Recent Results of ALICE: Heavy quarks in a Quark-Gluon Plasma at the LHC

- heavy quark production cross section
- energy loss of charm and beauty quarks in a QGP
- elliptic flow of heavy quarks
- charmonia and QGP

ALICE

LHC Days in Split - Croatia, October 1-6, 2012

EMMI
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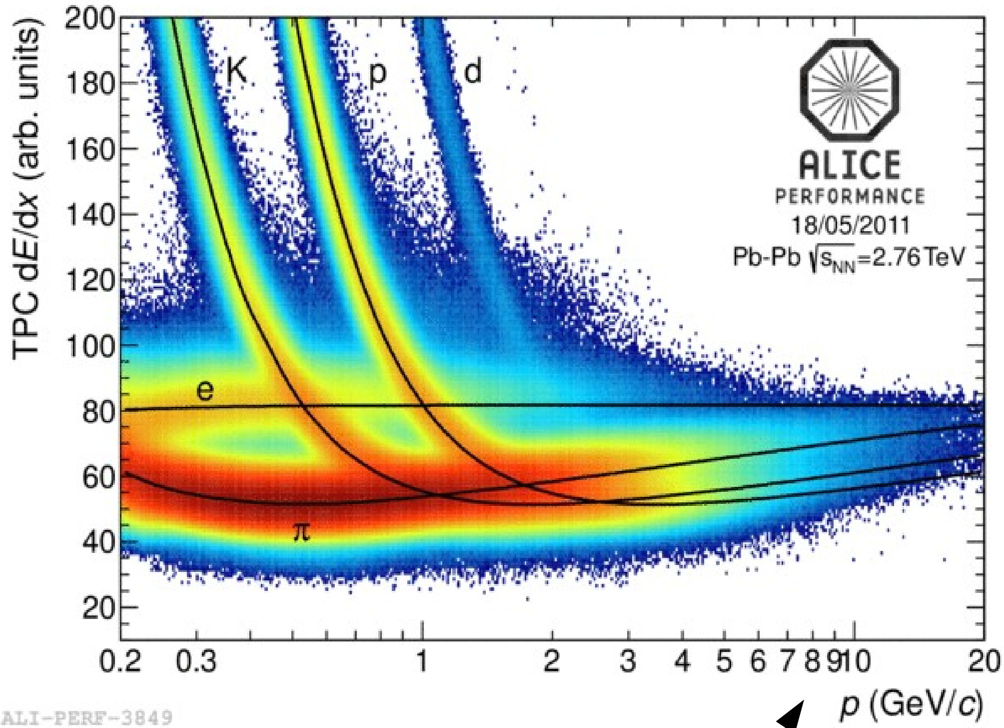
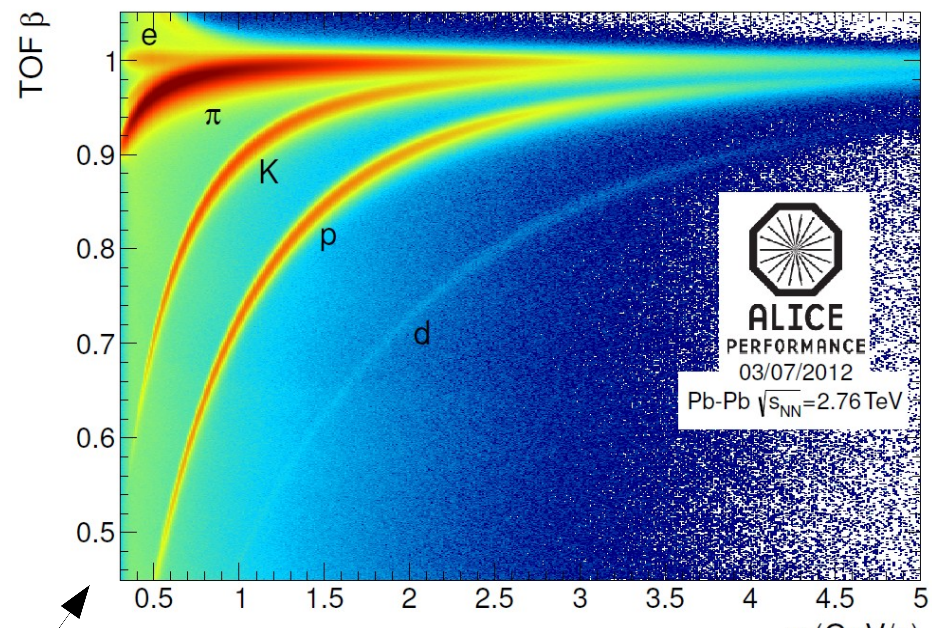
ALICE
Ruprecht-Karls-Universität Heidelberg

Particle identification in ALICE central barrel

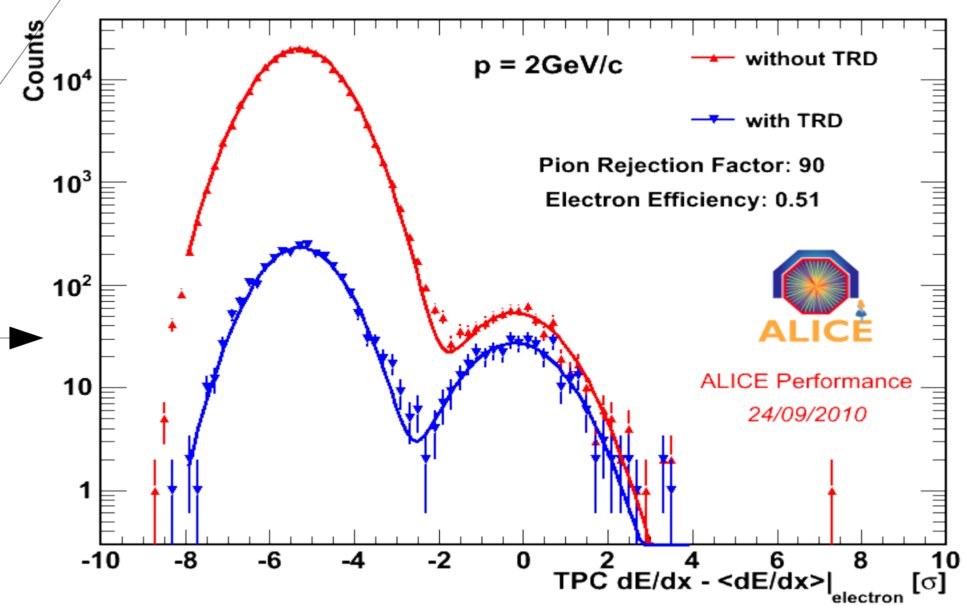




specific energy loss in TPC

time-of-flight TOF

transition radiation with TRD

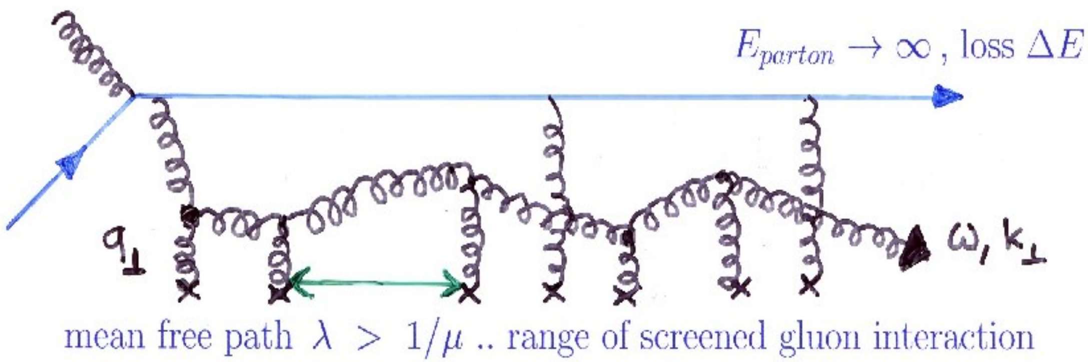


Jet Quenching and Parton Energy Loss in QGP

jet: a parton (quark or gluon) from an initial hard scattering hadronizes into a collimated cone of hadrons
typical cone angle < 1 rad
leading hadron carries 10-20 % of jet momentum, rest softer

prediction: in dense partonic matter a jet is losing energy rapidly, order GeV/fm
governed by a transport coefficient dependent e.g. on density of color charge carriers

$$\hat{q} = \frac{\langle k_\perp^2 \rangle}{\lambda}$$



final jet carries information about the medium it traverses

in an analytic approximation (BDMPS)

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

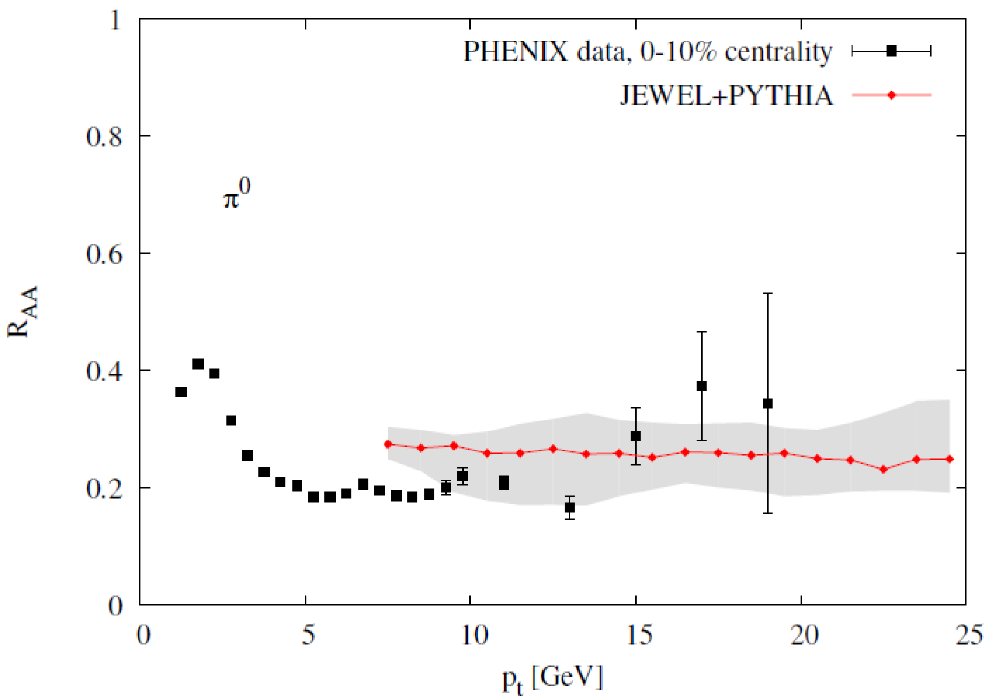
Evolution of pQCD jet in the QGP medium

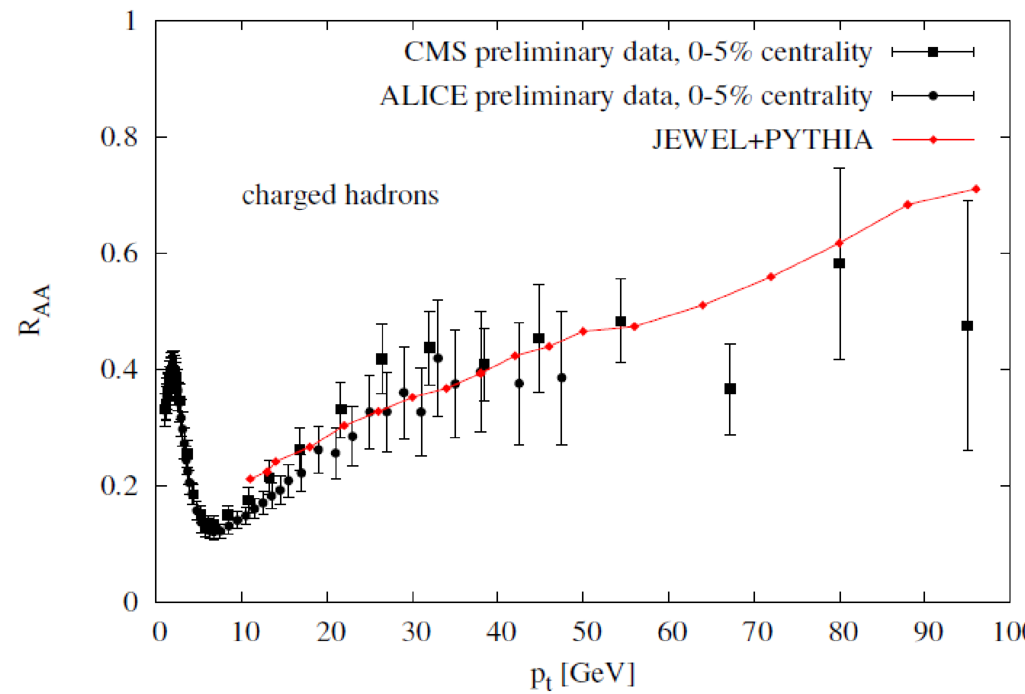
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$

see dedicated talk by A.O.Velasquez

K. Zapp, F. Krauss, U. Wiedemann arXiv:1111.6838

modeling of multiple scattering in the medium via infrared continued 2 → 2 scattering matrix element in pQCD and in-medium parton shower for further emissions





RHIC: Ti = 350 MeV τi = 0.8 fm/c
scale is set by final state particle multiplicity

LHC: Ti = 530 MeV τi = 0.5 fm/c
different shape vs RHIC due to √s dependence of hard scattering processes

Open charm - charm quarks in the quark gluon plasma

interest 2-fold:

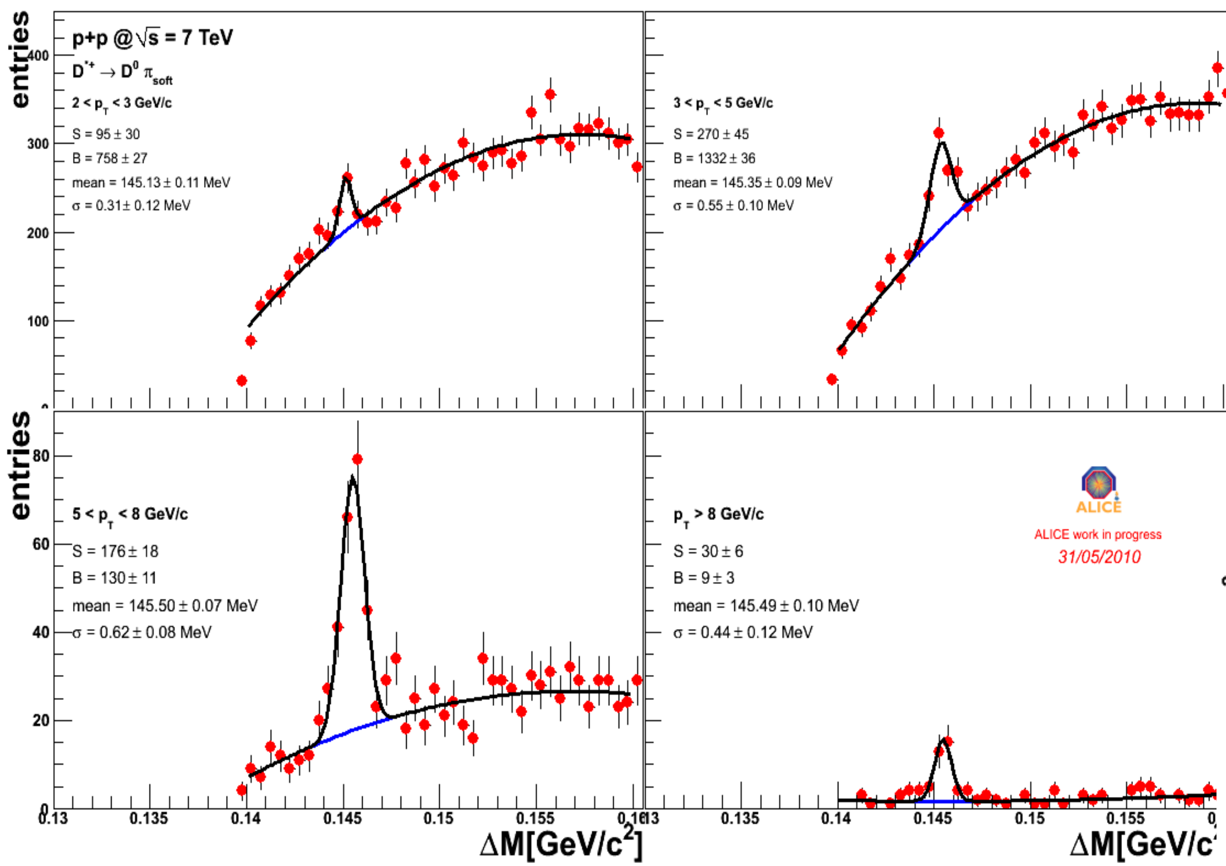
- transport coefficient for heavy quarks?

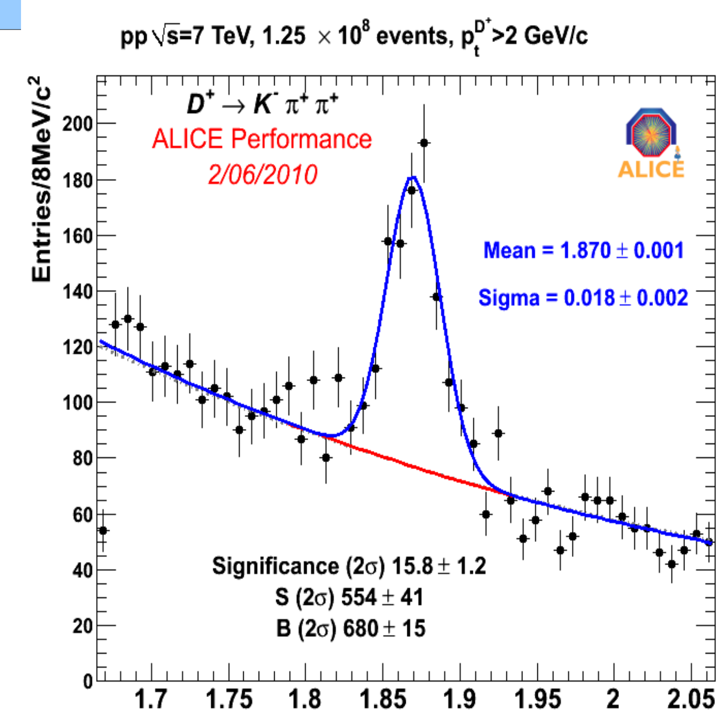
also energy loss of heavy quark - radiative energy loss should be suppressed due to large mass (1.2 GeV); in vaccum gluon radiation into angles $\theta \leq \frac{m_q}{E_q}$ suppressed (Dokshitzer and Kharzeev)
and Casimir factor $C_q = 4/3$ vs $C_{gluon} = 3$

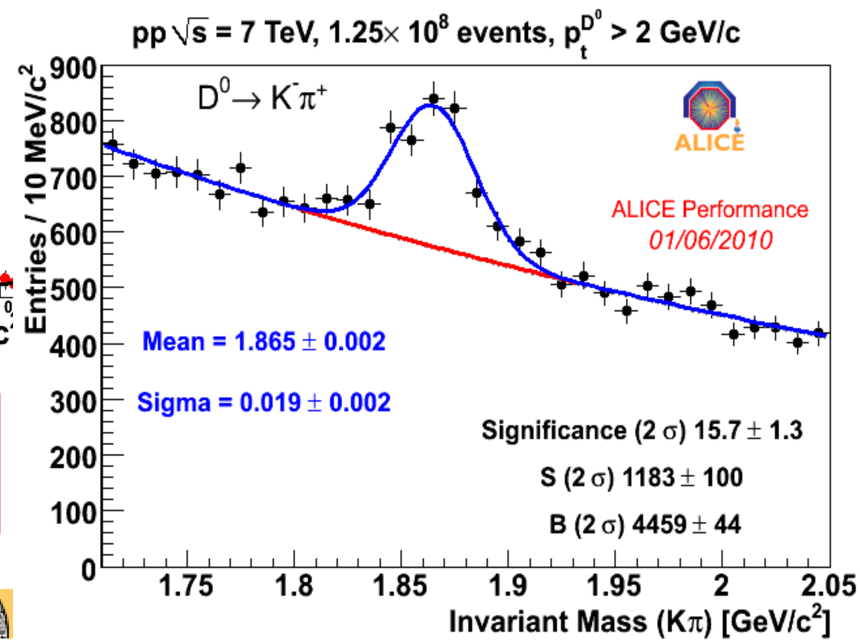
- need total charm cross section for understanding of charmonia (ccbar states)

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

1.25 10^8 events

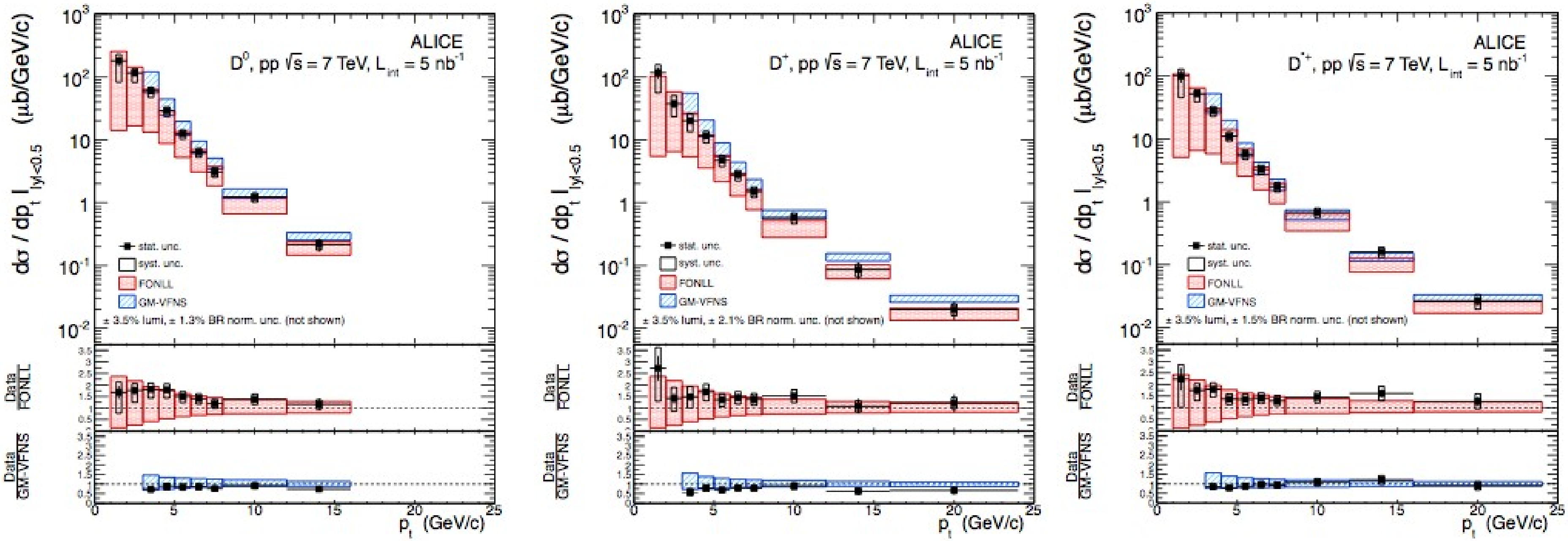






for 10^9 events, expect to measure open charm for
p_t = 0.5 – 15 GeV/c

Measurements agree well with state of the art pQCD calculations



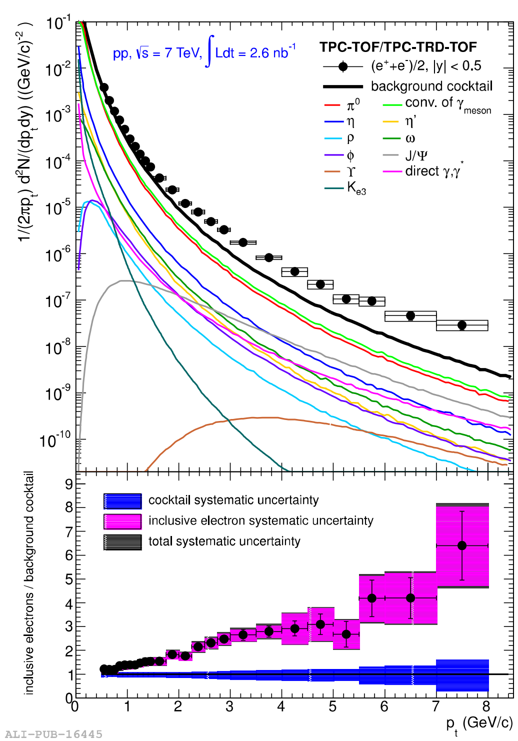
JHEP1201(2012)128

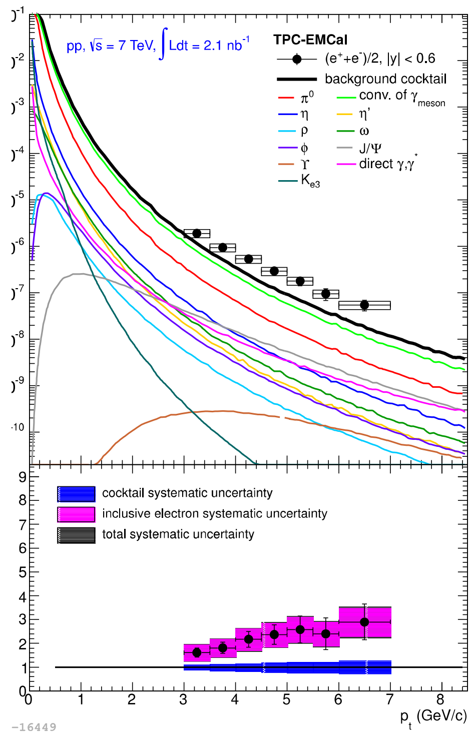
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

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

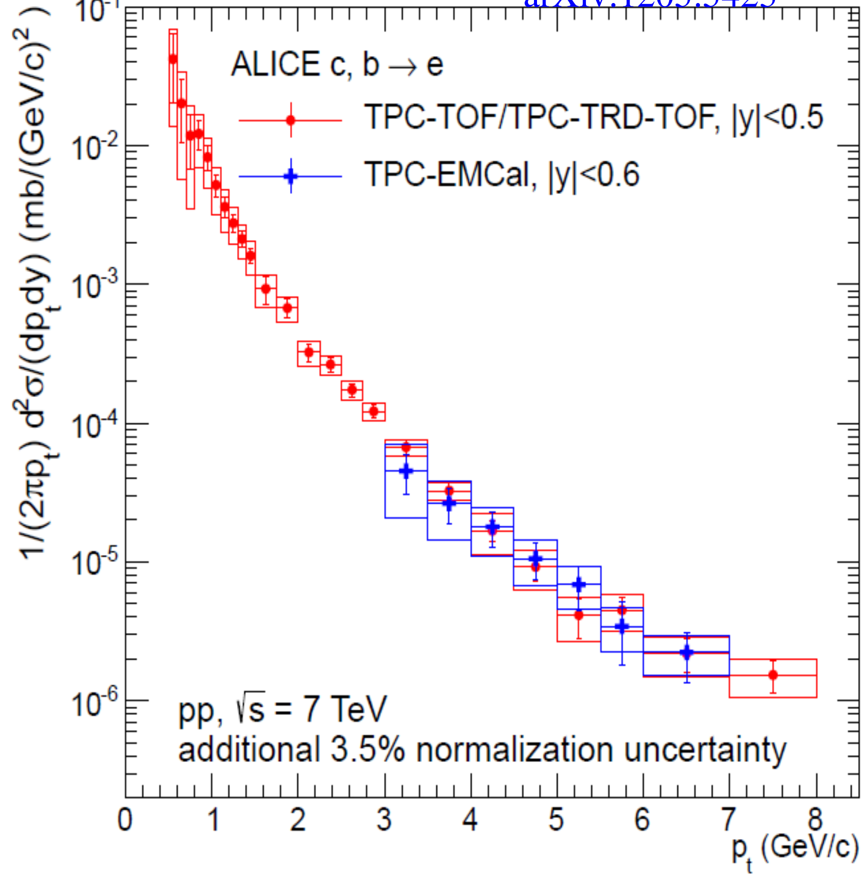
Charm and beauty via semi-leptonic decays

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





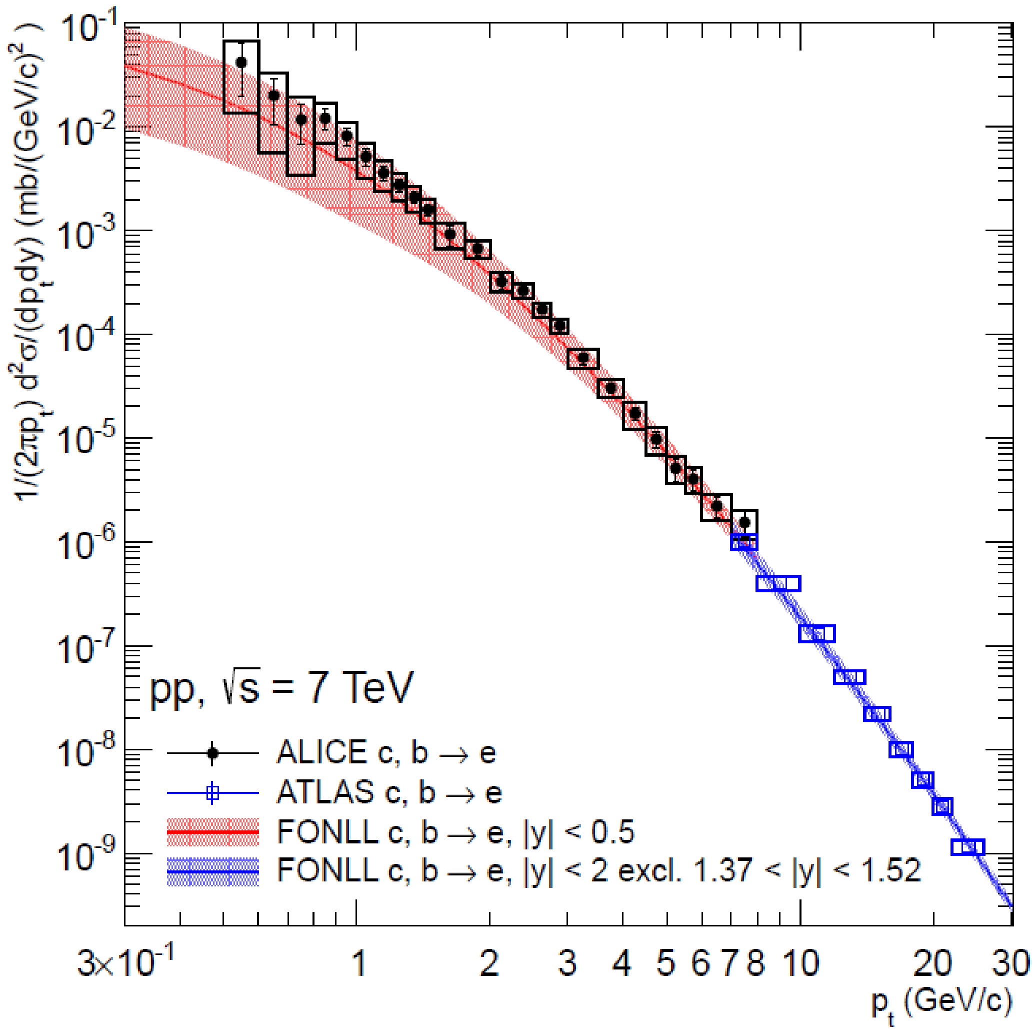
arXiv:1205.5423



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

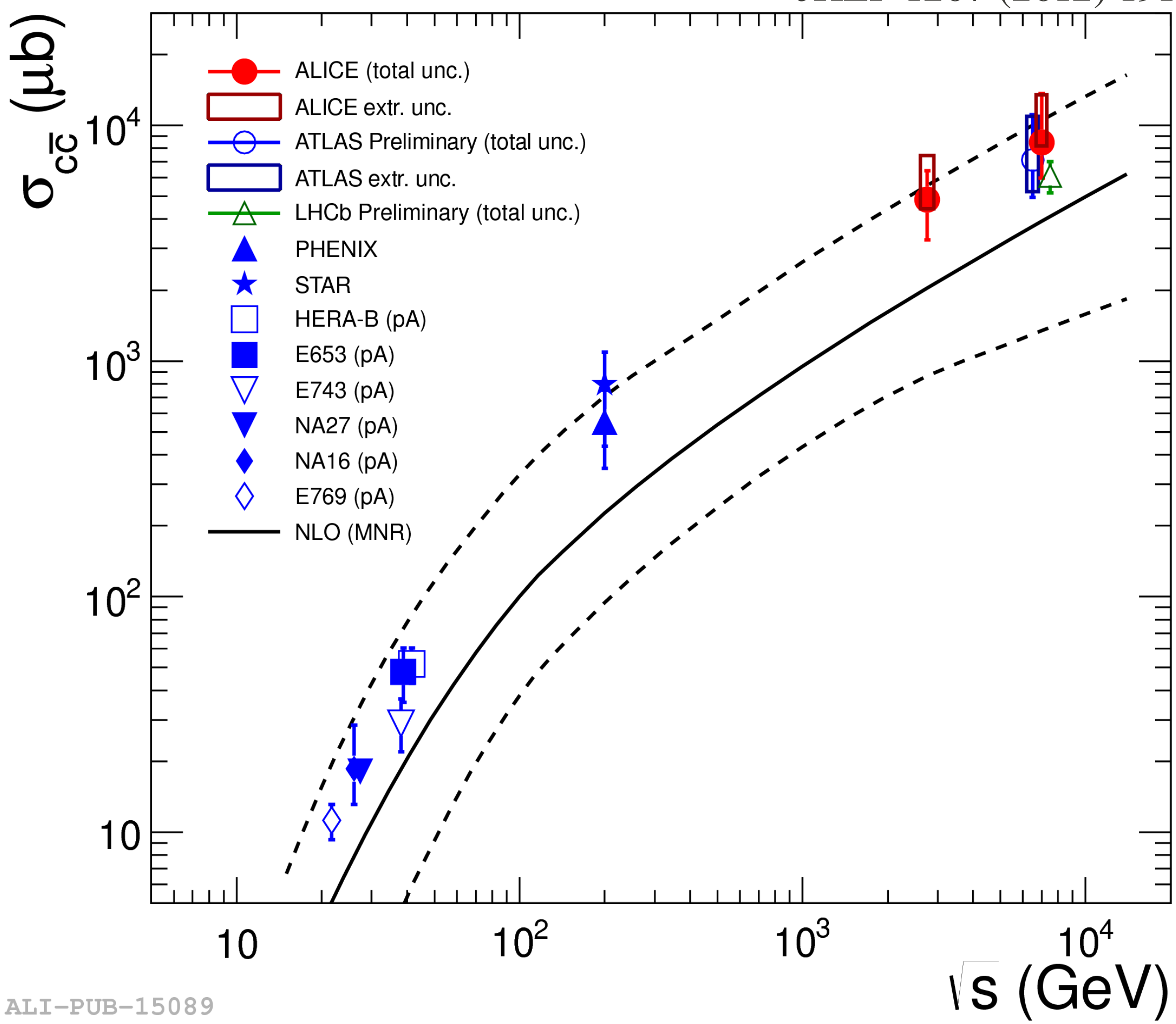


- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

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

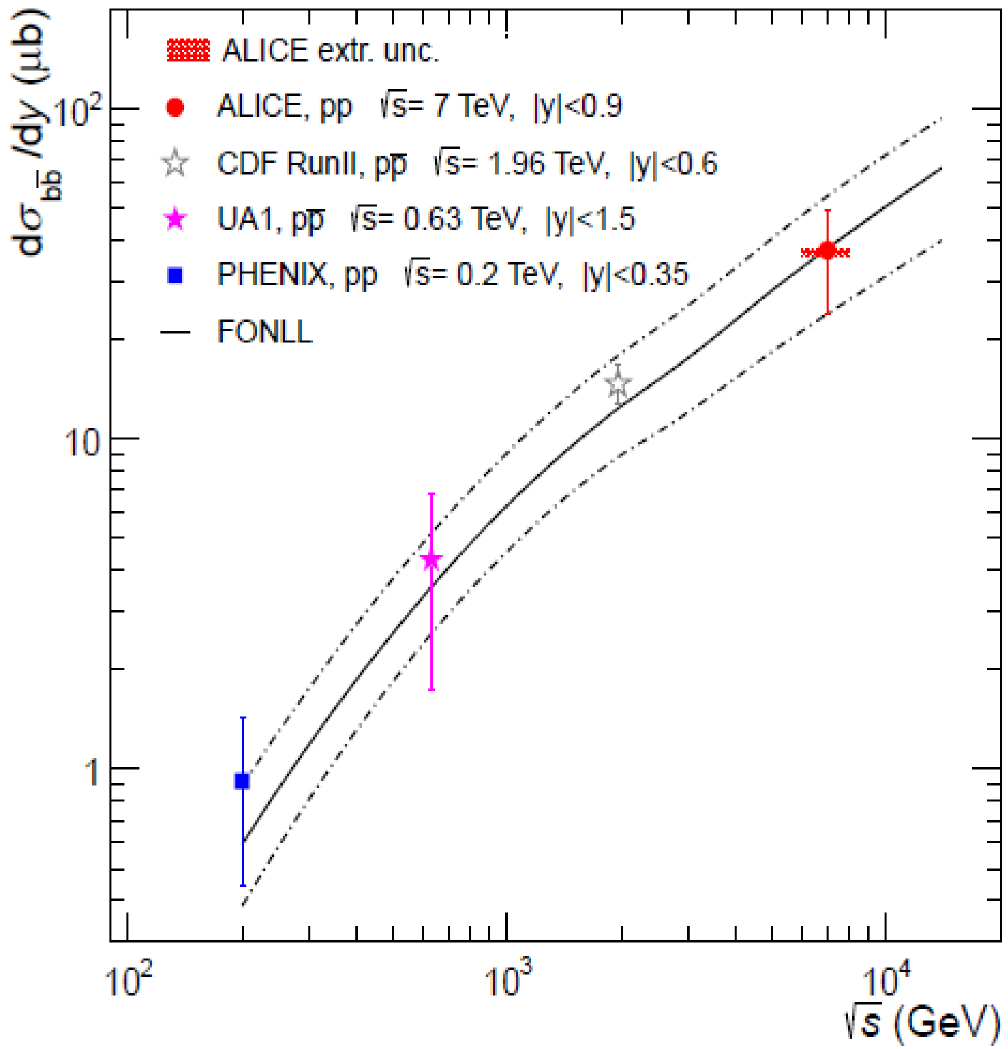
a first try at the total ccbar cross section in pp collisions

JHEP 1207 (2012) 191



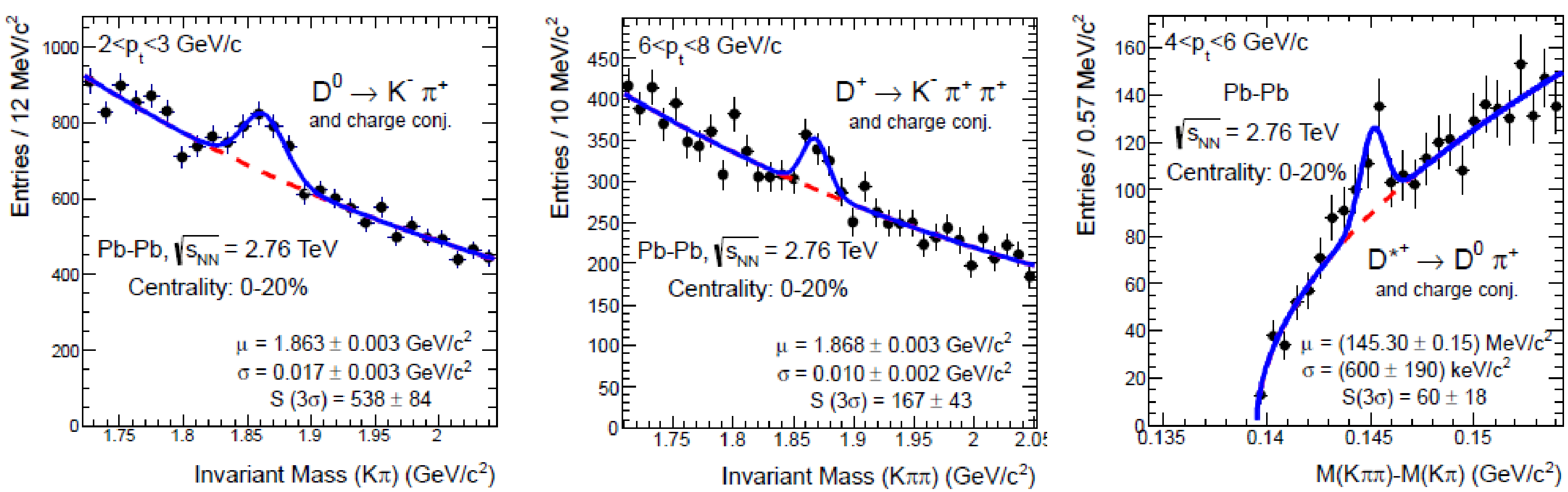
- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

Beauty cross section in pp and ppbar collisions



D meson signals in Pb Pb collisions

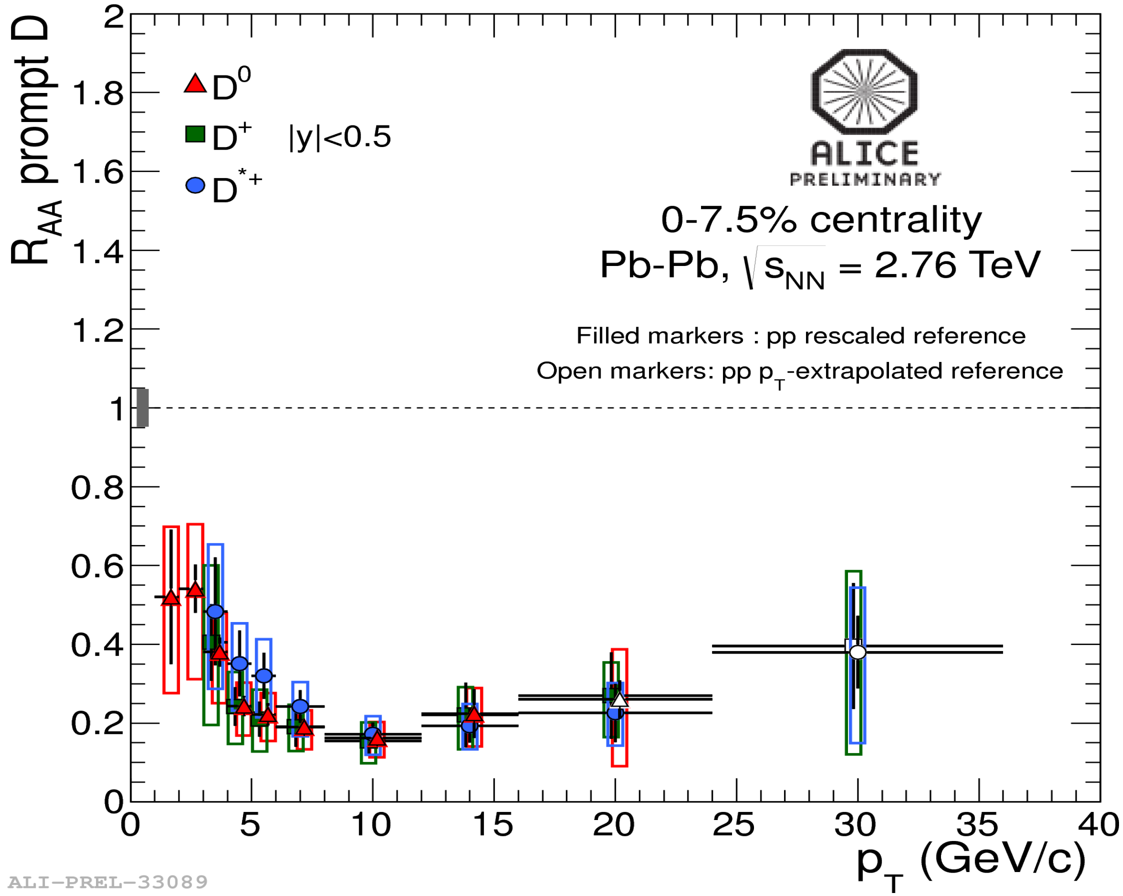
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
“ into muons (ATLAS, ALICE)



data: ALICE arXiv:1203.2160

Suppression of charm at LHC energy

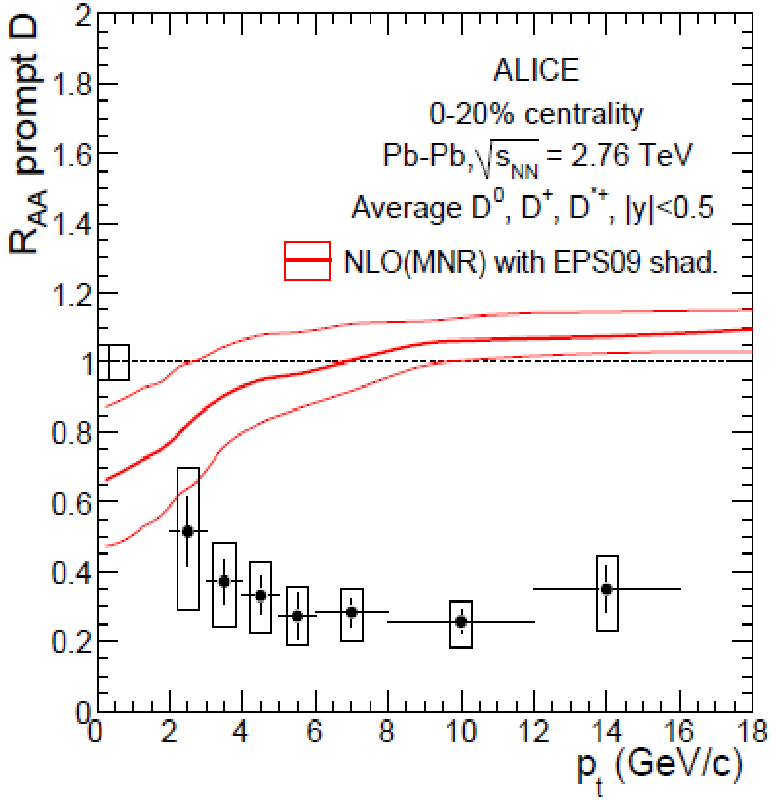
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)

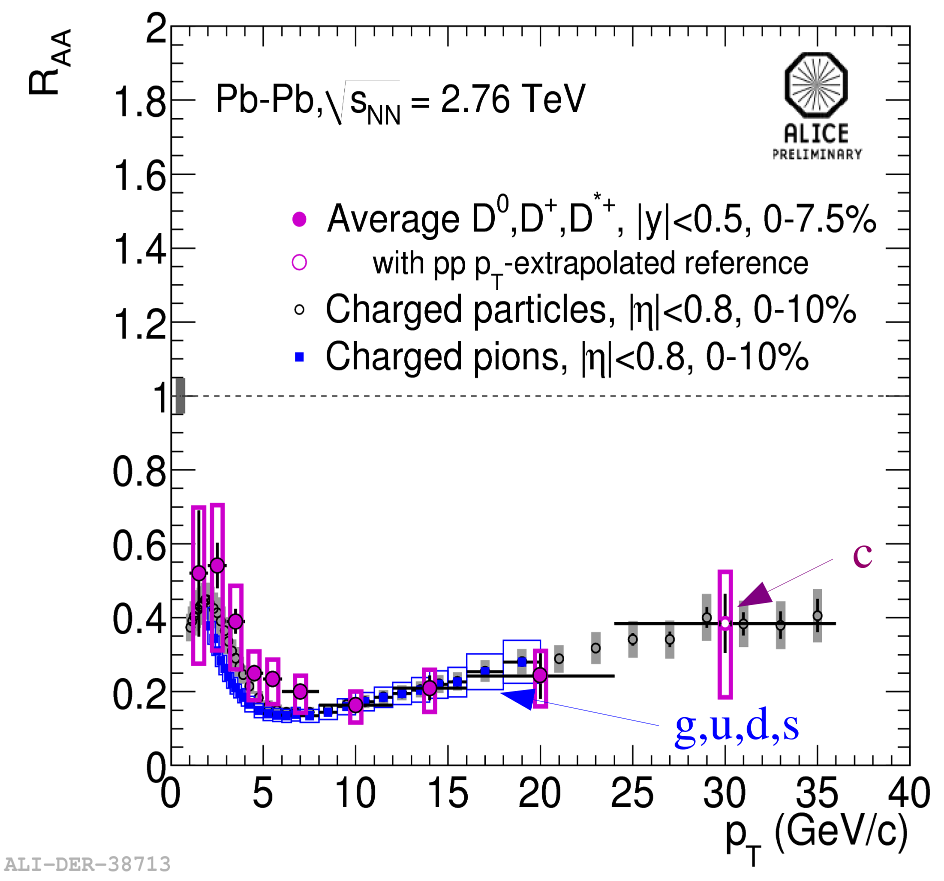


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

Suppression of charm at LHC energy

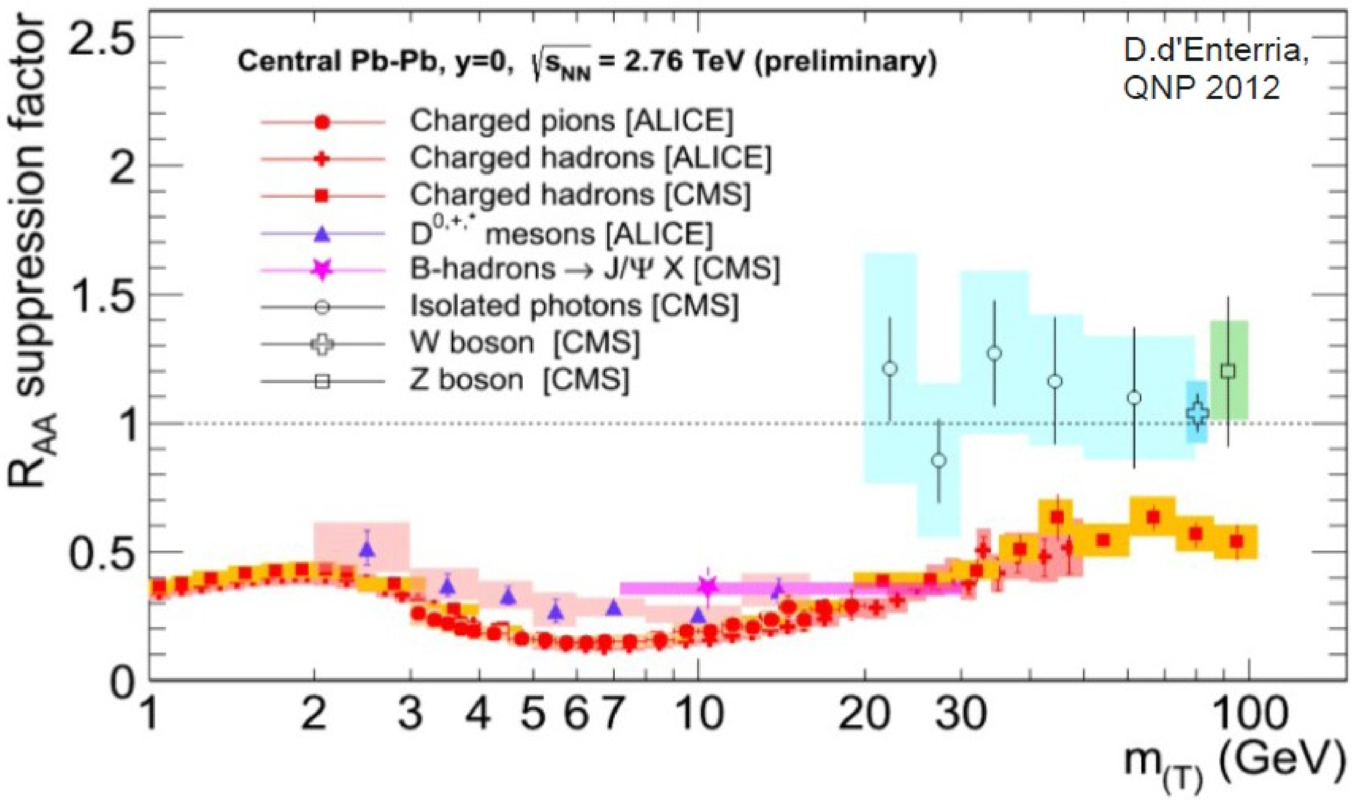
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions





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

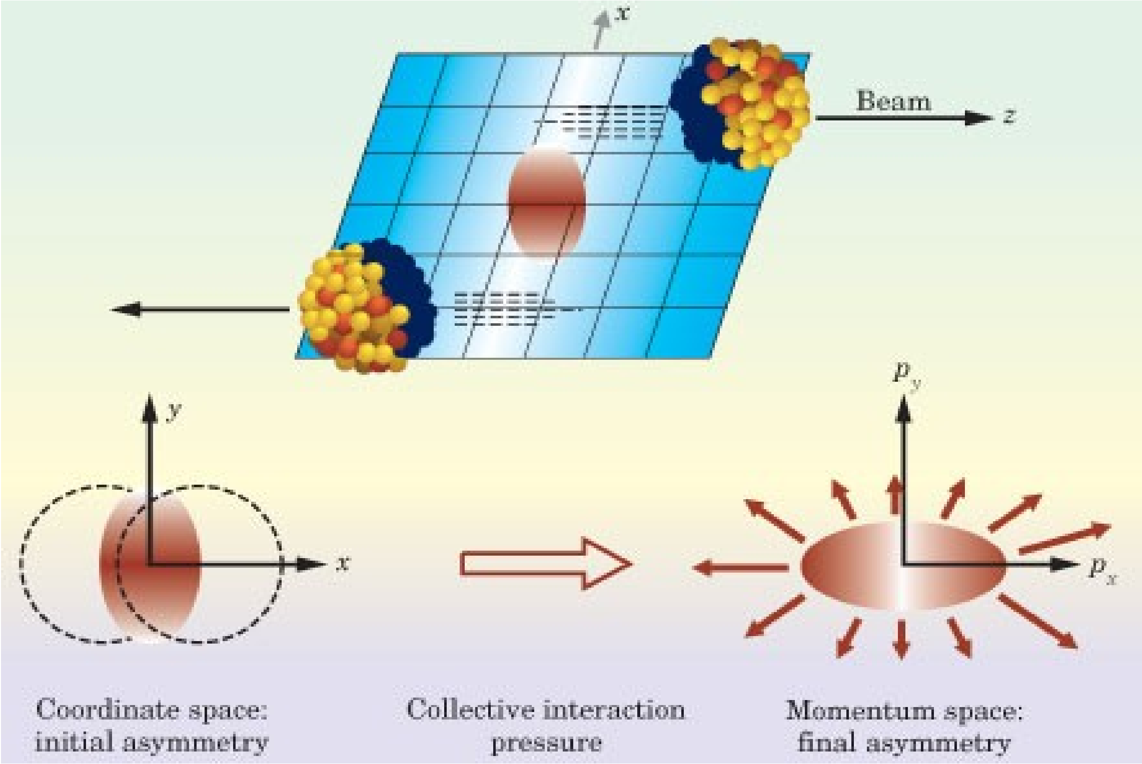
Suppression only for Strongly Interacting Hard Probes



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

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

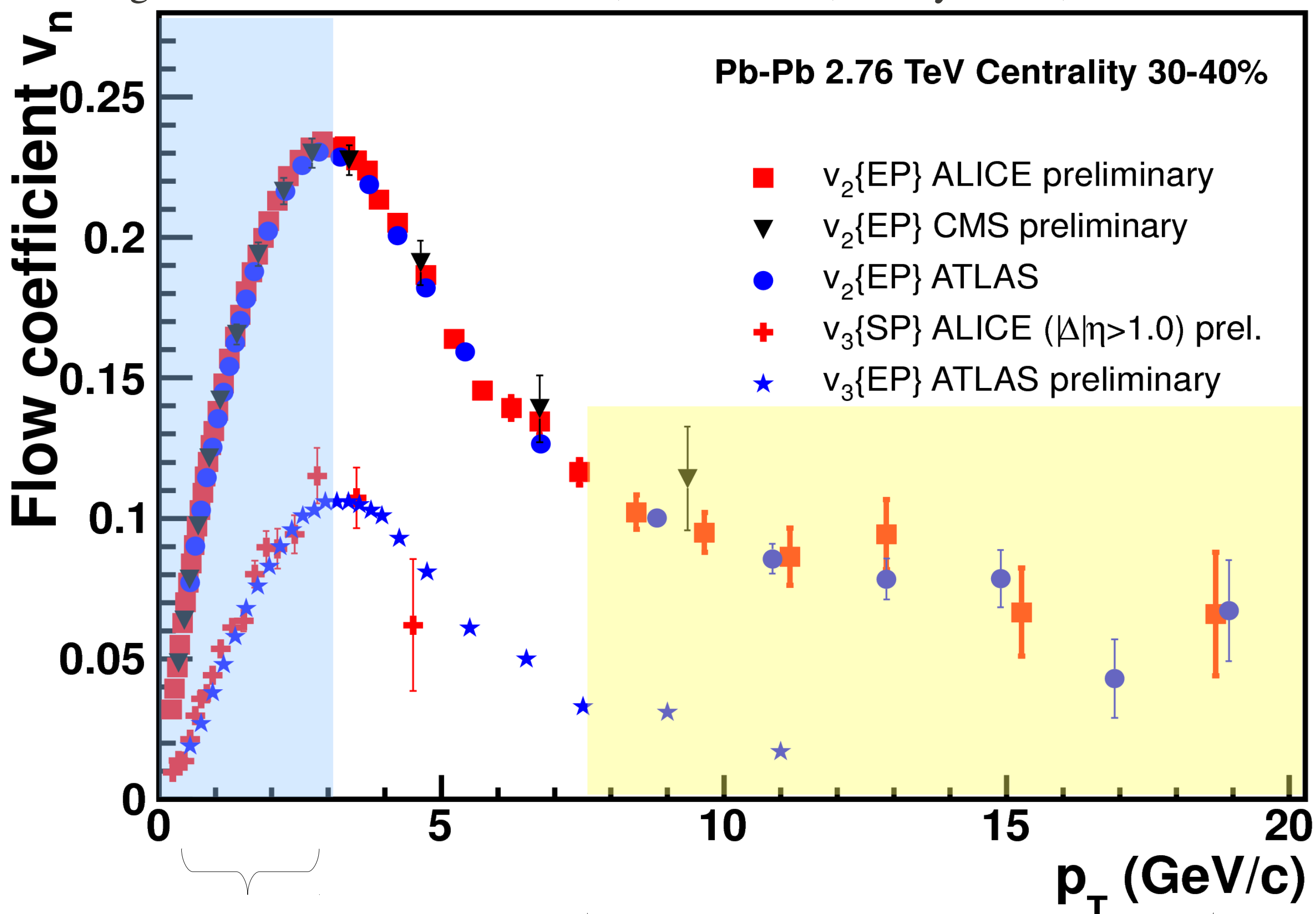
$$\frac{dN}{dp_t\, dy\, d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2 v_i \left(y, p_t \right) \cos\left(i \phi \right) \right]$$

quadrupole component v_2
"elliptic flow"

effect of expansion (positive v_2)
seen from top AGS energy upwards

Elliptic Flow of Charged Particles at LHC

figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1



hydrodynamic regime

v_2 driven by pressure gradient

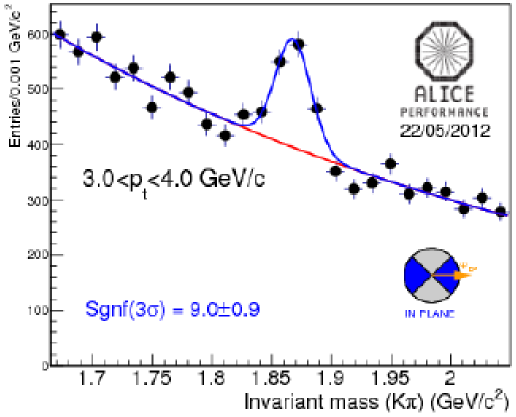
jet fragmentation regime

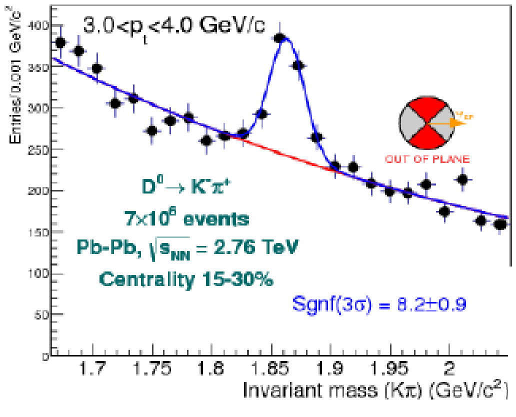
v_2 driven by energy loss

elliptic flow (v_2) as function of p_t :

- excellent agreement between all 3 LHC experiments
- same for v_3

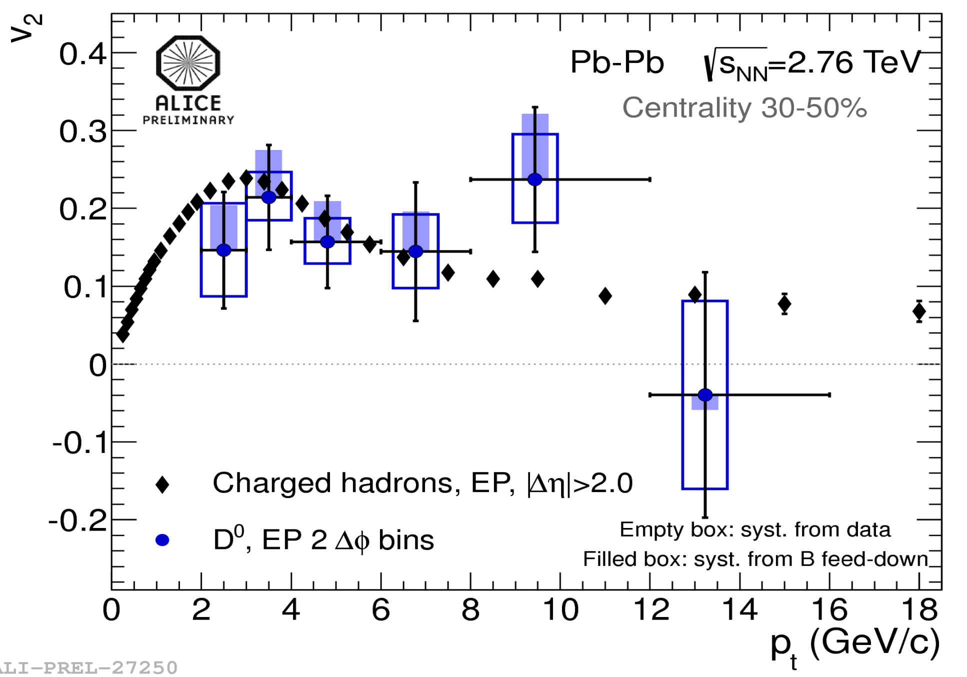
Charm Quarks also Exhibit Elliptic Flow





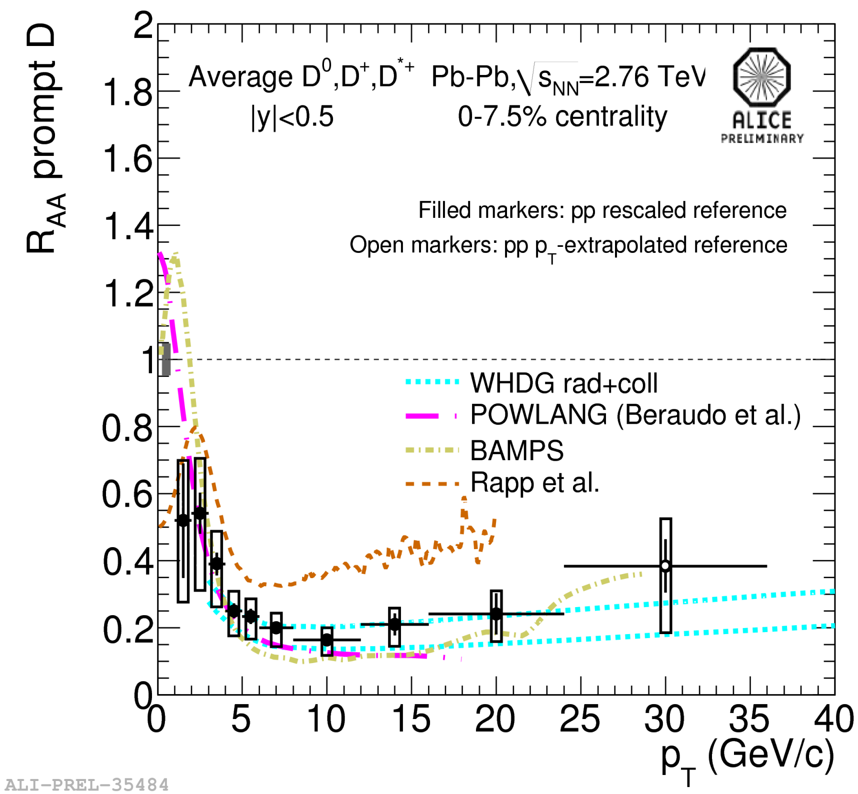
$$v_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

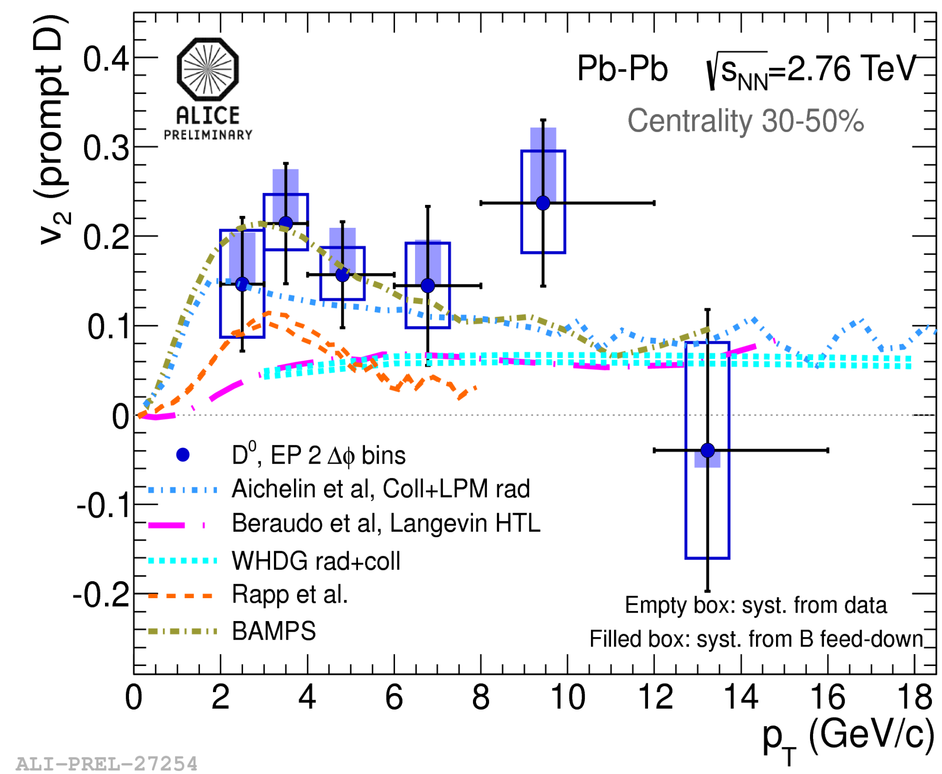
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)



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





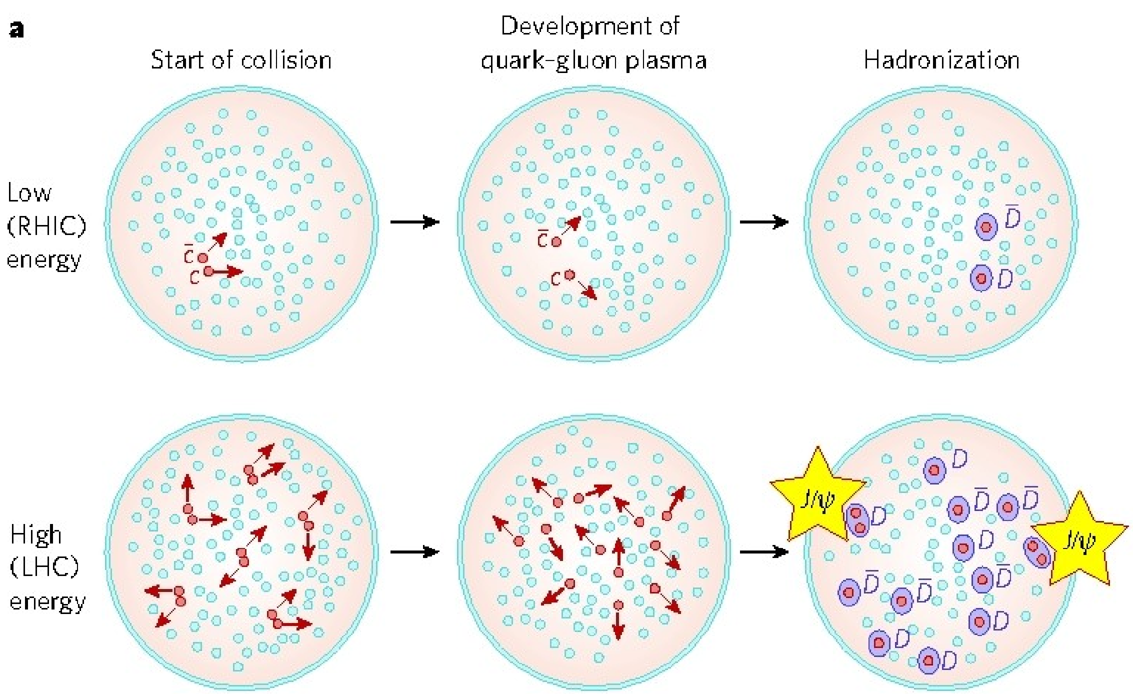
both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

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

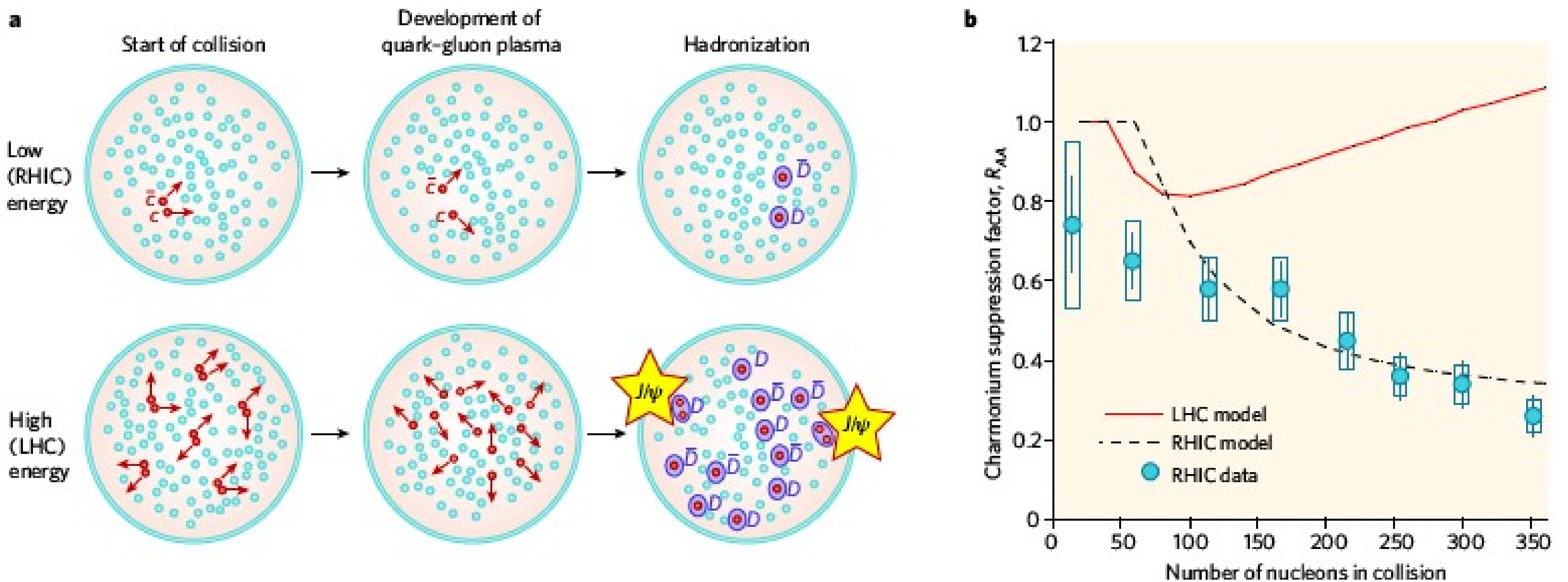
Charmonia as probe of deconfinement at LHC



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



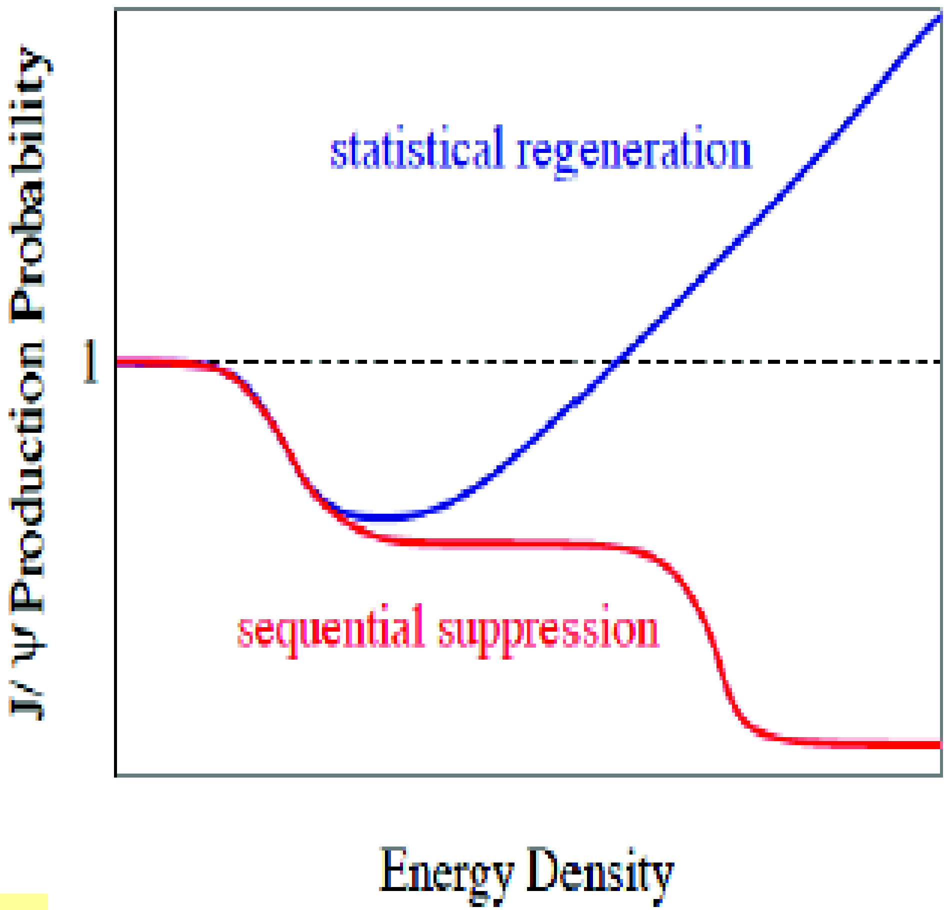
charmonium enhancement as fingerprint of deconfinement at LHC energy

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

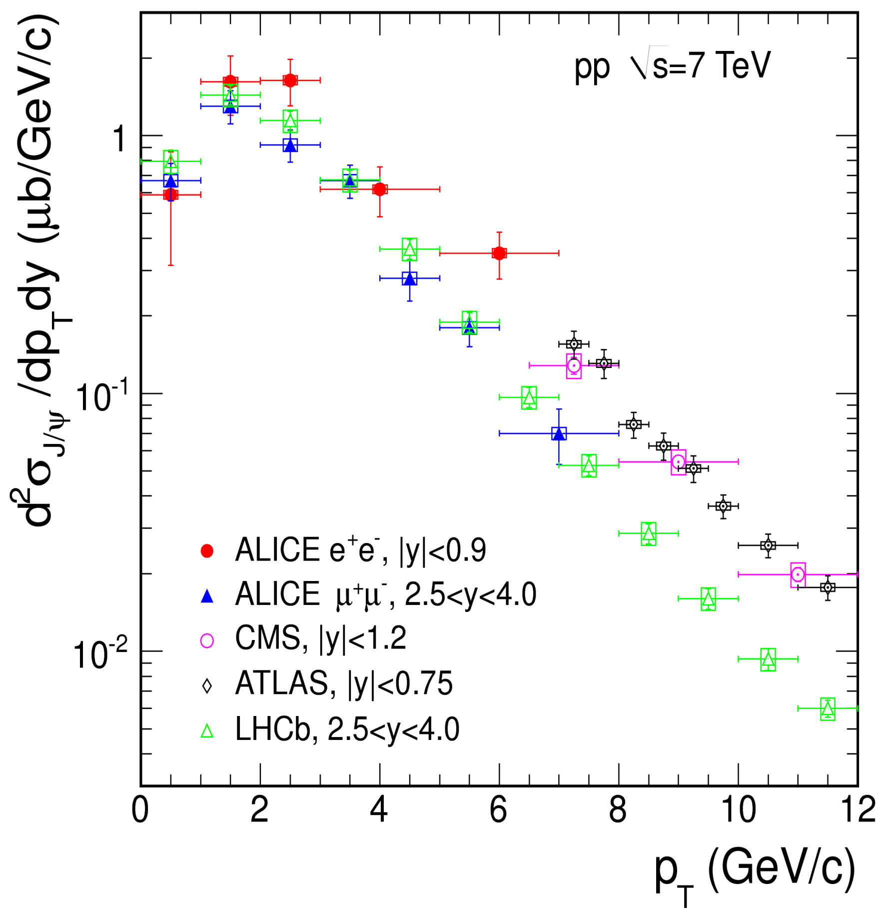


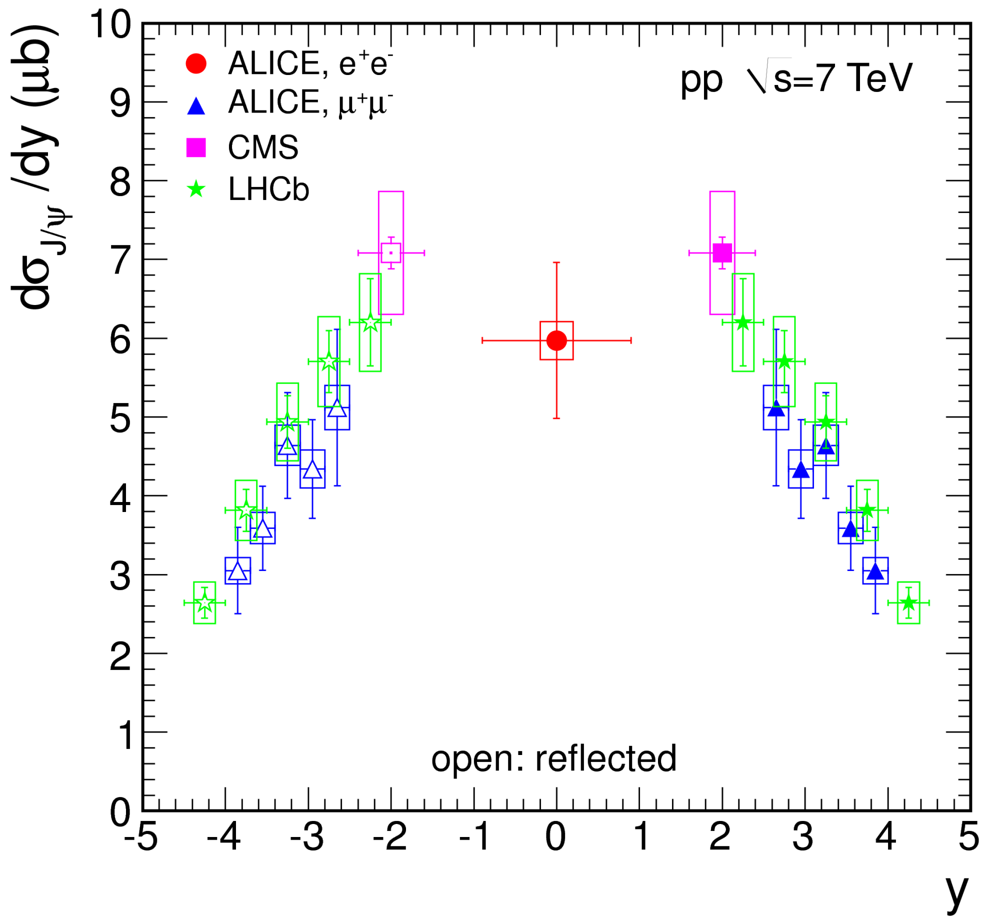
SPS RHIC LHC

Picture:
H. Satz 2009

J/psi spectrum and cross section in pp Collisions

ALICE PRL 704 (2011) 442 arXiv:1105.0380





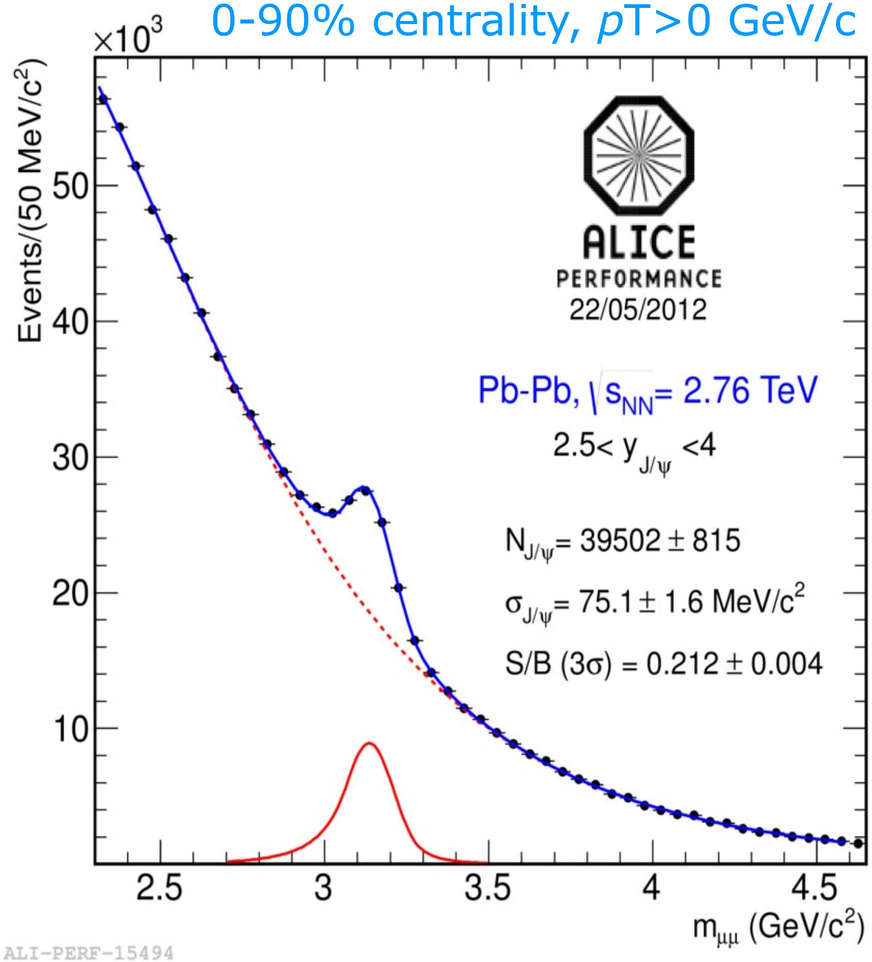
- good agreement between experiments
- complementary in acceptance: only ALICE has acceptance below 6 GeV at mid-rapidity

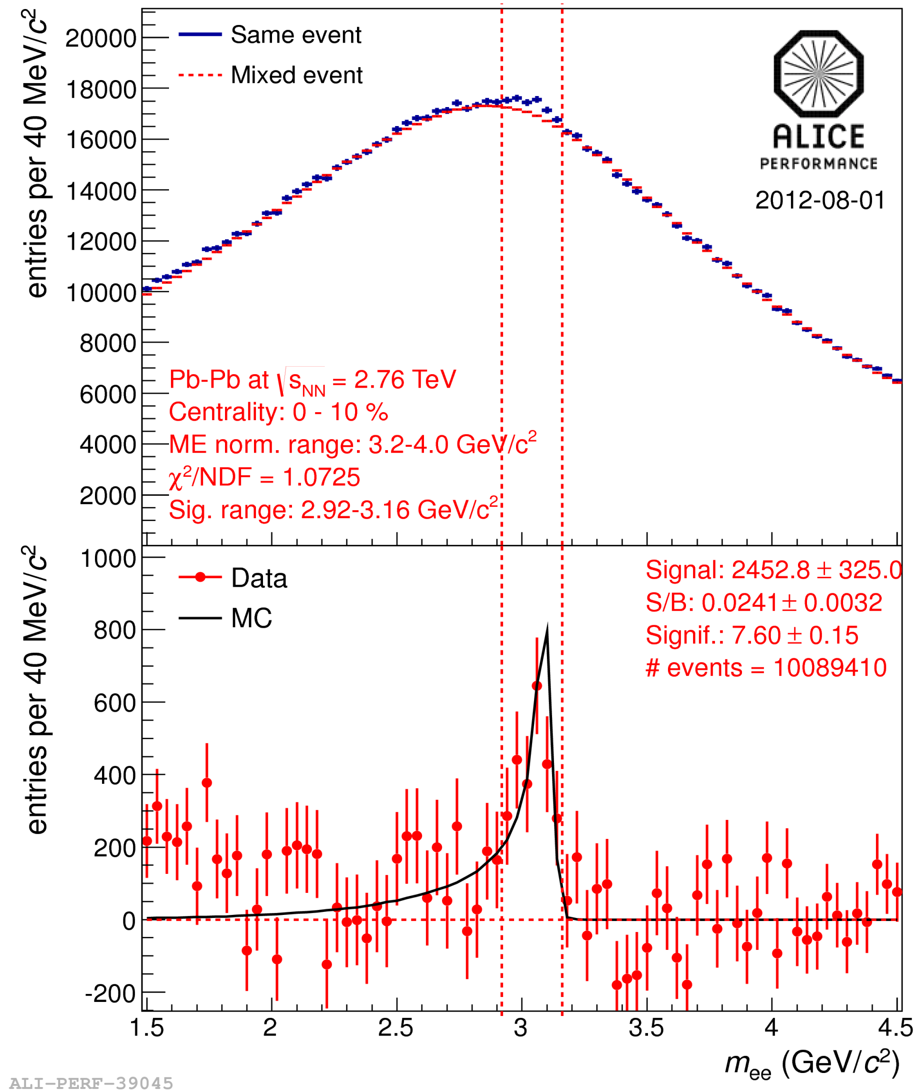
measured both at 7 and 2.76 TeV

<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





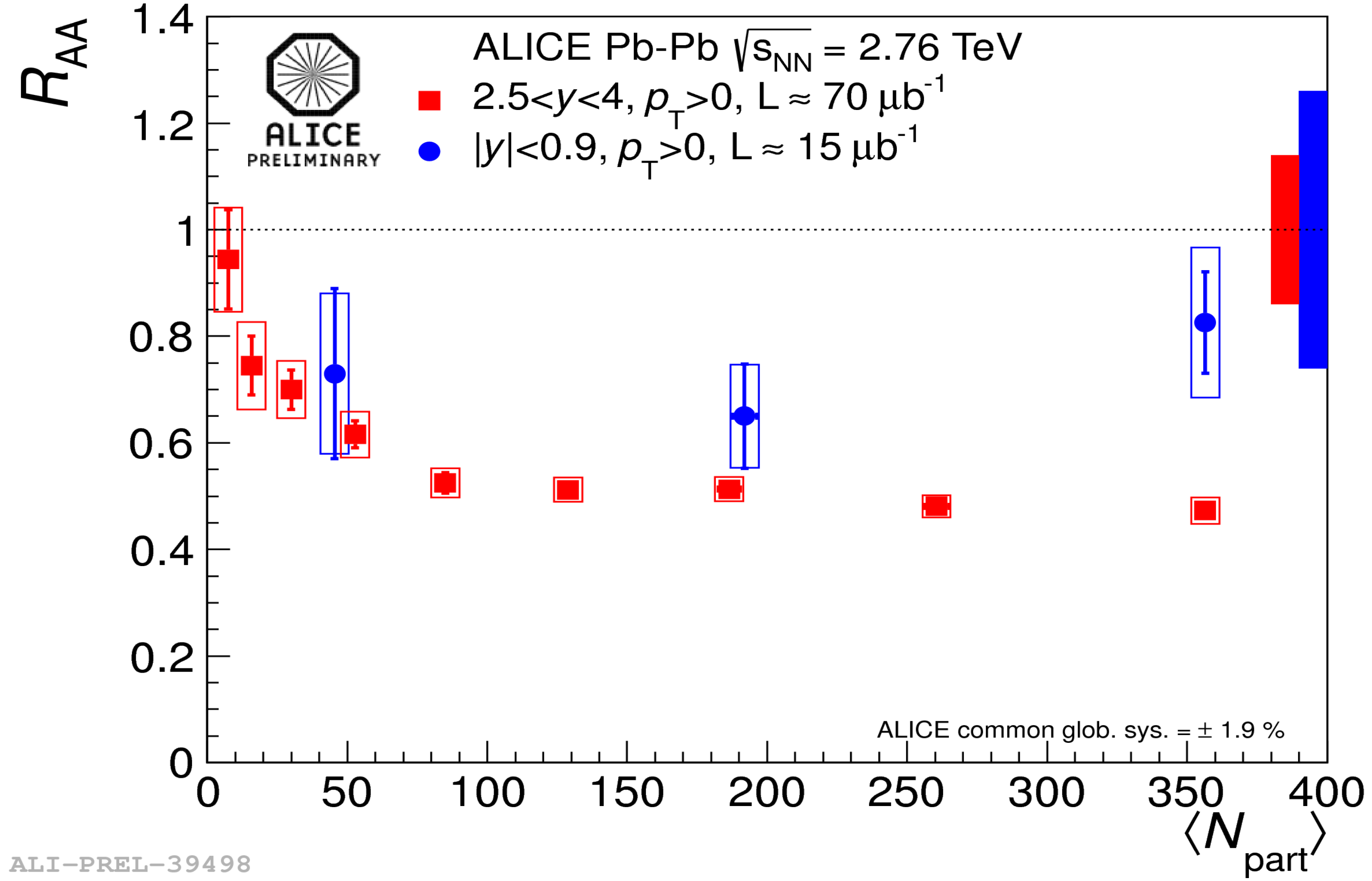
<u>most challenging:</u> PbPb collisions

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

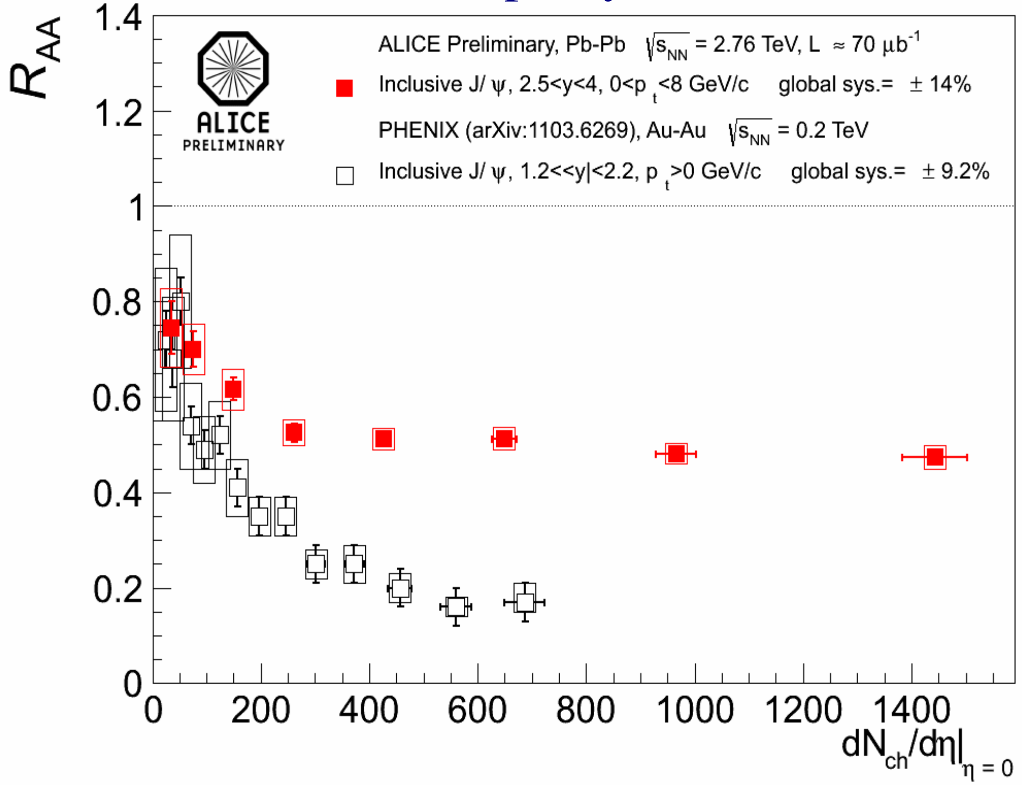
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



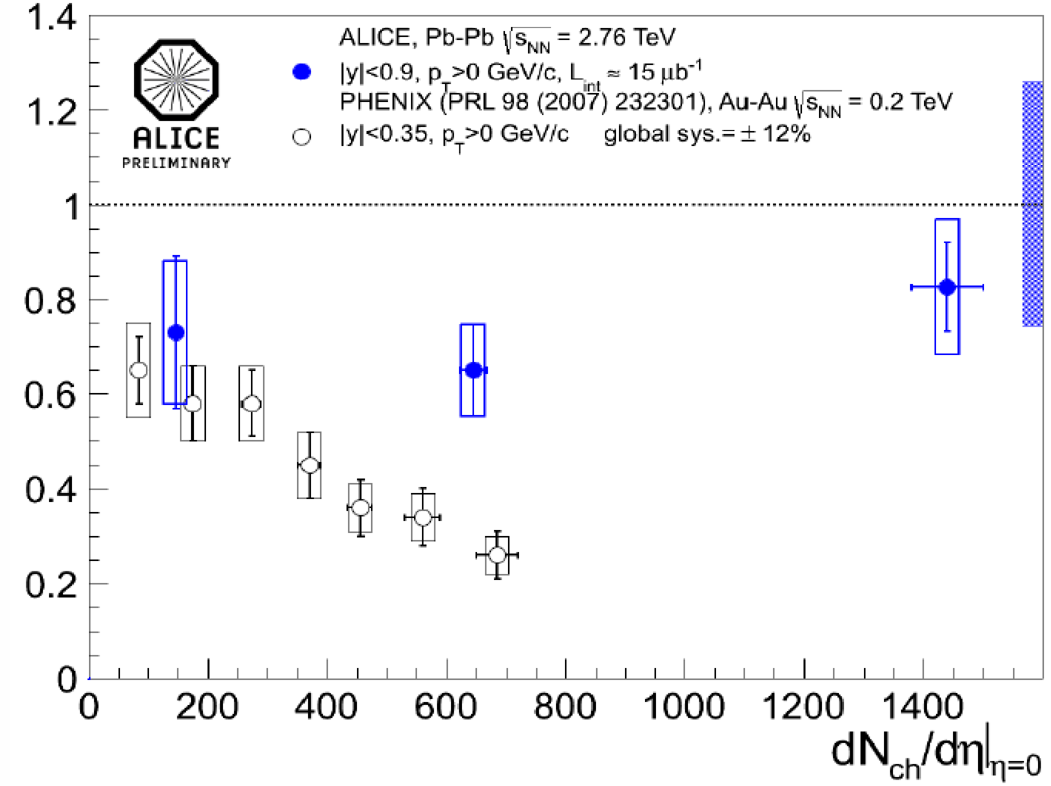
- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

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

forward rapidity

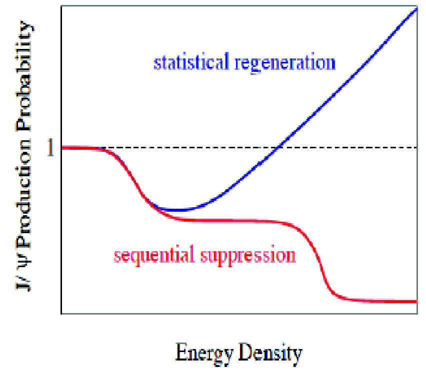


mid-rapidity

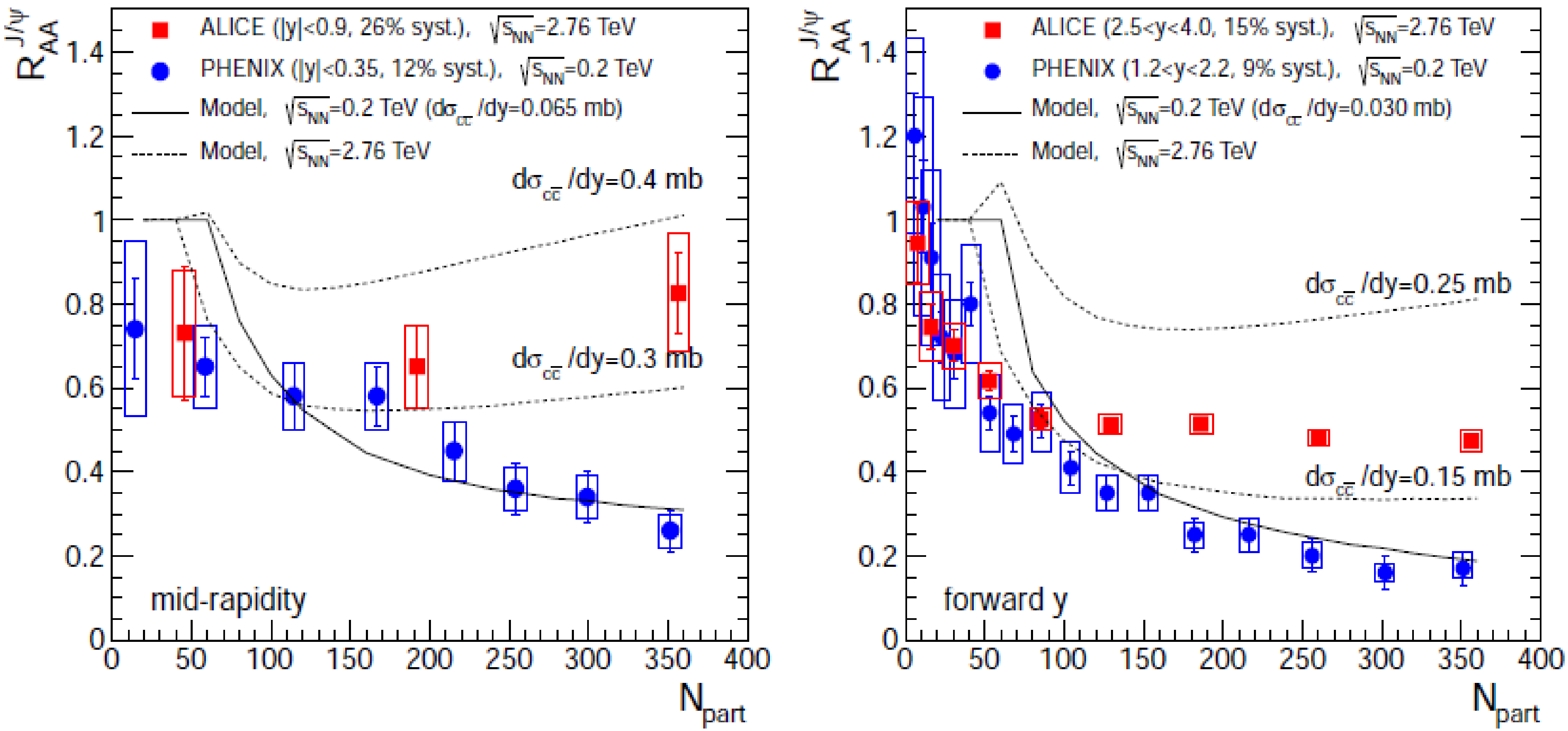


energy density -->

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



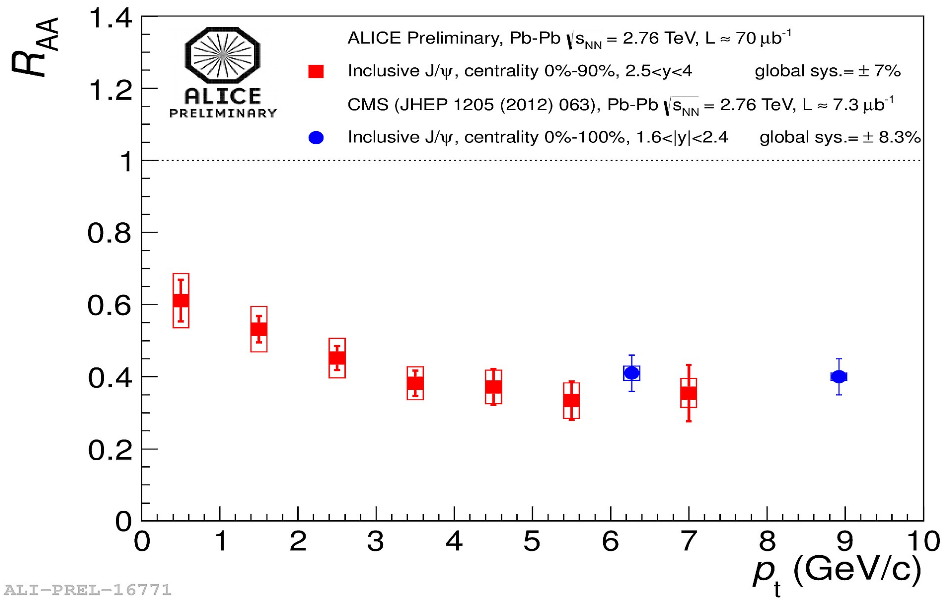
J/psi and Statistical Hadronization



in AA collisions: strong indication of J/ψ regeneration

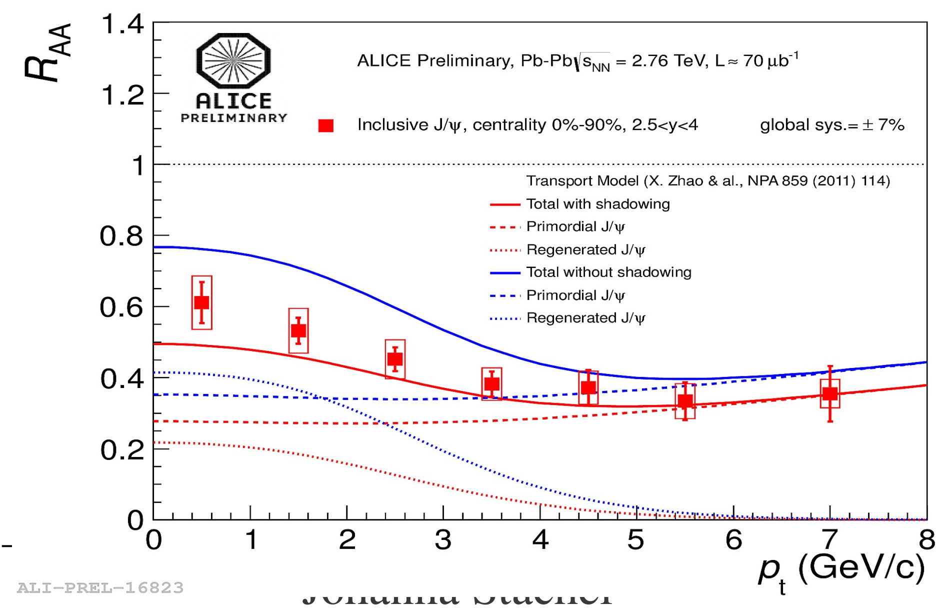
- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- need to precisely measure charm cross section in PbPb and pPb collisions

p_t Dependence of R_{AA}



relative yield larger at low p_t in nuclear collisions

good agreement with CMS at high p_t

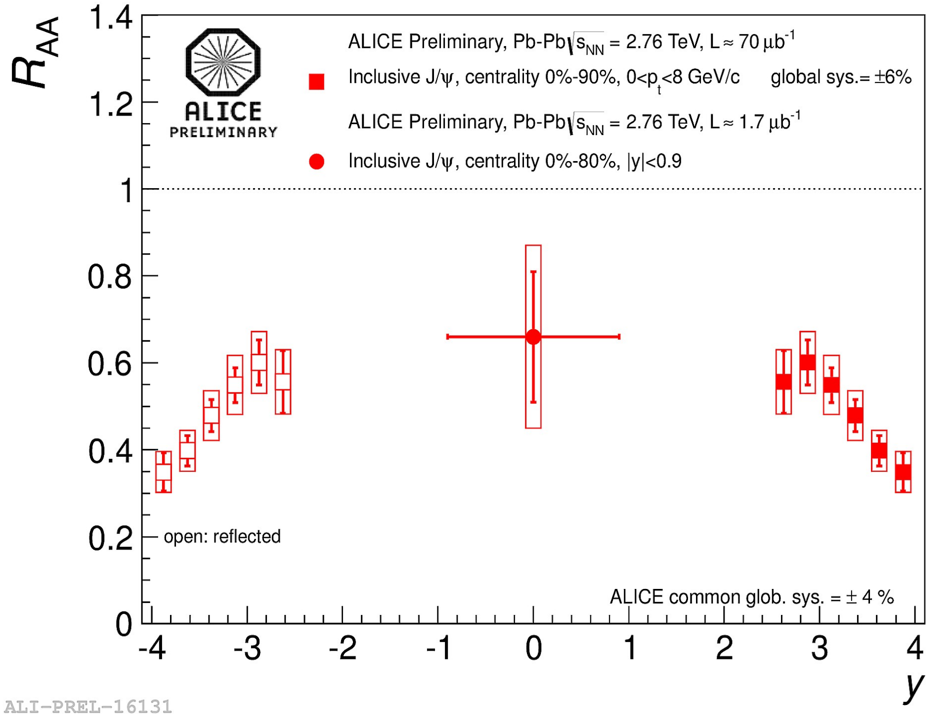


statistical hadronization only expected for charm quarks thermalized in the QGP

p_t dependence in line with this prediction

in CMS only suppression

Rapidity Dependence of J/psi R_{AA}

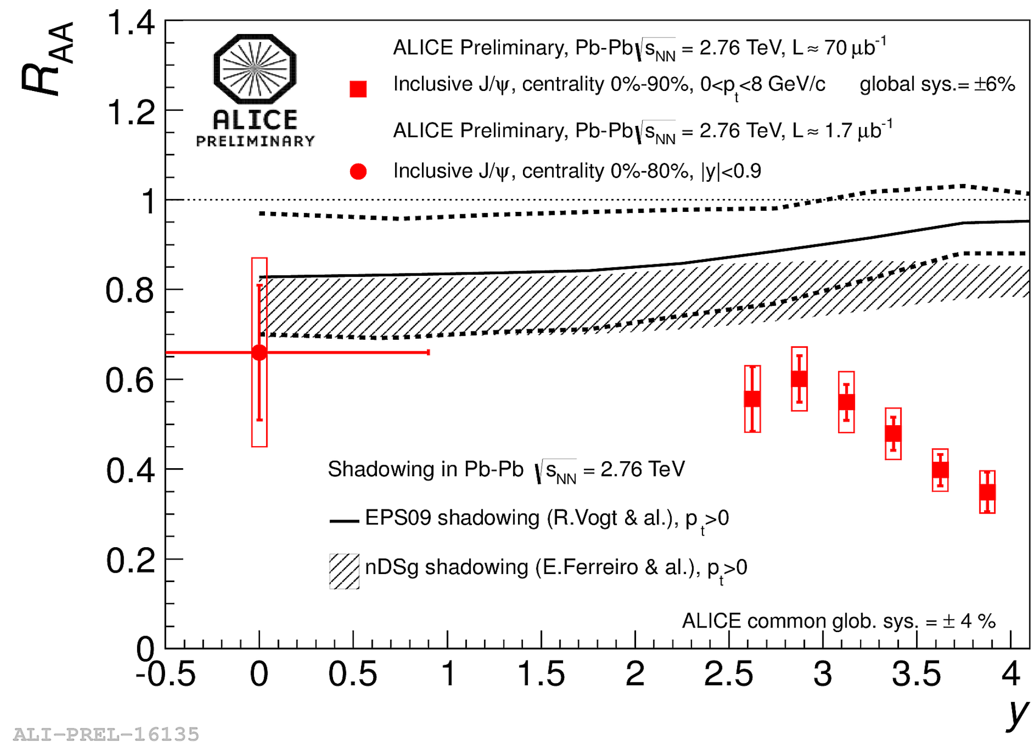


for statistical hadronization J/ψ yield proportional to N_c^2

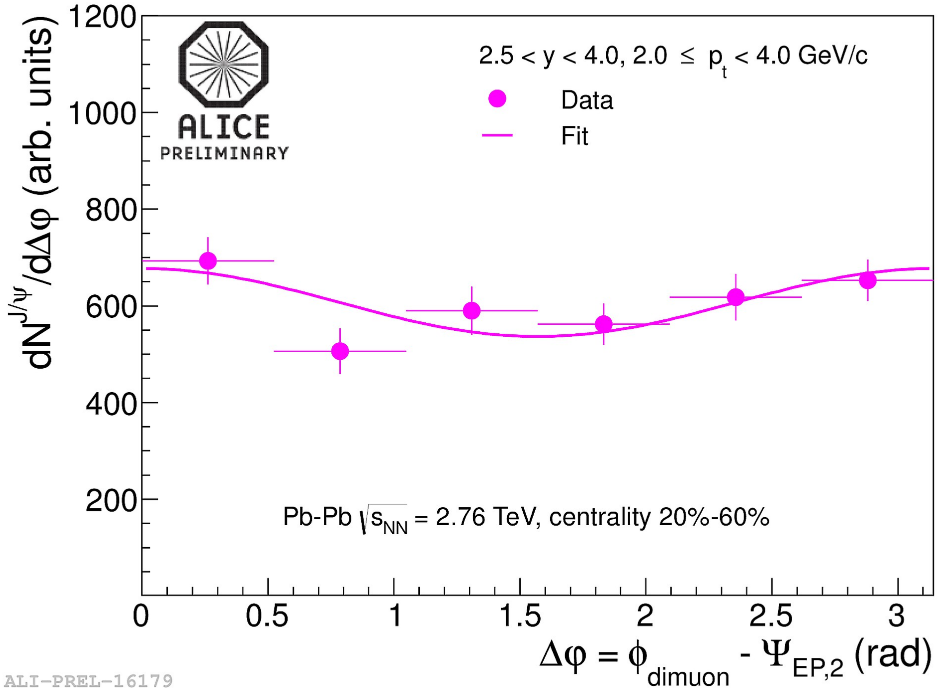
higher yield at mid-rapidity predicted in line with observation

comparison to shadowing calculations:

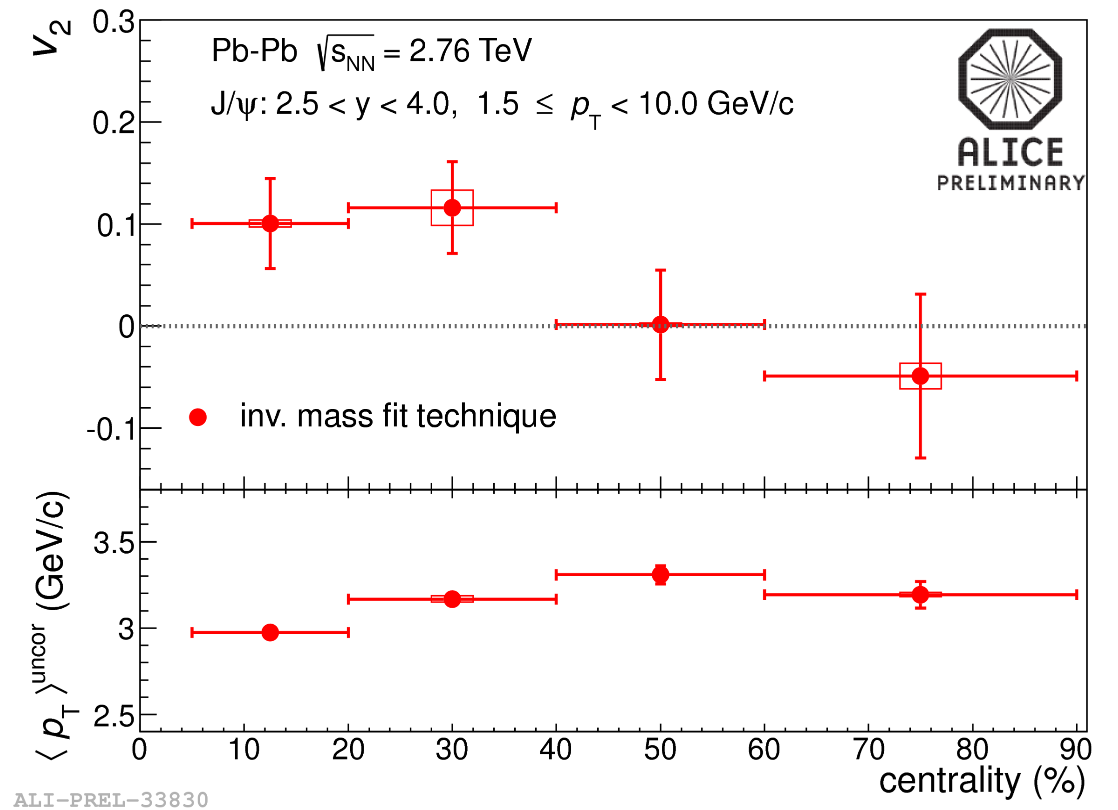
- at mid-rapidity suppression could be explained by shadowing only
- at forward rapidity there seems to be additional suppression
- need to measure shadowing



Elliptic Flow of J/psi

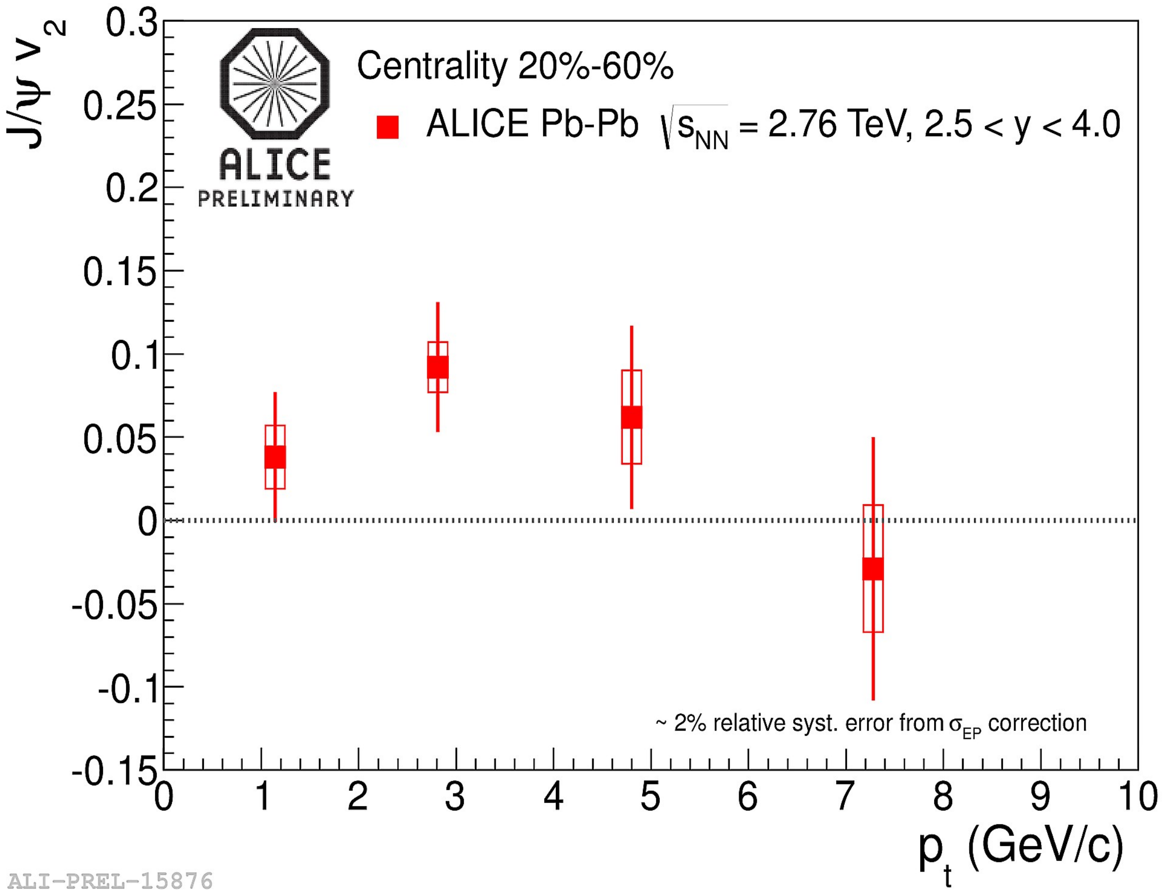


charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase



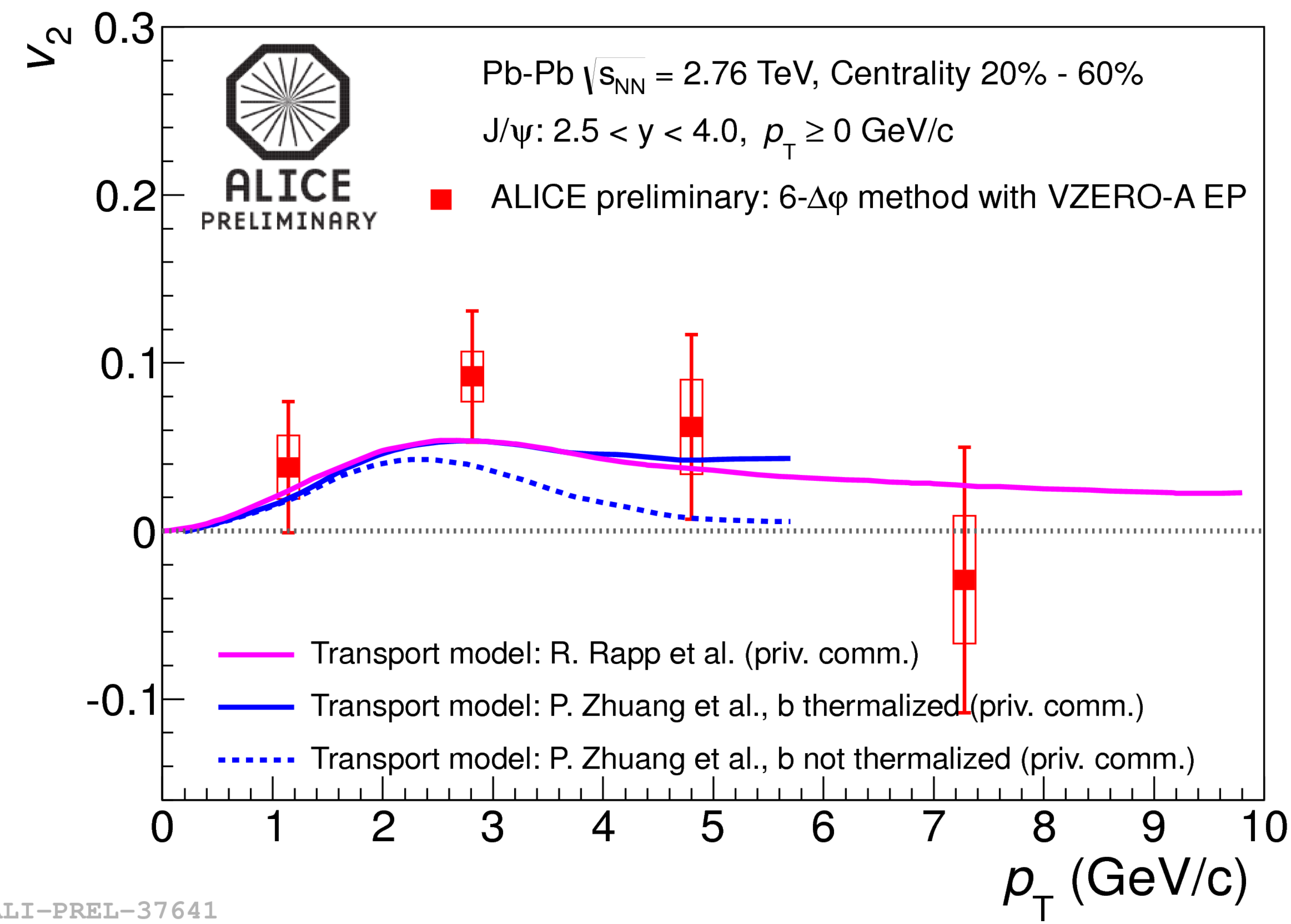
first observation of significant J/ψ v_2

Elliptic Flow of J/psi vs pt



- 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



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

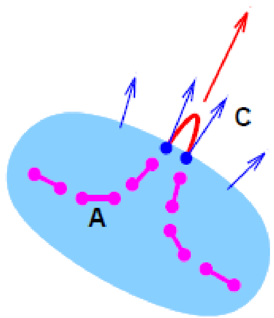
Conclusions

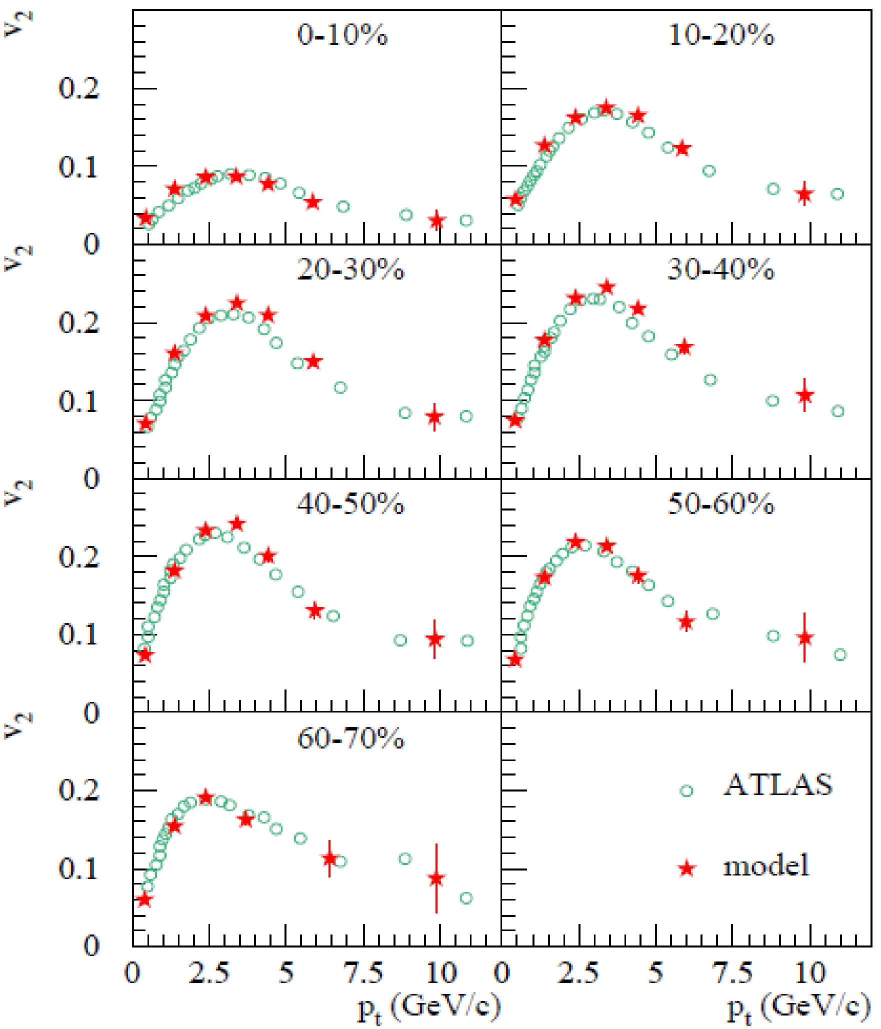
- Charm and beauty and J/spi cross section and spectra in pp in good agreement with pQCD predictions
- energy loss of partons in QGP: charm quarks loose energy nearly as effectively as gluons and light quarks
- heavy quarks also appear to thermalize
  need total cross section and charm quark observables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

backup

Unified Description of Different Regimes

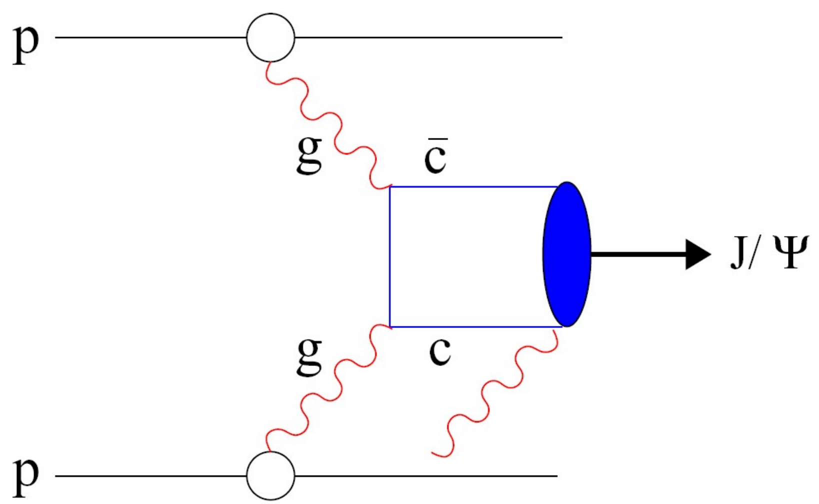
K. Werner et al. arXiv:1203.5704
jets, expanding bulk and their interactions





reproduces inclusive spectra, jets, azimuthal anisotropies

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

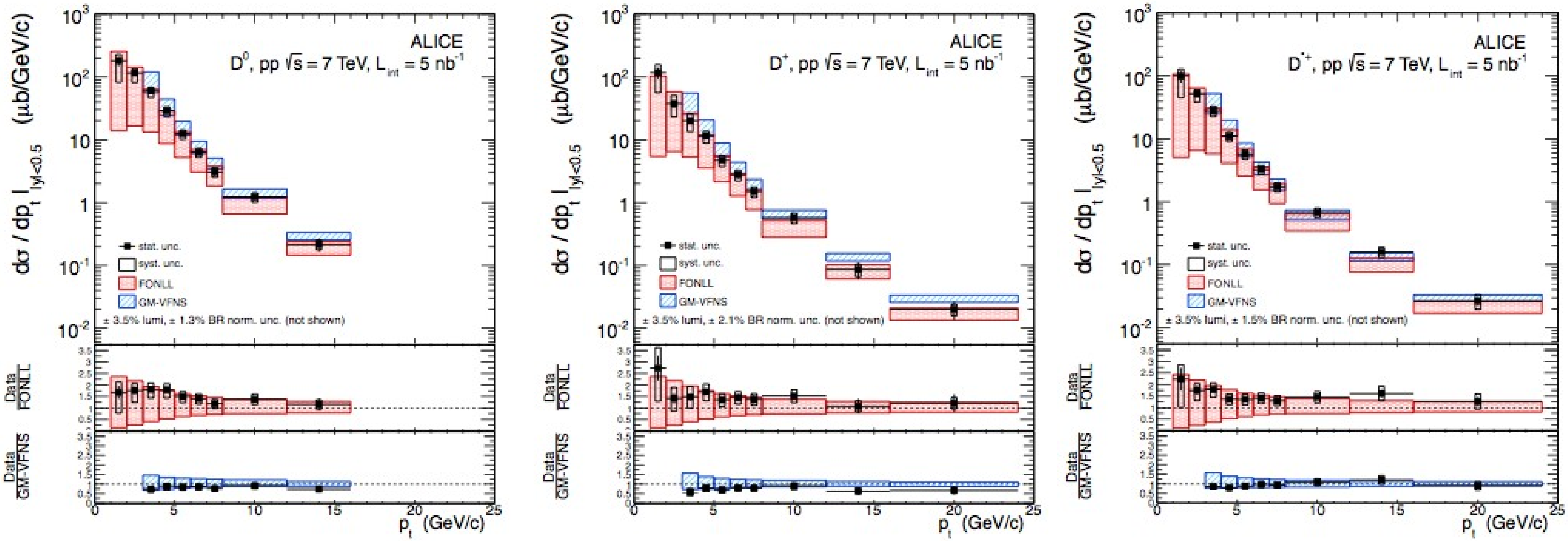
not pure perturbative QCD anymore, some modelling required

CEM Color Evaporation Model

CSM Color Singlet Model

now reasonably successful

Measurements agree well with state of the art pQCD calculations



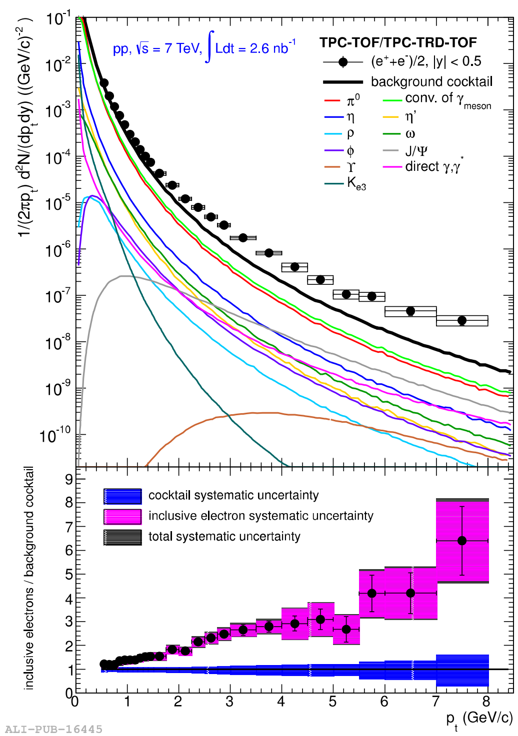
JHEP1201(2012)128

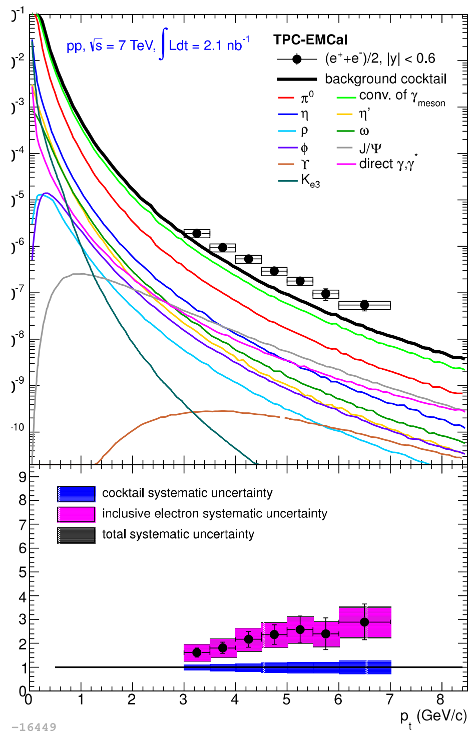
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

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

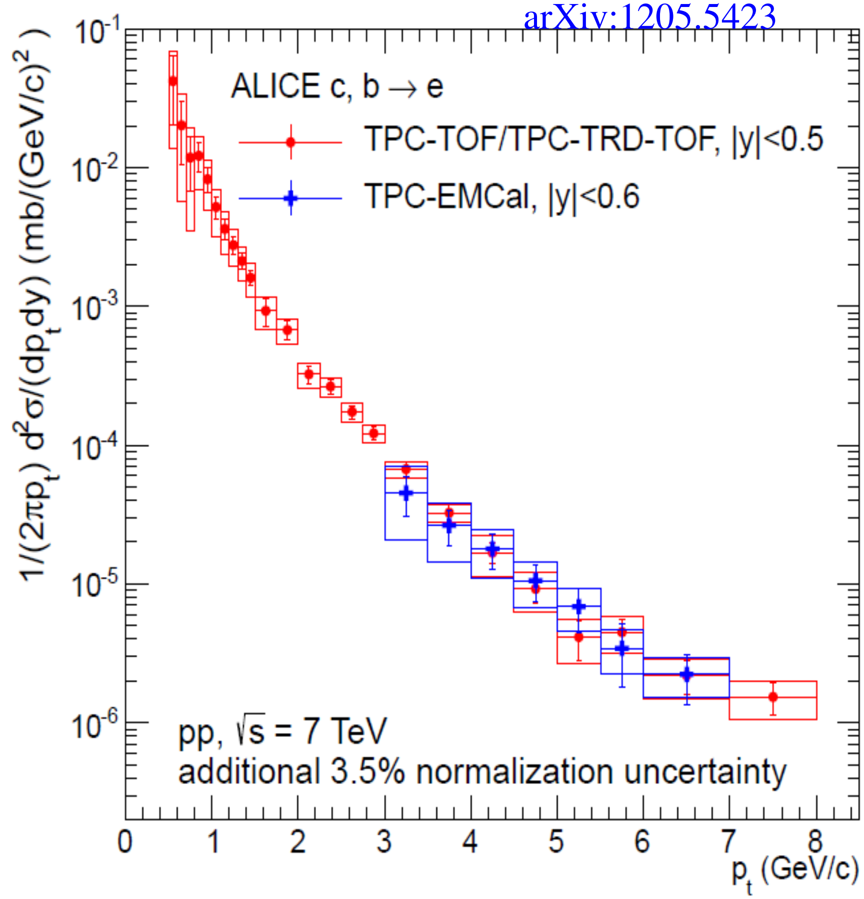
Charm and beauty via semi-leptonic decays

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





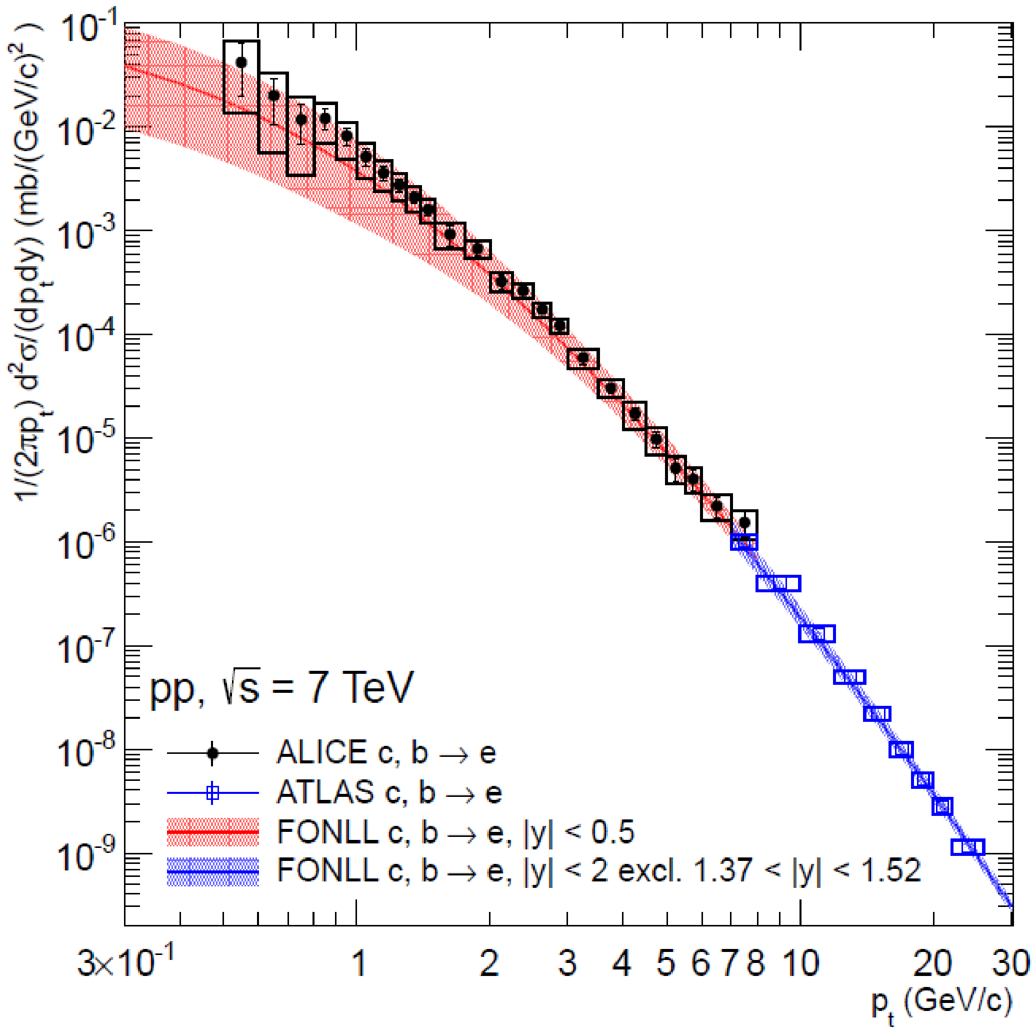
arXiv:1205.5423



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

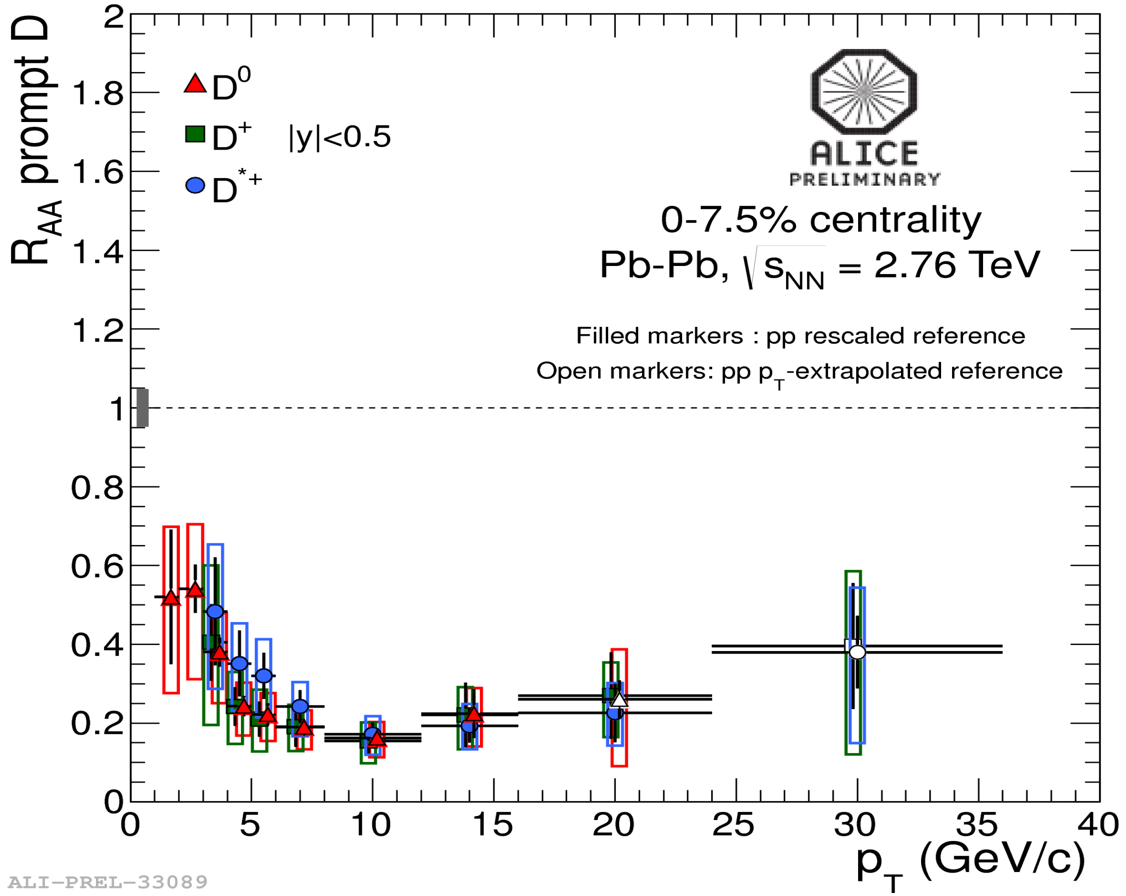


- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

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

Suppression of charm at LHC energy

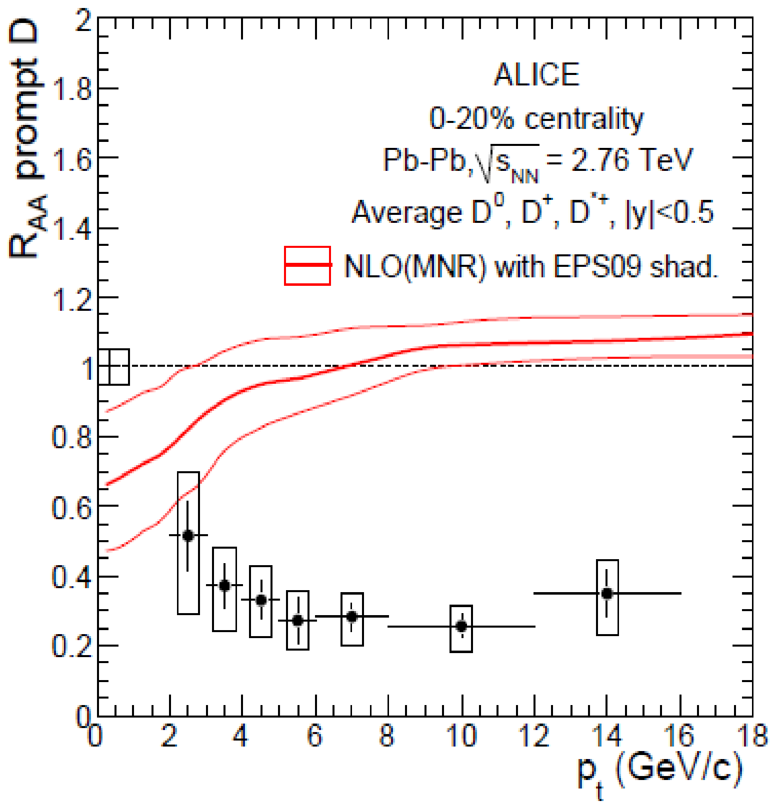
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity

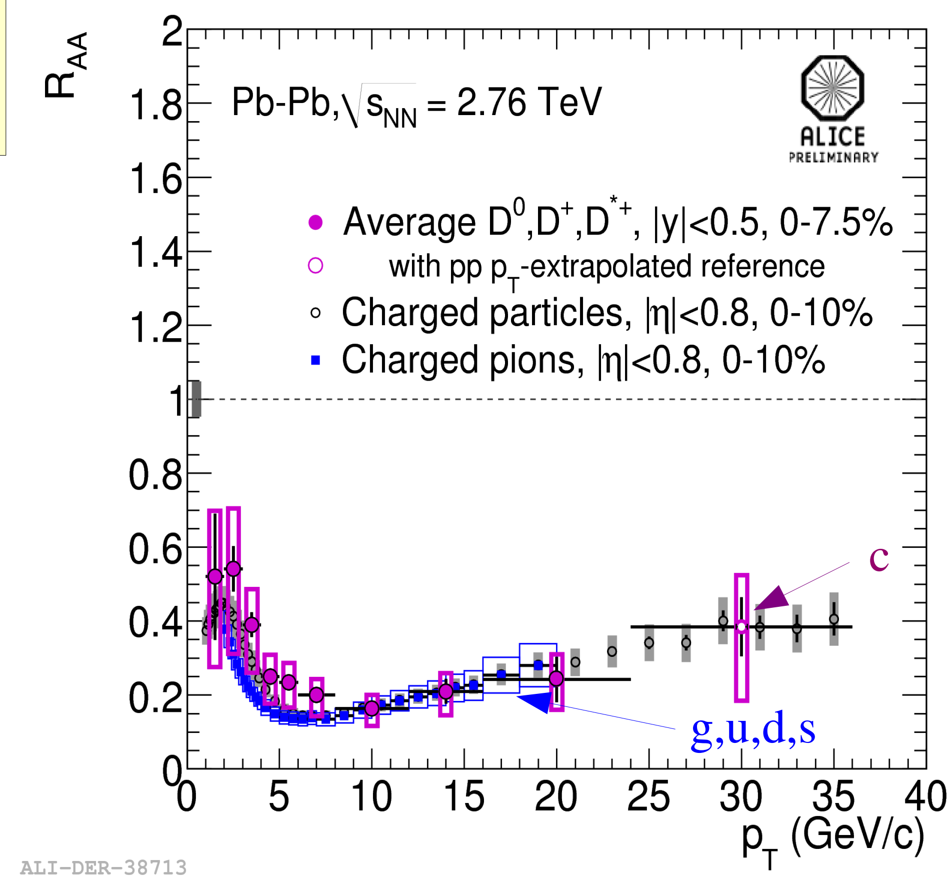


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

Suppression of charm at LHC energy

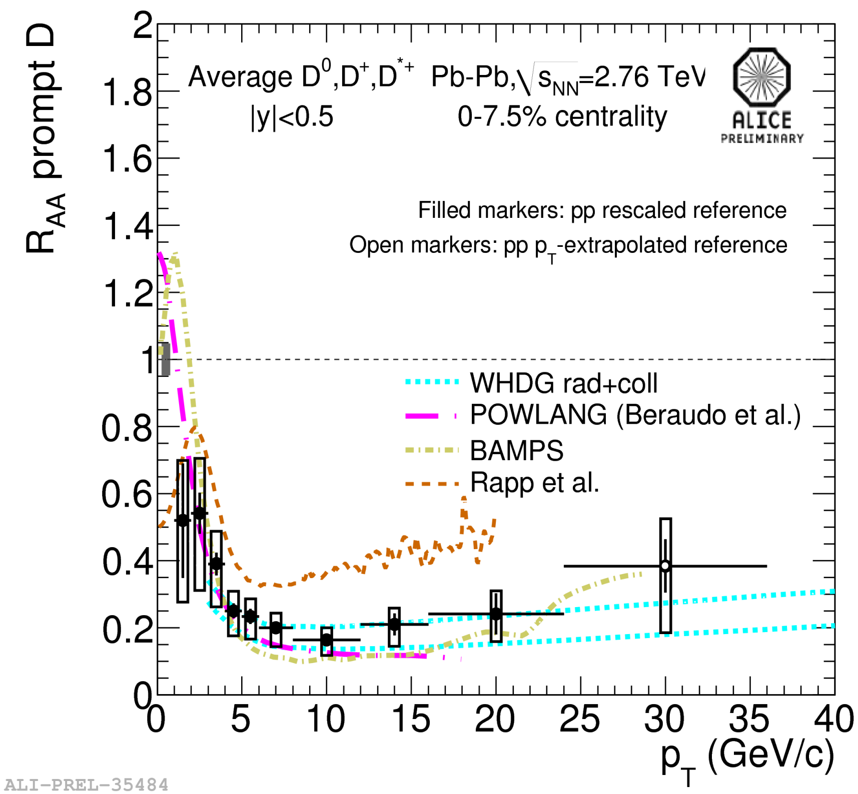
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions

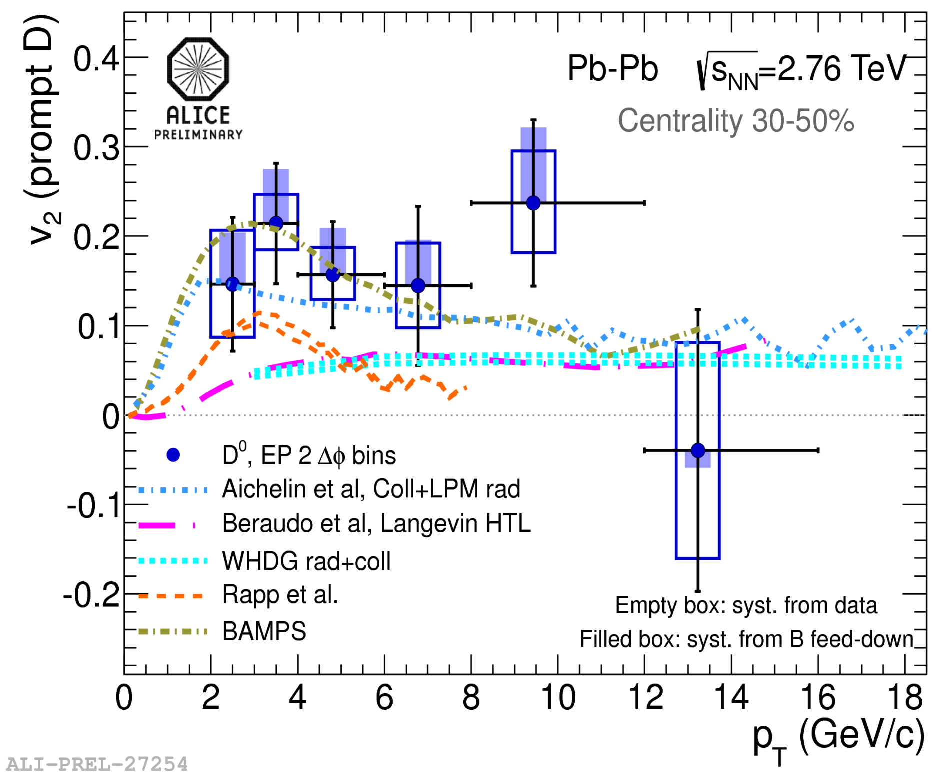




energy loss of charm quarks only slightly less than that for light quark → thermalization

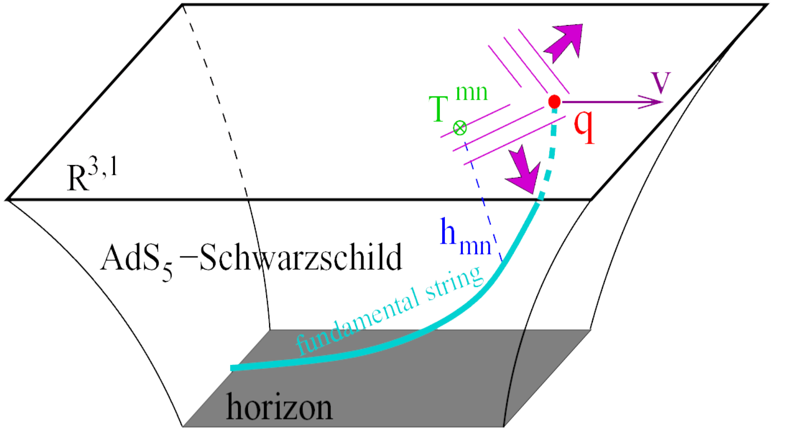
Model Description of Energy Loss and Flow of D-mesons



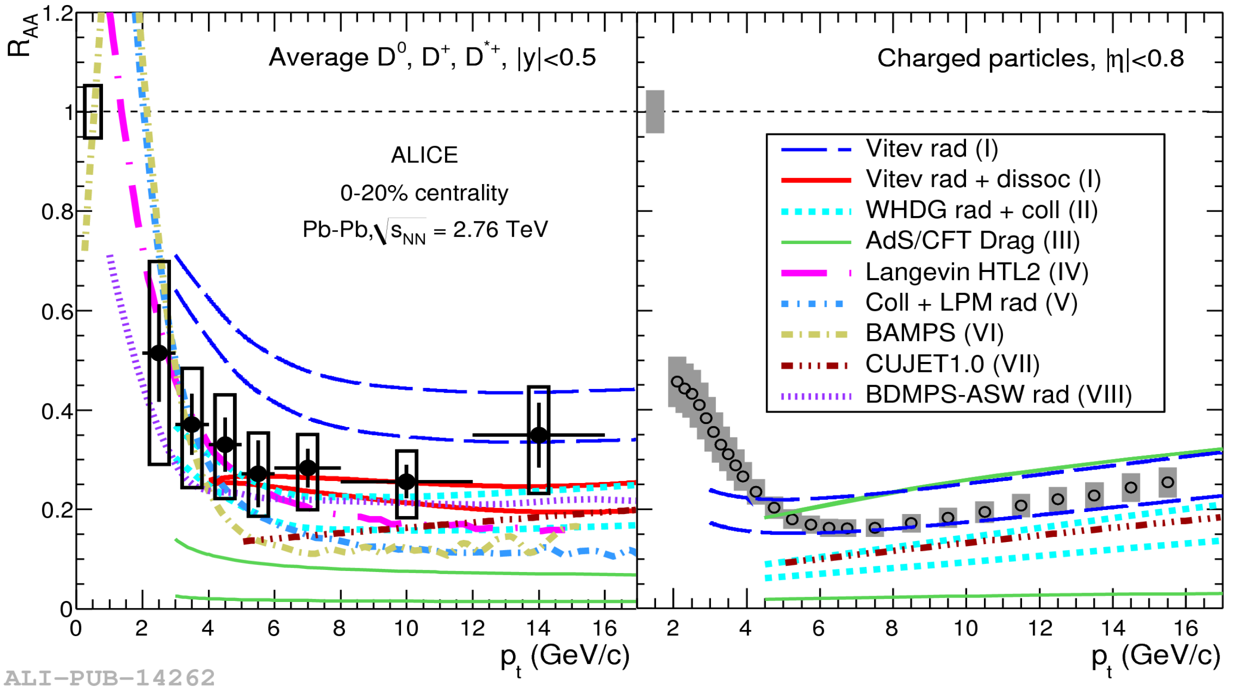


both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

AdSxS5 string theory does not describe charm quark energy loss and elliptic flow at LHC

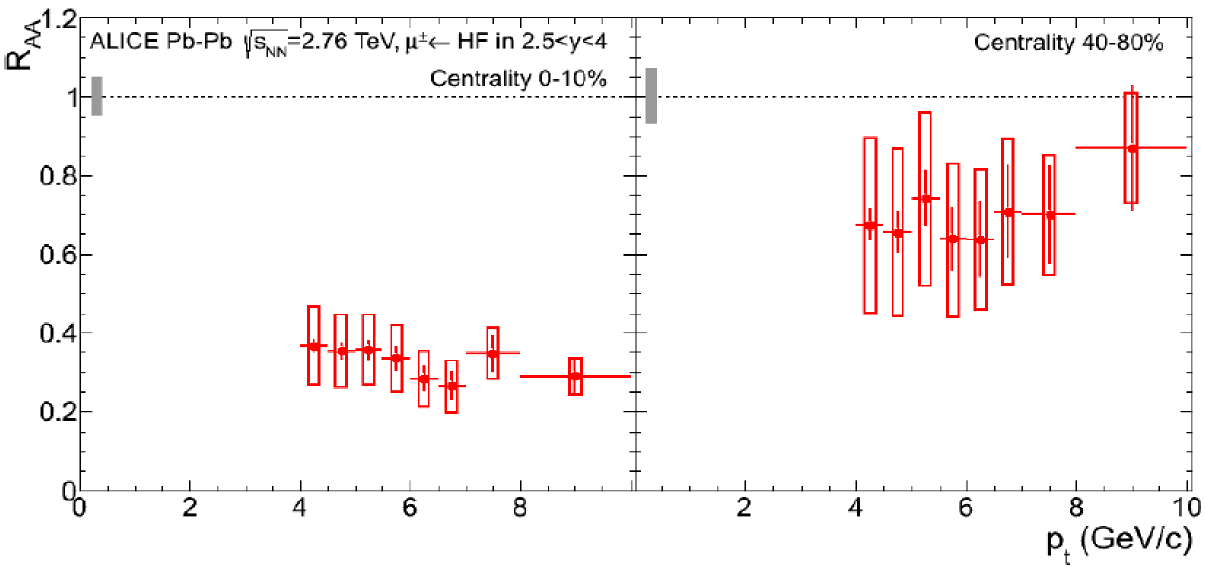


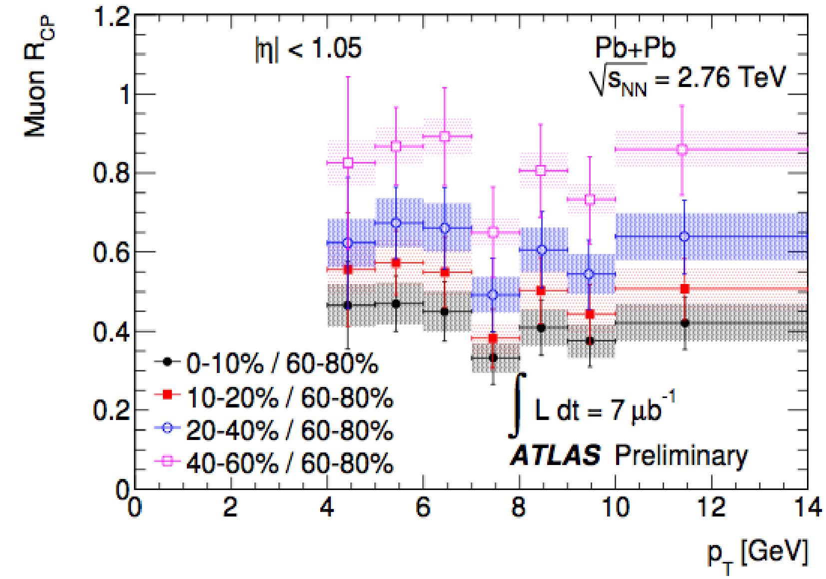
J Friess, Phys Rev D75 (2007)

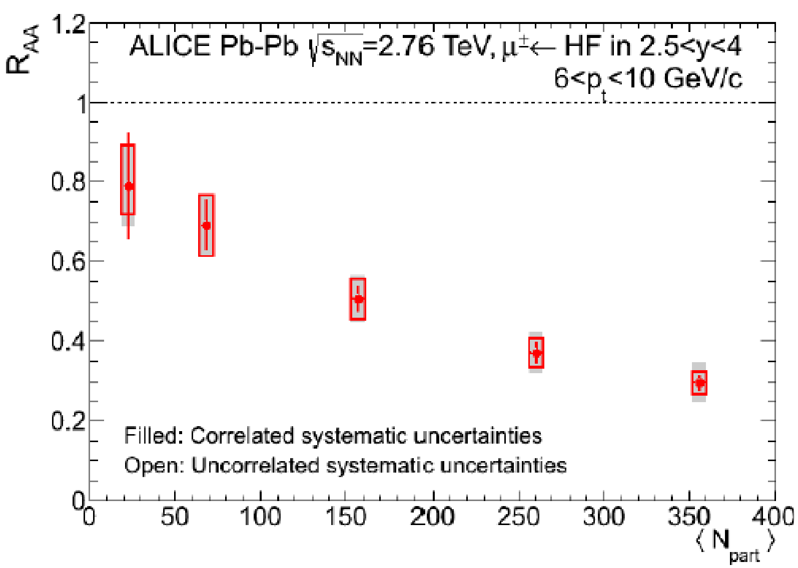


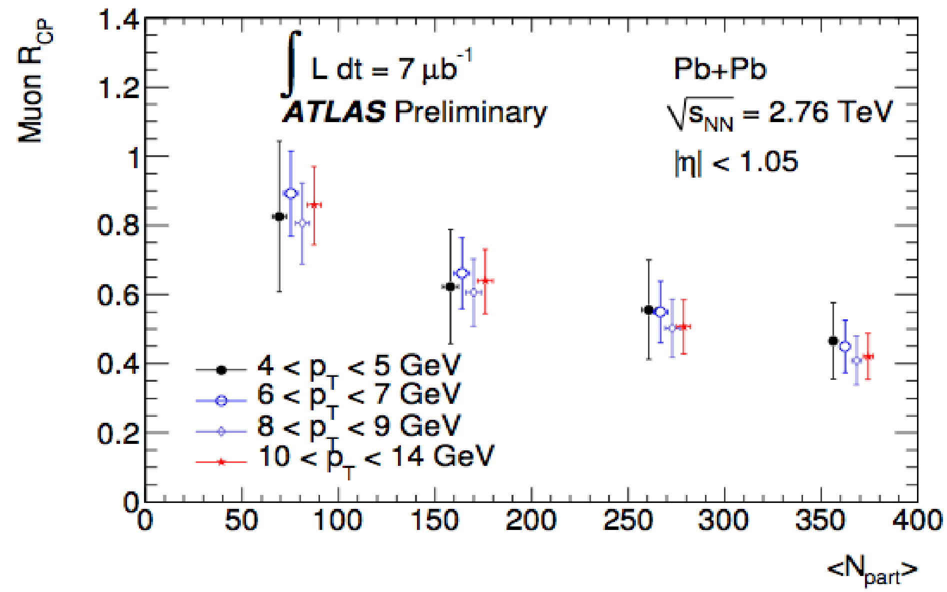
systems appears not as strongly coupled!

Decay muons from heavy flavor mesons



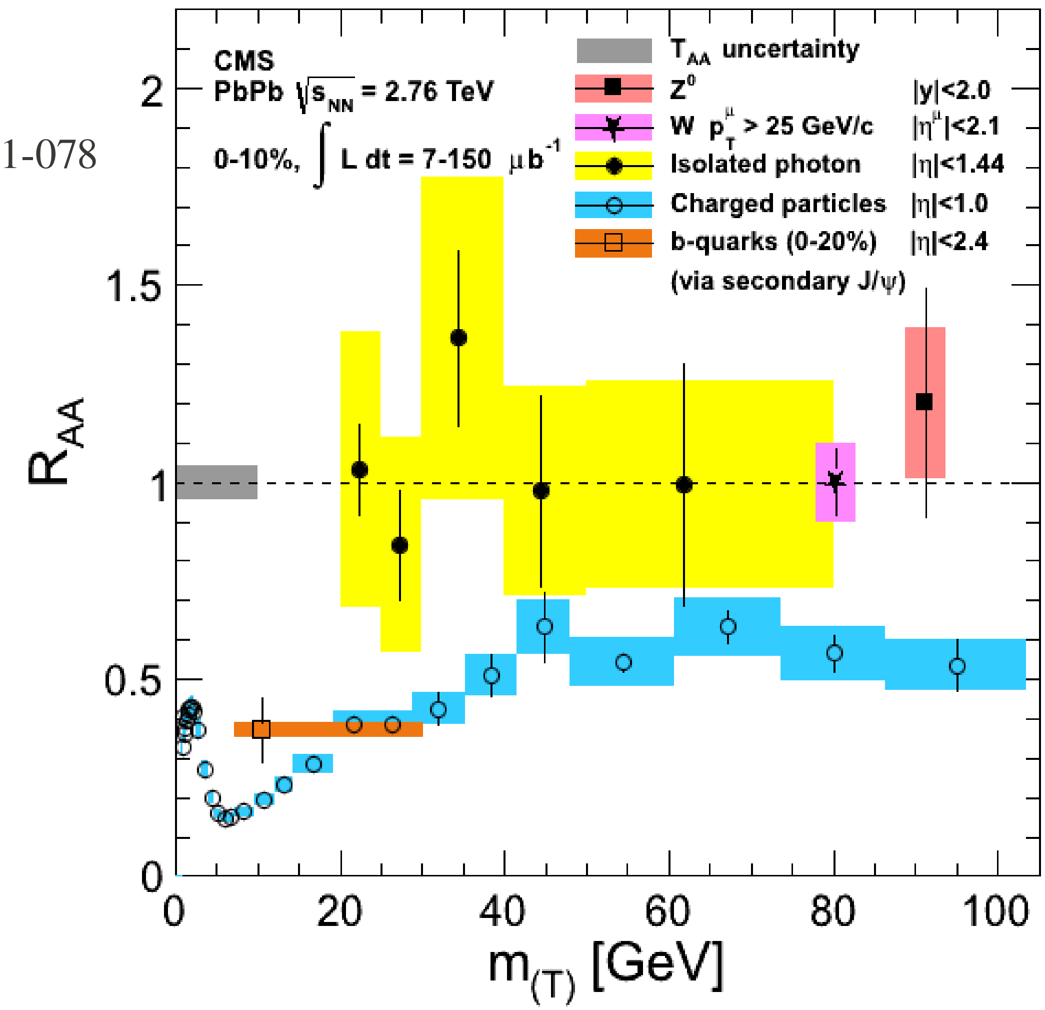






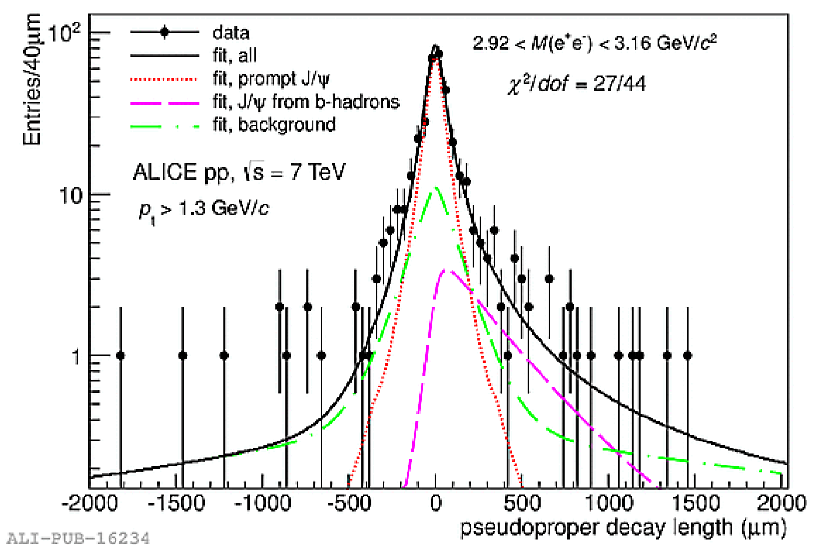
Suppression only for Strongly Interacting Hard Probes

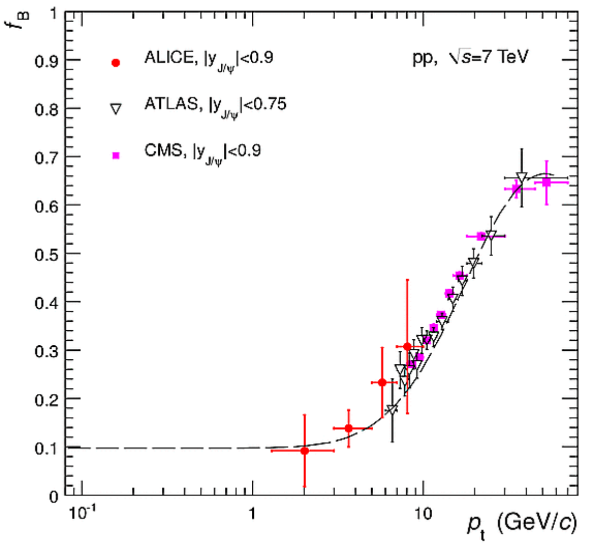
CMS photon: PLB 710 (2012) 256
CMS Z: PRL 106 (2011) 212301
CMS W: arXiv:1205.6334
also ATLAS W: ATLAS-CONF-2011-078



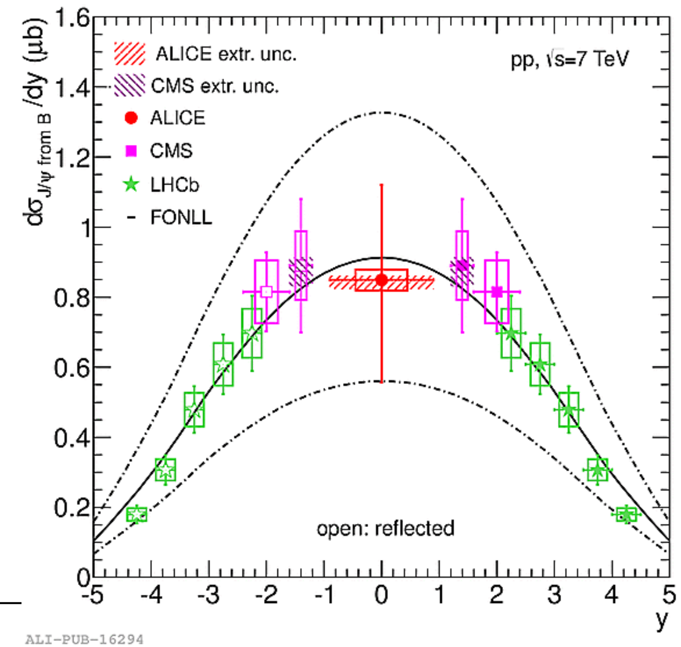
photons, Z and W scale with number of binary collisions in PbPb – not affected by medium
→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

J/psi from B-decays in pp collisions



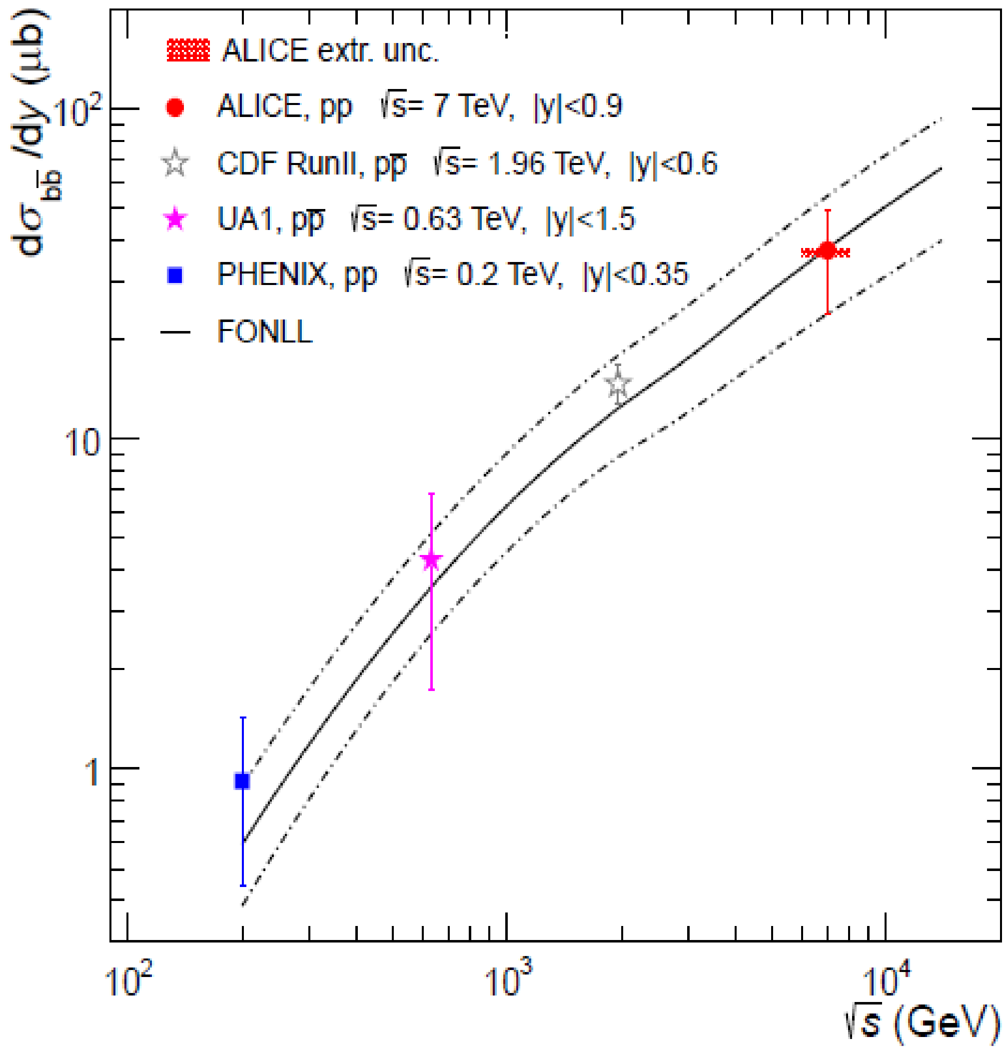


- simultaneous fit of mass spectrum and pseudo-proper decay length
- J/psi from B-decays for pt > 1.3 GeV/c at mid-rapidity - unique at LHC
- obtain prompt J/psi spectrum

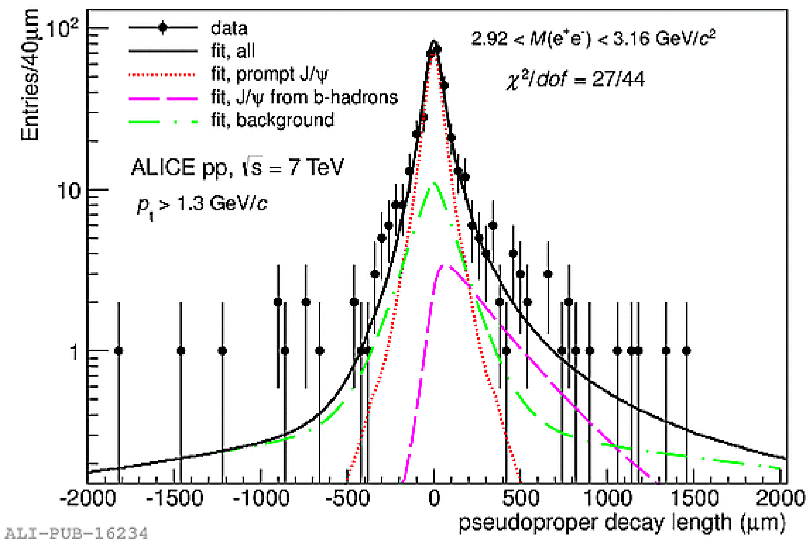


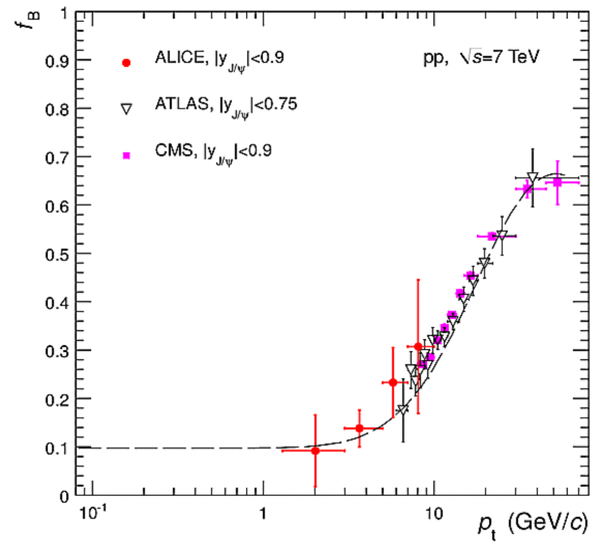
arXiv:1205.5880
FONLL: Cacciari et al., arXiv:1205.6344

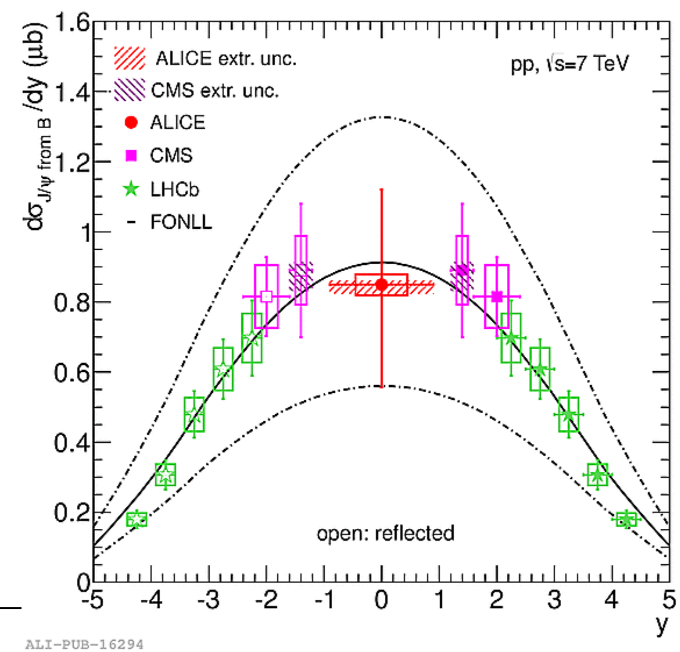
Beauty cross section in pp and ppbar collisions



J/psi from B-decays in pp collisions







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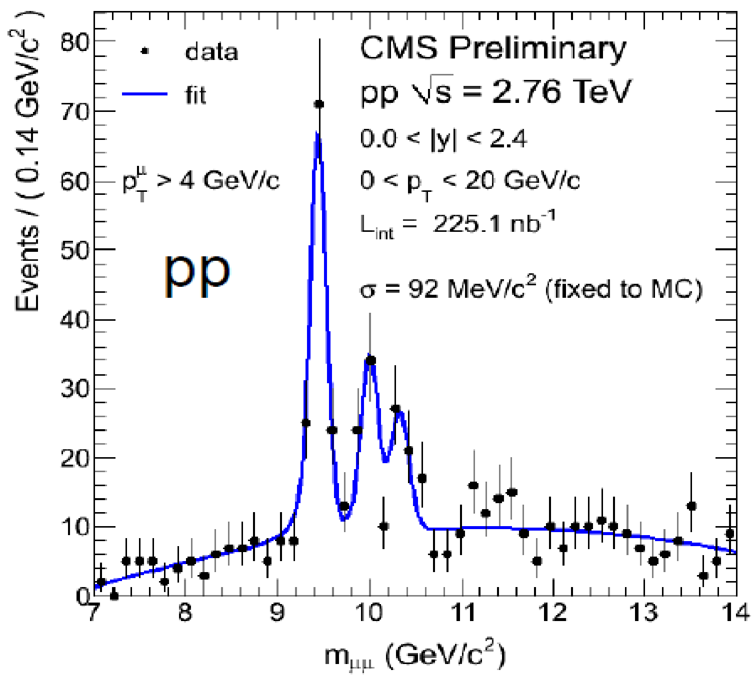
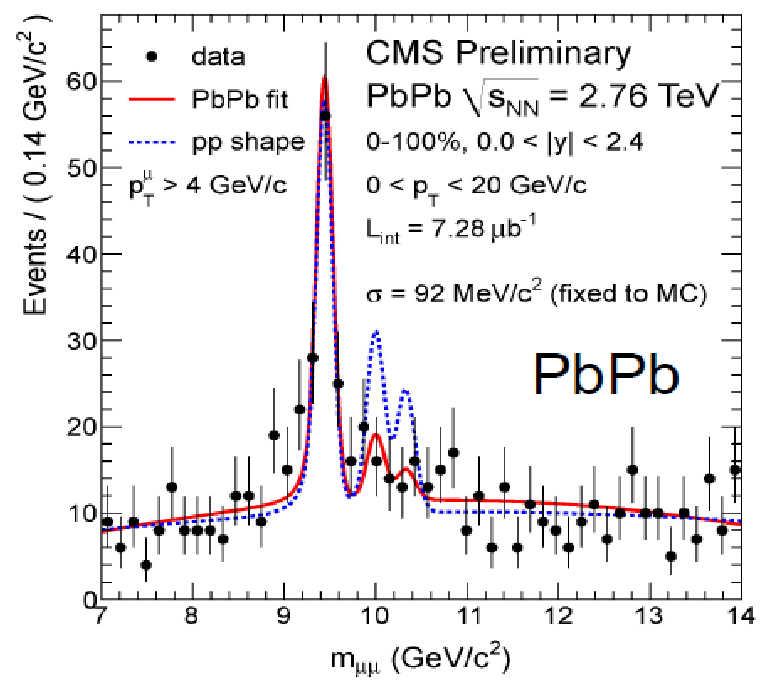
- obtain prompt J/psi spectrum

arXiv:1205.5880
FONLL: Cacciari et al., arXiv:1205.6344

Suppression of higher Upsilon states in CMS

in thermal models: expect suppression due to Boltzmann factors





raw ratios: $\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$ $\quad\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

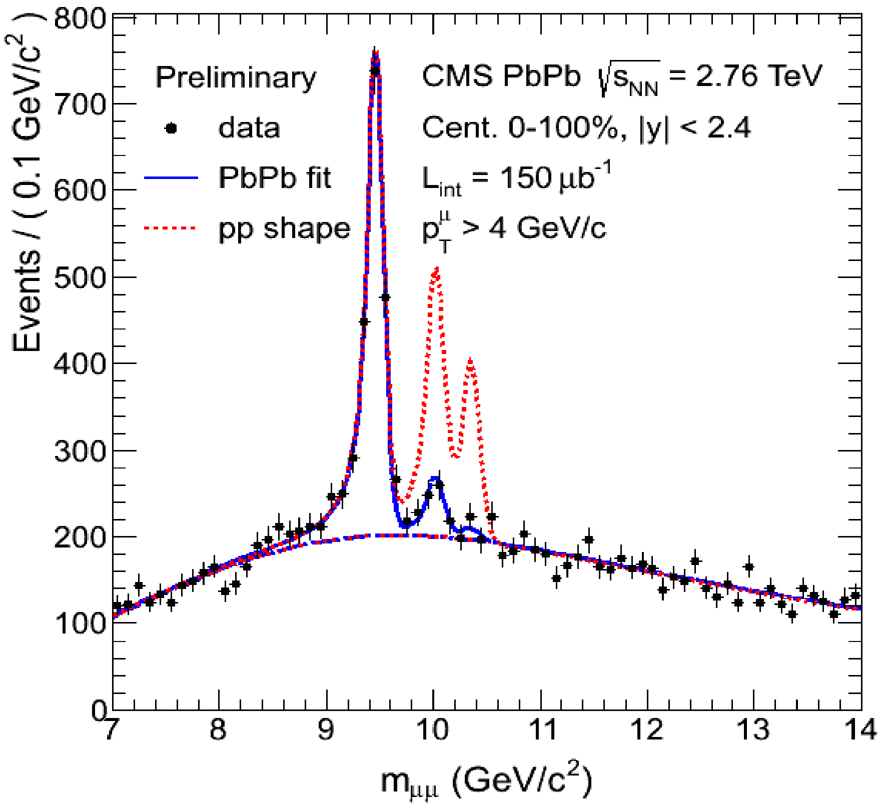
from CMS cross section measurements:

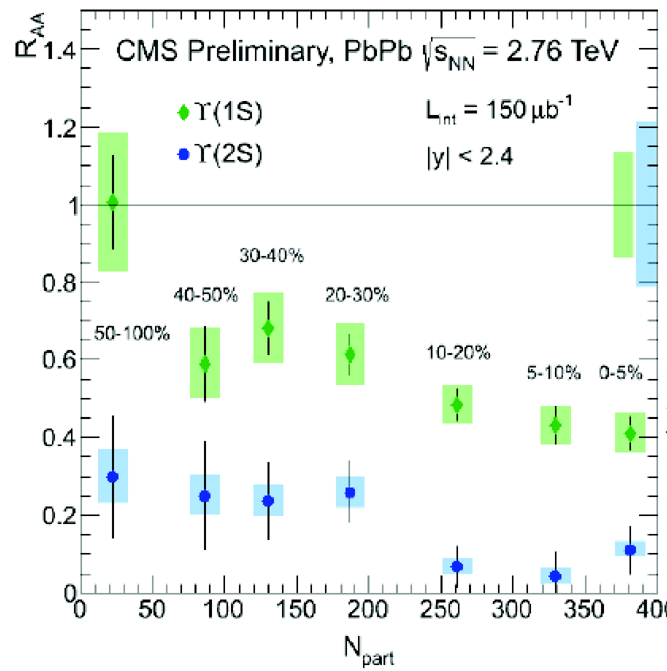
$(\Upsilon(2S) + \Upsilon(3S))/\Upsilon(1S)_{PbPb} = 0.14 +0.08 - 0.07$

vs thermal model at T=170 MeV: 0.046

ok within the current uncertainties

Suppression of Upsilon States 2011 data





CMS-HIN-11-011

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