Recent Results from ALICE on heavy flavor probes of the Quark-Gluon Plasma

- introduction
- open charm and beauty
  brief here, afternoon talks by A. Mischke and J. Norman
- charmonium data
- bottomonium

Johanna Stachel, Universität Heidelberg
55th Int.Winterworkshop on Nuclear Physics
Bormio, Italy, January 24, 2017

ALICE

ISOQUANT
SFB1225

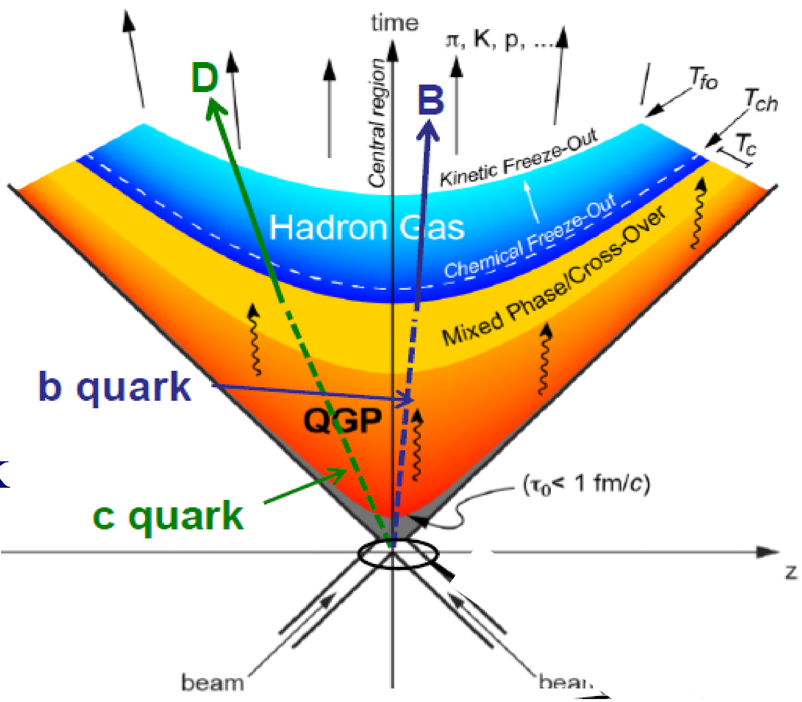
EMMI

charm quarks in the quark gluon plasma

ALICE

interest 2-fold:

- charm and beauty quarks are produced in early hard scattering processes; time scale $\tau \approx 1/2m_q \approx 0.02 - 0.1$ fm   i.e. before QGP is even formed
  access to transport coefficient for heavy quarks
  diffusion coefficient vs energy loss of heavy quark
  do charm quarks thermalize?
  do they follow collective dynamics of bulk?



- need total charm cross section for understanding of charmonia (ccbar states)

- in pp and pA charm physics interesting on it's own right, tests pQCD and parton distribution functions as well as nuclear effects

charmonia as a probe of deconfinement

- the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation → sequential melting

- 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,
→ enhanced production at colliders – signal for deconfinement
production probability from thermalized charm quarks scales with $N(_{ccbar})^2$

- alternative to statistical hadronization: implementation of screening into space-time evolution of the fireball → continuous destruction and (re)generation
Thews et al., 2001, Rapp et al. 2001, Gorenstein et al. 2001, P.F. Zhuang et al. 2005

Methods for open heavy flavor measurement

reconstruction of hadronic decays: $|\eta|<0.5$ PID TPC, TOF

$D^0 \rightarrow K\pi$ $D^\pm \rightarrow K\pi\pi$ $D^* \rightarrow D\pi$ $D_s \rightarrow Kk\pi$ $\Lambda_c \rightarrow \Lambda\pi$

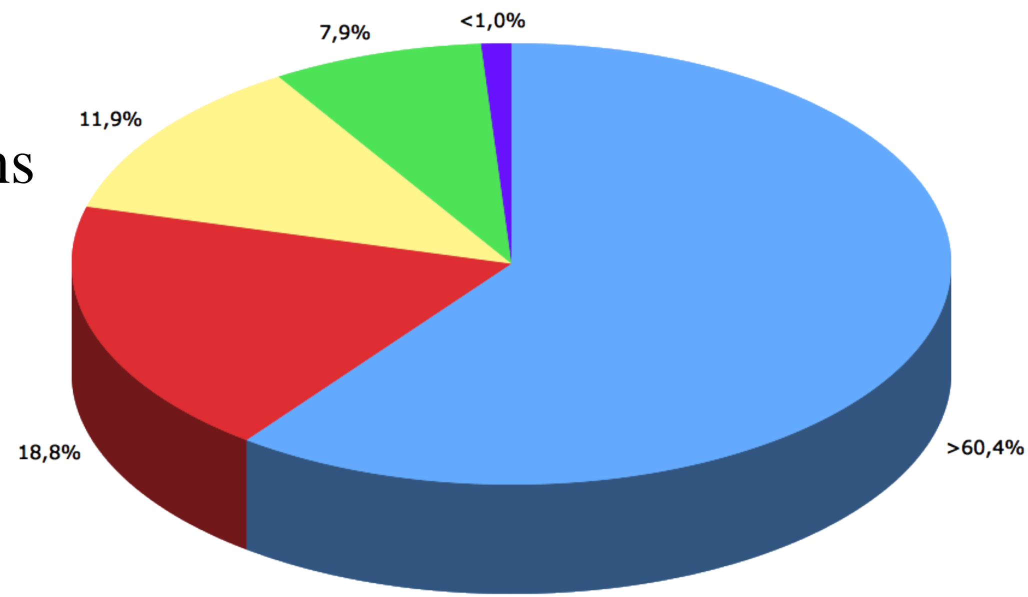
semi-leptonic decays:

$c,b \rightarrow e$ $|\eta| < 0.8$ PID TPC, TRD, TOF, EMCal

$c,b \rightarrow \mu$ $|\eta| = 2.5–4.0$ PID muon RPCs

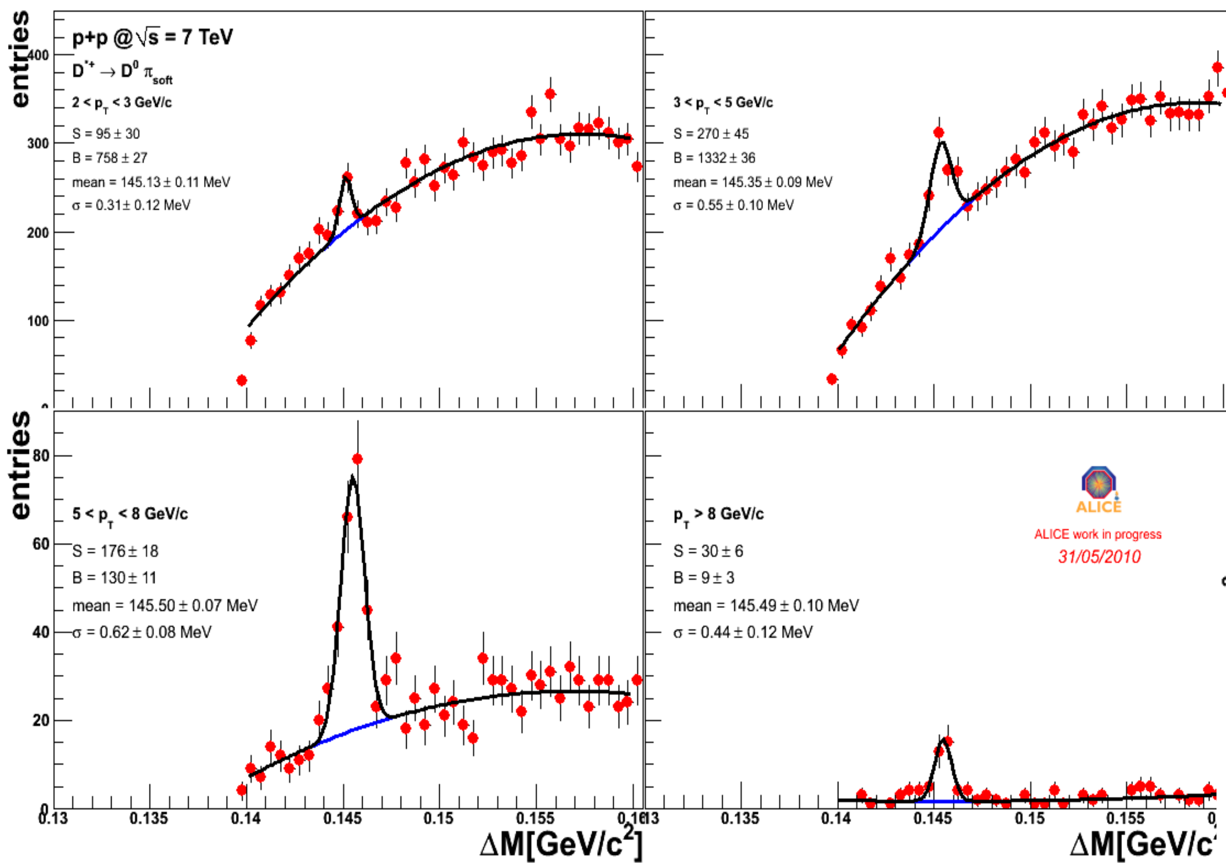
beauty from secondary J/ψ

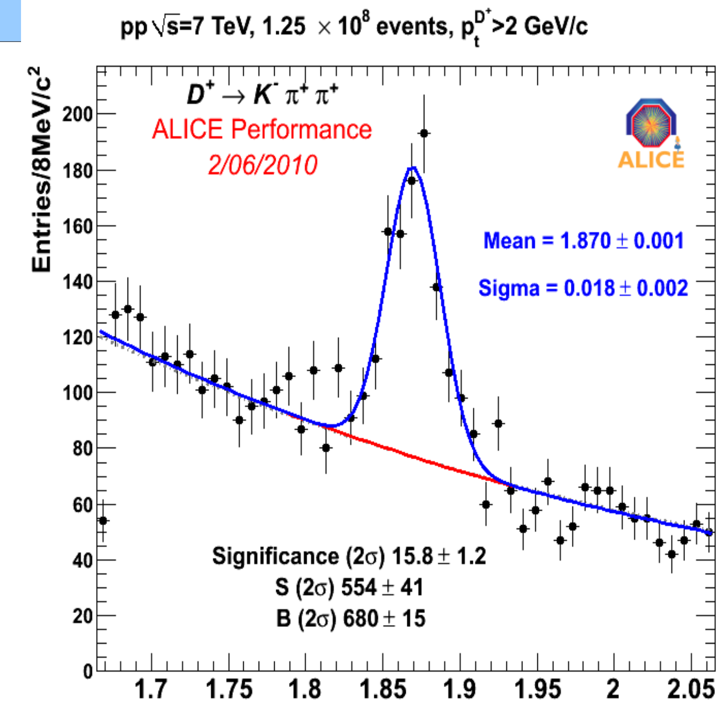
beauty from e-hadron correlations

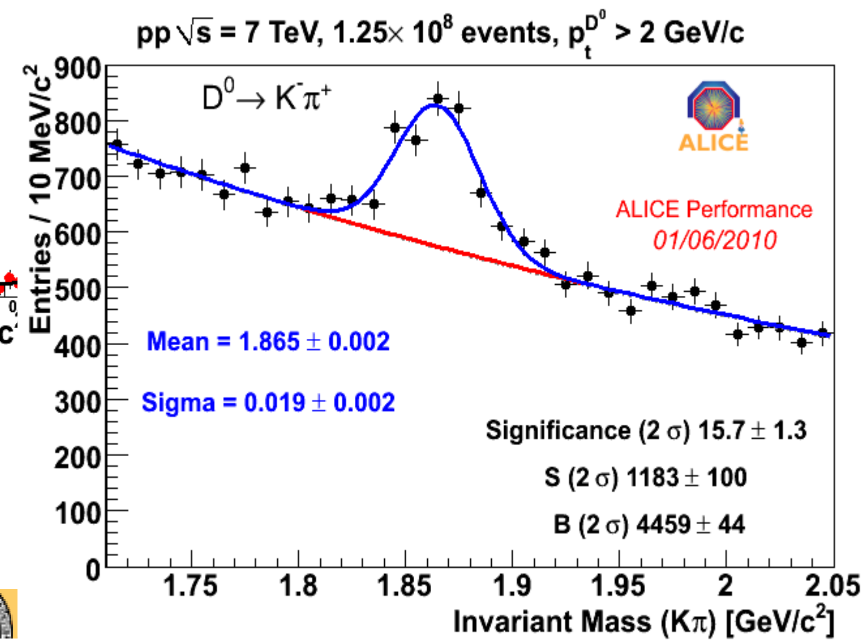


D^0, D^+ and D^{0*} in 7 TeV pp data

1.25 10^8 events

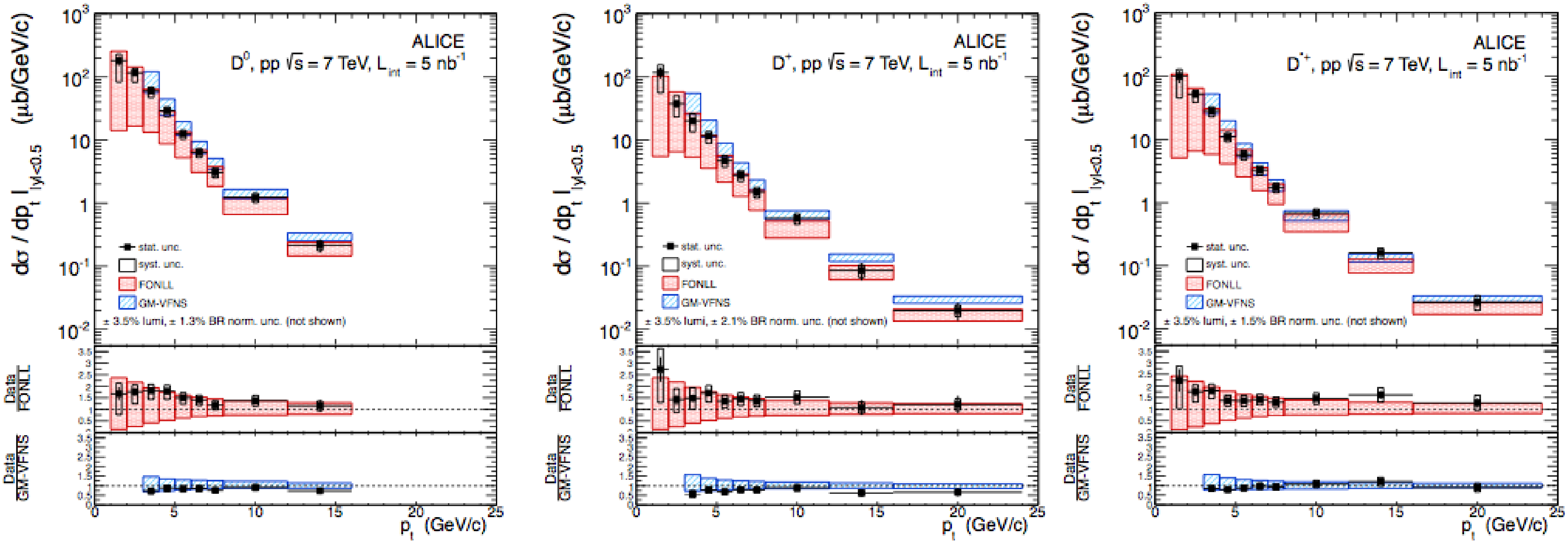






for 10^9 events, expect to measure open charm for p_t = 0.5 – 15 GeV/c

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



JHEP1201(2012)128

data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and at lower end of GM-VFNS
measure 80% of charm cross section for |y| < 0.5

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

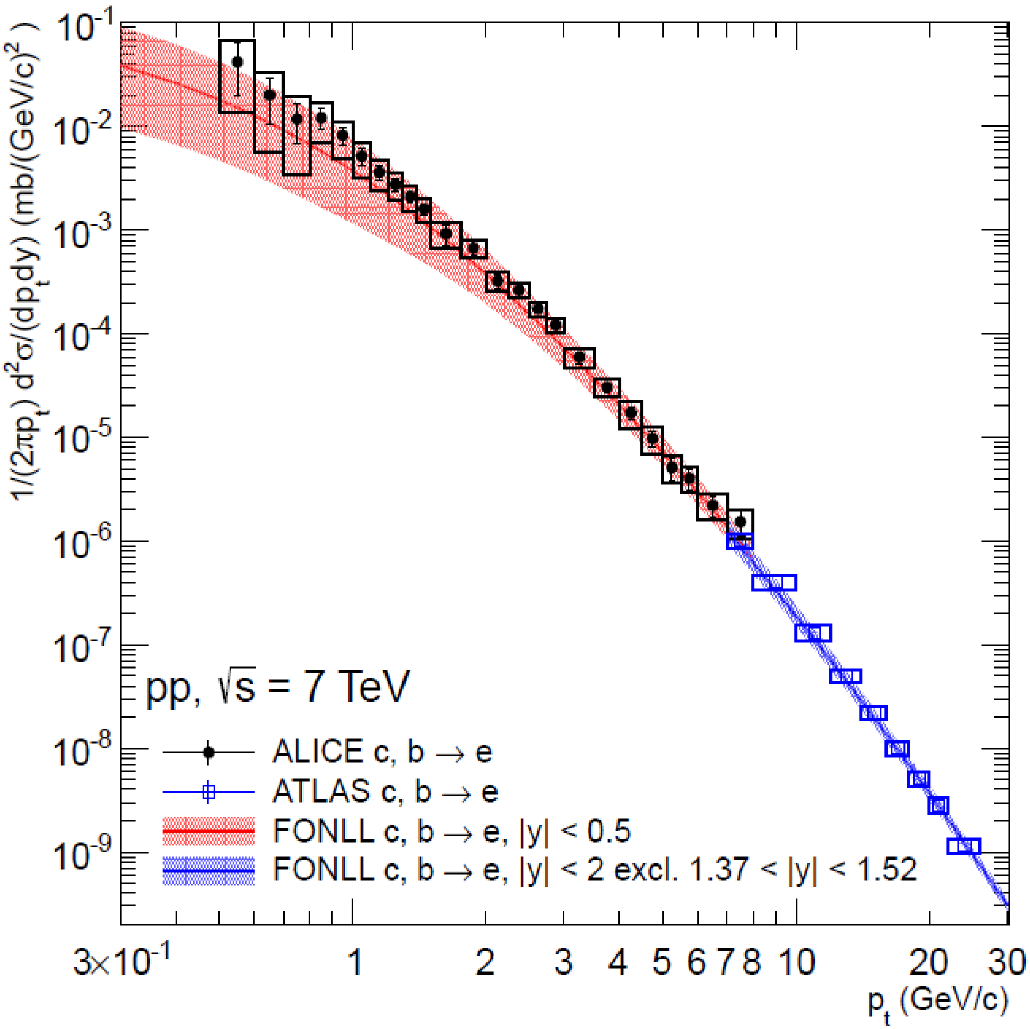
mid-y cross sections:

$$d\sigma^{D^0}/dy = 516 \pm 41(\mathrm{stat.})^{+\ 69}_{-175}(\mathrm{syst.}) \pm 18(\mathrm{lumi.}) \pm 7(\mathrm{BR})^{+120}_{-\ 37}(\mathrm{extr.})\ \mu\mathrm{b},$$

$$d\sigma^{D^+}/dy = 248 \pm 30(\mathrm{stat.})^{+52}_{-92}(\mathrm{syst.}) \pm 9(\mathrm{lumi.}) \pm 5(\mathrm{BR})^{+57}_{-18}(\mathrm{extr.})\ \mu\mathrm{b},$$

$$d\sigma^{D^{*+}}/dy = 247 \pm 27(\mathrm{stat.})^{+36}_{-81}(\mathrm{syst.}) \pm 9(\mathrm{lumi.}) \pm 4(\mathrm{BR})^{+57}_{-16}(\mathrm{extr.})\ \mu\mathrm{b}.$$

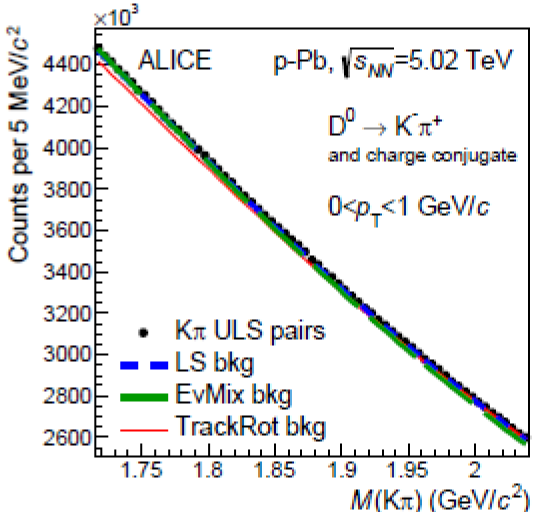
alternative: semi-leptonic decay charm and beauty electrons compared to pQCD

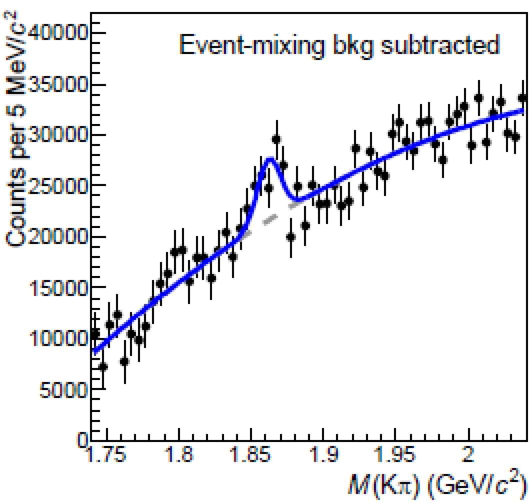


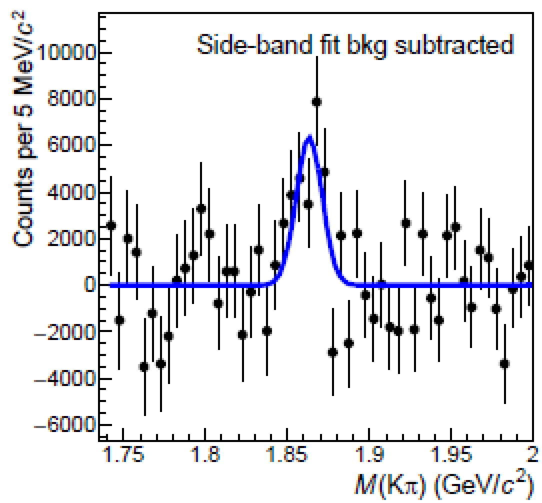
- ALICE data complementary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

PRD76 (2012) 112007 arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

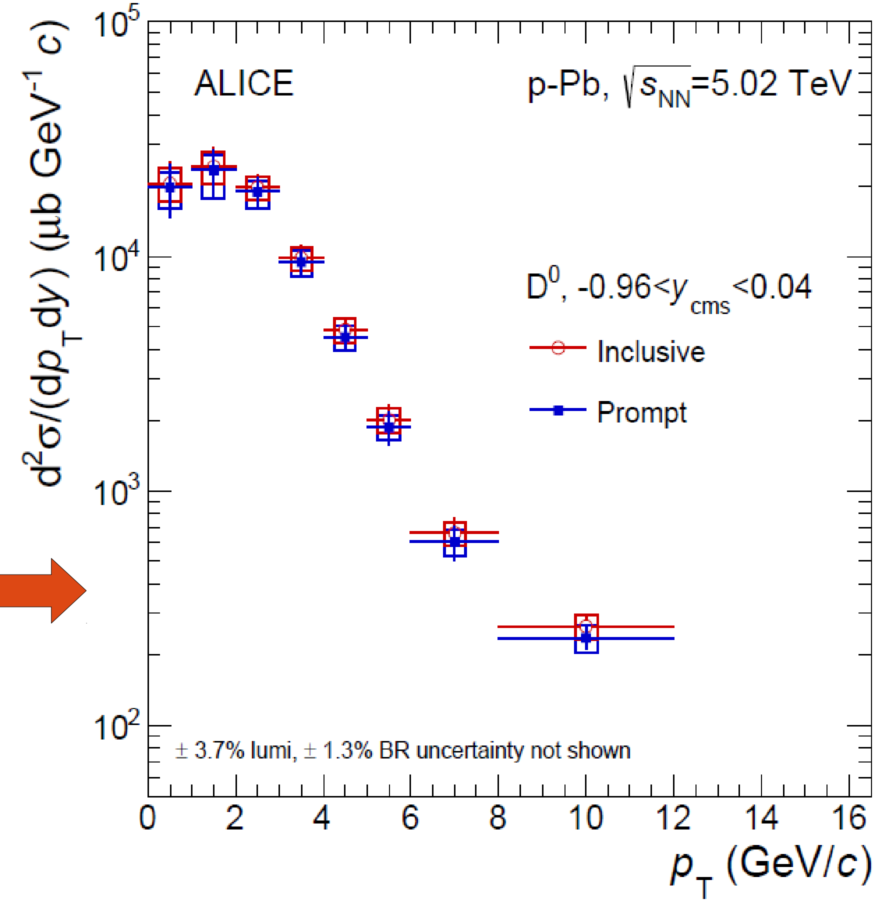
first measurements of open charm down to $p_t = 0$ at y=0







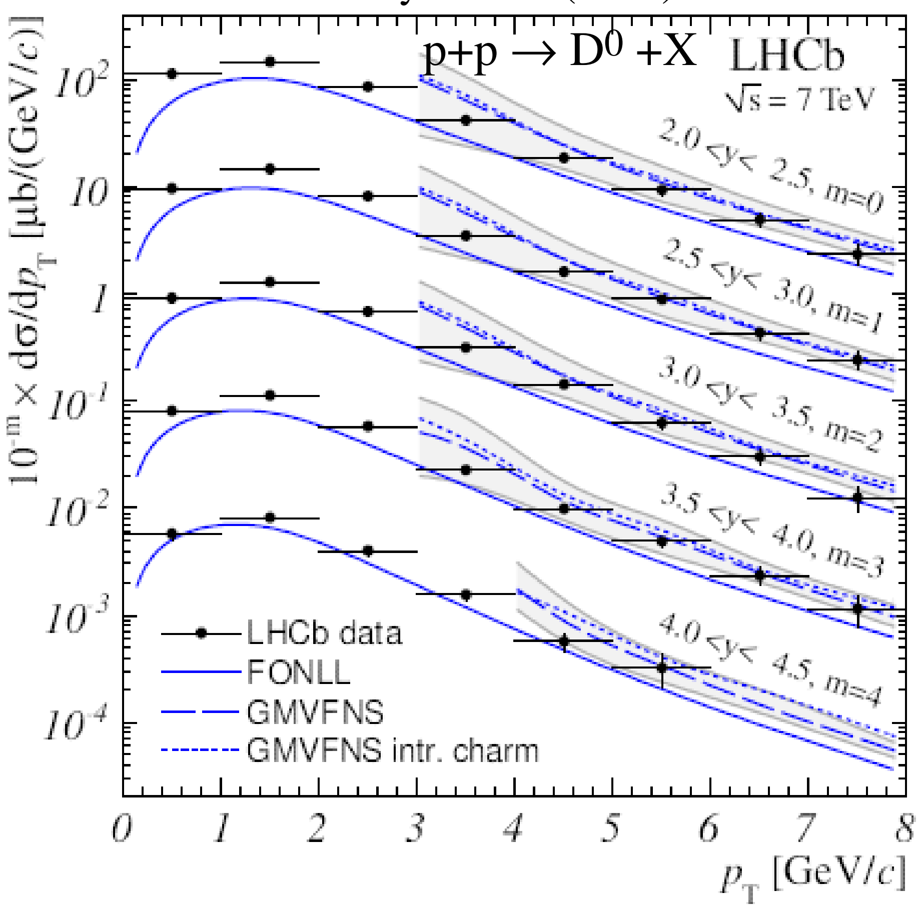
PRC94(2016) 054908 arXiv: 1605.07569

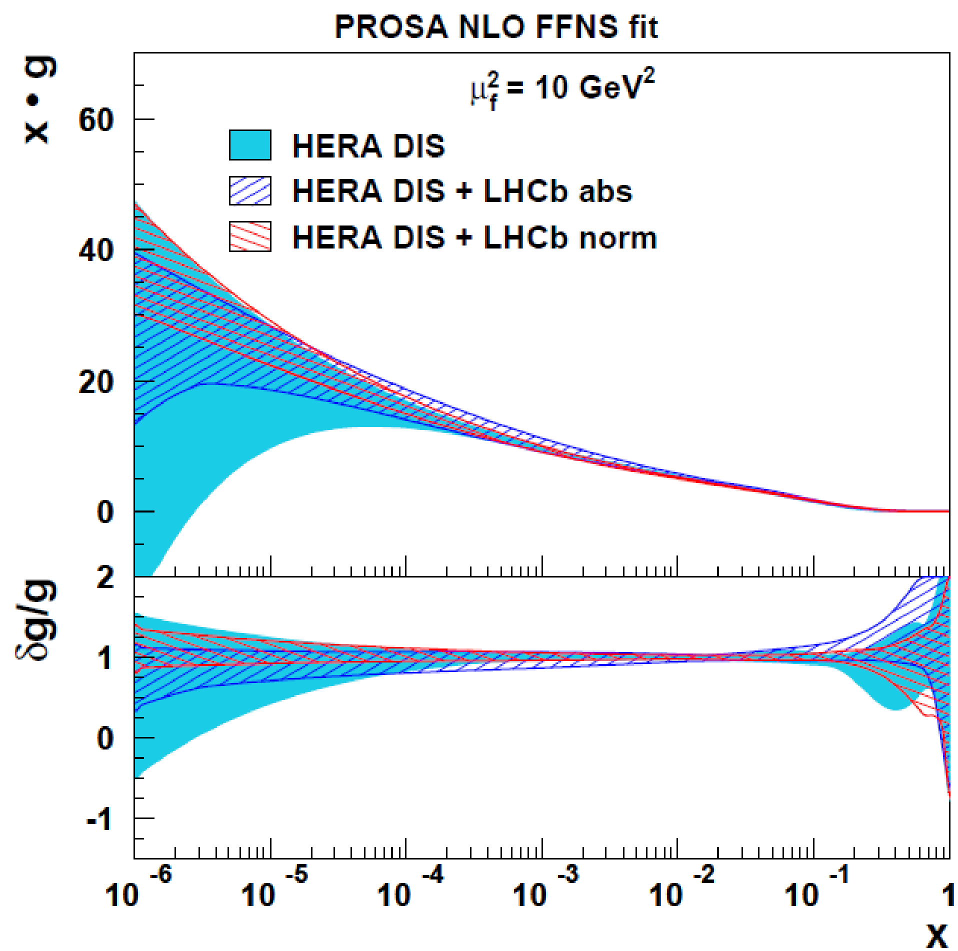


very hard struggle to deal with (irreducible) combinatorial background,
very recently successful in pp and pPb

charm production in pp and pQCD at forward rapidity - LHCb data

data: Nucl. Phys. B871 (2013) 1

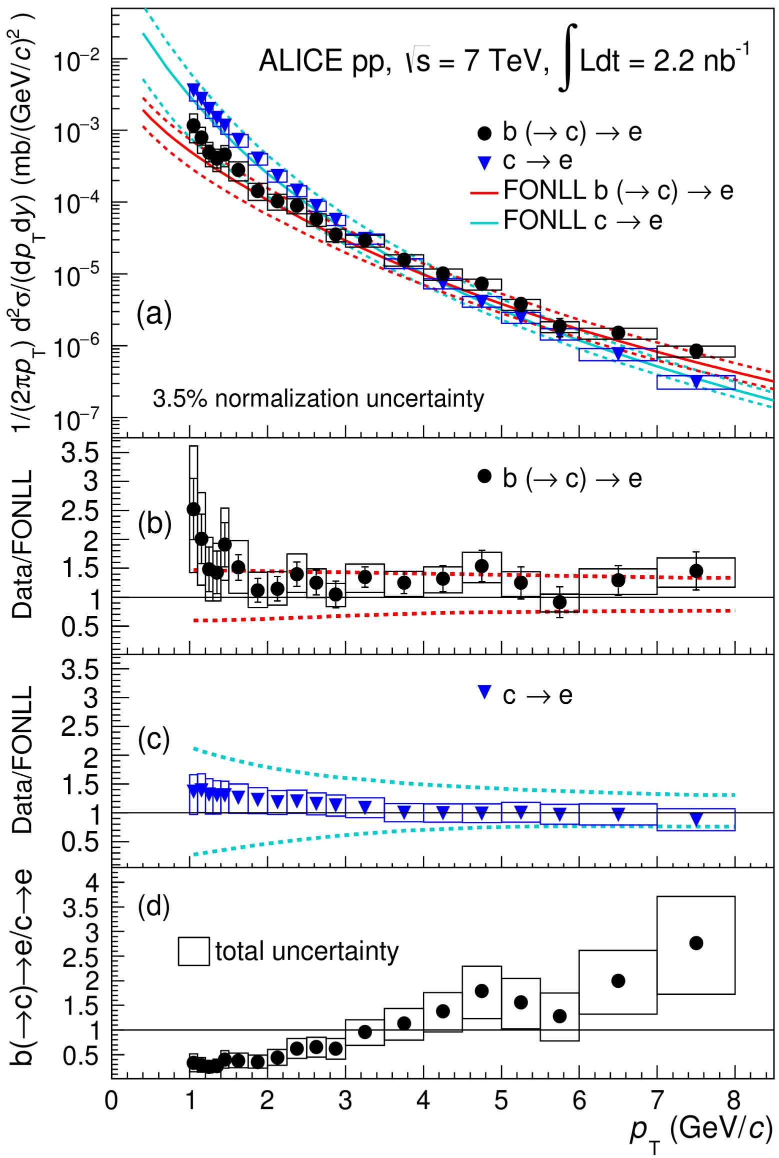




for a recent summary of data and pQCD predictions see:
Guzzi, Geiser, Rizatdinova, 1509.04582 and Beraudo, 1509.04530
additional constraint of gluon PDF in particular at low x (down to 5 10^{-6})

comparison electrons from beauty and charm decays

PLB763 (2016) 507



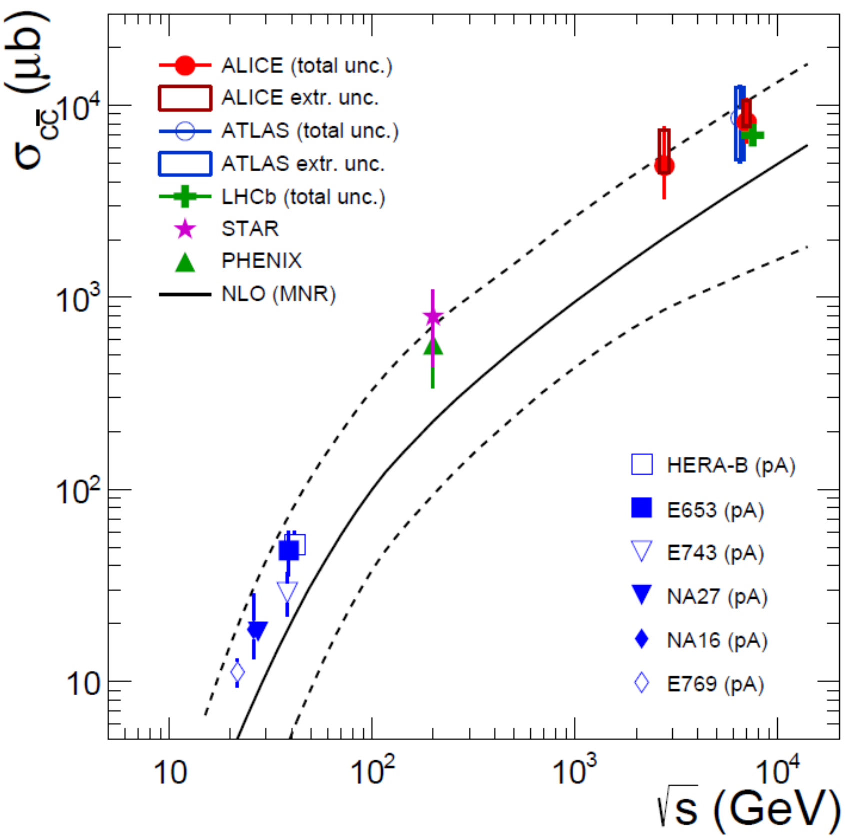
electrons from charm and beauty decays:
separation via impact parameter distribution
measured separately from 1-8 GeV/c

beyond 4 GeV/c beauty larger than charm

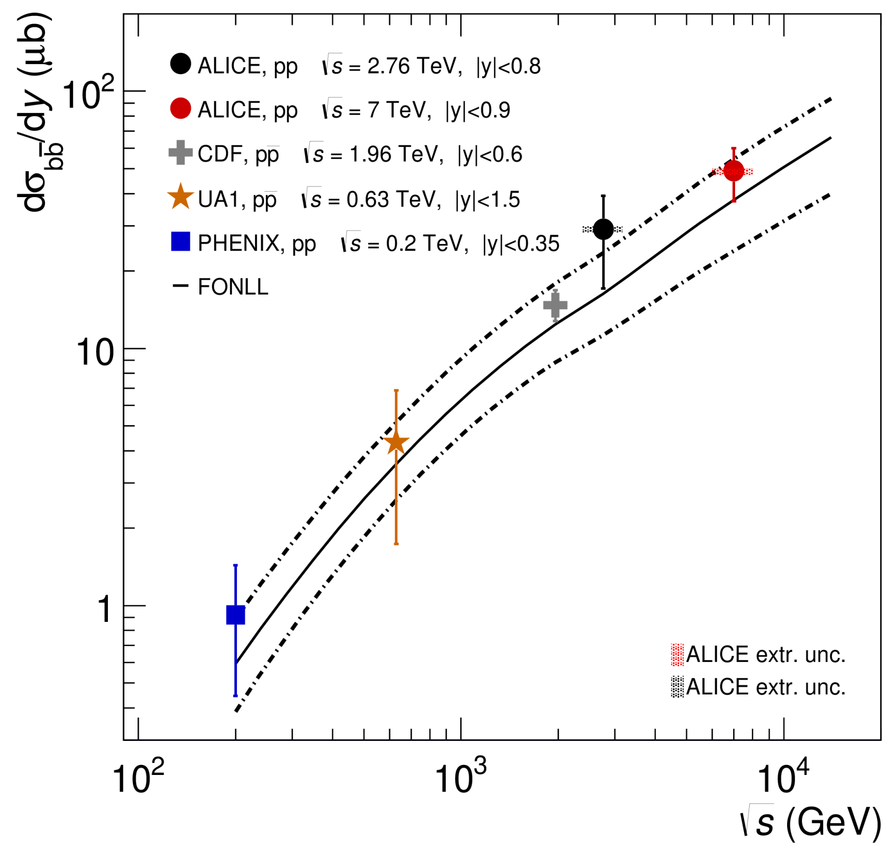
good agreement with pQCD, data lie in
upper half of FONLL band

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

PRC94(2016) 054908 arXiv: 1605.07569



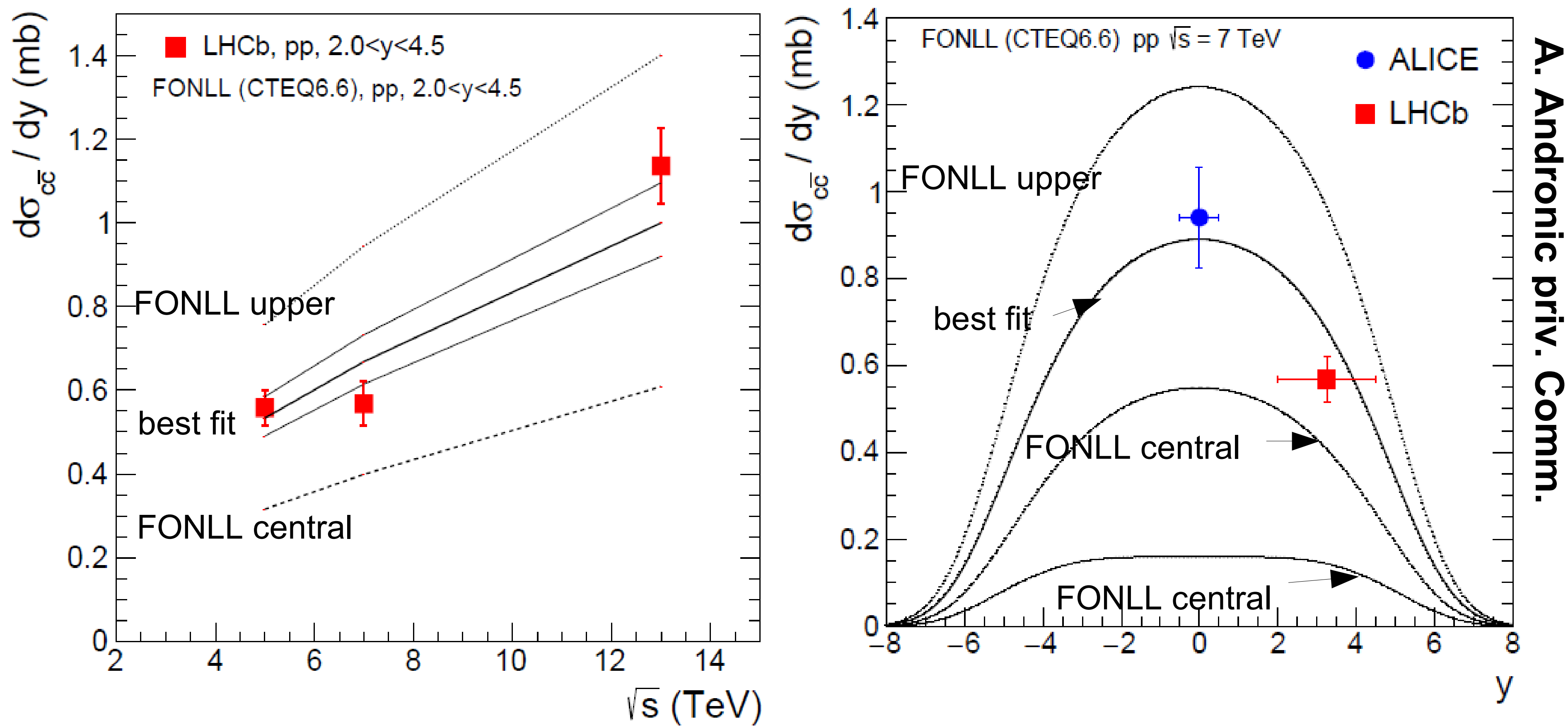
PLB 721 (2013) 13; PLB763 (2016) 507 PLB 738 (2014) 97



- 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 √s and y-interval



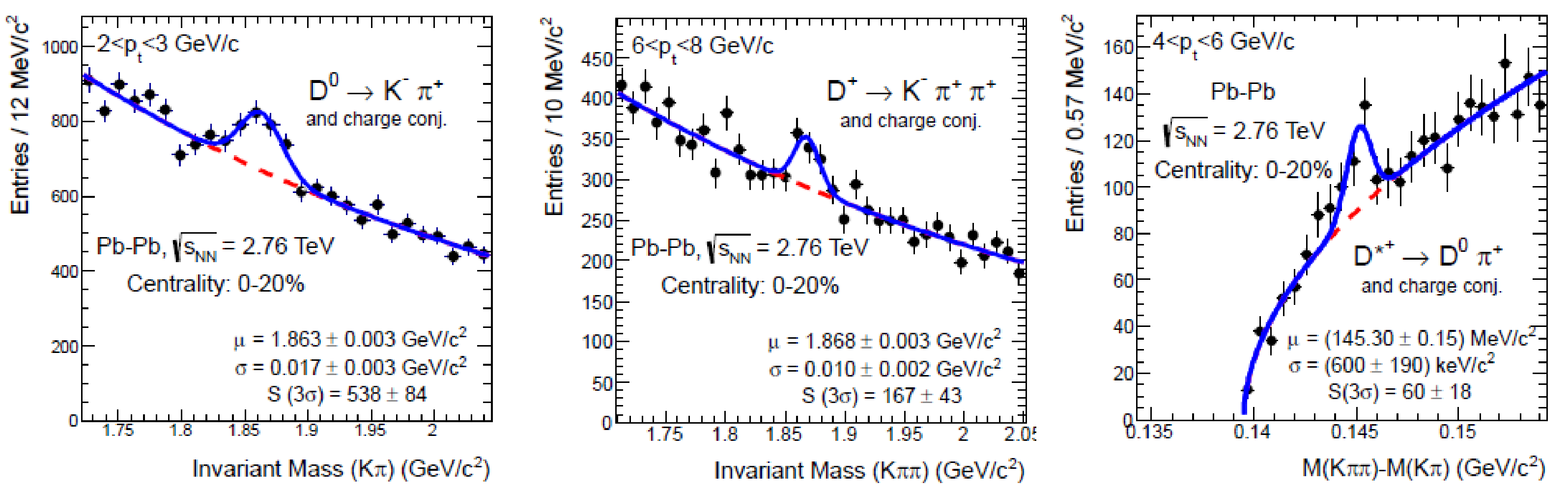
LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159

ALICE: 7 TeV PRC94(2016) 054908
and manuscript in preparation

D meson signals in Pb Pb collisions

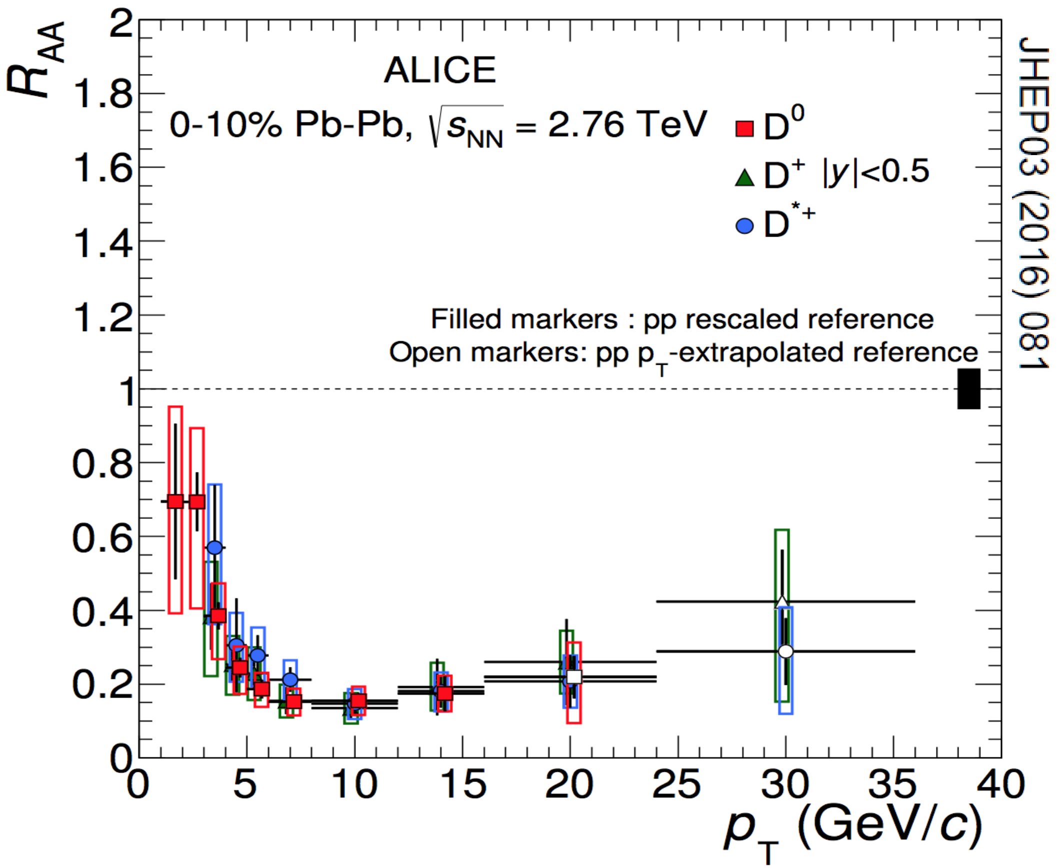
measurement:
reconstruction of hadronic decays of D-mesons (ALICE, CMS)
semi-leptonic decays into electrons (ATLAS, ALICE)
      “   into muons (ATLAS, ALICE)
J/ψ from secondary vertex from B-decay (CMS)

data: ALICE JHEP 1209 (2012) 112 arXiv:1203.2160



suppression of charm at LHC energy

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

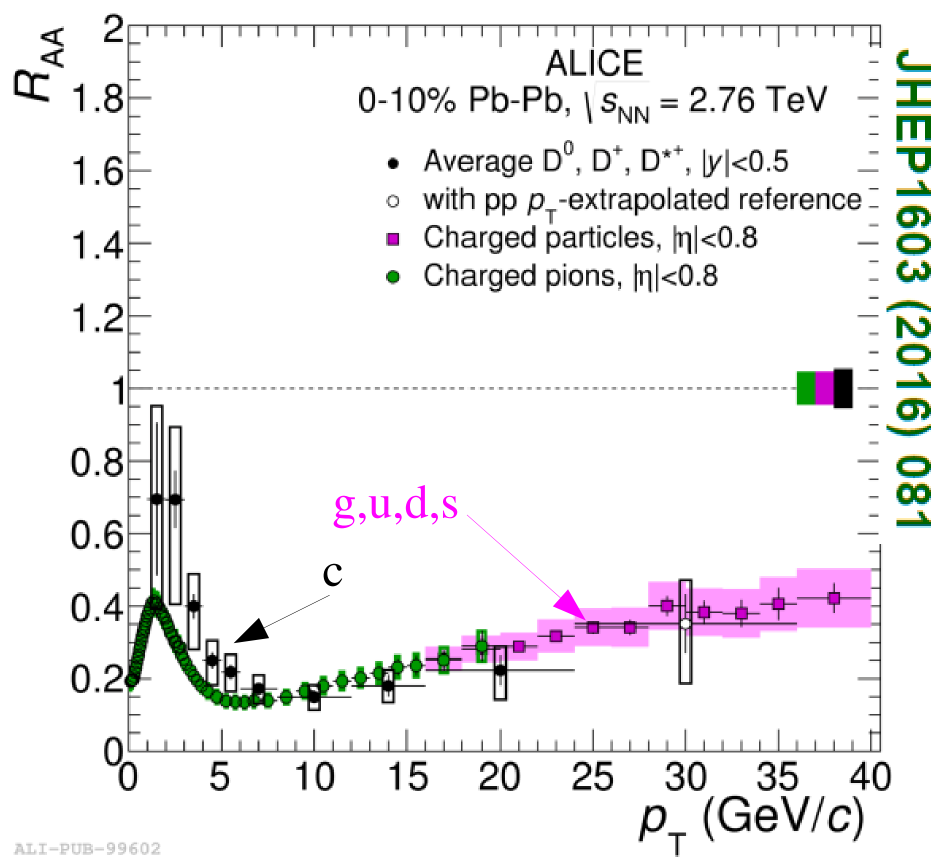


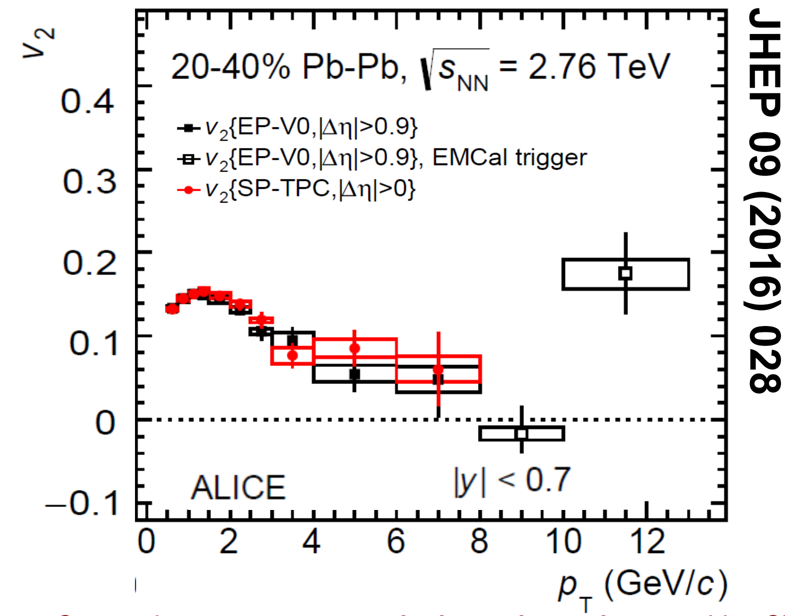
energy loss for all species of D-mesons within errors equal - not trivial

energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

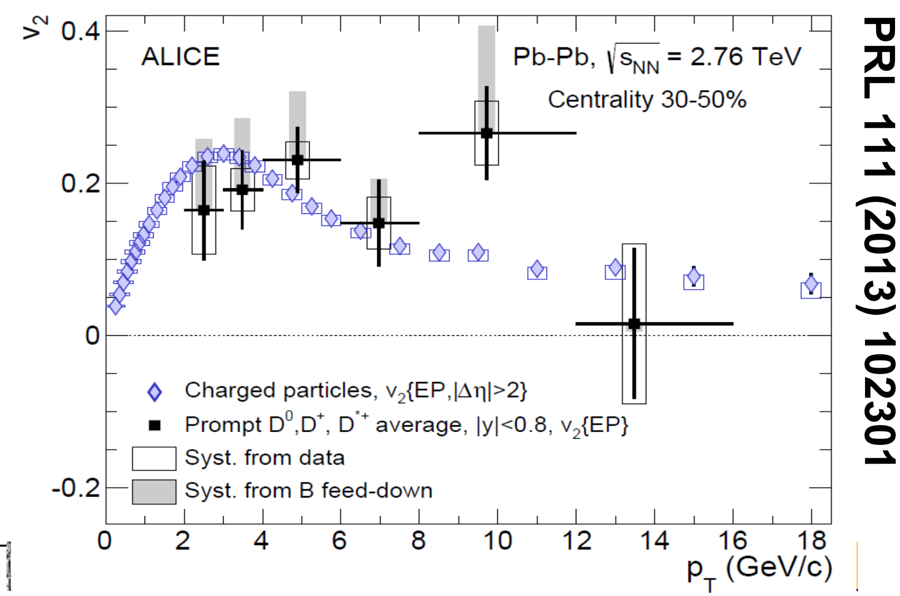
charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks





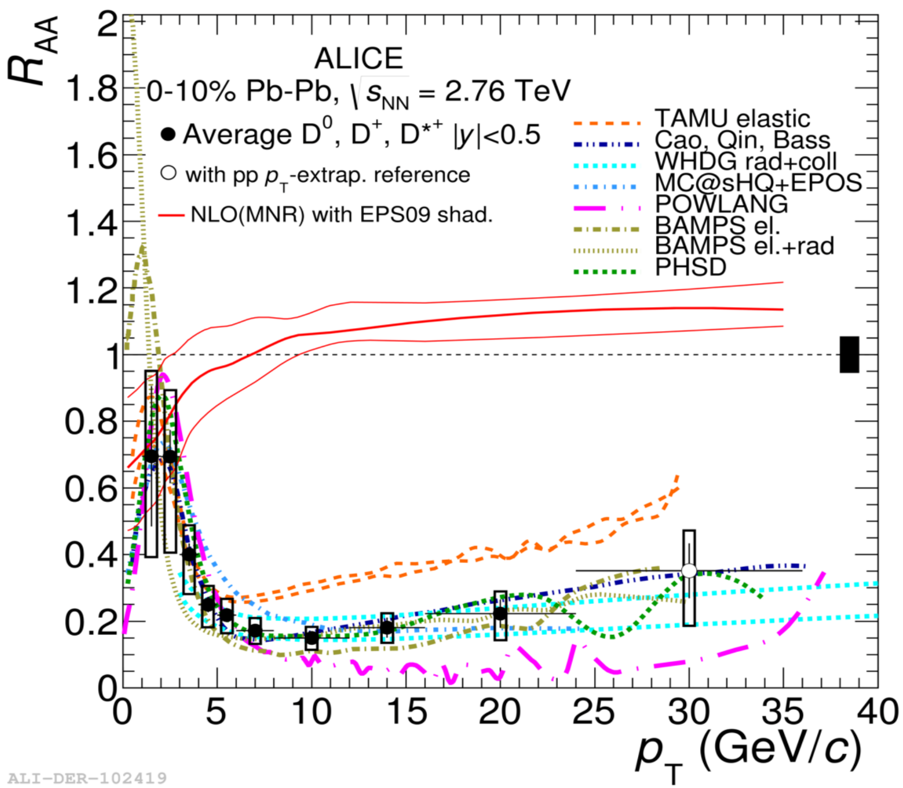
elliptic flow for charm – participation in coll. flow

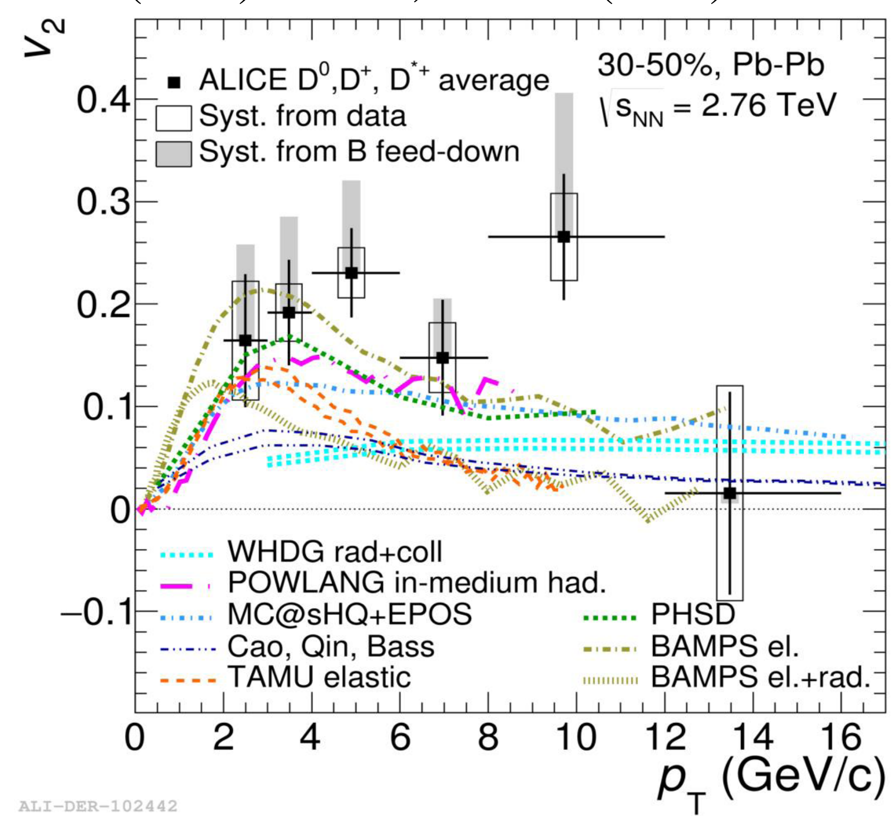


M.Djordjevic, arXiv:1307.4098:
equal R_{AA} is a conspiracy of different fragmentation functions of light quarks, gluons, charm and different color factors in energy loss

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

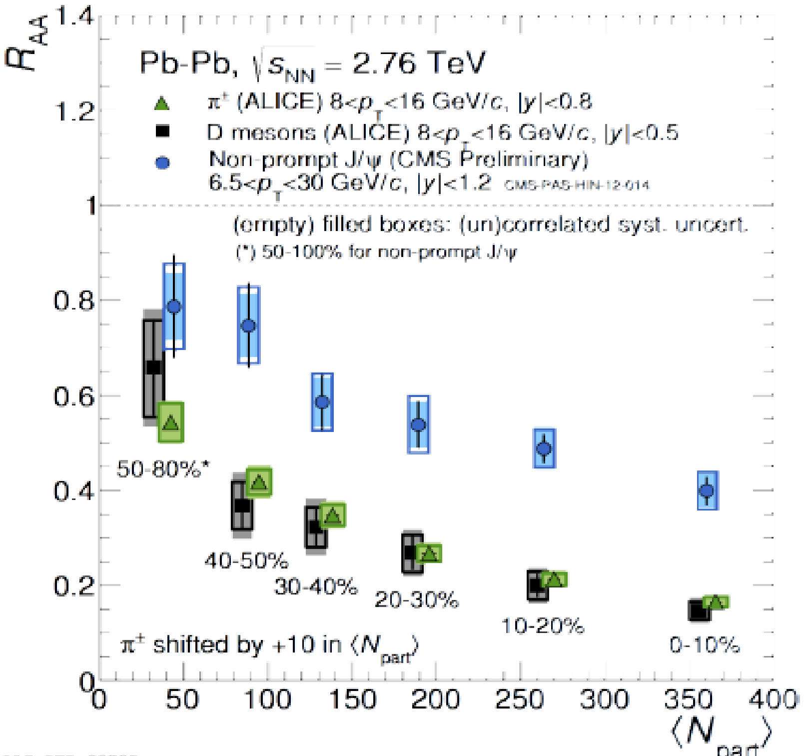
PRL 111 (2013) 102301, PRC 90 (2014) 034904





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)

what about b-quark energy loss and thermalization?

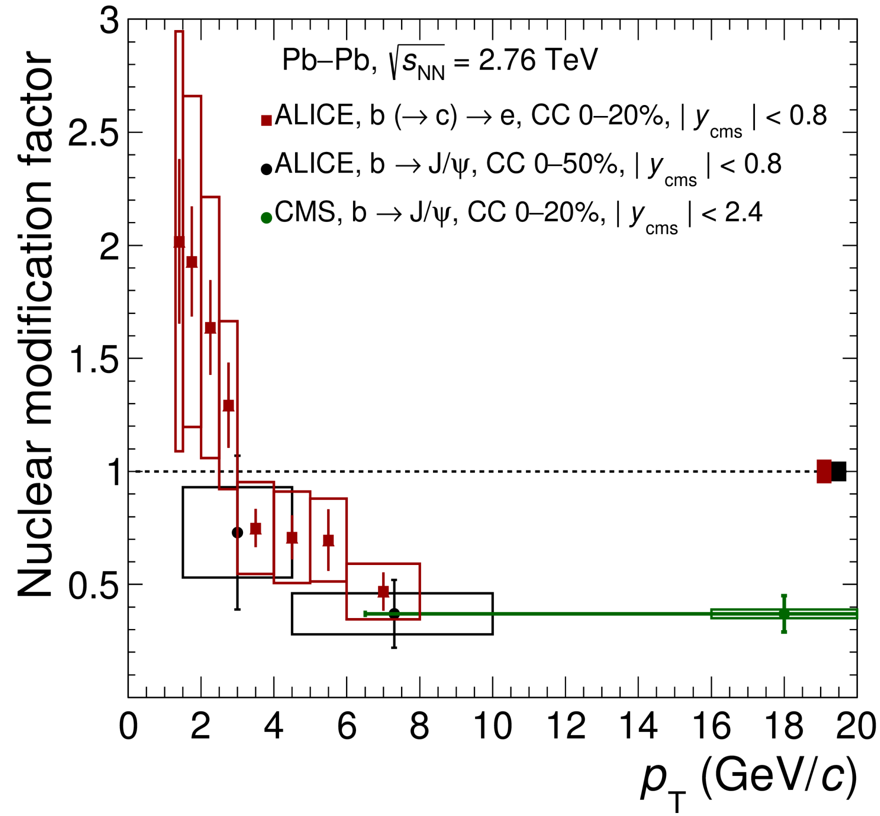


Charm: D mesons

JHEP 11 (2015) 205

Beauty: non-prompt J/ψ

arXiv:1610.00613



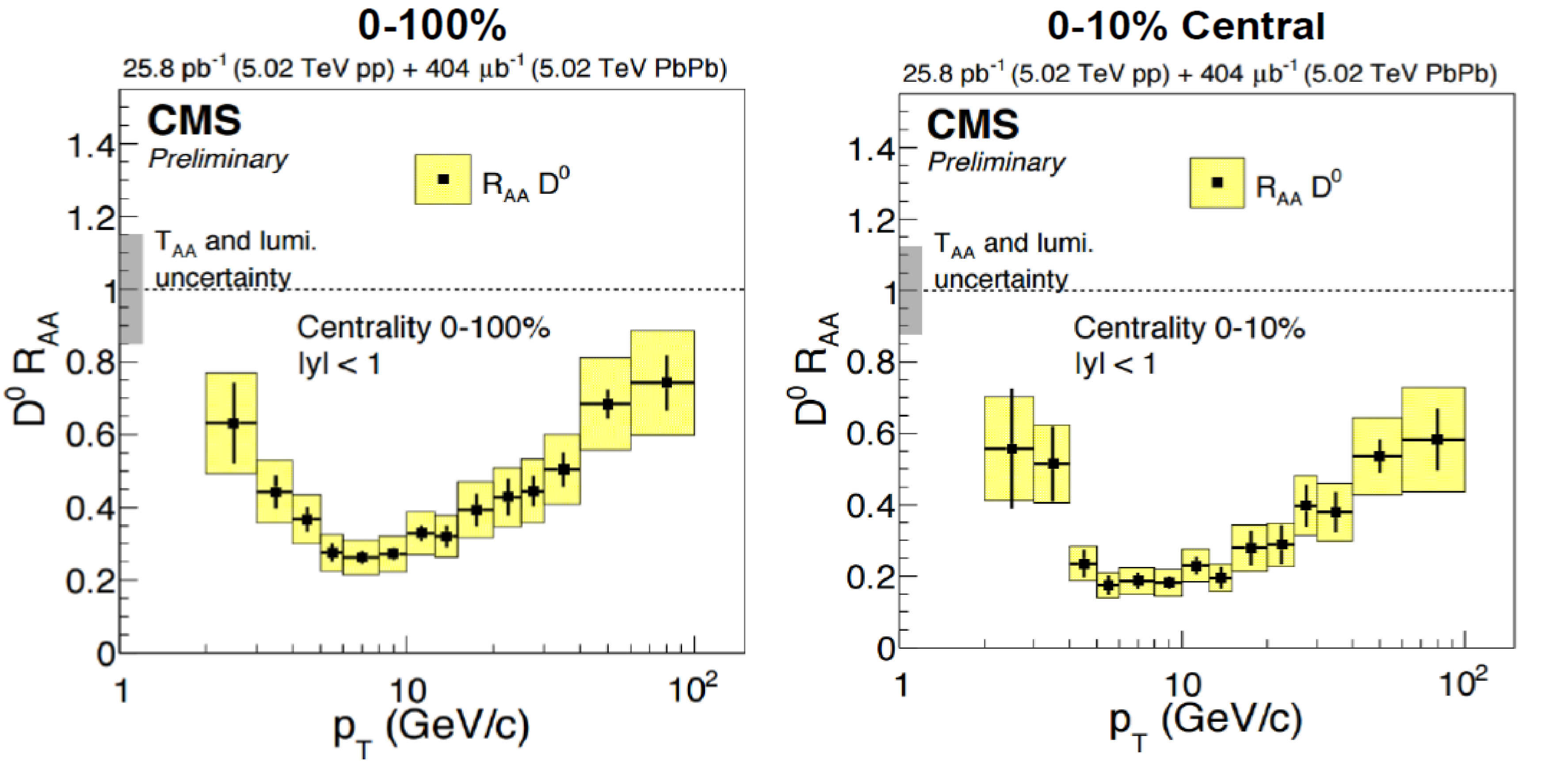
b → c → e arXiv:1609.03898

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

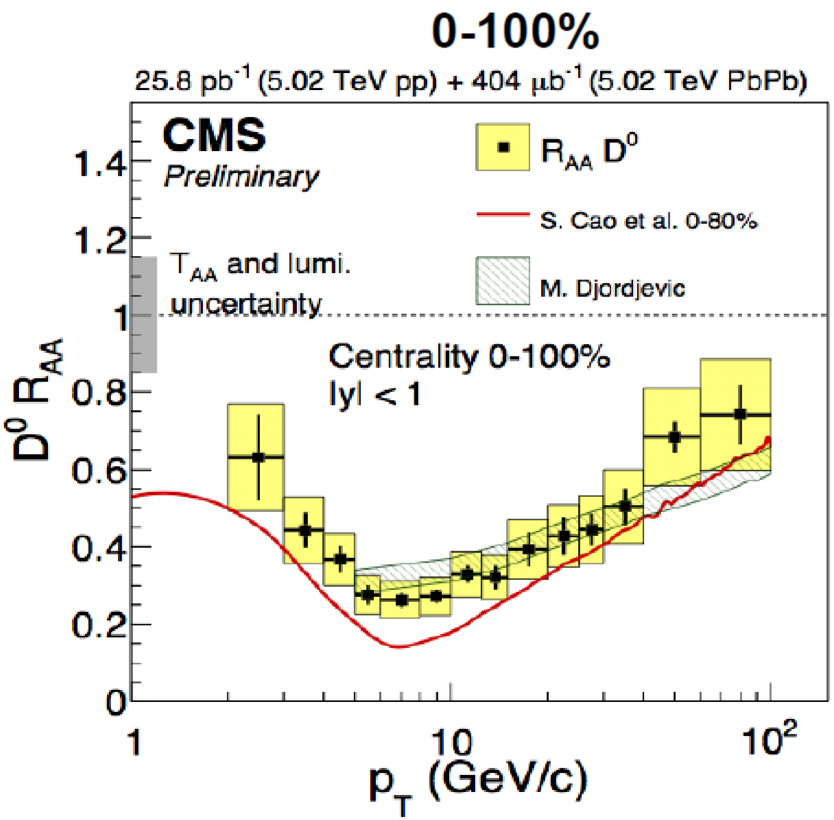
first D^0 results from run2 PbPb at $\sqrt{s_{NN}} = 5$ TeV

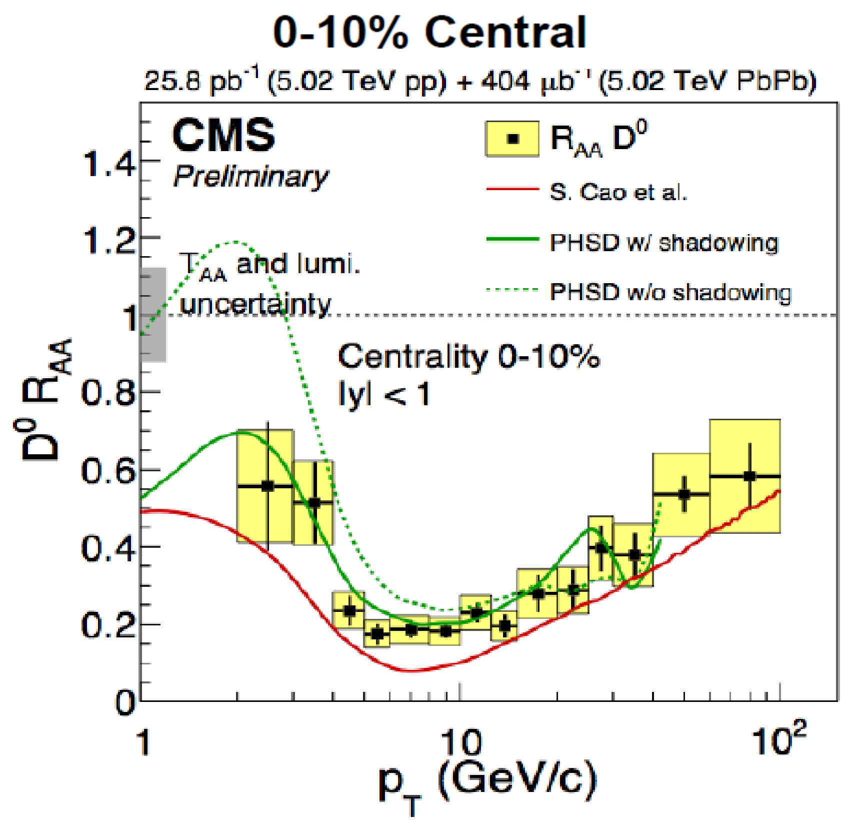
CMS-PAS-HIN-16-001



D^0 production measured from 2-100 GeV/c
strong suppression and shape very similar to charged particles and pions

D^0 R_{AA} compared to models



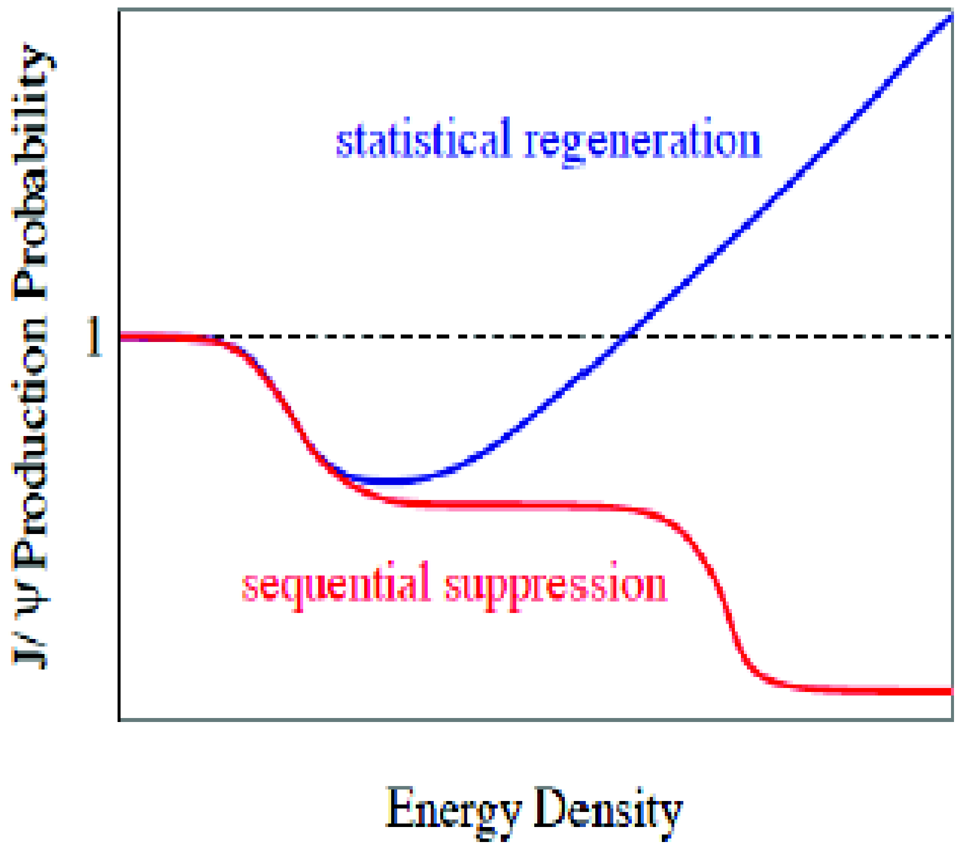


models: predictions before run2 data

- 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

charmonia

expectation for LHC data on decision of regeneration vs. sequential suppression

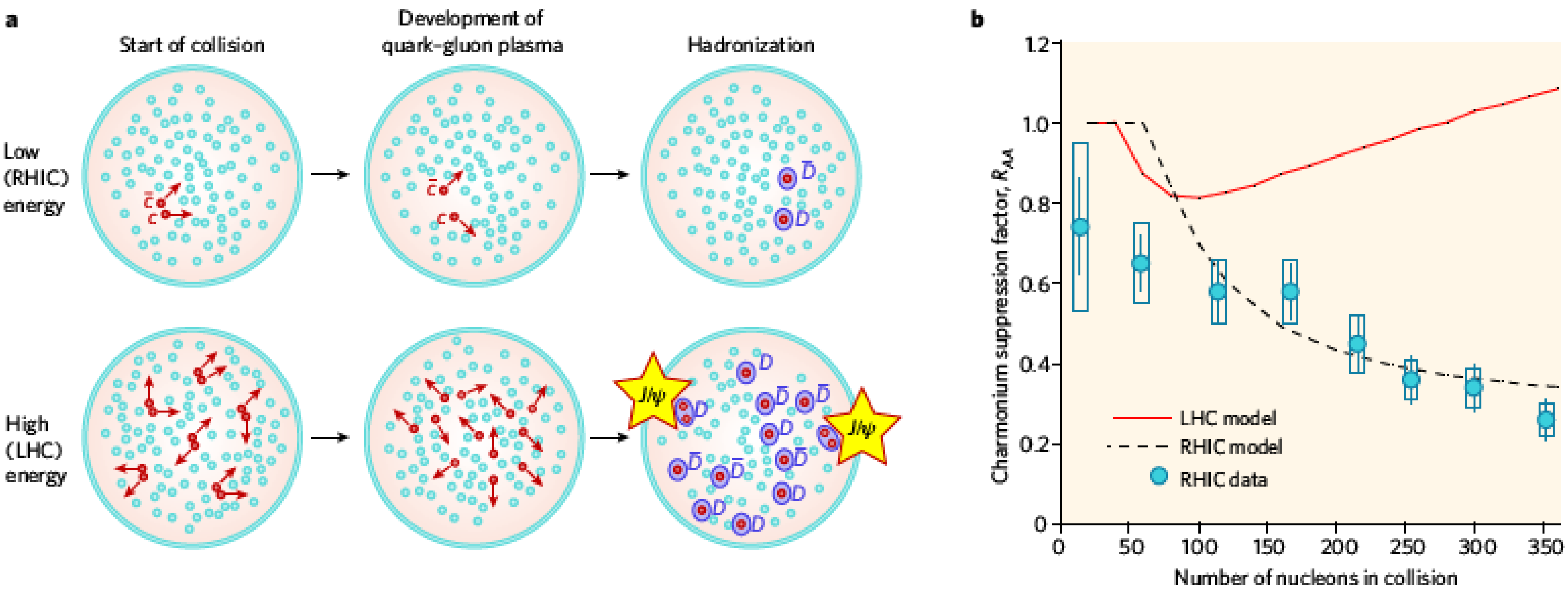


SPS RHIC LHC

Picture:
H. Satz 2009

little excursion from my ALICE talk to phenomenology

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



charmonium enhancement as fingerprint of deconfinement at LHC energy

only free parameter: open charm cross section in nuclear collision

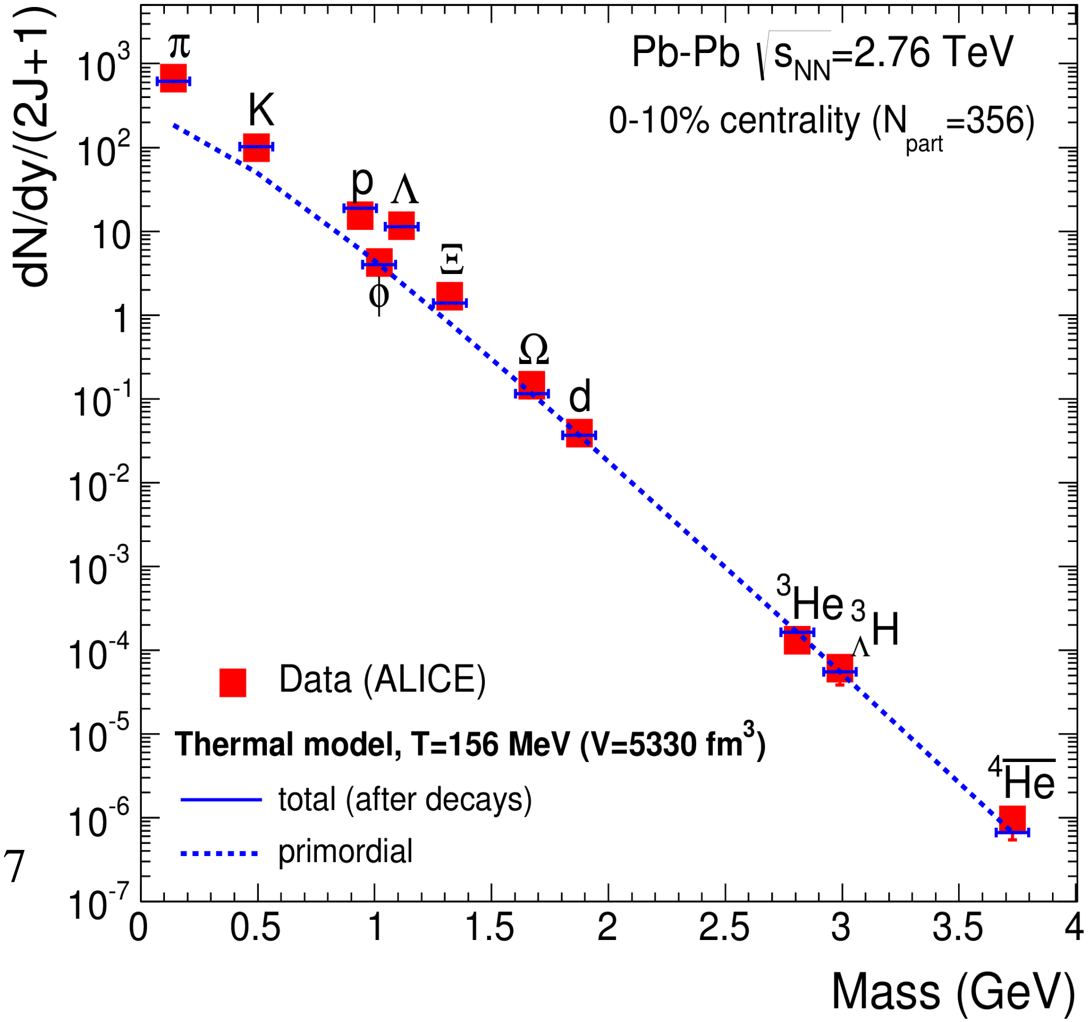
Braun-Munzinger, J.S., Phys. Lett. B490 (2000) 196 and

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

statistical model (grand canonical) describes production of hadrons with u,d,s valence quarks from AGS to LHC

2 free parameters: T, mu_B

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



works equally well for nuclei and loosely bound (anti)hyper-nuclei

prediction P. Braun-Munzinger, J.S., J.Phys. G28 (2002) 1971-1976, J.Phys. G21 (1995) L17

strong indication of isentropic expansion in hadronic phase

extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP

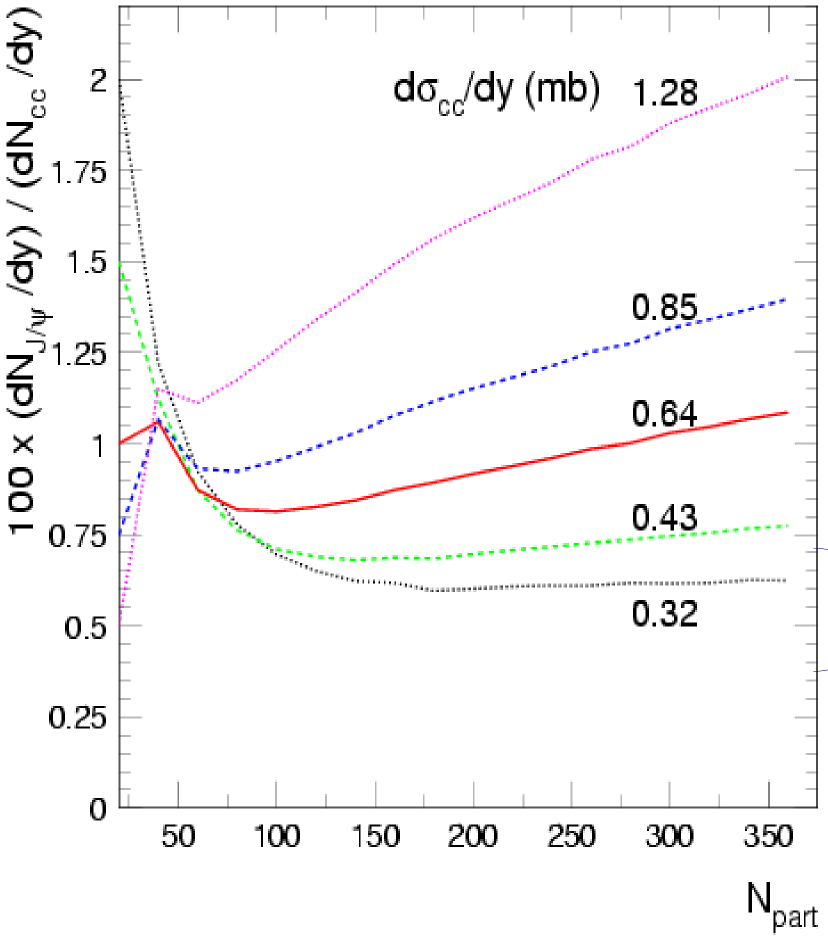
  $N_{c\bar{c}}^{direct}$ from data (total charm cross section) or from pQCD

- 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

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

the only additional free parameter

statistical model predictions for LHC energies



open charm is natural and essential normalization

precision measurement needed

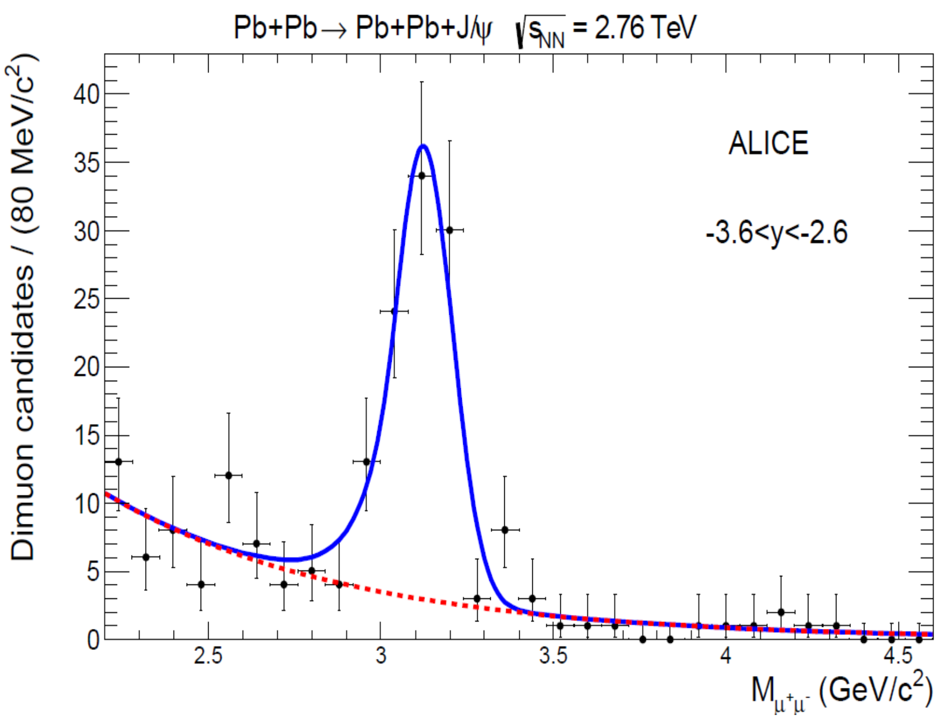
LHC 2.76 TeV including shadowing (more below)

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

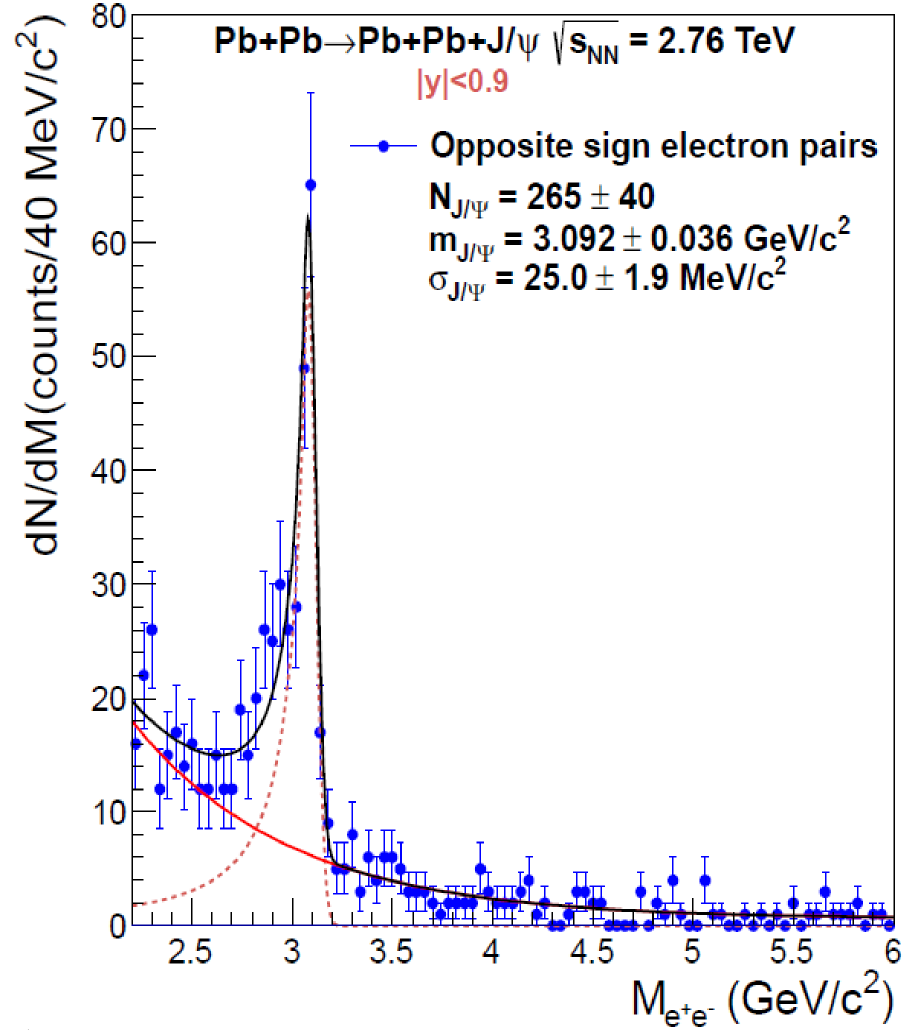
Back to experiment

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

PLB 718 arXiv:1209.3715



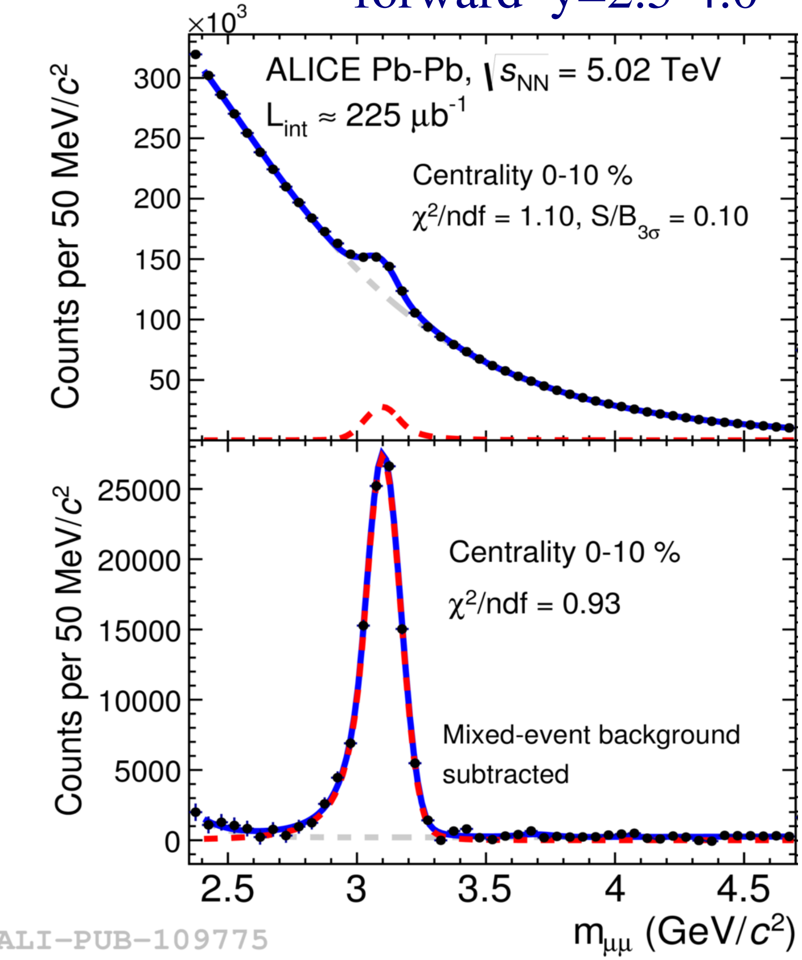
ALICE EPJ C73 arXiv:1305.1467



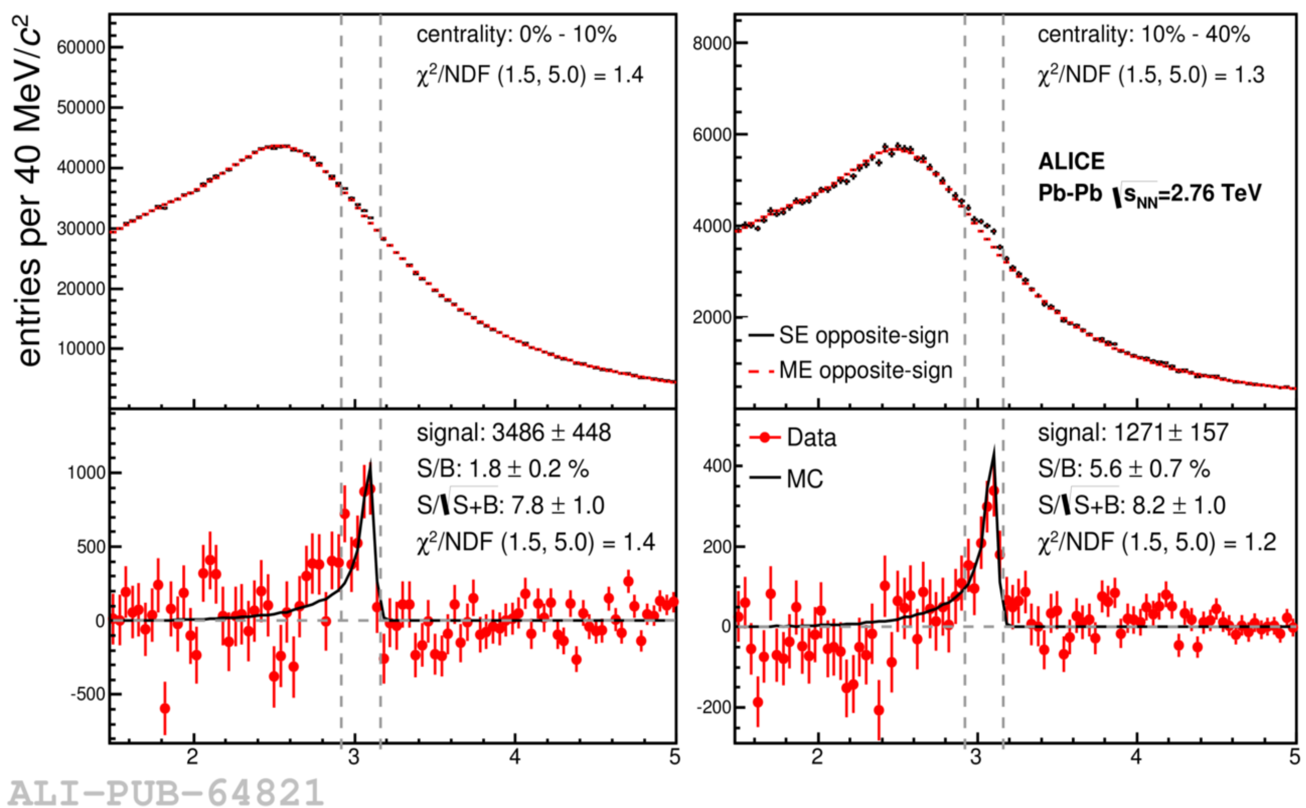
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background
very good understanding of line shape
(probes nuclear gluon shadowing, not discussed here)

reconstruction of J/ψ for central nuclear collisions

forward y=2.5-4.0

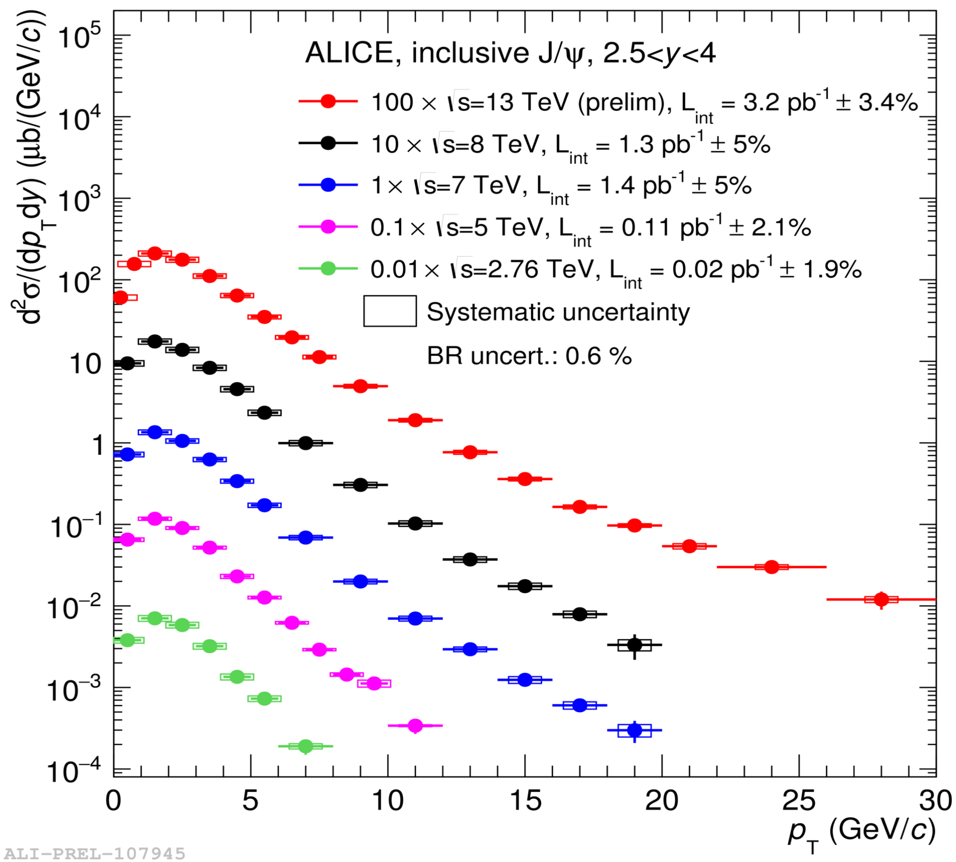


mid |y| < 0.8

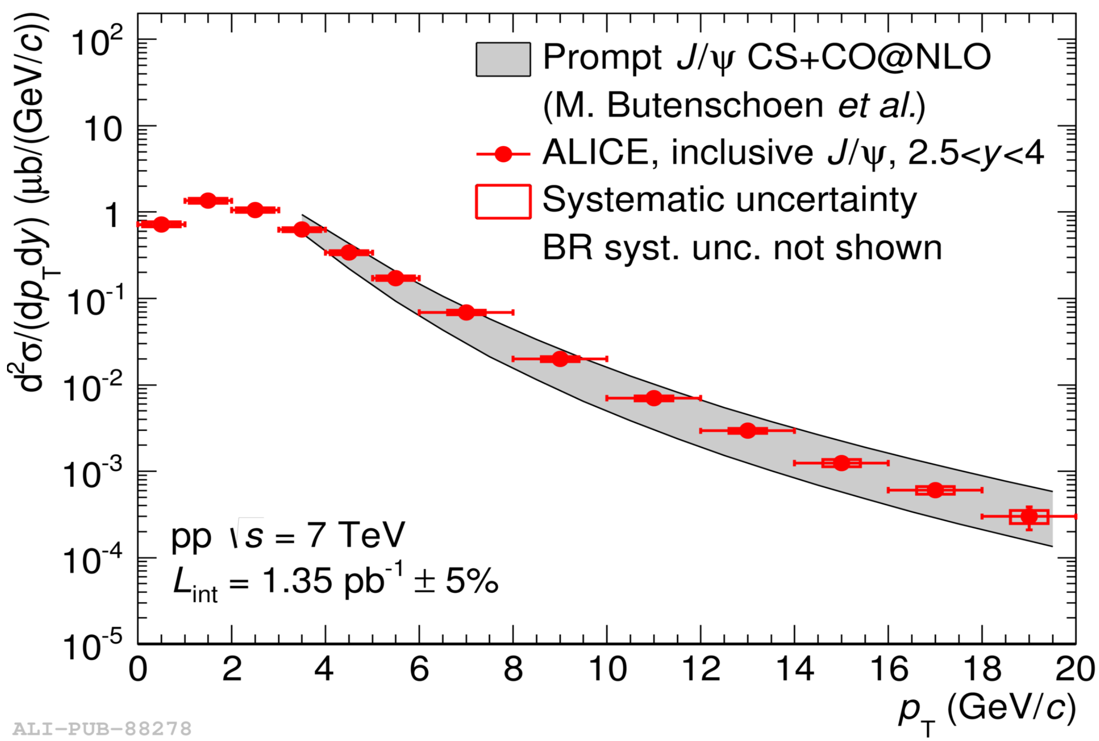


most challenging: central PbPb collisions
in spite of formidable combinatorial background
(true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

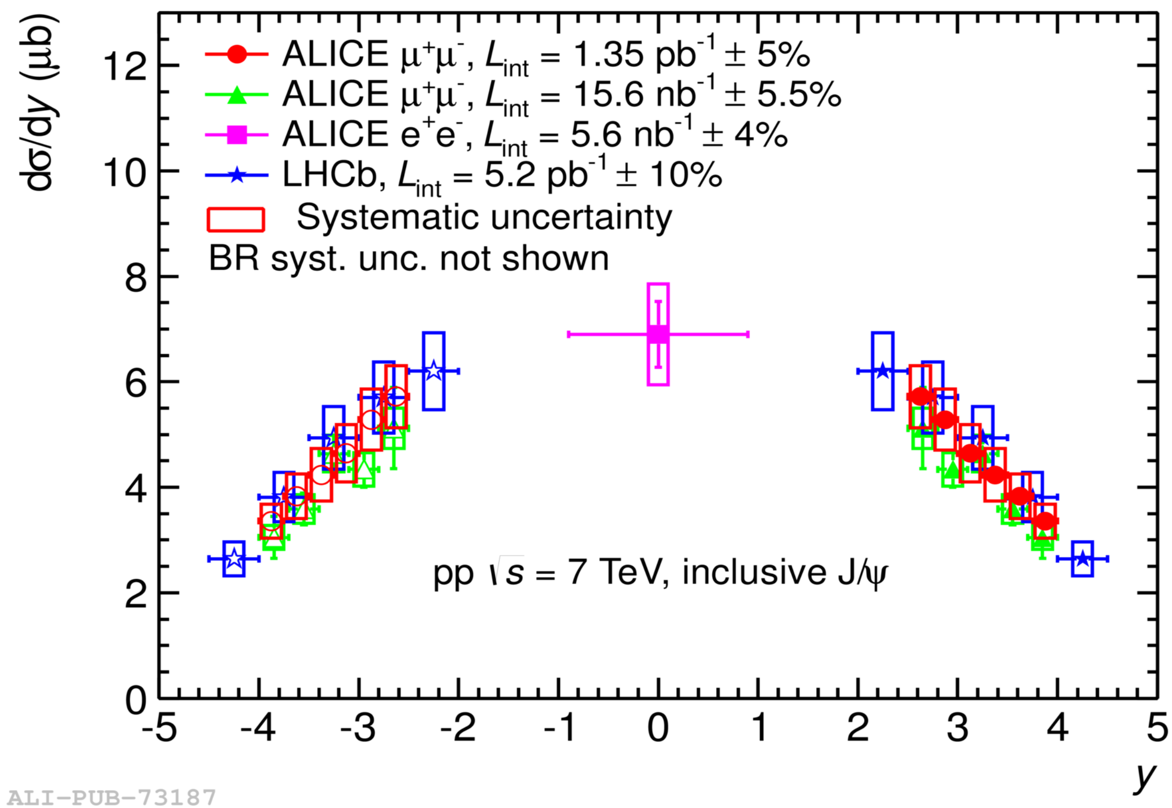
the baseline: p_t spectra in pp collisions



- good systematics of spectra now available
- pQCD modelling now close to data



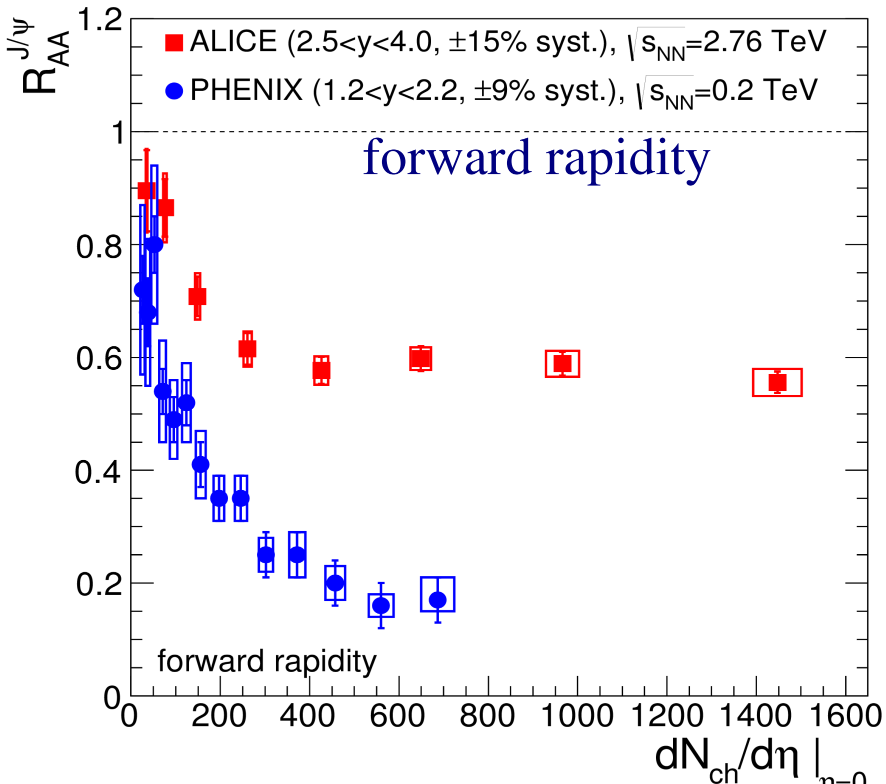
the baseline: rapidity distribution in pp collisions

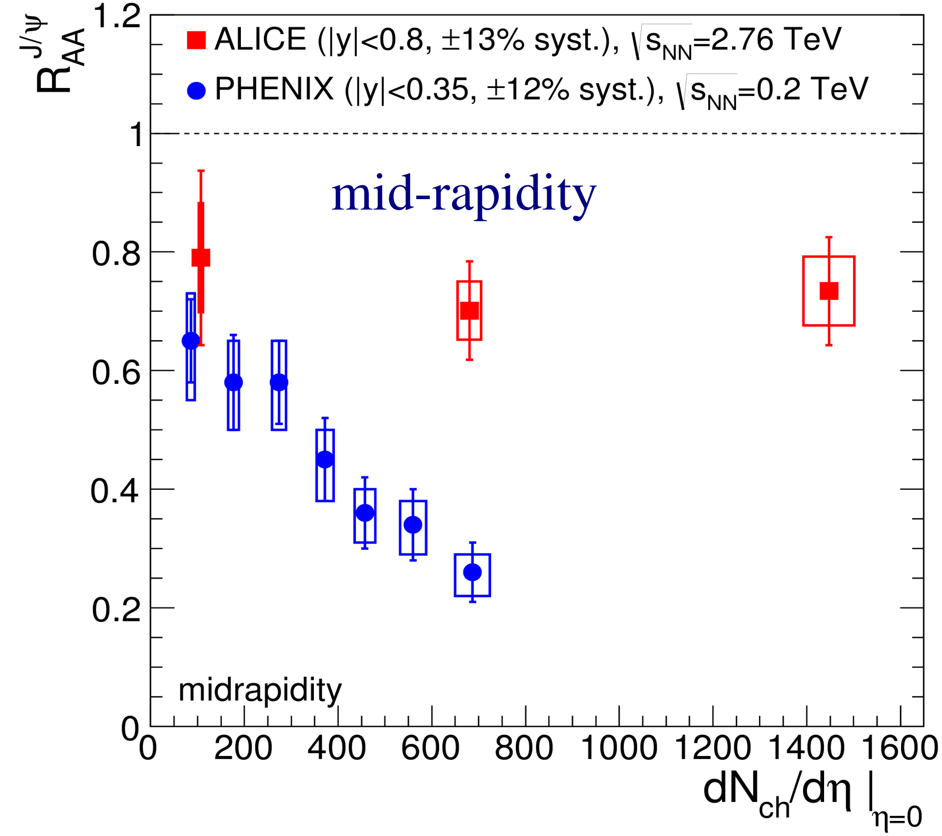


- nice agreement between experiments
- good baseline for AA collisions

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

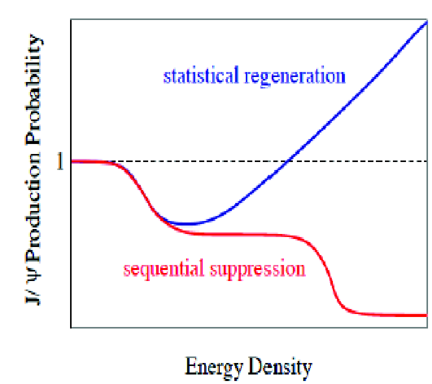
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta\, dp_T}{\langle N_{\rm coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta\, dp_T}$$



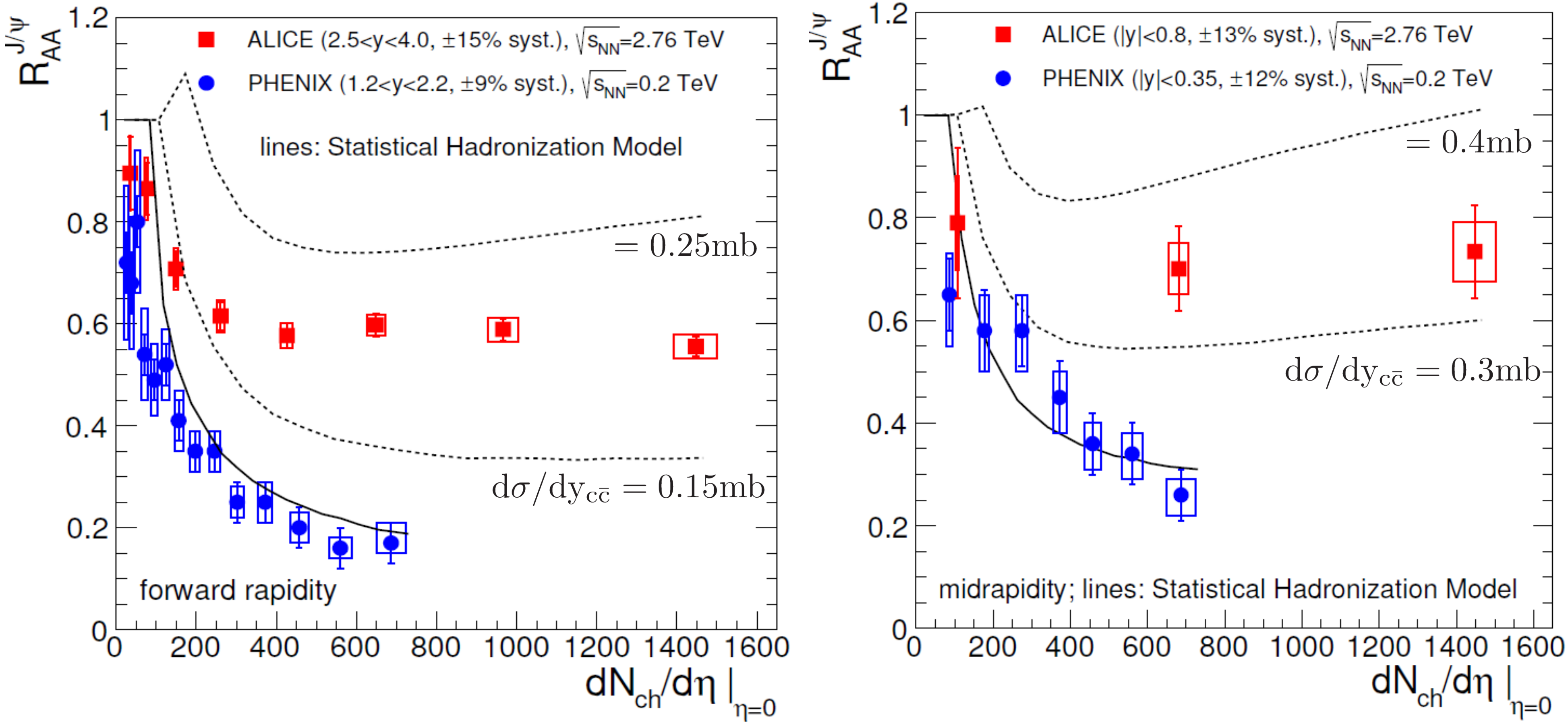


energy density -->

major new discovery at LHC: enhancement with increasing energy density points to new production mechanism!



J/ψ and statistical hadronization



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

transport models also in line with R_{AA} 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) more below

— main uncertainties for models: open charm cross section, shadowing in Pb

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

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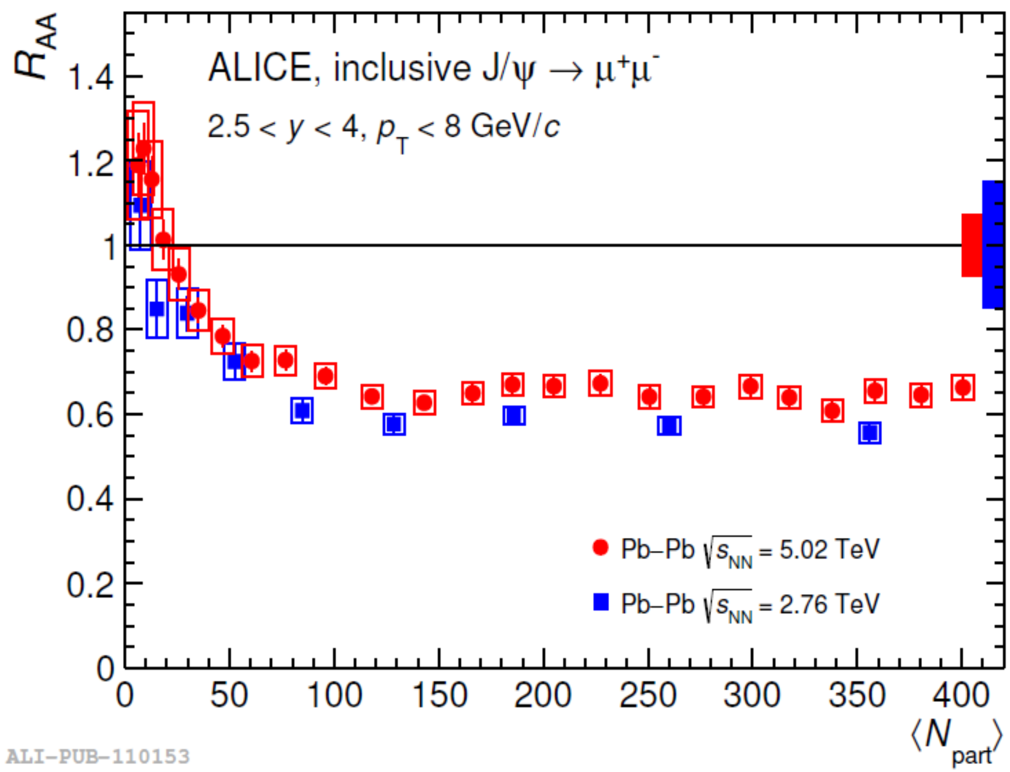
arXiv:1606.08197 [nucl-ex]

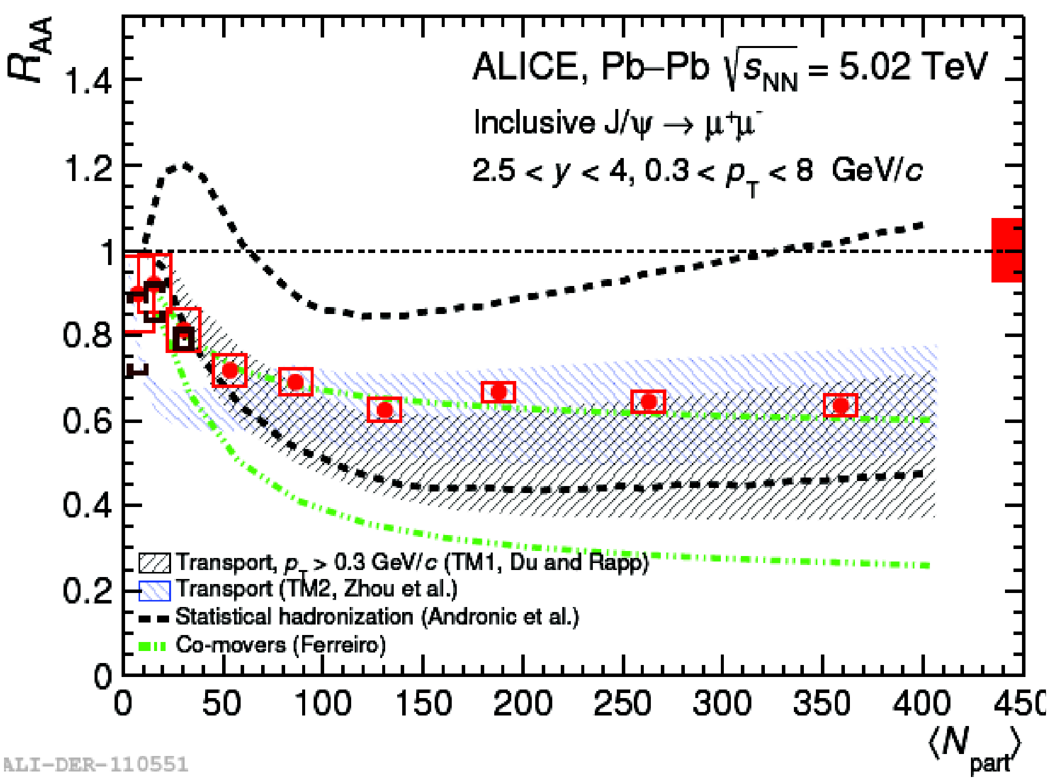


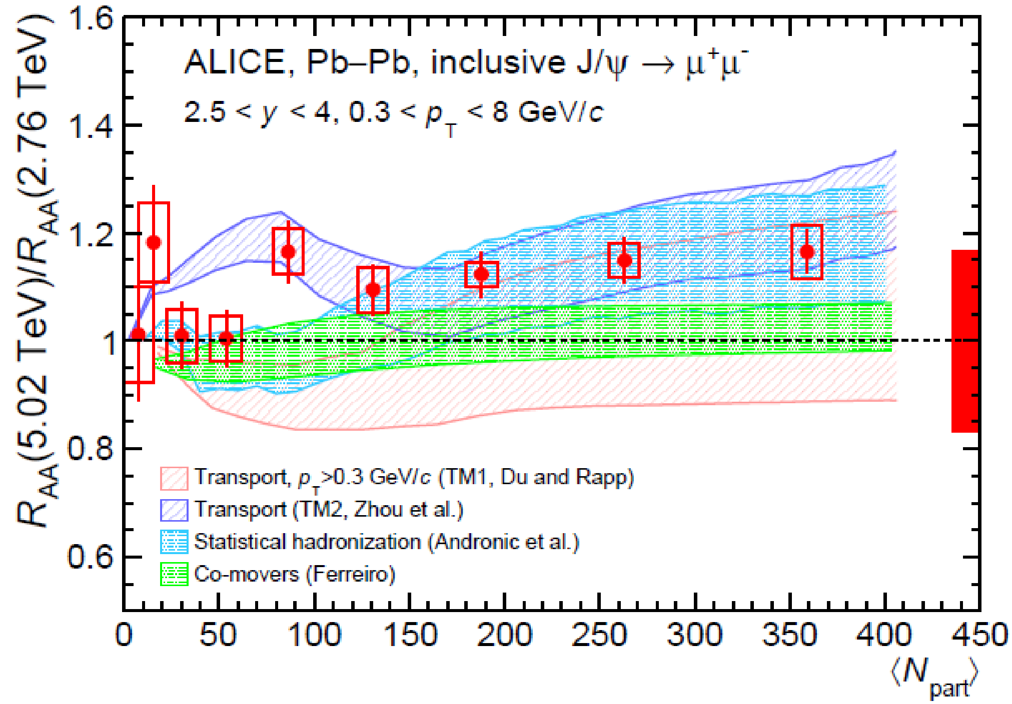
$$R_{AA}^{0\text{-}90\%}(5.02\ \text{TeV}) / R_{AA}^{0\text{-}90\%}(2.76\ \text{TeV}) = 1.13 \pm 0.02(\text{stat}) \pm 0.18(\text{syst})$$

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

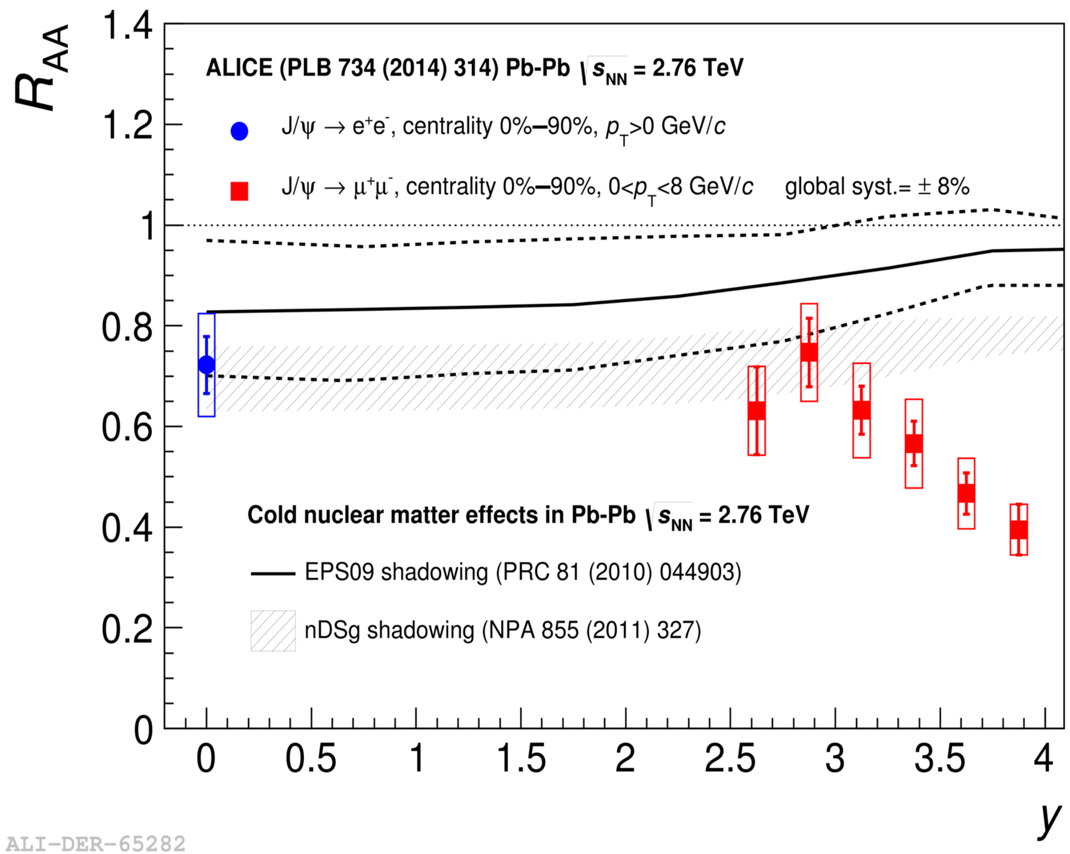
J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV compared to stat. hadronization and transport models

arXiv:1606.08197 [nucl-ex]





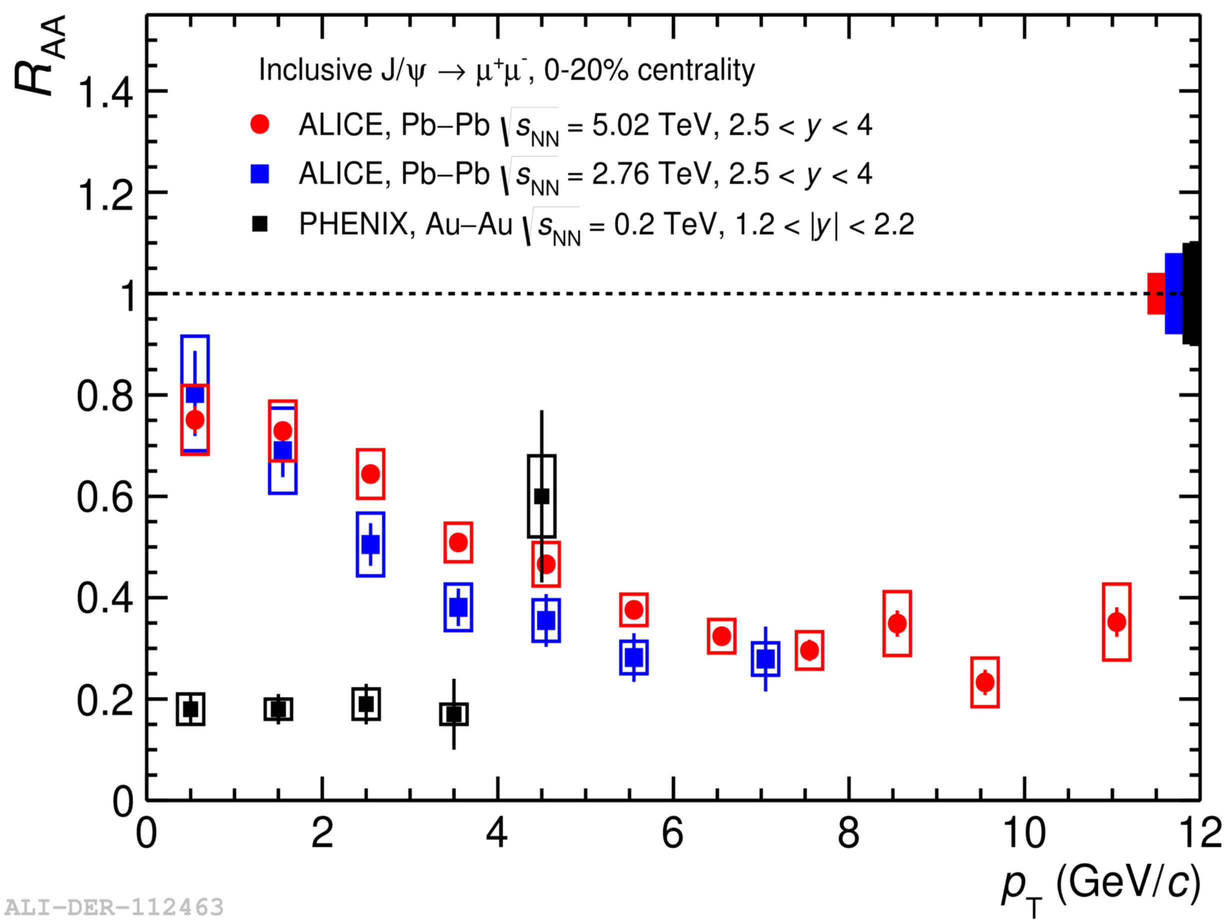
rapidity dependence of R_{AA}



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)

transverse momentum spectrum



softer in PbPb as compared to pp

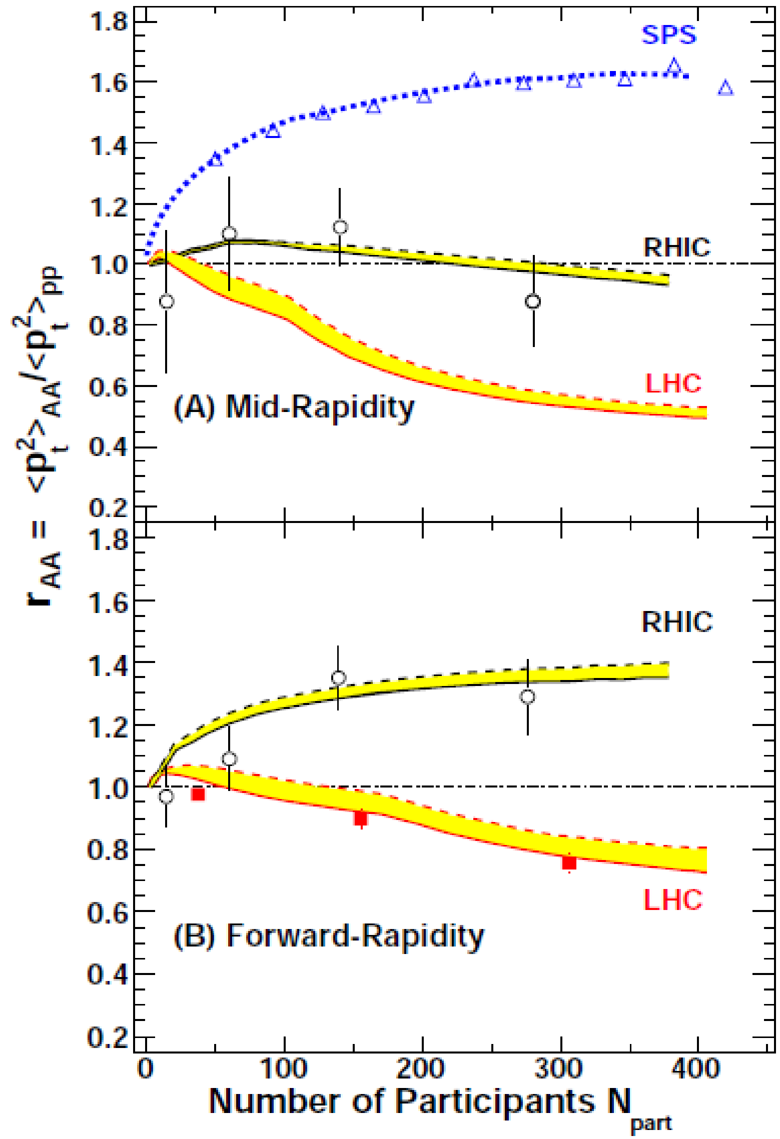
a qualitatively new feature as compared to RHIC where the trend is opposite

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

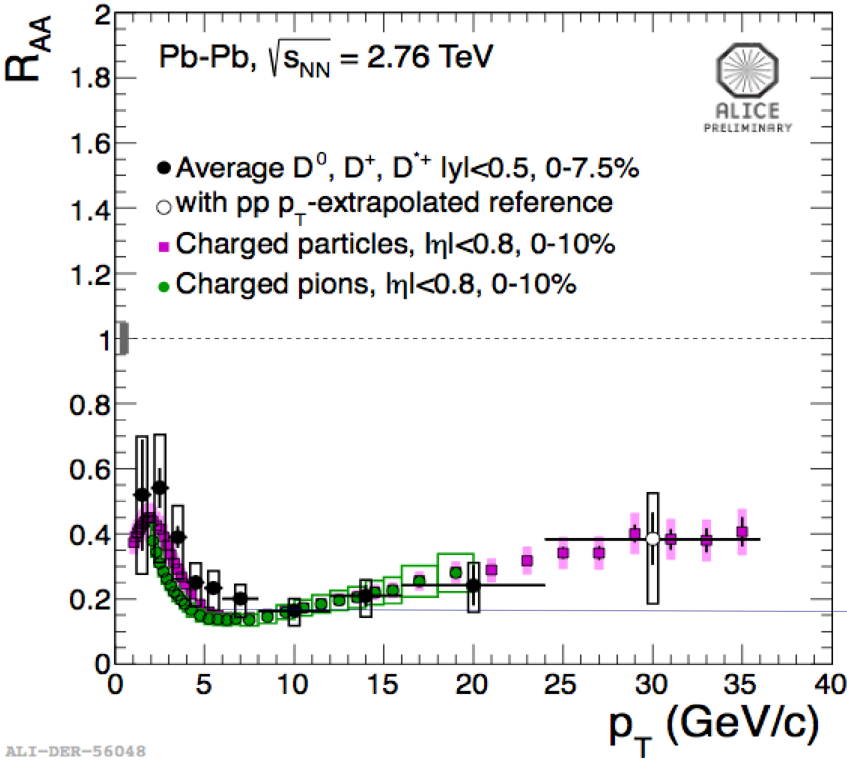
analysis of transverse momentum spectra

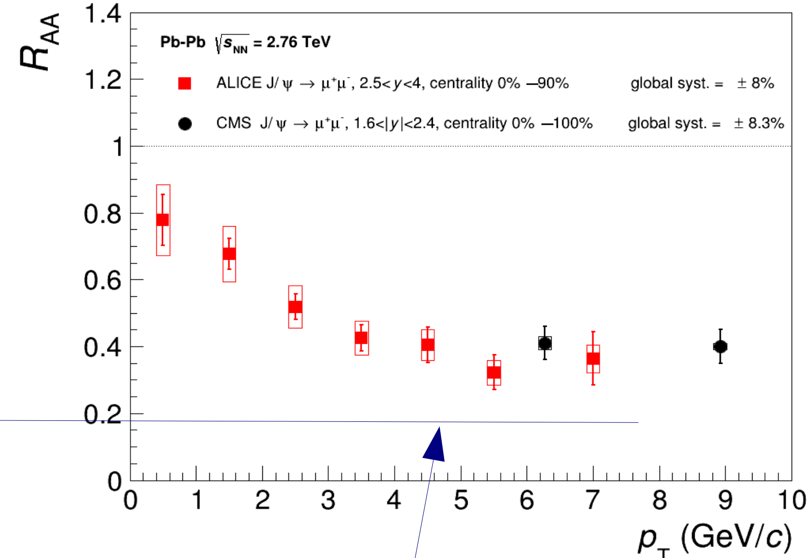
- at LHC energy, mostly (re-) generation of charmonium
- p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks

Zhou, Xu, Zhuang, arXiv:1309.7520



p_t dependence of R_{AA}



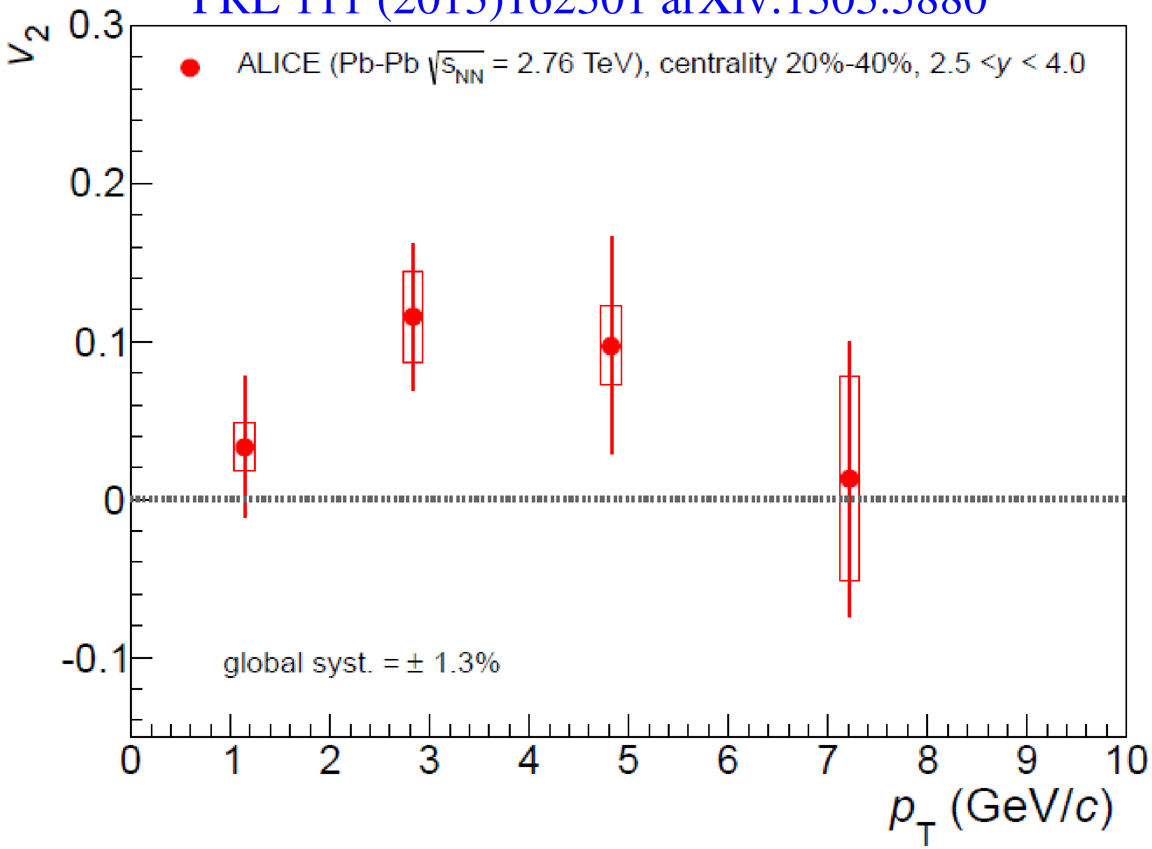


is high p_t part indicative of the same charm quark energy loss seen for D's

out to what p_t is statistical hadronization/regeneration relevant?

elliptic flow of J/ψ vs p_t

PRL 111 (2013)162301 arXiv:1303.5880



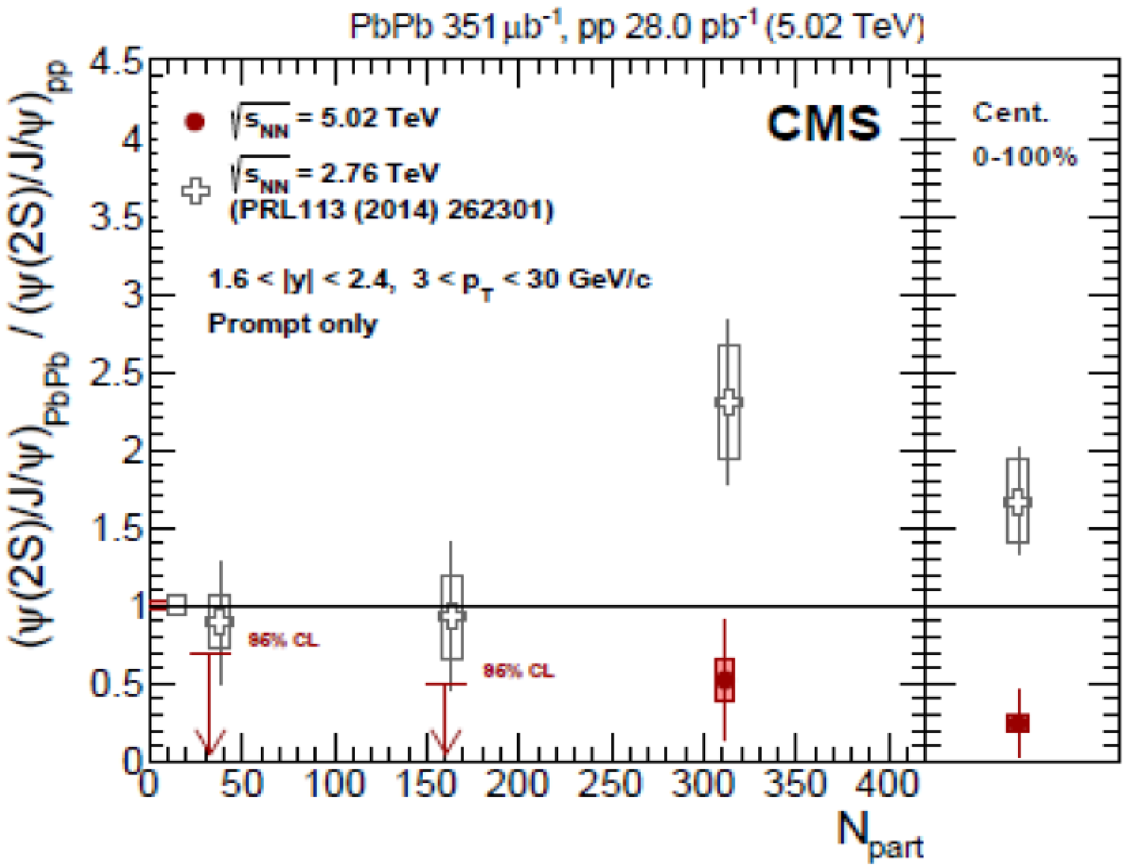
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- 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

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!

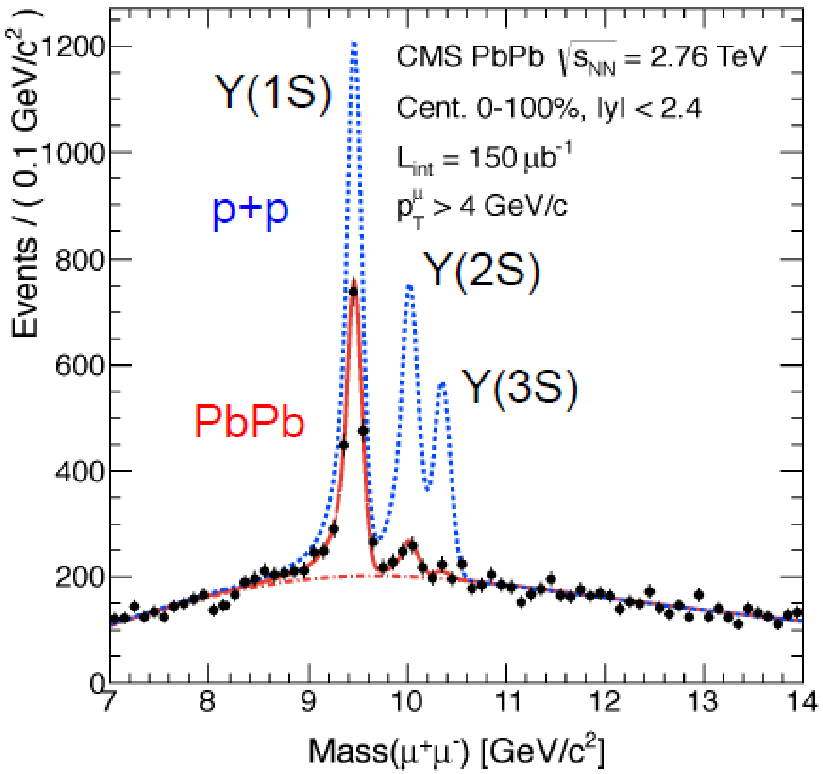


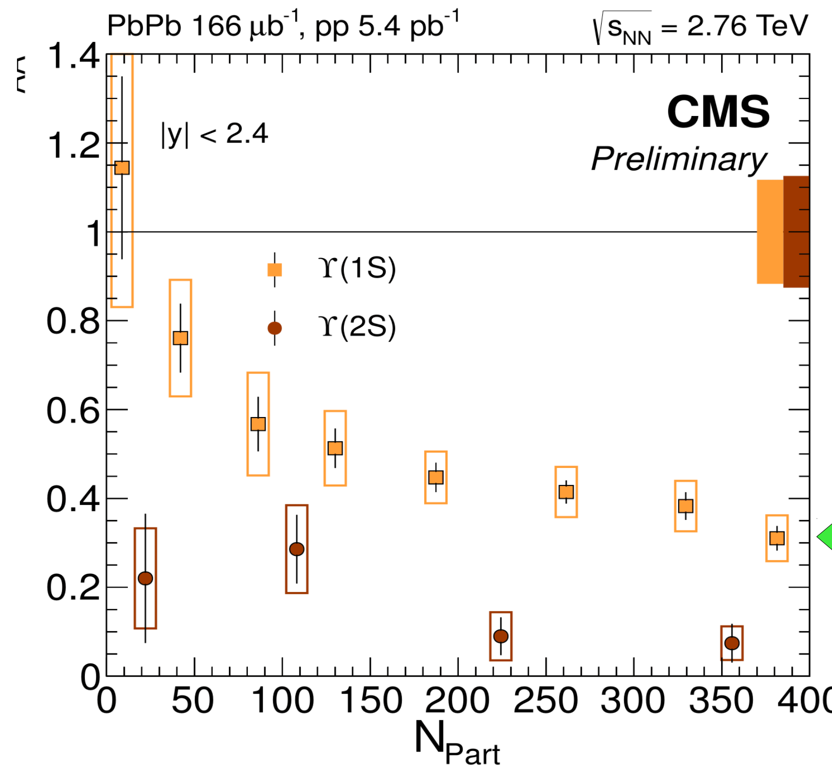
expect value of 1/3 for inclusive pt and central collisions

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

Upsilon – bbar states

suppression of Upsilon states





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

$$R_{AA}(\Upsilon(1S)) = 0.425 \pm 0.029 \pm 0.070$$
$$R_{AA}(\Upsilon(2S)) = 0.116 \pm 0.028 \pm 0.022$$
$$R_{AA}(\Upsilon(3S)) < 0.14 \text{ at } 95\% \text{ CL},$$

+ R_{AA} (Y(1S)) = 0.30 ± 0.05 ± 0.04
(at forward rapidity)

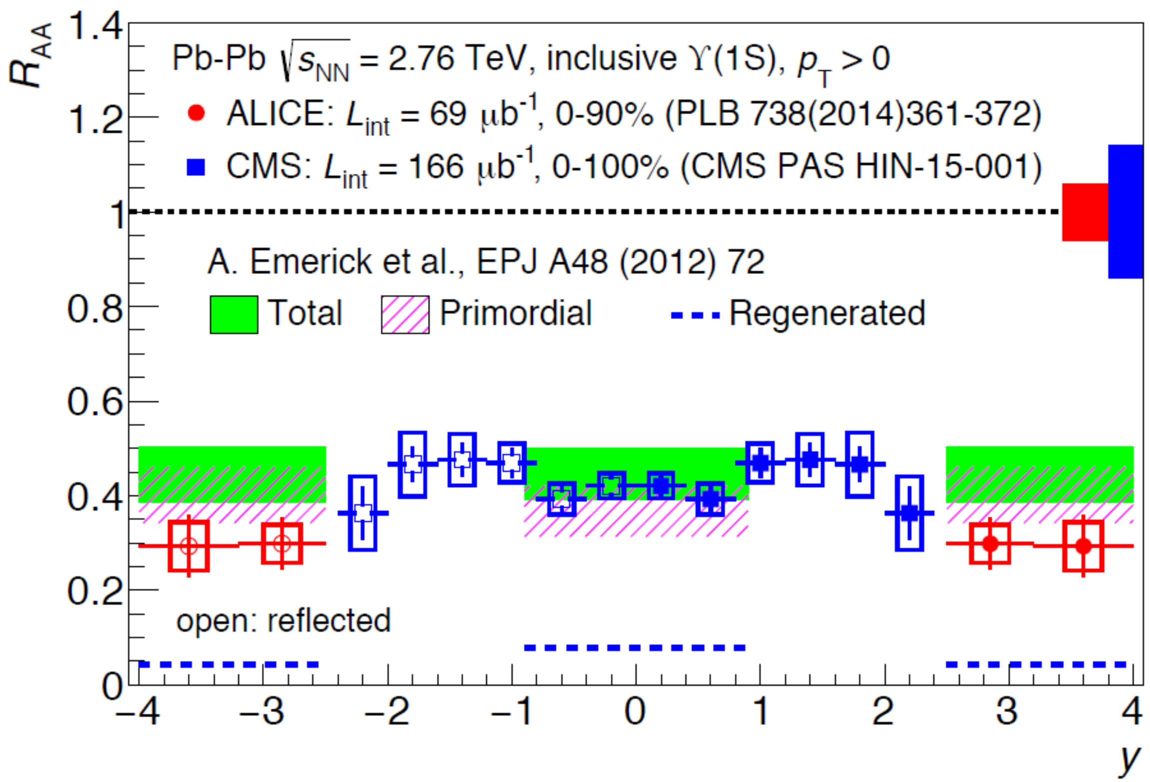
CMS, PRL109 (2012) 222301
ALICE, PLB738 (2014) 361

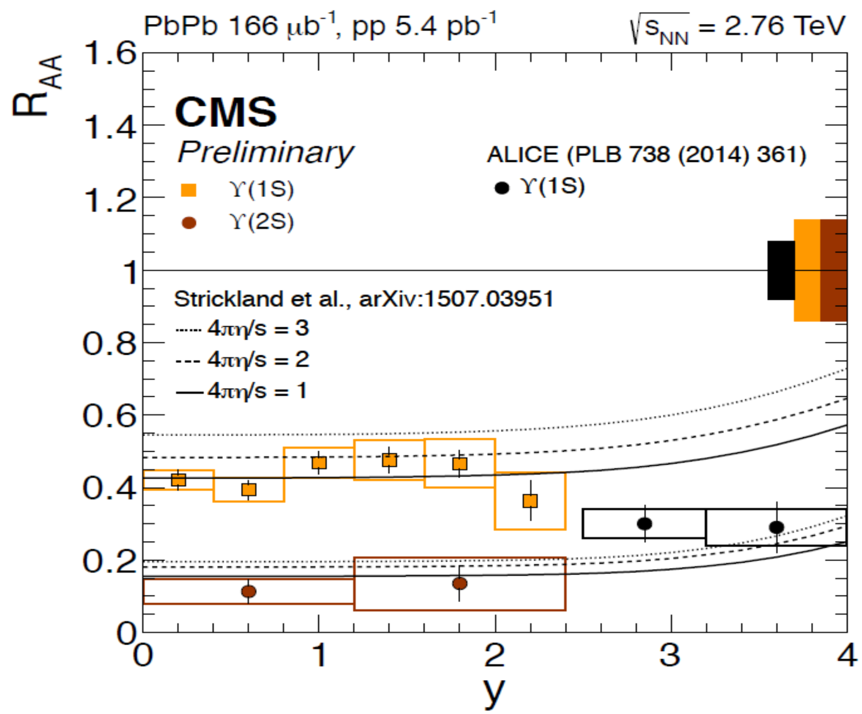
another puzzle: radius of Upsilon(2S) similar to radius J/ψ, but at mid-y R_{AA} = 0.12 vs 0.70

Upsilon R_{AA} rapidity dependence

CMS 20 times more statistics in pp than previously published

M. Jo, CMS-HIN-15-001

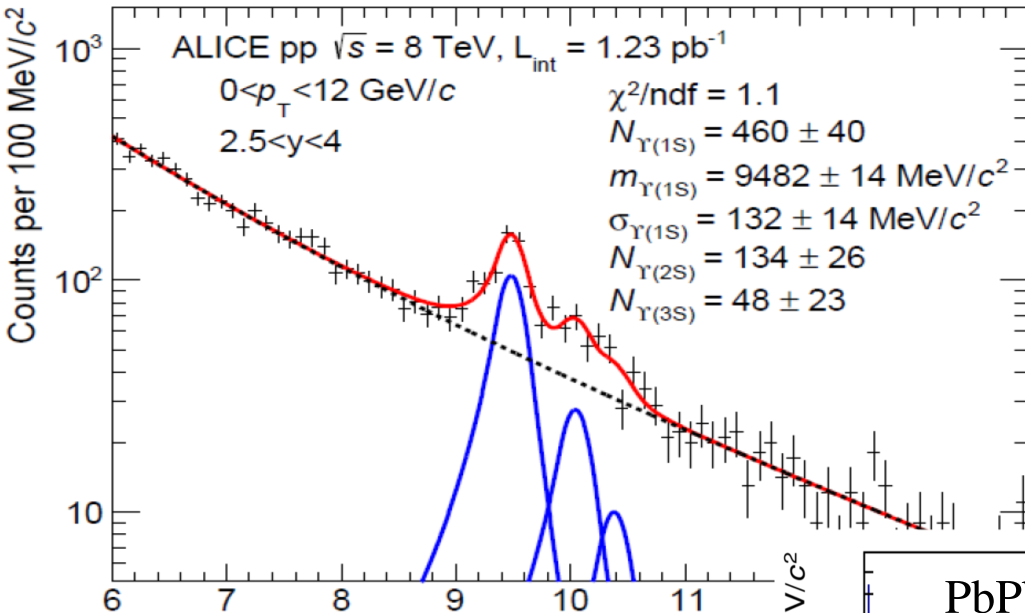




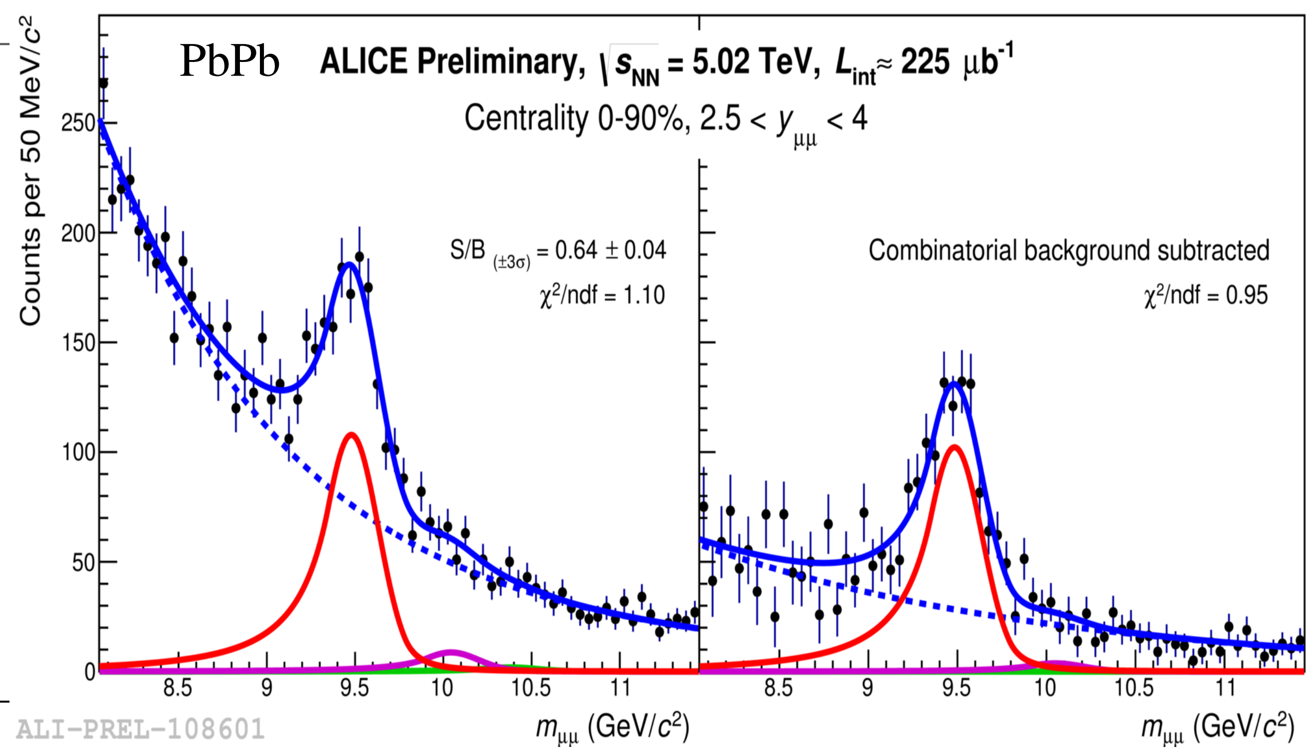
R_{AA} still peaked at mid-y like for J/ψ not in line with collisional damping in expanding medium (Strickland)

Upsilon in ALICE in PbPb at 5.02 TeV

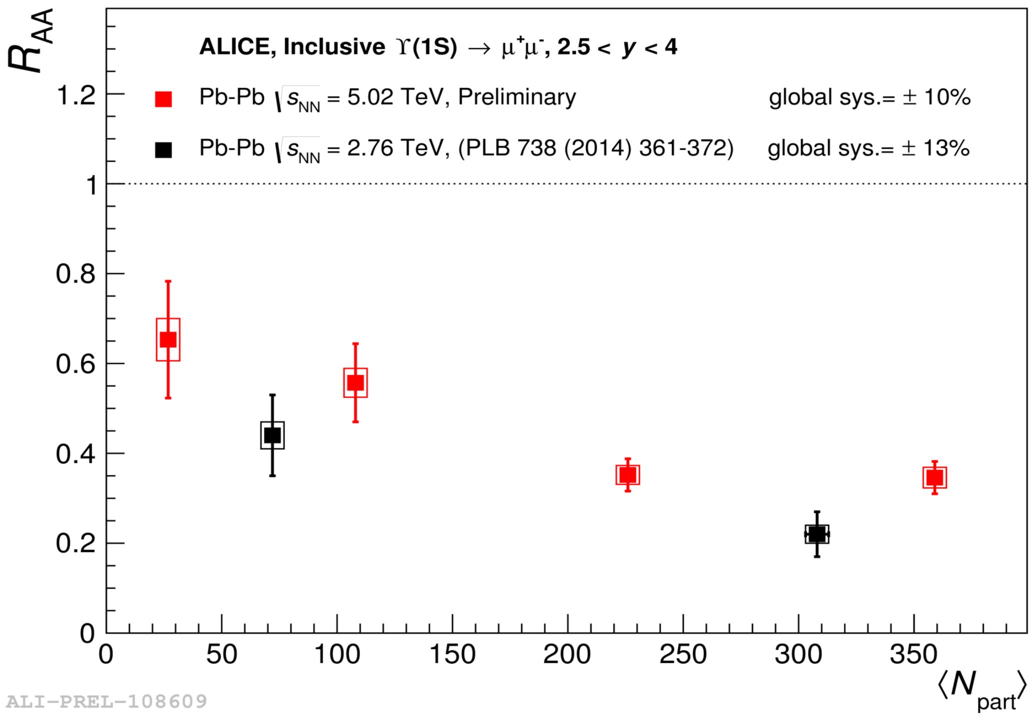
arXiv:1606.08197



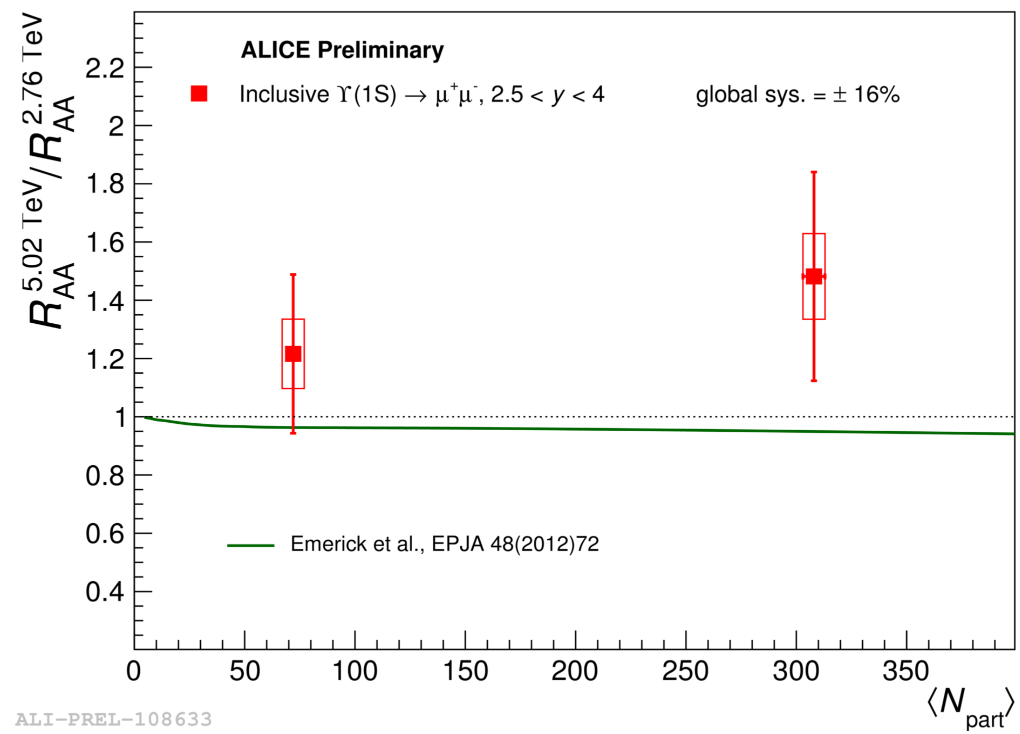
Eur. Phys. J C 76 (2016) 184



Upsilon in PbPb at 5 TeV compared to 2.76 TeV



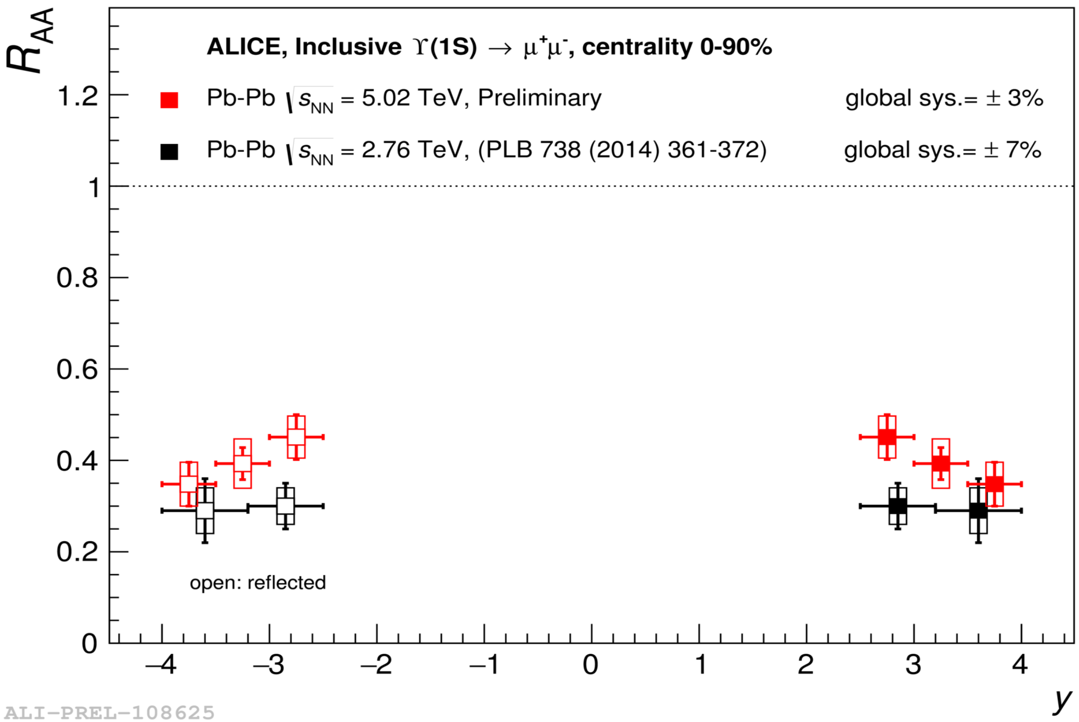
yield of Upsilon(1S) increases with beam energy



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

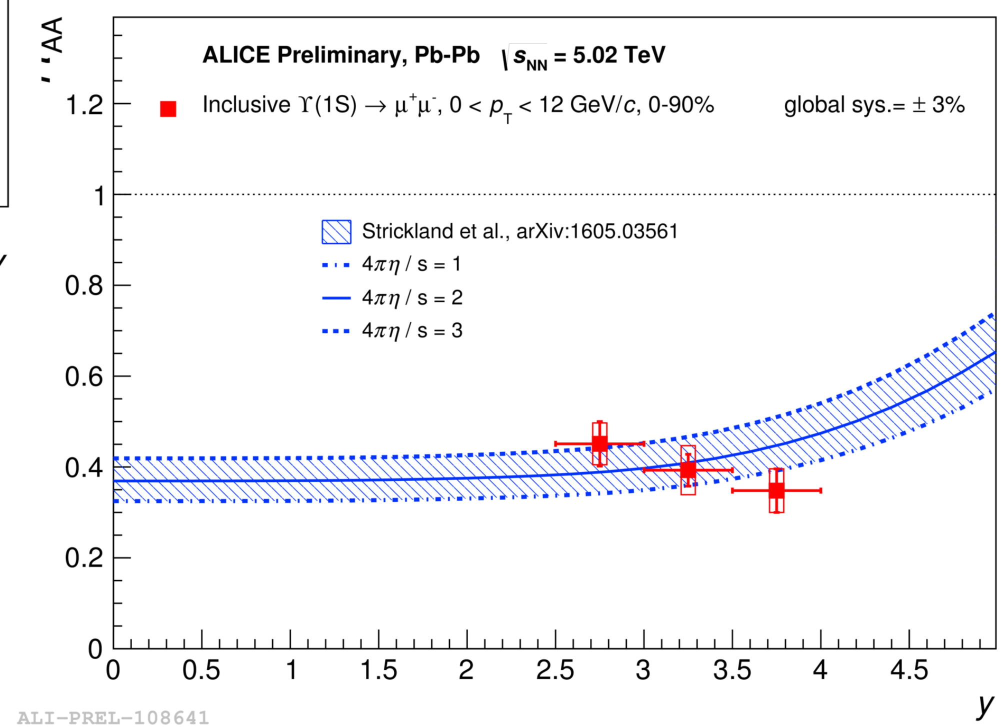
$R_{AA}^{0\text{-}90\%}(5.02\text{ TeV}) / R_{AA}^{0\text{-}90\%}(2.76\text{ TeV}) = 1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})$

Upsilon in PbPb at 5 TeV – rapidity distribution



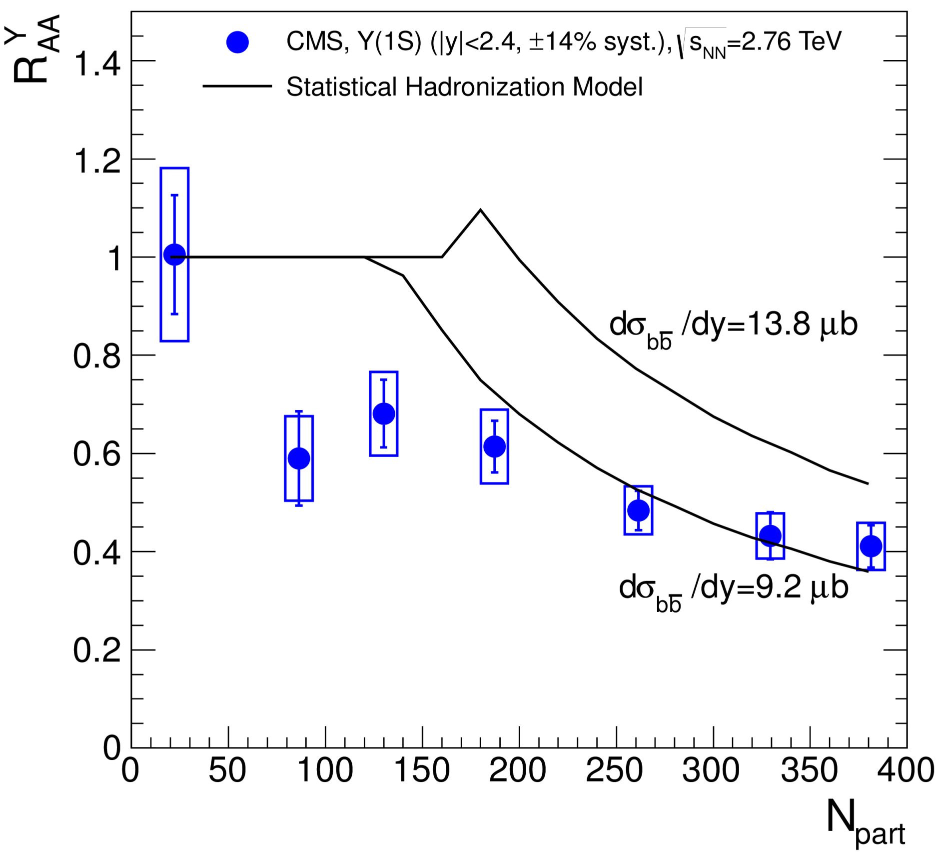
yield of Upsilon(1S) increases towards mid-rapidity

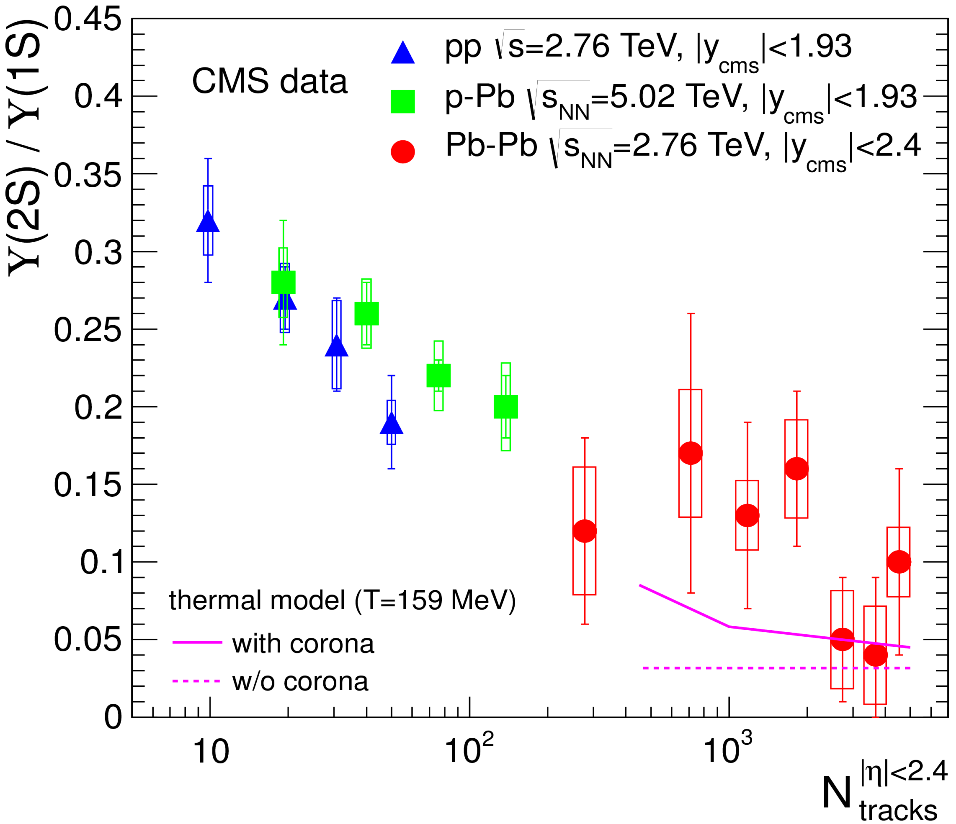
increasing dissociation with increasing particle and energy density will not do this



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

summary

strong indication for charm quark thermalization

complete theoretical understanding still a challenge (being addressed)

clear indication of new producion mechanism for charmonia at LHC

supported by yields, spectra, rapidity distribution, v2

data consistent with statistical hadronization model and transport model approaches

limitation in interpretation:

precision measurement of open charm cross section in PbPb

statistics of charmonium observables

bottomonium data not in line with simple screening picture

statistical hadronization as well? Does beauty thermalize in QGP?

expect significant progress from run2 and run3 LHC data from all experiments

backup

Quarkonium Properties and Debye Screening

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
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

table from H. Satz, J. Phys. G32 (2006) R25

In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

formation time of quarkonia

heavy quark velocity in charmonium rest frame:

v = 0.55 for J/ψ see, e.g. G.T. Bodwin et al., hep-ph/0611002

Implies minimum formation time: t = separation/v = 0.45 fm

see also:

Hüfner, Ivanov, Kopeliovich, and Tarasov, Phys. Rev. D62 (2000) 094022

J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D39 (1989) 232

formation time of order 1 fm

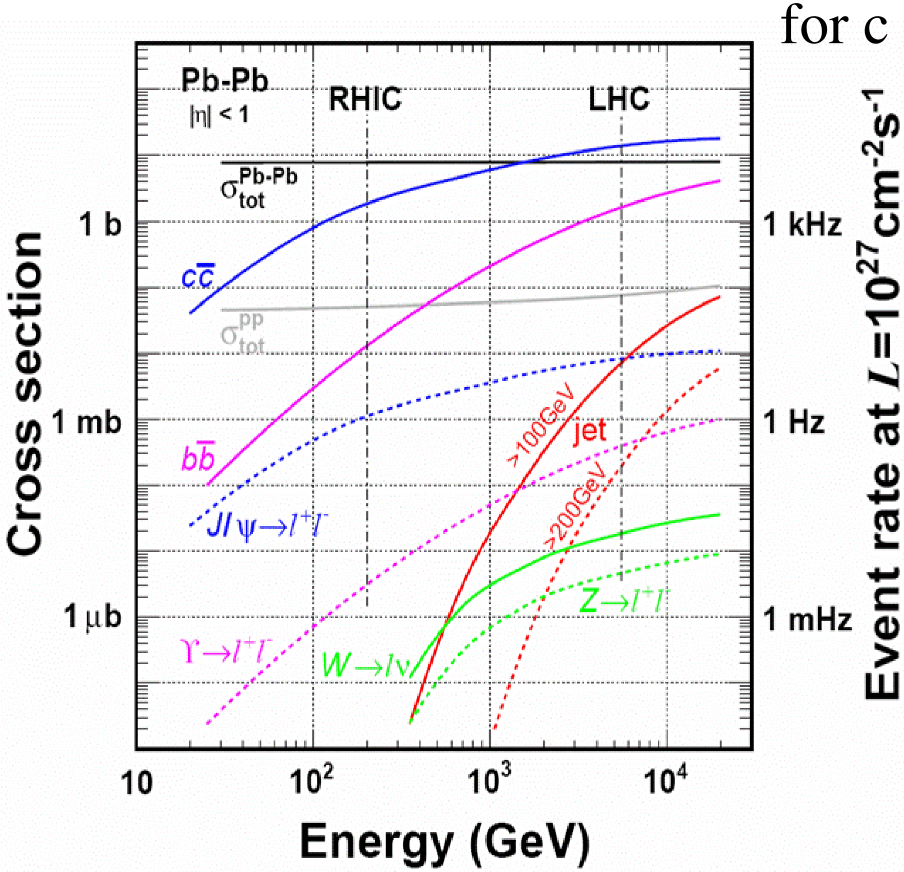
formation time is not short compared to QGP formation time

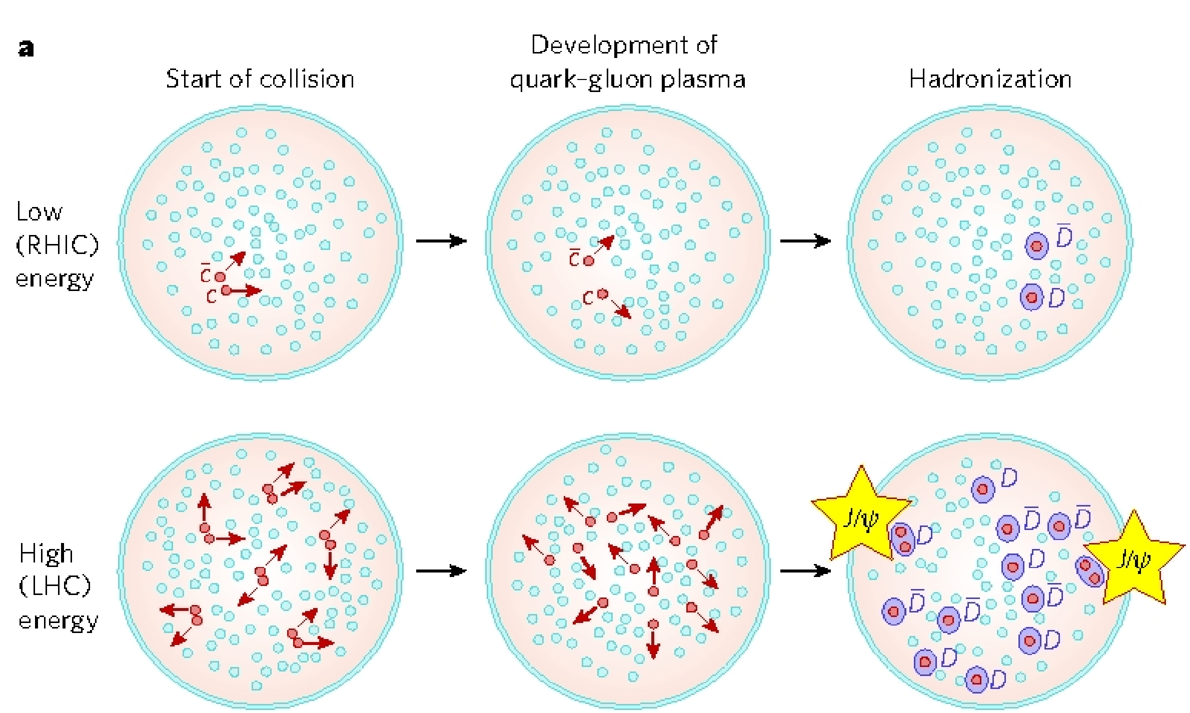
→ if J/ψ forms at all, it does so in QGP

→ if high color densith QGP screens interaction, J/ψ never forms until screening seizes

what happens to deconfined charm quarks as beam energy increases at colliders?

as more and more charm quarks produced, probability for c and cbar to hadronize into J/psi grows quadraticaly





low energy: few c-quarks per collision → **suppression** of J/ψ

high energy: many " " → **enhancement** "

reversal unambiguous signature for QGP!

extension of statistical model to include 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: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

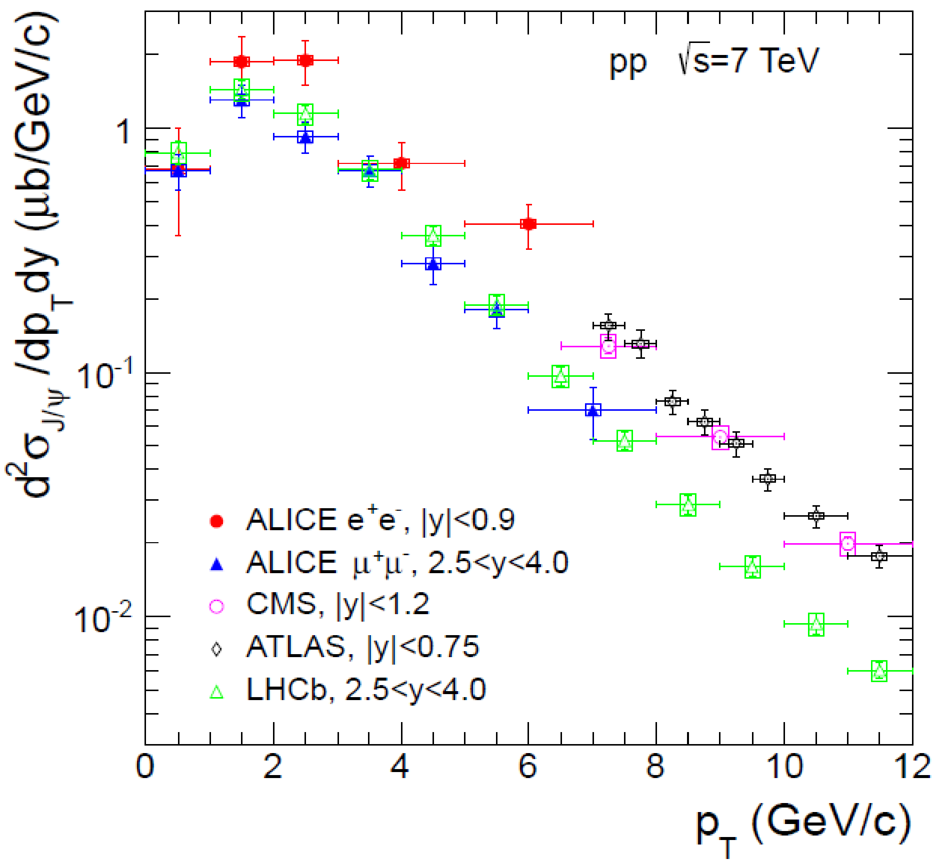
obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and same for all other charmed hadrons

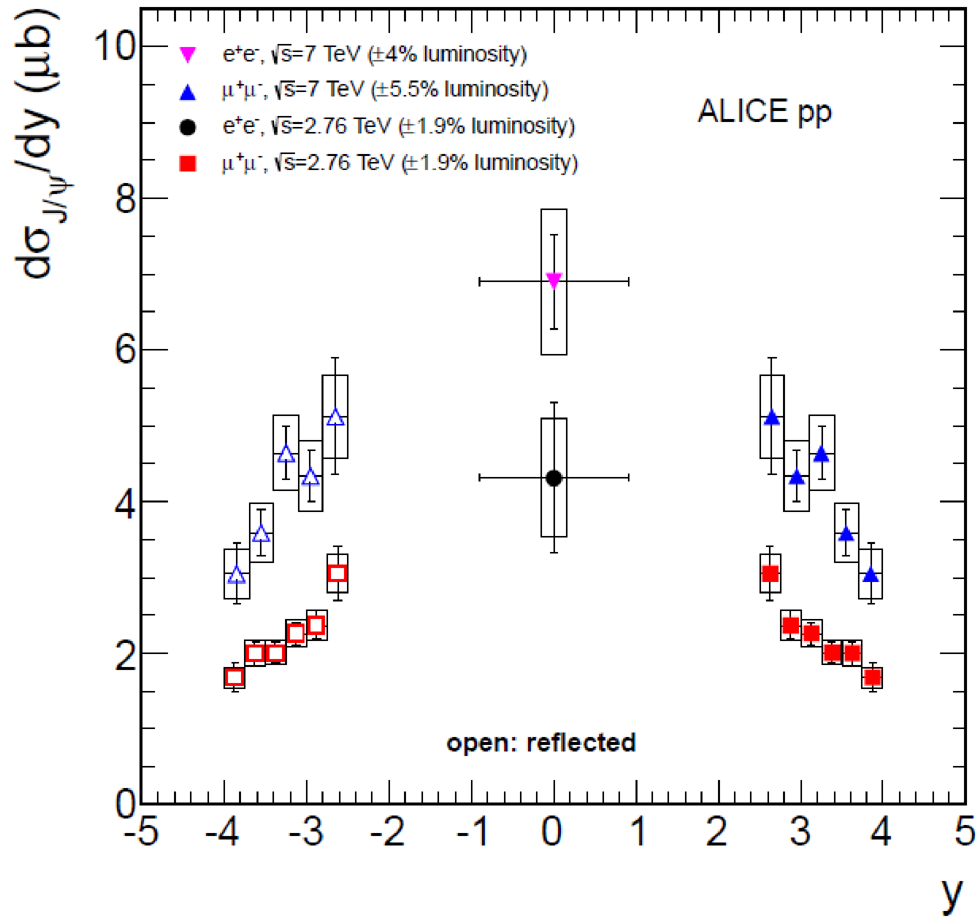
additional input parameters (beyond T,μ_b
fixed by fitting light flavor hadron yields: $V, N_{c\bar{c}}^{direct}$

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

J/psi spectrum and cross section in pp collisions

ALICE PLB704 (2011) 442 arXiv:1105

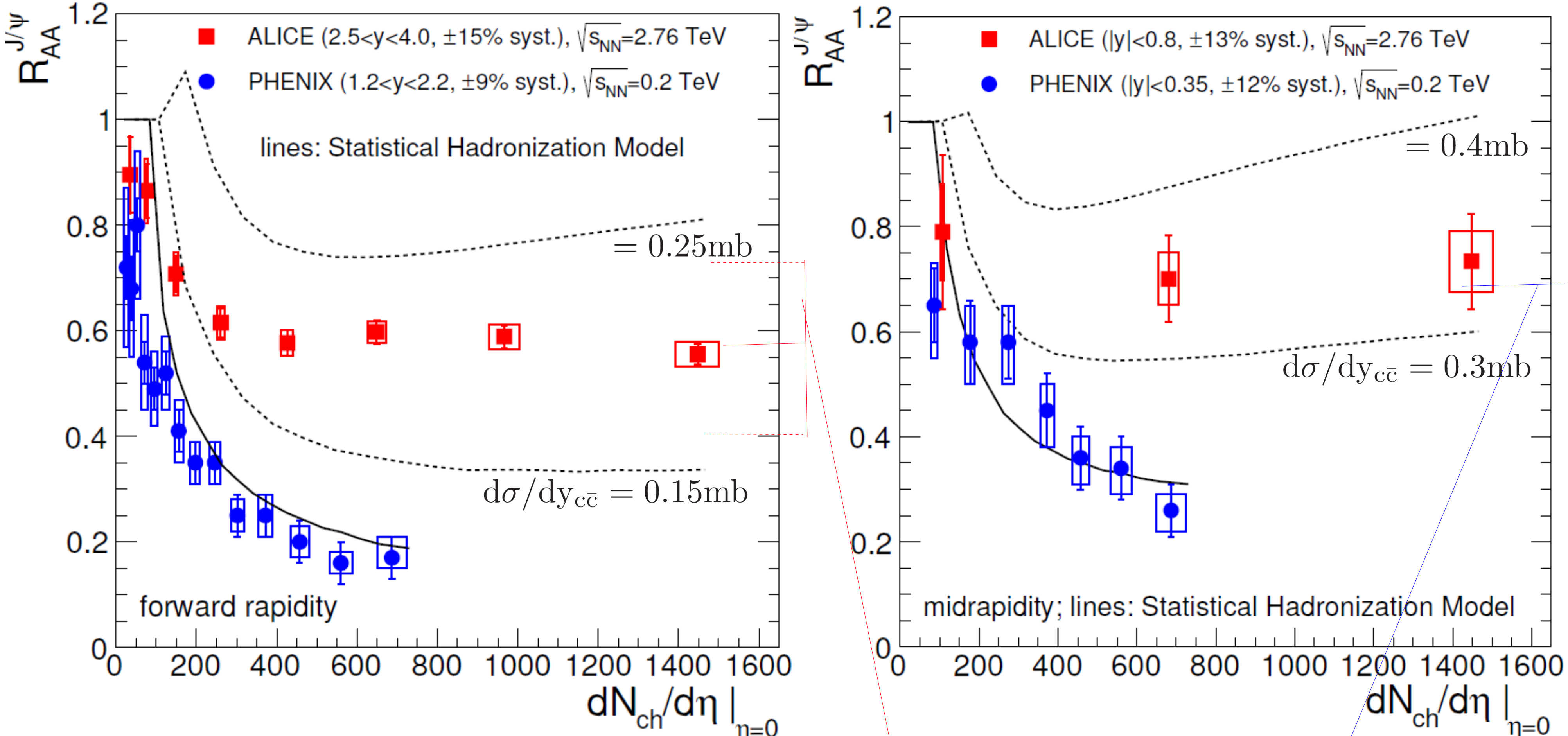




- good agreement between experiments
- complementary in acceptance:
  only ALICE has acceptance below
  6 GeV at mid-rapidity

measured both at 7 and 2.76 TeV
<u>open issues:</u> statistics at mid-rapidity
polarization (biggest source of syst error)

J/psi and statistical hadronization

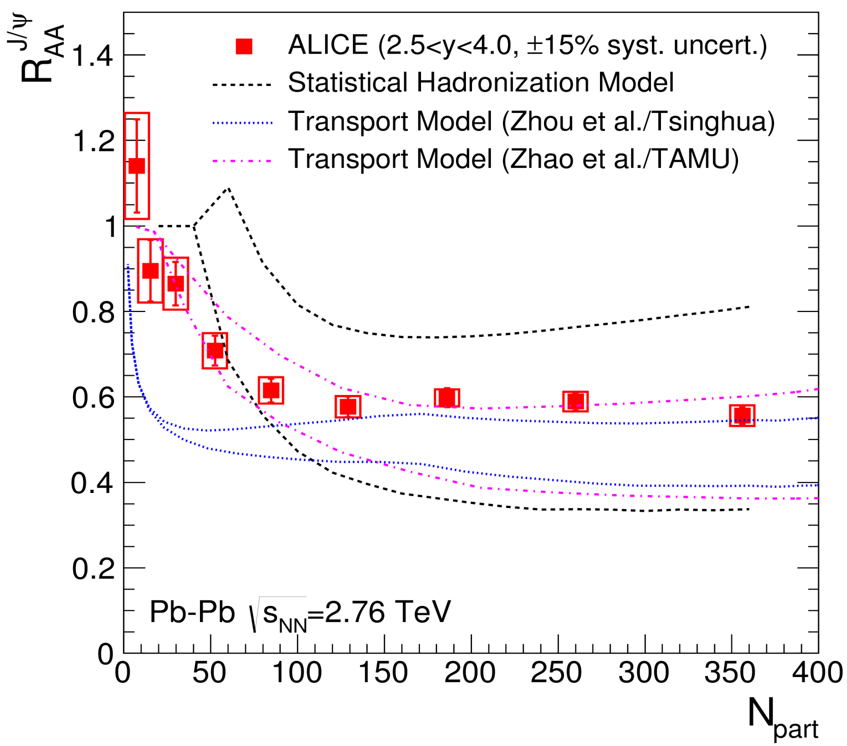


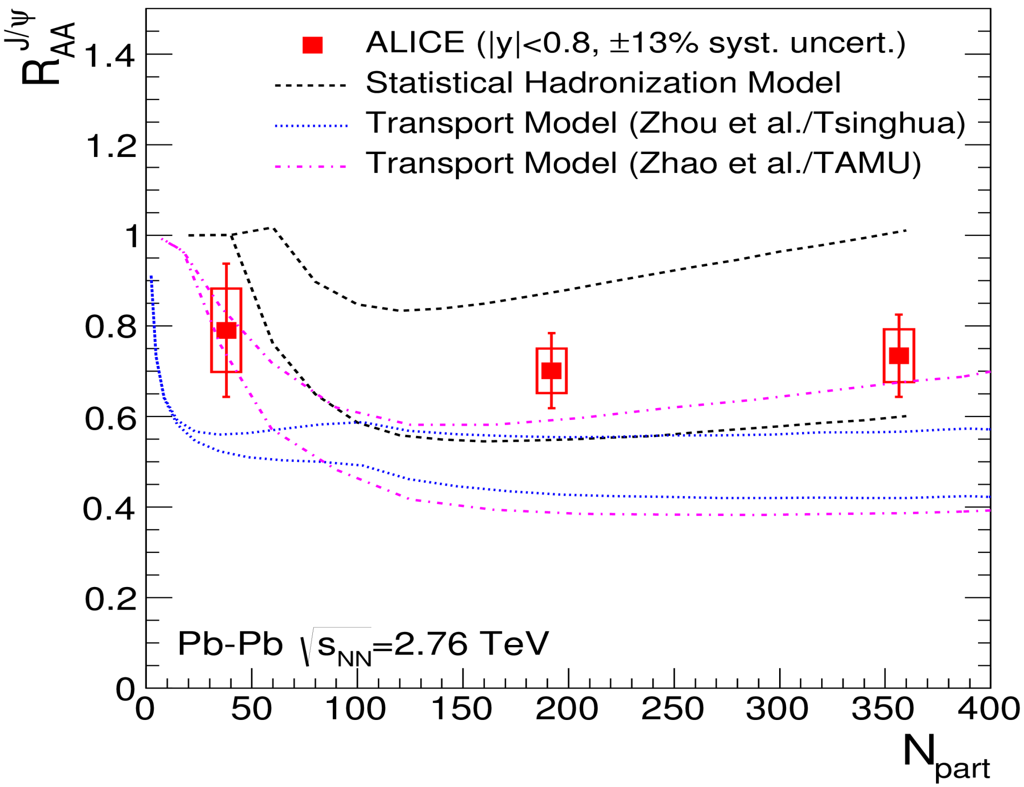
- main uncertainties for models: open charm cross section, shadowing in Pb

y = 2.4-4.0 dsigma(ccbar)/dy = 0.206 ± 0.035 mb
mid-y “ = 0.329 + 0.128 – 0.138 mb

transport models should use same cross section!

J/psi and transport models (and stat hadronization)

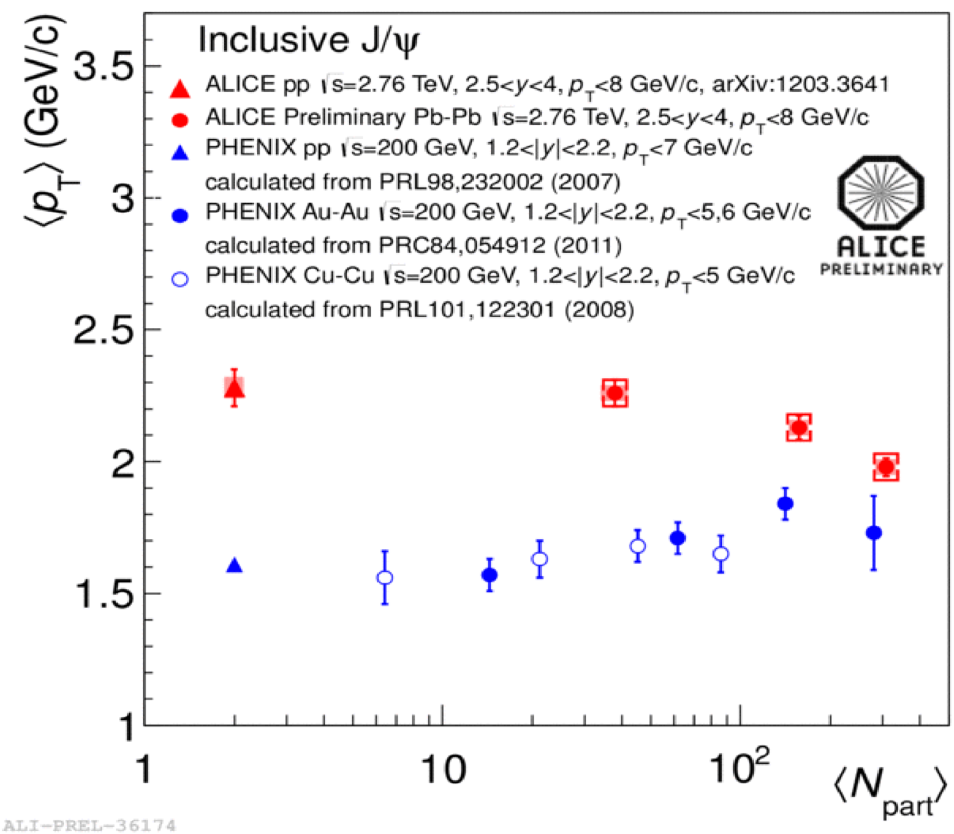


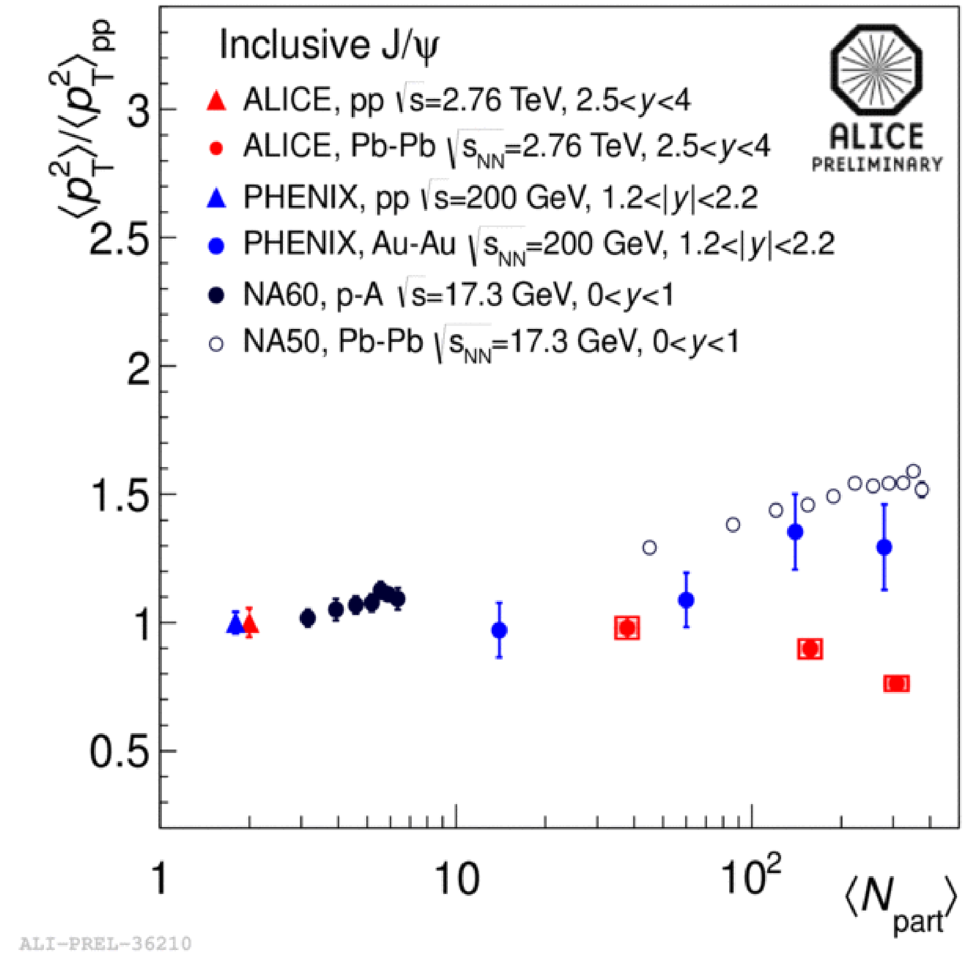


in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- 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)

softening of J/psi p_t distributions for central PbPb coll.

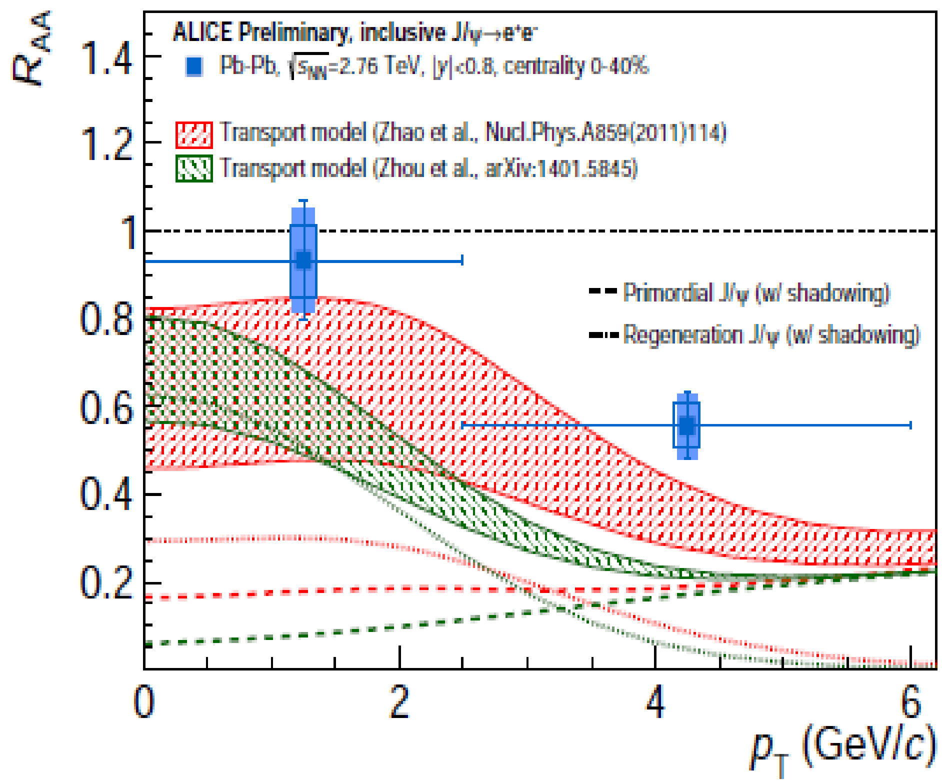




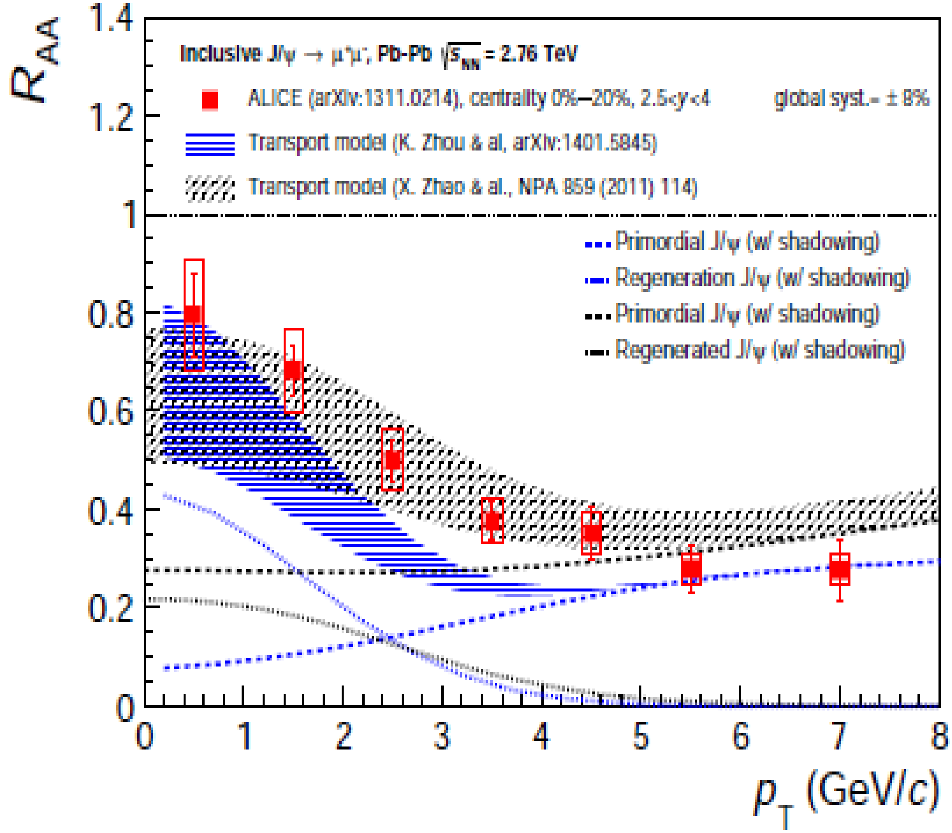
At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

comparison with (re-)generation models

midrapidity



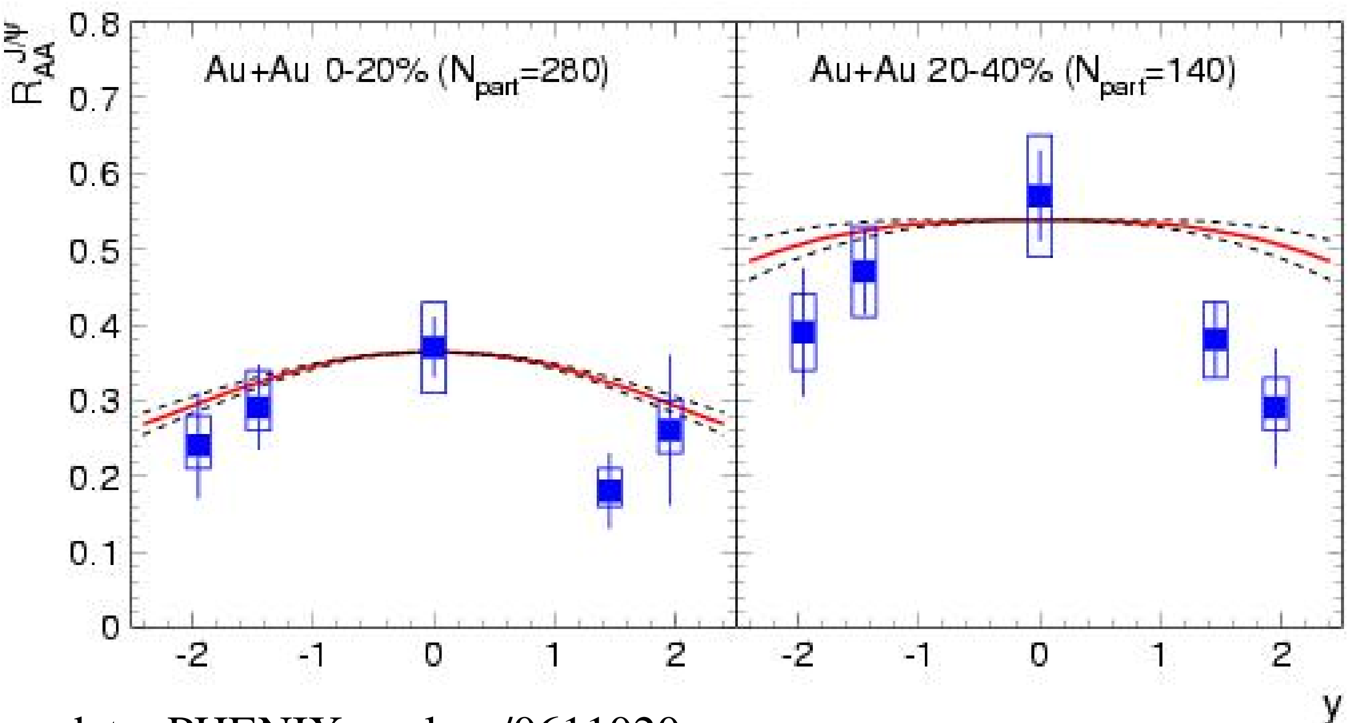
forward rapidity



good agreement lends further strong support to the
'full color screening and late J/psi production' picture

comparison of model predictions to RHIC data:

R_{AA}: J/ψ yield in AuAu / J/ψ yield in pp times N_{coll}



data: PHENIX nucl-ex/0611020

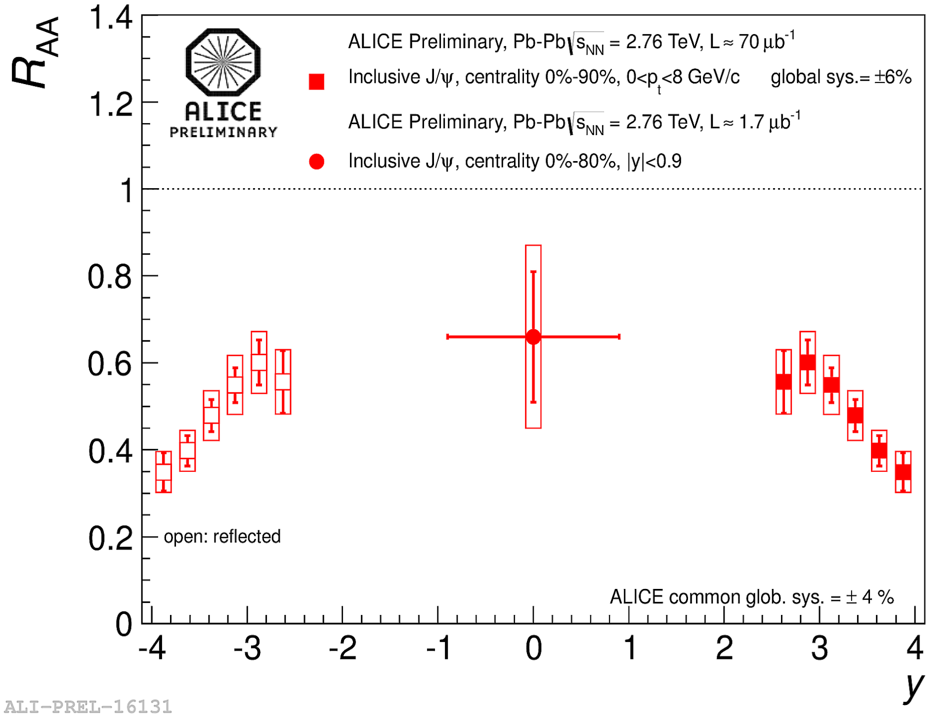
additional 14% syst error beyond shown

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

good agreement, no free parameters
same holds for centrality dependence

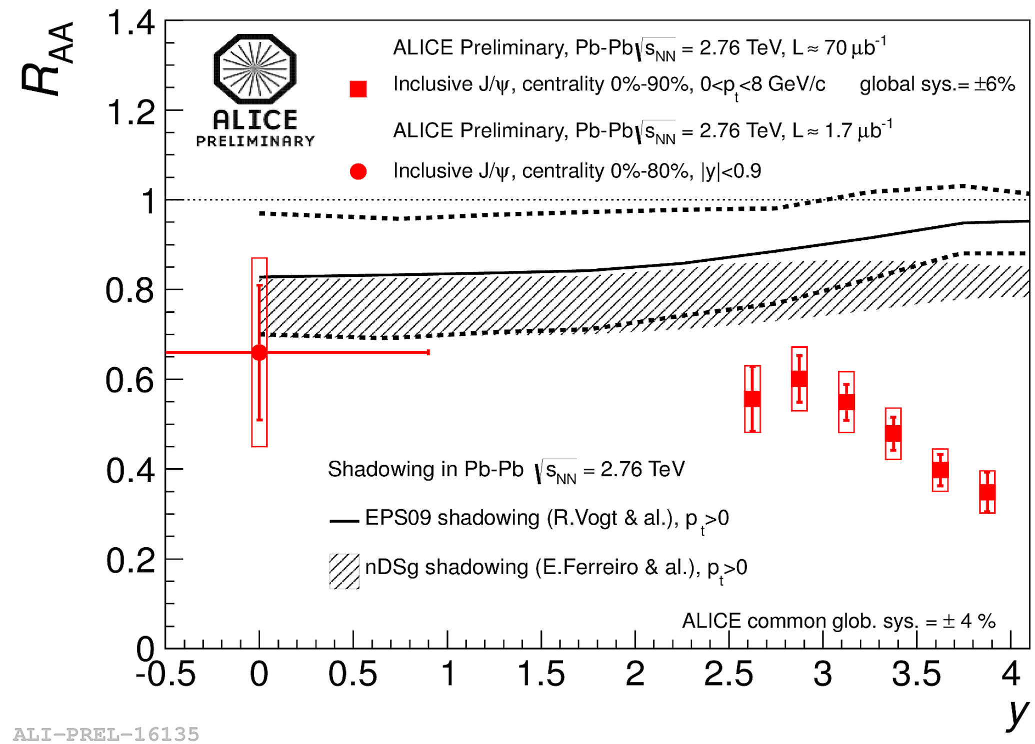
remark: y-dep opposite in 'normal Debye screening' picture; suppression strongest at midrapidity (largest density of color charges)

rapidity dependence of J/psi R_{AA}

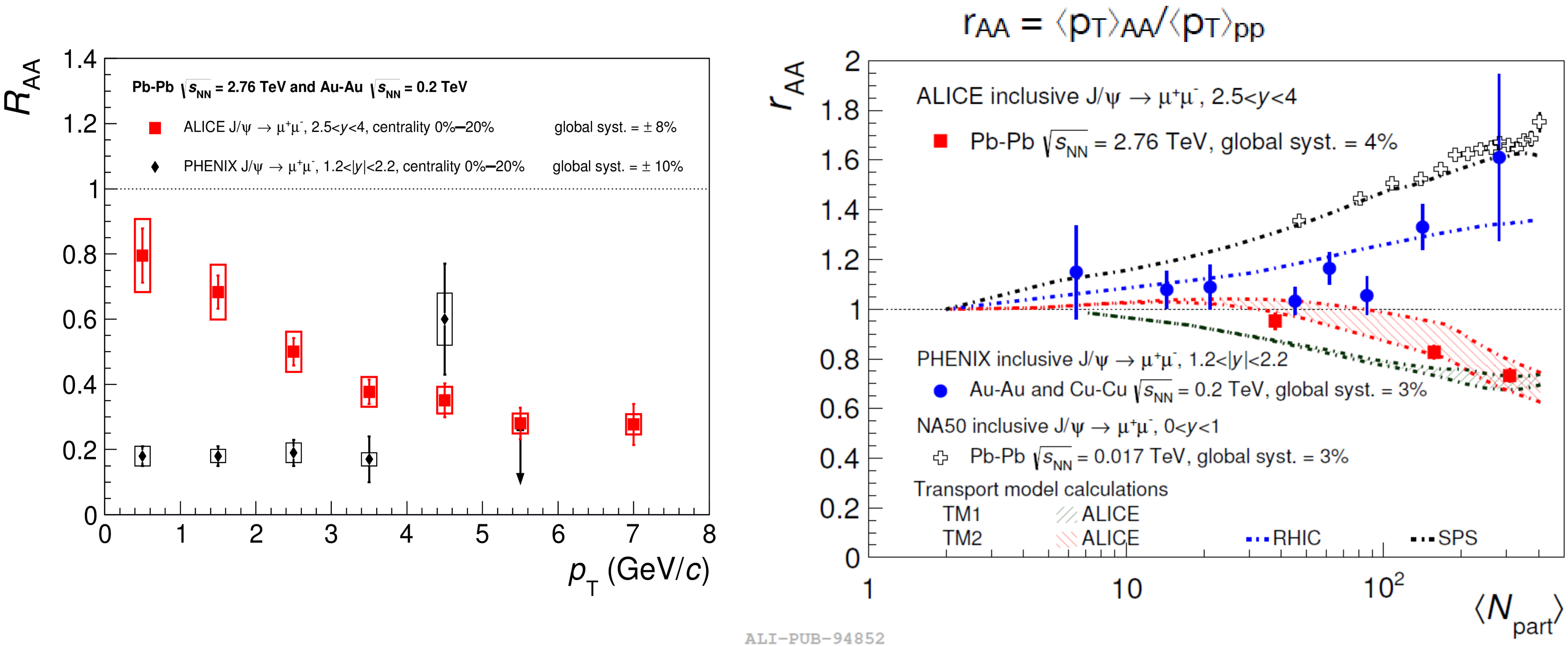


for statistical hadronization J/ψ yield proportional to N_c^2
higher yield at mid-rapidity predicted in line with observation

comparison to shadowing calculations:
- at mid-rapidity suppression could be explained by shadowing only
- at forward rapidity there seems to be additional suppression
- need to measure shadowing



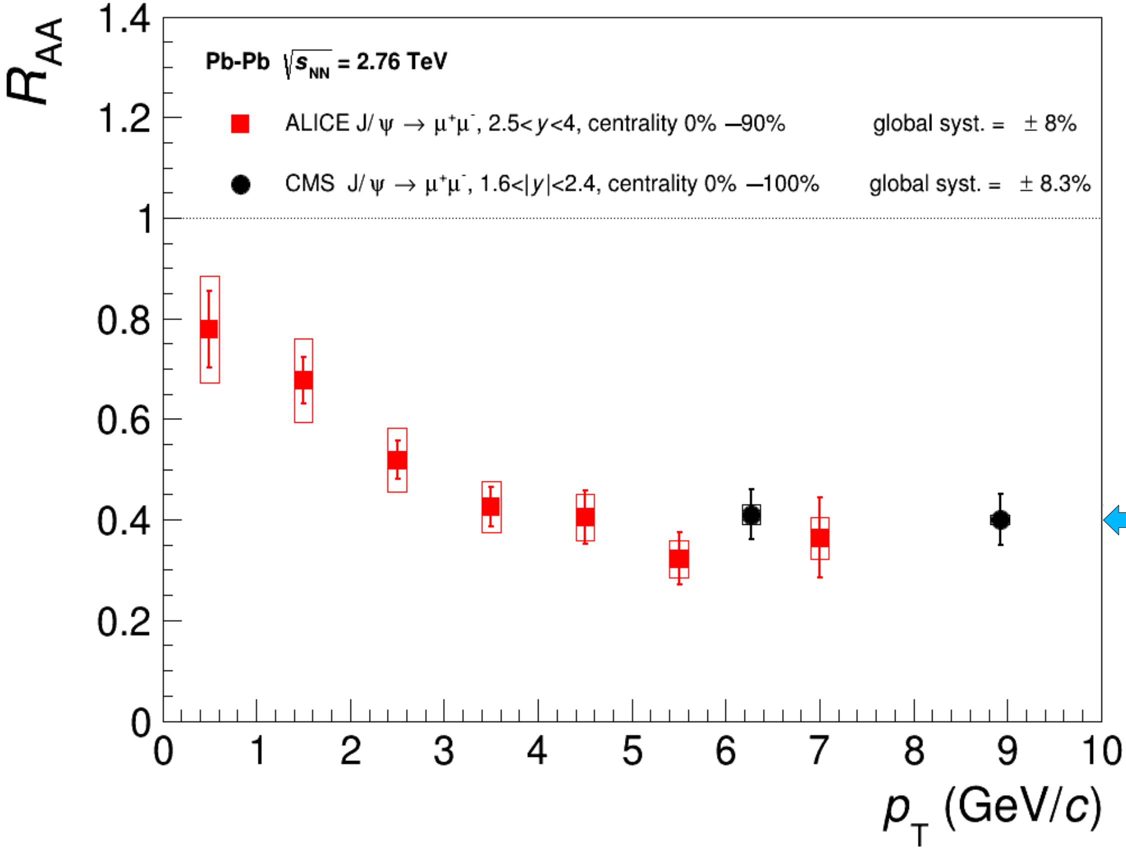
p_t dependence of R_{AA} supports dominance of new production mechanism at LHC at small p_t



p_t dependence at LHC opposite to RHIC and SPS

supports argument: thermalized deconfined charm quarks hadronize into J/ψ

p_t dependence of R_{AA}



relative yield larger at low p_t in nuclear collisions

what effects to expect?

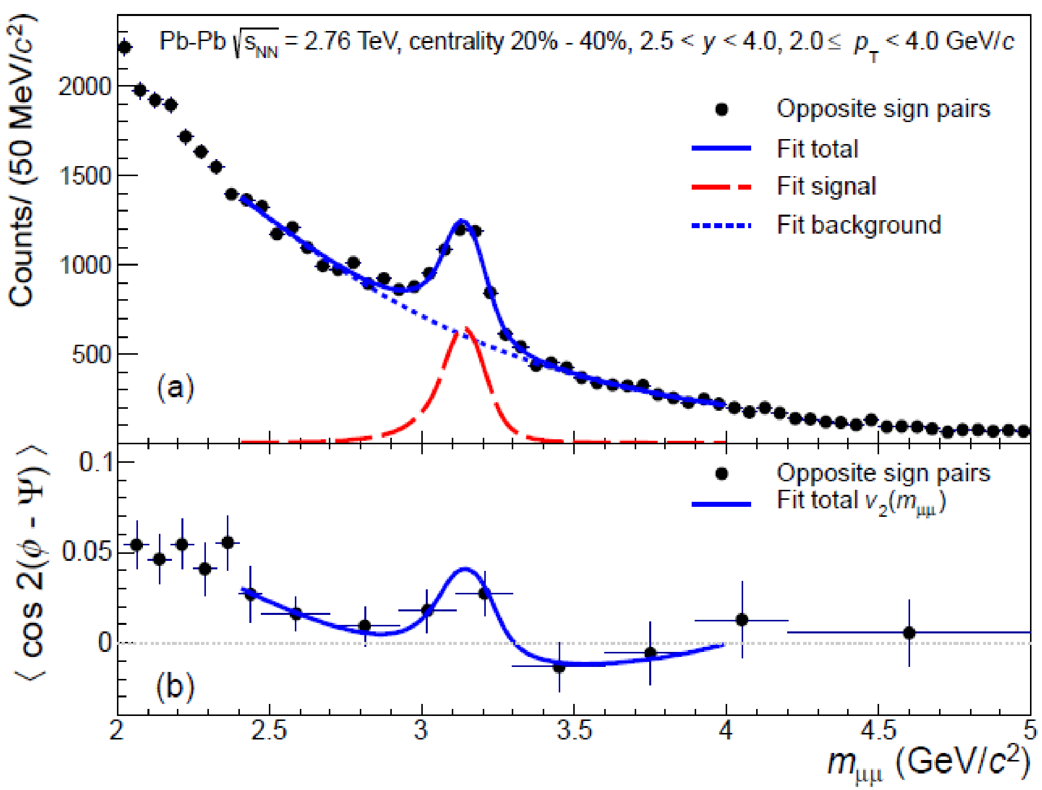
- statistical hadronization in p_t range where charm quarks are reasonably thermal
- modification of spectrum relative to pp due to radial flow
- suppression in R_{AA} due to charm quark energy loss (see D mesons)

elliptic flow of J/psi

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

Centrality	$\langle N_{part} \rangle$	EP resolution ± (stat.) ± (syst.)
5%–20%	283 ± 4	0.548 ± 0.003 ± 0.009
20%–40%	157 ± 3	0.610 ± 0.002 ± 0.008
40%–60%	69 ± 2	0.451 ± 0.003 ± 0.008
60%–90%	15 ± 1	0.185 ± 0.005 ± 0.013
20%–60%	113 ± 3	0.576 ± 0.002 ± 0.008

ALICE data analysis in 4 centrality bins



analyze opposite sign muon pairs relative to the V0 event plane as function of mass and for each pt bin

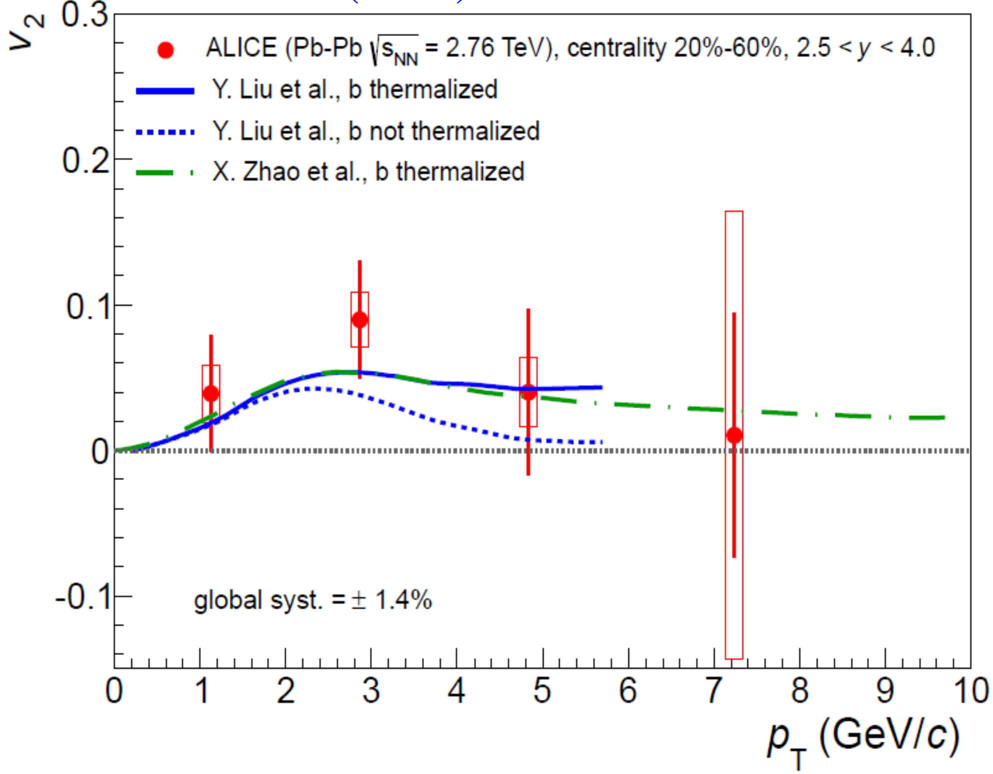
- fit distribution with

$$v_2(m_{\mu\mu}) = v_2^{sig}\alpha(m_{\mu\mu}) + v_2^{bkg}(m_{\mu\mu})[1-\alpha(m_{\mu\mu})]$$

where $\alpha(m_{\mu\mu}) = S / (S+B)$ fitted to the mass spectrum

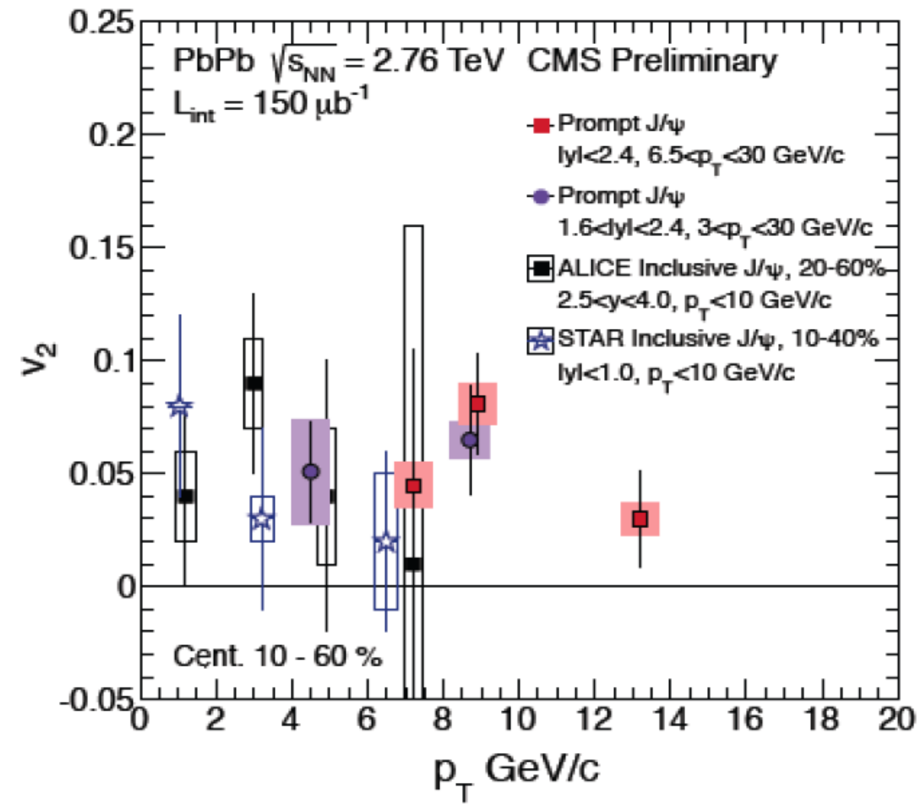
J/psi flow compared to models including (re-) generation

PRL 111 (2013)162301 arXiv:1303.5880



but:

CMS observes similar v_2 at higher p_t

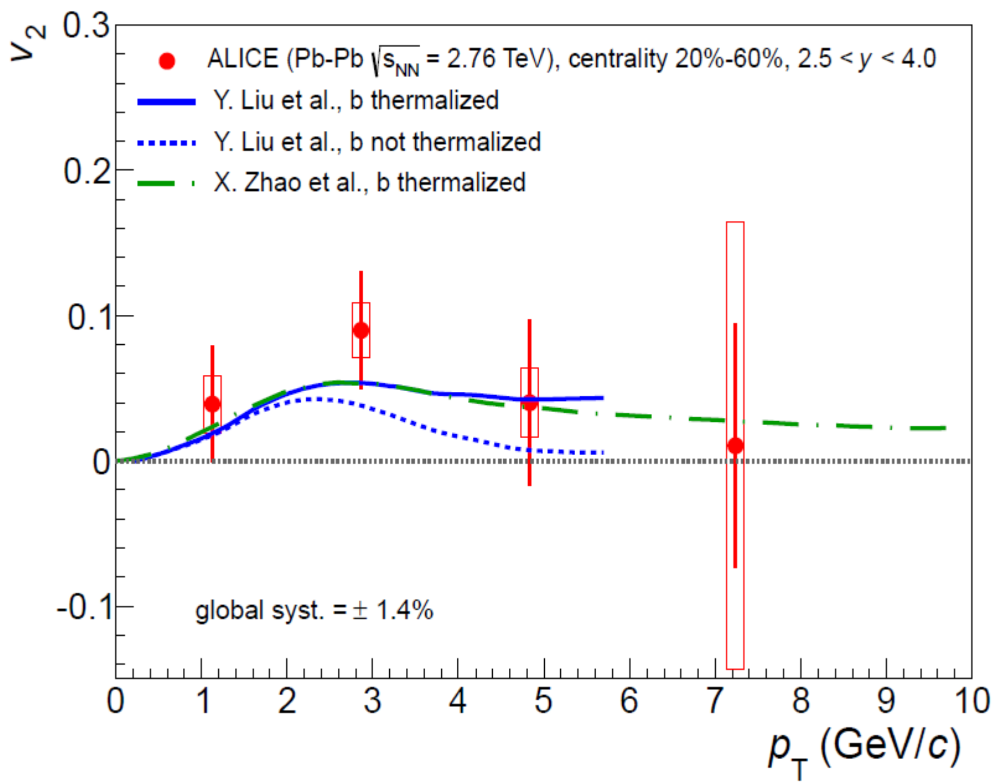


v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

this calls for more and better data

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

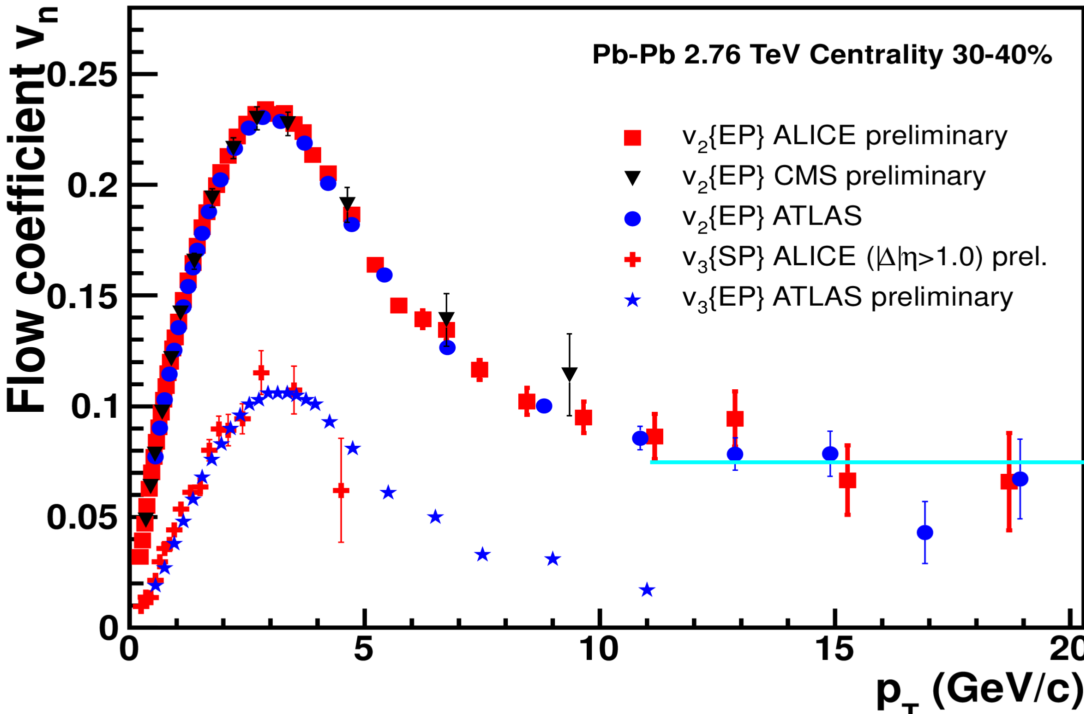
PRL 111 (2013)162301 arXiv:1303.5880

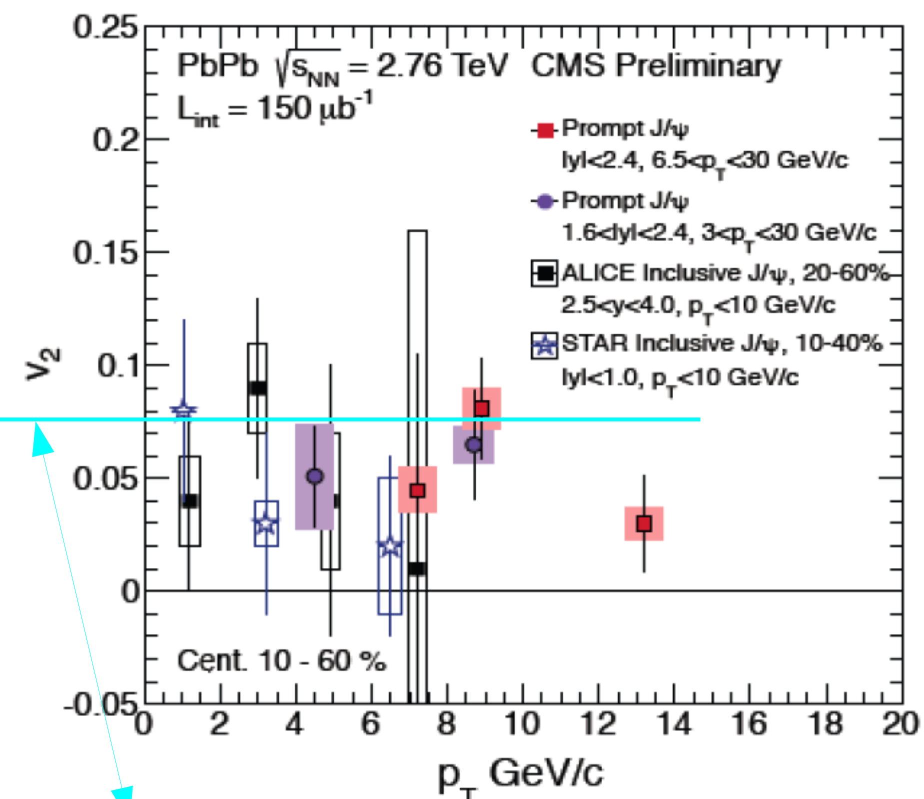


v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

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

charged particles ⟷ J/psi

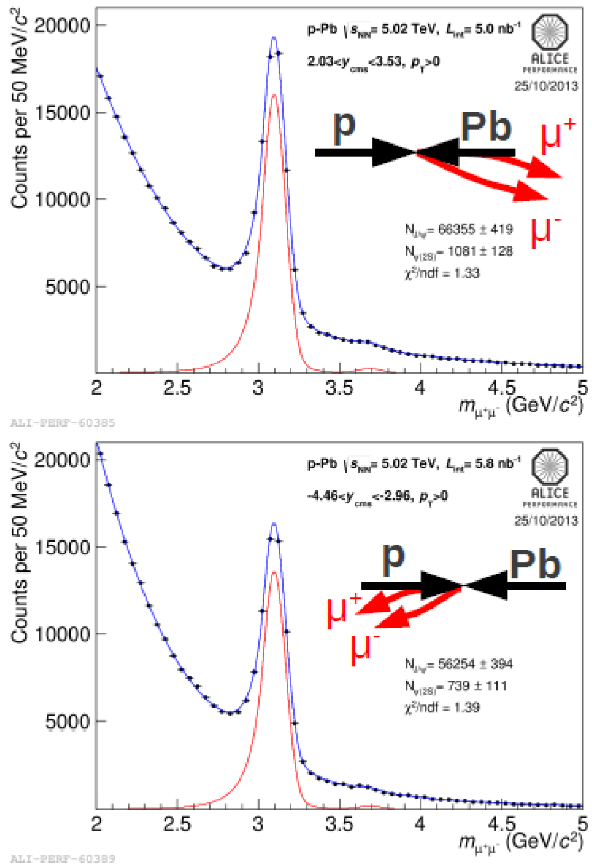


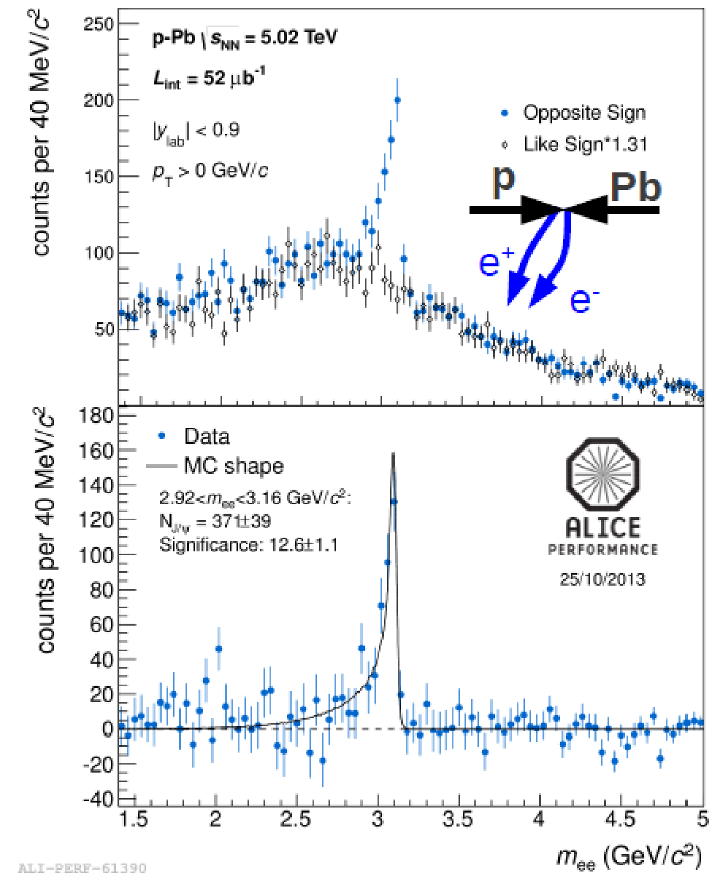


jet fragmentation regime
v_2 driven by energy loss

is high p_t v_2 of the same origin?
i.e. path length dependence of E-loss?
calls for more data

modification of charm production in nuclei: pA collisions





Dimuons: dedicated trigger

L_{int}=5.0 nb^{-1} (forward)

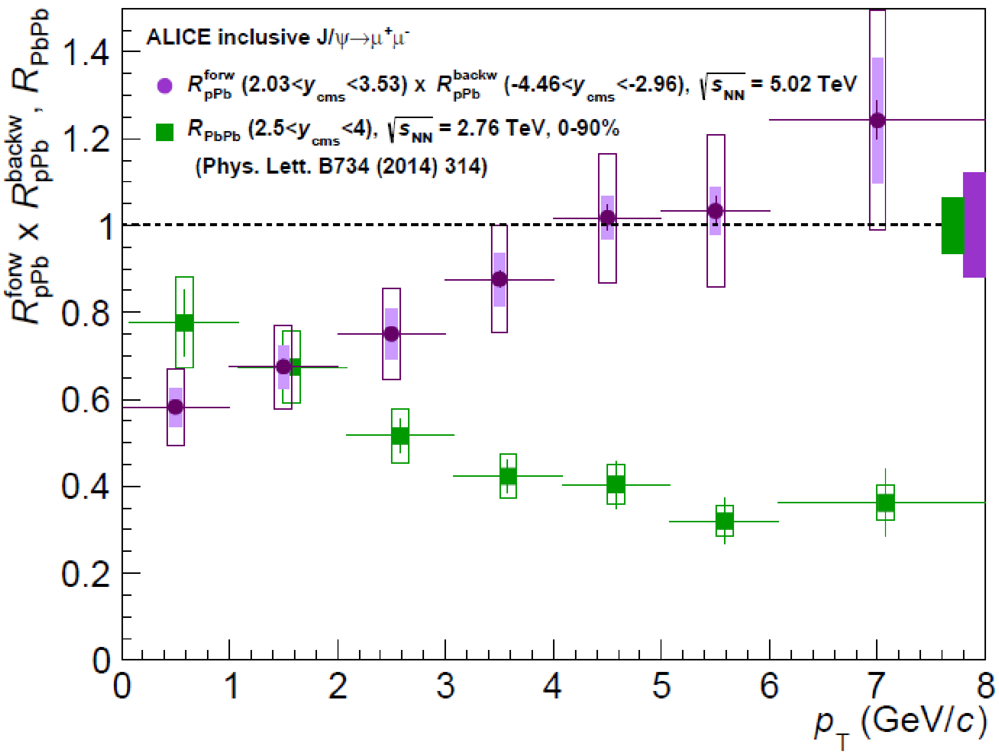
L_{int}=5.8 nb^{-1} (backward)

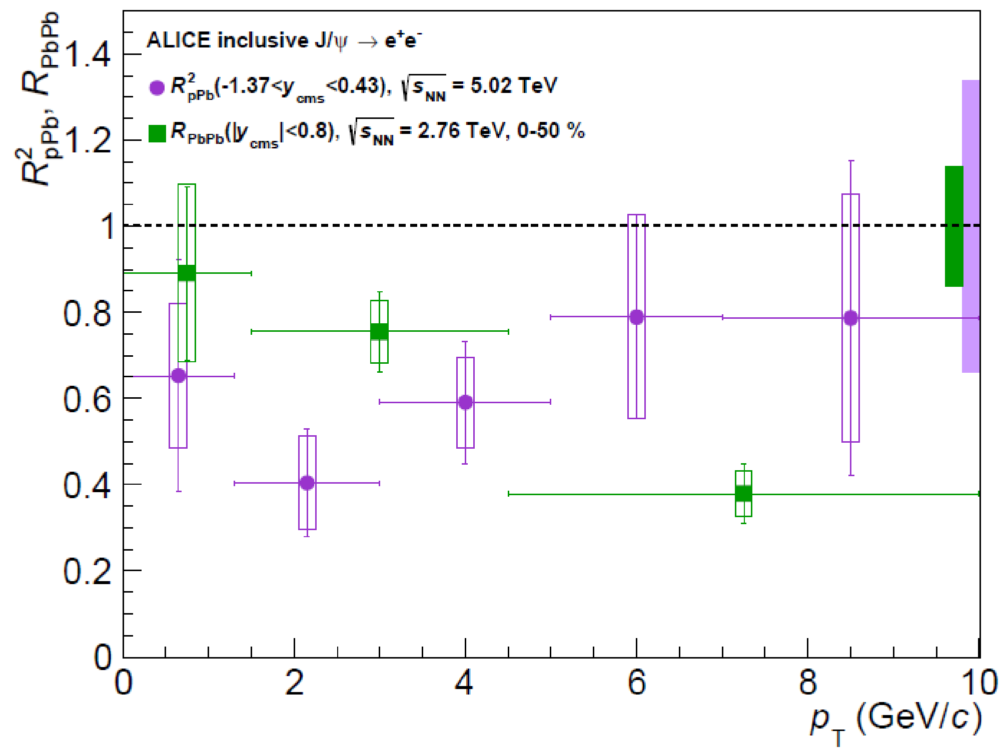
Dielectrons: Minimum Bias

L_{int}= 52 μb^{-1}

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

JHEP 1506 (2015) 055, arXiv:1503.07179

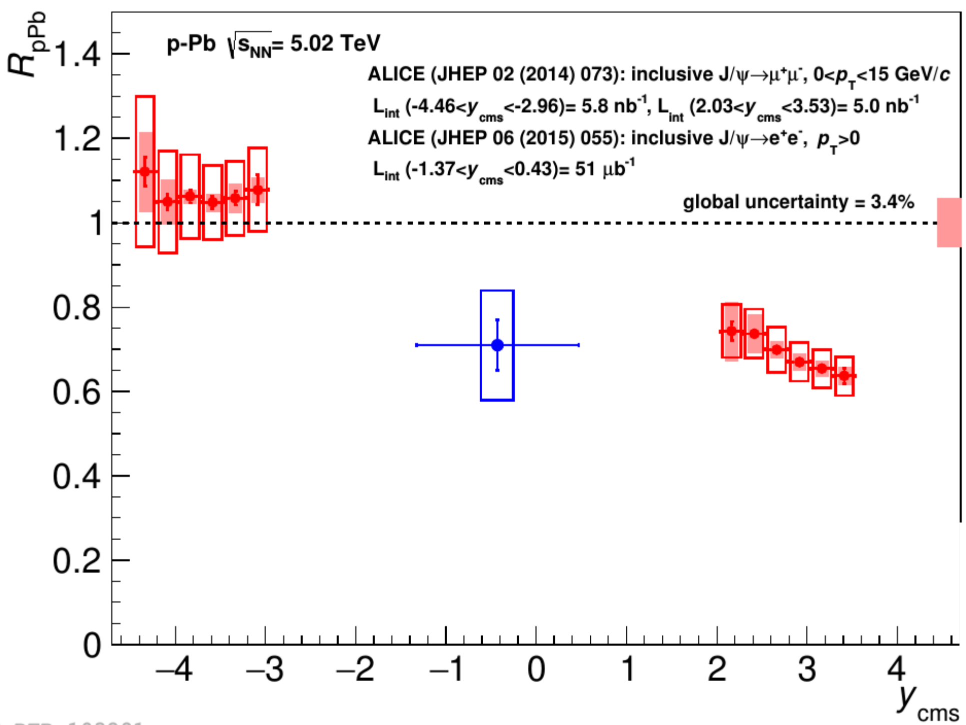




at low p_t yield in nuclear collisions above pPb collisions

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

J/psi rapidity distribution in pPb compared to pp



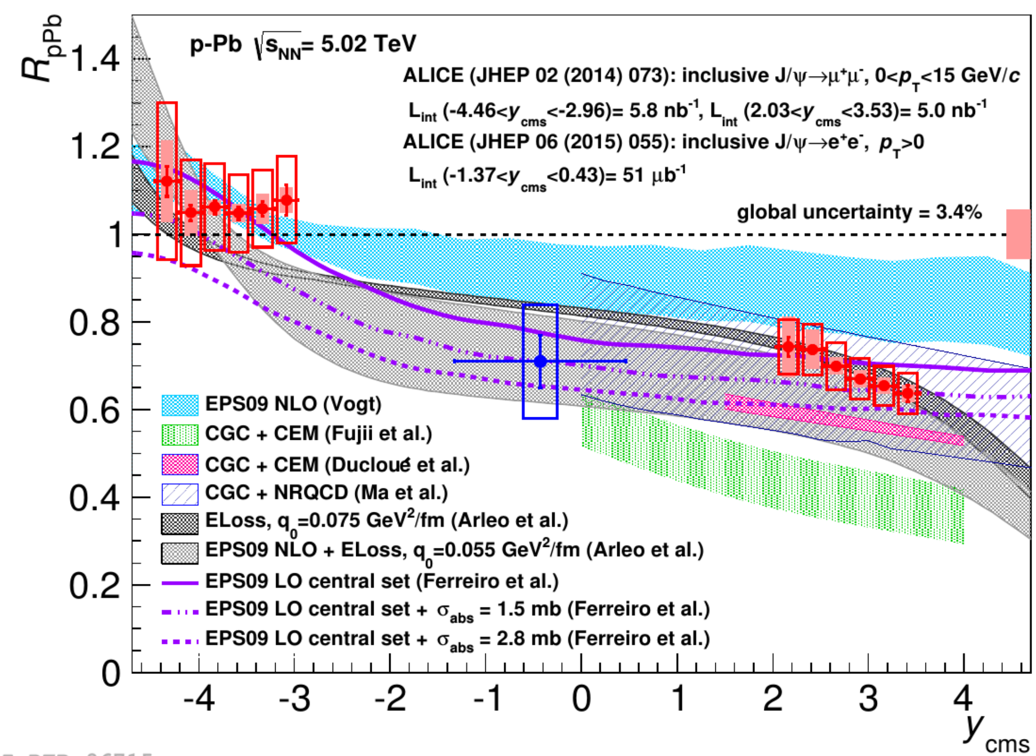
ALI-DER-103291

ALICE forward/backward
arXiv:1308.6726 JHEP 1402 (2014) 073
good agreement with LHCb
arXiv:1308.6729 JHEP 1402 (2014) 072
ALICE mid-y
arXiv:1503.07179 JHEP 1506 (2015) 055

use these data to extract relevant shadowing for J/psi production in PbPb:

for mid-y suppression by 0.56 ± 0.20
(all data + consult R.Vogt)

for y = 2.5-4.0 " 0.71 ± 0.10
(forward/backward data + consult R.Vogt)



ALI-DER-96715

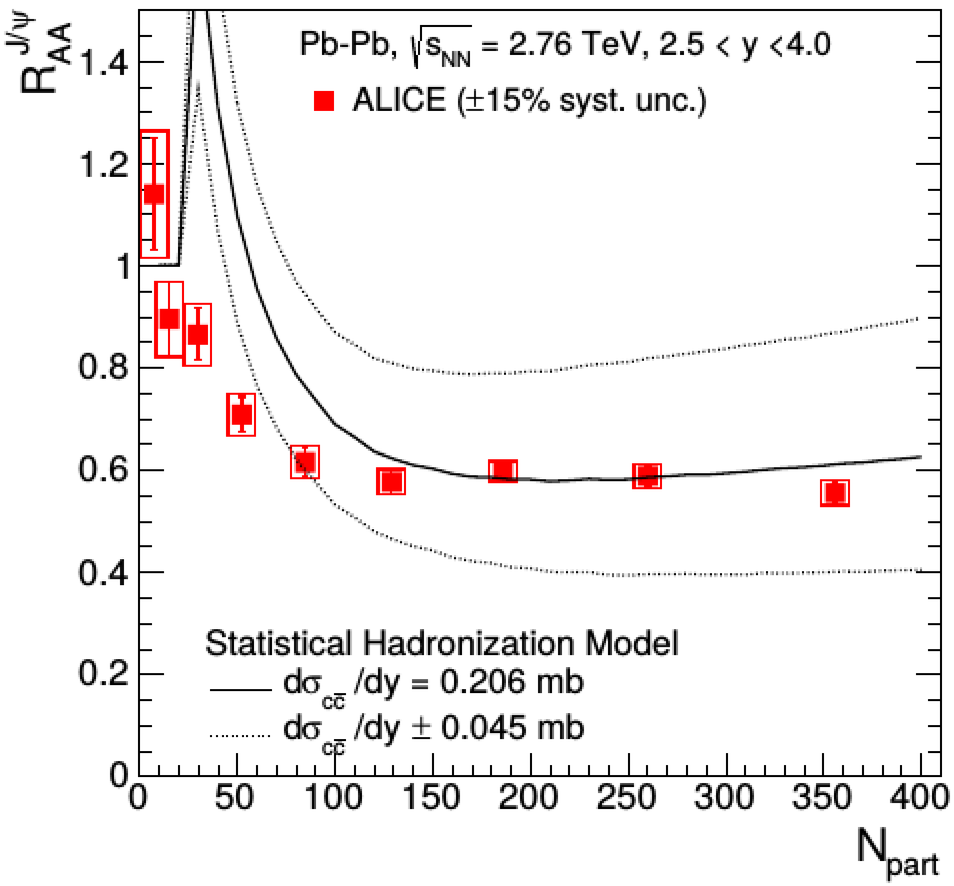
back to ccbar cross section

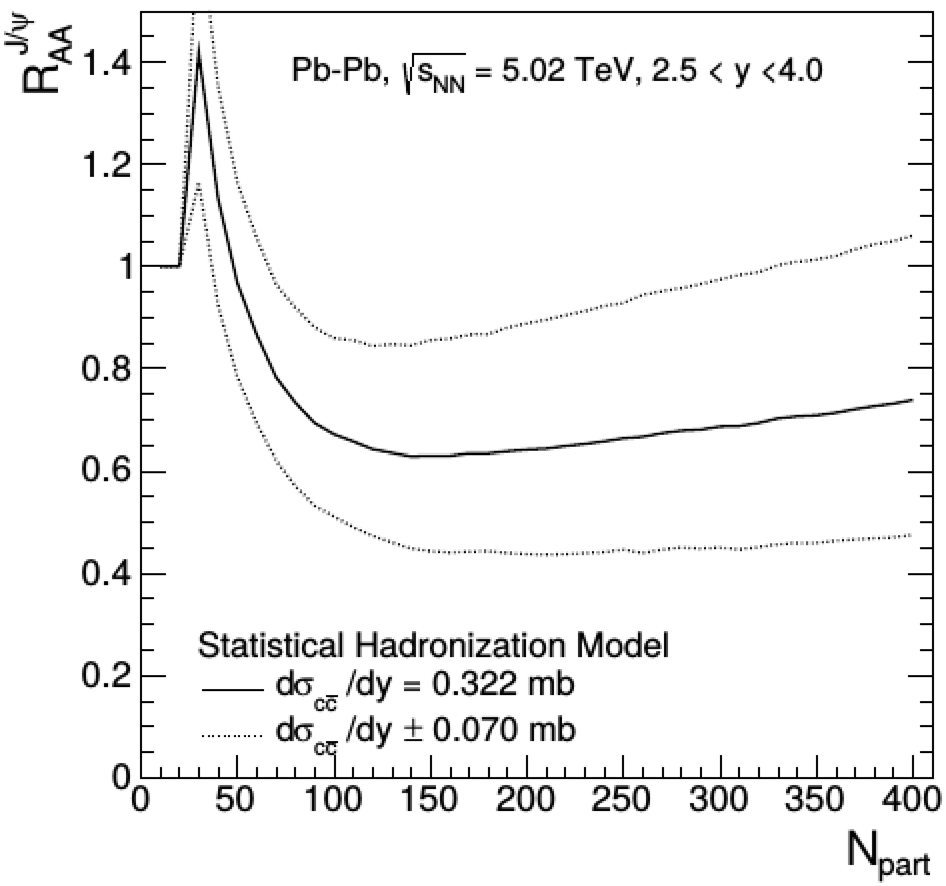
crucial input for both statistical hadronization model and transport models for destruction and regeneration of charmonia
sofar, no measurement of the cross section for PbPb
proxy: take pp cross section at 7 TeV and scale to 2.76 TeV using FONLL $\sqrt{s}$ dependence
apply shadowing correction derived from pPb data

LHCb: NPB 871 (2013) 1 arXiv: 1302.2864
y=2.0-4.5 and 7 TeV dsigma(ccbar)/dy = 0.568 ± 0.054 mb
extrapolate to 2.76 TeV and y=2.4-4.0 " = 0.290 ± 0.028 mb
apply shadowing (x 0.71 ± 0.10) " = 0.206 ± 0.035 mb **baseline for PbPb**

ALICE: arXiv:1605.07569, D-measurement down to pt=0
$|y| \leq 0.5$ and 7 TeV dsigma(ccbar)/dy = 0.988 + 0.150 – 0.221 mb
extrapolate to 2.76 TeV " = 0.588 + 0.089 – 0.132 mb
apply shadowing (x 0.56 ± 0.20) " = 0.329 + 0.128 - 0.138 mb **baseline for PbPb**

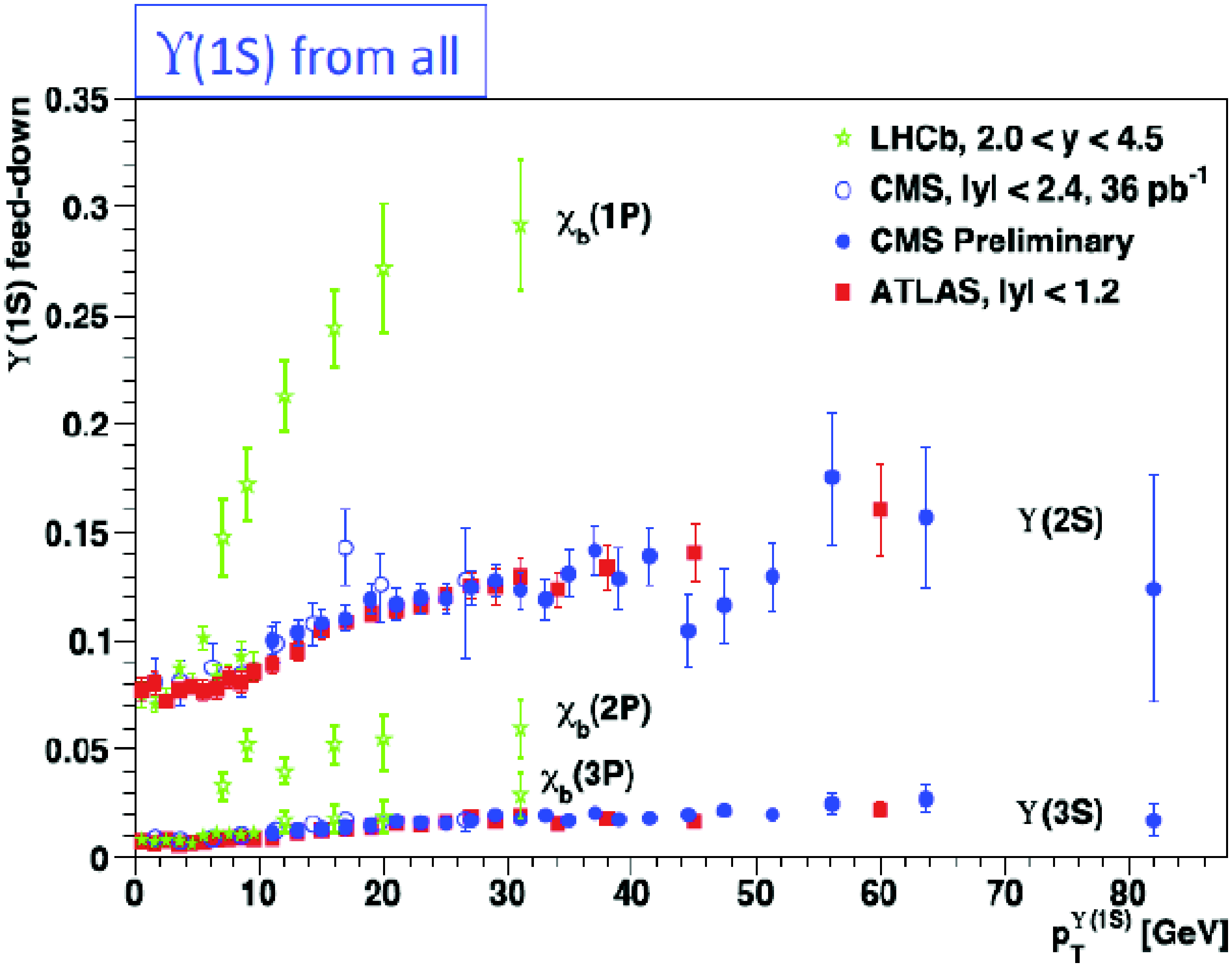
newest results with updated charm cross section





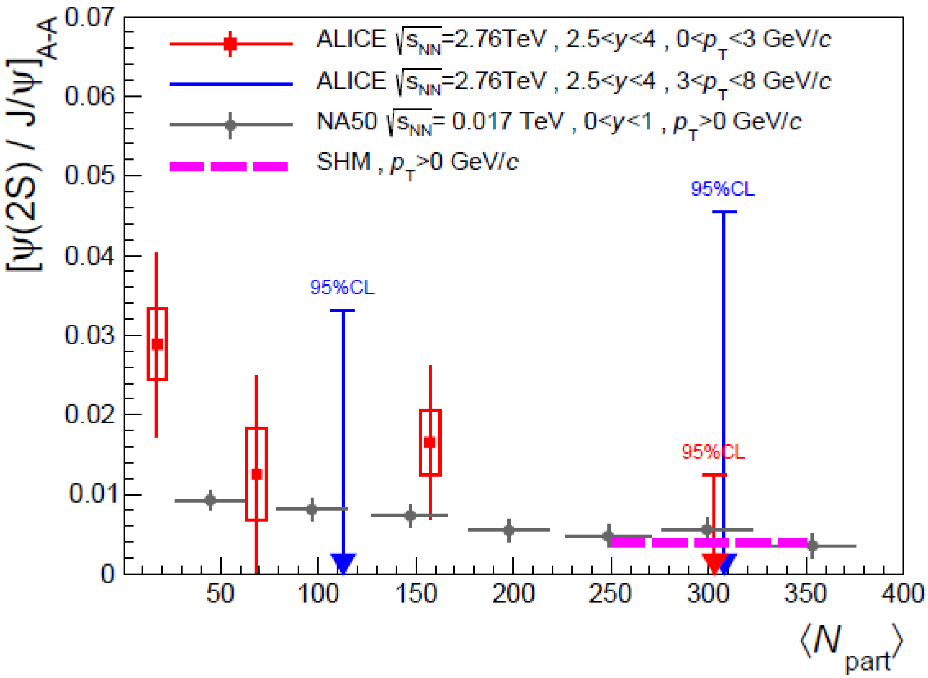
to constrain models more: need precise ccbar cross section for PbPb
for sqrt(s_NN) = 5 TeV expect increase for central collisions by about 10-15%
transport models should use this same ccbar cross section

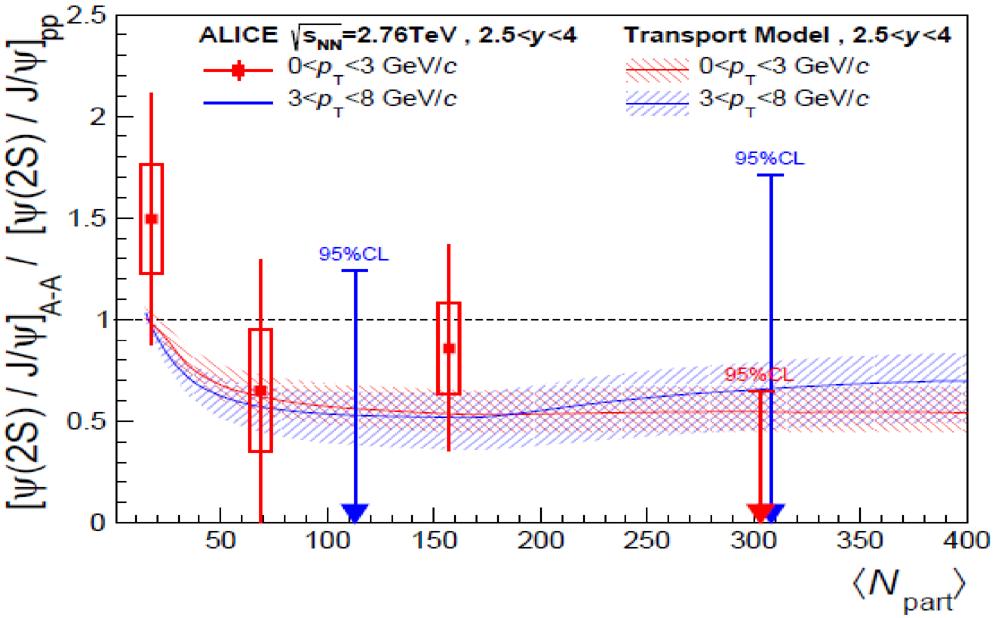
Feeding into Upsilon (1S)



psi' to J/psi at LHC

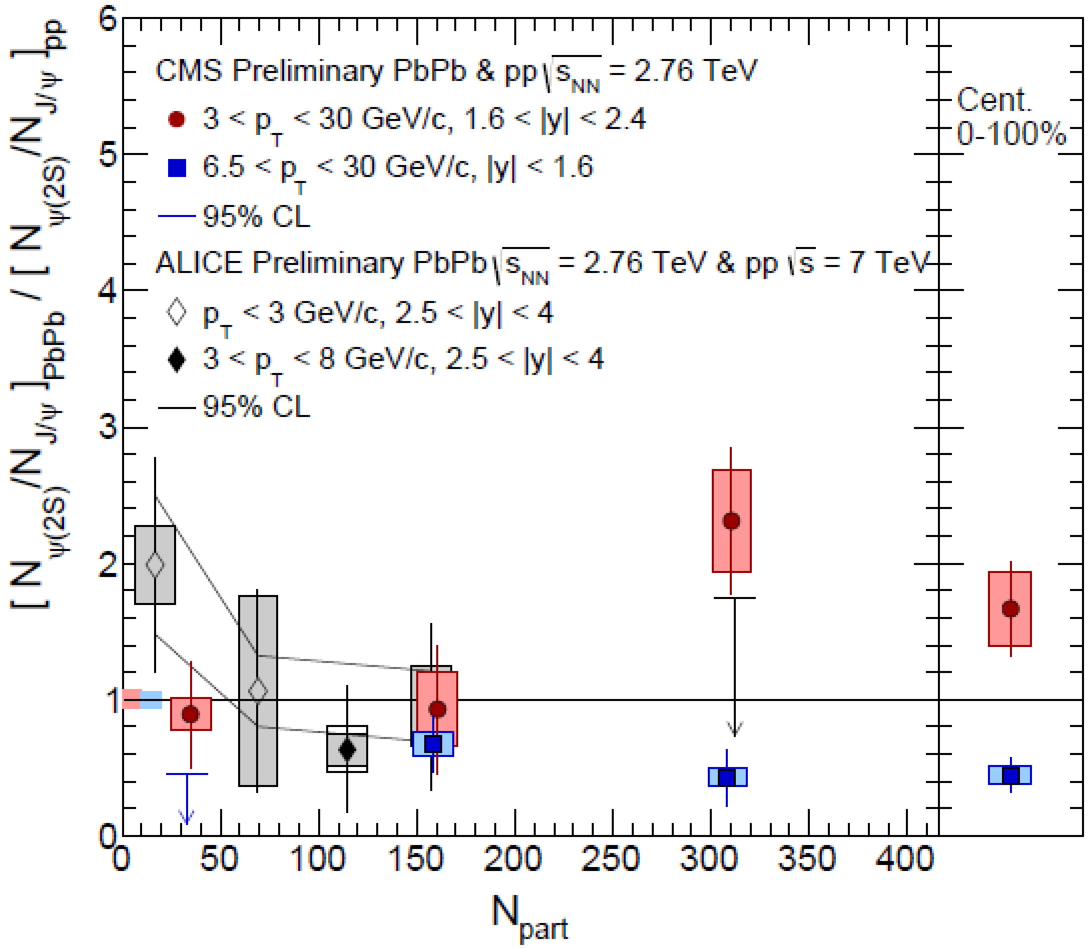
arXiv: 1506.08804





- experimental errors still significant
- within errors consistent with low value in statistical model due to suppression with Boltzmann factor
- also consistent with larger values resulting from transport models

psi' to J/psi at LHC - not yet conclusive



- errors of data still large
- are we seeing a peculiar pt dependence? If so, could we see effect of collective flow of charm quarks before hadronization?

First determination of Debye mass from data

J/psi formation via statistical hadronization at T_c implies experimental determination of Debye length (mass) and temperature

$\lambda_D < 0.4$ fm at T = 156 MeV or $\omega_D/T > 3.3$

can compare to theory:

quite ok

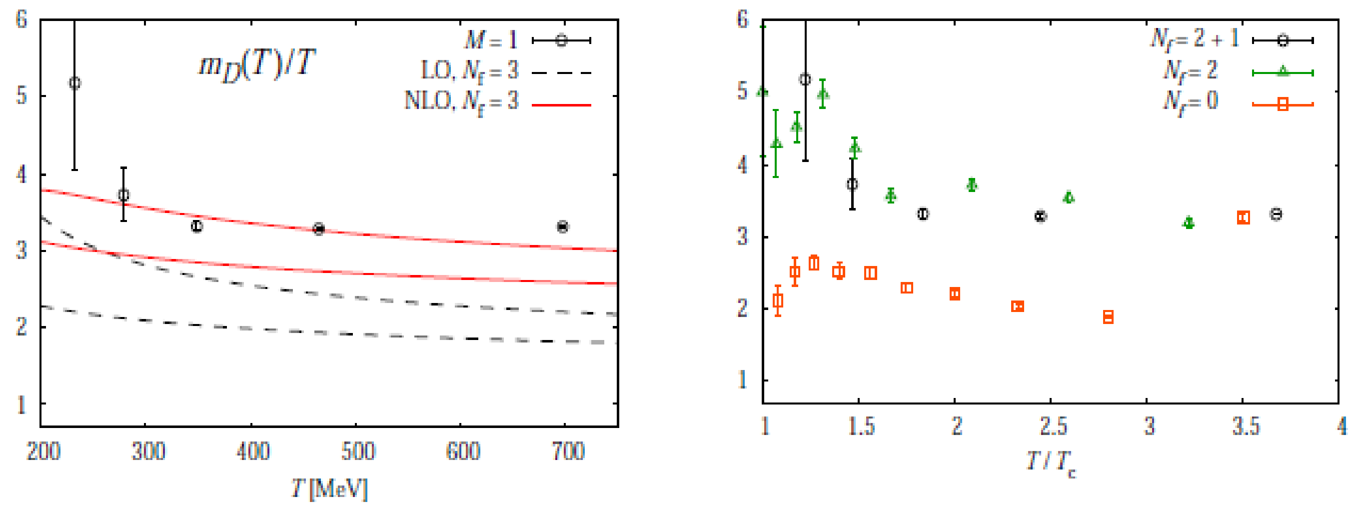


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, 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.

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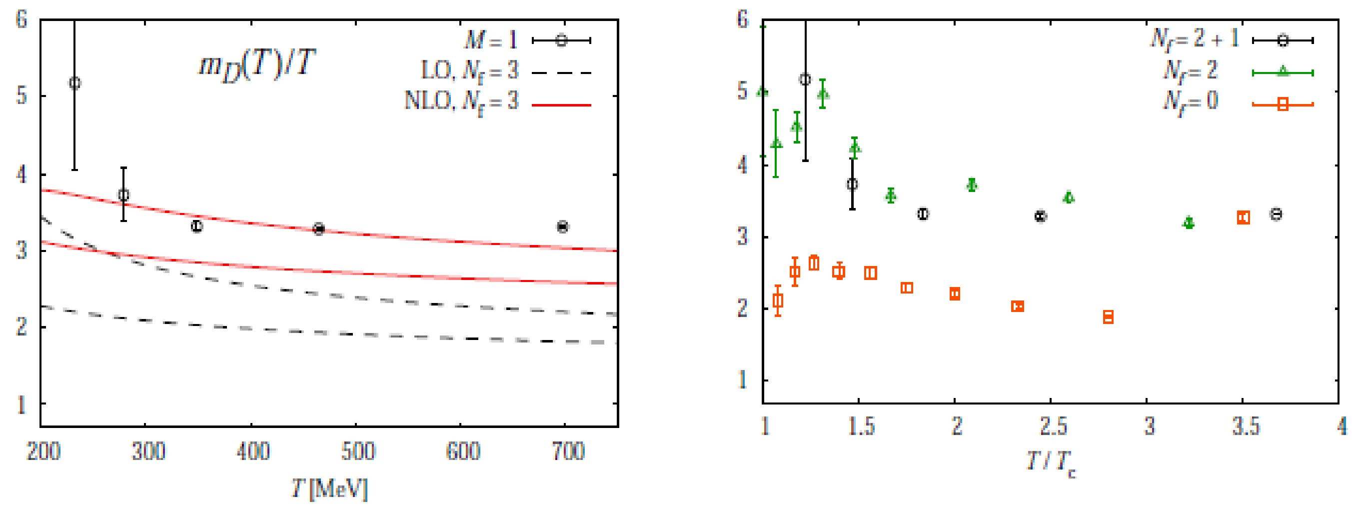

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arXiv:1112.2756 WHOT-QCD Coll.

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

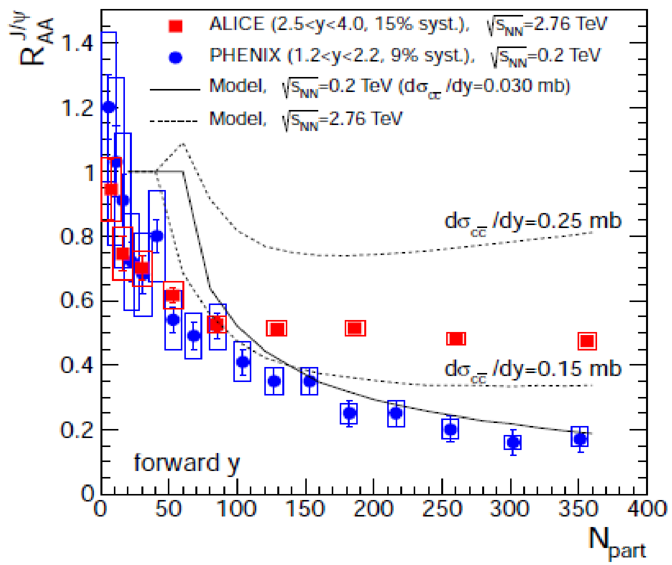
LHC run2: 2015-2018 PbPb running at $\sqrt{s_{NN}} = 5.5$ TeV

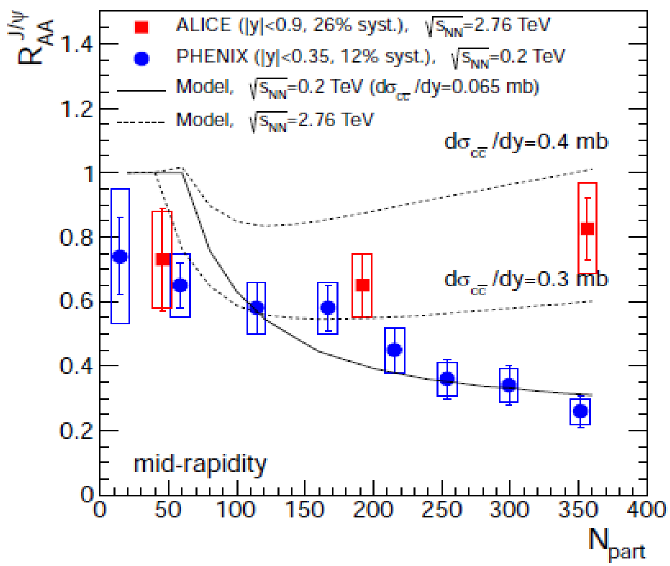
to achieve approved initial goal of 1 nb^{-1}

late 2018 start LS2 – increase of LHC luminosity und experiment upgrade

LHC run3: 2020 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





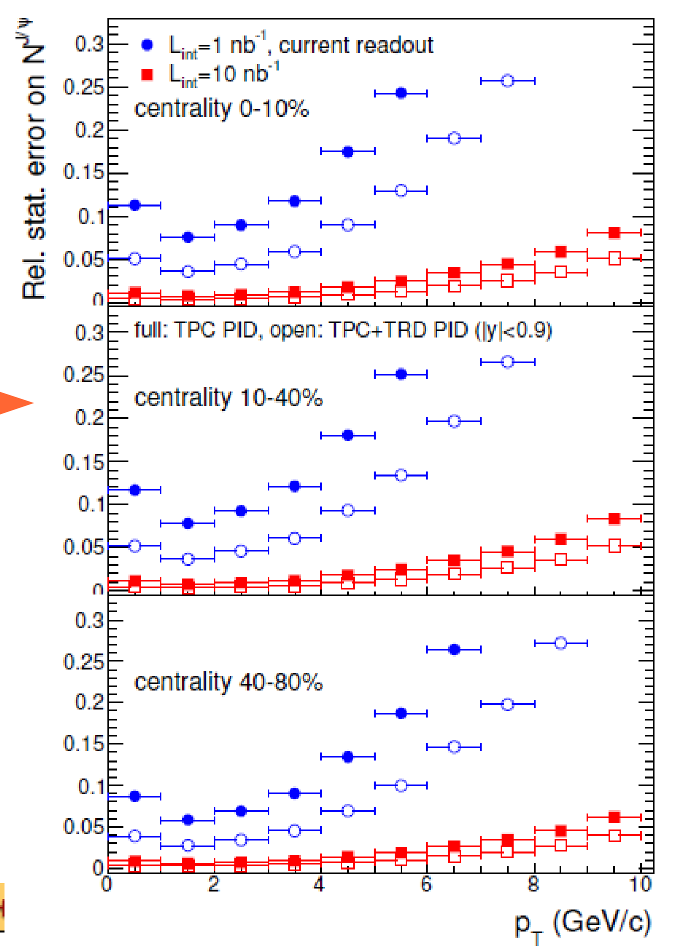
di-electrons statistics limited, 10 nb^{-1} will have huge effect

but also syst uncertainties will decrease with upgrade:

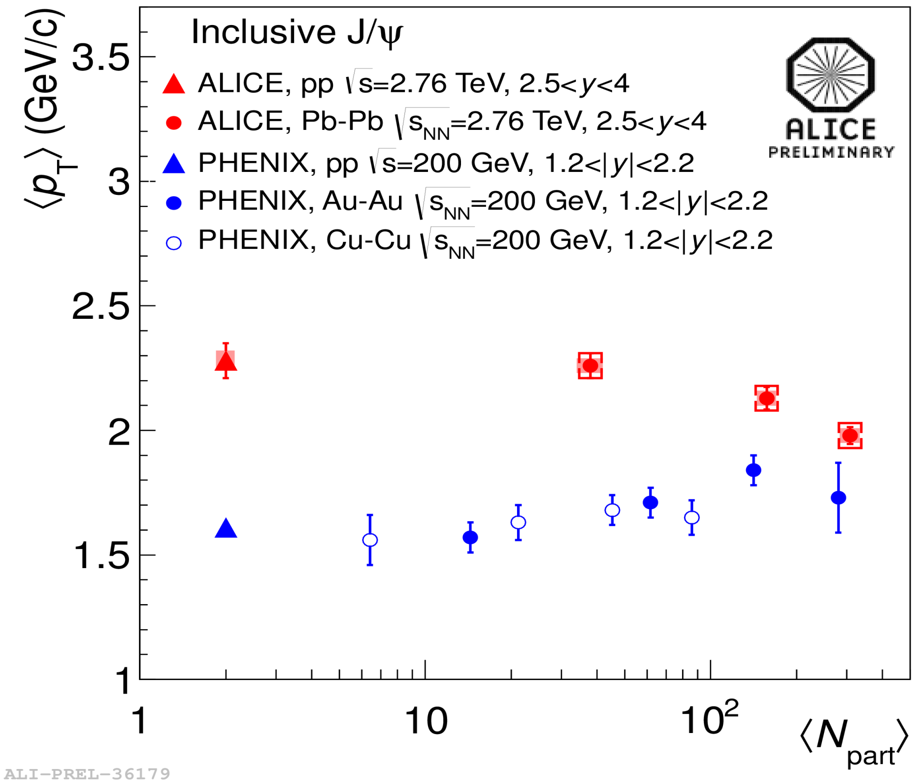
will also add TRD for electron id - reduced comb background

thinner ITS reduced radiation tail

both affect signal extraction

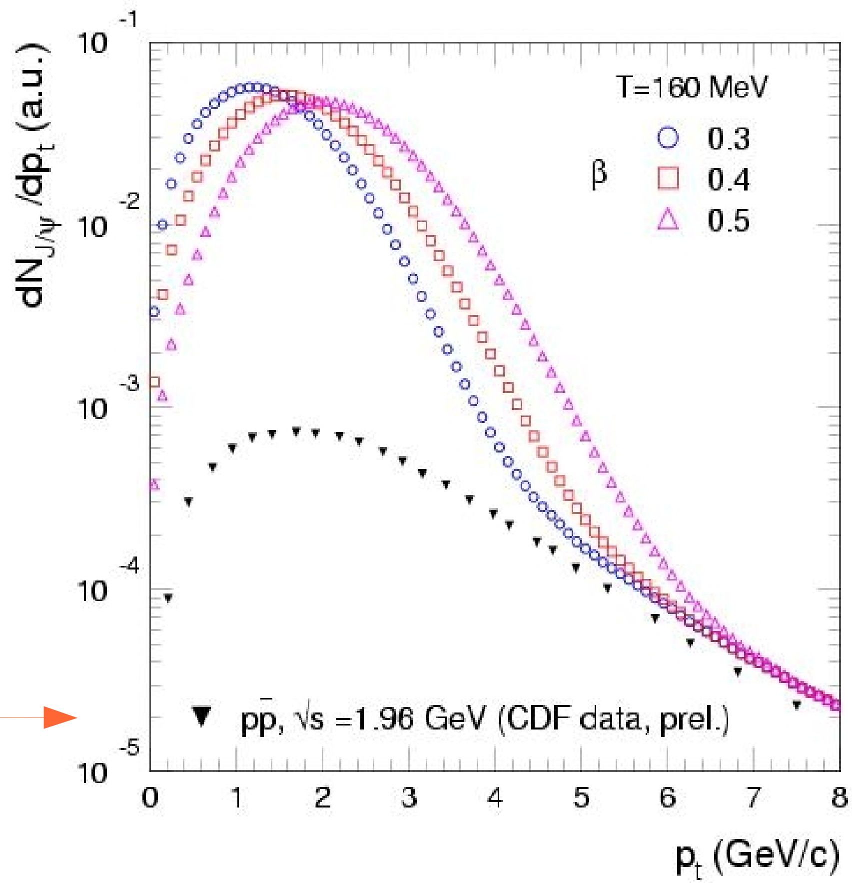


spectral distribution is key to thermalization

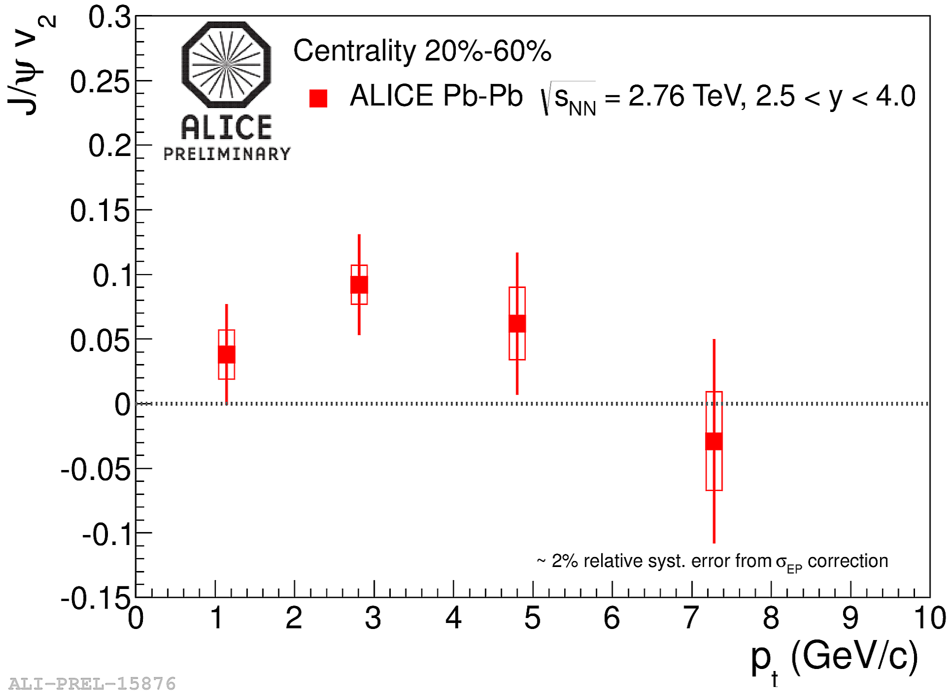


at LHC shift of paradigm: more central collision → narrower momentum distribution
my interpretation: thermalization

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



J/psi elliptic flow

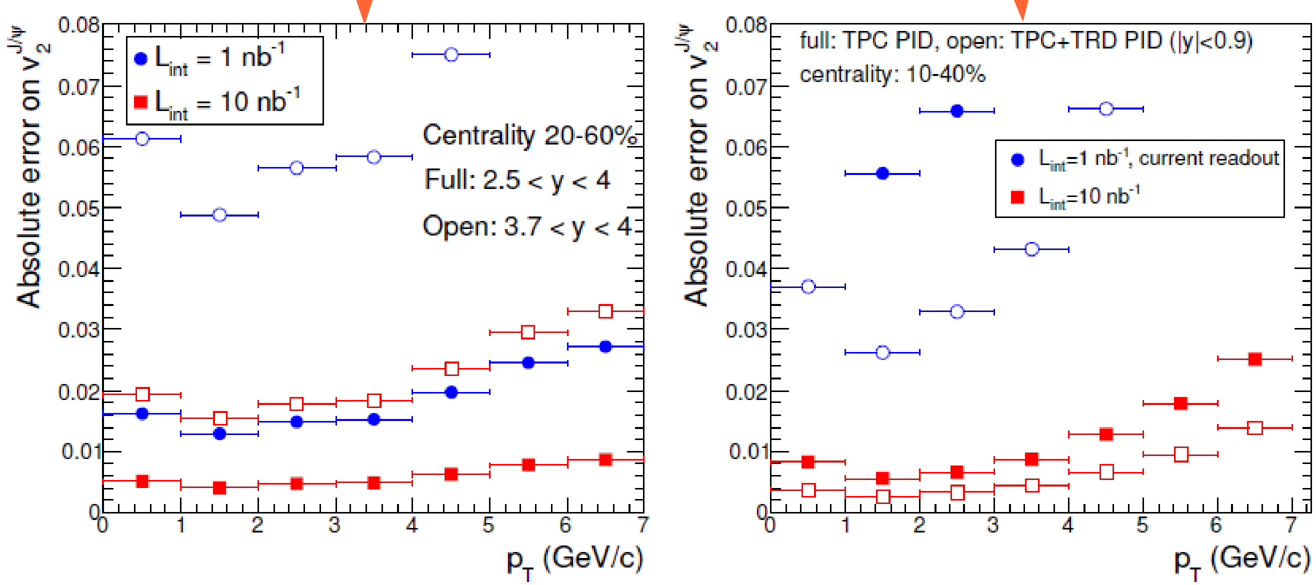


observation of flow with muon arm
presently 3 sigma
needs statistics to make model comparison meaningful

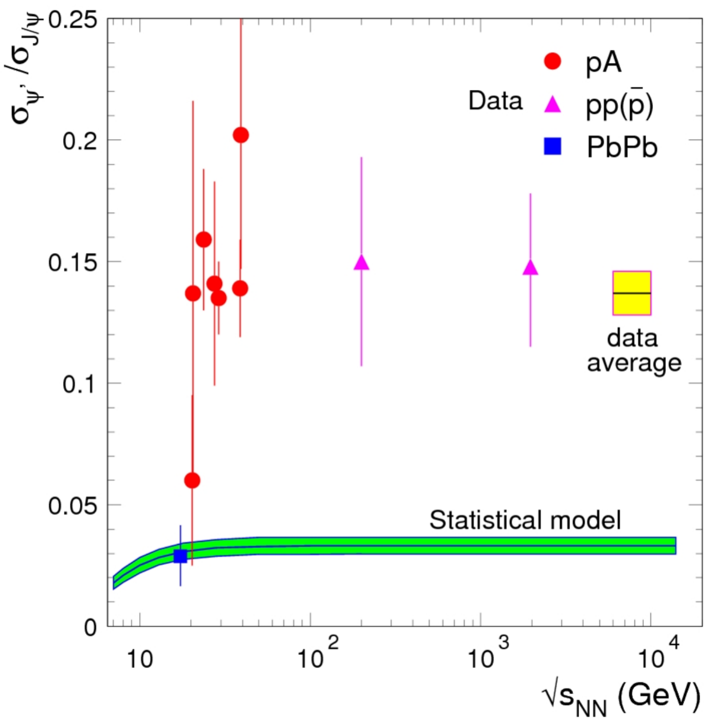
future statistical errors

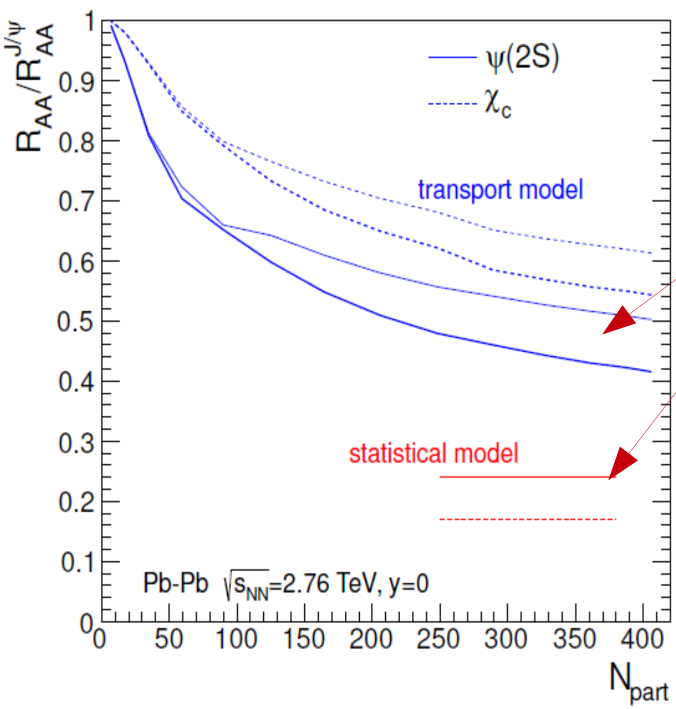
muon arm

central barrel



excited charmonia crucial to distinguish between models



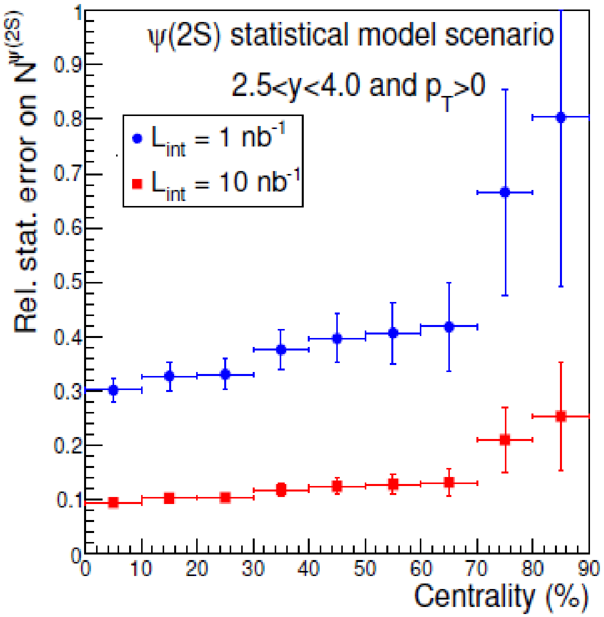


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

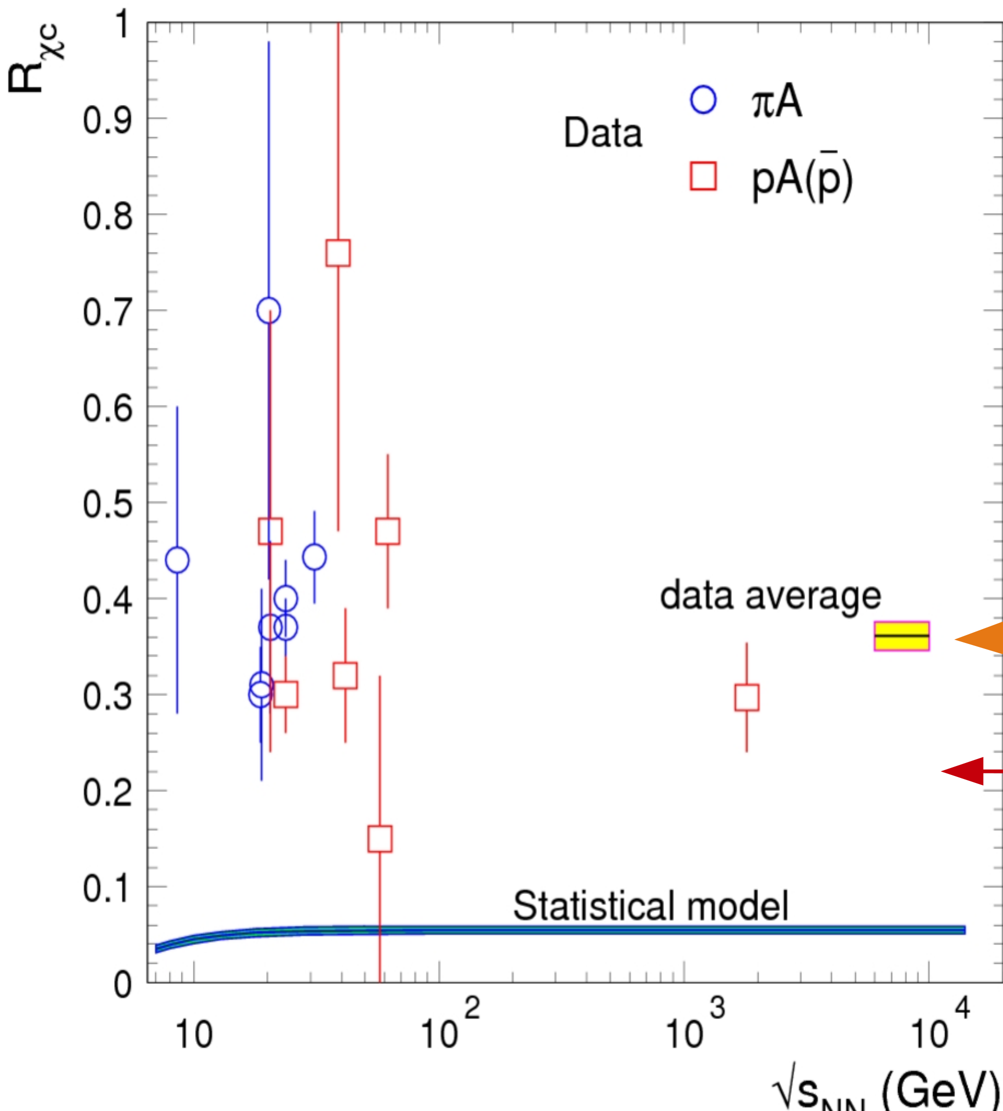
for statistical hadronization need to see suppression by Boltzmann factor

χ_c even bigger difference

expected ALICE performance muon arm run2 and run3



situation even more dramatic for P-states



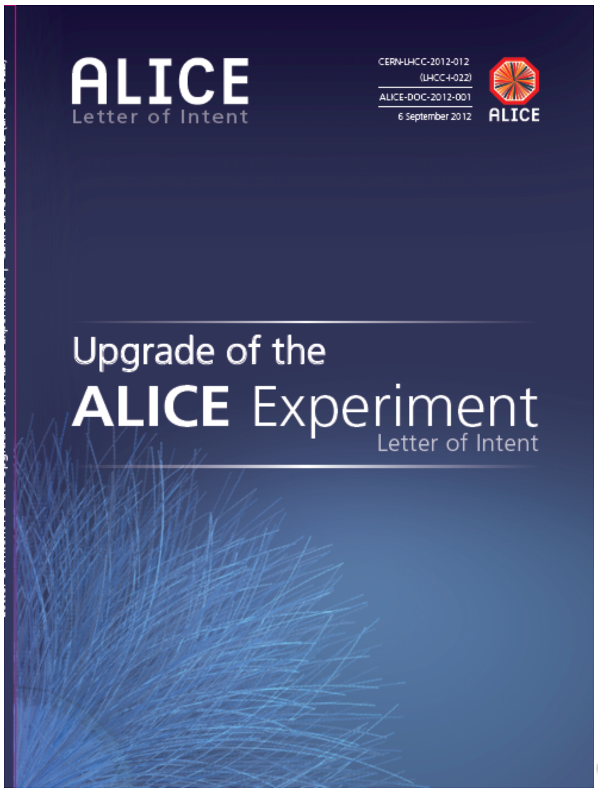
pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

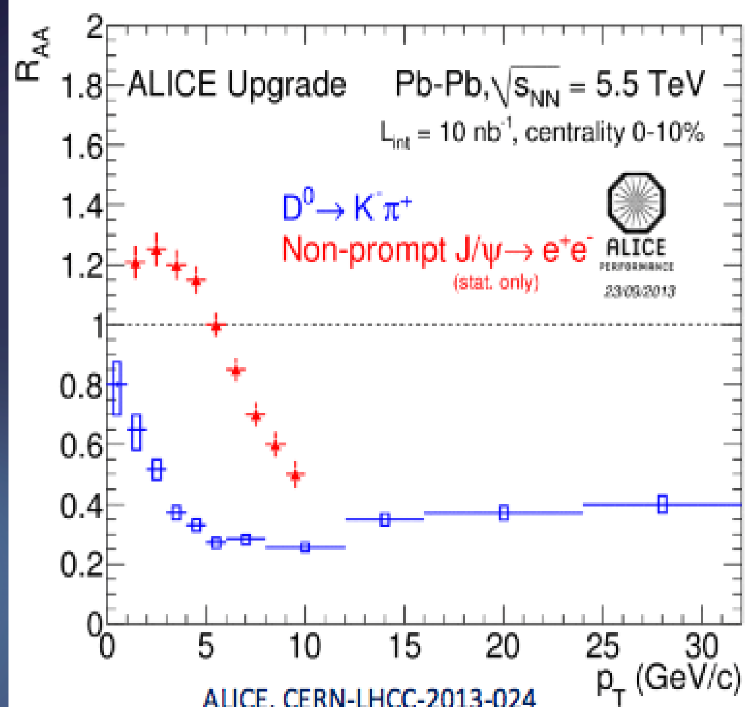
A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase (TPC upgrade)



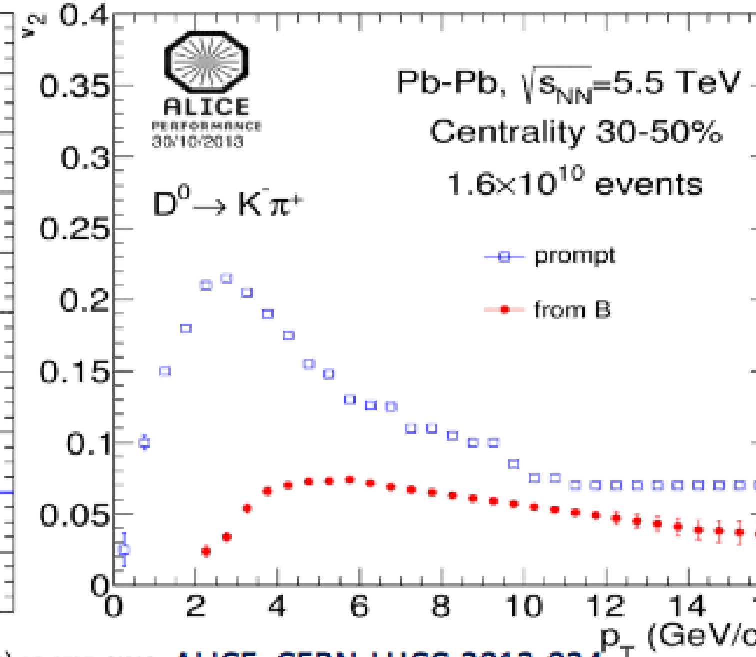
Upgrade



ALICE, CERN-LHCC-2013-024

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

Upgrade



ALICE, CERN-LHCC-2013-024

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

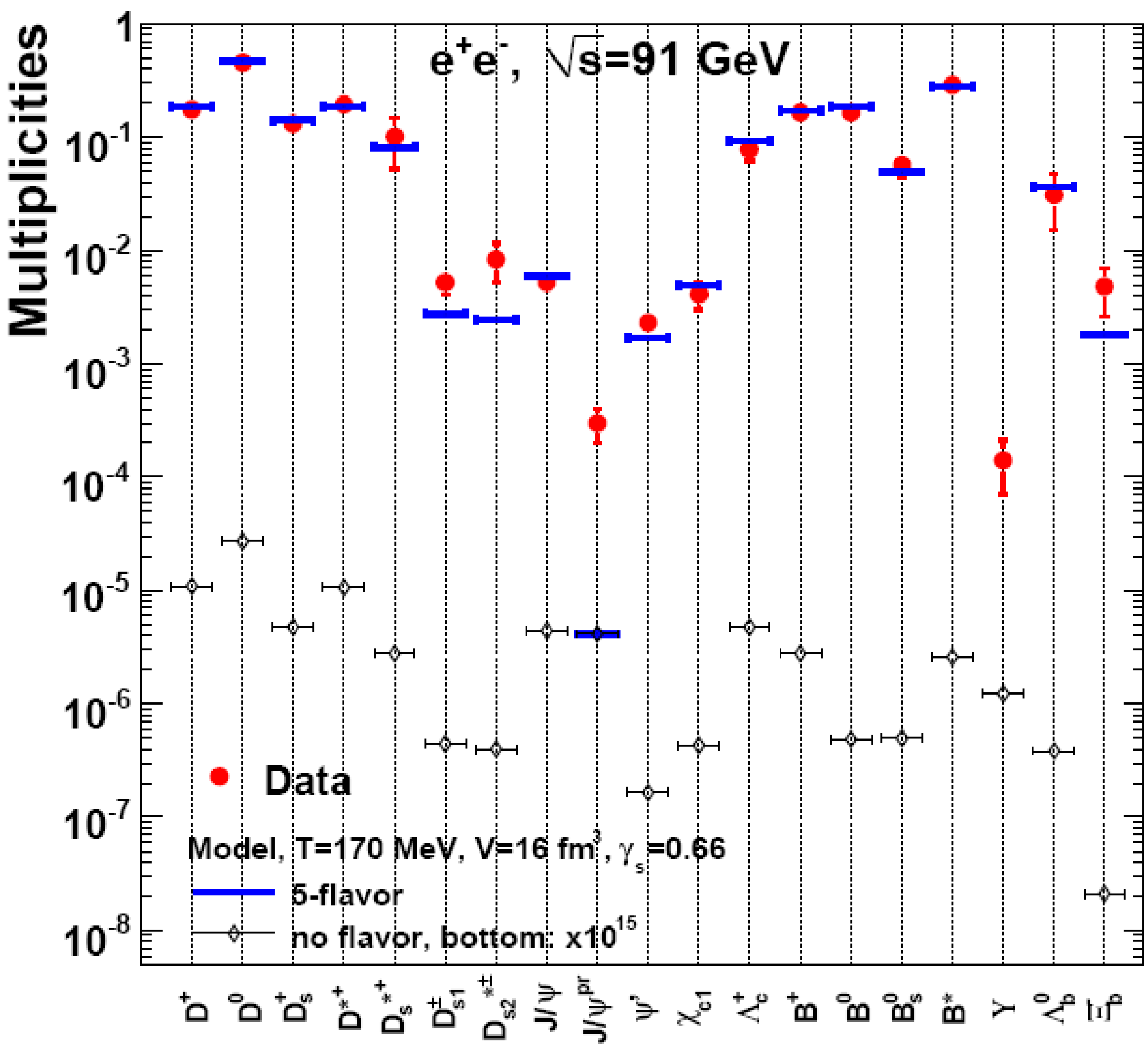
Charm v_2 down to p_T~0 using prompt and beauty v_2 down to B p_T~0 using B-decay D^0

physics reach after ALICE upgrade

Topic	Observable	Approved (1/nb delivered, 0.1/nb m.b.)	Upgrade (10/nb delivered, 10/nb m.b.)
Heavy flavour	D meson RAA	pT>1, 10%	pT>0, 0.3%
	D from B RAA	pT>3, 30%	pT>2, 1%
	D meson elliptic flow (for v2=0.2)	pT>1, 50%	pT>0, 2.5%
	D from B elliptic flow (for v2=0.1)	not accessible	pT>2, 20%
	Charm baryon/meson ratio (Λc/D)	not accessible	pT>2, 15%
	Ds RAA	pT>4, 15%	pT>1, 1%
Charmonia	J/ψ RAA (forward y)	pT>0, 1%	pT>0, 0.3%
	J/ψ RAA (central y)	pT>0, 5%	pT>0, 0.5%
	J/ψ elliptic flow (forward y, for v2 =0.1)	pT>0, 15%	pT>0, 5%
	ψ'	pT>0, 30%	pT>0, 10%
Dielectrons	Temperature IMR	not accessible	10% on T
	Elliptic flow IMR (for v2=0.1)	not accessible	10%
	Low-mass vector spectral function	not accessible	pT>0.3, 20%
Heavy nuclei	hyper(anti)nuclei, H-dibaryon	35% (4ΛH)	3.5% (4ΛH)

stat. error at min pt

heavy quark and quarkonium production in e+e- collisions



Comparison of stat. model calcs. with data

Phys. Lett. B678 (2009) 350, arXiv:0903.1610 [hep-ph]

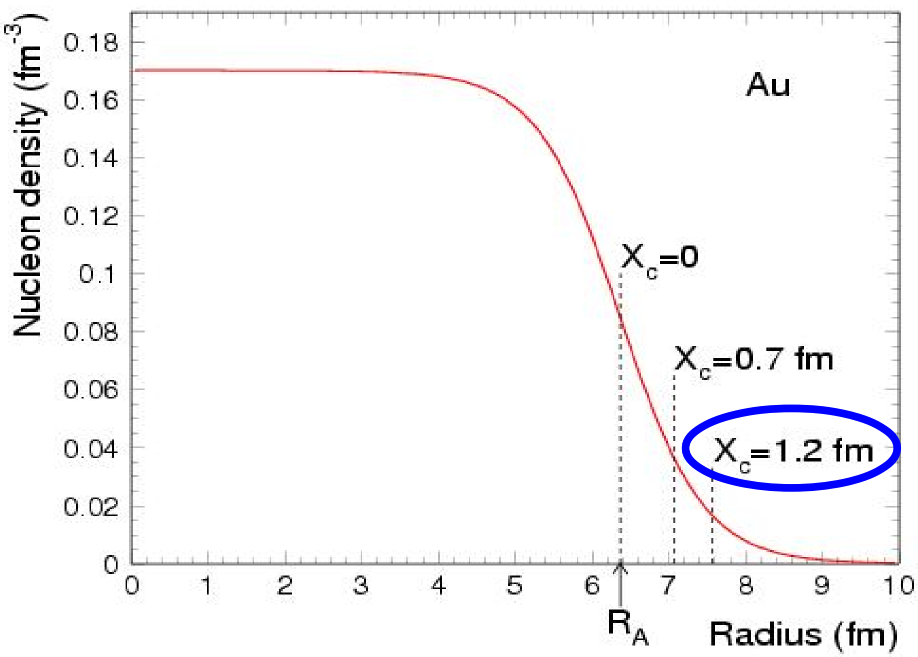
charmonium cannot be described at all in this approach

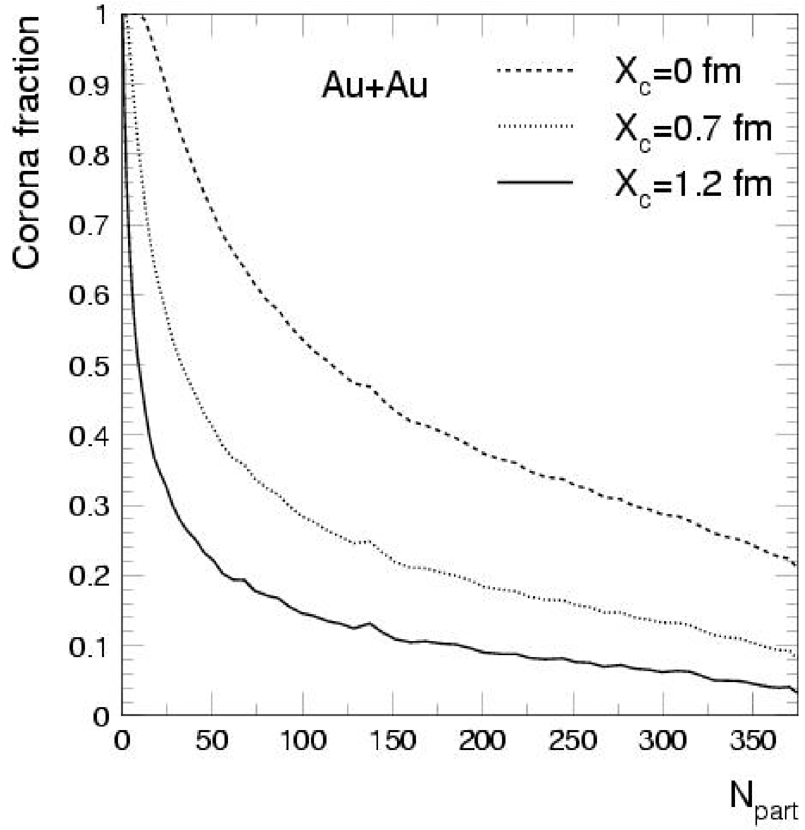
But: all charm quarks hadronize at 170 MeV

extension of statistical model to include charmed hadrons

core-corona effect considered: important for more peripheral collisions

"core" up to $R_A + X_c$ "corona" outside





$$N_{part}(b) = N_{core}(b) + N_{corona}(b)$$

Collisions in corona region treated as in pp, core: medium, e.g. QGP

$dN_{ch}/d\eta/N_{part}(b) = dN_{ch}/d\eta/N_{core}(b) + dN_{ch}^{pp}/d\eta/N_{corona}(b)$ and same for J/psi

core-corona effect