Heavy Quarks and the QCD Phase Boundary

motivation and link to phase boundary
a wealth of results from run1/run2 at the LHC
- charmonia
- statistical hadronization vs transport
- bottomonia

work done over the past 18 years in collaboration with Peter Braun-Munzinger, Anton Andronic, Krzysztof Redlich and recently Markus Köhler

Johanna Stachel – Universität Heidelberg
EMMI Workshop 'Constraining the QCD Phase Boundary with Data from Heavy Ion Collisions'
GSI, Darmstadt, Feb. 12-14, 2018

Charmonia as probe of deconfinement

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with plasma formation

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

table from H. Satz, J. Phys. G32 (2006) 25

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

→ notion of charmonia as thermometer – sequential melting
signature of deconfinement, but no direct link to phase boundary

Charmonia and statistical hadronization

new insight (Braun-Munzinger, J.S. 2000):
QGP screens all charmonia (as proposed by Matsui and Satz), but charmonium production takes place at the phase boundary,

$\longrightarrow$ enhanced production at colliders – signal for deconfinement
production probability from thermalized charm quarks scales with N_{ccbar}^2

yields of charmonia (and open charm hadrons) directly linked to phase boundary and hadronization temperature
still probe of deconfinement

Extension of statistical model to charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (A. Andronic, P. Braun-Munzinger, J.S. or J. Cleymans, K. Redlich or F. Becattini)
- number of charm quarks fixed by a charm-balance equation containing fugacity g_c

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

and for $N_{c,\bar{c}} << 1 \rightarrow$ canonical: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and same for all other charmed hadrons

additional input parameters (beyond T, μ_b fixed from light flavor hadron yields): $V, N_{c\bar{c}}^{direct}$

- volume V fixed by $dN_{ch}/d\eta$
- $N_{c\bar{c}}^{direct}$ from data (or pQCD where data are lacking)
- causally connected region – use 1 unit y (but tested a range)
- core-corona: treat overlap in the tails of nuclear density distribution as pp physics

Alternative - generation and formation in QGP

implementation of screening into space-time evolution of the fireball

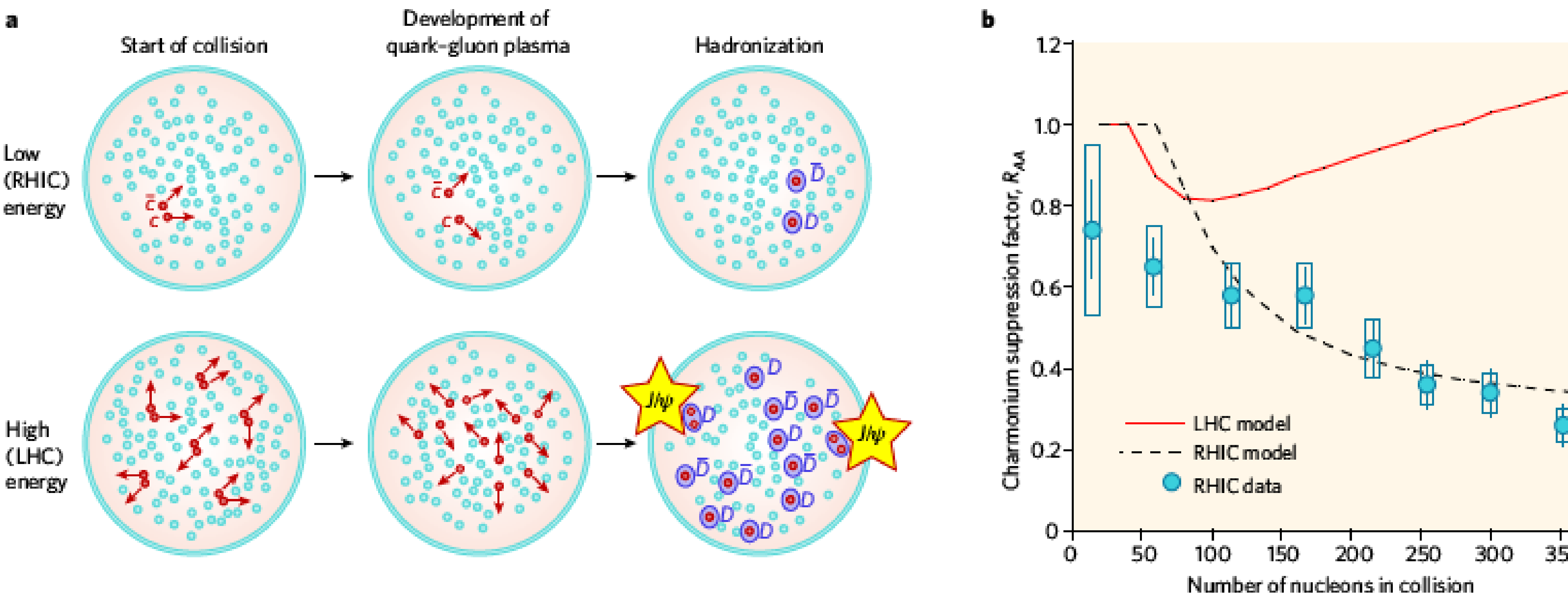
→ continuous destruction and (re)generation in QGP

Thews et al., 2001, Rapp et al. 2001, Gorenstein et al. 2001, P.F. Zhuang et al. 2005

enhancement at colliders possible

notion of hadron-like states in QGP
make use of modified spectral functions and gluon distribution
again no direct link to phase boundary

Quarkonium as a probe for deconfinement at the LHC
the statistical hadronization picture



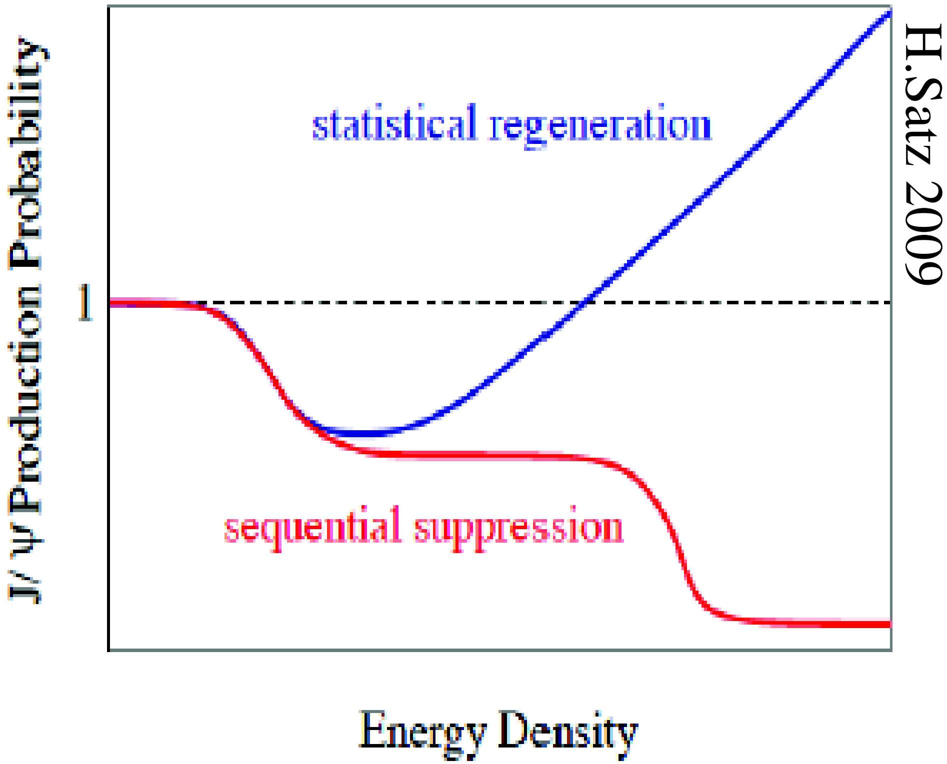
charmonium enhancement as fingerprint of deconfinement at LHC energy - a prediction!

Braun-Munzinger, J.S. Phys. Lett. B490 (2000) 196

Andronic, Braun-Munzinger, Redlich, J.S., Phys. Lett. B652 (2007) 659

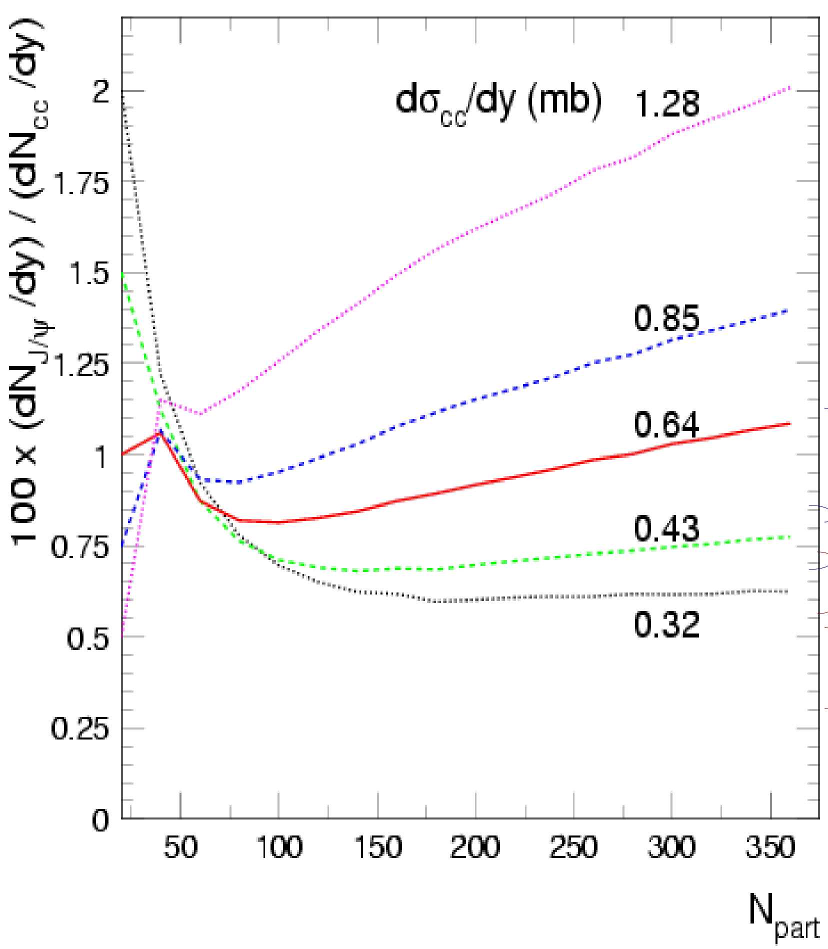
Expectations for LHC

2 possibilities:



Expectations for LHC from measured ccbar cross section in pp collisions

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



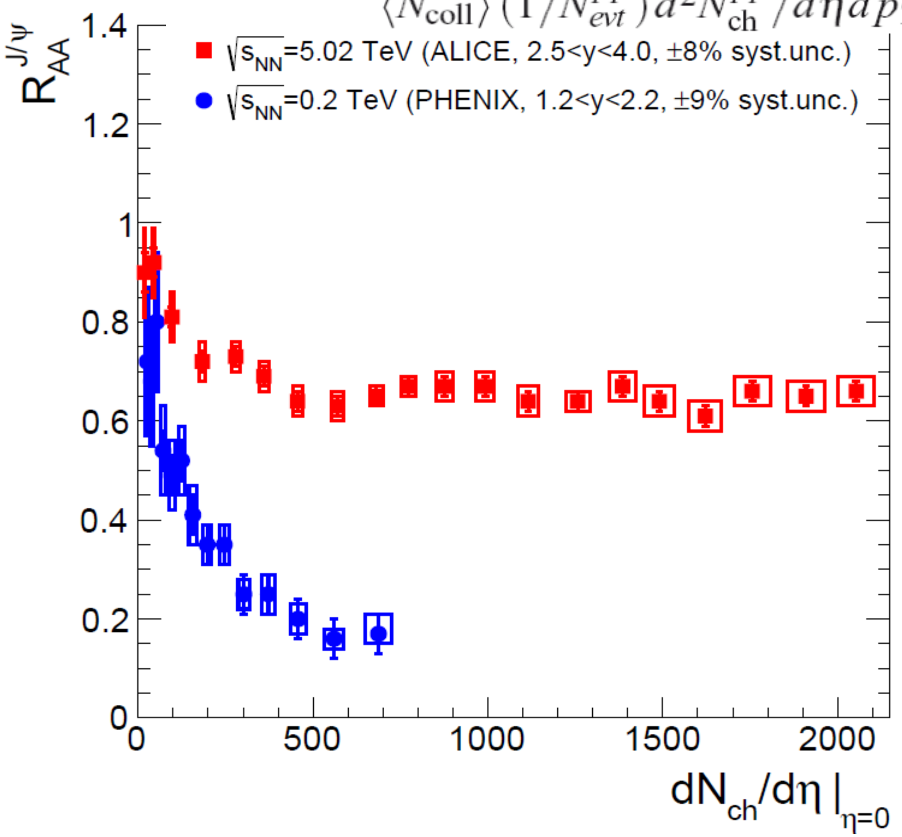
mid-y LHC 2.76 and 5.02 TeV including shadowing

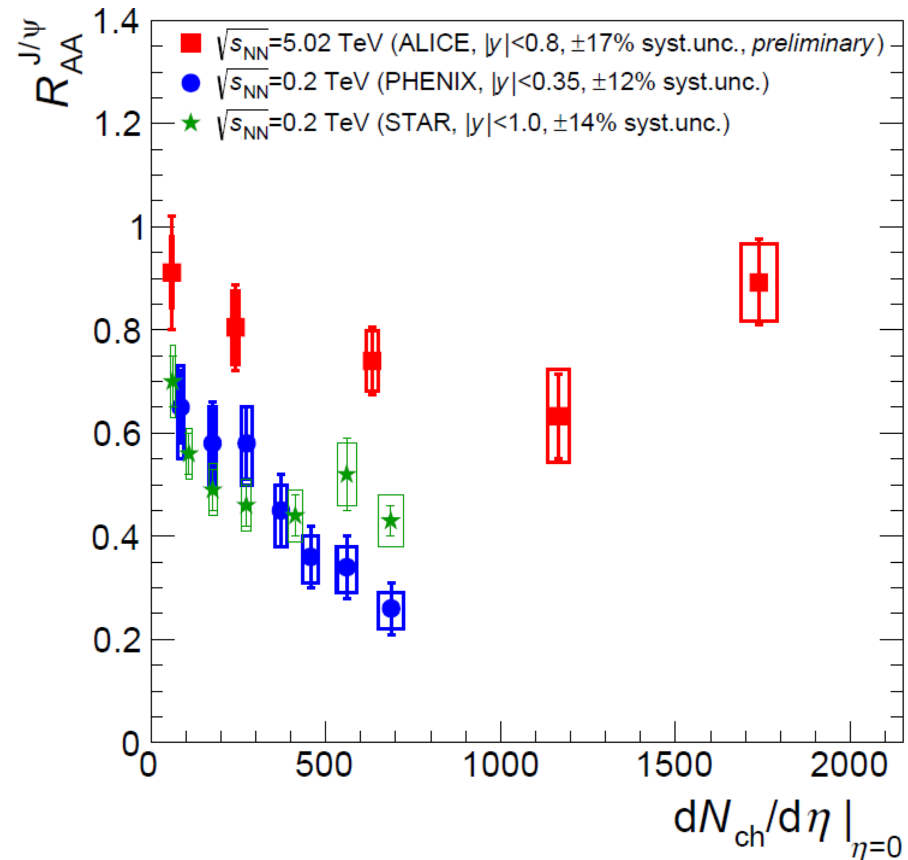
forward-y LHC 2.76 and 5.02 TeV including shadowing

measured ccbar cross sections at appropriate rapidity by ALICE and LHCb and shadowing from measured J/psi production in pPb collisions compared to pQCD

J/ψ production in PbPb collisions: LHC rel. to RHIC

$$R_{AA}(p_T) = \frac{(1/N^{AA}_{evt})\, d^2N^{AA}_{ch}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N^{pp}_{evt})\, d^2N^{pp}_{ch}/d\eta dp_T}$$



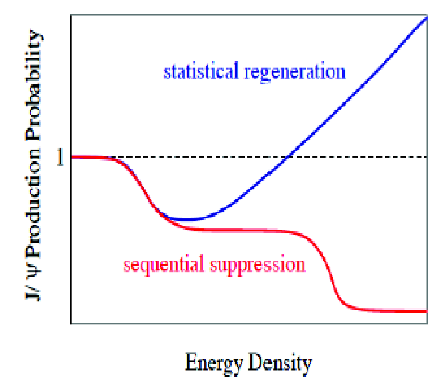


energy density -->

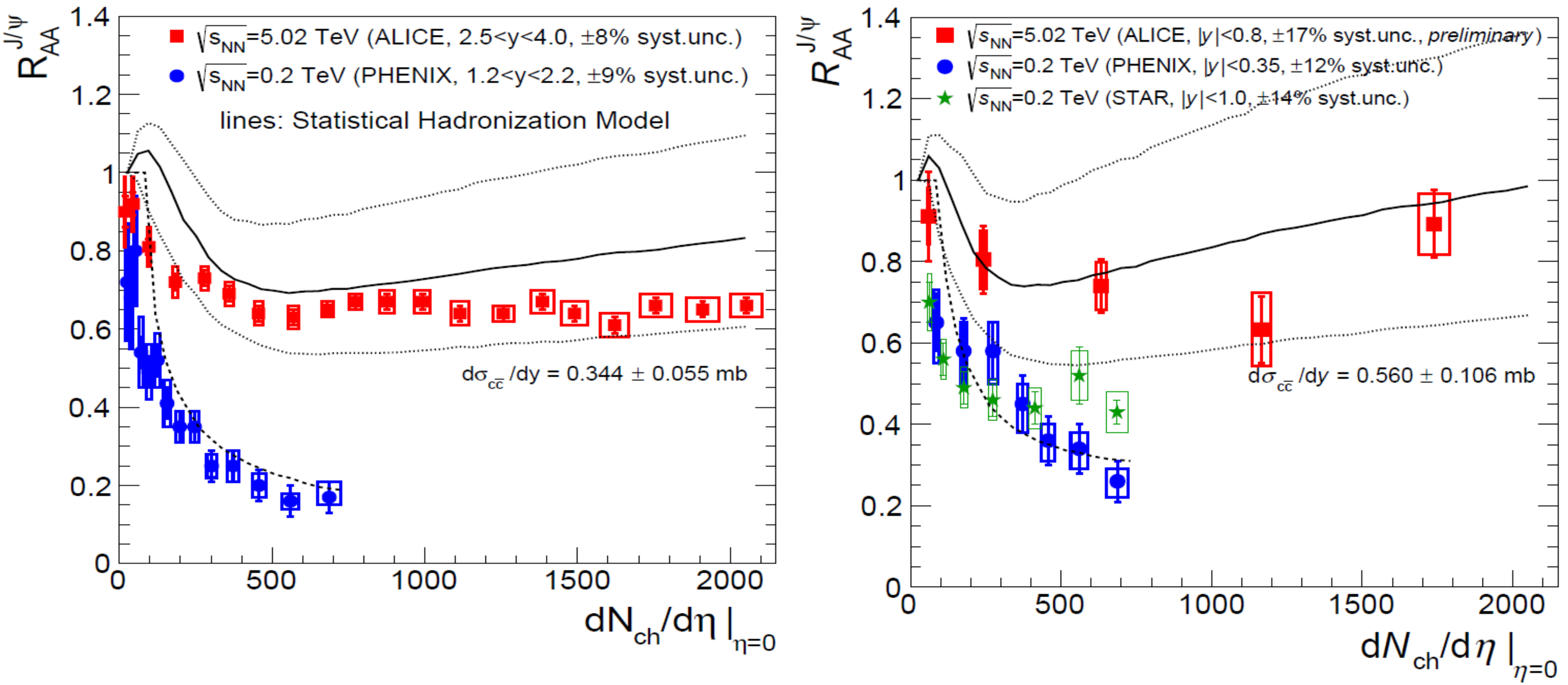
melting scenario not observed

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, shadowing in Pb

Attempt to determine Debye mass from data

J/ψ formation via statistical hadronization at T_c implies in classical picture:

$\lambda_D < r_{J/\psi} \simeq 0.5$ fm at T = 156 MeV or $\omega_D/T > 2.5$

can compare to theory:

quite ok

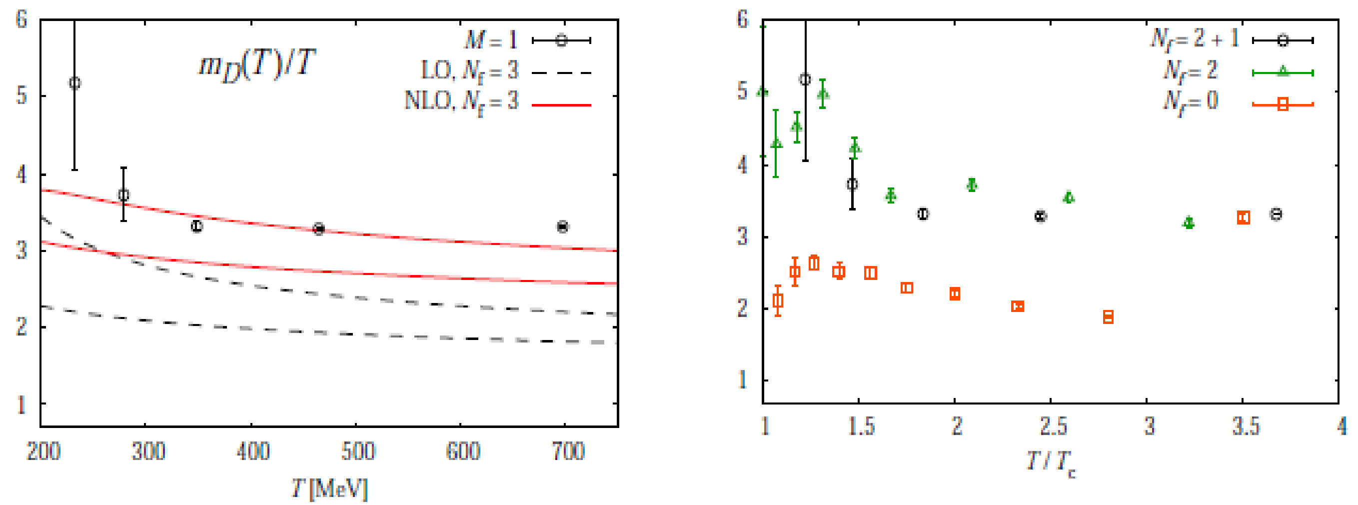


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, where μ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for 2 + 1-flavor QCD as $T_c \sim 190$ MeV.

arXiv:1112.2756 WHOT-QCD Coll.

Attempt to determine Debye mass from data

J/ψ formation via statistical hadronization at T_c implies in classical picture:

$\lambda_D < r_{J/\psi} \simeq 0.5$ fm at T = 156 MeV or $\omega_D/T > 2.5$

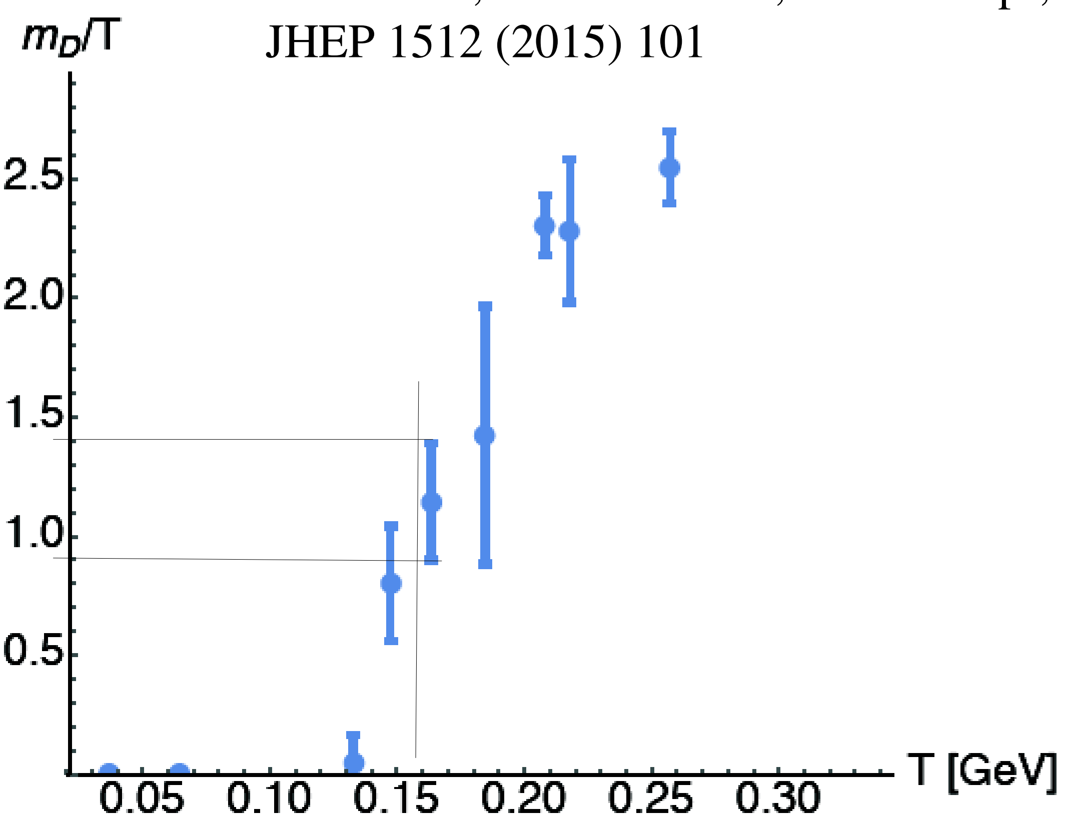
compare to recent finite temperature lQCD potential result:

- value at T_c lower
- systematics?
- and: lattice potential has real and imaginary part, both contribute to screening

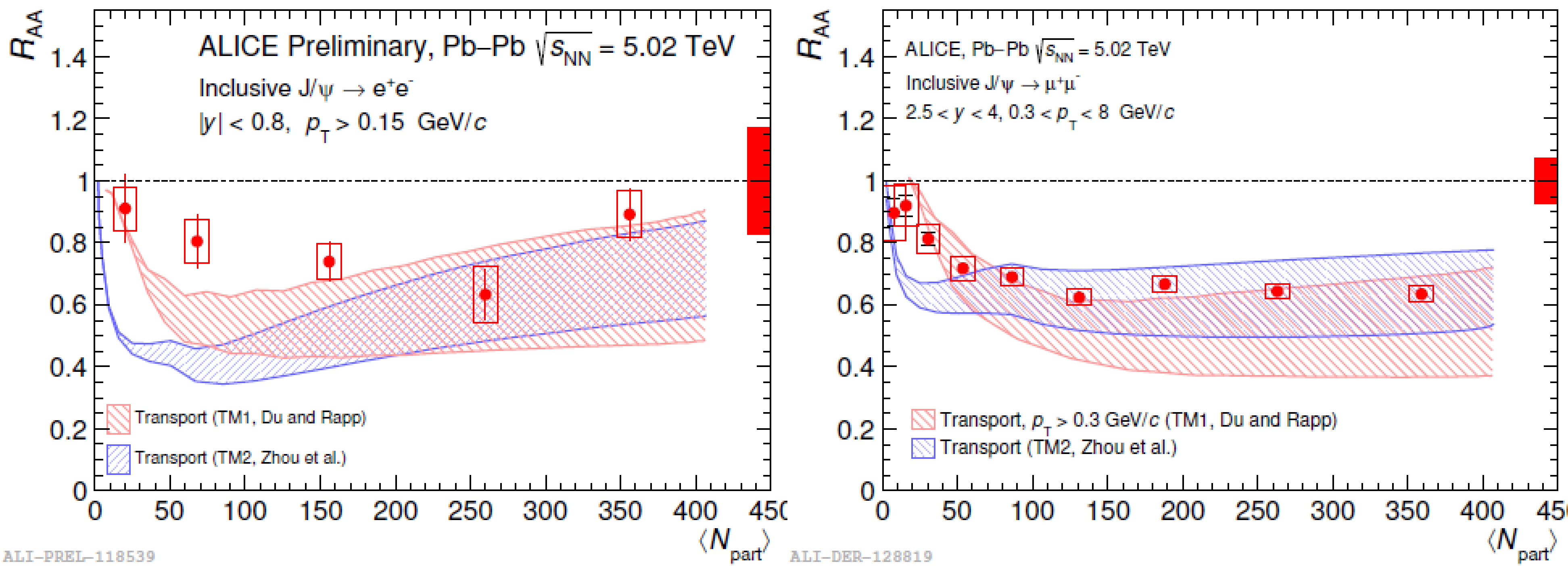
other observable to determine λ_D ?

e.g. ψ' vs J/ψ

Y. Burnier, O. Kaczmarek, A. Rothkopf, JHEP 1512 (2015) 101



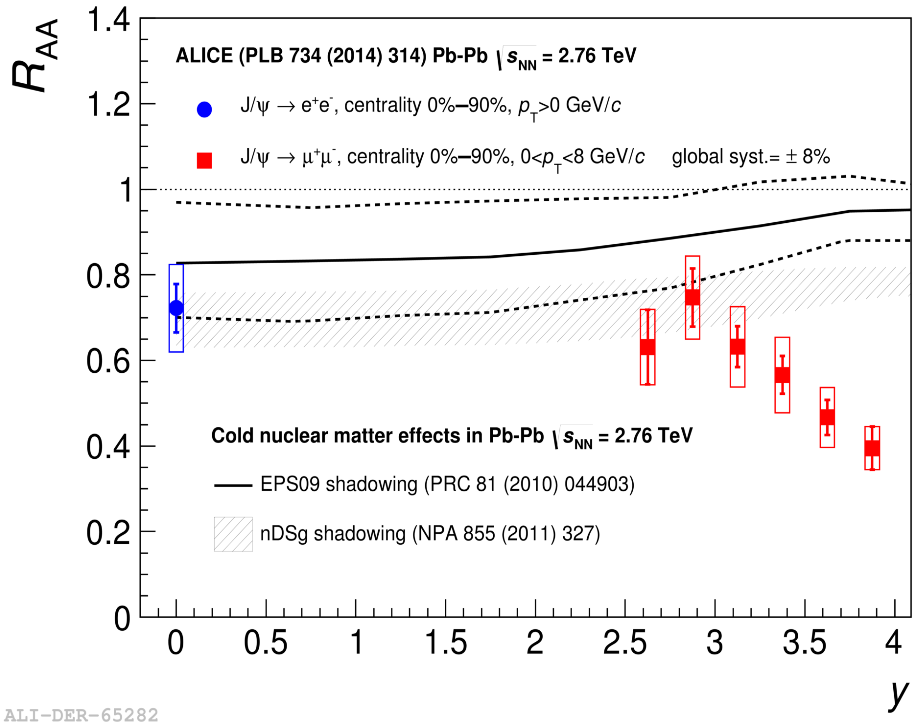
J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV compared to transport models



ALICE, PLB 766 (2017) 212

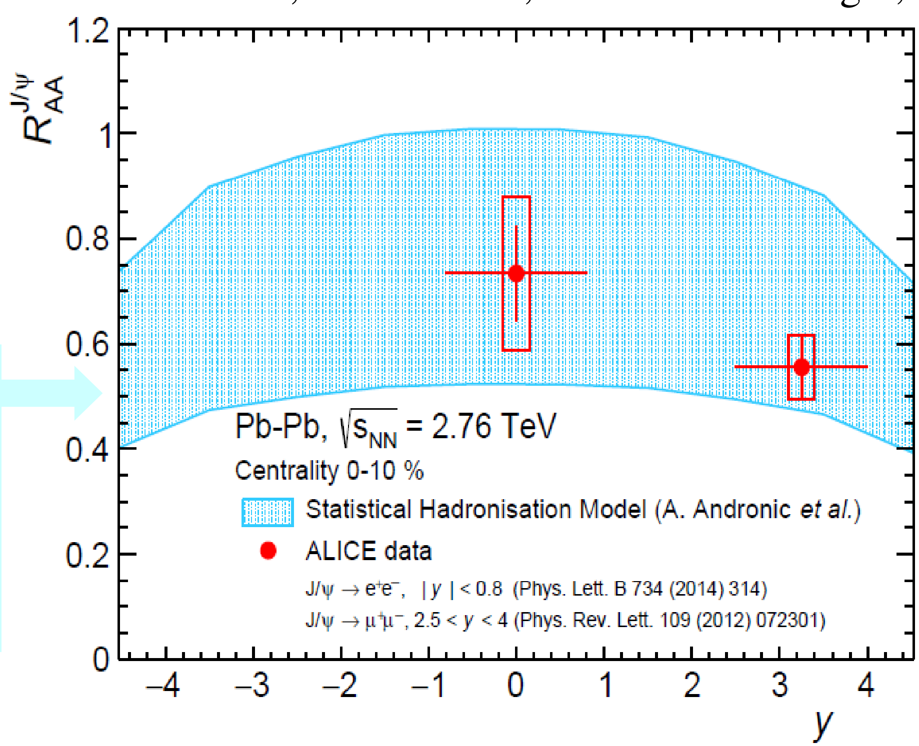
transport models also in line with R_{AA}
but a much larger open charm cross section used and a smaller uncertainty were used in these calculations

Rapidity dependence of R_{AA}



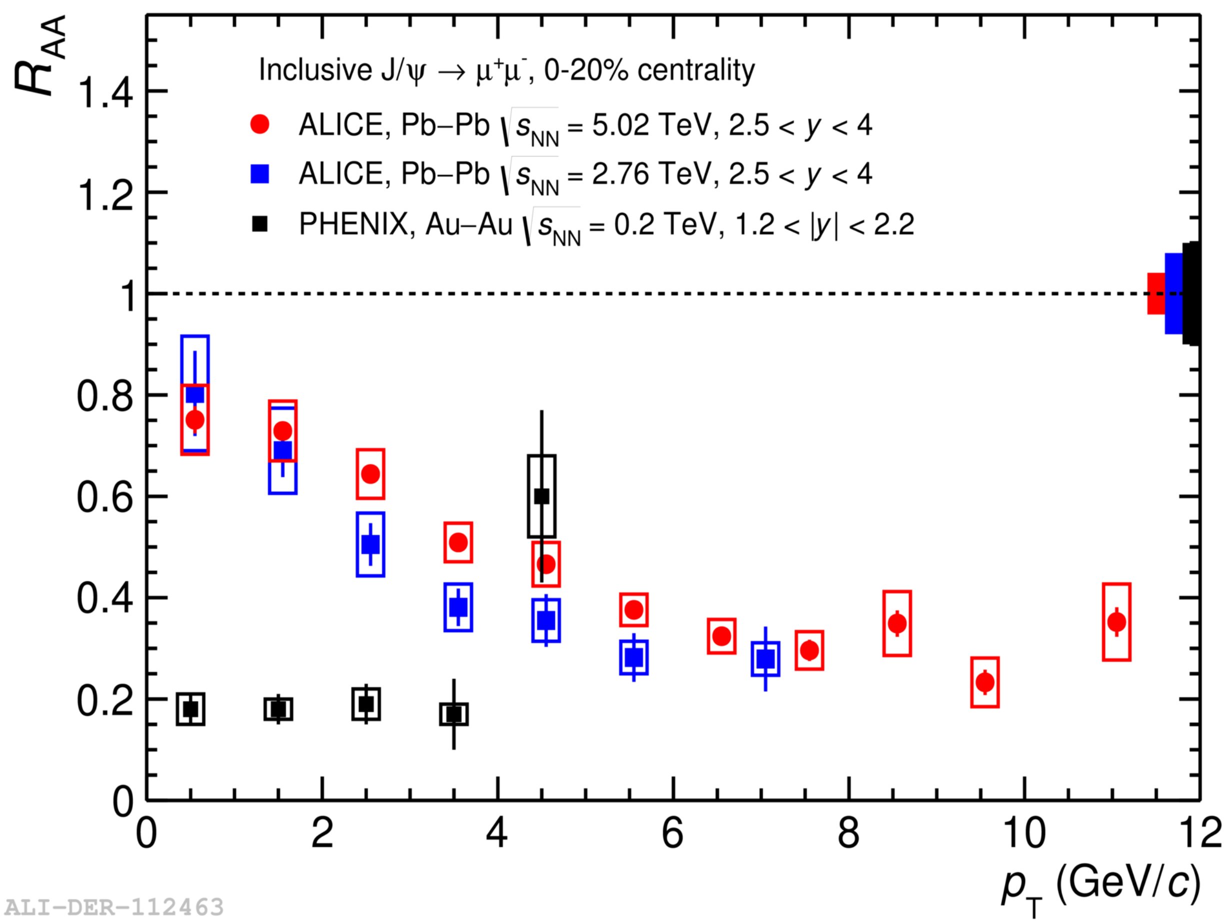
yield in PbPb peaks at mid-y where energy density is largest

M. Köhler, A. Andronic, P. Braun-Munzinger, JS



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)

Transverse momentum spectrum

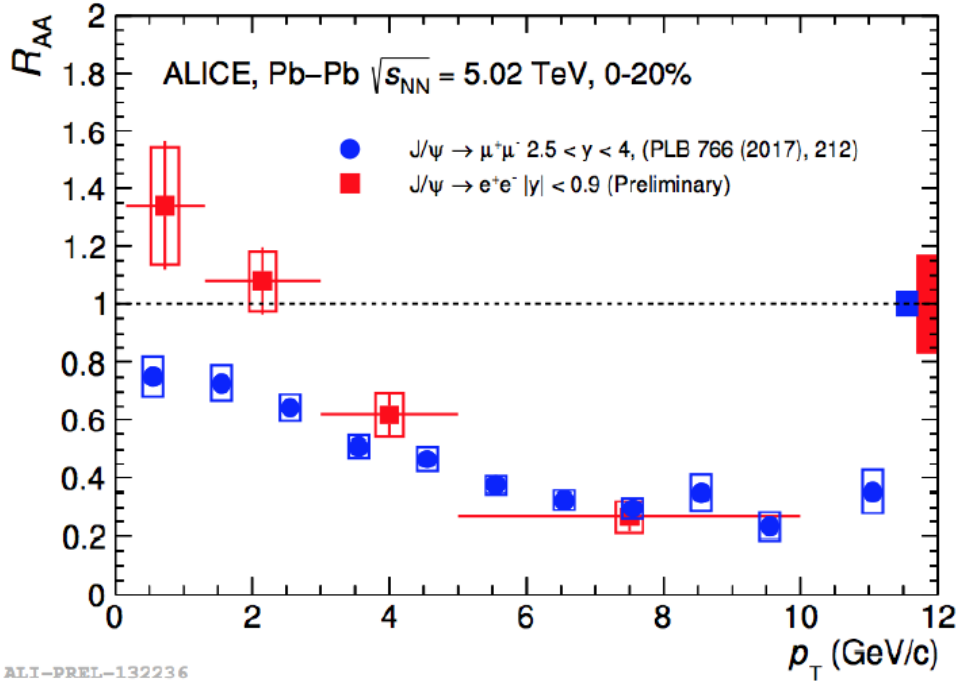


softer in PbPb as compared to pp

a qualitatively new feature as compared to RHIC where the trend is opposite

in line with thermalized charm in QGP at LHC, forming charmonia

Transverse momentum dependence



enhancement at small p_t as compared to pp collisions!

– was predicted for statistical hadronization component

what does statistical hadronization have to say about p_t spectrum?

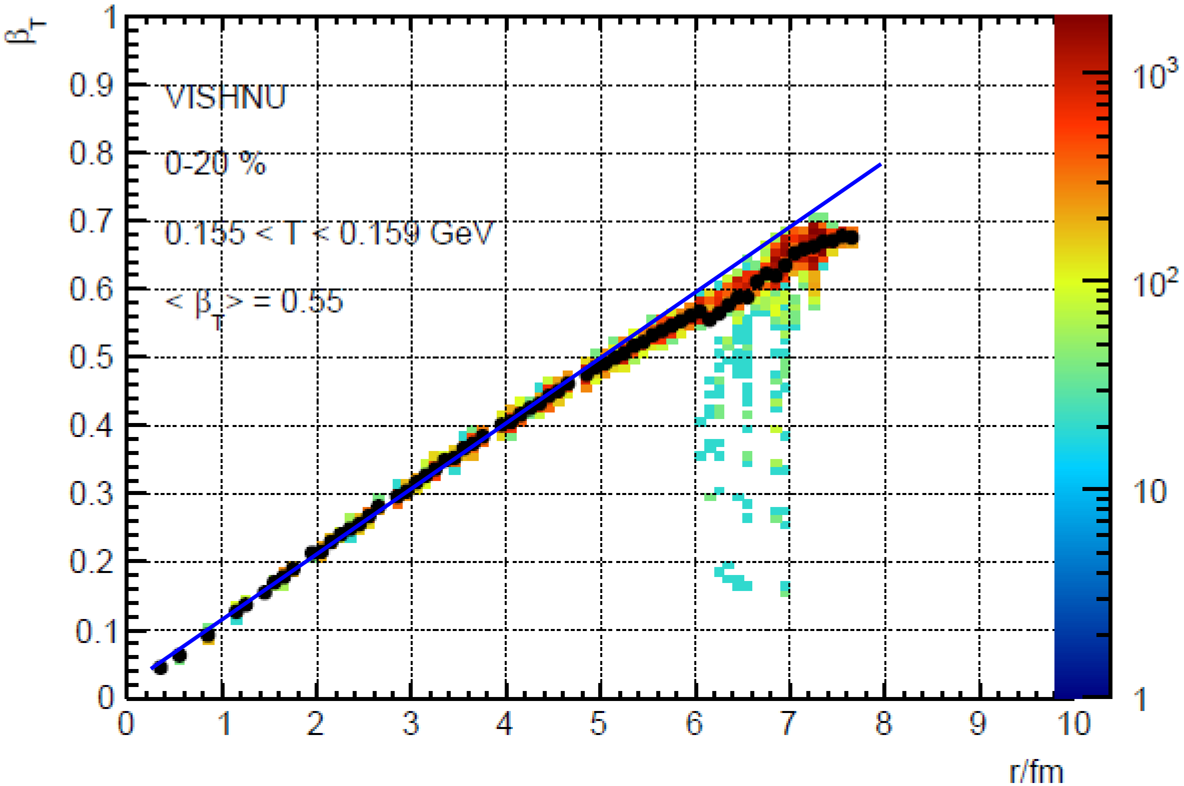
<u>the physical picture:</u> charmonia are formed at hadronization from charm quarks in the medium

<u>implies:</u> they should exhibit – as other hadrons – a spectrum characterized by the temperature and the flow of the surrounding medium

<u>recipe:</u> take flow characteristics at T_c from a good hydro describing the other light flavor observables, normalization given by ccbar cross section (see above)

in the following first results in this direction – work in progress, plenty of systematics to be checked

Transverse hydro velocity profile at T_c

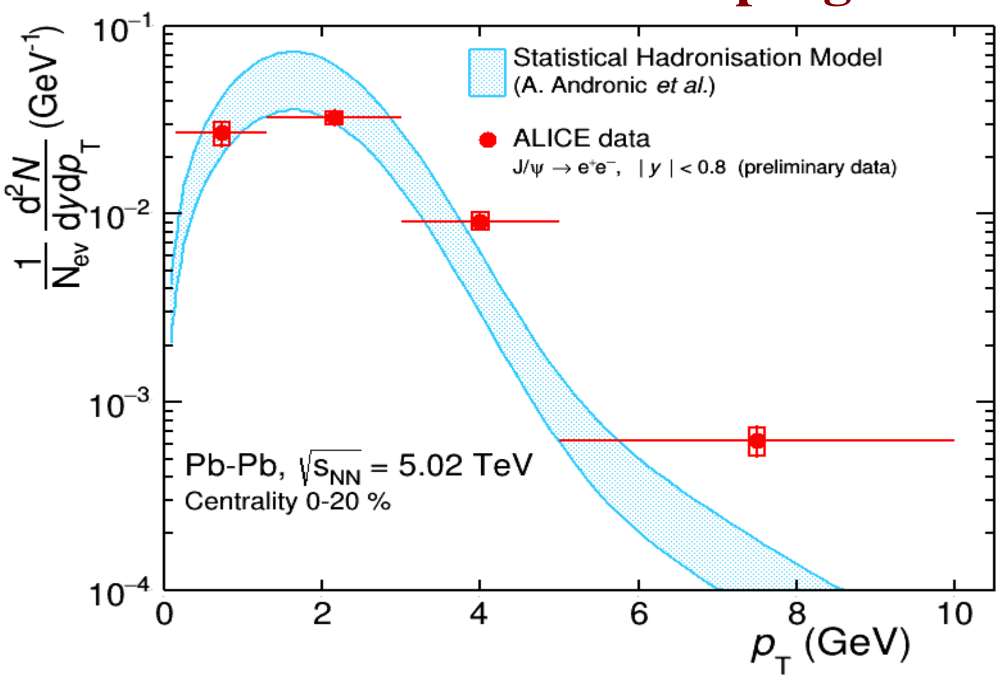


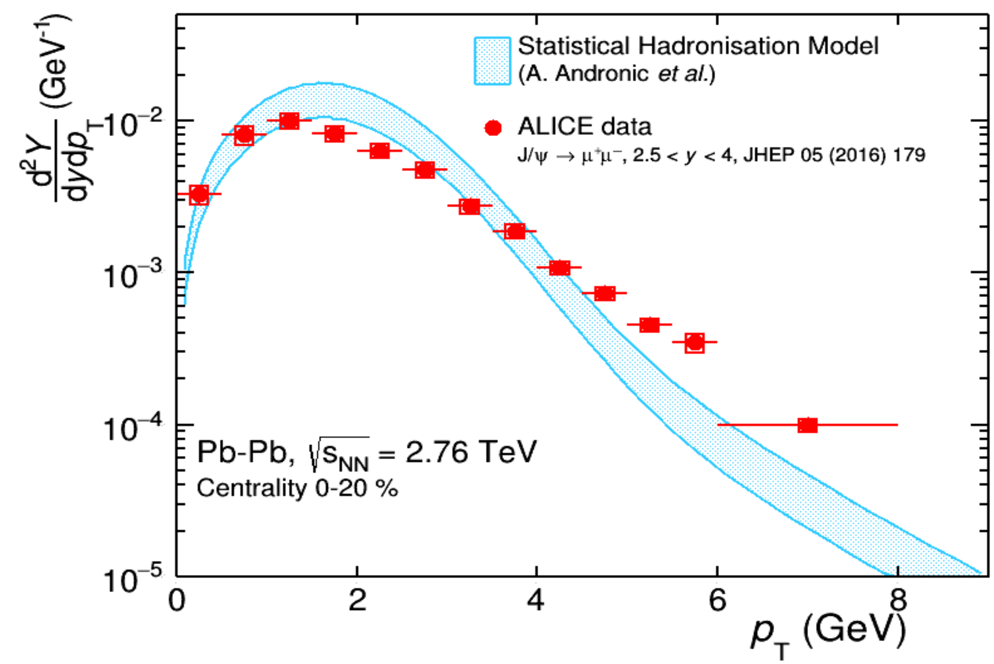
- velocity profile linear in r
- average transverse velocity: 0.55 c

<u>first approach:</u> use blast wave parameterization with hydro input, i.e. linear velocity profile and correct mean velocity and T_c for J/ψ mass for core and pp spectrum for corona

J/ψ transverse momentum spectra from stat. hadr.

work in progress!





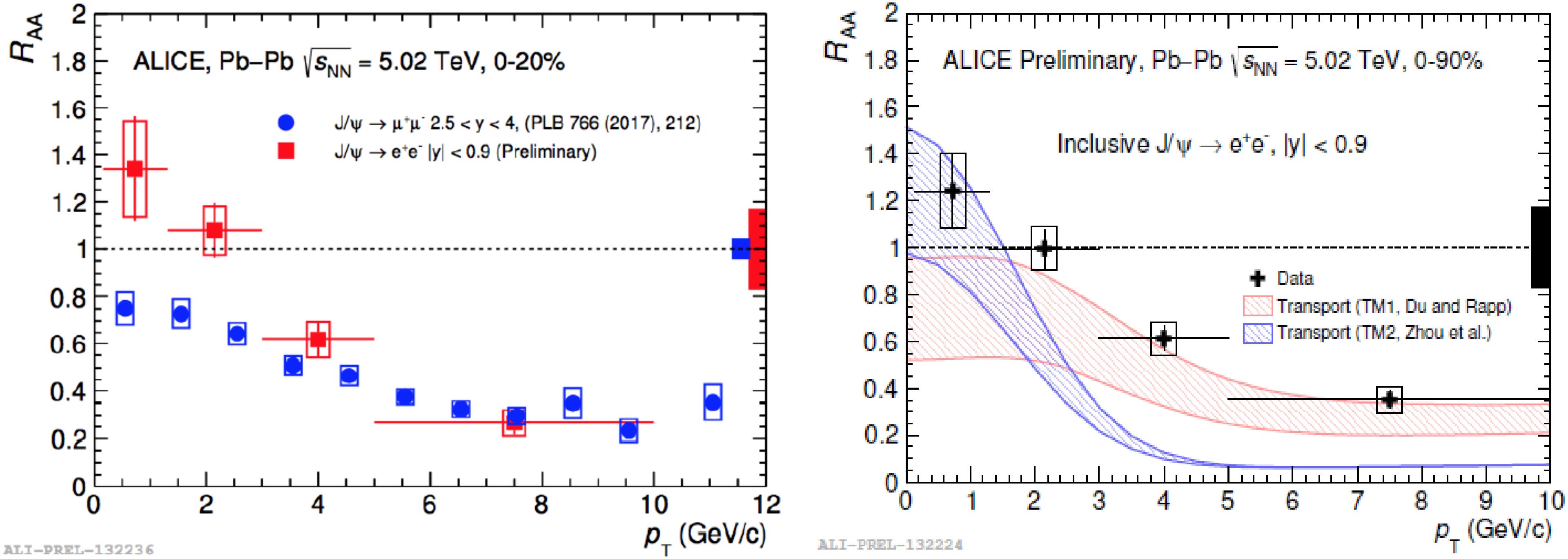
quite reasonable agreement

to explore: corona fraction (presently starting at 10% ρ_0 or 20% ρ_0) ,

radial density profile + $\beta(r)$,

3+1 d hydro vs 2+1, ...

Transverse momentum dependence



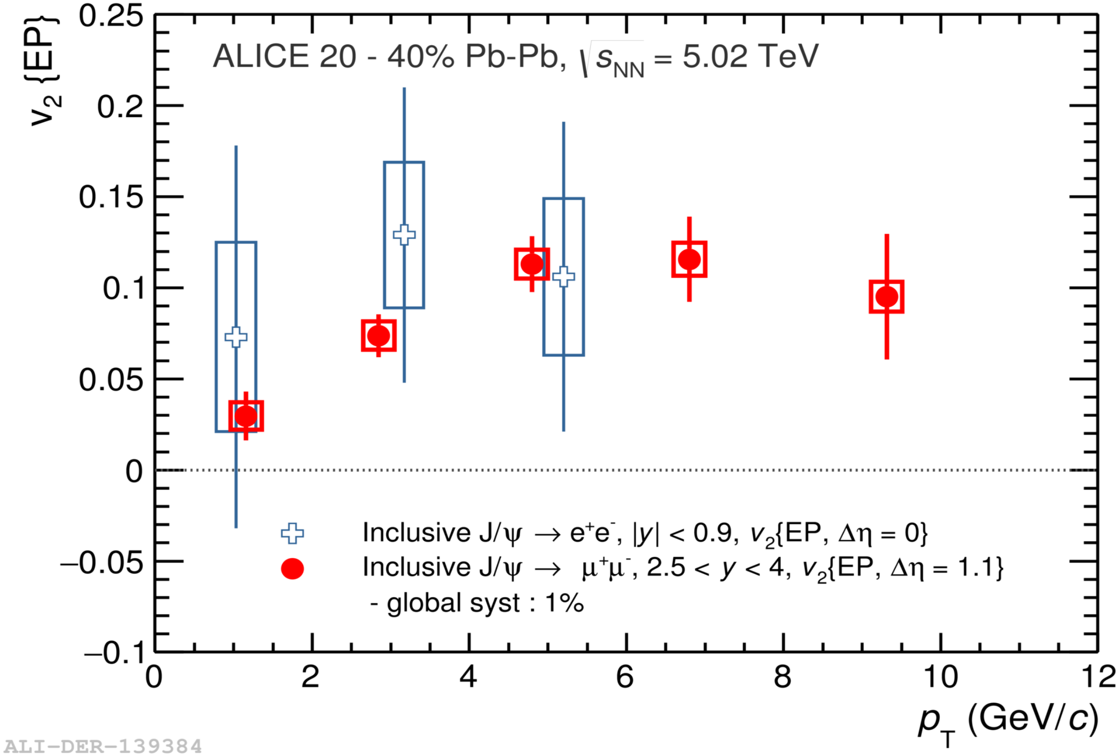
enhancement at small p_t as compared to pp collisions!

– was predicted for statistical hadronization component

also new formation of charmonia in transport model description reproduces features roughly, but starts to be challenged

Elliptic flow of J/ψ vs p_t

arXiv:1709.05260



charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, … and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

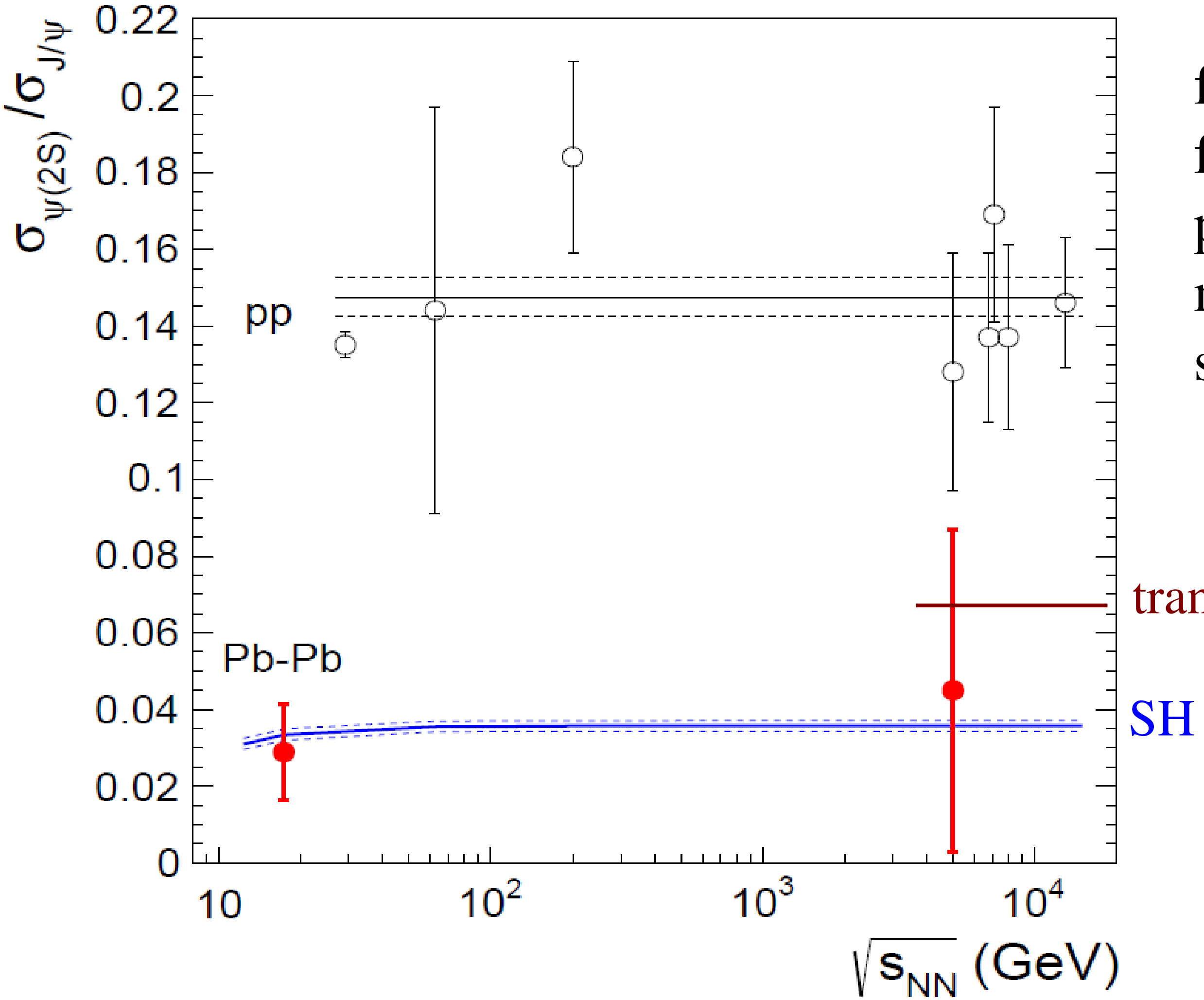
first observation of significant J/ψ v_2 in line with expectation from statistical hadronization
can be computed following approach above with hydro velocity profile

How to distinguish between statistical hadronization and transport models with J/ψ beyond T_c?

not a detail, which model is right, but fundamental question
link to phase boundary and existence of bound states beyond T_c at stake

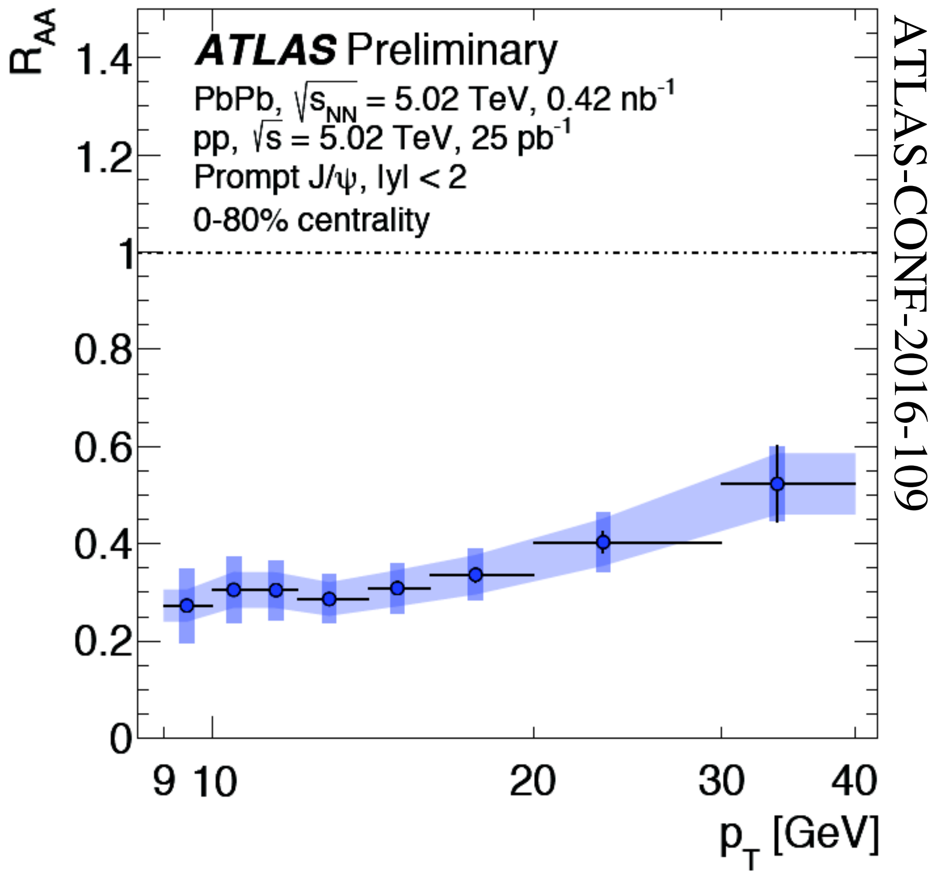
- R_{AA} can be reproduced by both, albeit with different charm cross sections
  go away from R_{AA}, normalize to open charm cross
- spectra: transport models start to be challenged, need more precise data
  and more refined hydro based computation
- similar: v_2 of J/ψ
- maybe decisive: excited state population

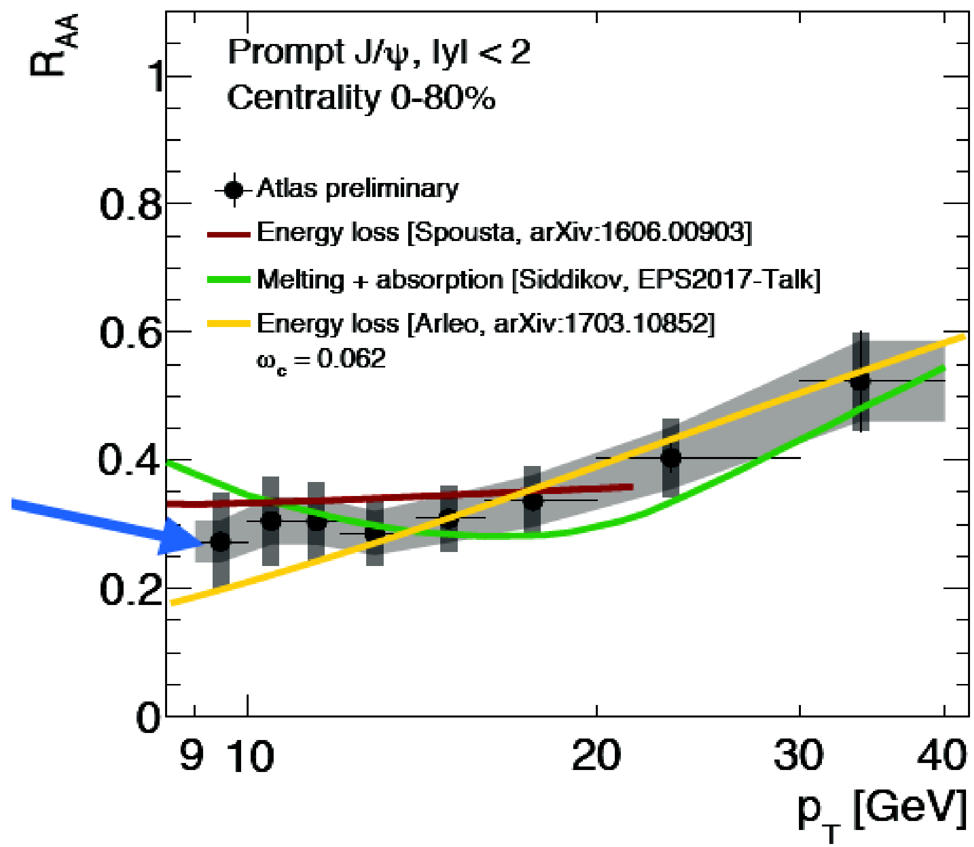
ψ(2S)



first data in line with expectation from statistical hadronization at phase boundary but transport model prediction also inside 1 sigma error

J/ψ in PbPb to high p_t





looks like R_{AA} of other hadrons, understood in terms of energy loss

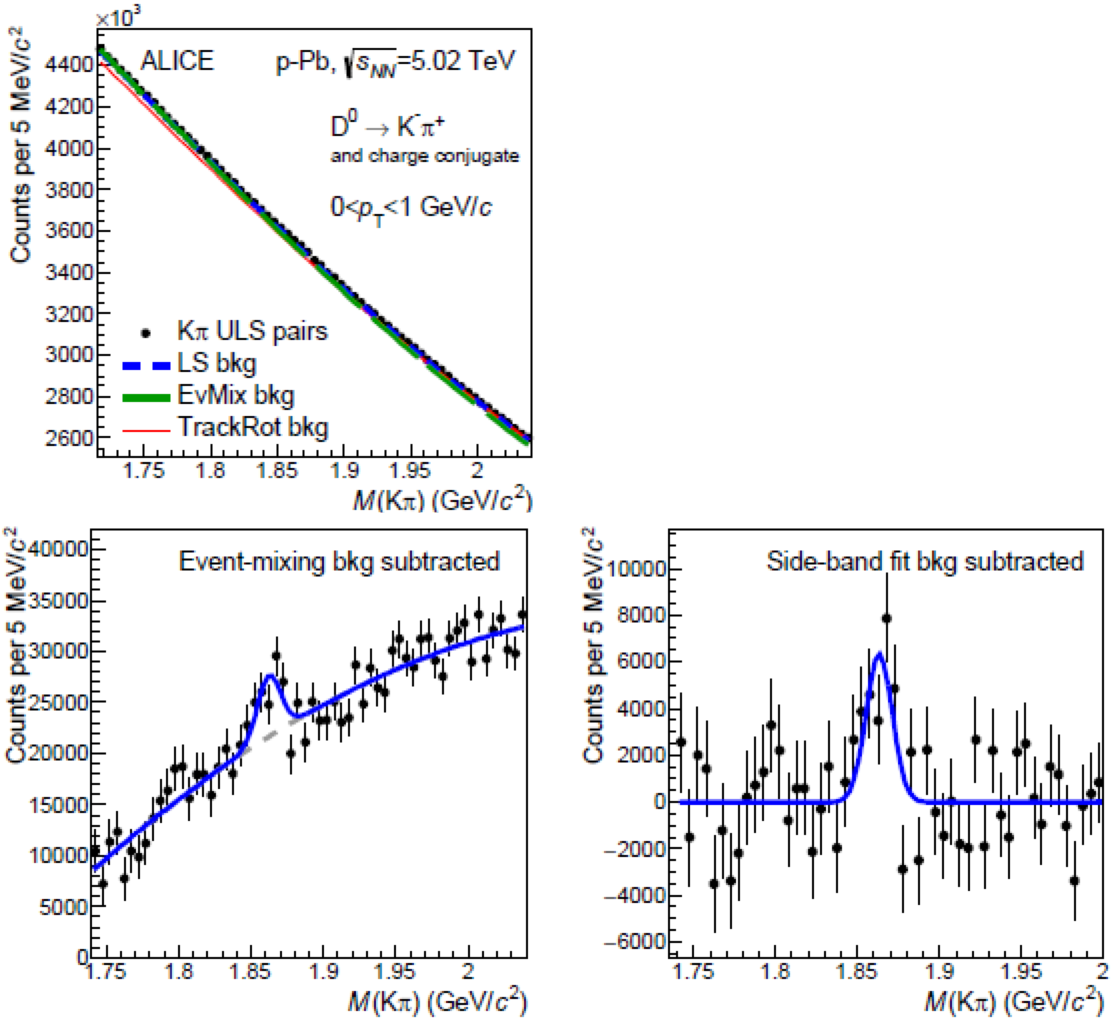
very implausible that this is primordial J/ψ

how far out does statistical hadronization mechanism reach?

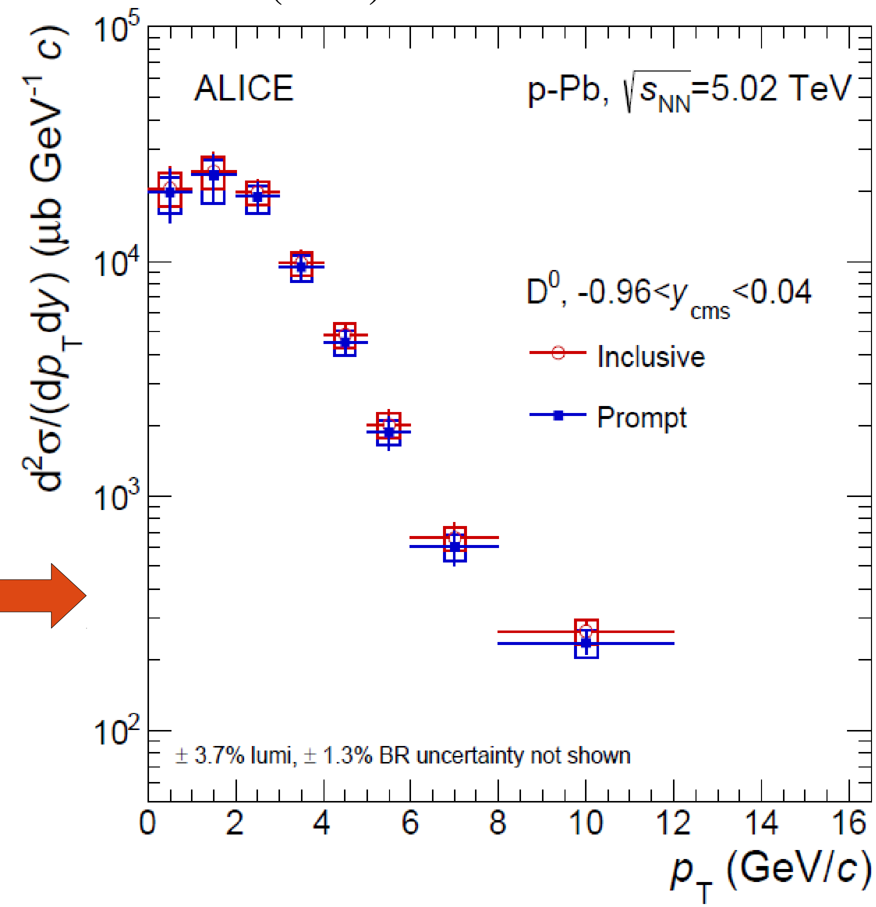
backup

Production of ccbar - open charm

first measurements of open charm down to p_t = 0 at y=0

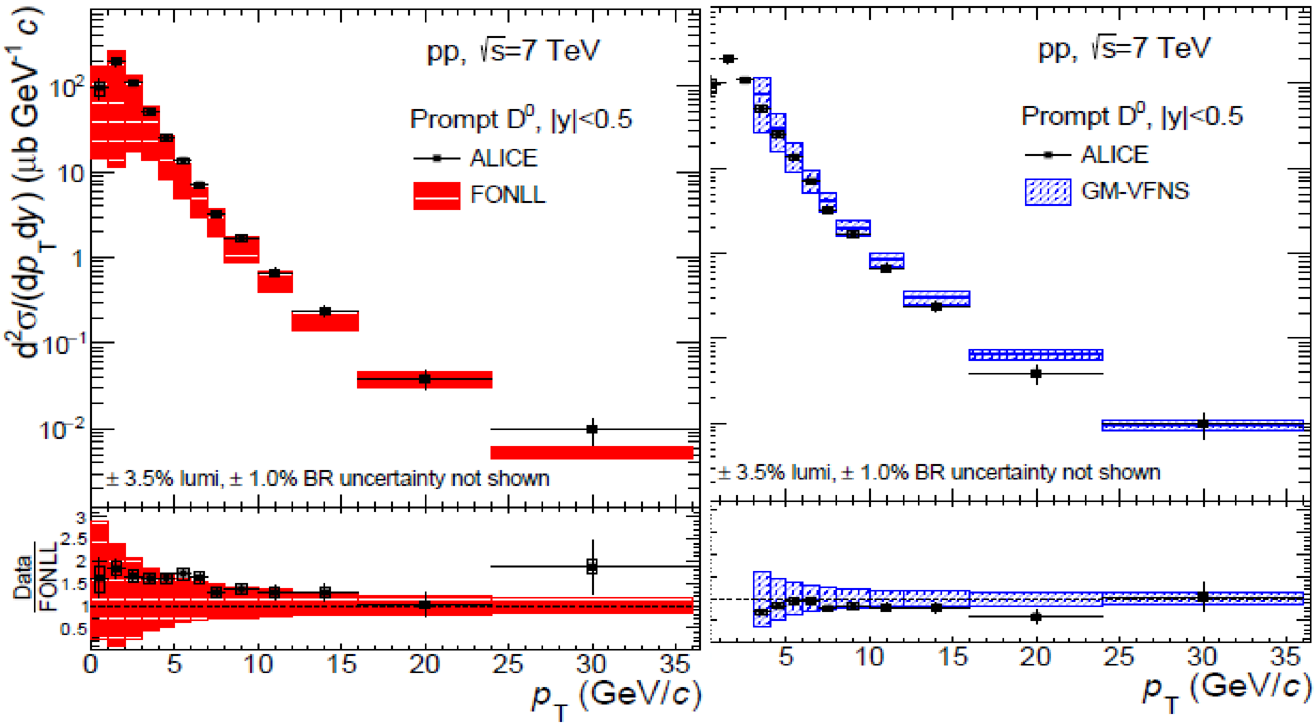


PRC94(2016) 054908 arXiv: 1605.07569



very hard struggle to deal with (irreducible) combinatorial background, very recently successful for D^0 in pp and pPb

measurements in pp at 7 TeV agree well with state of the art pQCD calculations



ALICE: 1702.00766
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

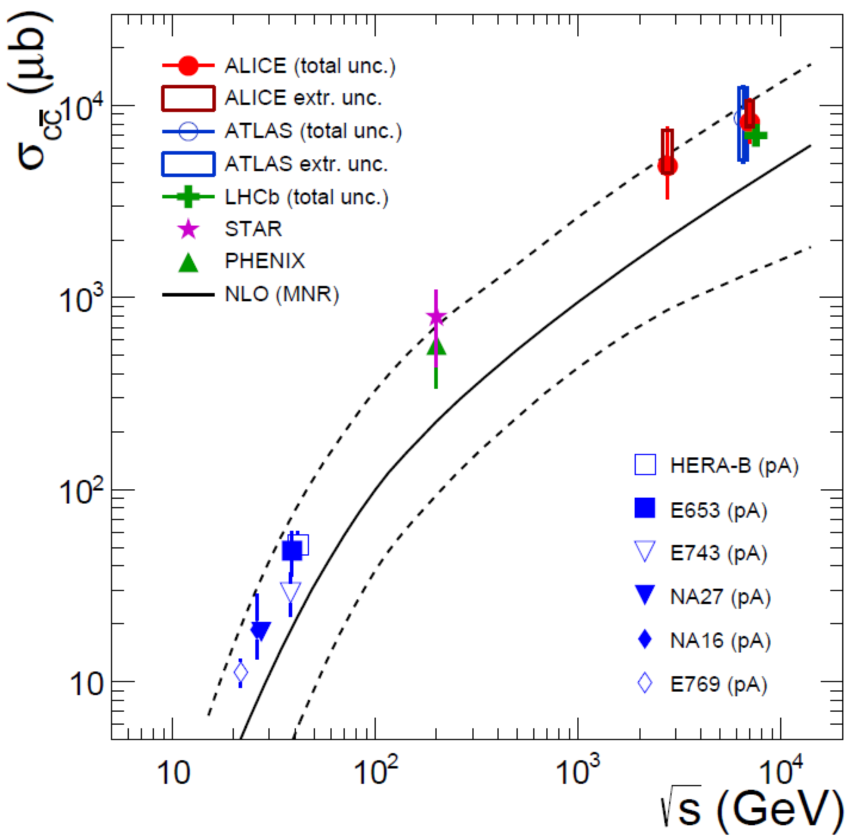
data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and
  at lower end of GM-VFNS

mid-y cross sections

	Extr. factor to $p_T > 0$	$\mathrm{d}\sigma/\mathrm{d}y\,|_{|y|<0.5}$ (μb)
D^0	$1.0002^{+0.0004}_{-0.0002}$	$512 \pm 37(\mathrm{stat}) \pm 39(\mathrm{syst}) \pm 18(\mathrm{lumi}) \pm 5(\mathrm{BR})$
D^+	$1.25^{+0.29}_{-0.09}$	$235 \pm 19(\mathrm{stat}) \pm 26(\mathrm{syst}) \pm 8(\mathrm{lumi}) \pm 6(\mathrm{BR})^{+54}_{-16}(\mathrm{extrap})$
D^{*+}	$1.21^{+0.28}_{-0.08}$	$251 \pm 29(\mathrm{stat}) \pm 24(\mathrm{syst}) \pm 9(\mathrm{lumi}) \pm 3(\mathrm{BR})^{+58}_{-16}(\mathrm{extrap})$
D_s^+	$2.23^{+0.71}_{-0.65}$	$89 \pm 18(\mathrm{stat}) \pm 11(\mathrm{syst}) \pm 3(\mathrm{lumi}) \pm 3(\mathrm{BR})^{+28}_{-26}(\mathrm{extrap})$

currently best measurement of the total ccbar cross section in pp at LHC

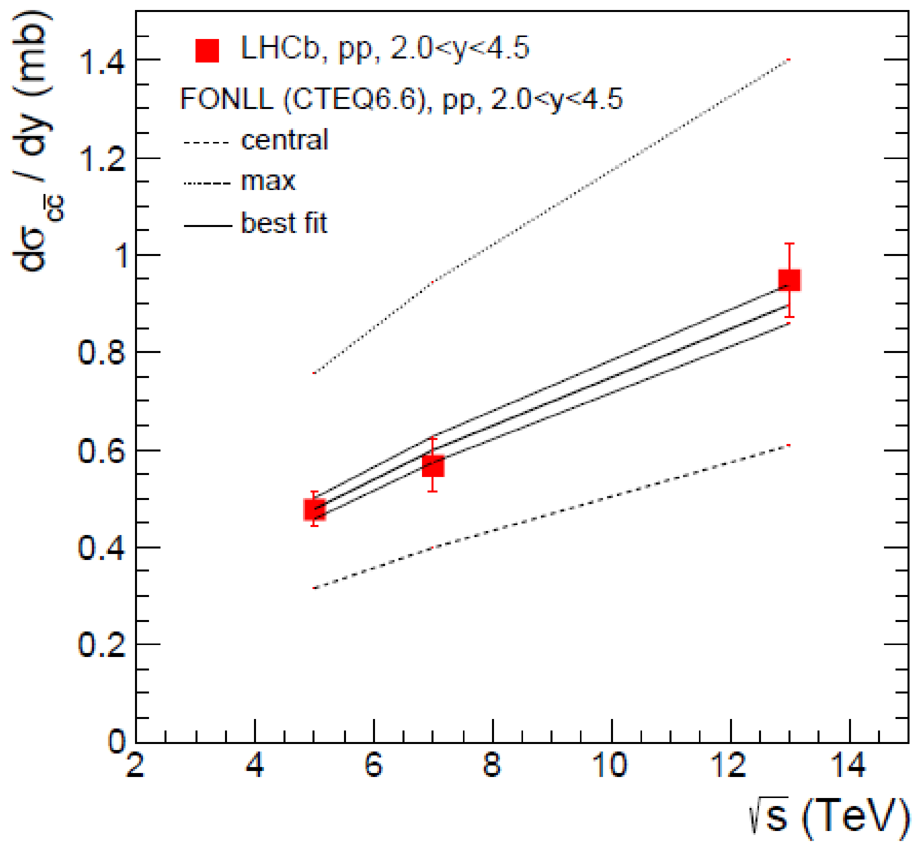
PRC94(2016) 054908 arXiv: 1605.07569

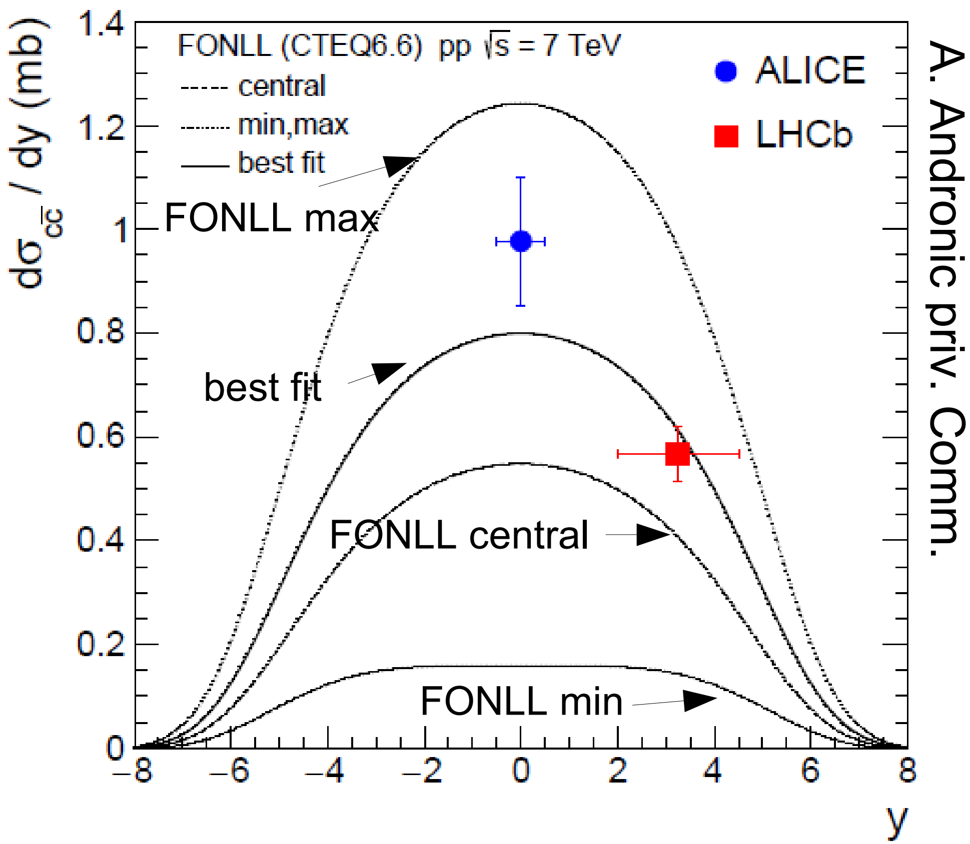


- cross sections in good agreement with NLO pQCD
  (at upper end of band but well within uncertainty)
- beam energy dependence follows well NLO pQCD

the baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper $\sqrt{s}$ and y-interval

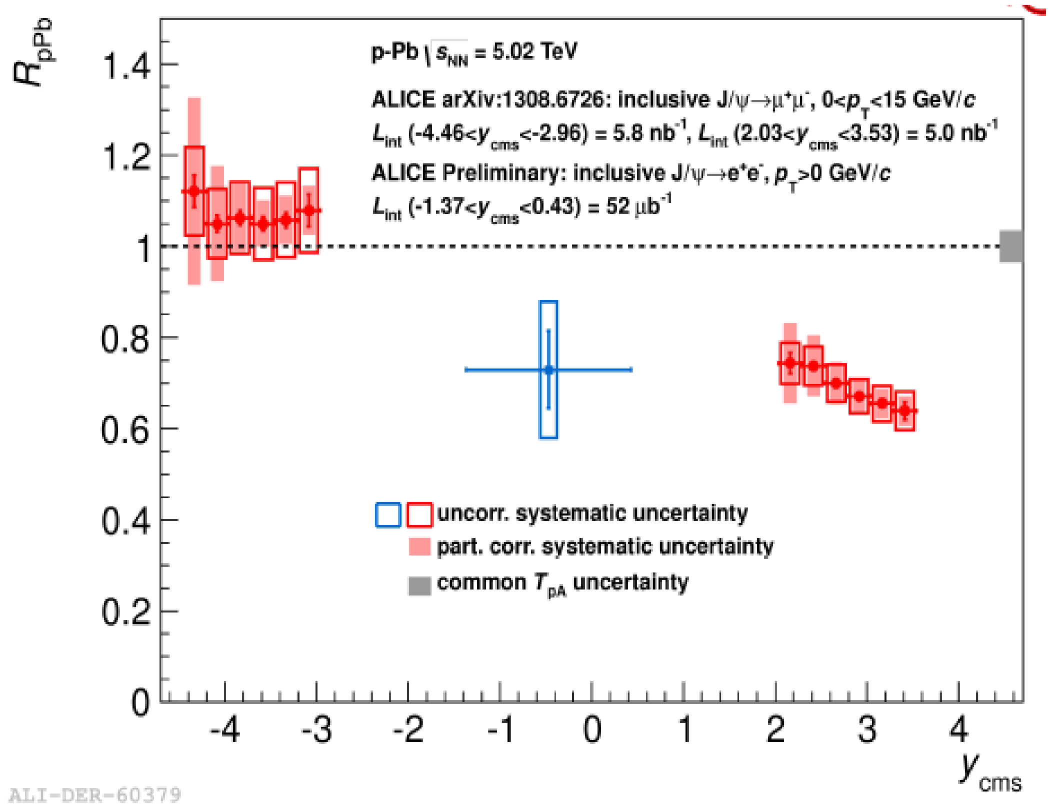




LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159
plus erratum

ALICE: 7 TeV PRC94(2016) 054908
and 1702.00766

J/psi rapidity distribution in pPb compared to pp

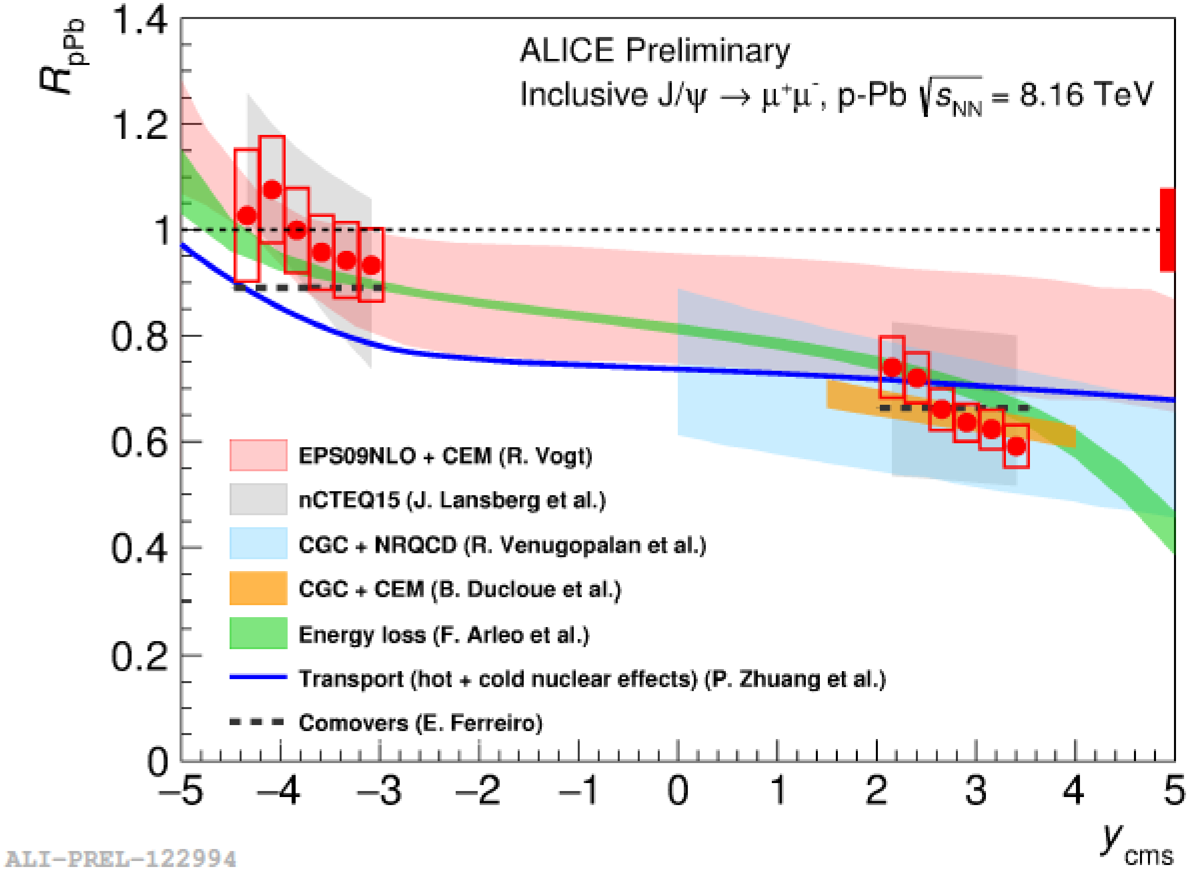


ALICE forward/backward arXiv:1308.6726

good agreement with LHCb arXiv:1308.6729

ALICE mid-y hard probes 2013

J/psi rapidity distribution in pPb compared to pp

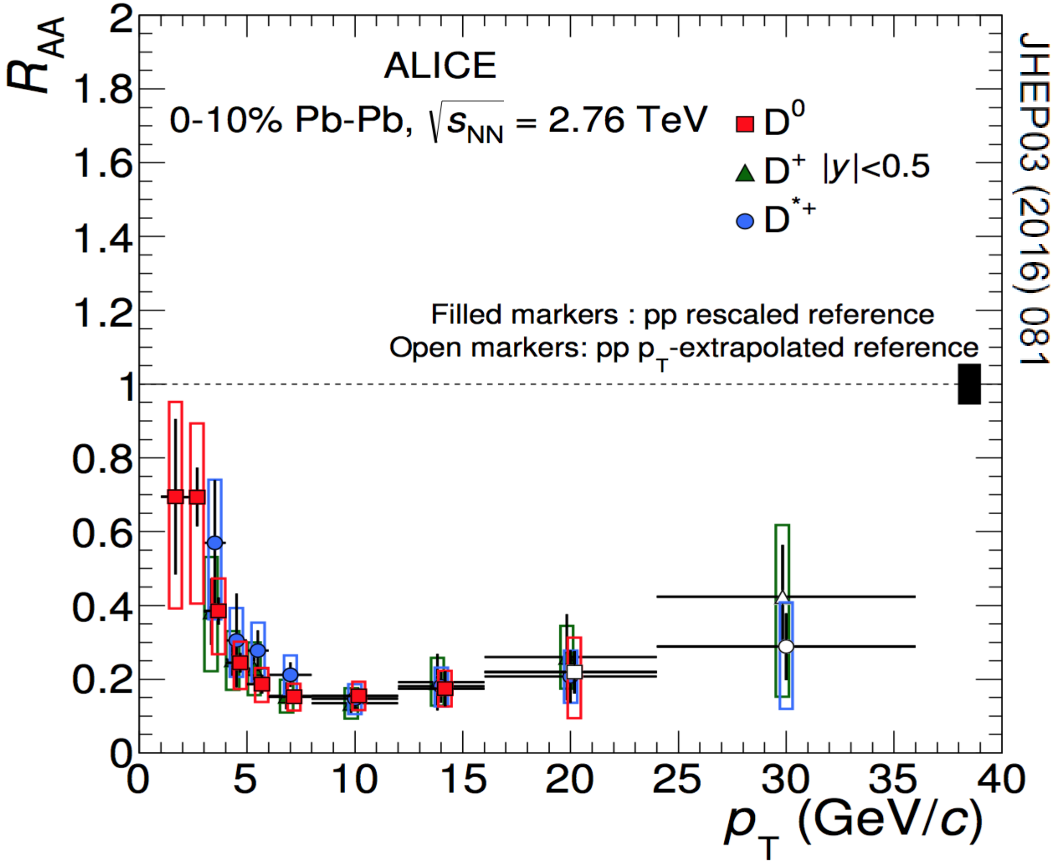


ALICE new 8.16 TeV data

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

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

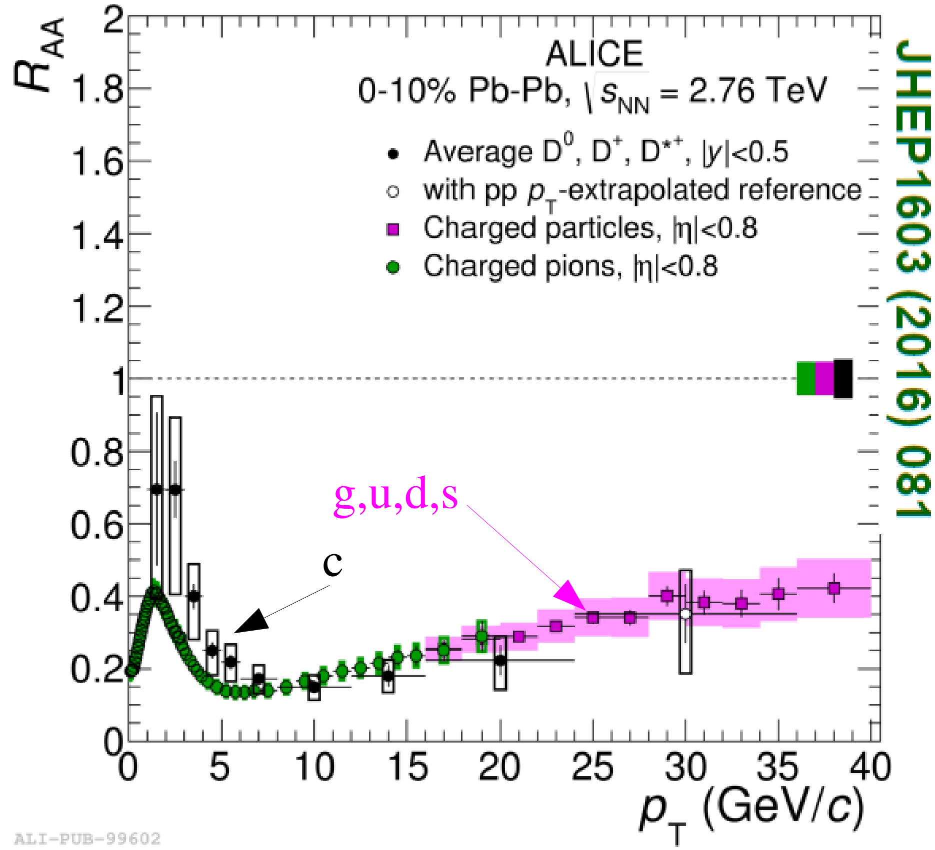
suppression of charm at LHC energy



energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

charm quarks thermalize to large degree in QGP

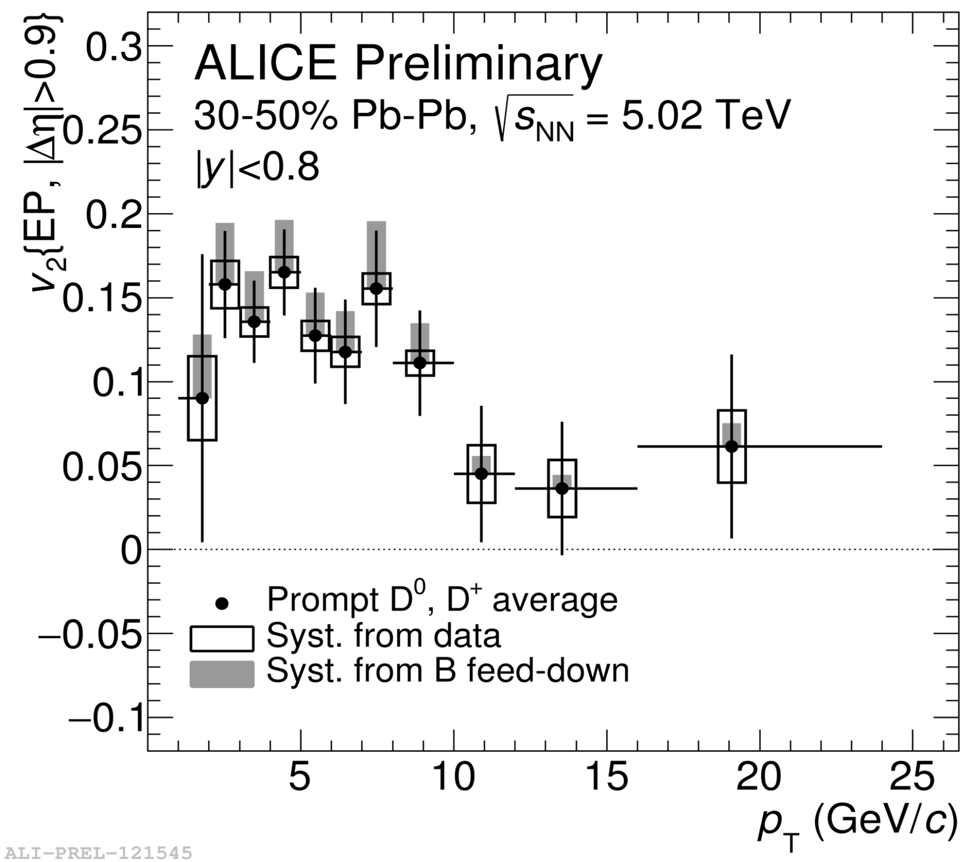
strong energy loss of charm quarks



M.Djordjevic, arXiv:1307.4098:
equal R_{AA} is a conspiracy of different fragmentation functions of light quarks, gluons, charm and different color factors in energy loss

elliptic flow for charm – participation in coll. flow

ell



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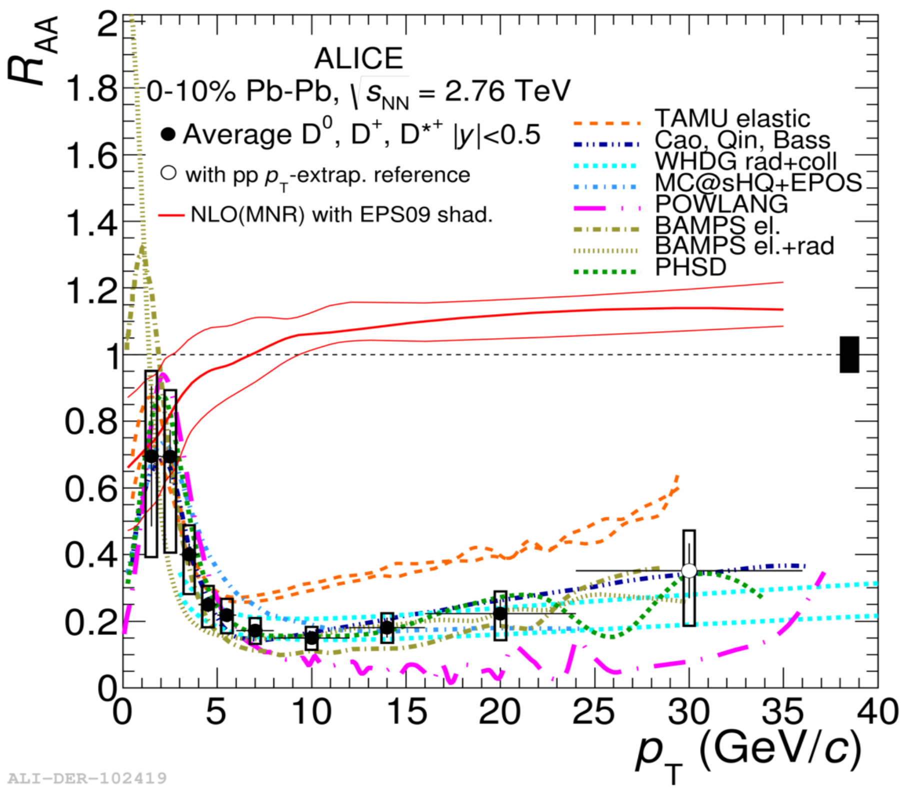
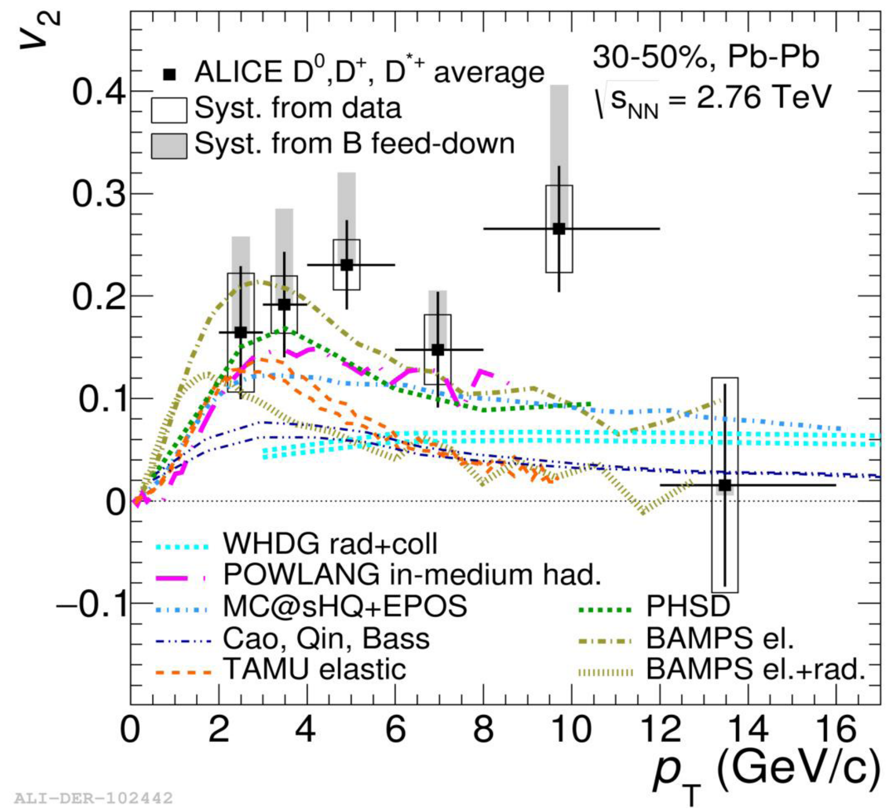
models constrained by simultaneous fit of R_{AA} and v_2

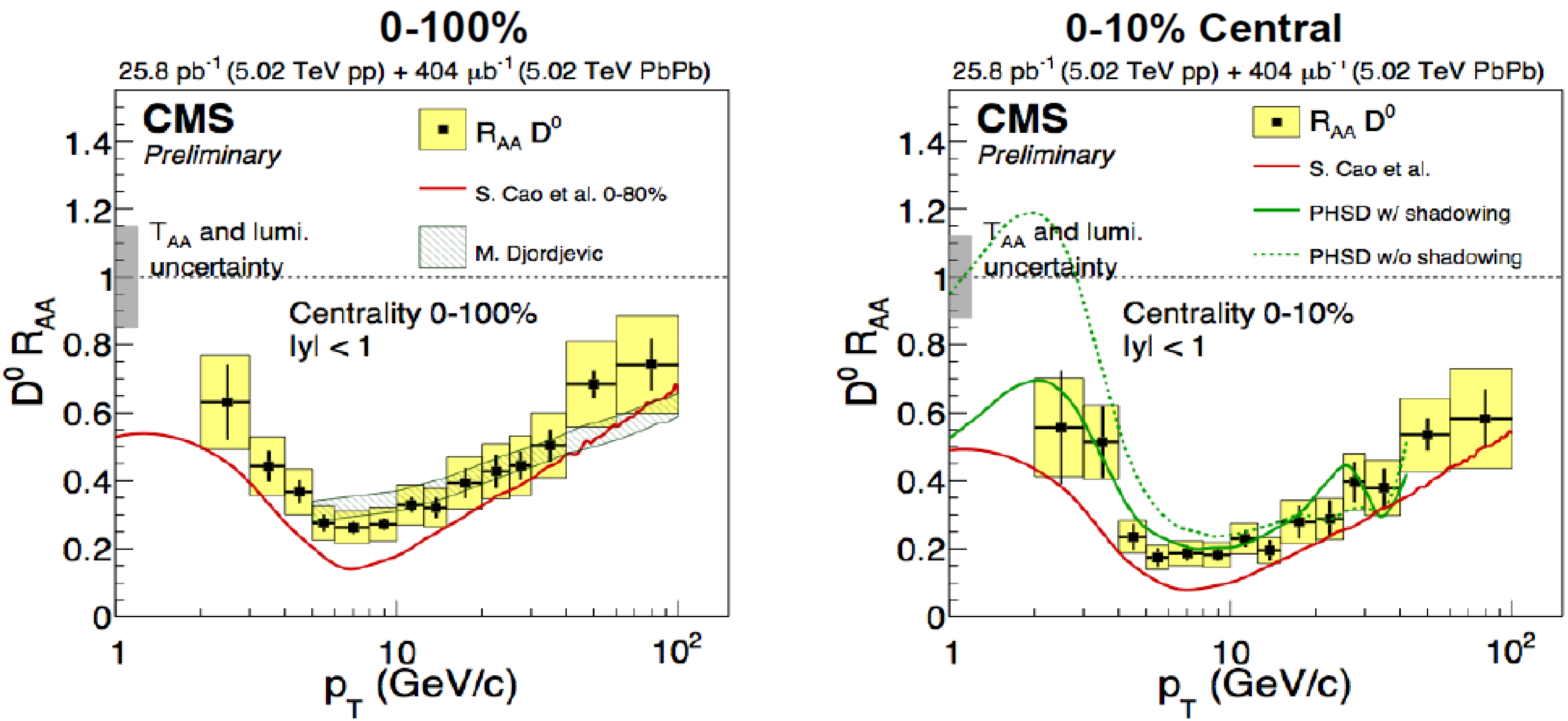
PRL 111 (2013) 102301, PRC 90 (2014) 034904





models capture various relevant aspects leading to thermalization of charm
– serious need to put together a coherent picture
- a difficult theoretical challenge, that is being addressed
- recently an EMMI rapid reaction task force took up the issue
(Andronic, Averbeck, Gossiaux, Masciocchi, Rapp)

D^0 R_{AA} compared to models

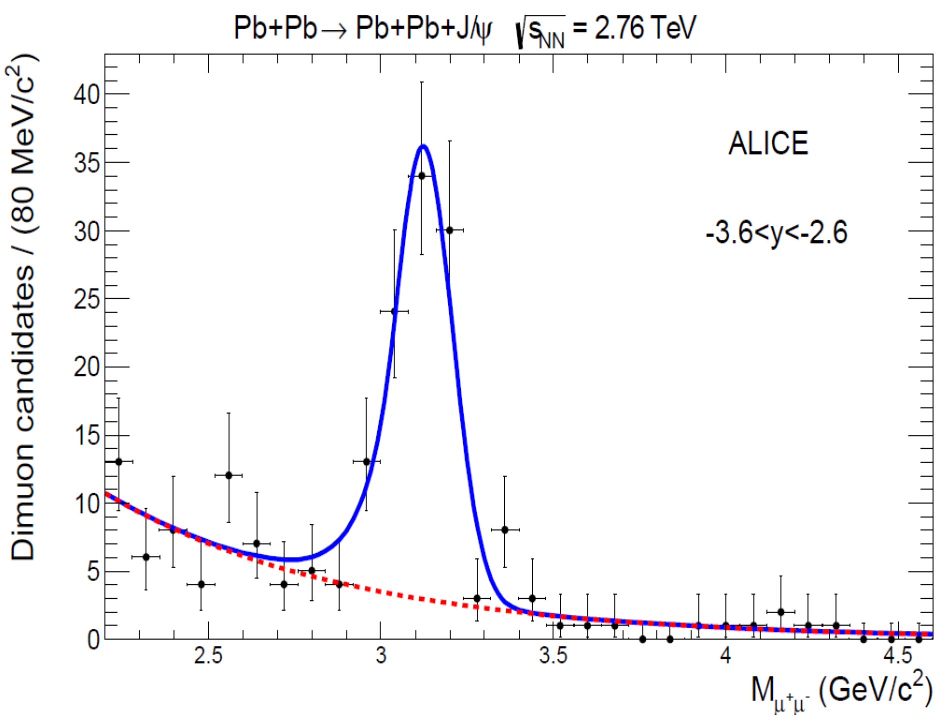


models: predictions before run2 data

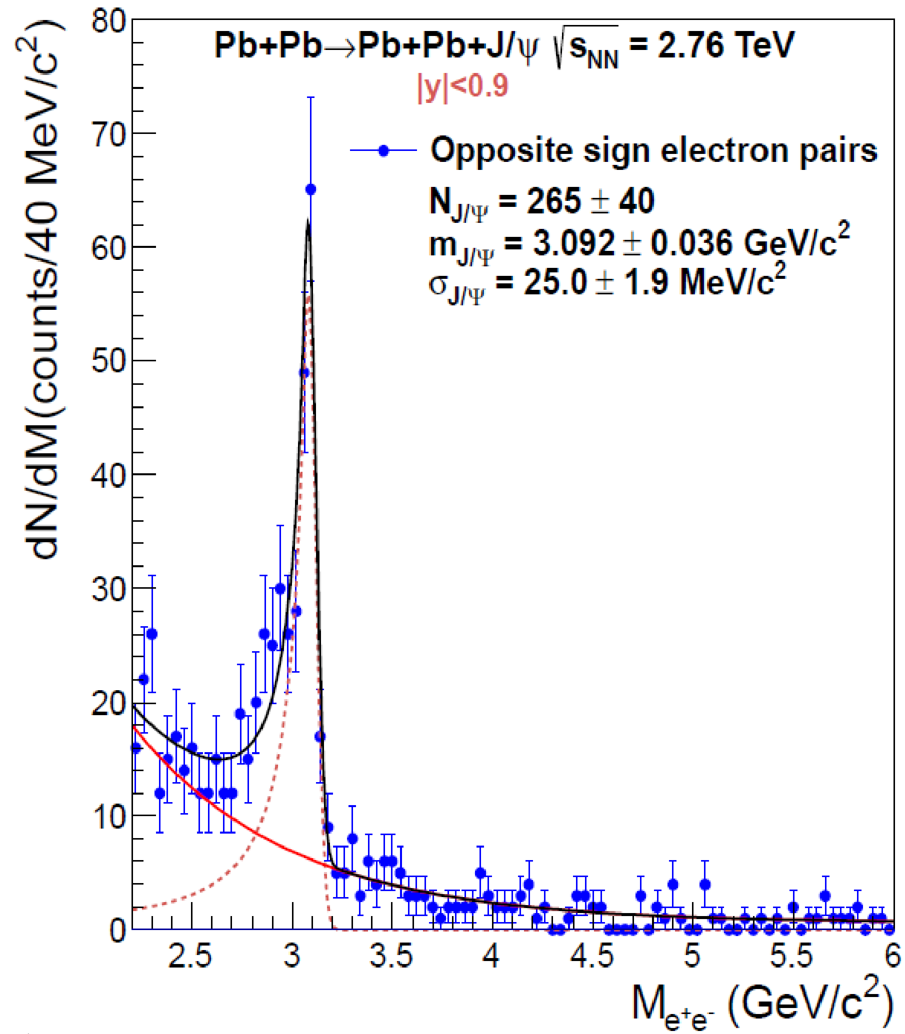
- PHSD (Parton-Hadron-String Dynamics model[2])
- S.Cao et al. (Linearized Boltzmann transport model + hydro) arXiv:1605.06447v1
- M. Djordjevic (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss) Phys. Rev. C 92 (Aug, 2015) 024918

reconstruction of J/ψ via mu⁺mu⁻ and e⁺e⁻ decay

PLB 718 arXiv:1209.3715



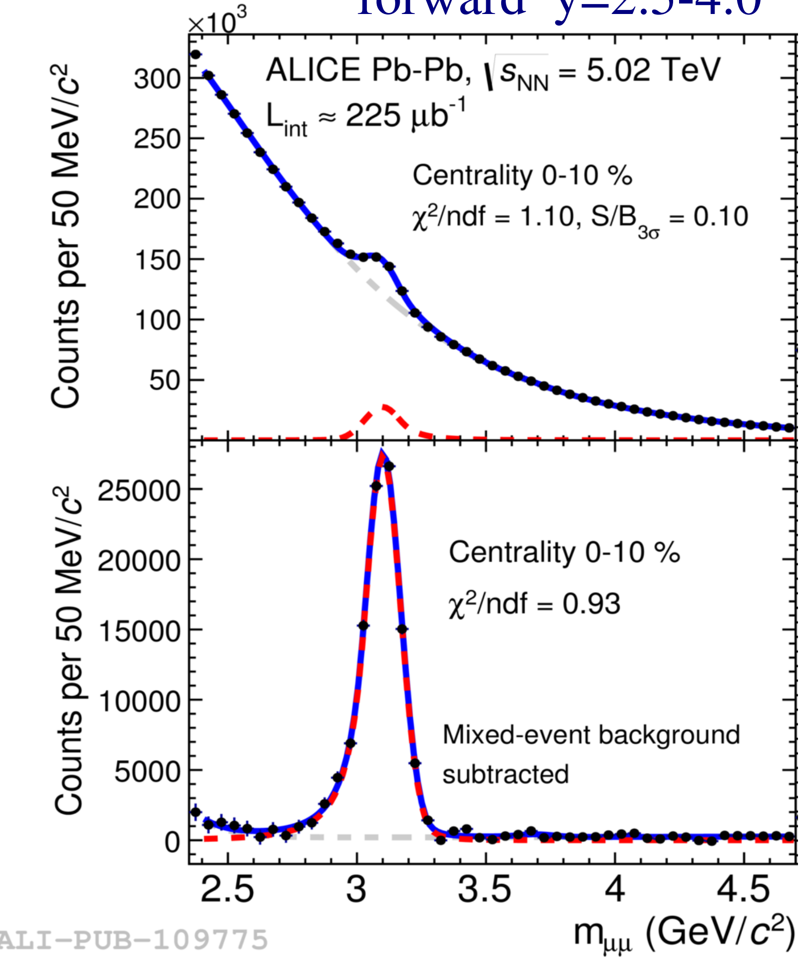
ALICE EPJ C73 arXiv:1305.1467



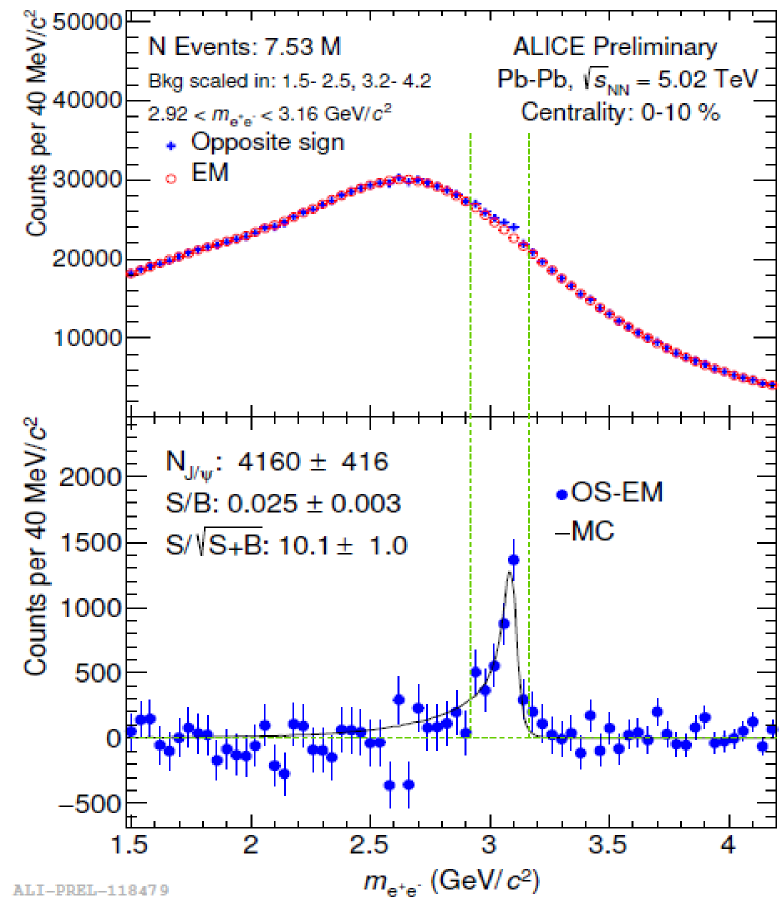
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background
very good understanding of line shape
(probes nuclear gluon shadowing, not discussed here)

Reconstruction of J/ψ via μ⁺μ⁻ and e⁺e⁻ decays

forward y=2.5-4.0

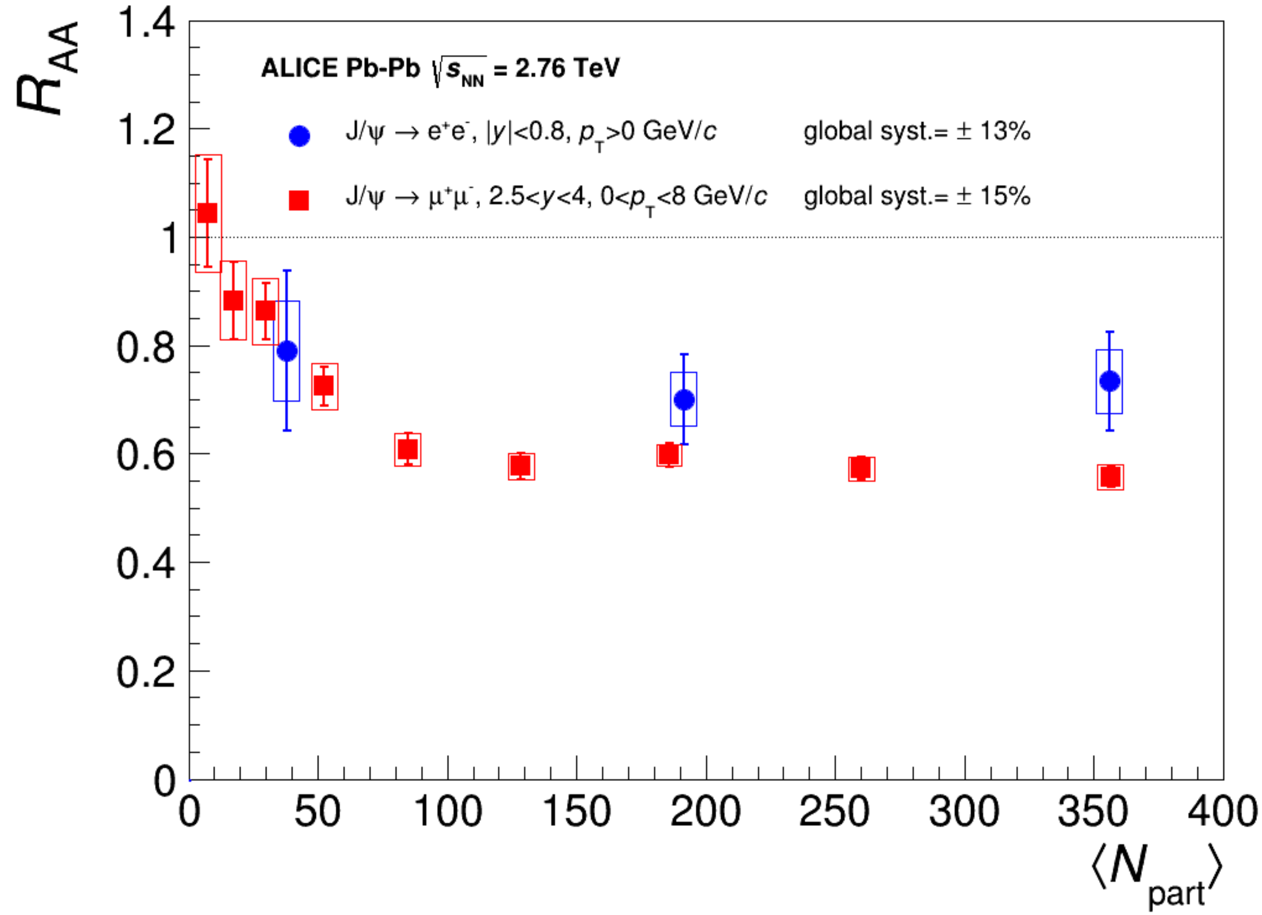


mid |y| < 0.8

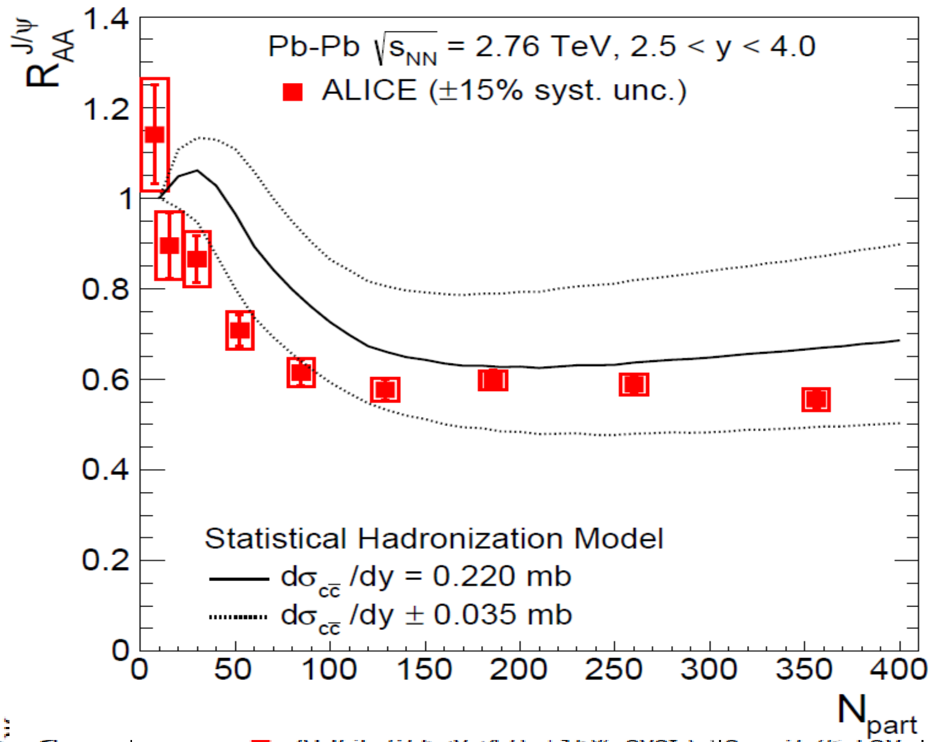


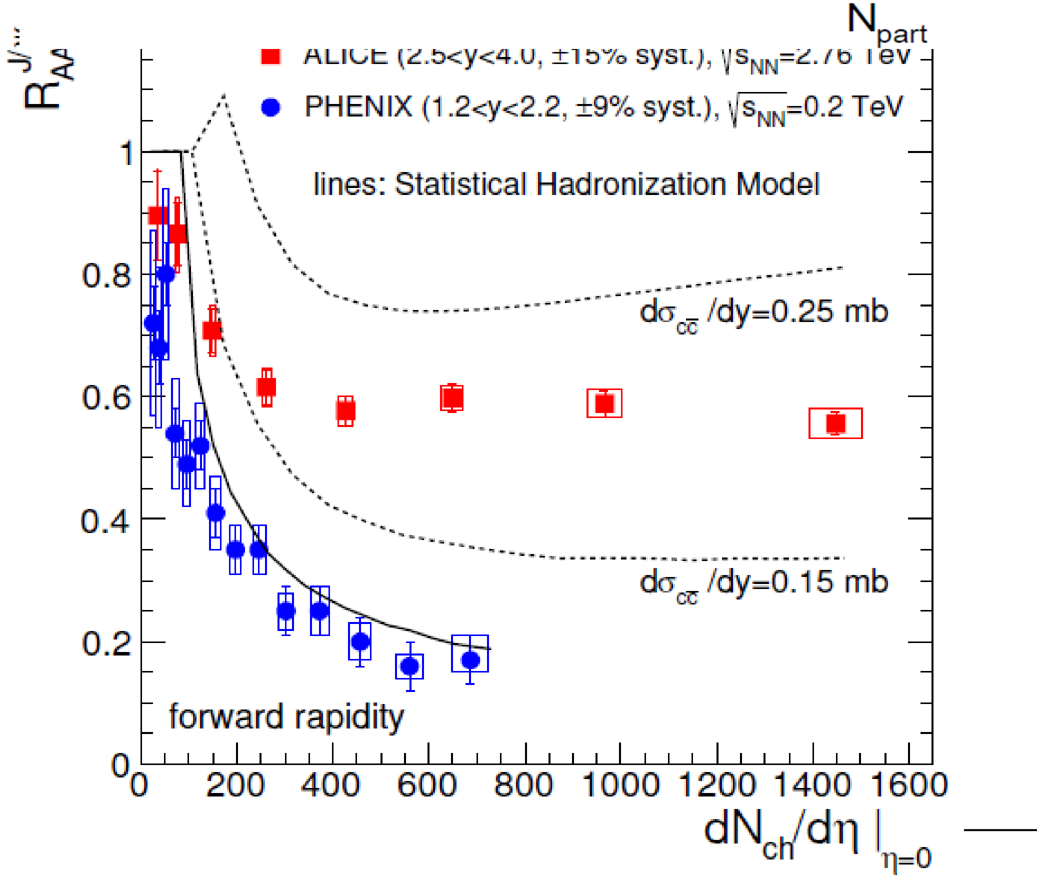
most challenging: central PbPb collisions
in spite of formidable combinatorial background
(true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

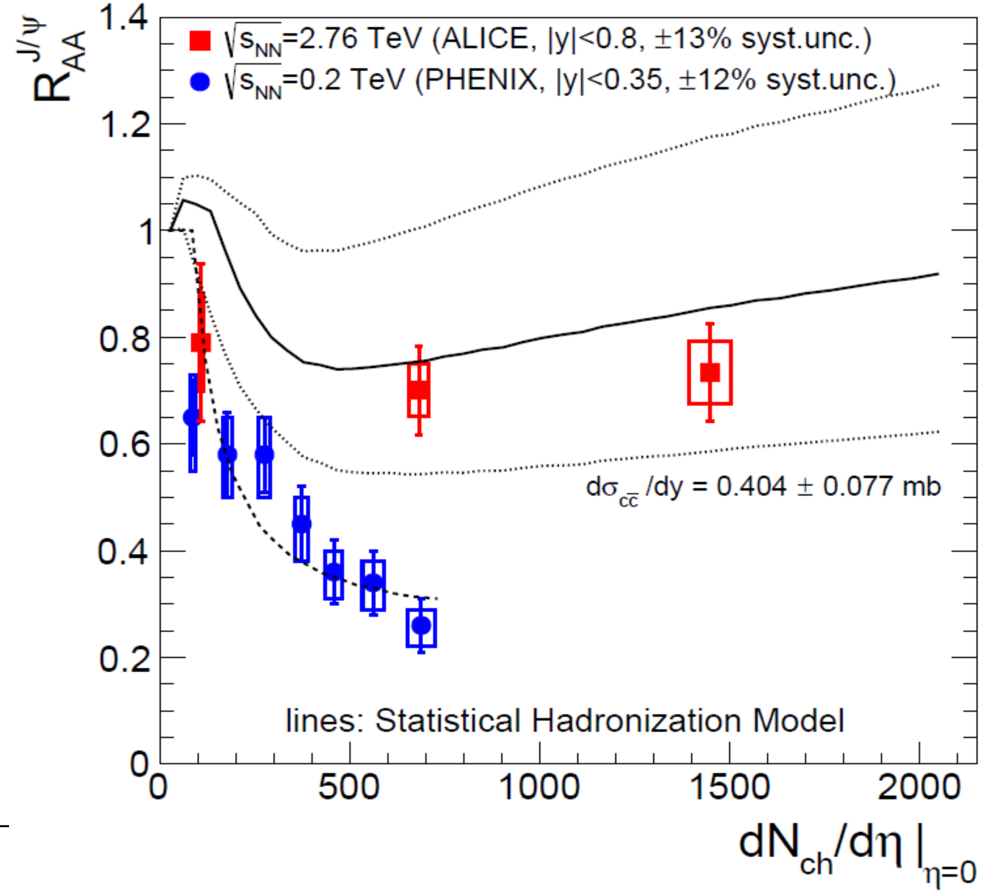
J/psi in PbPb collisions relative to pp



- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

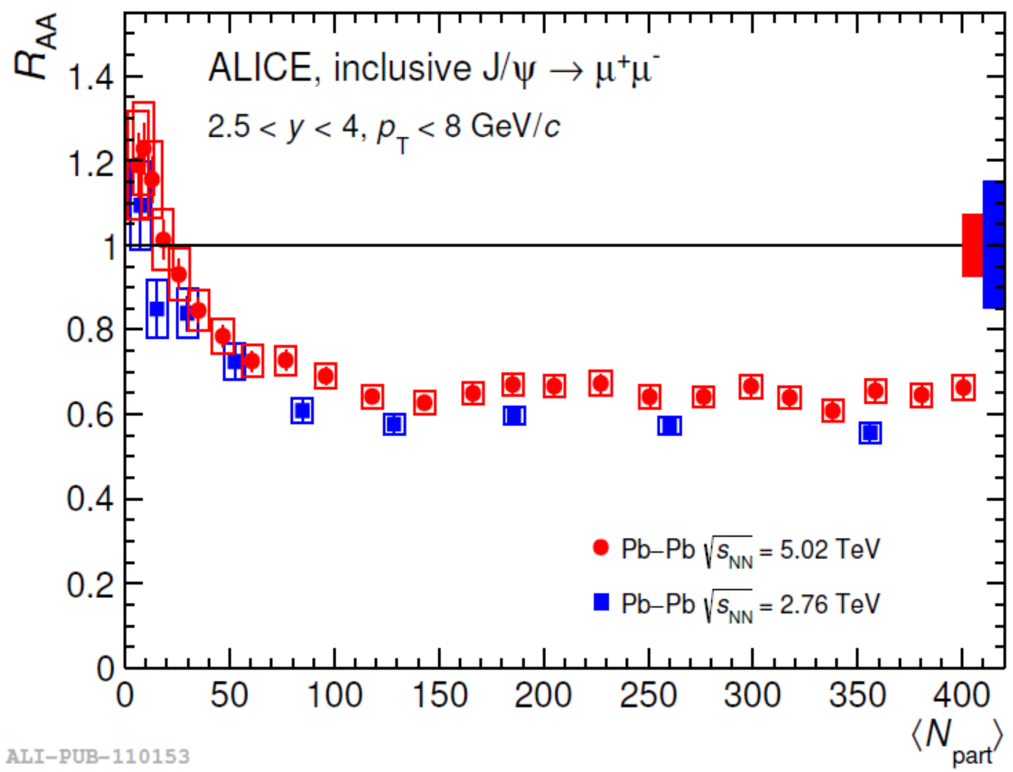

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV, 2.5 < y < 4.0
ALICE (±15% syst. unc.)
Statistical Hadronization Model
$d\sigma_{c\bar{c}}/dy$ = 0.220 mb
$d\sigma_{c\bar{c}}/dy \pm$ 0.035 mb
$R_{AA}^{J/\psi}$
N_{part}


PHENIX (1.2<y<2.2, ±9% syst.), $\sqrt{s_{NN}}$=0.2 TeV
lines: Statistical Hadronization Model
$d\sigma_{c\bar{c}}/dy$=0.25 mb
$d\sigma_{c\bar{c}}/dy$=0.15 mb
forward rapidity
$dN_{ch}/d\eta|_{\eta=0}$


$\sqrt{s_{NN}}$=2.76 TeV (ALICE, |y|<0.8, ±13% syst.unc.)
$\sqrt{s_{NN}}$=0.2 TeV (PHENIX, |y|<0.35, ±12% syst.unc.)
$d\sigma_{c\bar{c}}/dy$ = 0.404 ± 0.077 mb
lines: Statistical Hadronization Model
$R_{AA}^{J/\psi}$
$dN_{ch}/d\eta|_{\eta=0}$

J/ψ in PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

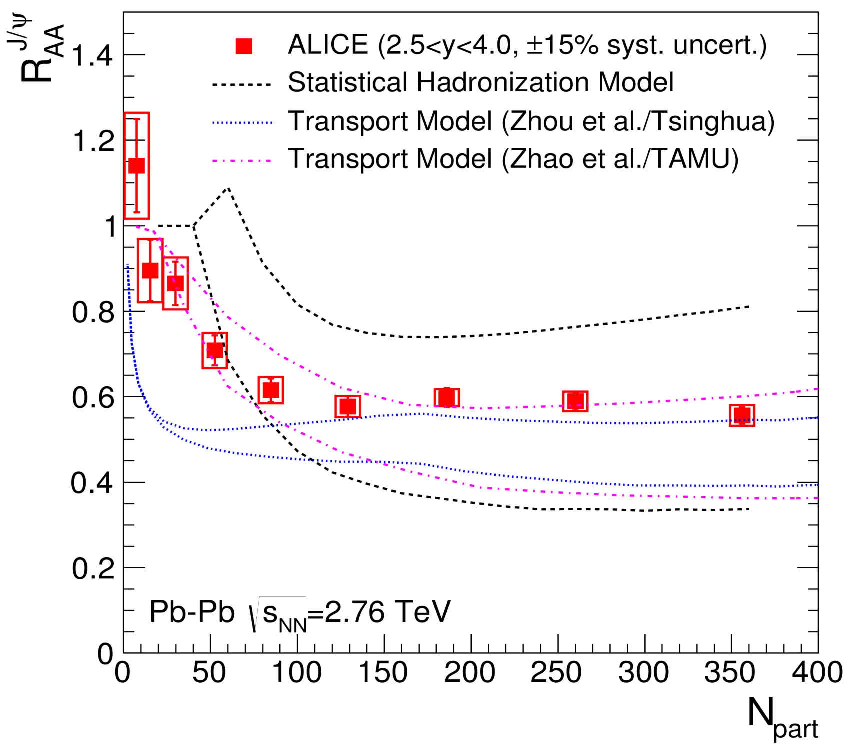
arXiv:1606.08197 [nucl-ex]

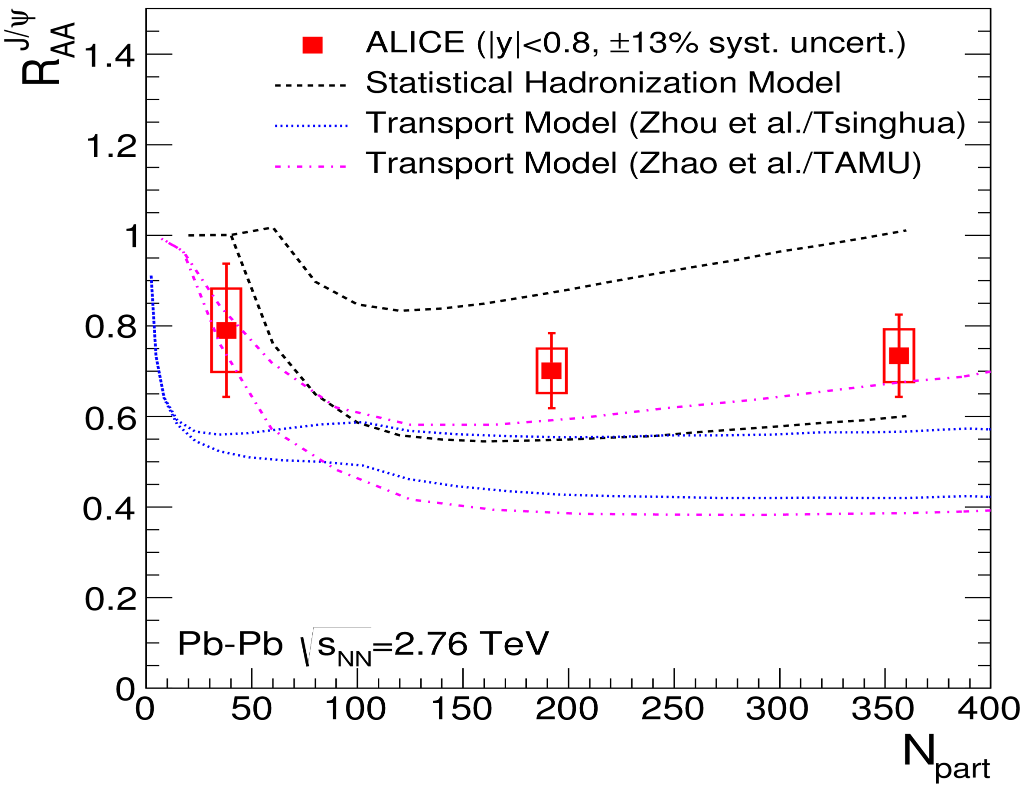


$R_{AA}^{0\text{-}90\%}$(5.02 TeV) / $R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 1.13 ± 0.02(stat) ± 0.18(syst)

increase of J/ψ R_{AA} for all centralities and over large range of p_t (but within 1 σ)

J/psi and transport models (and stat hadronization)





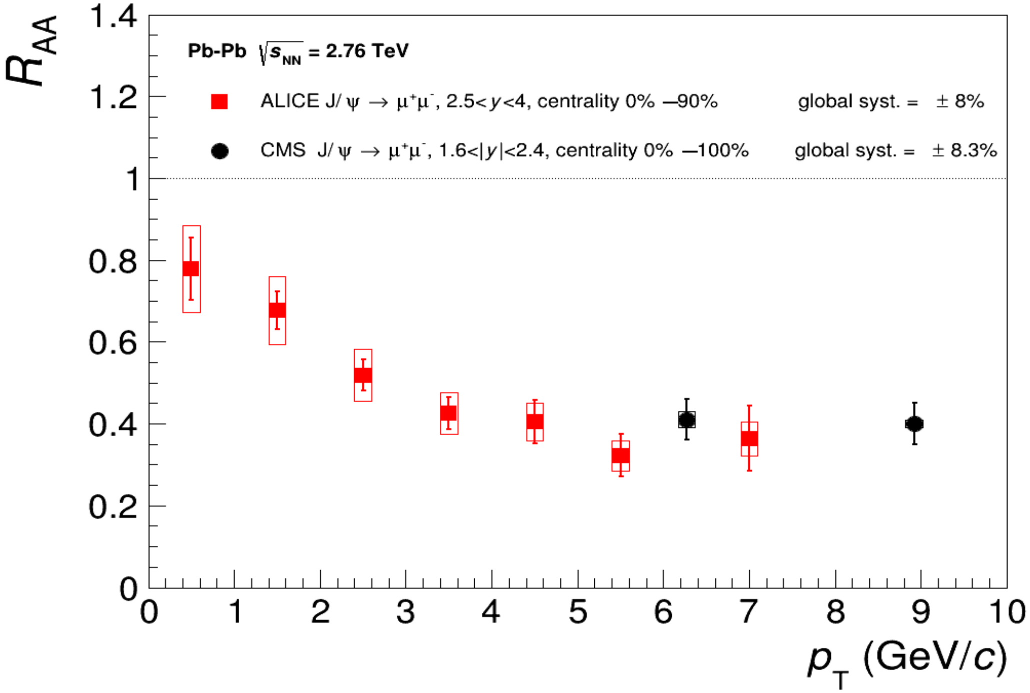
in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with R_{AA}

  part of J/psi from direct hard production, part dynamically generated in QGP, part at hadronization, but different open charm cross section used

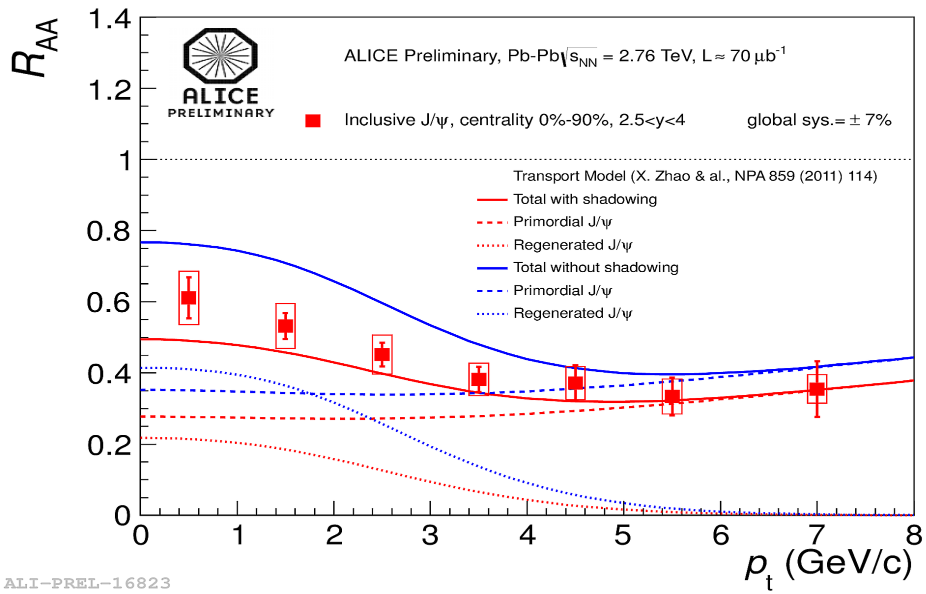
  (0.5-0.75mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM)

p_t Dependence of J/psi R_{AA}



relative yield larger at low p_t in nuclear collisions

good agreement with CMS at high pt

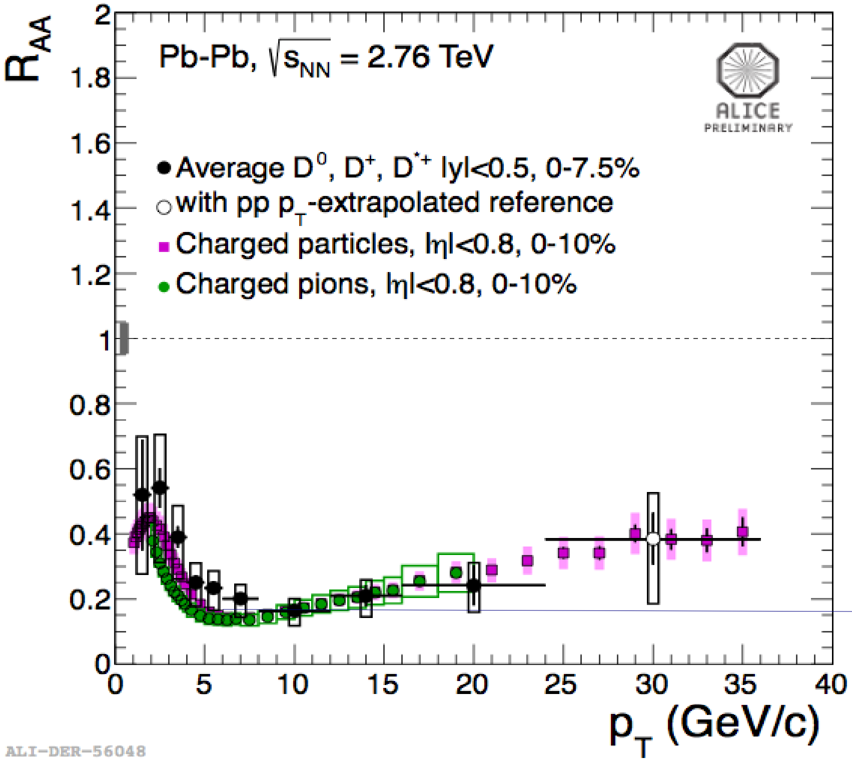


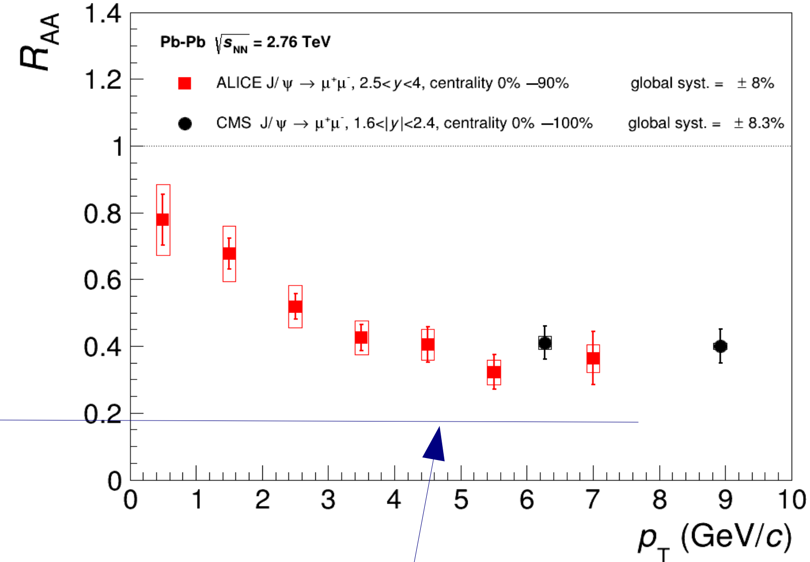
statistical hadronization only expected for charm quarks thermalized in the QGP

p_t dependence in line with this prediction

in CMS only suppression

p_t dependence of R_{AA}

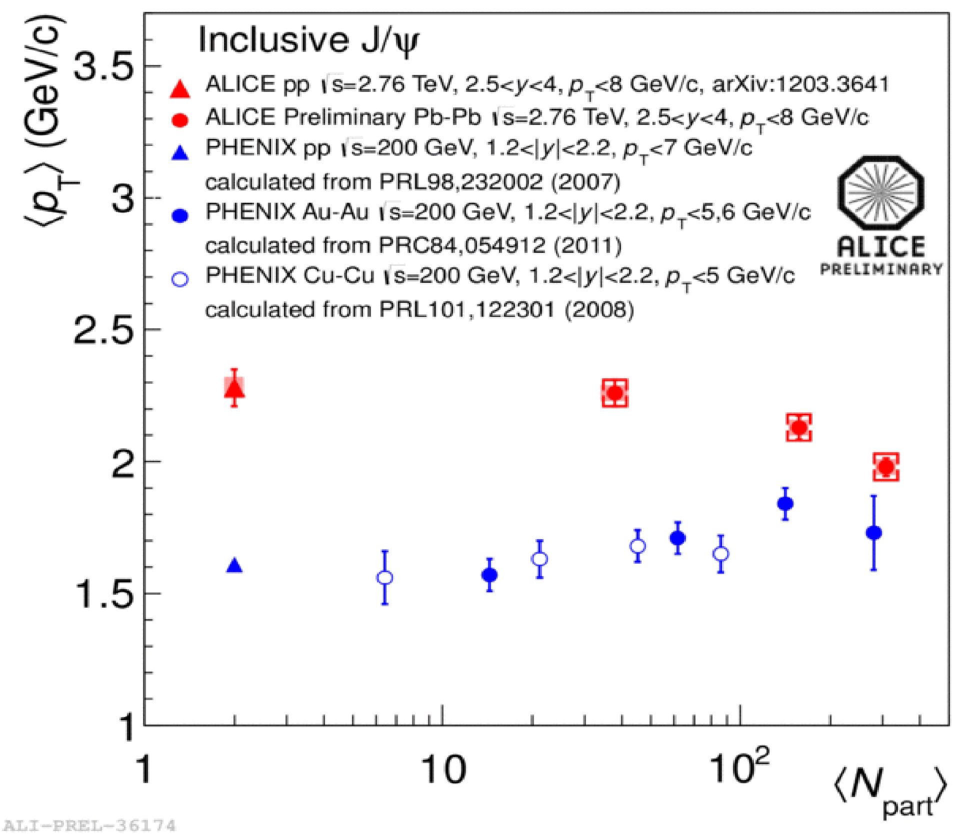


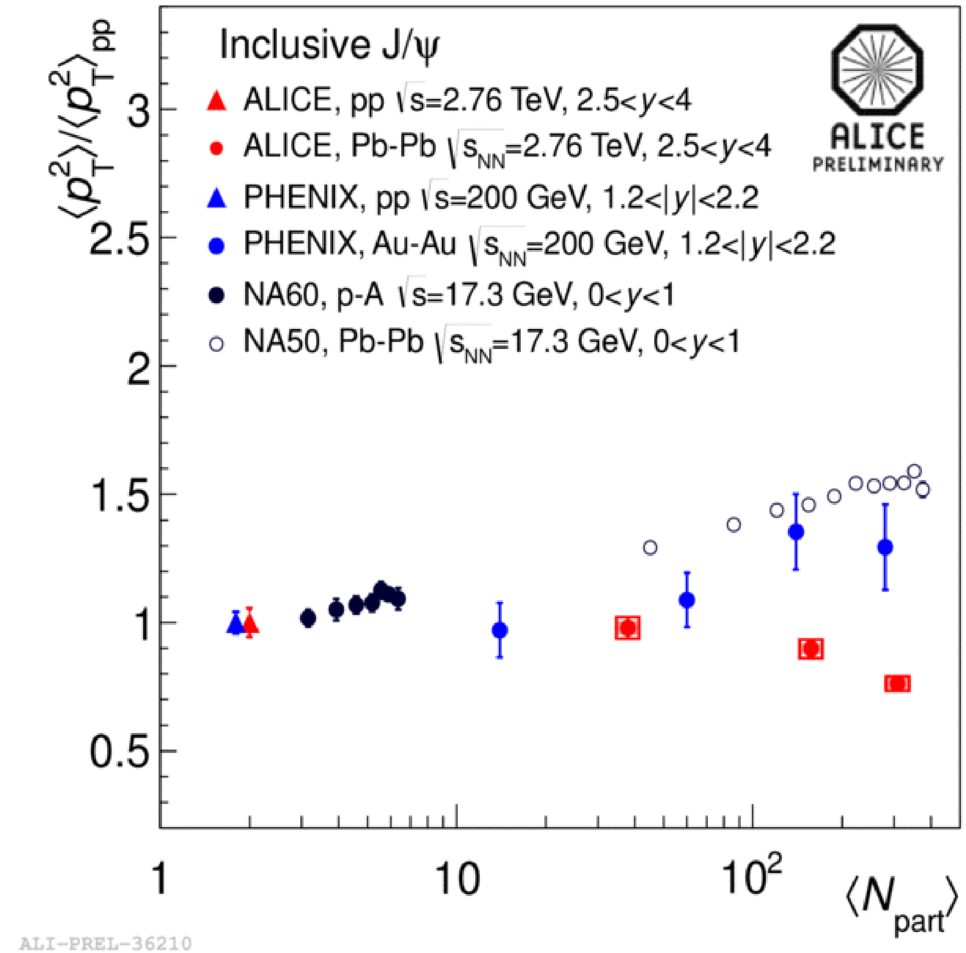


is high p_t part indicative of the same charm quark energy loss seen for D's

out to what p_t is statistical hadronization/regeneration relevant?

Softening of J/psi p_t distributions for central PbPb collisions

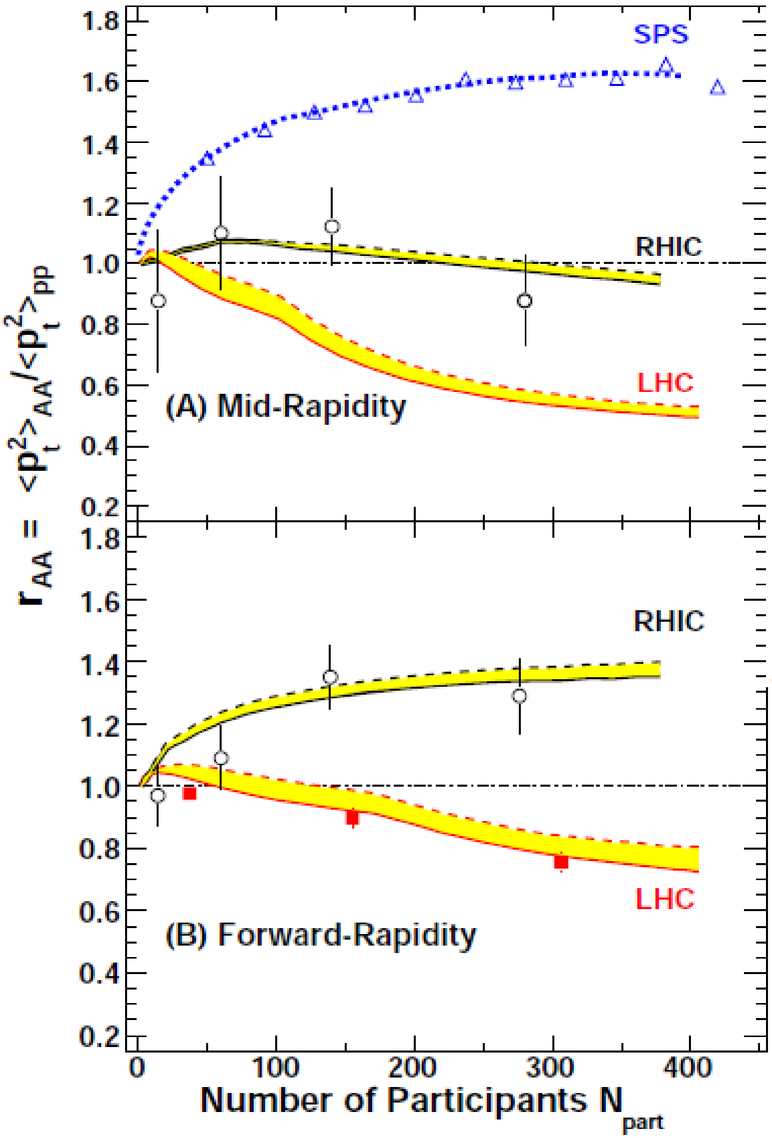


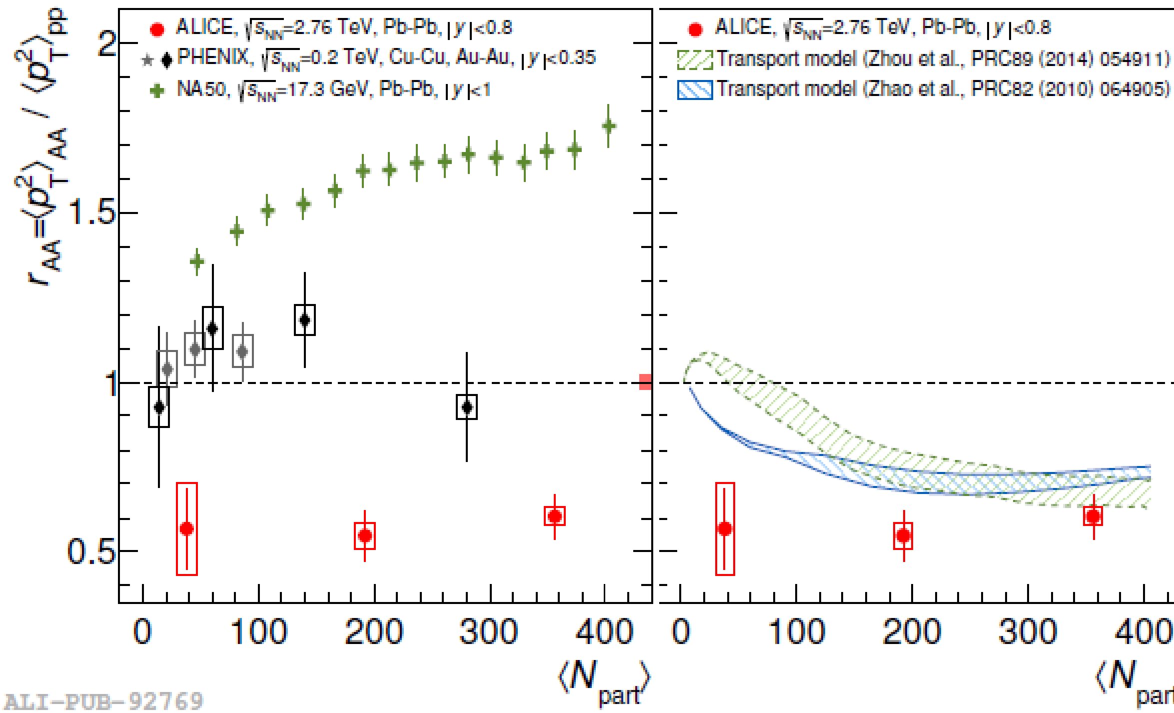


At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

Analysis of transverse momentum spectra

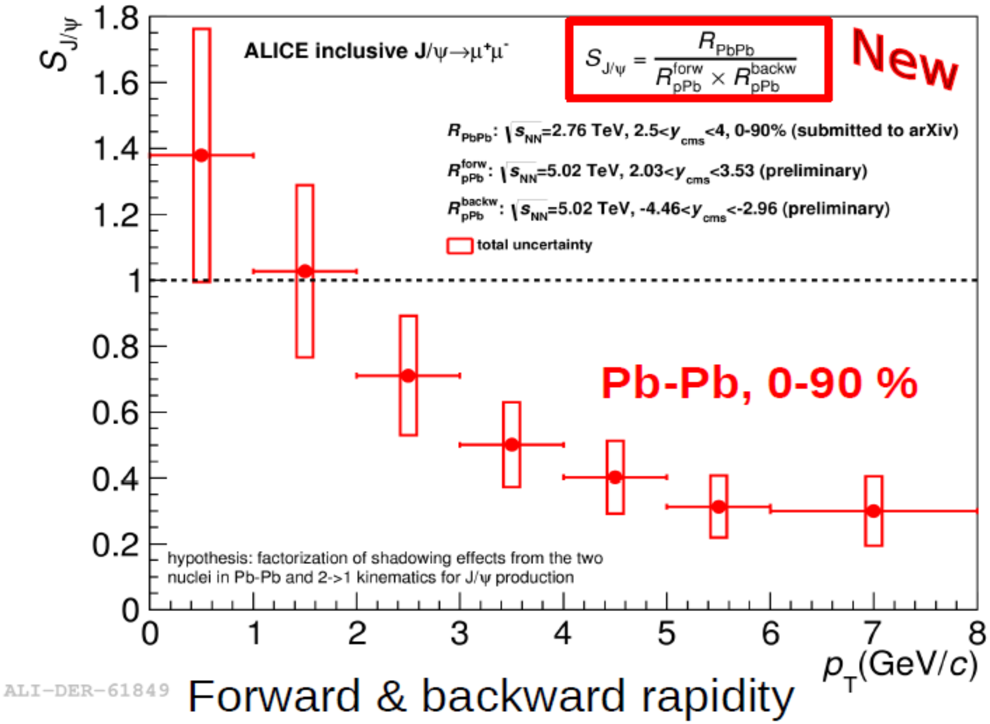
Zhou, Xu, Zhuang, arXiv:1309.7520

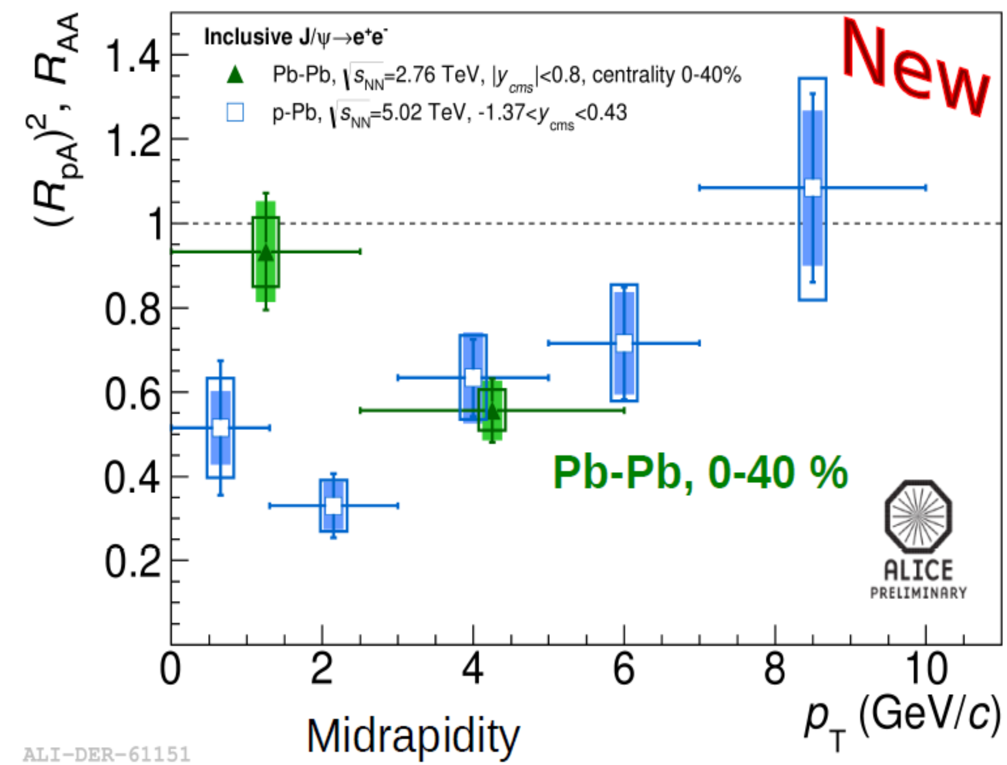




- at LHC energy, mostly (re-) generation of charmonium
- p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks
- **challenge to regeneration models**

J/psi vs pt in PbPb collisions relative to pPb collisions



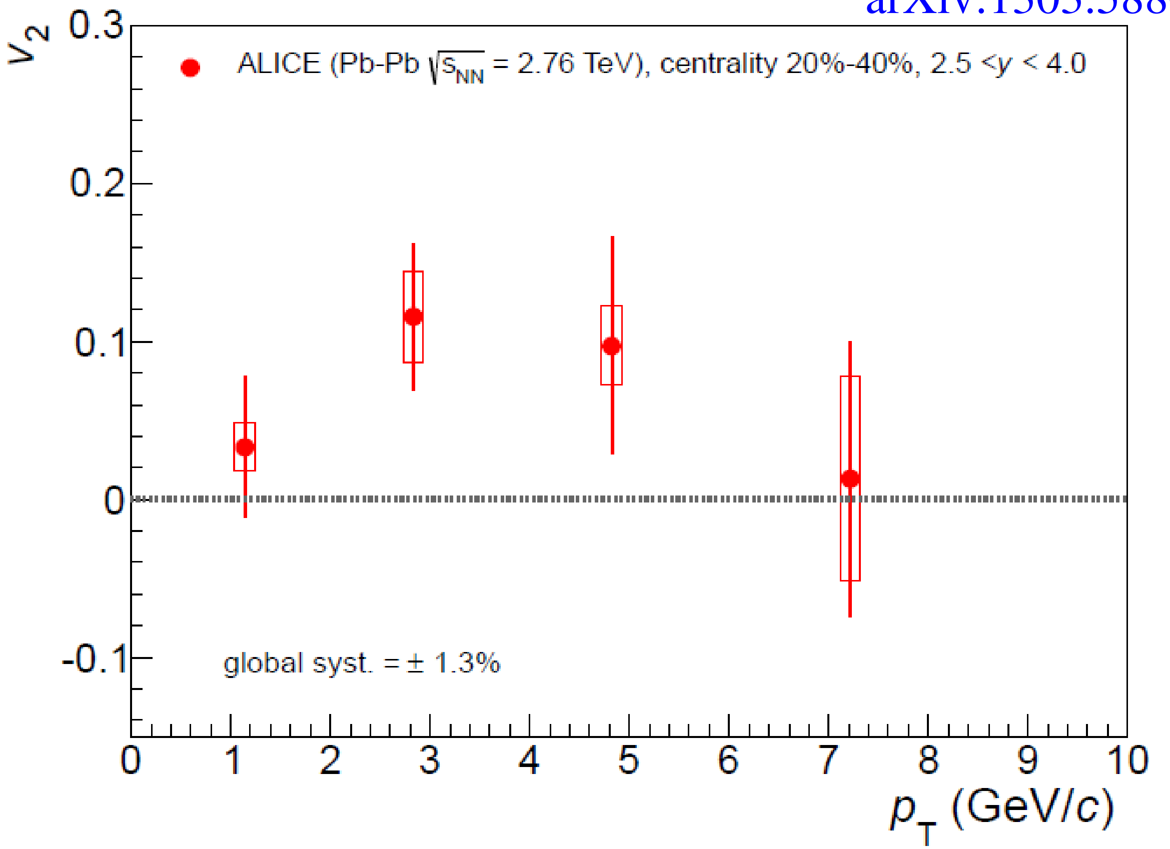


at low pt yield in nuclear collisions above pPb collisions

J/psi production enhanced in nuclear collisions over mere shadowing effect

Elliptic Flow of J/psi vs pt

arXiv:1303.5880



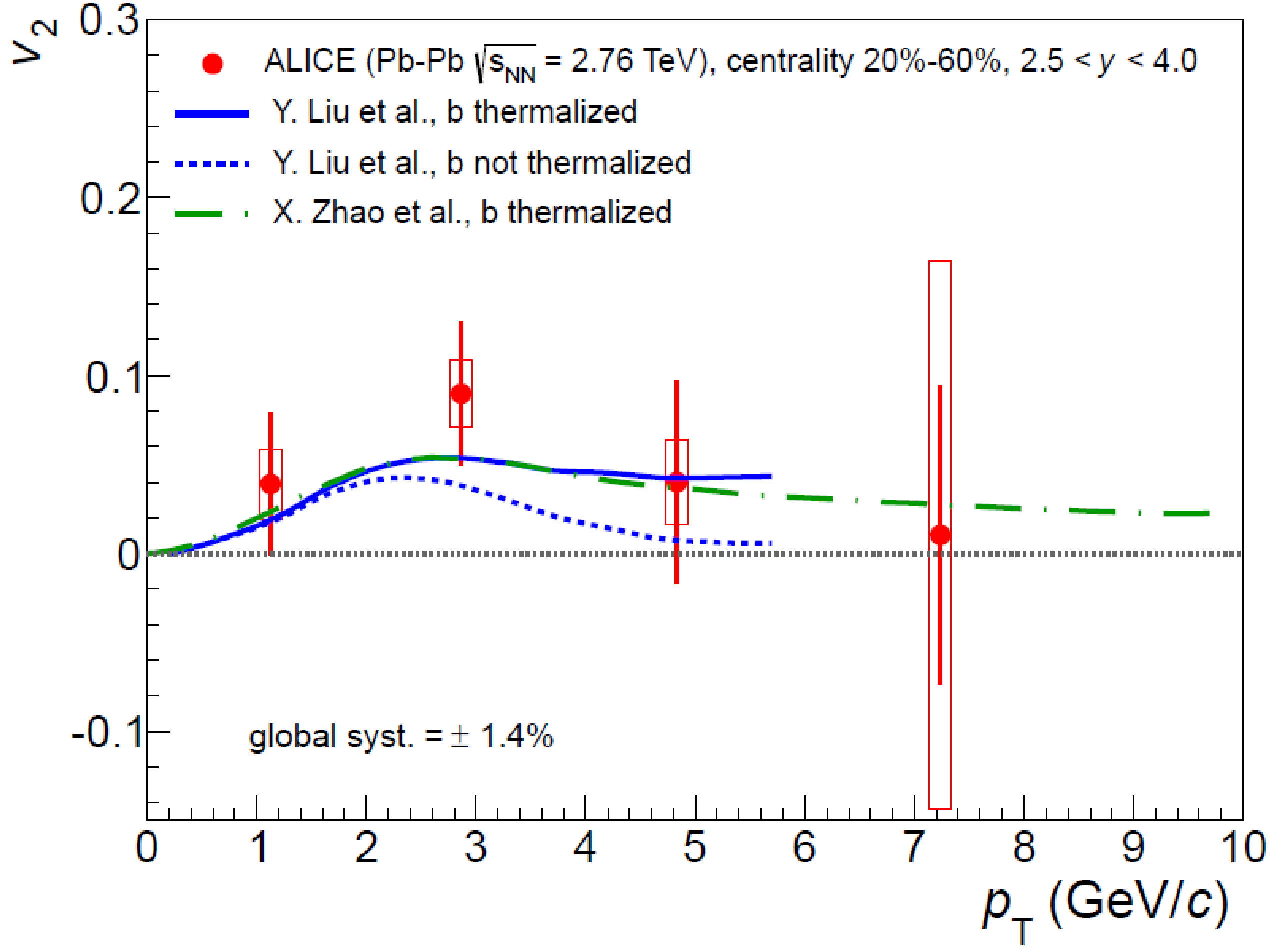
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, …
and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

first observation of J/ψ v_2
in line with expectation from statistical hadronization

J/psi flow compared to models including (re-) generation

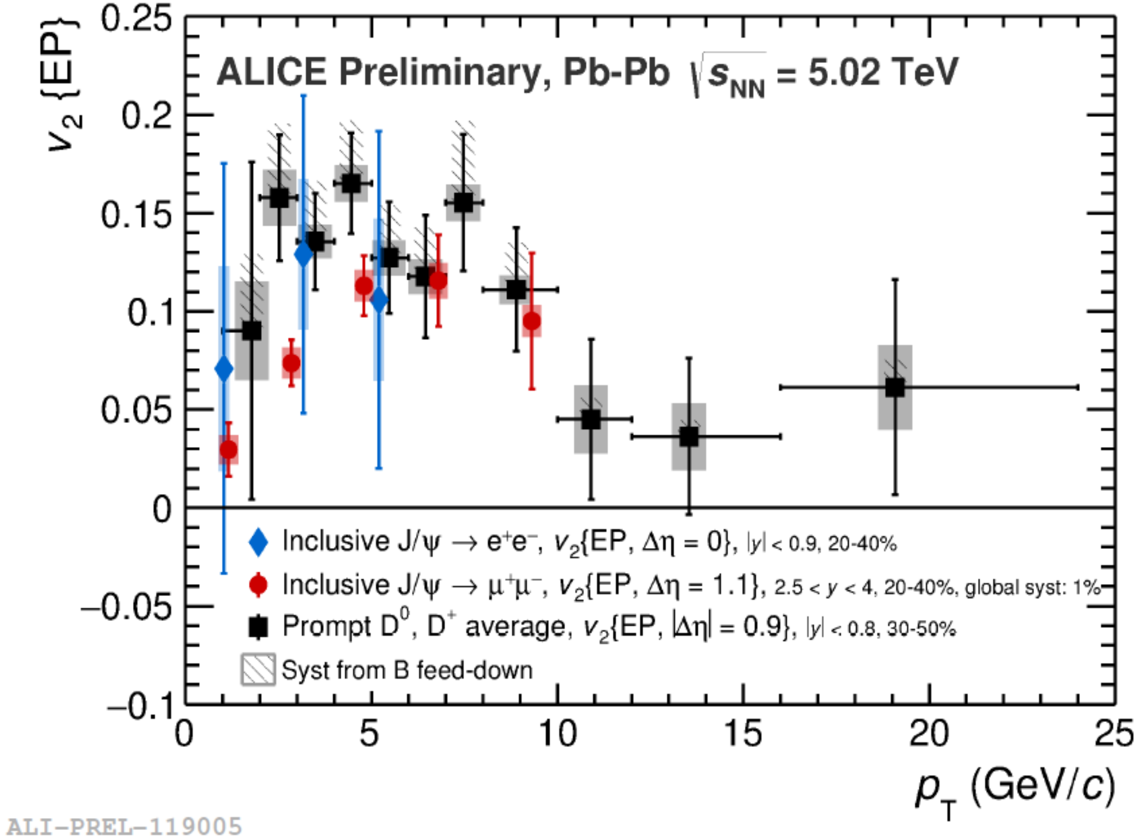
arXiv:1303.5880



v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

Elliptic flow of J/ψ vs p_t

arXiv:1705.05810



charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

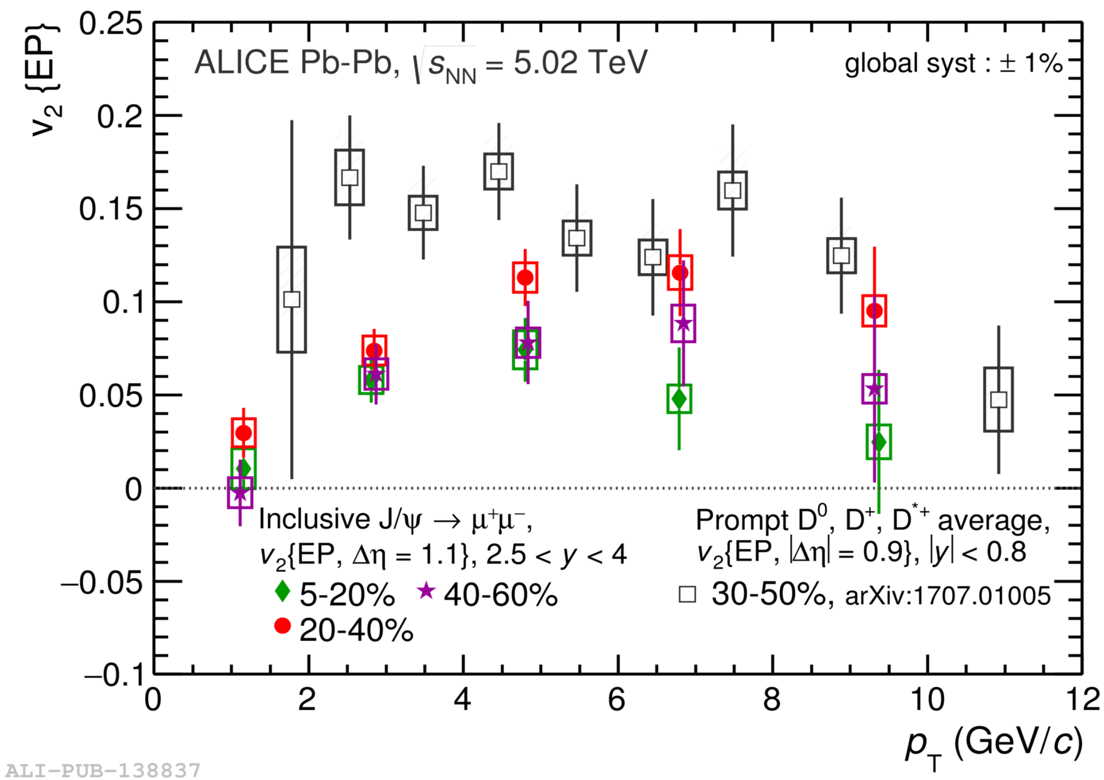
- expect build-up with p_t as observed for π, p. K, Λ, …

and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

first observation of significant J/ψ v_2 in line with expectation from statistical hadronization

Elliptic flow of J/ψ vs p_t

arXiv:1709.05260

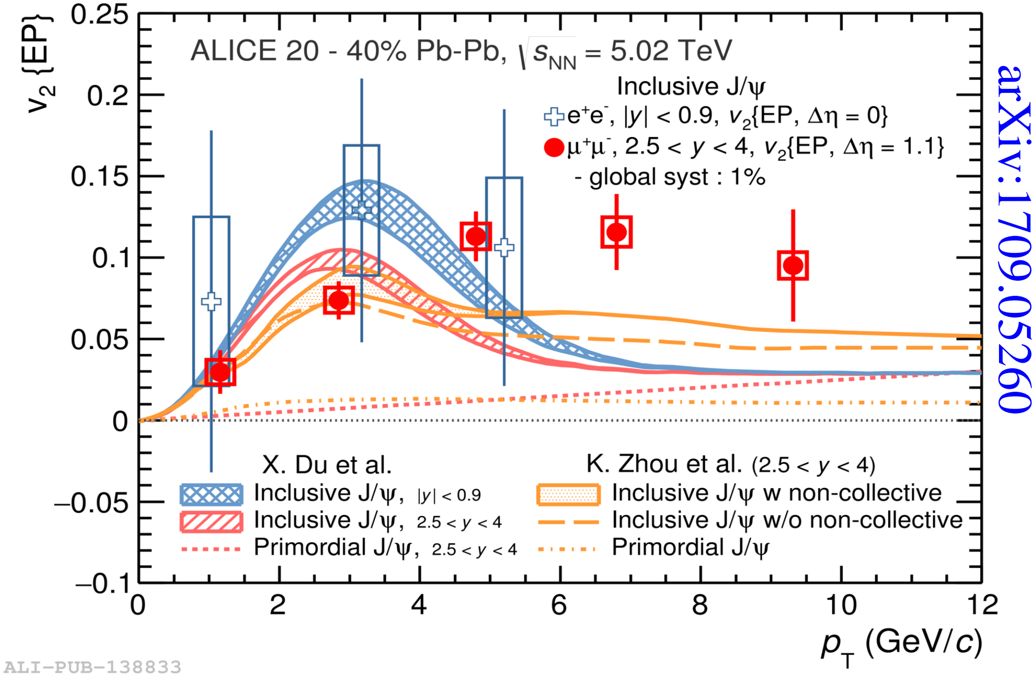


Strength of J/ψ v_2 similar to D-mesons

Elliptic flow of J/ψ

charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

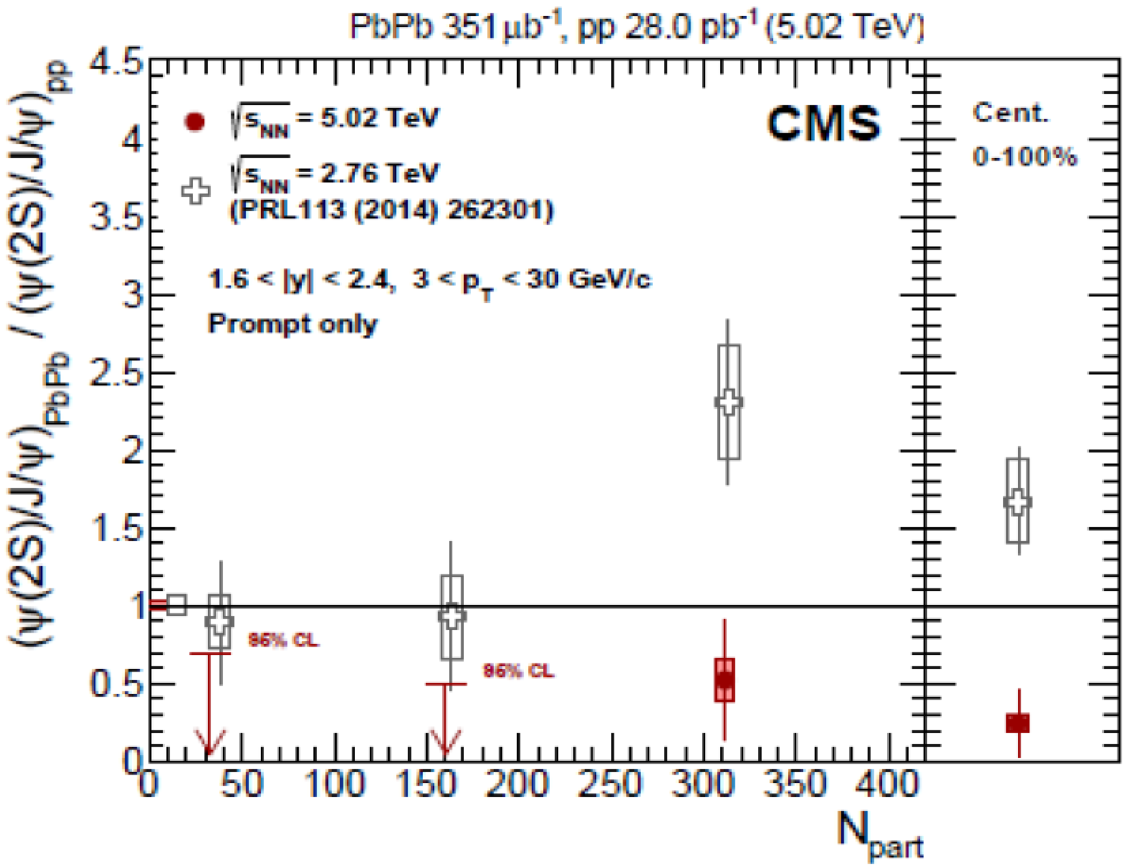
first observation of significant J/ψ v_2 both at forward and mid rapidity



J/ψ elliptic flow in line with expectation from statistical hadronization

ψ(2S)

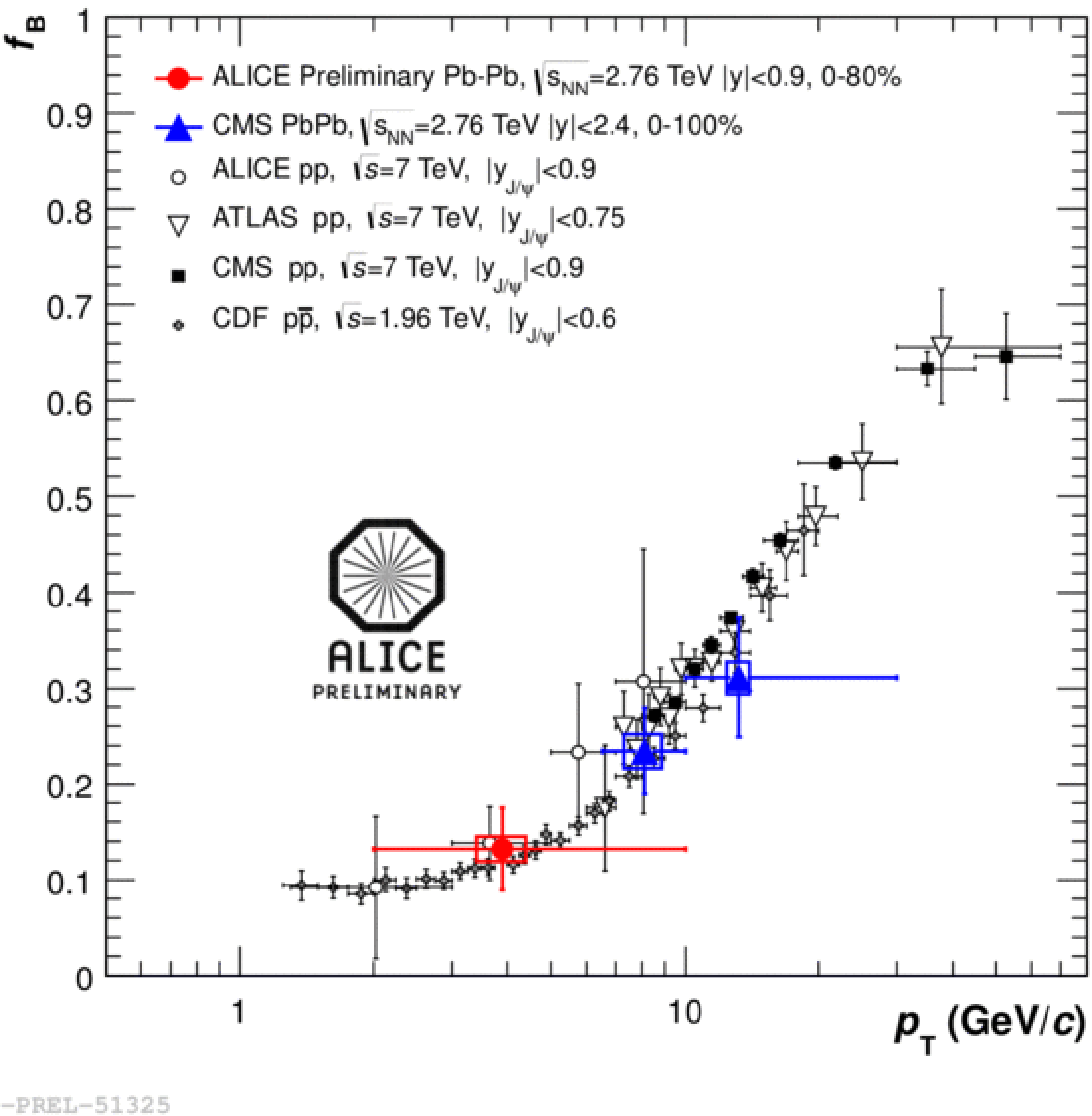
in picture where psi is created from deconfined quarks in QGP or at hadronization, psi(2S) is suppressed more than J/psi – run1 CMS results indicate the opposite!



expect value of 1/3 for inclusive pt and central collisions

the anomaly (enhancement relative to pp) from 2.76 TeV is not there at 5.02 TeV - very nice ALICE data from pt=0 to be approved this week

Fraction of J/psi from B-decays



p_t integrated non-prompt B-fraction of small
within current errors no significant difference in pp and PbPb collisions

Outlook – what ALICE can do in the future

LHC run1:

2 PbPb runs

- 2010 $O(10\ \mu b^{-1})$
- 2011 $O(150\ \mu b^{-1})$

luminosity reached $\mathscr{L}=2\ 10^{26}\ cm^{-2}\ s^{-1}$ twice design lumi at this energy

1 pPb run

- 2012/2013 $O(30\ nb^{-1})$

from 2/2013 until end of 2014 LS1: consolidation of LHC to allow full energy

LHC run2: 2015-2018 PbPb running at $\sqrt{s_{NN}} = 5.5$ TeV

to achieve approved initial goal of 1 nb^{-1}

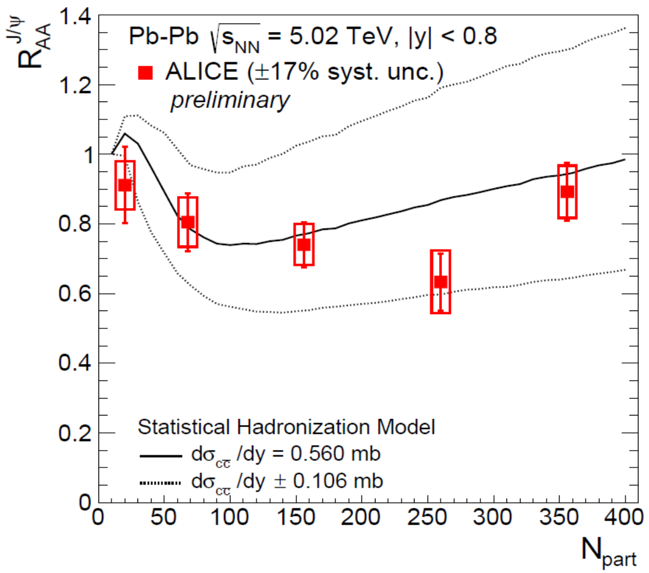
2019 start LS2 – increase of LHC luminosity und experiment upgrade, LHCb will join PbPb!

LHC run3: 2021 onwards - expect $\mathscr{L}=6\ 10^{27}\ cm^{-2}\ s^{-1}$ or PbPb interactions at 50 kHz

achieve for PbPb 10 nb^{-1} corresponding to $8\ 10^{10}$ collisions sampled

plus a low field run of 3 nb^{-1} + pp reference running + pPb - a program for about 6 years

J/psi as probe of deconfinement



well on the way towards goal for run2
expect still a huge jump in performance
for runs3/4

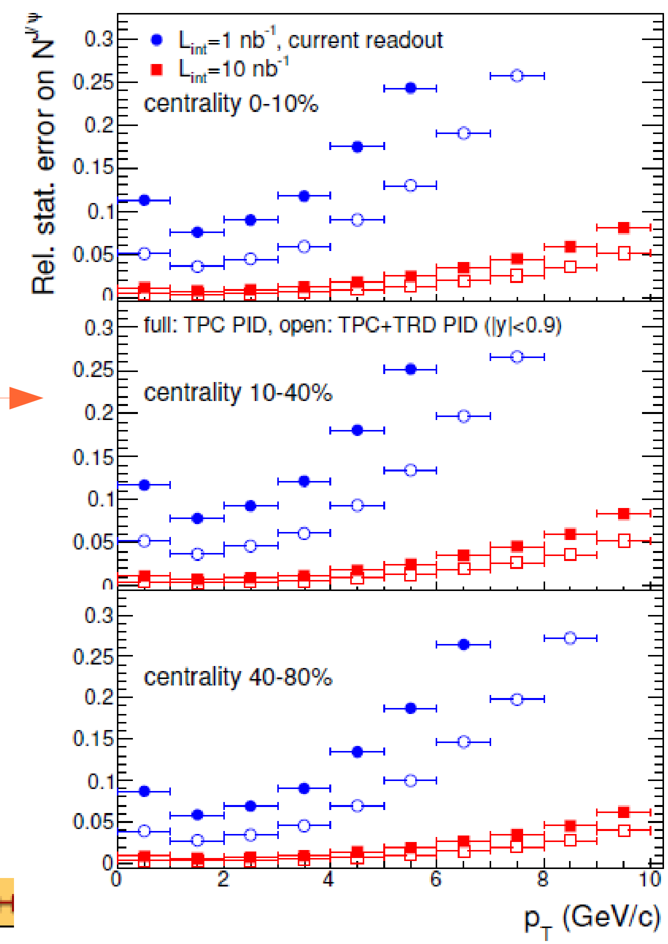
di-electrons statistics limited, 10 nb^{-1} will have huge effect

but also syst uncertainties will decrease with upgrade:

will also add TRD for electron id - reduced comb background

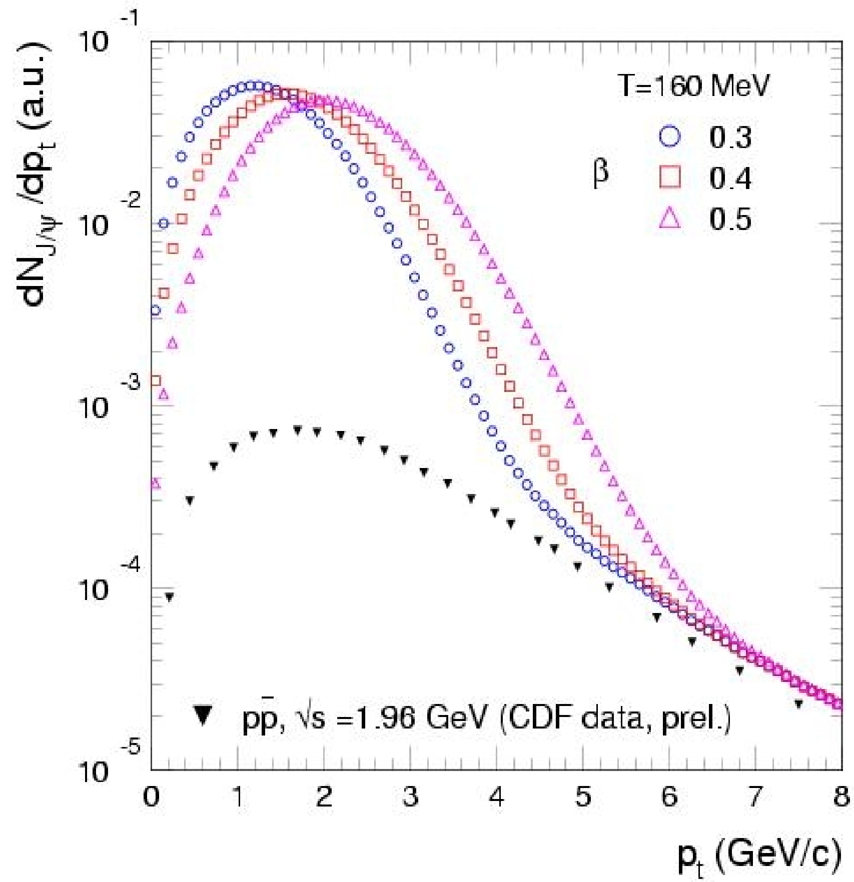
thinner ITS reduced radiation tail

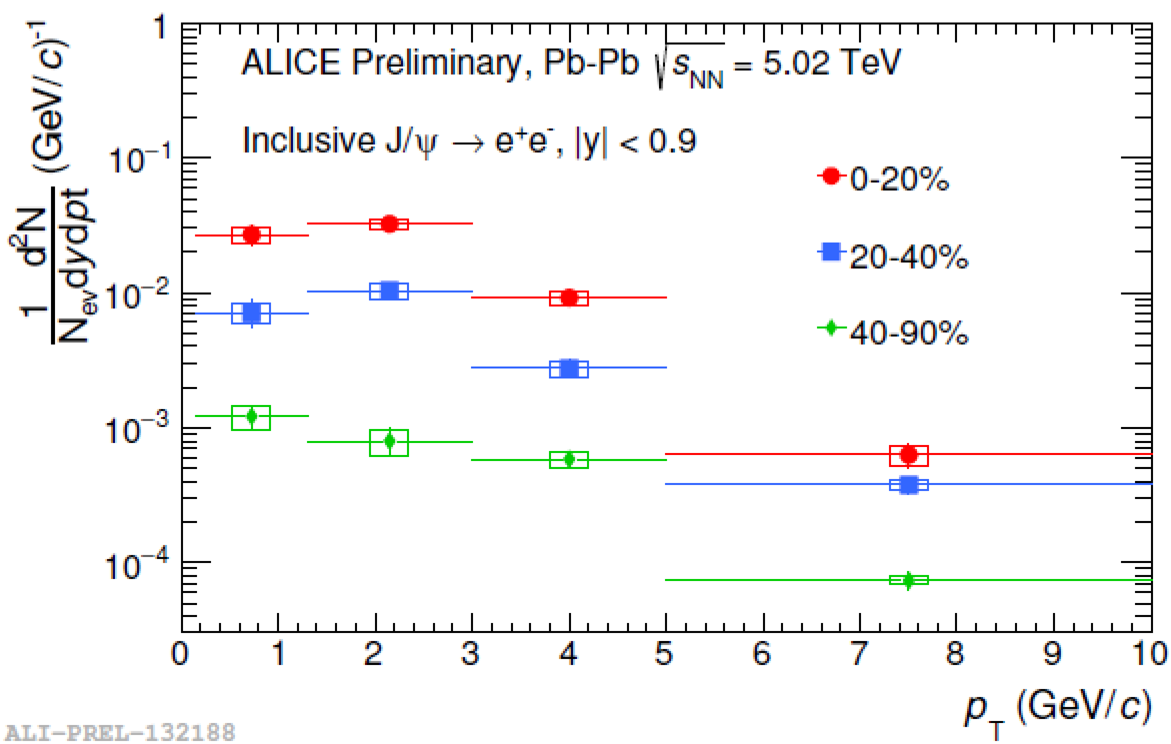
both affect signal extraction



spectral distribution is key to thermalization

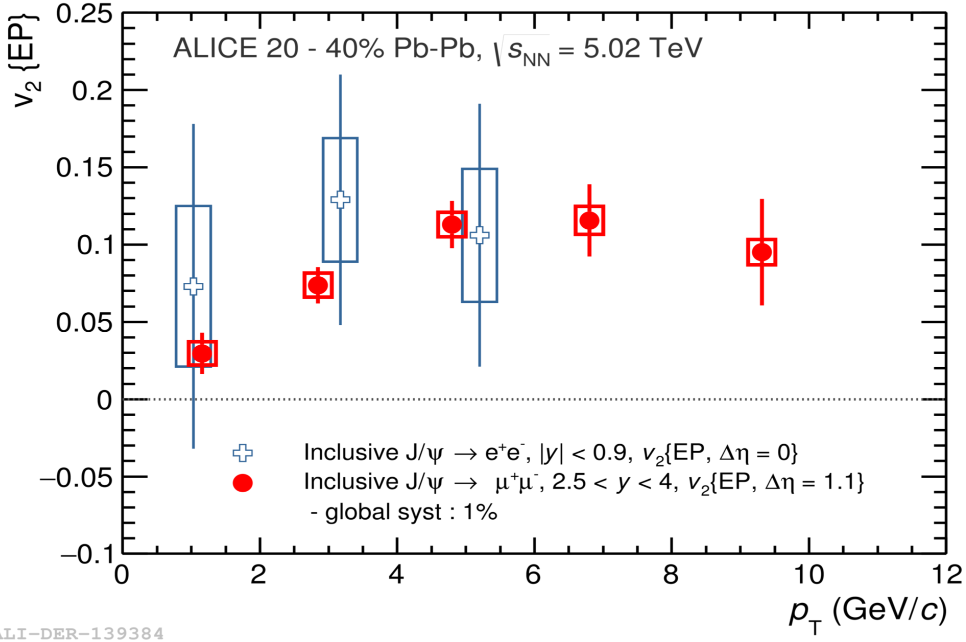
if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid





first spectra a mid-y appearing
much more to come
we are computing spectra

J/psi elliptic flow



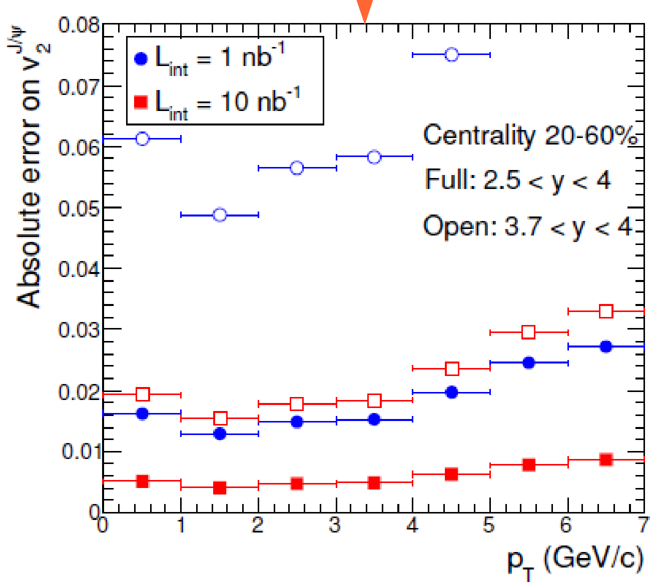
ALI-DER-139384

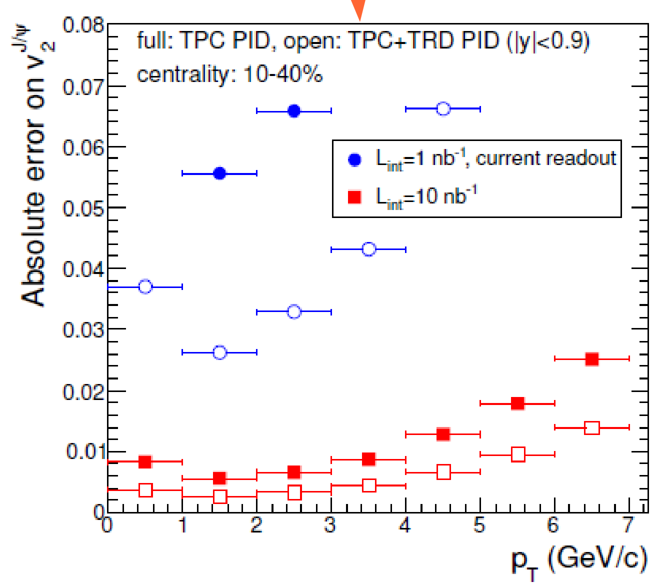
goal for run2 in muon arm already achieved
for e+e- at mid-y getting there

future statistical errors

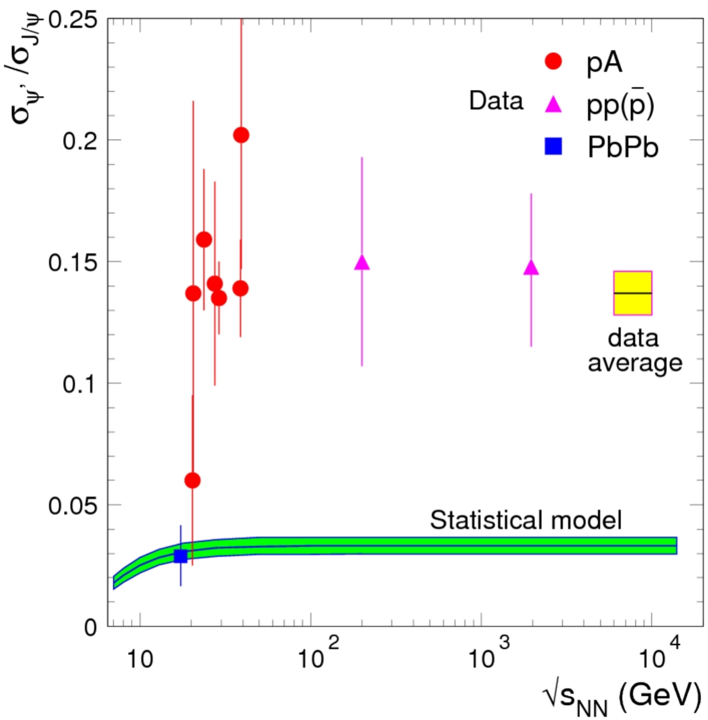
muon arm

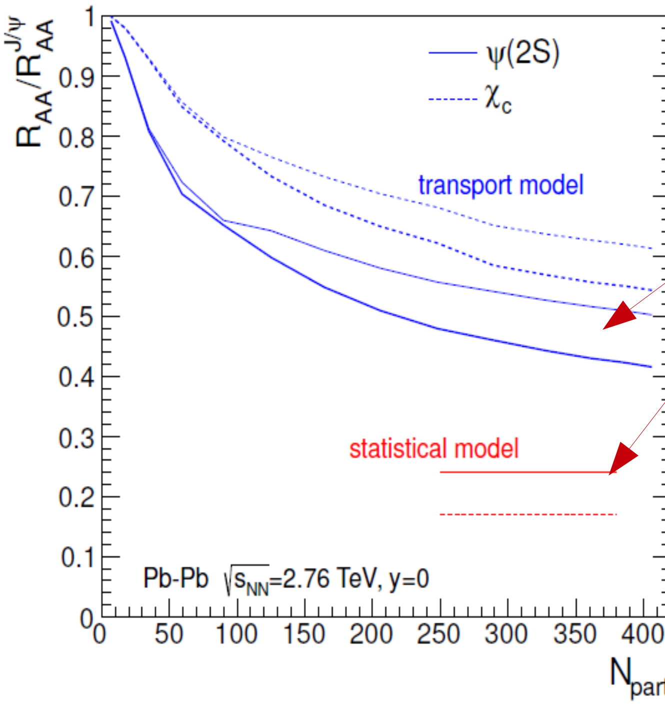
central barrel





excited charmonia crucial to distinguish between models



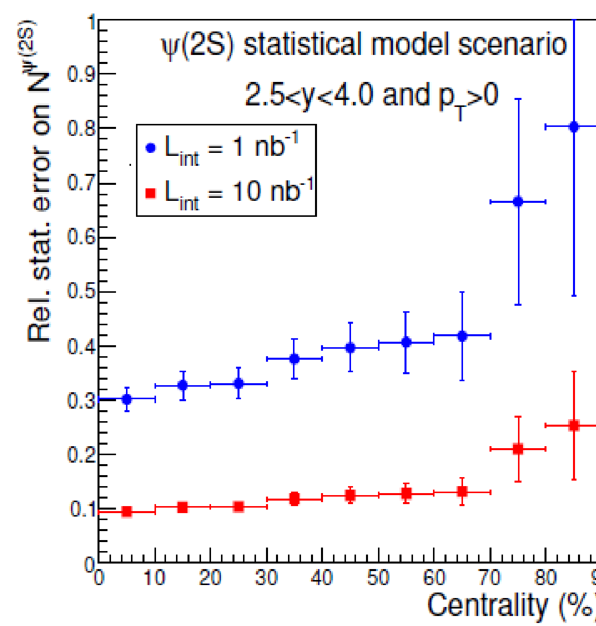


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

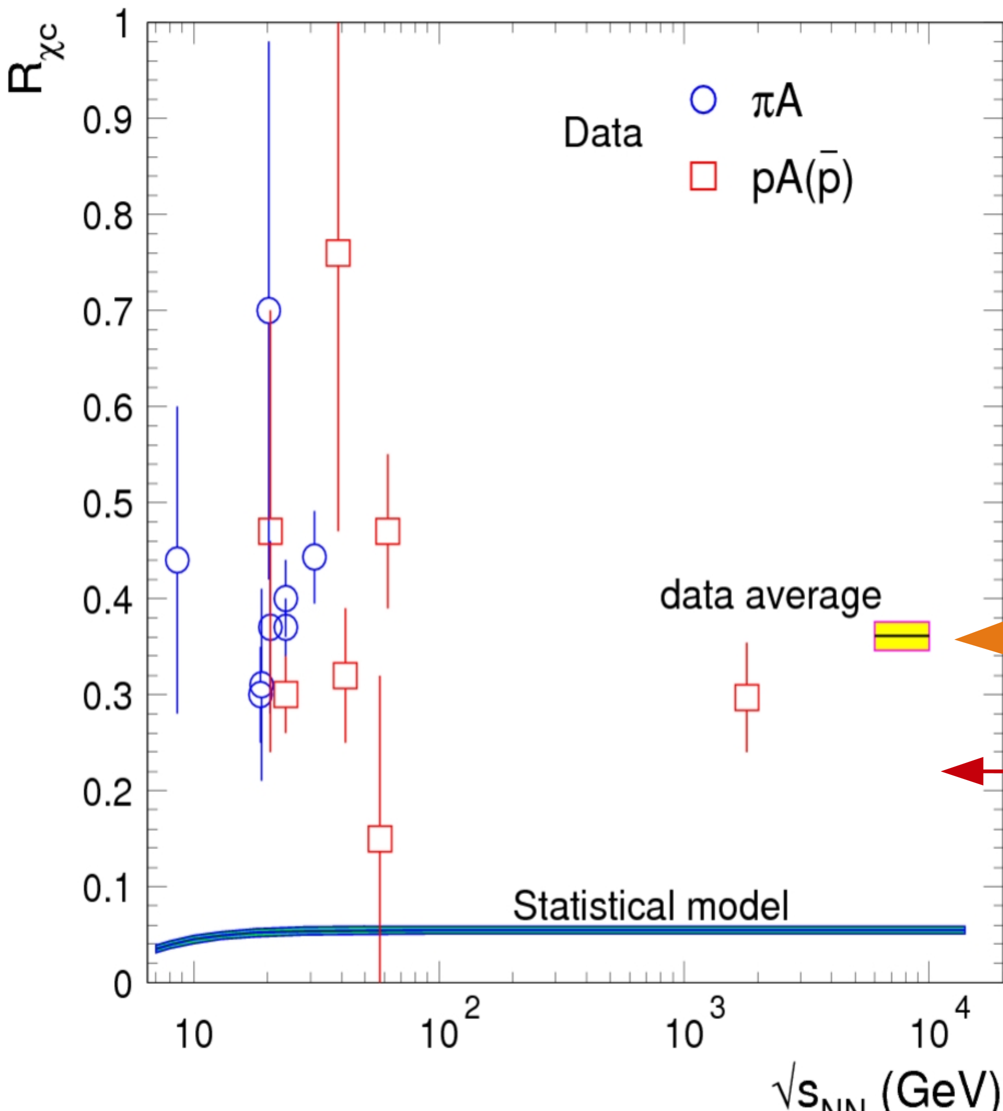
for statistical hadronization need to see suppression by Boltzmann factor

χ_c even bigger difference

expected ALICE performance muon arm run2 and run3



Situation even more dramatic for P-states

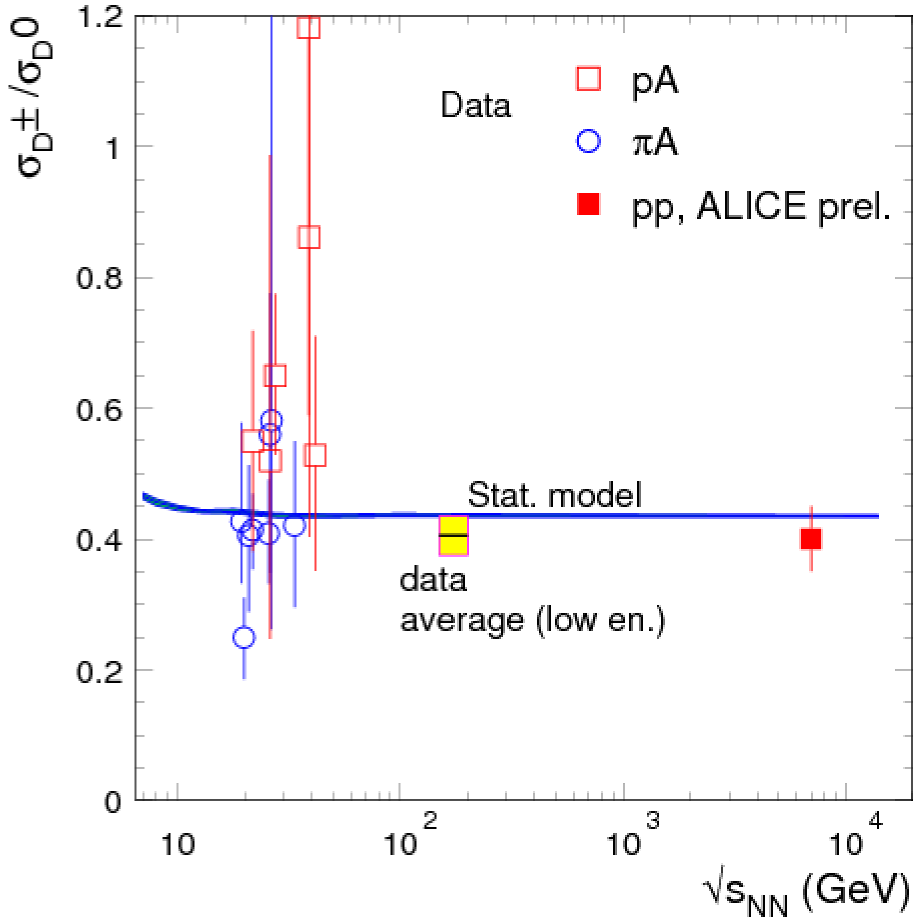


pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

Charged to neutral D-mesons

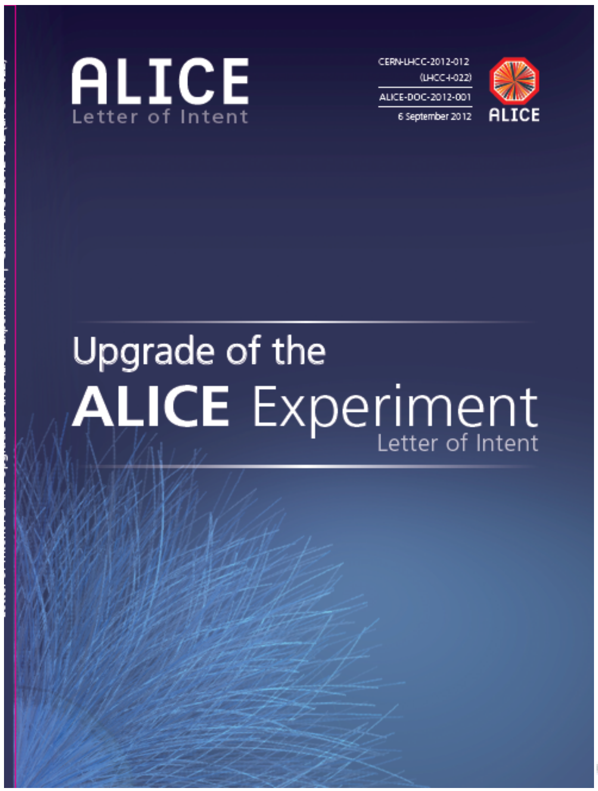


open charm hadrons in pp collisions consistent with quarks hadronizing at about T = 165 MeV

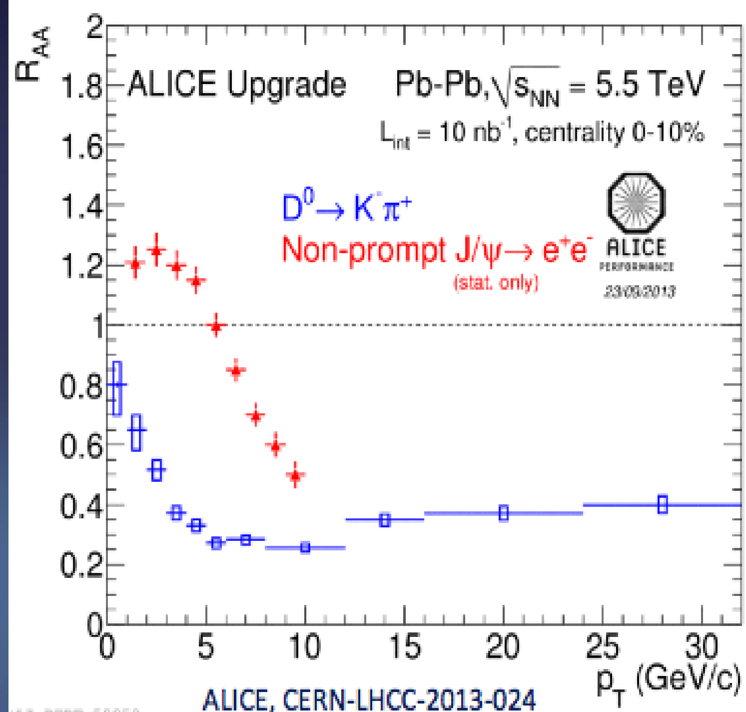
what about PbPb collisions? all D and Λ_c states predicted. Data to come soon!

outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase (TPC upgrade)

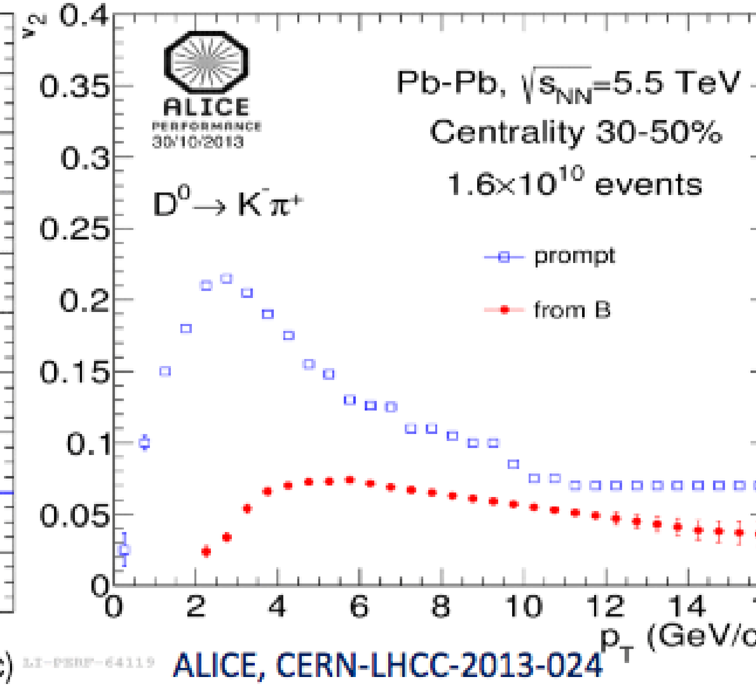


Upgrade



Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ

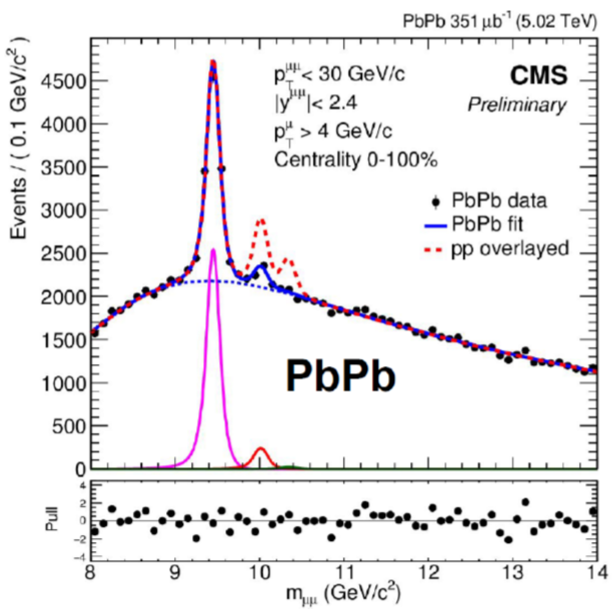
Upgrade

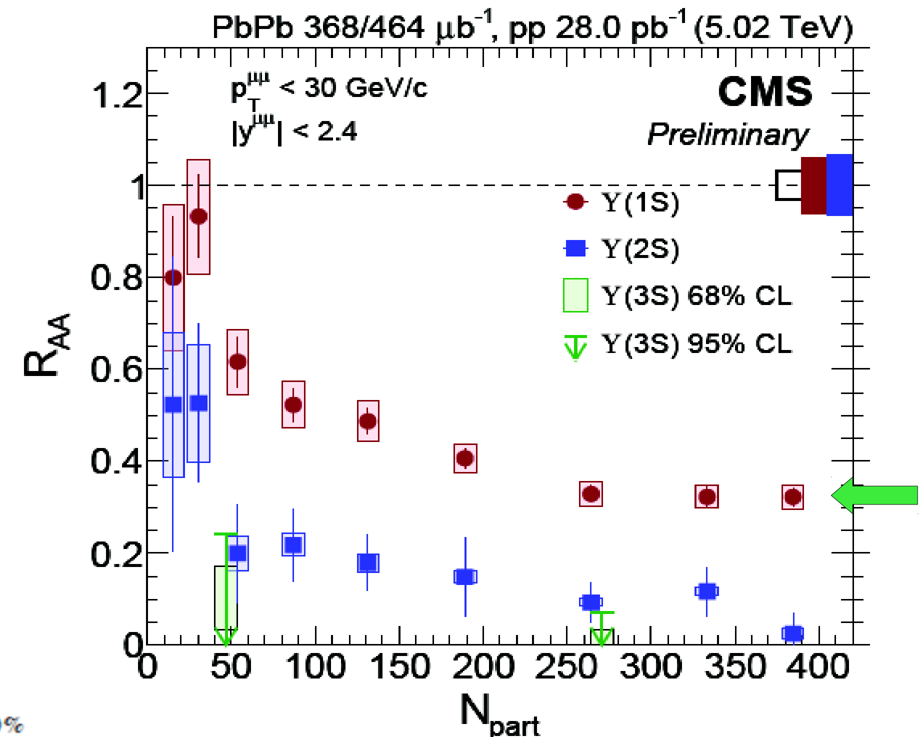


Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

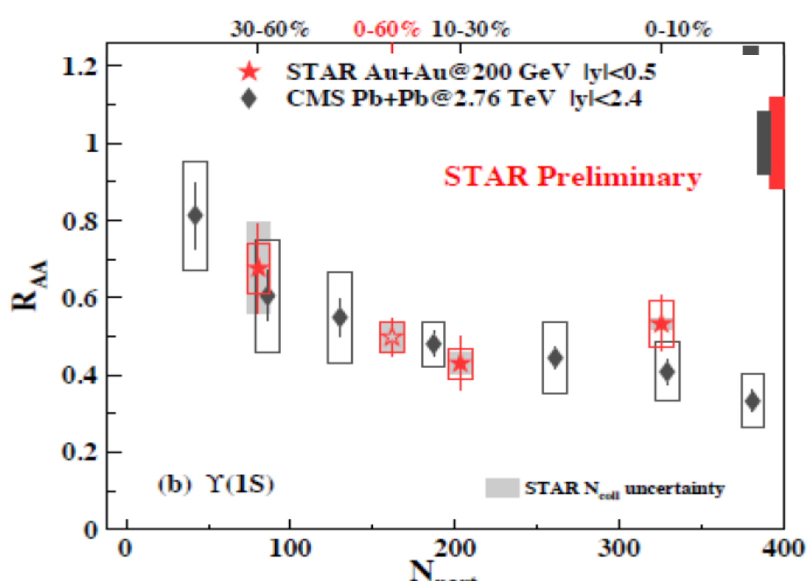
Charm v_2 down to p_T~0 using prompt and beauty v_2 down to B p_T~0 using B-decay D^0

Suppression of Upsilon states



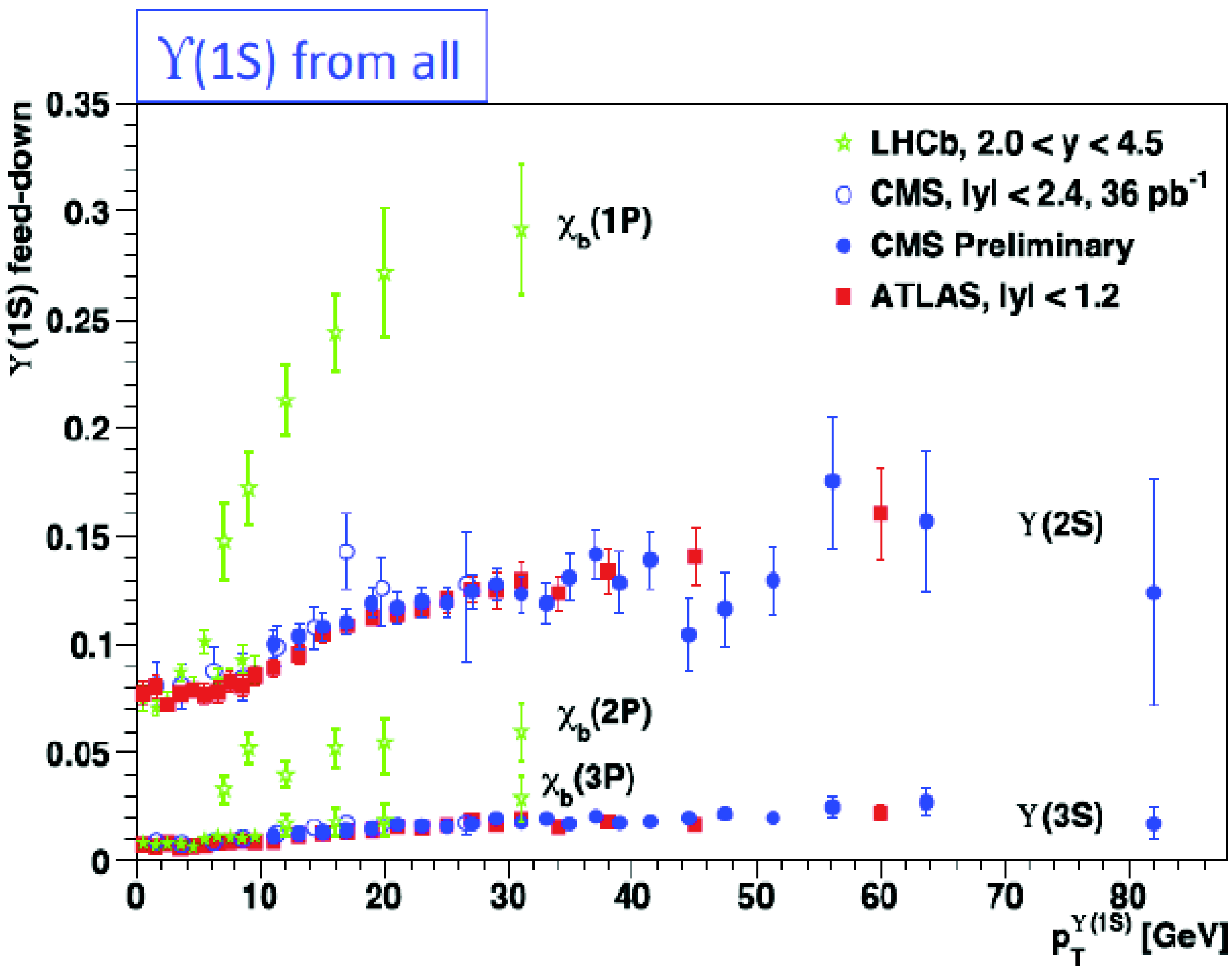


not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)

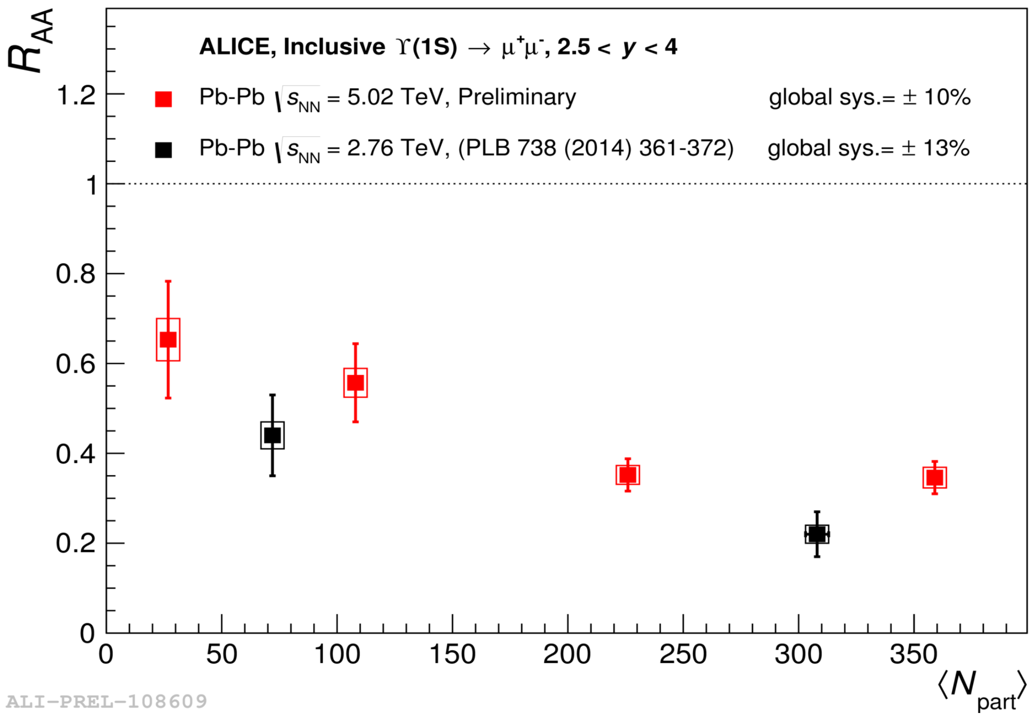


genuine Upsilon suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

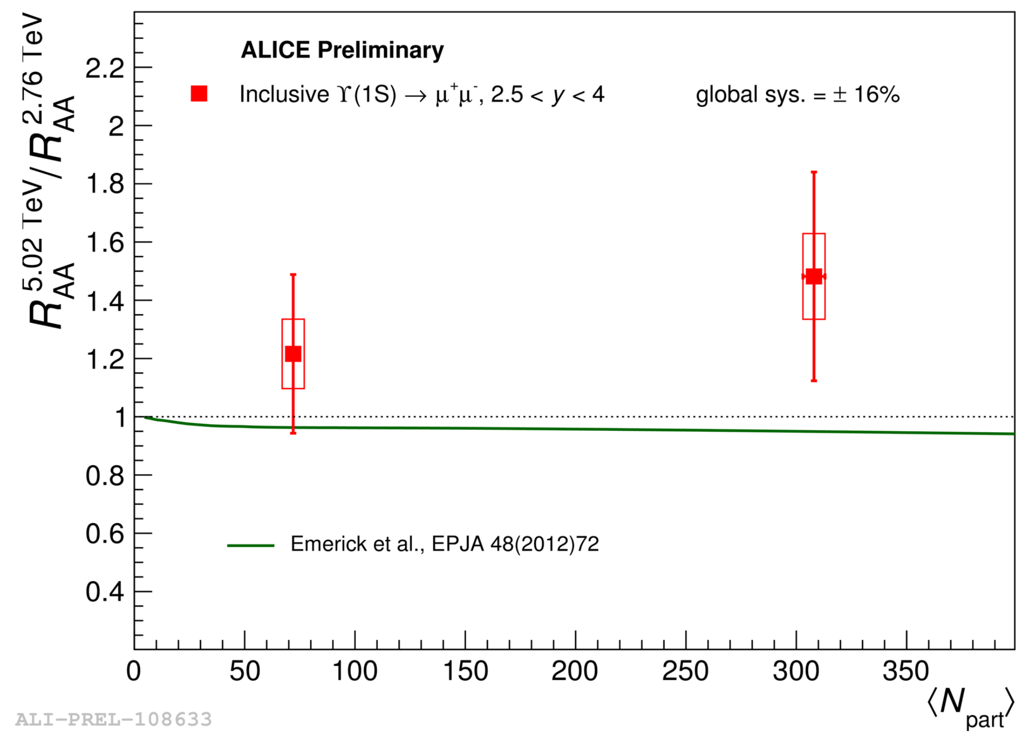
Feeding into Upsilon (1S)



Upsilon in PbPb at 5 TeV compared to 2.76 TeV



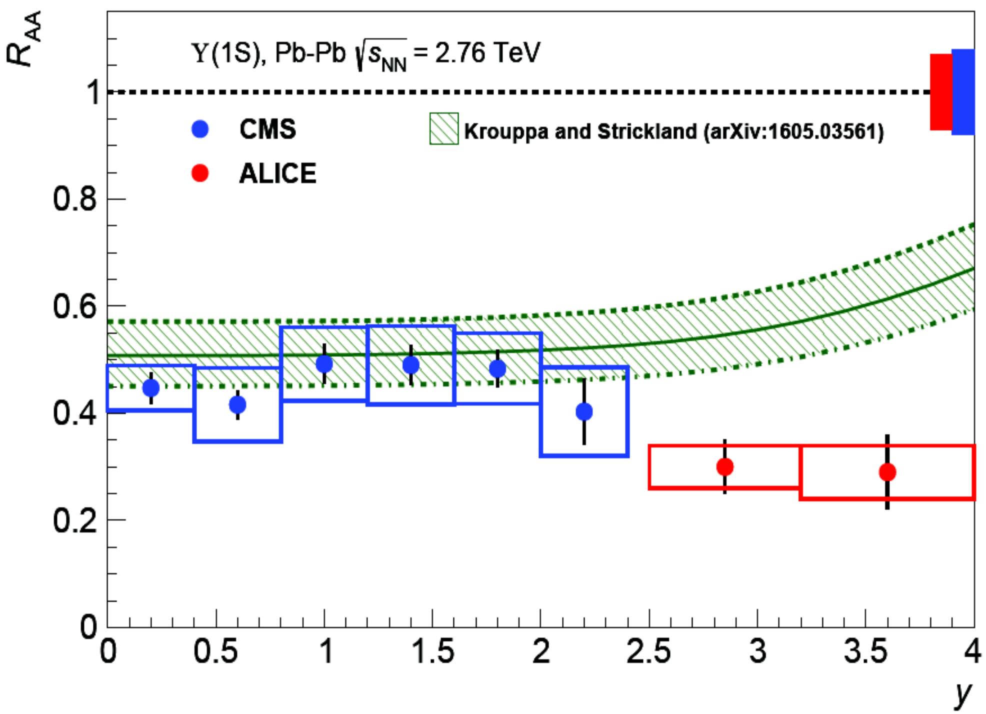
yield of Upsilon(1S) increases with beam energy

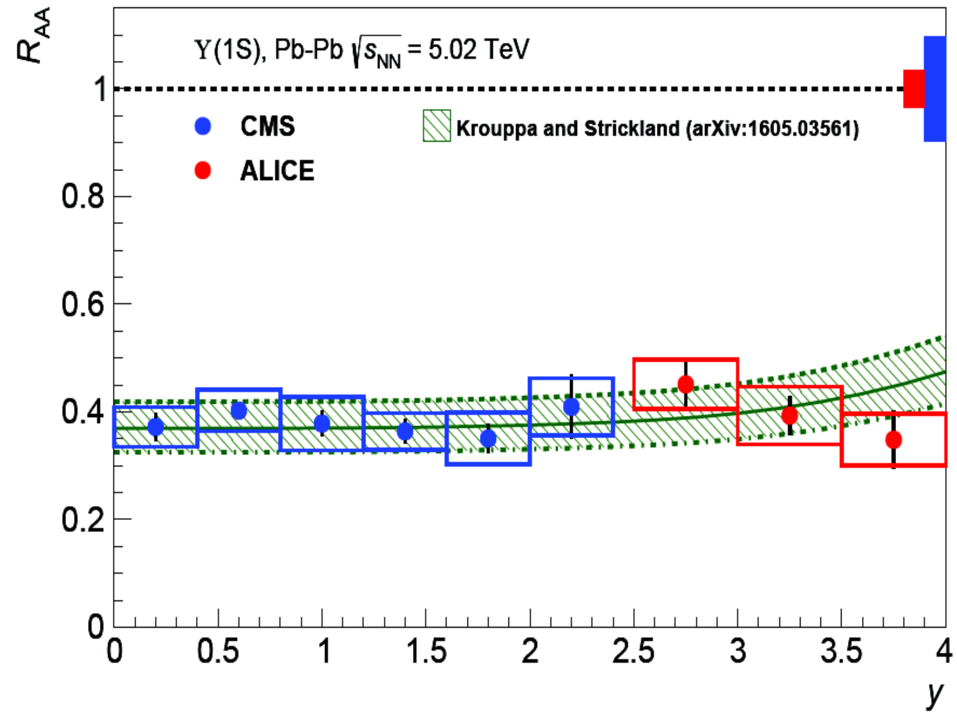


dissociation of Upsilon in a hydrodynamically medium will not produce an increase with increasing energy density

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

Upsilon R_{AA} rapidity dependence

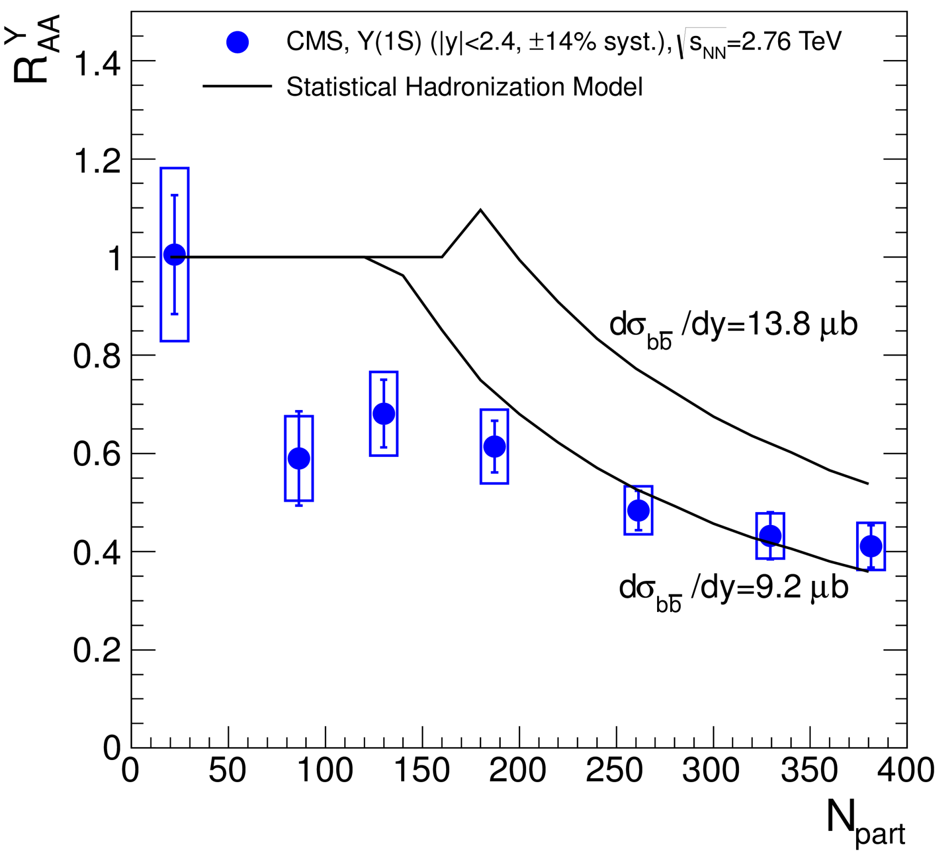


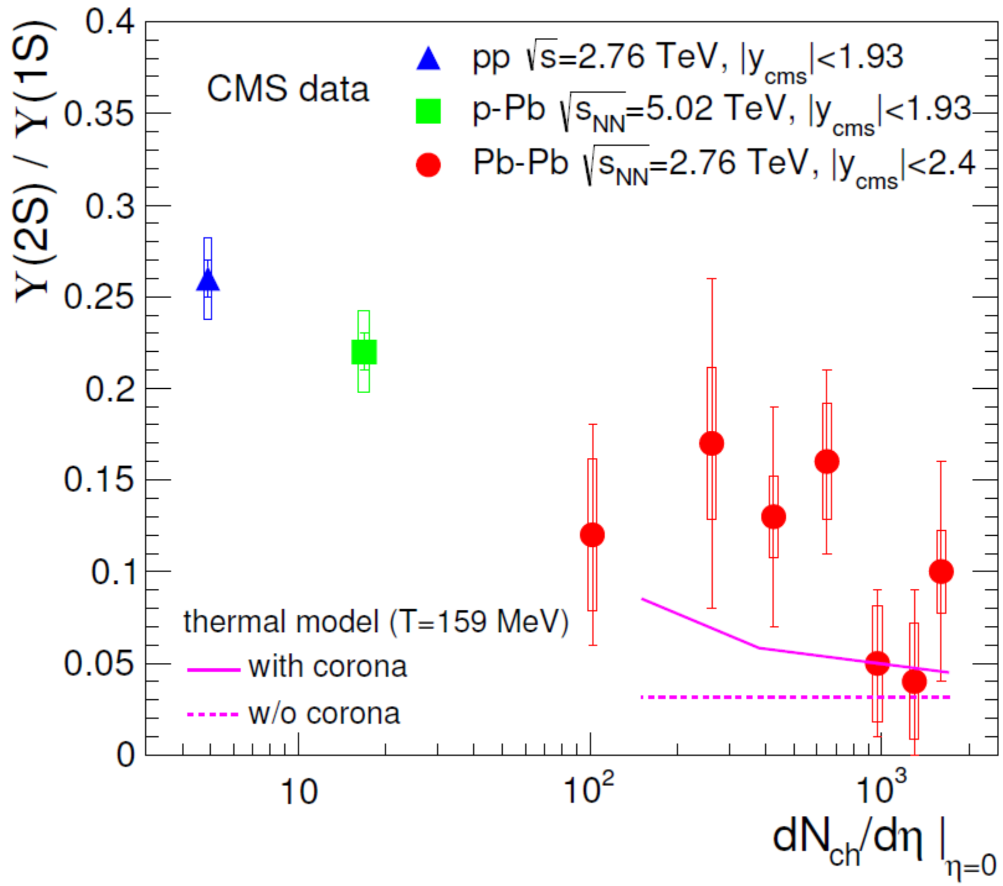


Indication: R_{AA} peaked at mid-y like for J/ψ
not in line with collisional damping in expanding medium

the Upsilon could also come from statistical hadronization

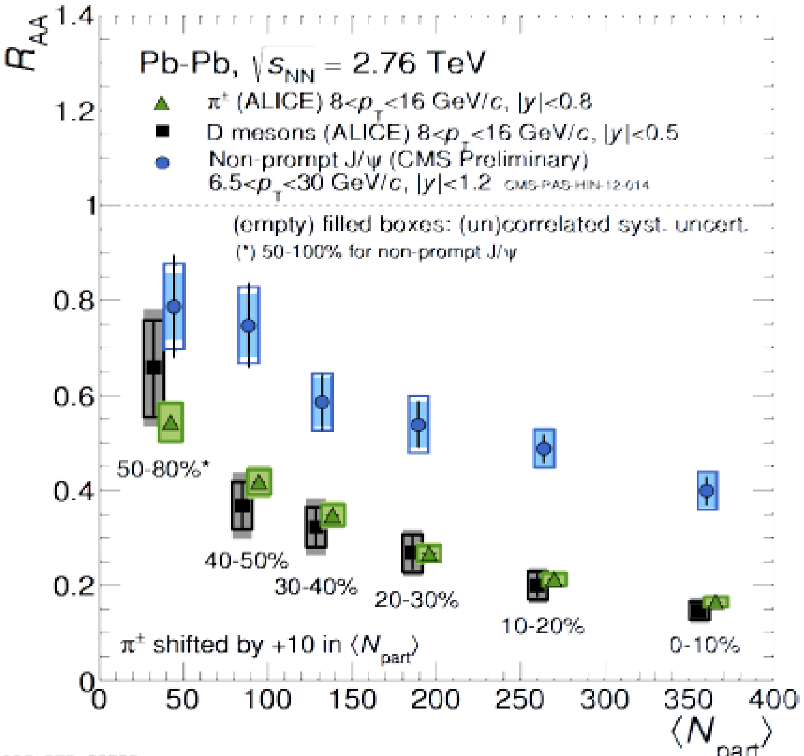
SHM/thermal model: Andronic et al.





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

what about b-quark energy loss and thermalization?

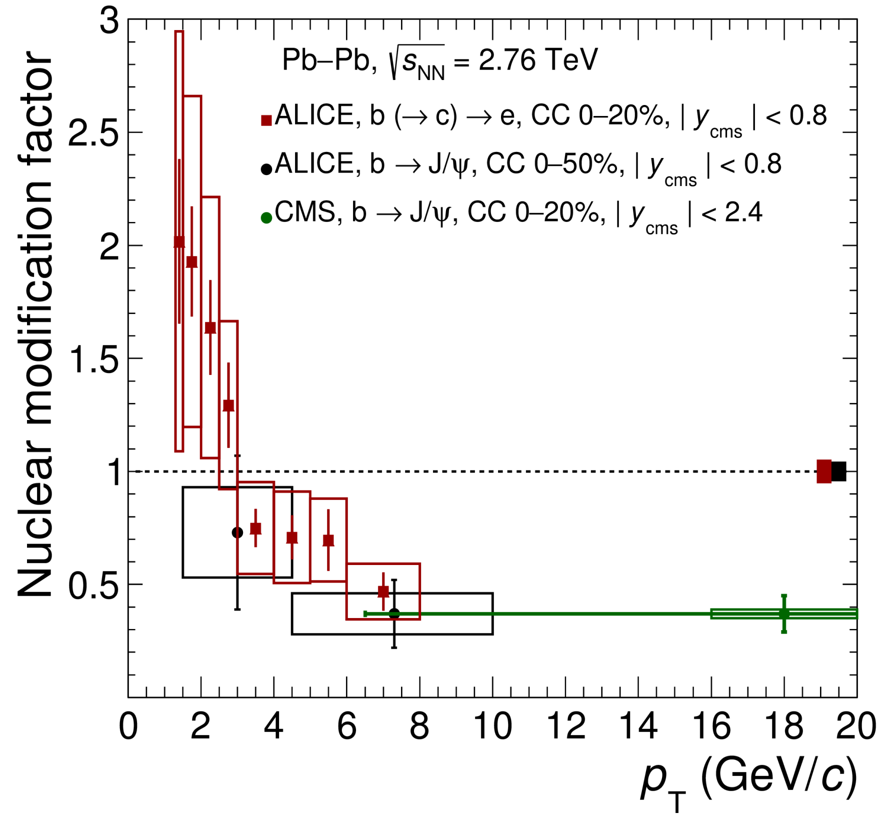


Charm: D mesons

JHEP 11 (2015) 205

Beauty: non-prompt J/ψ

arXiv:1610.00613



b → c → e arXiv:1609.03898

separation via impact parameter distribution

- mass ordering between charm and beauty observed
- for more central collisions, electrons from b-decay show suppression for p_t > 3 GeV/c