Heavy-flavor hadron measurement with ALICE

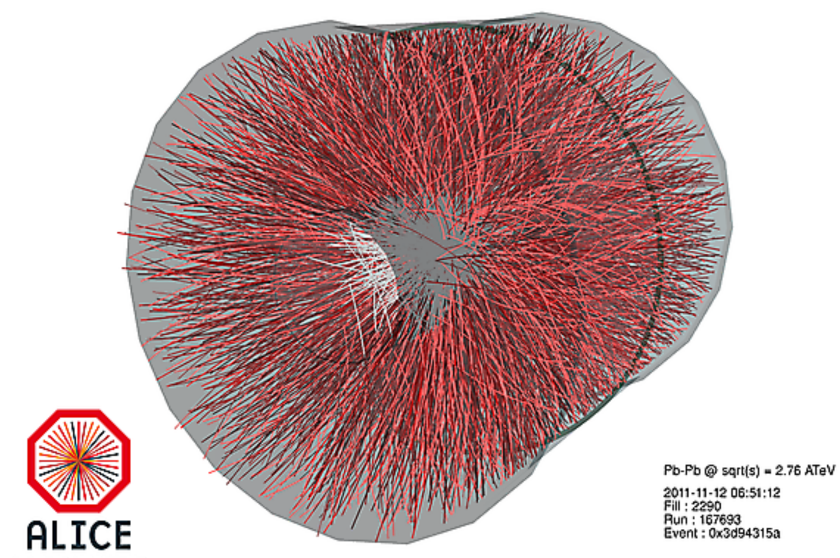
Jacek Otwinowski *
for the ALICE Collaboration

X Polish Workshop on Relativistic Heavy-Ion Collisions,
Institute of Physics, Jan Kochanowski University
Kielce, Poland
December 13-15, 2013

* GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

Outline

- Physics motivation
- ALICE detector
- Results
  - Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} ~ 0.1 nb^{-1} (2011 run)
  - p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} ~ 30 nb^{-1} (2013 run)
- Summary

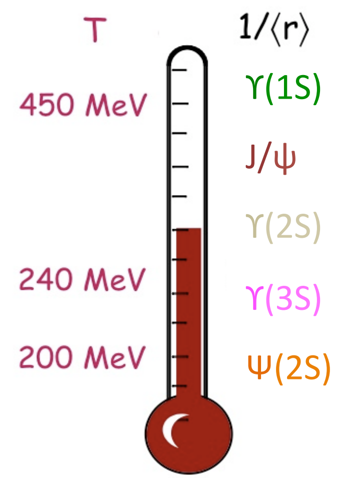


Heavy quark production

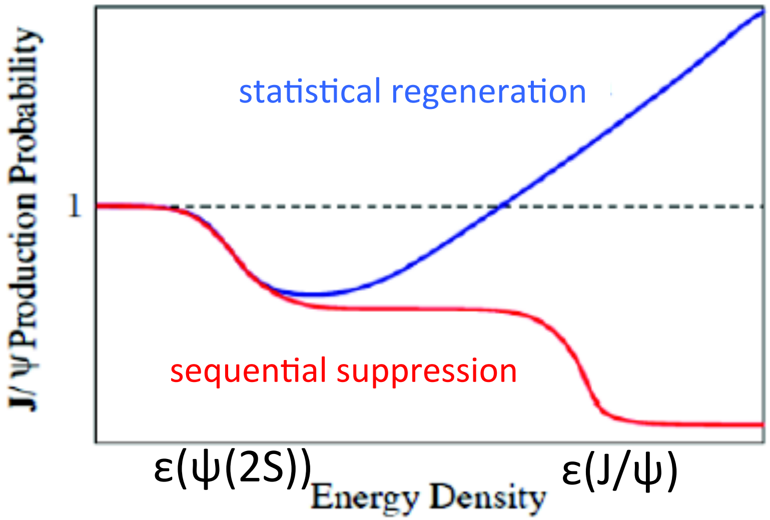
- pp
  - Test of perturbative QCD in vacuum
  - Reference for p-Pb and Pb-Pb
- p-Pb
  - Initial state effects (gluon saturation/shadowing)
  - Indication of flow and final state effects
  - Is it reference for Pb-Pb?
- Pb-Pb
  - Heavy quarks are ideal to probe the QGP ($\tau_{prod} = 1/2m << \tau_{QGP} \sim 10$ fm/c)
  - Study the interaction of heavy quarks with dense and hot QCD medium
    - Energy loss dependence on color charge ($\Delta E_g > \Delta E_{q,Q}$) and mass "dead cone" ($\Delta E_q > \Delta E_c > \Delta E_b$) [Dokshitzer and Kharzeev, PLB 519 (2001) 199]
    - Test of collectivity in QGP – do heavy quarks participate in flow?
    - Probe the level of heavy quark thermalization – heavy flavor production mechanism [Kuznetsova and Rafelski, EPJC 51 (2007) 113]

Quarkonium production in HI collisions

- Quarkonia – bound states ($c\bar{c}$, $b\bar{b}$) produced in the early stage of HI collisions
- Quarkonia sequential suppression in QGP due to color screening [Matsui and Satz, PLB 168 (1986) 415; Karsch and Satz, ZPC 51, (1991) 209]
- Charmonia production via regeneration ($c\bar{c}$ combination) in the QGP or at the phase boundary ($T \sim T_{ch}$) [Braun-Munzinger and Stachel, PLB 490 (2000) 196; Thews et al., PRC 63 (2000) 054905]



Sequential suppression vs. regeneration



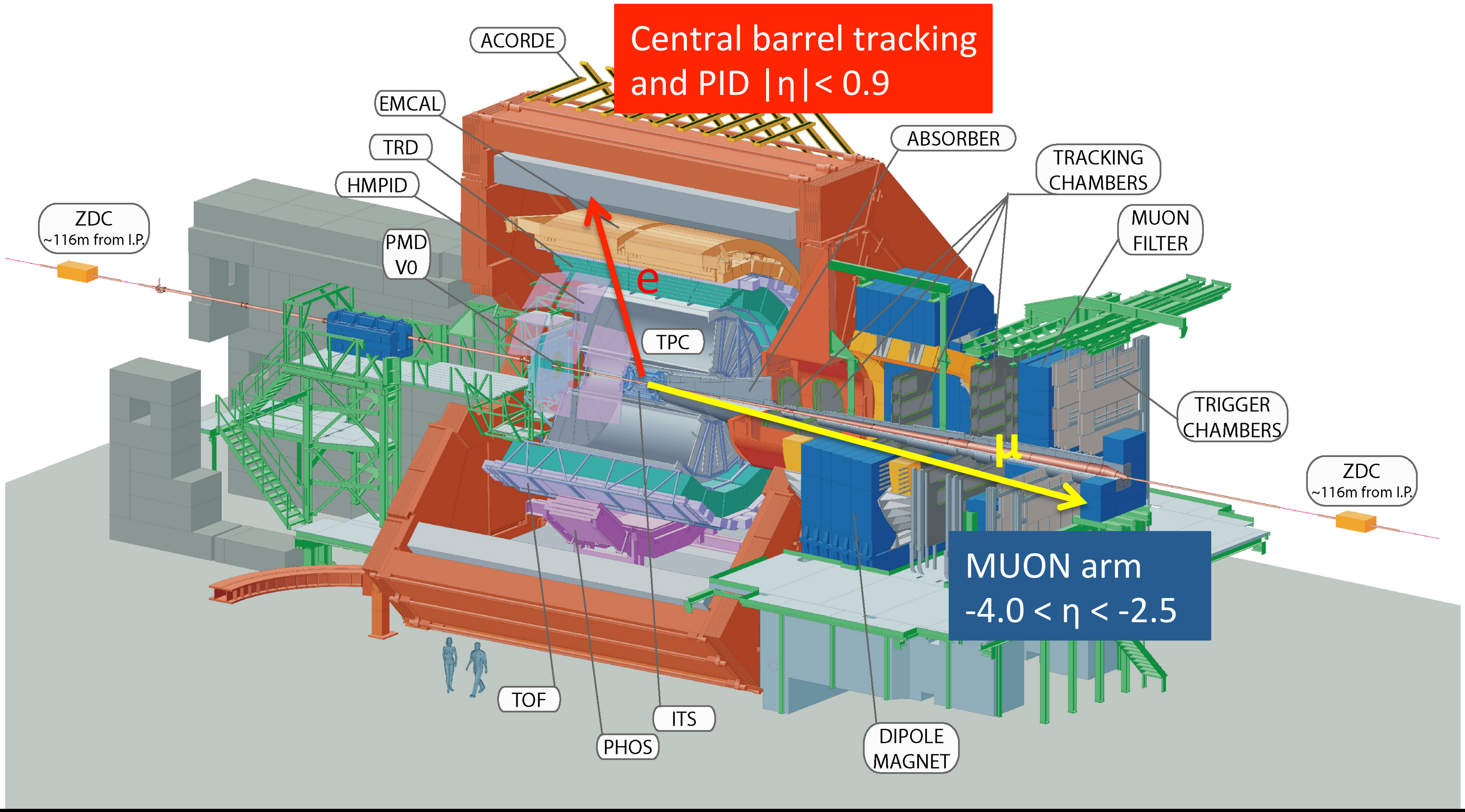
Central Pb-Pb collisions at LHC:

- $N_{c\bar{c}}$/event ~ 115, $N_{b\bar{b}}$/event ~ 3 (10x more than at RHIC)

→ Enhancement of charmonium production via regeneration (depending on open charm cross section)?
→ Evidence for charm thermalization?
→ Charmonium inherits flow from charm?
→ Small regeneration for bottomonia?

Heavy-flavor hadrons and quarkonia in ALICE

- D, B … → e + X and quarkonia (e.g. $J/\psi \rightarrow e^+e^-$) in central rapidity $|\eta| < 0.9$
- D, B … → μ + X and quarkonia (e.g. $J/\psi \rightarrow \mu^+\mu^-$) in forward rapidity $-4.0 < \eta < -2.5$



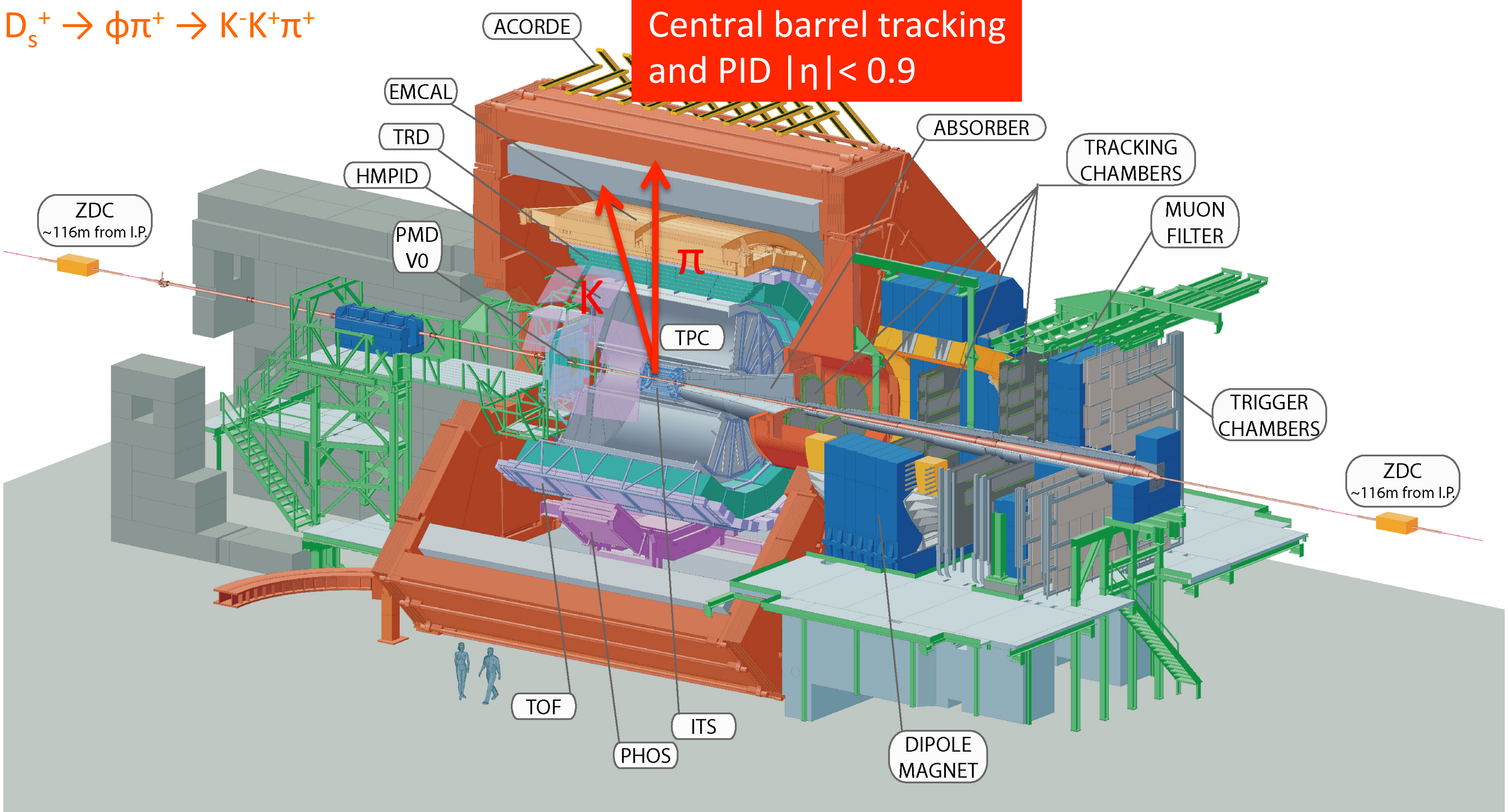
D mesons in ALICE

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

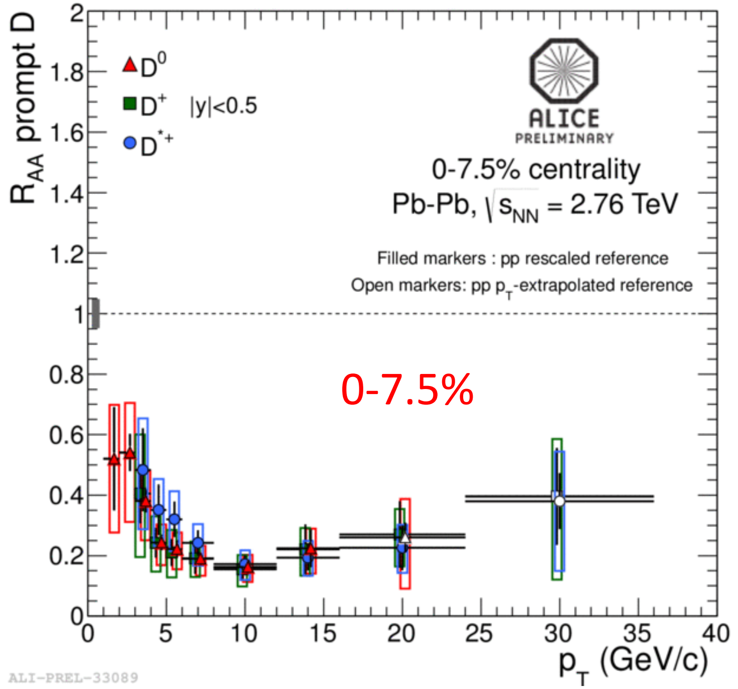


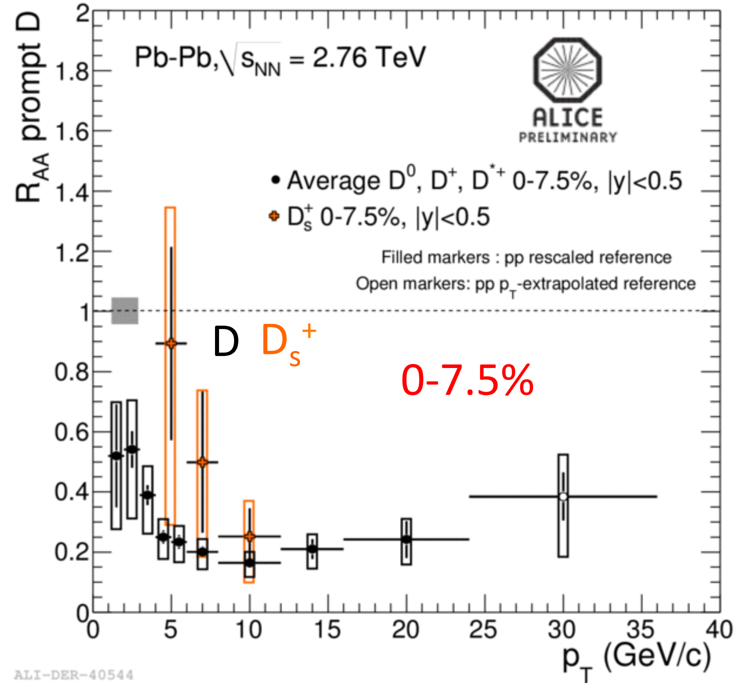
RESULTS FROM PB-PB COLLISIONS

D-meson R_{AA} vs. p_T

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$R_{AA} = 1 \rightarrow$ no modificiation



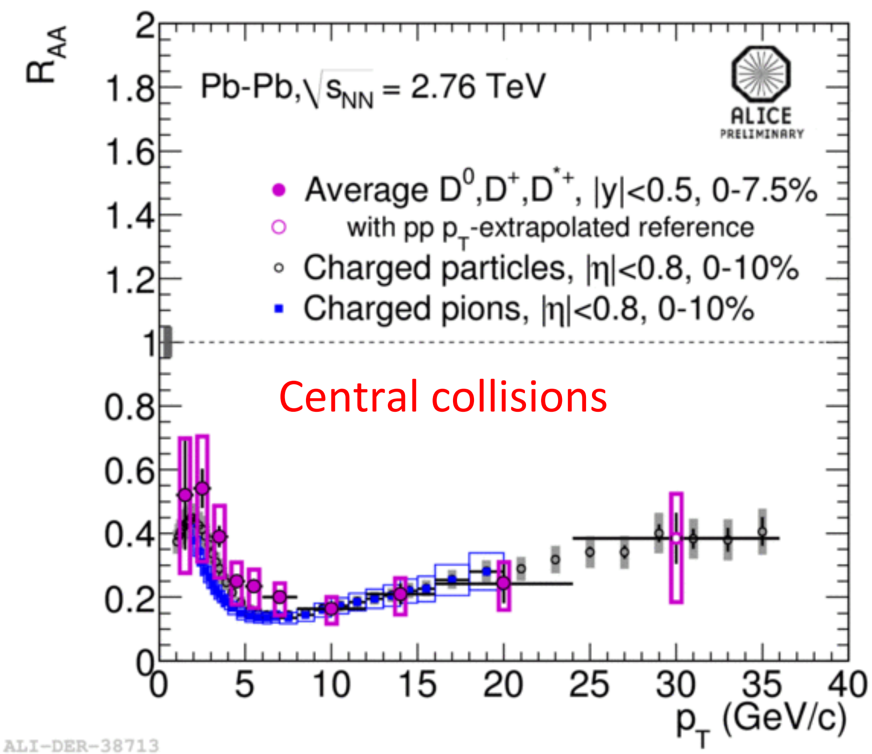


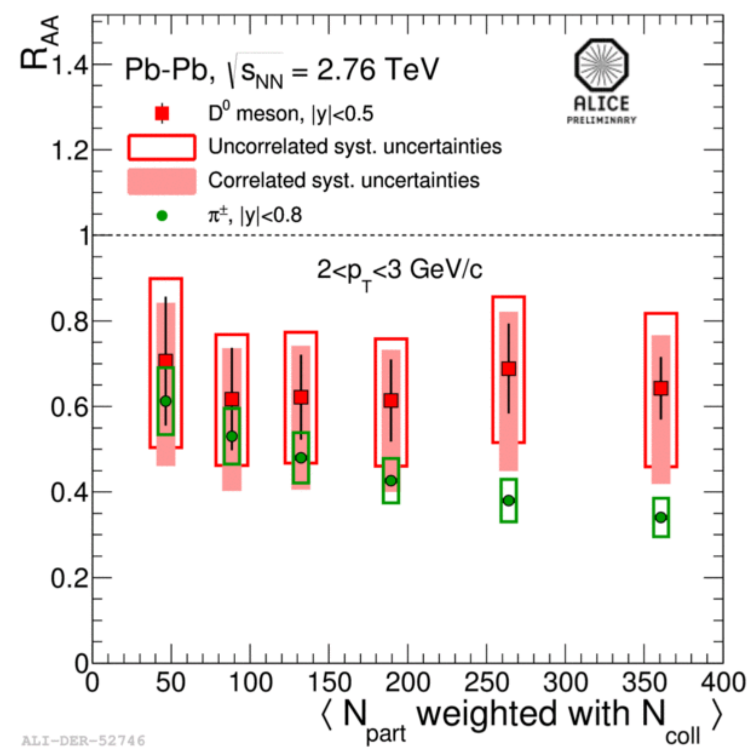
- Strong suppression of all D mesons at high-p_T (factor ~5 at p_T=10 GeV/c) in central collisions
- Different D_s^+ R_{AA} compared to other mesons (first measurement in HI collisions, large uncertainties)? Expected if D_s^+ production vie coalescence in QGP [Kuznetsova and Rafelski, EPJC 51 (2007) 113; Andronic et. al, PLB 659 (2008) 149]

R_{AA} - D mesons vs. pions

$\Delta E_{g,q} > \Delta E_c \rightarrow R_{AA}(\pi) < R_{AA}(D)$?

not trivial relation: parton p_T spectral shape and fragmentation





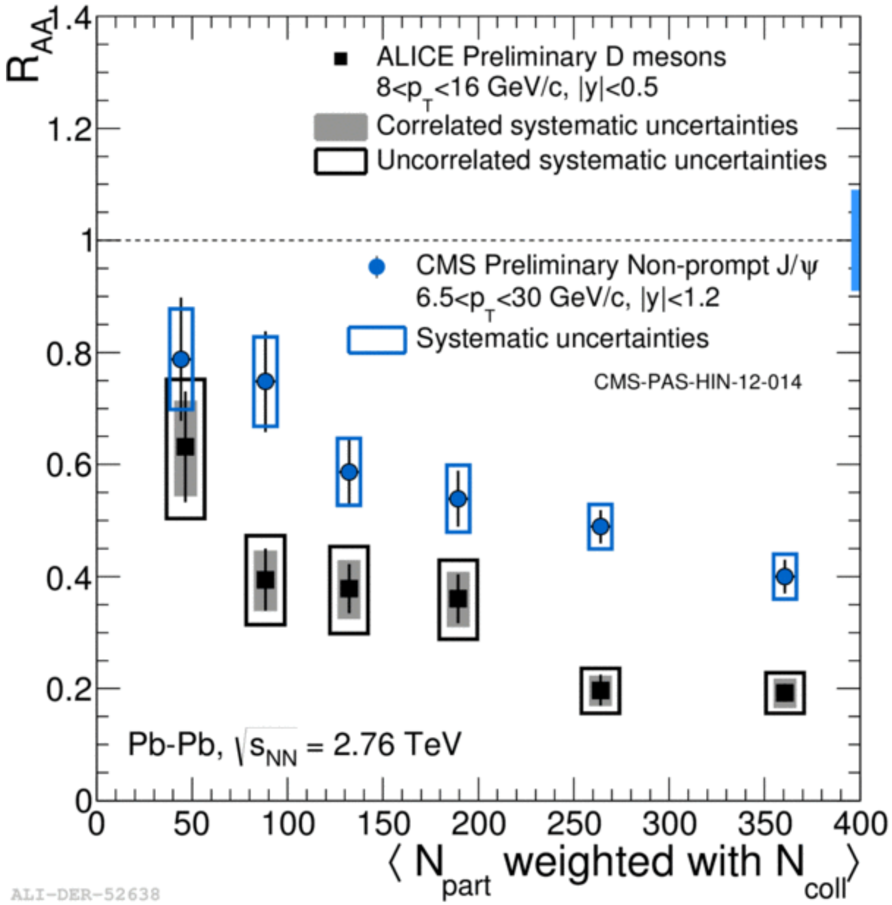
- $R_{AA}(\pi) \sim R_{AA}(D)$ for $p_T > 7$ GeV/c
- Sign of $R_{AA}(\pi) < R_{AA}(D)$ for $2 < p_T < 3$ GeV/c in central collisions

→ Color charge dependence? Data not conclusive yet (large systematic uncertainties)

R_{AA} - D vs. B mesons

$\Delta E_c > \Delta E_b \rightarrow R_{AA}(D) < R_{AA}(B)$?

energy loss mass dependence



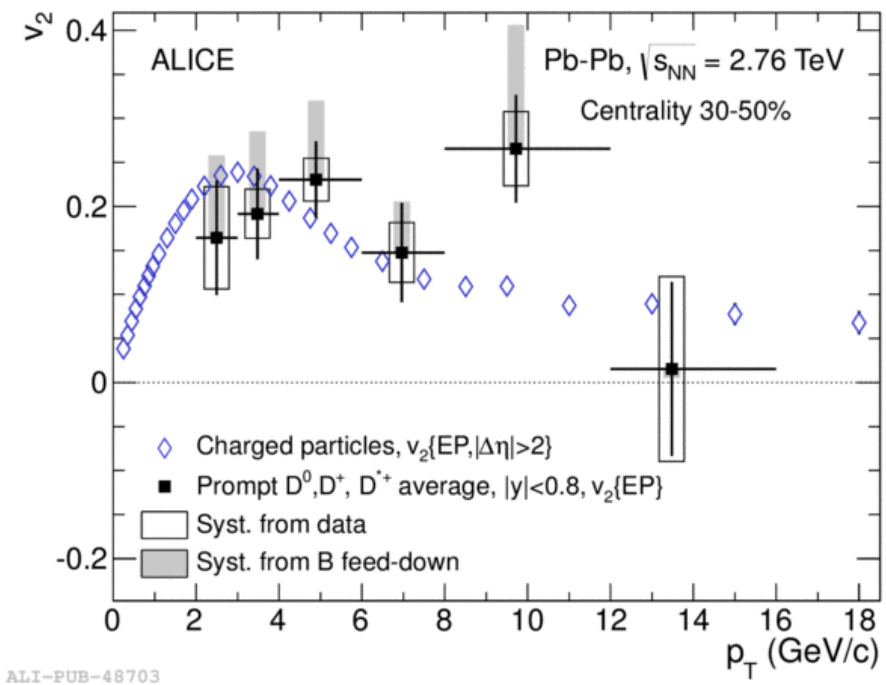
- D $<p_T>$~10 GeV/c: ALICE
- B (non prompt J/ψ) $<p_T>$~11 GeV/c: CMS

$R_{AA}(D) > R_{AA}(B)$

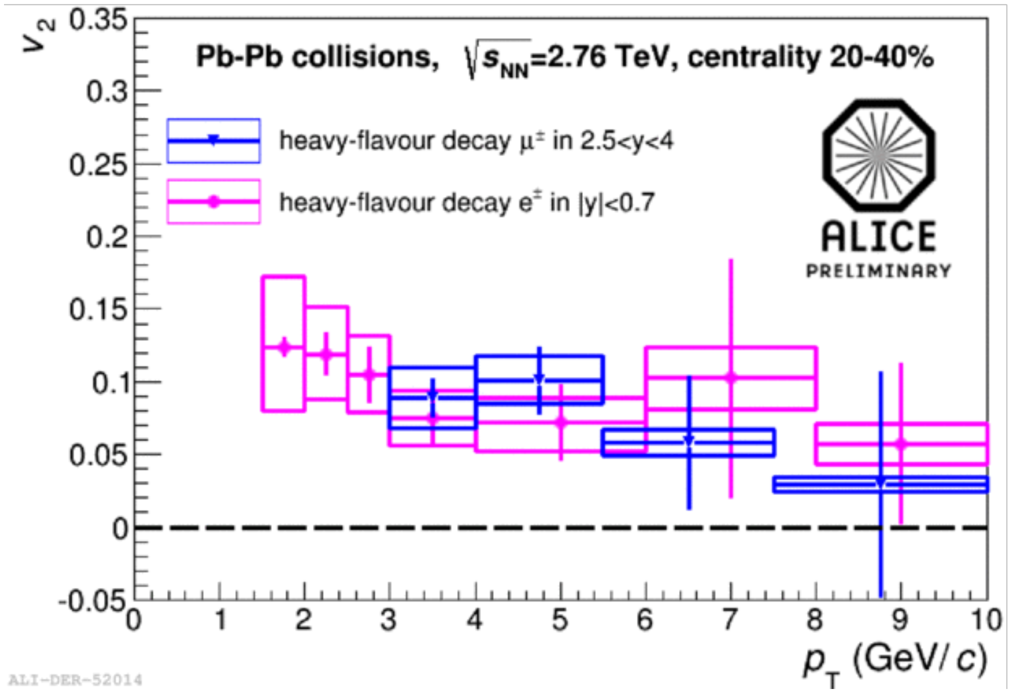
→ indication of larger energy loss for charm than for beauty

Heavy-flavor elliptic flow v_2

D mesons [ALICE PRL 111, 102301 (2013)]



Heavy-flavor decay electrons and muons



- All channels show elliptic flow $v_2 > 0$ at intermediate p_T
- D-meson v_2 comparable to pion v_2
- Similar values of v_2 in central and forward rapidity

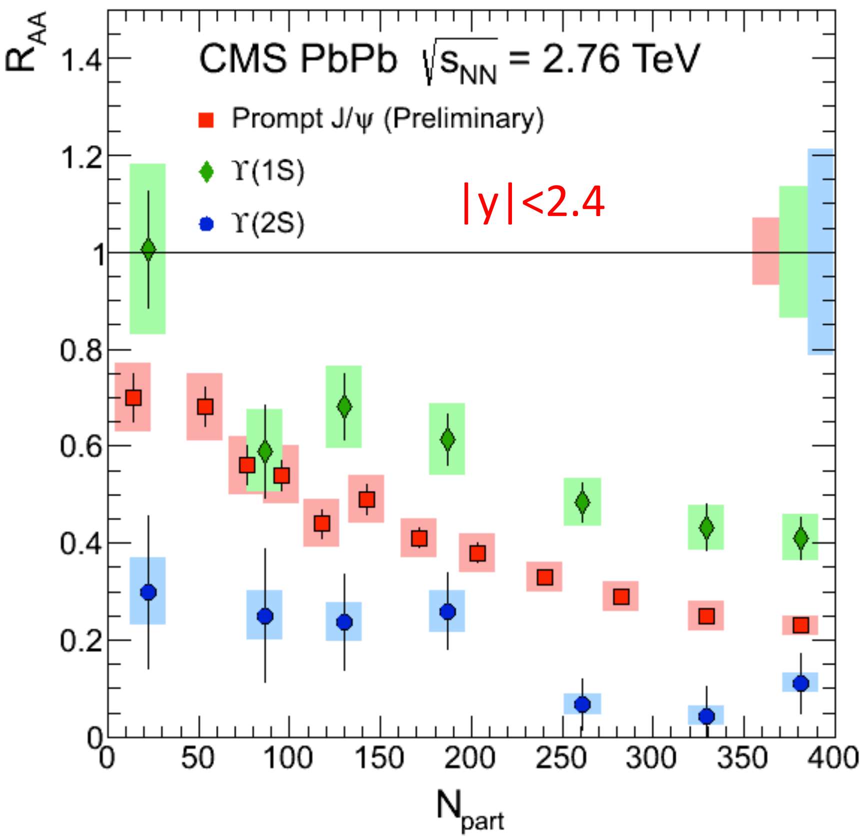
→ Charm participates in flow

QUARKONIA FROM PB-PB COLLISIONS

Sequential ϒ(1S), ϒ(2S), ϒ(3S) suppression at the LHC

ϒ(1S), ϒ(2S), ϒ(3S) p_T>0: CMS, PRL 109 (2012) 222301

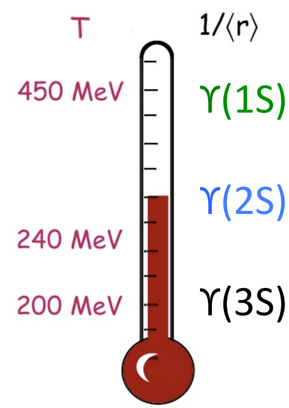
J/ψ p_T > 6.5 GeV/c: CMS, PAS HIN-12-014



- Suppression of ϒ(2S)
- Suppression of ϒ(1S) consistent with excited state suppression (50% feed down)

Centrality 0-100%

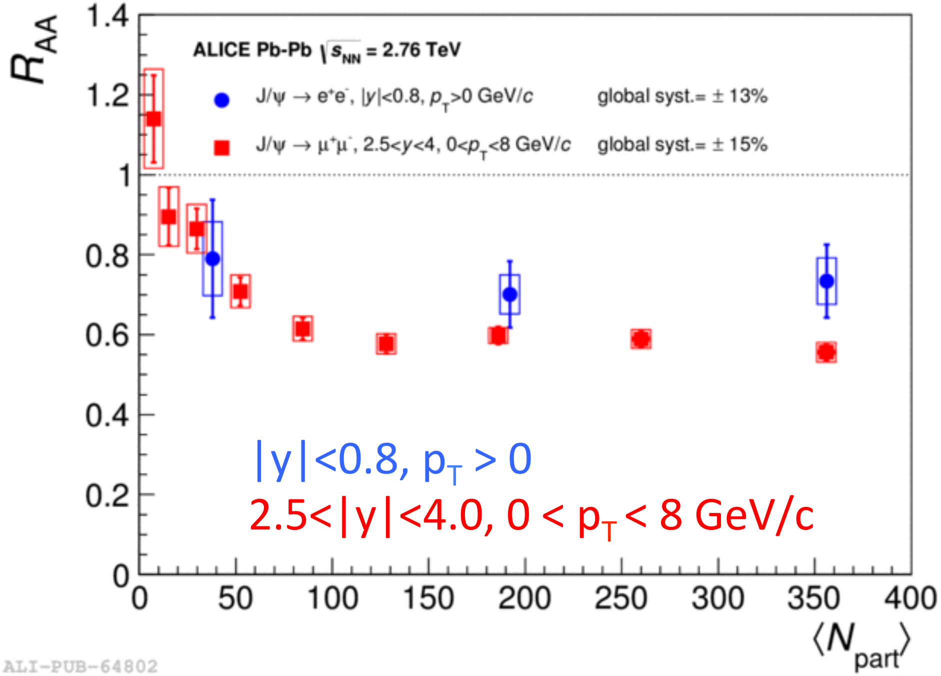
- R_{AA}(ϒ(1S)) ~ 0.56 ± 0.08 (stat.) ± 0.07 (syst.)
- R_{AA}(ϒ(2S)) ~ 0.12 ± 0.04 (stat.) ± 0.02 (syst.)
- R_{AA}(ϒ(3S)) < 0.1 (at 95% C.L.)

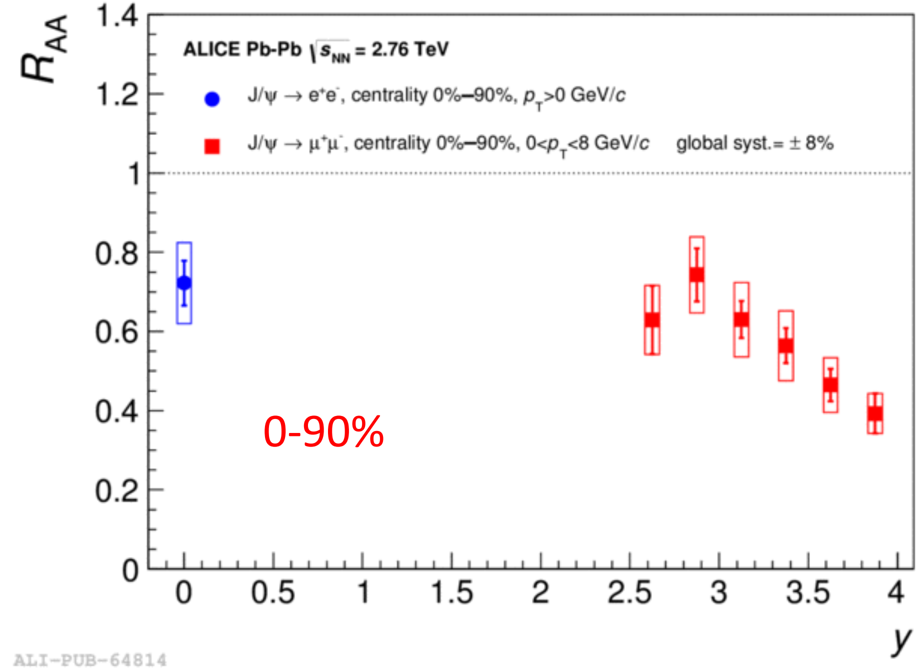


Sequential suppression of ϒ(1S), ϒ(2S), ϒ(3S) states in order of their binding energy

J/ψ R_{AA} in ALICE

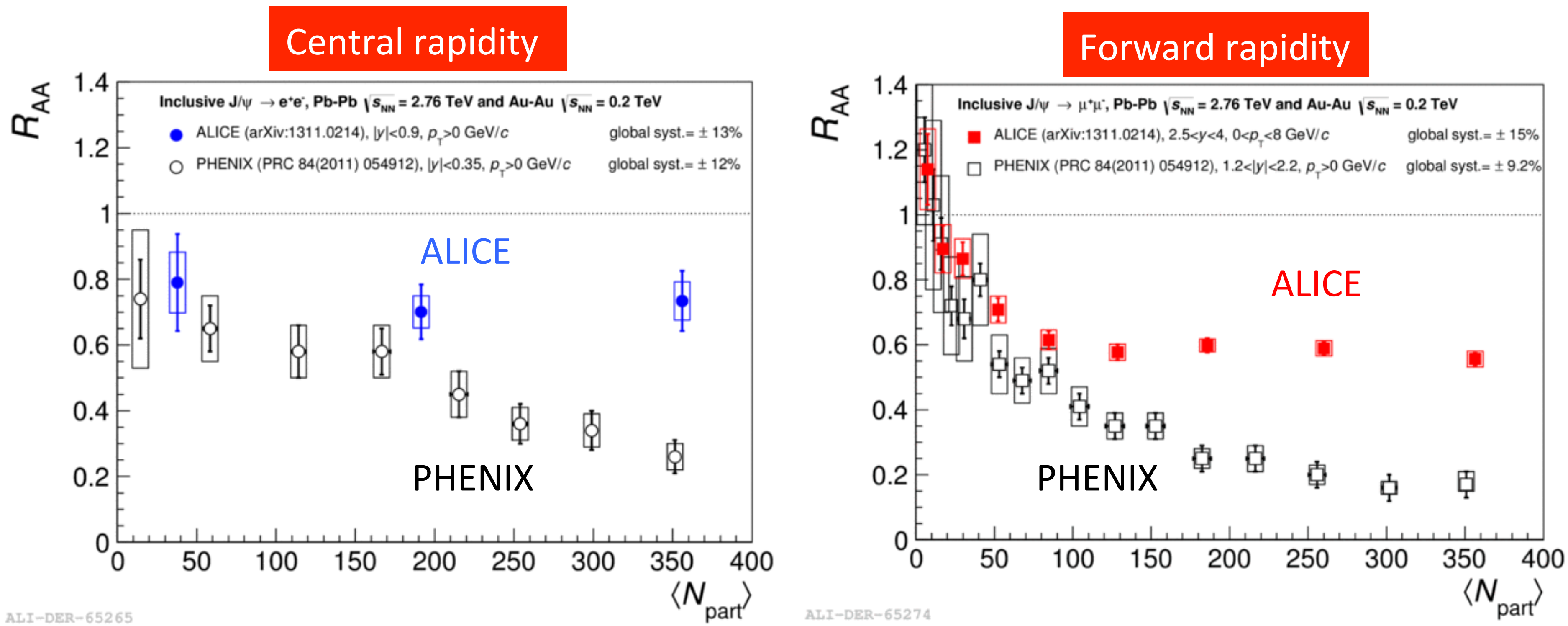
ALICE, arXiv:1311.0214





- J/ψ suppressed at forward and central rapidity
- Suppression increasing with rapidity

J/ψ R_{AA} vs. centrality vs. RHIC

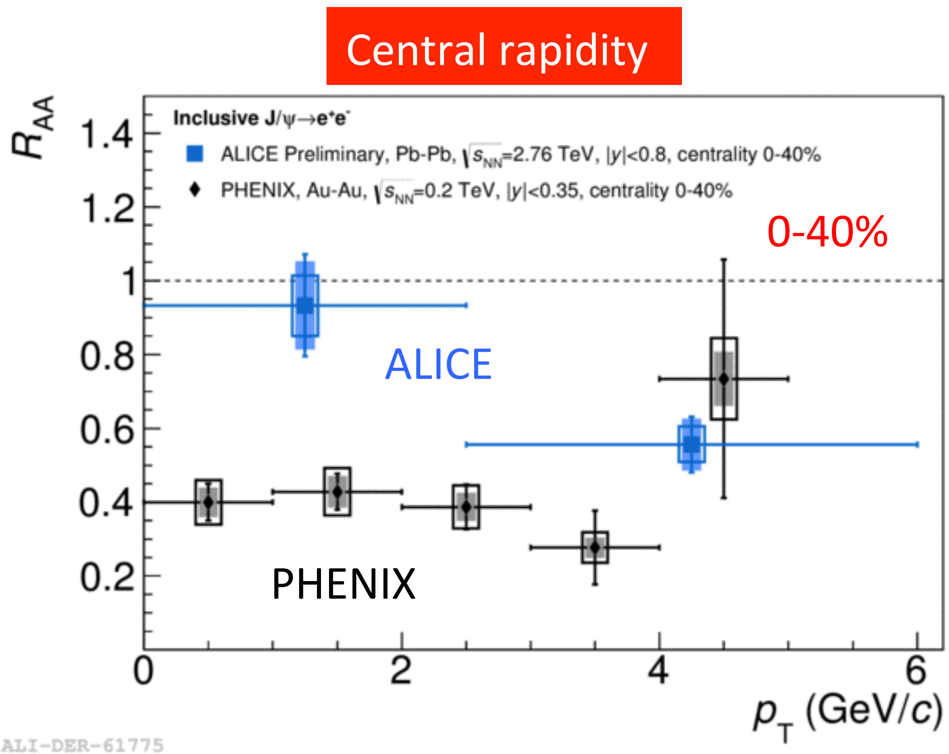


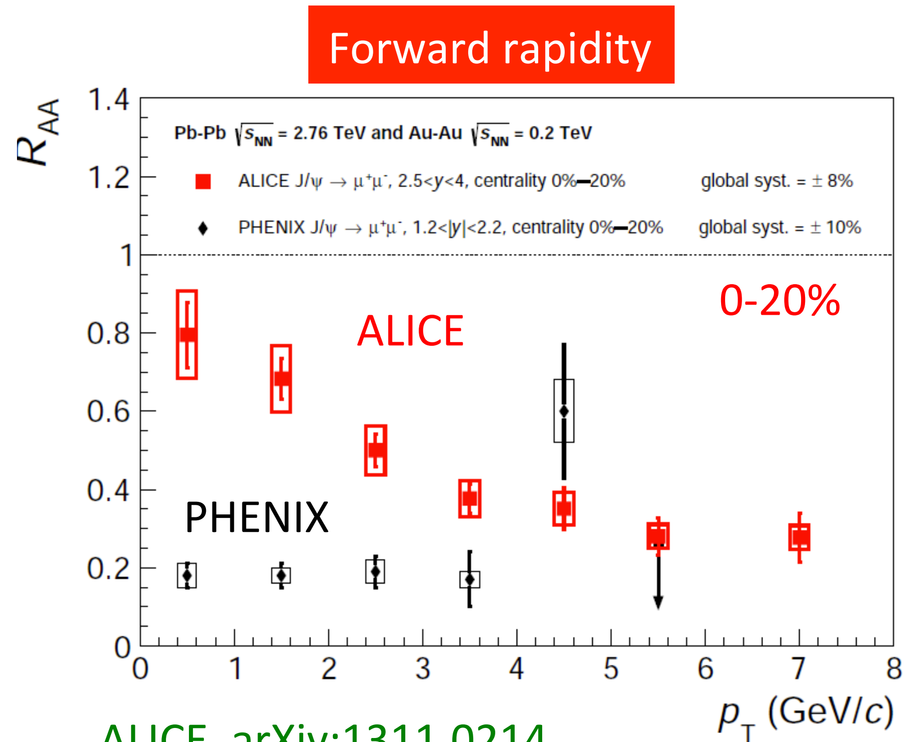
- Different suppression pattern compared to RHIC at central and forward rapidity

→ Different source of J/ψ in central collisions at the LHC
→ Indication of regeneration in central collisions?

ALICE, arXiv:1311.0214
PHENIX, PRC 84 (2011) 054912

J/ψ R_{AA} vs. p_T vs. RHIC





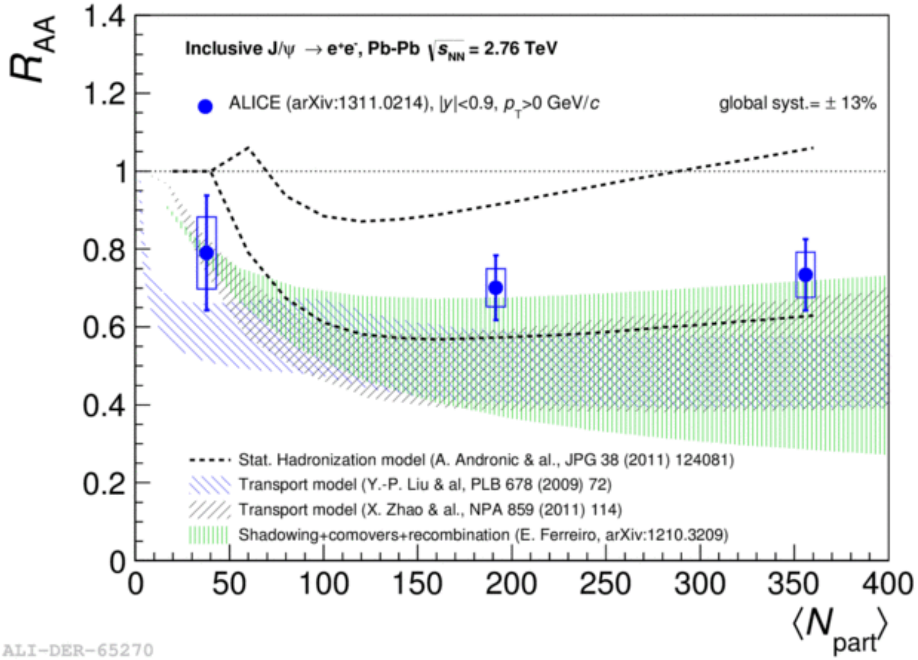
ALICE, arXiv:1311.0214
PHENIX, PRC 84 (2011) 054912

- At low p_T: different suppression compared to RHIC at central and forward rapidity
- At high p_T: similar suppression compared to RHIC

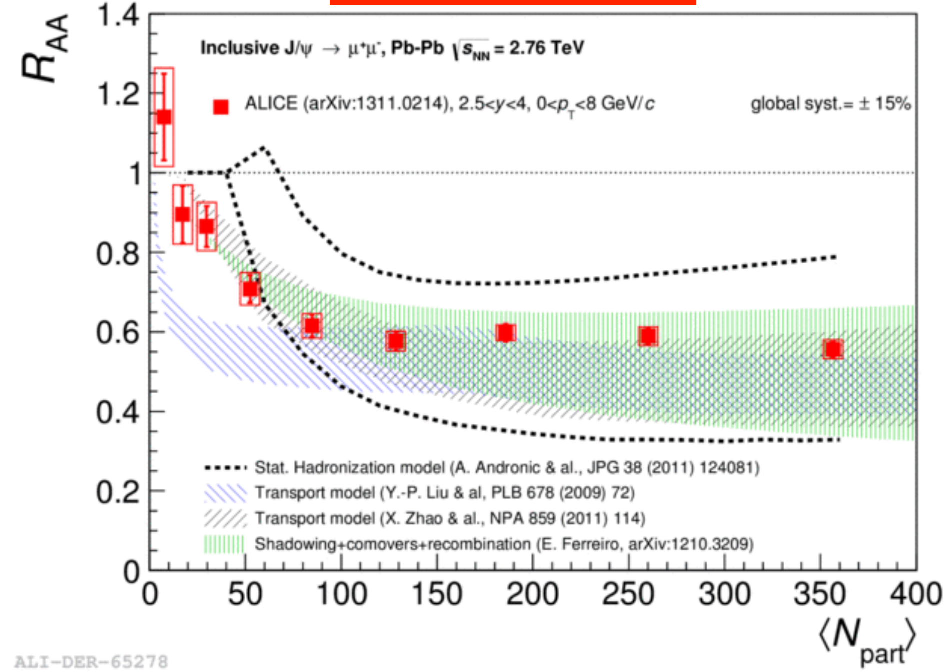
→ Different source of low-p_T J/ψ in central collisions at the LHC (regeneration?)

J/ψ R_{AA} vs. collision centrality vs. models

Central rapidity



Forward rapidity



Statistical hadronization model:

Andronic et al. (J/ψ production at chemical freeze-out)

Transport models:

Liu et al. (J/ψ dissociation + regeneration + p_T broadening + shadowing)

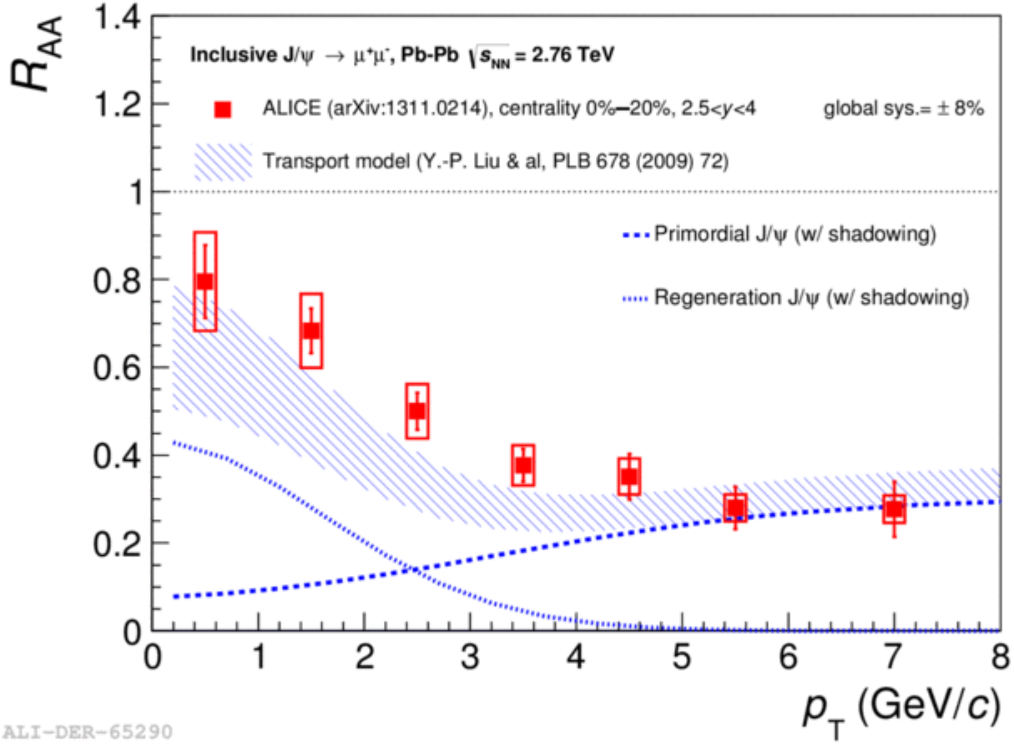
Zhao at al. (J/ψ dissociation + regeneration + shadowing)

Ferreiro (J/ψ comover dissociation + regeneration + shadowing)

J/ψ R_{AA} vs. p_T vs. models

Forward rapidity

ALICE, arXiv:1311.0214

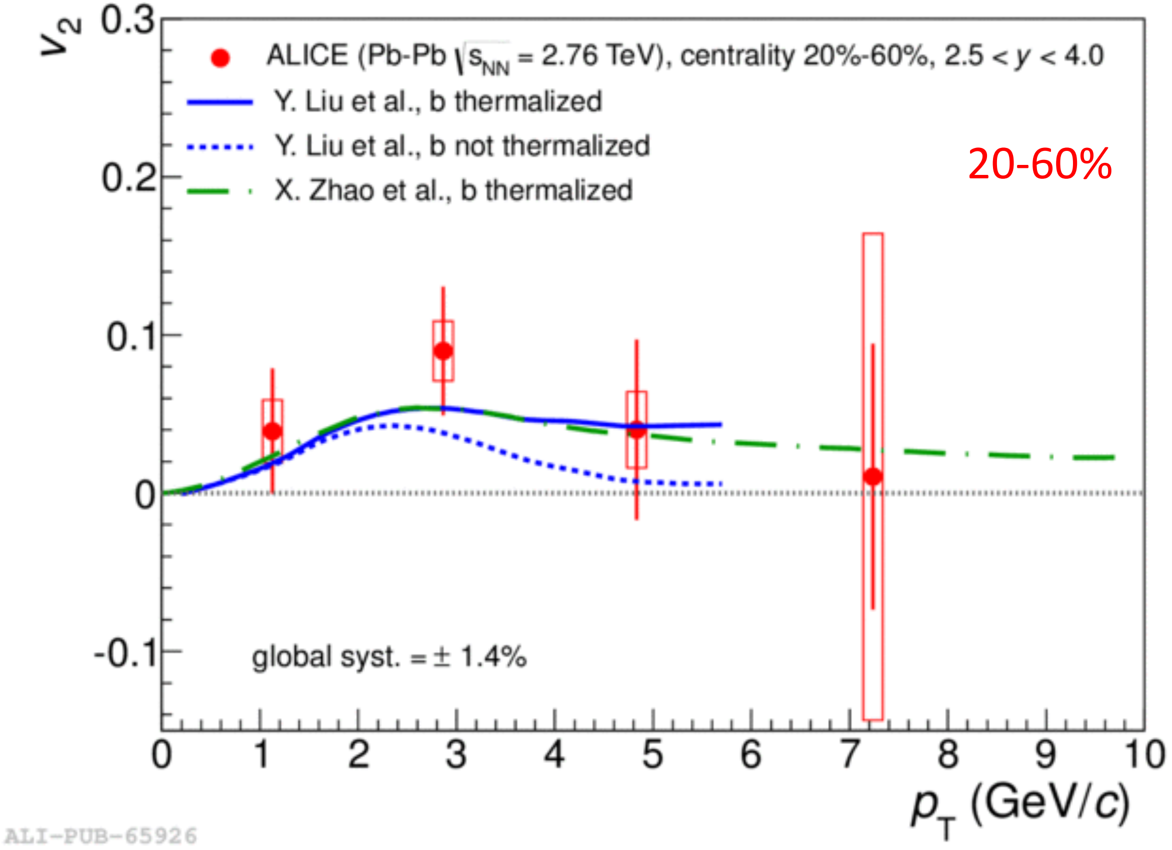


Transport model:
Liu et al. (J/ψ dissociation + regeneration + p_T broadening + shadowing) consistent with data

→ Production of low-pT J/ψ via regeneration

J/ψ v_2 vs. p_T

Forward rapidity



ALICE, PRL 111 (2013) 162301

J/ψ elliptic flow $v_2 > 0$ at intermediate p_T in semi-central Pb-Pb collisions

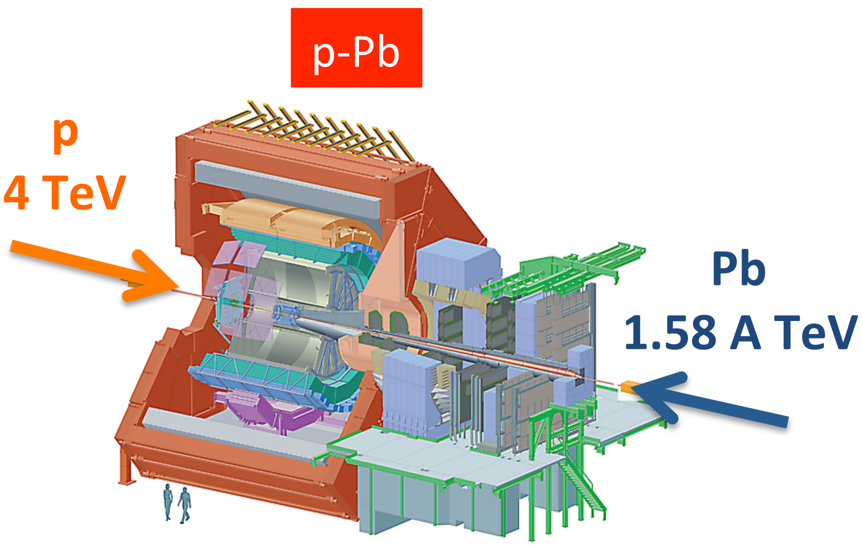
Transport models (Liu et al. / Zhao et al.):

- J/ψ dissociation and regeneration

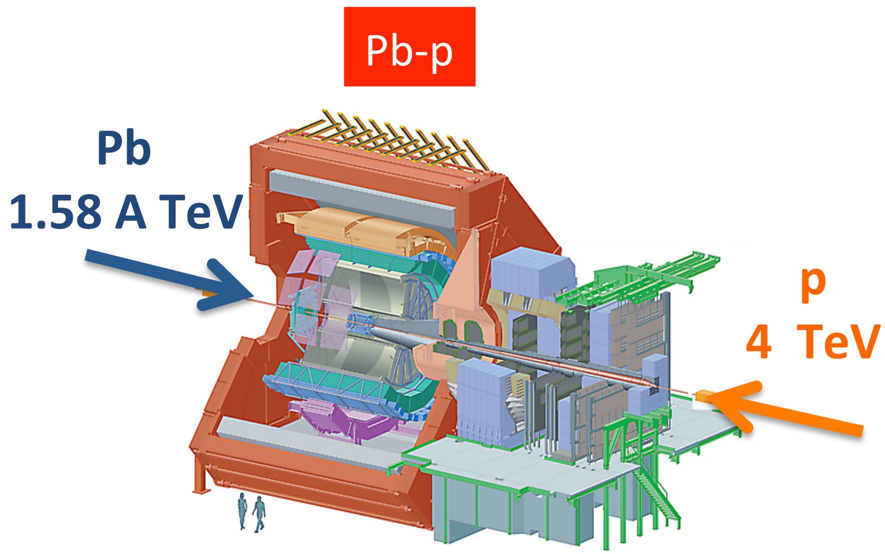
RESULTS FROM P-PB COLLISIONS

p-Pb measurements

- Asymmetric p-Pb collisions ($\sqrt{s_{NN}}$=5.02 TeV): Δy_{NN} = 0.465 in the p-beam direction
- 2 beam configurations (p-Pb and Pb-p): 2 rapidity ranges for the MUON spectrometer



MUON spectrometer in p-beam direction
Forward rapidity: 2.03 < y_{cms} < 3.53
x_{Pb} ~ 10^{-5} – 10^{-4}



MUON spectrometer in Pb-beam direction
Backward rapidity: -4.46 < y_{cms} < -2.96
x_{Pb} ~ 10^{-2} – 10^{-1}

x_{Pb} – momentum fraction of probed gluons in Pb nucleus assuming 2→1 quarkonia production mechanism

Central rapidity: -1.37 < y_{cms} < 0.43
x_{Pb} ~ 10^{-3}

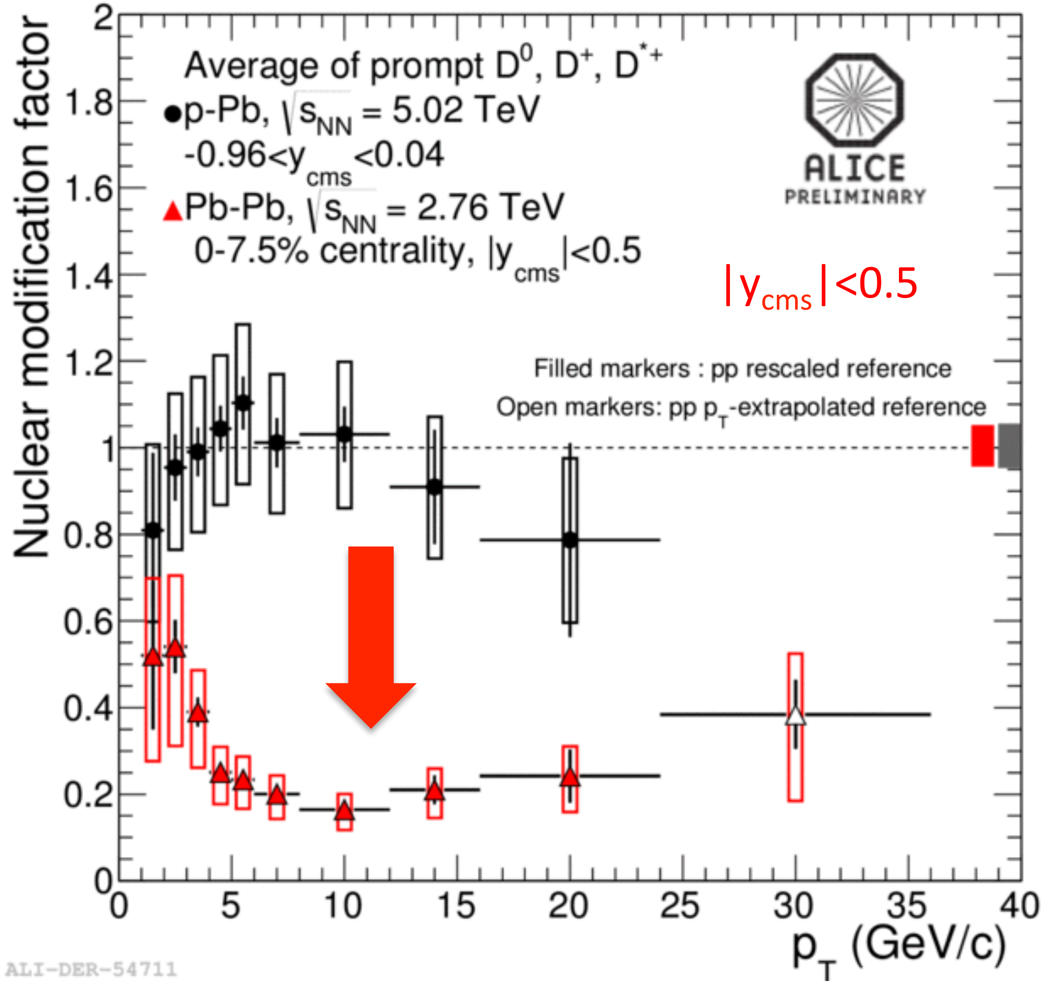
D-meson R_{pPb} vs. R_{AA}

$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

$$\langle N_{coll} \rangle = A \cdot \frac{\sigma_{pN}}{\sigma_{pA}} = 208 \cdot \frac{70\ mb}{2100\ mb} = 6.9$$

No modification at high-p_T (R_{pPb}~ 1) in minimum bias p-Pb

→ Particle production suppression in Pb-Pb central collisions related to final state effects

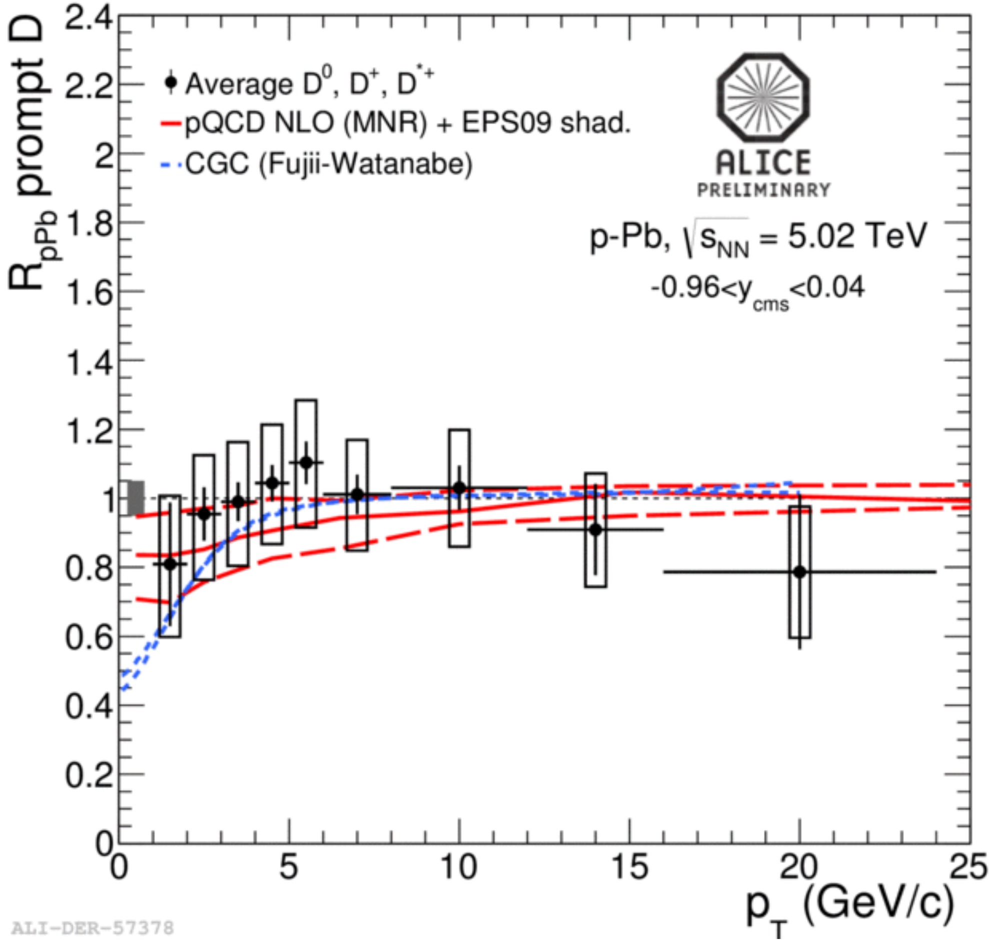


D-meson R_{pPb} vs. models

Models:

- pQCD NLO (MNR) with EPS09 parameterization of nuclear PDFs [Mangano et al., Nucl. Phys. B 373 (1992) 295; Eskola et al., JHEP 0904 (2009) 065]
- Color Glass Condensate (CGC) [Fuji-Watabe, arXiv:1308.1258]

→ Models including cold nuclear matter effects describe the data



Heavy flavor e-h correlations in p-Pb

Heavy flavor decay electrons correlation with hadrons

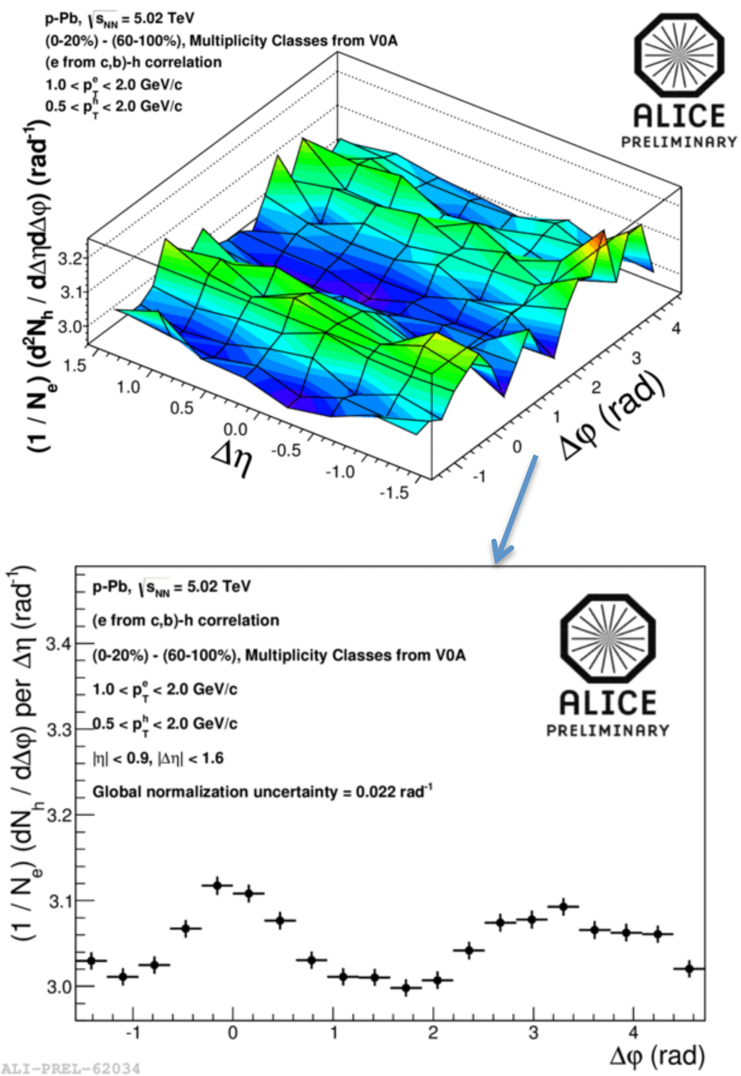
(0-20%) - (60-100%)

Analysis in multiplicity classes defined using V0A detector (2.8 < η < 5.1):

- 0-20% - high multiplicity
- 60-100% - low multiplicity

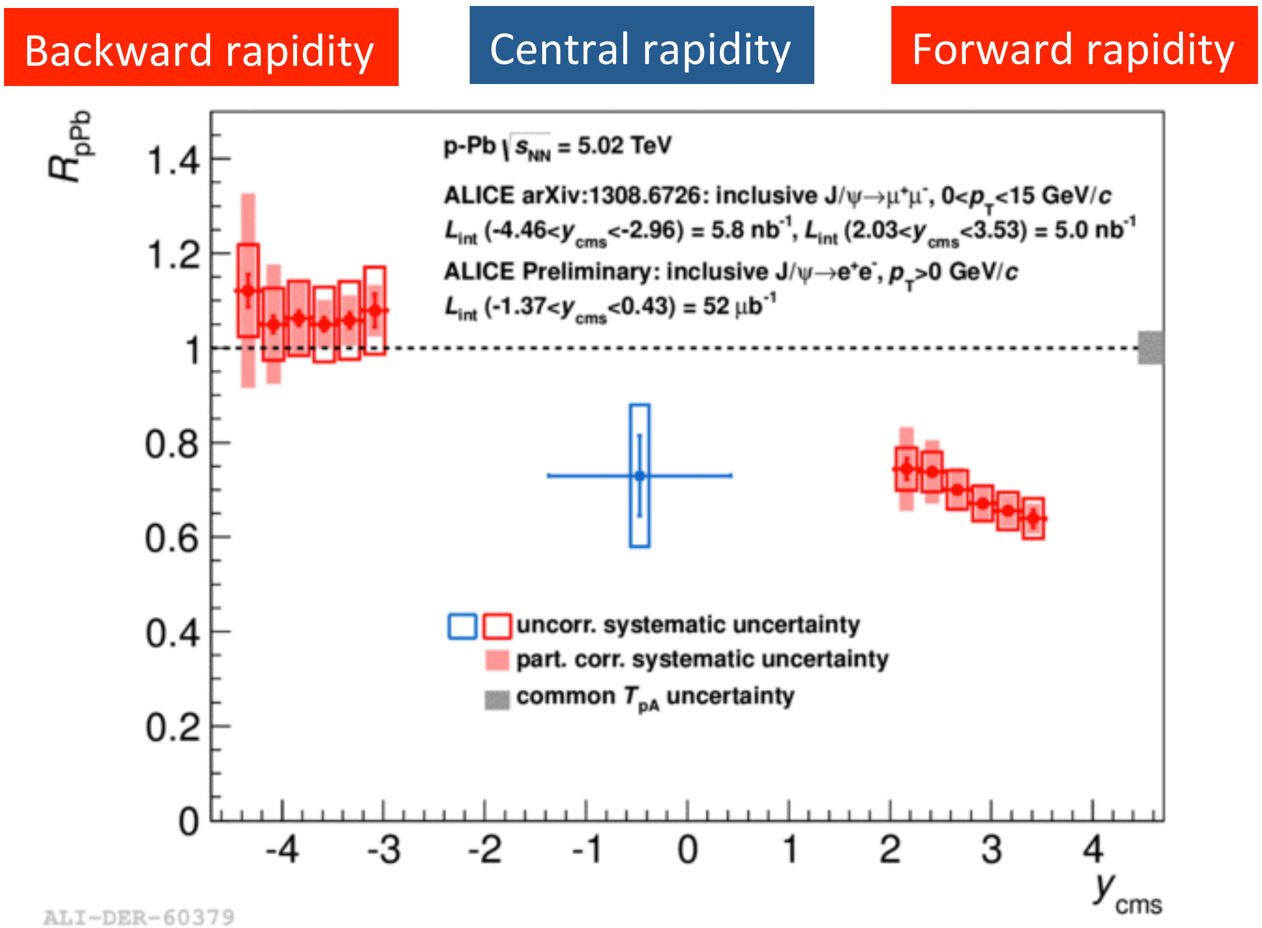
Double ridge structure as in h-h correlations [ALICE, PLB 719 (2013) 29].

The h-h correlations are consistent with flow [Bożek and Broniowski PLB718 (2013) 1557] or CGC [Dusling and Venugopalan, PRD 87 (2013) 054014].



QUARKONIA FROM P-PB COLLISIONS

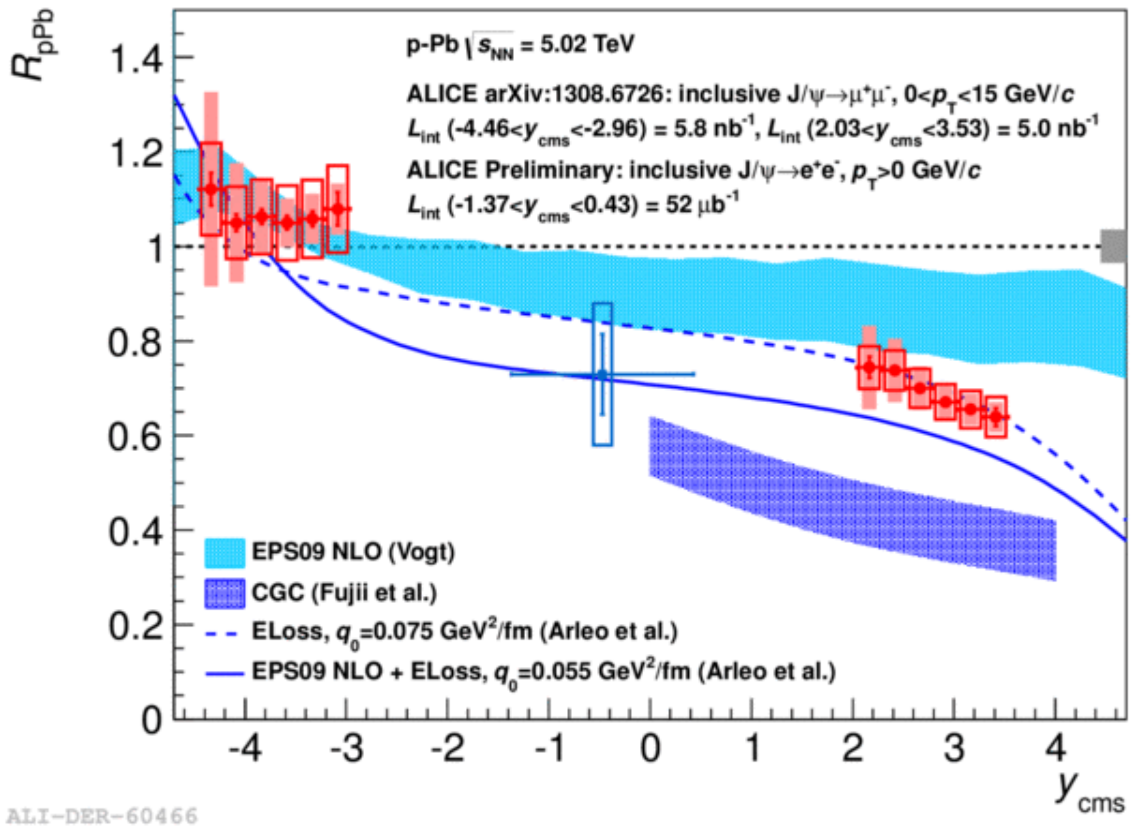
J/ψ R_{pPb} vs. y_{cms}



Backward rapidity: No modification R_{pPb}~1
Suppression at central and forward rapidity (increasing with rapidity)

J/ψ R_{pPb} vs. y_{cms} vs. models

Backward rapidity | Central rapidity | Forward rapidity



Models:

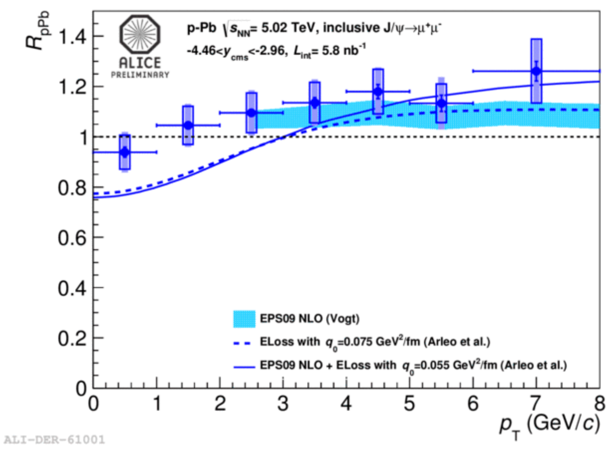
CEM + EPS09 NLO shadowing [Vogt arXiv: 1301.3395] – agreement at backward rapidity

Gluon saturation [Fuji et al., arXiv:1304.2221]: CGC + LO CEM – disagreement

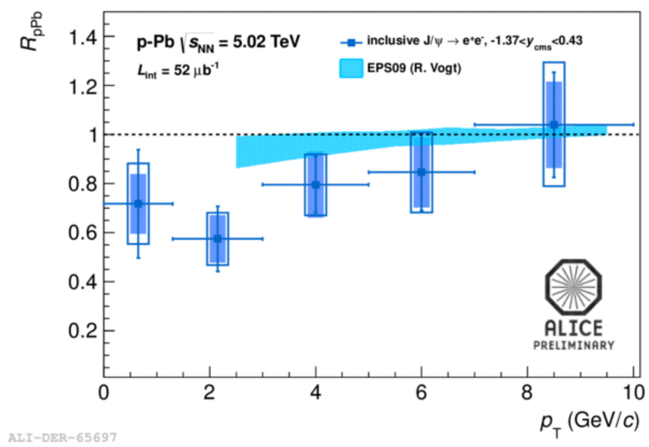
Coherent energy loss with/without EPS09 NLO shadowing [Arleo et al. arXiv:1212.0434] – better agreement without shadowing

J/ψ R_{pPb} vs. p_T vs. models

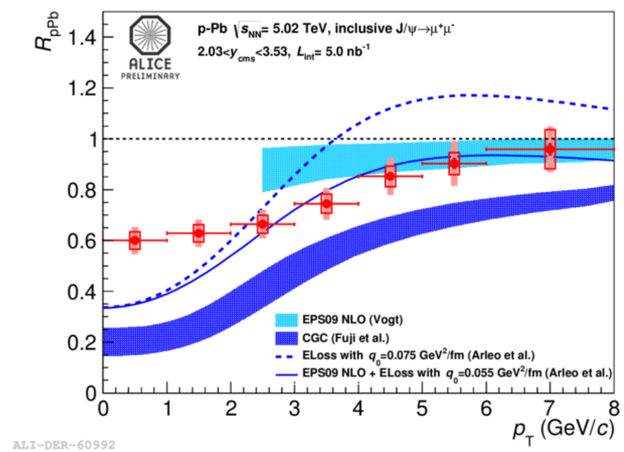
Backward rapidity



Central rapidity



Forward rapidity



Data:

Backward rapidity: R_{pPb} = 1-1.2, small dependence on p_T

Central rapidity: R_{pPb} < 1 at low p_T and increases with p_T

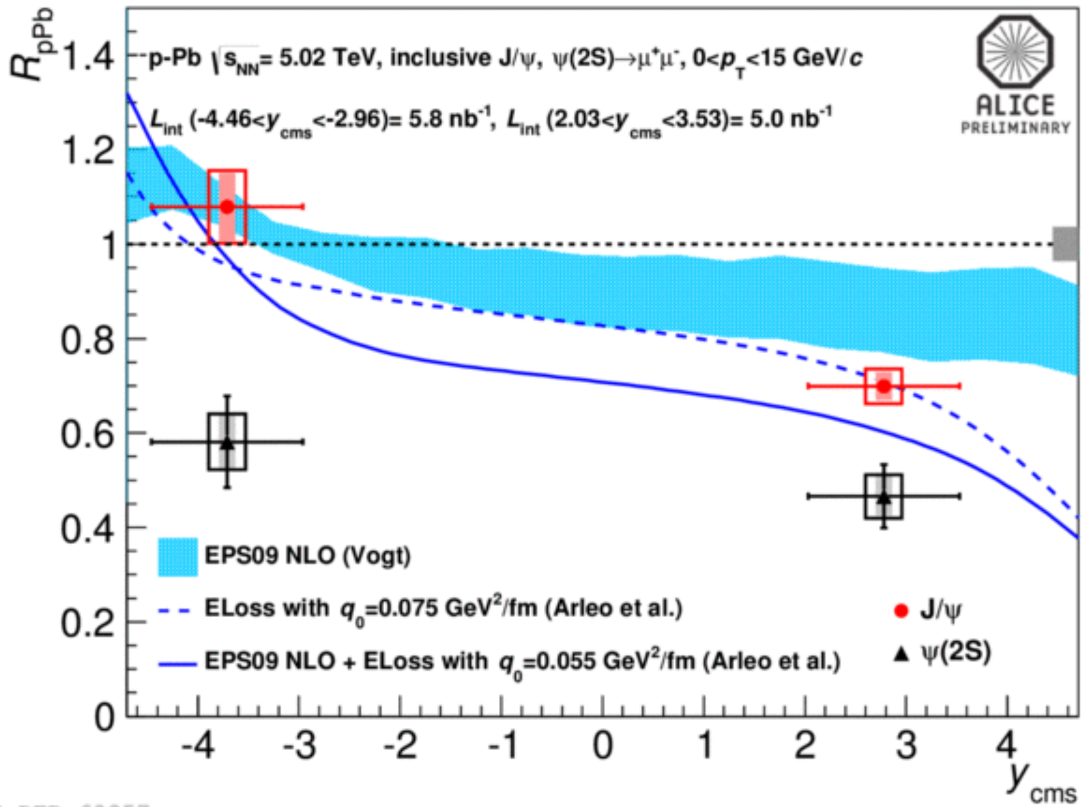
Forward rapidity: R_{pPb} < 1 at low p_T and increases with p_T , R_{pPb}~ 1 above p_T = 5 GeV/c

Comparison with models:

- Data consistent with energy loss (Arleo et al.) and shadowing (Vogt) models at high p_T
- Model based on CGC (Fuji et al.) does not describe data

Ψ(2S) R_{pPb} vs. y_{cms} vs. models

$$R_{pPb}^{\psi(2S)} = R_{pPb}^{J/\psi} \frac{\sigma_{pPb}^{\psi(2S)}}{\sigma_{pPb}^{J/\psi}} \frac{\sigma_{pp}^{J\psi}}{\sigma_{pp}^{\psi(2S)}}$$



ALI-DER-60957

Strong suppression of Ψ(2S) in minimum bias p-Pb collisions (R_{pPb} ~ 0.5)

Ψ(2S) suppressed stronger than for J/Ψ (similar observation at RHIC Phys. Rev. Lett. 111, 202301 (2013))

Shadowing (Vogt) and energy loss (Arleo et al.) models cannot explain data

→ Final state effects? Other mechanisms?

Summary

Pb-Pb collisions

- D and B production is strongly suppressed at high-p_T in central Pb-Pb collisions
  - Mass dependence observed
- First D_s^+ R_{AA} measurement in HI collisions
- Charm and beauty $v_2 > 0$ at intermediate p_T (D meson v_2 comparable to pion v_2)
- Upsilon sequential suppression observed at LHC (color screening)
- J/ψ suppression and regeneration observed in central Pb-Pb collision
- J/ψ elliptic flow $v_2 > 0$ at intermediate p_T in semi-central Pb-Pb collisions

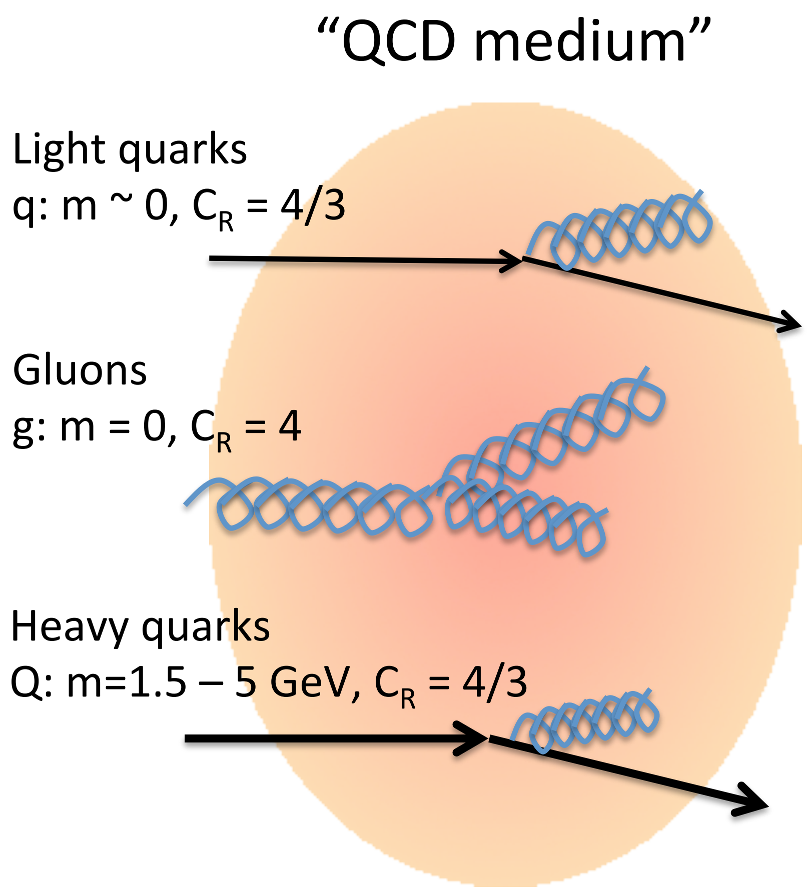
p-Pb collisions

- D-meson R_{AA} ~ 1 in minimum bias Pb-Pb collisions
- Double ridge in heavy flavor e-h correlations in high multiplicity p-Pb collisions
- J/ψ production is suppressed in central and forward rapidity ($p_T < 5$ GeV/c), and not at backward rapidity
- Ψ(2S) R_{pPb} < J/Ψ R_{pPb} in p-Pb → Final state effects? Other mechanisms?

Era of high precision measurements of heavy flavor hadrons has just started!

Backup

Parton energy loss in QCD medium



Radiative and collisional parton energy loss:
ΔE (ε_{medium}; m, C_R, L)

- Color charge dependence C_R: $\Delta E_g > \Delta E_{q,Q}$
- Mass dependence m: $\Delta E_q > \Delta E_c > \Delta E_b$

→ $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

Not trivial relation between energy loss and R_{AA}: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

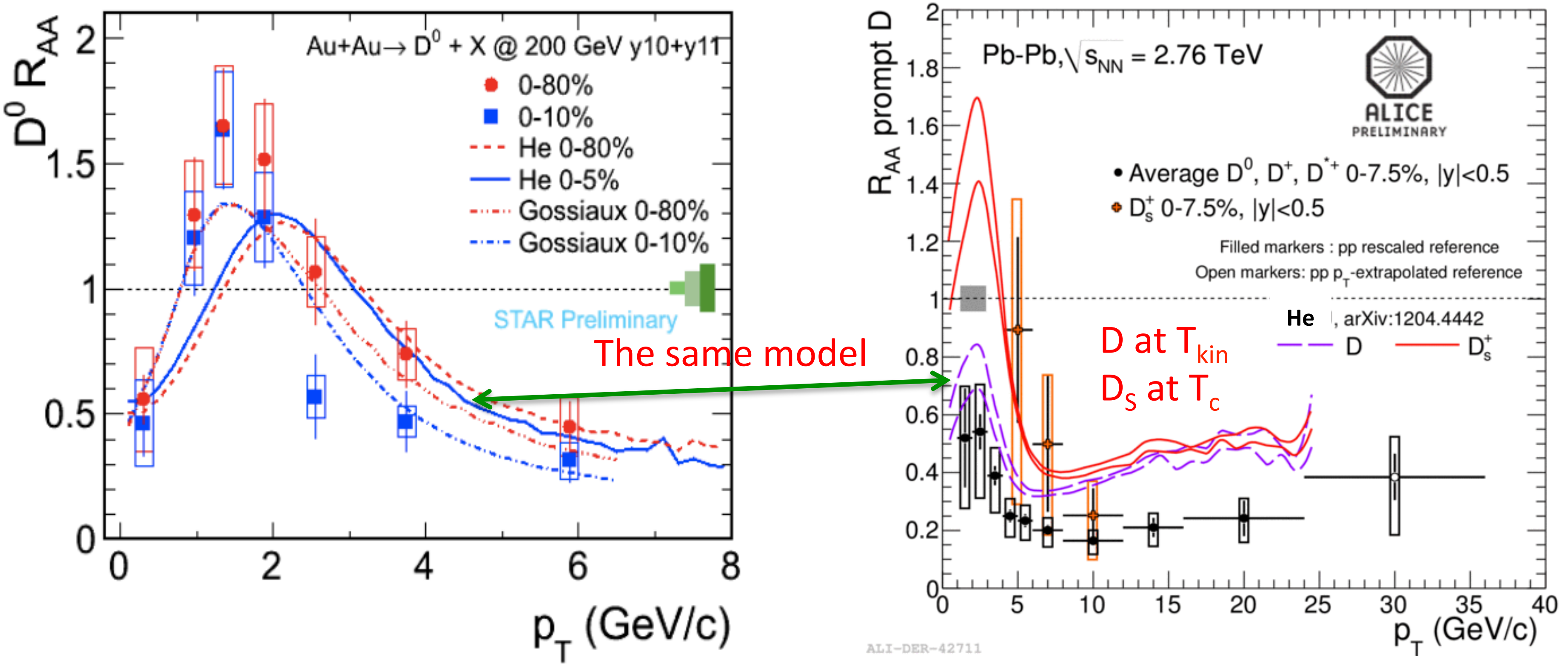
- Need to account for different parton p_T spectra and fragmentation functions

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Dokshitzer, et al., JPG 17 (1991) 1602
Dokshitzer and Kharzeev, PLB 519 (2001) 199
Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493

D-meson R_{AA} at RHIC and LHC

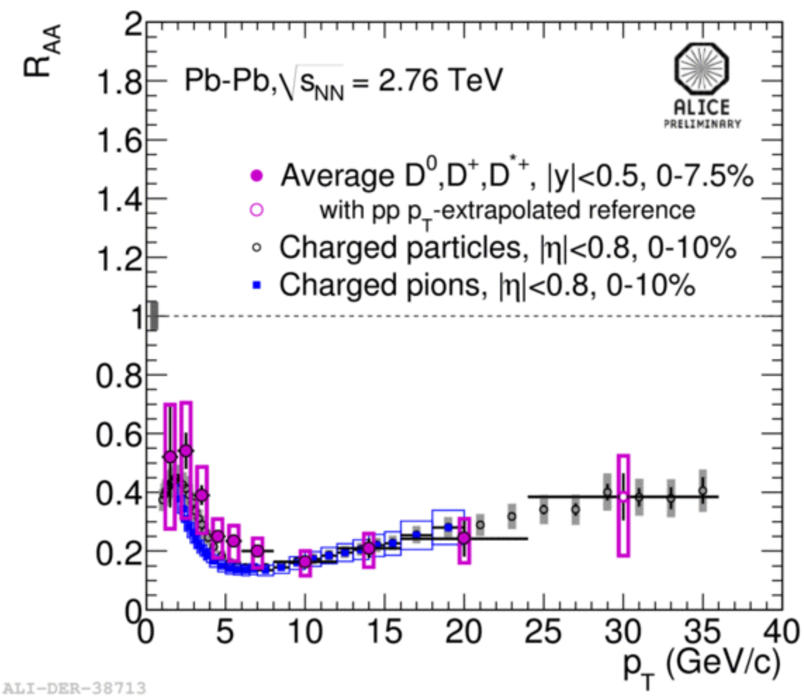
F.Geurts (Hard Probes 2013) Z.Conesa (Quark Matter 2012)



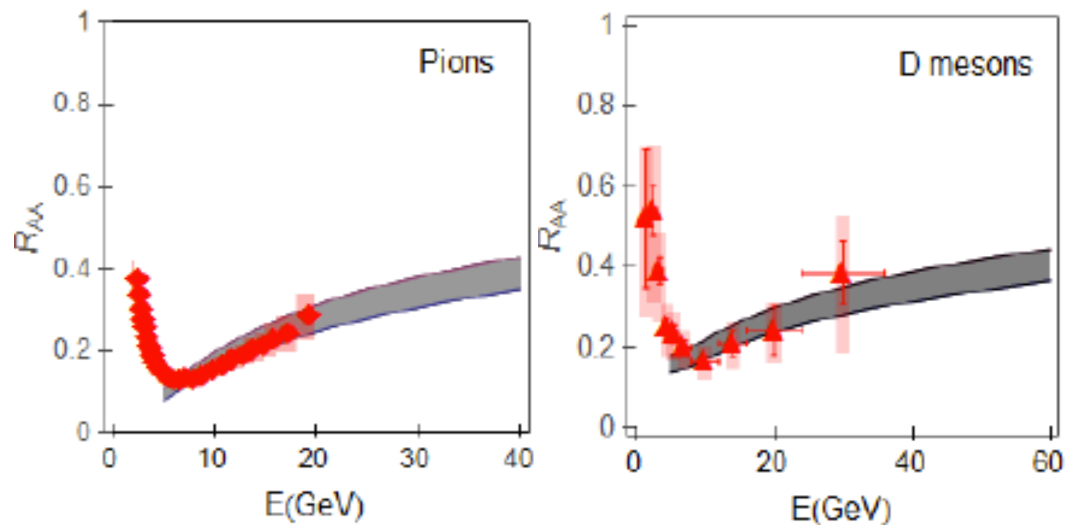
- Similar D suppression at high-p_T (~ 5-6 GeV/c) at RHIC and LHC
- Different behavior at lower p_T ~ 1.5 GeV/c (enhancement at RHIC)
- Model predictions [He, Fries and Rapp, PRL 110 (2013) 112301] (hydro + non-perturbative QCD + coalescence with strange quarks + diffusion in hadronic phase) → "D vs. D_S comparison (spectra and flow) helps to disentangle transport properties of QGP and hadronic medium"

R_{AA} - D mesons vs. pions

$\Delta E_{g,q} > \Delta E_c$ → $R_{AA}(\pi) < R_{AA}(D)$?
not trivial relation: parton p_T spectral shape, fragmentation and bulk particles



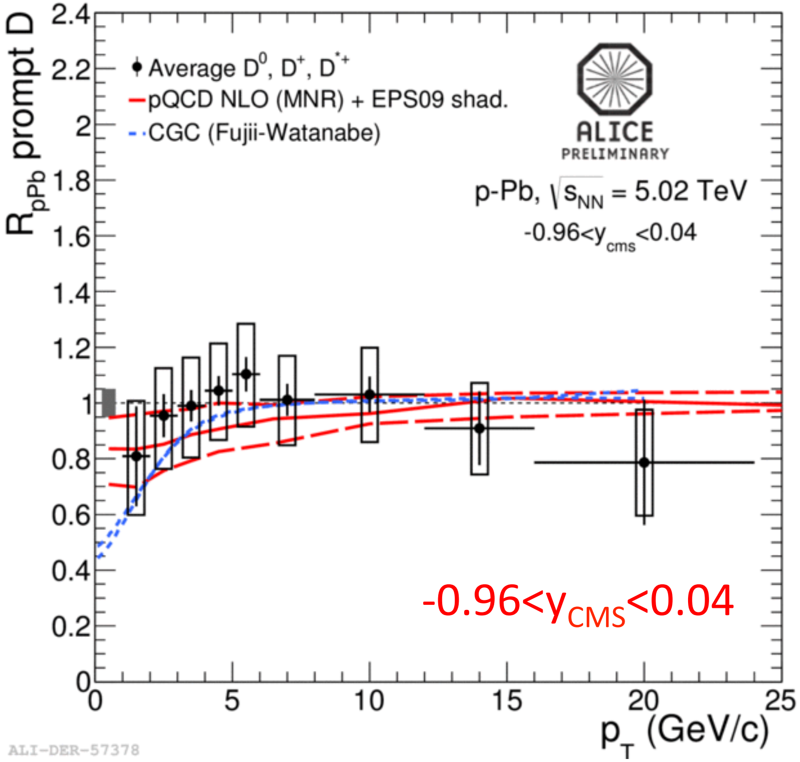
Model [M. Djordjevic at al.]:



$R_{AA}(\pi)$ ~ $R_{AA}(D)$ for p_T > 7 GeV/c
Hint for $R_{AA}(\pi) < R_{AA}(D)$ for pT<

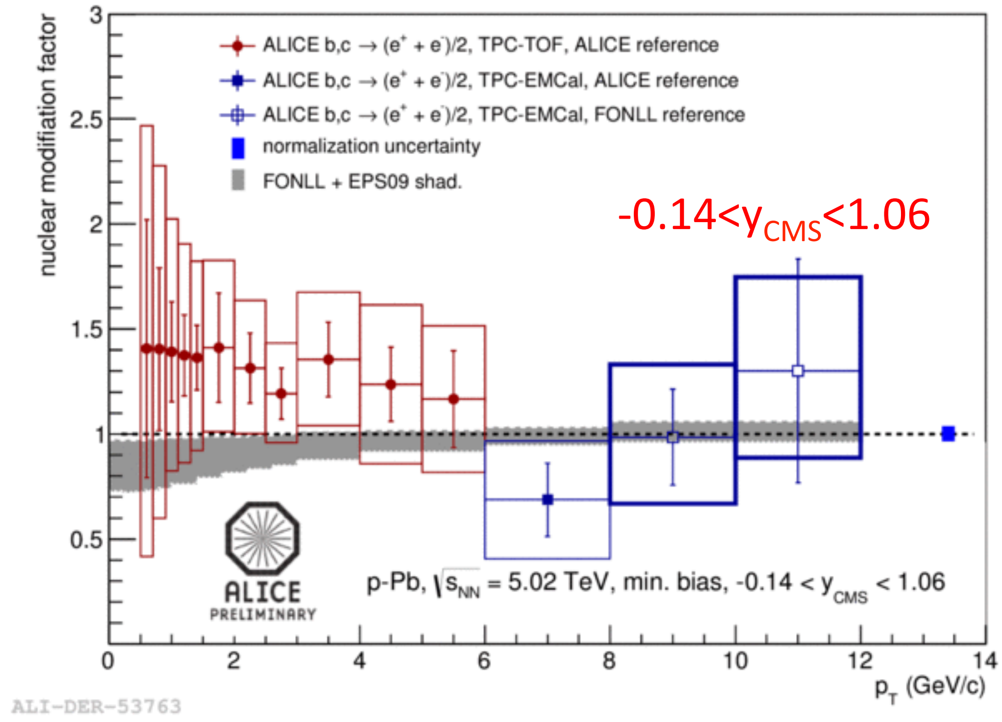
Heavy-flavor R_{AA} in p-Pb vs. models

D mesons



-0.96<y_{CMS}<0.04

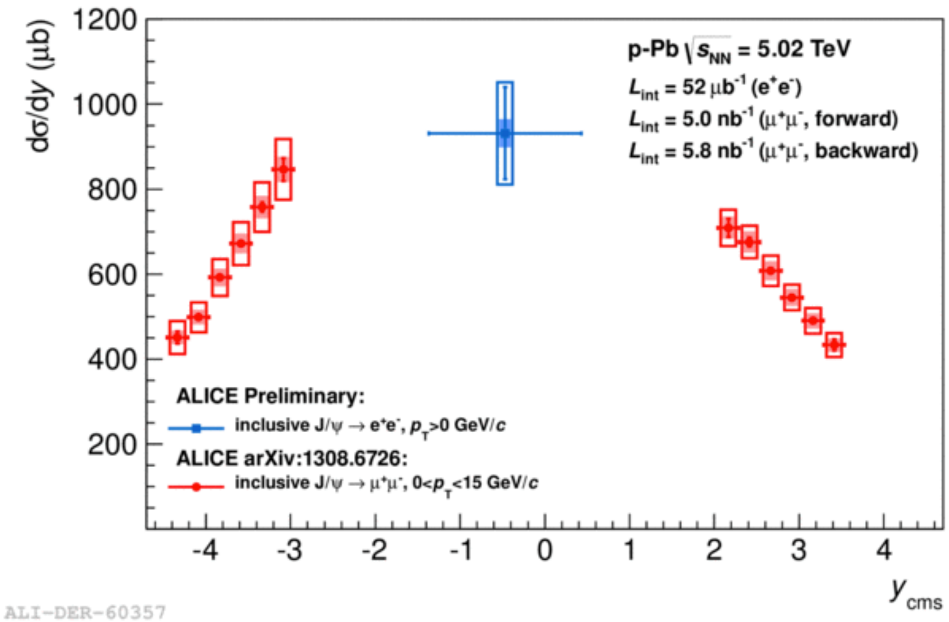
b,c → e⁺+e⁻/2

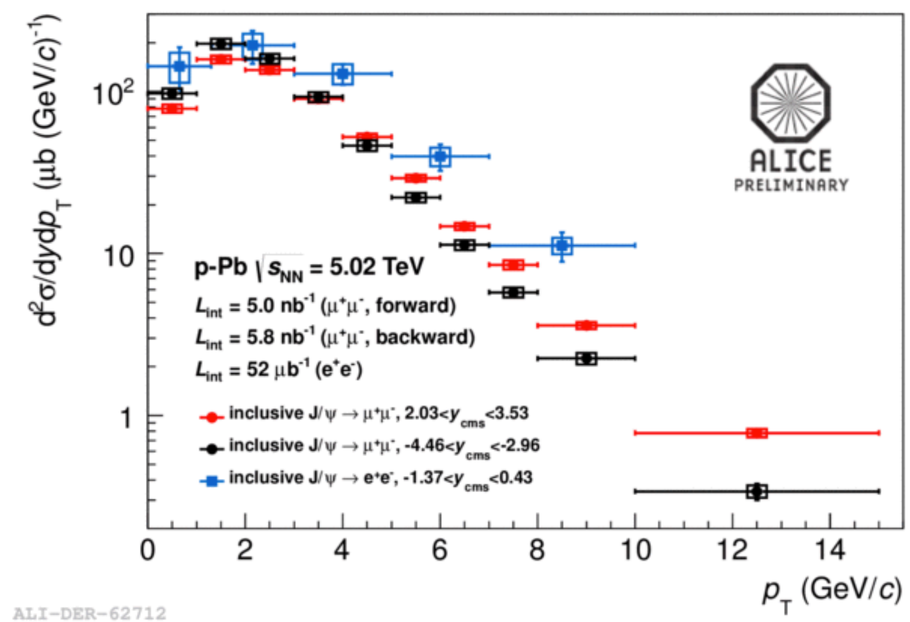


-0.14<y_{CMS}<1.06

J/ψ cross section in p-Pb

$$\sigma_{J/\psi} = \frac{N_{J/\psi \to l^+ l^-}}{L_{int}\, A\, \epsilon\, BR_{J/\psi \to l^+ l^-}}$$



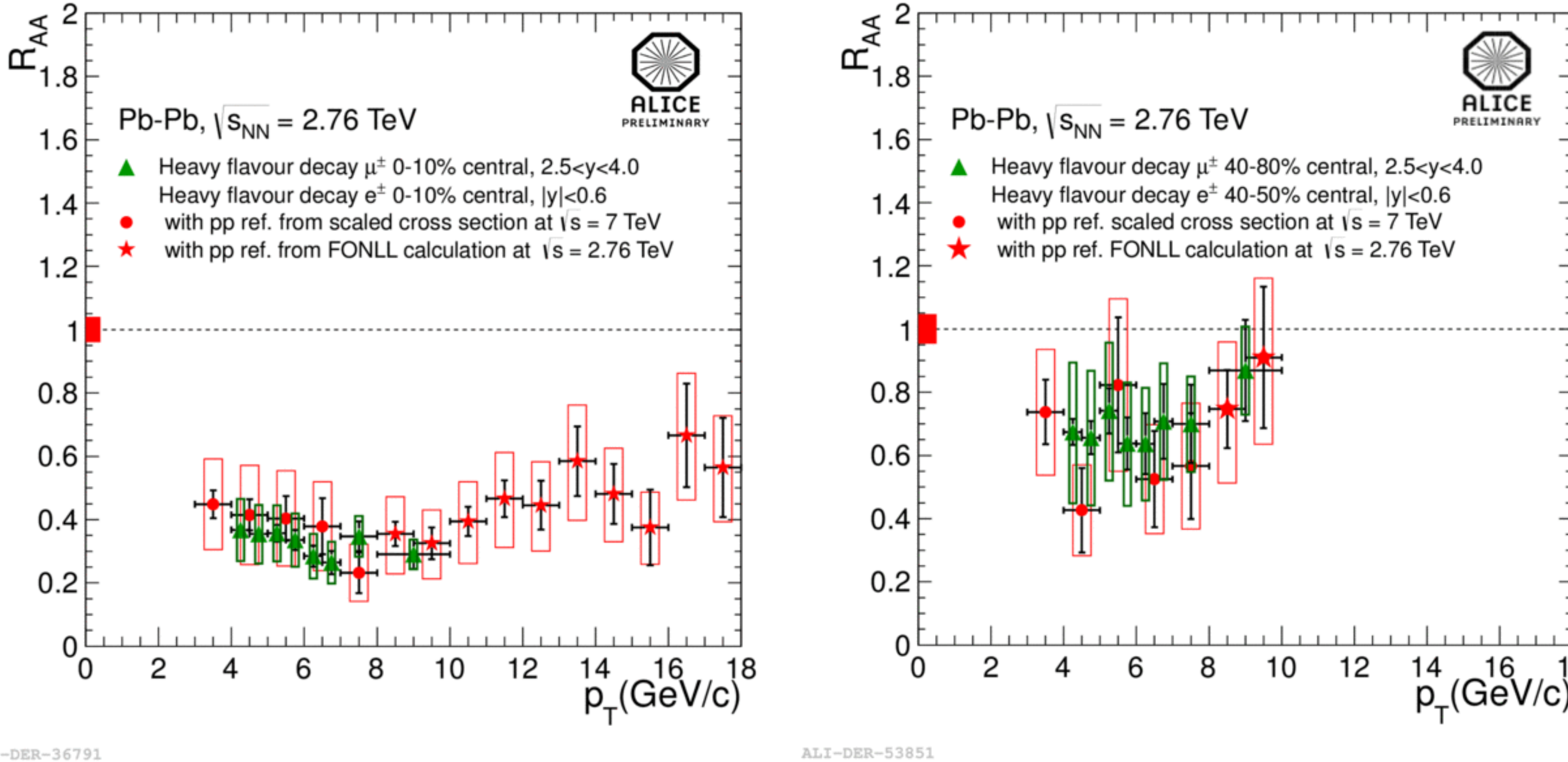


Heavy-flavor decay muon and electron R_{AA}

D+B → e,μ + X

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Muons: PRL 109 (2012) 112301

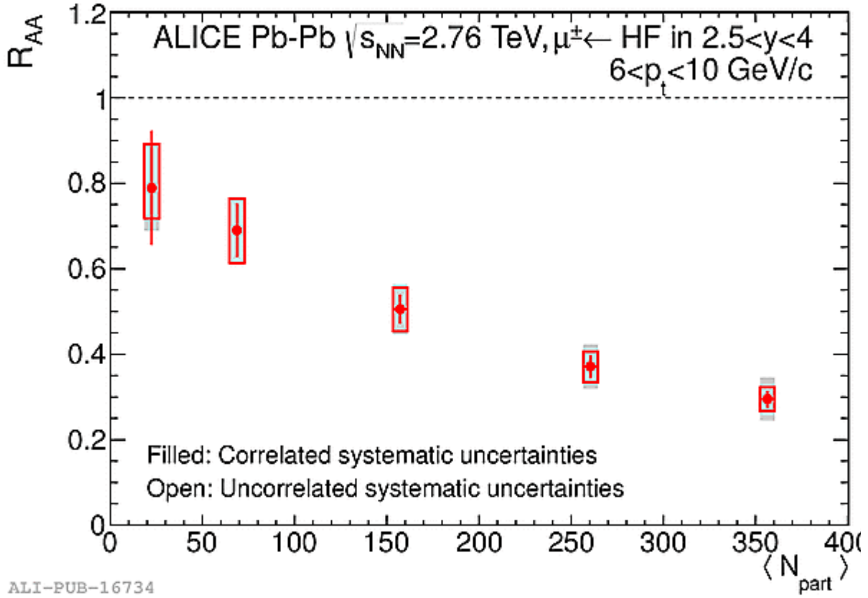


- Strong suppression (factor ~2) in central collisions ($p_T^{hadron} \sim 2p_T^{lepton}$)
- Smaller suppression in peripheral collisions
- Comparable suppression in central and forward rapidity
- Dominated by beauty at such high-p_T (from FONLL calculations)

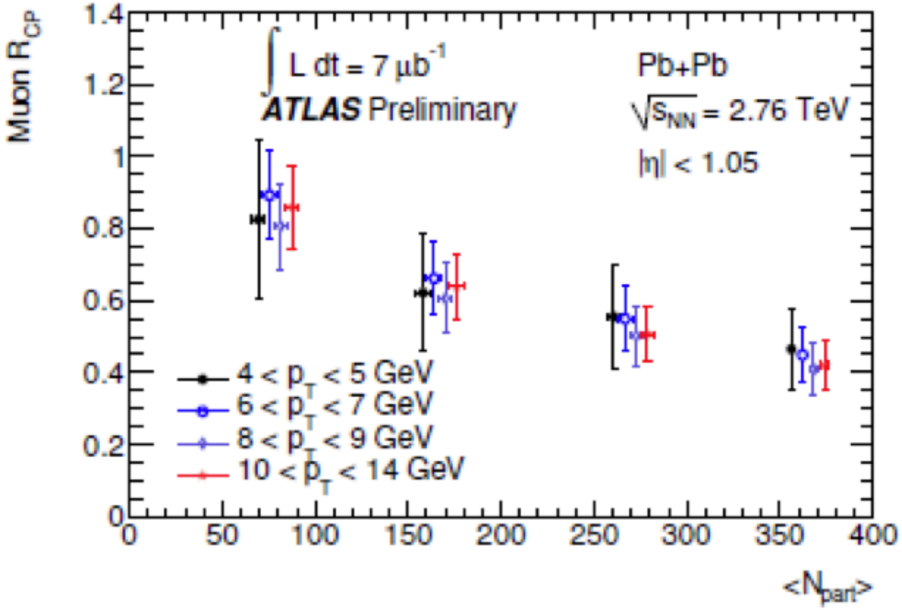
Heavy-flavor decay muon and electron R_{AA}

D+B → μ + X

ALICE, PRL 109 (2012) 112301



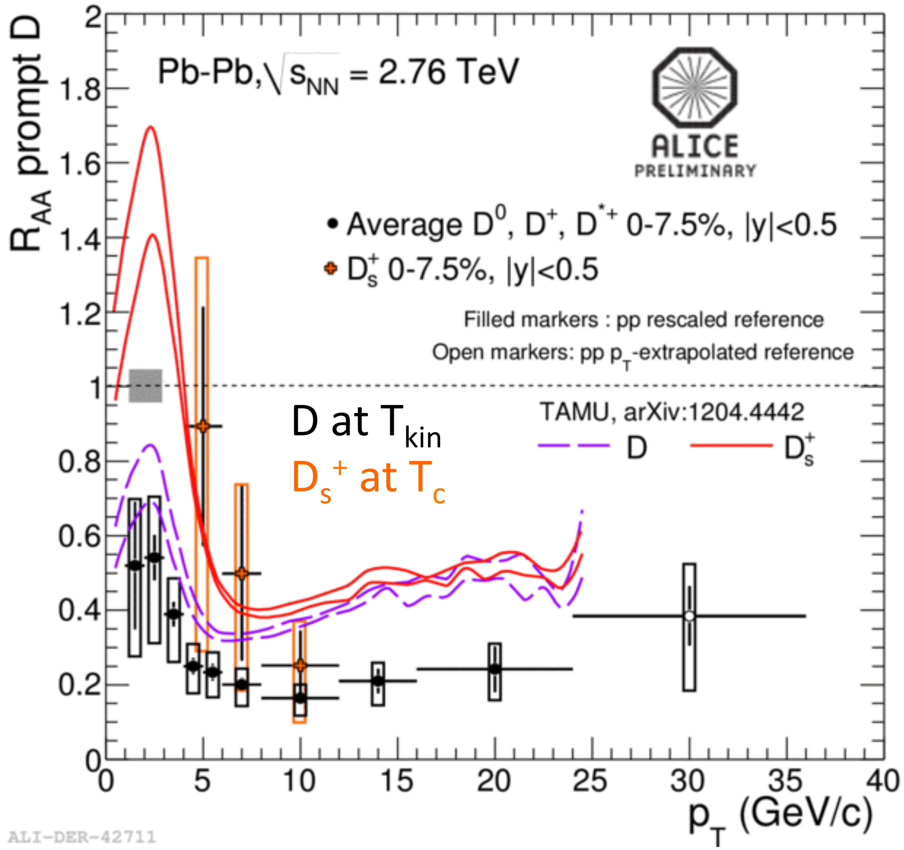
ATLAS-CONF-2012-081



- ALICE R_{AA}: Suppression increases with centrality for high-p_T muons
- ATLAS R_{CP}: Strong suppression in central collisions, and no sign of p_T dependence for muons with p_T=4-10 GeV/c

D_s^+-meson R_{AA} vs. p_T

Different D_s^+ R_{AA} expected if production by combination/coalescence in the QGP (*)



Model predictions [He, Fries and Rapp, PRL 110 (2013) 112301]

- Hydro
- non-perturbative QCD
- coalescence with strange quarks
- diffusion in hadronic phase

(*)
Kuznetsova and Rafelski, EPJC 51 (2007) 113
Andronic, Braun-Munzinger, Redlich and Stachel, PLB 659 (2008) 149

R_{AA} - D vs. B mesons

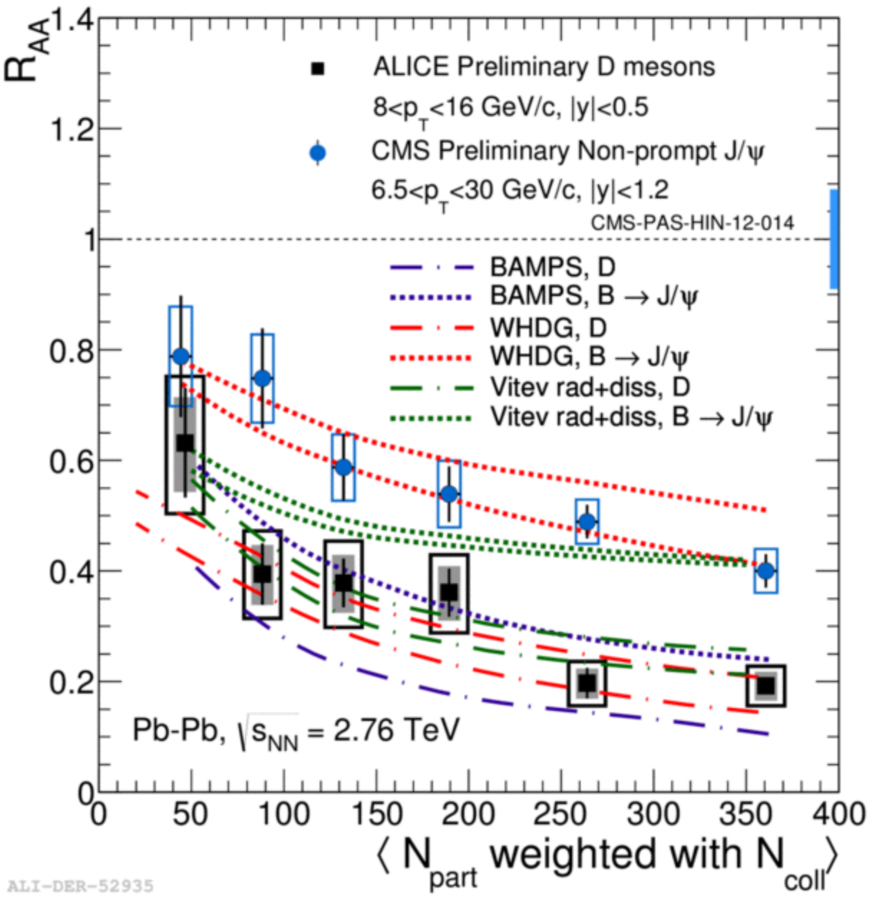
$\Delta E_C > \Delta E_B \rightarrow R_{AA}(D) < R_{AA}(B)$?
energy loss mass dependedence

- D $<p_T>$~10 GeV/c: ALICE
- B (non prompt J/ψ) $<p_T>$~11 GeV/c: CMS

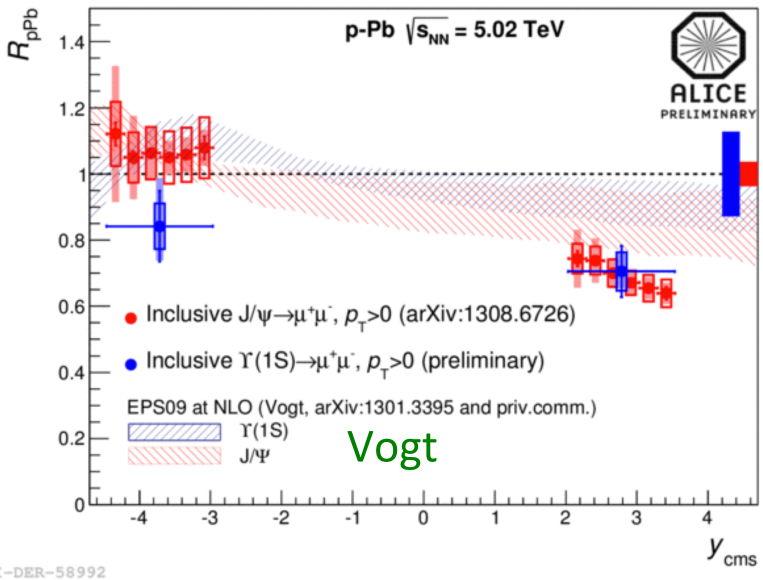
$R_{AA}(D) > R_{AA}(B)$
→ indication of larger energy loss for charm than for beauty

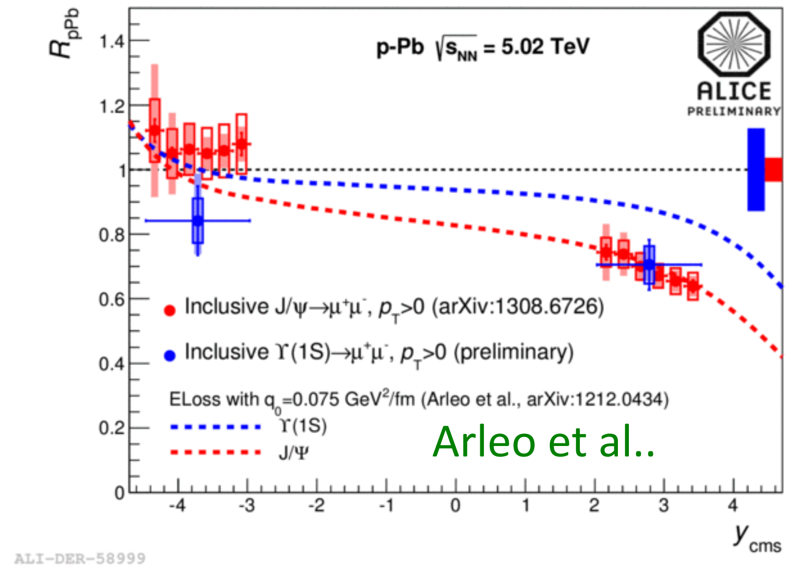
The difference predicted by energy loss models:

BAMPS: JPG 38 (2011) 124152
WHDG: JPG 38 (2011) 124114
Vitev et al., PRC 80 (2009) 054902



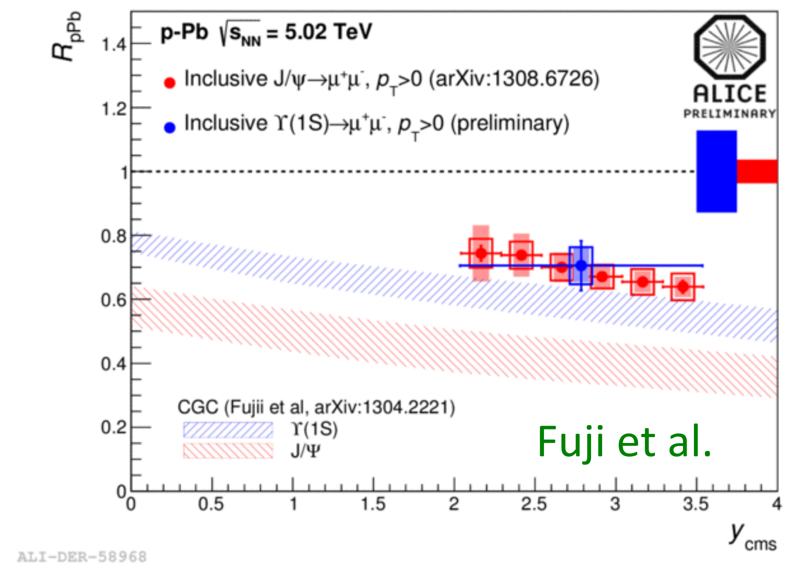
ϒ(1S) R_{pPb} vs. y_{cms} vs. models





ϒ(1S) suppressed similar to J/Ψ
(large normalisation uncertainties)

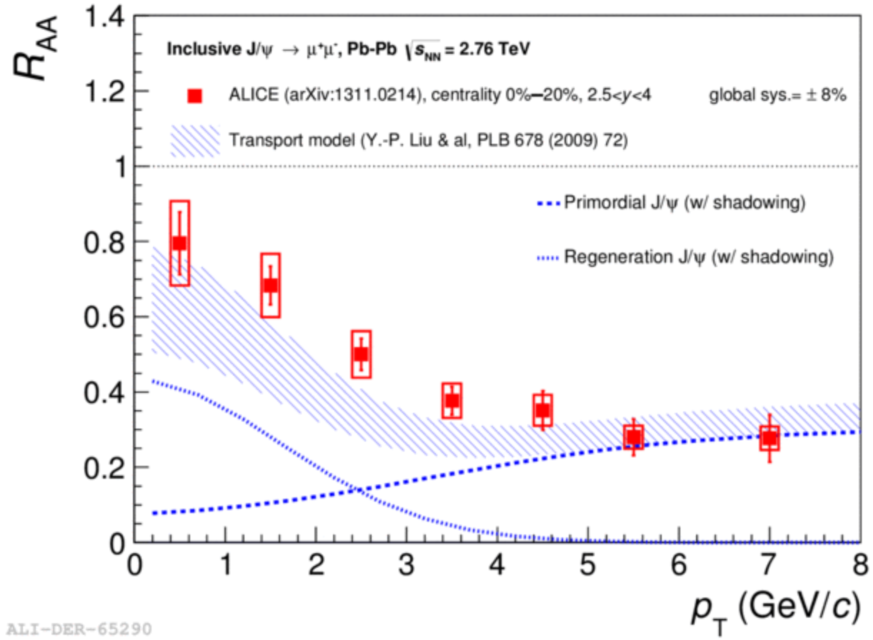
Shadowing model (Vogt), energy loss models (Arleo et al..) and CGC model (Fuji et al.) consistent with data

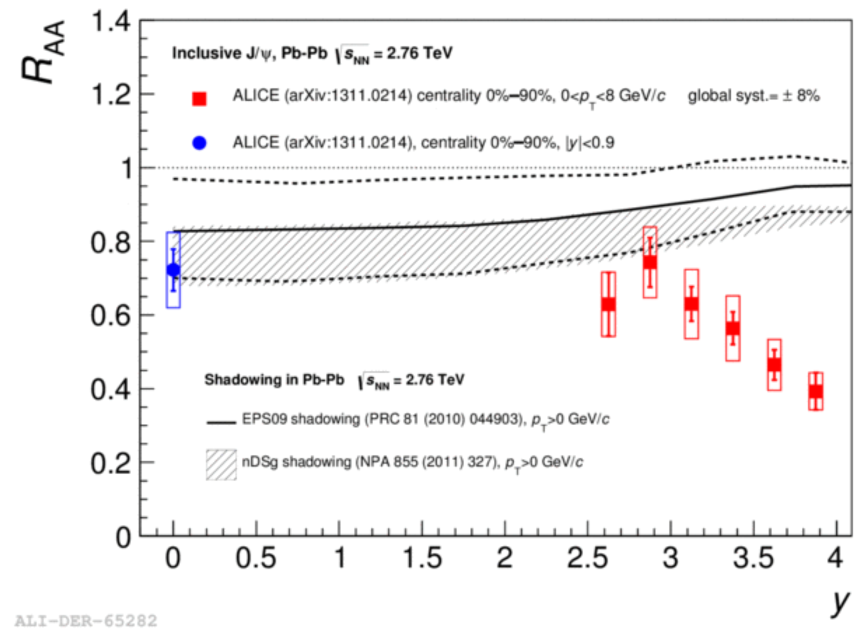


J/ψ R_{AA} vs. p_T and rapidity vs. models

Forward rapidity

ALICE, arXiv:1311.0214





Transport model:
Liu et al. (J/ψ dissociation + regeneration + p_T broadening + shadowing) consistent with data
→ production of low-pT J/ψ via regeneration

Models (Cold Nuclear Matter effects):

- R. Vogt (CEM + EPS09 NLO shadowing)
- Ferreiro et al. (CSM + nDSg NLO shadowing)