Charmonium and the Quark-Gluon Plasma at the LHC

Motivation
Open charm – thermalization of heavy quarks
Charmonium – a probe of deconfinement
Outlook

a Tribute to Gerald E. Brown – Stony Brook November 24-26, 2013

Johanna Stachel

BMBF Forschungsschwerpunkt
ALICE Experiment 201
ALICE

Ruprecht-Karls-Universität Heidelberg

prologue

30 years of a very close friendship

and …

1 joint paper

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Pions from resonance decay
in Brookhaven relativistic heavy-ion collisions ☆

G.E. Brown, J. Stachel and G.M. Welke

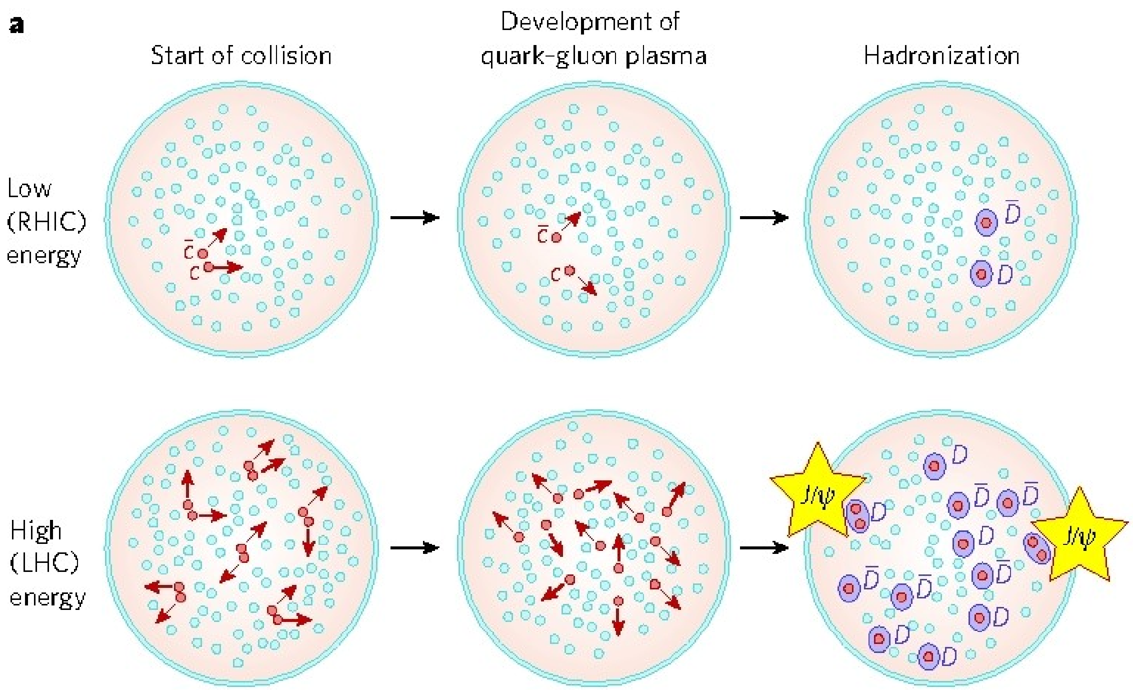
Physics Department, State University of New York at Stony Brook, Stony Brook, NY 11794-3800, USA

Received 21 September 1990

which Gerry dubbed 'cool pions from hot nucleons'

Charm (and Beauty) quarks in QGP – impurities in matter of mostly gluons and also light quarks (u,d,s)

P. Braun-Munzinger and J.Stachel, Nature 448 (2007)



look at slice of 1 unit in rapidity
– the causally connected region

- ccbar formed in hard scattering event in early stage of the collision ($t = 1/2m_c = 0.08$ fm)
- medium with high density of color charges screens strong interaction (Debye screening, Satz/Matsui 1986)
- charm quarks diffuse, loose energy, thermalize – see D-meson R_{AA} and v_2
- once T_c is reached, system hadronizes and D-mesons and maybe ccbar bound states form

Open Charm: charm quarks in the quark gluon plasma

<u>interest 2-fold:</u>

- do charm quarks thermalize in a QGP?

  transport coefficient for heavy quarks?

  energy loss of heavy quark (radiative energy loss should be suppressed due to large mass (1.2 GeV); in vaccum gluon radiation into angles $\theta \leq \frac{m_q}{E_q}$ suppressed (Dokshitzer and Kharzeev)

  and Casimir factor $C_q = 4/3$ vs $C_{gluon} = 3$

- need total charm cross section for understanding of charmonia

Measurement of open charm cross section at the LHC

all LHC experiments contribute:

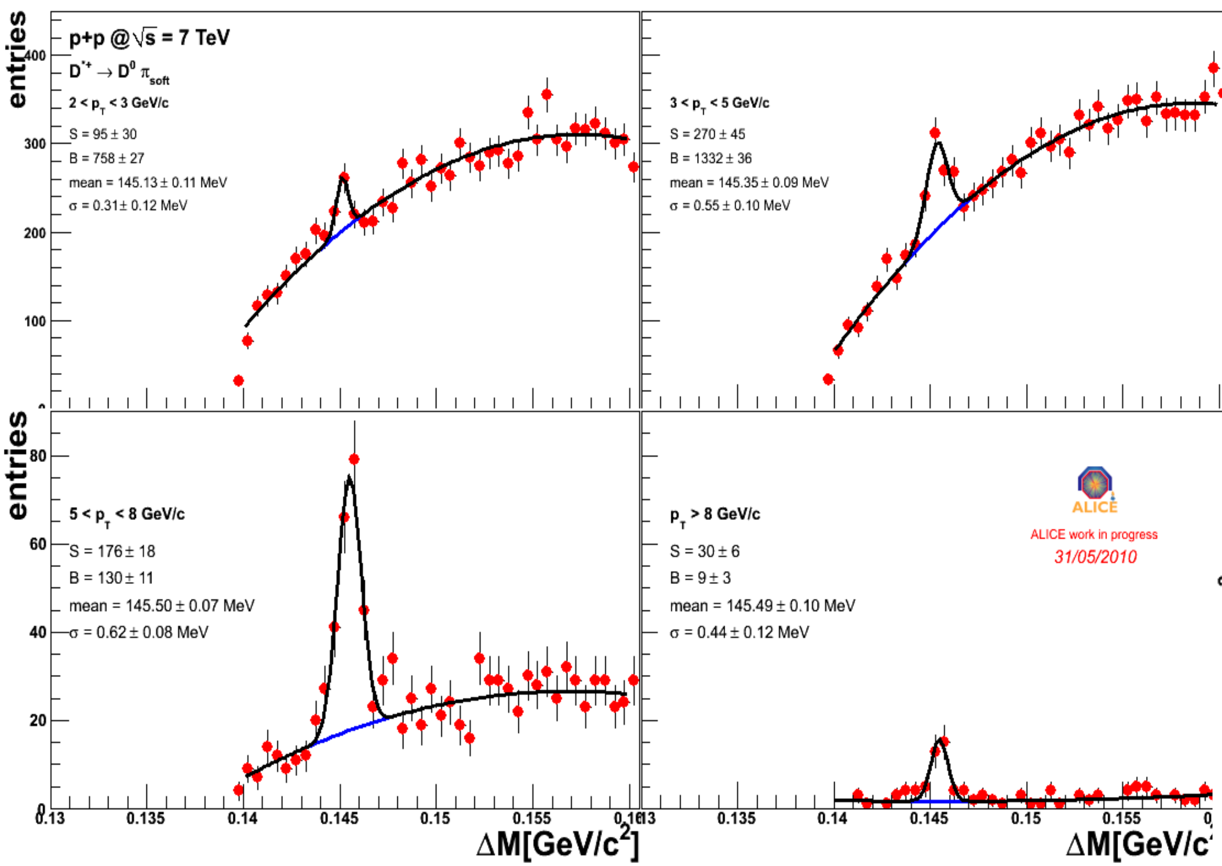
ALICE at $p_t > 2$ GeV/c and $0 < y < 4$
ATLAS and CMS at $p_t > 6$ GeV/c and $0 < y < 2.5$
LHCb at $p_t > 2$ GeV/c and $2.5 < y < 4$

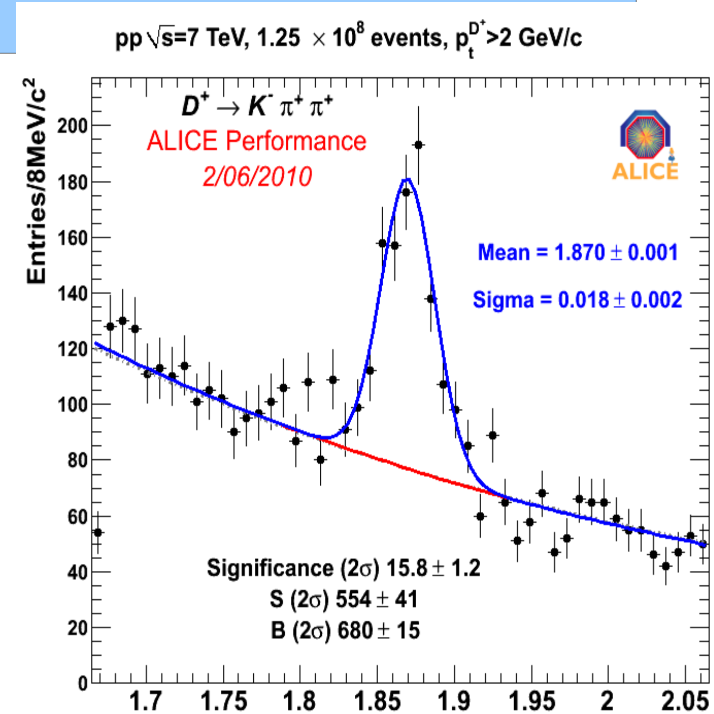
all detectors employ sophisticated Si vertex detectors

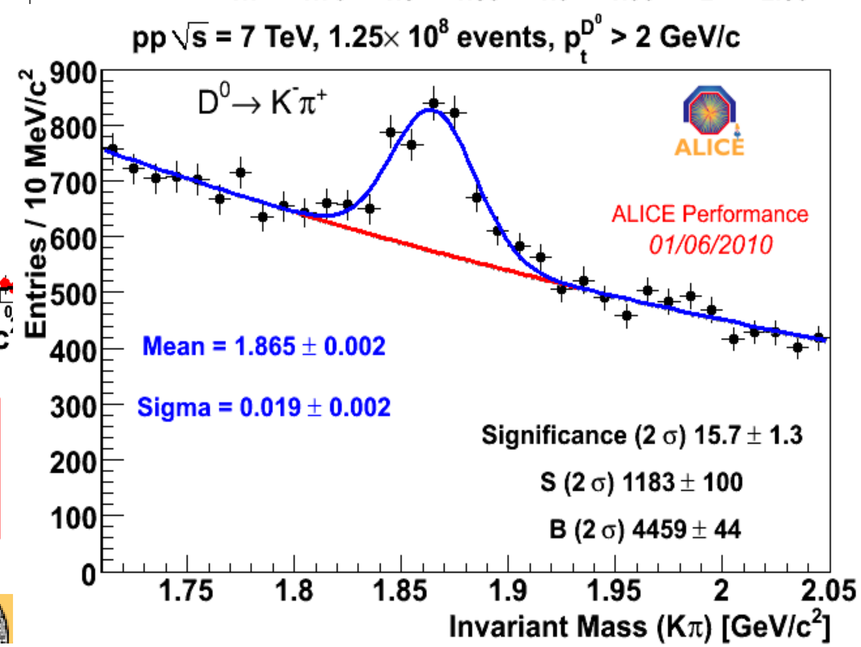
measurement technique:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
" into muons (ATLAS, ALICE)

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

1.25 10^8 events

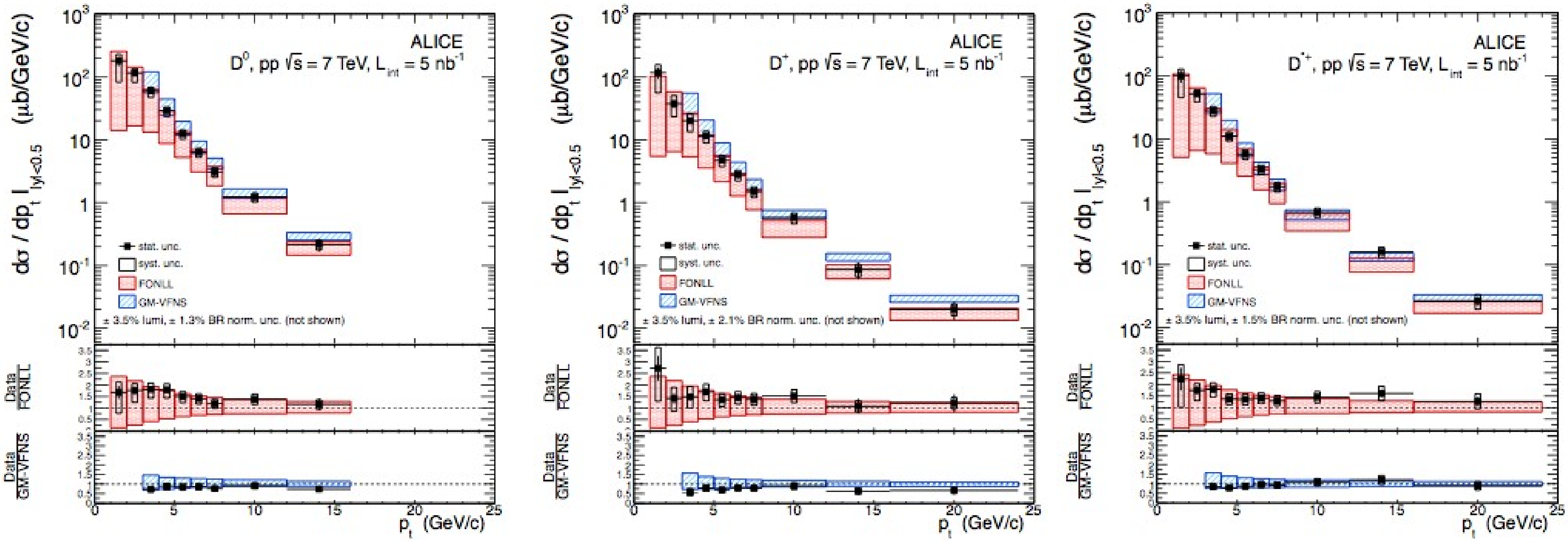






for 10^9 events, expect to measure open charm for p_t = 0.5 – 15 GeV/c

Measurements agree well with state of the art pQCD calculations



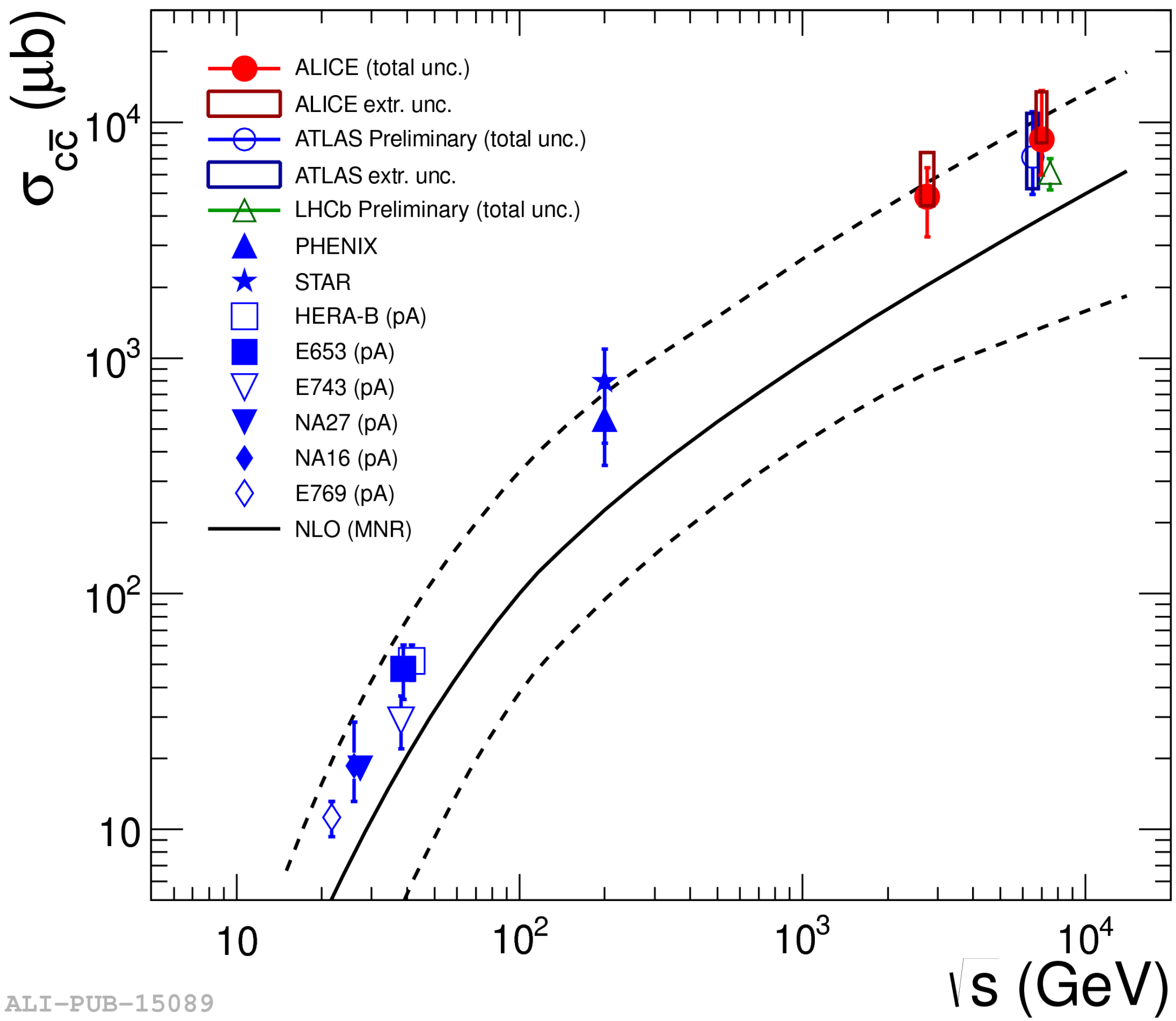
JHEP1201(2012)128

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
measure 80% of charm cross section for |y| < 0.5

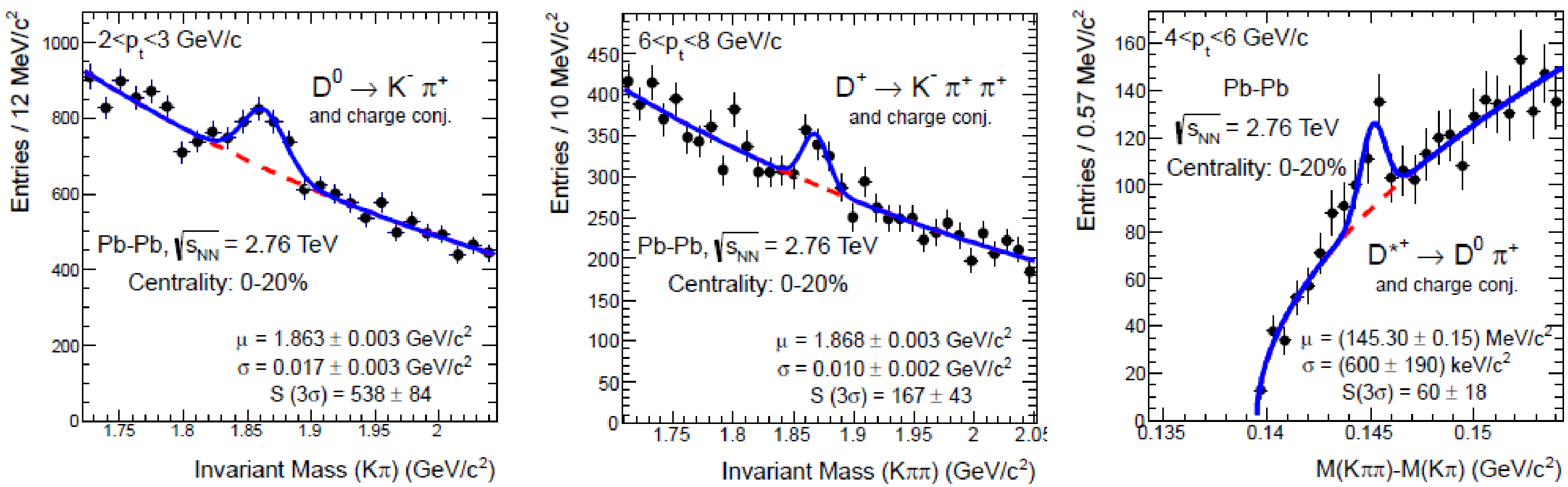
a first try at the total ccbar cross section in pp collisions

JHEP 1207 (2012) 191



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

D meson signals in Pb Pb collisions

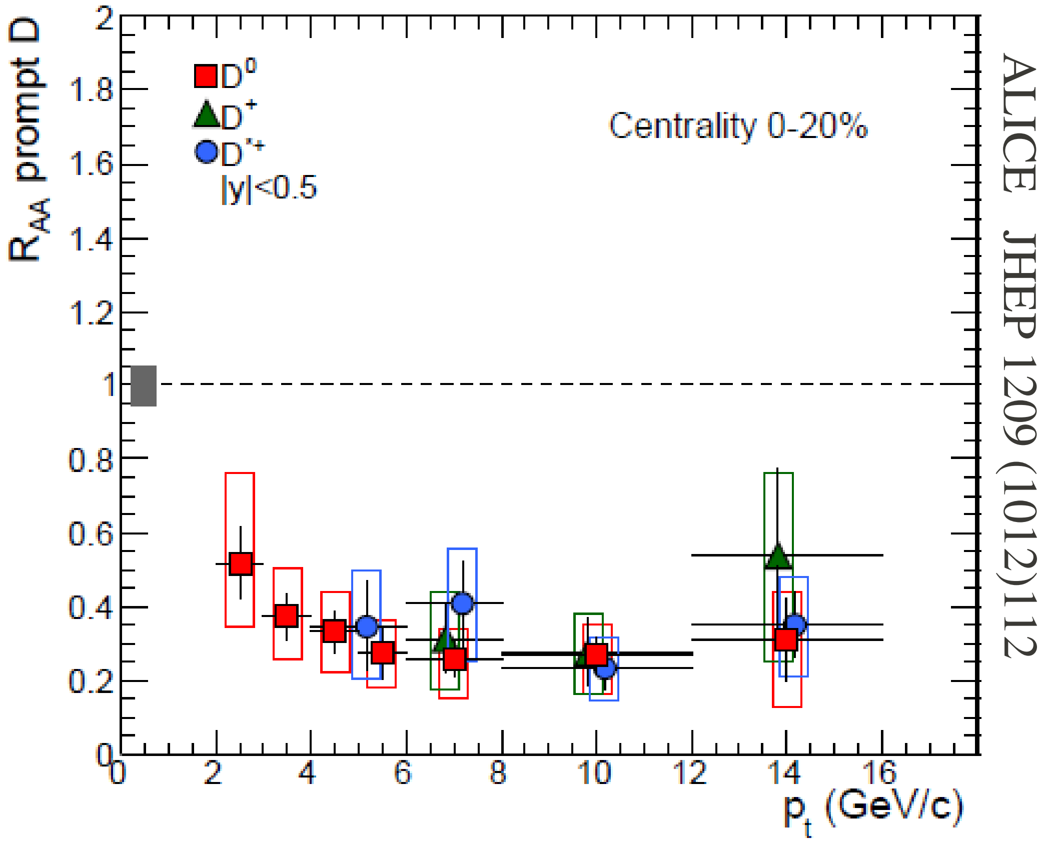


data: ALICE JHEP 1209 (1012)112

Suppression of charm at LHC energy

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$

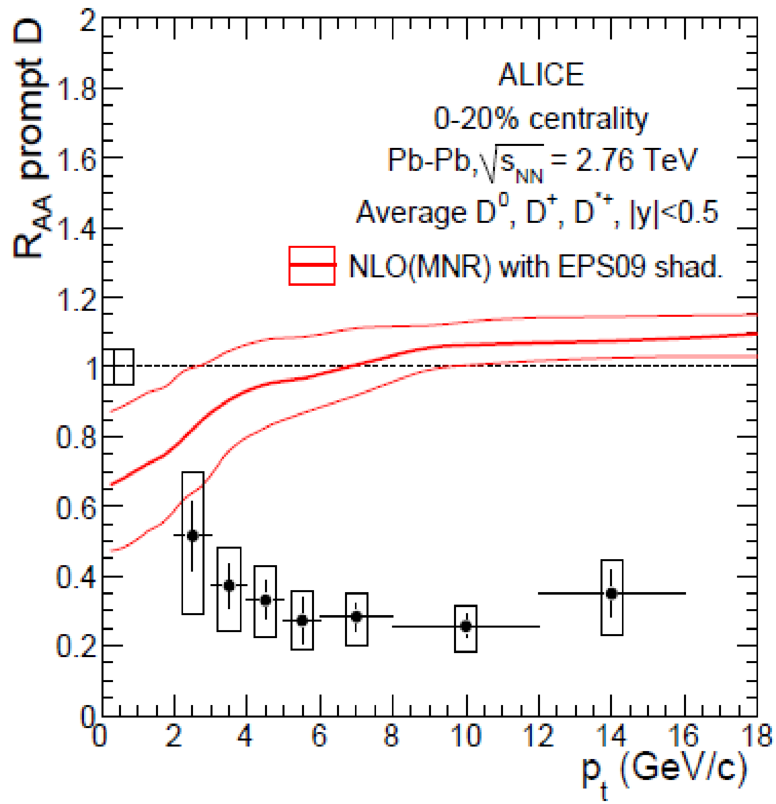
yield in PbPb/(number binary collisions times yield in pp)

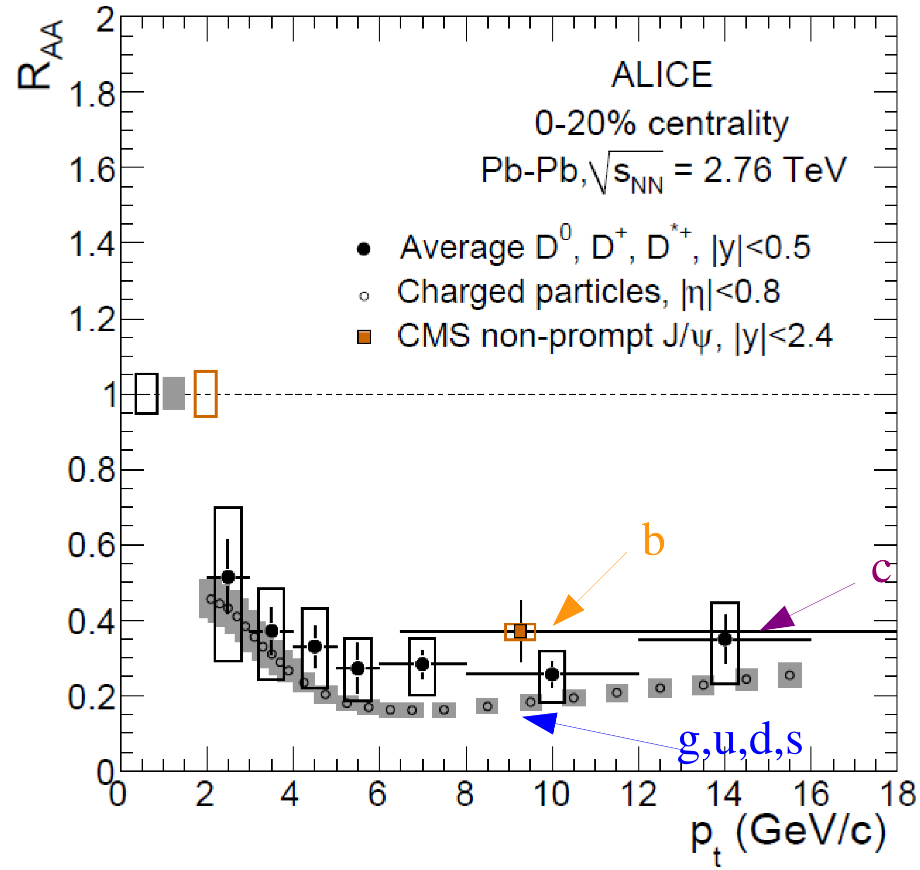


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 4 for 6-12 GeV/c

Suppression of charm at LHC energy

comparison to EPS09 shadowing:
suppression not an initial state effect

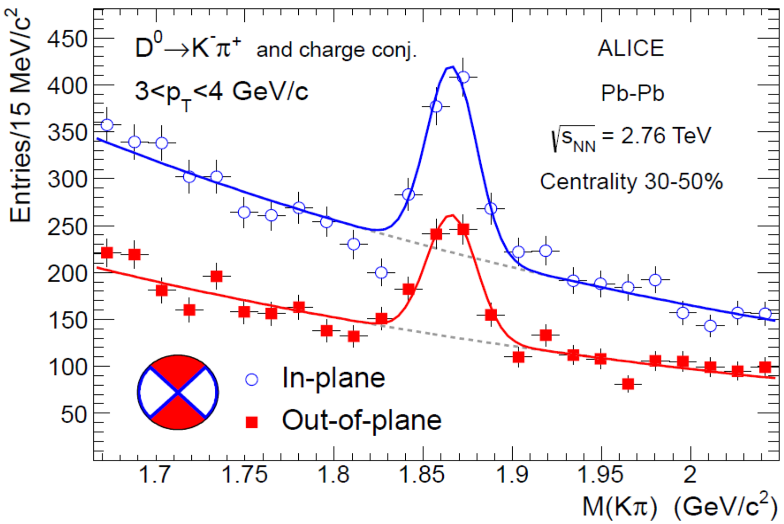




JHEP 1209 (1012)112

energy loss of charm quarks only little less than that for light quarks/gluons → thermalization

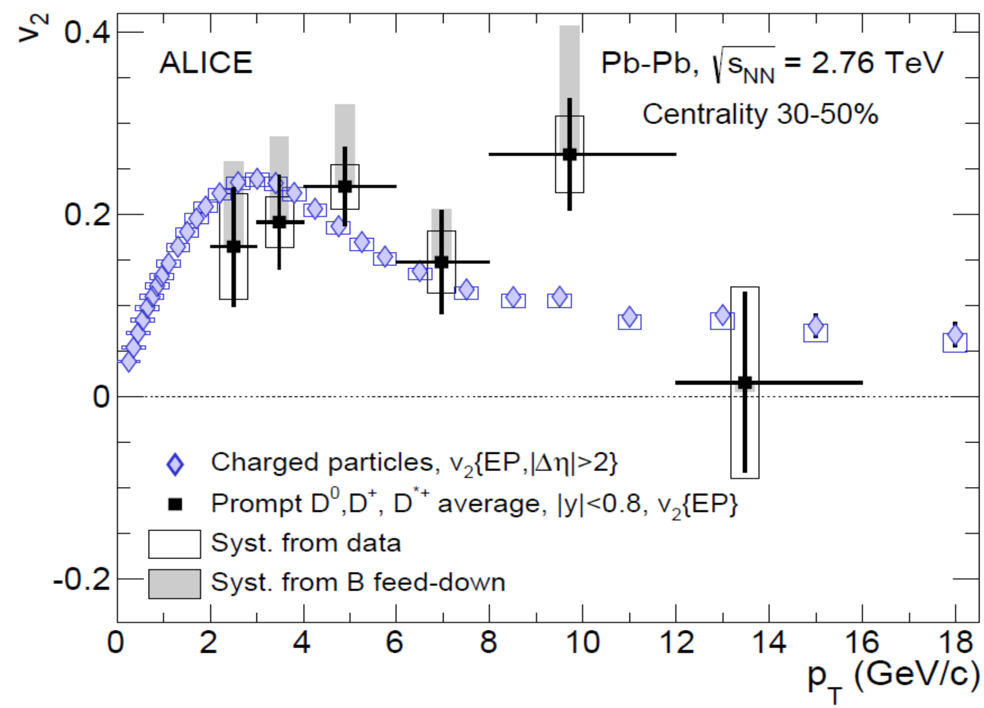
Charm Quarks also Exhibit Elliptic Flow



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

$$R_2 = 0.8$$

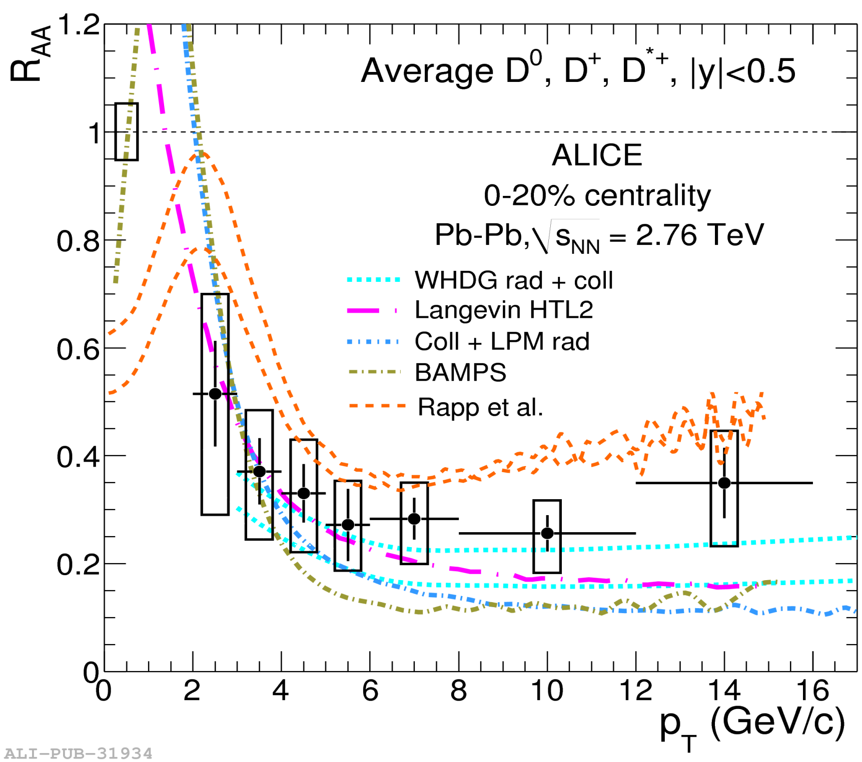
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)

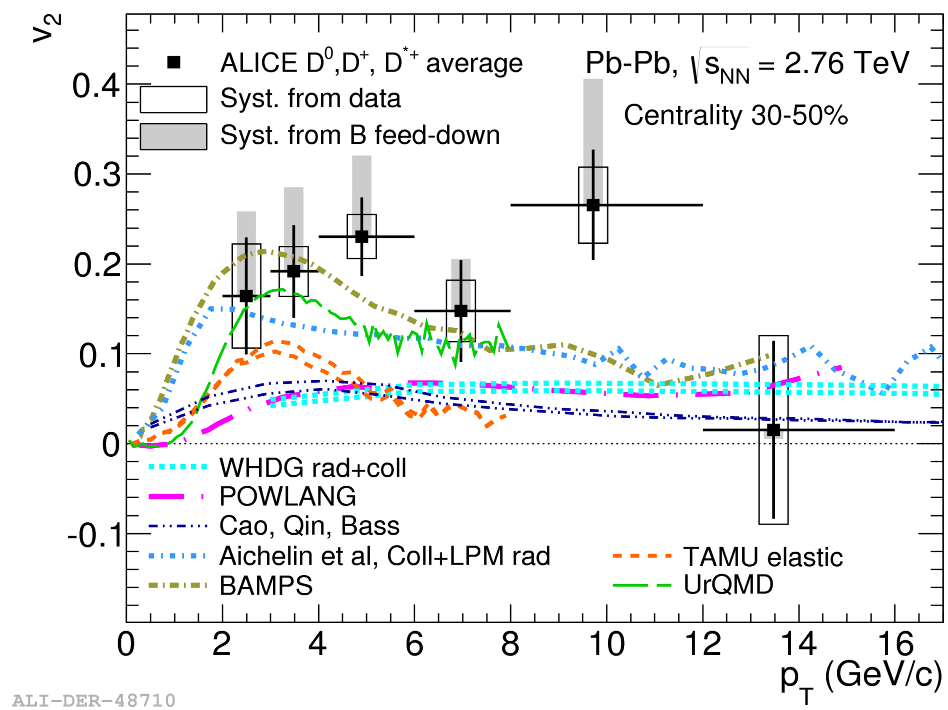


Phys. Rev. Lett. 111 (2013) 102301

non-zero elliptic flow 5.7 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

Model Description of Energy Loss and Flow of D-mesons





both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for models

Charmonia as a probe of Deconfinement

Charmonia: bound states of charm and anticharm quarks, e.g. →

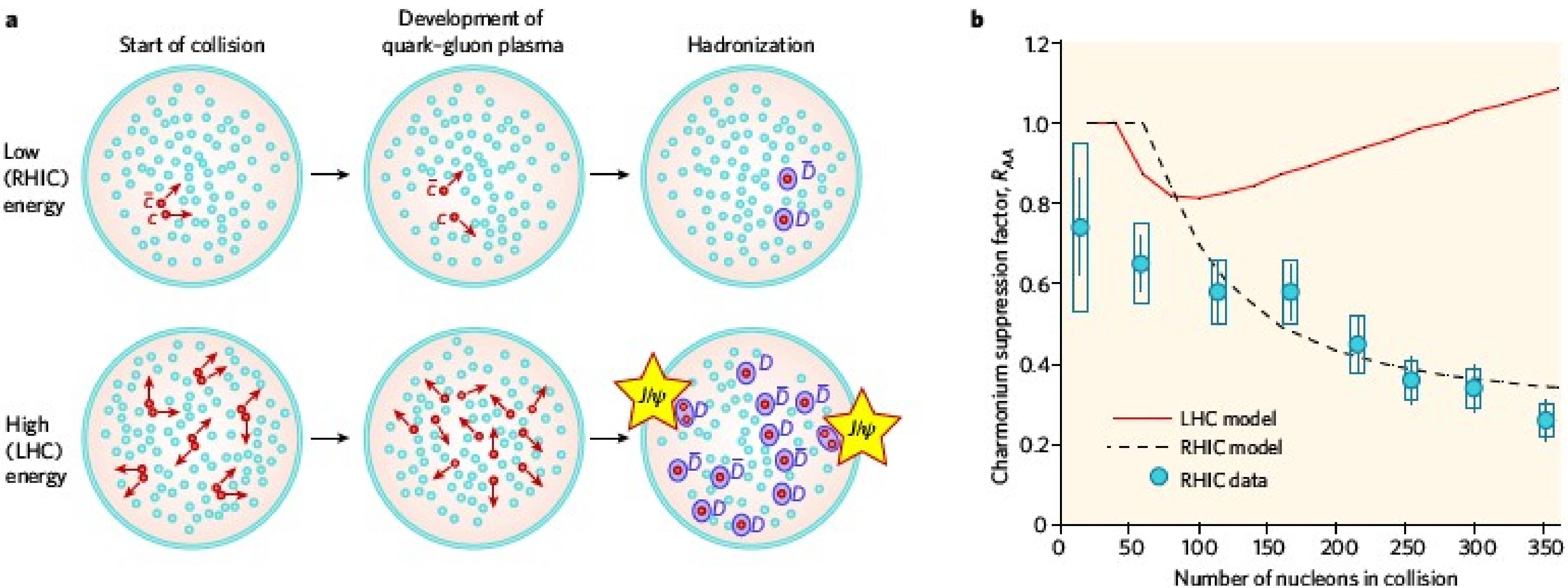
J/ψ 1s state of ccbar
mass 3.1 GeV
radius 0.45 fm

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 or without plasma formation – sequential melting

new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfinement

Quarkonium as a Probe for Deconfinement at the LHC
the Statistical (re-)Generation Picture

P. Braun-Munzinger and J.Stachel, Nature 448 (2007)



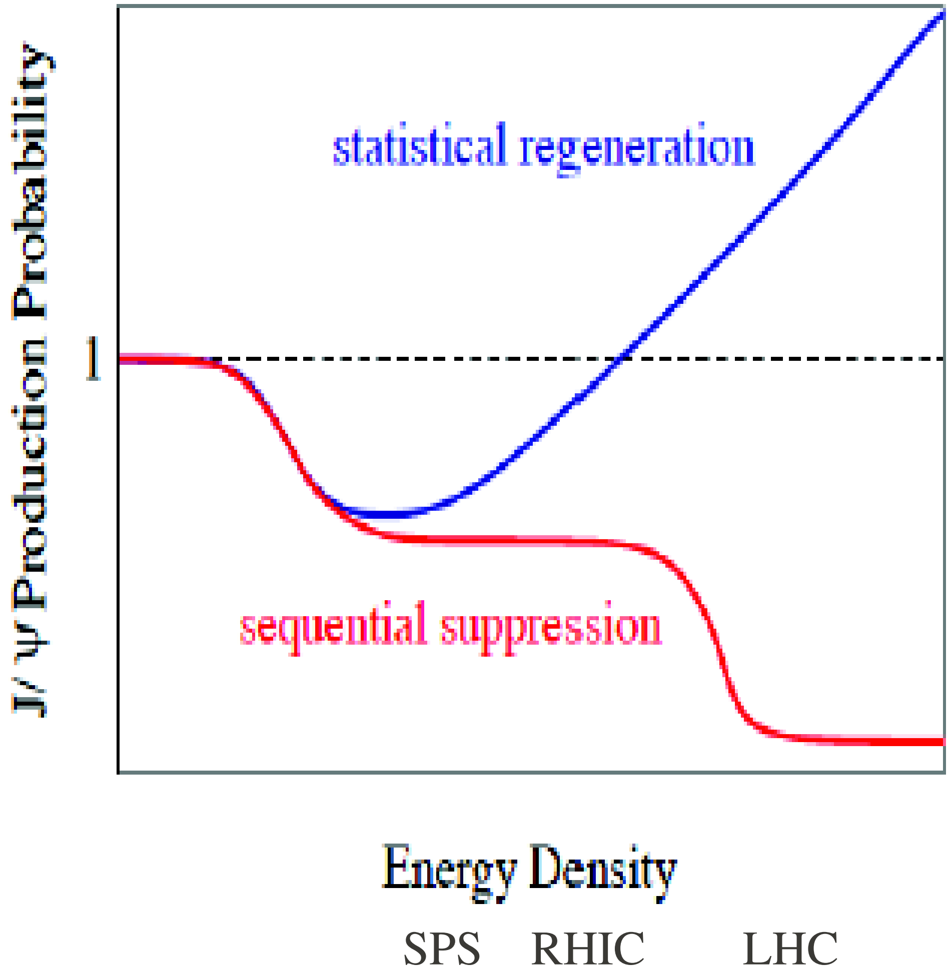
charmonium enhancement as fingerprint of deconfinement at LHC energy

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

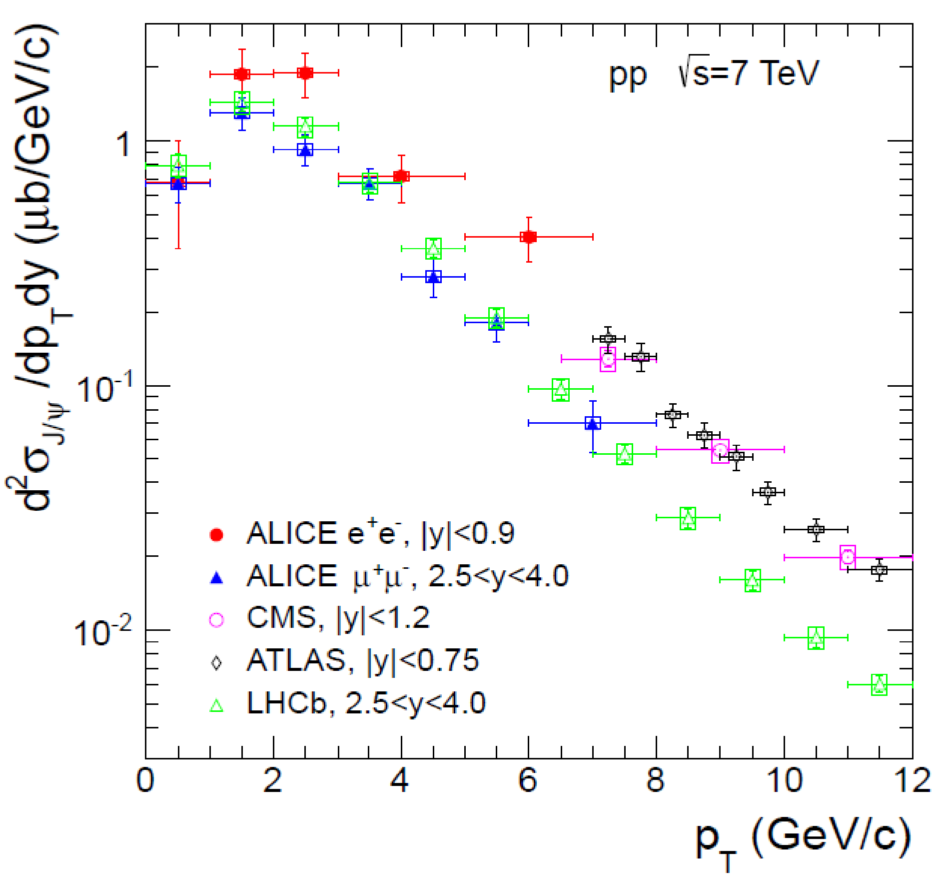
Decision on Regeneration vs. Sequential Suppression from LHC Data

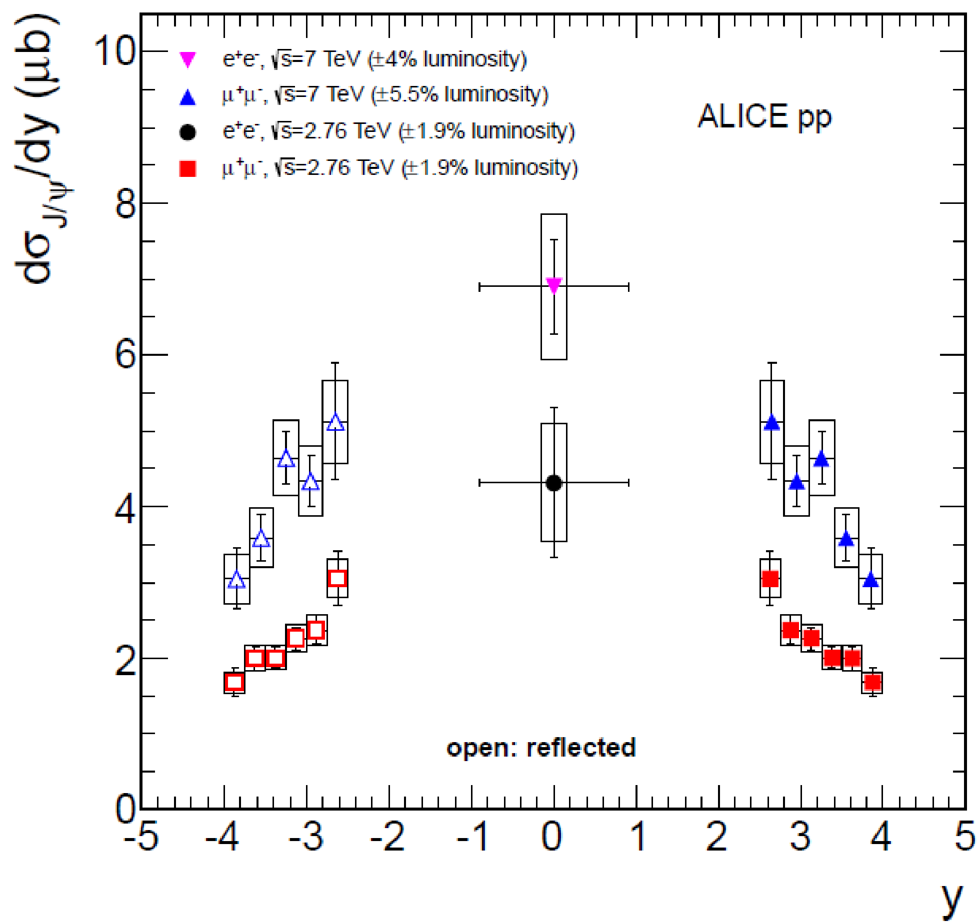


Picture:
H. Satz 2009

J/psi spectrum and cross section in pp collisions

ALICE PLB704 (2011) 442 arXiv:1105.0380 and PLB718 (2012) 295





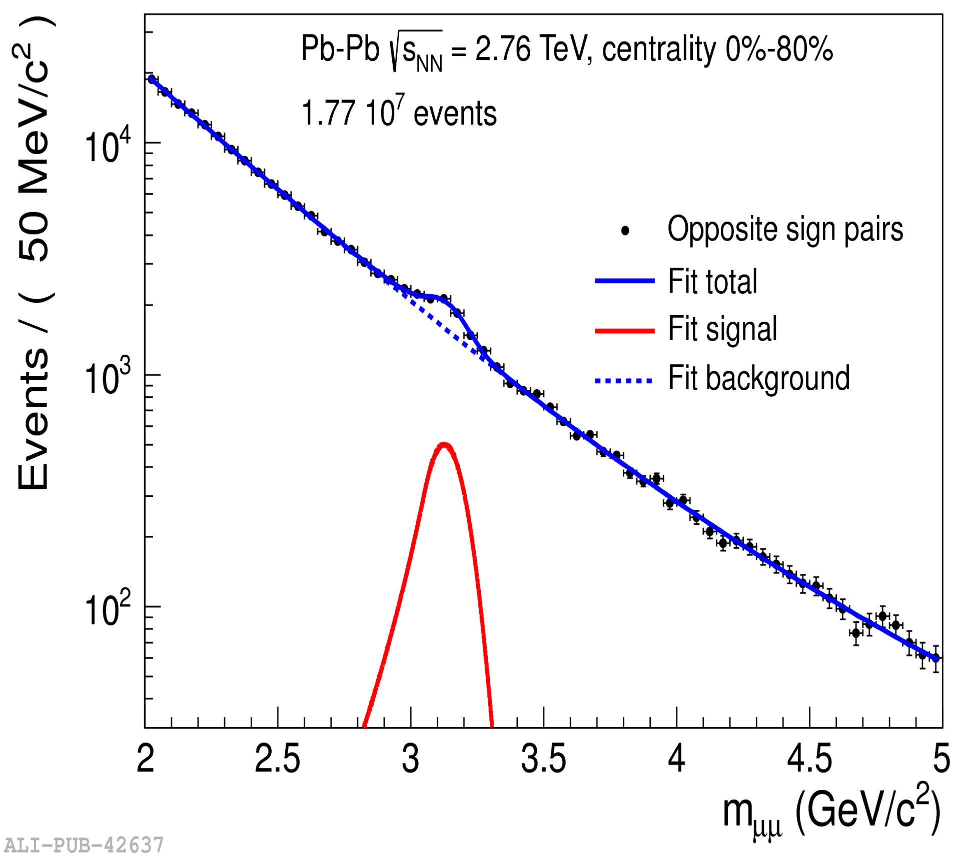
- good agreement between experiments
- complementary in acceptance:
  only ALICE has acceptance below
  6 GeV at mid-rapidity

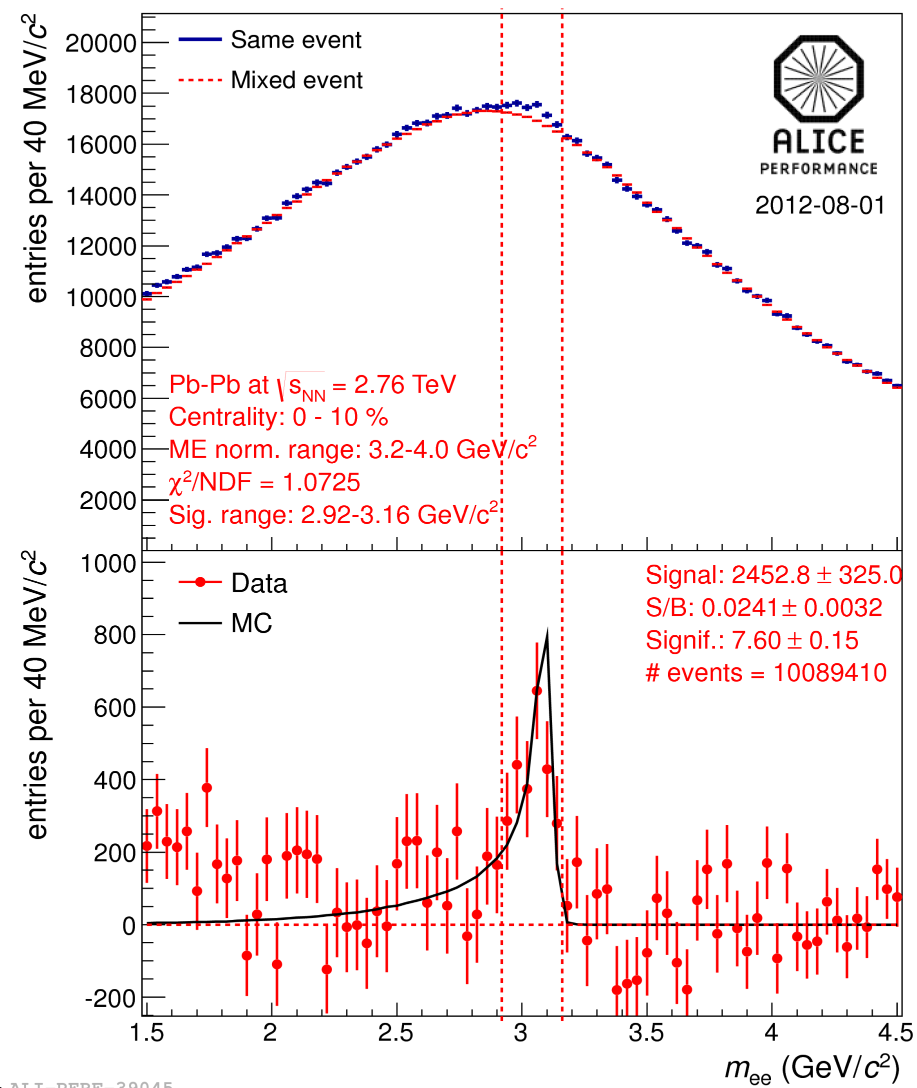
measured both at 7 and 2.76 TeV

open issues: statistics at mid-rapidity

polarization (biggest source of syst error)

Reconstruction of J/psi in PbPb via mu+mu- and e+e- decay



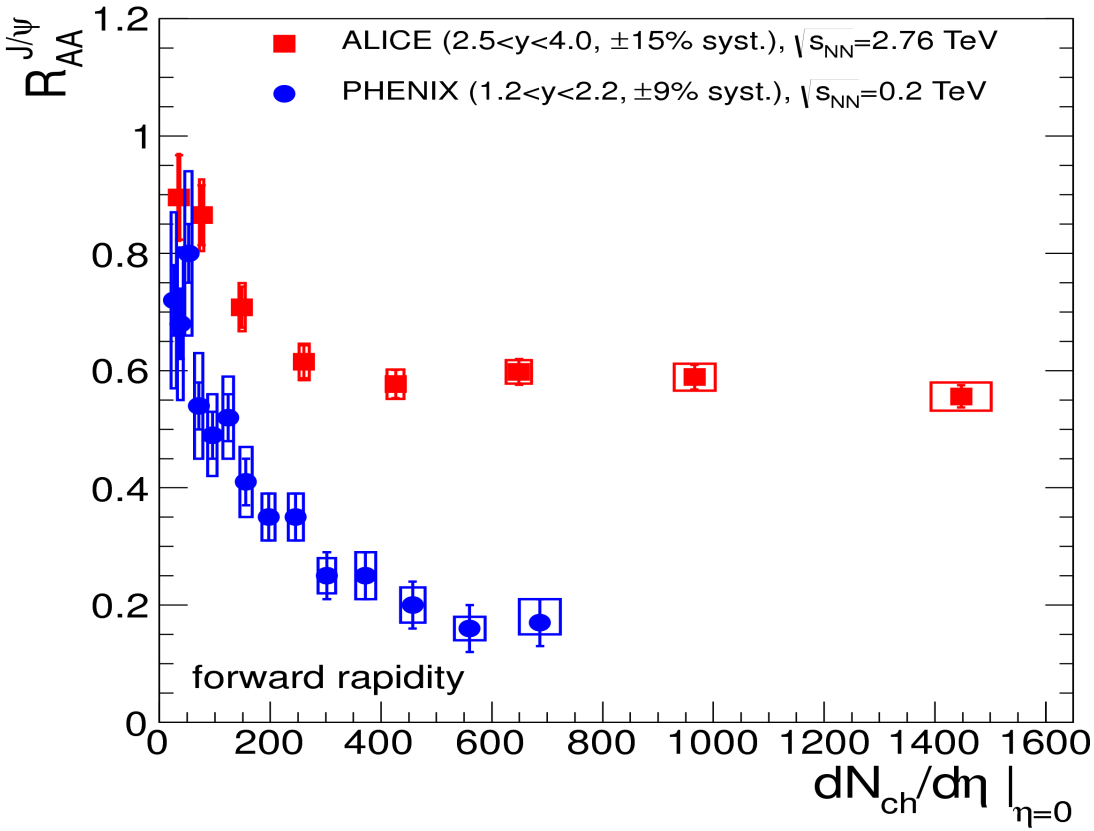


<u>most challenging:</u> PbPb collisions

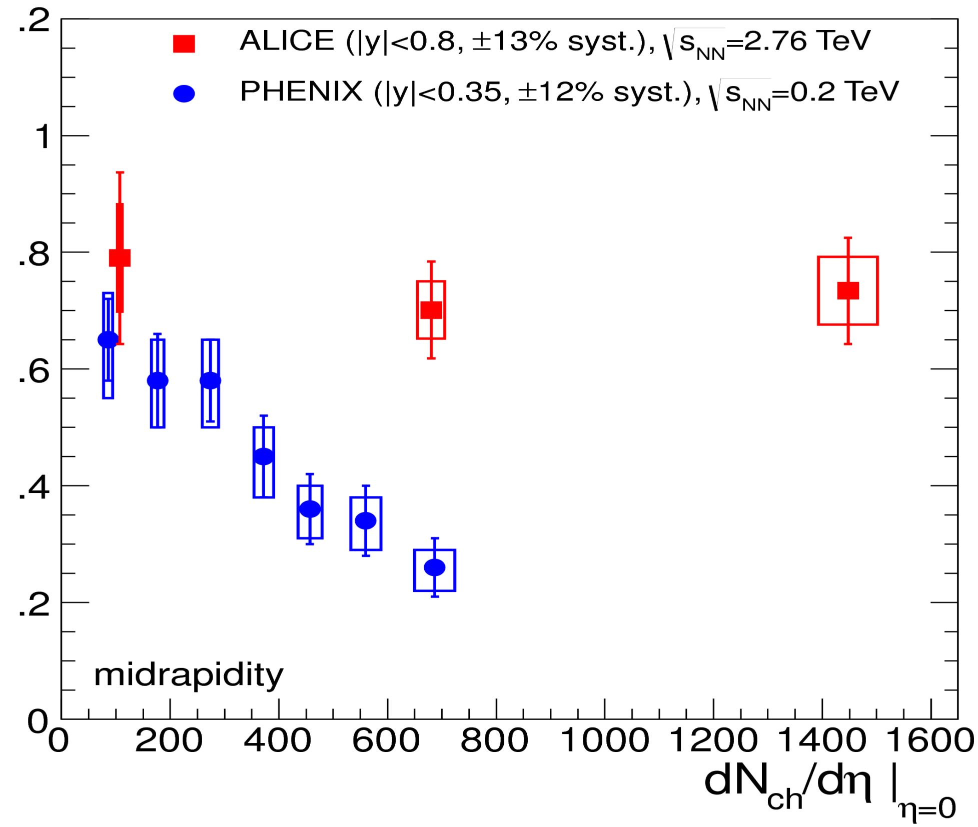
in spite of significant irreducible combinatorial background
 (true electrons, not from J/ψ decay but from D- or B-mesons) resonance well visible

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

forward rapidity



mid-rapidity

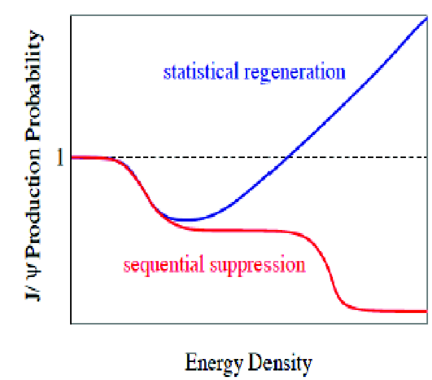


energy density -->

melting scenario not observed

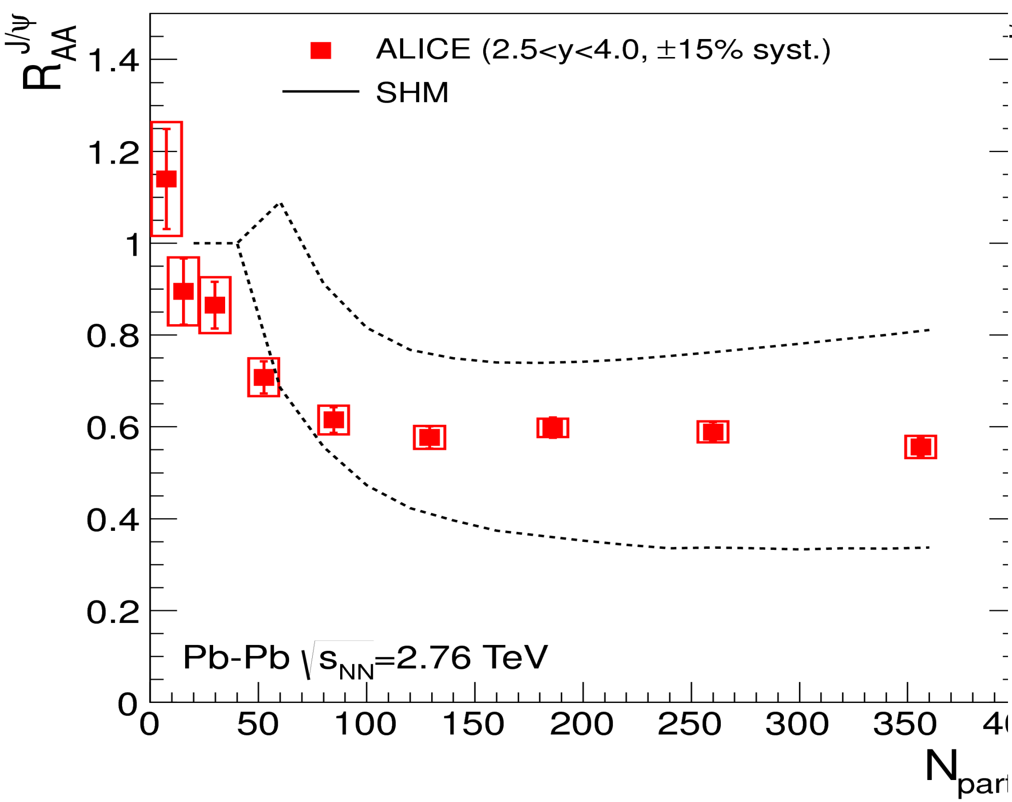
rather: enhancement with increasing energy density!

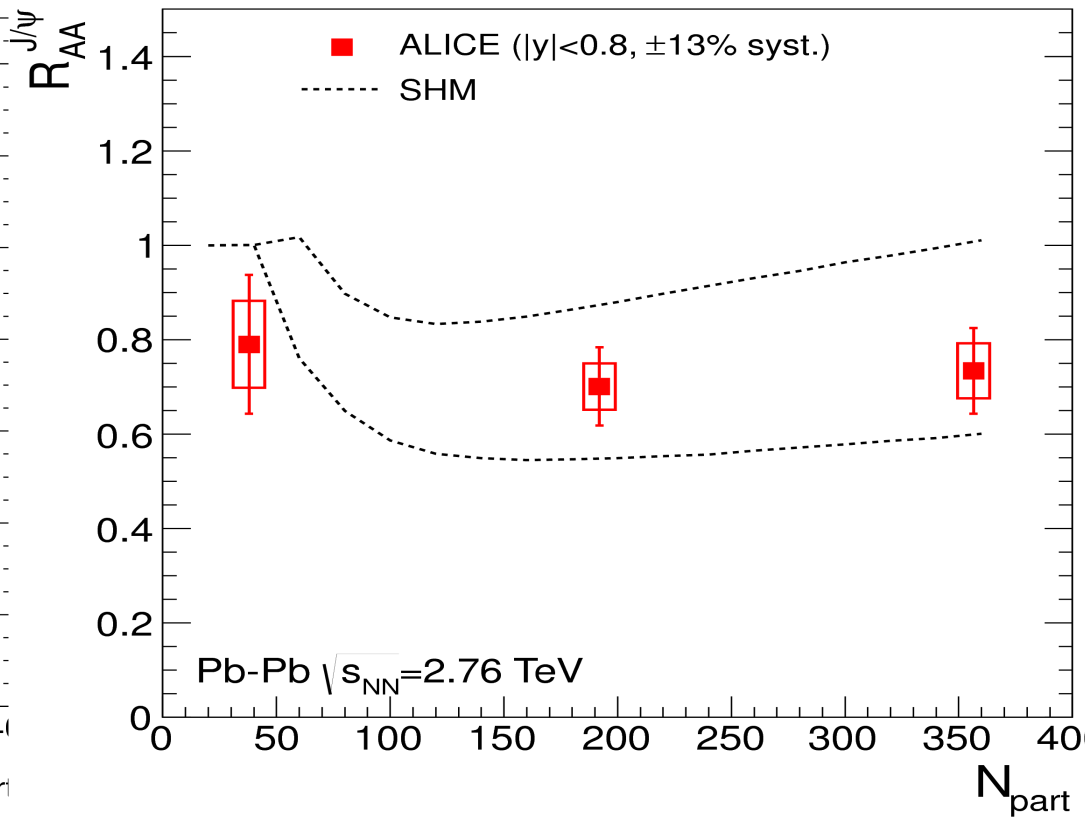
(from RHIC to LHC and from forward to mid-rapidity)



J/psi and Statistical Hadronization

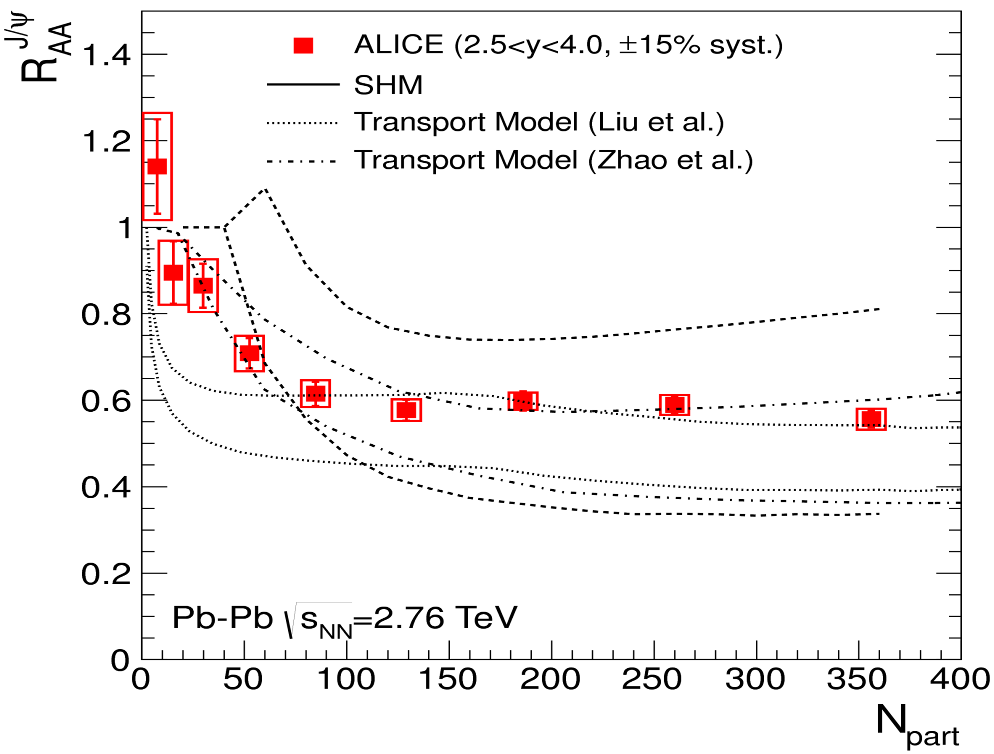
---- Statistical hadronization model: Andronic, Braun-Munzinger, Redlich, J.S.

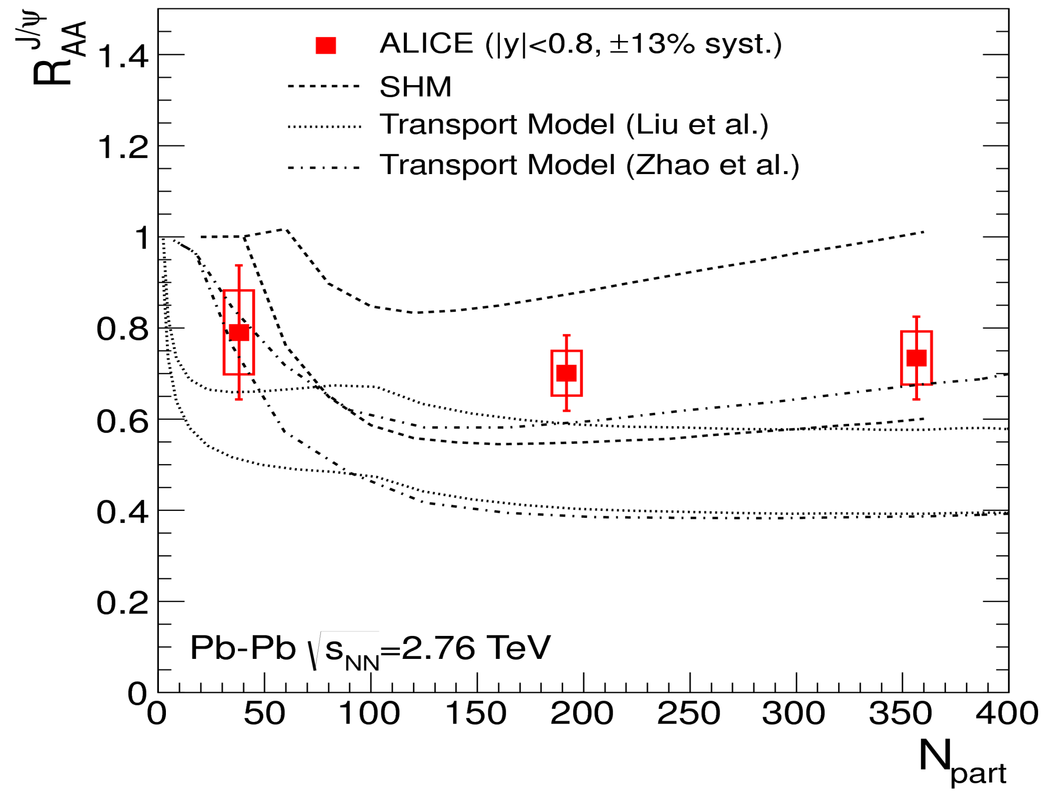




- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb (see next)

J/psi and transport models (and stat hadronization)





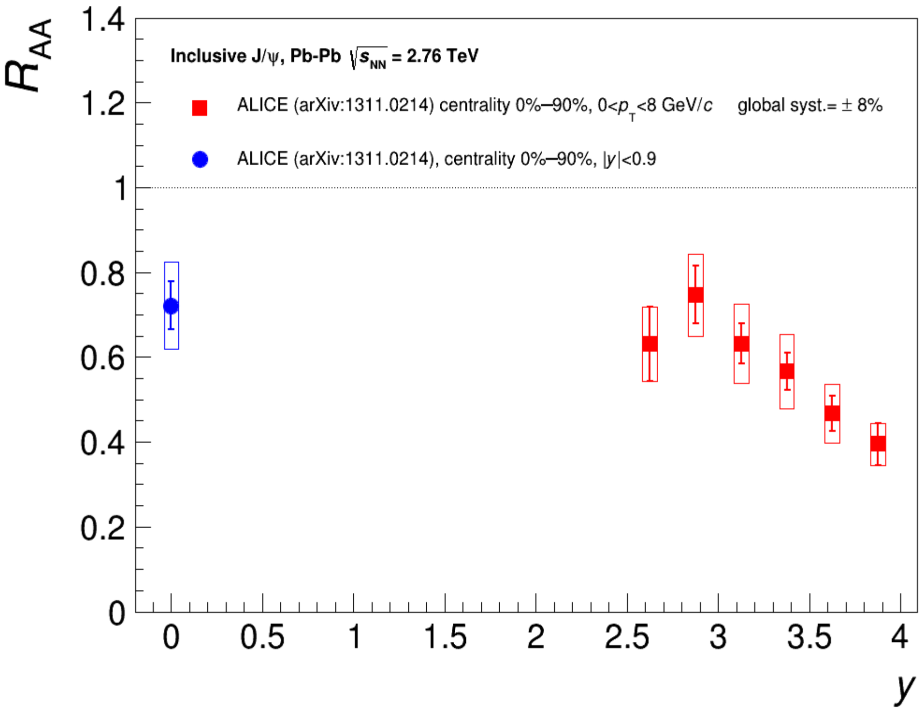
in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with R_{AA}

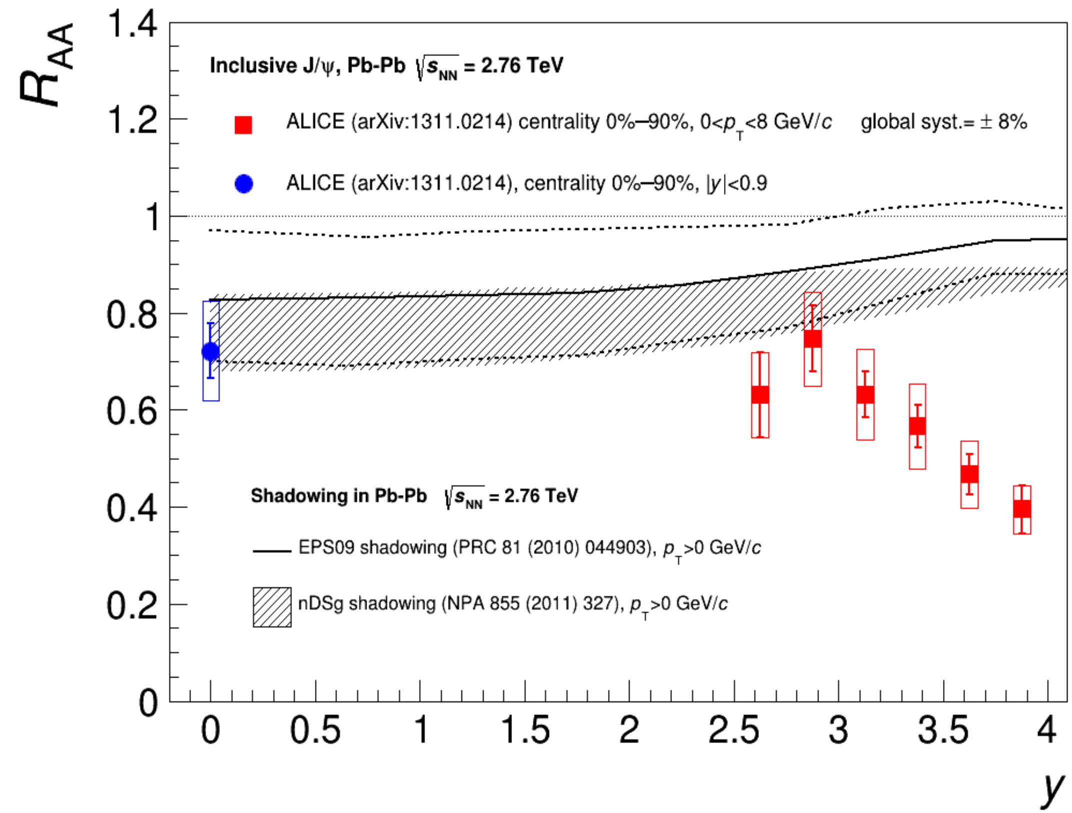
  part of J/psi from direct hard production, part dynamically generated in QG

  what I do not understand: how can error band be narrower than ours? Error open charm ...

Rapidity Dependence of J/psi R_{AA}

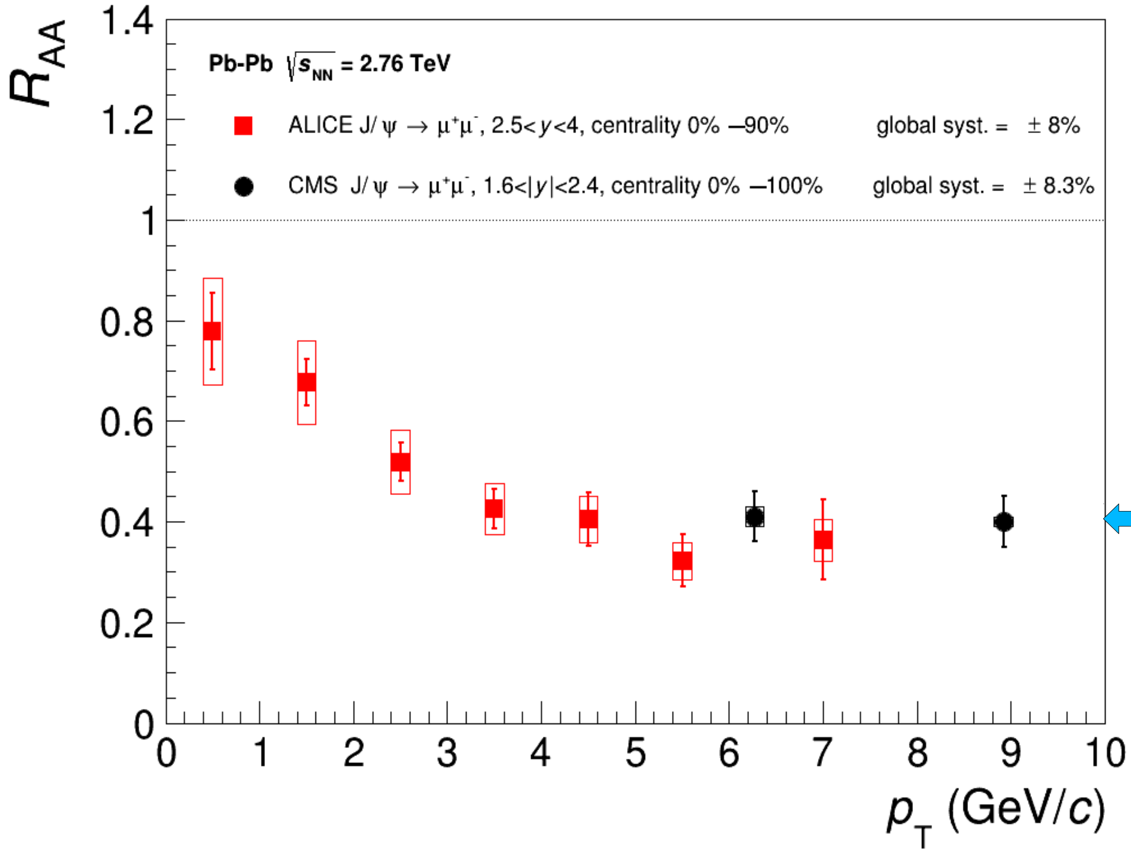


for statistical hadronization J/ψ yield proportional to N_c^2
higher yield at mid-rapidity predicted in line with observation



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

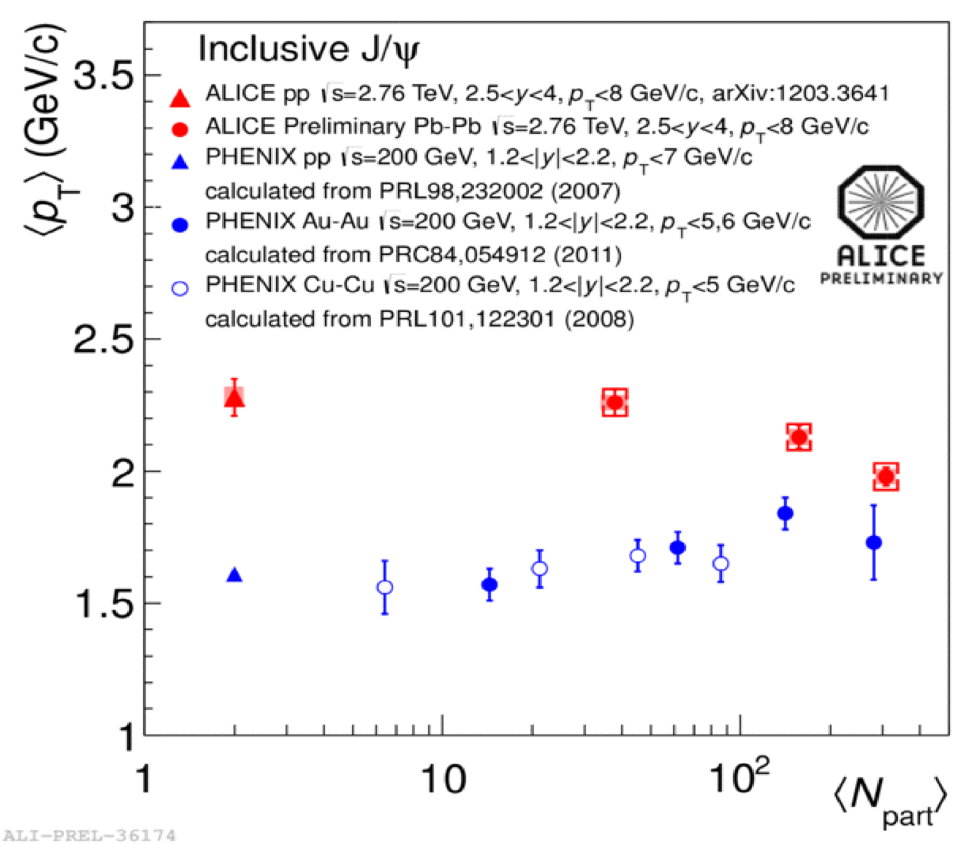
p_t dependence of R_{AA}

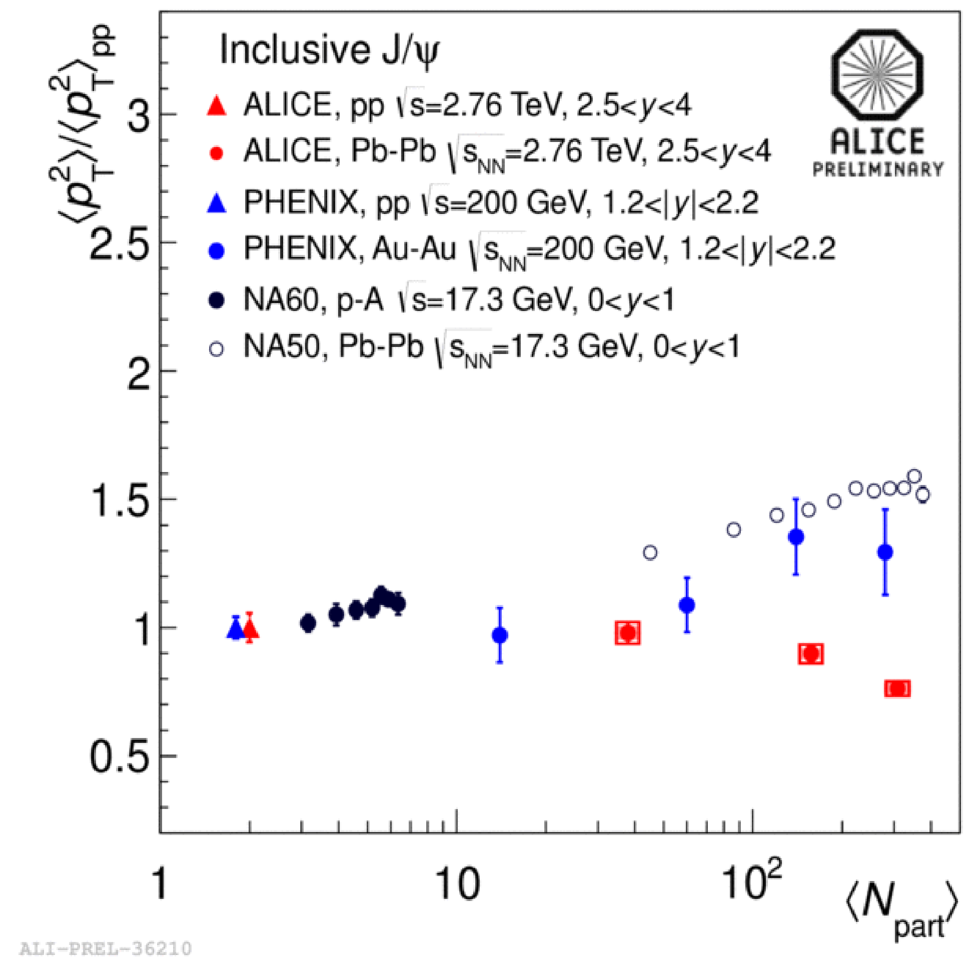


relative yield larger at low p_t in nuclear collisions

good agreement with CMS at high p_t

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

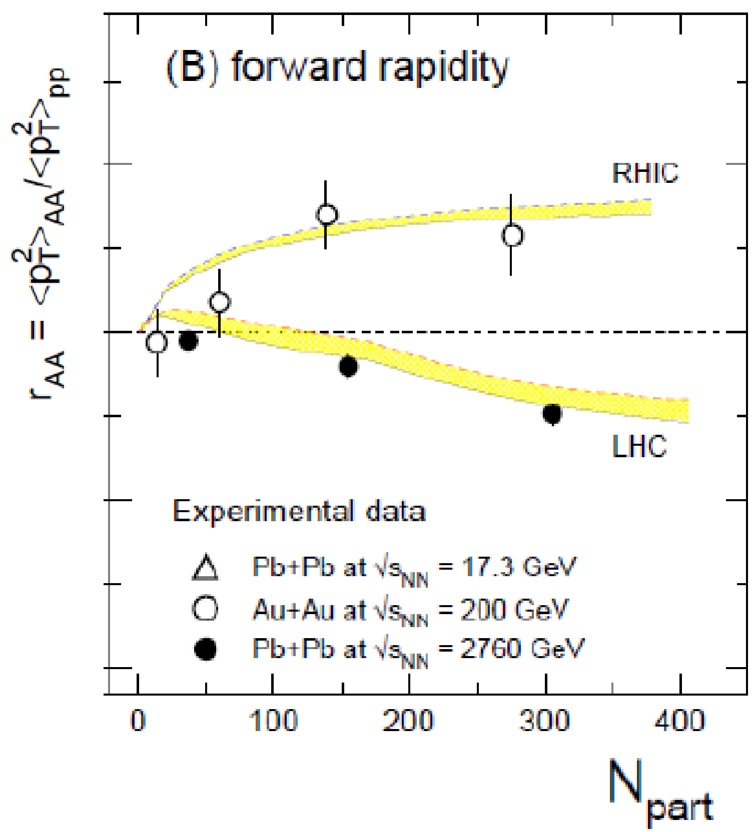


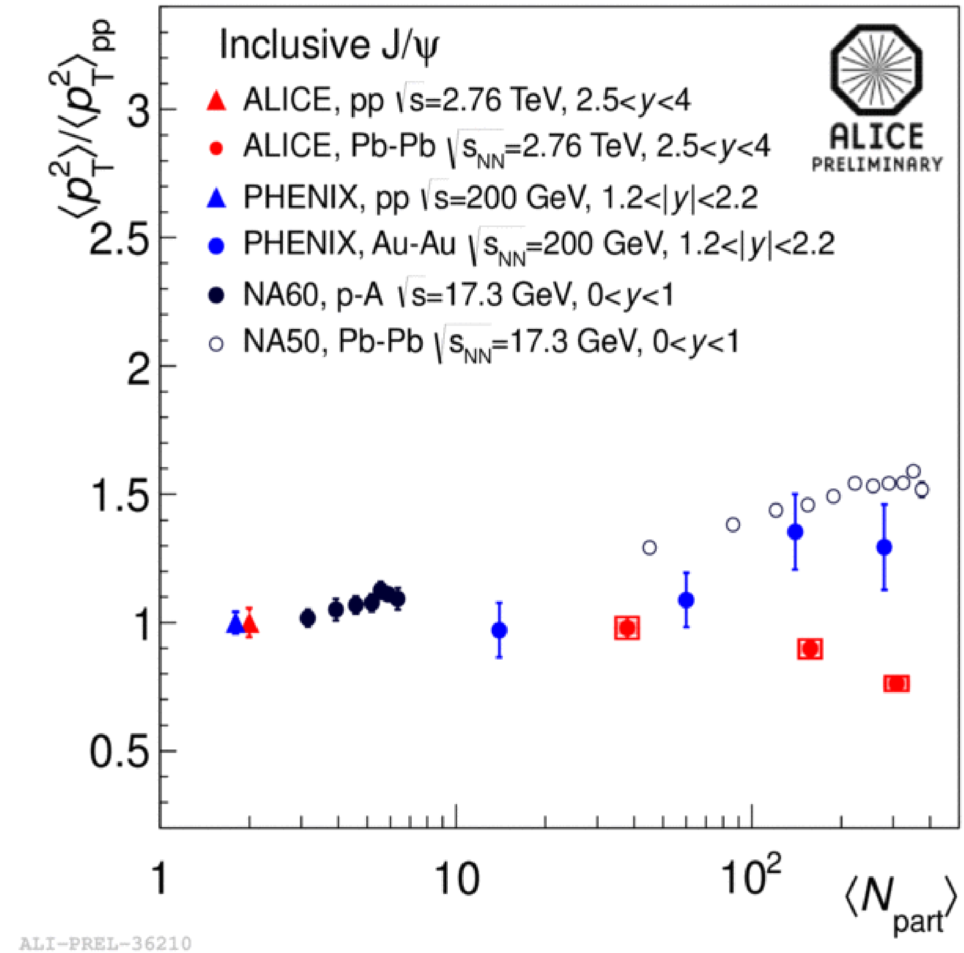


At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

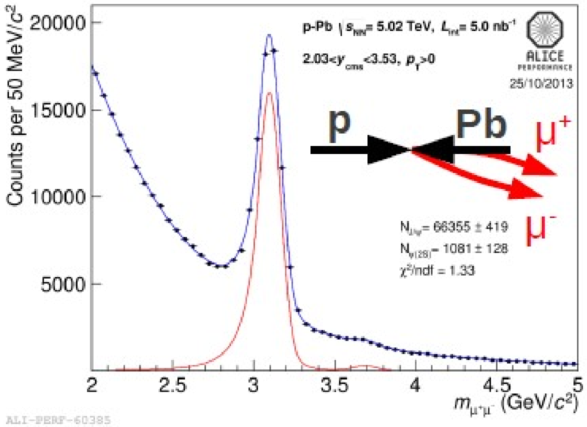
Softening of J/psi p_t distributions for central PbPb coll.

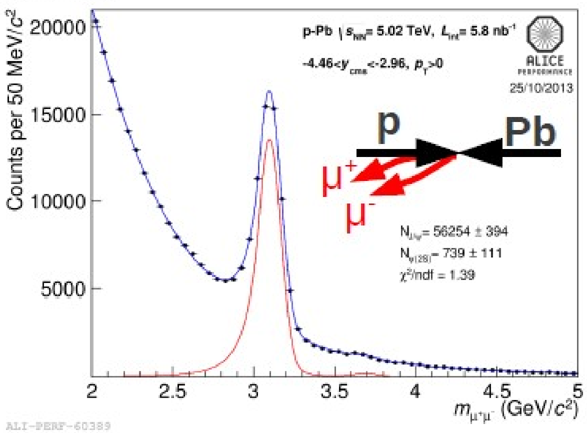
P.Zhuang et al. regeneration of J/psi
90% at mid-y, > 60% at forward y

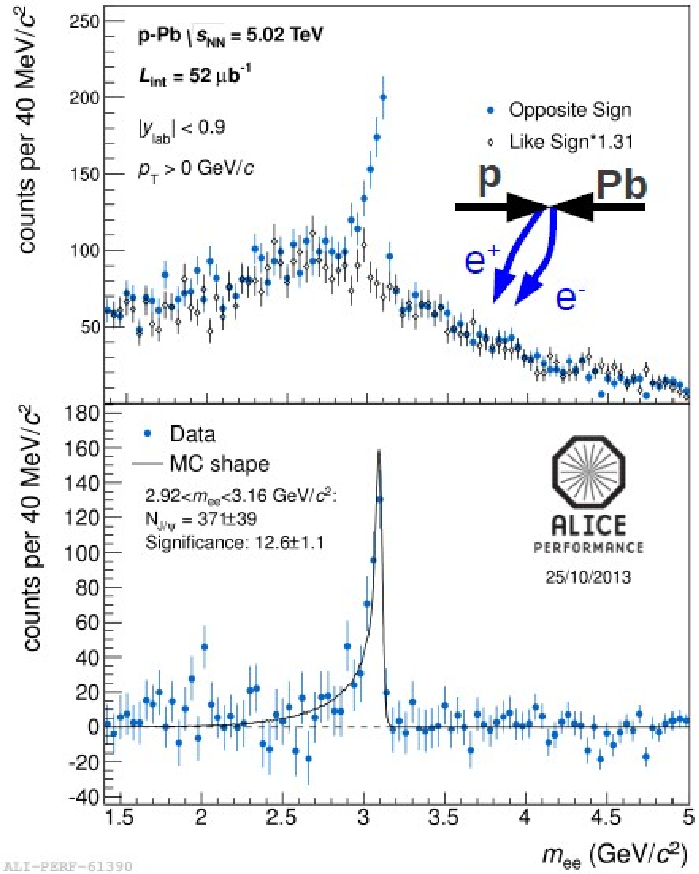




Modification of charm production in nuclei: pA collisions







Dimuons: dedicated trigger

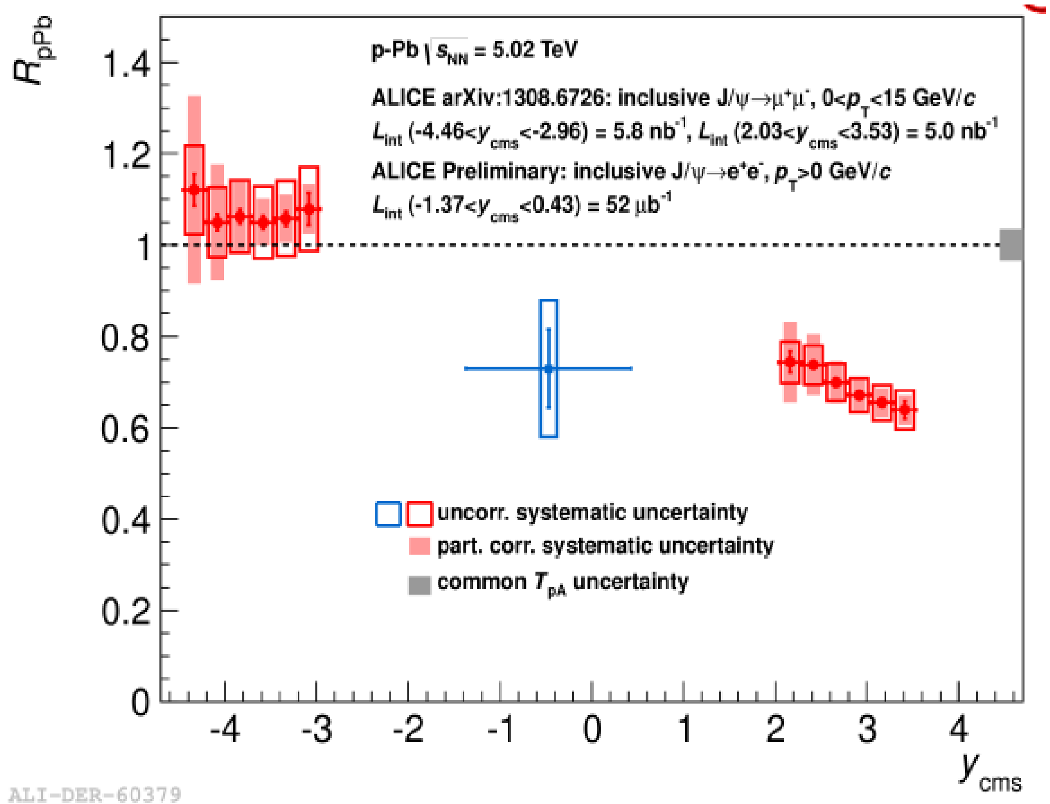
L_{int}=5.0 nb^{-1} (forward)

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

Dielectrons: Minimum Bias

L_{int}= 52 μb^{-1}

J/psi rapidity distribution in pPb compared to pp

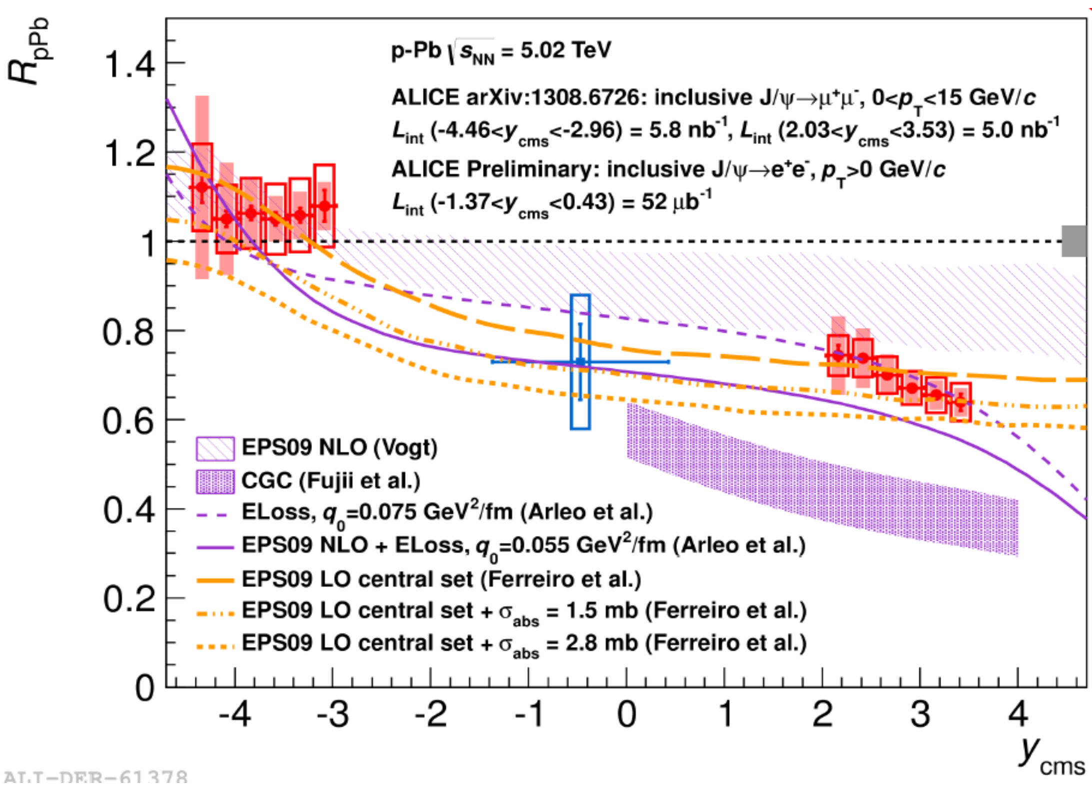


ALICE forward/backward arXiv:1308.6726

good agreement with LHCb arXiv:1308.6729

ALICE mid-y hard probes 2013

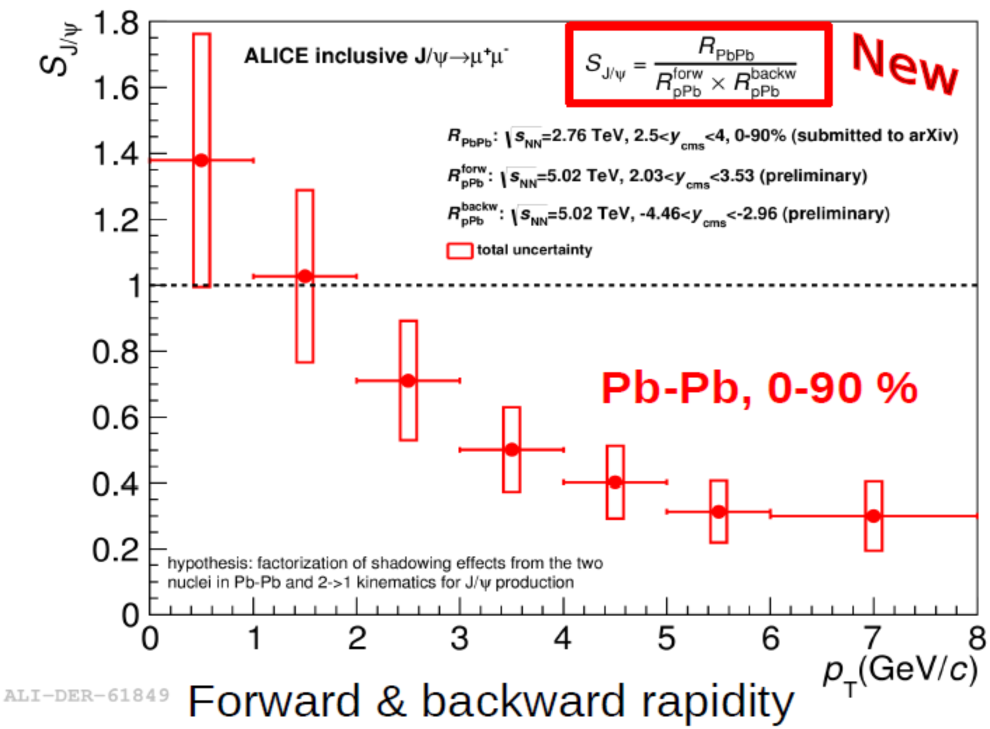
J/psi rapidity distribution in pPb compared to pp

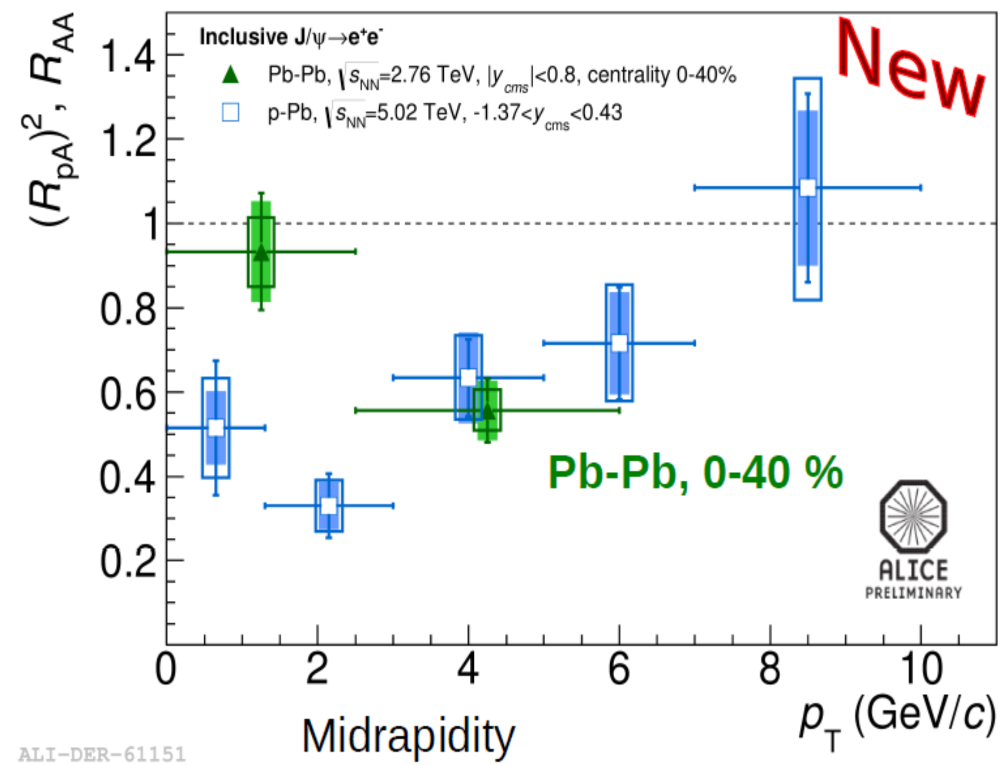


ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

good agreement with EPS09 shadowing wo absorption (Ferreiro)
also consistent w energy loss models wo shadowing (Arleo)
CGC calculation disfavored (Fuji)

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





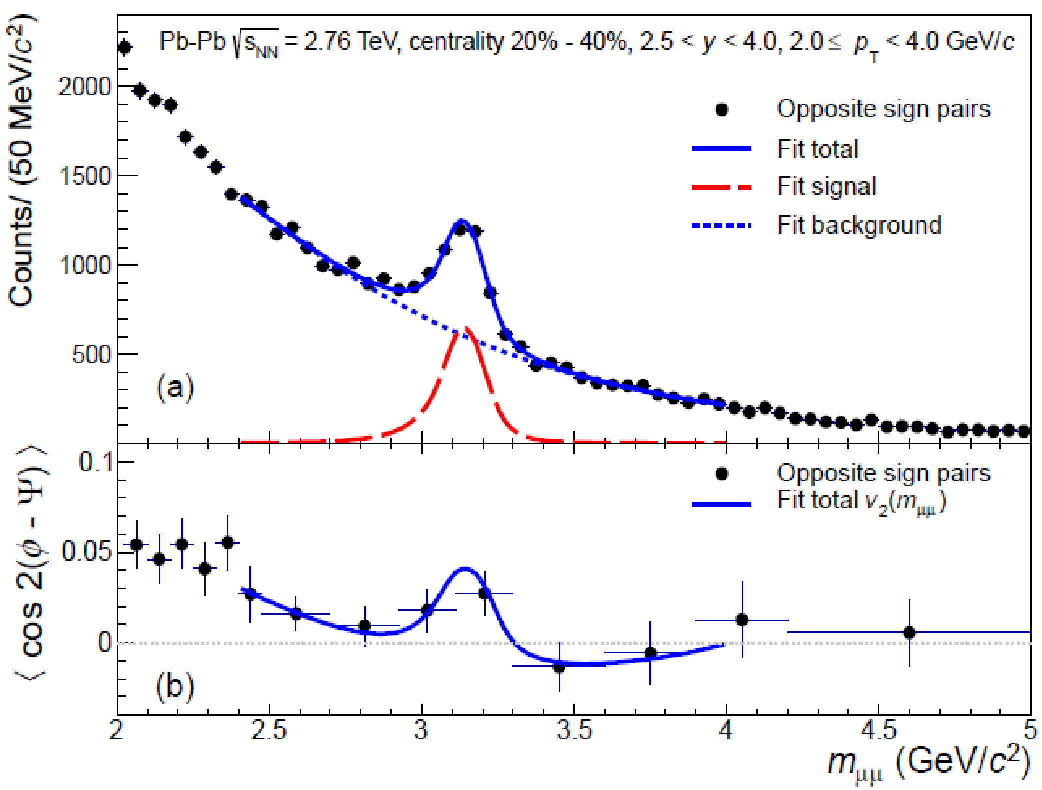
at low pt yield in nuclear collisions above pPb collisions
J/psi production enhanced in nuclear collisions over mere shadowing effect

Elliptic Flow of J/psi

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

ALICE data analysis in 4 centrality bins
arXiv:1303.5880 and PRL (2013)

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



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

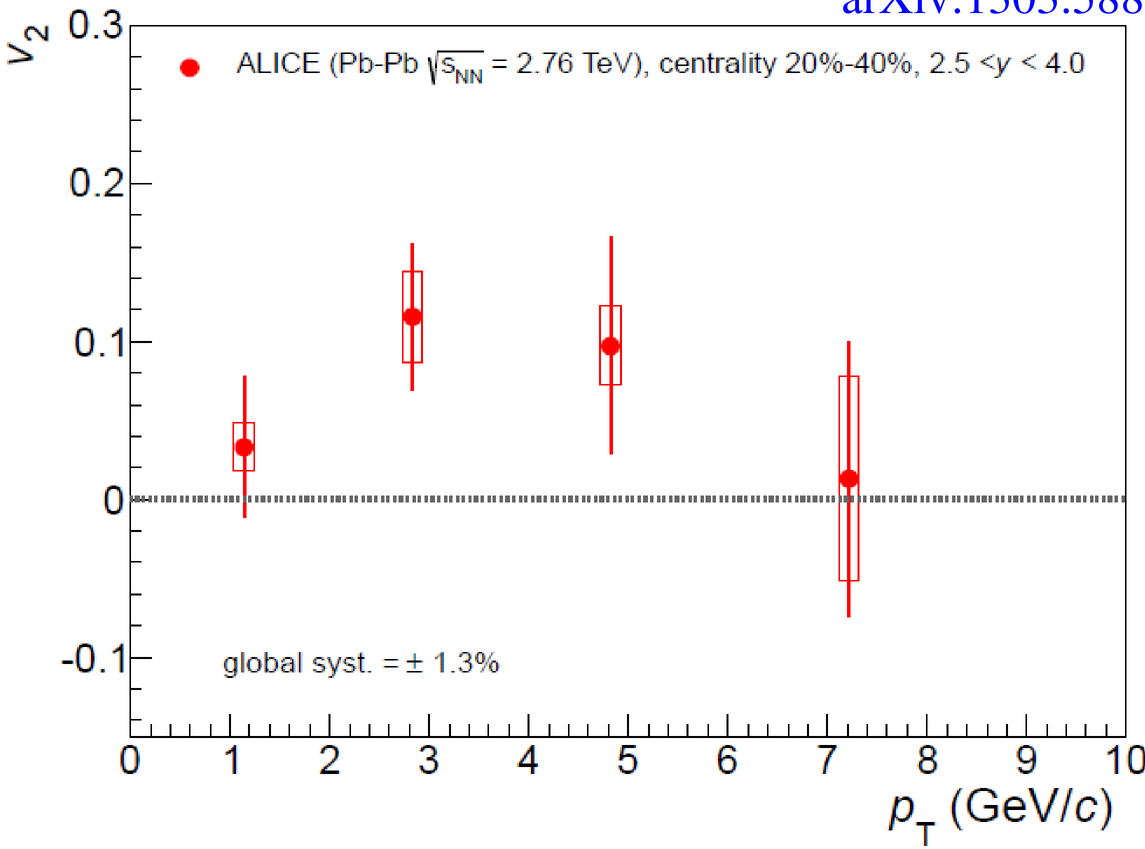
- fit distribution with

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

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

Elliptic Flow of J/psi vs pt

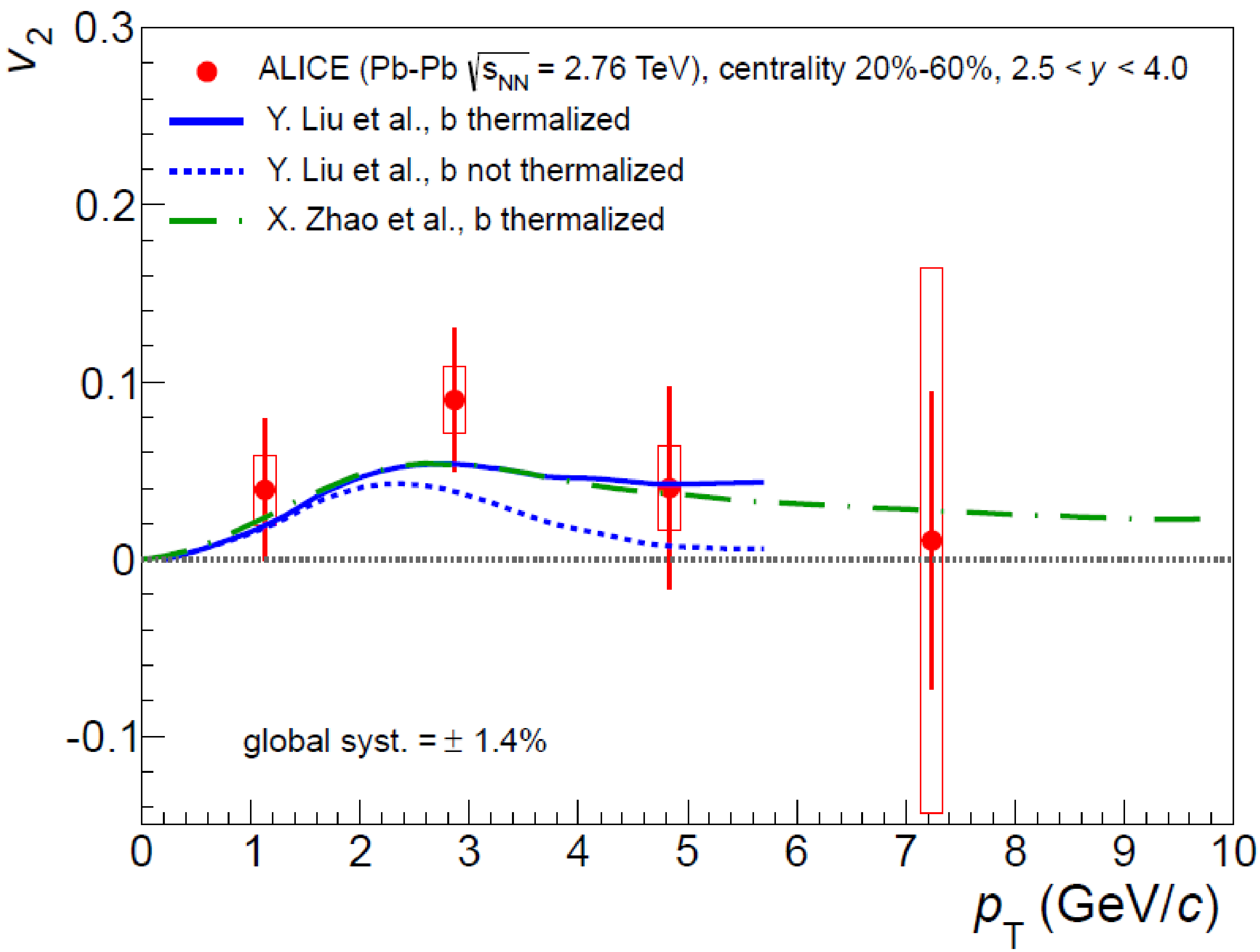
arXiv:1303.5880



- 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
- observed

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

Summary charm quark story

- Charm and beauty and J/spi cross section and spectra in pp in good agreement with pQCD predictions (baseline)
- Open charm
  - spectra and elliptic flow indicate: charm quarks thermalize in QGP
- J/ψ
  - completely new picture at LHC compared to RHIC: R_{AA}, spectra, and elliptic flow indicate we are well on the way towards proof of deconfinement:
  - thermalized c-quarks form charmonia at hadronization

1990 Cemetary Lane

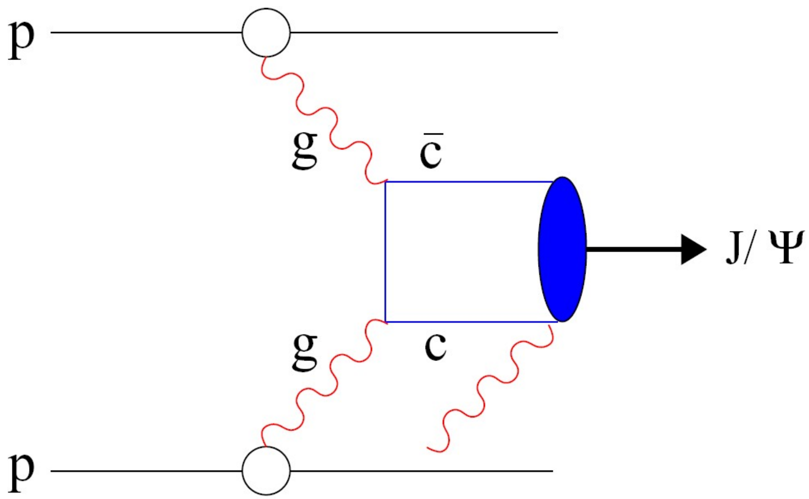
Aug 1995 Great Wall - China

Nov 1995 Conscience Circle

Gerry, we will always miss you!

backup

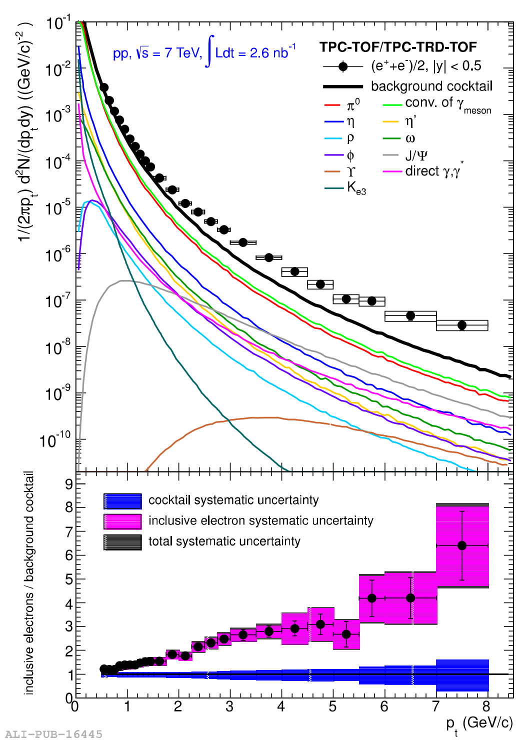
Production of charm quarks and charmonia in hadronic collisions

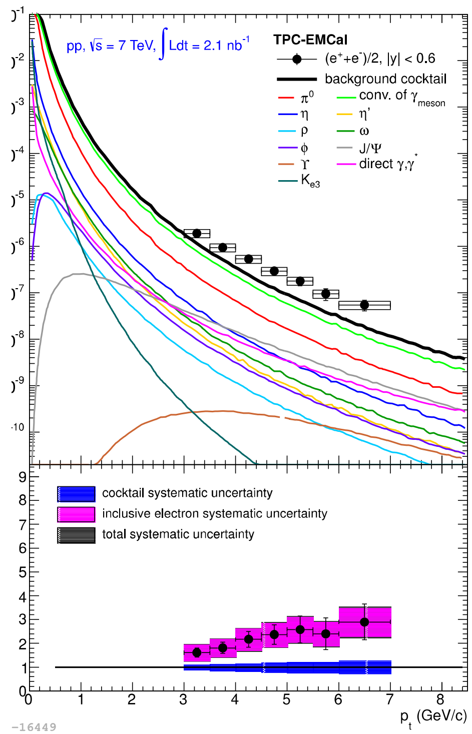


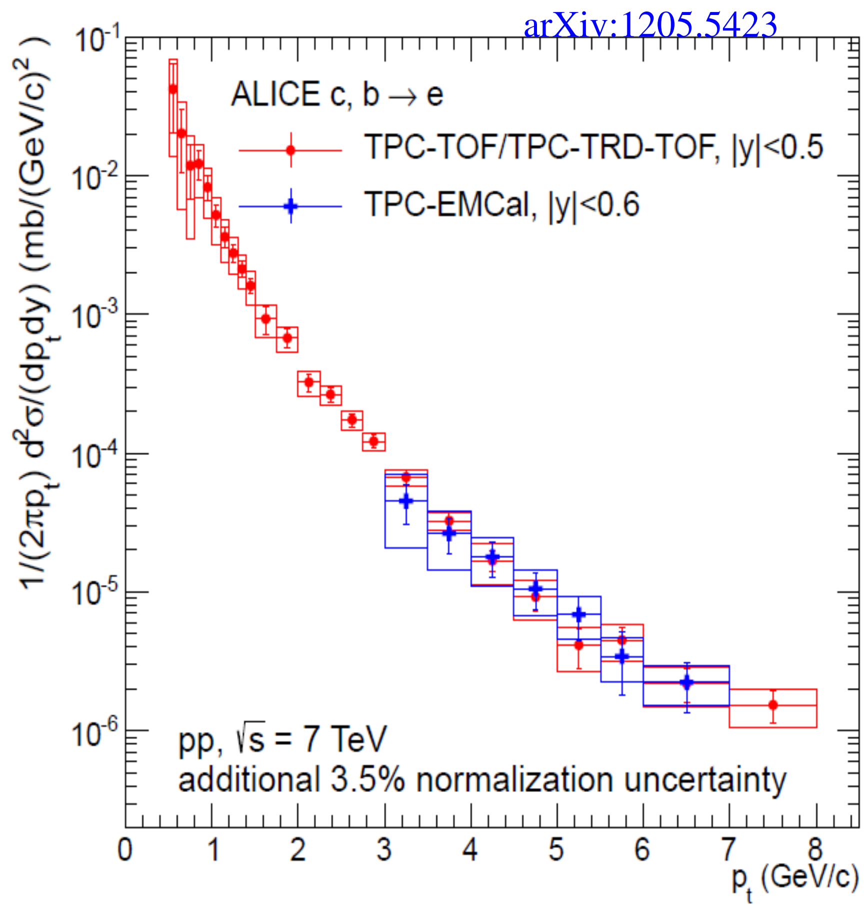
- charm and beauty quarks are produced in early hard scattering processes
- most important Feynman diagram: gluon fusion
- formation of quarkonia: with about 1% probability the c and cbar form $^{3}1S$ state = J/ψ - requires transition to a color singlet state
not pure perturbative QCD anymore, some modelling required
CEM Color Evaporation Model
CSM Color Singlet Model
now reasonably successful

Charm and beauty via semi-leptonic decays

Inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL



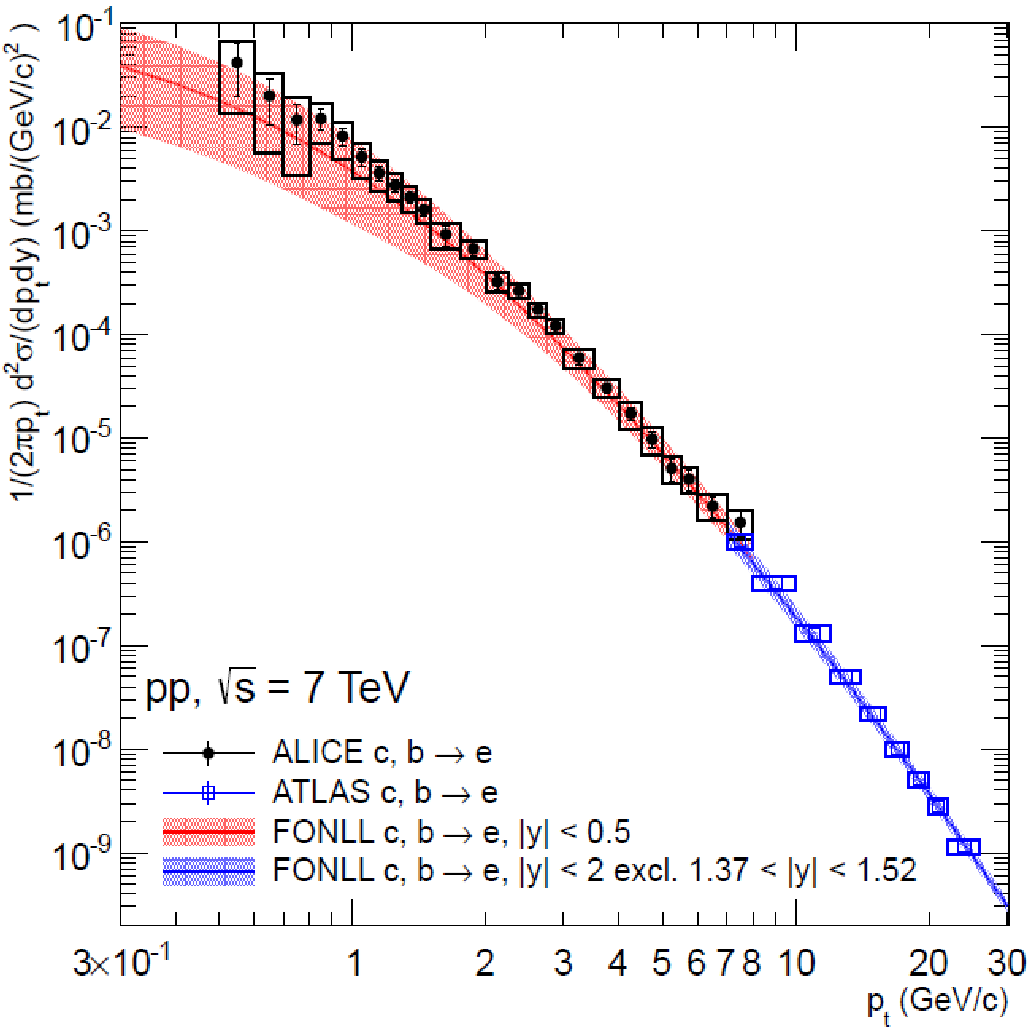




subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ), direct γ from pQCD

electrons from c and b decays

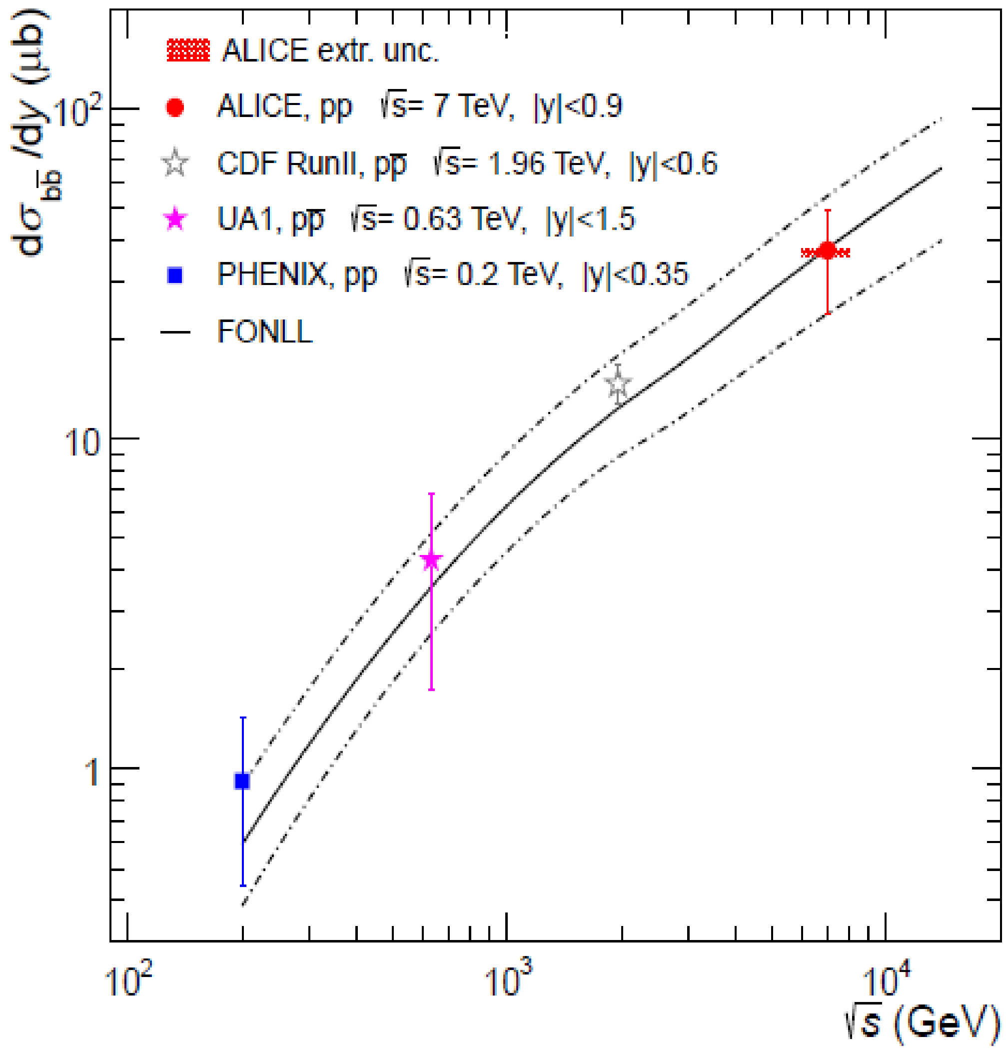
Charm and beauty electrons compared to pQCD

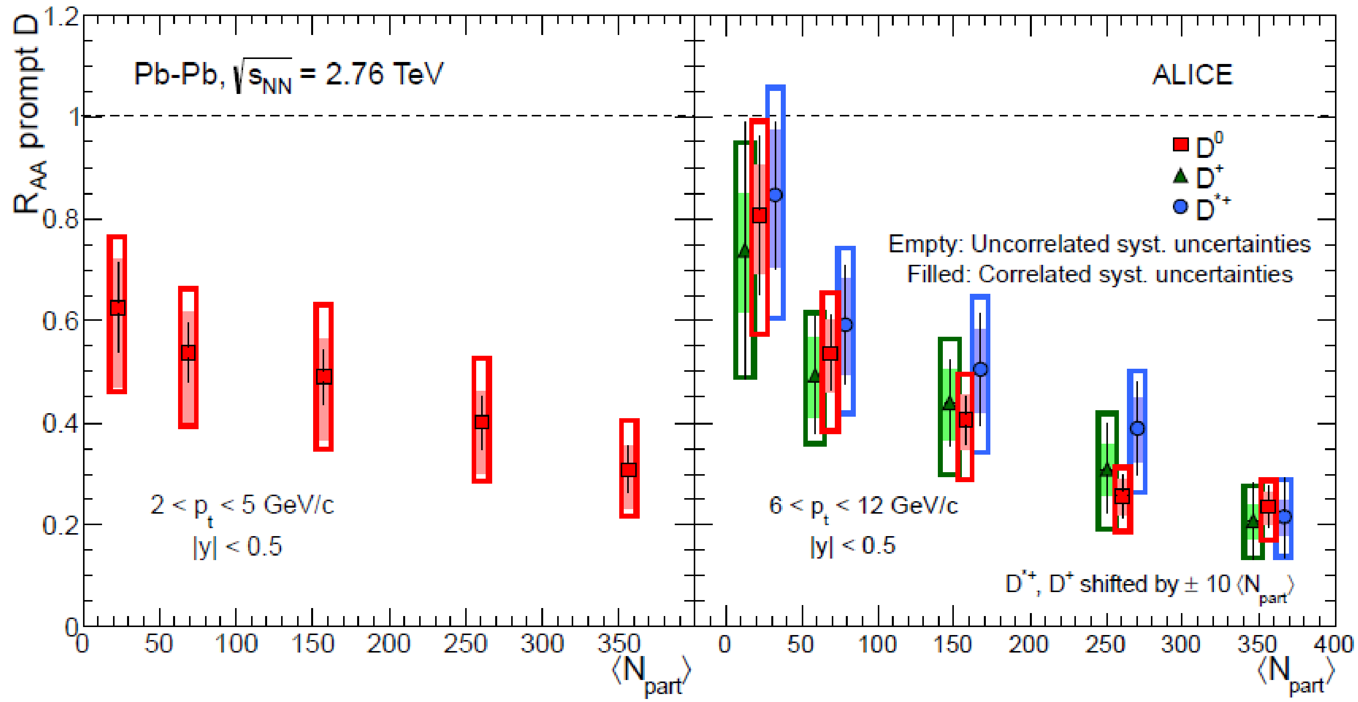


- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for $p_t <$ 3 GeV/c where charm dominates

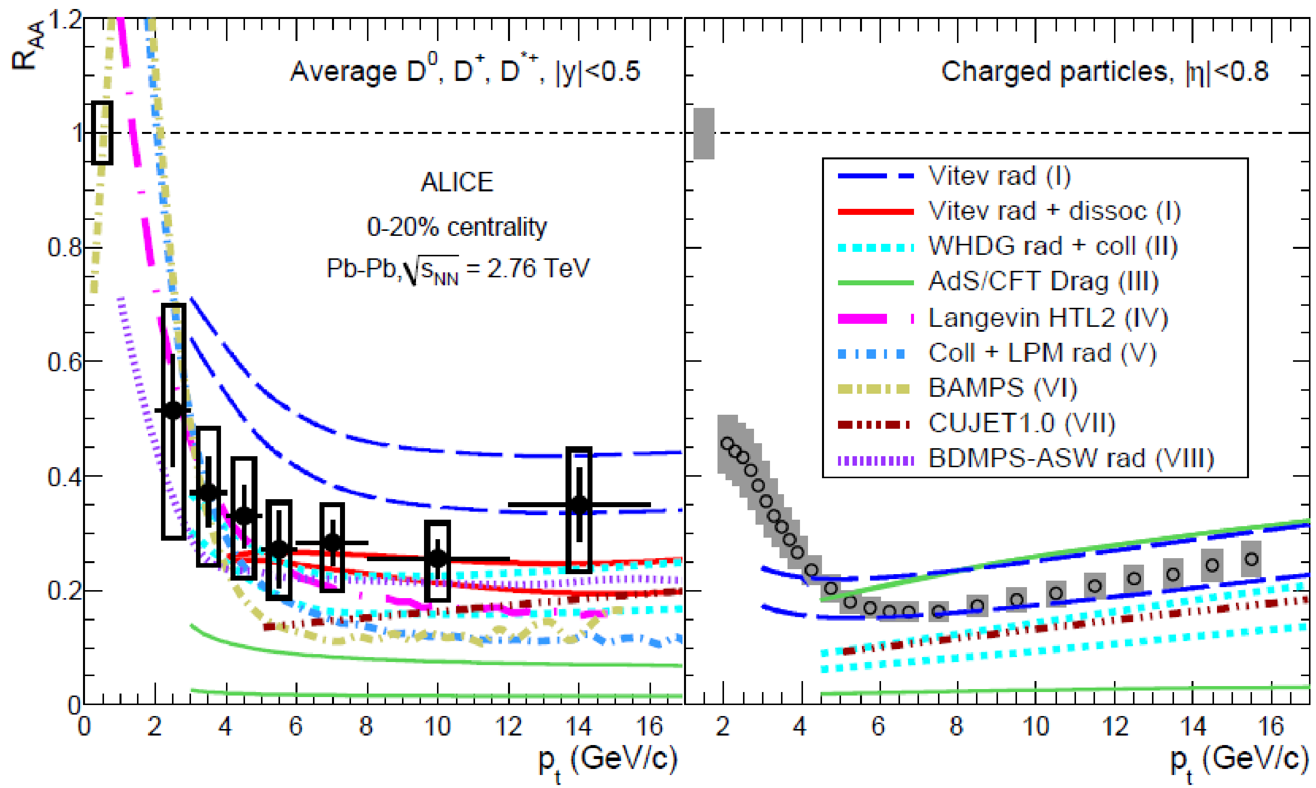
arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

Beauty cross section in pp and ppbar collisions



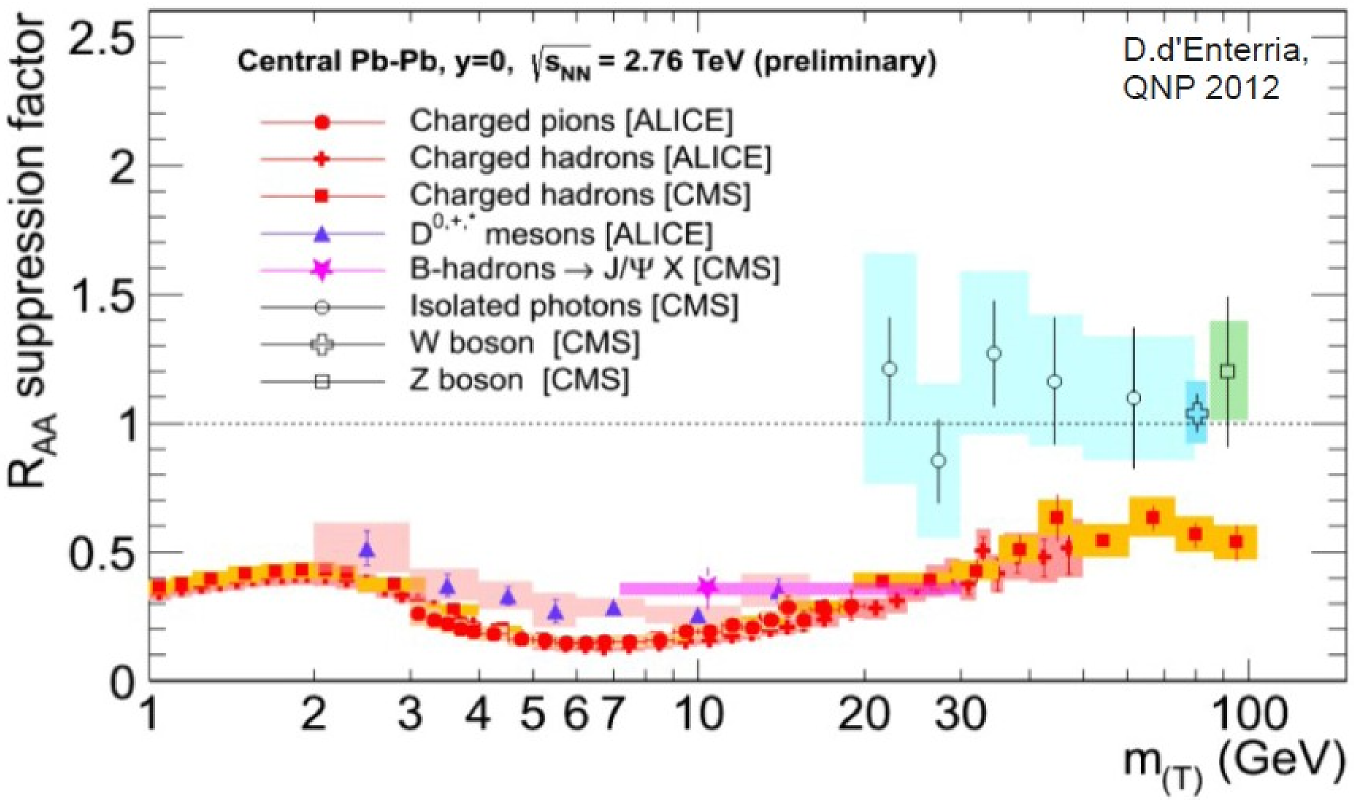


R_{AA} prompt D
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE
D^0
D^+
D^{*+}
Empty: Uncorrelated syst. uncertainties
Filled: Correlated syst. uncertainties
2 < p_t < 5 GeV/c
|y| < 0.5
6 < p_t < 12 GeV/c
|y| < 0.5
D^{*+}, D^+ shifted by ± 10 $\langle N_{part} \rangle$
$\langle N_{part} \rangle$



R_{AA}
Average D^0, D^+, D^{*+}, $|y|<0.5$
ALICE
0-20% centrality
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Charged particles, $|\eta|<0.8$
Vitev rad (I)
Vitev rad + dissoc (I)
WHDG rad + coll (II)
AdS/CFT Drag (III)
Langevin HTL2 (IV)
Coll + LPM rad (V)
BAMPS (VI)
CUJET1.0 (VII)
BDMPS-ASW rad (VIII)
p_t (GeV/c)
p_t (GeV/c)

Suppression only for Strongly Interacting Hard Probes

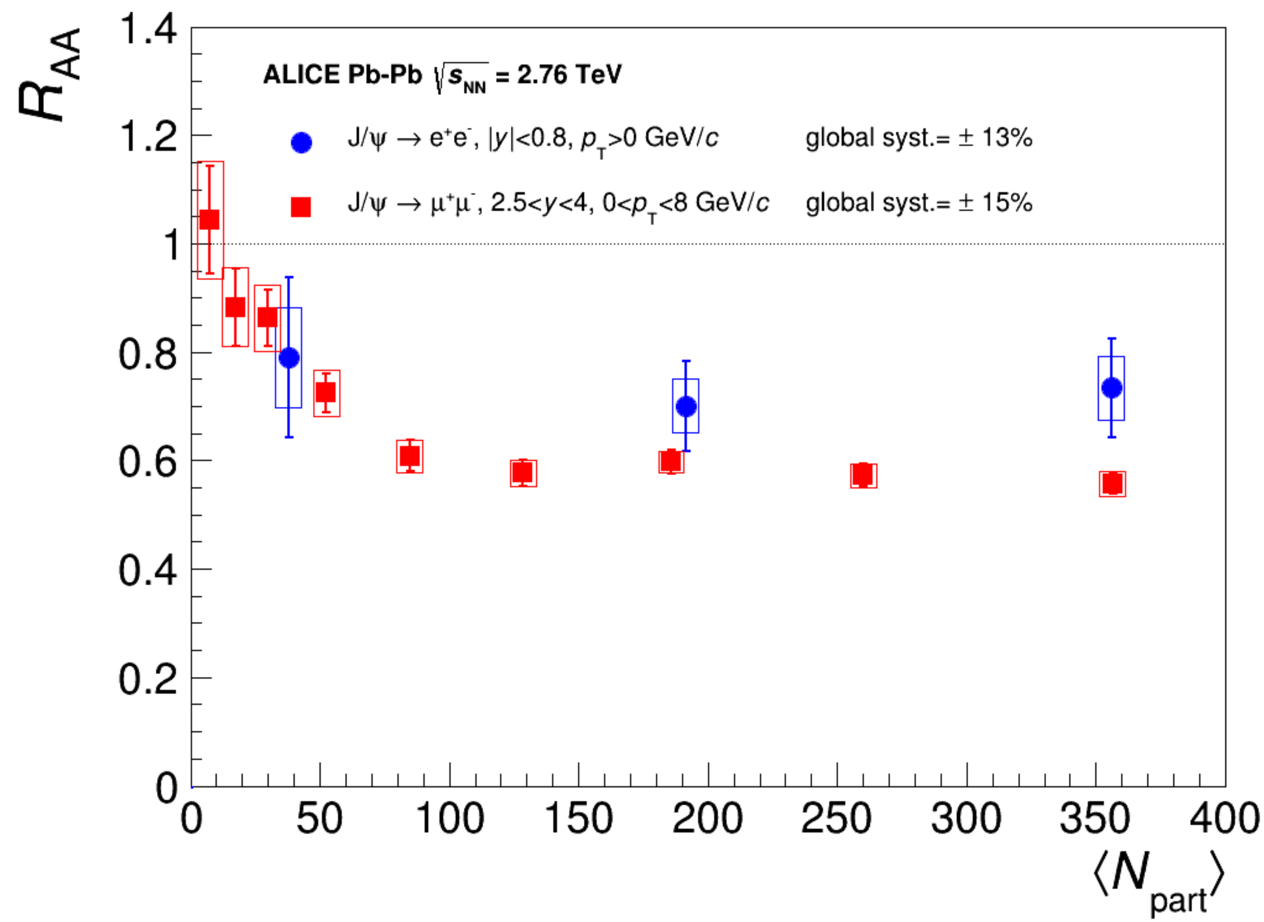


photons, Z and W scale with number of binary collisions in PbPb – not affected by medium

→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

J/psi in PbPb collisions relative to pp

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

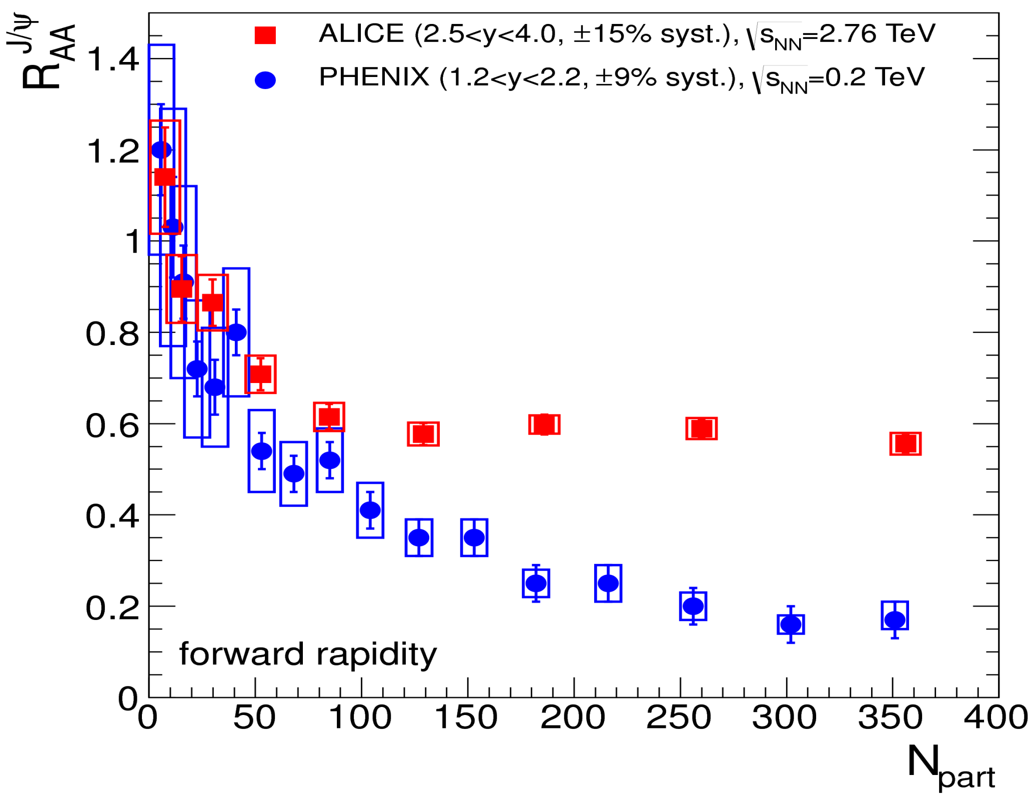


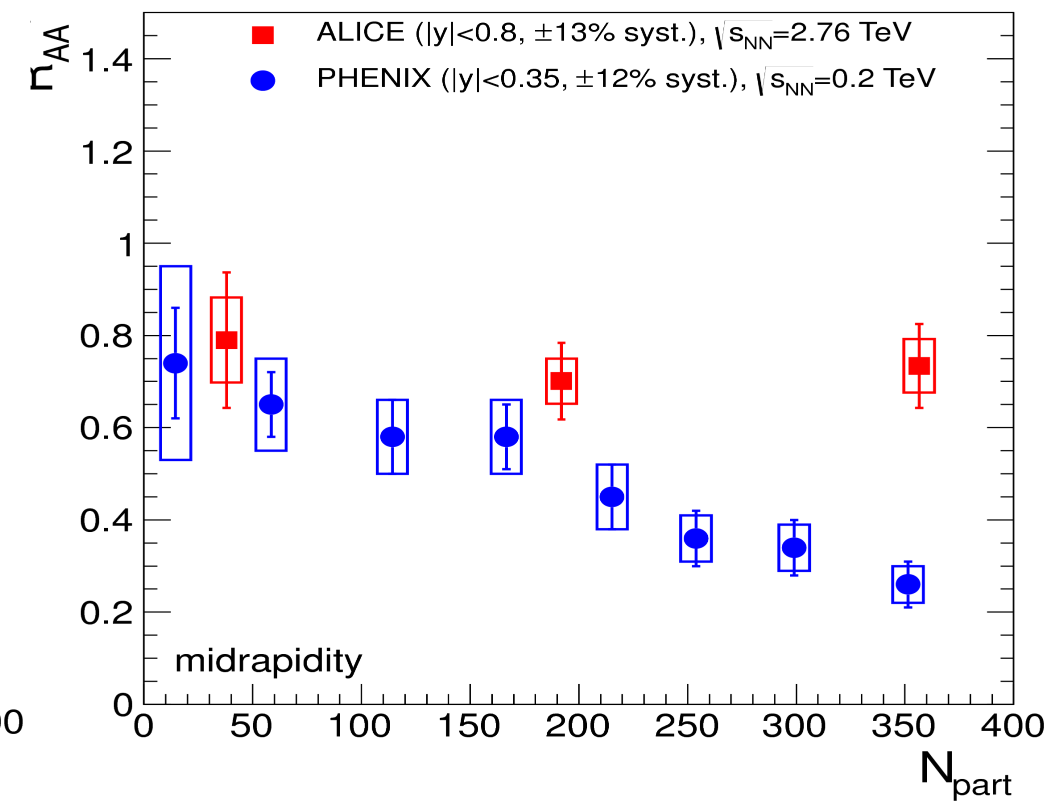
- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

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

forward rapidity

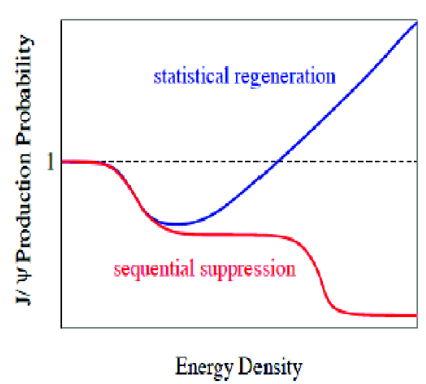
mid-rapidity



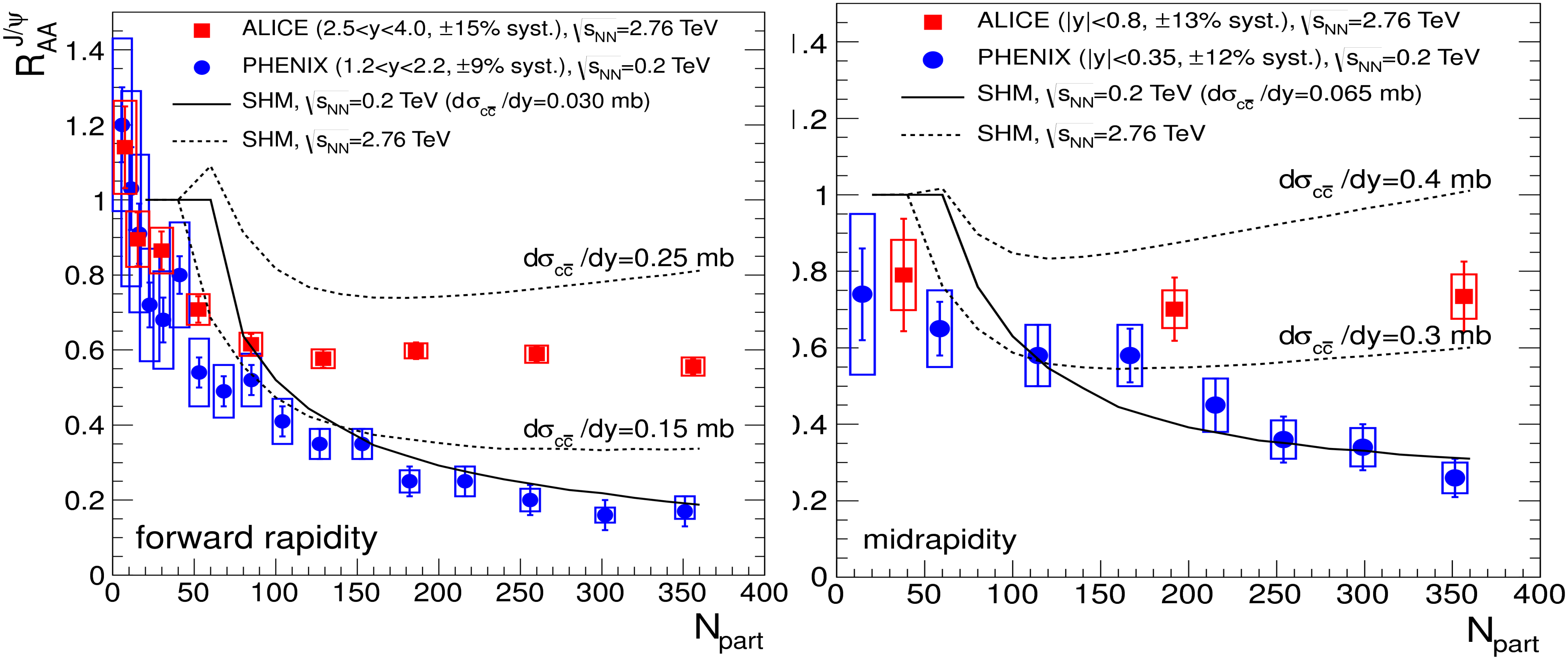


energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)

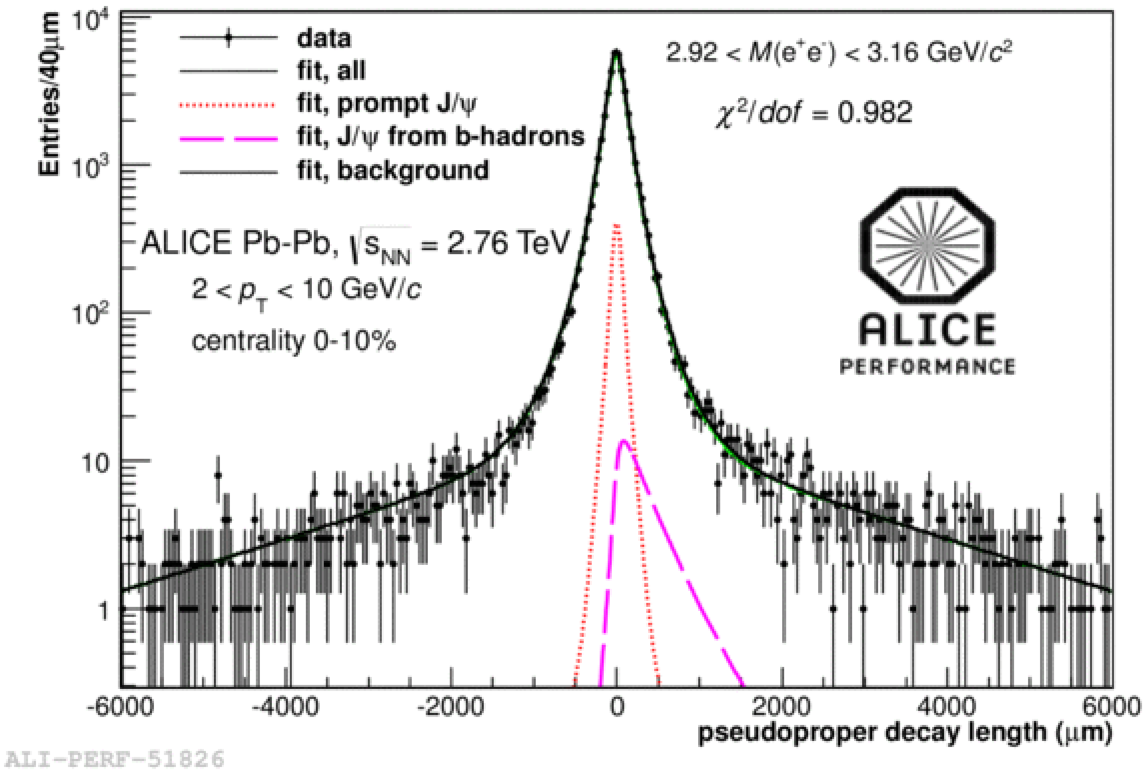


J/psi and Statistical Hadronization



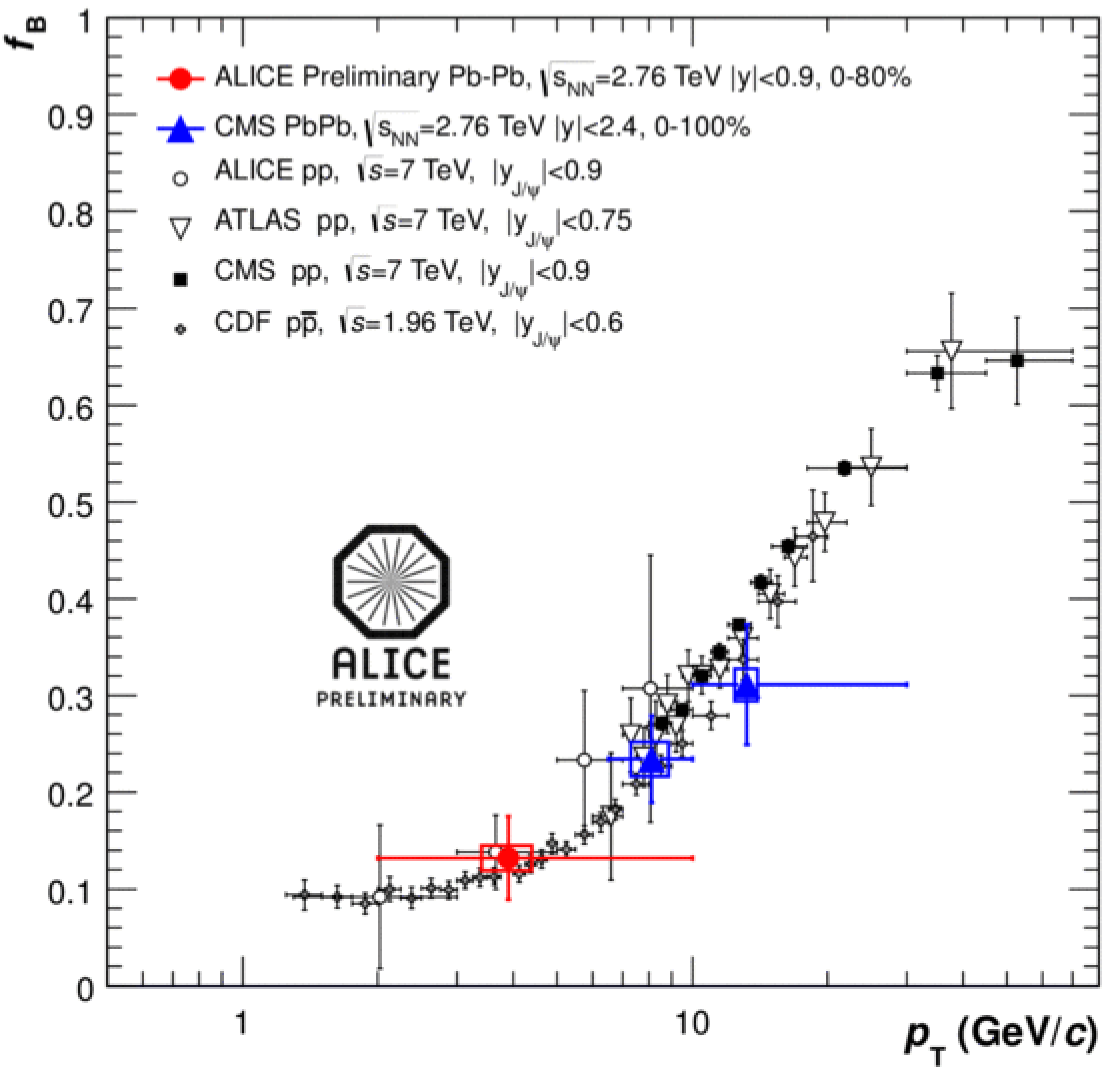
- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- shadowing from pPb collisions: forward y: R_{AA} = 0.76(12) mid-y R_{AA} (estim) =0.72(15)

Fraction of J/psi from B-decays



due to displaced decay-vertices, pseudoproper decay length can be used to determine B-fraction

Fraction of J/psi from B-decays

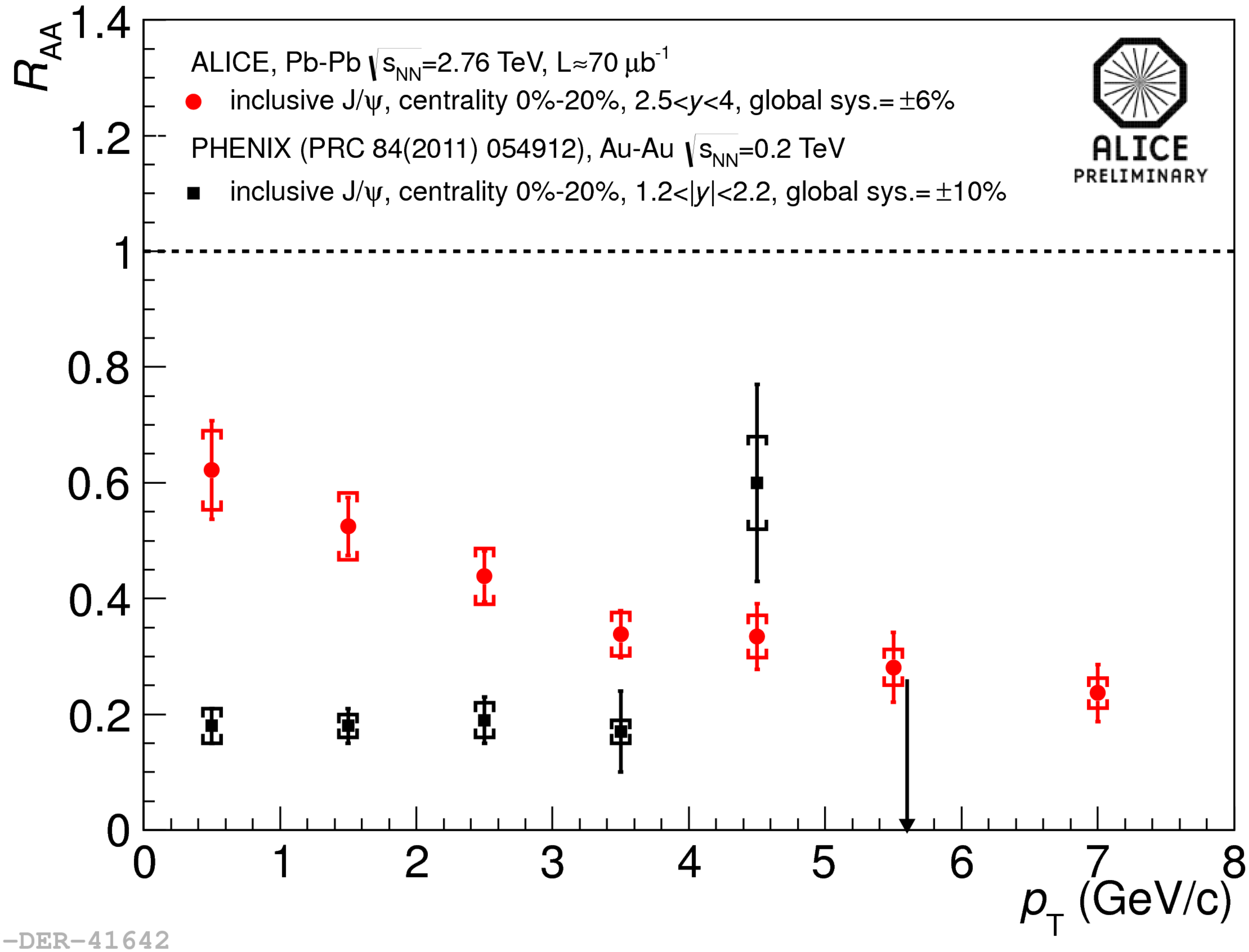


p_t integrated non-prompt B-fraction of small

within current errors no significant difference in pp and PbPb collisions

J/psi p_t distributions as function of centrality

new feature: distributions get narrower (softer) for more central collisions

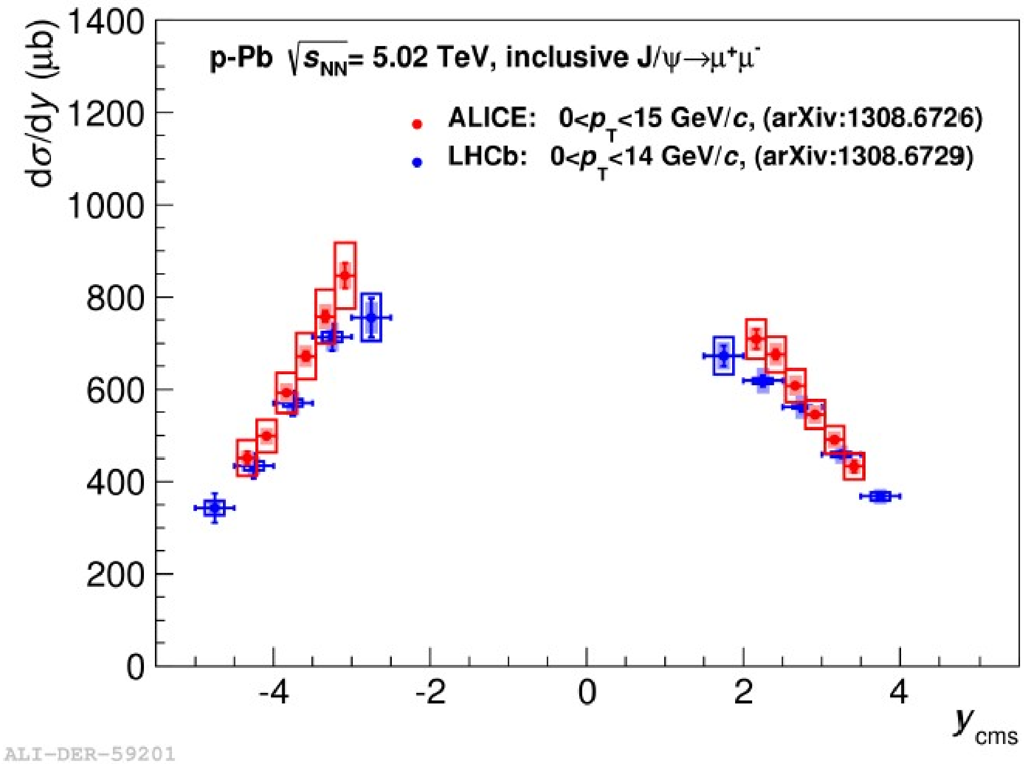


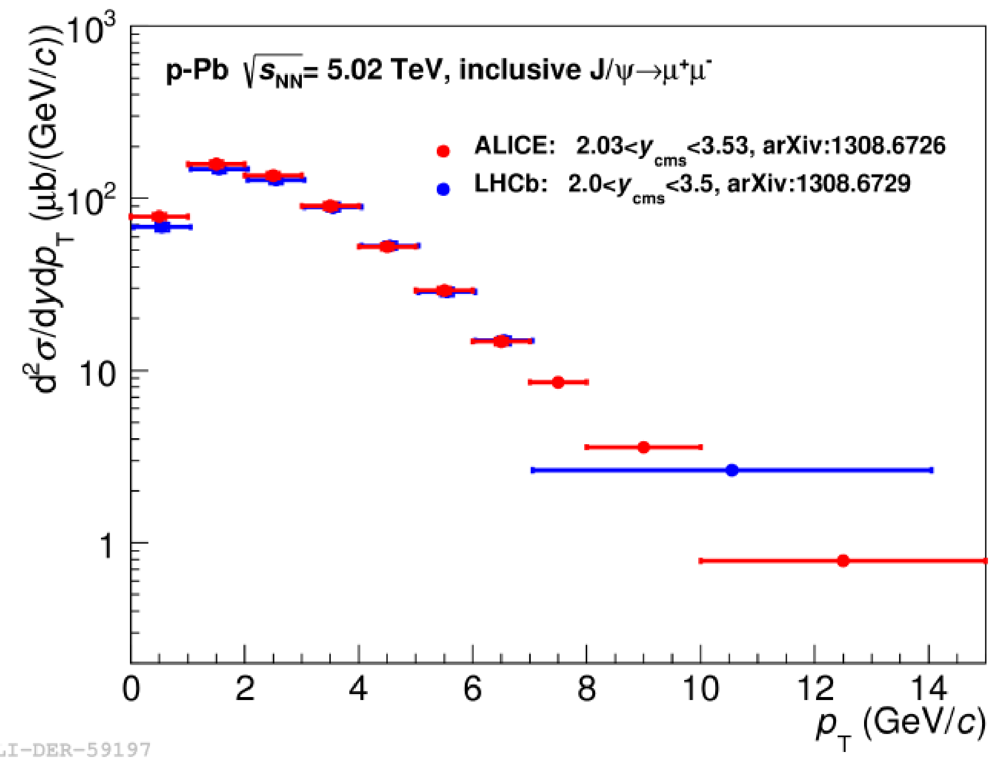
ALICE, Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV, L≈70 μb^{-1}
inclusive J/ψ, centrality 0%-20%, 2.5<y<4, global sys.=±6%
PHENIX (PRC 84(2011) 054912), Au-Au $\sqrt{s_{NN}}$=0.2 TeV
inclusive J/ψ, centrality 0%-20%, 1.2<|y|<2.2, global sys.=±10%
ALICE
PRELIMINARY
R_{AA}
p_T (GeV/c)
ALI-DER-41642

Rapidity dependence of J/psi R_{AA}

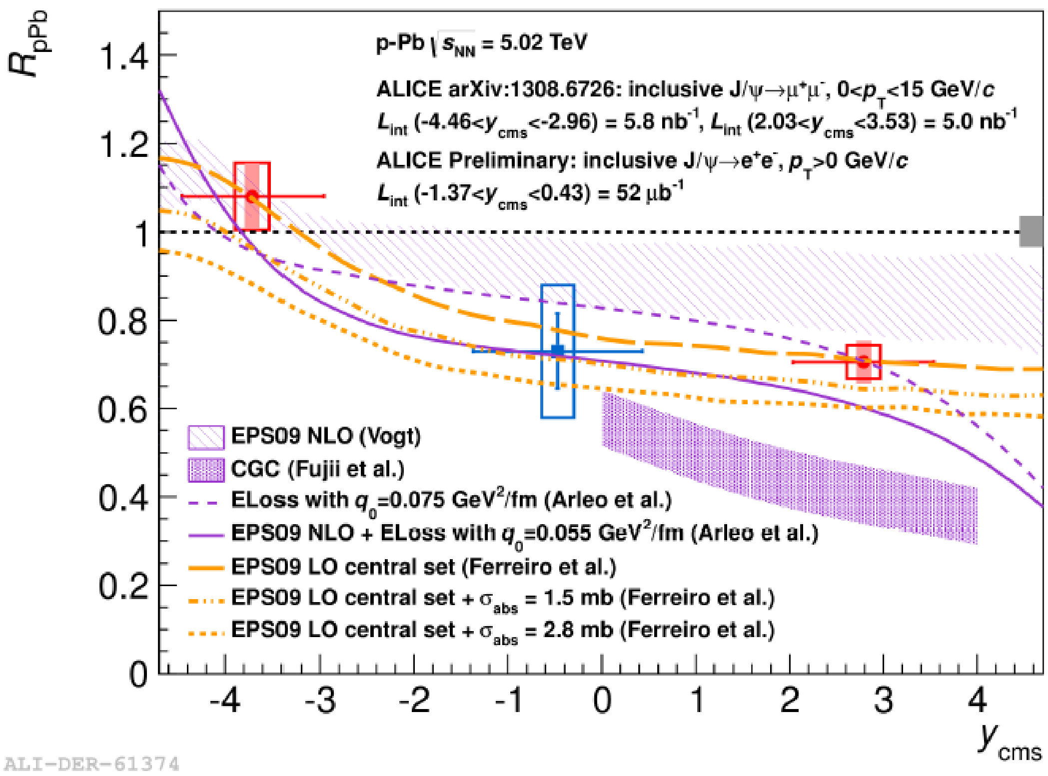
Least amount of suppression at mid-rapidity

J/psi in pPb - ALICE compared to LHCb





Ppb model comparison – data in larger pt bins



Kinematics for J/psi production in pPb vs PbPb

For 2 → 1 kinematics: $x_{1/2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(-/+y_{cms})$

Values for p_T= 0 GeV/c for the analysed data samples in 2010-2013:

Dimuons:

p-Pb forward rapidity ($\sqrt{s_{NN}}$ = 5.02 TeV) x_{Pb} = 1.8 - 8.1 • 10^{-5}

p-Pb backward rapidity ($\sqrt{s_{NN}}$ = 5.02 TeV) x_{Pb} = 1.1 - 5.3 • 10^{-2}

Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV) x_{Pb1} = 1.4 - 6.1 • 10^{-2}

x_{Pb2} = 2.1 - 9.2 • 10^{-5}

Dielectrons:

p-Pb ($\sqrt{s_{NN}}$ = 5.02 TeV) x_{Pb} = 2.4 - 4.0 • 10^{-3}

Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV) x_{Pb} = 2.5 - 5.0 • 10^{-3}

Relevance of pPb results for PbPb collisions

$$R_{\mathrm{pPb}} = 0.70 \pm 0.01(\mathrm{stat.}) \pm 0.04(\mathrm{syst.uncorr.}) \pm 0.03(\mathrm{syst.part.corr.}) \pm 0.03(\mathrm{syst.corr.})$$
$$R_{\mathrm{Pbp}} = 1.08 \pm 0.01(\mathrm{stat.}) \pm 0.08(\mathrm{syst.uncorr.}) \pm 0.07(\mathrm{syst.part.corr.}) \pm 0.04(\mathrm{syst.corr.})$$

if interpreted as shadowing (consistent with model comparisons), these results can be used to calculate the "cold nuclear matter effect" due to shadowing for PbPb collisions:

the x_F-ranges probed by J/psi production in pPb and Pbp are very close to the ones for gluon fusion selected in PbPb collisions
$2.1\ 10^{-5} - 9.2\ 10^{-5}$ and $1.4\ 10^{-2} - 6.1\ 10^{-2}$ for nucleons moving away from and towards the muon spectrometer

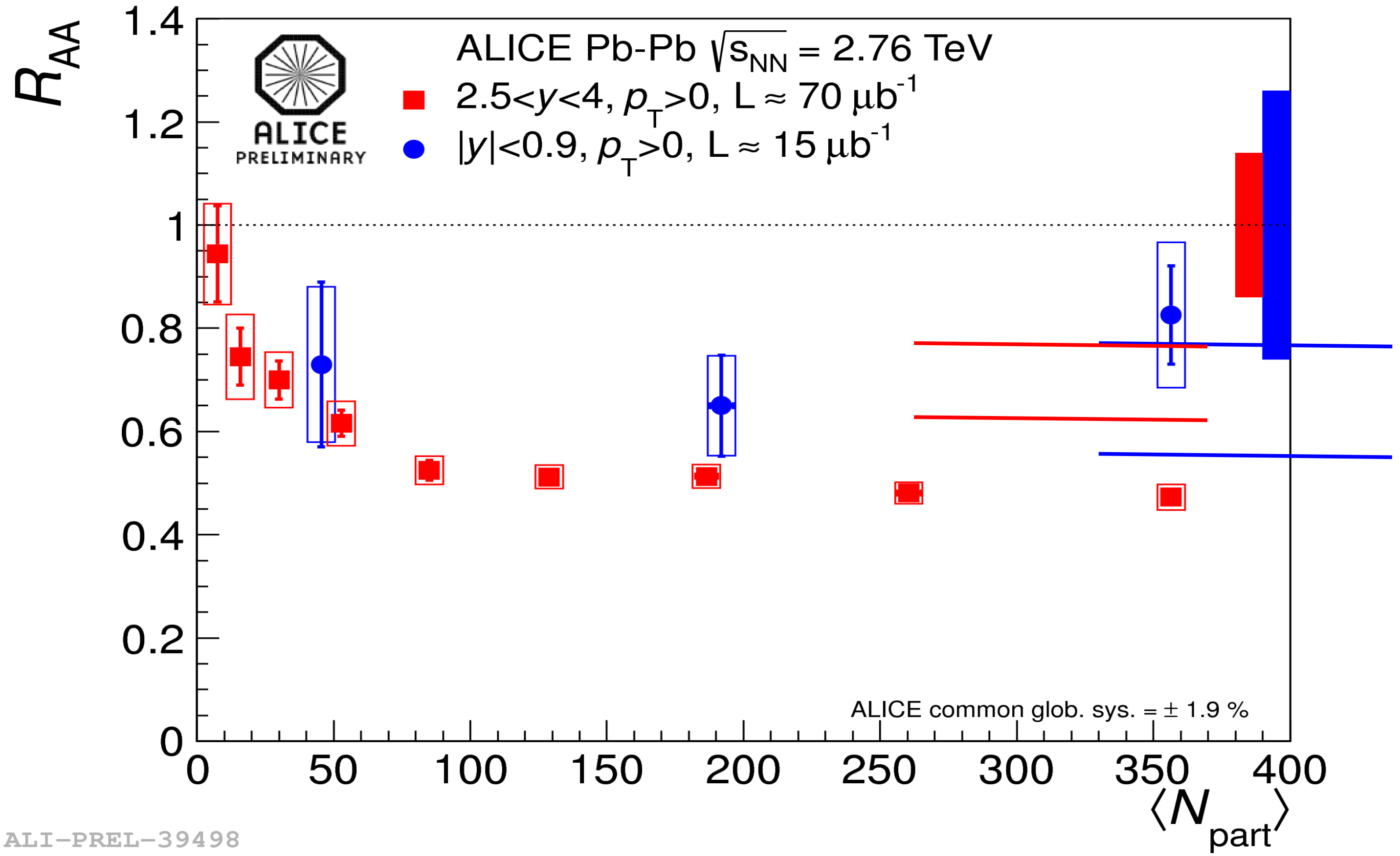
and then

$R_{PbPb} = R_{pPb} \cdot R_{Pbp} = 0.76 \pm 0.07 \pm 0.10$ for y=2.5-4.0

and

$R_{PbPb} \approx 0.72 \pm 0.15$ for midrapidity

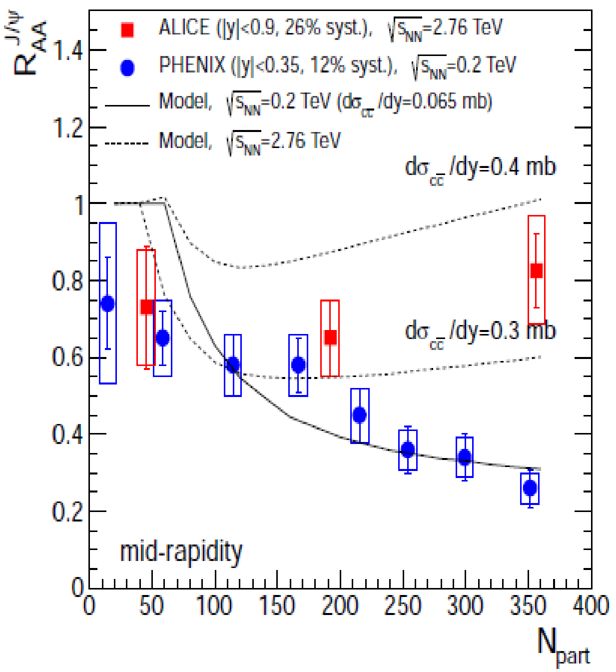
R_{AA} in PbPb collisions: shadowing contribution

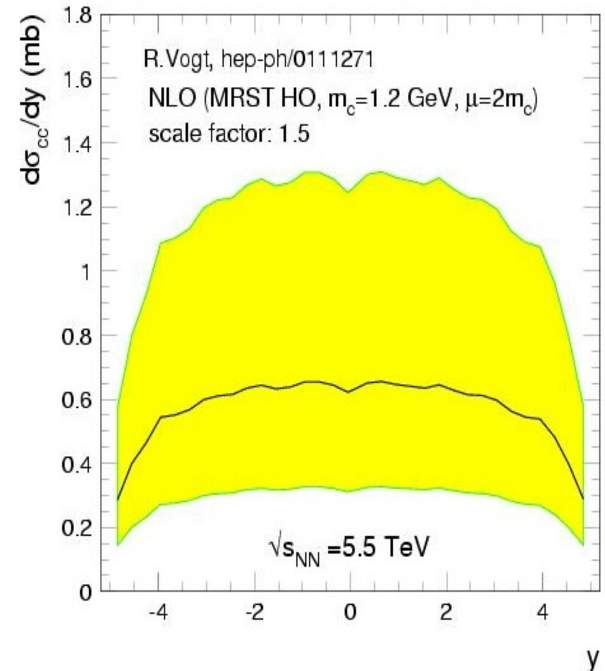


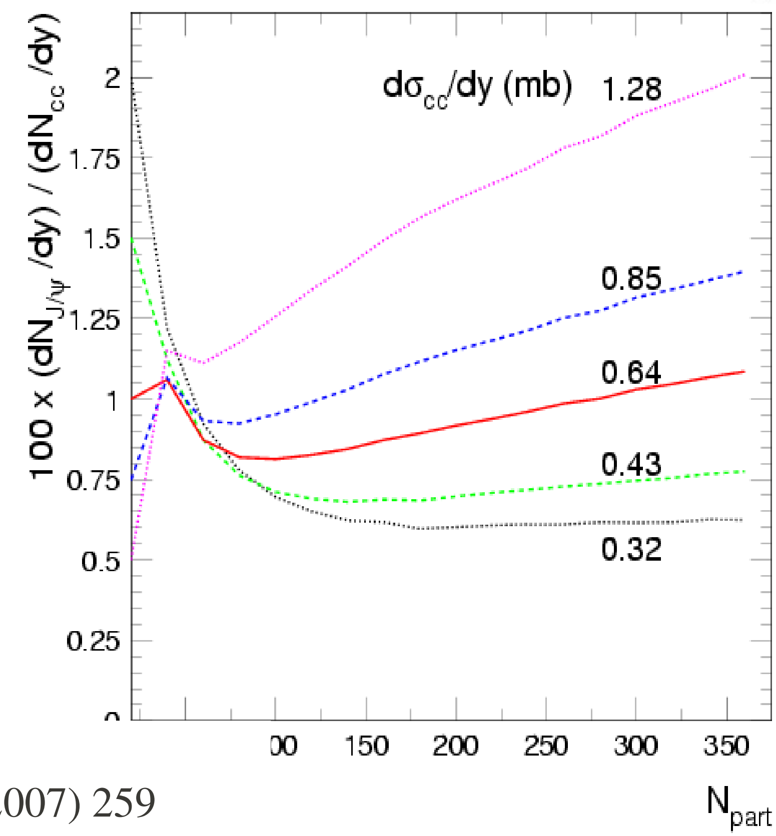
mid-y J/psi RAA consistent with or slightly above shadowing estimate

J/psi at forward y below shadowing

Predictions for statistical hadronization





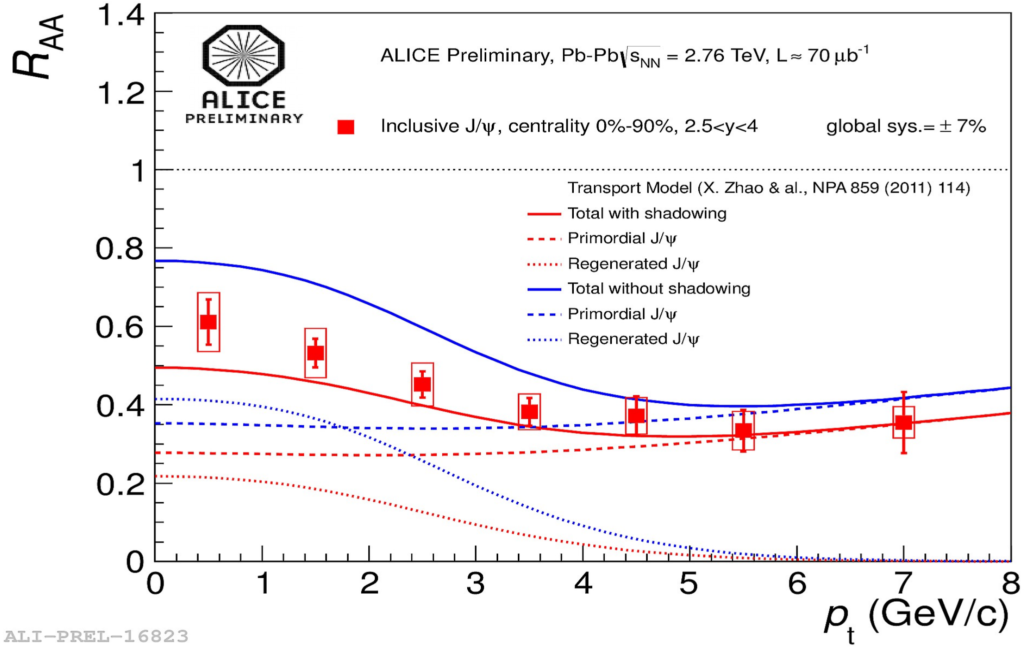


in line with current pp charm cross section at $\sqrt{s_{NN}}$ = 2.76 TeV and pPb shadowing
need more precise ccbar cross section measurement and full LHC energy data

Predictions based on pQCD cross section for full LHC energy

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

p_t Dependence of R_{AA}

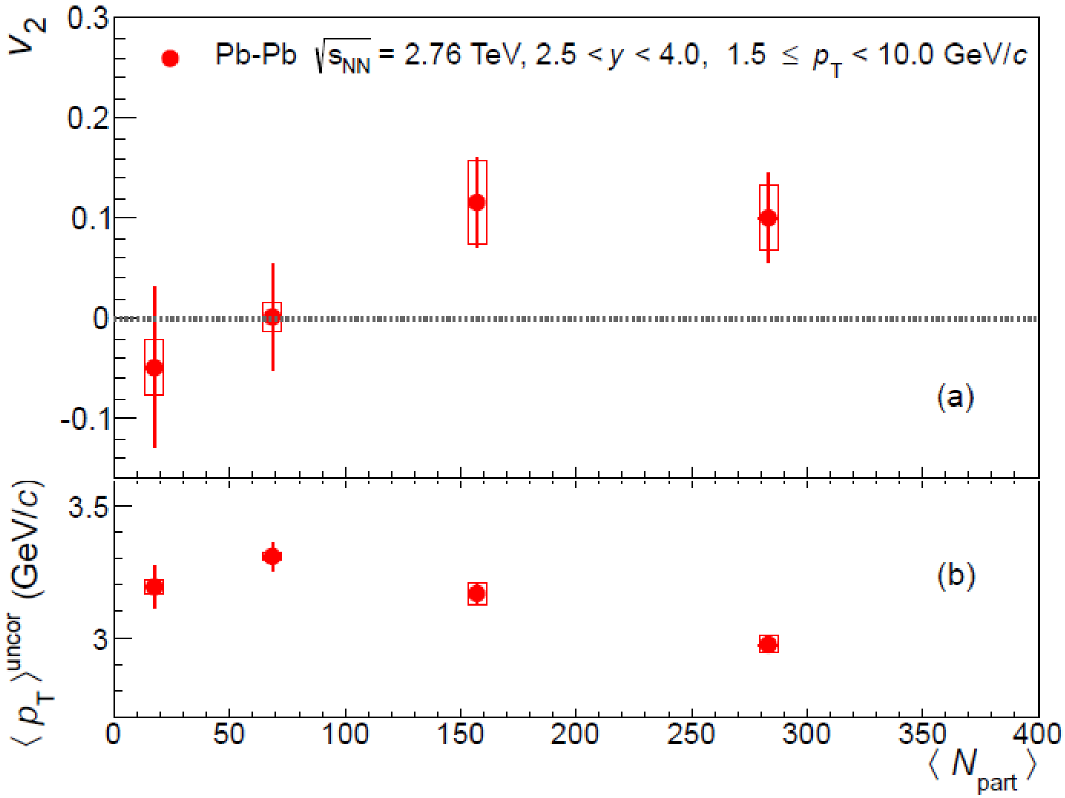


statistical hadronization only expected for charm quarks thermalized in the QGP
p_t dependence in line with this prediction

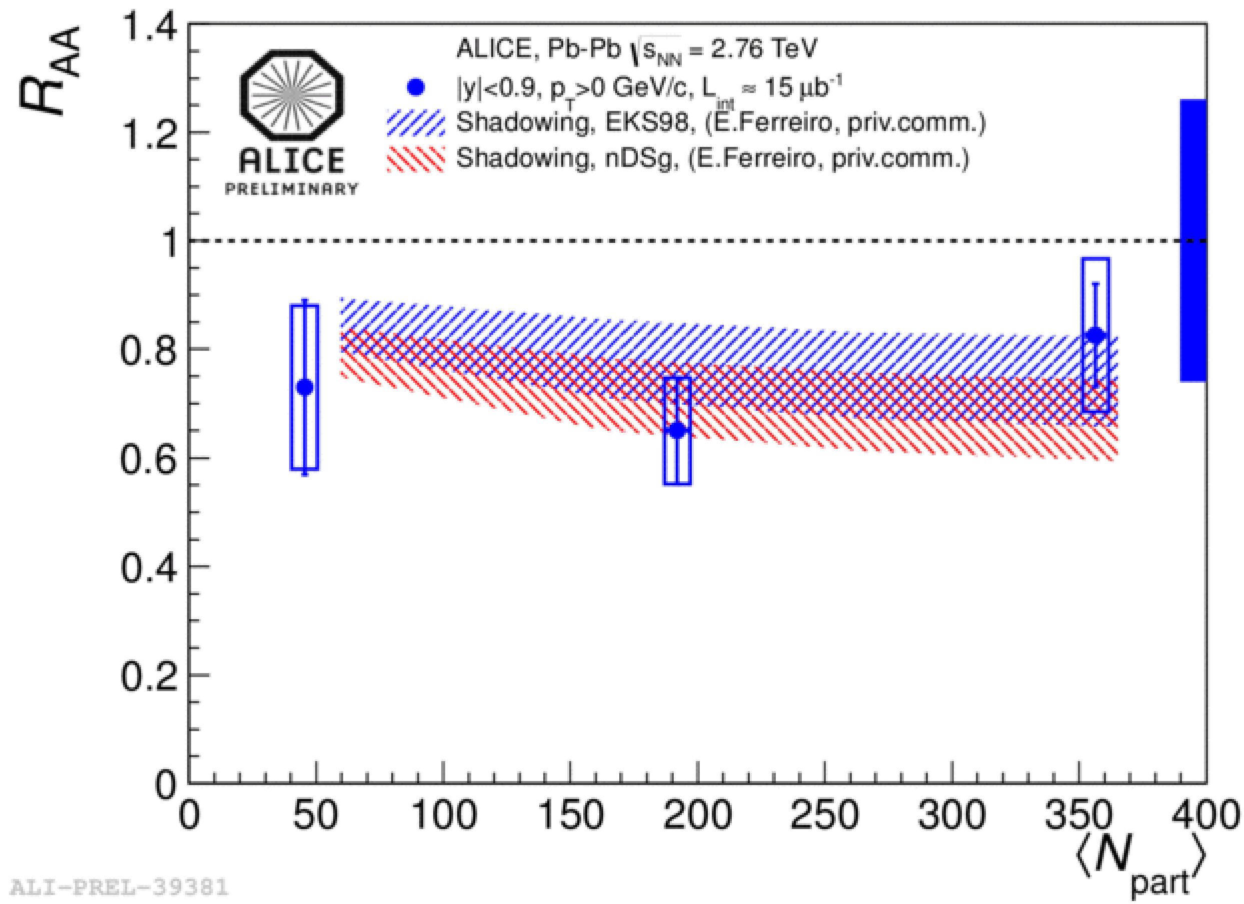
in CMS only suppression

Elliptic Flow of J/psi

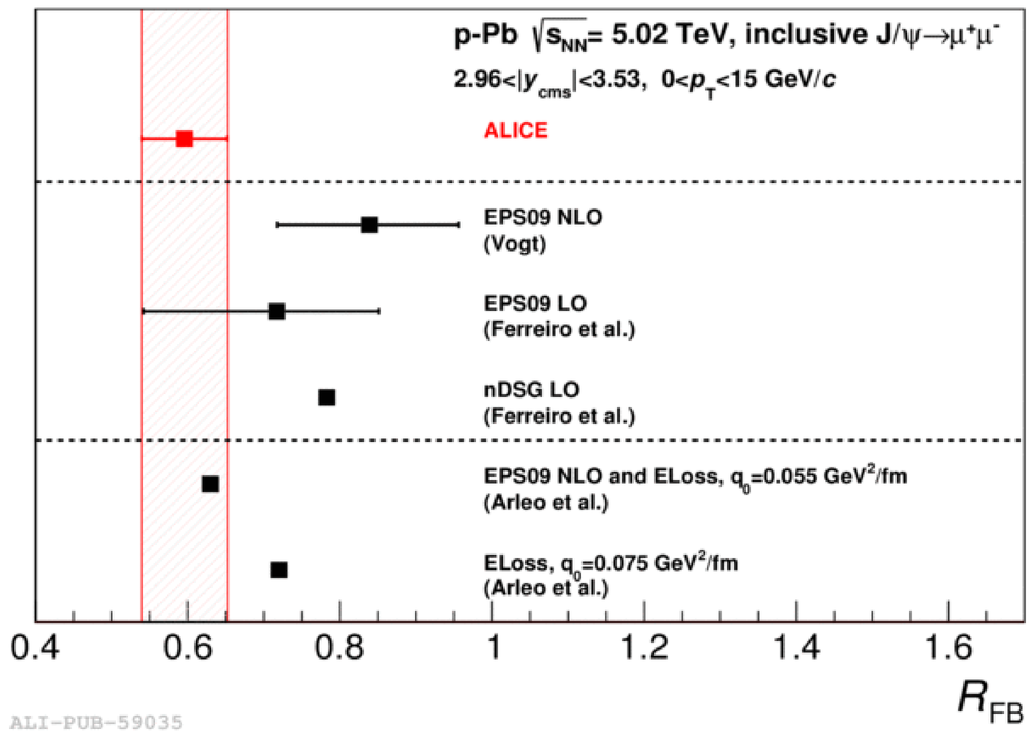
arXiv:1303.5880



first observation of significant J/ψ v_2

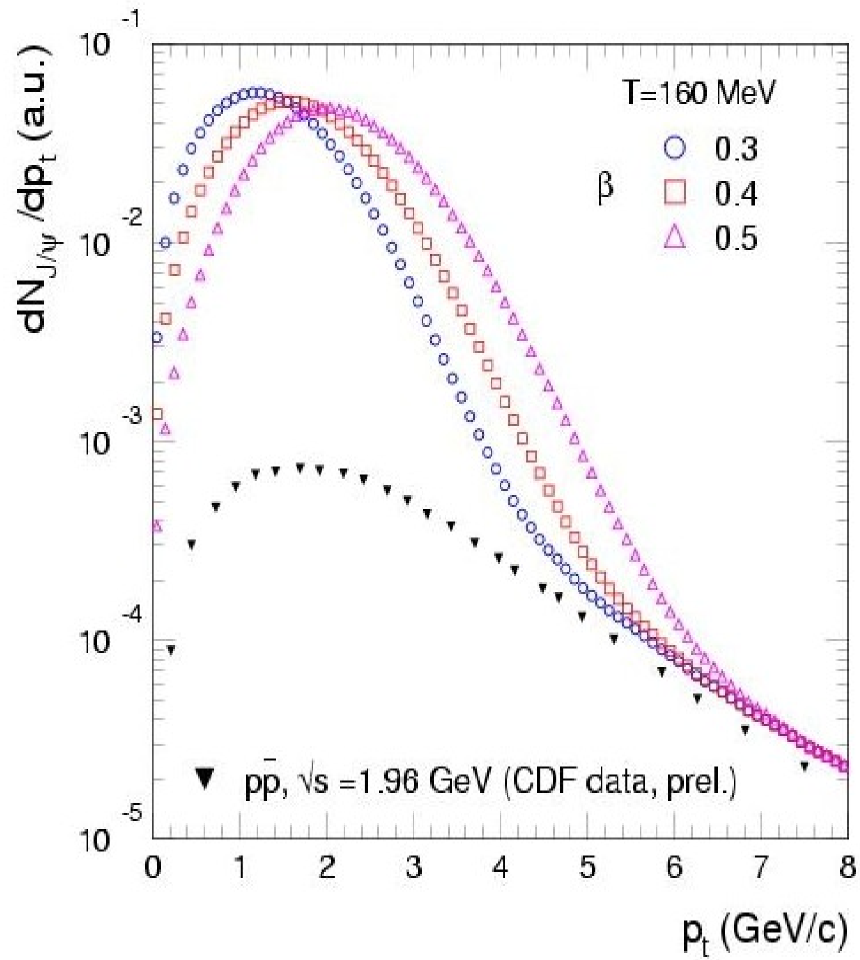


ALICE
PRELIMINARY
ALICE, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
|y|<0.9, p_T>0 GeV/c, $L_{int} \approx 15\ \mu b^{-1}$
Shadowing, EKS98, (E.Ferreiro, priv.comm.)
Shadowing, nDSg, (E.Ferreiro, priv.comm.)
R_{AA}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
$\langle N_{part} \rangle$
ALI-PREL-39381


p-Pb $\sqrt{s_{NN}}$= 5.02 TeV, inclusive J/ψ→μ⁺μ⁻
2.96<|y_{cms}|<3.53, 0<p_T<15 GeV/c
ALICE
EPS09 NLO
(Vogt)
EPS09 LO
(Ferreiro et al.)
nDSG LO
(Ferreiro et al.)
EPS09 NLO and ELoss, q_0=0.055 GeV^2/fm
(Arleo et al.)
ELoss, q_0=0.075 GeV^2/fm
(Arleo et al.)
0.4
0.6
0.8
1
1.2
1.4
1.6
R_{FB}
ALI-PUB-59035

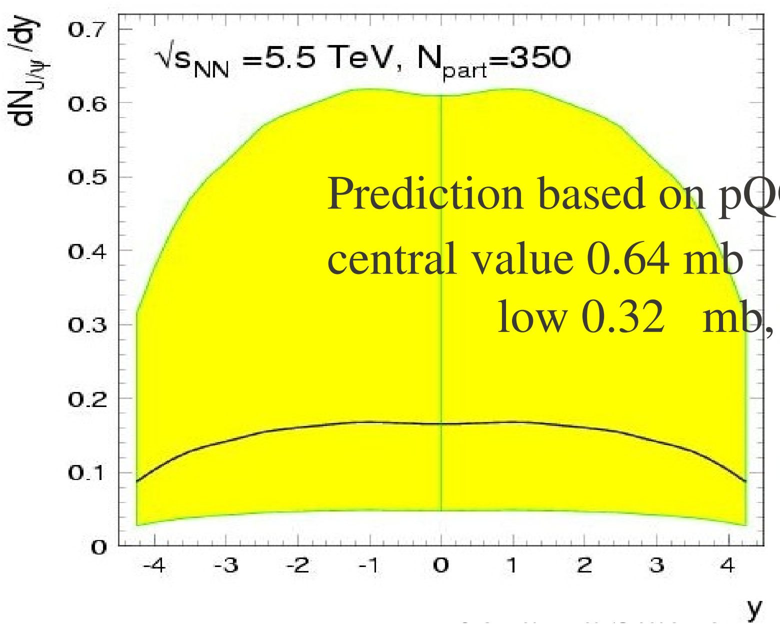
Precision spectra of J/psi should reveal flow and direct production at high pt

predictions A. Andronic, P. Braun-Munzinger, K. Redlich, J.S.



for statistical hadronization J/ψ yield proportional to N_c^2

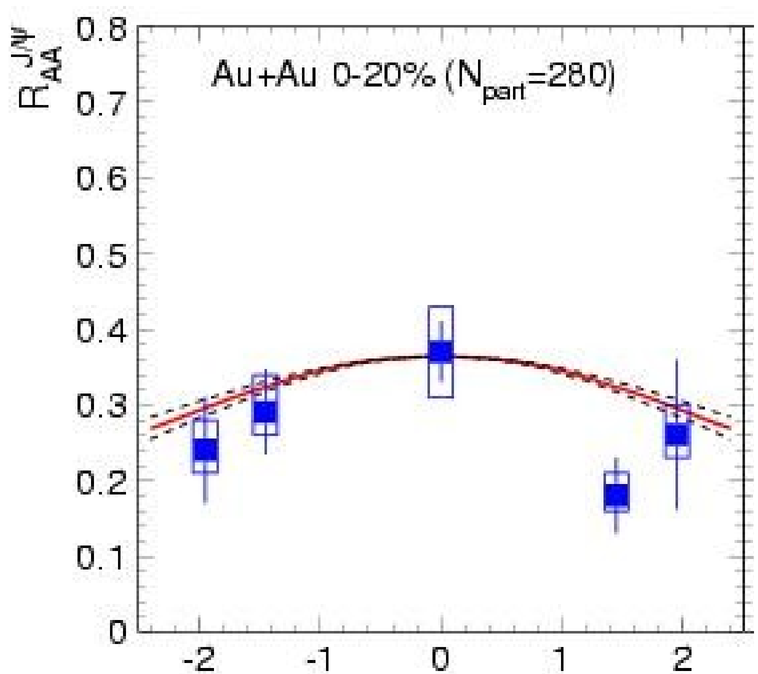
higher yield at mid-rapidity predicted in line with observation already seen at RHIC by PHENIX



Prediction based on pQCD $d\sigma_{cc}/dy$

central value 0.64 mb

low 0.32 mb, high 1.28 mb

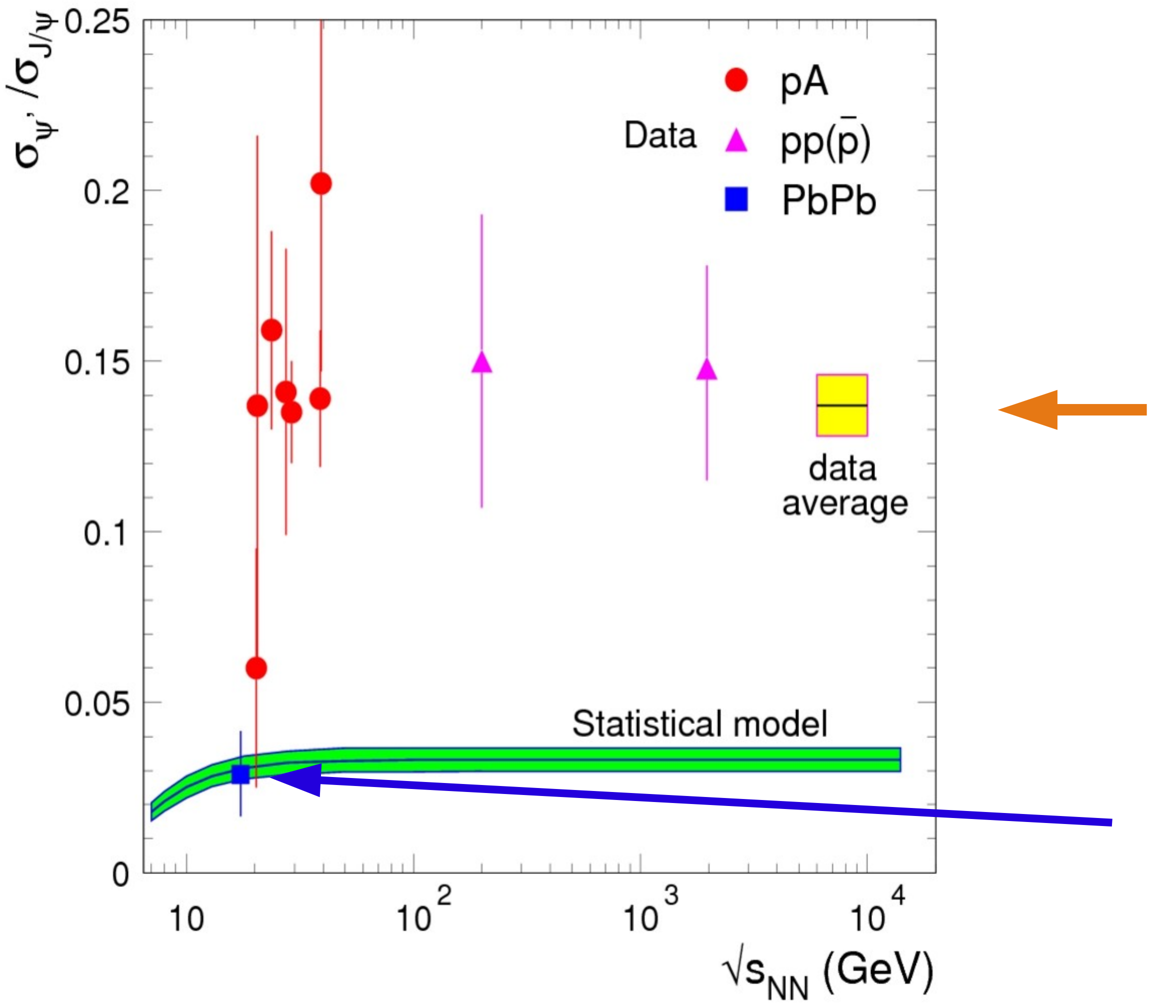


data: PHENIX nucl-ex/0611020

additional 14% syst error beyond shown

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

Statistical hadronization model predictions for psi'



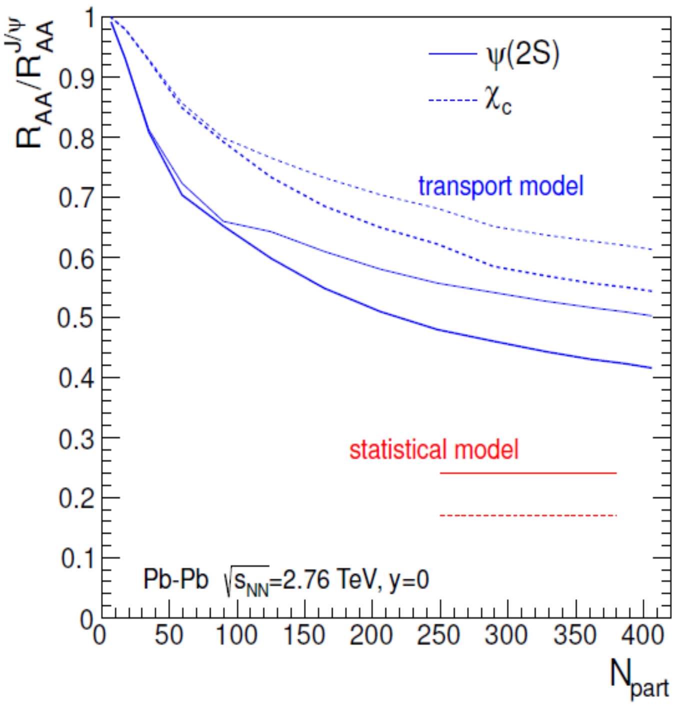
pp and pA data factor 3 above statistical hadronzation value

only result for AA at SPS energy; very close agreement

data at higher energies will be crucial test

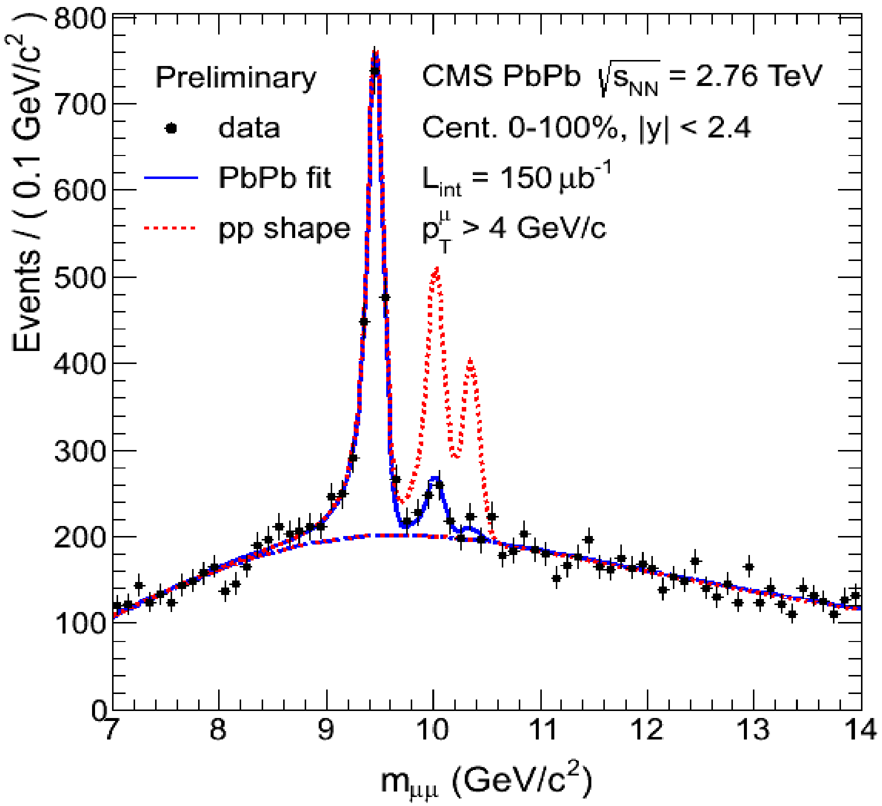
A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

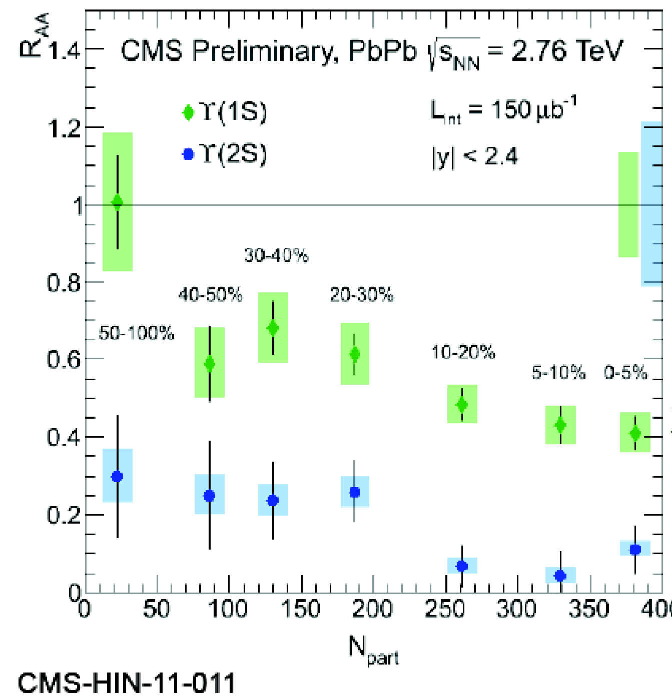
Population of excited states



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

Suppression of Upsilon States





consistent with excited state suppression (50% feed-down)

centrality integrated:
2S/1S PbPb relative to pp 0.21+-0.07+-0.02
3S/1S " < 0.1 95% C.L.

higher upsilon states expected to melt earlier because of larger radius
but also: statistical population much reduced beyond pp value due to Boltzmann factors