

Heavy quarks in a Quark-Gluon Plasma at the LHC

- energy loss of partons in a QGP
 - light quarks
 - charm and beauty quarks
- elliptic flow of heavy quarks
- charmonia and QGP



International School of Nuclear Physics – 34th Course
Probing the Extremes of Matter with Heavy Ions
Erice – Sicily, September 17, 2012

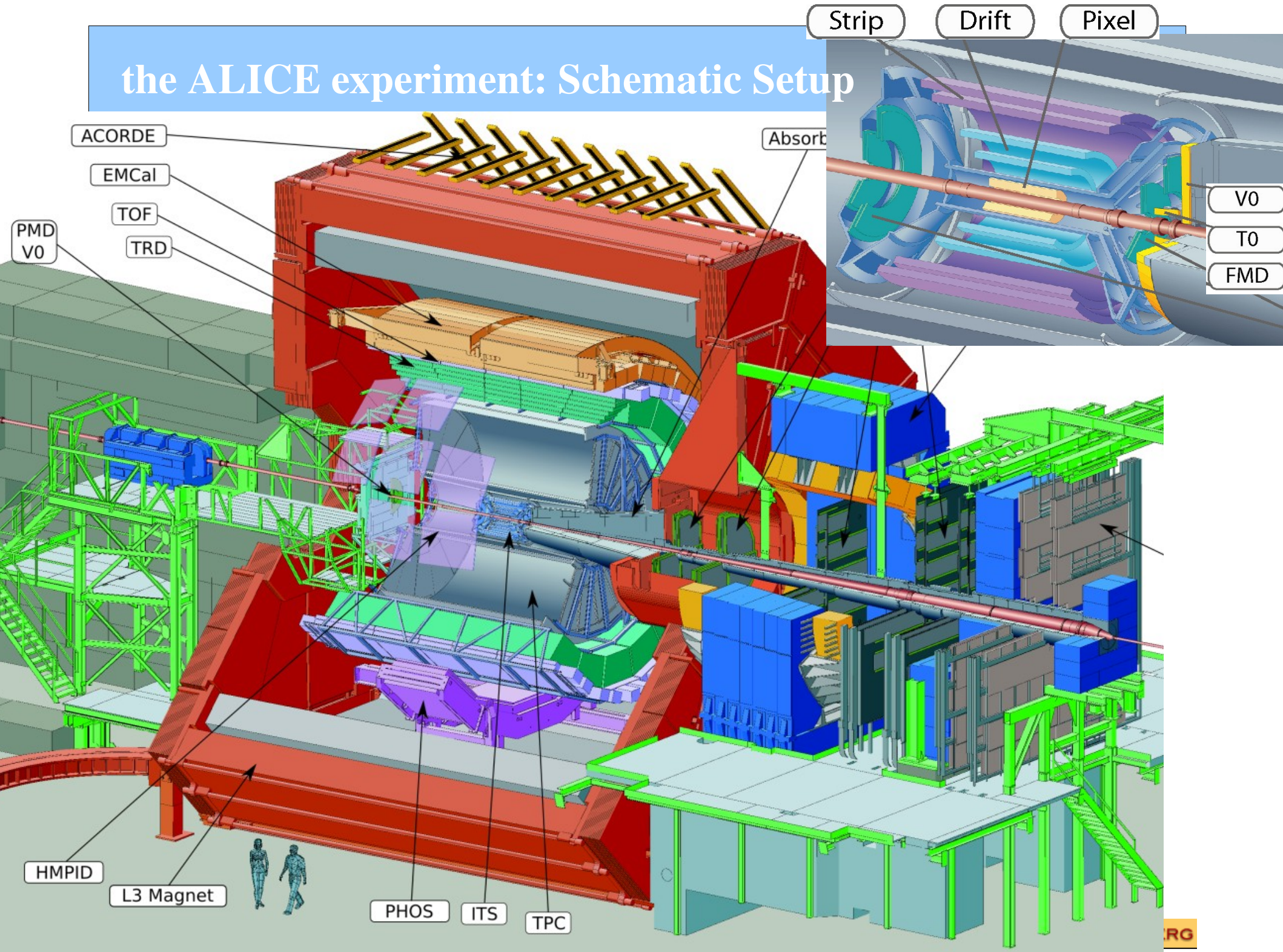


Johanna Stachel



RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

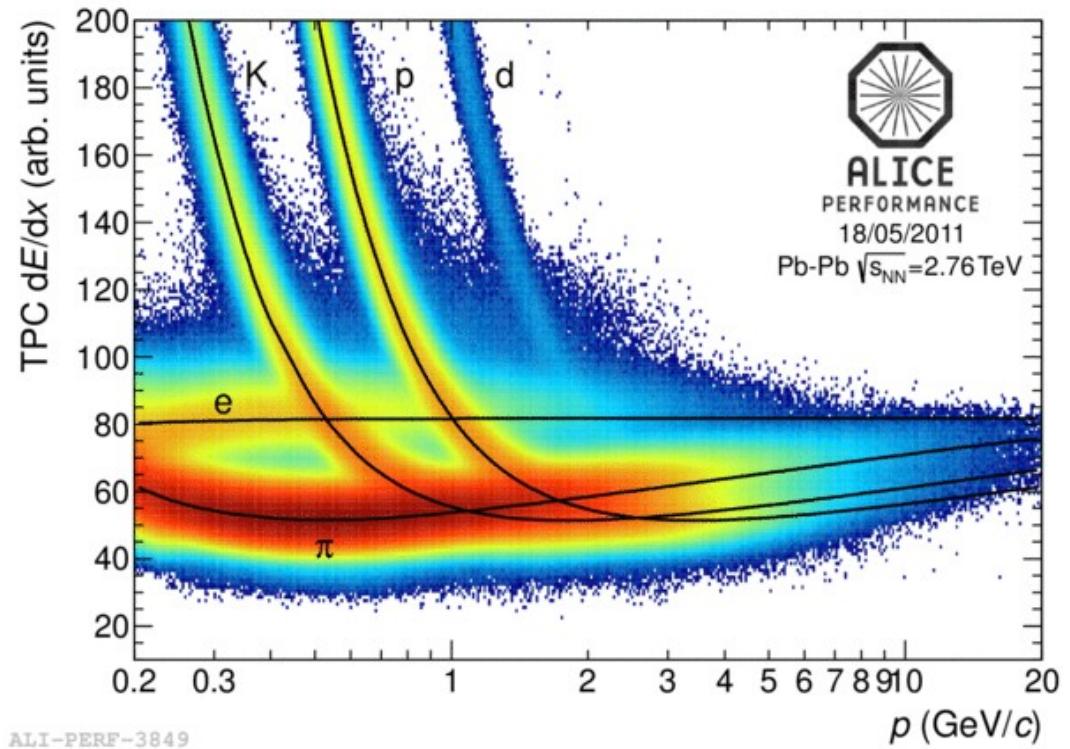
the ALICE experiment: Schematic Setup



a look into the interior of the TPC – 95 m³
165 space and charge points measured for every track



Particle identification by specific energy loss in TPC



first PbPb collisions at LHC at $\sqrt{s} = 2.76$ A TeV

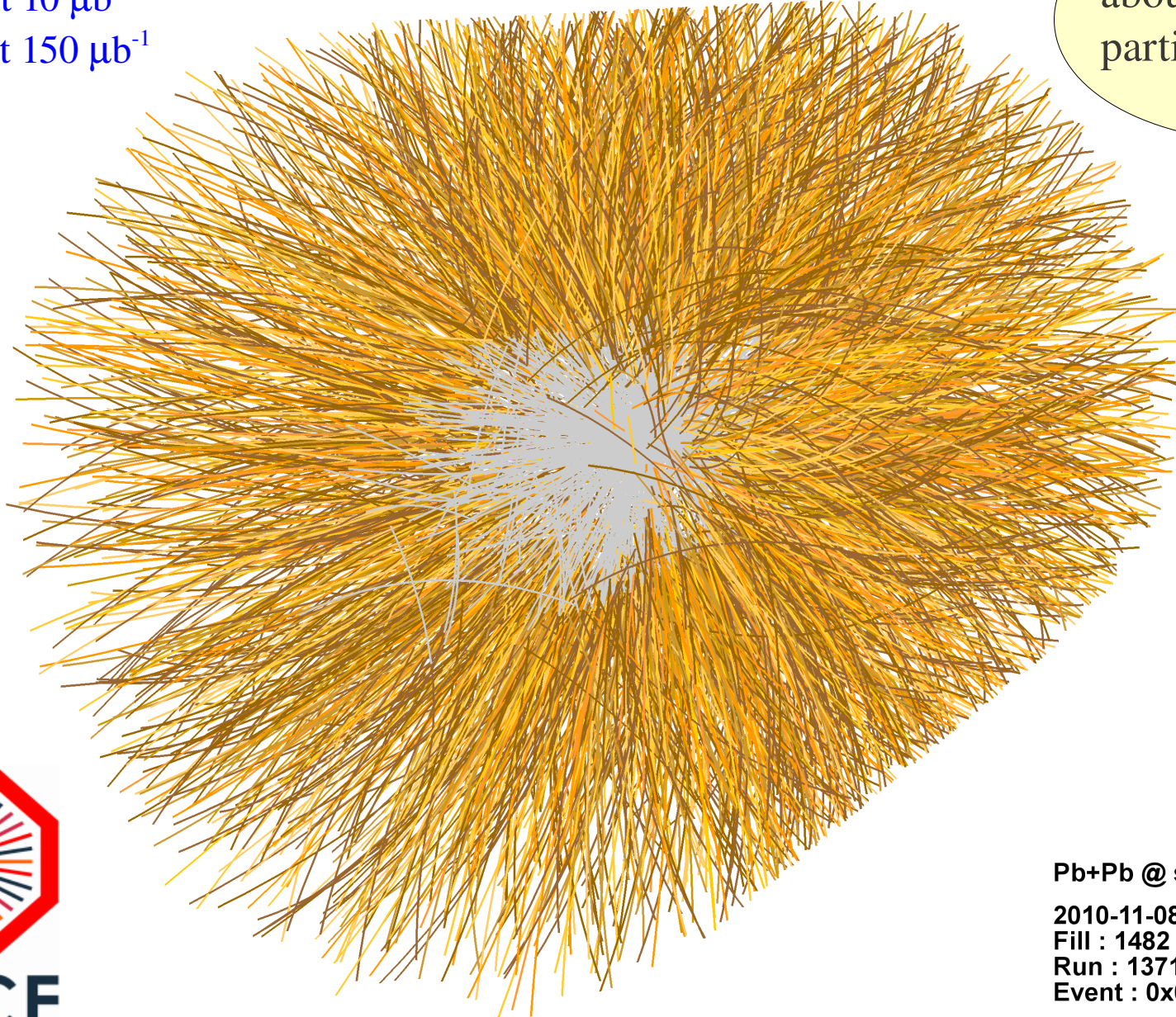
setup for ion collisions: November 4, 2010

first collisions with stable beams: November 8

in 2010 about $10 \mu\text{b}^{-1}$

in 2011 about $150 \mu\text{b}^{-1}$

about 3000 charged particles in $\pm 45^\circ$



ALICE

Pb+Pb @ $\sqrt{s} = 2.76$ ATeV

2010-11-08 11:30:46

Fill : 1482

Run : 137124

Event : 0x0000000D3BBE693

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**

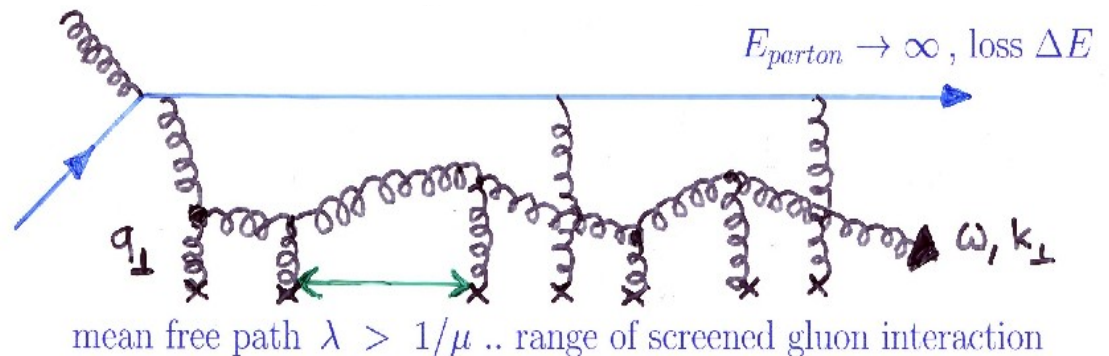
typical cone angle < 1 rad

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

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

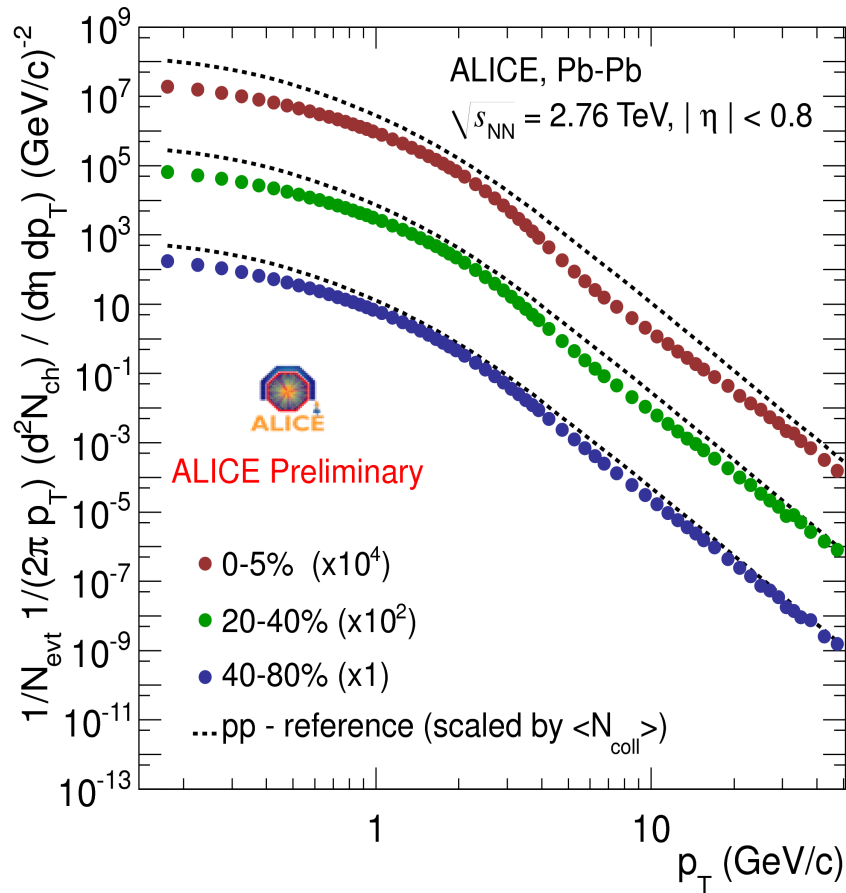


final jet carries information about the medium it traverses

in an analytic approximation (BDMPS)

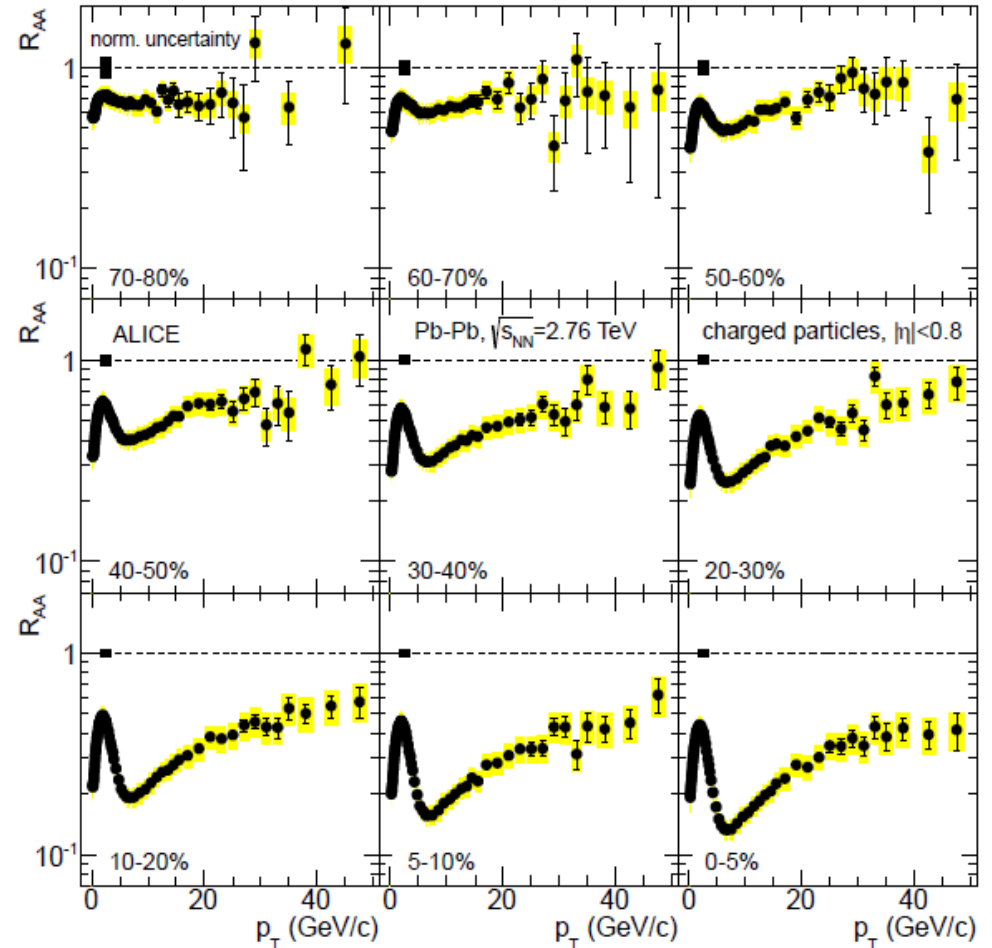
$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

Spectra in Central and Peripheral PbPb Collisions at LHC



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

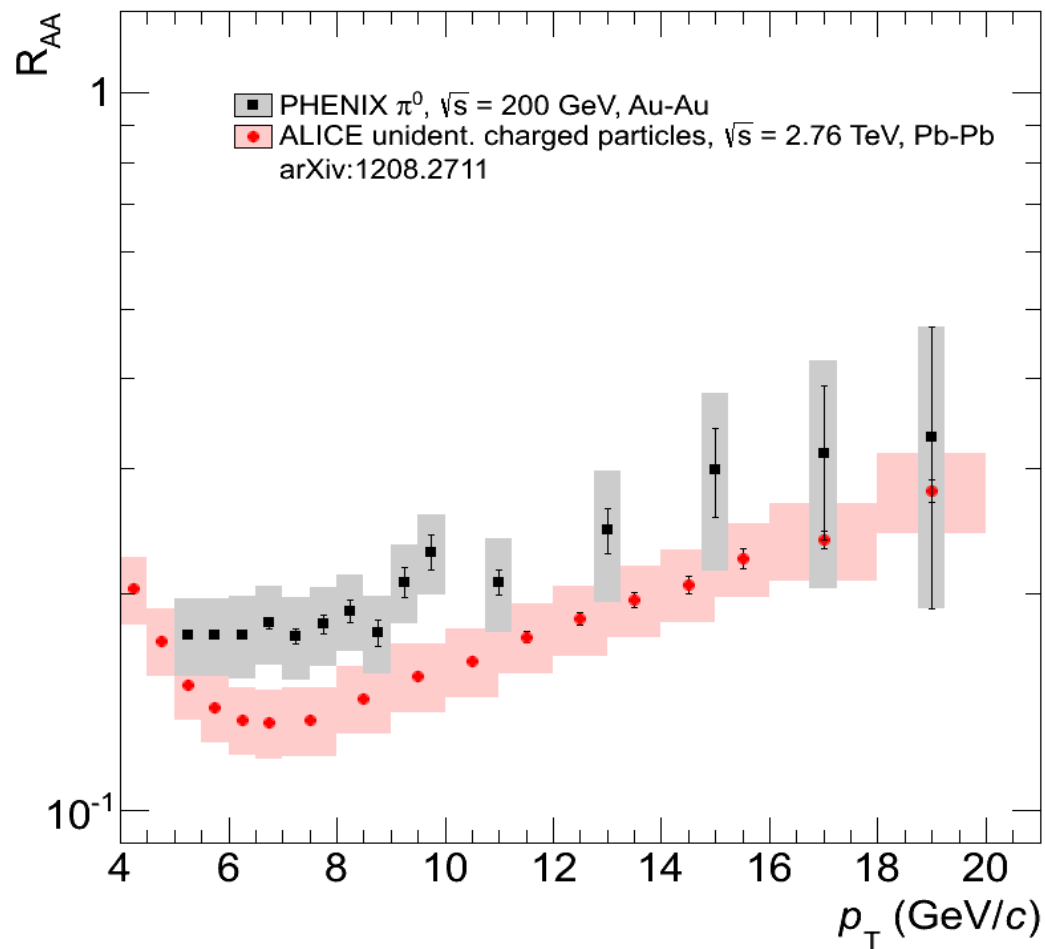
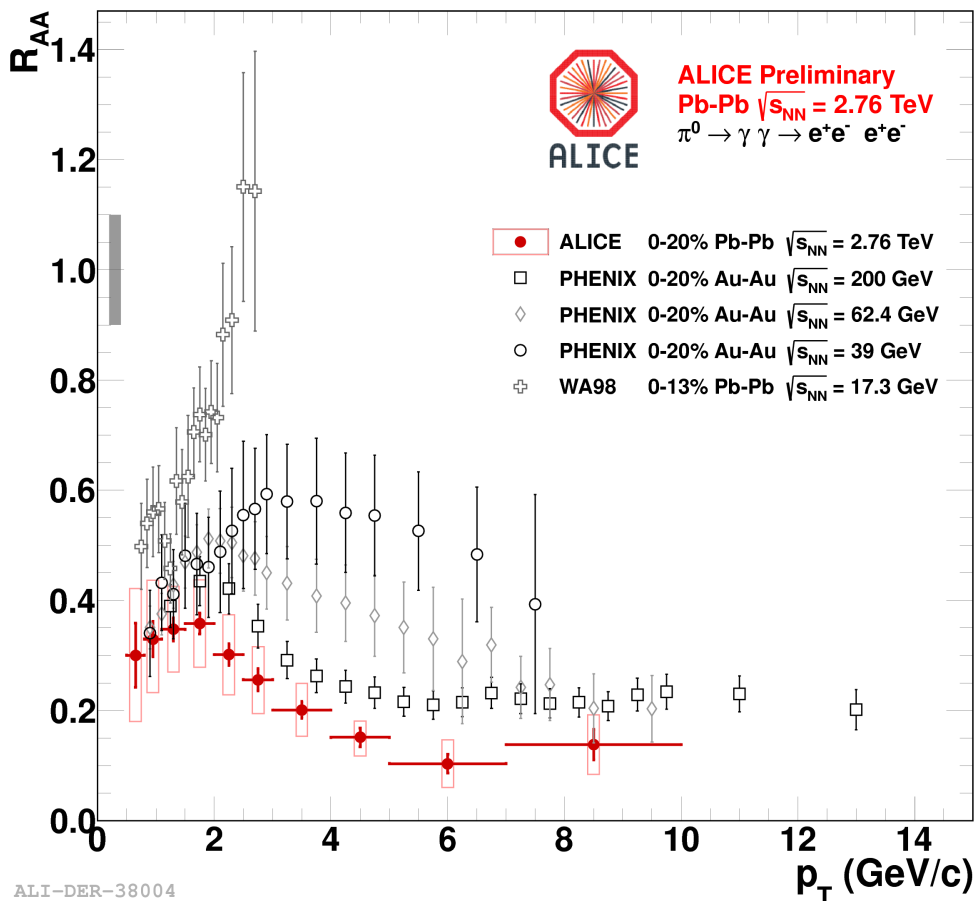
ALICE arXiv:1208.2711



strong suppression relative to pp reference in central PbPb collisions above 3 GeV/c
 effect of dense QGP on jets - determined by transport coefficient of QGP and parton type
 rise above 6 GeV/c but levelling off around 30 GeV/c - is pQCD limit of 1 never reached?

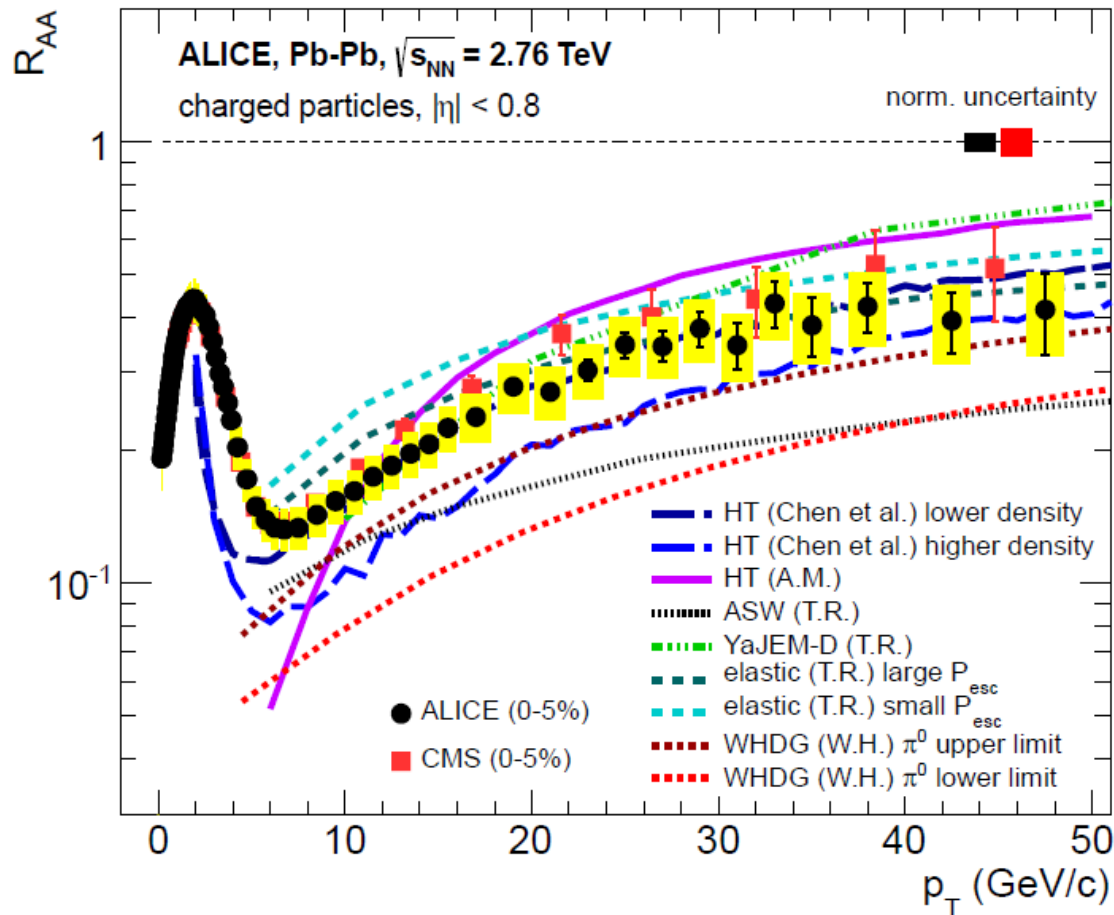
Beam energy dependence of R_{AA}

Systematic drop with increasing energy
high pt behavior: see next



First Comparison to Models

– Goal to Extract Transport Coefficient



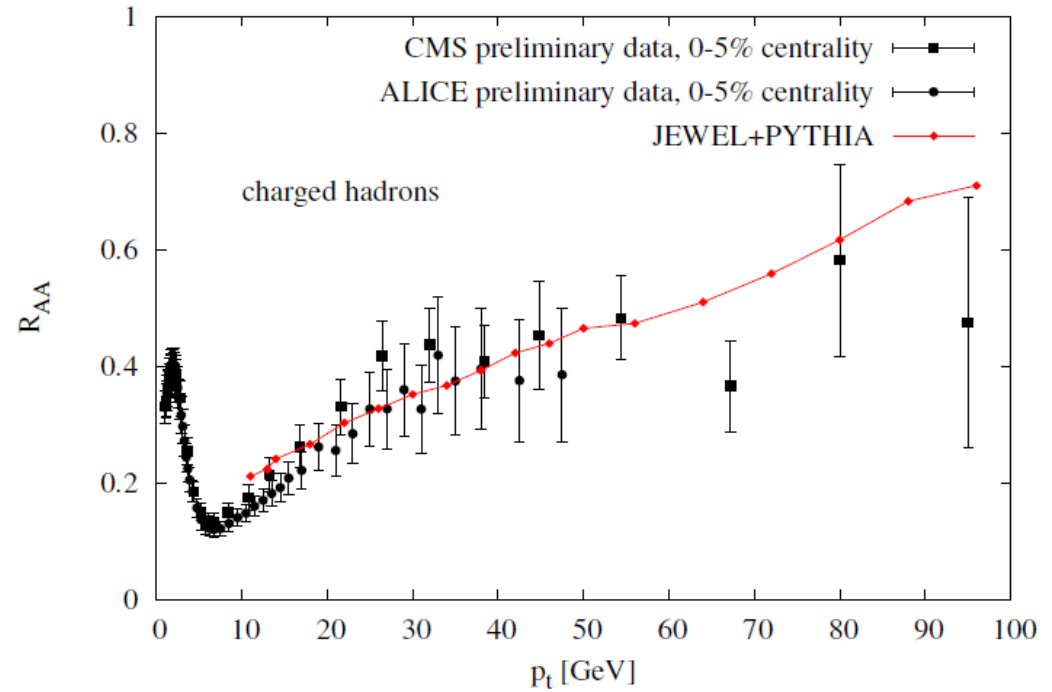
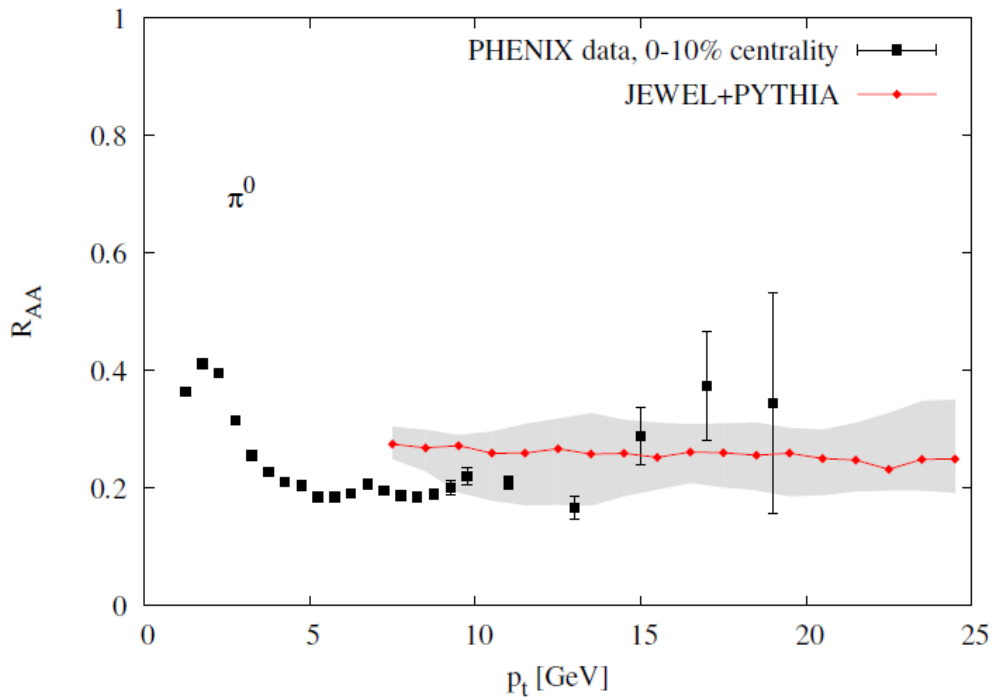
data show sensitivity
program for next years
- precision info for
different quark flavors &
large kinematic range
- determine effect of
medium (QGP) on jets
and vice versa

background info: data at RHIC show weak sensitivity to transport coefficients due to very steeply falling spectrum

Evolution of pQCD jet in the QGP medium

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

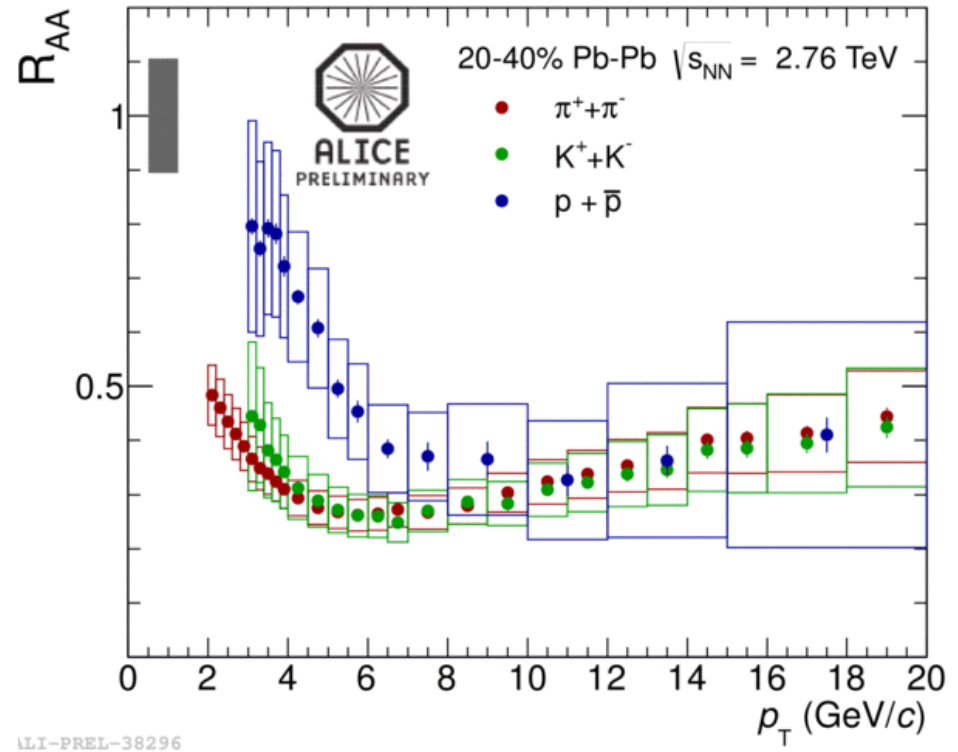
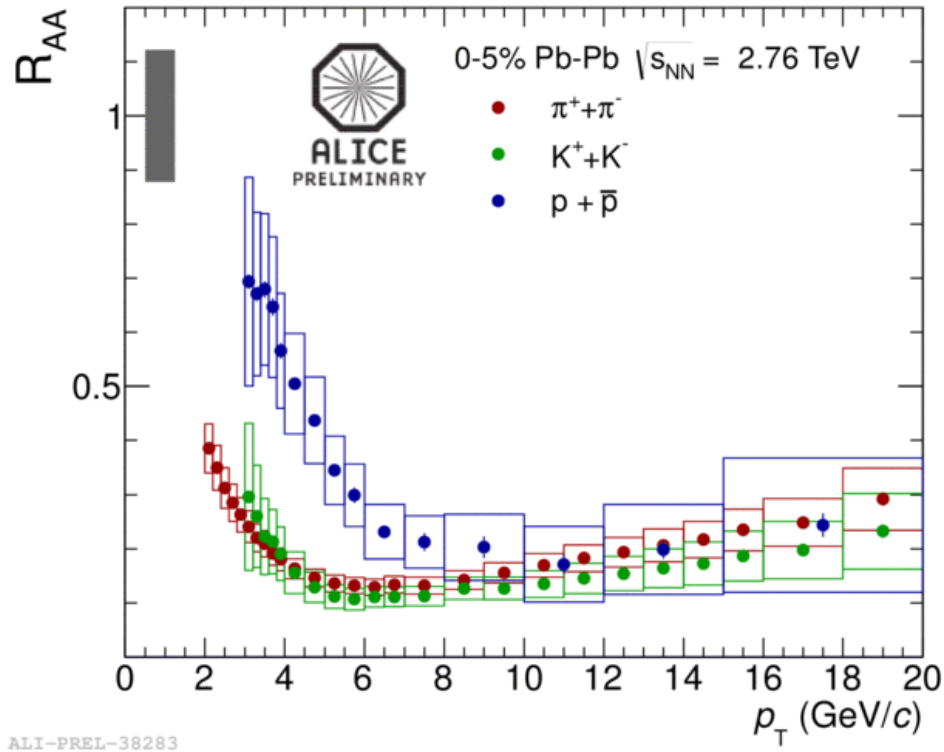
modeling of multiple scattering in the medium via infrared continued $2 \rightarrow 2$ scattering matrix element in pQCD and in-medium parton shower for further emissions



RHIC: $T_i = 350$ MeV $\tau_i = 0.8$ fm/c
scale is set by final state particle
multiplicity

LHC: $T_i = 530$ MeV $\tau_i = 0.5$ fm/c
different shape vs RHIC due to \sqrt{s}
dependence of hard scattering processes

R_{AA} of identified hadrons



for $p_T < 8$ GeV/c: R_{AA} for π and K are compatible and they are smaller than R_{AA} for proton.

at high p_T above 10 GeV/c the R_{AA} for π , K and proton are compatible within systematic error.

This suggest that leading particle jet hadron chemistry effects are small if present, unlike in the jet hadrochemistry model of Sapeta and Wiedemann.

Eur. Phys. J. C. 55, 293-302 (2008)

Open charm - charm quarks in the quark gluon plasma

interest 2-fold:

- transport coefficient for heavy quarks?

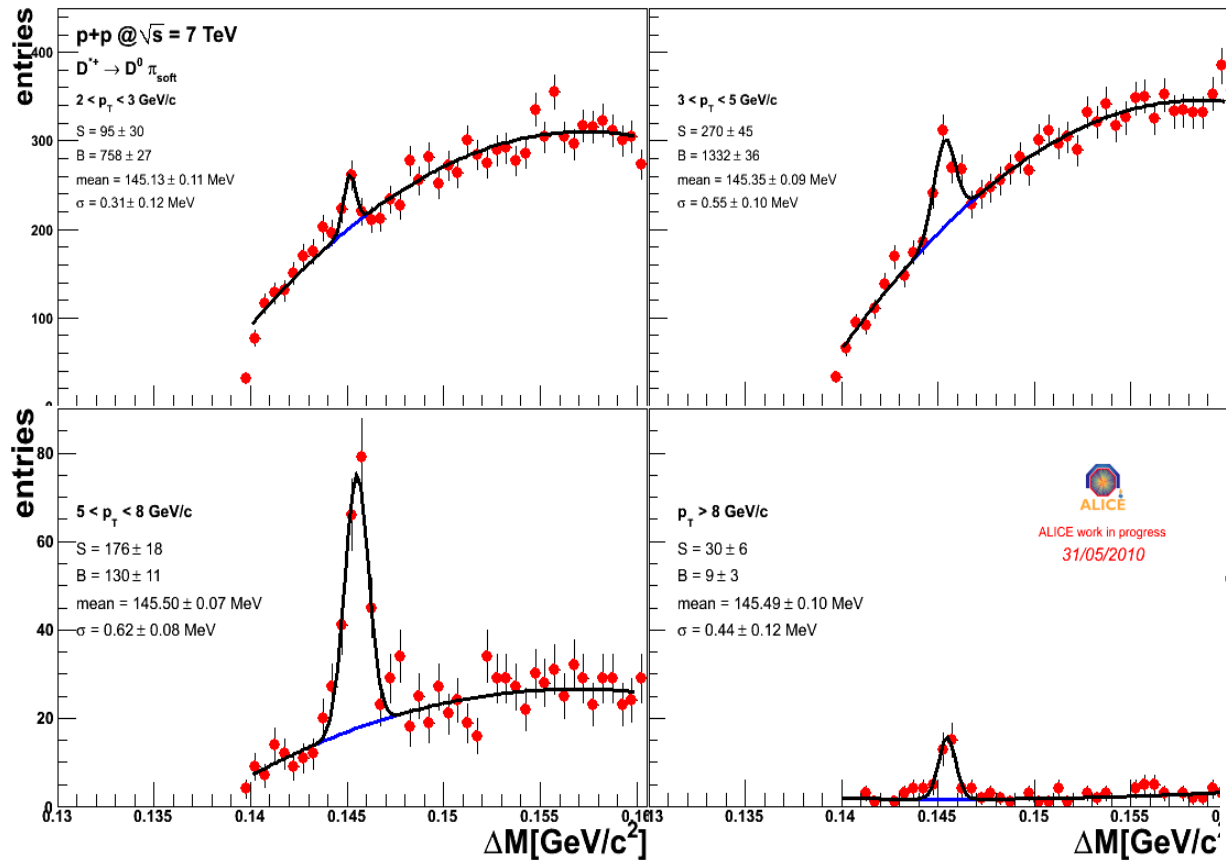
also energy loss of heavy quark - radiative energy loss should be suppressed due to large mass (1.2 GeV); in vacuum gluon radiation into angles $\theta \leq \frac{m_q}{E_q}$ suppressed (Dokshitzer and Kharzeev)

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

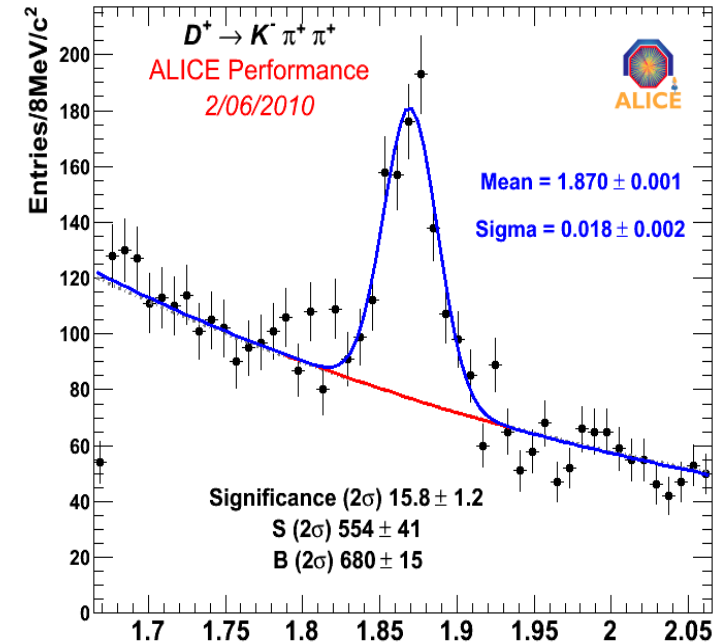
- need total charm cross section for understanding of charmonia (ccbar states)

D⁰, D⁺ and D^{0*} in 7 TeV pp data

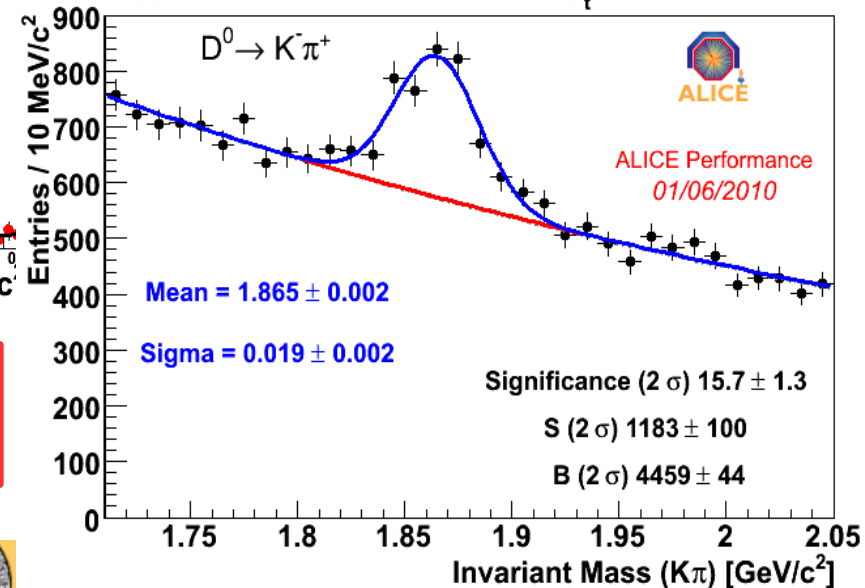
1.25 10⁸ events



pp $\sqrt{s} = 7$ TeV, 1.25 × 10⁸ events, p_t^{D⁺} > 2 GeV/c

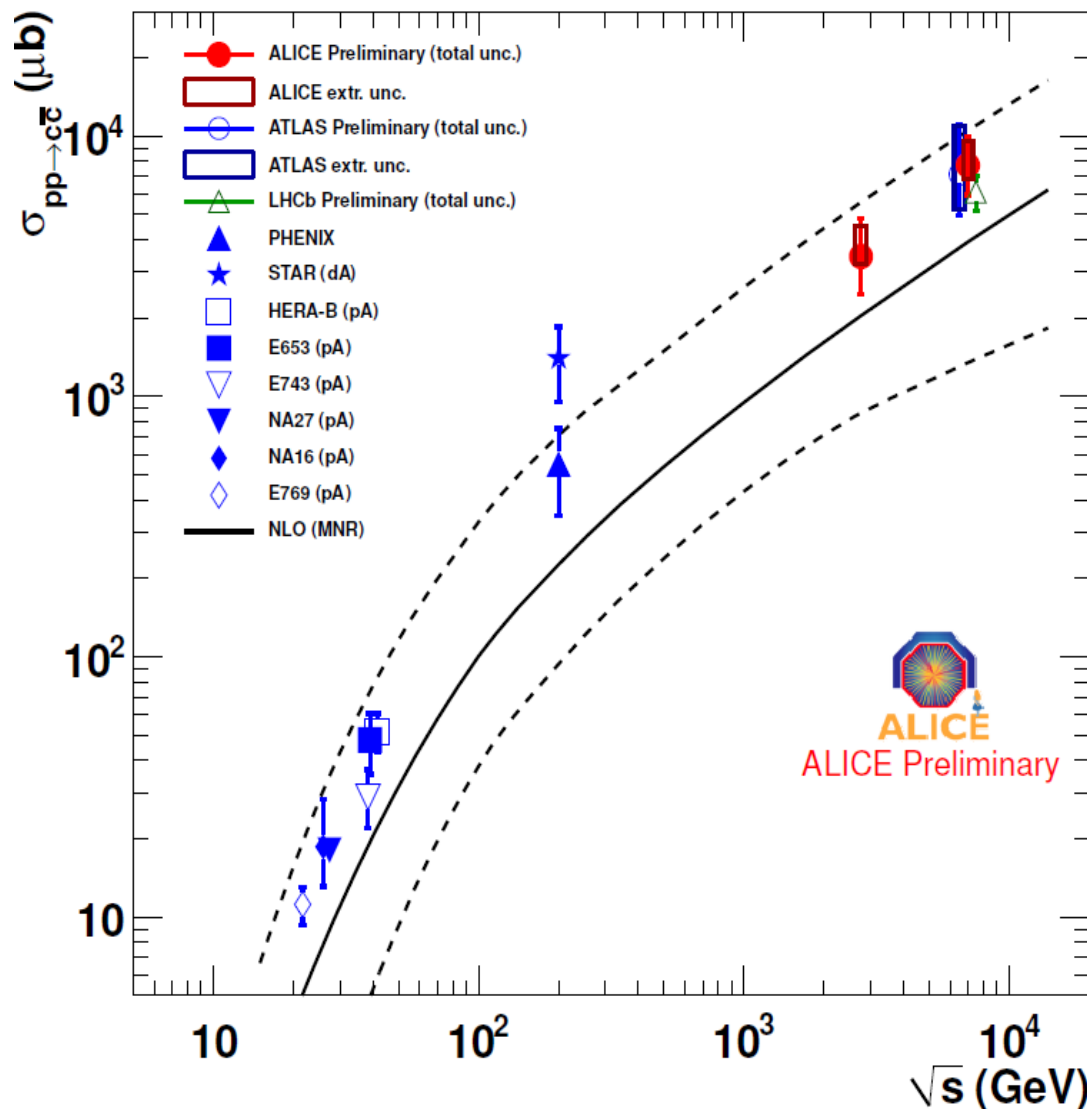


pp $\sqrt{s} = 7$ TeV, 1.25 × 10⁸ events, p_t^{D⁰} > 2 GeV/c



for 10⁹ events, expect to measure open charm for p_t = 0.5 – 15 GeV/c

a first try at the total $c\bar{c}$ cross section in pp collisions



- good agreement between ALICE, ATLAS and LHCb
- large syst error due to extrapolation to low p_t , 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

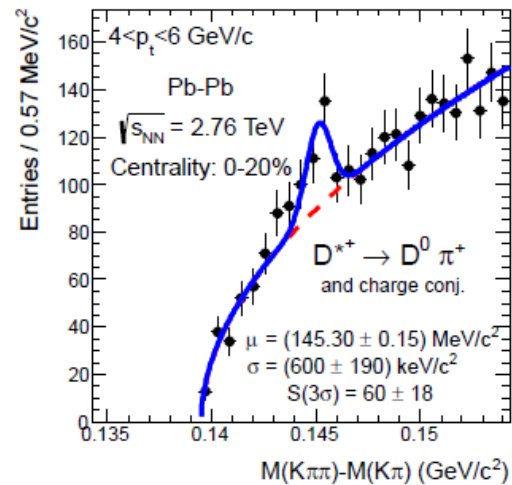
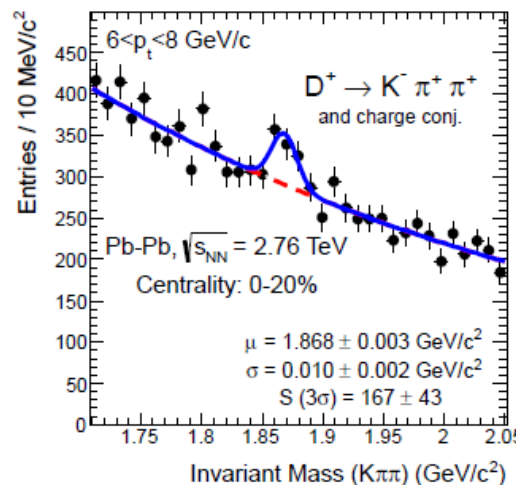
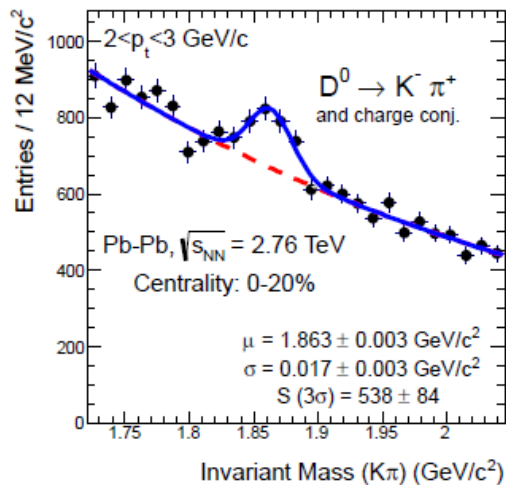
measurement:

reconstruction of hadronic decays of D-mesons (ALICE)

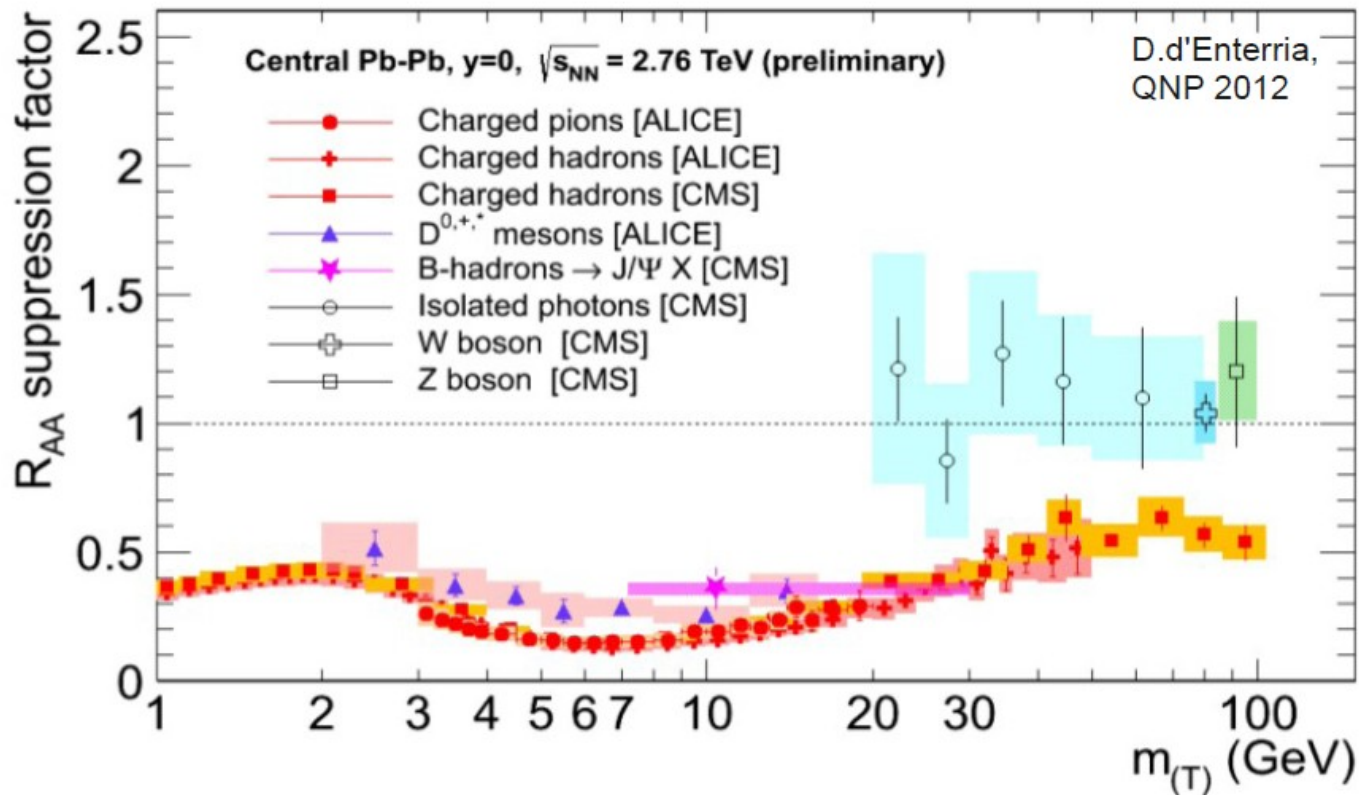
semi-leptonic decays into electrons (ATLAS, ALICE)

“

into muons (ATLAS, ALICE)



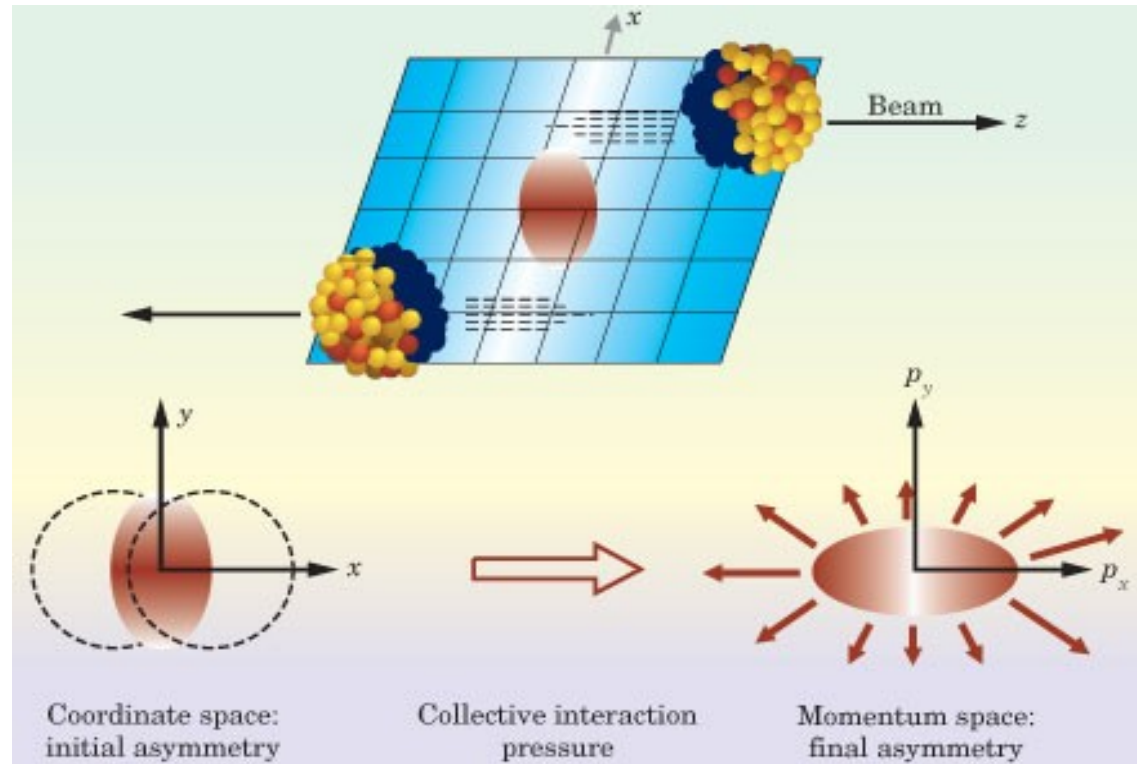
Suppression only for Strongly Interacting Hard Probes



for more details and most recent data see talk of Kai Schweda

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:

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

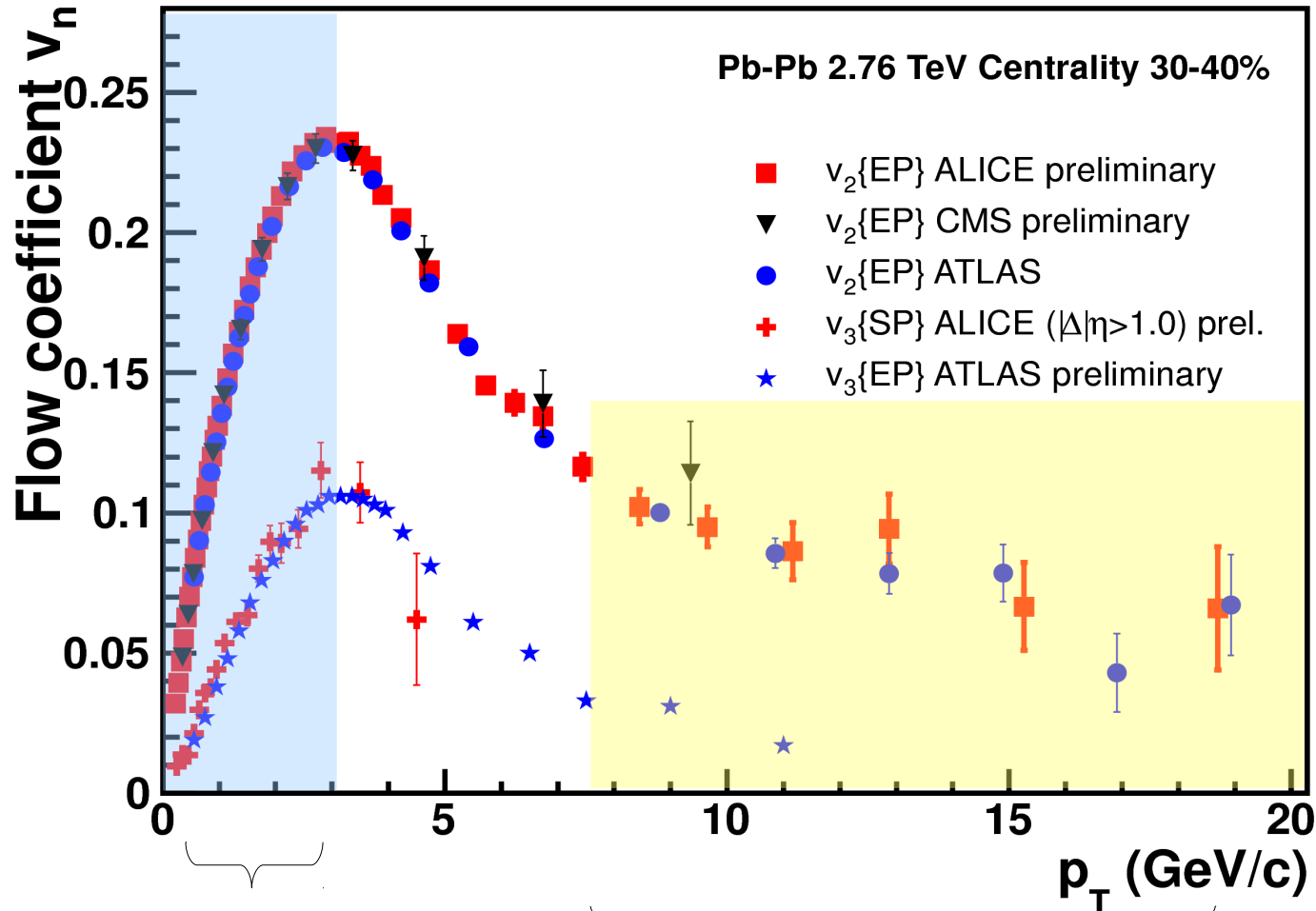
quadrupole component v_2
 “elliptic flow”
 effect of expansion (positive v_2)
 from top AGS energy

seen

the v_n are the equivalent of the power spectrum of cosmic microwave rad.

Elliptic Flow of Charged Particles at LHC

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



elliptic flow (v_2) as function of p_t :

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

hydrodynamic regime

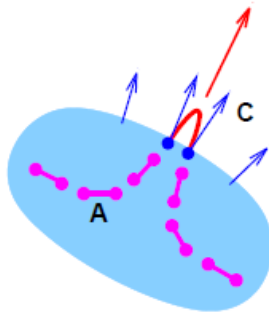
v_2 driven by pressure gradient

jet fragmentation regime

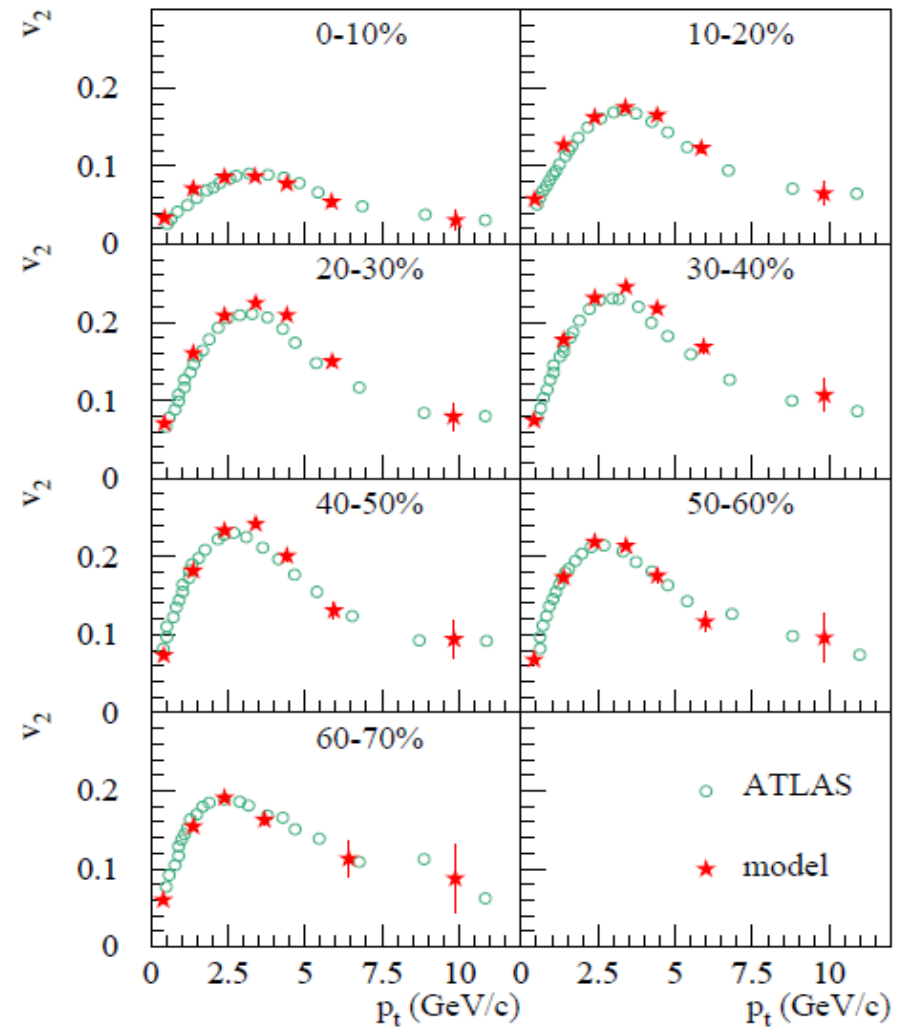
v_2 driven by energy loss

Unified Description of Different Regimes

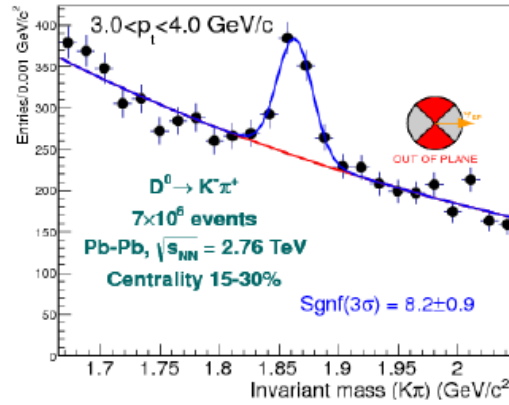
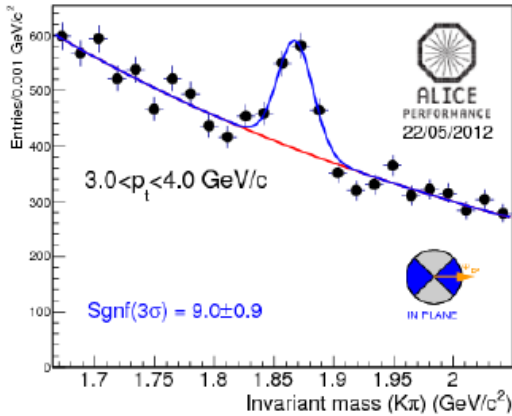
K. Werner et al. arXiv:1203.5704
jets, expanding bulk and their interactions



reproduces inclusive spectra, jets,
azimuthal anisotropies

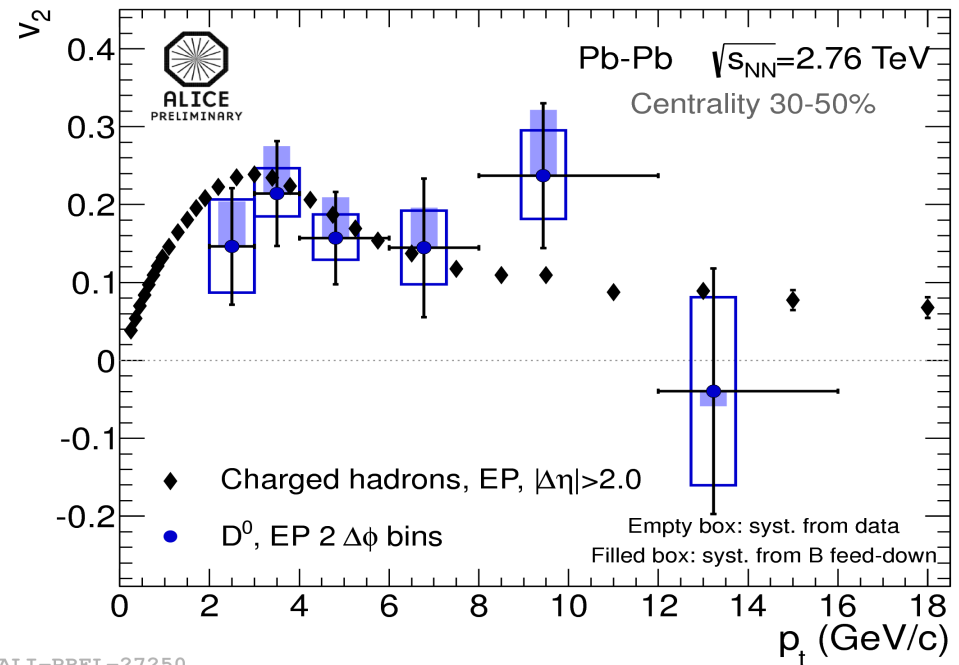


Charm Quarks also Exhibit Elliptic Flow



$$V_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

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



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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

Charmonia as Probe of Deconfinement

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



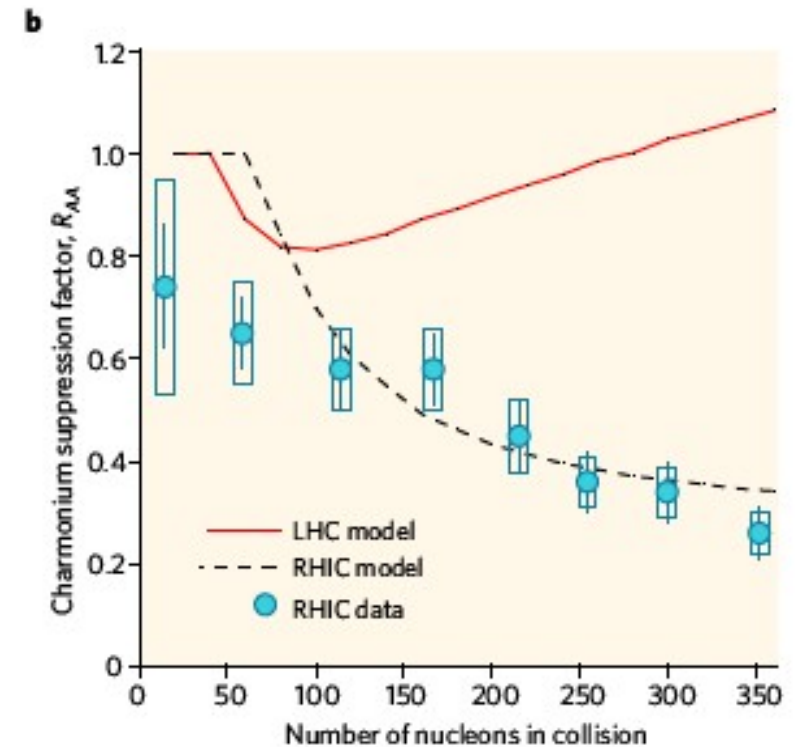
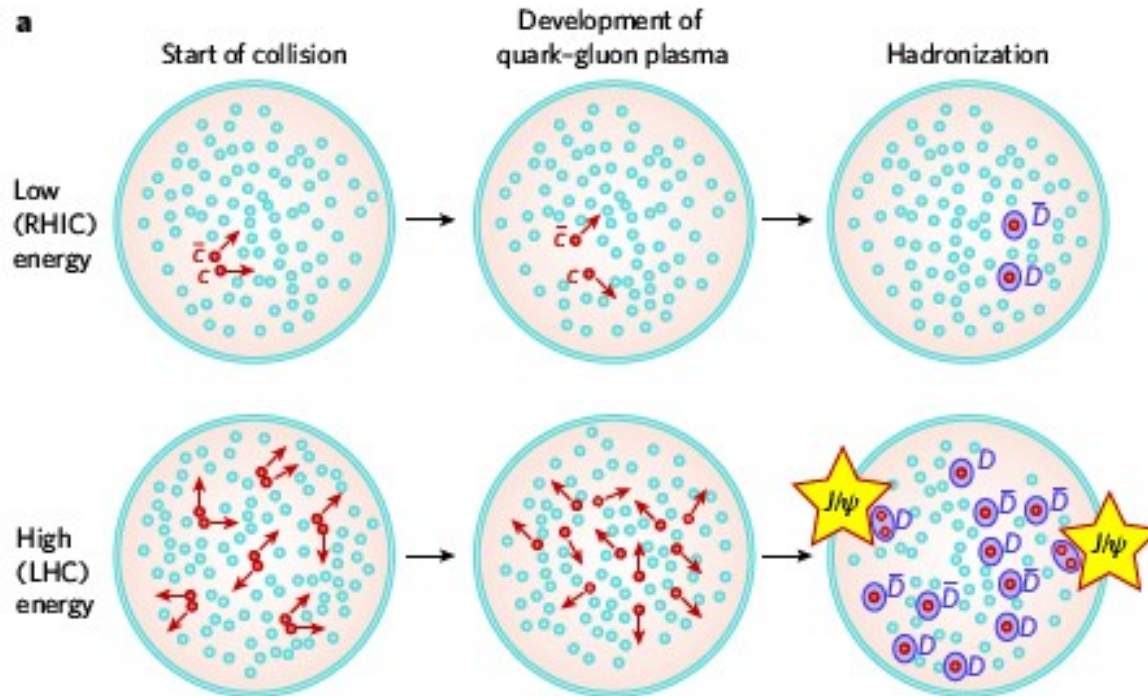
J/ψ 1 s state of c cbar
mass 3.1 GeV
radius 0.45 fm

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

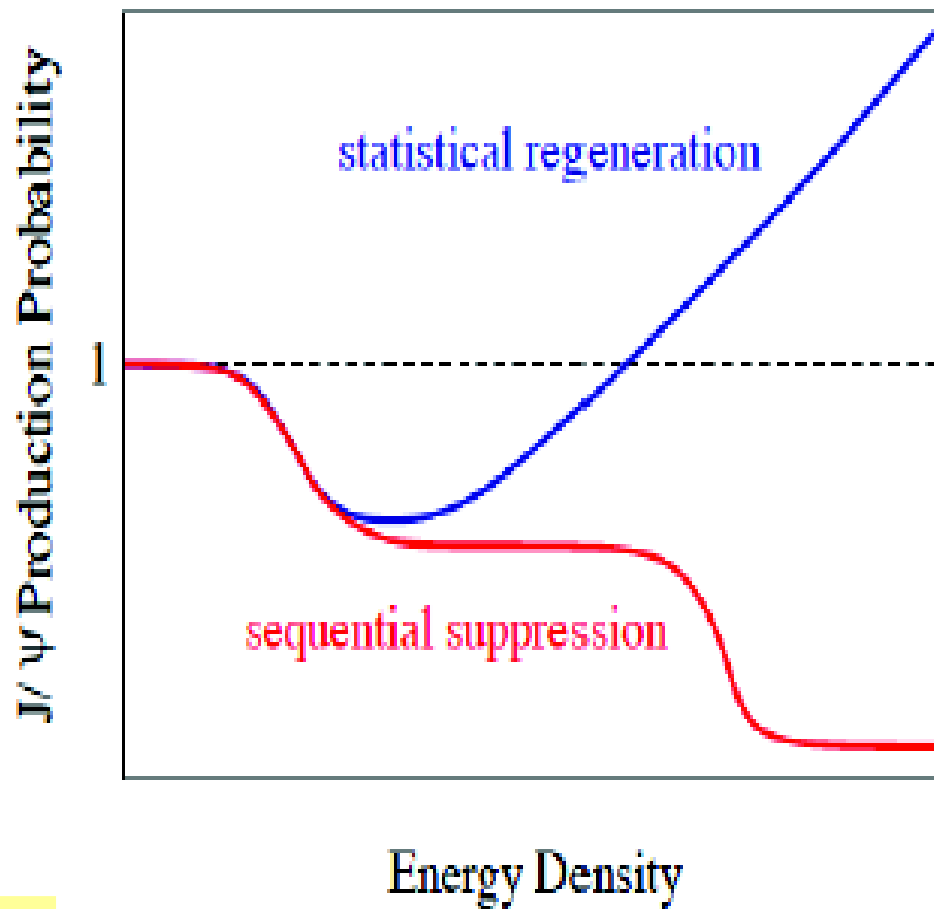
the Statistical (re-)Generation Picture



charmonium enhancement as fingerprint of deconfinement at LHC energy

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

Decision on Regeneration vs. Sequential Suppression from LHC Data



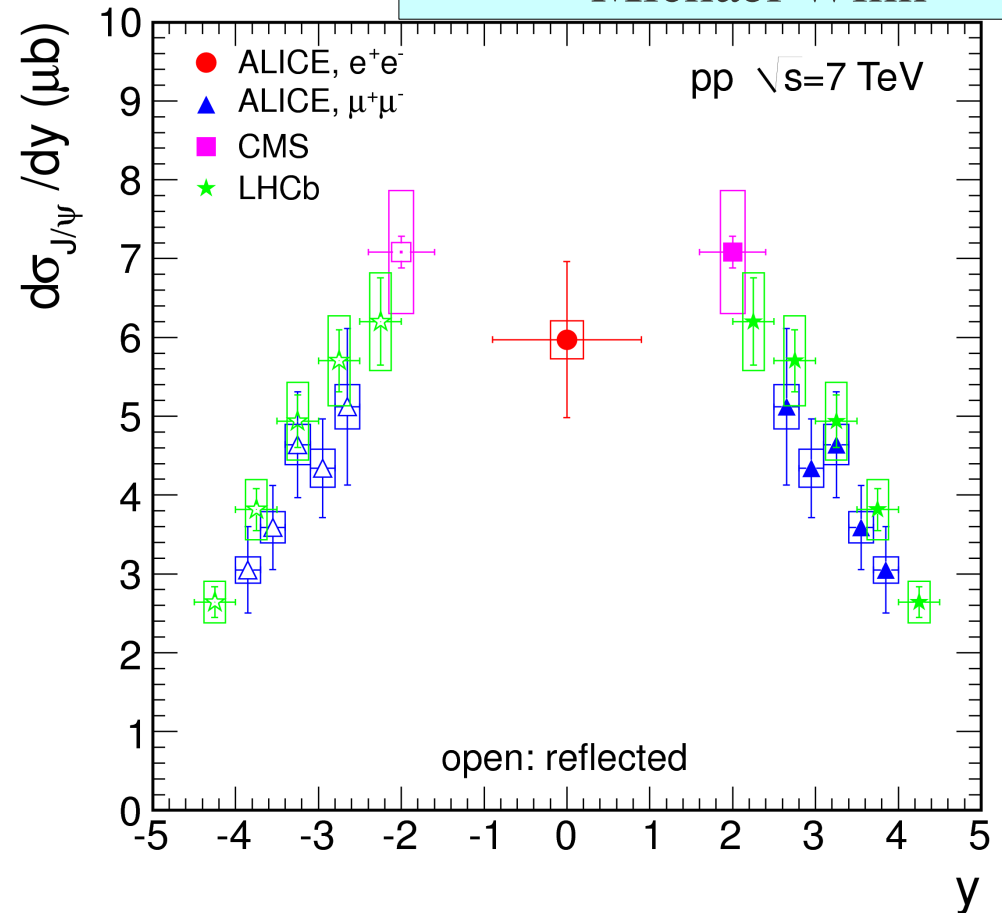
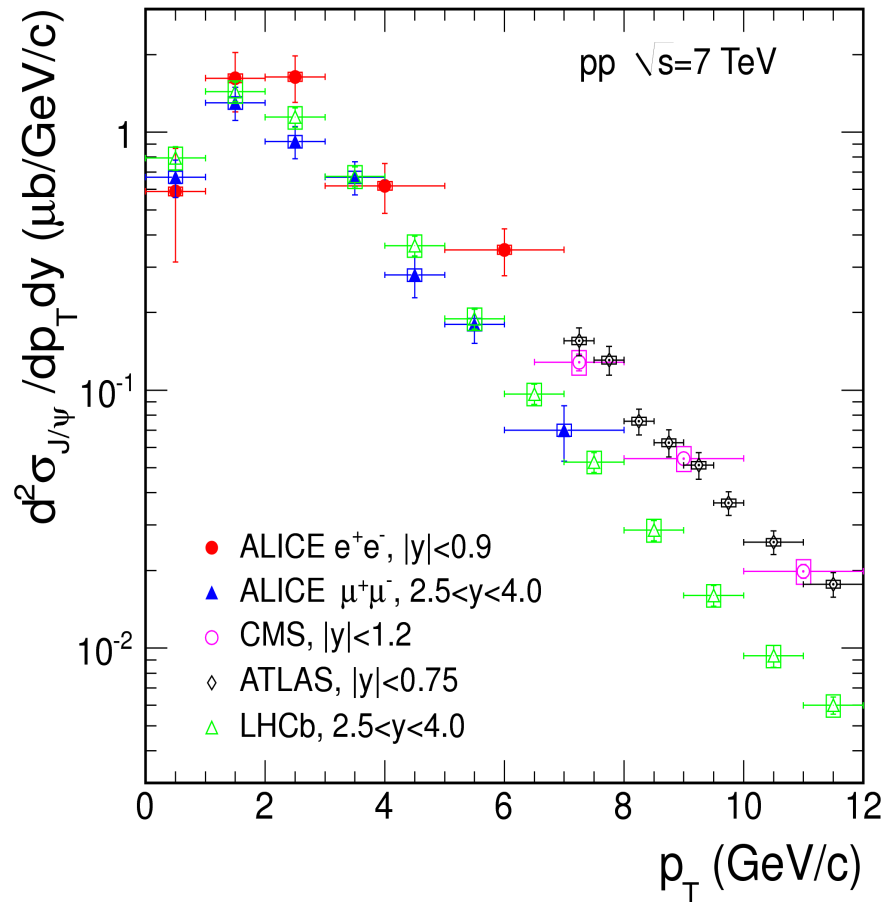
Picture:
H. Satz 2009

SPS RHIC LHC

J/psi spectrum and cross section in pp Collisions

ALICE PRL 704 (2011) 442 arXiv:1105.0380

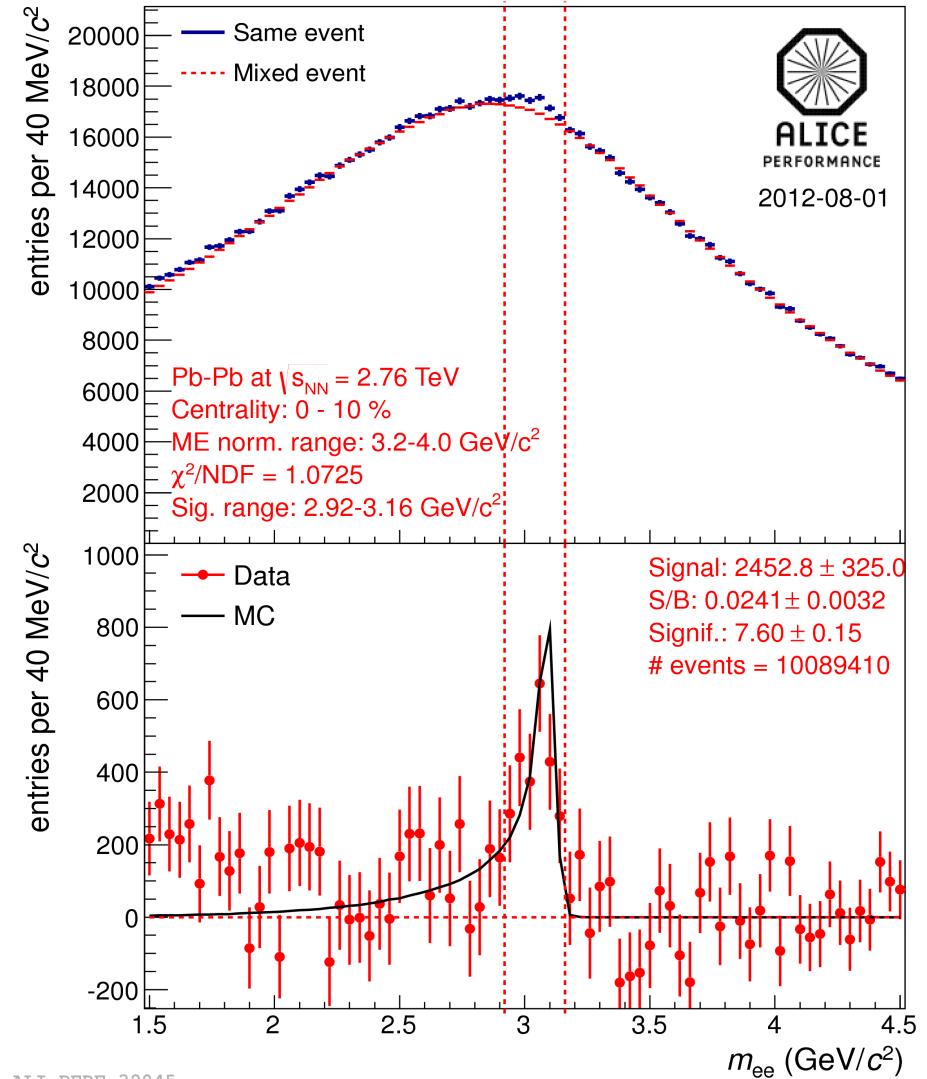
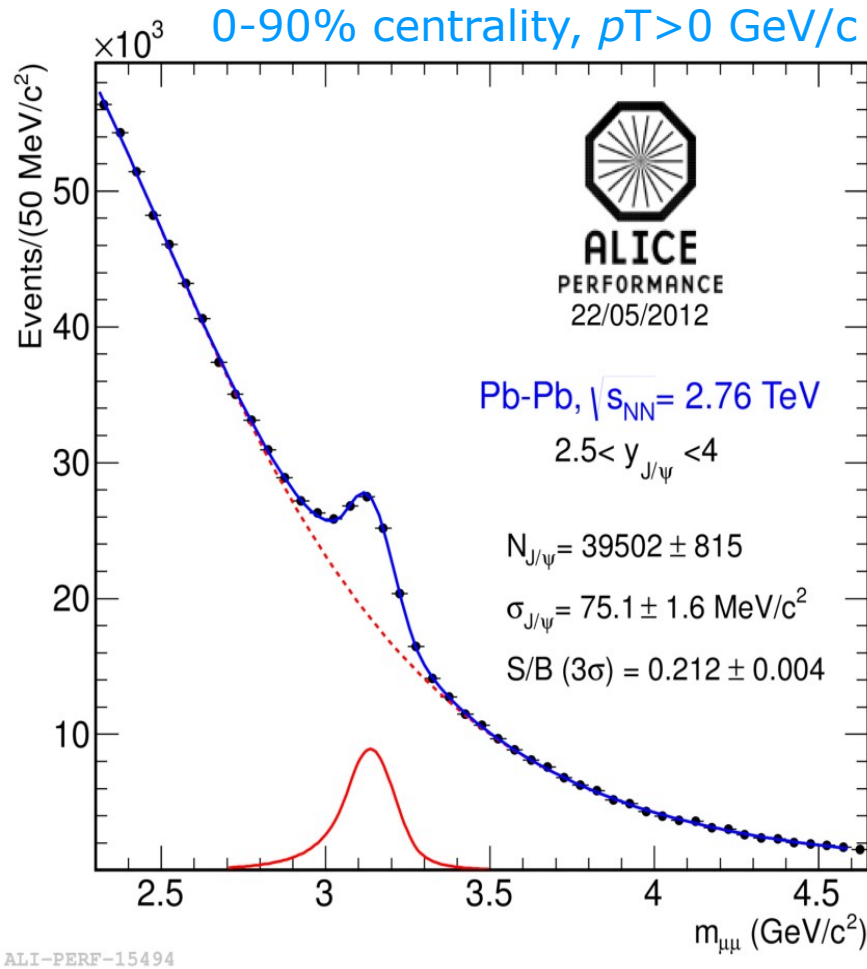
more details see talk of
Michael Winn



- 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



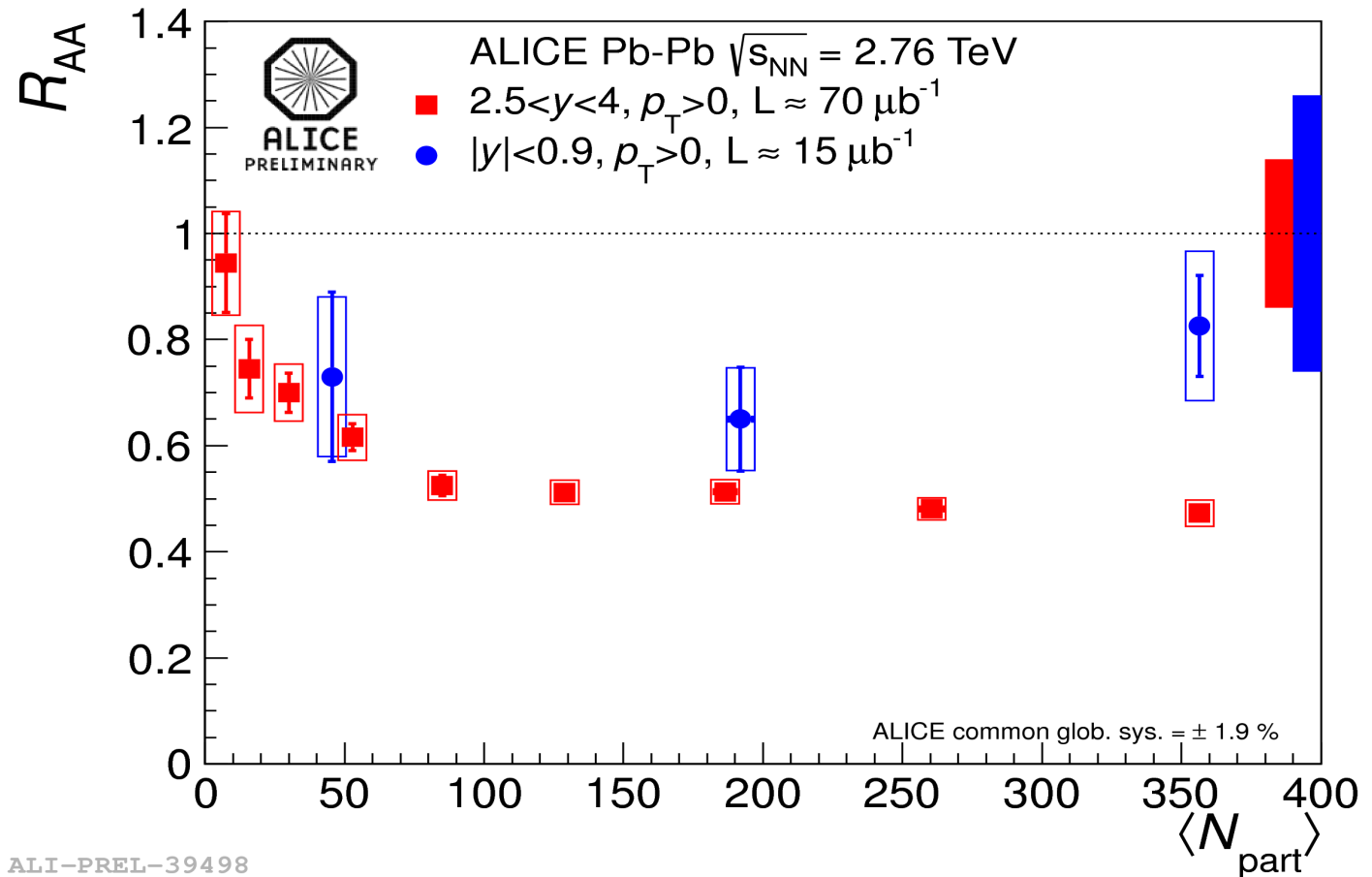
most challenging: PbPb collisions

in spite of significant combinatorial background

(true electrons, not from J/psi decay but e.g. D- or B-mesons) resonance well visible

J/psi in PbPb collisions relative to pp

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

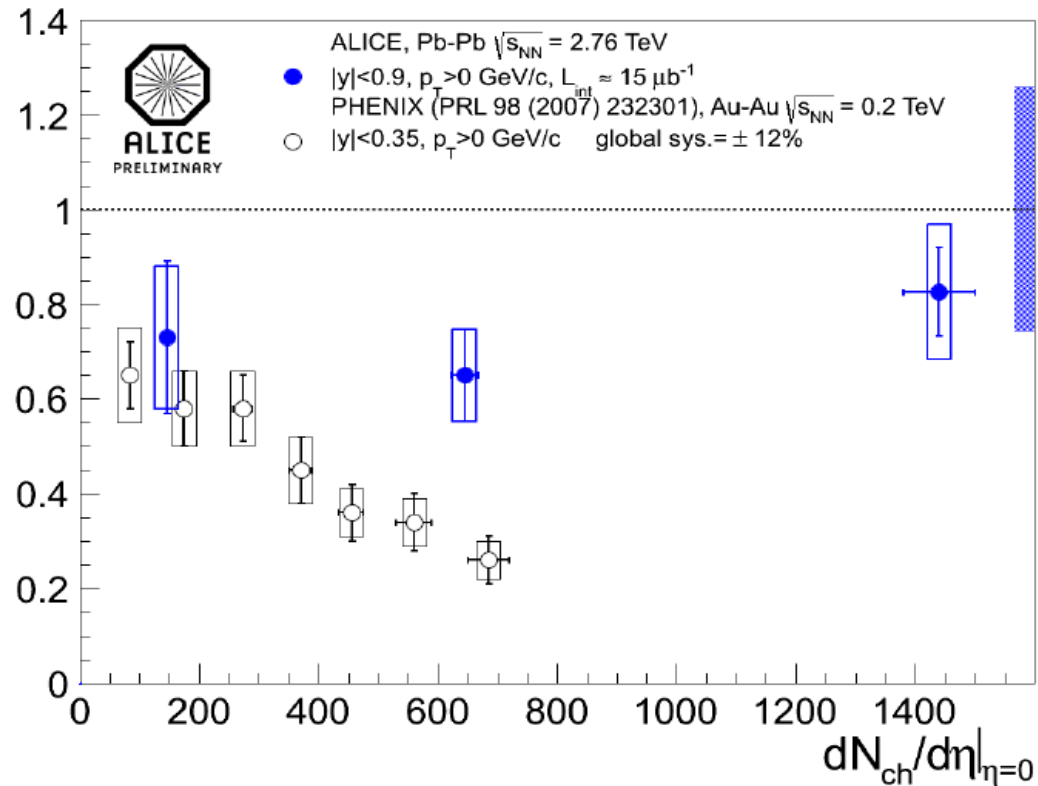
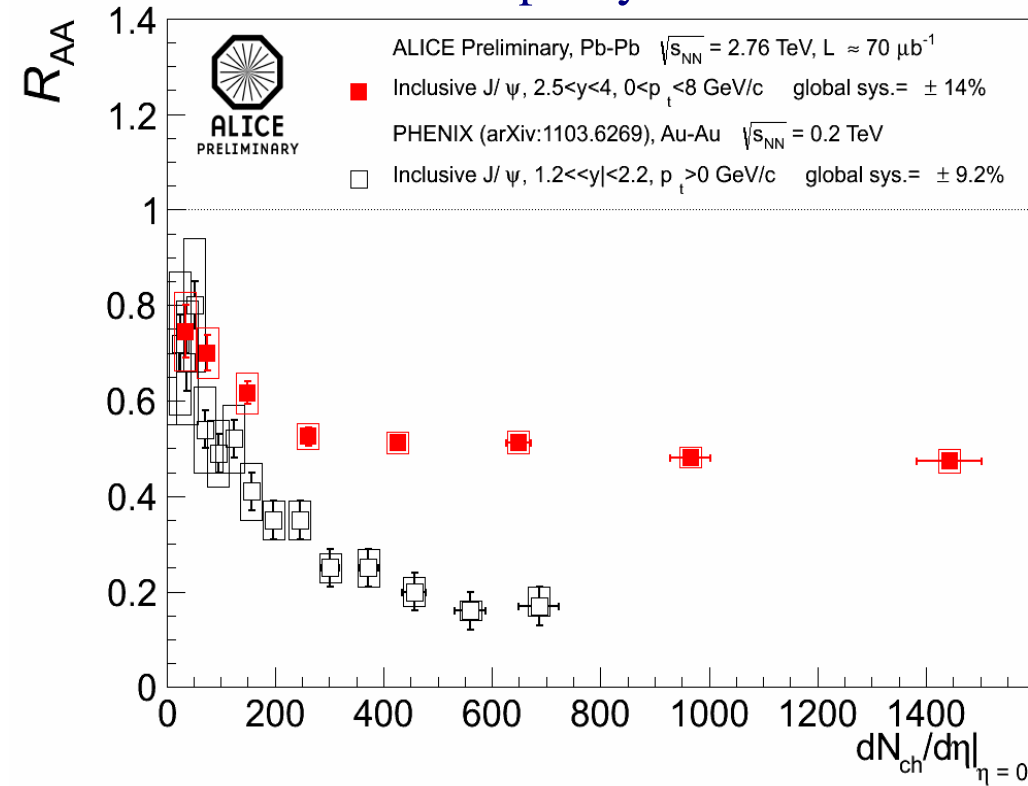


- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

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

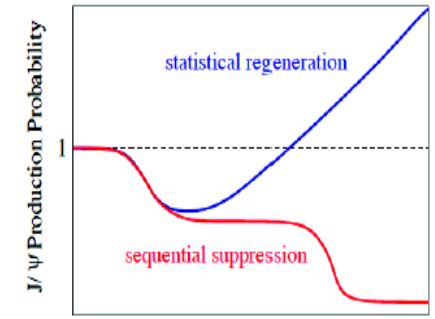
forward rapidity

mid-rapidity

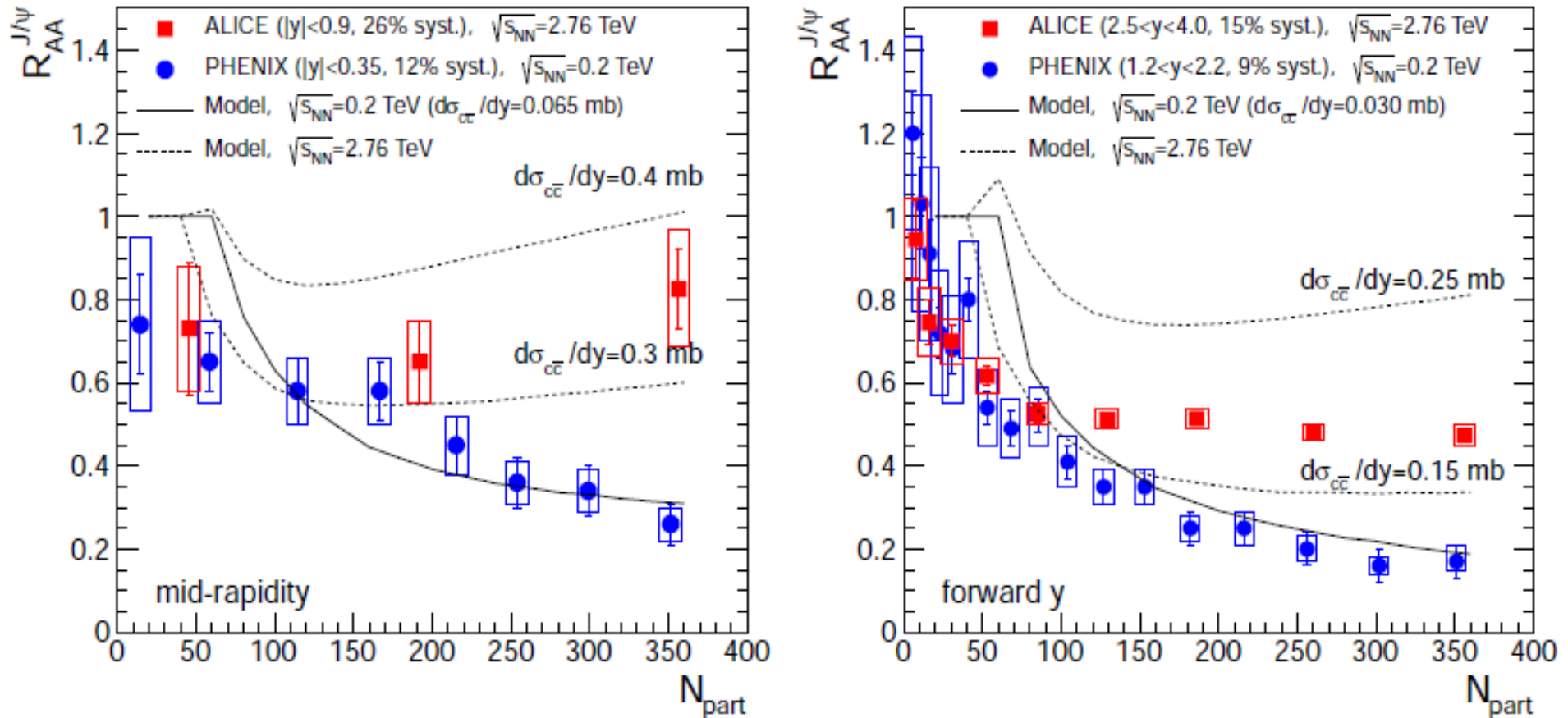


energy density -->

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



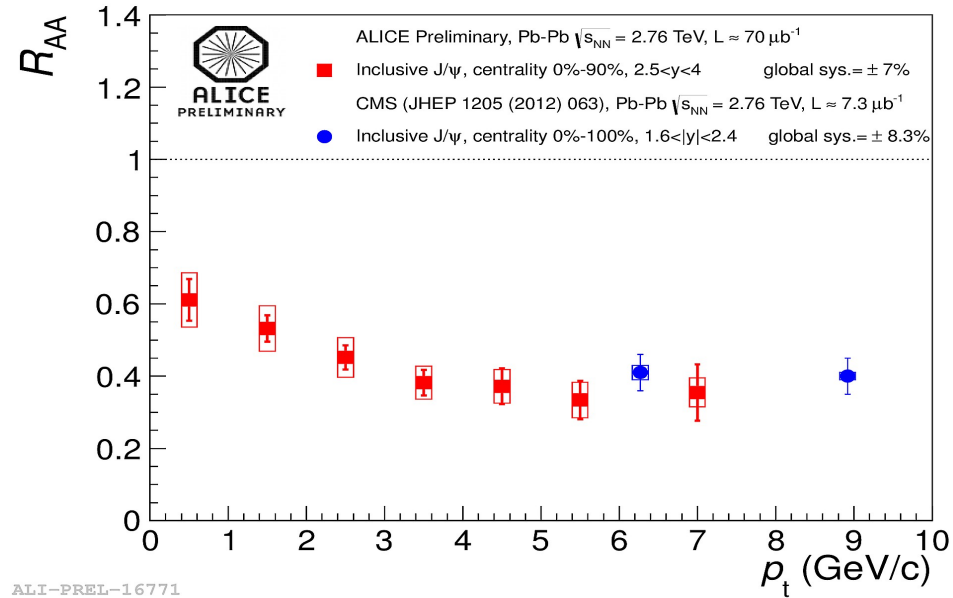
J/psi and Statistical Hadronization



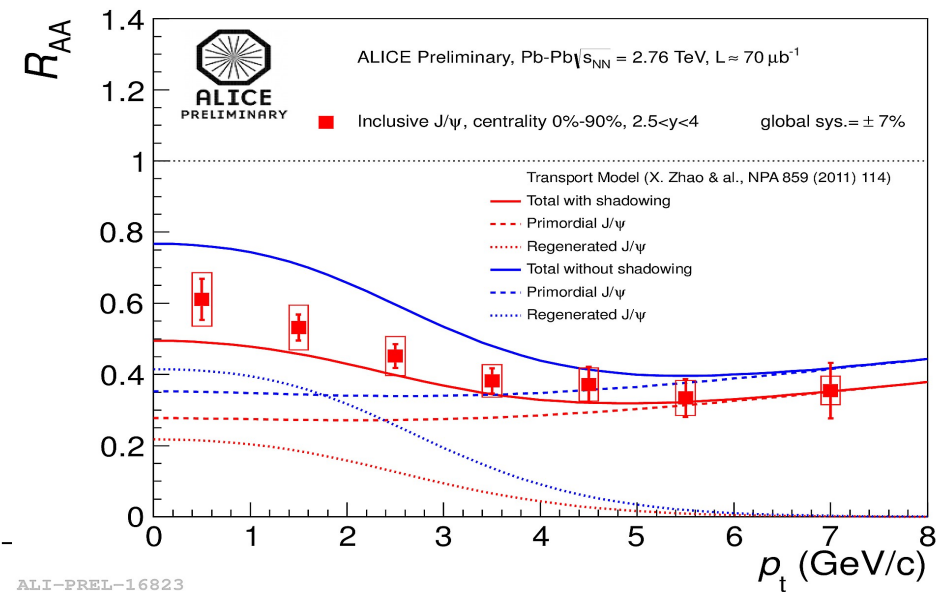
in AA collisions: strong indication of J/psi regeneration

- 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}

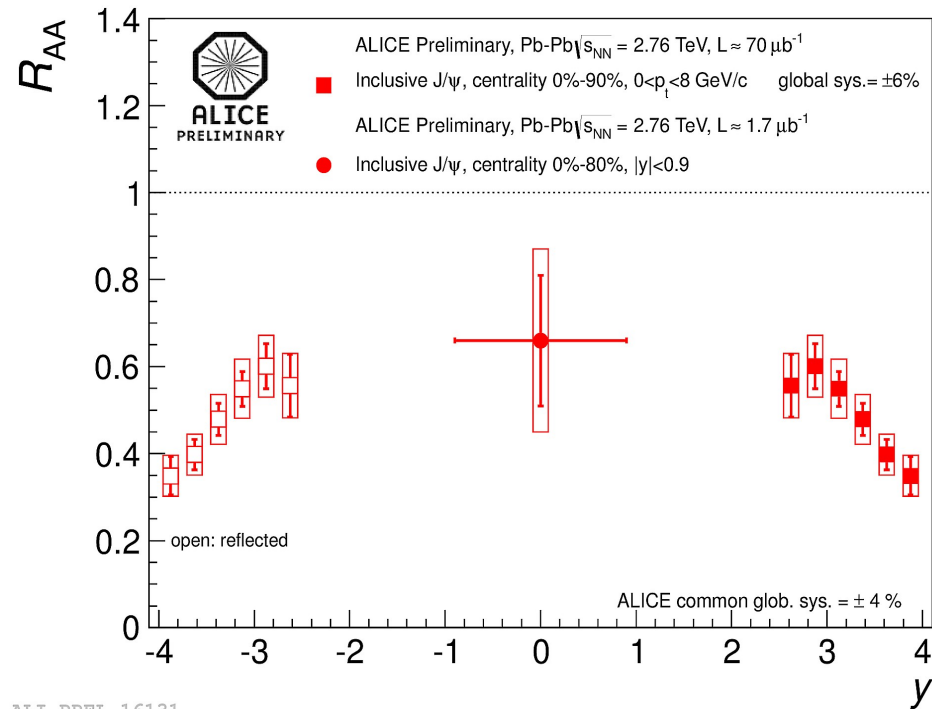


relative yield larger at low p_t in nuclear collisions
 good agreement with CMS at high p_t



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

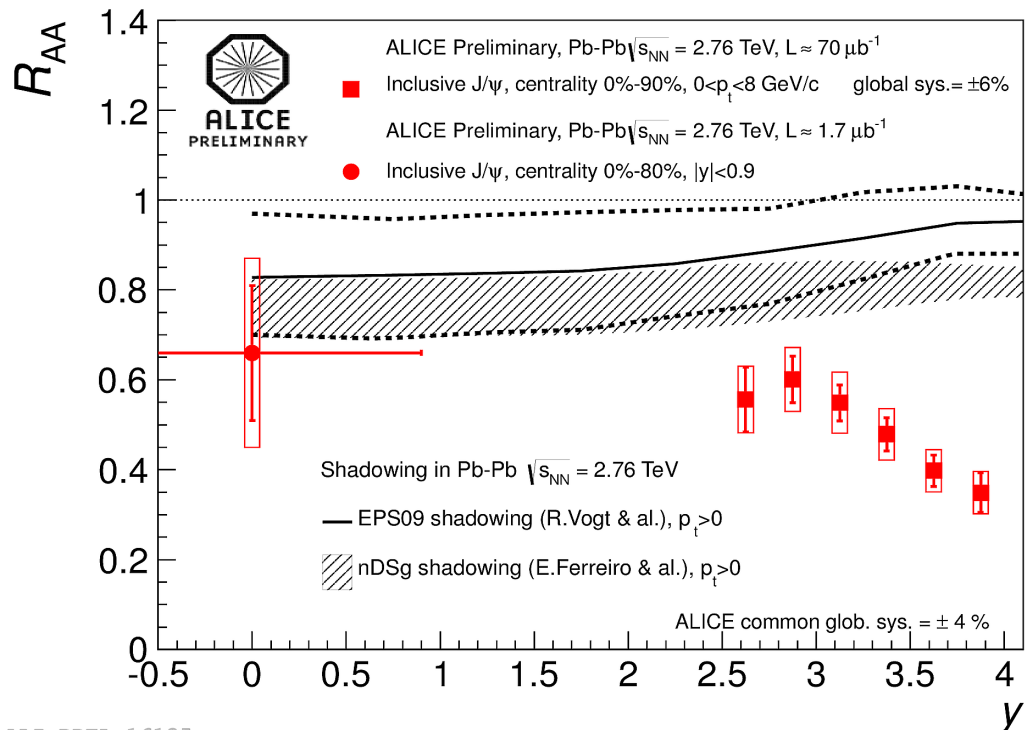
Rapidity Dependence of J/ψ R_{AA}



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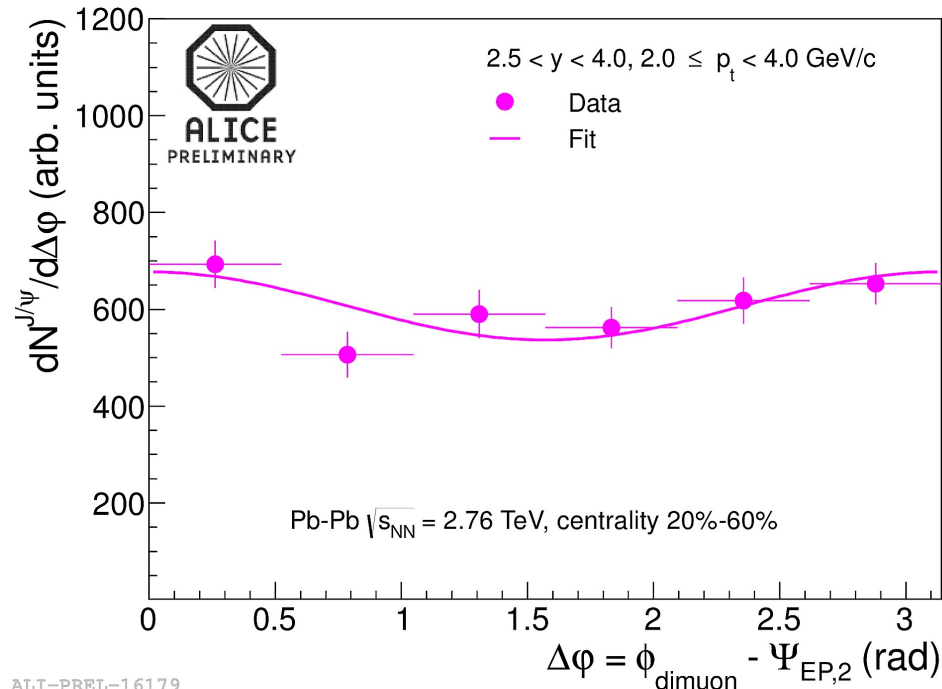
comparison to shadowing calculations:
 - at mid-rapidity suppression could be explained by shadowing only
 - at forward rapidity there seems to be additional suppression
 - need to measure shadowing

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



ALI-PREL-16135

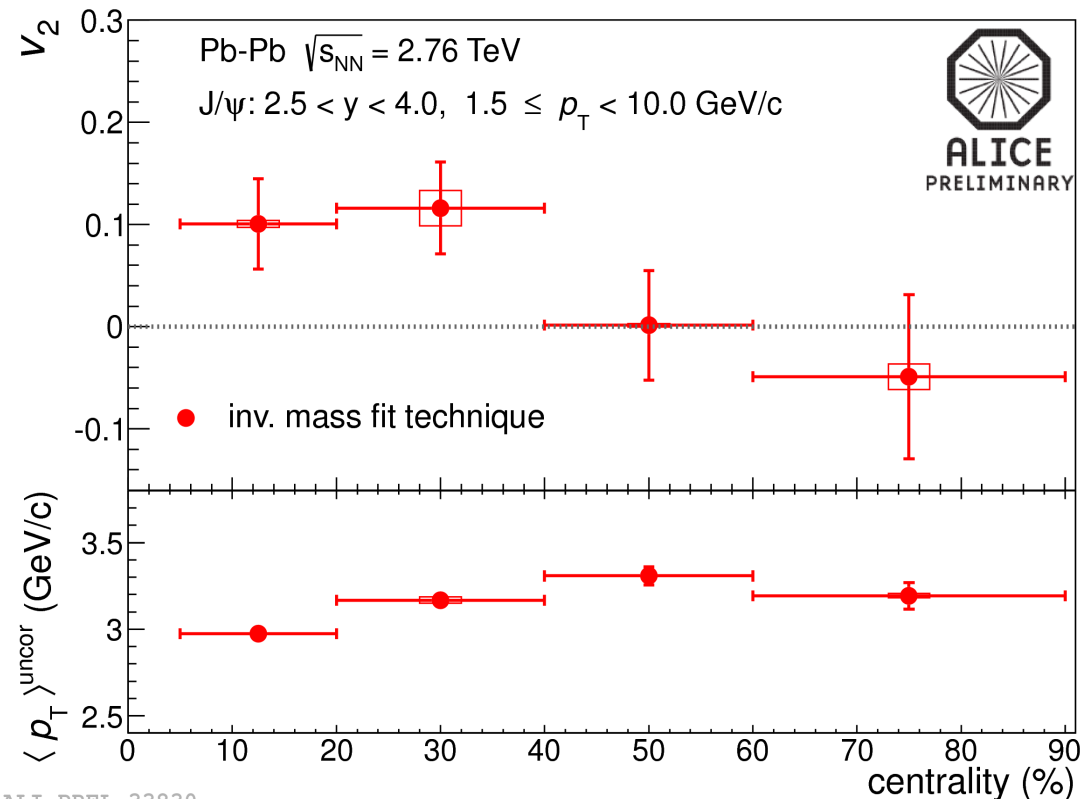
Elliptic Flow of J/psi



ALI-PREL-16179

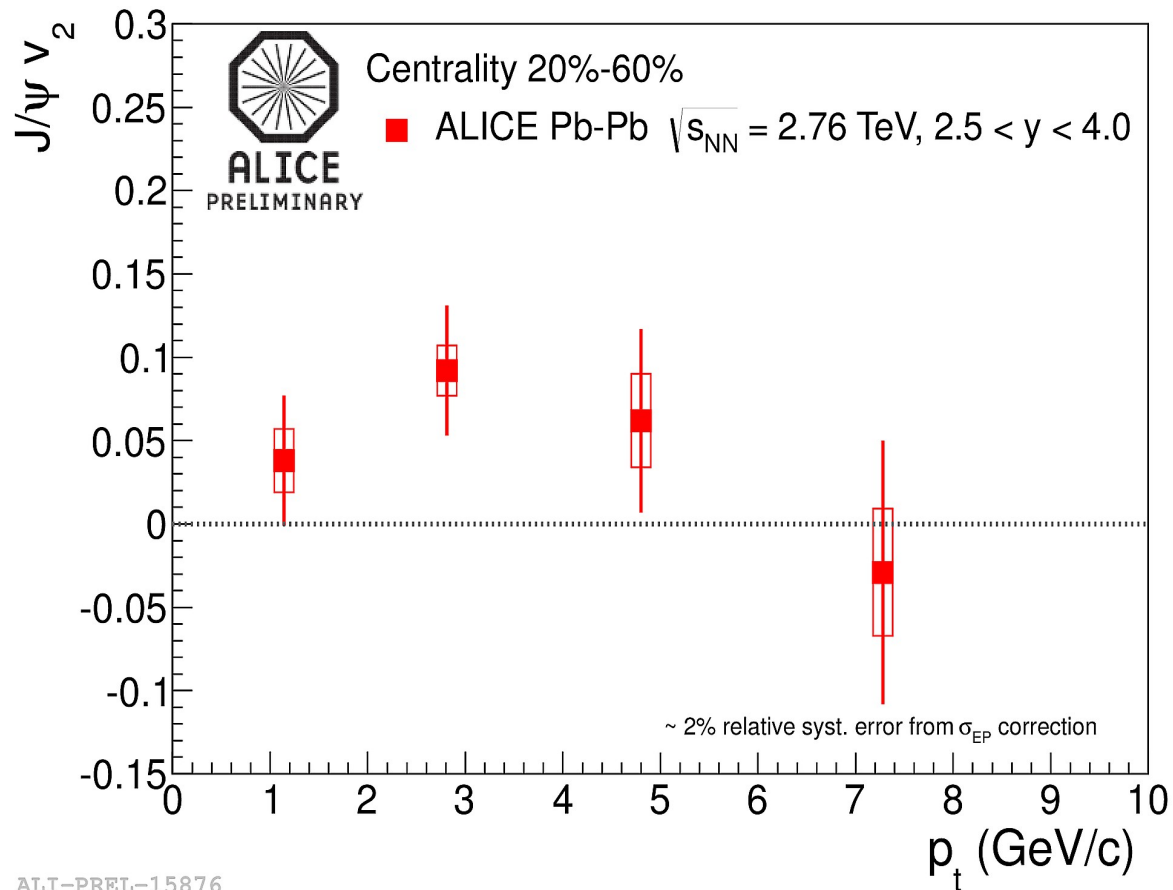
first observation of J/ψ v₂
in line with expectation from statistical
hadronization

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



ALI-PREL-33830

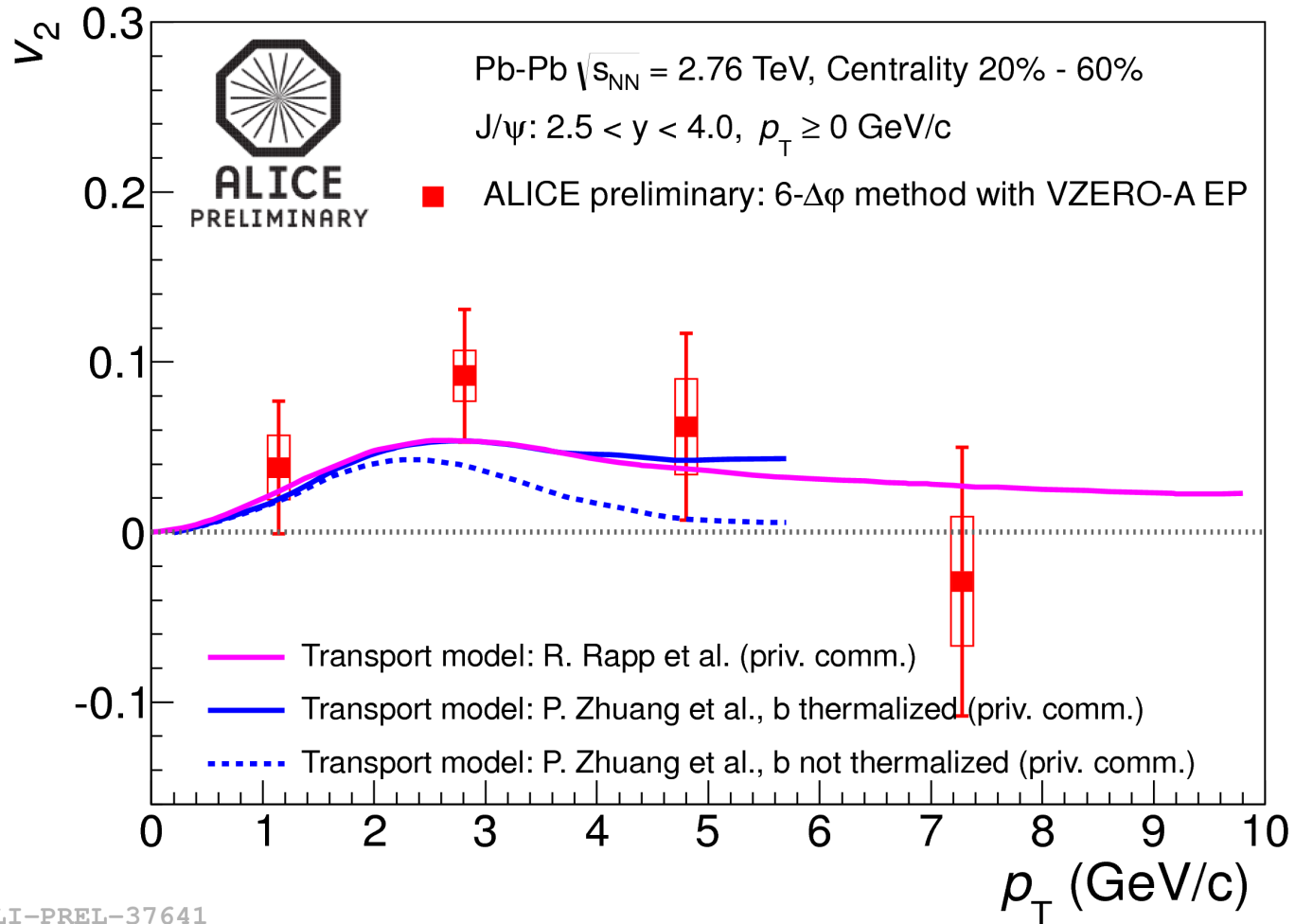
Elliptic Flow of J/psi vs p_t



ALI-PREL-15876

- 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

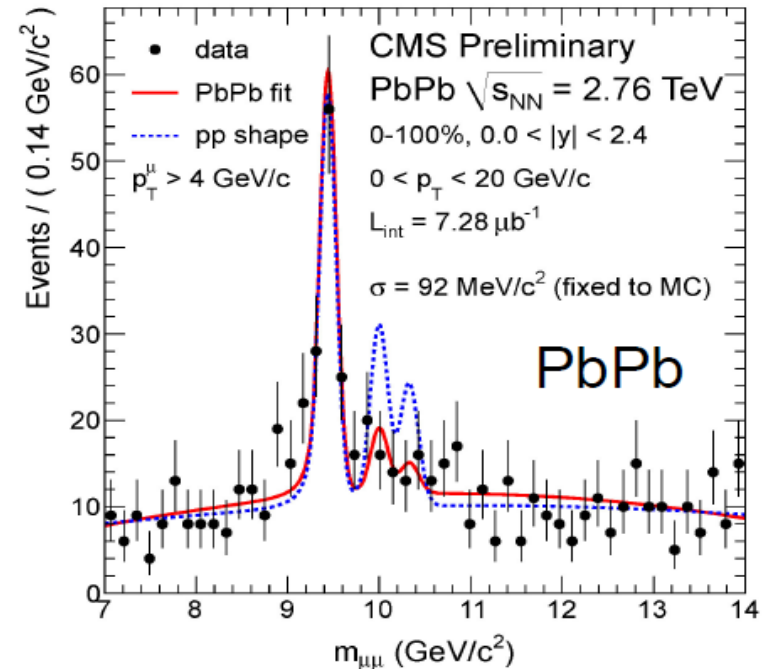
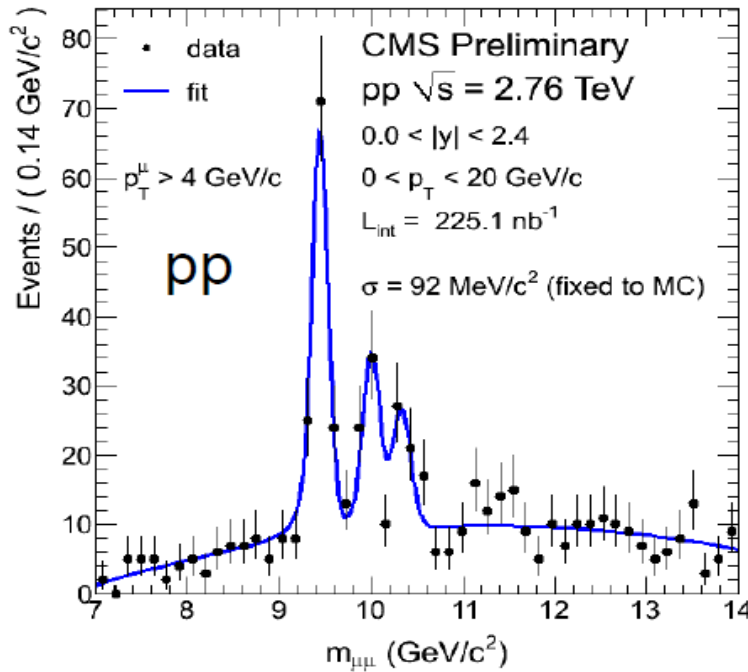


ALI-PREL-37641

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

Suppression of higher Upsilon states in CMS

in thermal models: expect suppression due to Boltzmann factors



raw ratios: $\Upsilon(2S + 3S)/\Upsilon(1S) \Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\Upsilon(2S + 3S)/\Upsilon(1S) \Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

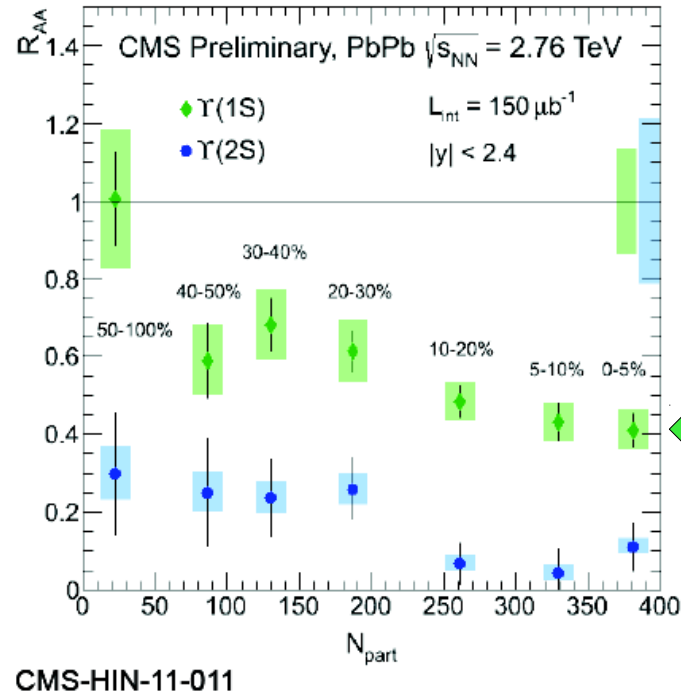
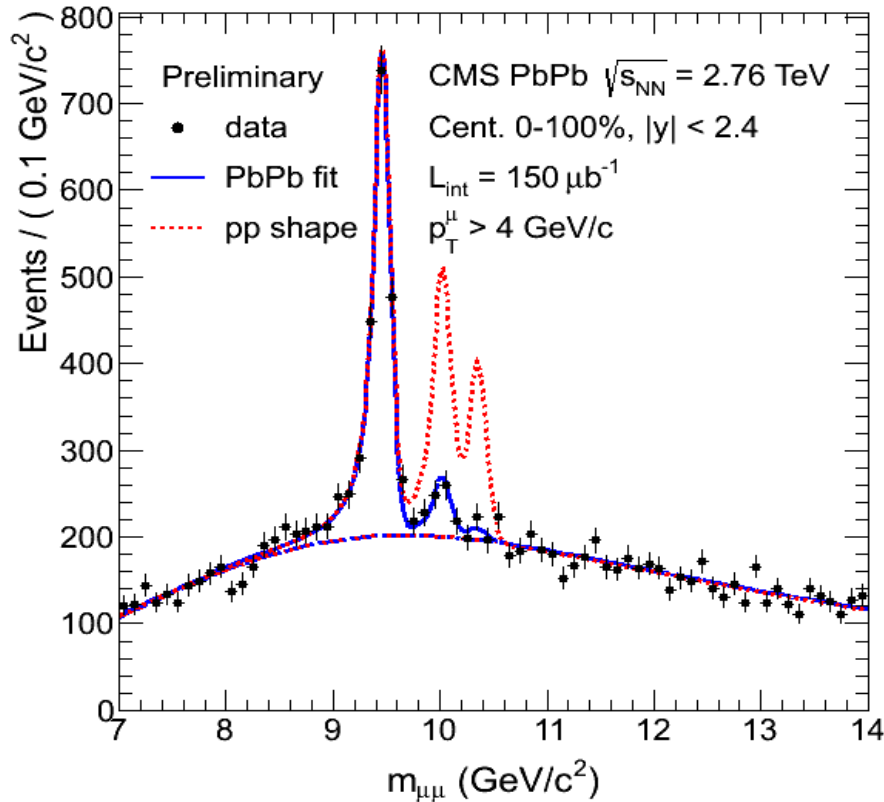
from CMS cross section measurements:

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

vs thermal model at $T=170$ MeV: 0.046

ok within the current uncertainties

Suppression of Upsilon States 2011 data



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

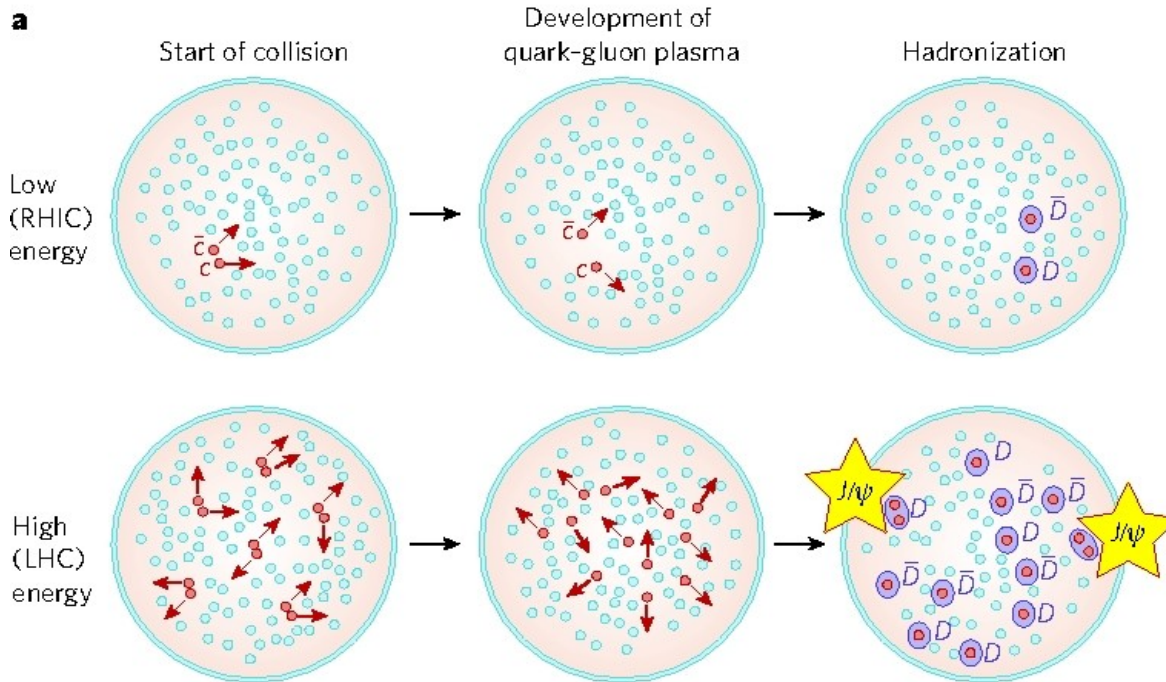
CMS-HIN-11-011

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

centrality integrated:
2S/1S PbPb relative to pp $0.21 \pm 0.07 \pm 0.02$
3S/1S “ “ < 0.1 95% C.L.

backup

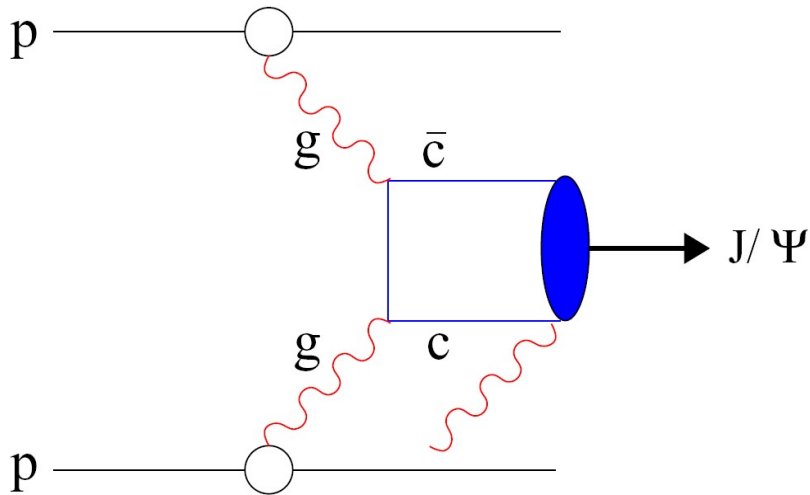
Charm (and Beauty) quarks in QGP – impurities in matter of mostly gluons and also light quarks (u,d,s)



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

- $c\bar{c}$ 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 1982)
- charm quarks diffuse, loose energy, thermalize? All this is of interest!
- once T_c is reached, system hadronizes and D-mesons and maybe $c\bar{c}$ bound states form

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 \bar{c} form 3S_1 state = J/ψ - requires transition to a color singlet state not pure perturbative QCD anymore, some modelling required

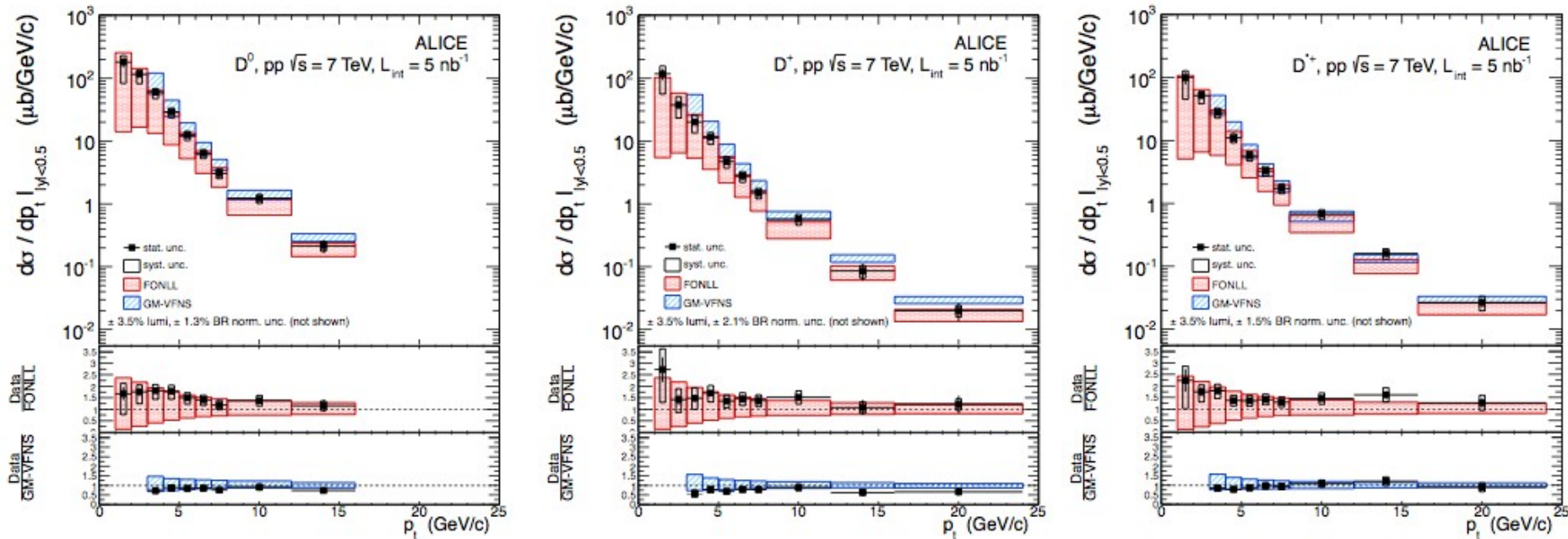
CEM Color Evaporation Model

CSM Color Singlet Model

now reasonably successful

Measurements agree well with state of the art pQCD calculations

JHEP1201(2012)128

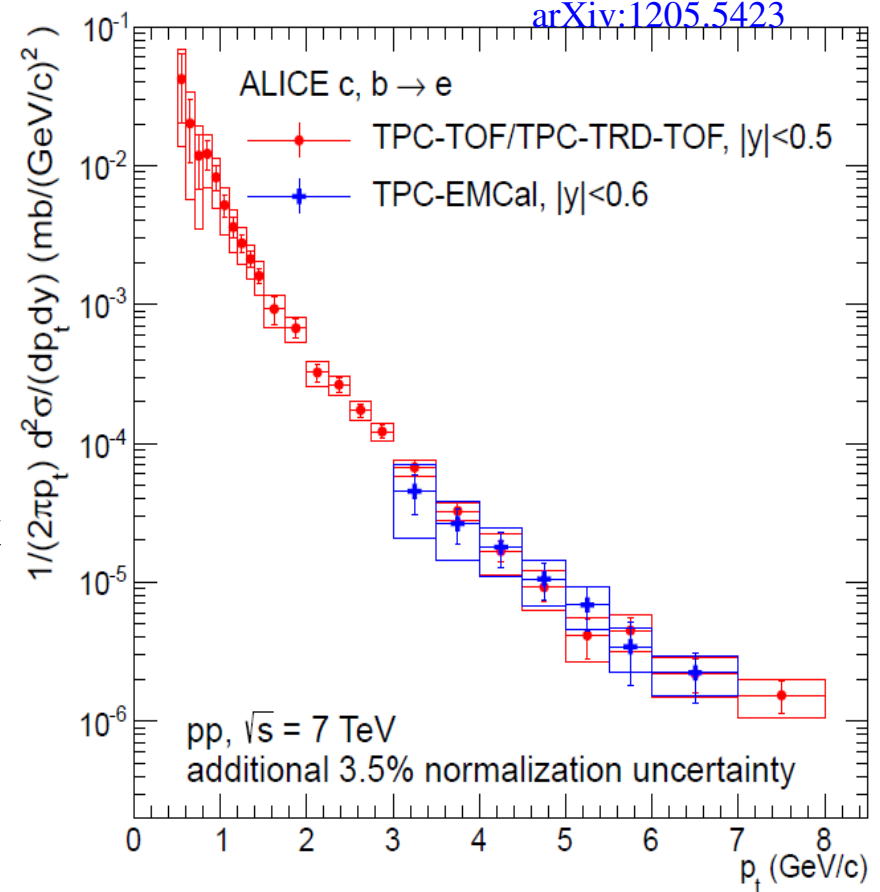
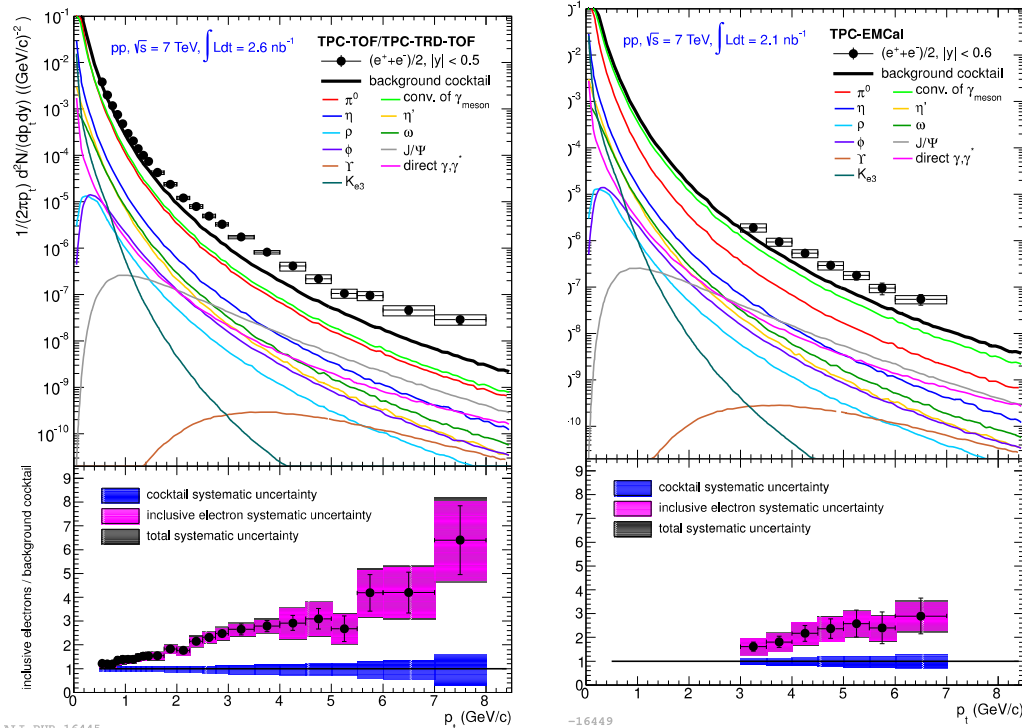


data are compared to perturbative QCD calculations
 reasonable agreement
 - at upper end of FONLL and at lower end of GM-VFNS
 measure 80% of charm cross section for $|y| < 0.5$

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

Charm and beauty via semi-leptonic decays

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

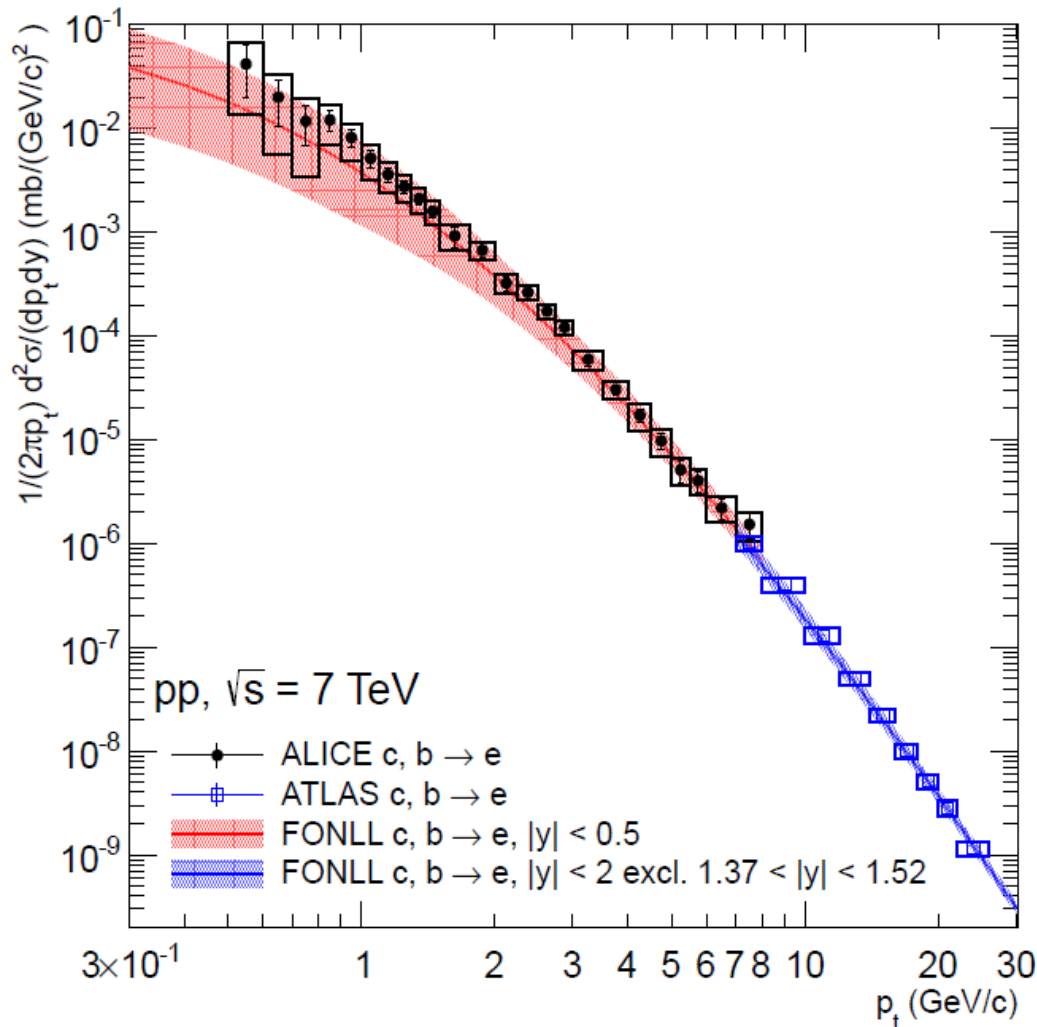


subtract hadronic decay cocktail
using measurements where
possible (π^0, η, m_t scaling for
other mesons, J/ψ),
direct γ from pQCD



electrons from c and b decays

Charm and beauty electrons compared to pQCD



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

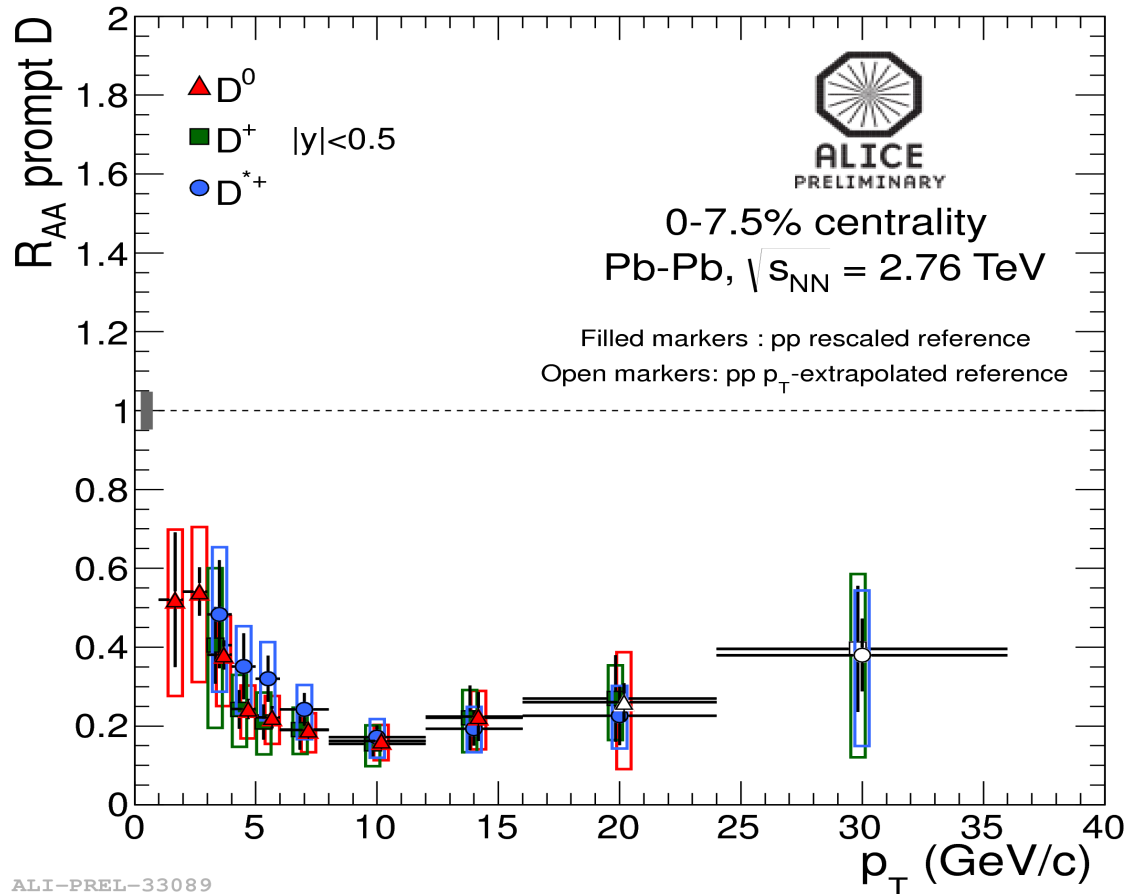
arXiv:1205.5423

ATLAS: PLB707 (2012) 438

FONLL: Cacciari et al., arXiv:1205.6344

Suppression of charm at LHC energy

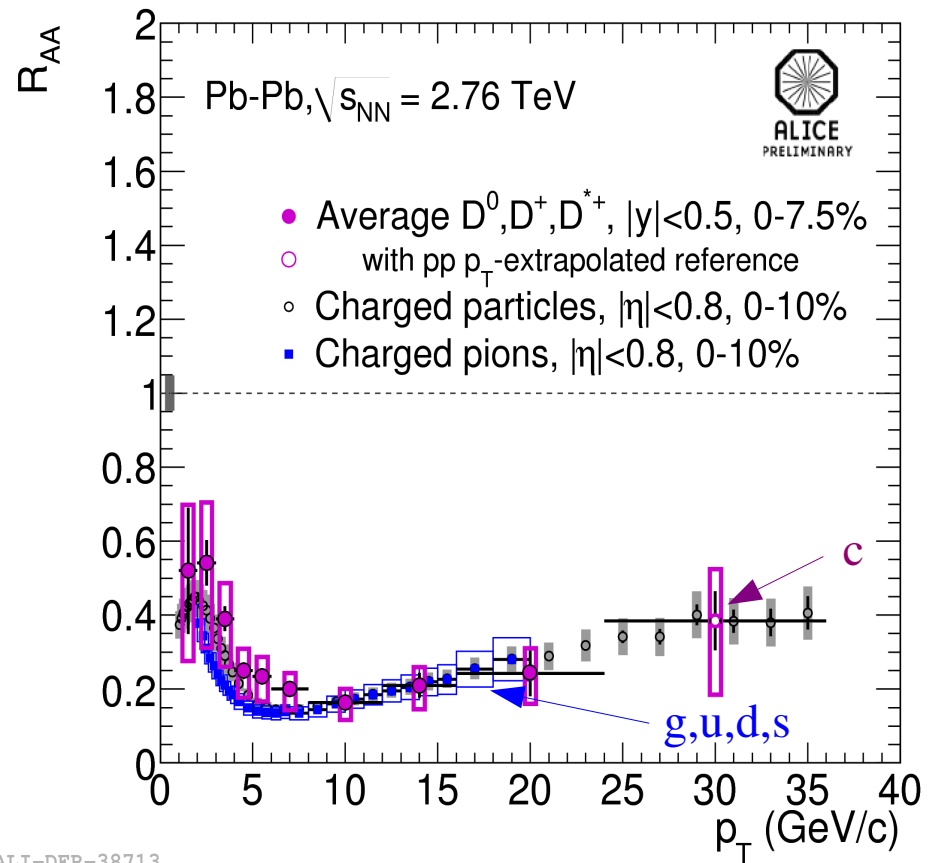
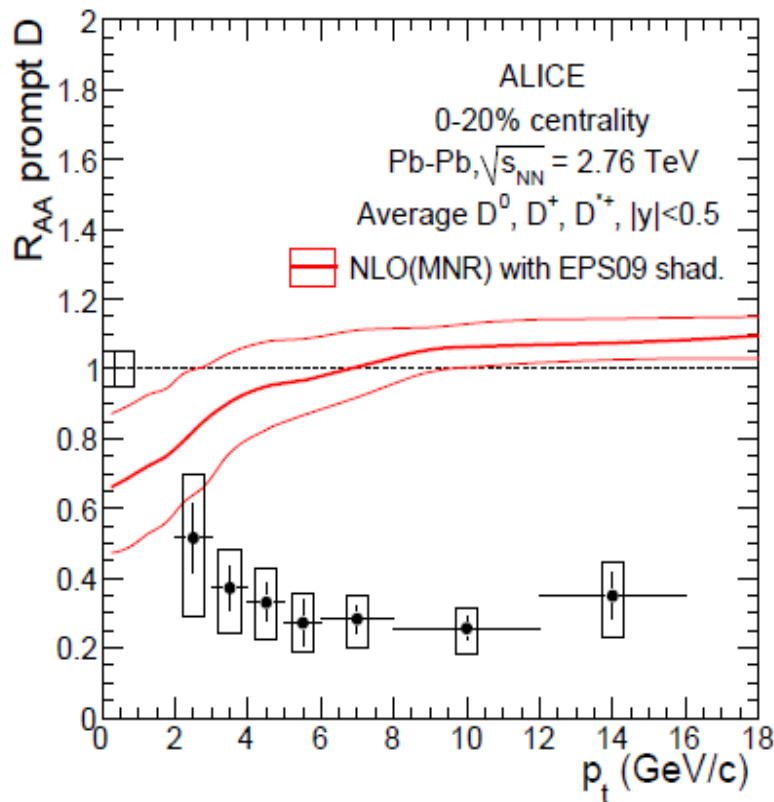
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)



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

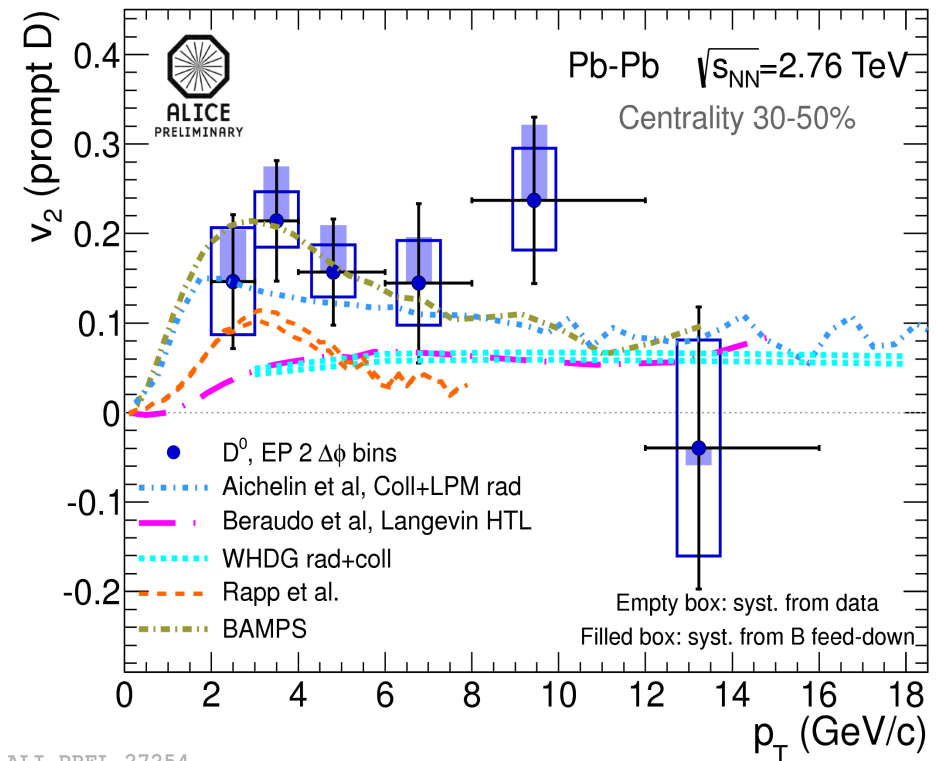
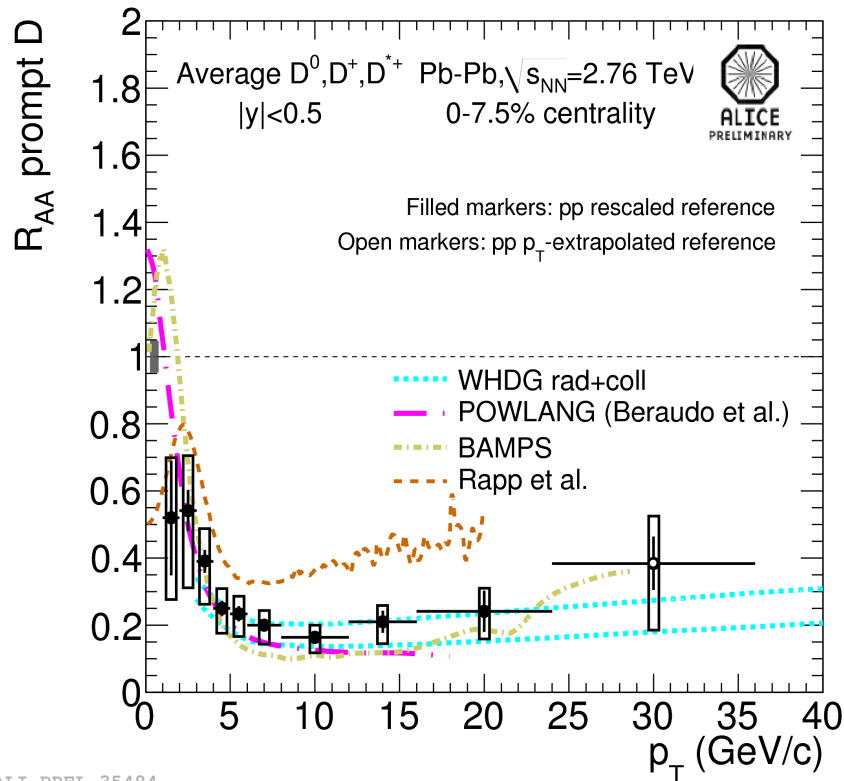
comparison to EPS09 shadowing:
 suppression not an initial state effect
 will be measured directly in pPb collisions



ALI-DER-38713

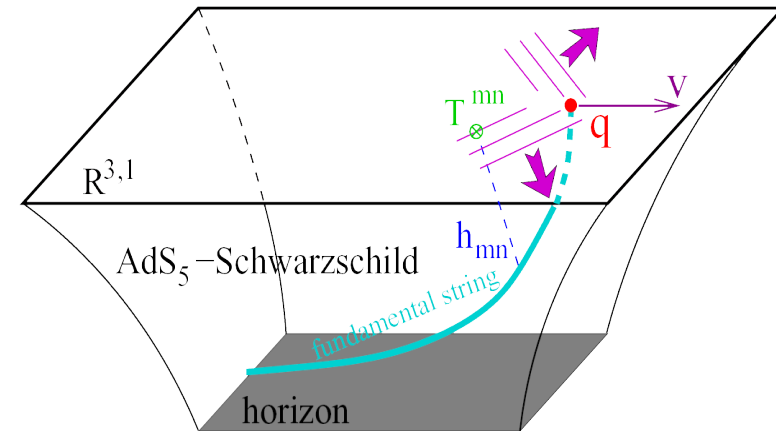
energy loss of charm quarks only slightly less than that for light quark \rightarrow thermalization

Model Description of Energy Loss and Flow of D-mesons

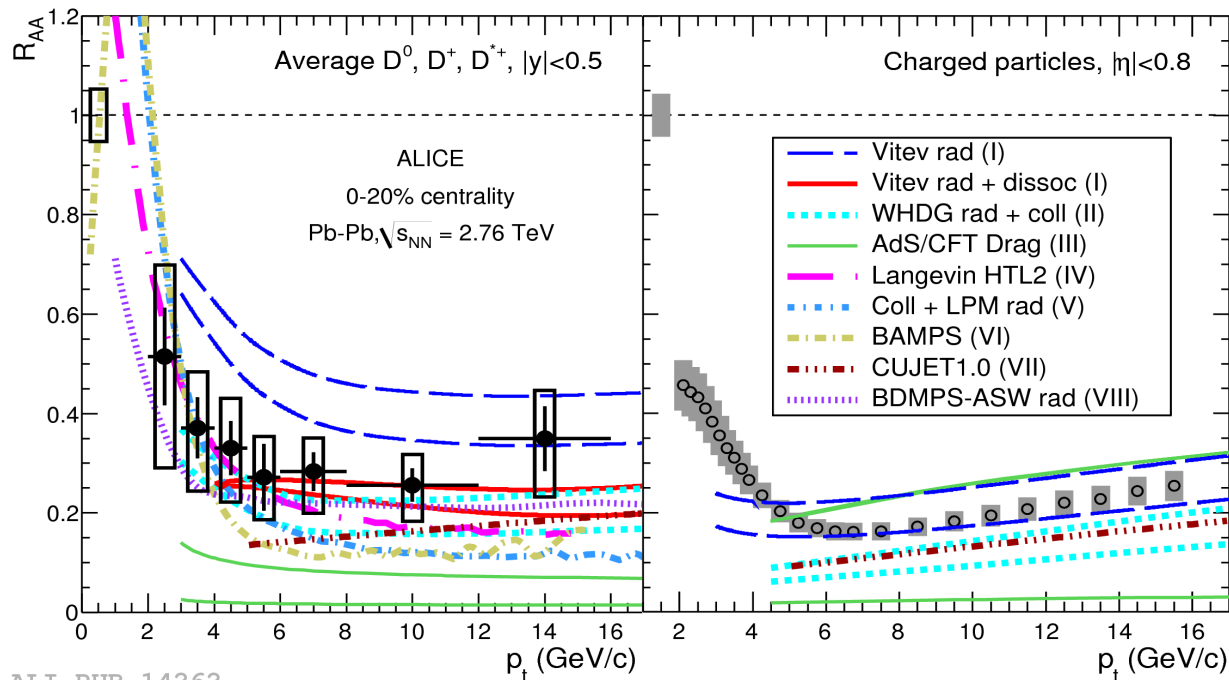


both are determined by transport properties of the medium (QGP)
 simultaneous description still a challenge for some models

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



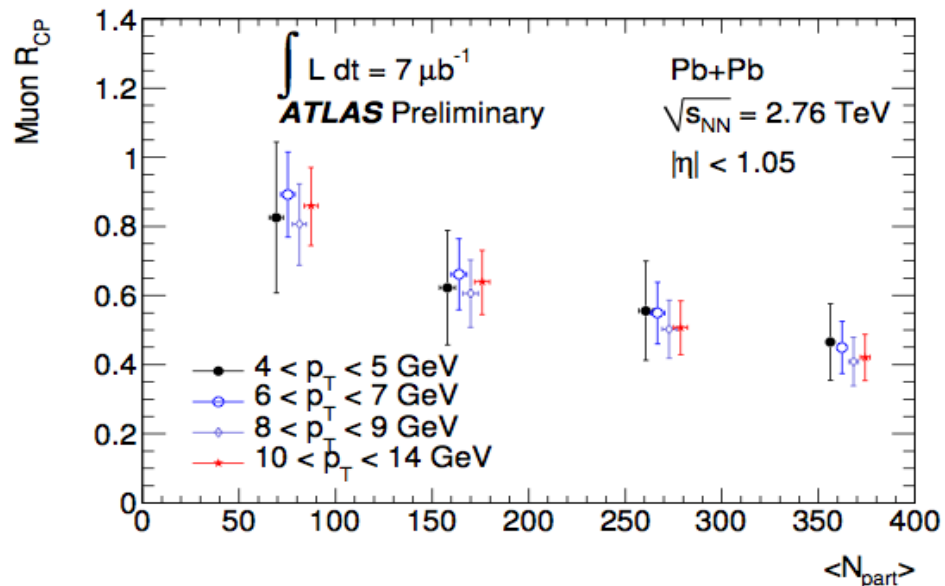
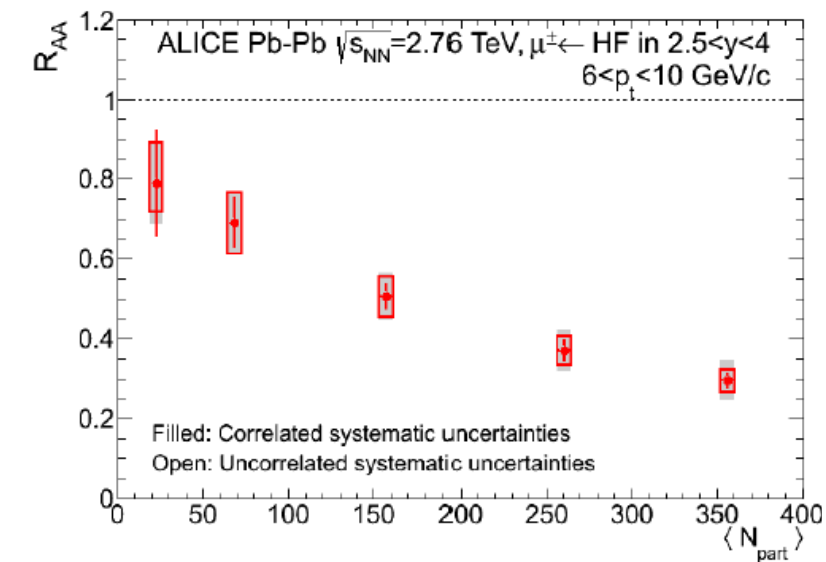
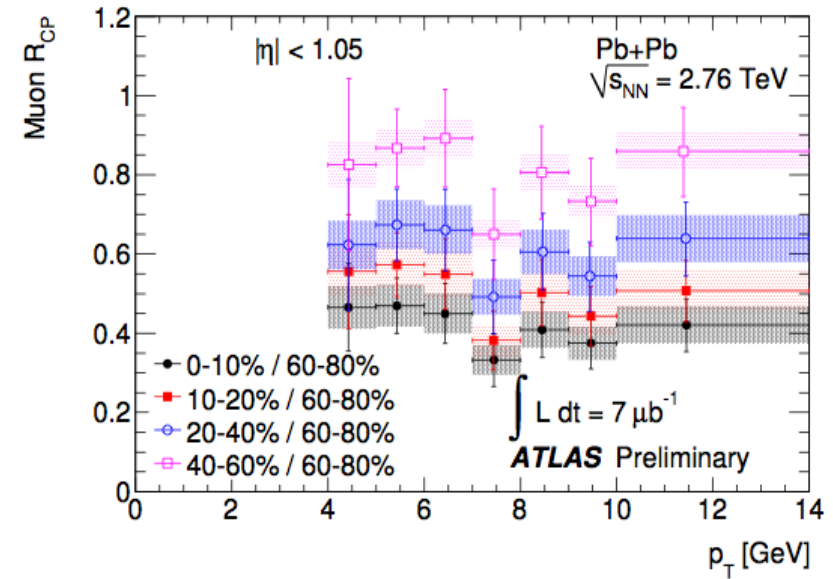
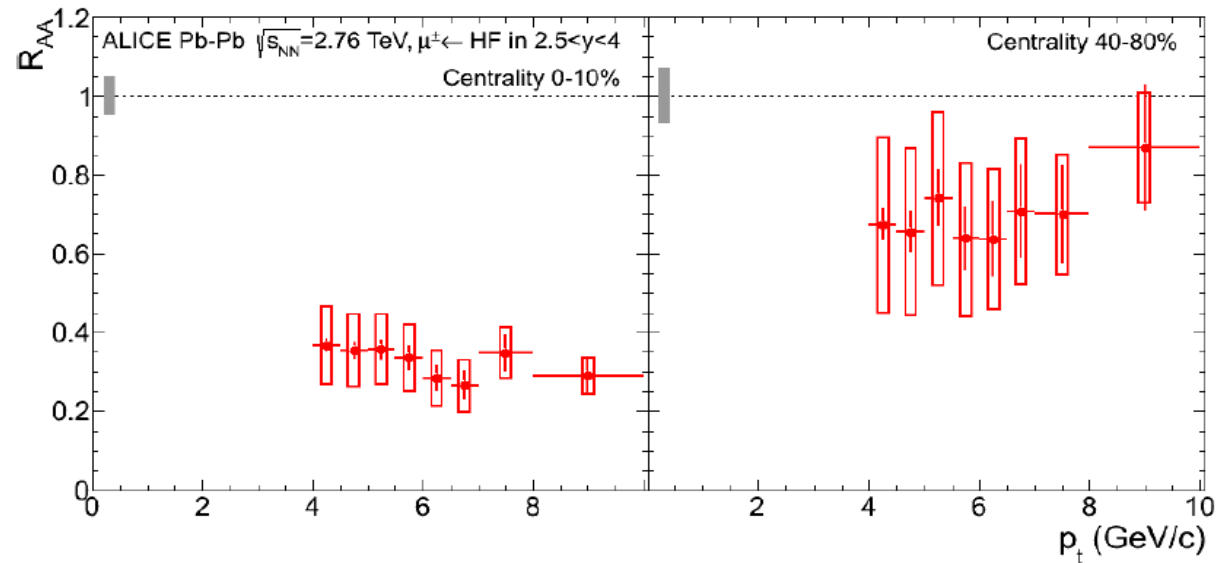
J Friess, Phys Rev D75 (2007)



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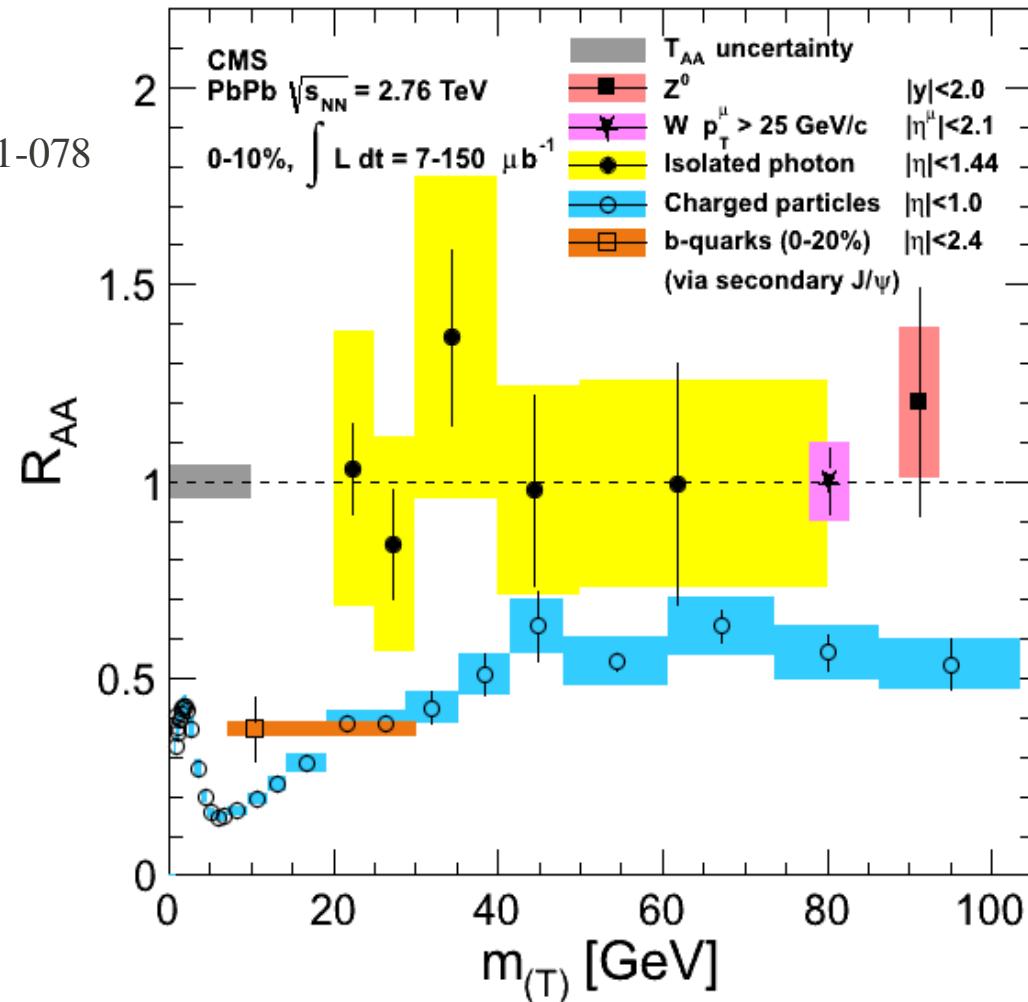
systems appears not as strongly coupled!

Decay muons from heavy flavor mesons



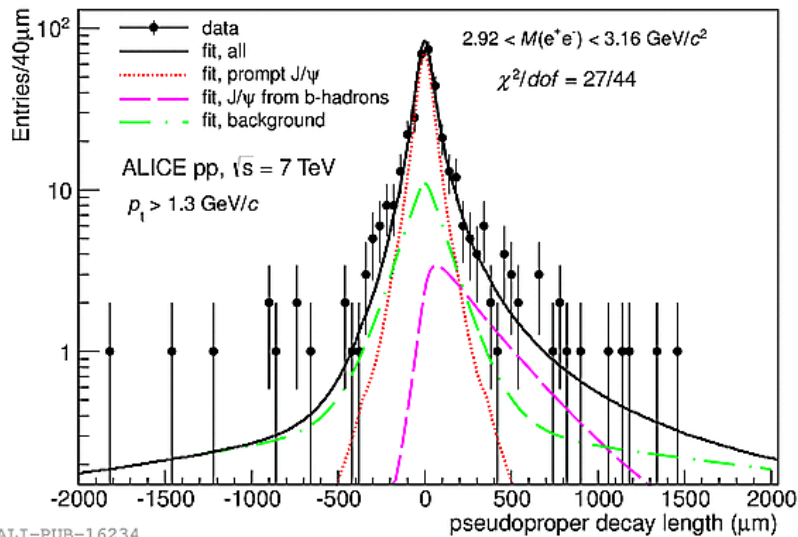
Suppression only for Strongly Interacting Hard Probes

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



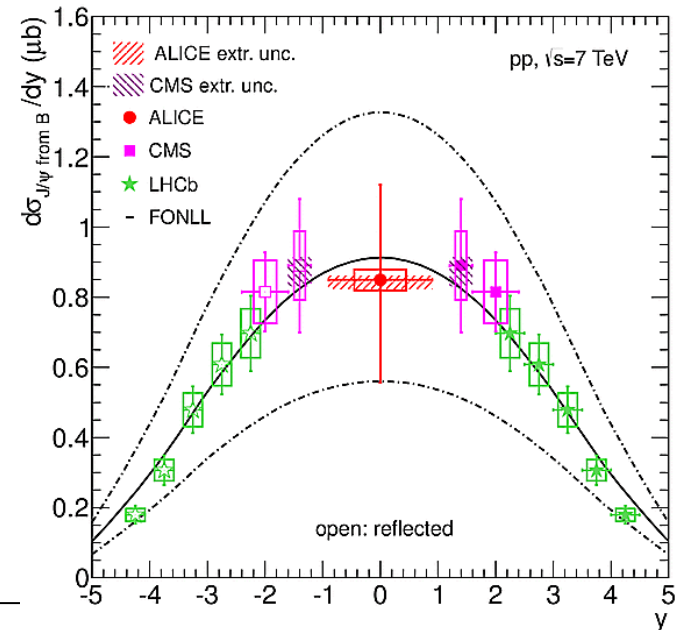
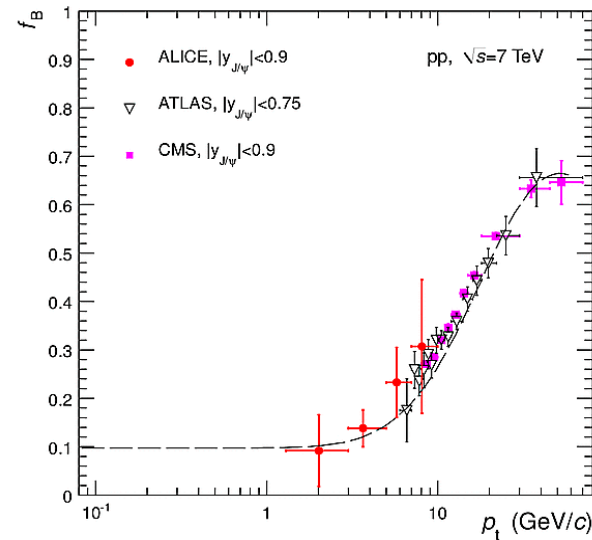
photons, Z and W scale with number of binary collisions in PbPb – not affected by medium
 → demonstrates that charged particle suppression is medium effect: energy loss in QGP

J/psi from B-decays in pp collisions



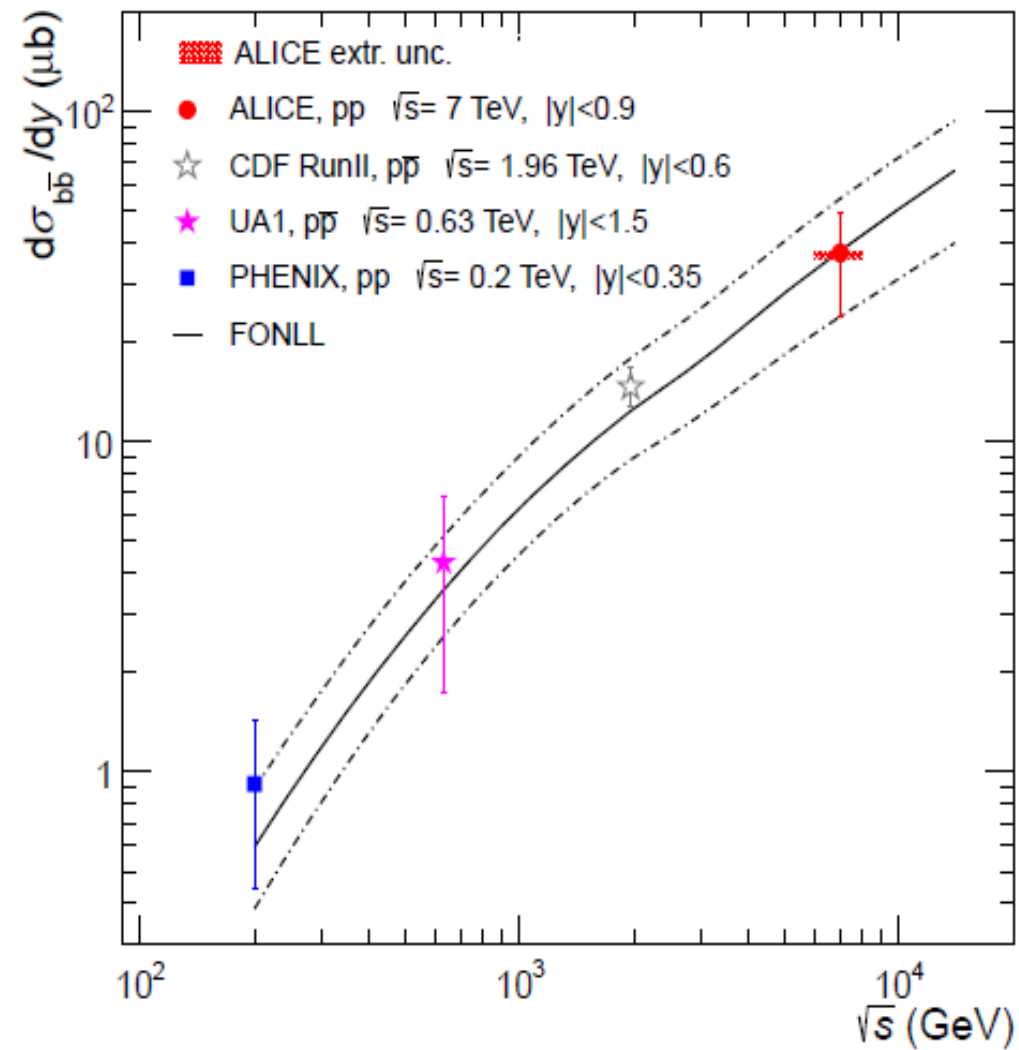
ALI-PUB-16234

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

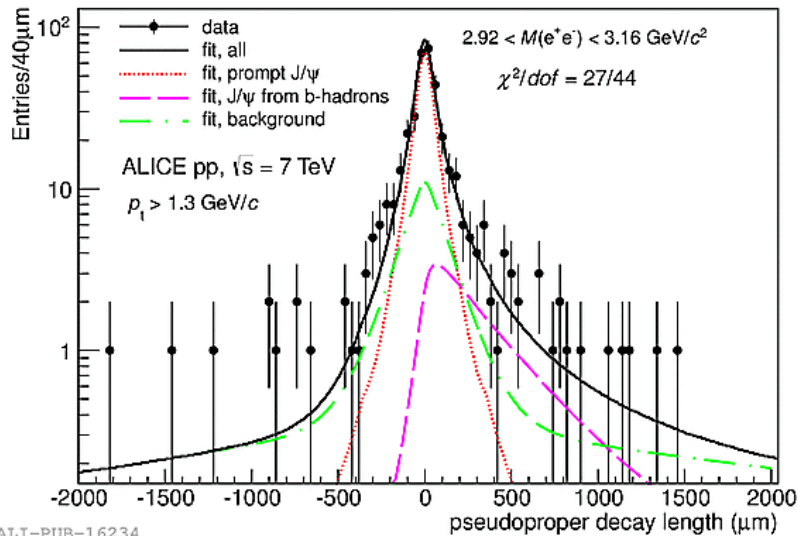


ALI-PUB-16294

Beauty cross section in pp and ppbar collisions



J/psi from B-decays in pp collisions



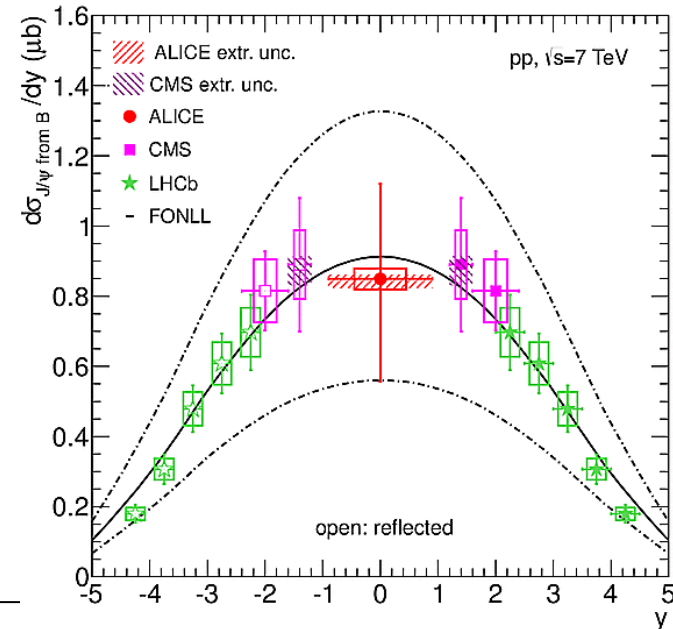
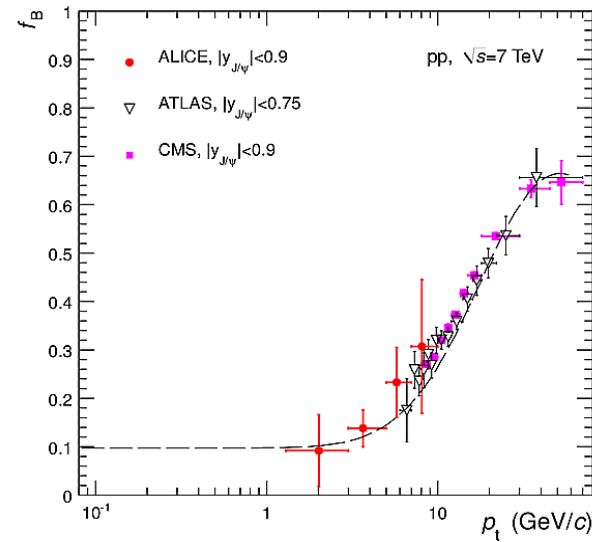
ALI-PUB-16234

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



[arXiv:1205.5880](https://arxiv.org/abs/1205.5880)

FONLL: Cacciari et al., [arXiv:1205.6344](https://arxiv.org/abs/1205.6344)



ALI-PUB-16294