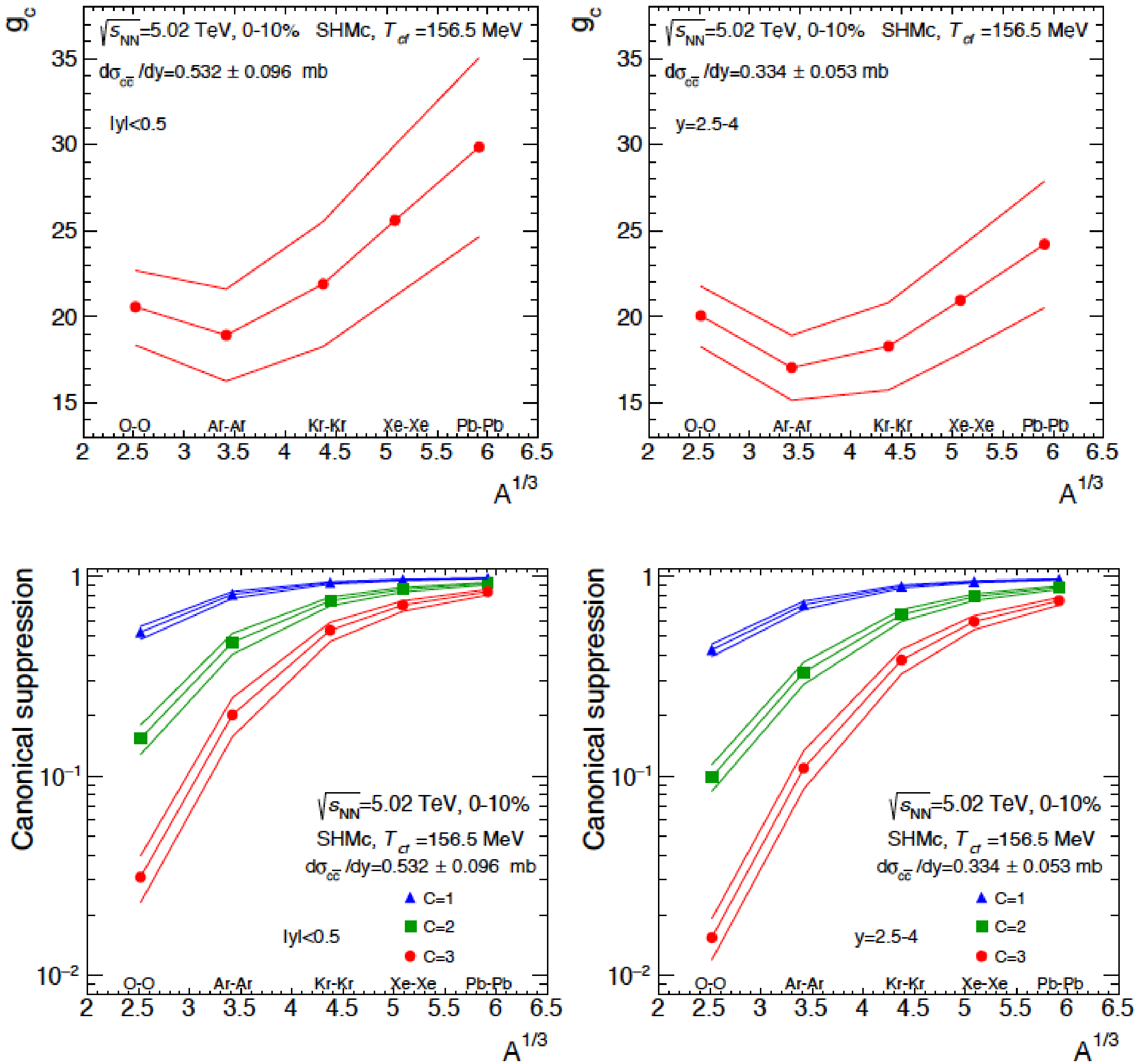
N^{th}_{oc}: # of thermal open charm hadrons

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

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

charm fugacities and canonical suppression factors

different collision systems:



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
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$	

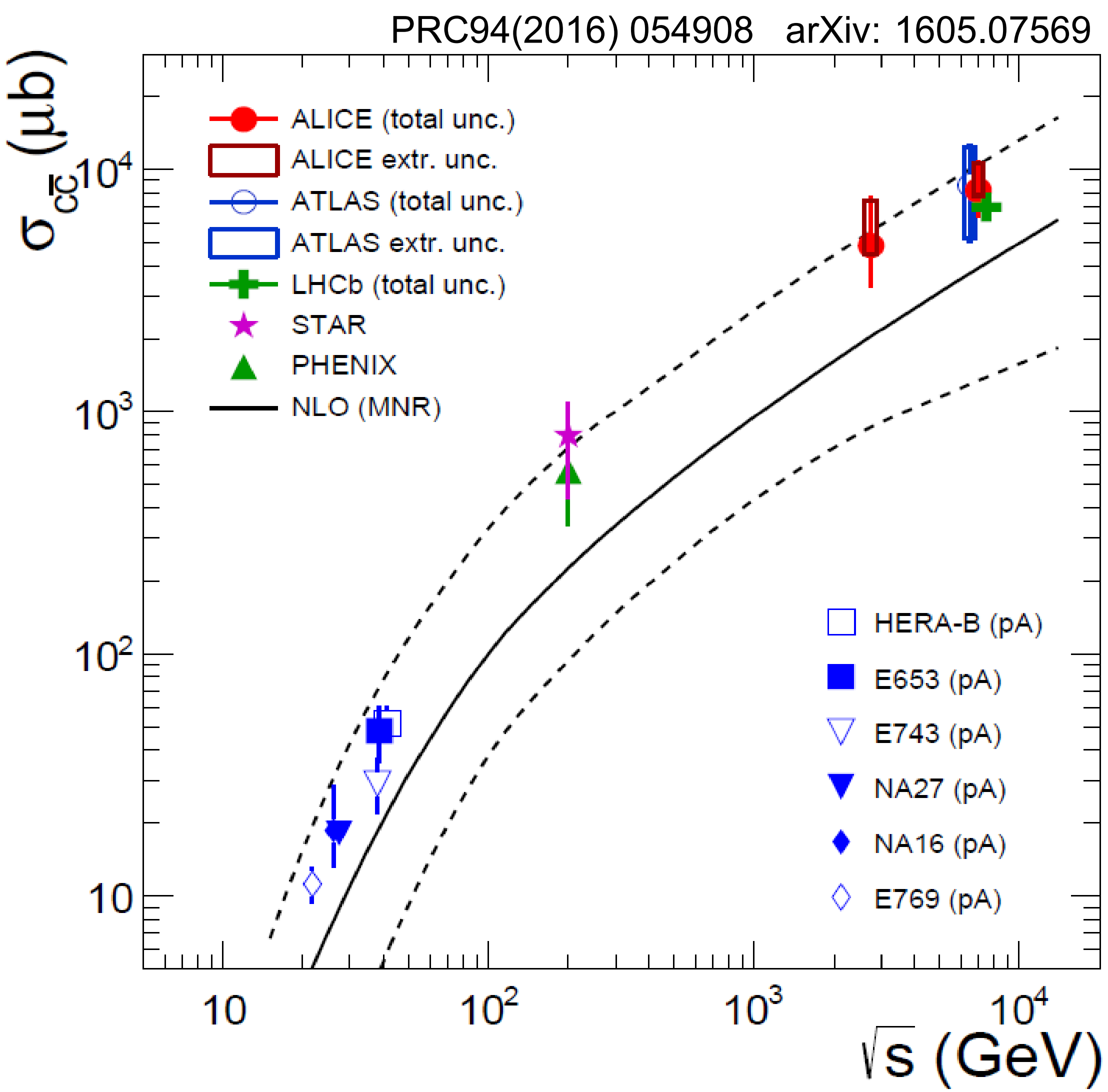
ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

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

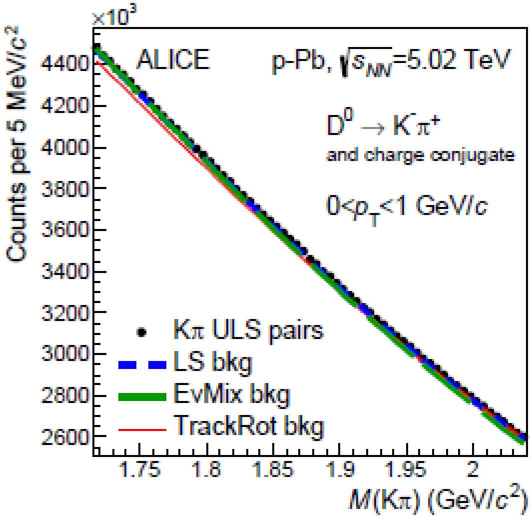
Charm production cross section in pp at LHC

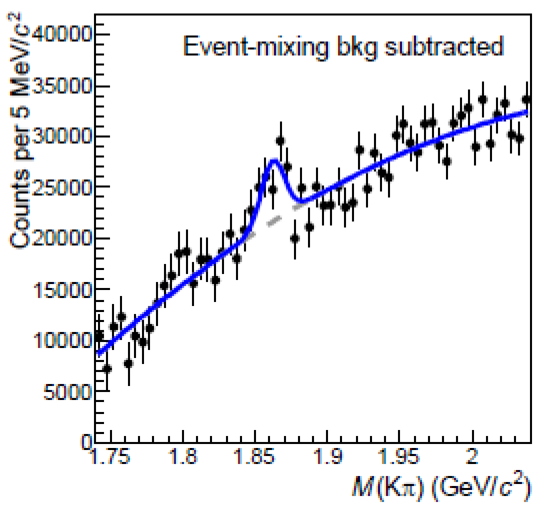


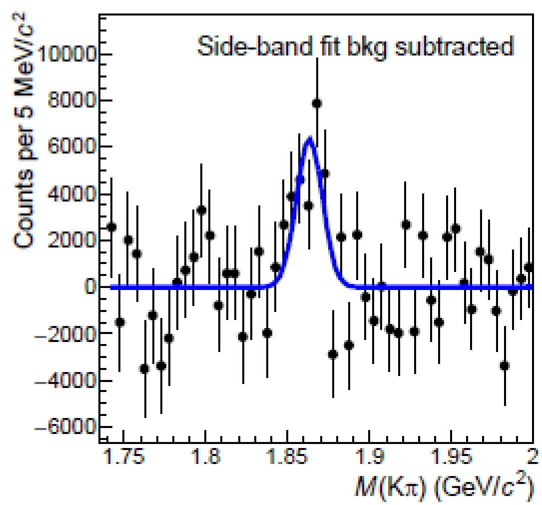
- good agreement between ALICE, ATLAS and LHCb
- still large syst. error due to extrapolation to low p_t, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of pQCD but well within uncertainty

Measurement of charm production cross section

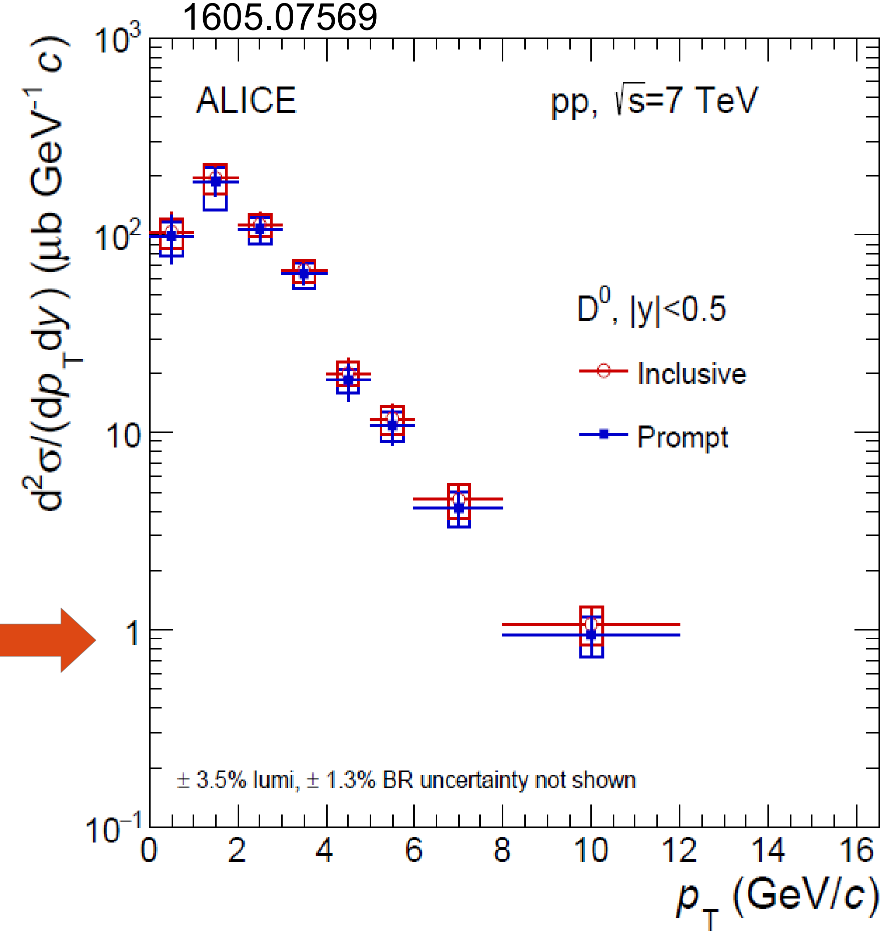
first measurement of cross section down to $p_t = 0$







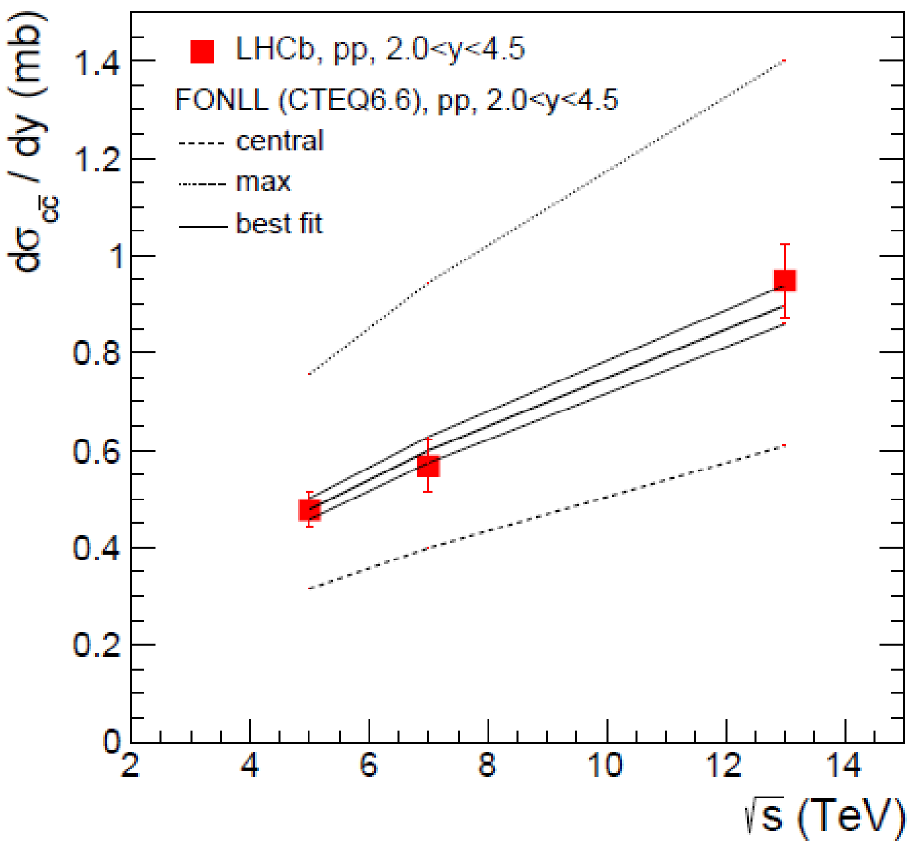
PRC94(2016) 054908 arXiv: 1605.07569

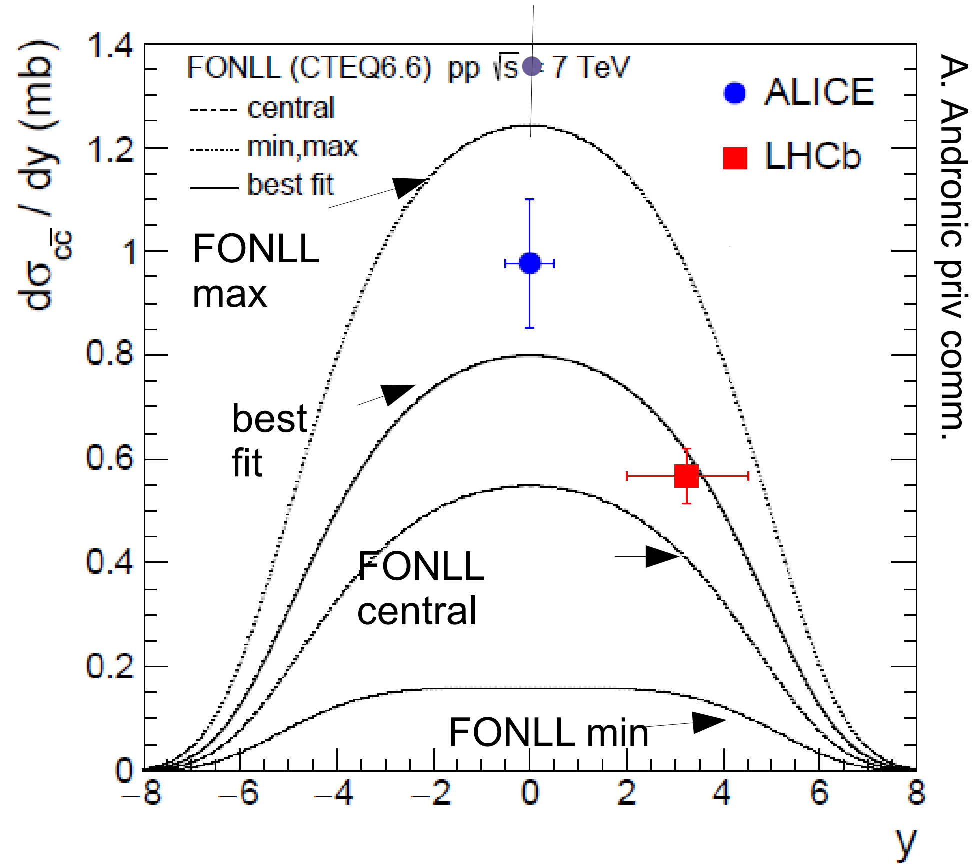


very hard struggle to deal with (irreducible) combinatorial background, successful

Baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper √s and y-interval
long. momentum measure = rapidity y: 0 (at rest in cm) to 8 (= beam momentum)

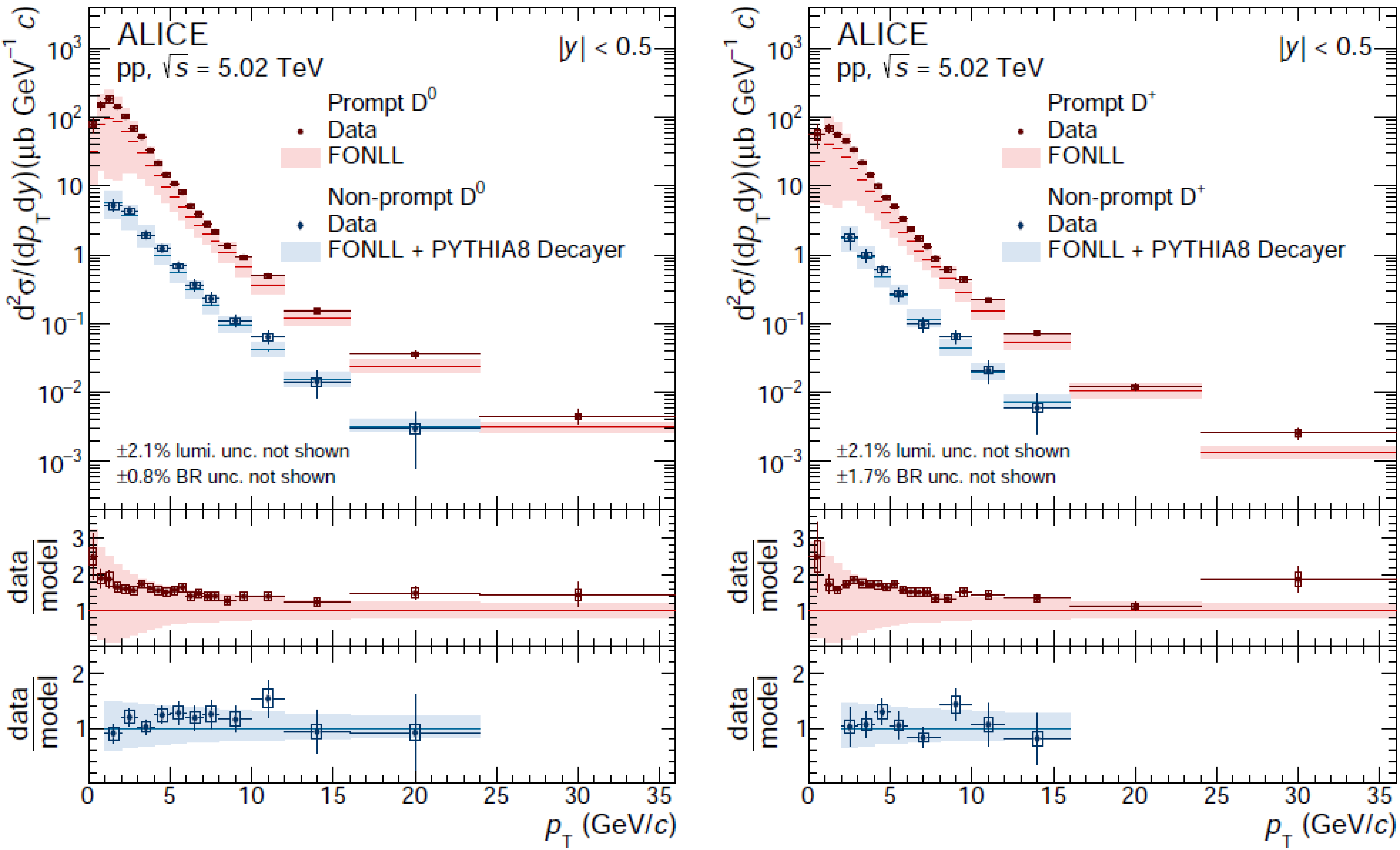




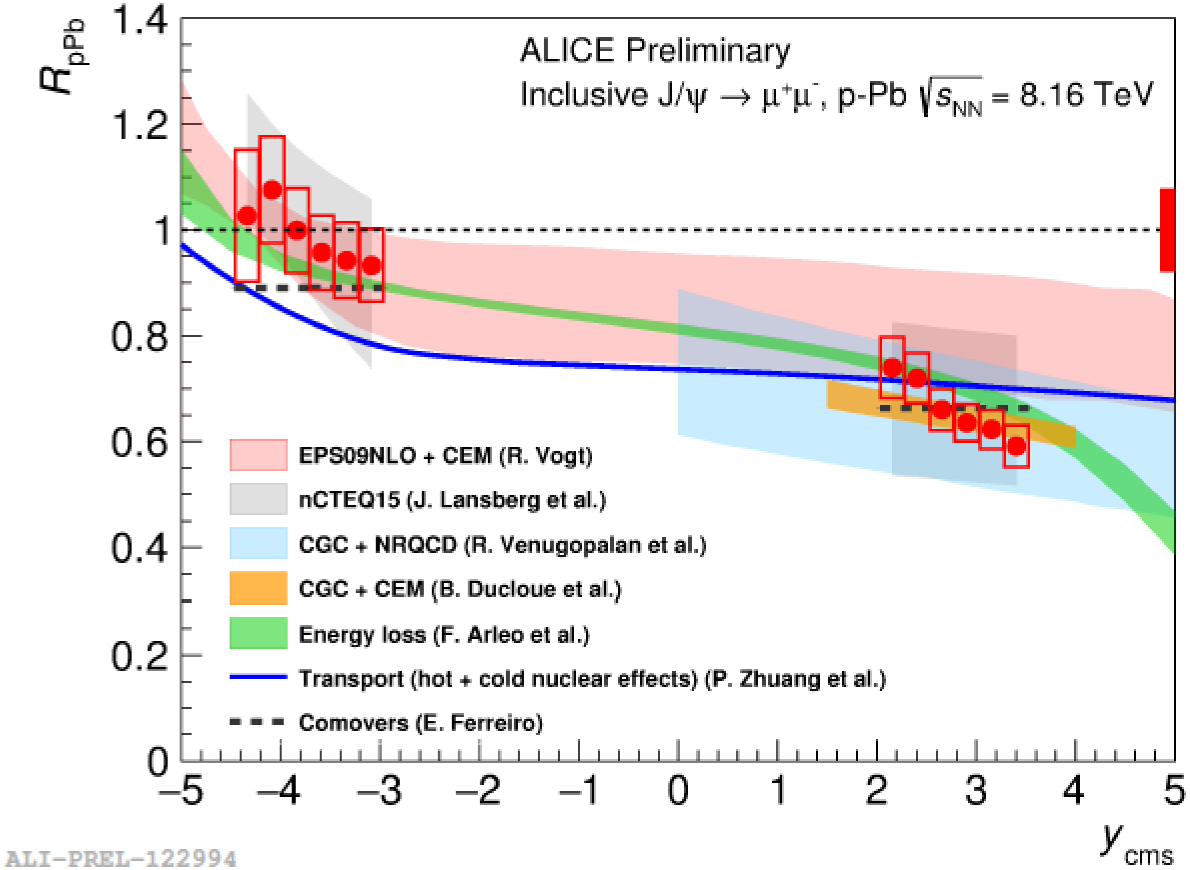
LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159 plus erratum

ALICE: 7 TeV PRC94 (2016) 054908
and 1702.00766

ALICE Collaboration, S. Acharya *et al.*, "Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons", `arXiv:2102.13601 [nucl-ex]`.



J/psi rapidity distribution in pPb compared to pp

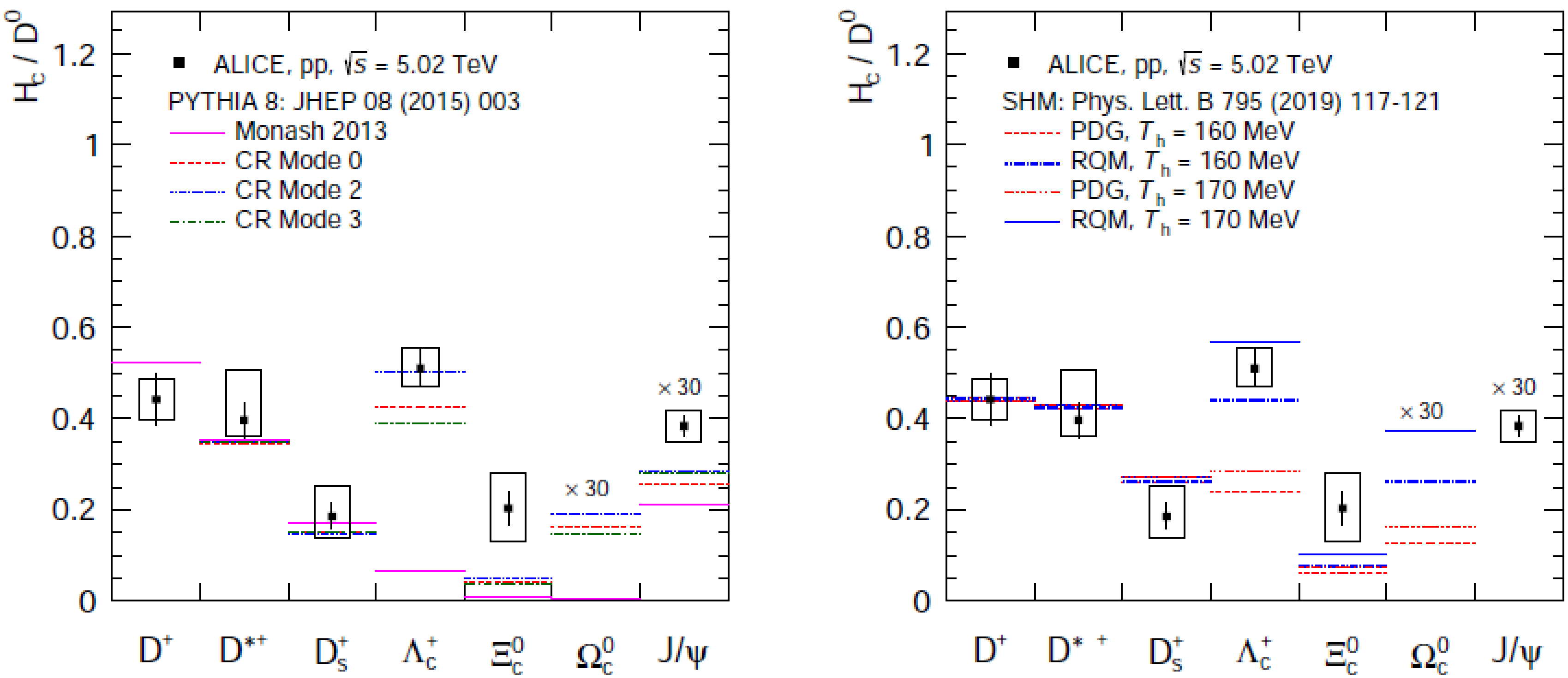


ALICE new 8.16 TeV data

pp open charm dσ/dy plus nuclear effects from D and J/ψ in pPb form current baseline for charmonia in PbPb

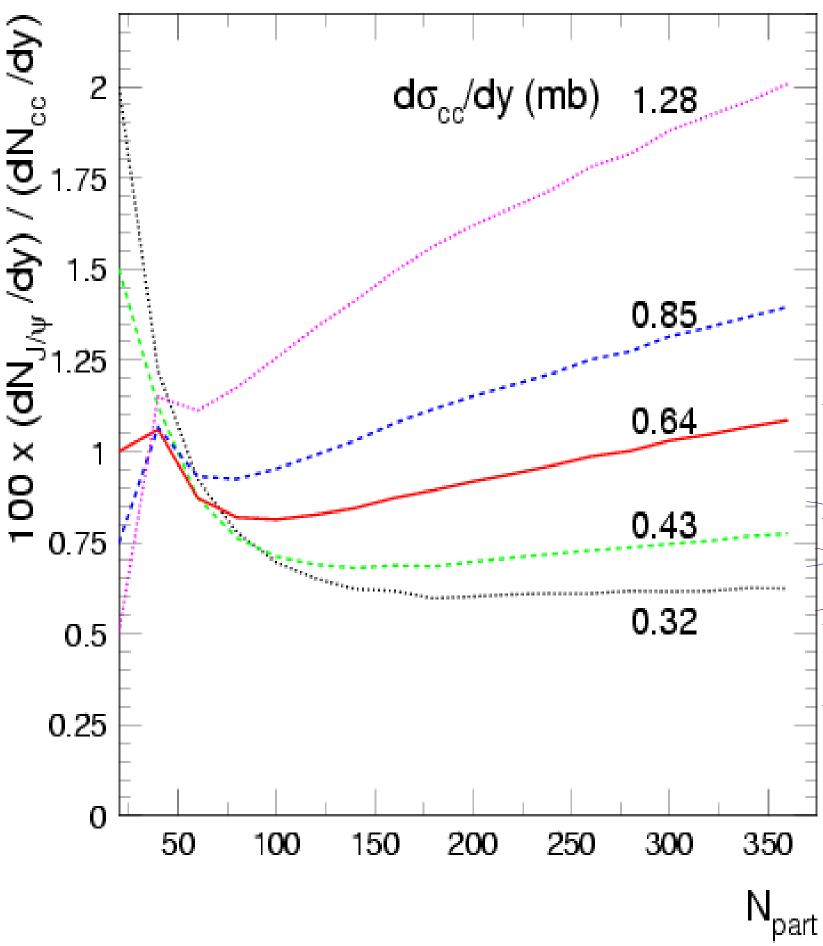
good agreement with shadowing calculations
also with energy loss models wo shadowing and CGC calculation

Fragmentation in pp collisions at LHC



Energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259



note: stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/psi enhancement

mid-y LHC 2.76 and 5.02 TeV including shadowing

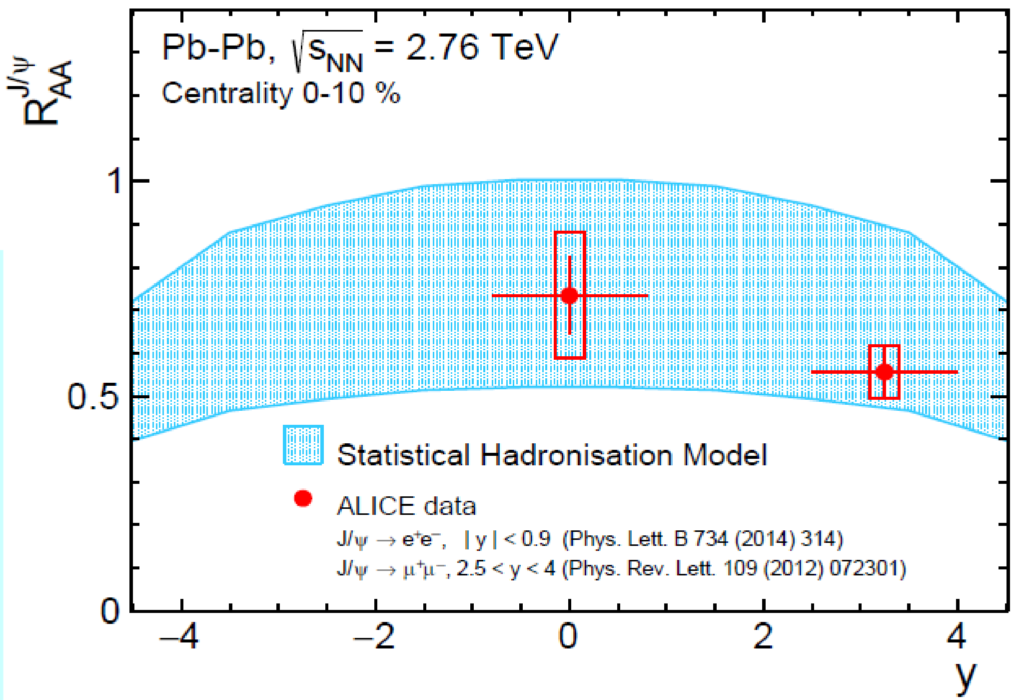
forward-y LHC 2.76 and 5.02 TeV including shadowing

Rapidity dependence of R_{AA}

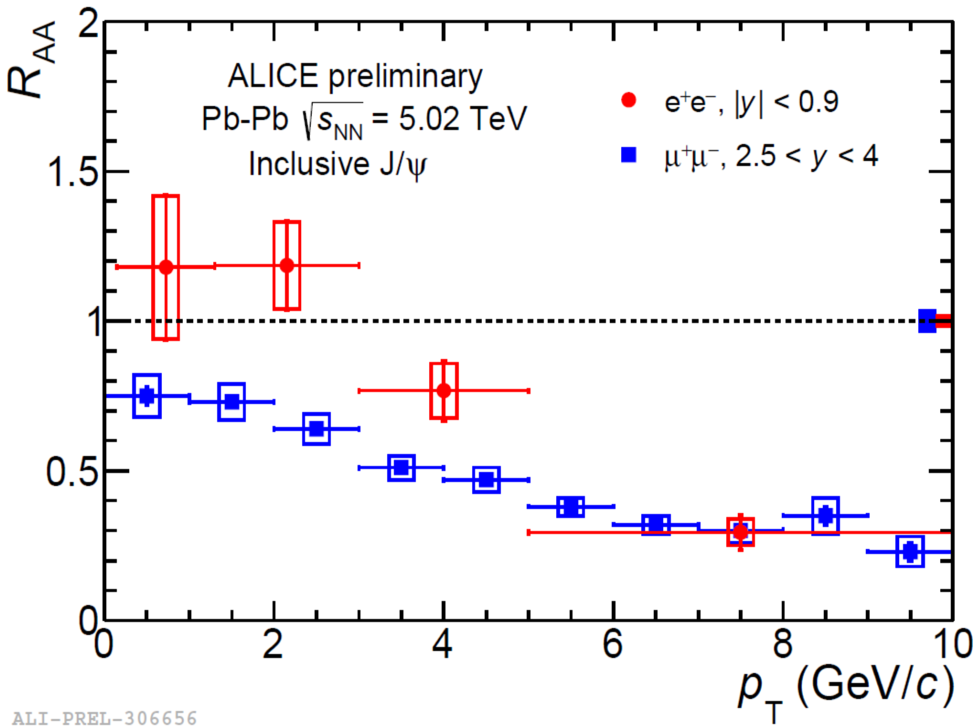
yield in PbPb peaks at mid-y where energy density is largest
?

for statistical hadronization
J/ψ yield proportional to N_c^2
- higher yield at mid-rapidity predicted in line with observation at RHIC and LHC

M. Köhler, A. Andronic, P. Braun-Munzinger, JS arXiv:1807.01236



Transverse momentum dependence

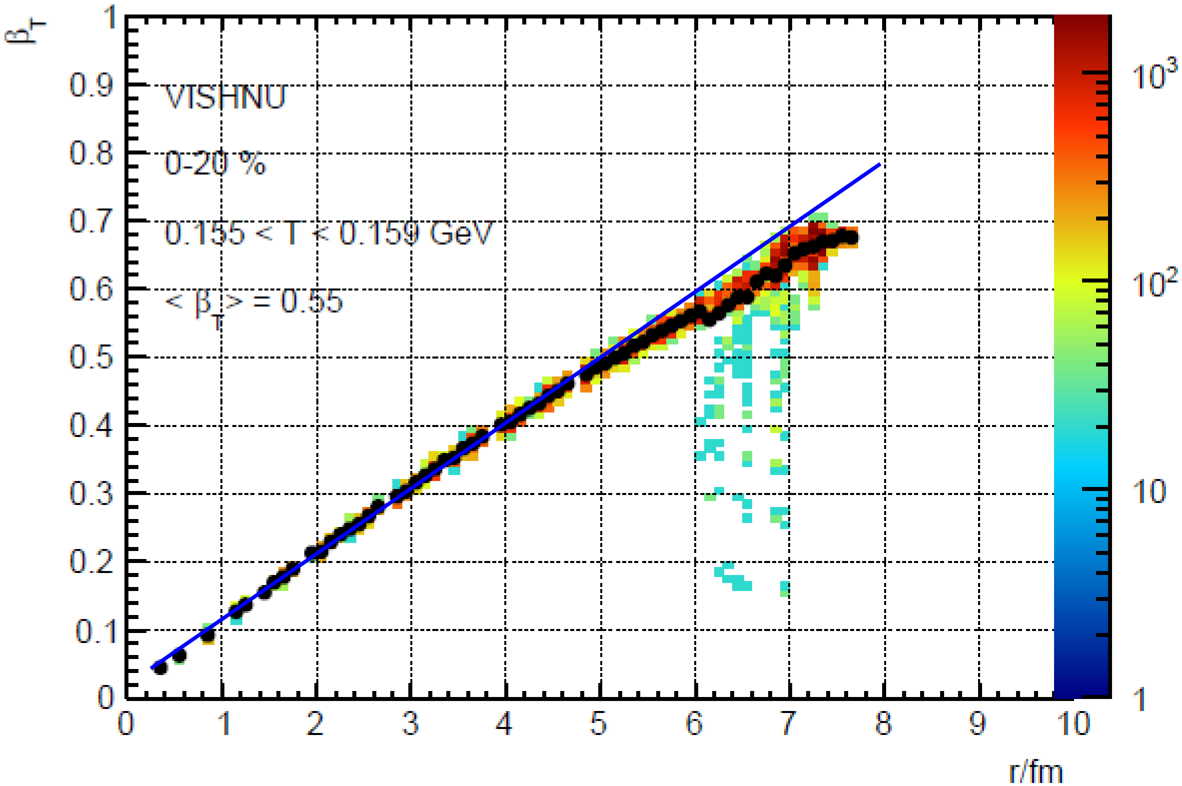


compared to pp collisions enhancement at small p_t!

– was predicted for statistical hadronization component

what does statistical hadronization have to say about p_t spectrum?

Transverse velocity profile at T_c from hydrodynamics



- velocity profile linear in r
- average transverse velocity: $\langle\beta_T\rangle = 0.55$ c

first approach: use blast wave parameterization with hydro input, i.e. linear velocity profile and correct mean velocity and $T=T_c$ and $m=m(J/\psi)$ for core and pp spectrum for corona

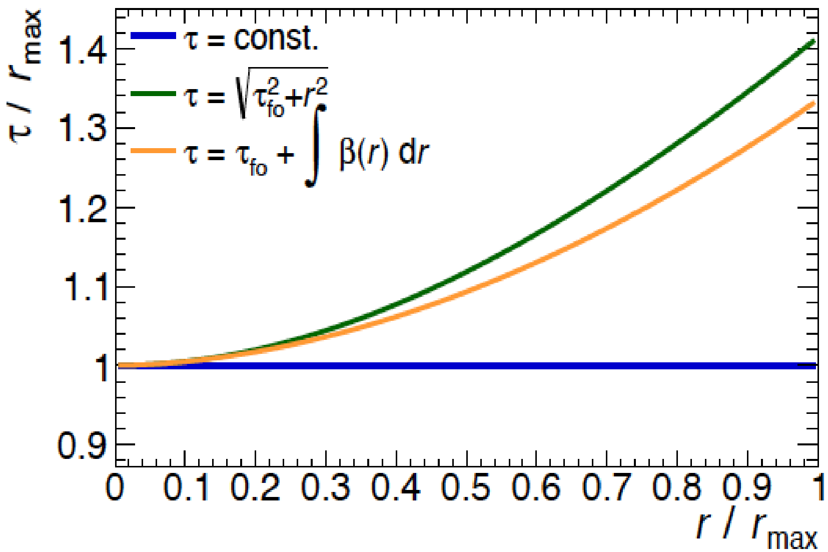
blast wave parametrization of transverse momentum spectrum

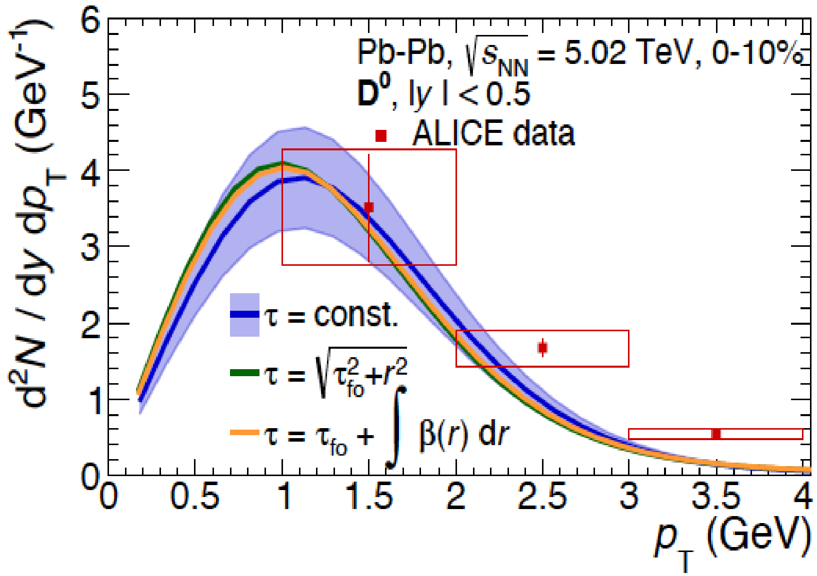
$$\frac{\mathrm{d}^2N}{2\pi p_\mathrm{T} dp_\mathrm{T} dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p)$$

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

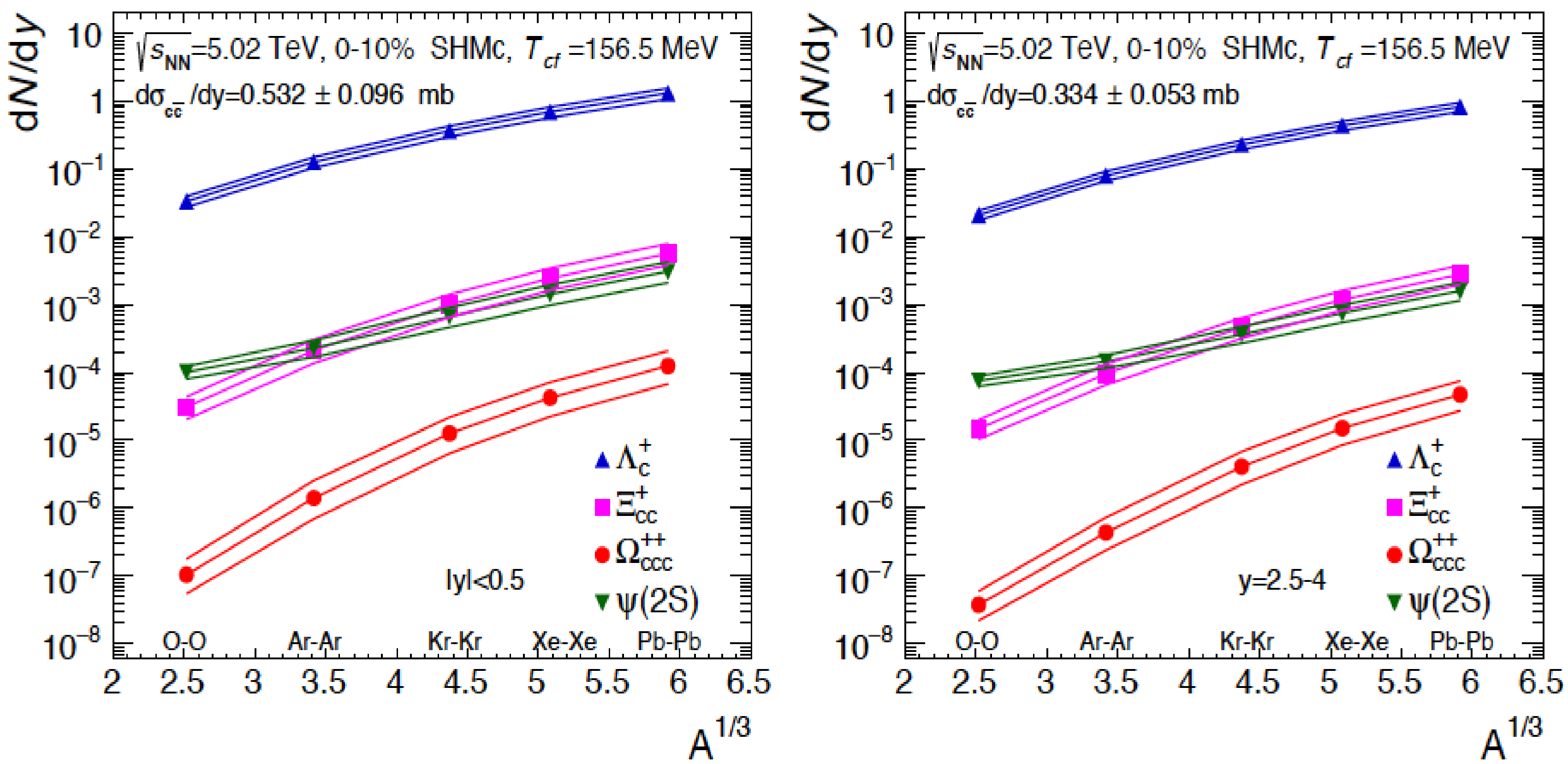
$$K_1^\mathrm{eq}(p_\mathrm{T}, u^r) = 4\pi m_\mathrm{T} I_0\left(\frac{p_\mathrm{T} u^r}{T}\right) K_1\left(\frac{m_\mathrm{T} u^\tau}{T}\right)$$

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



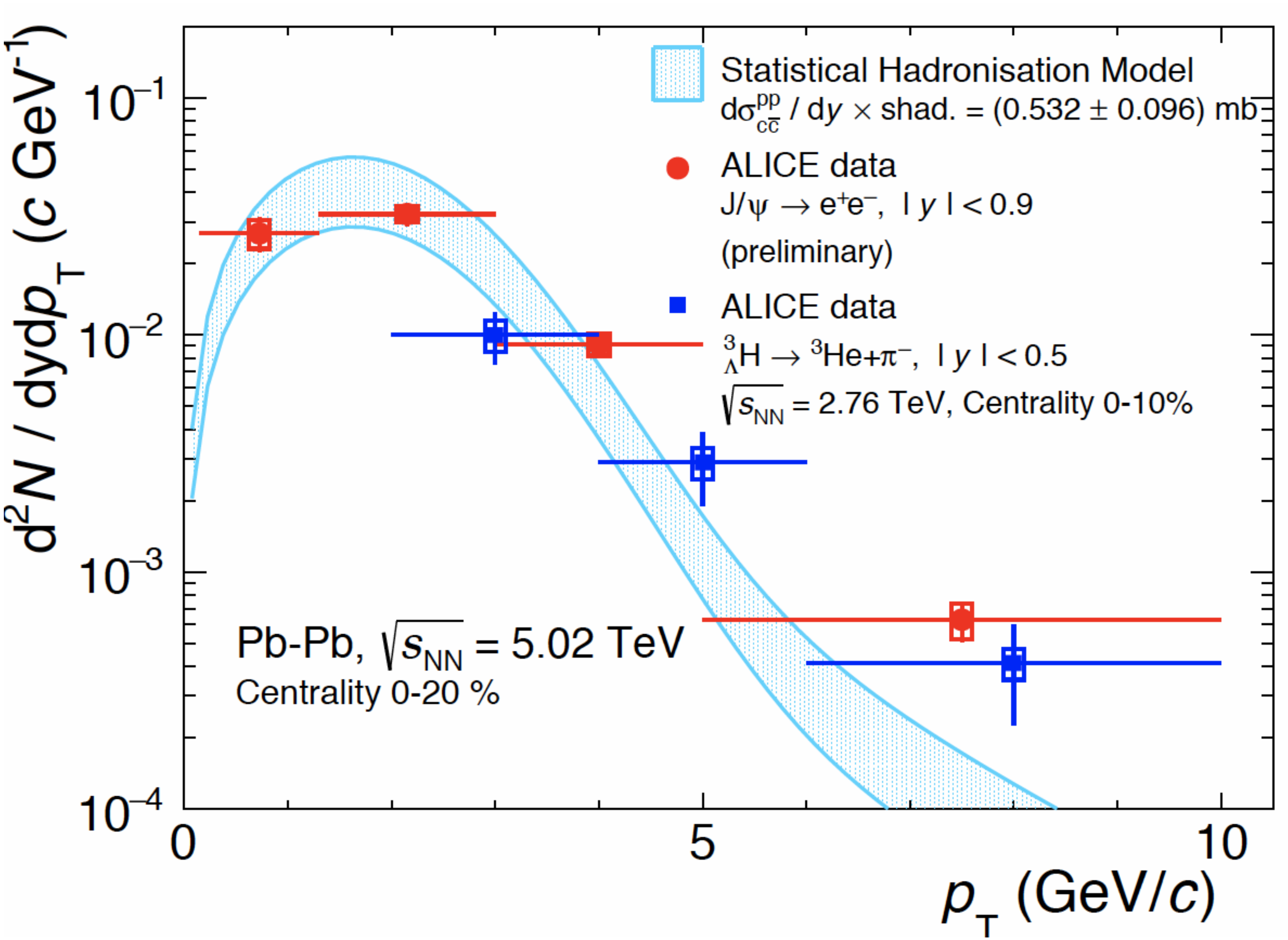


system size dependence of yields



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

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

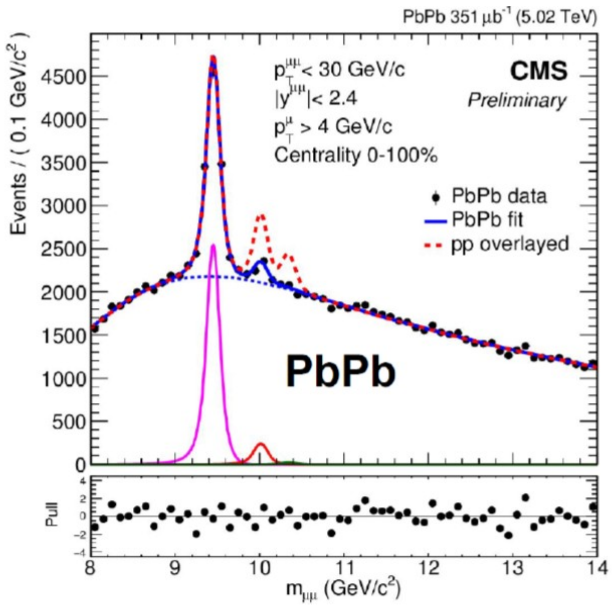


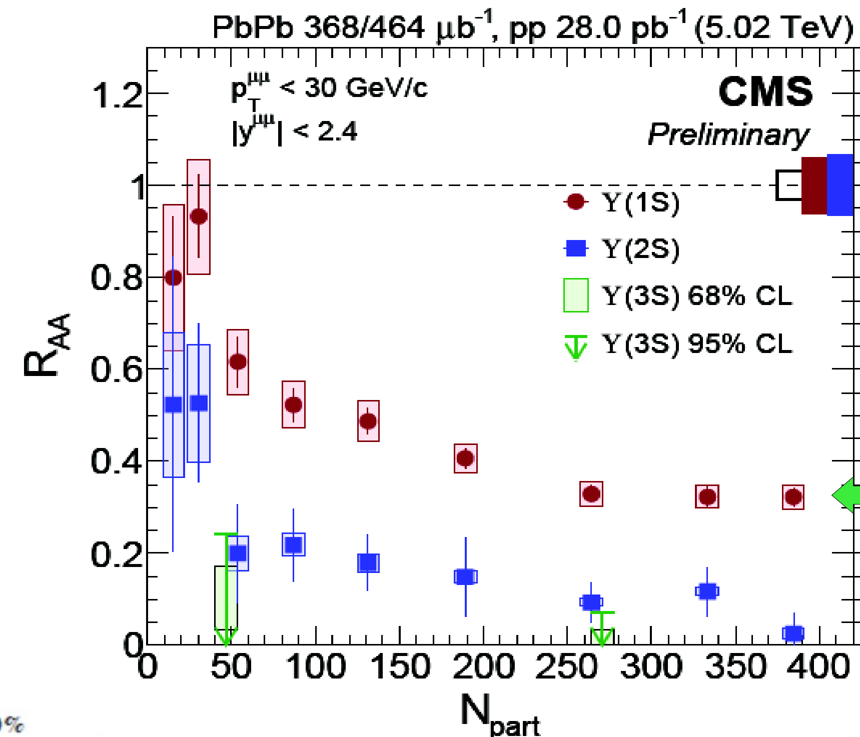
binding energies:
J/psi 600 MeV
hypertriton 2.2 MeV
Lambda S.E. 0.2 MeV

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

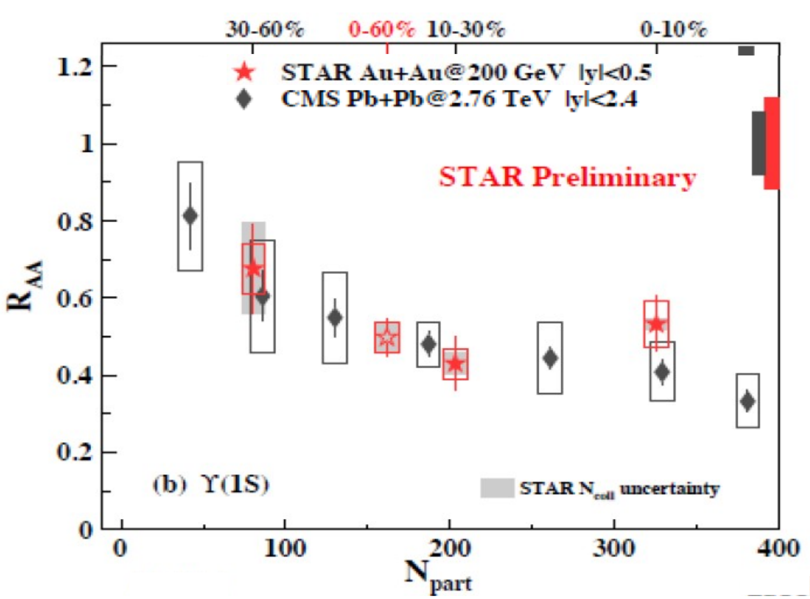
Bottomonia

Suppression of Upsilon states



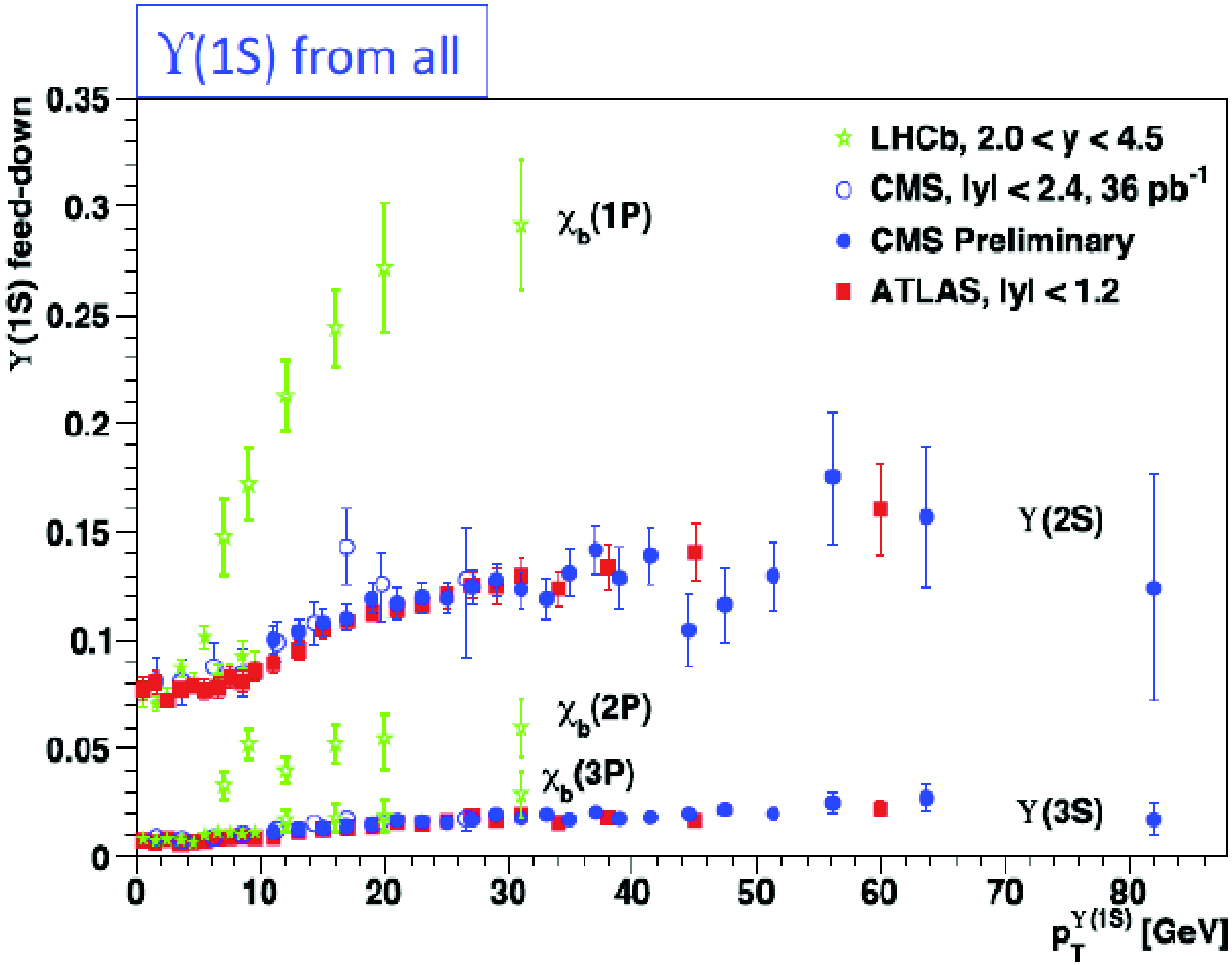


not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)

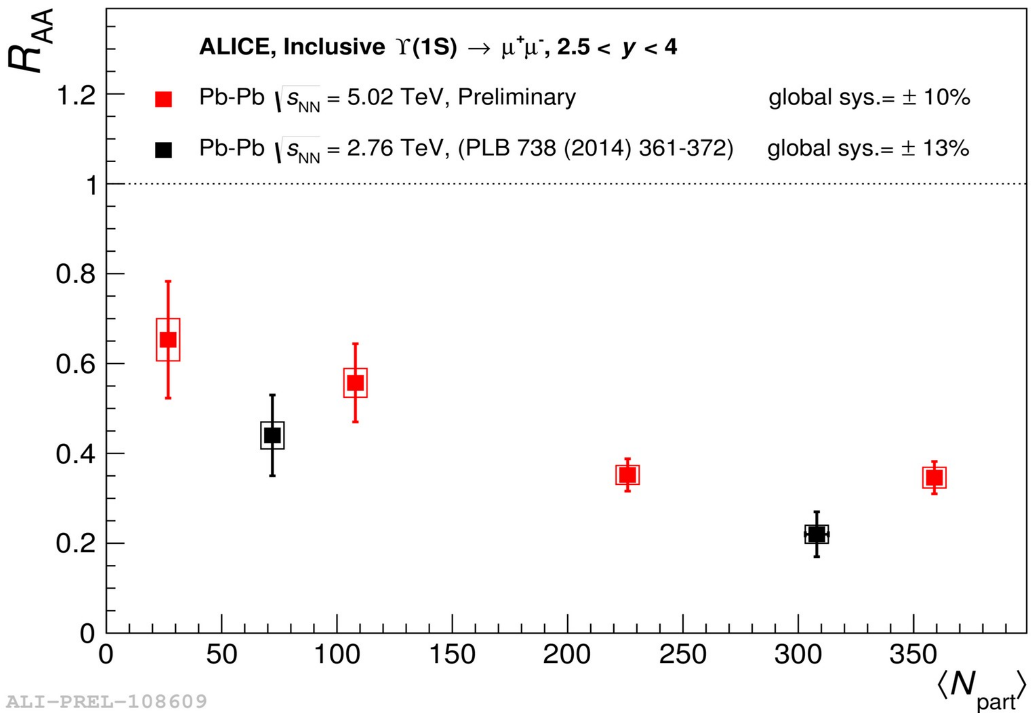


genuine Upsilon suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

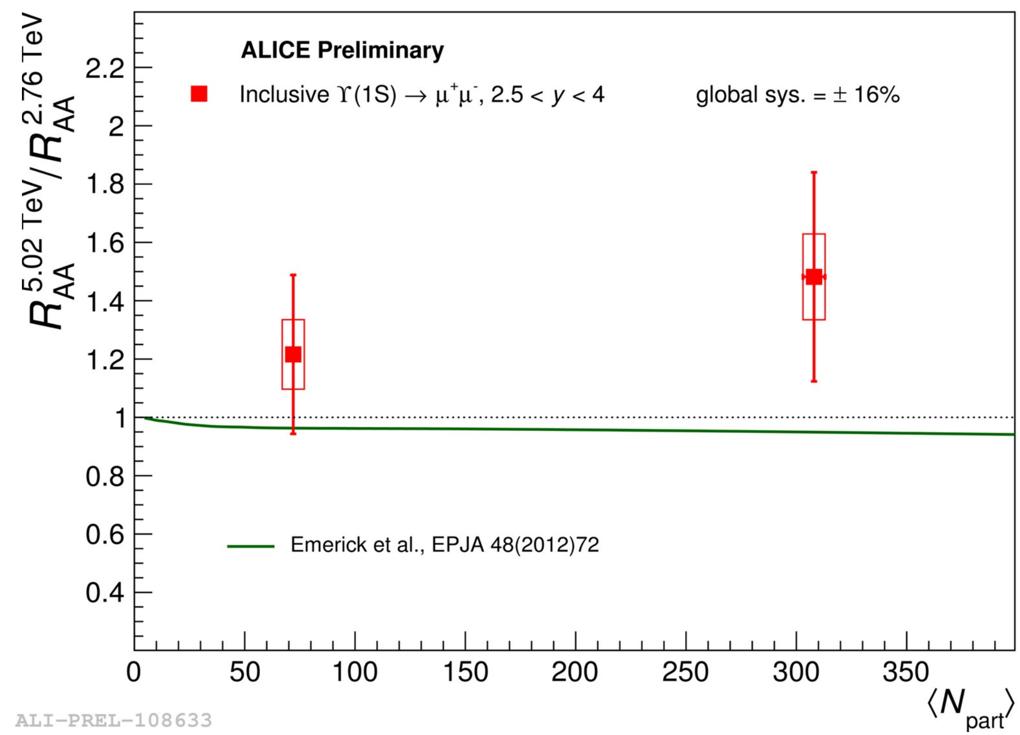
Feeding into Upsilon (1S)



Upsilon in PbPb at 5 TeV compared to 2.76 TeV



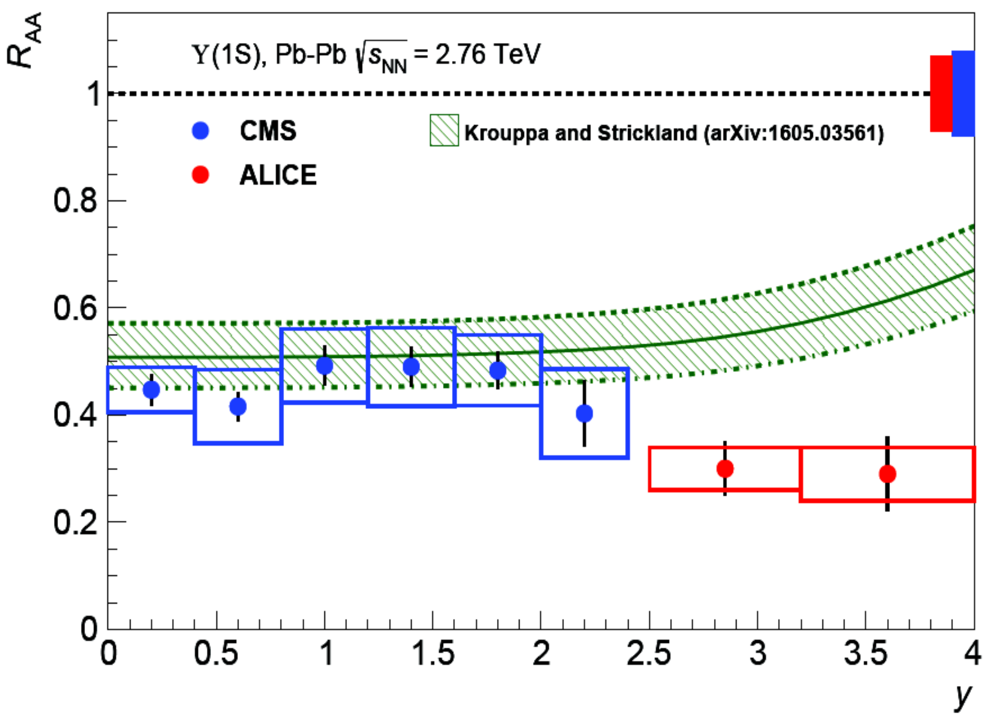
yield of Upsilon(1S) increases with beam energy

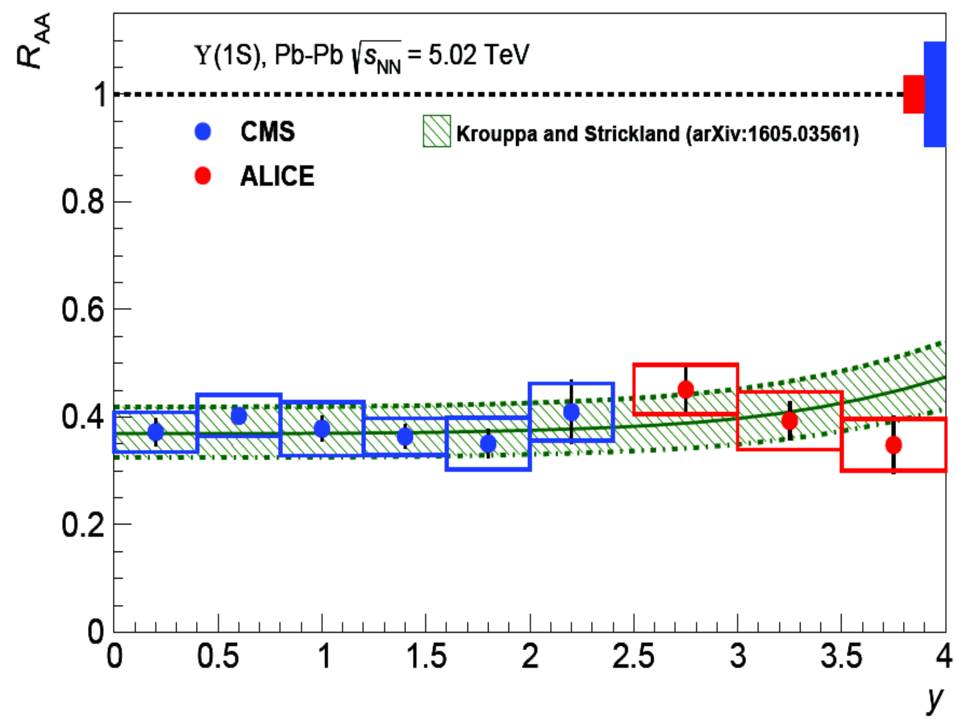


dissociation of Upsilon in a hydrodynamically medium will not produce an increase with increasing energy density

$R_{AA}^{0\text{-}90\%}(5.02\text{ TeV}) / R_{AA}^{0\text{-}90\%}(2.76\text{ TeV}) = 1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})$

Upsilon R_{AA} rapidity dependence

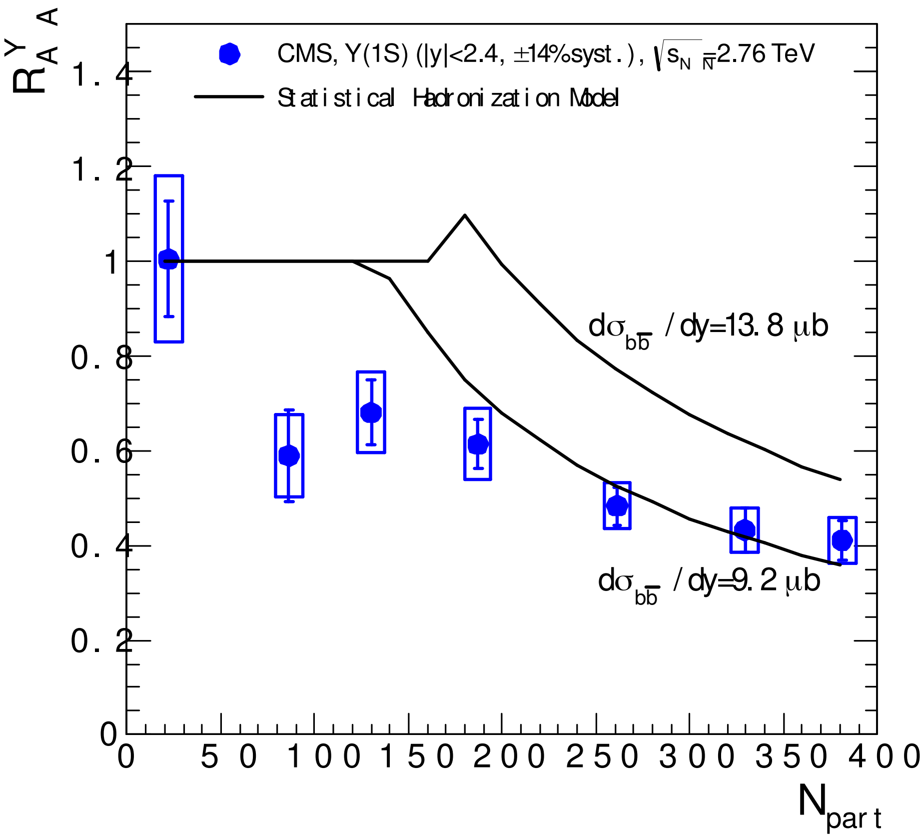


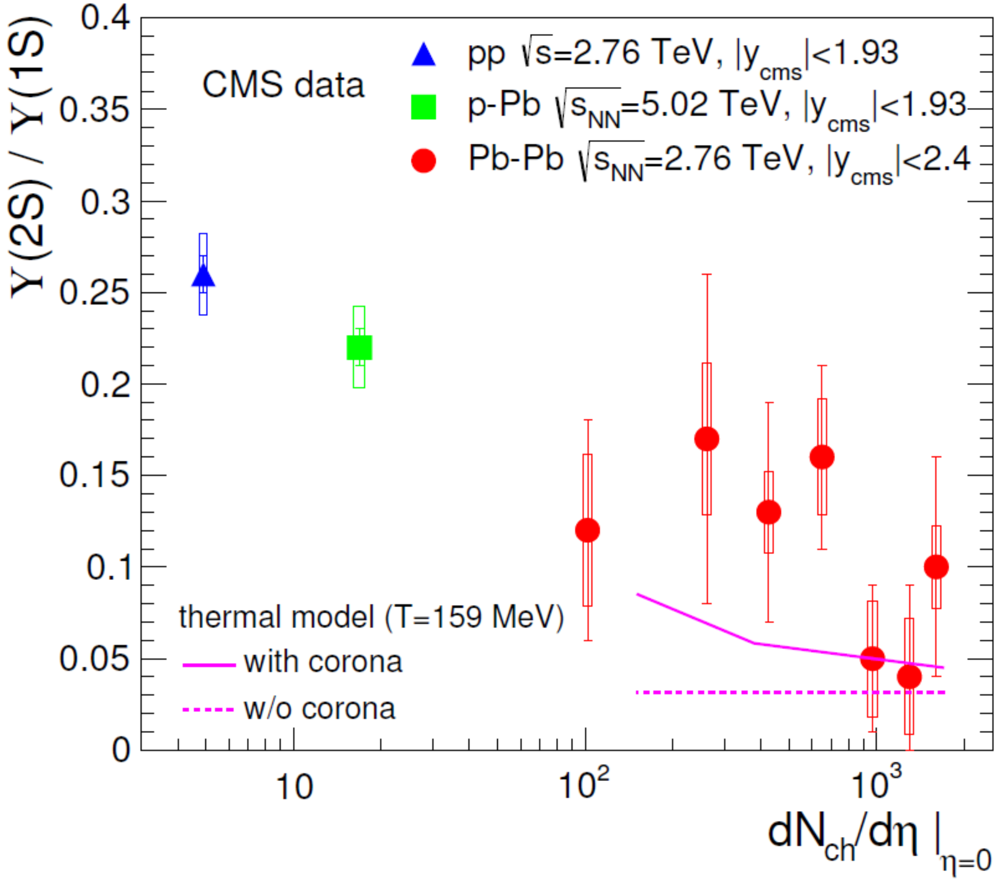


Indication: R_{AA} peaked at mid-y like for J/ψ
not in line with collisional damping in expanding medium

the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic et al.





in this picture, the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all? spectra of B
- total b-cross section in PbPb