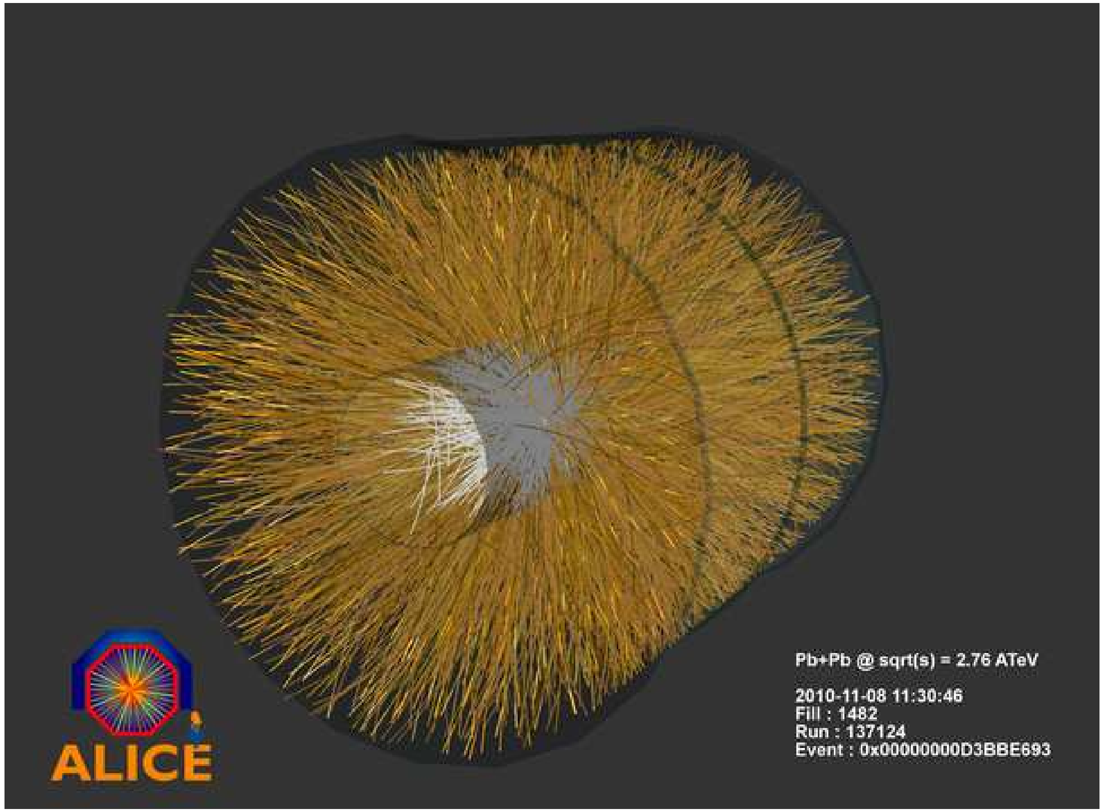
The charm of hot matter - charmonium and open charm measurements in Pb–Pb collisions with ALICE at the LHC

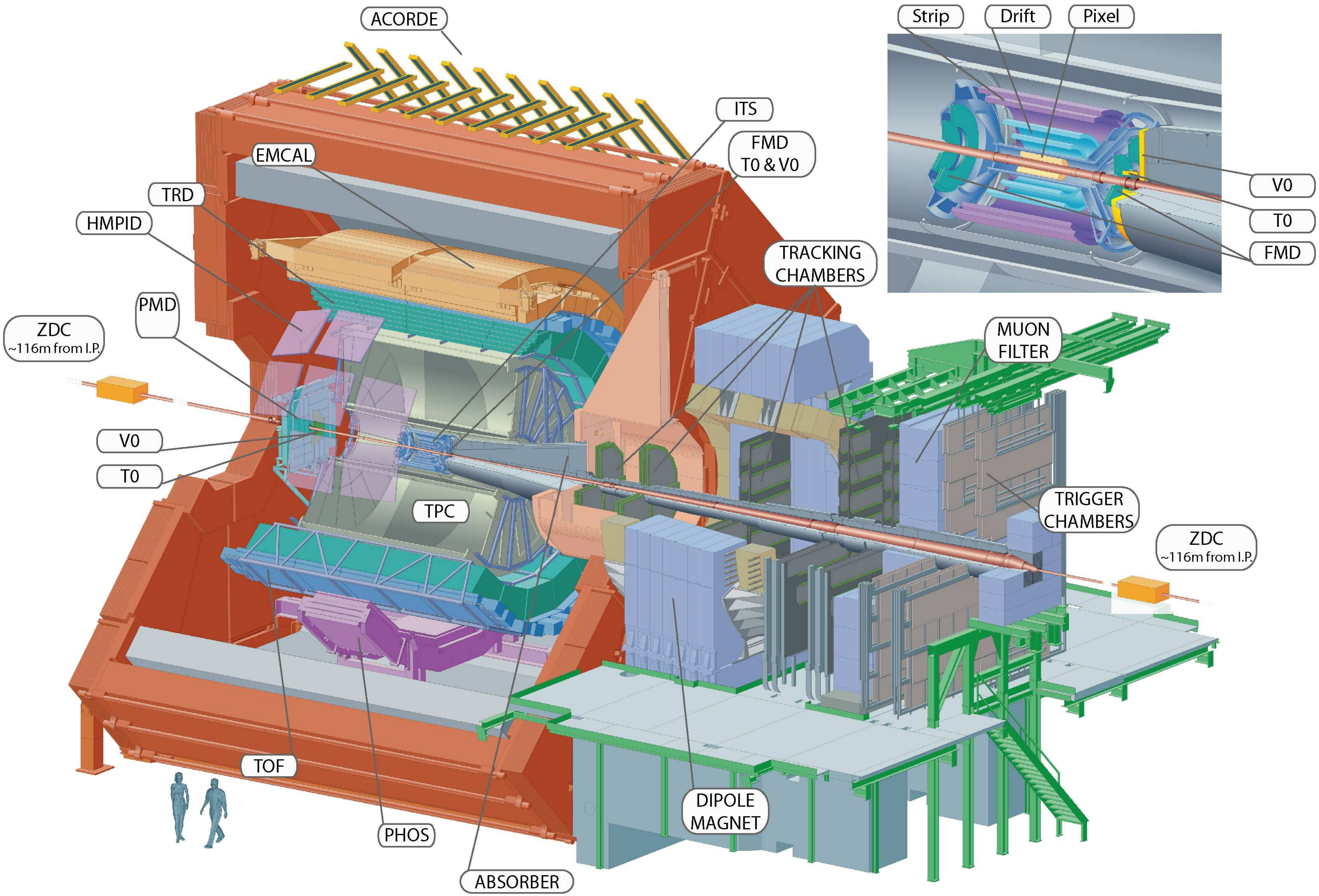
A.Andronic – GSI Darmstadt

for the ALICE Collaboration

- Introduction
- The open charm of hot matter
- Quarkonium measurements



The ALICE detector



Probing hot matter

...with "hard probes" ($m \gg T$): jets or high-p_T hadrons, heavy quarks produced very early in the collision, $t \simeq 1/m$

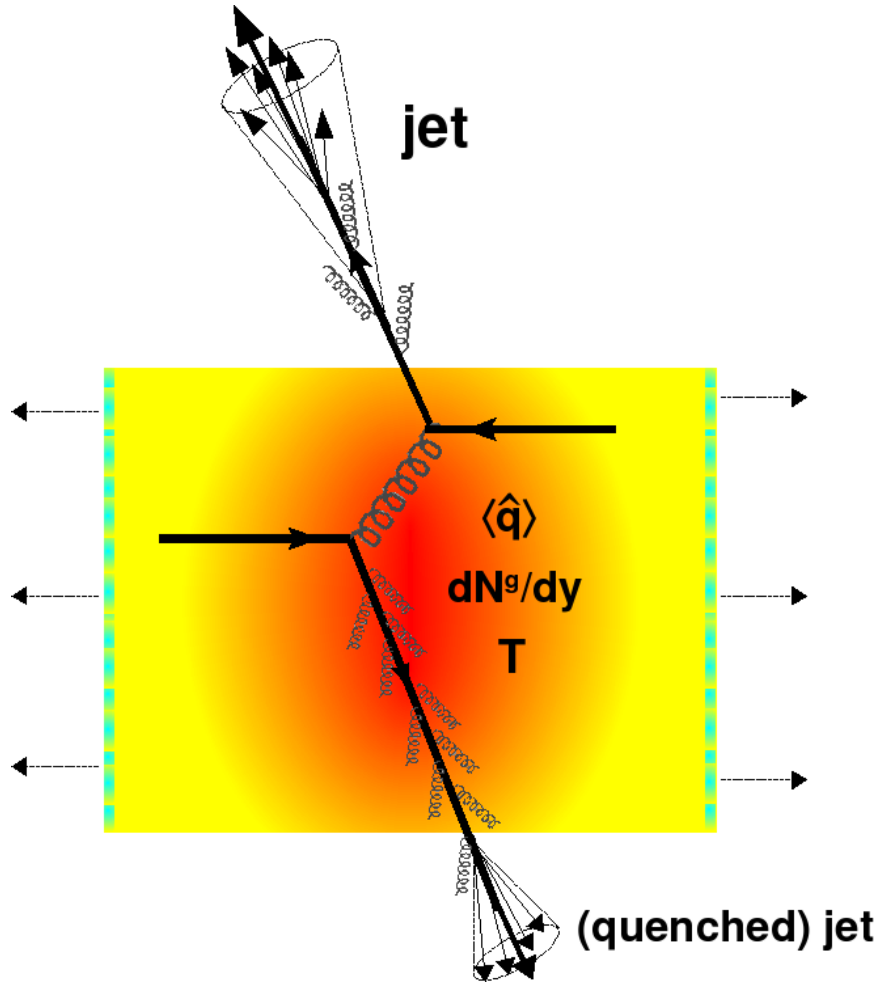
(jets - sprays of hadrons from high-speed quarks)

- $q, \bar{q}$ travel through QGP, lose energy "jet quenching"
- hadronize
- hadrons fly towards detectors

...where we would observe a deficit of jets or high-momentum (p_T) hadrons

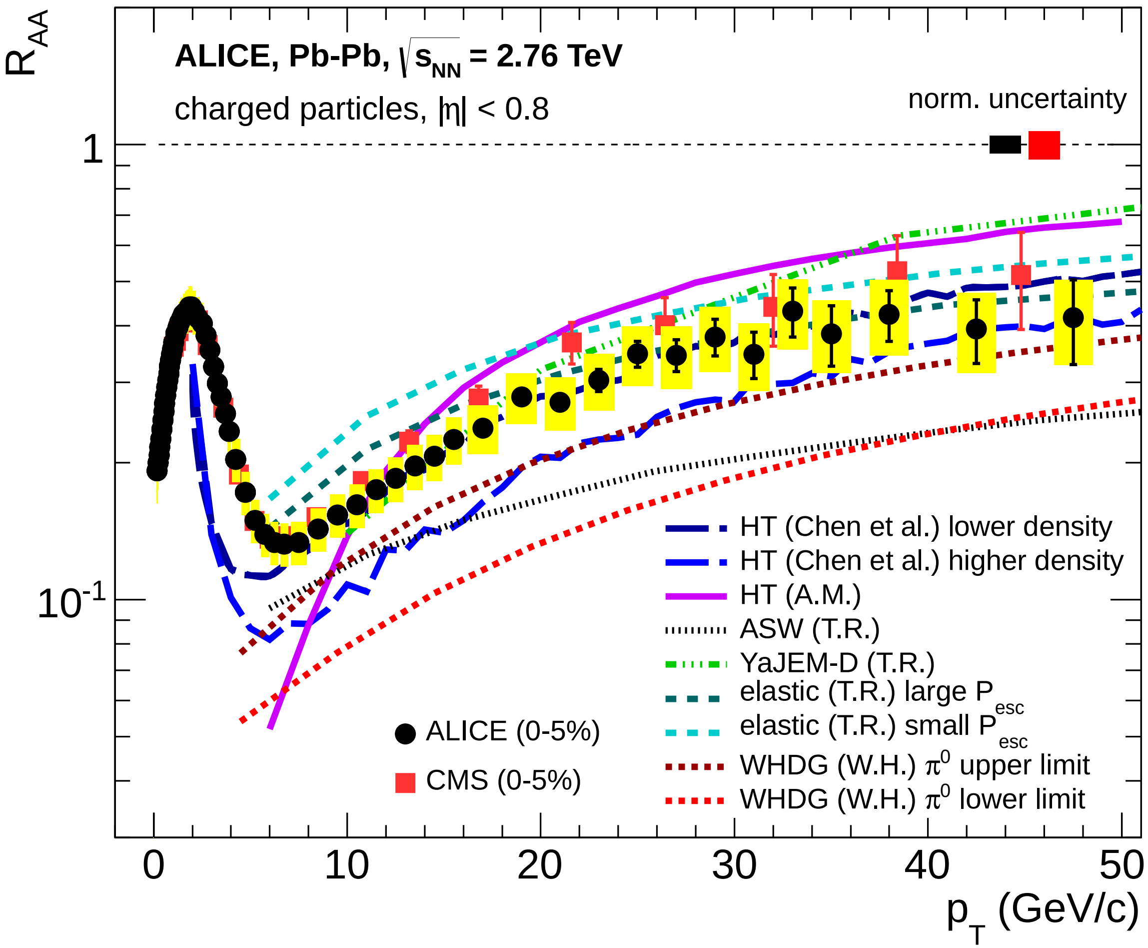
quantified by the nuclear modification factor:

$$R_{AA} = \frac{\mathrm{d}^2 N_{AA}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}{N_{coll} \cdot \mathrm{d}^2 N_{pp}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}$$



D. d'Enterria, arXiv:0902.2011

Jet quenching at the LHC



...stronger than previously measured at RHIC

reaching a factor of about 7 around p_T=7 GeV/c

remains substantial even at 50-100 GeV/c

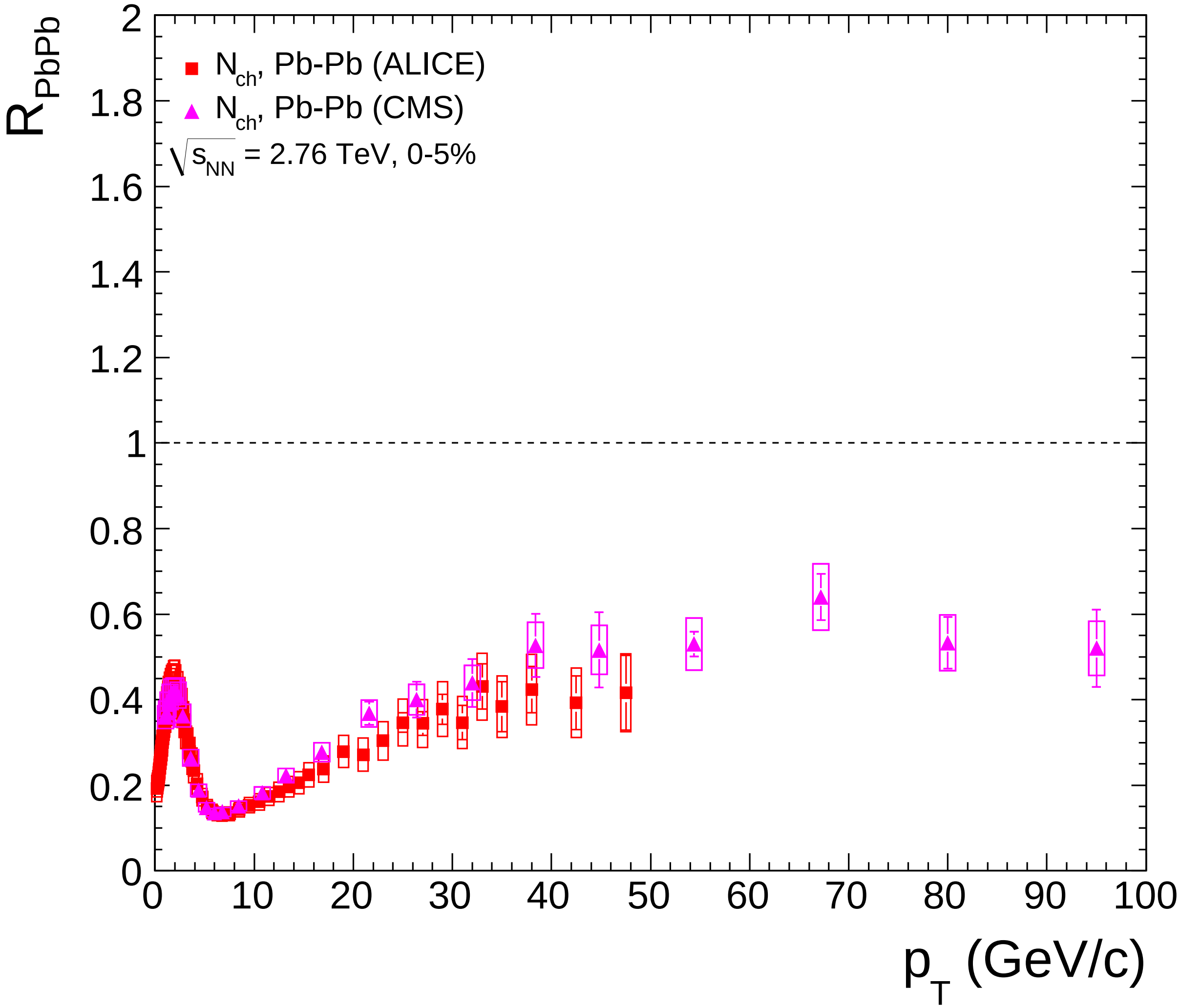
ALICE, arXiv:1208.2711

CMS, EPJC (2012) 72

a lot of activity in theoretical description of parton energy loss in hot deconfined matter

$p_T \lesssim 4-5$ GeV/c: bulk hadron production ($\sim N_{part}$) and flow (∼65% c) (talk by R. Preghenella)

Is there something wrong with the nuclei?

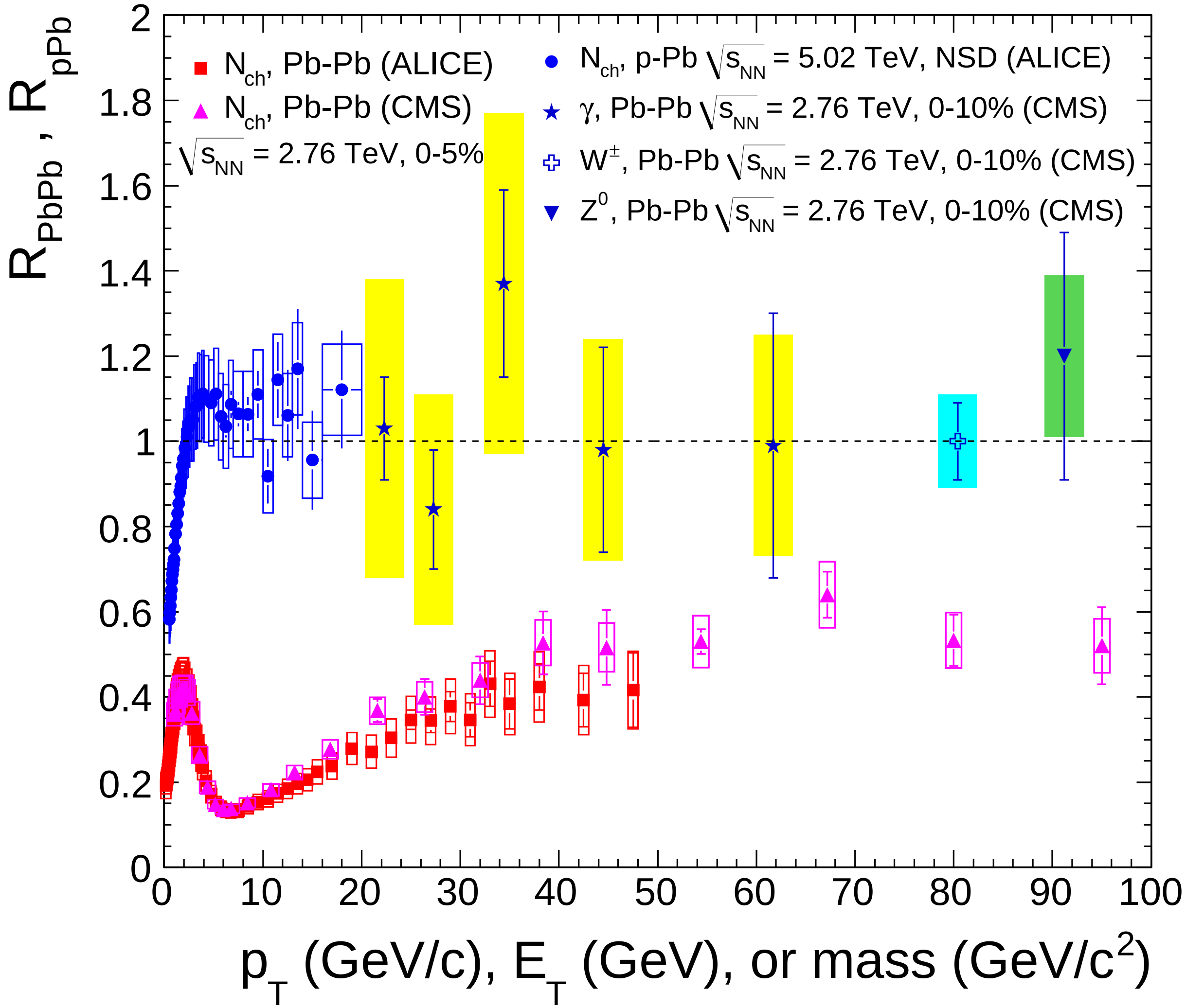


of course, not wrong but saturation / shadowing ?

not expected at multi-(10)GeV (we know from γ,...)

ALICE, arXiv:1208.2711
CMS, EPJC (2012) 72

Is there something wrong with the nuclei?



saturation / shadowing

visible only at low p_T

p–Pb: ALICE, arXiv:1210.4520

(talk by C. Oppedisano)

CMS

γ, PLB 710 (2012) 256

$W^{\pm}$, PLB 715 (2012) 66

Z^0, PRL 106 (2011) 212301

Pb–Pb: ALICE, arXiv:1208.2711

CMS, EPJC (2012) 72

heavy quarks are produced at early stages and maintain identity through the hot (and compressed) stage of the collision

charmonium has a peculiar charm in connection to deconfined matter (suppression via a Debye screening mechanism)

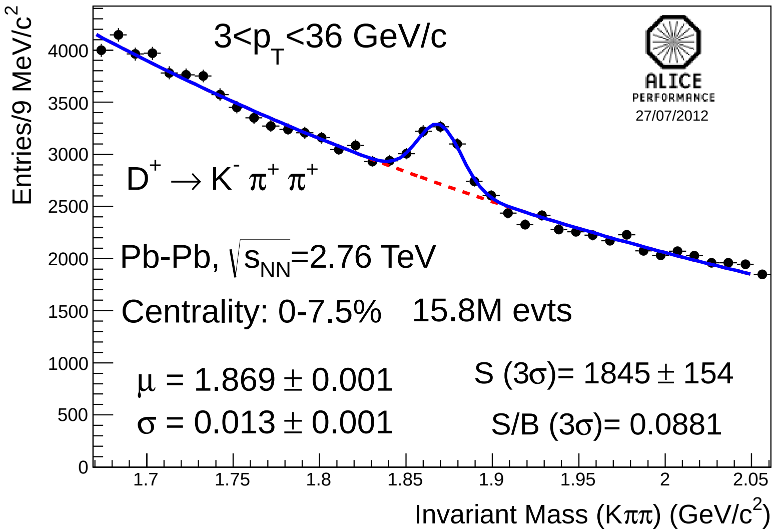
charm quarks are abundantly-produced at the LHC (about 100 pairs in a central collision)

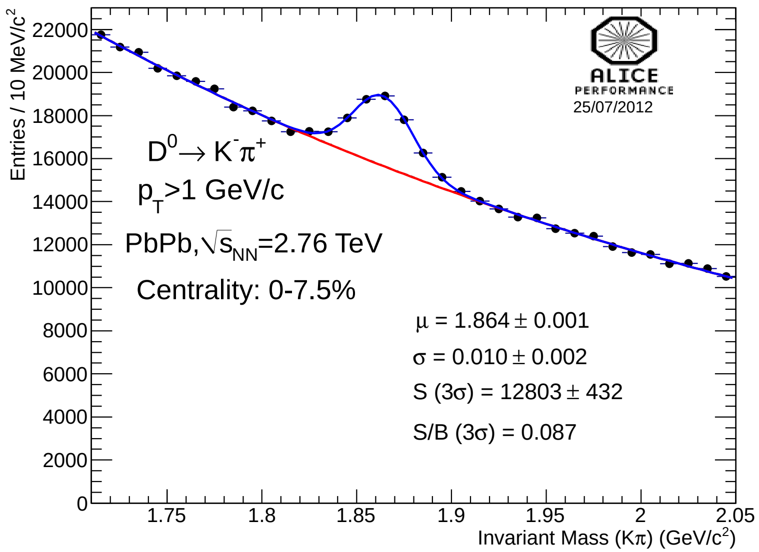
...and the questions it addresses

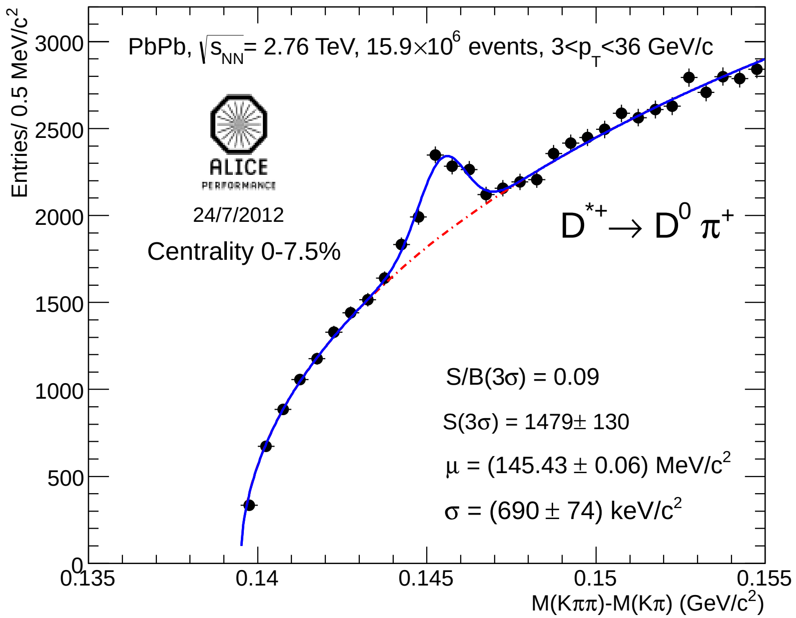
does parton energy loss (by gluon radiation) exhibit the expected mass pattern ("dead-cone effect")?

do heavy quarks thermalize alongside the light quarks and gluons?

The (open) charm in ALICE



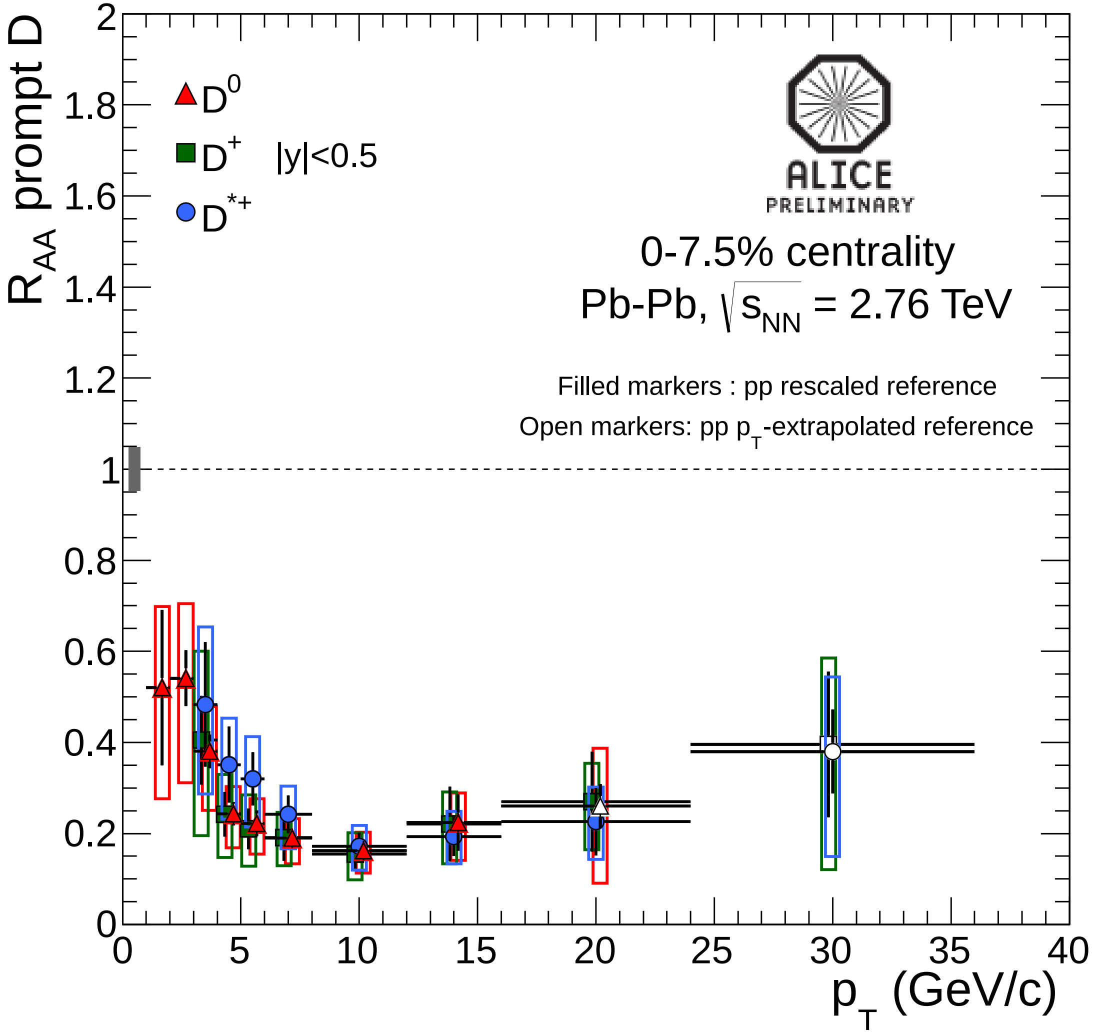




...and detection of
muons (2.5< y <4) and
electrons ($|y|$ <0.9)
from charm (and beauty) decays

(talk by Z. Buthelezi)

The charm in hot matter

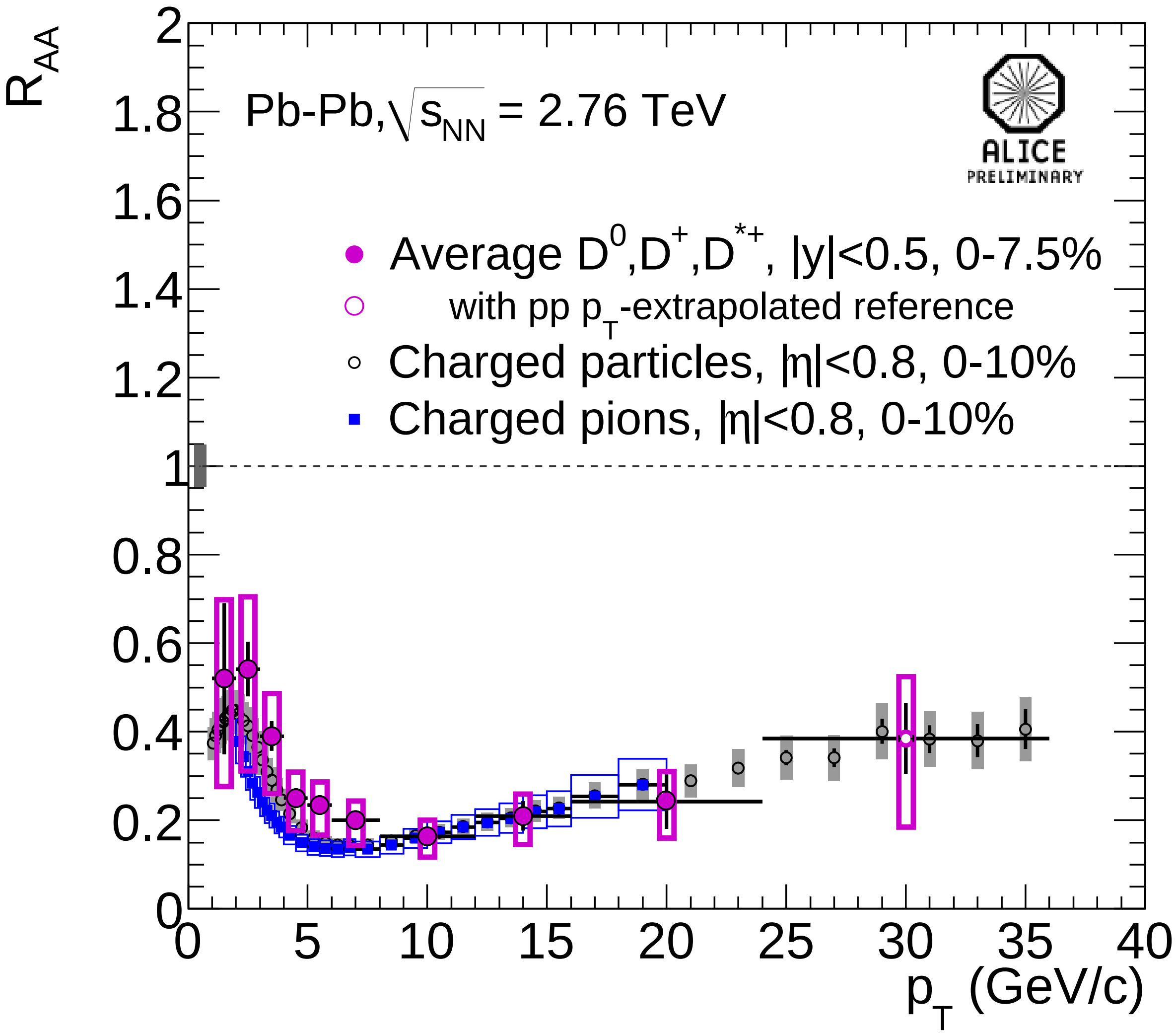


a strong suppression of yields at high p_T

seen for all charmed meson species

centrality-triggered data
(for MB, see JHEP 09 (2012) 112)

The charm in hot matter



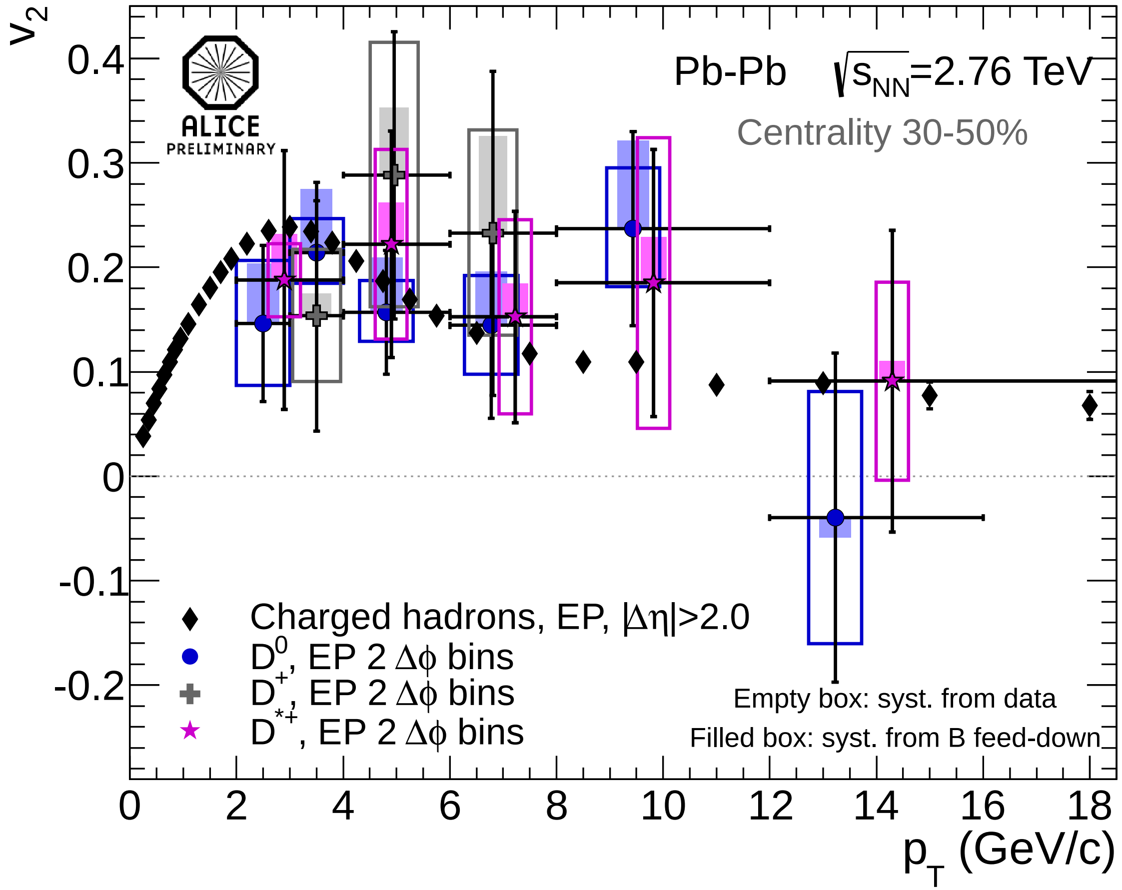
a strong suppression of yields at high p_{T}

...(almost) as strong as that of overall charged particles (or pions)

NB: small diff. in centrality

(talk by R. Preghenella)

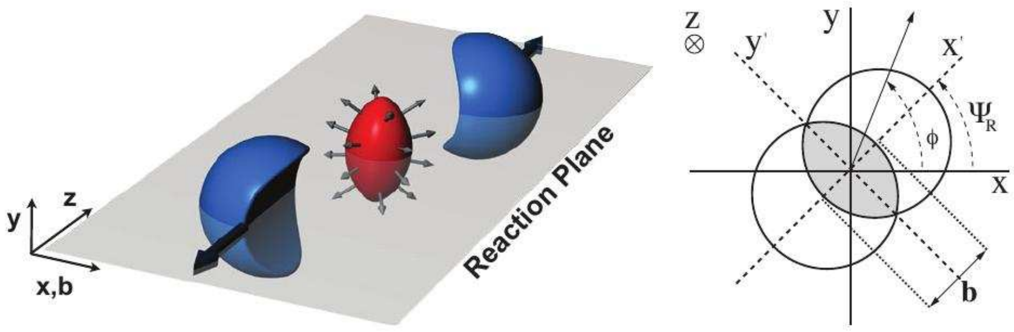
Charm flows



...as strong as charged particles (or pions)?

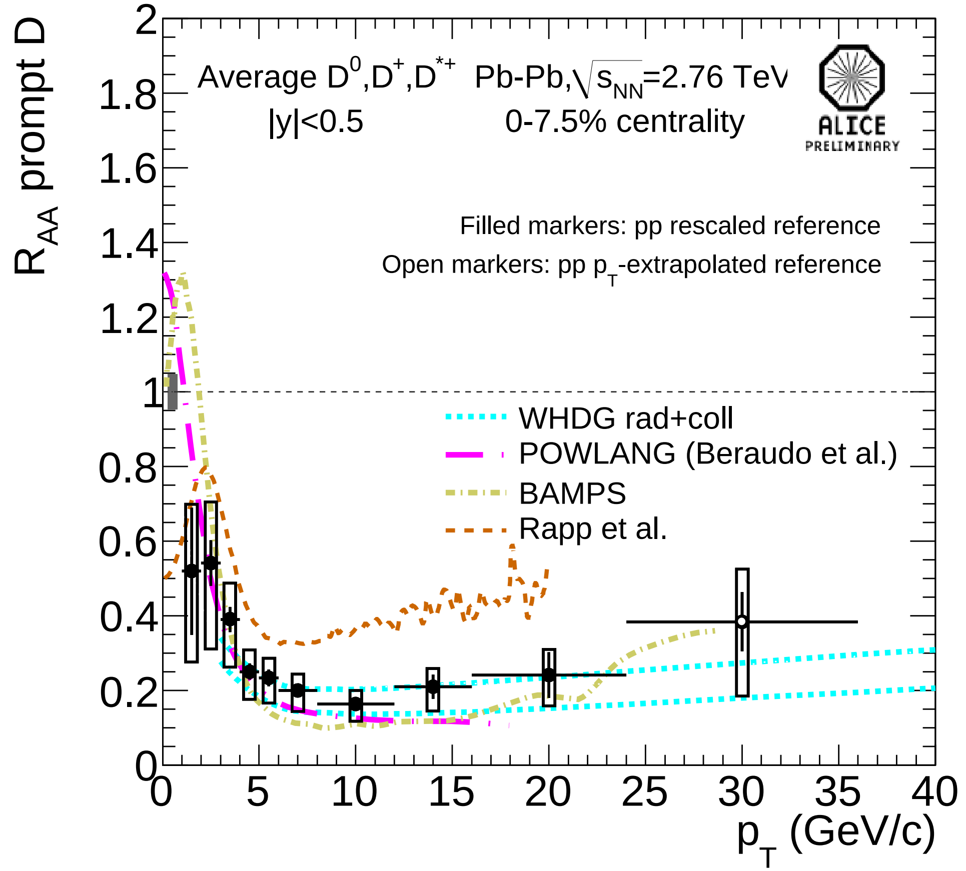
with large uncertainties, though

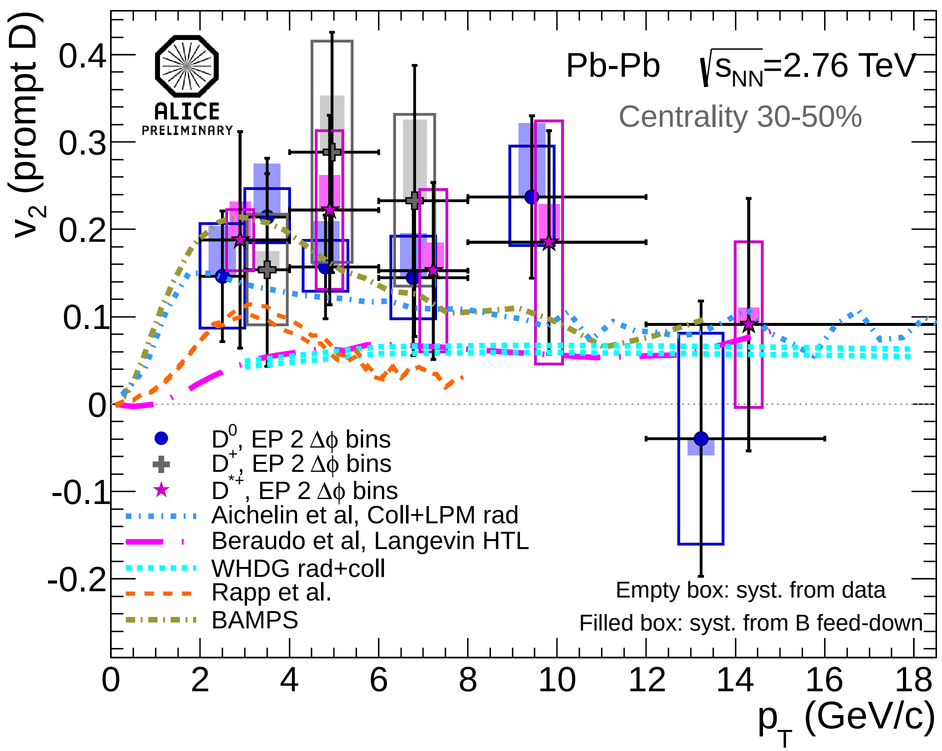
$v_2 = \langle \cos(2(\phi - \Psi_{RP})) \rangle$
quantifies collective (elliptic) flow (wrt reaction plane)



(talk by M. Krzewicki)

The charm in hot matter: data and models

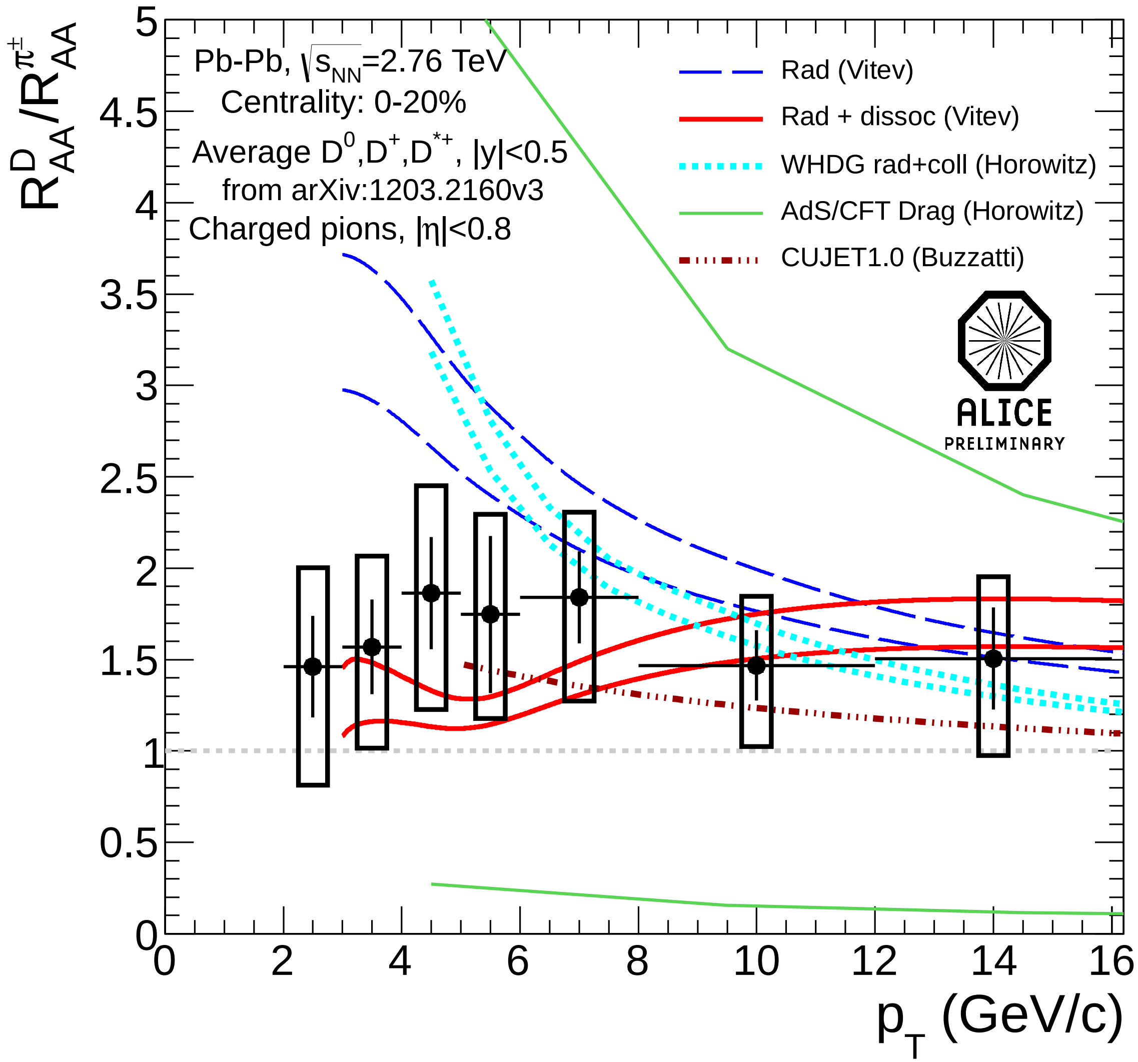




models of charm propagation in a deconfined medium reproduce (with various degree of success) suppression and flow (see refs. in JHEP 09 (2012) 112)

not all reproduce consistently that of light-quarks hadrons

The stringent test: charm vs. light quarks



a hint of $R^{D}_{\rm AA} > R^{\pi}_{\rm AA}$

($p_{\rm T}$ spectra, fragmentation?)

partonic energy loss models achieve a consistent description at high $p_{\rm T}$

some more theoretical effort needed for low $p_{\rm T}$ description

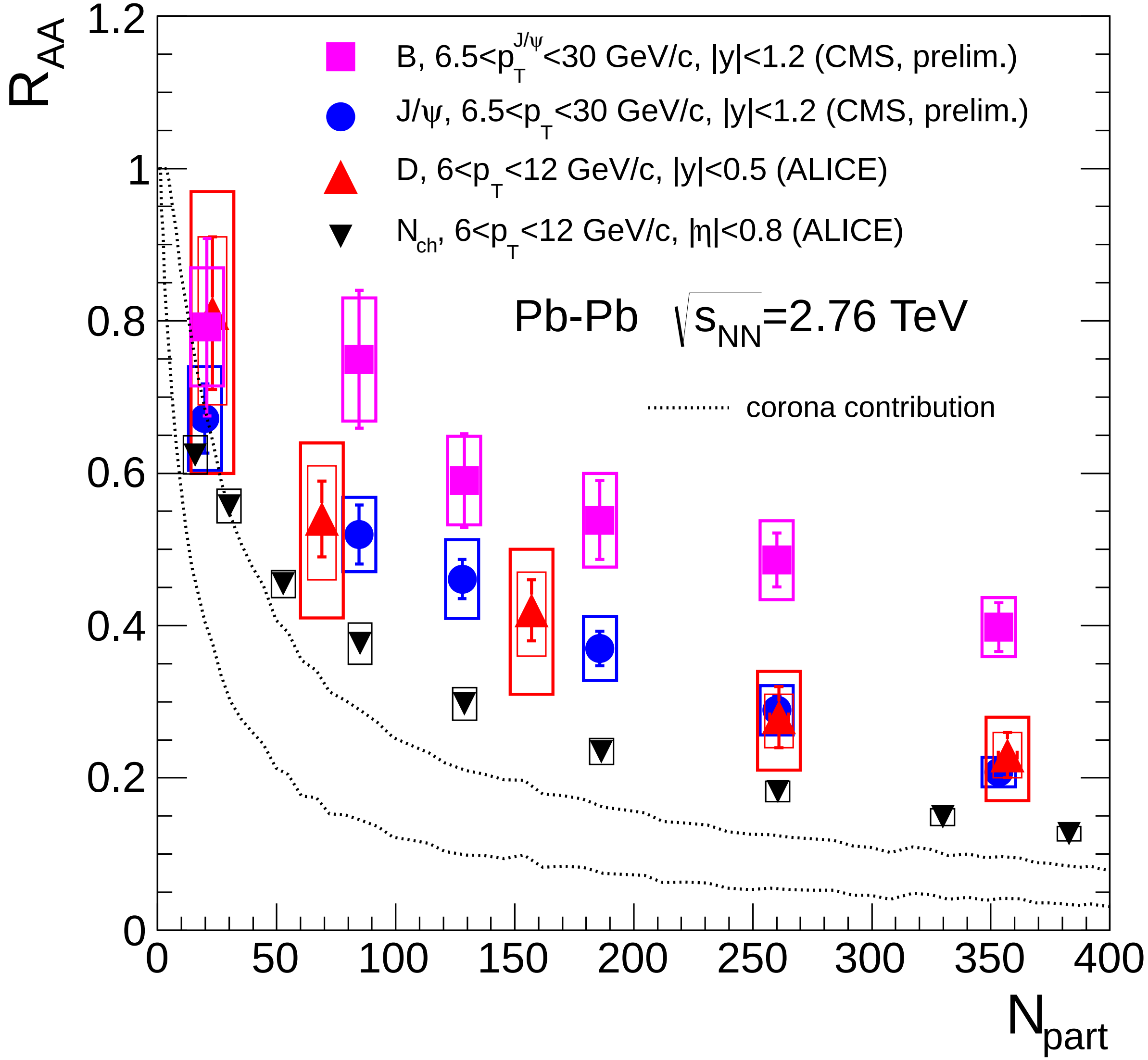
(towards extraction of the charm diffusion coefficient?)

Sharma, Vitev, Zhang, PRC80 (2009) 054902

Buzzatti, Gyulassy, PRL 108 (2012) 022301

Horowitz, arXiv:1210.8330 (talk)

In-medium energy loss as a function of quark flavor



ordering vs. quark mass seen in data
...deep meaning or conspiracy?

NB: not identical p_T ranges

similar values for D and J/ψ mesons

determined by $c,\bar{c}$ quarks (and their fate in the medium)?

ALICE, JHEP 09 (2012) 112

CMS-PAS-HIN-12-014

ALICE, arXiv:1208.2711 (N_{ch})

the original idea: Matsui & Satz, Phys. Lett. B 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. ... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon-plasma formation."

"Debye screening": no J/ψ if $\lambda_D < r_{J/\psi}$ (mean separation between c and $\bar{c}$)

Debye length in QGP: $\lambda_D \simeq 1/(g(T)\cdot T)$ ...so J/ψ is "thermometer" of QGP

Coulomb Debye screening: $\phi(r) = \frac{Q}{4\pi\varepsilon r}\exp(-\frac{r}{\lambda_D})$, $\lambda_D = \sqrt{\frac{k\varepsilon_0 k_B T}{e^2\sum z^2 n_j^0}}$

Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

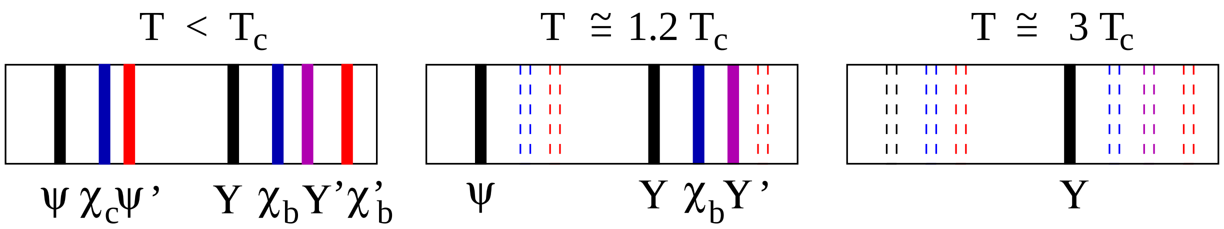
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi} \simeq$0.5 fm

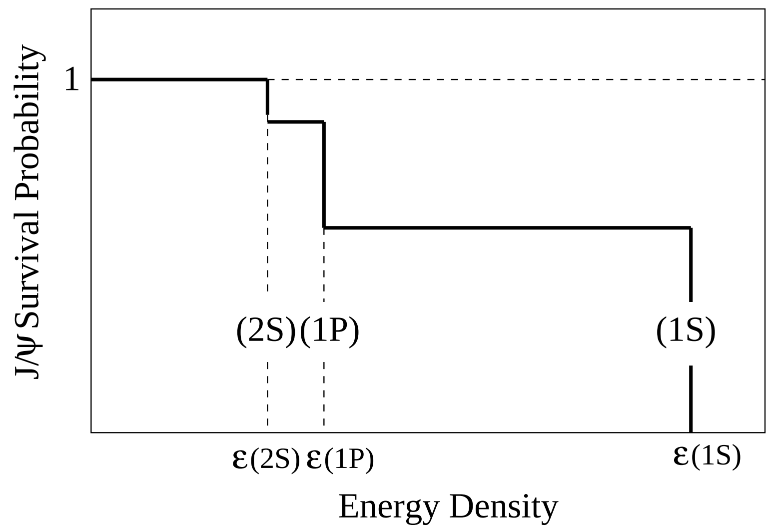
Dynamical picture: $J/\psi + g \rightarrow c + \bar{c}$

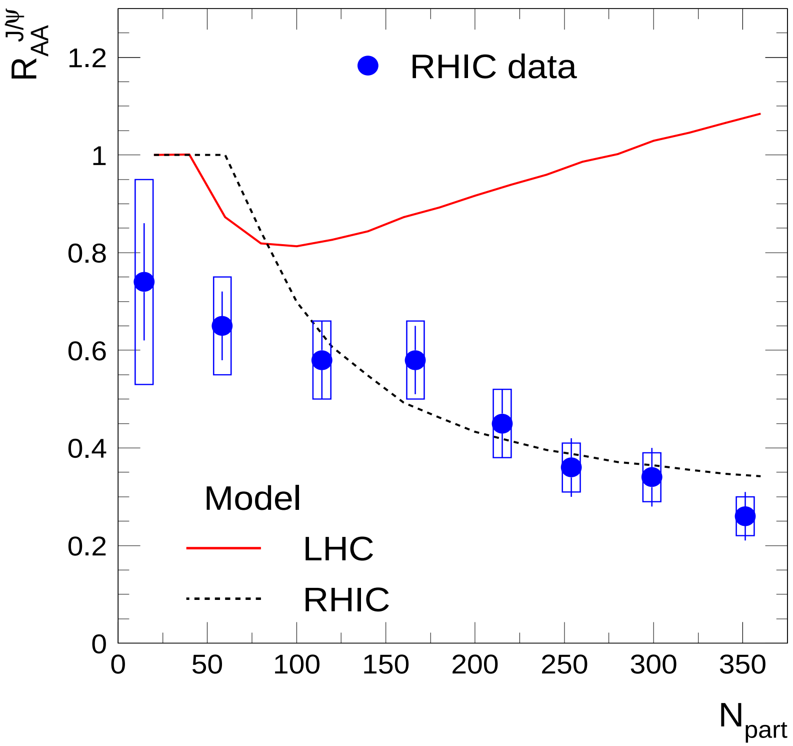
Color screening or statistical hadronization?

H.Satz, hep-ph/0609197

LQCD results (still debated)







color screening? Matsui-Satz

(sequential) suppression (ψ',$\chi_c \rightarrow J/\psi \rightarrow 0$)

or statistical hadronization at chemical freeze-out (QCD phase boundary)?

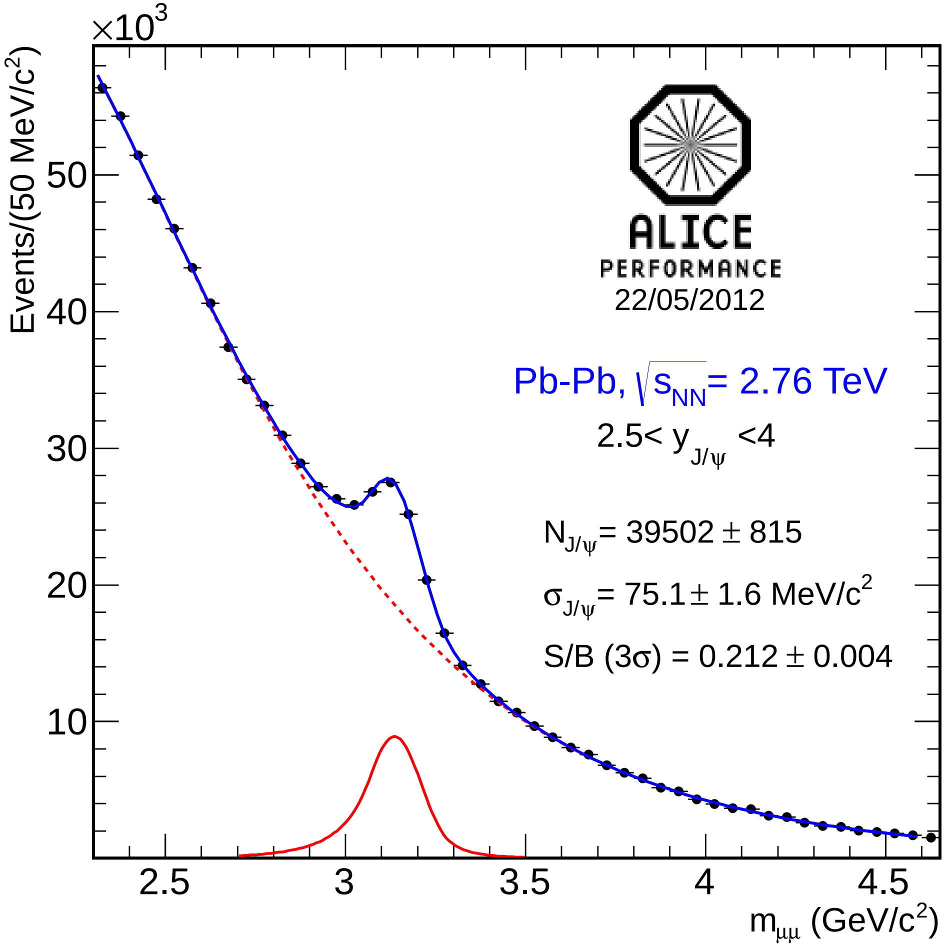
Braun-Munzinger, Stachel, PLB 490 (2000) 196

What is so different at LHC? (full en.)

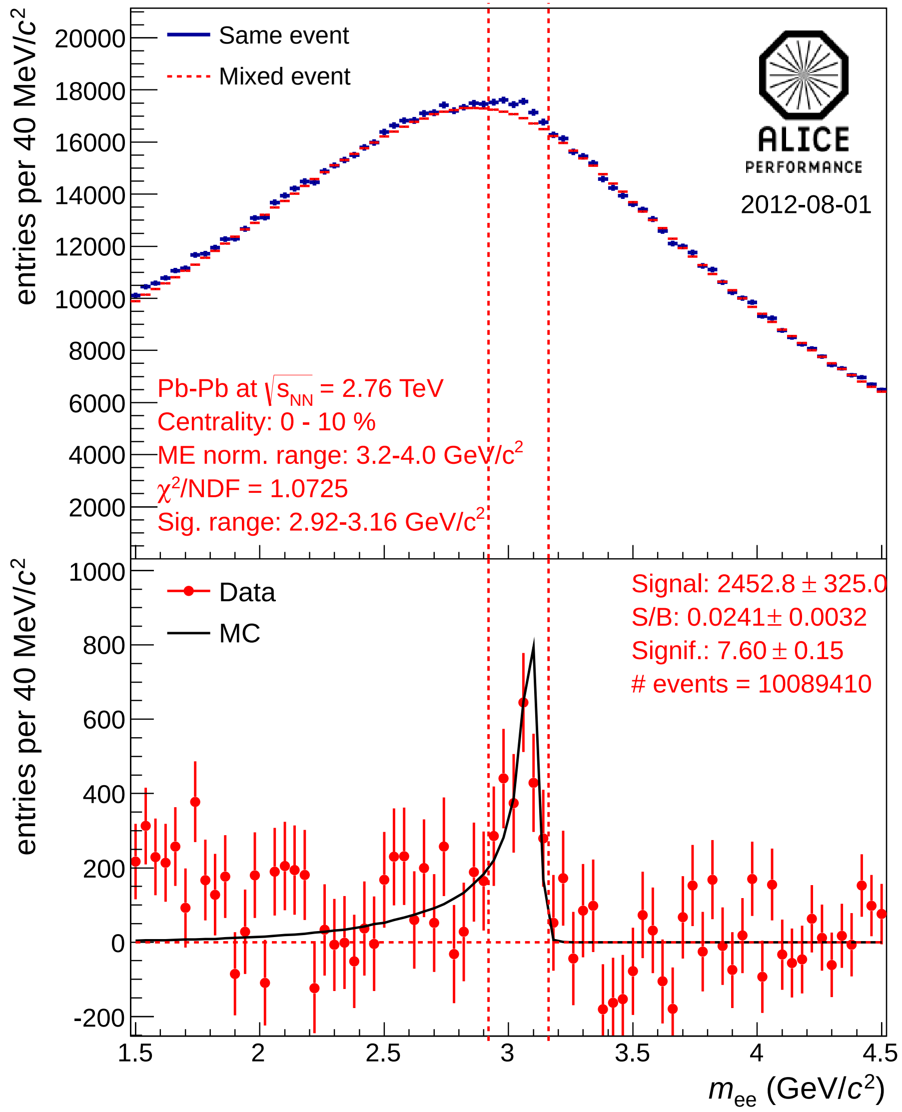
comp. to RHIC: $\sigma_{c\bar{c}}$: $\sim$10x, Volume: $\sim$3x

The (bound) charm in ALICE

Muon Spectrometer (2.5< y <4)
di-muon trigger, 0-90% centrality



Central Barrel (|y| <0.9)
centrality trigger, 0-10% centrality

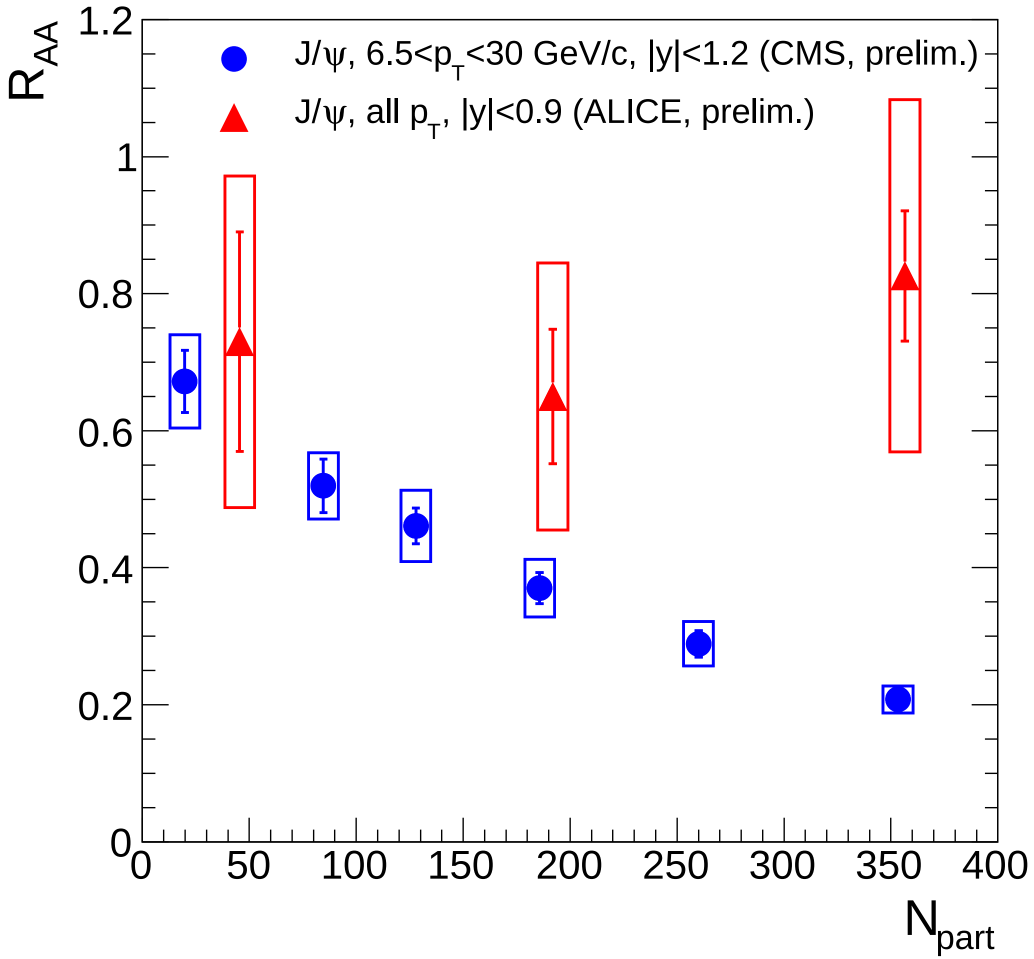


So, what do we see?

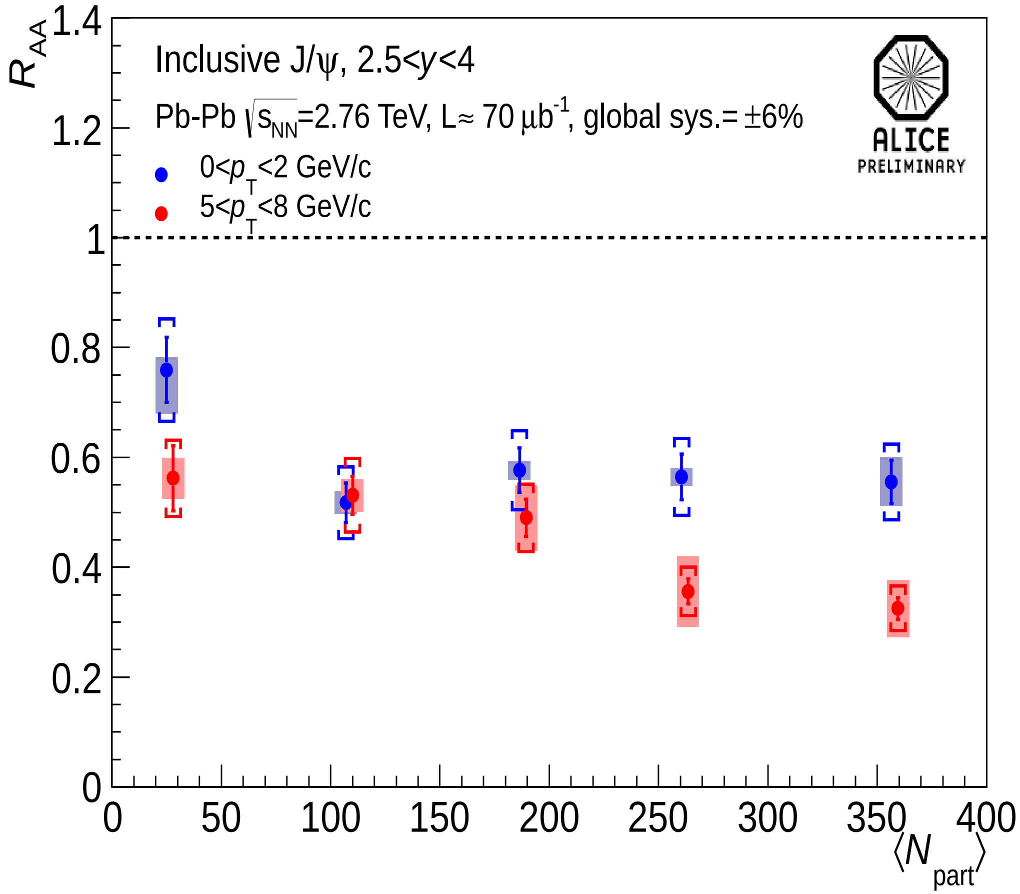
Less suppression of the overall yield (dominated by low-p_{T} production)

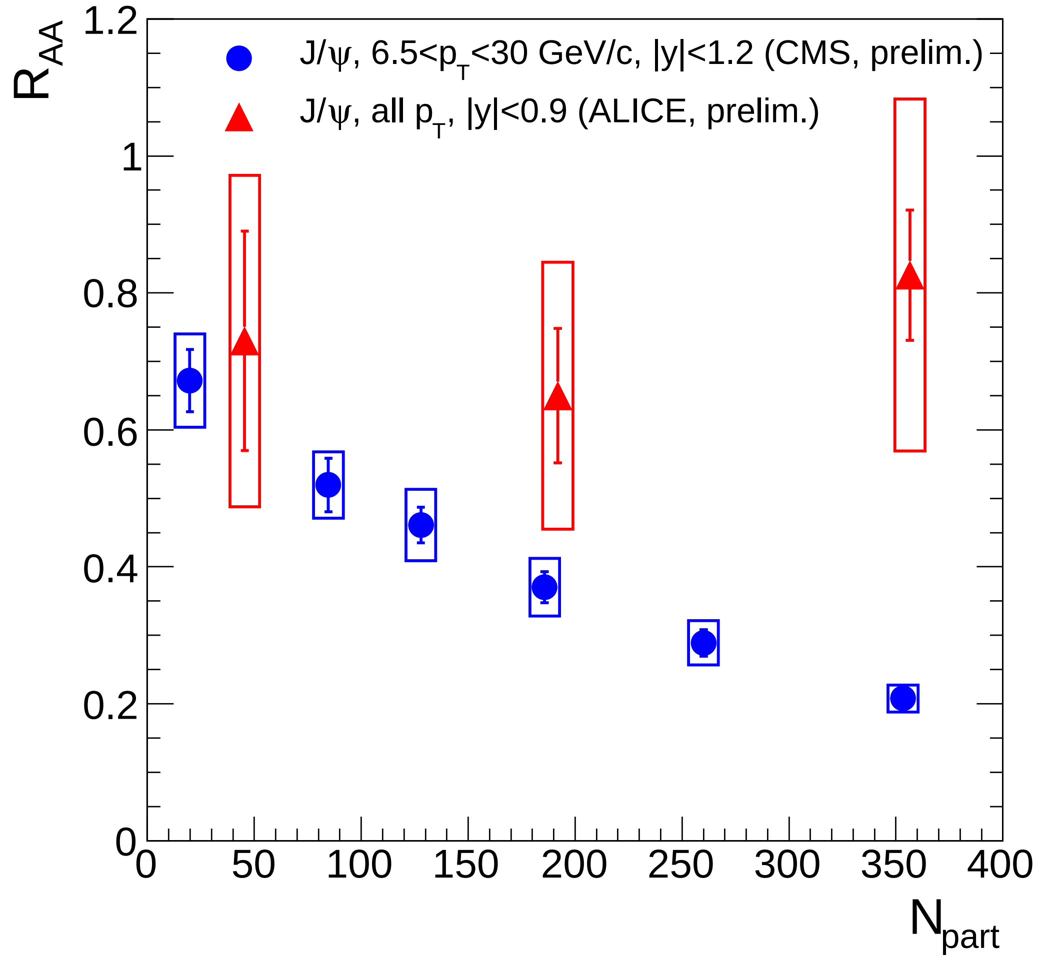
compared to high-p_{T} production

CMS-PAS-HIN-12-014
ALICE arXiv:1210.5818



So, what do we see?



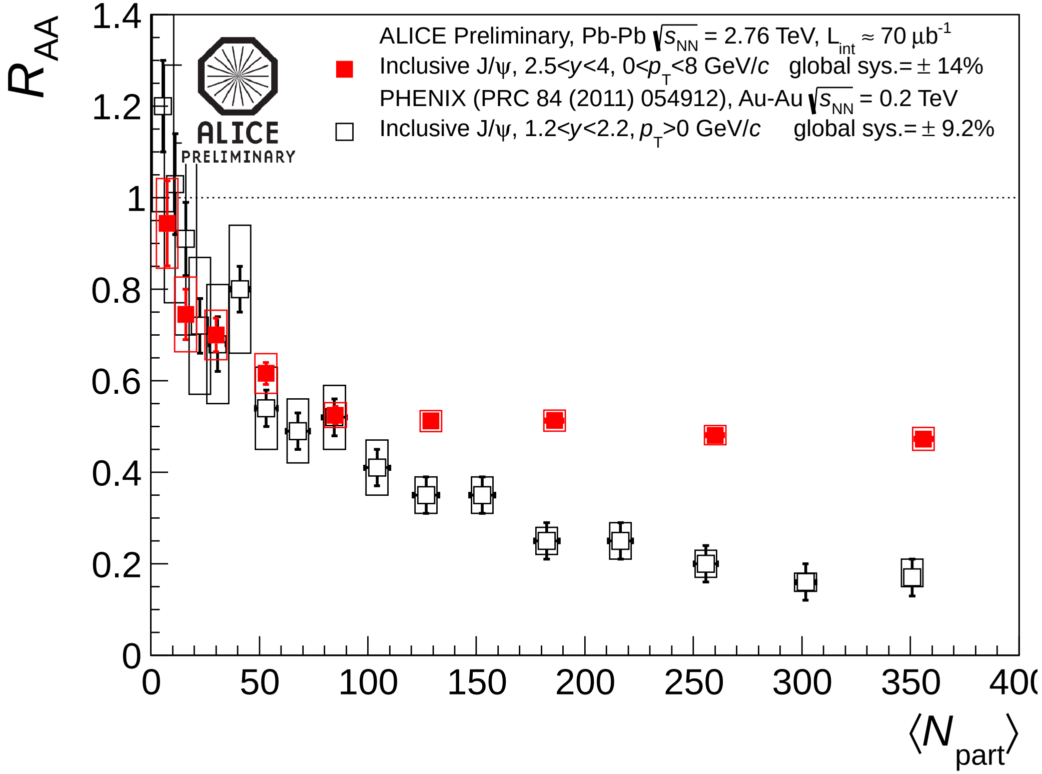


ALICE arXiv:1211.2578, 1210.5818
CMS-PAS-HIN-12-014

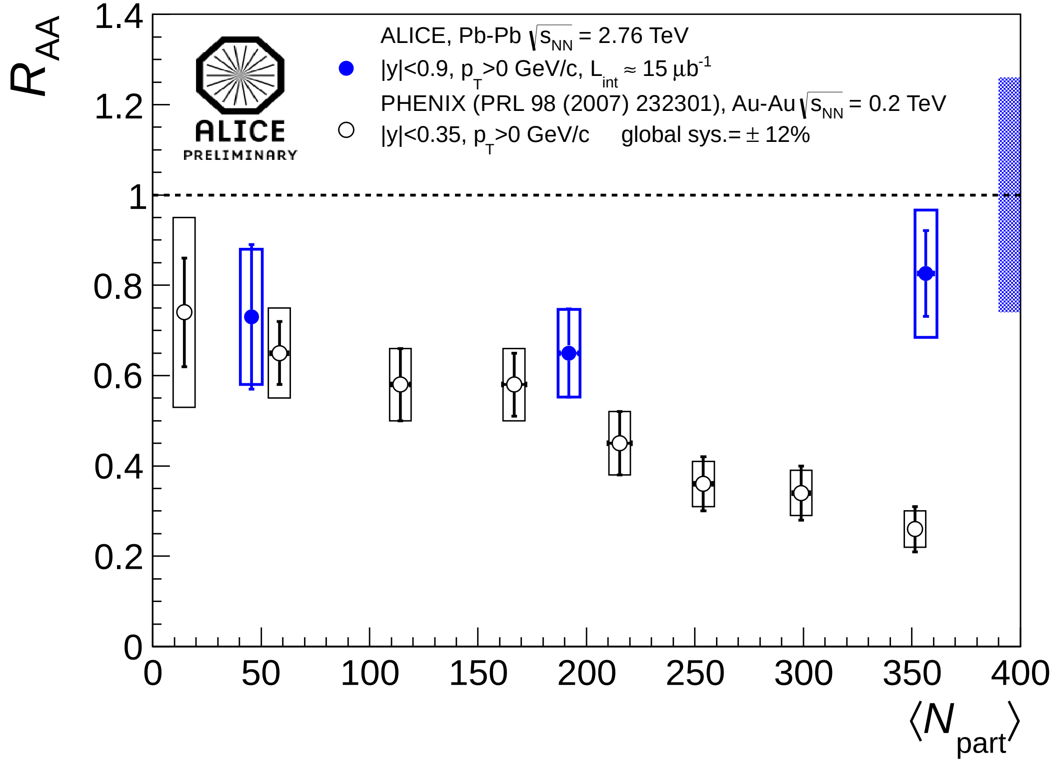
less suppression at low p_{T} ...hint for a new production mechanism?

J/ψ production: LHC vs. RHIC

Forward rapidity



Central rapidity

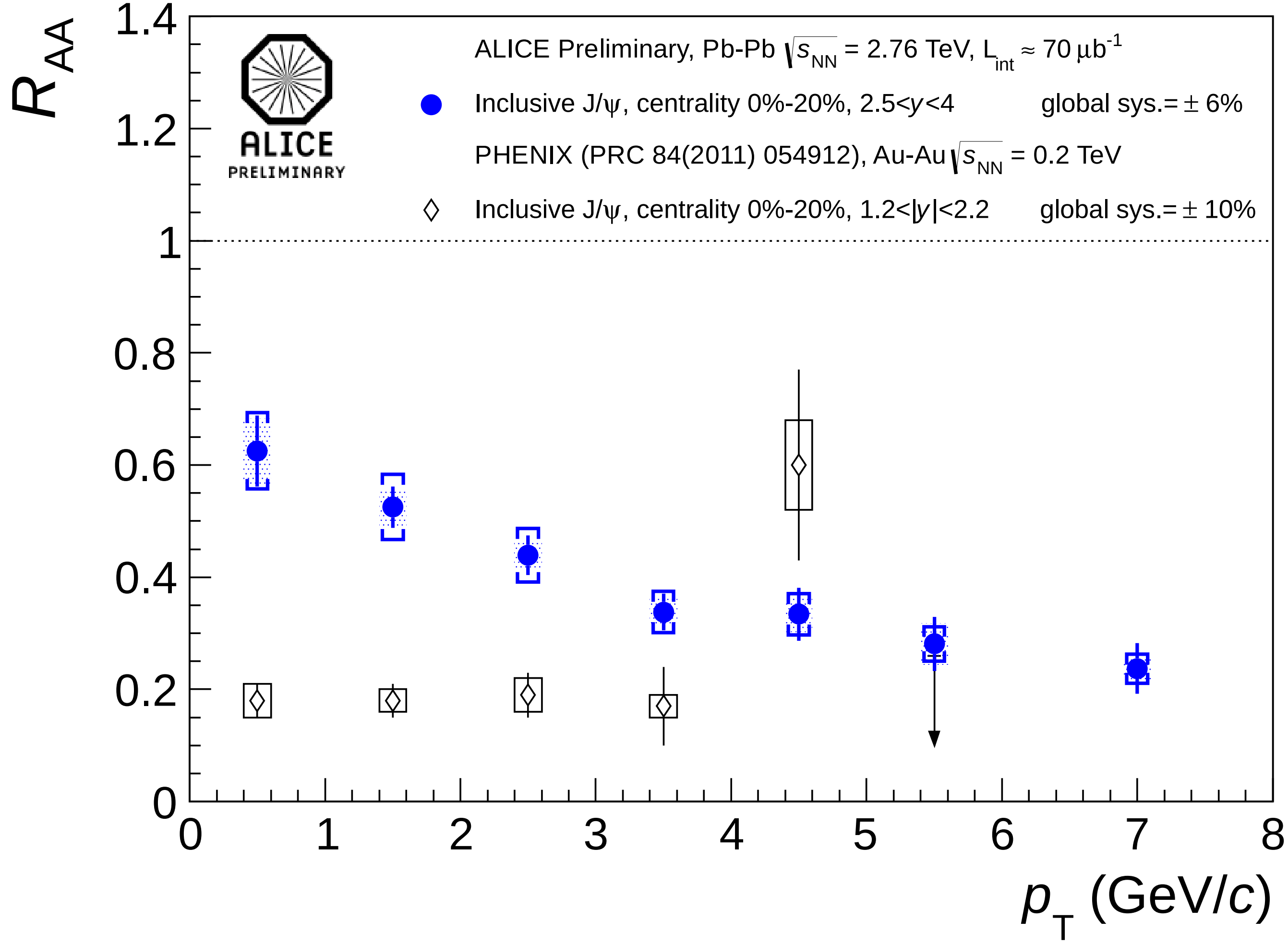


Different production patterns at the LHC compared to RHIC energy

...although energy densities (T) larger at LHC, so color screening shall be at work
...followed by regeneration in QGP or by statistical hadronization?

J/ψ production: LHC vs. RHIC

Forward rapidity

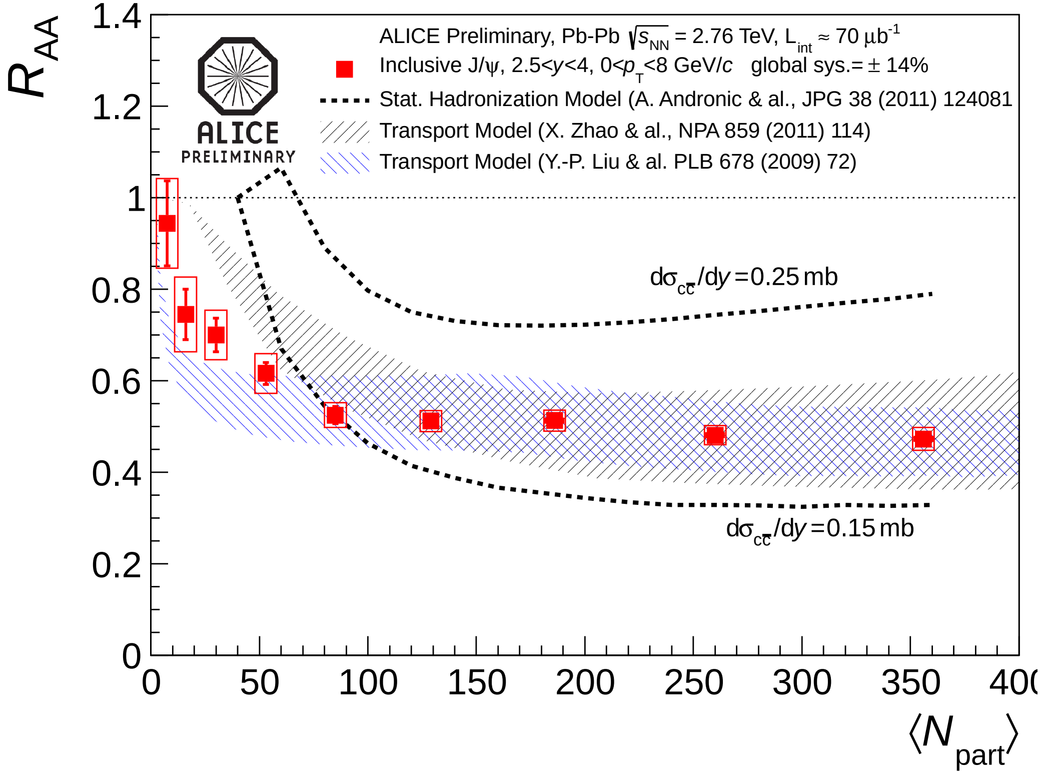


Different production patterns at the LHC compared to RHIC energy

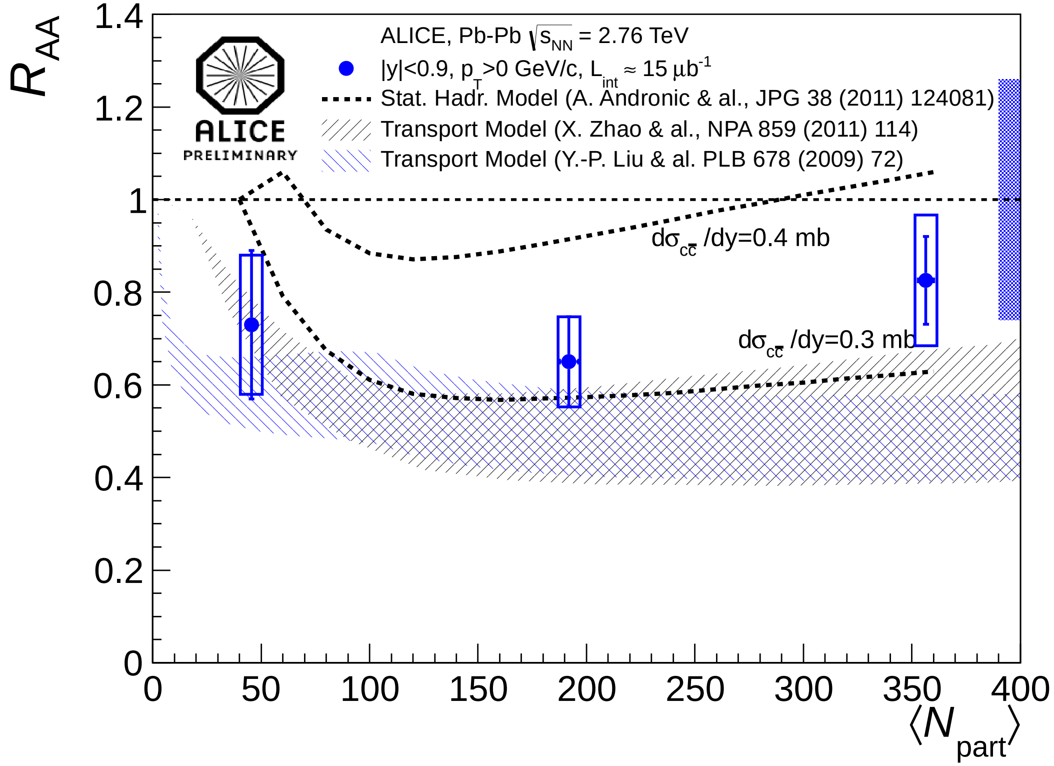
further support for (re)generation mechanisms

J/ψ production: ALICE data vs. models

Muon Spectrometer (2.5< y <4)



Central Barrel (|y| <0.9)



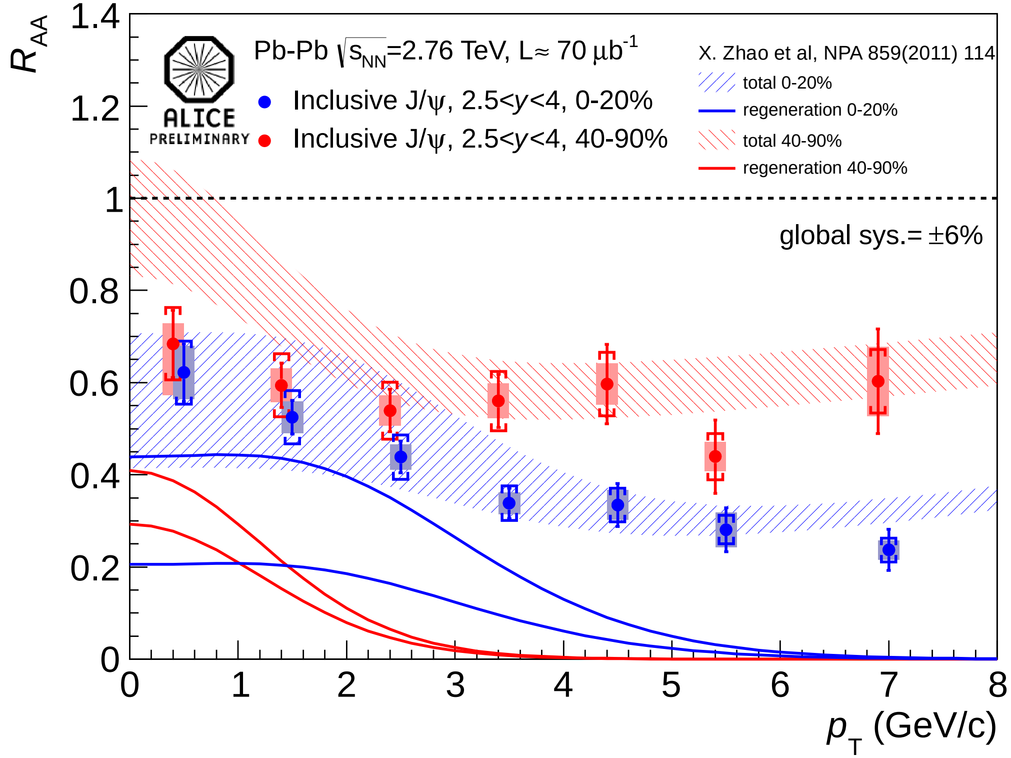
Both the transport and the statistical hadronization models reproduce the data

...with a component of production in deconfined matter ($\simeq$50%) or, respectively, at hadronization

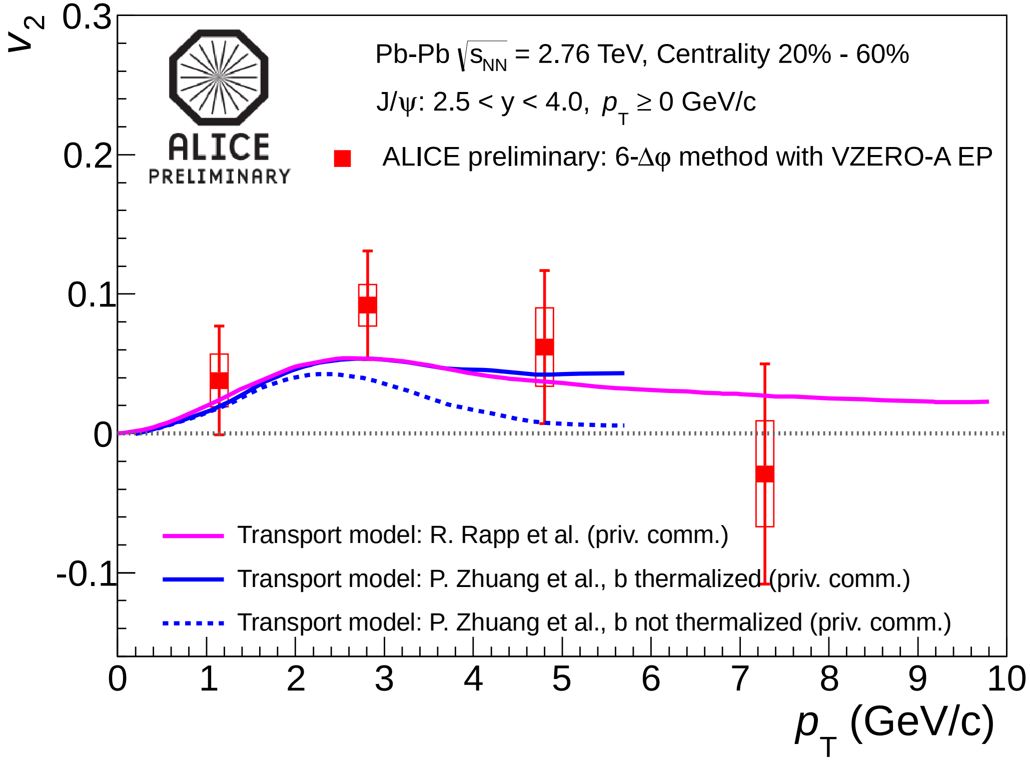
J/ψ production: ALICE data vs. models 2

Muon Spectrometer (2.5< y <4)

Nuclear modif. factor



Elliptic flow



further support of production in QGP or at chemical freeze-out

(requiring thermalization of $c, \bar{c}$ and generically leading to flow)

Two models describe the data well, with two rather different physics.

While in the statistical model the hadronization is a process in which all quark flavors take part concurrently, in the kinetic model J/ψ survives as a hadron in the hot medium dominated by deconfined gluons and light quarks.

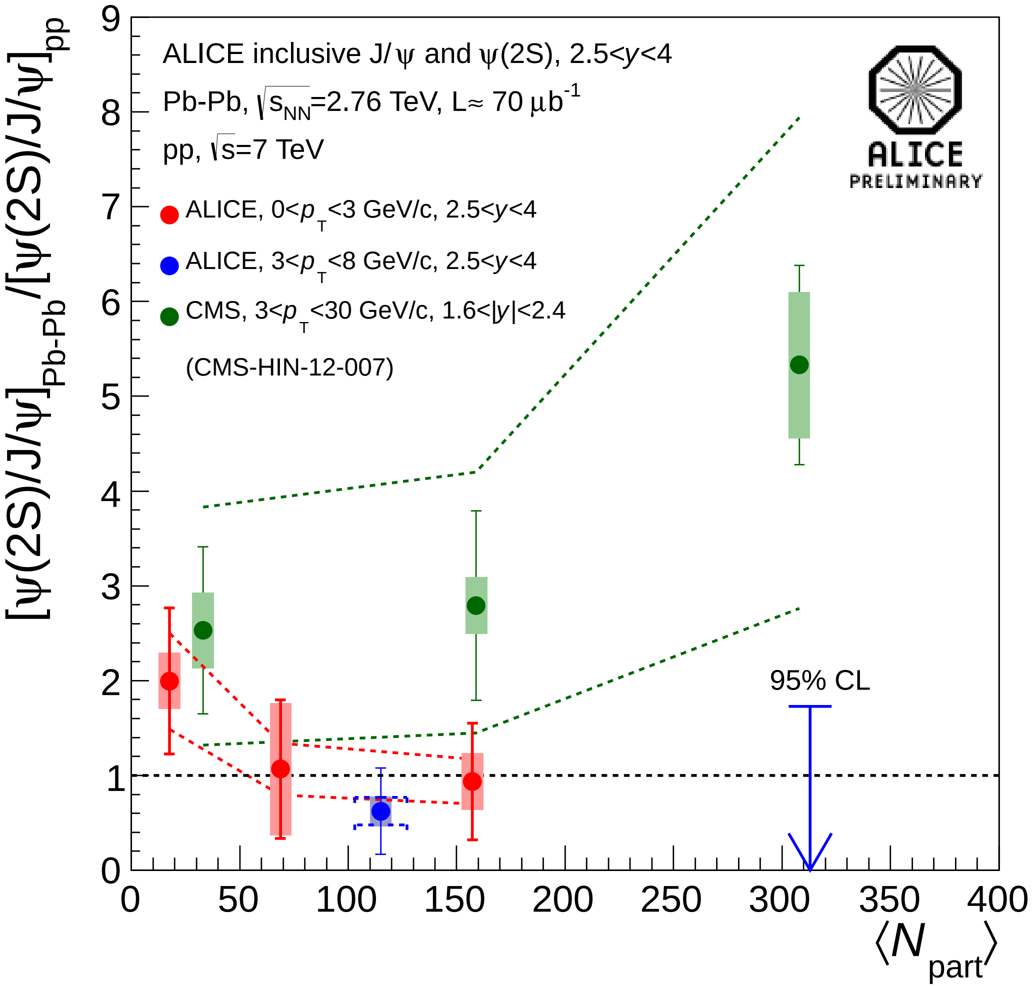
In the statistical model all charmonium states are generated exclusively at hadronization, while in the kinetic model only about half of the J/ψ yield (in central collisions) originates from deconfined charm and anti-charm quarks.

Discriminating the two pictures implies providing an answer to fundamental questions related to the fate of hadrons in a hot medium.

A precision measurement of $\sigma_{c\bar{c}}$ in Pb-Pb collisions, within reach with the proposed ALICE upgrade, will place an important constraint to models.

...and data on other charmonium states is crucial

$\psi(2S)$ production at the LHC



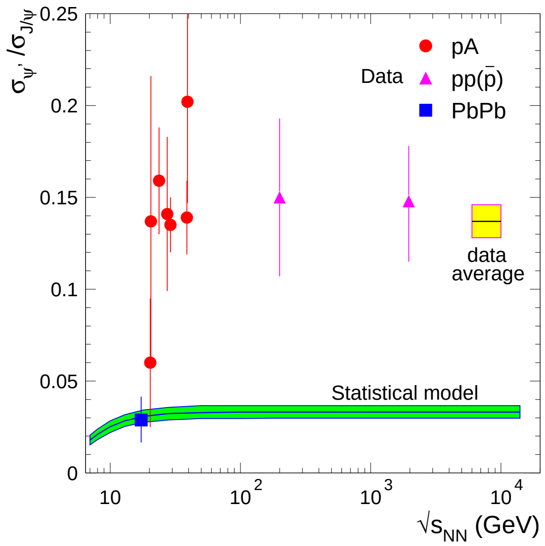
$$R = \frac{N^{\psi(2S)}_{\rm Pb-Pb}/N^{J/\psi}_{\rm Pb-Pb}}{N^{\psi(2S)}_{\rm pp}/N^{J/\psi}_{\rm pp}} = \frac{R^{\psi(2S)}_{\rm AA}}{R^{J/\psi}_{\rm AA}}$$

N - production yields

discrepancy ALICE / CMS ?

not conclusive as uncertainties are large

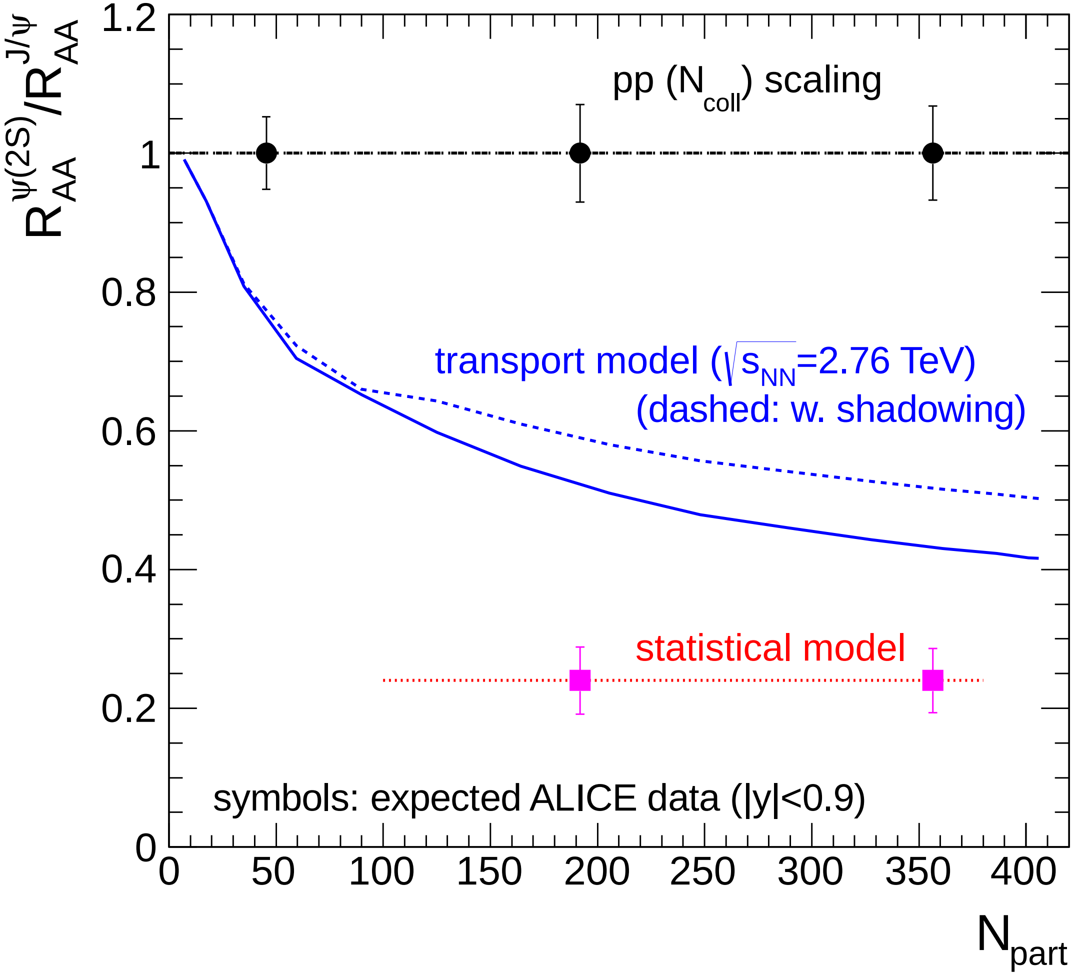
at SPS (NA50): $R \simeq 0.24$



$R < 1$ expected in both models, different magnitudes predicted ($p_{\rm T}$-integrated)

Transport model:
Zhao, Rapp, NPA 859 (2011) 114 and priv. comm.

Statistical model:
AA et al., NPA 789 (2007) 334



Central Barrel: measurement possible only with upgrade (10 nb^{-1})
Muon Spectrometer: a first glimpse with baseline data (1 nb^{-1}), a real measurement only with upgrade

Summary

data indicate a strong energy loss of charm quarks and collective (elliptic) flow implying charm thermalization ...and described by models at partonic level

hints of the expected mass ordering (rather weak, though) of energy loss

at LHC, the final act (?:) of the (intricate) story of J/ψ as a probe for QGP

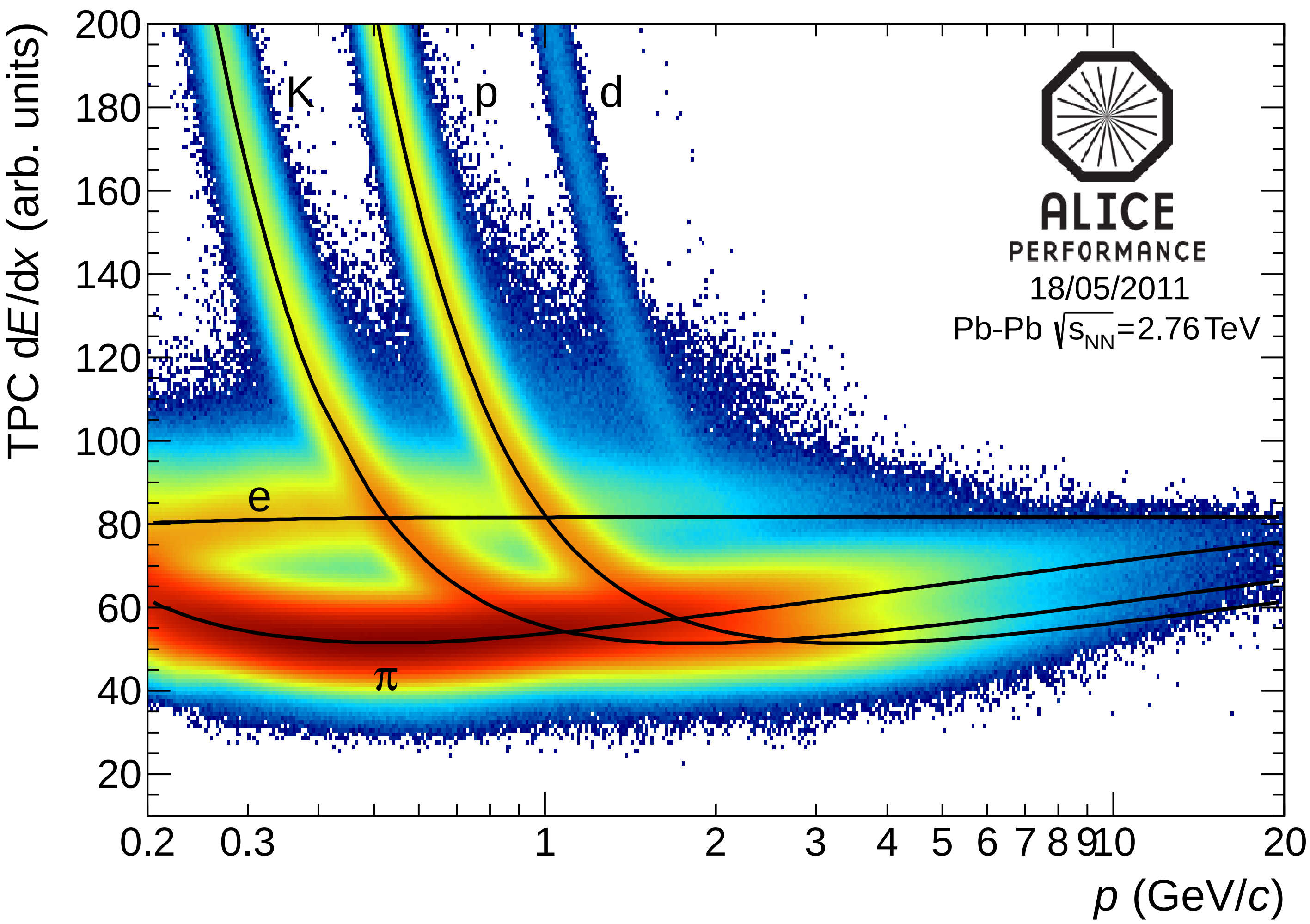
went from "thermometer" to more "active" probe of deconfinement or of the QCD phase boundary (story continues) ...re?generation

precision measurements of open charm and of J/ψ and $\psi(2S)$ production envisaged within the ALICE Upgrade project

while measurements in p–A and at (close to) top LHC energy are eagerly awaited

Extra slides

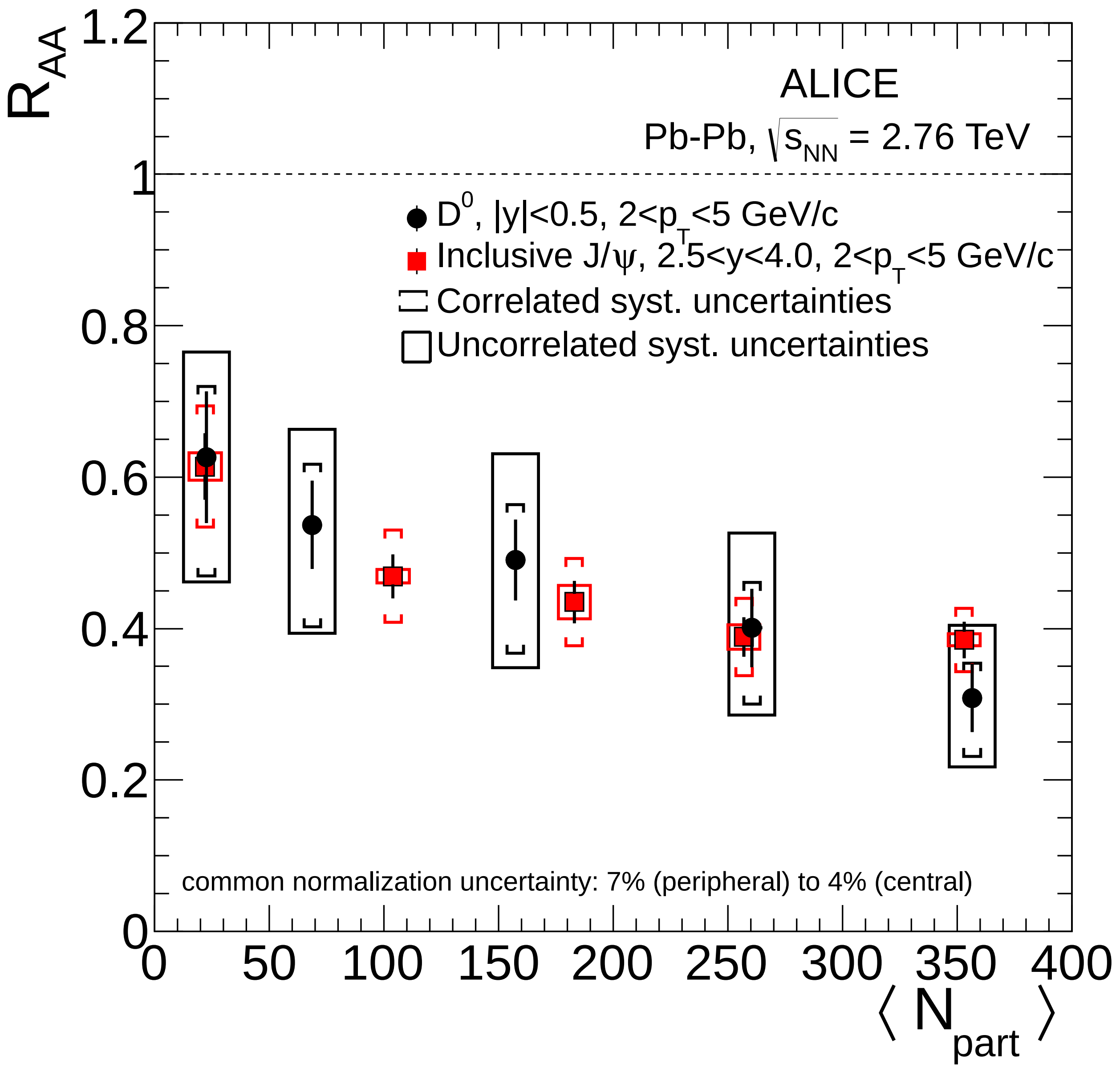
x0



ALI−DER−38773

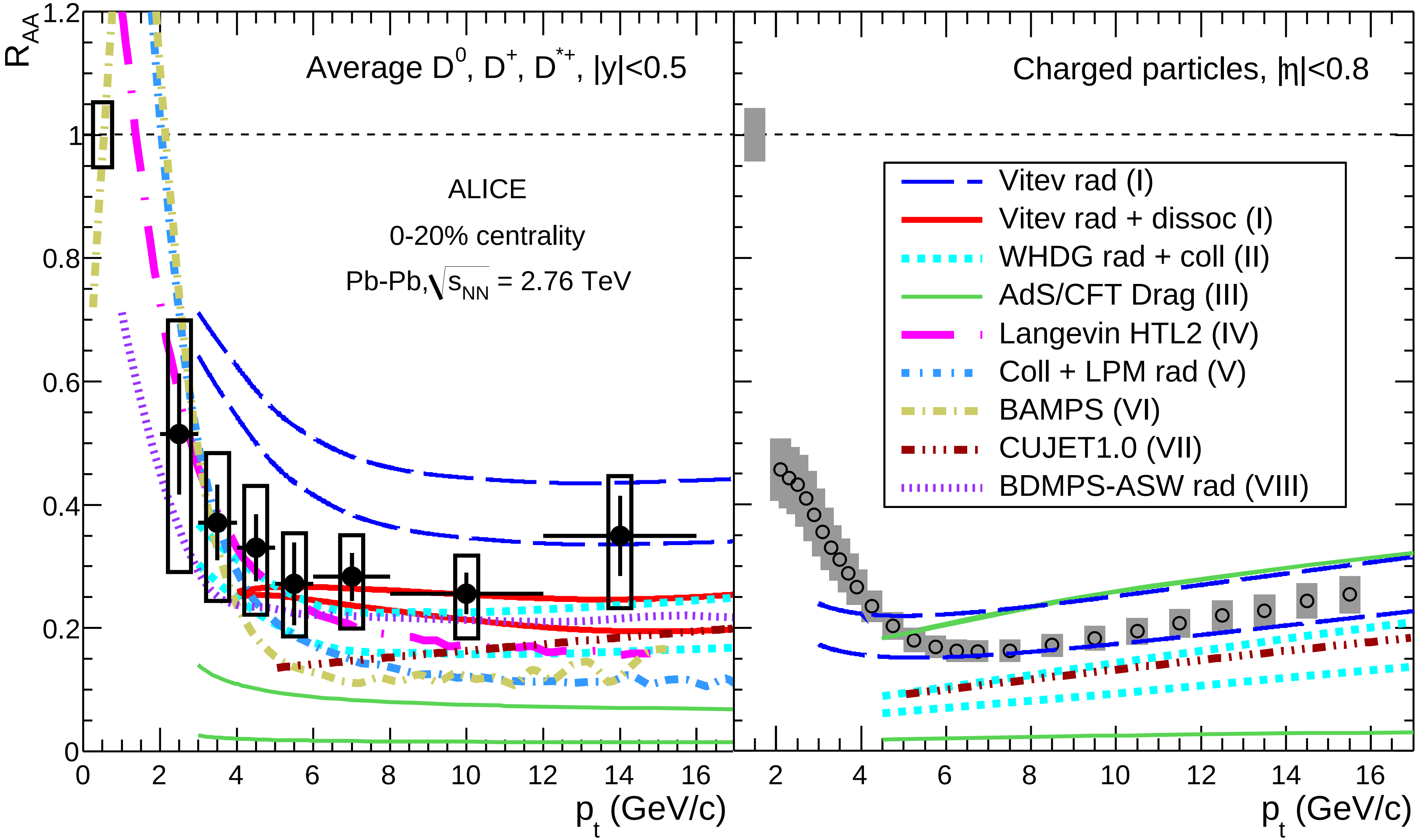
Open and bound charm suppression

x1



Flavor-dependent parton energy loss

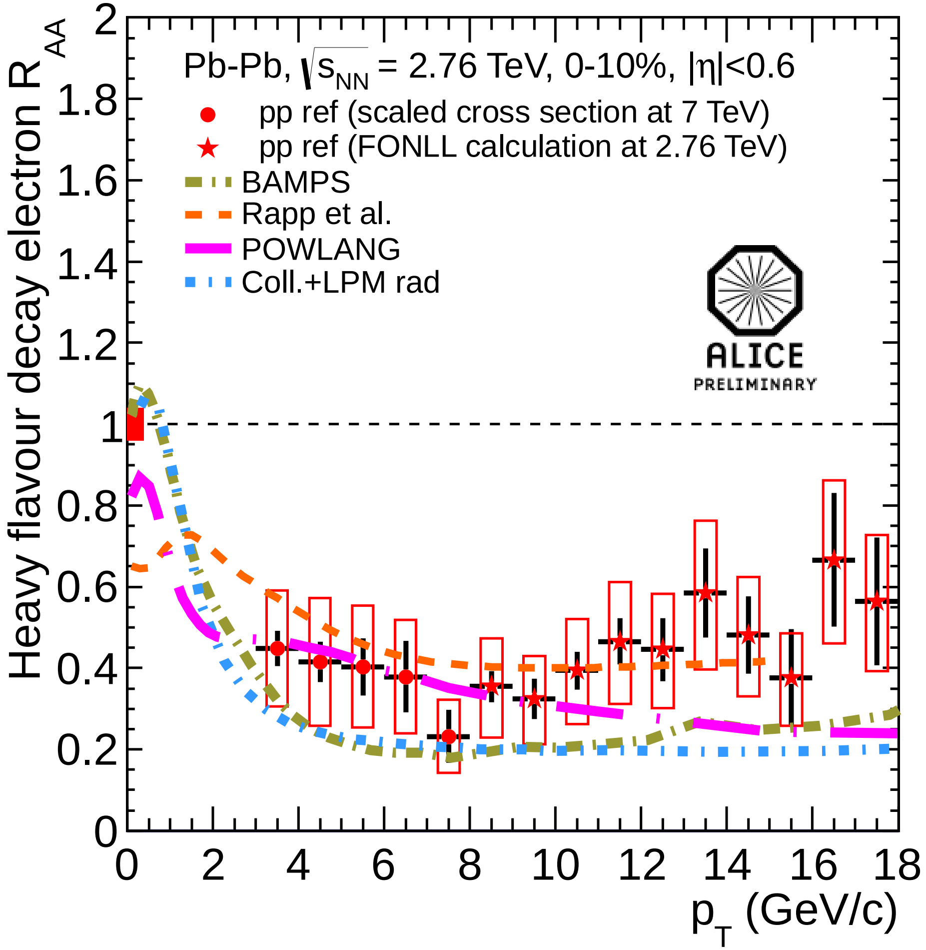
x2

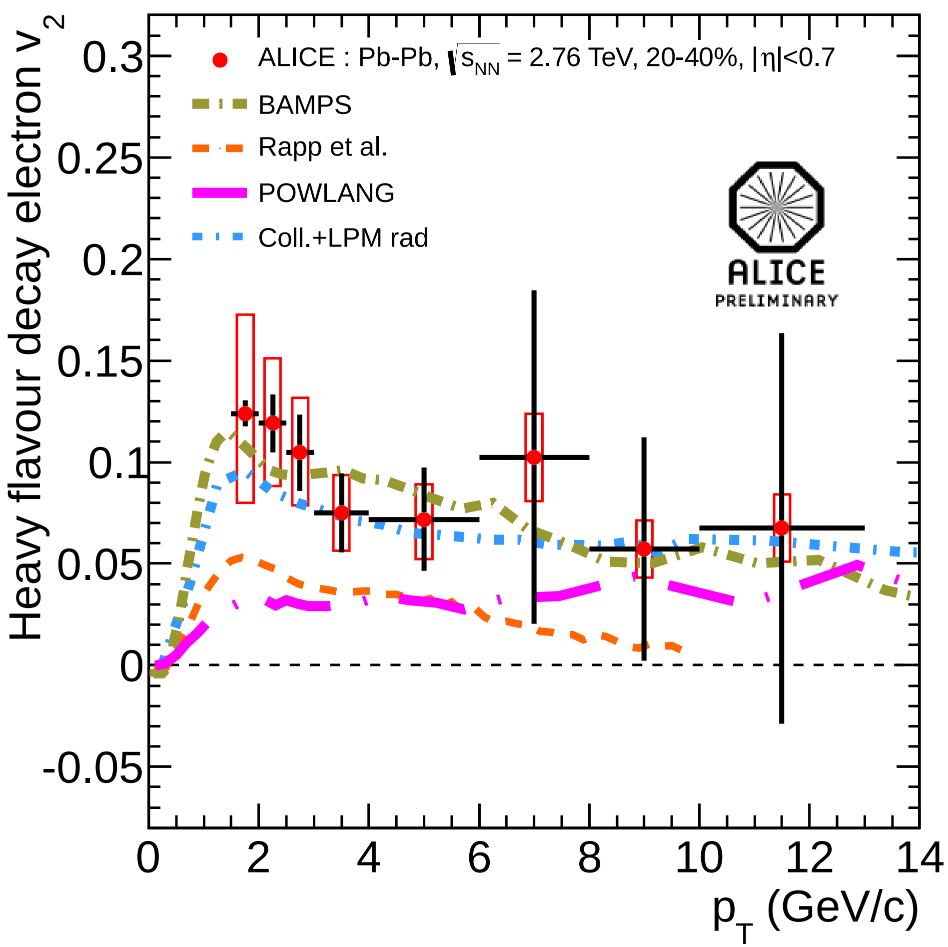


Electrons from charm and beauty

x3

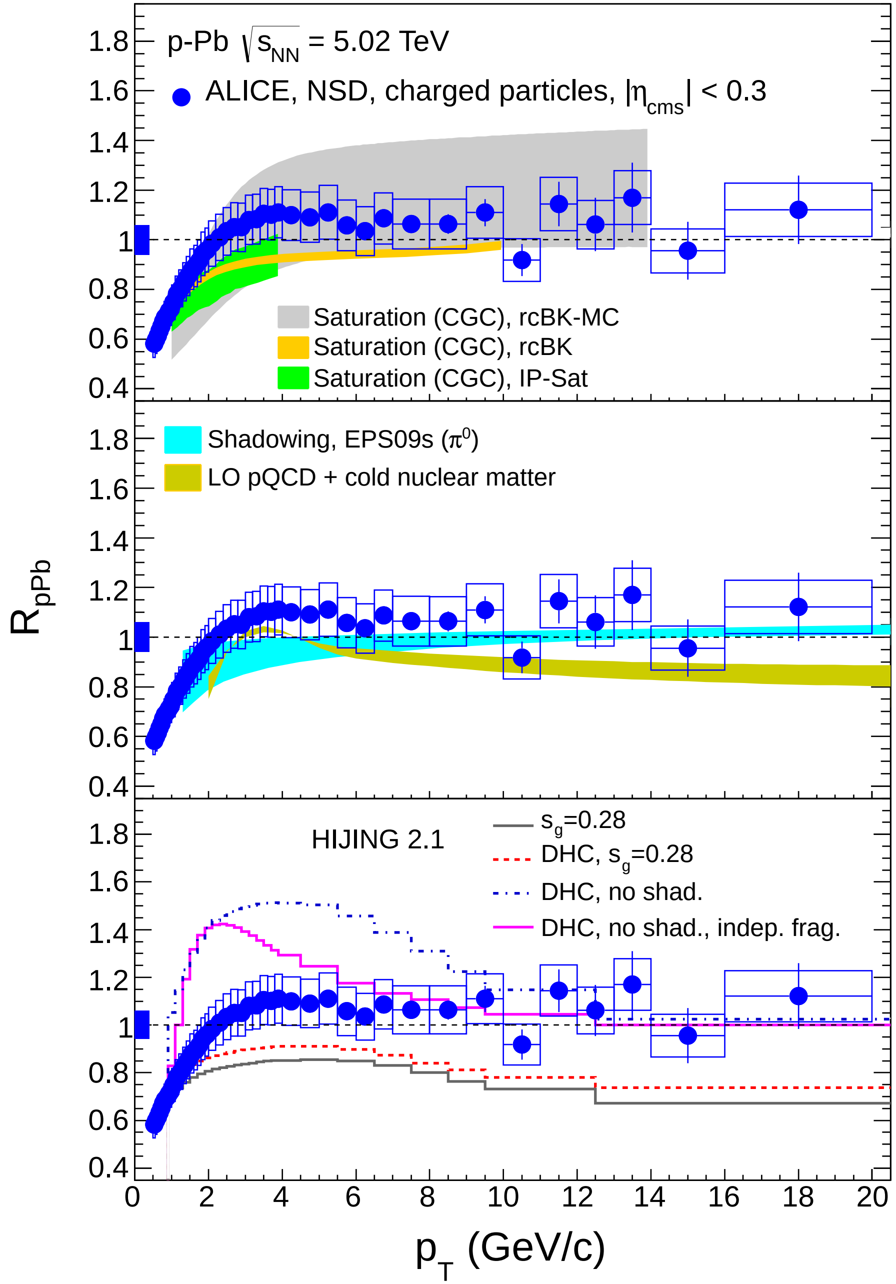
ALI–PREL–35153





The nuclear modification factor in p–Pb

x4



ALICE, arXiv:1210.4520

Models

saturation
Albacete et al., NPA 897 (2013) 1 (rcBK-MC)
Tribedy, Venugopalan, PLB 710 (2012) 125 (rcBK, IP-Sat)

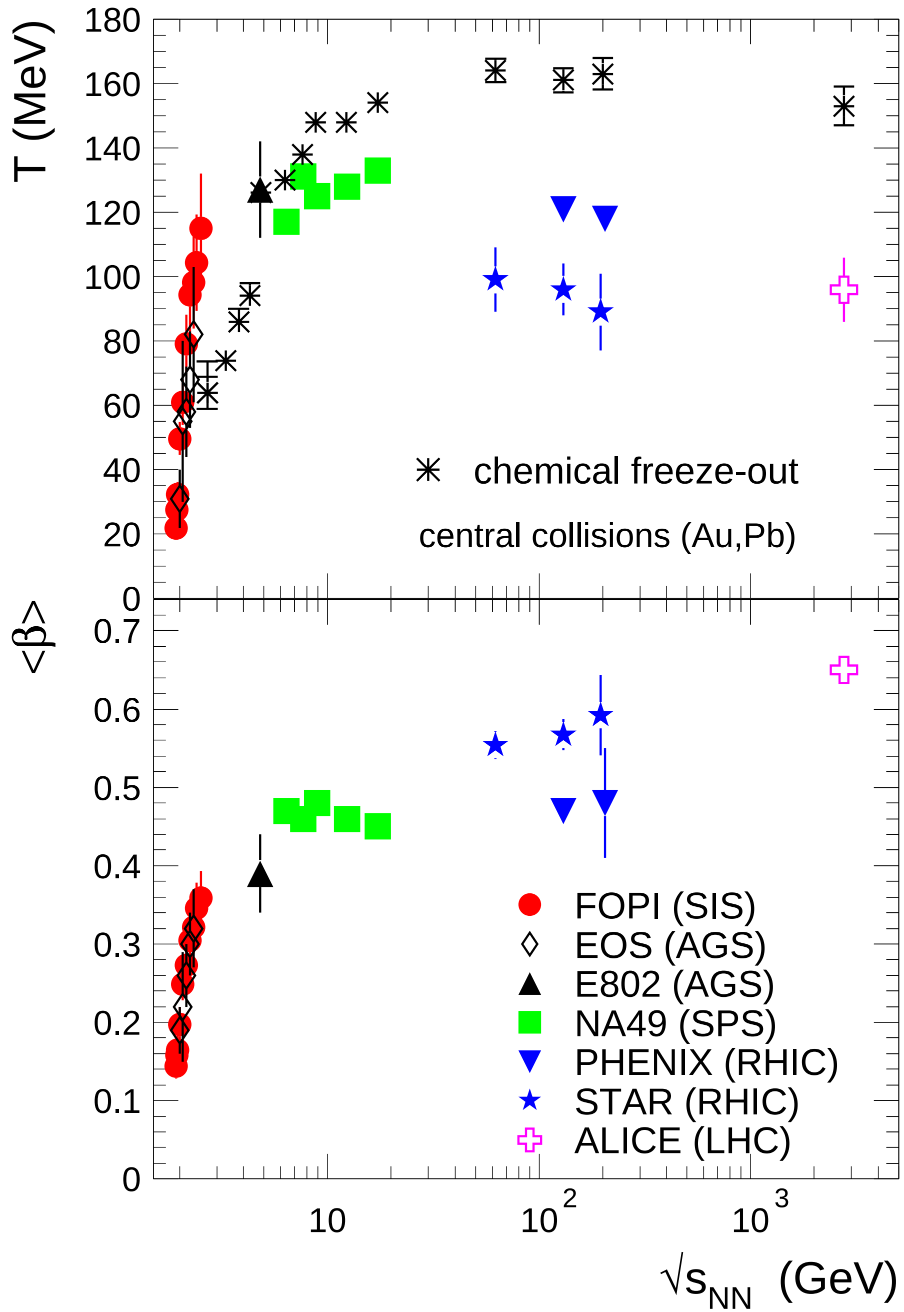
shadowing
Helenius et al., JHEP 1207 (2012) 073

pQCD + cold nuclear matter
Kang, Vitev, Xing, PLB 718 (2012) 482

HIJING 2.1
Xu et al., PRC 86 (2012) 051901

Kinetic and chemical freeze-out

x5



central collisions (radial flow)

hadrons (with light quarks) flow with a collective velocity of up to 65% c

complex azimuthal asymmetries in non-central collisions (allow extraction of viscosity)

AA, arXiv:1210.8126