Charmonium production as probe of deconfinement – putting LHC results into perspective

Motivation
J/psi data PbPb collisions at LHC
- yields, RAA, pt and rapidity dependence, feeding from B

J/psi data pPb collisions at LHC
Interpretation in terms of statistical hadronization model*

* work done in collaboration with A. Andronic, P. Braun-Munzinger and K. Redlich

9th conference on relativistic aspects of nuclear Physics, Rio de Janeiro, Sept. 23 – 27, 2013
in honor of the 70th birthday of Takeshi Kodama

EMMI

Johanna Stachel

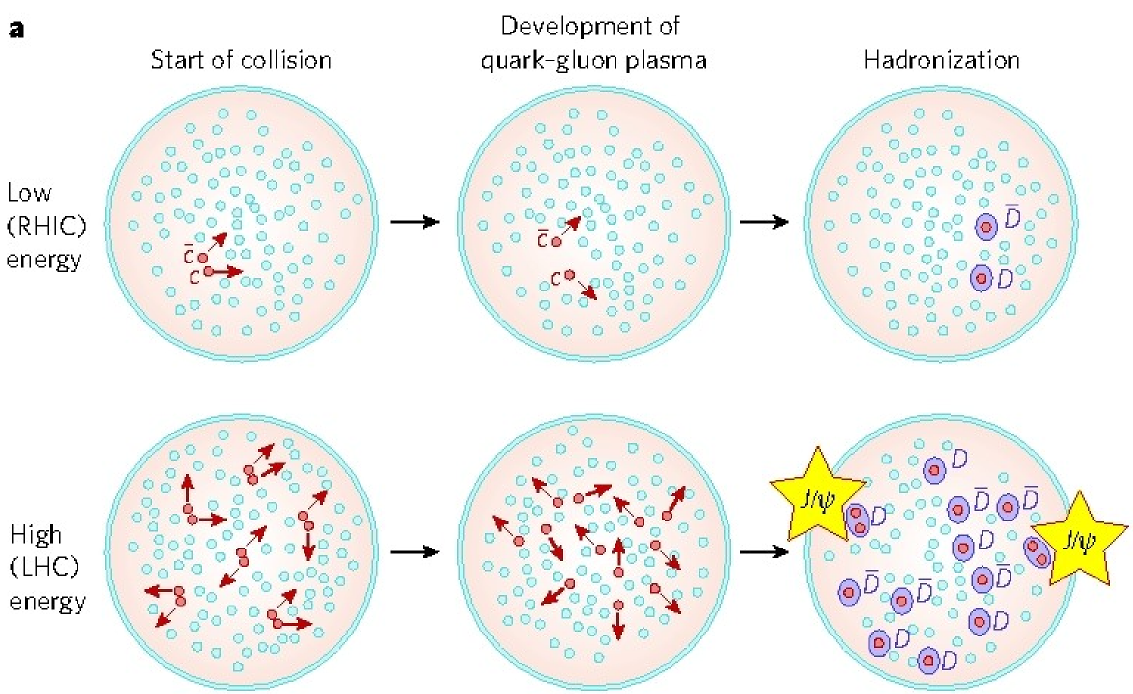
BMBF Forschungsschwerpunkt ALICE Experiment 201 ALICE

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 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

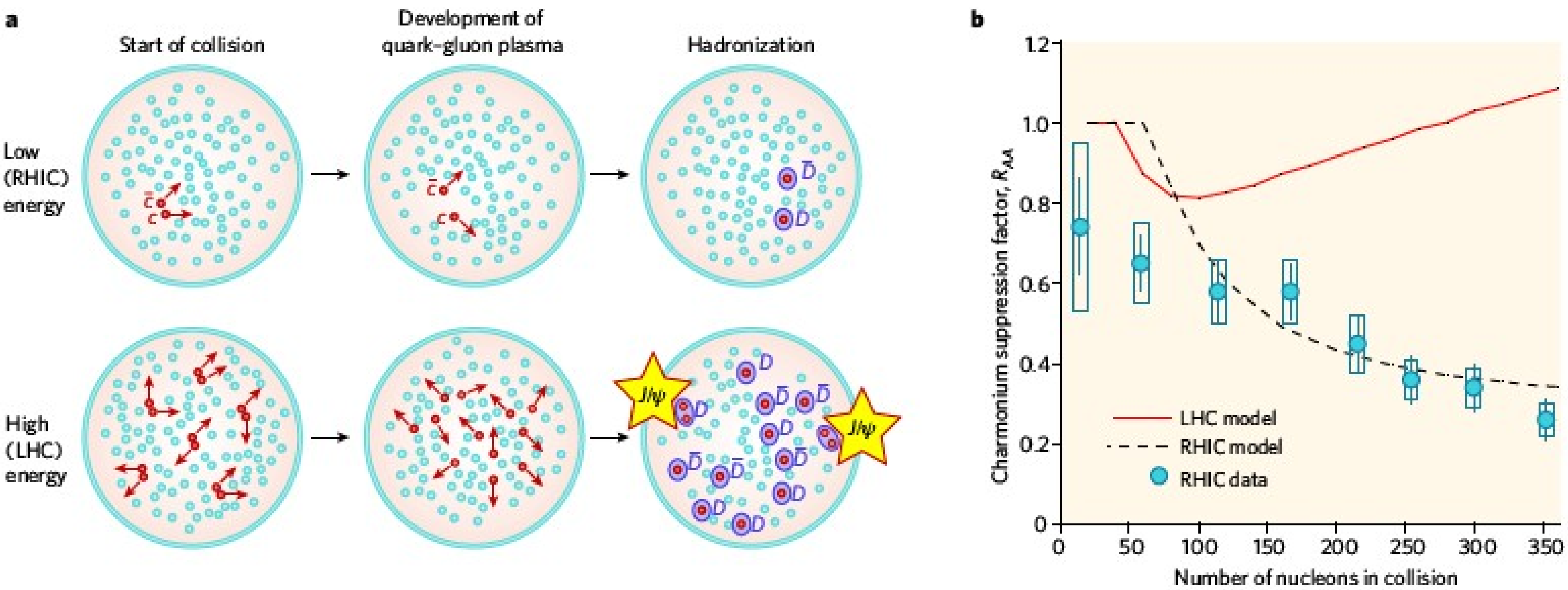
Charmonia as probe of deconfinement at LHC



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

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



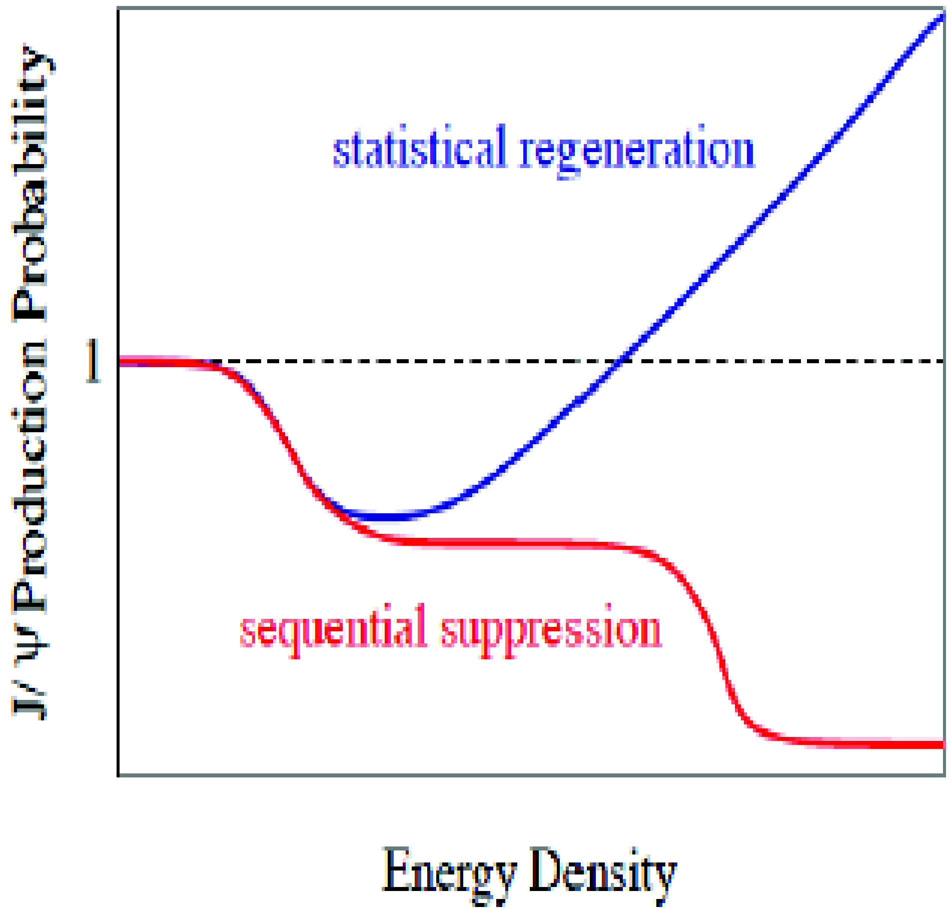
charmonium enhancement as fingerprint of deconfinement at LHC energy

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

Decision on Regeneration vs. Sequential Suppression from LHC Data

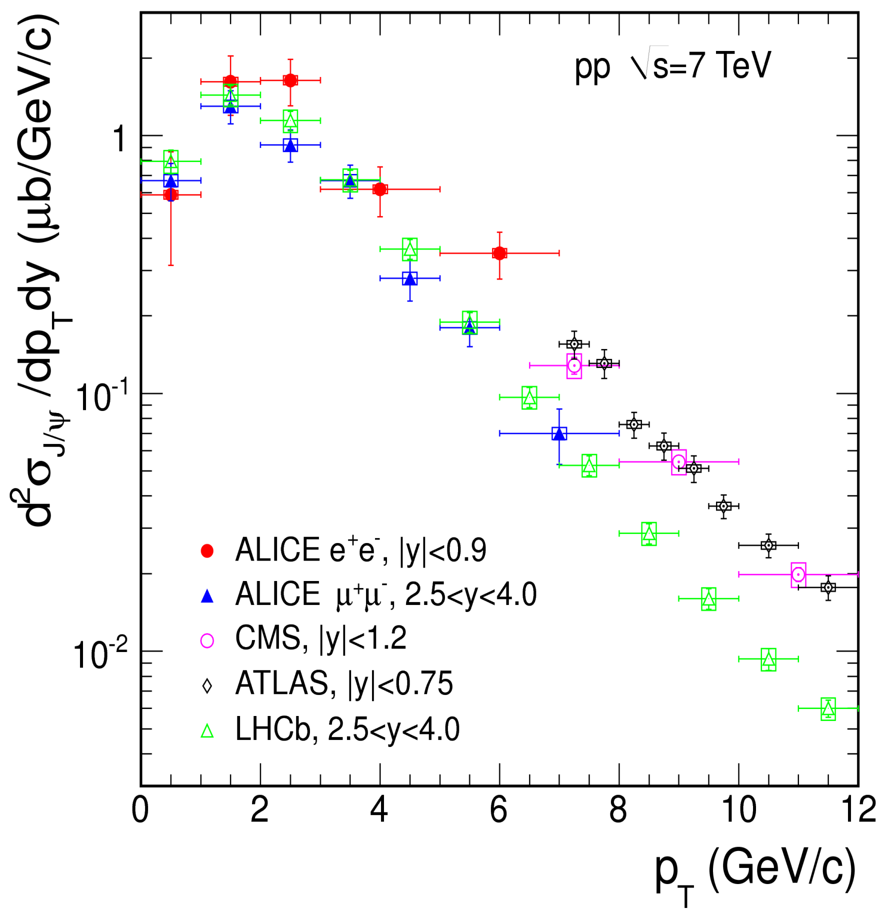


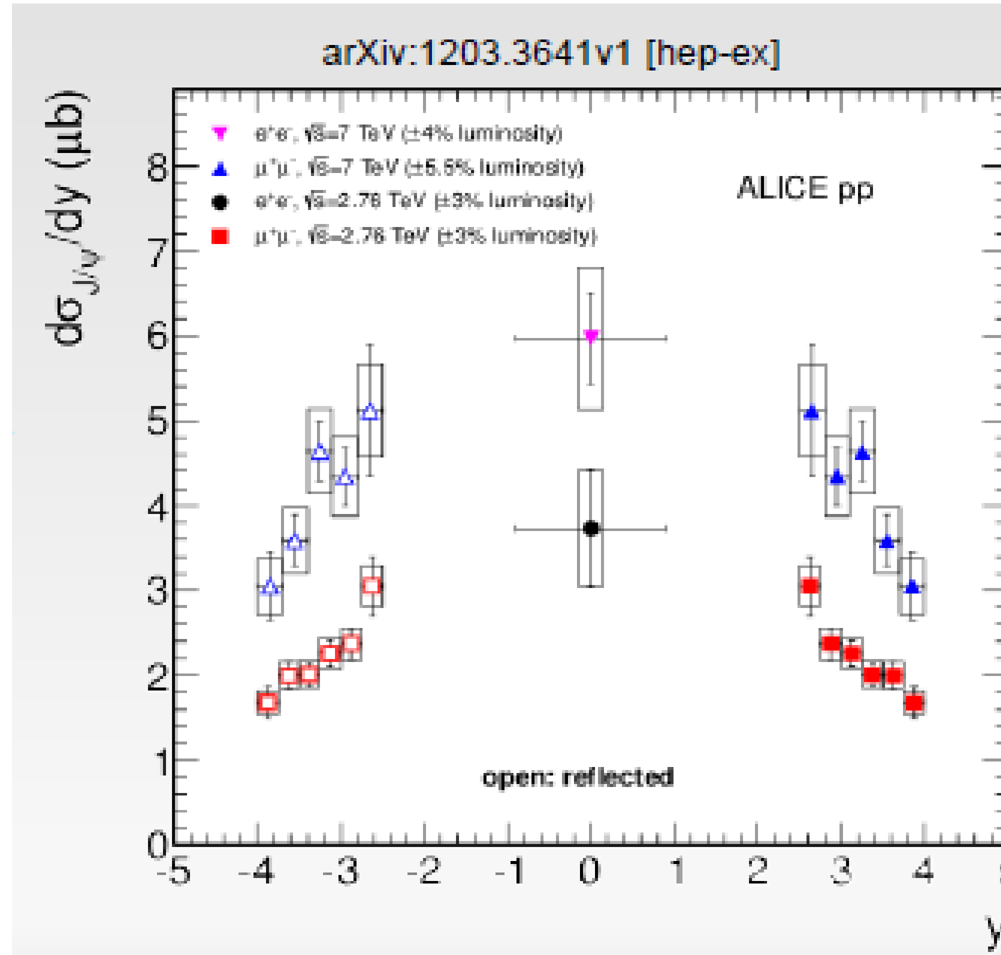
SPS RHIC LHC

Picture:
H. Satz 2009

J/psi spectrum and cross section in pp collisions

ALICE PRL 704 (2011) 442 arXiv:1105.0380





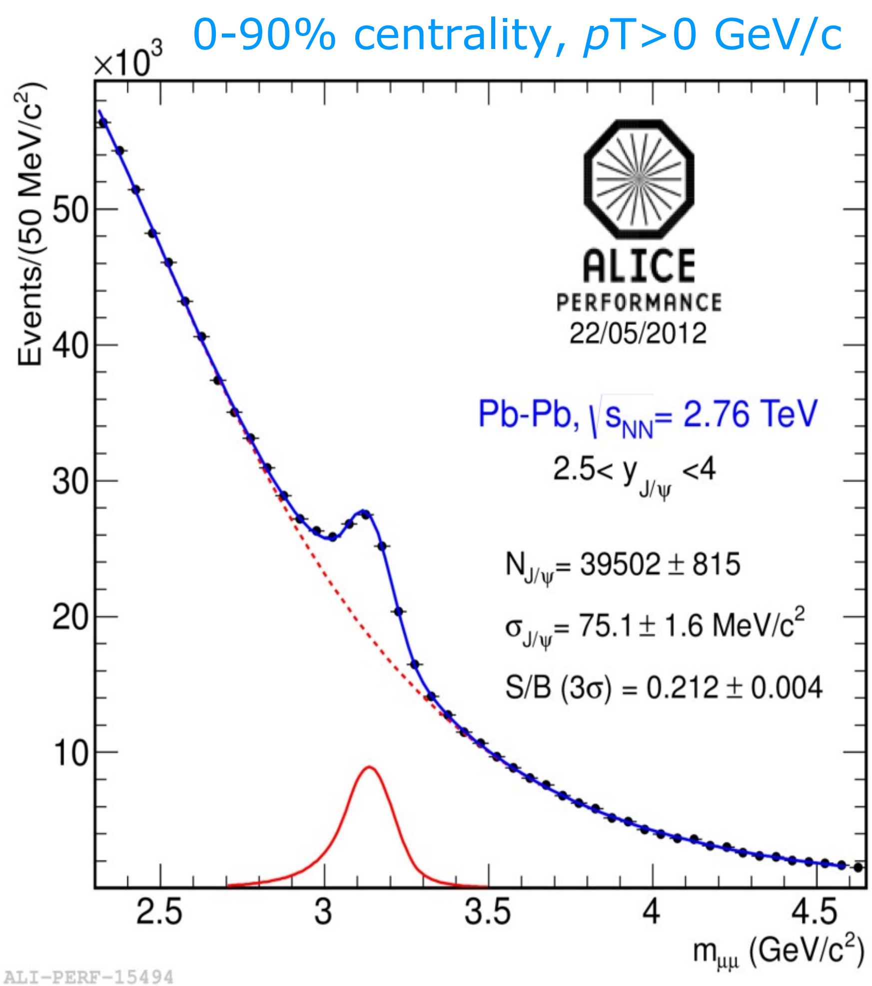
- good agreement between experiments
- complementary in acceptance:
  only ALICE has acceptance below 6 GeV at mid-rapidity

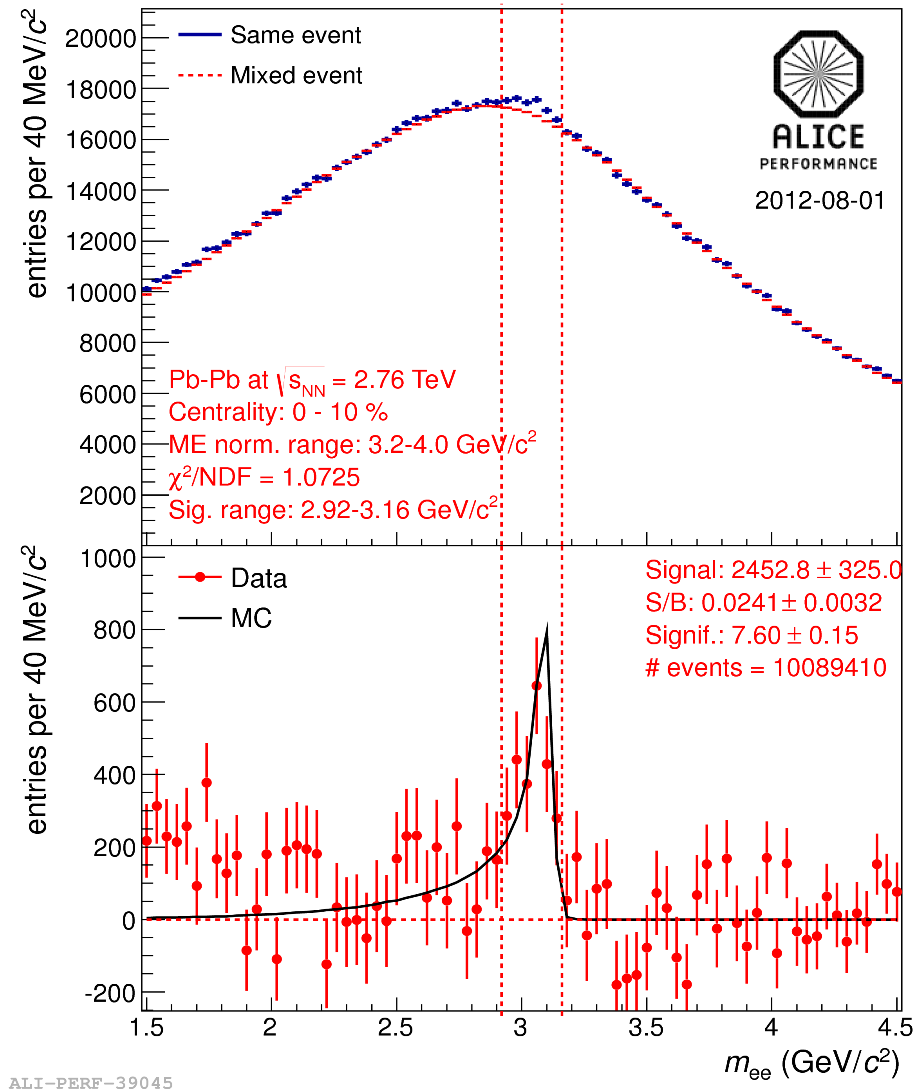
measured both at 7 and 2.76 TeV

<u>open issues:</u> statistics at mid-rapidity

polarization (biggest source of syst error)

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





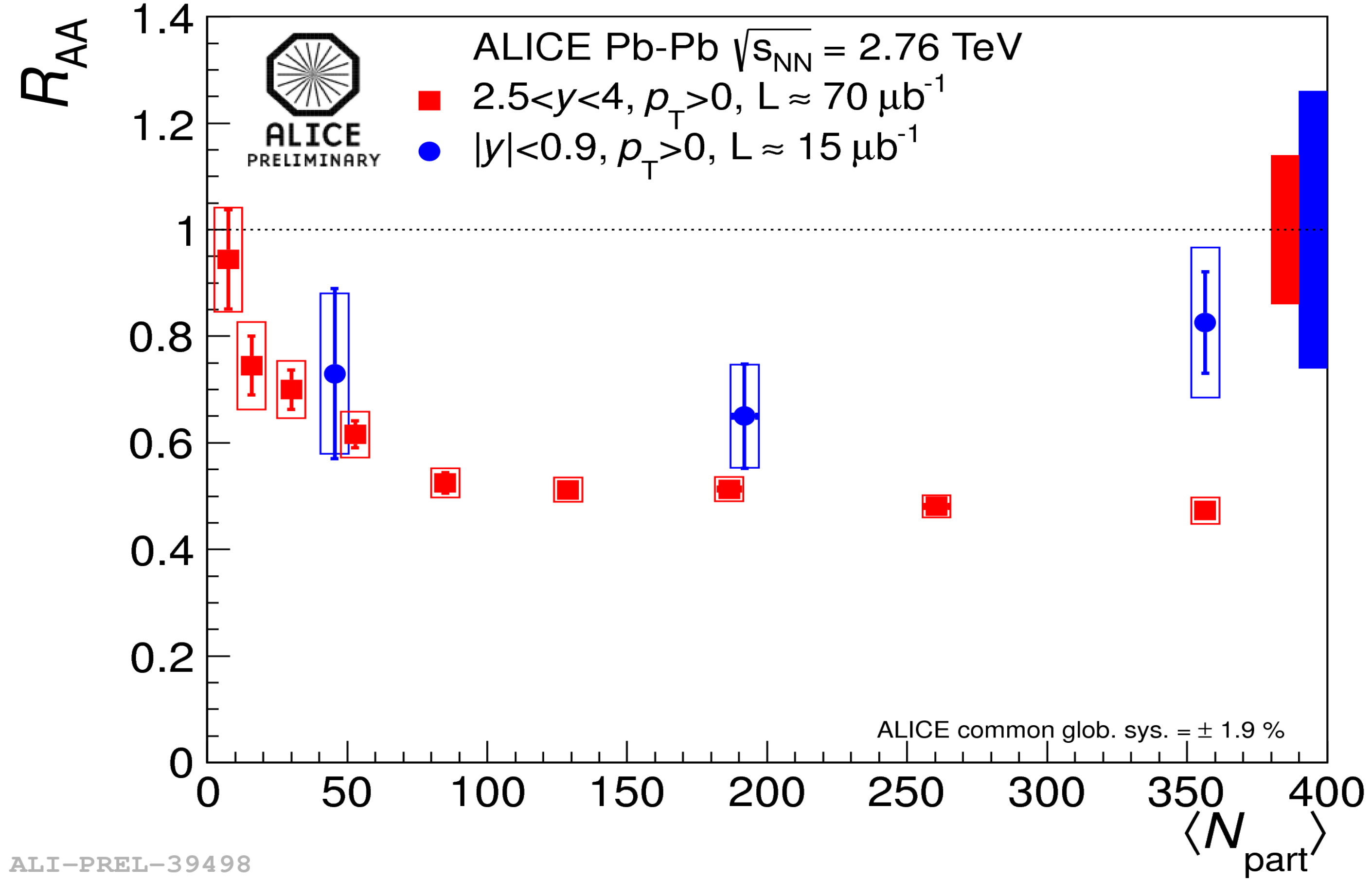
most challenging: PbPb collisions

in spite of significant 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

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

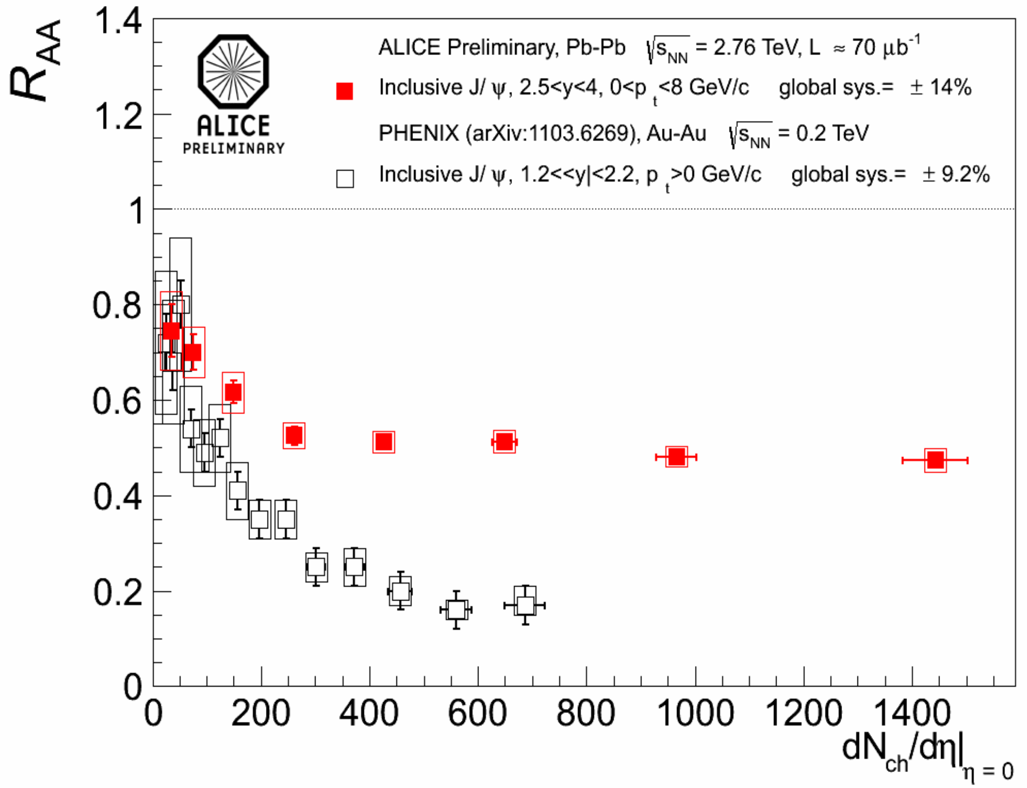


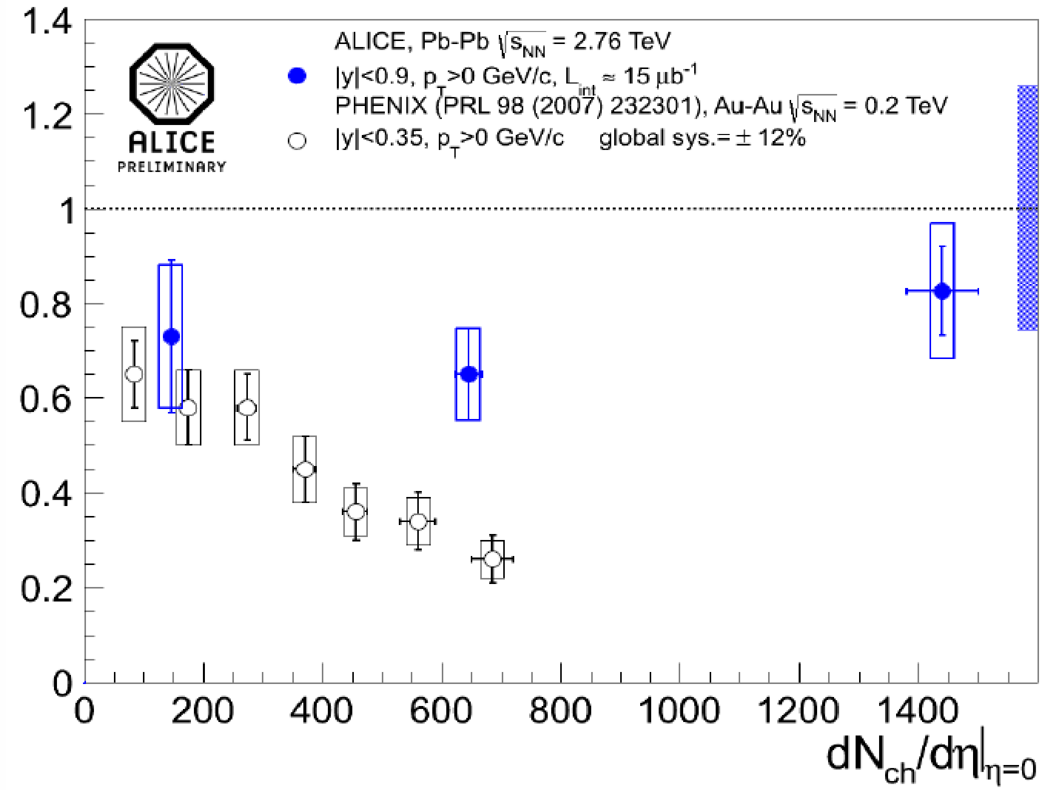
- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

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

forward rapidity

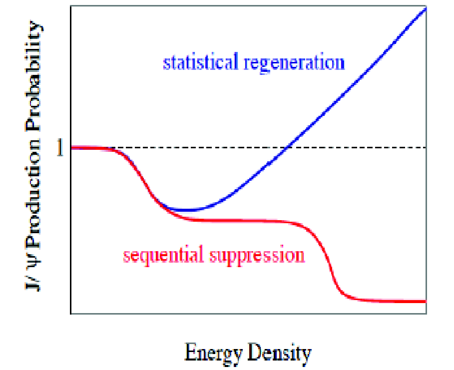
mid-rapidity



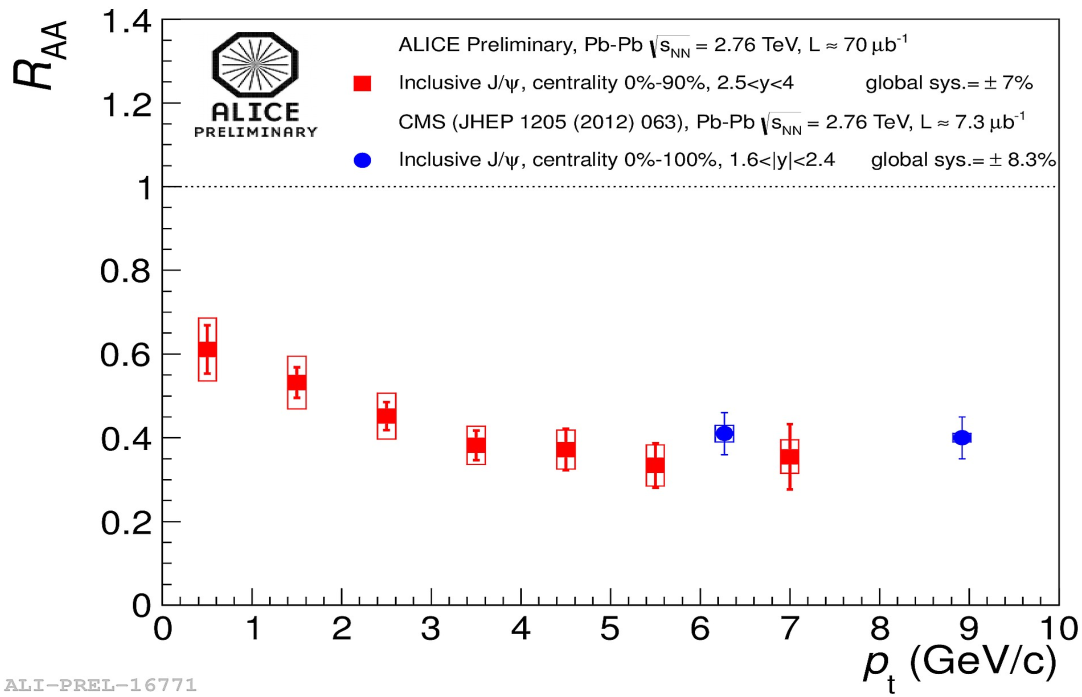


energy density -->

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



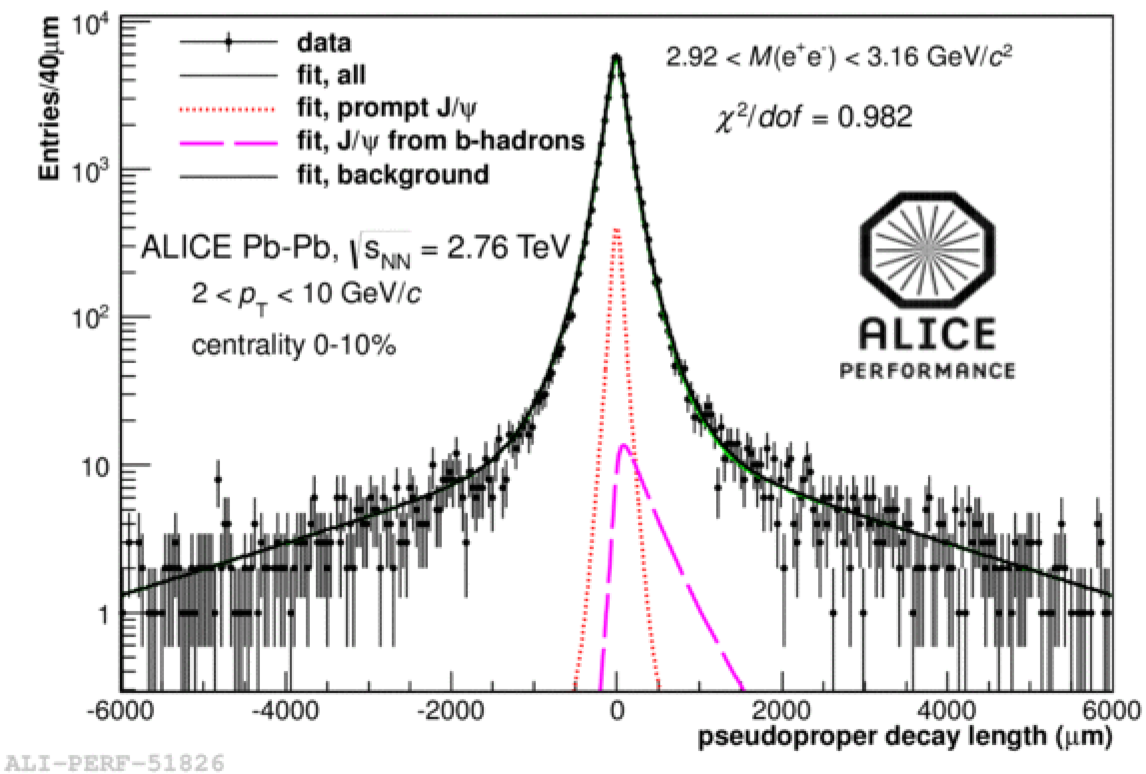
p_t dependence of R_{AA}



relative yield larger at low p_t in nuclear collisions

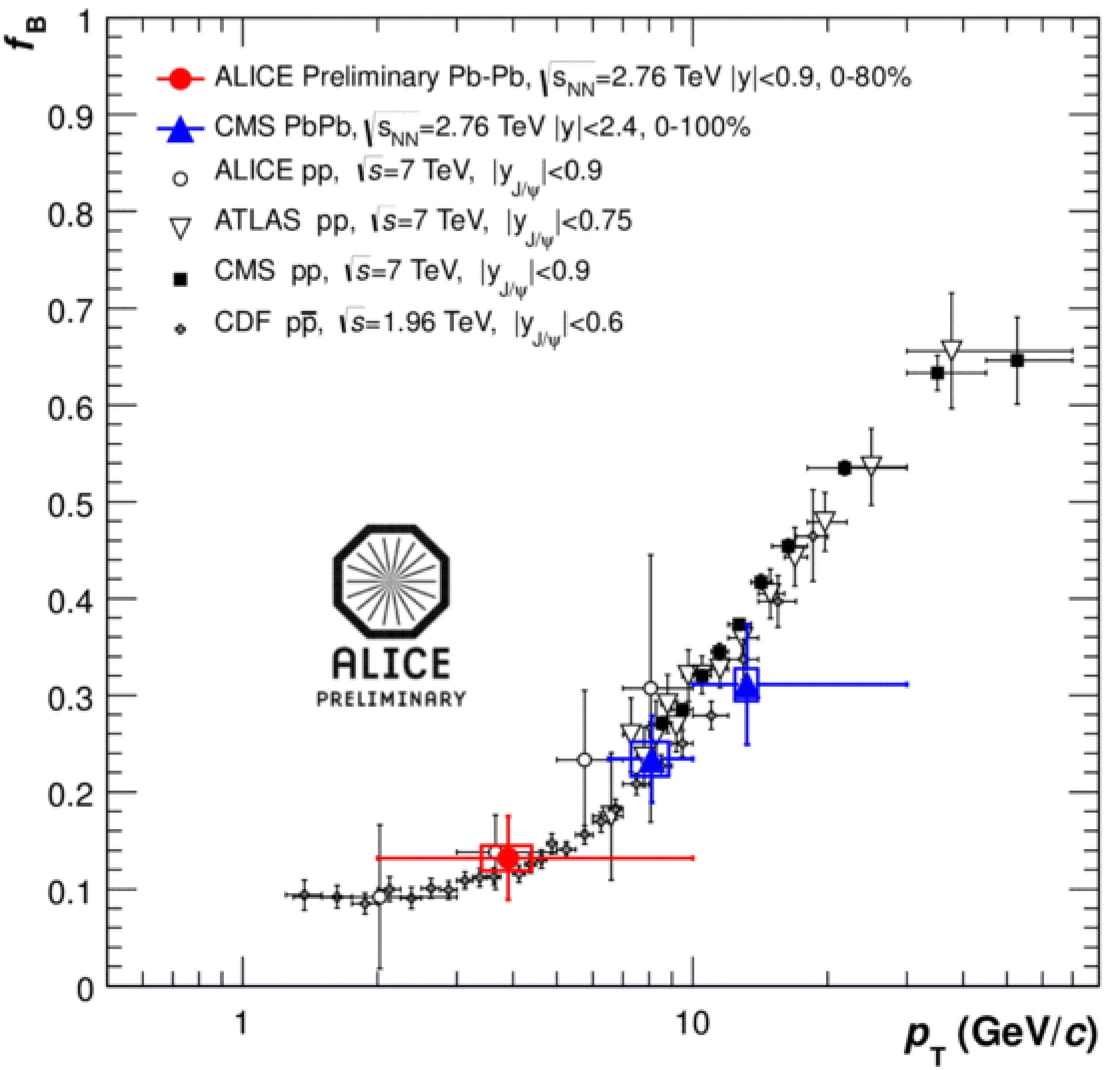
good agreement with CMS at high p_t

Fraction of J/psi from B-decays



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

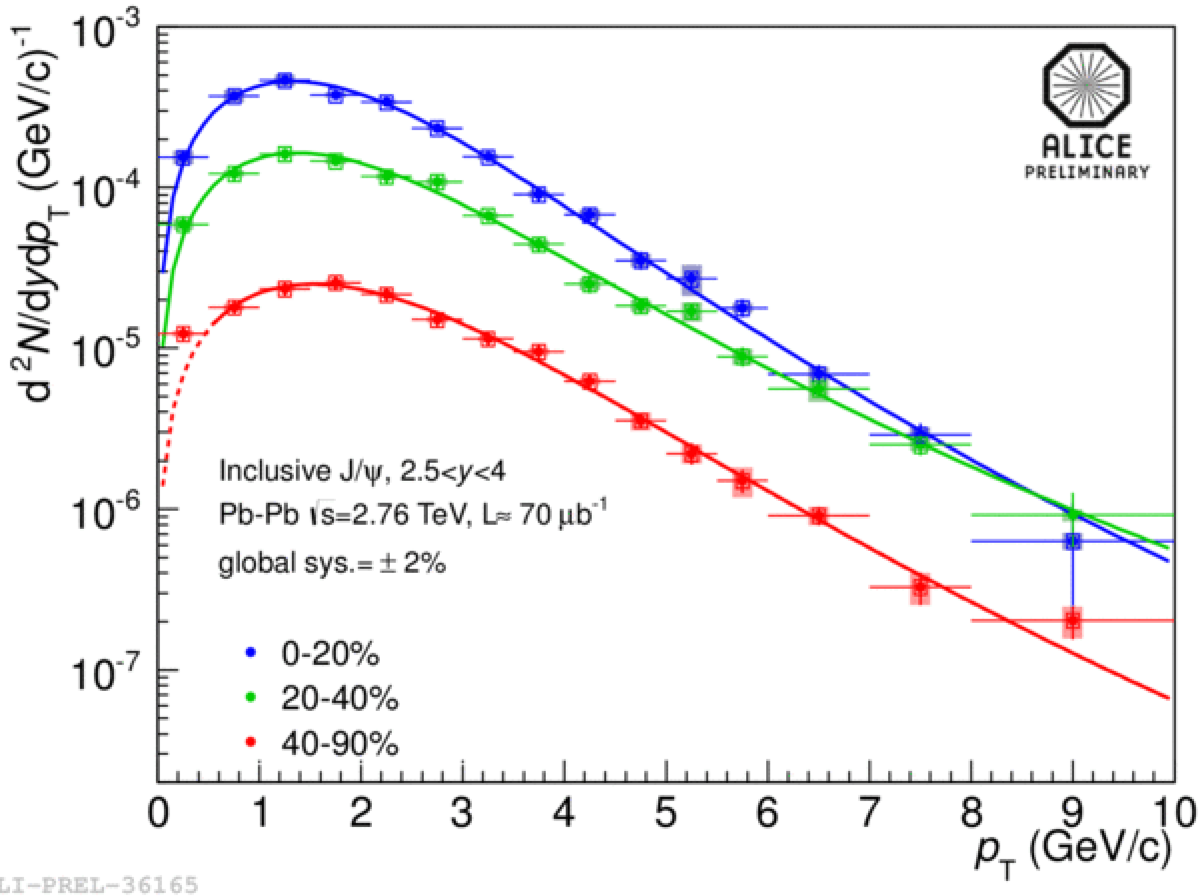
Fraction of J/psi from B-decays



p_t integrated non-prompt B-fraction of small

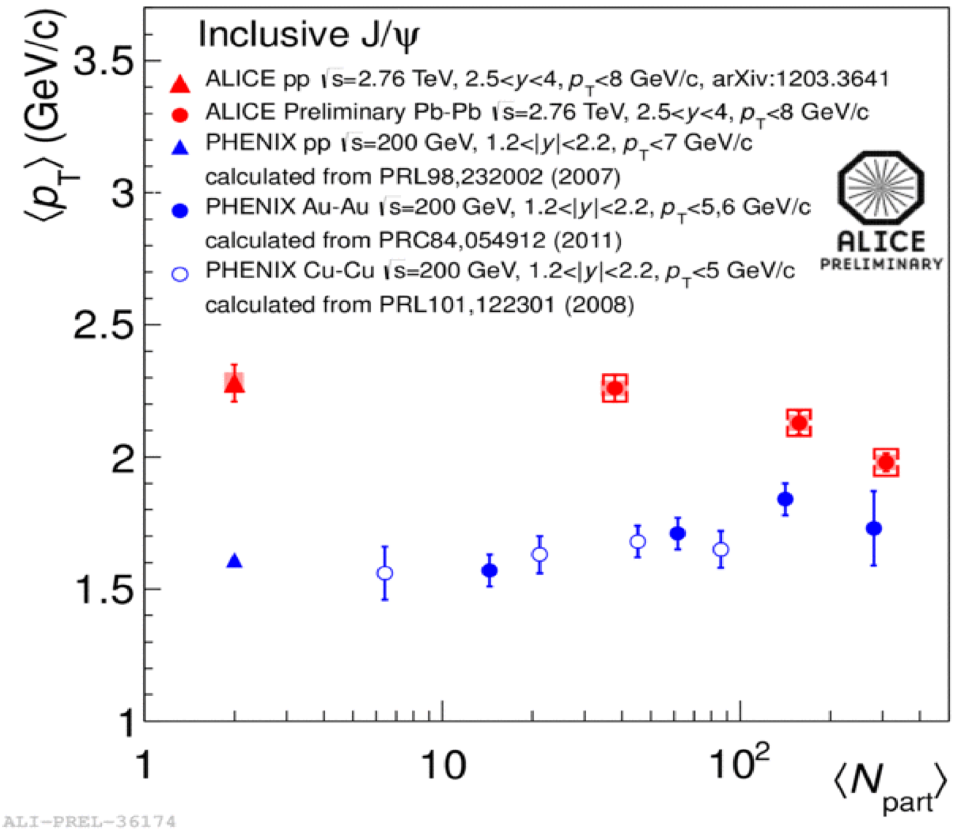
within current errors no significant difference in pp and PbPb collisions

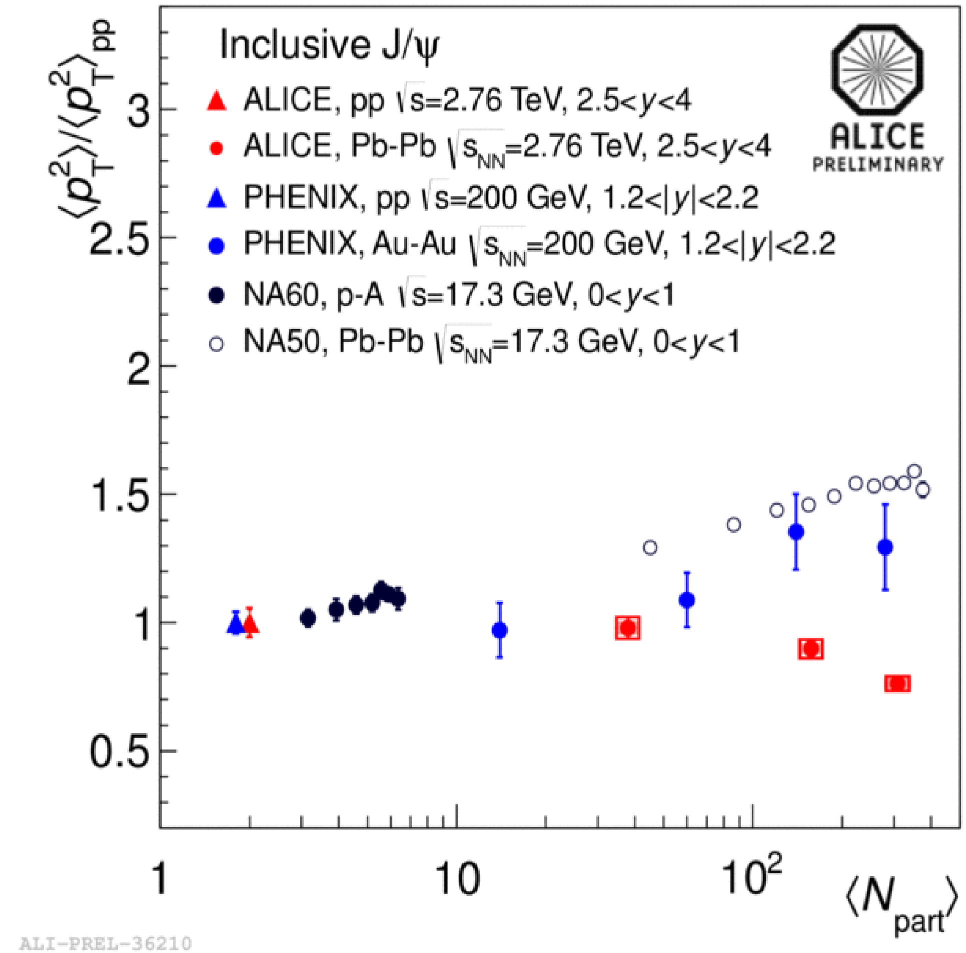
J/psi p_t distributions as function of centrality



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

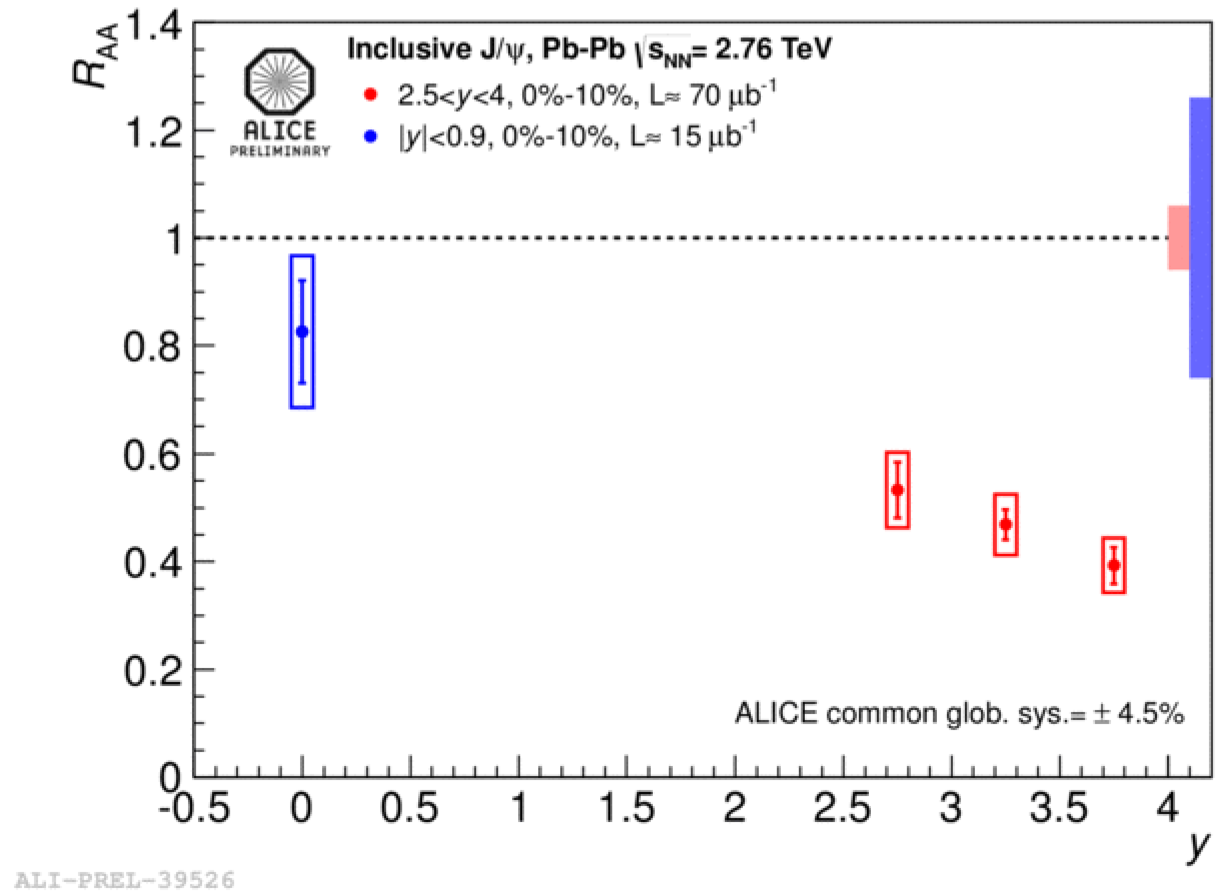
Softening of J/psi pt distributions for central PbPb coll.





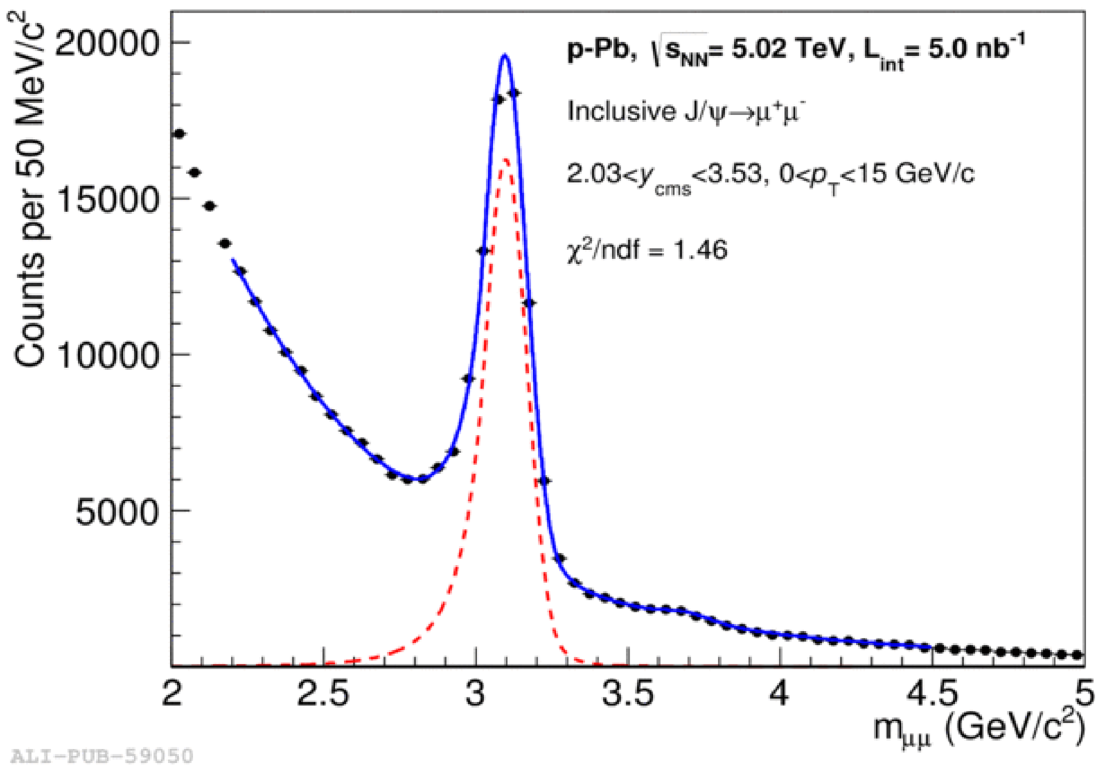
At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

Rapidity dependence of J/psi R_{AA}



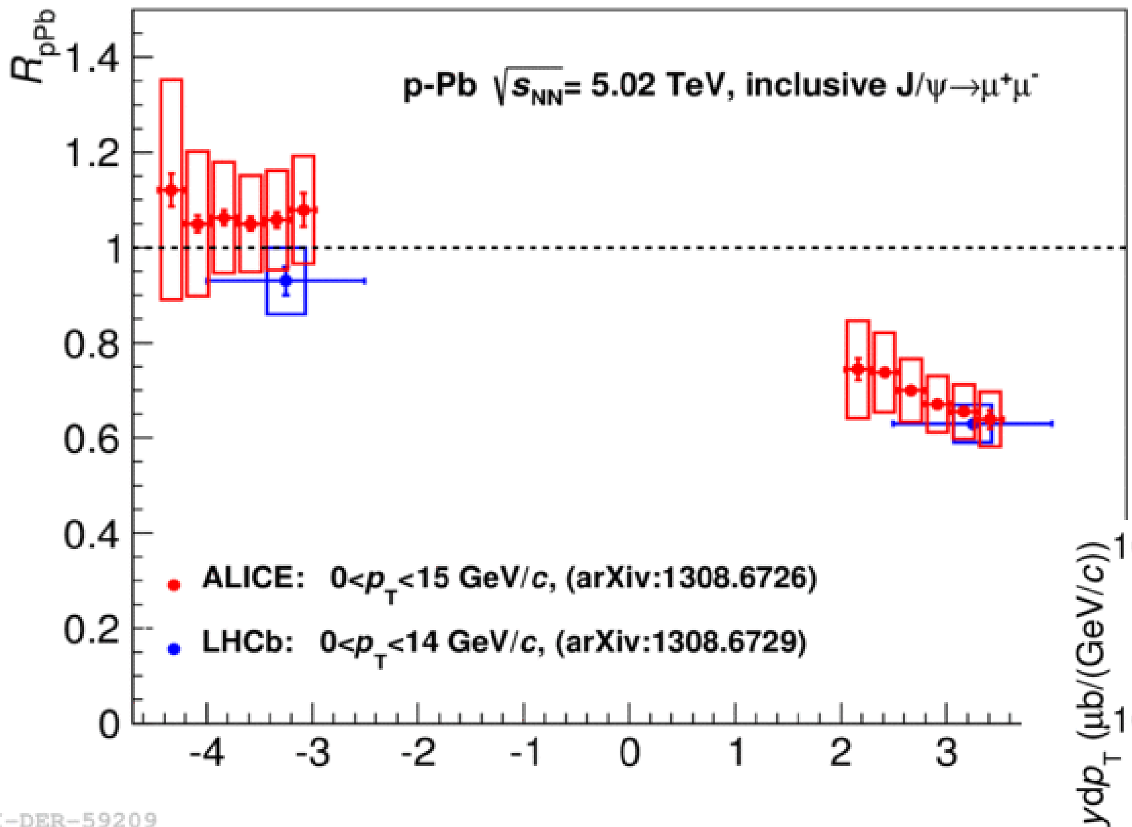
Least amount of suppression at mid-rapidity

J/psi production in pPb collisions



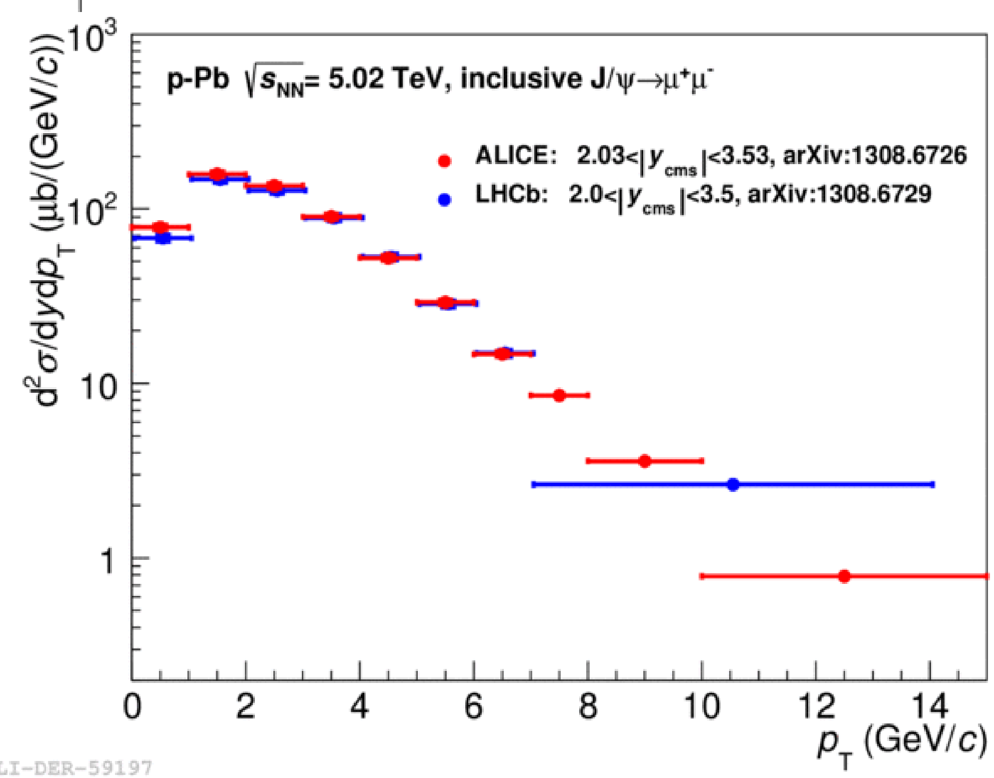
measurement in ALICE muon spectrometer submitted for publication arXiv:1308.6726
first results for mid-rapidity to be released soon

Rapidity and p_t distributions in pPb compared to pp



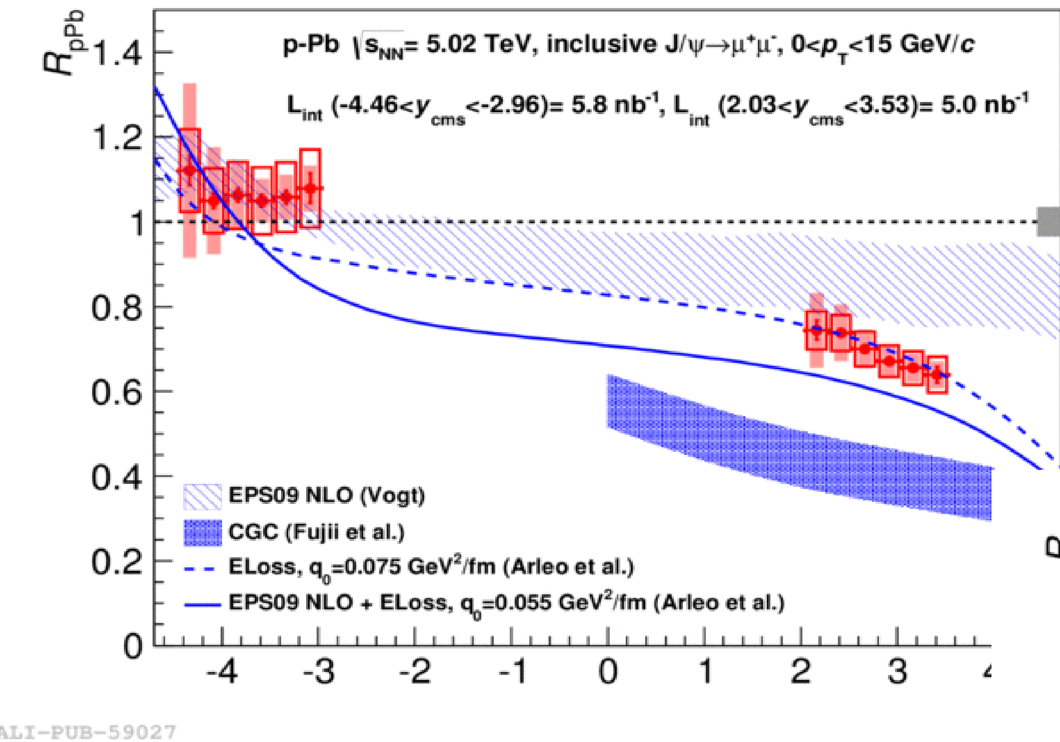
$$R_{\mathrm{pPb}} = \frac{N^{\mathrm{cor}}_{\mathrm{J}/\psi\to\mu\mu}}{\langle T_{\mathrm{pPb}}\rangle \cdot N_{\mathrm{MB}} \cdot \mathrm{B.R.}(\mathrm{J}/\psi \to \mu\mu) \cdot \sigma^{\mathrm{J}/\psi}_{\mathrm{pp}}}$$

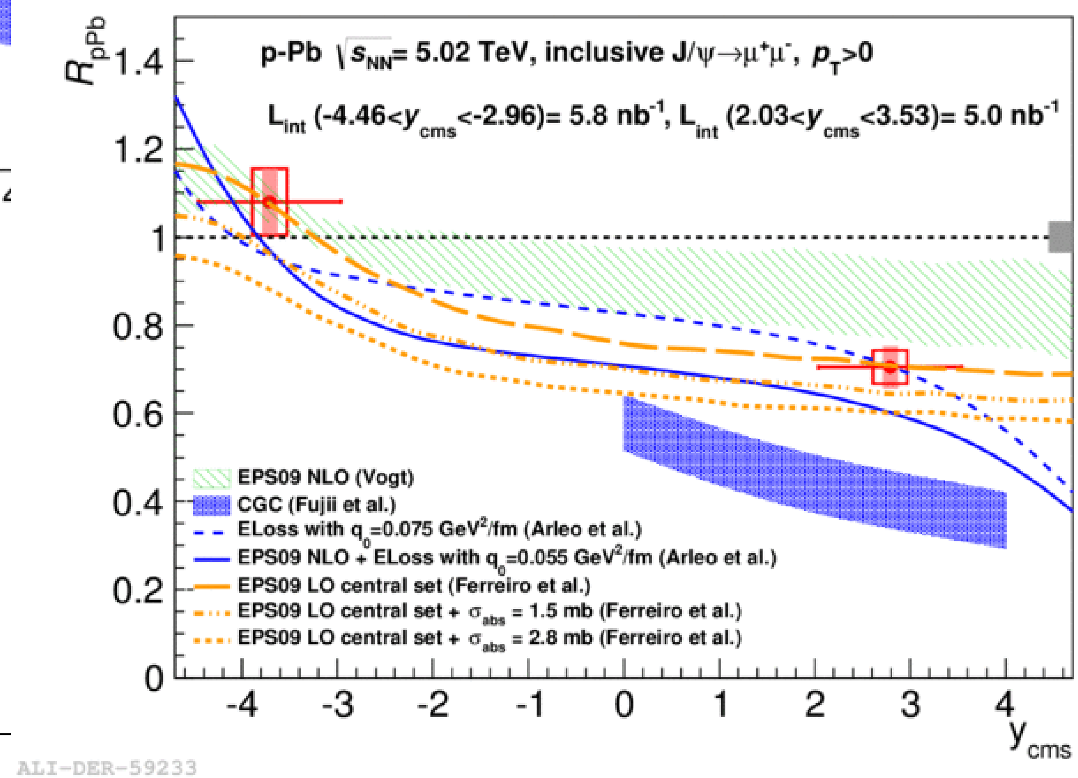
with T_{pPb} = 0.0983 (35) mb^{-1} from Glauber model



good agreement between ALICE and LHCb data

Comparison J/psi production in pPb and Pbp to models





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

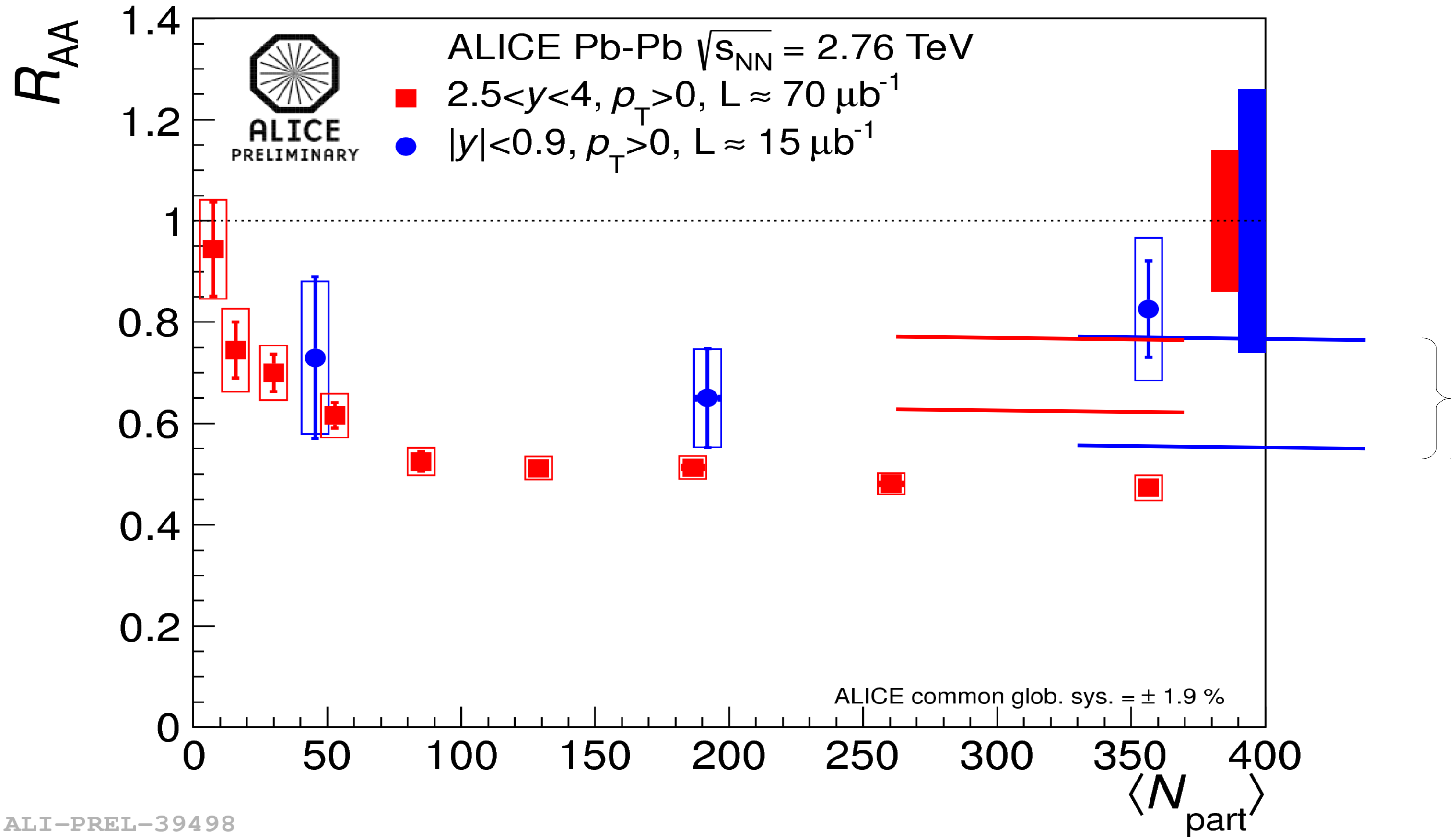
and then

$R_{PbPb} = R_{pPb} \cdot R_{Pbp} = 0.76 \pm 0.07 \pm 0.10$ 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

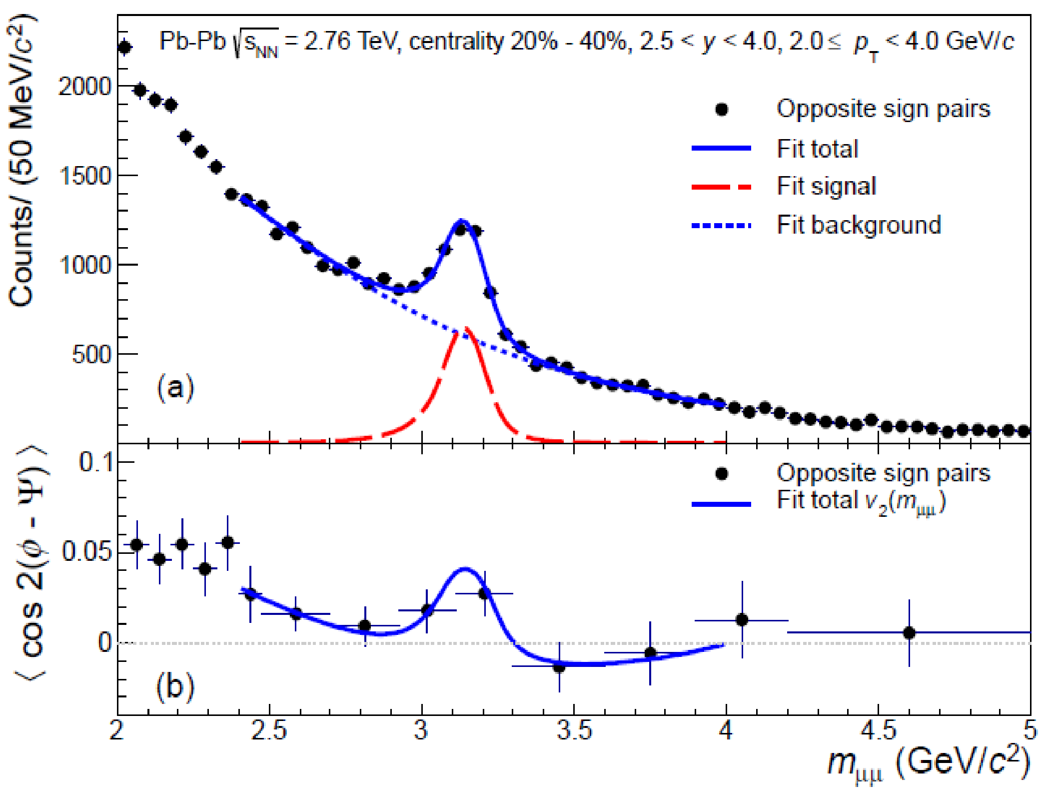
J/psi at forward y below shadowing

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

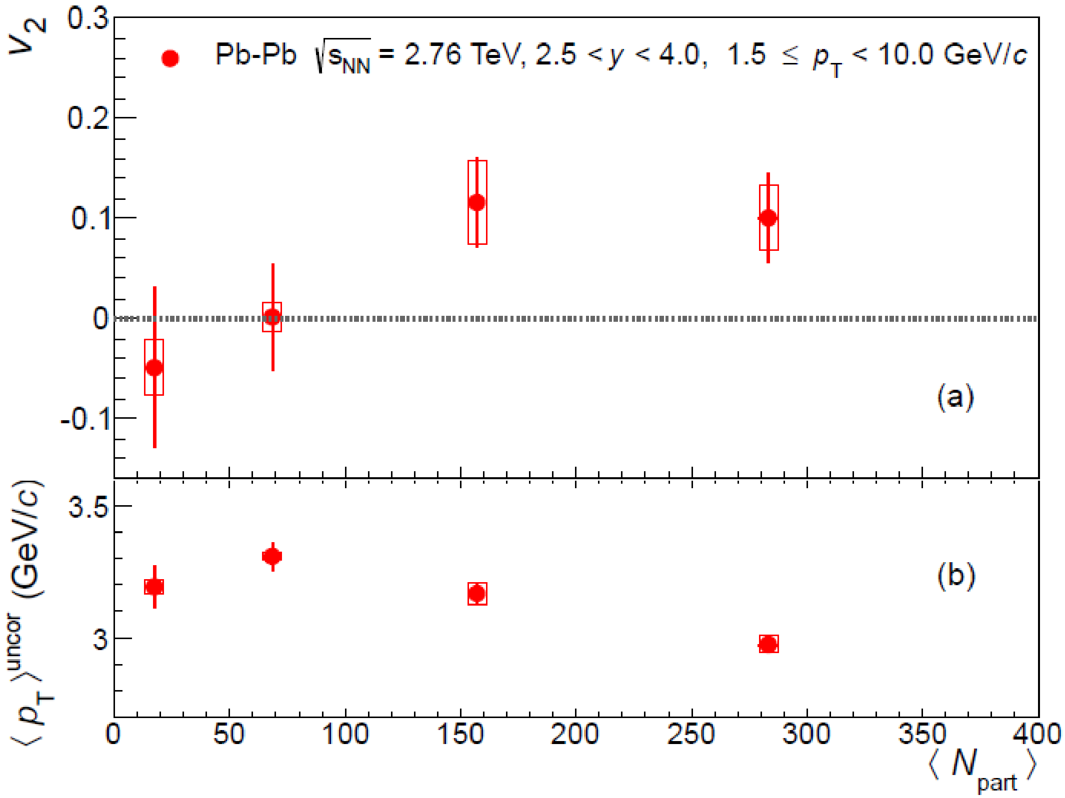
- fit distribution with

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

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

Elliptic Flow of J/psi

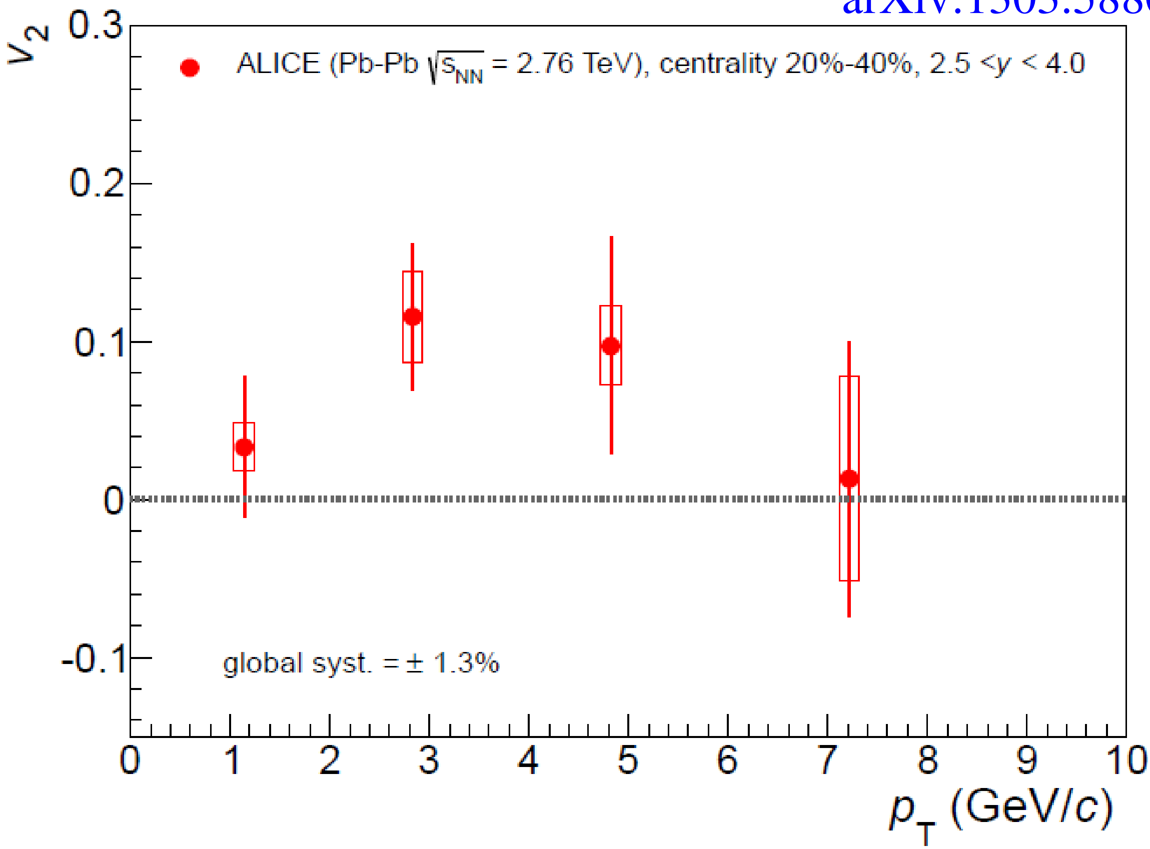
arXiv:1303.5880



first observation of significant J/ψ v_2

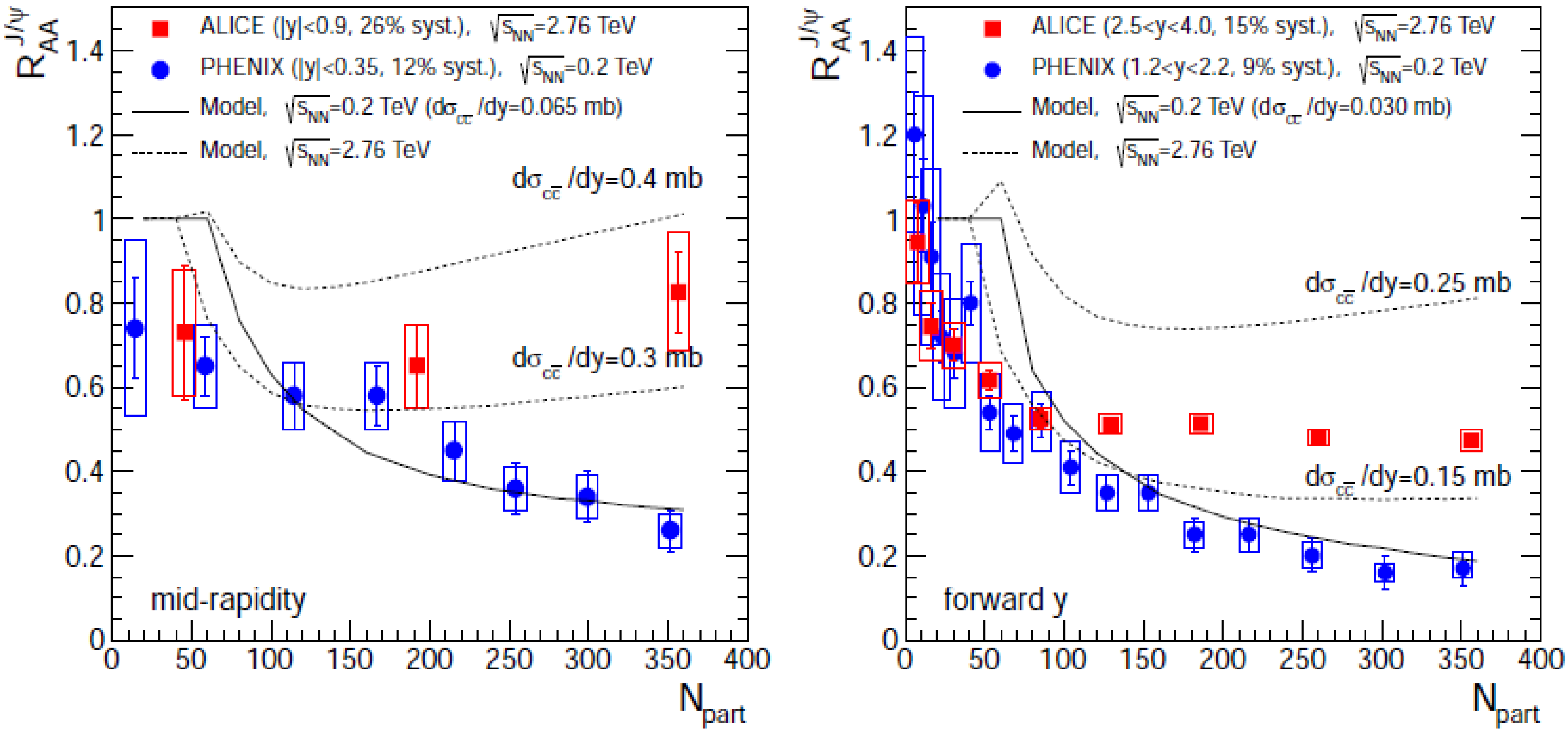
Elliptic Flow of J/psi vs pt

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

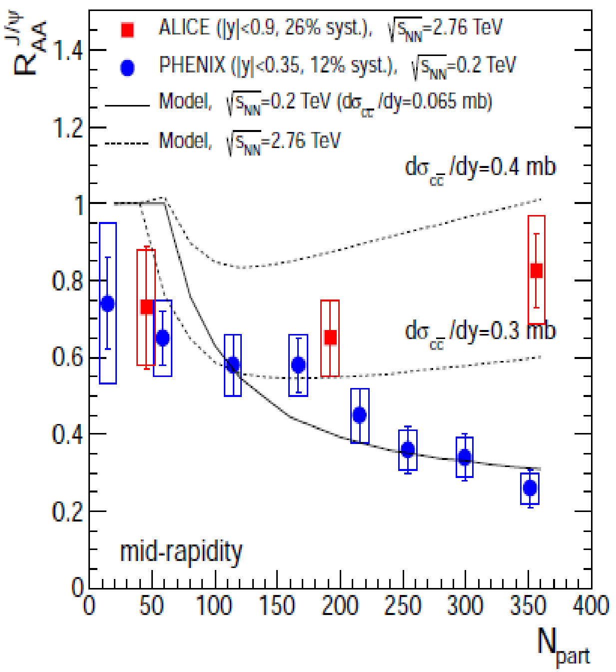
J/psi and Statistical Hadronization

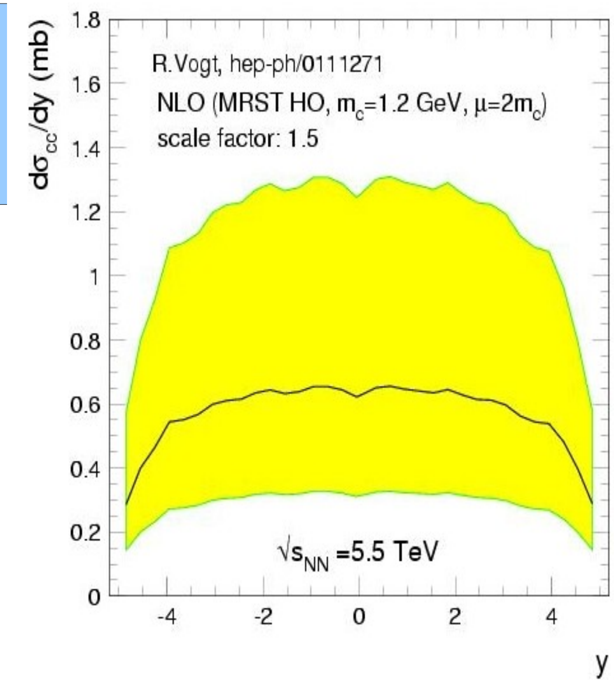


in AA collisions: strong indication of J/ψ regeneration

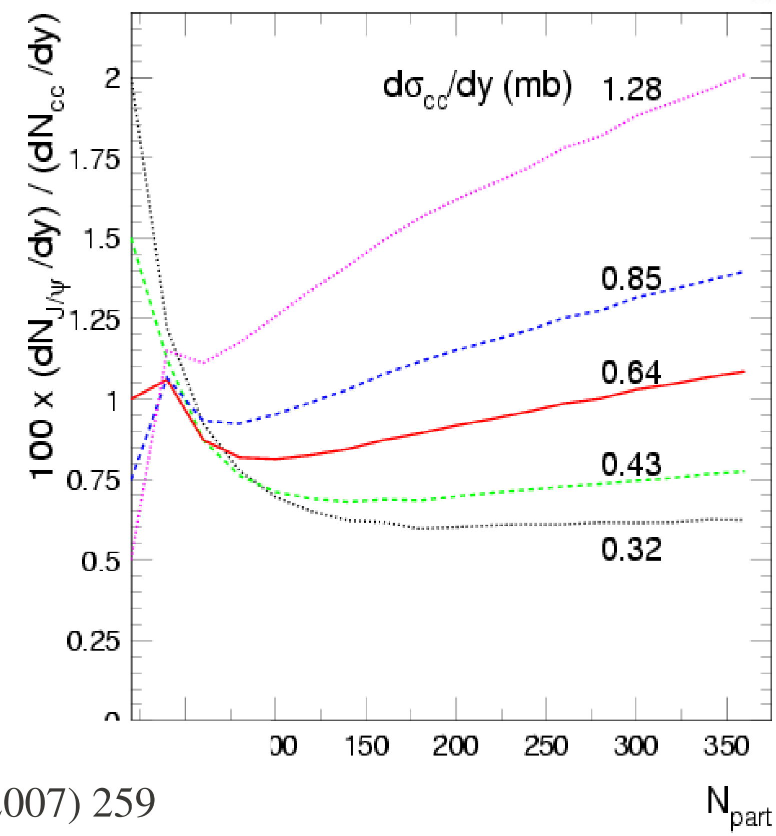
- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- shadowing from pPb collisions: forward y: R_{AA} = 0.76(12) mid-y R_{AA} (estim) =0.72(15)

Predictions for statistical hadronization





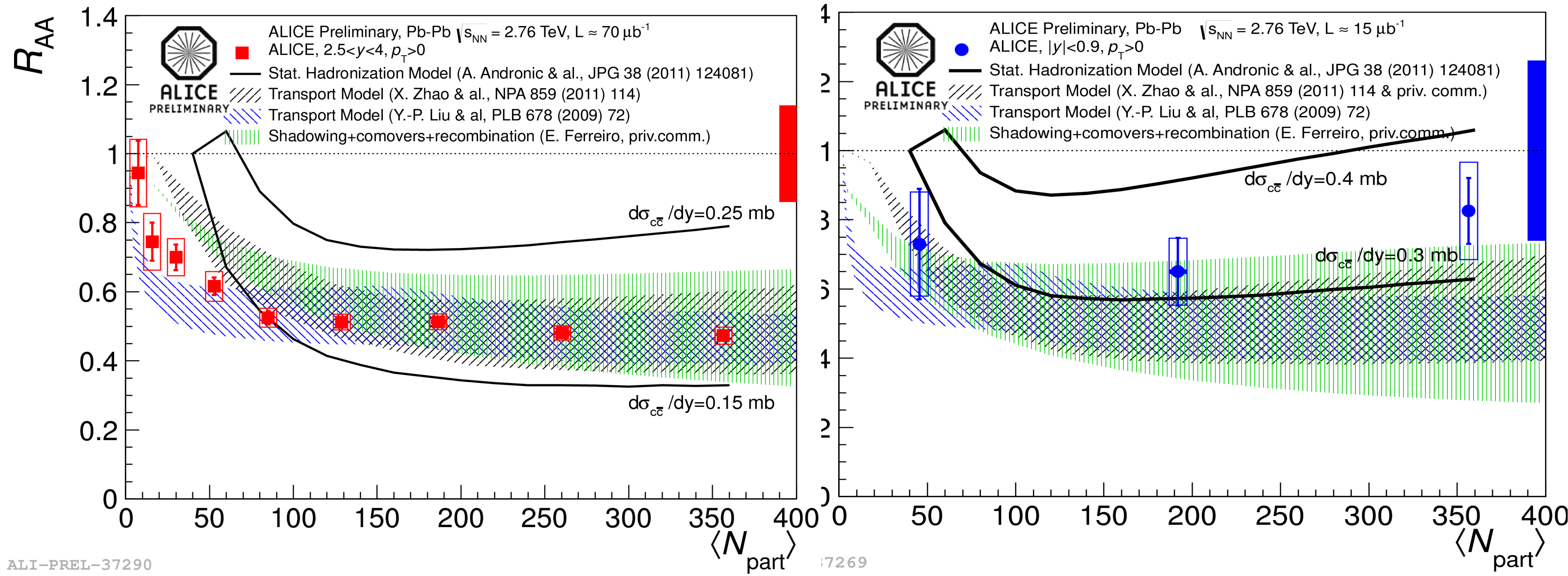
in line with current pp charm cross section at
$\sqrt{s_{NN}}$ = 2.76 TeV and pPb shadowing
need more precise ccbar cross section measurement
and full LHC energy data



Predictions based on pQCD cross section for full LHC energy

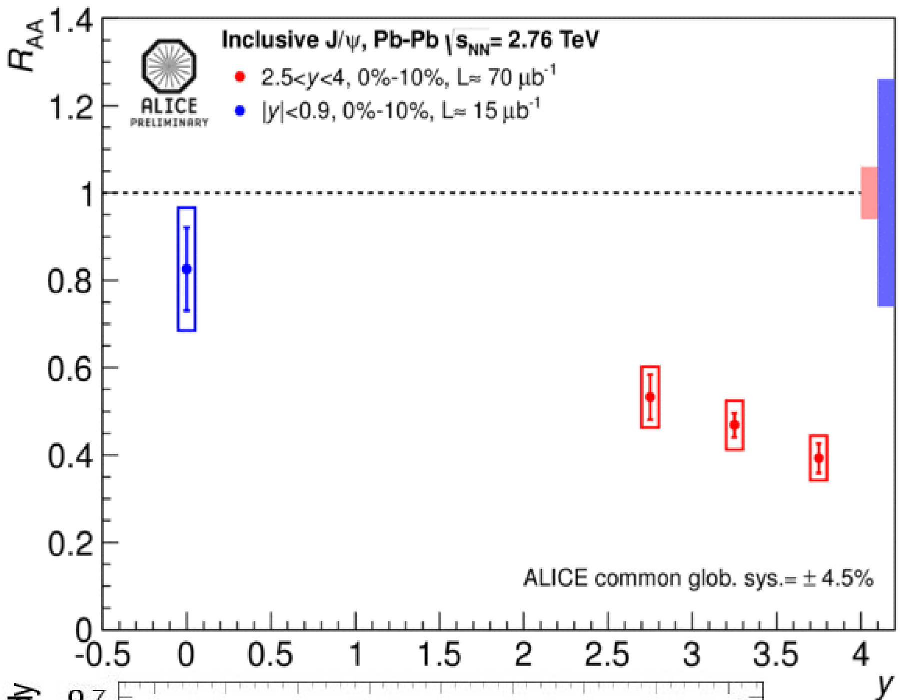
A. Andronic, P. Braun-Munzinger, K. Redlich, J. S. Phys. Lett. B652 (2007) 259

J/psi and transport models (and stat hadronization)



in AA collisions: strong indication of J/ψ regeneration

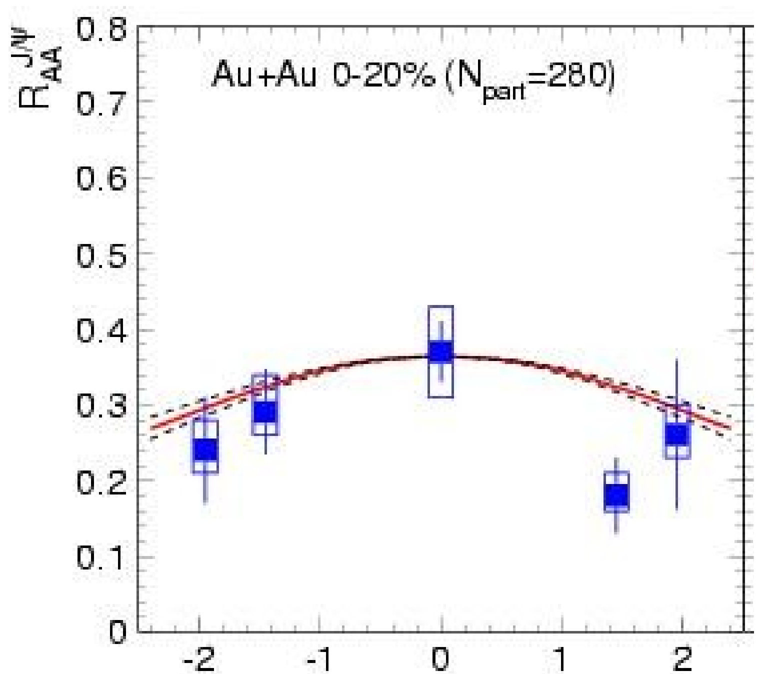
- transport models also well in line with R_{AA}
  part of J/psi from direct hard production, part dynamically generated in QGP
- How to distinguish?
  flow of J/psi and excited state population – precision 2nd and 3rd generation data



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

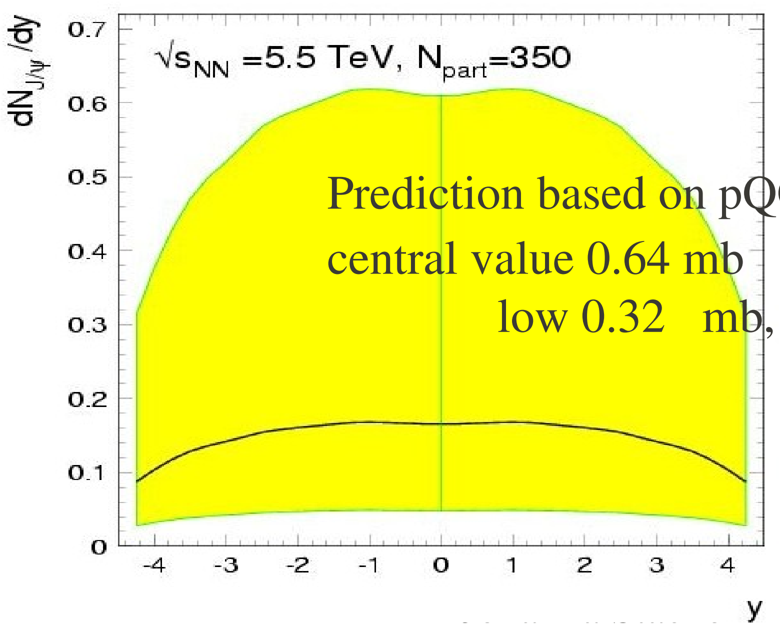
higher yield at mid-rapidity predicted in line with observation

already seen at RHIC by PHENIX



data: PHENIX nucl-ex/0611020

additional 14% syst error beyond shown



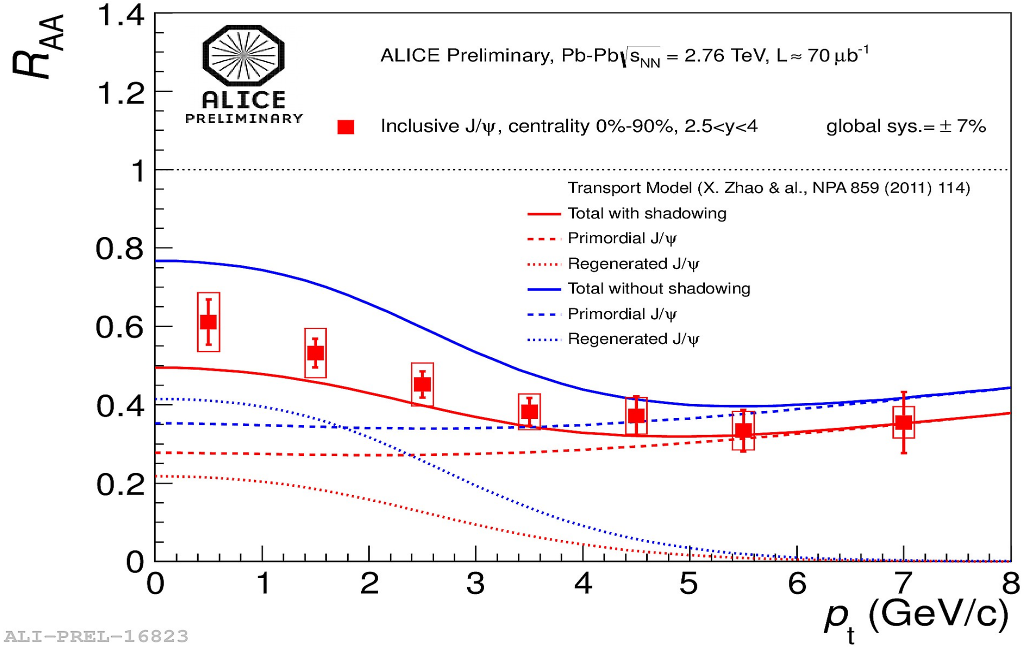
Prediction based on pQCD $d\sigma_{cc}/dy$

central value 0.64 mb

low 0.32 mb, high 1.28 mb

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

p_t Dependence of R_{AA}

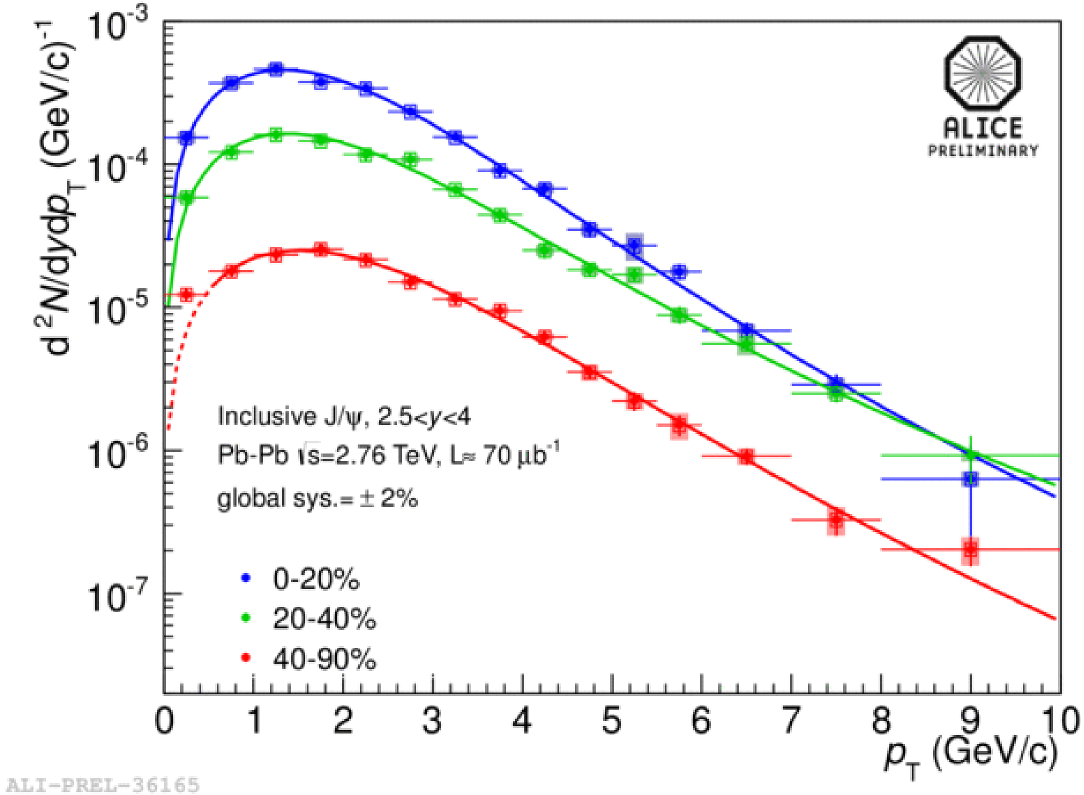


statistical hadronization only expected for charm quarks thermalized in the QGP

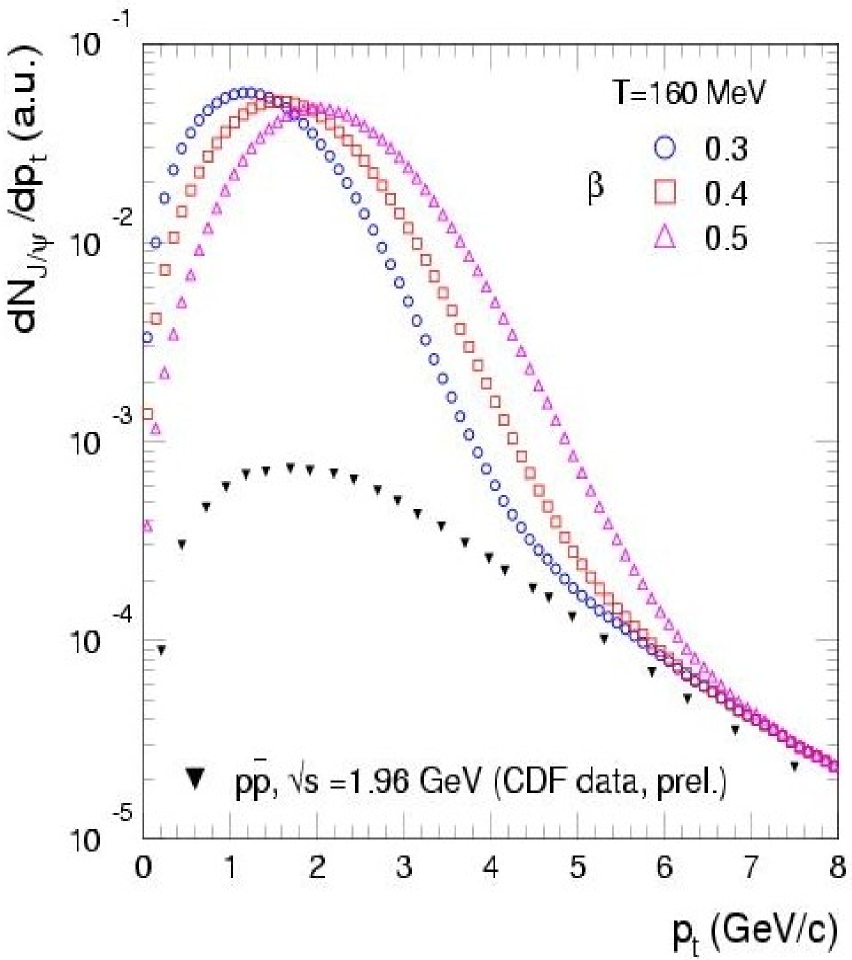
p_t dependence in line with this prediction

in CMS only suppression

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

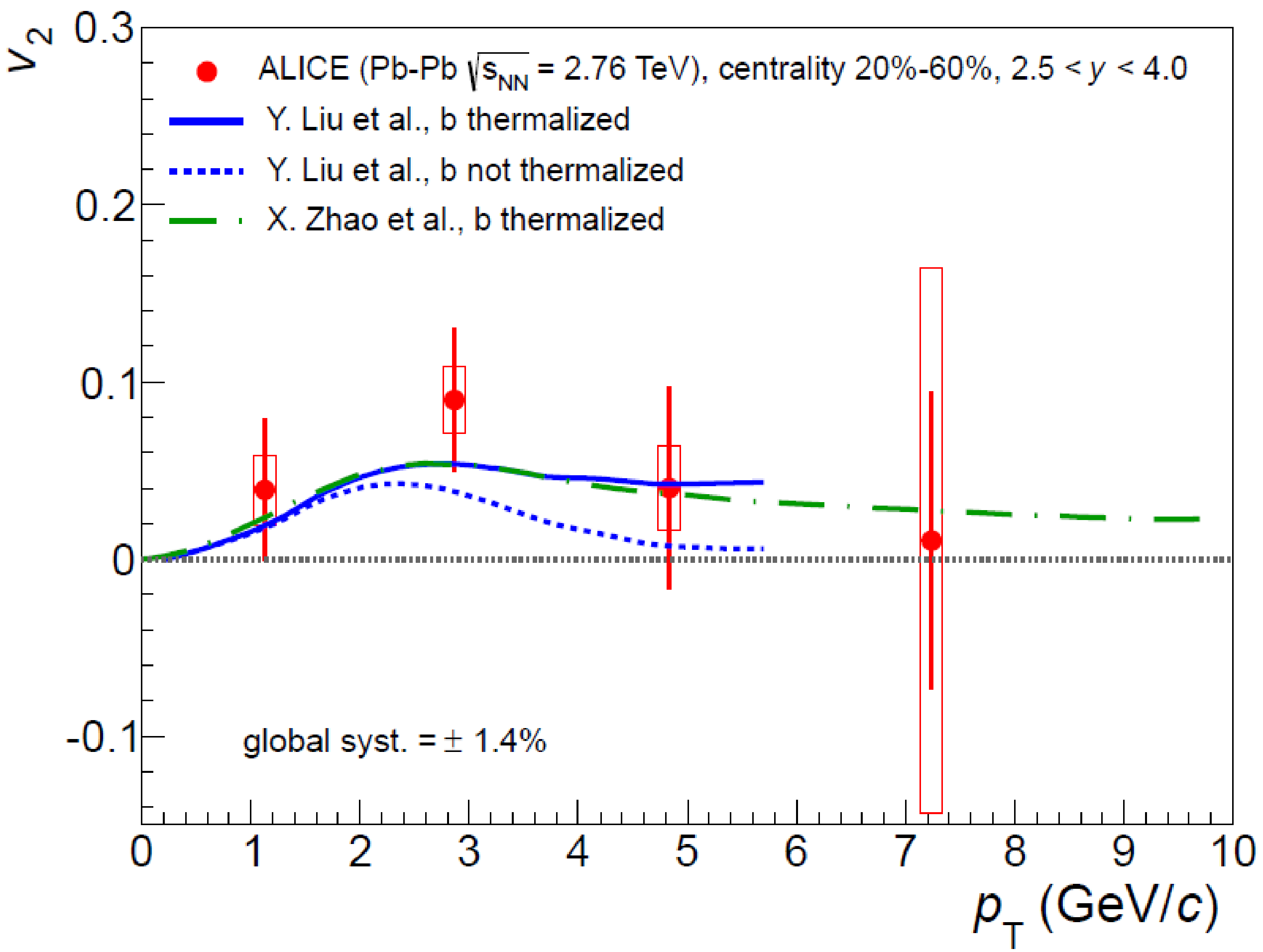


predictions A. Andronic, P. Braun-Munzinger, K. Redlich, J.S.



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

Conclusions

- Charm and beauty and J/spi cross section and spectra in pp in good agreement with pQCD predictions
- energy loss of partons in QGP: charm quarks lose energy nearly as effectively as gluons and light quarks
- heavy quarks also appear to thermalize

  need total cross section and charm quark observables at low p_t
- J/ψ: well on the way towards proof of deconfinement

  thermalized c-quarks form charmonia at hadronization, there charmonia exhibit collective elliptic flow

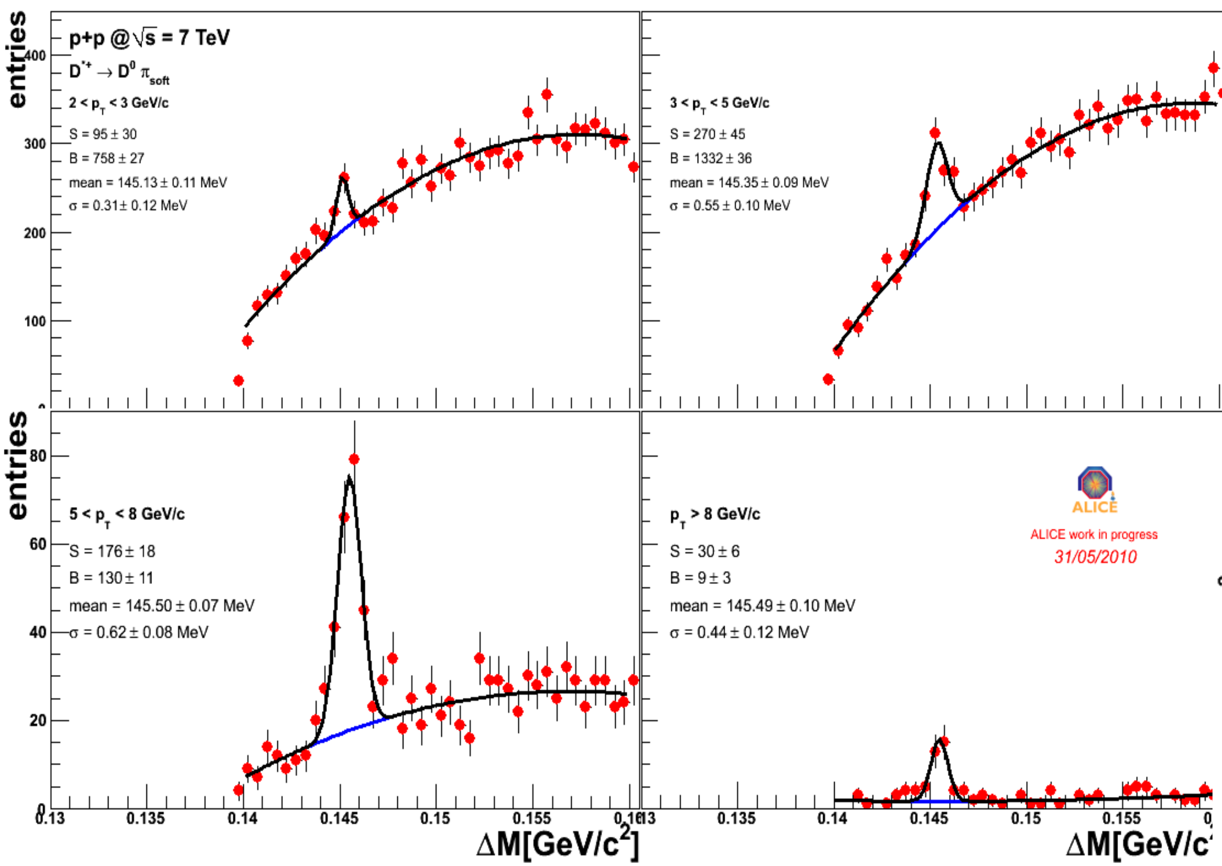
  need complete story of all charmonia and bottomonia (down to p_t=0)

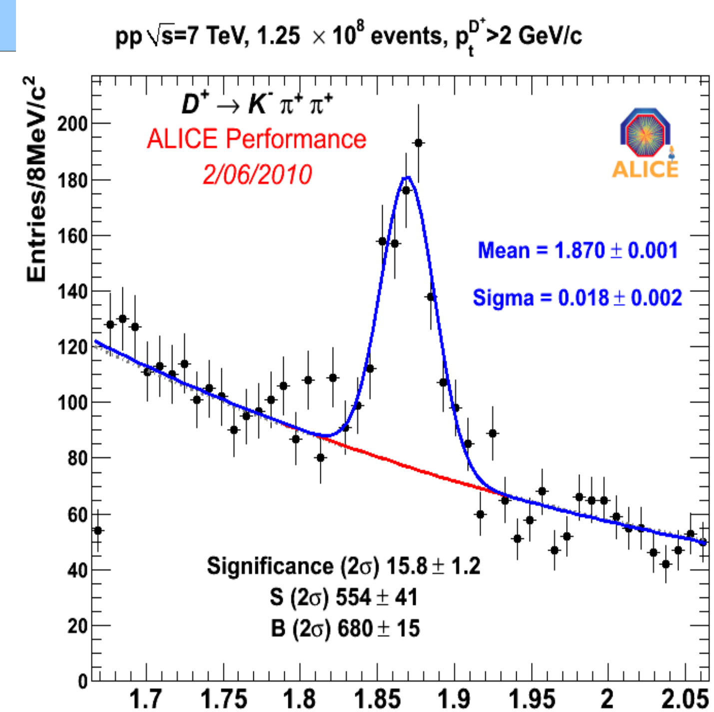
Happy birthday, dear Takeshi, and many happy returns!

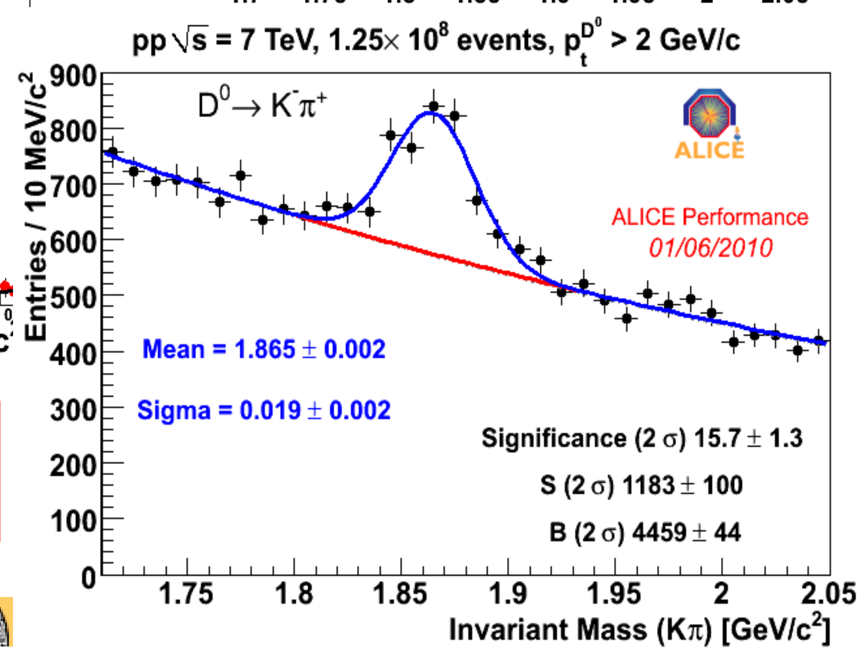
backup

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

$1.25\ 10^8$ events

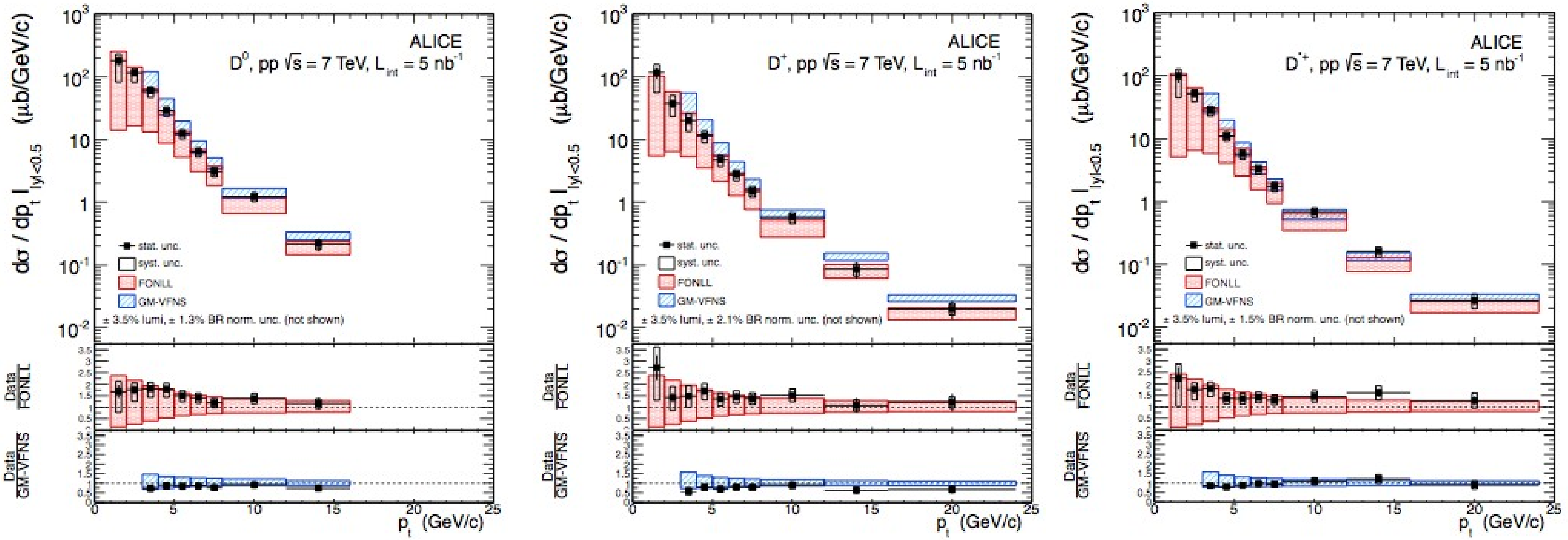






for 10^9 events, expect to measure open charm for $p_t = 0.5 - 15$ GeV/c

Measurements agree well with state of the art pQCD calculations



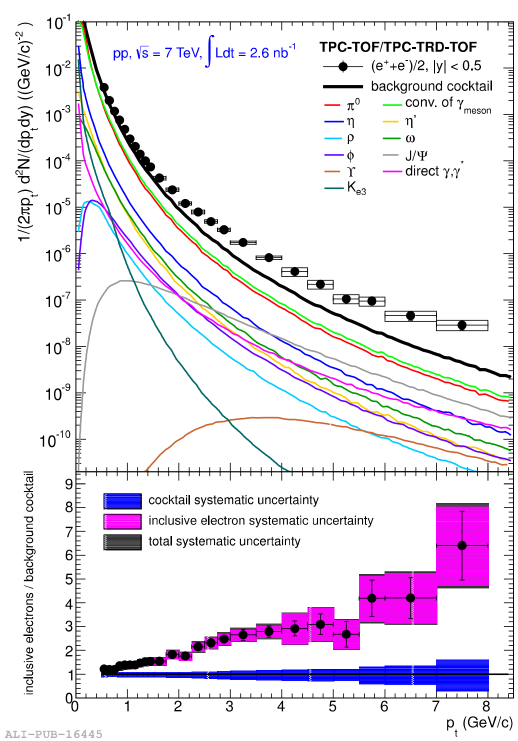
JHEP1201(2012)128

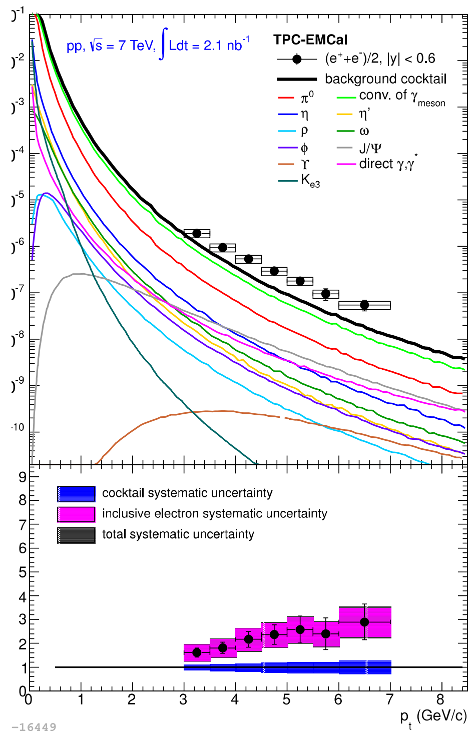
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

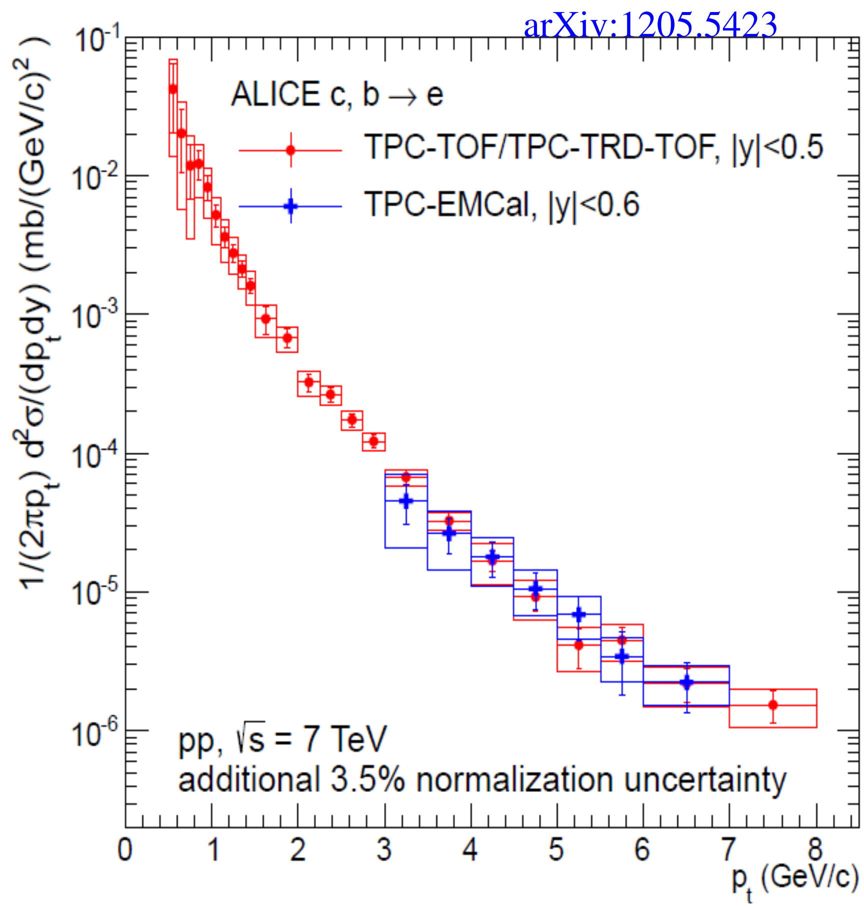
data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and at lower end of GM-VFNS
measure 80% of charm cross section for |y| < 0.5

Charm and beauty via semi-leptonic decays

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



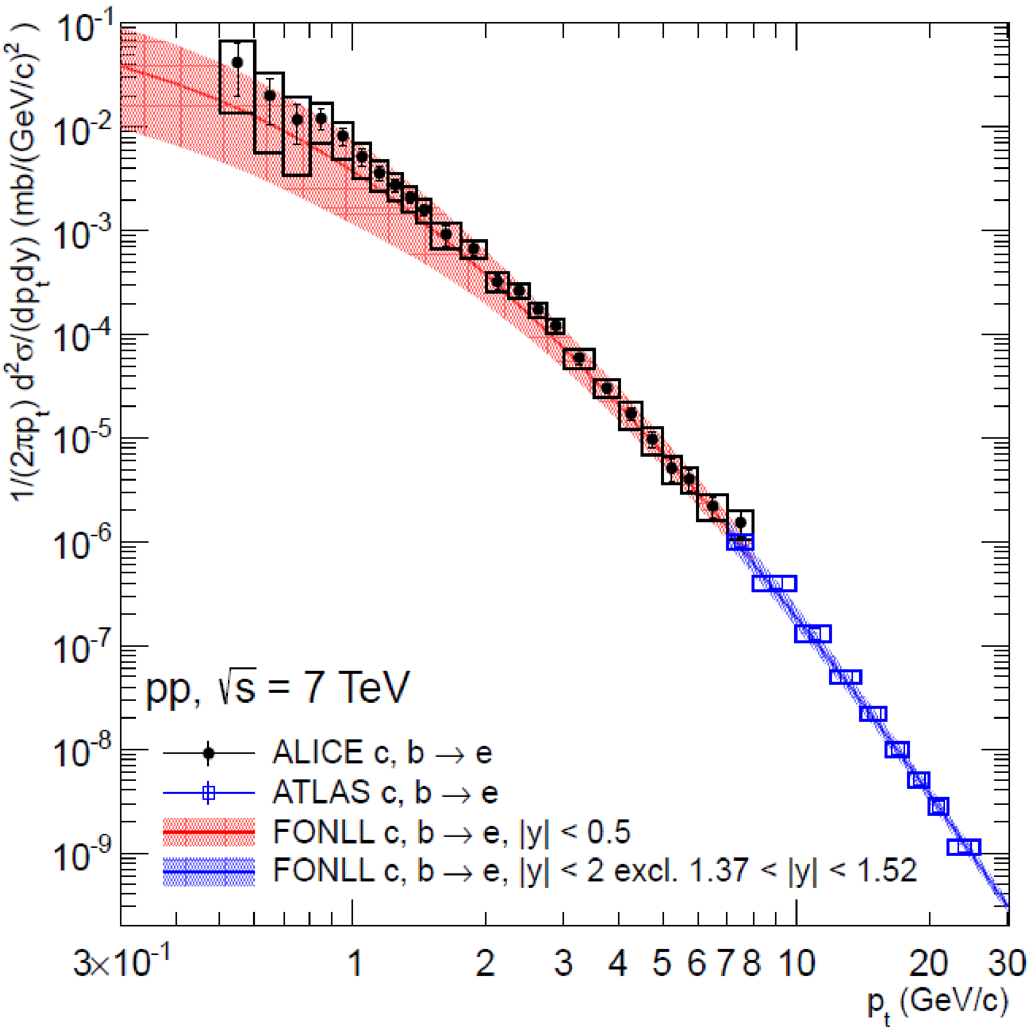




subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ), direct γ from pQCD

electrons from c and b decays

Charm and beauty electrons compared to pQCD

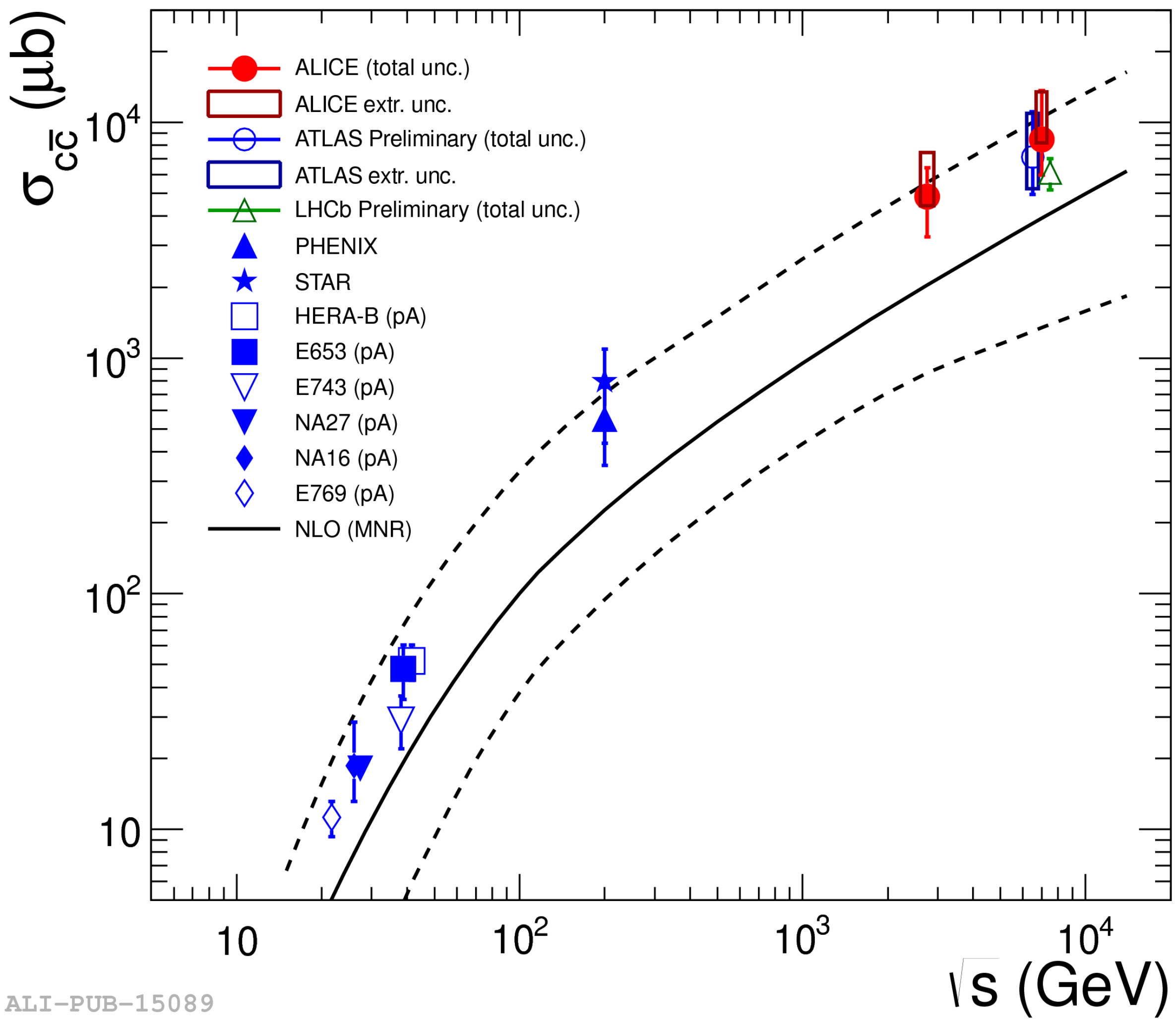


- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for $p_t <$ 3 GeV/c where charm dominates

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

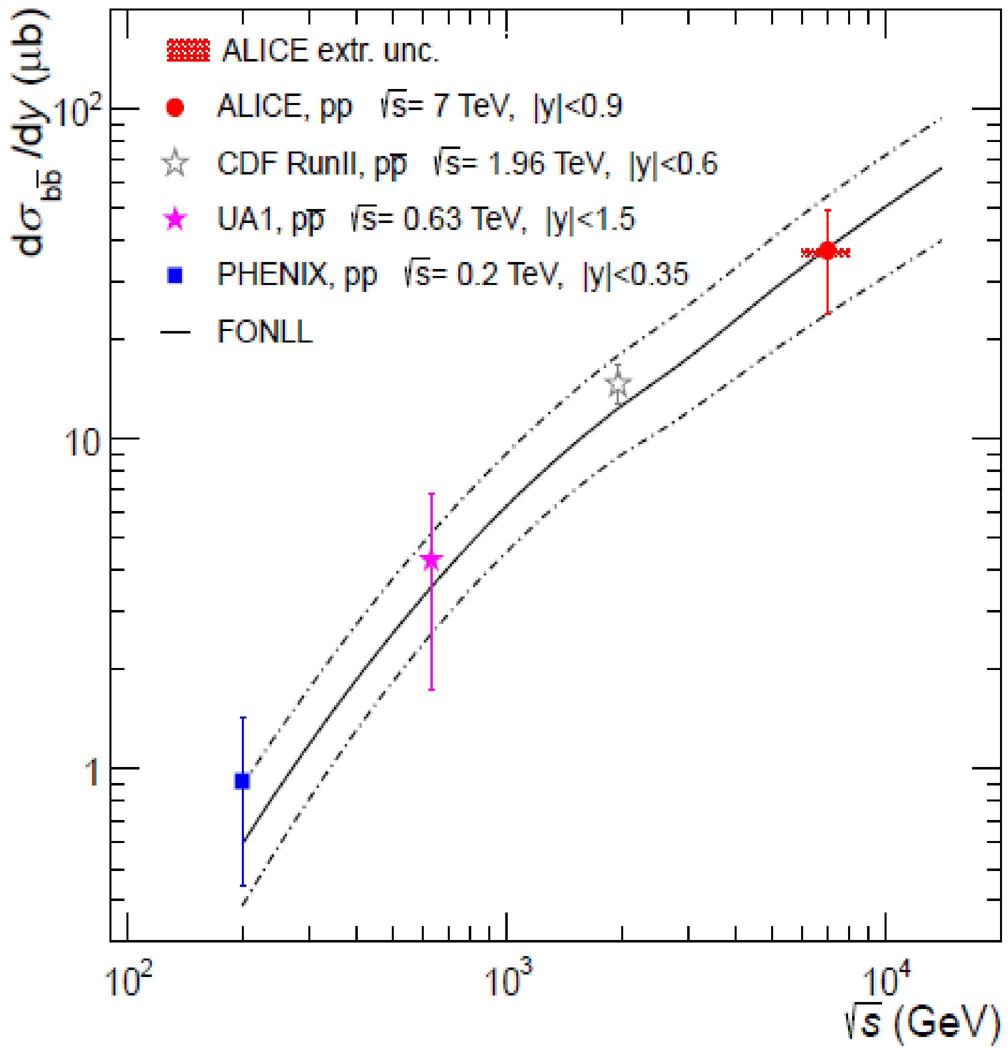
a first try at the total ccbar cross section in pp collisions

JHEP 1207 (2012) 191



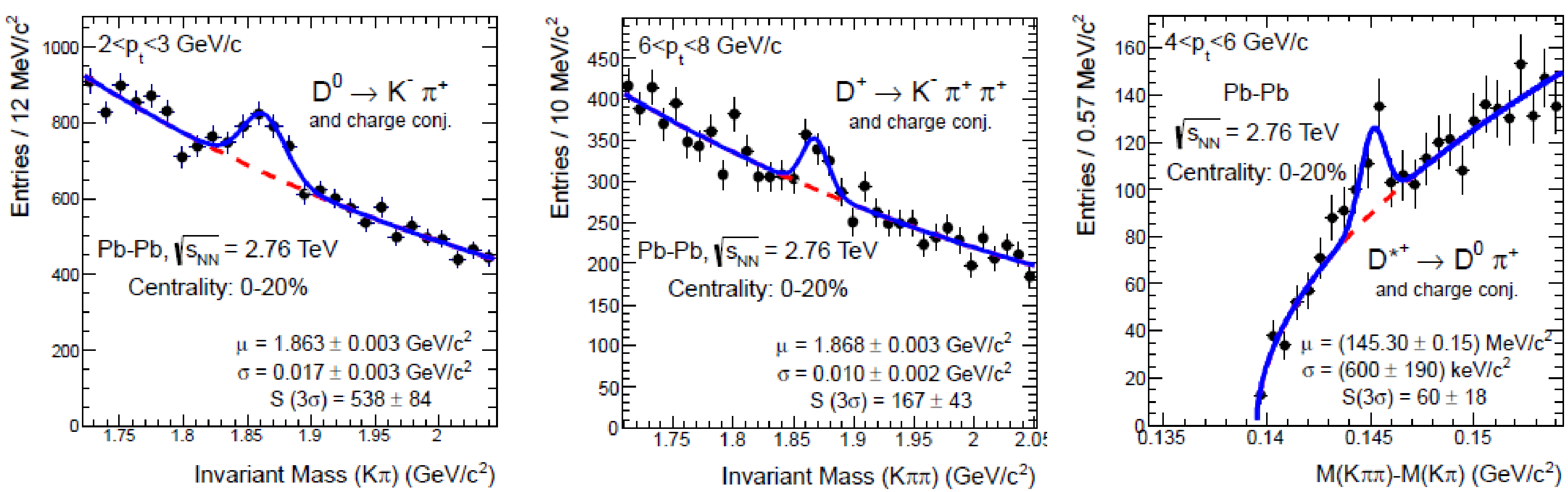
- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapola-tion to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

Beauty cross section in pp and ppbar collisions



D meson signals in Pb Pb collisions

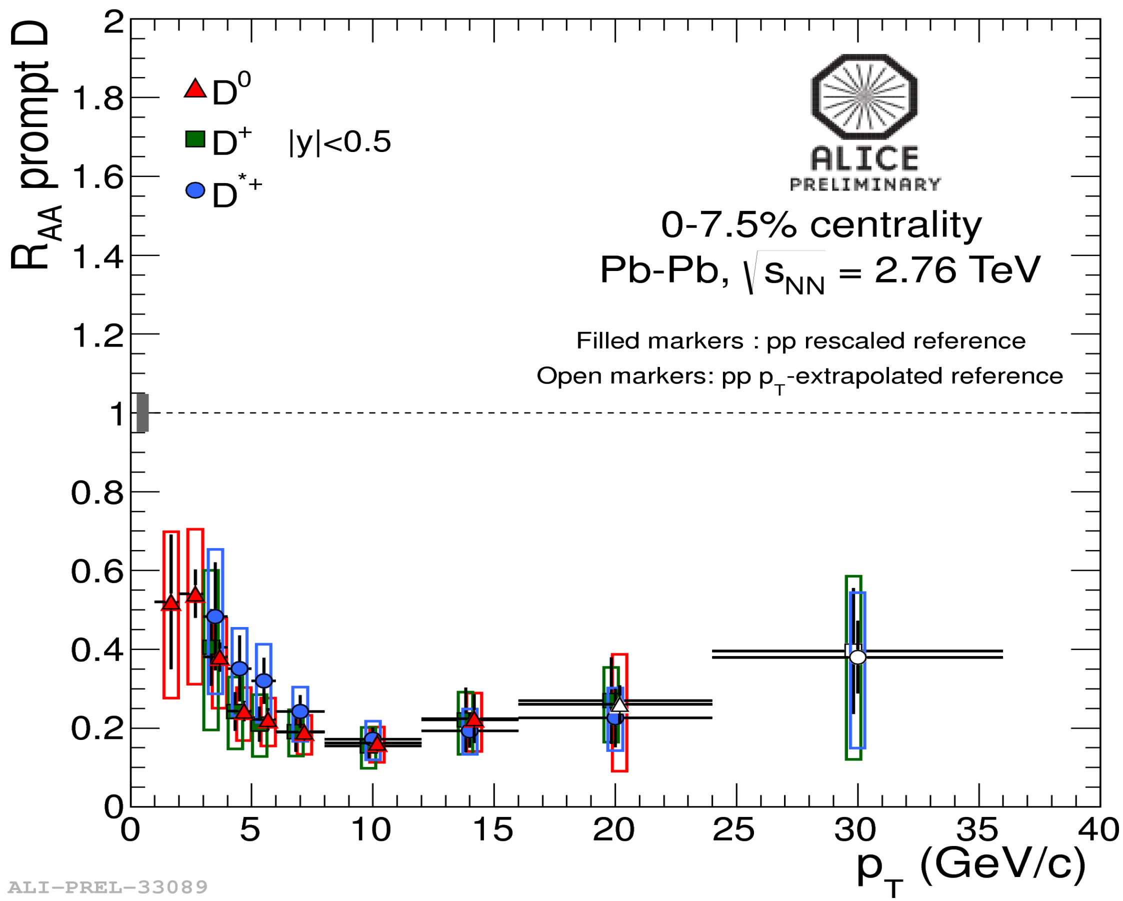
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
"   into muons (ATLAS, ALICE)



data: ALICE arXiv:1203.2160

Suppression of charm at LHC energy

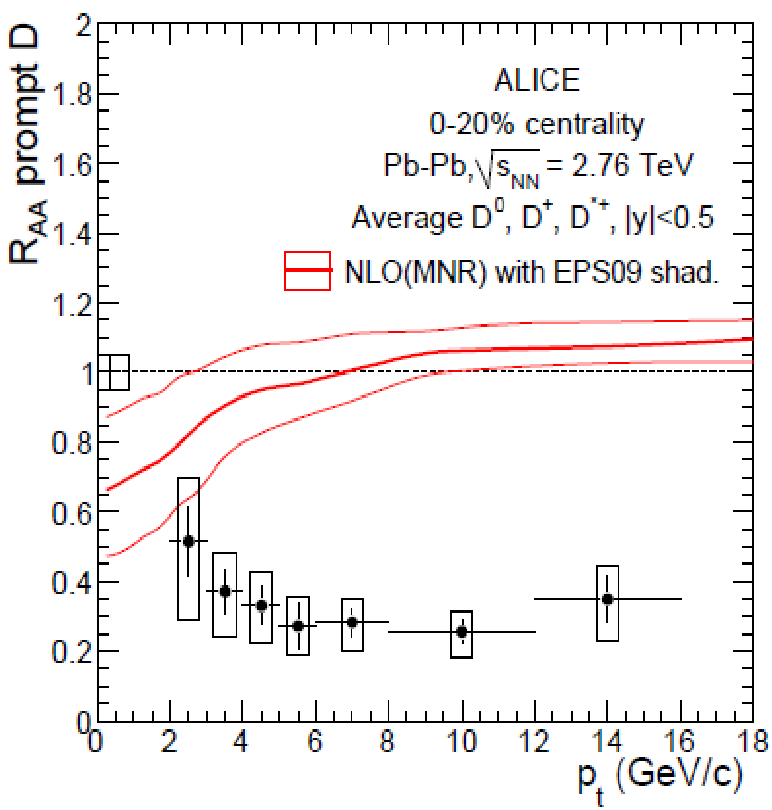
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)

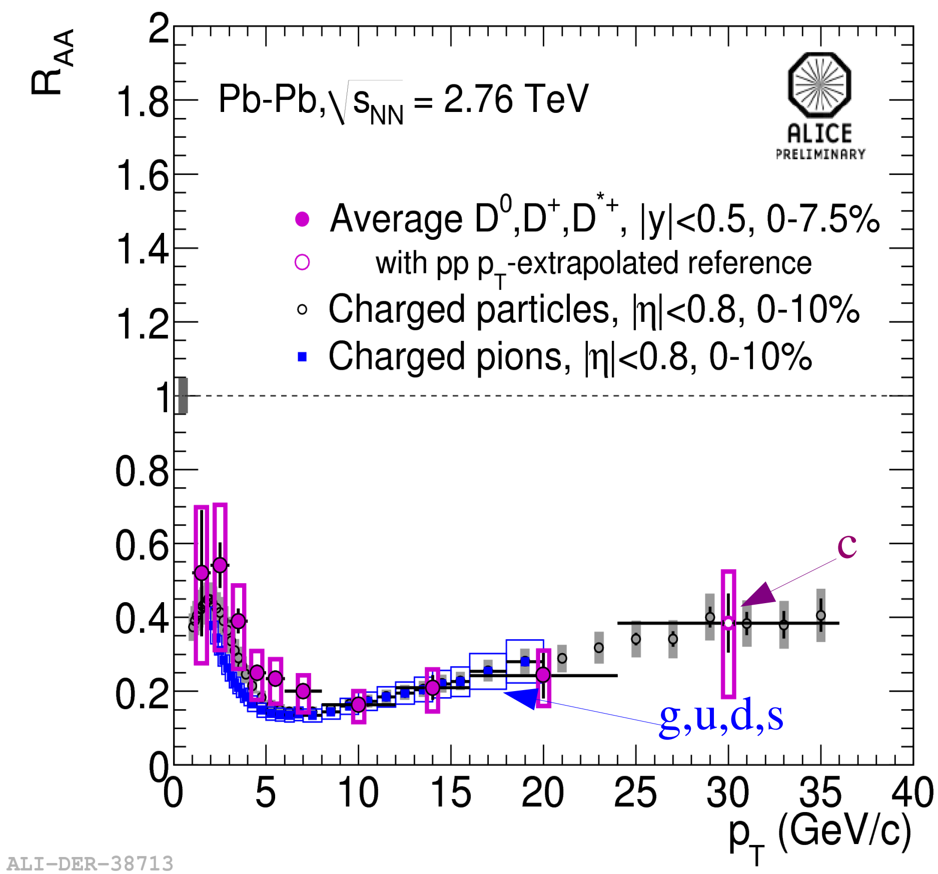


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

Suppression of charm at LHC energy

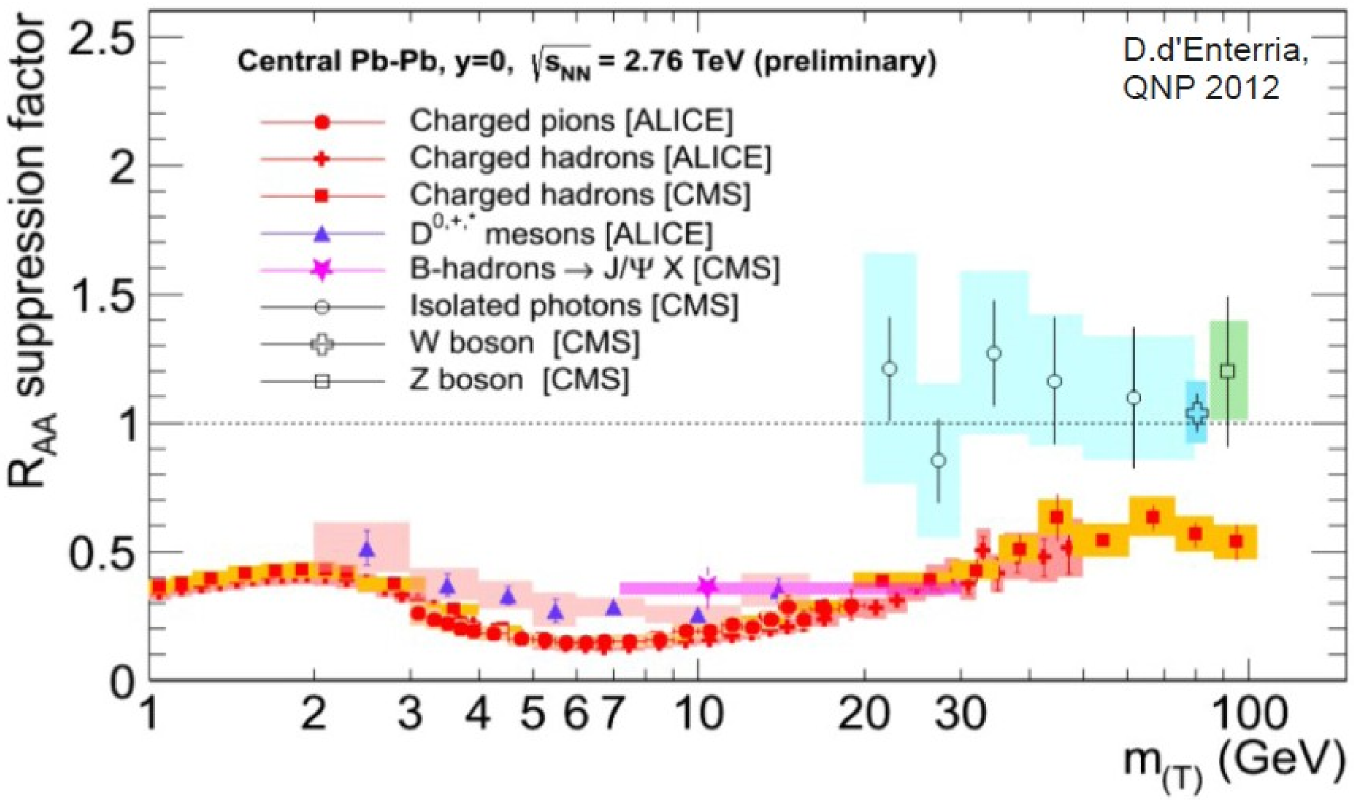
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions





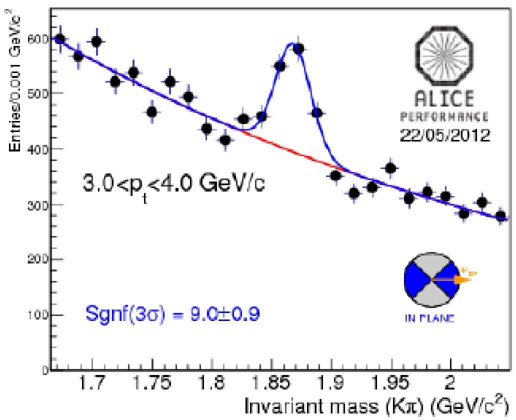
energy loss of charm quarks only slightly less than that for light quark → thermalization

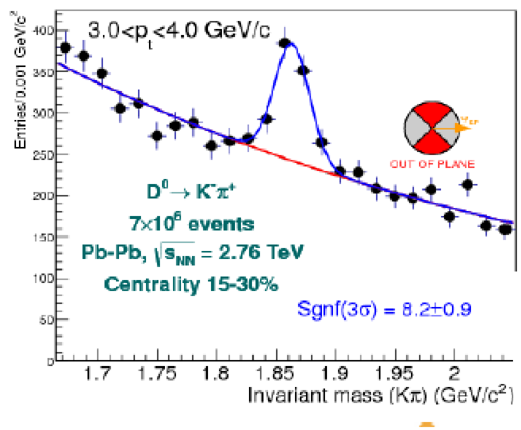
Suppression only for Strongly Interacting Hard Probes



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

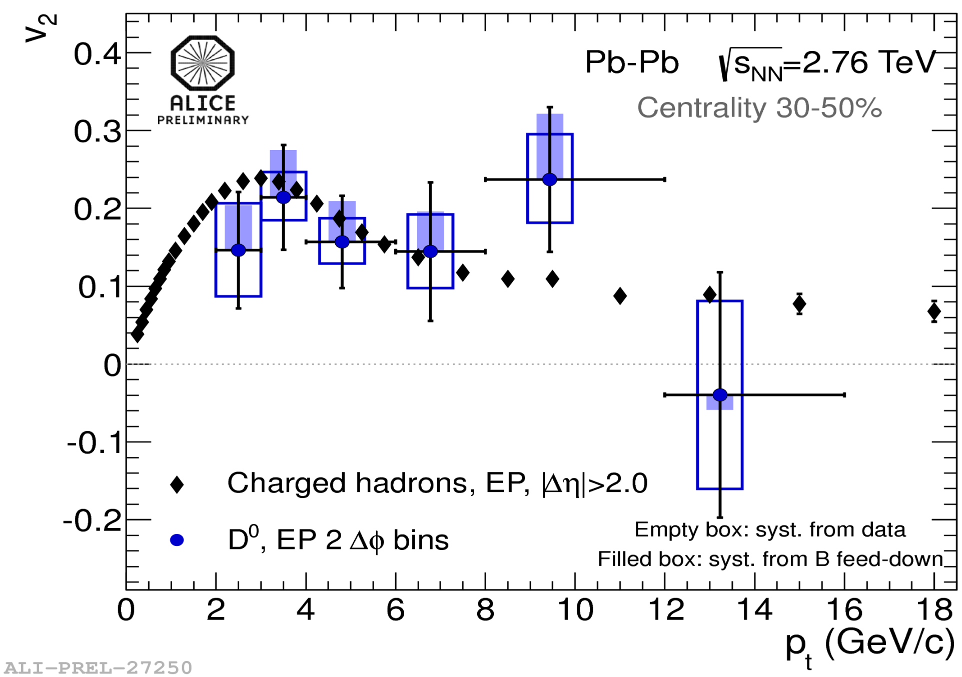
Charm Quarks also Exhibit Elliptic Flow





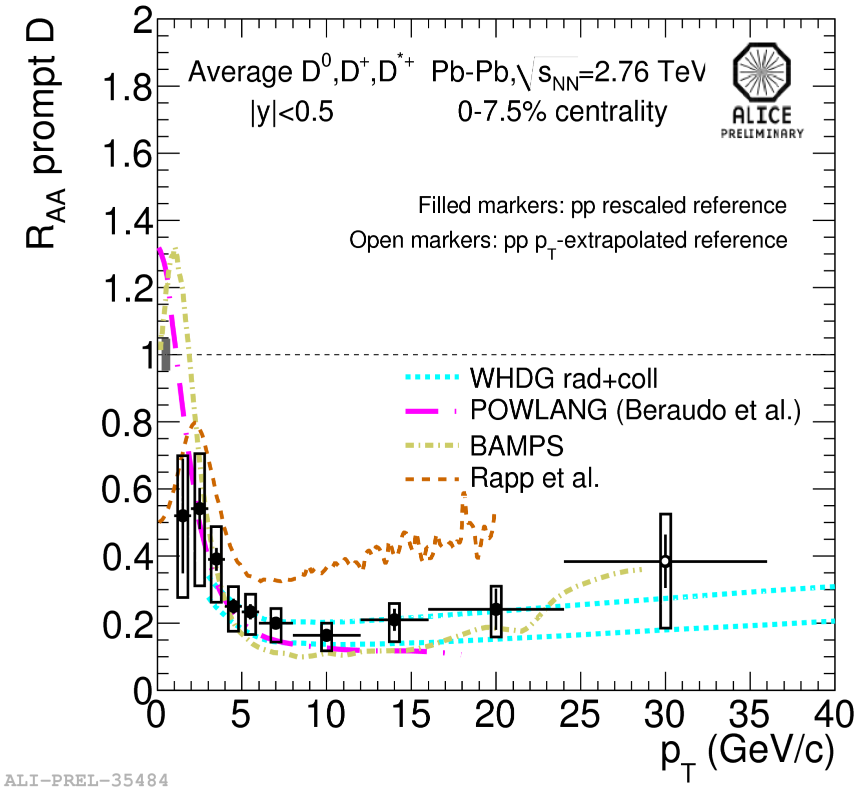
$$v_2 = \frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

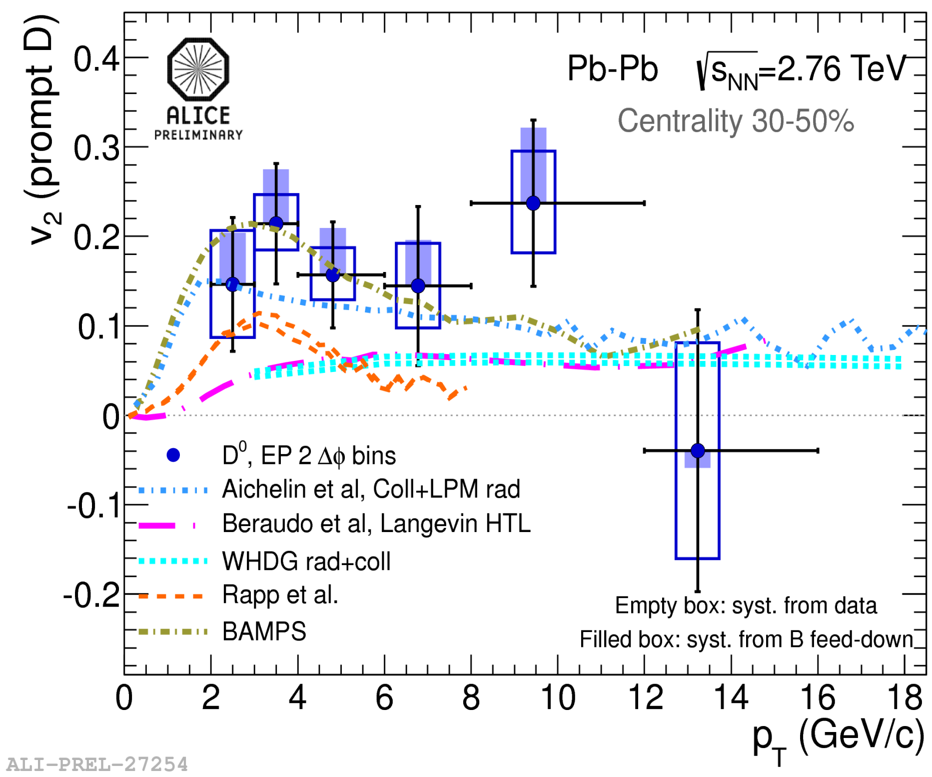
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)



non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

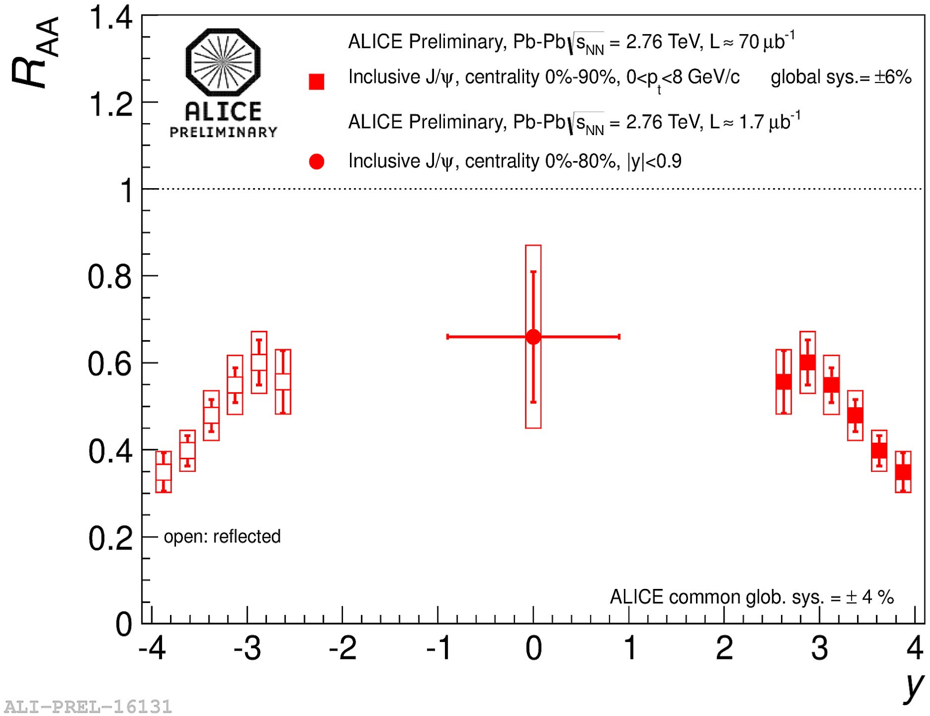
Model Description of Energy Loss and Flow of D-mesons





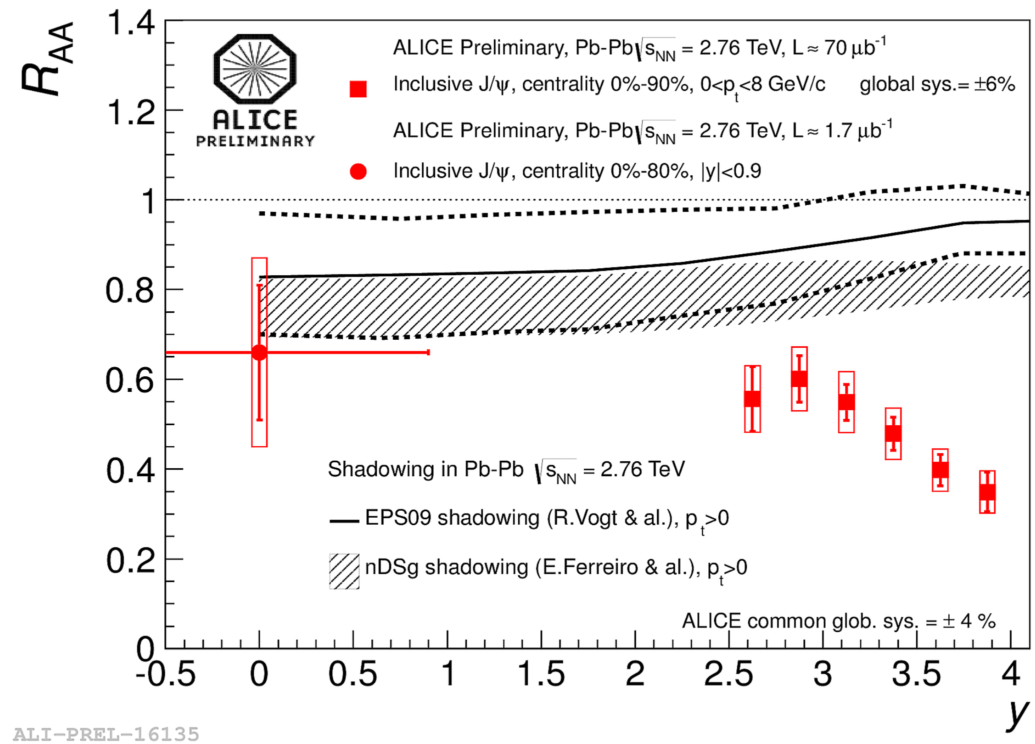
both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

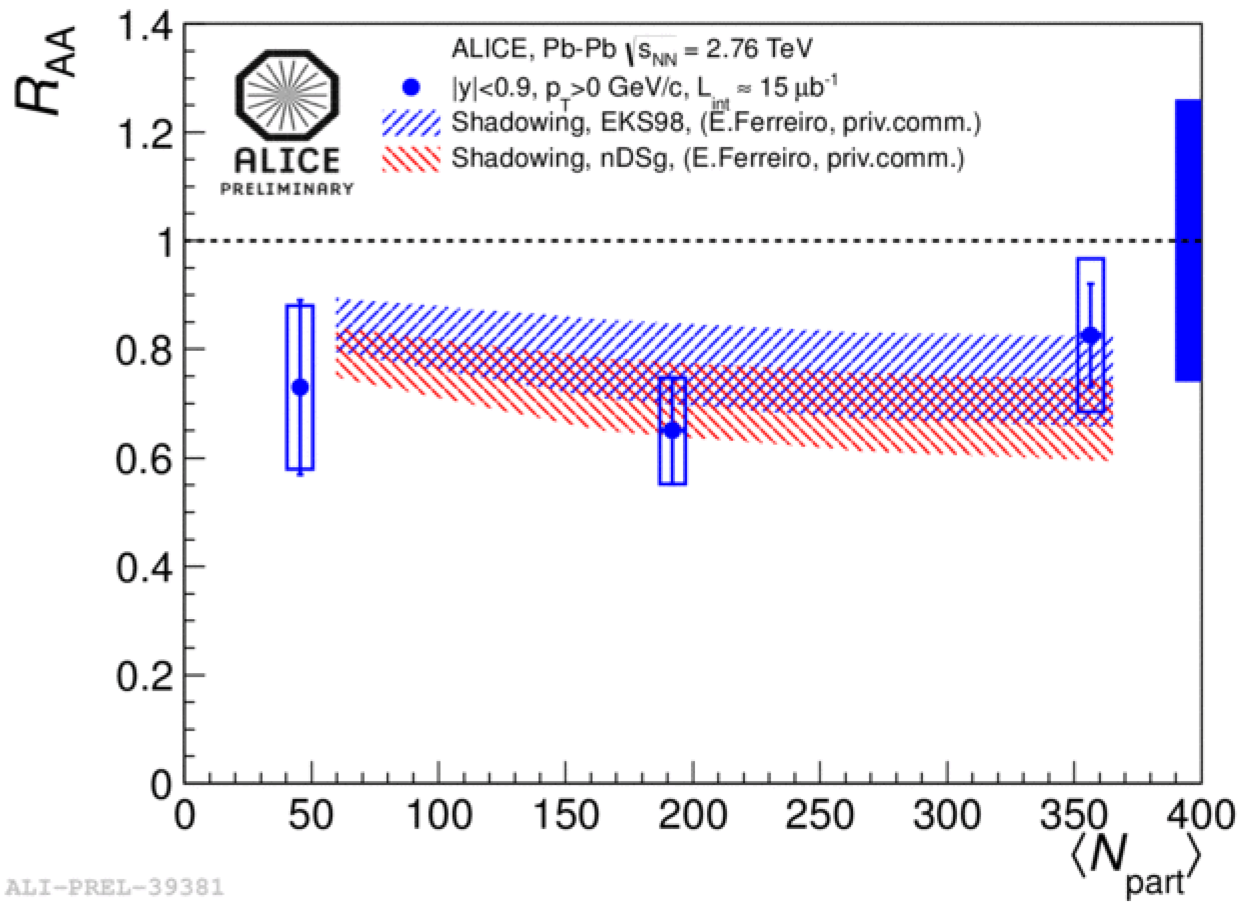
Rapidity Dependence of J/psi R_{AA}



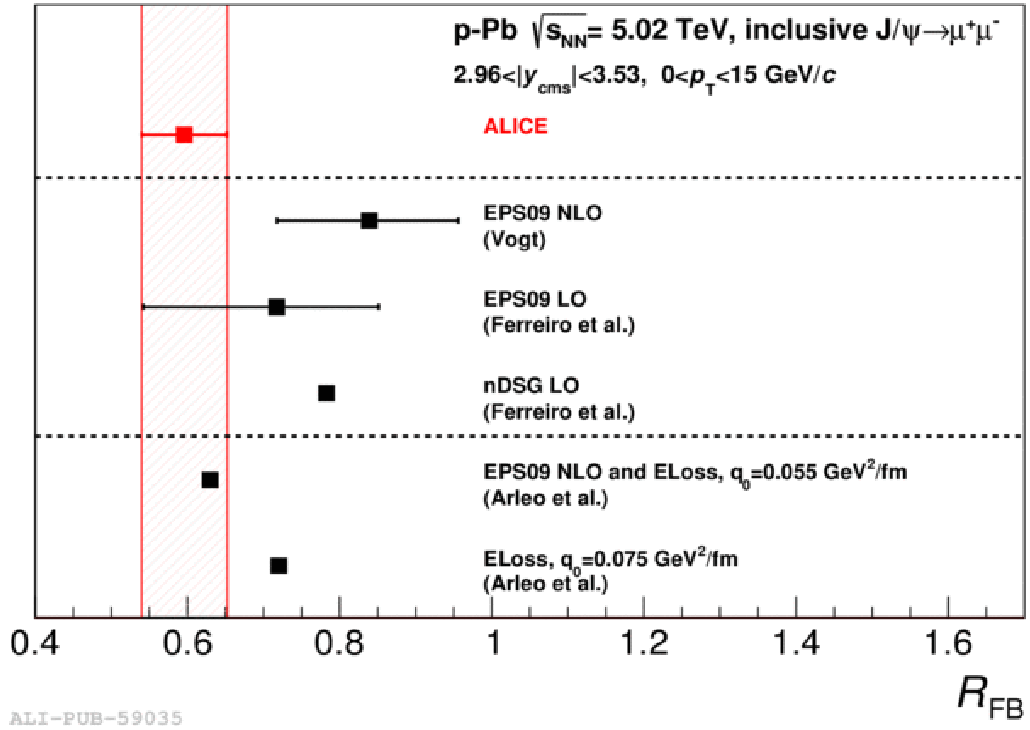
for statistical hadronization J/ψ yield proportional to N_c^2
higher yield at mid-rapidity predicted in line with observation

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



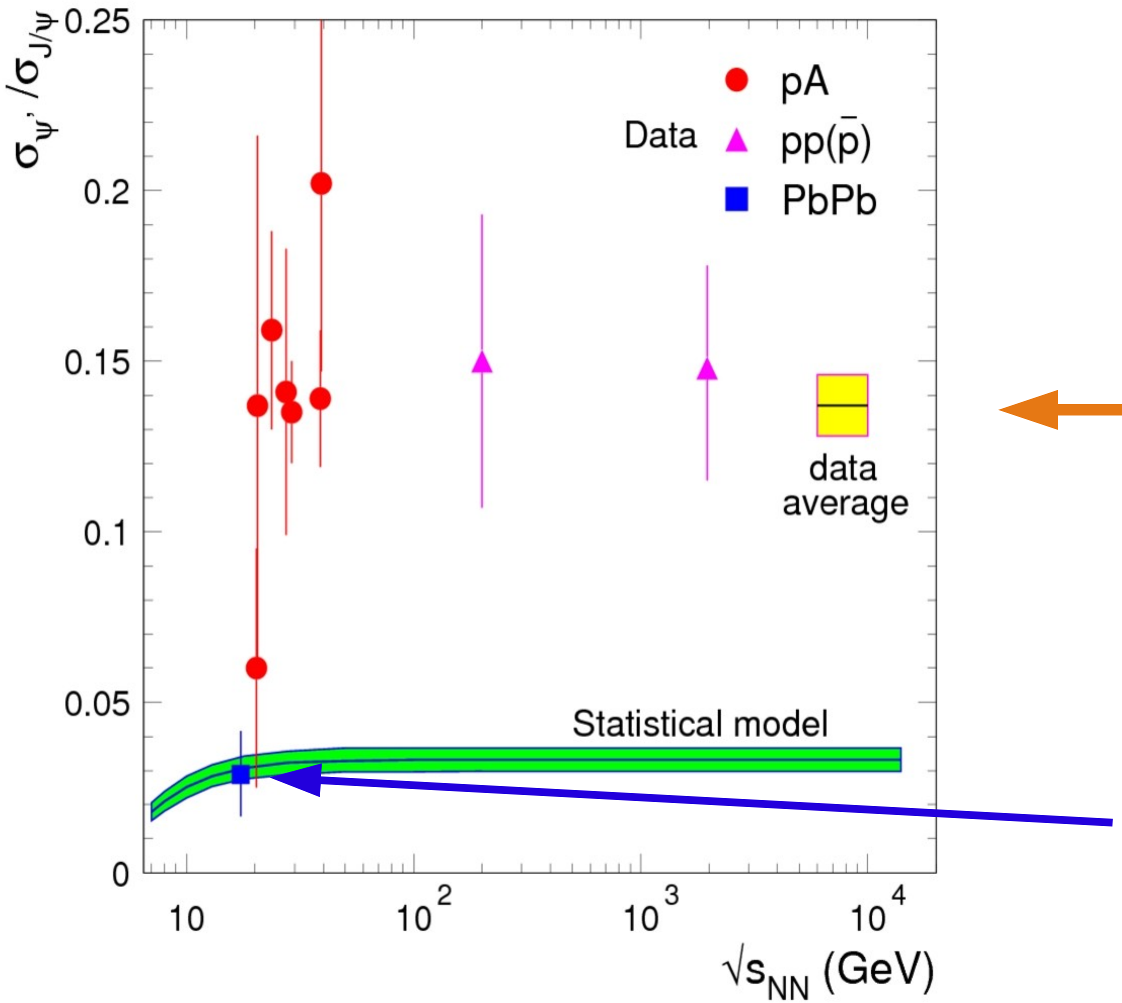


ALICE, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
|y|<0.9, p_T>0 GeV/c, $L_{int} \approx 15\ \mu b^{-1}$
Shadowing, EKS98, (E.Ferreiro, priv.comm.)
Shadowing, nDSg, (E.Ferreiro, priv.comm.)
ALICE
PRELIMINARY
R_{AA}
$\langle N_{part} \rangle$
ALI-PREL-39381



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

Statistical hadronization model predictions for psi'



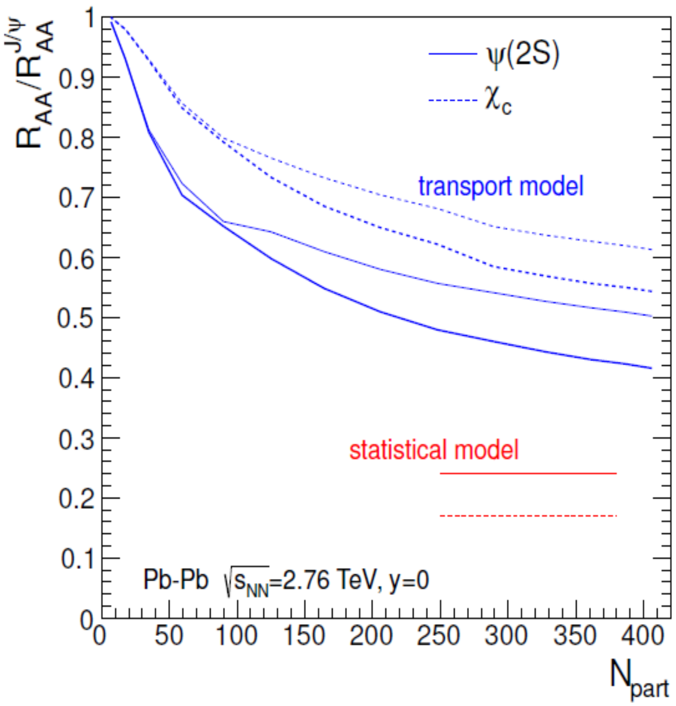
pp and pA data factor 3 above statistical hadronzation value

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!