Review on Experimental results on Heavy Flavor production

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1st Sapore Gravis Day Meeting - Orsay - November 2012

Disclaimer: biased view towards LHC, ALICE, friends,...

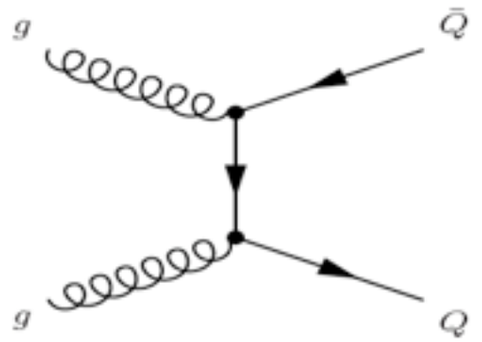
Outline

- Introduction : general ideas, concepts...
- Highlights of pp measurements
- Snapshot of pA data
- Results in AB collisions:
  - Nuclear modification factor: electrons, muons, D^0, D^+, D^{*+}, D_s^+, $B \rightarrow J/\psi$
  - Azimuthal anisotropy:
    - v_2: electrons, D^0, D^+, D^{*+}
    - D^0 v_2 vs. centrality and R_{AA} vs Event Plane
- Summary

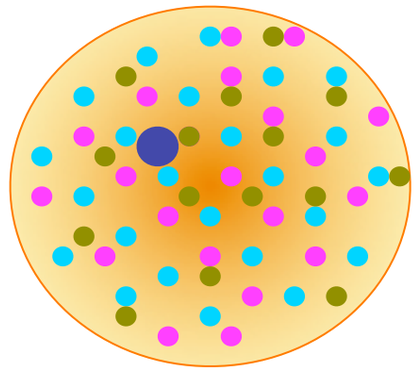
Experiments and some concepts

KeyWords: Heavy Quarks as QGP Probes

- Production in nucleon-nucleon collisions
  - Production time $\tau_p \sim 0.05 - 0.15$ fm/c
  - ➡ **Tool to test pQCD calculations**



- Nuclear medium influence: p-A collisions
  - Shadowing (PDF modifications in nuclei) and Gluon saturation
  - ➡ **Tool to study high density small-x gluons**



- Effects in a QGP: A-B collisions
  - Energy loss in the QGP (high pt)
  - Thermalisation in the QGP (low pt)
  - ➡ **Probe of the QCD medium**

Cartoons just for illustration

[Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493...]

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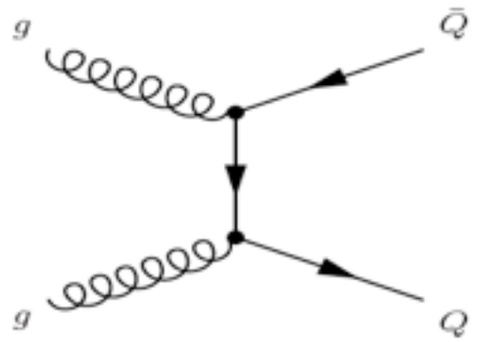

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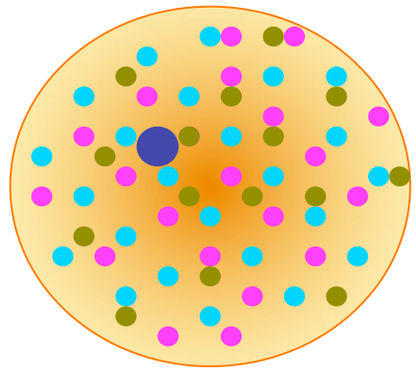

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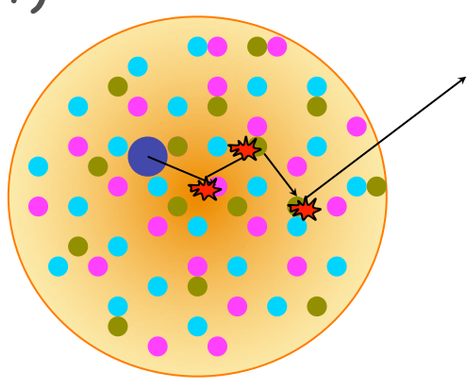

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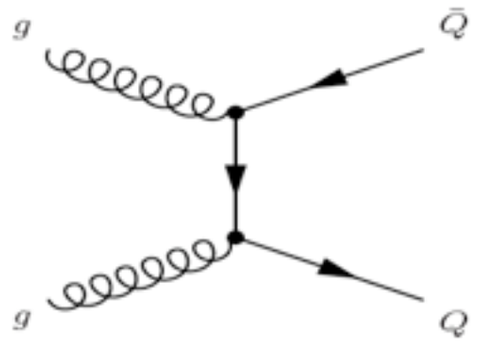

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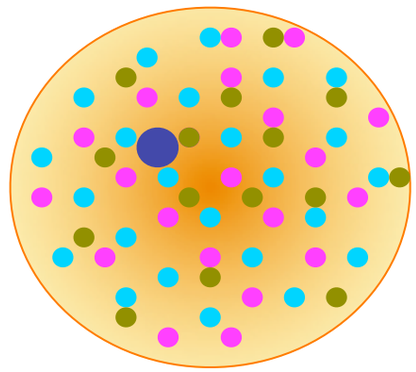

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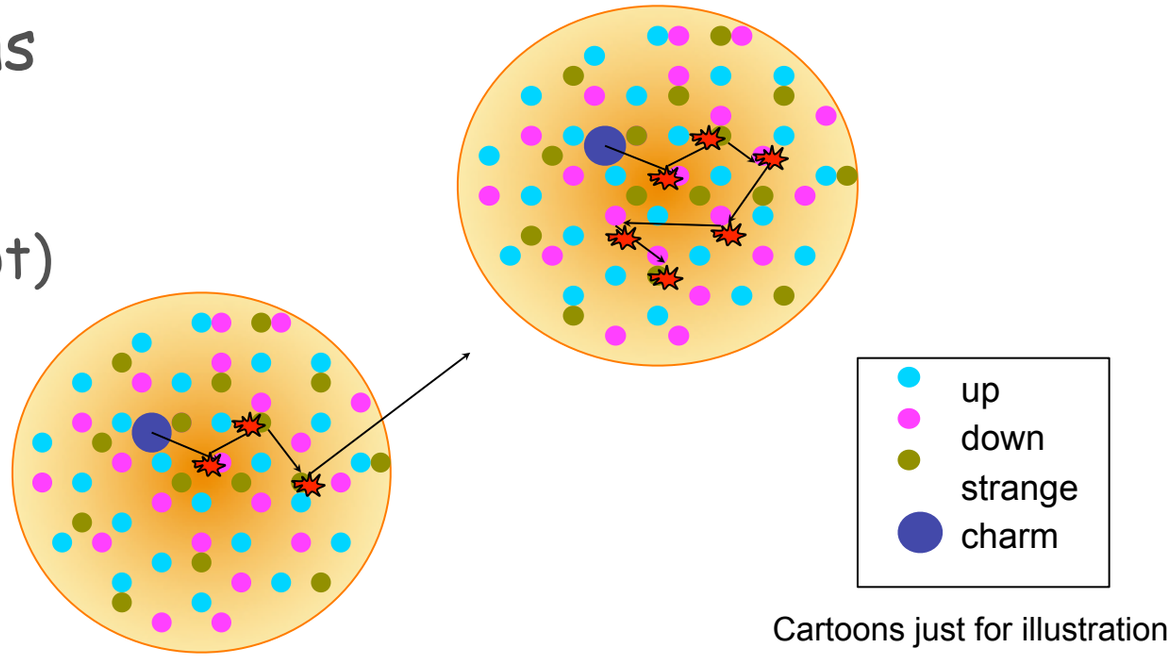

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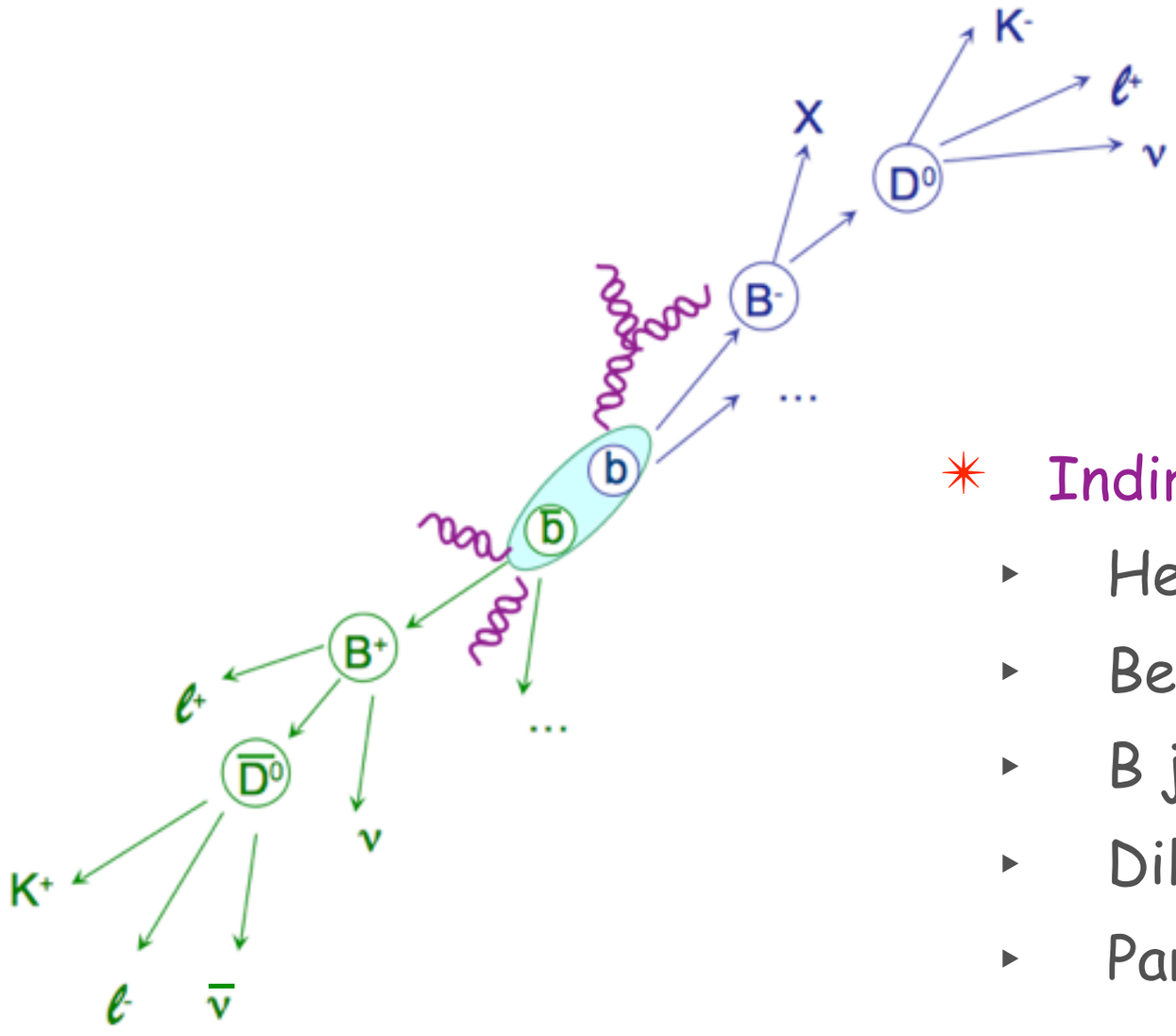
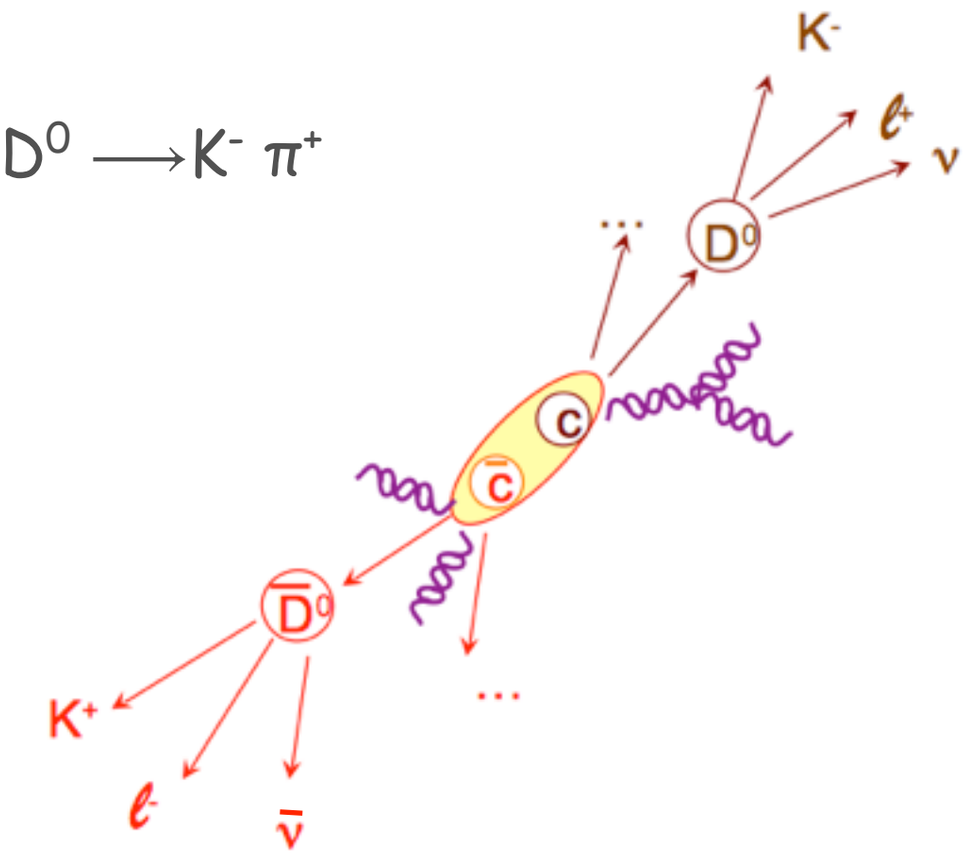
Experimentally, How ?

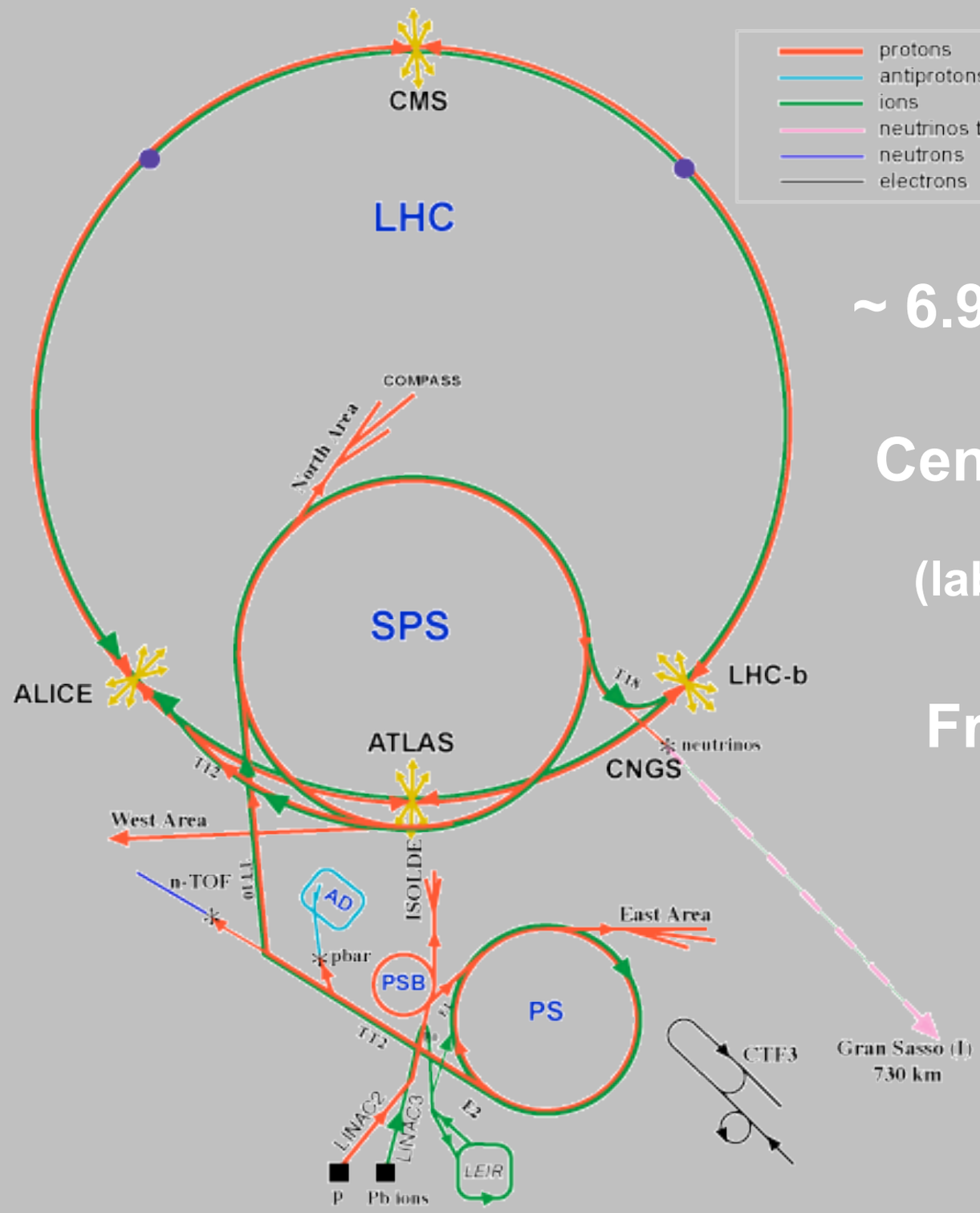
- Direct measurements
  - Inclusive D mesons (c+b ⟶D), e.g. $D^0 \longrightarrow K^- \pi^+$
  - Prompt D mesons (c ⟶D)
  - B hadron reconstruction ?





- Indirect measurements
  - Heavy flavor (c+b) decay leptons
  - Beauty decay leptons (B-tagging)
  - B jets
  - Dilepton invariant mass
  - Particle correlations

SPS at CERN



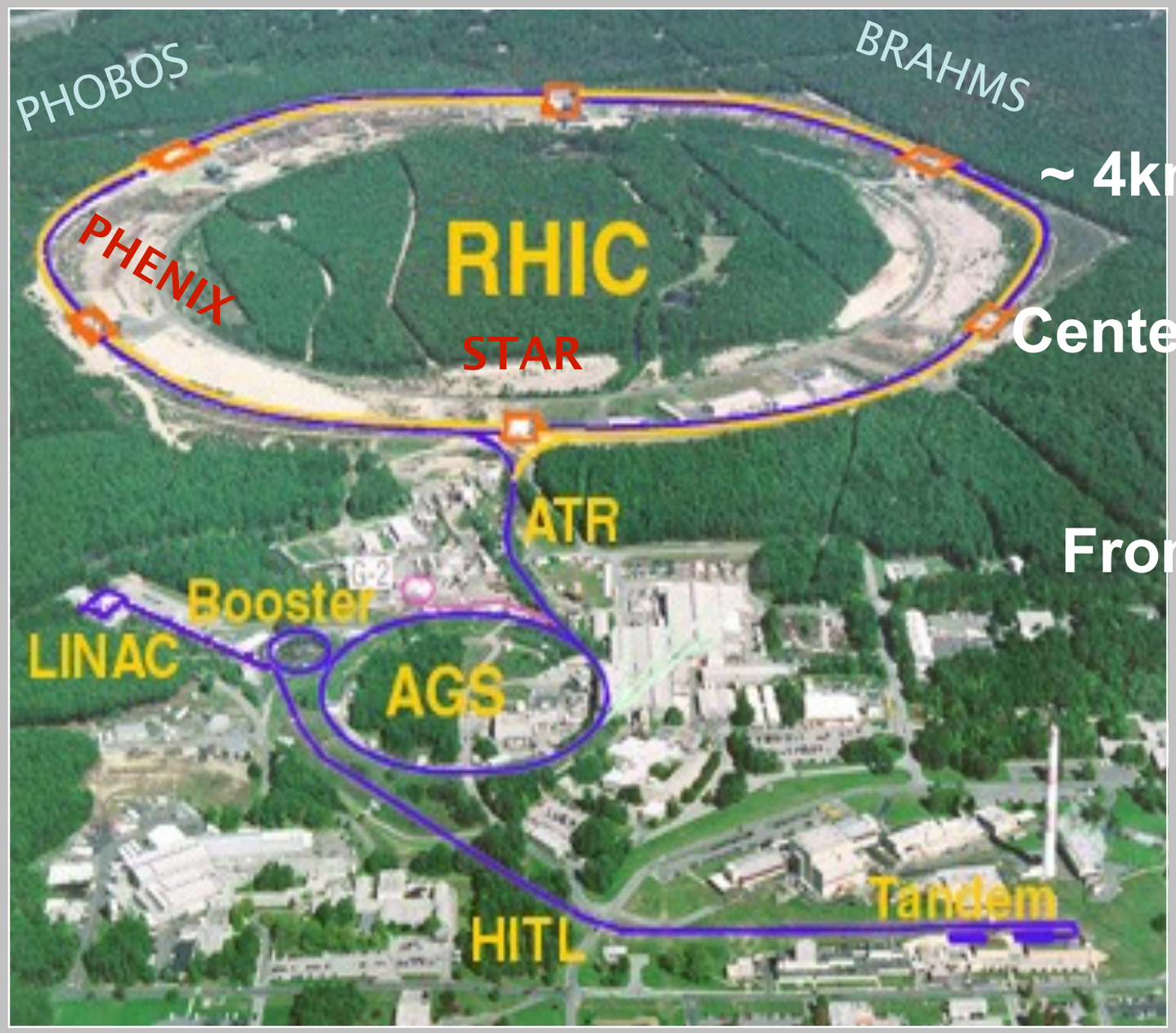
~ 6.9km of circumference

Center of Mass Energies of 17-30 GeV
(lab. Ref. frame 158-400 GeV)

From p up to Pb nuclei

…since the 90's

RHIC at BNL



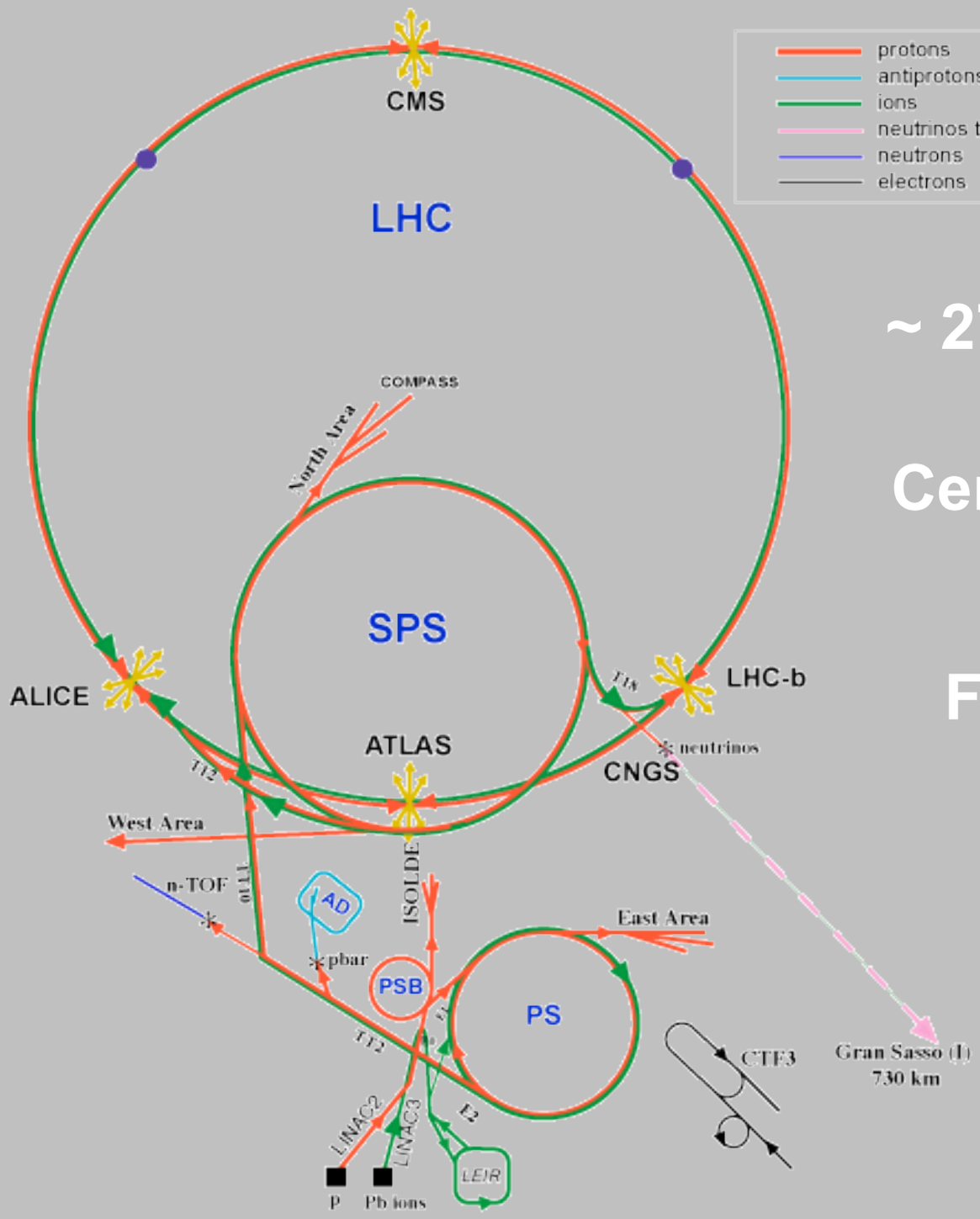
~ 4km of circumference

Center of Mass Energies of 62-200 GeV

From p up to Au nuclei

…since 2001

The LHC at CERN



~ 27km of circumference

Center of Mass Energies of 0.9-14 TeV

From p up to Pb nuclei

…since 2010

... THE MEASUREMENTS

✳ In proton-proton collisions...

	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF electrons	✔	✔	✔			
B-decay electrons	✔		✔			
HF muons			✔			
D^0, D^+, D^{*+}		✔	✔	✔	✔	✔
D_s^+			✔	✔	✔	✔
$B \rightarrow J/\psi$			✔	✔	✔	✔
B hadrons				✔	✔	✔
B jets				?	✔	

✳ In heavy-ion collisions...

	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF electrons	✔	✔	✔			
B-decay electrons	✔					
HF muons			✔	✔	✔	
D^0, D^+, D^{*+}		✔	✔			
D_s^+			✔			
$B \rightarrow J/\psi$					✔	
B hadrons						
B jets					✔	

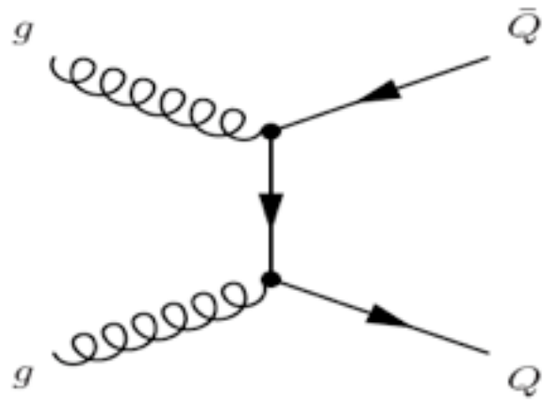
Proton-proton Results

c.f. this morning in Jibo's He talk

Production in hard partonic collisions

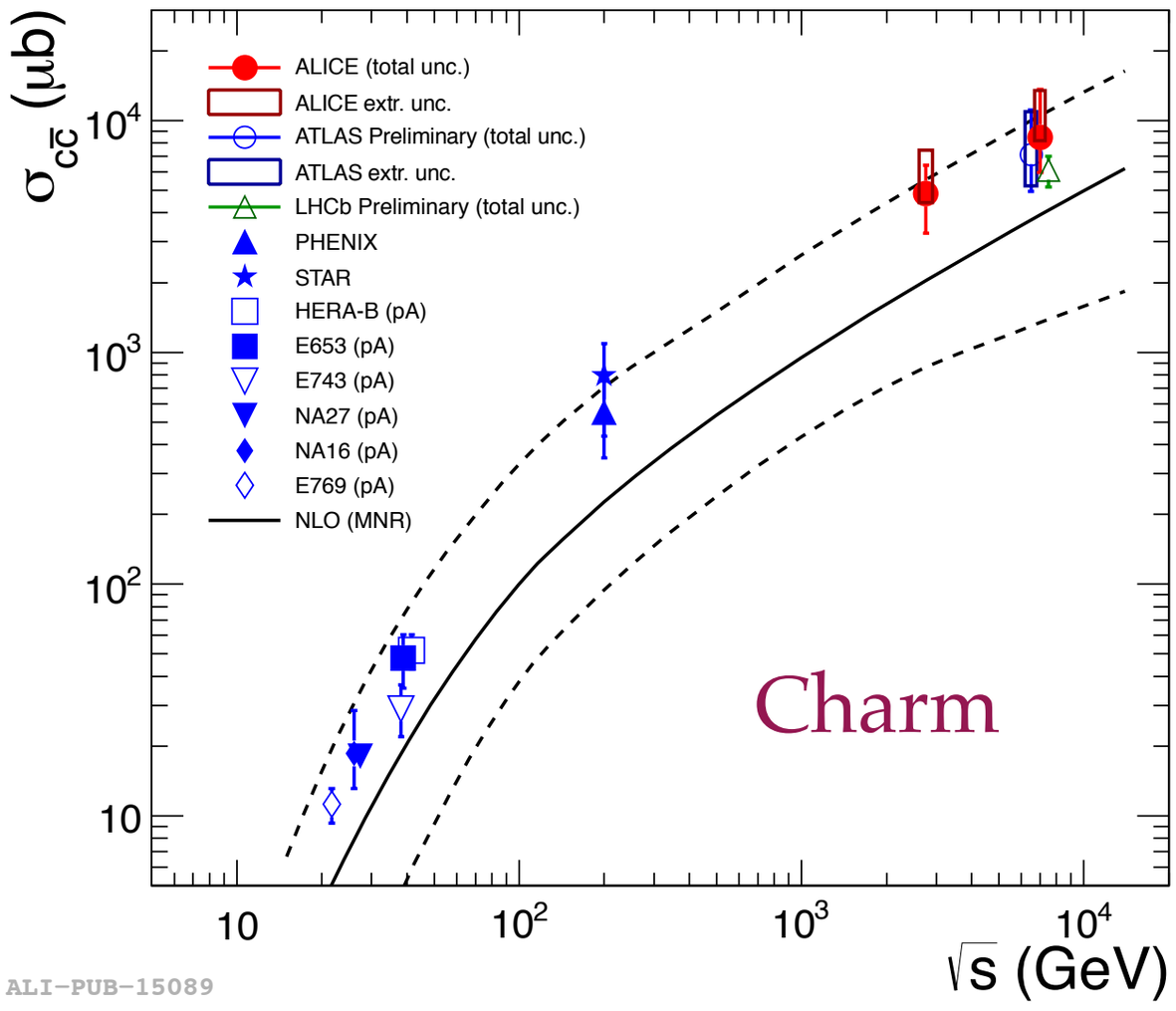
- Production time $\tau_p \sim 1/m_Q \sim 0.05$ - 0.15 fm/c

  ⇨ **Tool to test pQCD calculations**

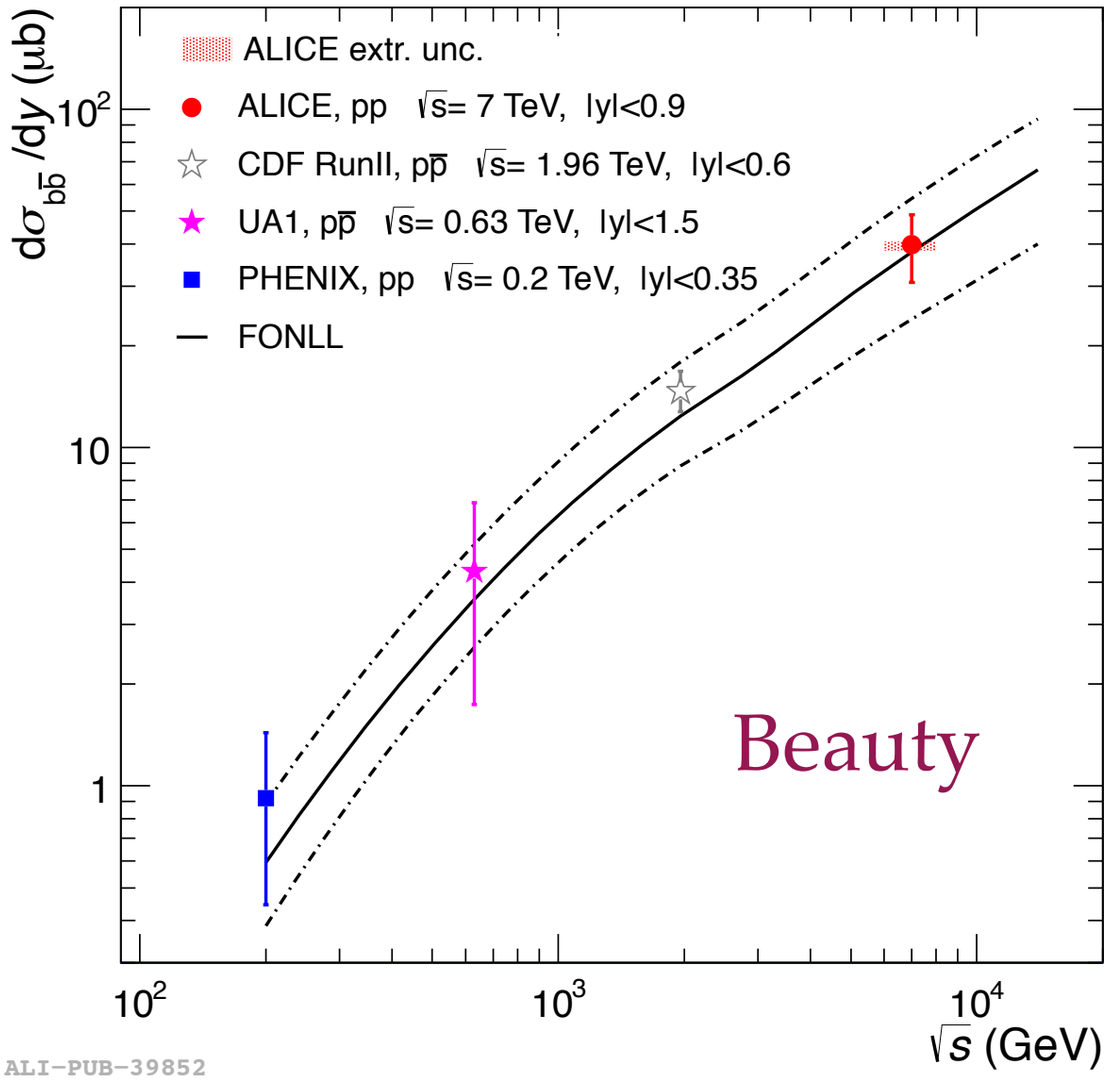


Charm & Beauty Cross Sections

[ALICE Coll. JHEP 07 (2012) 191]



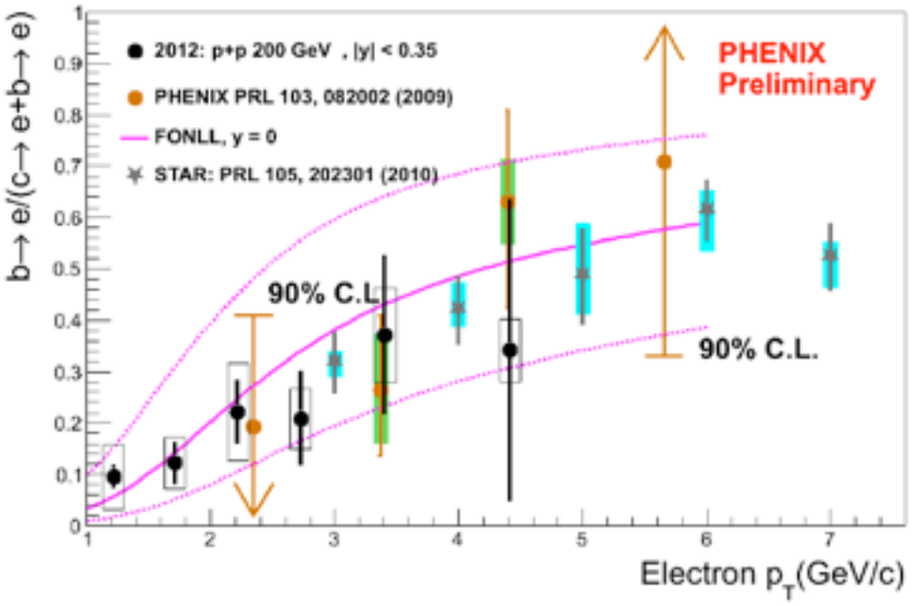
[ALICE Coll. arXiv: 1208.1902 (2012)]



- **Their cross section evolution with √s is well described by pQCD.**
- ~560 μb × 950 collisions / 42mb ~ 13 cc pairs in 0-10% AuAu at 200 GeV
- ~5 mb × 1500 collisions / 65mb ~ 115 cc pairs in 0-10% PbPb at 2.76 TeV

Separating Charm & Beauty

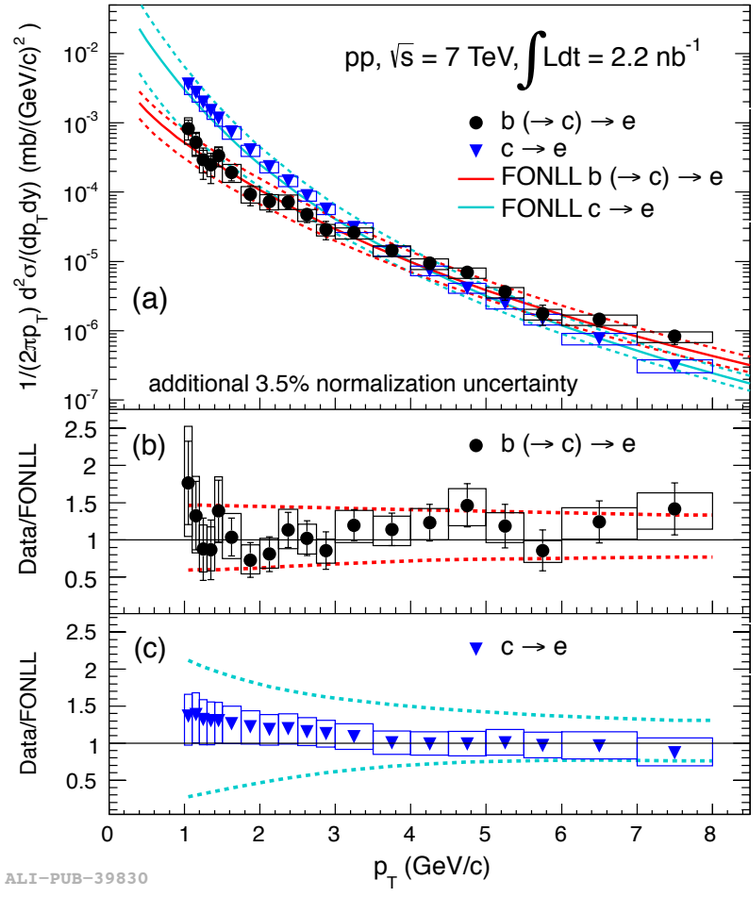
pp 200 GeV



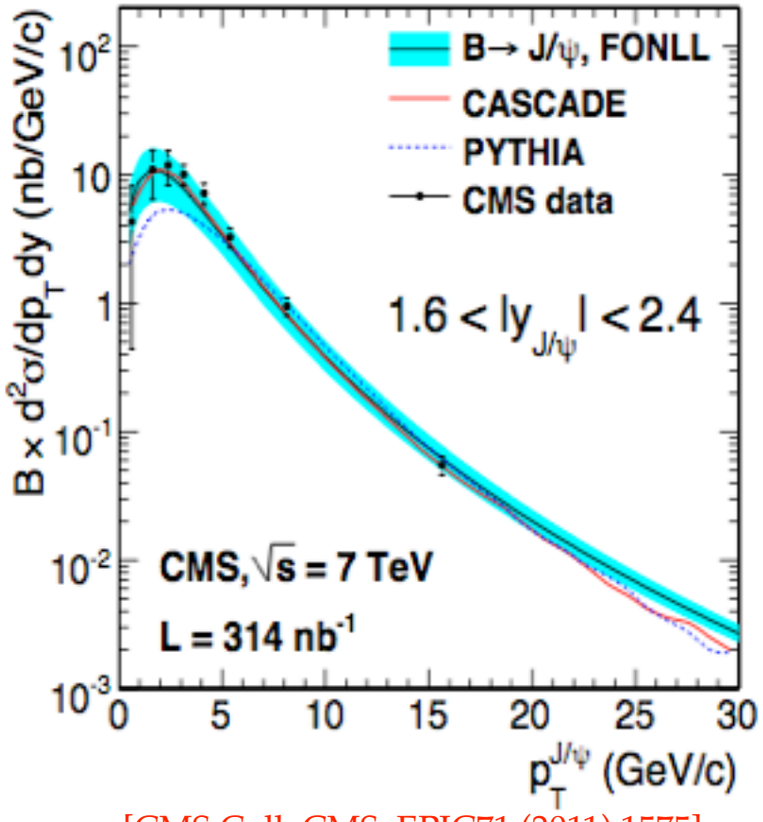
Ding, HQ12

Note : PHENIX QM12 Au+Au results being reviewed to include the B and D meson pt shape in-medium modification.

[ALICE Coll. arXiv:1208.1902 (2012)]



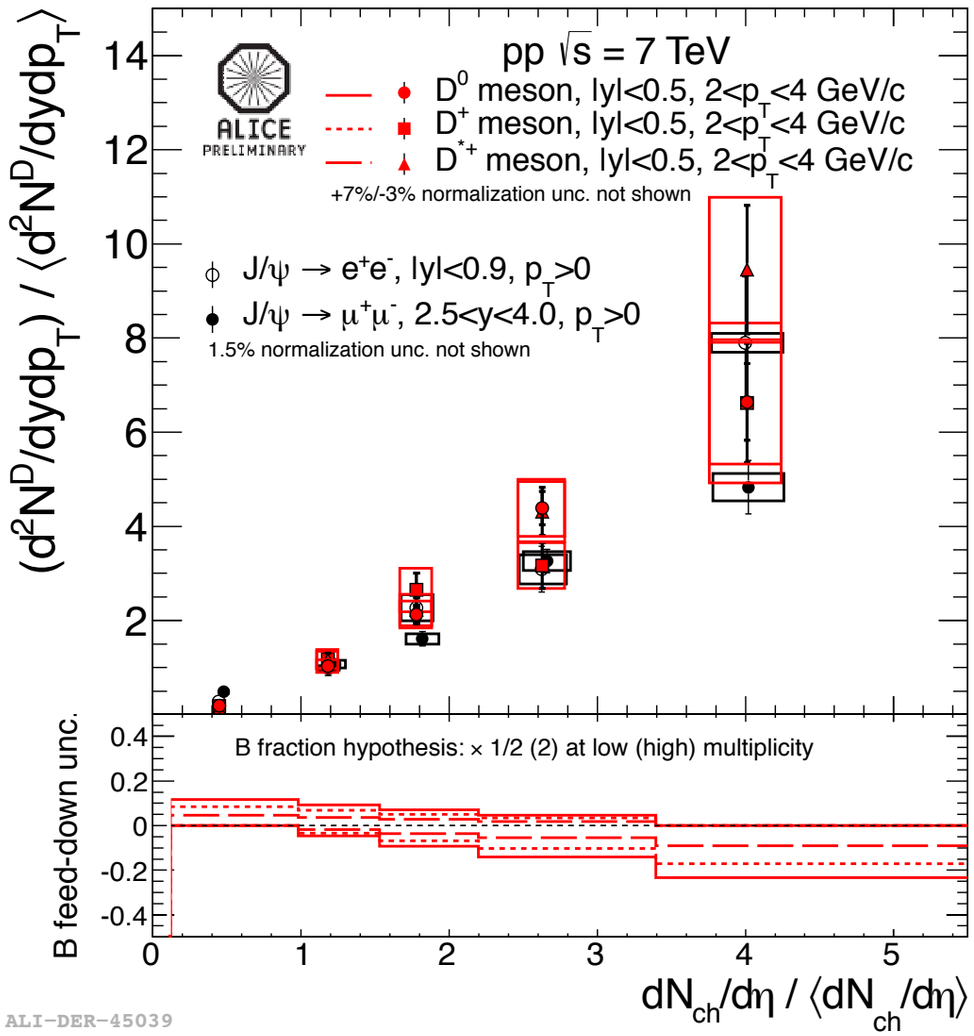
pp 7 TeV



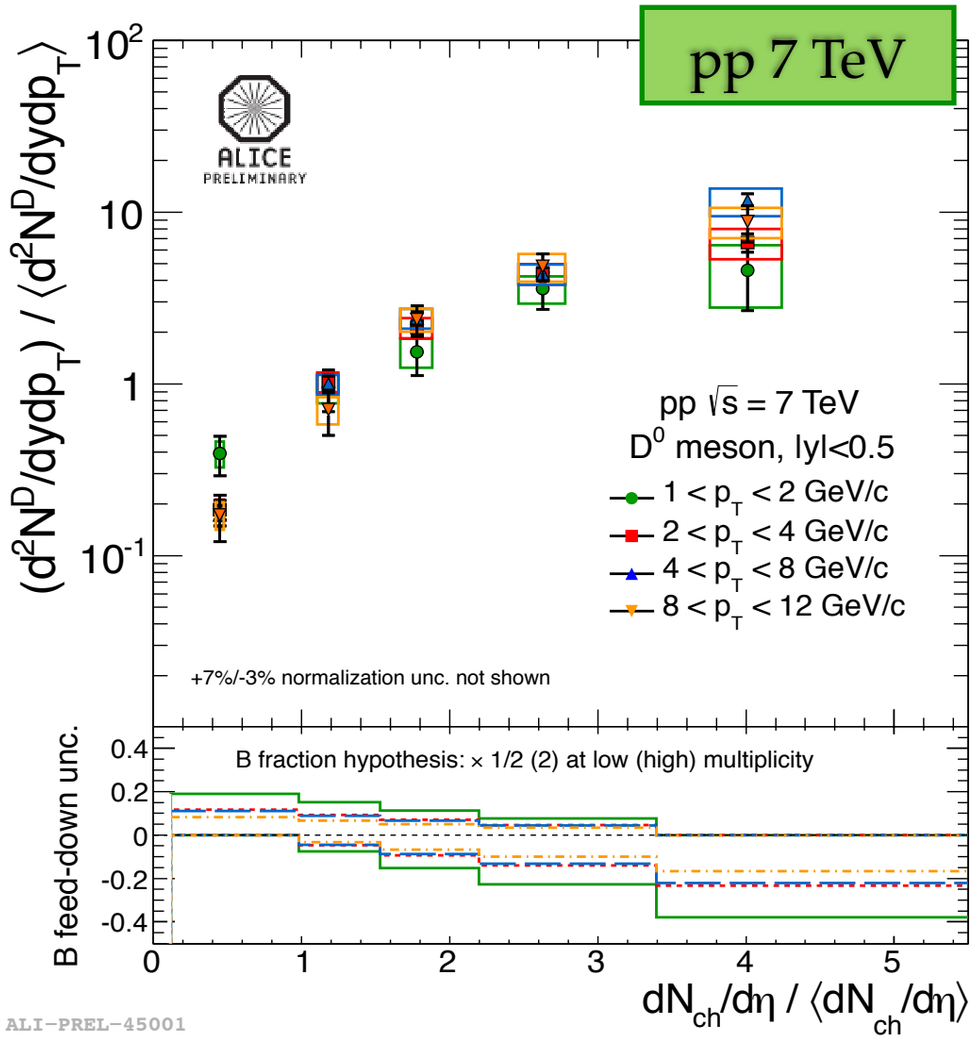
[CMS Coll. CMS, EPJC71 (2011) 1575]

➡ First direct measurements of the charm and beauty contributions to the heavy flavor lepton spectra in HI experiments.

Charm(onia) Multiplicity Dependence



ALI-DER-45039



ALI-PREL-45001

- Charged particle multiplicity in high-multiplicity pp collisions at 7 TeV is larger than the multiplicity in the peripheral CuCu collisions at 200 GeV
- **Similar increase of prompt-D and J/ψ production vs multiplicity**
- **No clear p_T dependence on the prompt-D relative yields vs multiplicity**
- **Hints for multi-parton interactions at a hard scale in pp collisions**

[ALICE Coll, Phys.Lett.B712 (2012) 165-175] [B.Alveretal.(PHOBOS Coll.),Phys.Rev.C83,024913(2011).]

d-Au & Cu-Cu Results

$\sqrt{s_{NN}} = 200$ GeV

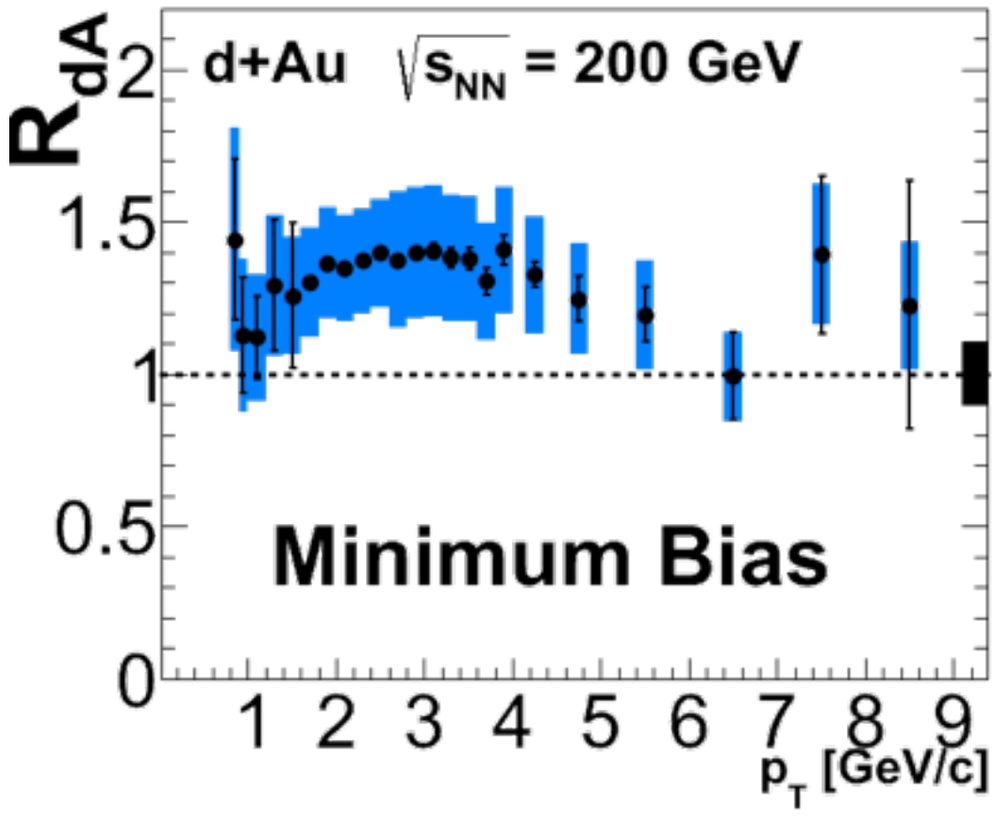
Nuclear environment influence: p-*A* collisions

- Shadowing (PDF modifications in nuclei) and Gluon saturation

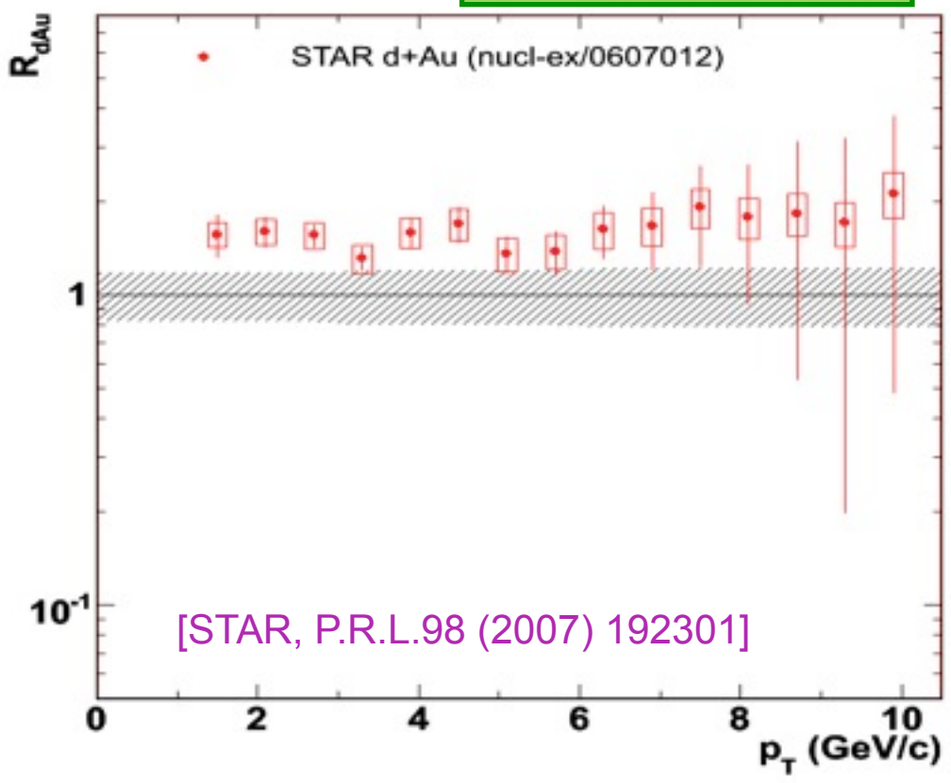
  ⇨ **Tool to study high density small-x gluons**

HF electrons at RHIC I

dAu 200 GeV



[PHENIX Coll, arXiv:1208.1293 (2012)]



➡ **No suppression observed for heavy flavor particles within uncertainties (flat-like shape & compatible with unity)**

✳ Largest difference within HFe and π^0 R_{dAu} seen in the p_T range where cold-nuclear-matter effects are expected to be more important

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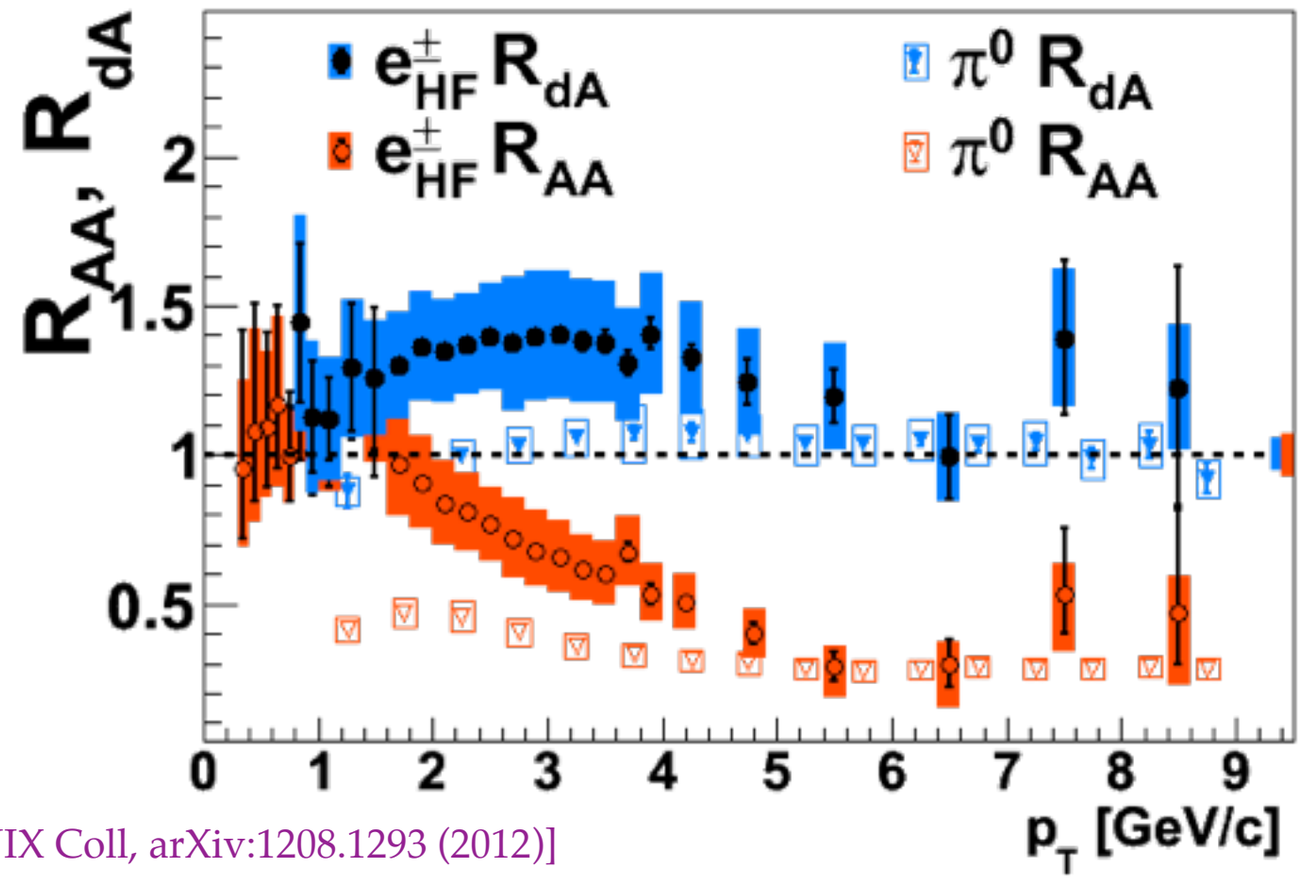

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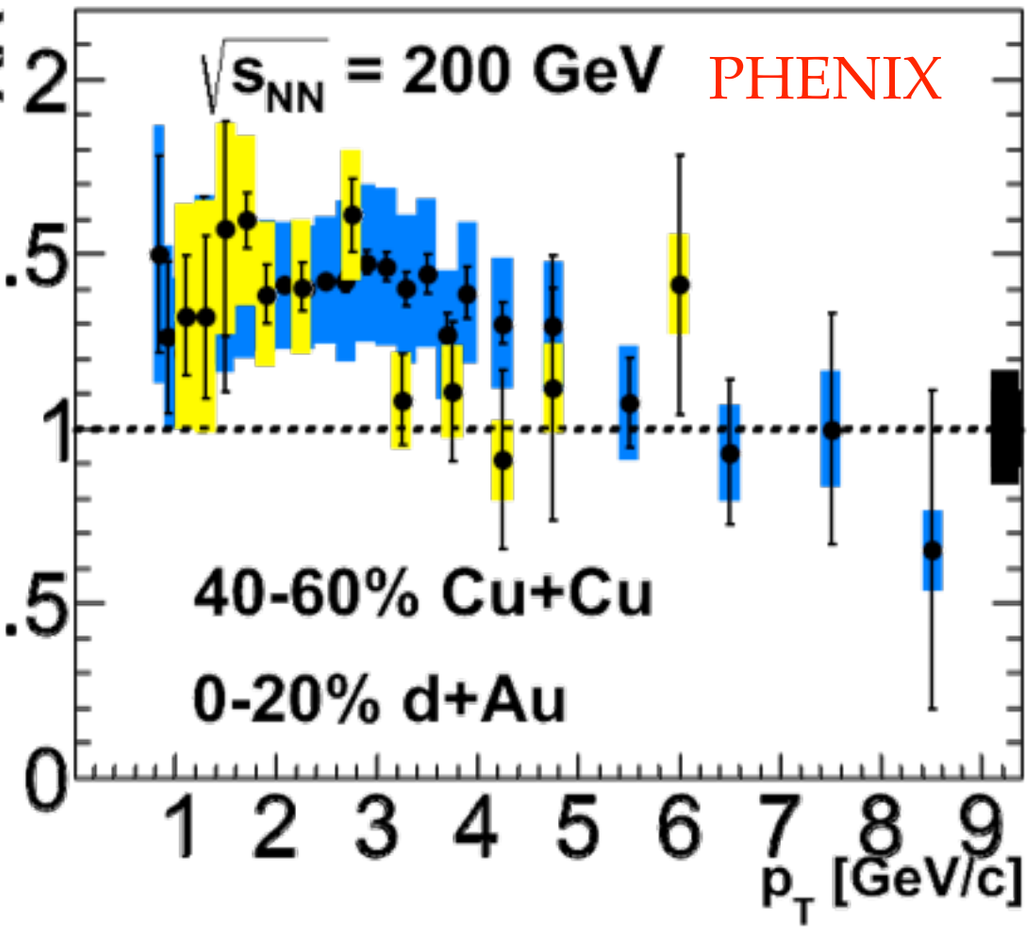
HF electrons at RHIC II

dAu 200 GeV | CuCu 200 GeV



M.Durham, Utrecht 12

- **Similar behavior to that of dAu for comparable <N_{part}>**
- **Un-expected further suppression at forward rapidity.**
  Similar effect to that observed for J/ψ ?

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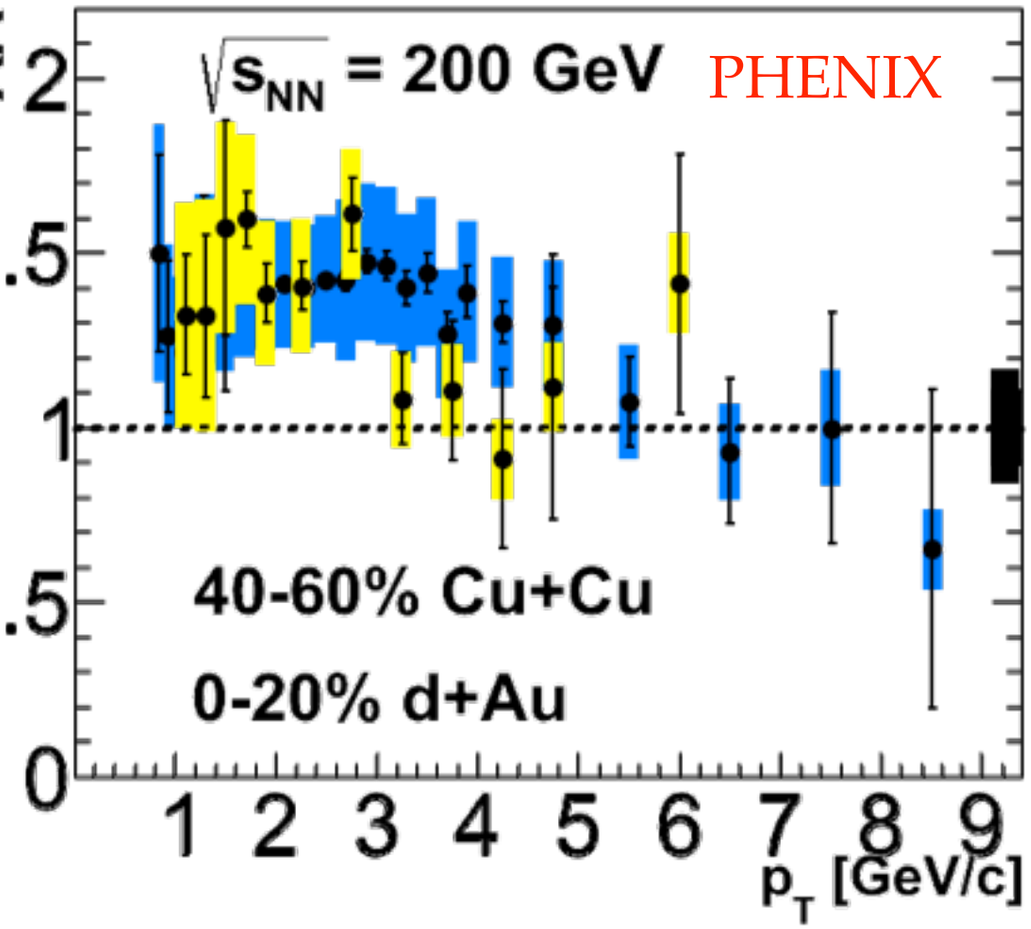

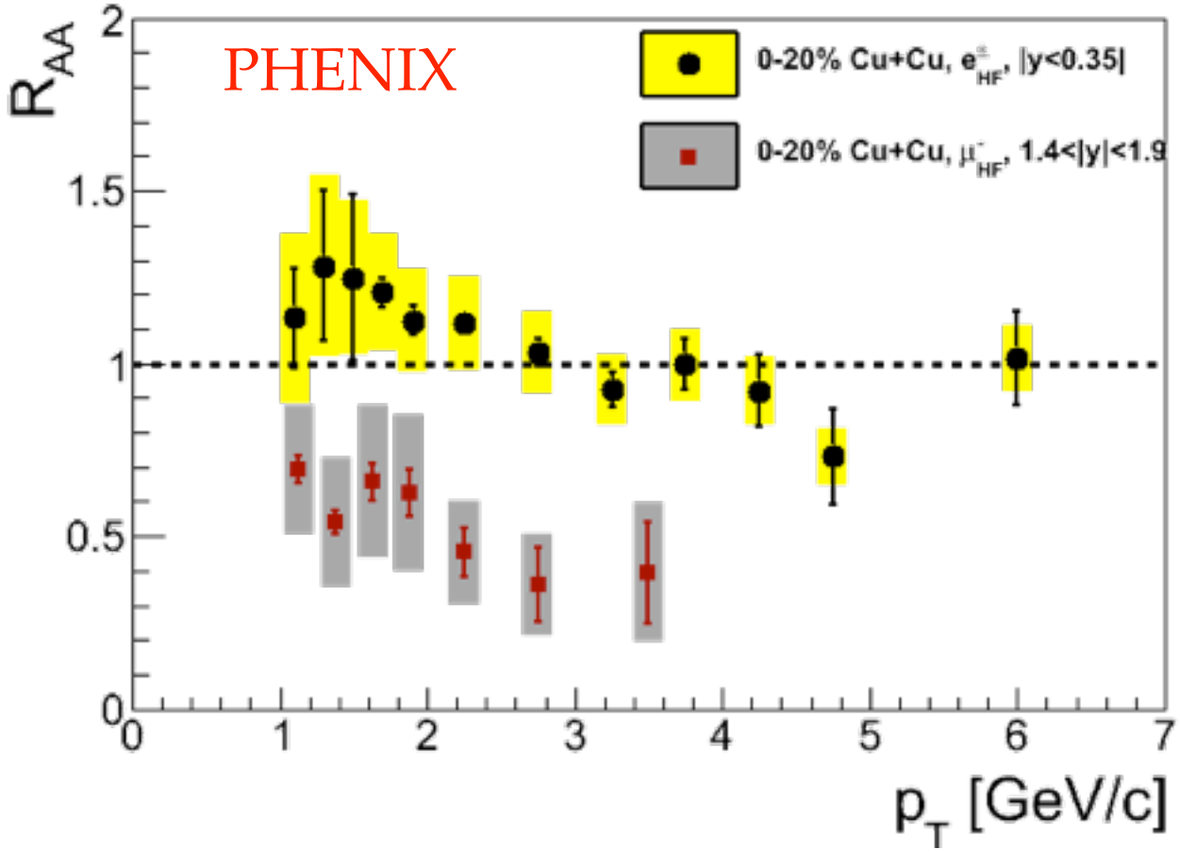

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Pb-Pb & Au-Au Results

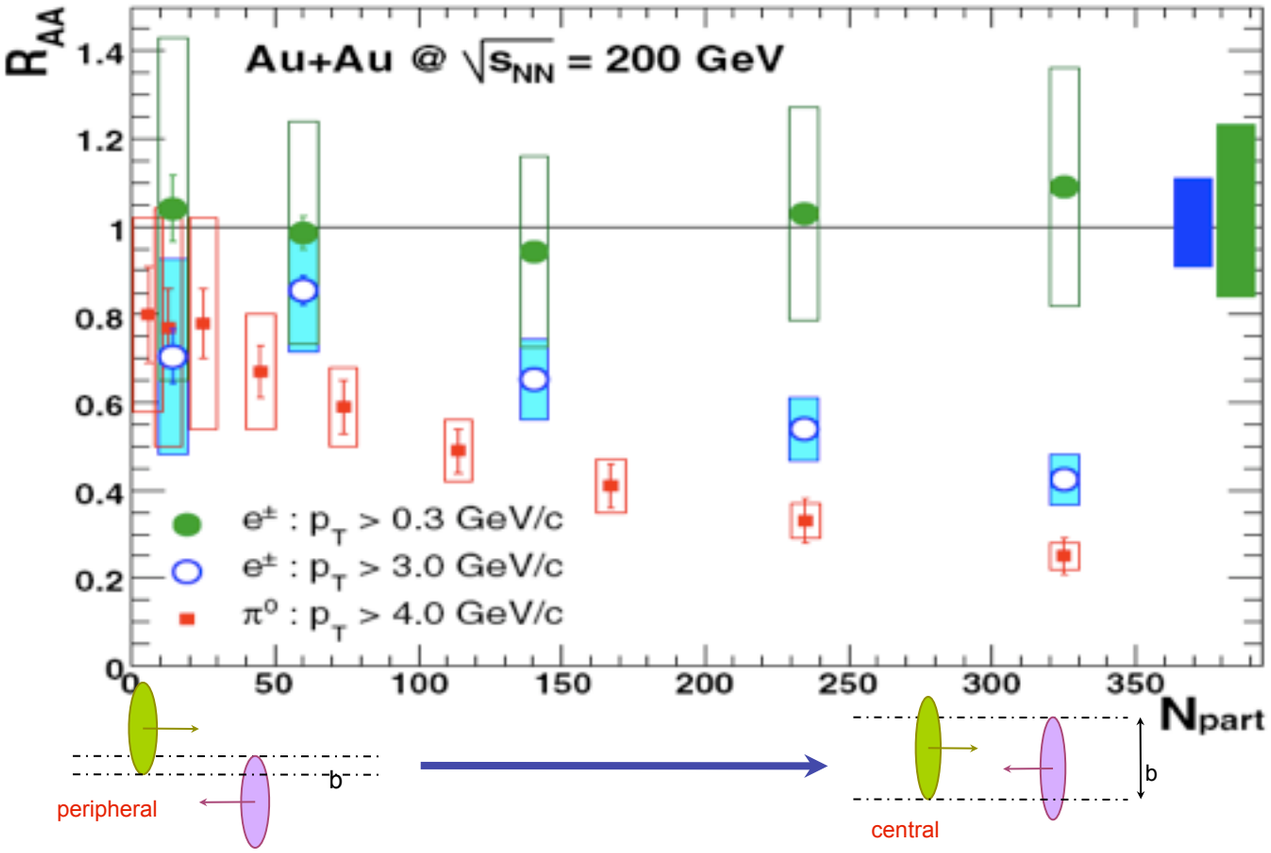
$\sqrt{s_{NN}}$ = 200 GeV and $\sqrt{s_{NN}}$ = 2.76 TeV

Effects in a QGP: A-B collisions ⇨ ⇨ Au-Au, Pb-Pb

- Thermalisation in the QGP (low p_T)
  - Medium transport properties ⇨ dN/dp_T, R_{AA}, v_2
- Energy loss in the QGP (high p_T)
  - Medium density and size ⇨ dN/dp_T, R_{AA}, v_2
  - Color charge (Casimir factor) : $\Delta E_{u,d,s} < \Delta E_g$ ⇨ compare to light hadrons
  - Parton mass (dead cone effect) : $\Delta E_b < \Delta E_c <$... ⇨ compare c and b production

⇨ **Probe of the QCD medium**

RHIC, Heavy Flavor Suppression



AuAu 200 GeV

[STAR, P.R.L.98 (2007) 192301]

[PHENIX, P.R.L.98 (2007) 172301]

➡ Binary scaling of the total HQ-yields, R_{AuAu}(all p_T)~1

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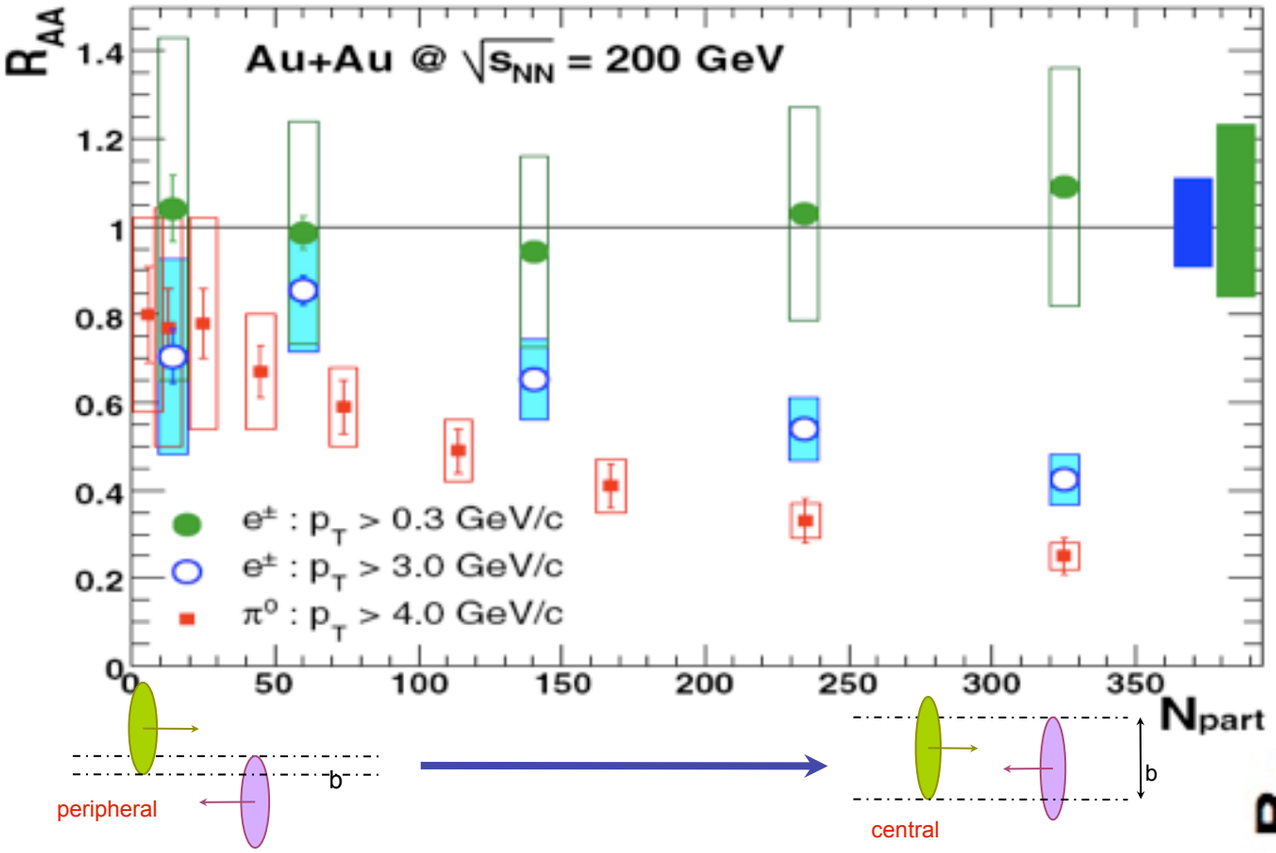
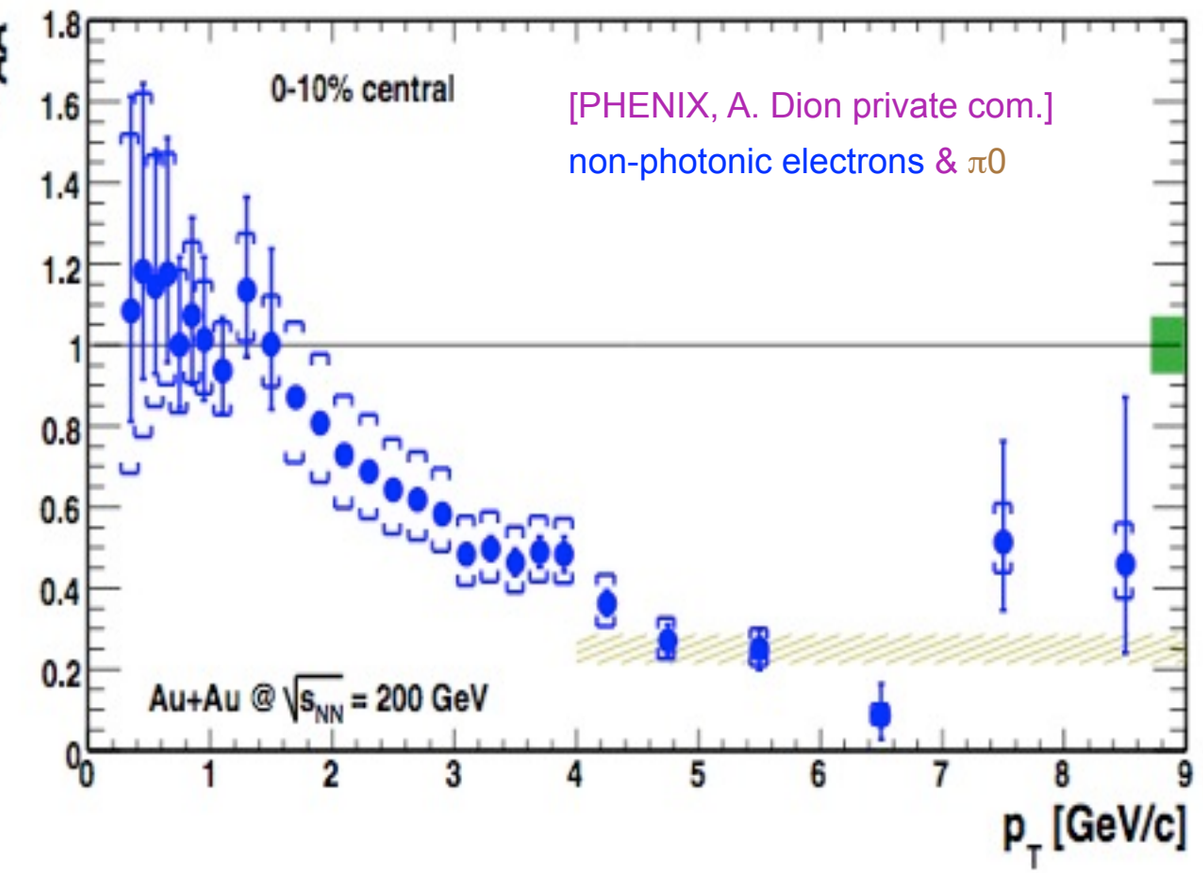
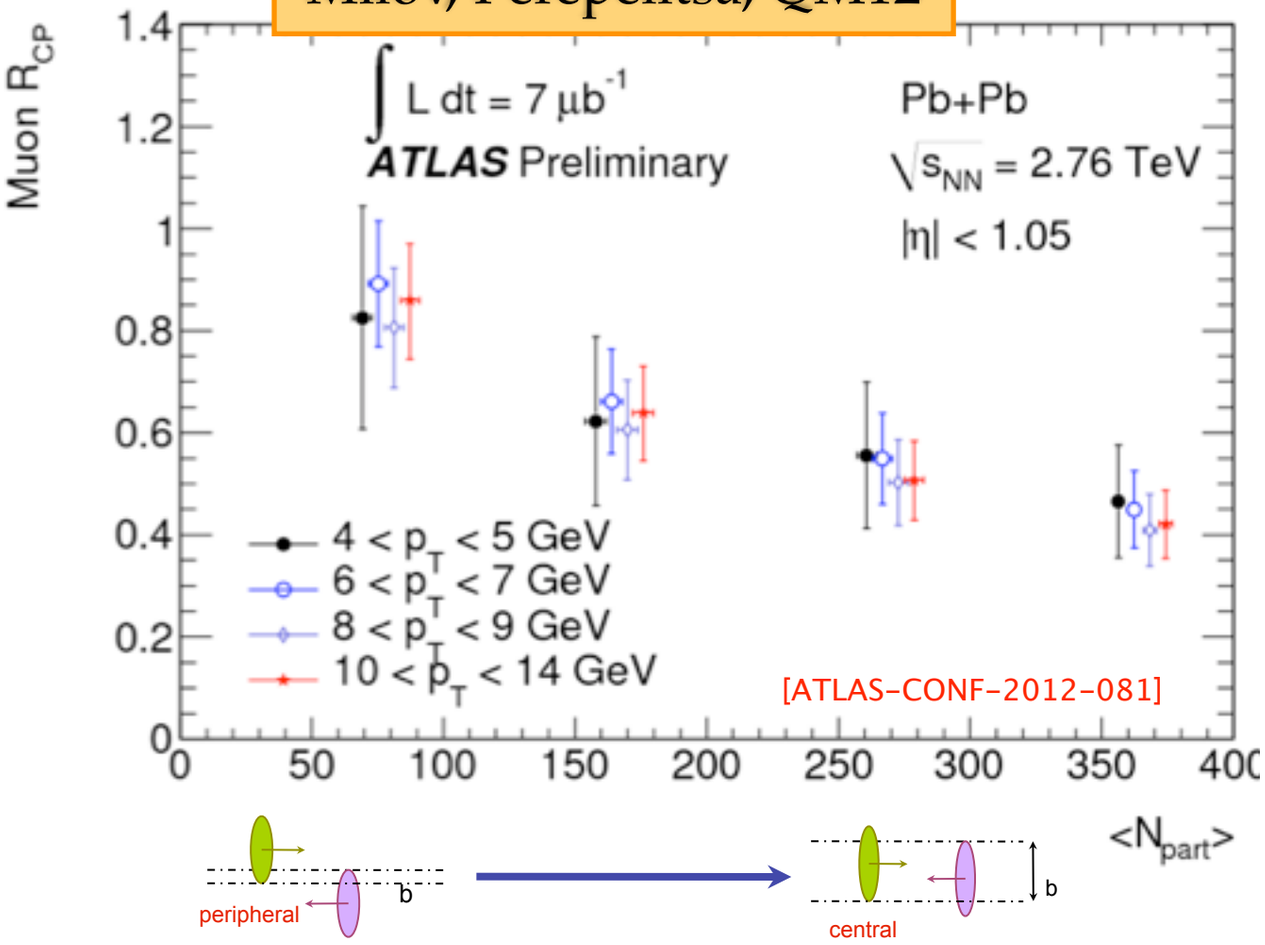


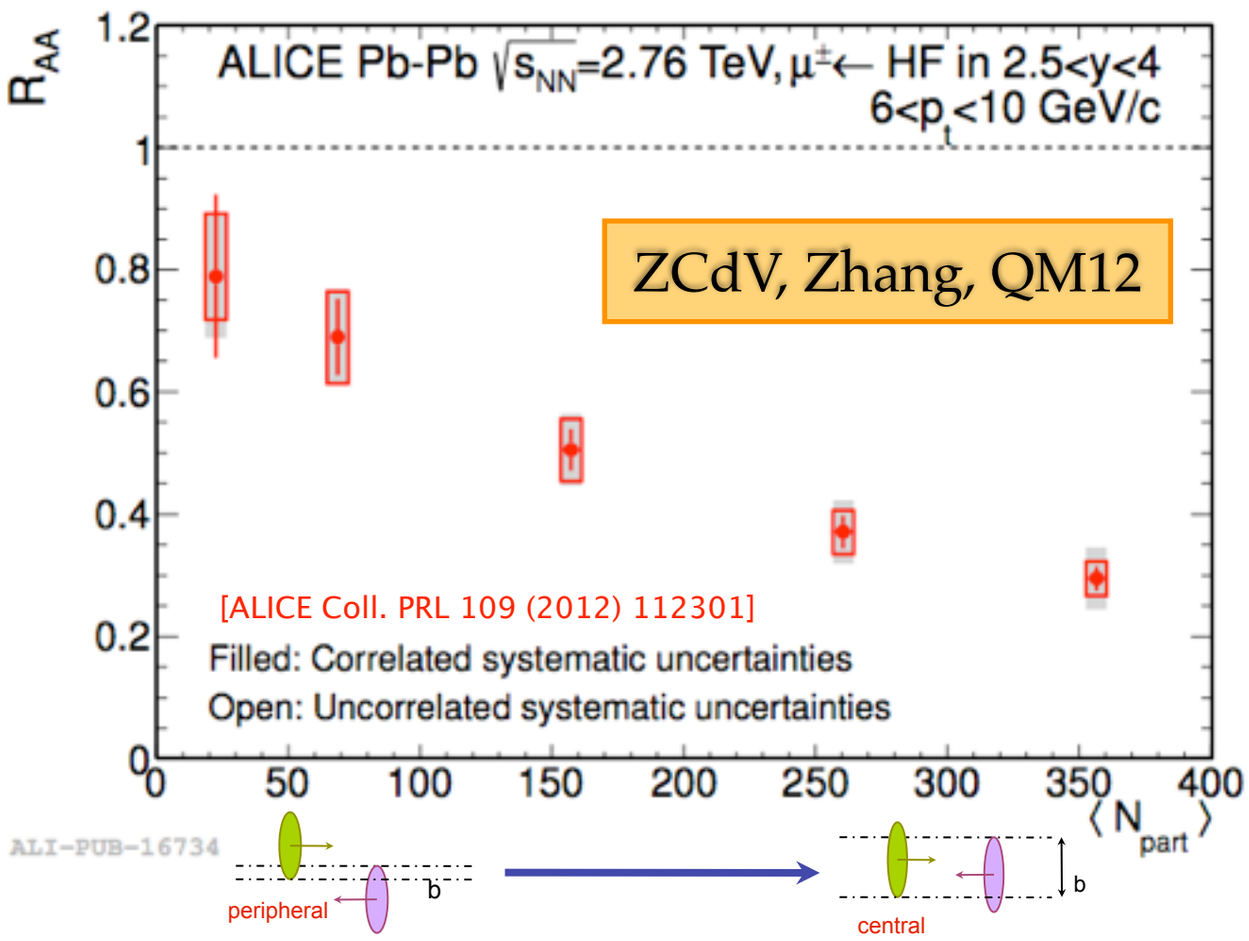
➡ Heavy quarks suffer from energy loss.
At large p_T, HF and π^0 present a similar suppression



HF muons at LHC

Milov, Perepelitsa, QM12





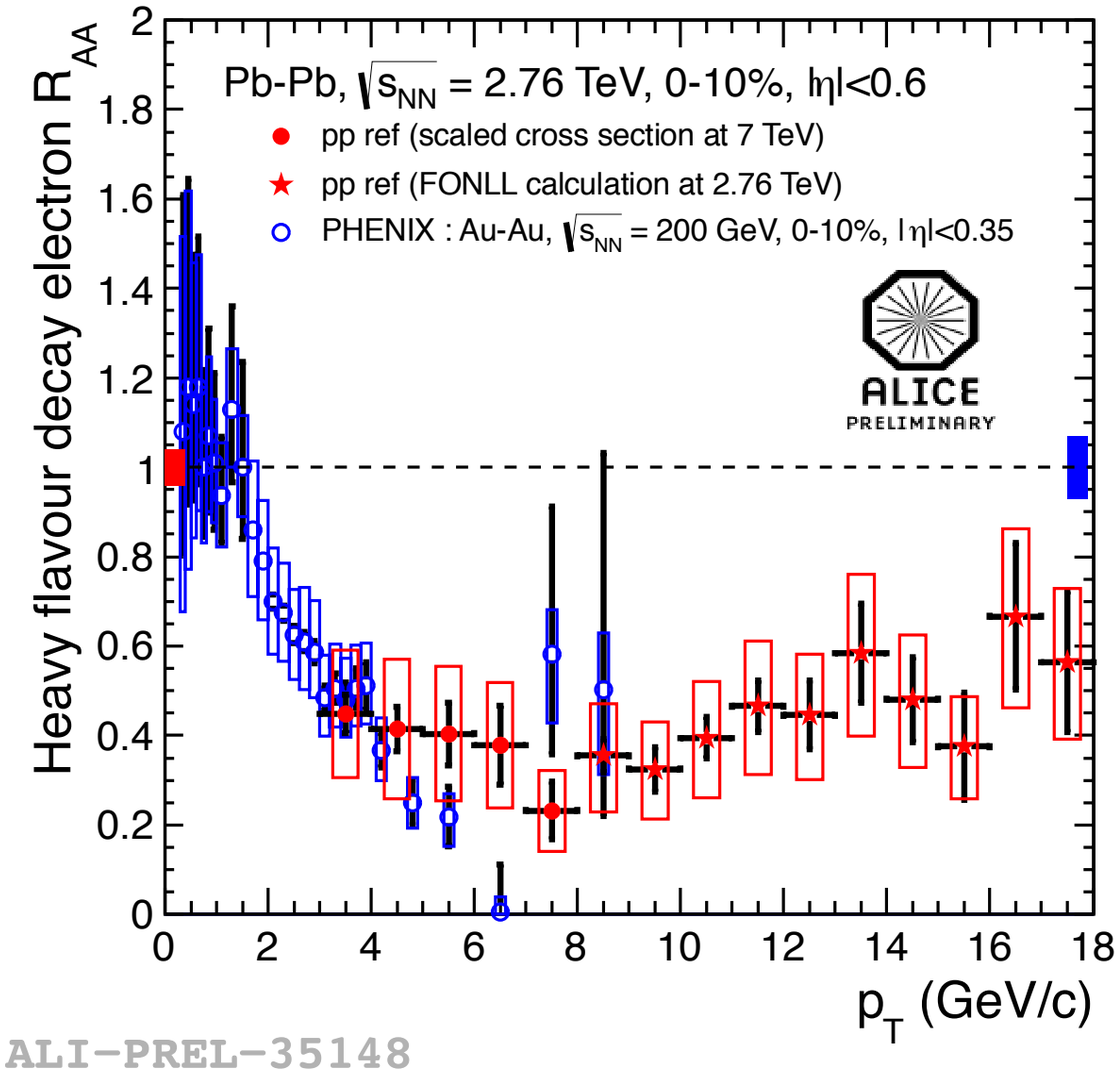
- Central to peripheral ratio at mid-rapidity by ATLAS, R_{CP}:
  - Systematic suppression with centrality
  - No pt dependence
- Consistent results with published RAA at forward rapidity by ALICE

➡ Suppression by a factor of 2-4 in 0-10%

PbPb 2.76 TeV

HFE R_{AA} AT RHIC AND LHC

AuAu 200 GeV | PbPb 2.76 TeV



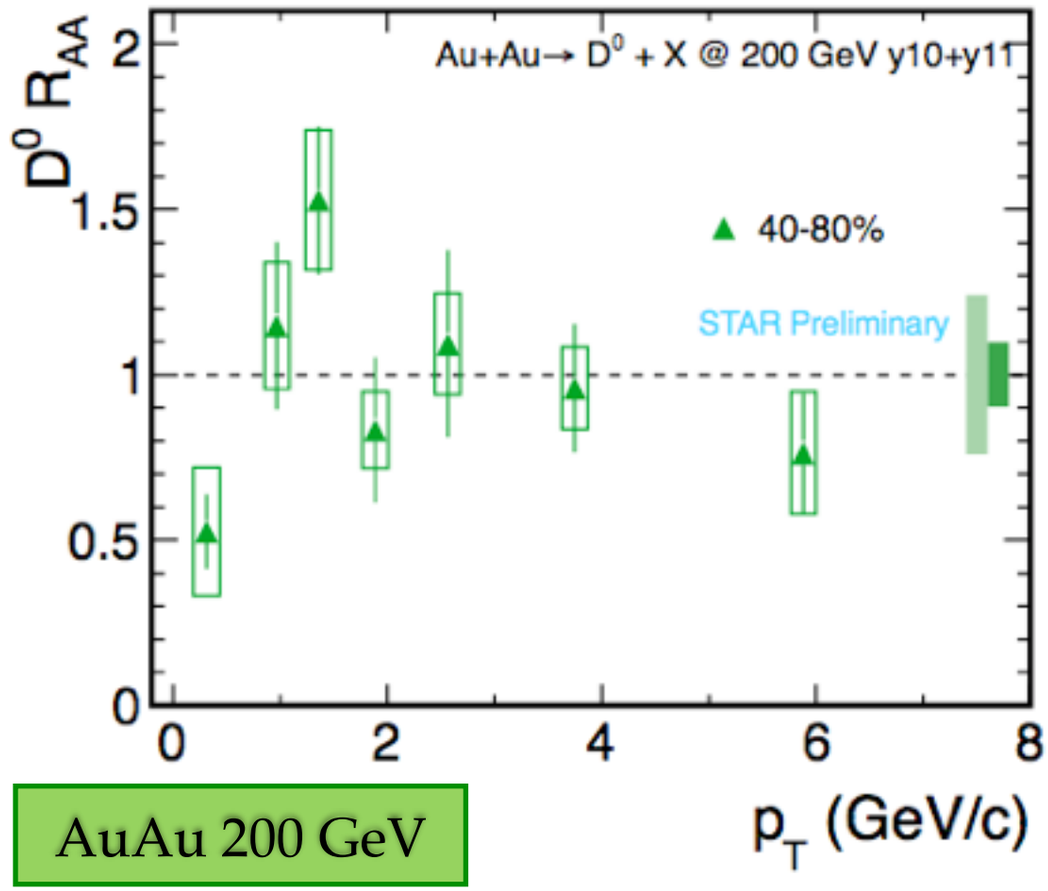
ZCdV, Sakai, QM12

[PHENIX, P.R.L.98 (2007) 172301]

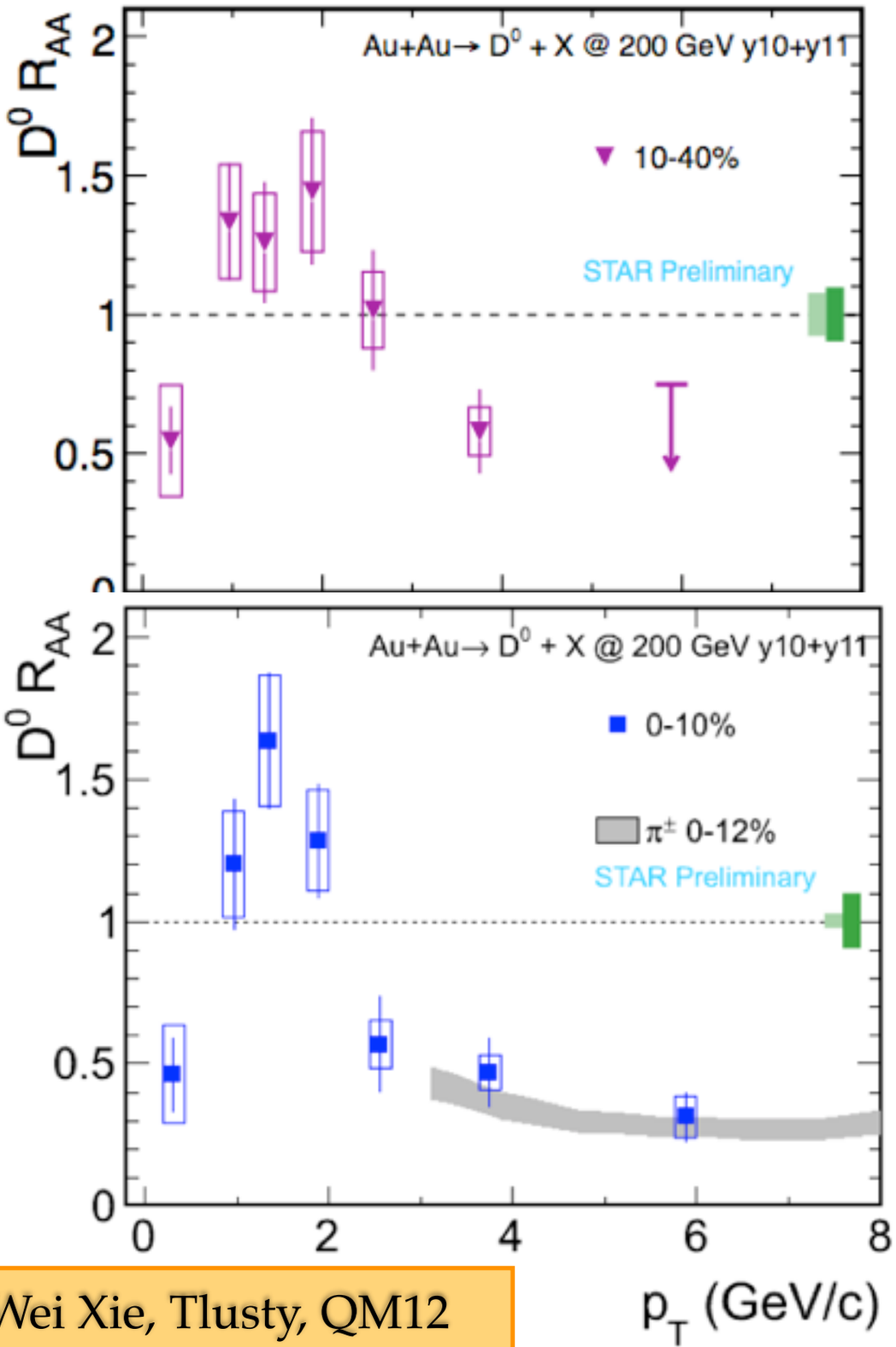
➡ **Similar magnitude of heavy flavor electron suppression at $\sqrt{s_{NN}}$=200GeV (PHENIX, RHIC) and $\sqrt{s_{NN}}$=2.76TeV (ALICE, LHC)**

✳ Caveat: c/b contribution to the HF electron spectra may differ at RHIC and LHC

STAR, Inclusive D^0 meson R_{AA}



AuAu 200 GeV

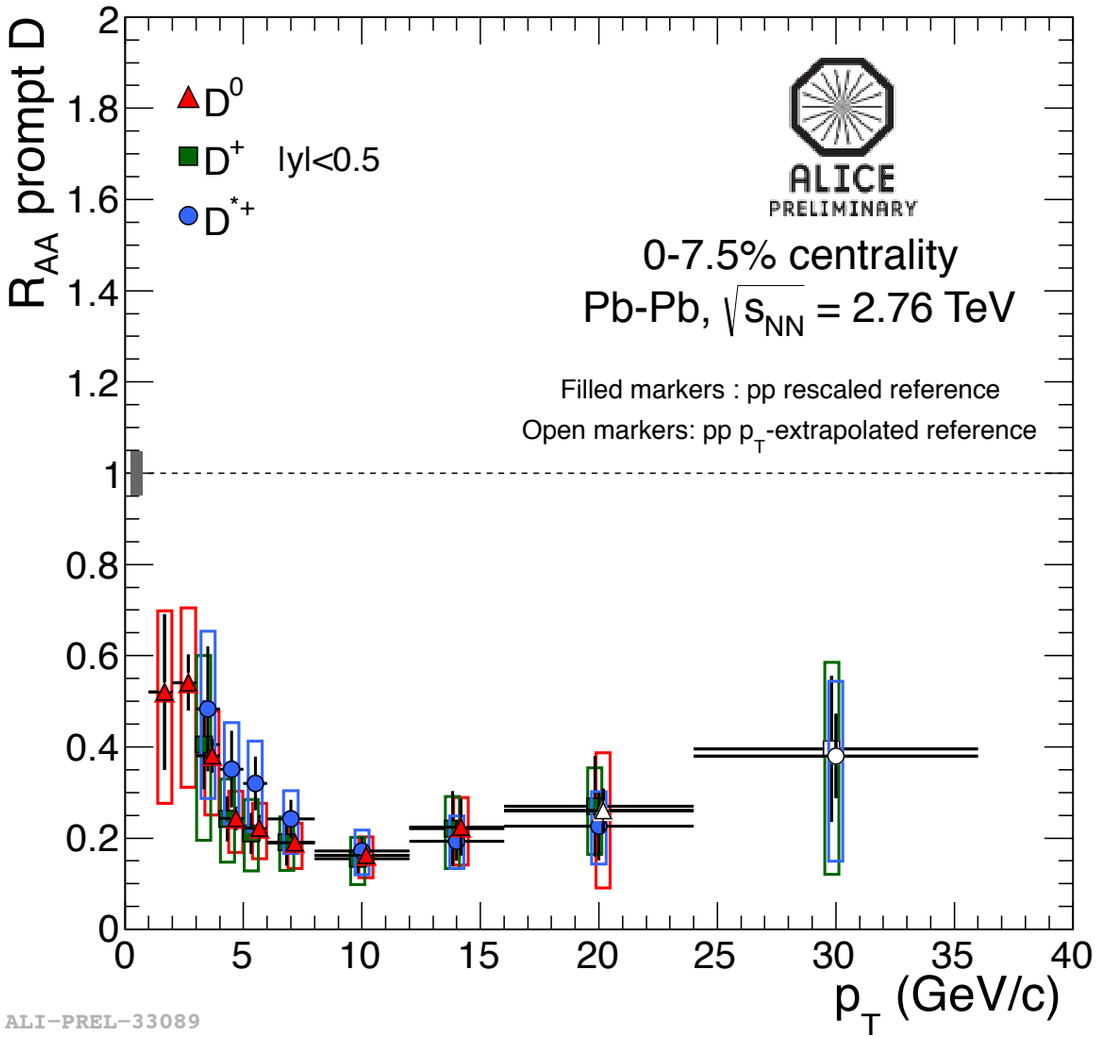


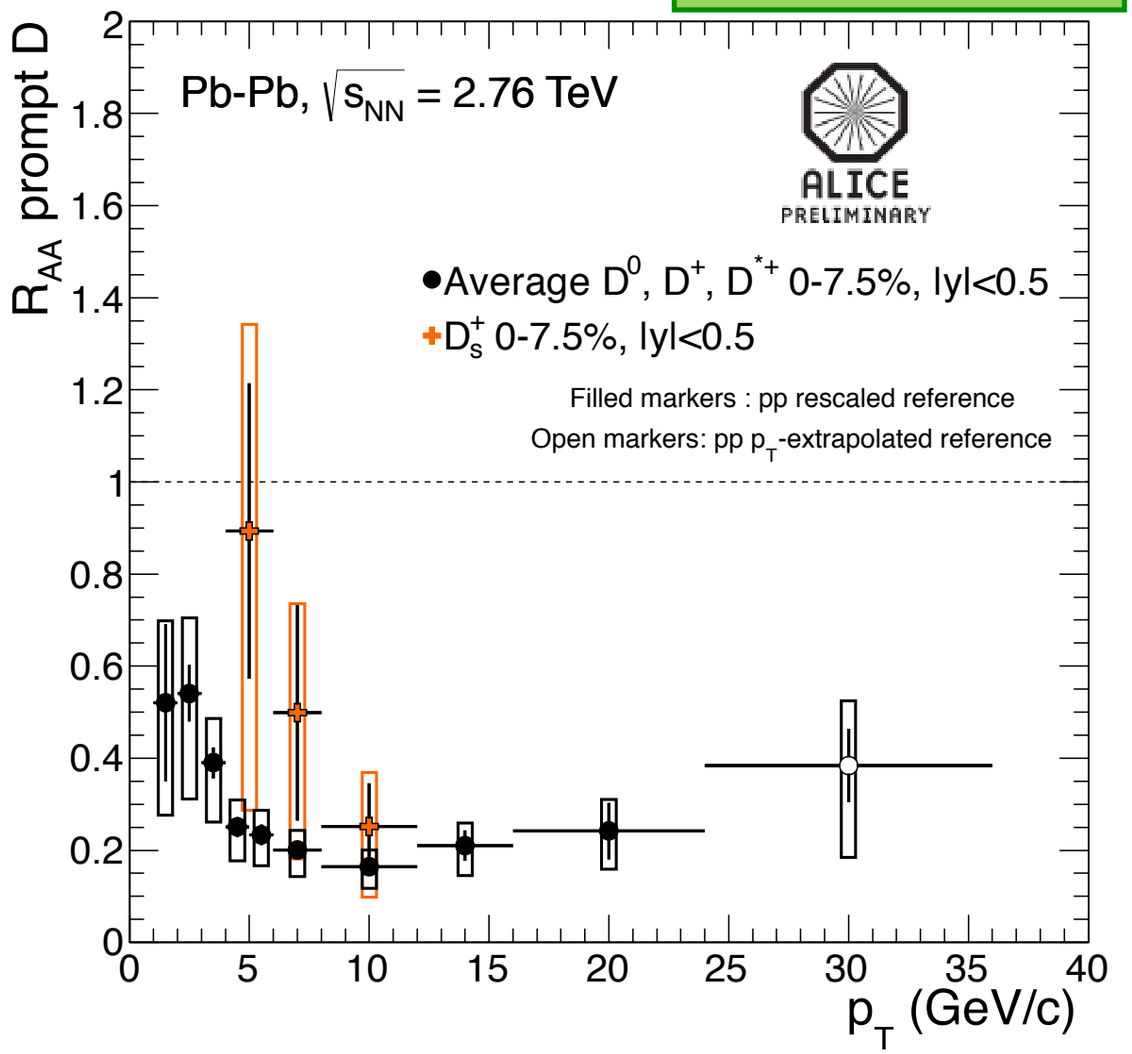
Wei Xie, Tlusty, QM12

- Inclusive D^0 mesons (c+b)
- **Suppression by a factor of 2-2.5 of high pt D^0 in the most central collisions,**
- **while there might be an enhancement at low pt ?**

ALICE, D^0, D^+, D^{*+} D_s^+ MESONS, 0-7.5%

PbPb 2.76 TeV



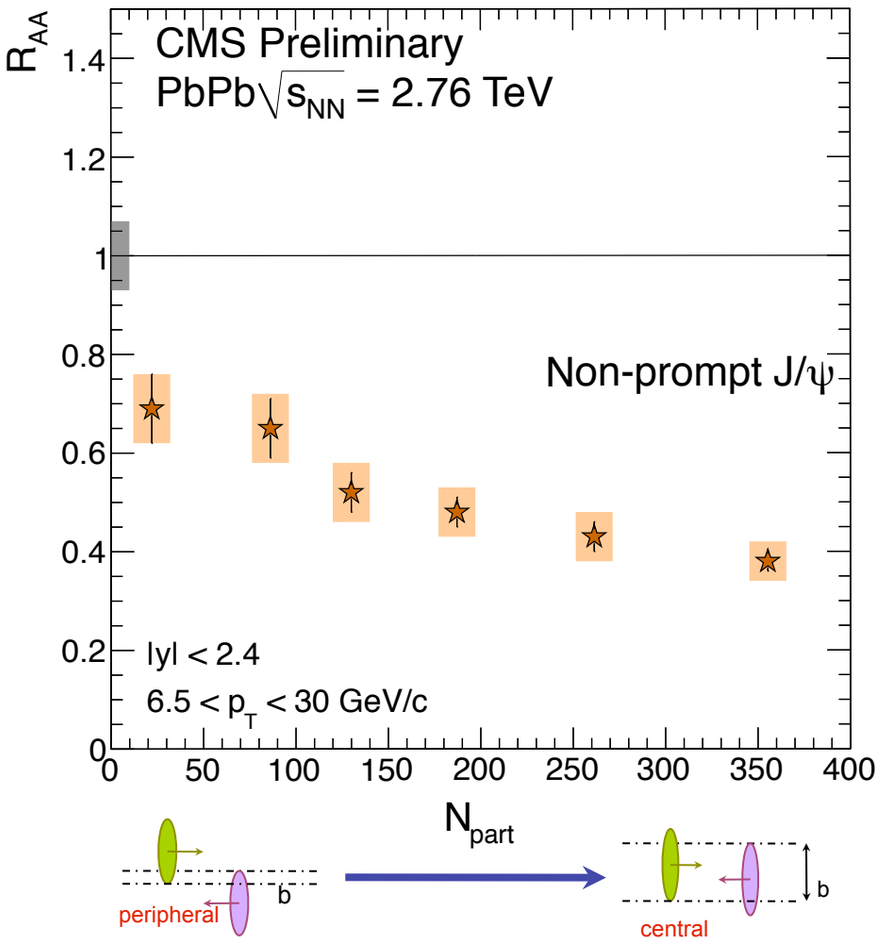


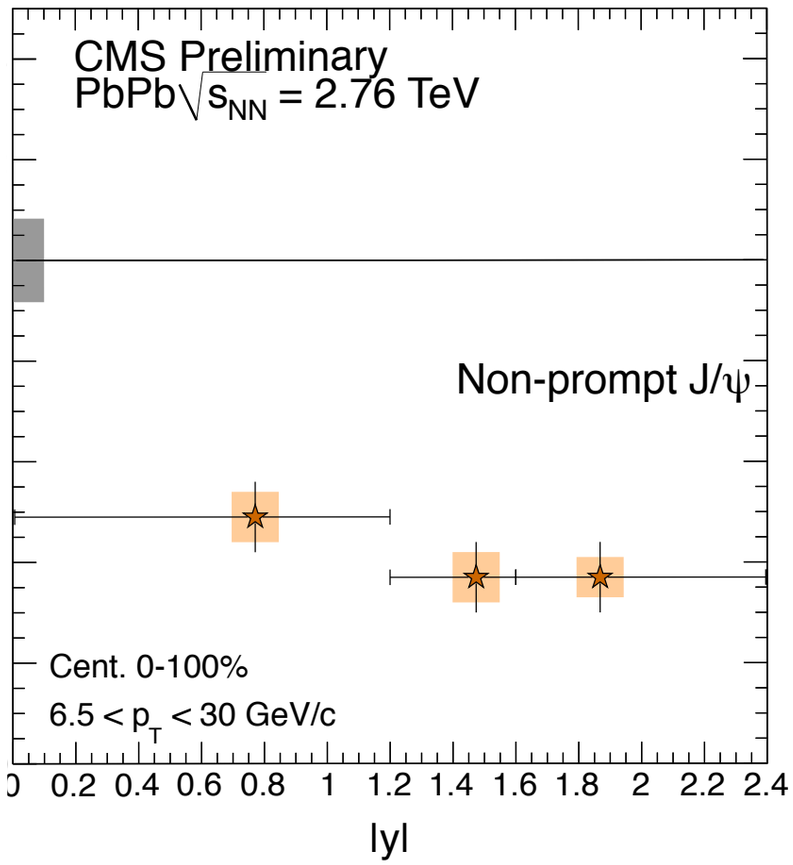
- Suppression by up to a factor of 5 at pT ~10 GeV/c in 0-7.5%
- First measurement of prompt D_s^+ in heavy ion collisions
- D_s^+ suppression similar to that of the D^0, D^+, D^{*+}

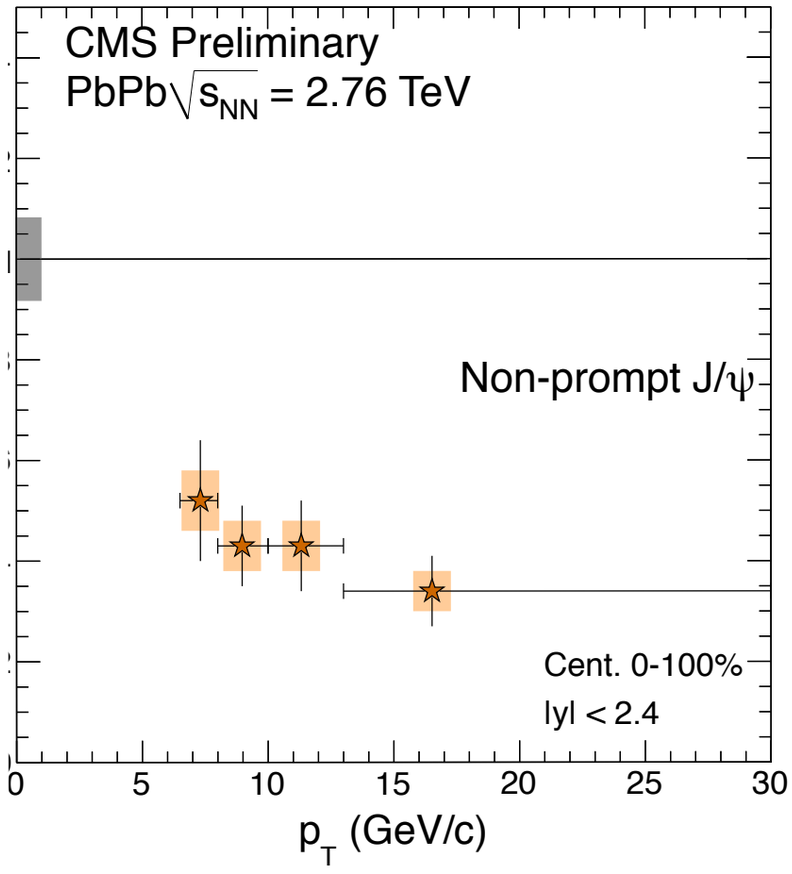
[ALICE Coll. arXiv:1203.2160 (2012)]

ZCdV, Grelli, Innocenti QM12

CMS, Non-Prompt J/ψ







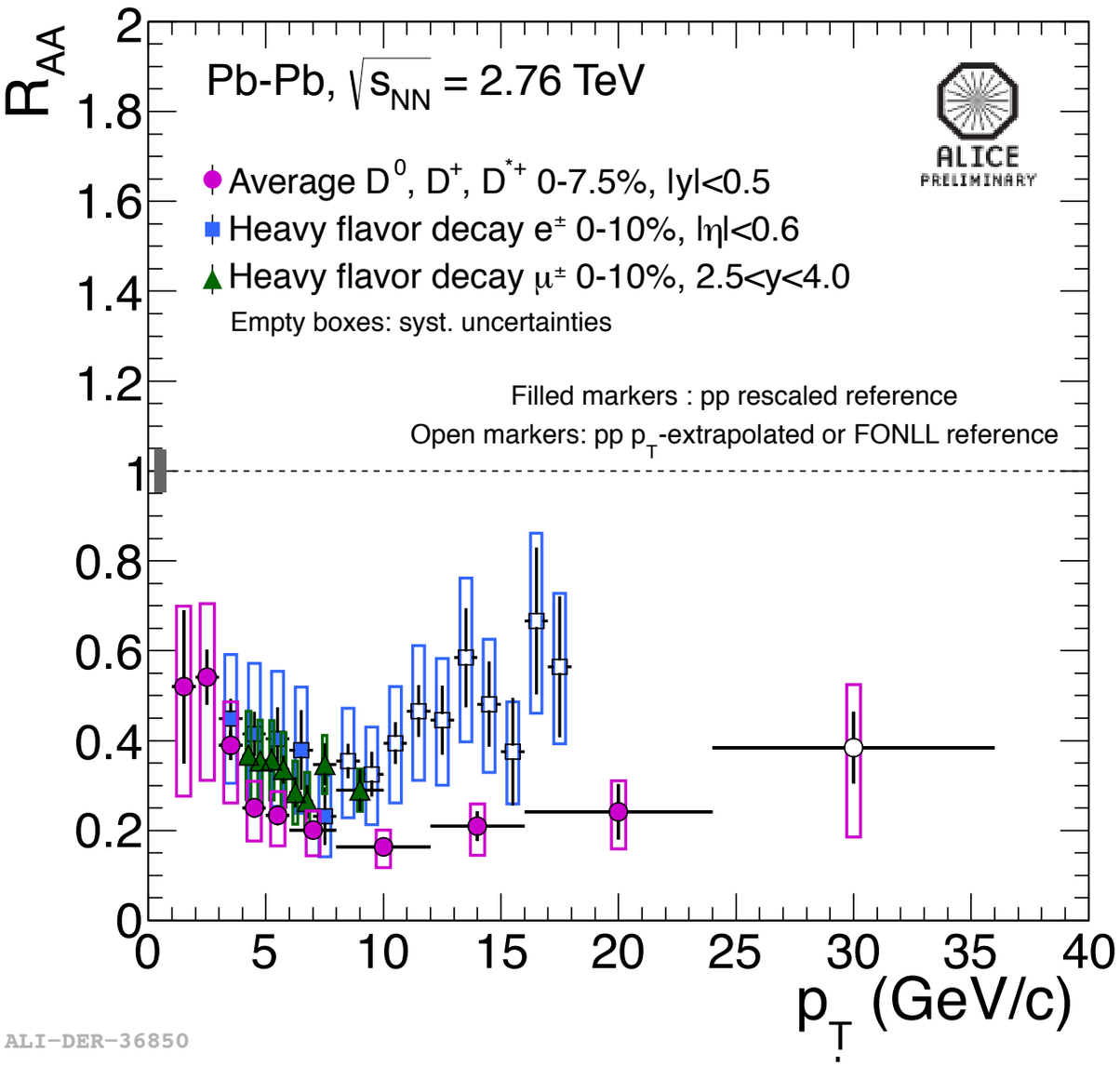
- Centrality dependence of B→J/ψ R_{AA}
  - 50-100%: factor ~1.4
  - 0-5%: factor ~2.5
- Hint of less suppression at mid-rapidity
- Hint of larger suppression at higher pt

PbPb 2.76 TeV

Mironov, Jo, QM12

LHC, R_{AA} p_T Dependence I

PbPb 2.76 TeV

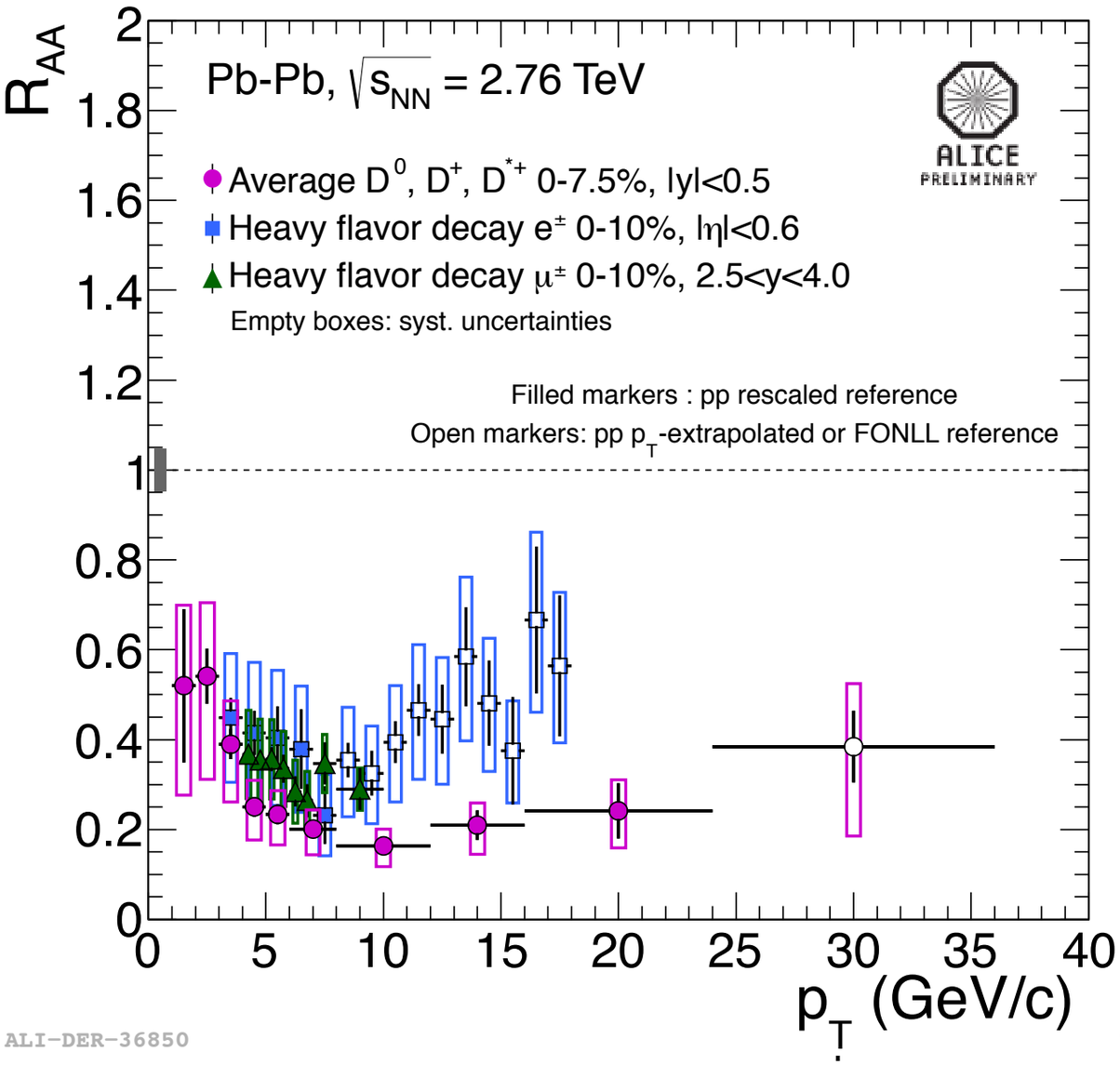


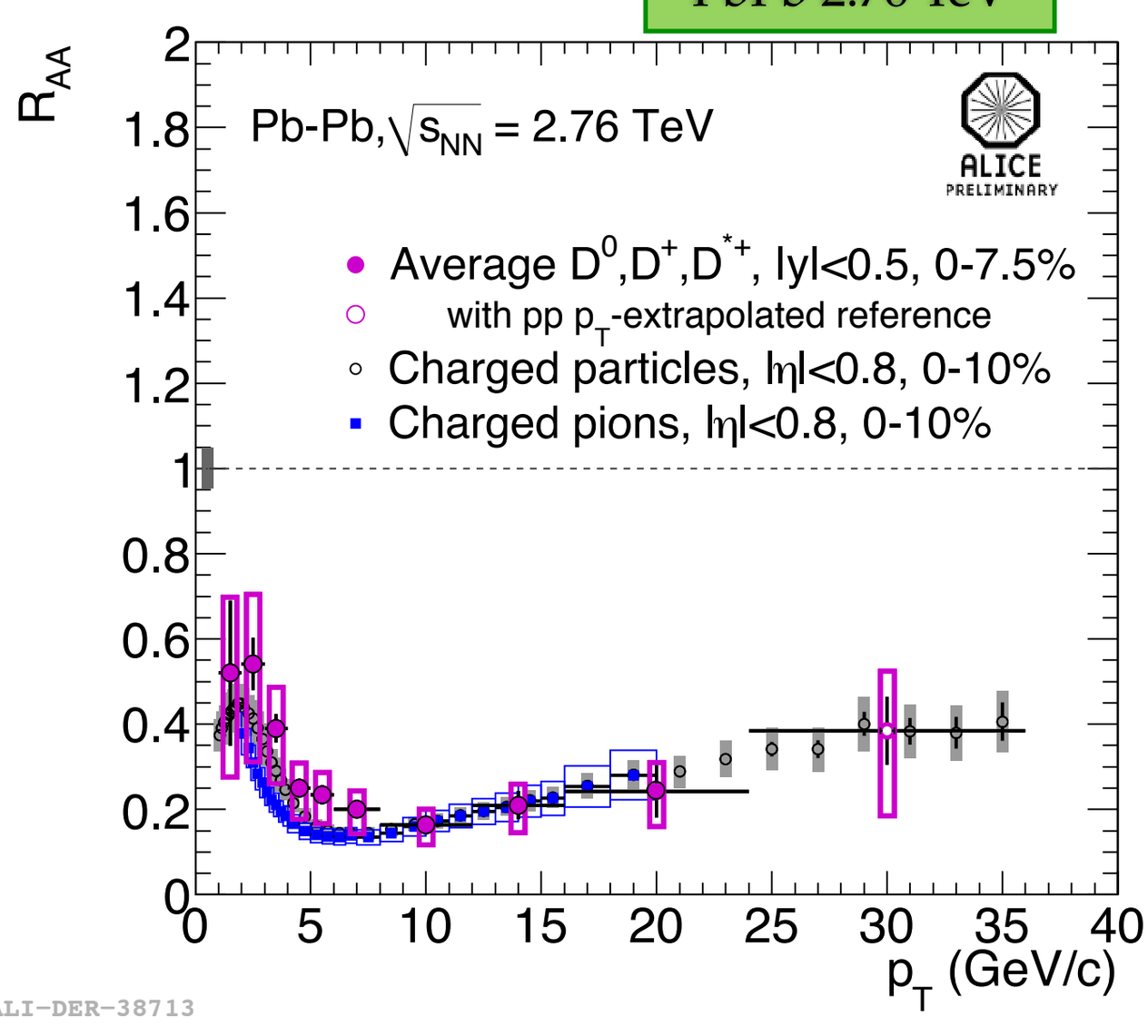
- Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%
- they are also comparable with D mesons R_{AA} (|y|<0.5) in 0-7.5% considering the semileptonic decay kinematics ($p_T^e \sim 0.5\ p_T^B$ at high p_T)

[ALICE Coll. arXiv:1205.6443 (2012)]

LHC, R_{AA} p_T Dependence I

PbPb 2.76 TeV

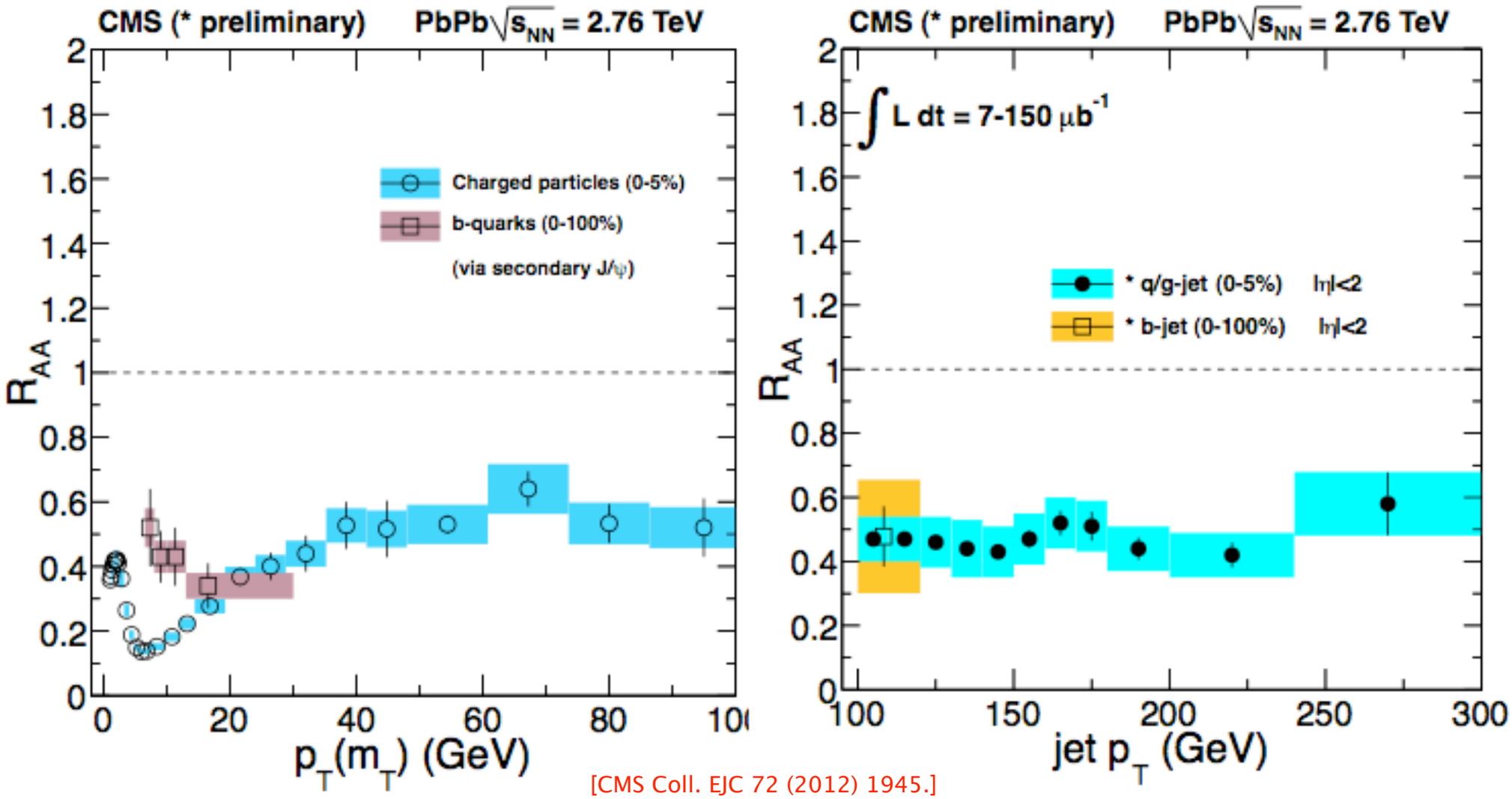




- Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%
- they are also comparable with D mesons R_{AA} (|y|<0.5) in 0-7.5% considering the semileptonic decay kinematics ($p_T^e \sim 0.5\ p_T^B$ at high p_T)
- D R_{AA} shows a similar trend as charged particles and $\pi^{\pm}$ in 0-10%

[ALICE Coll. arXiv:1205.6443 (2012)]

LHC, R_{AA} p_T Dependence II



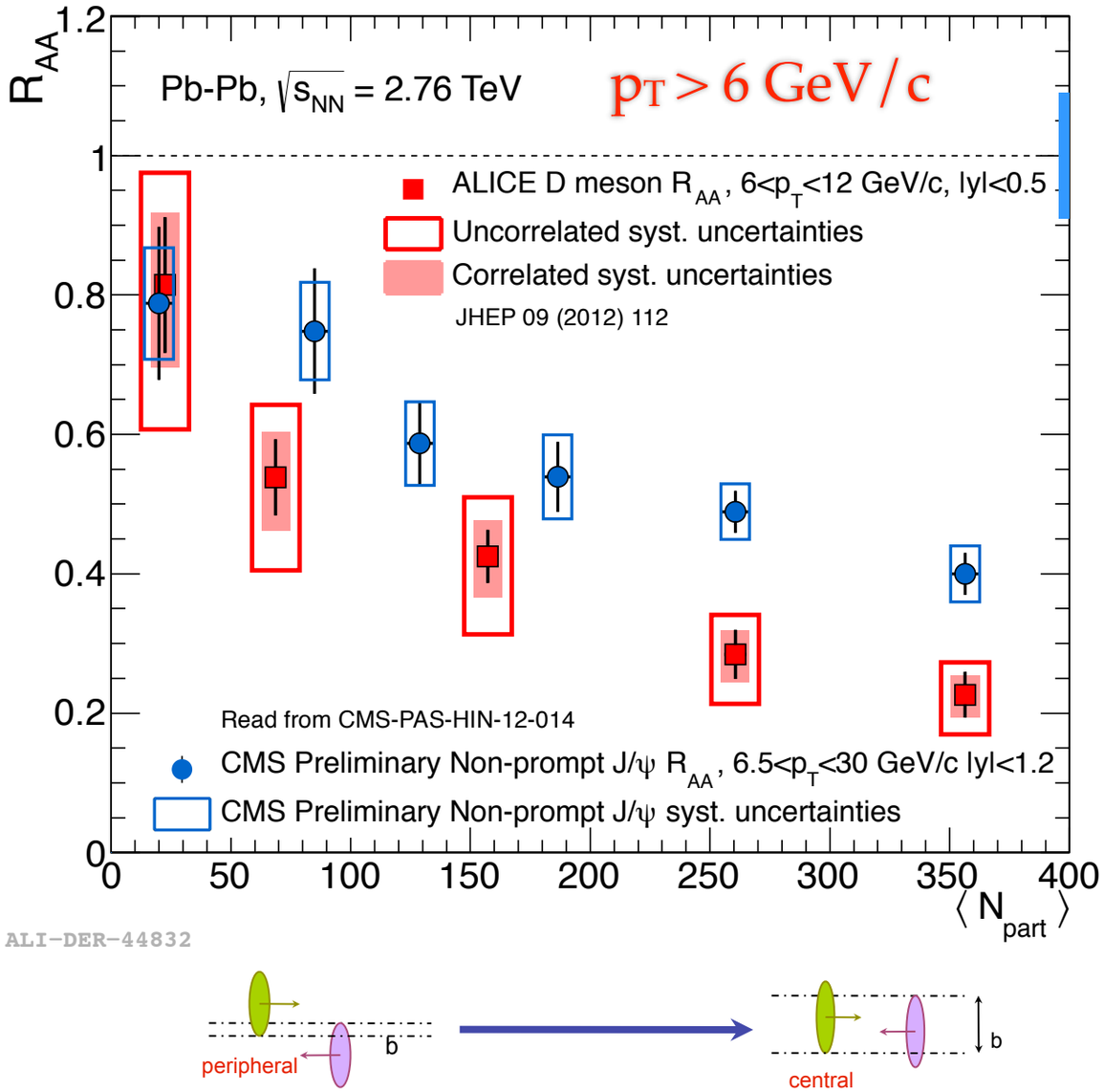
[CMS Coll. EJC 72 (2012) 1945.]

- Different suppression pattern than charged particles at low pt
- while at high pt the suppression is similar

PbPb 2.76 TeV

Mironov, Nguyen, QM12

LHC, R_{AA} Centrality Dependence



PbPb 2.76 TeV

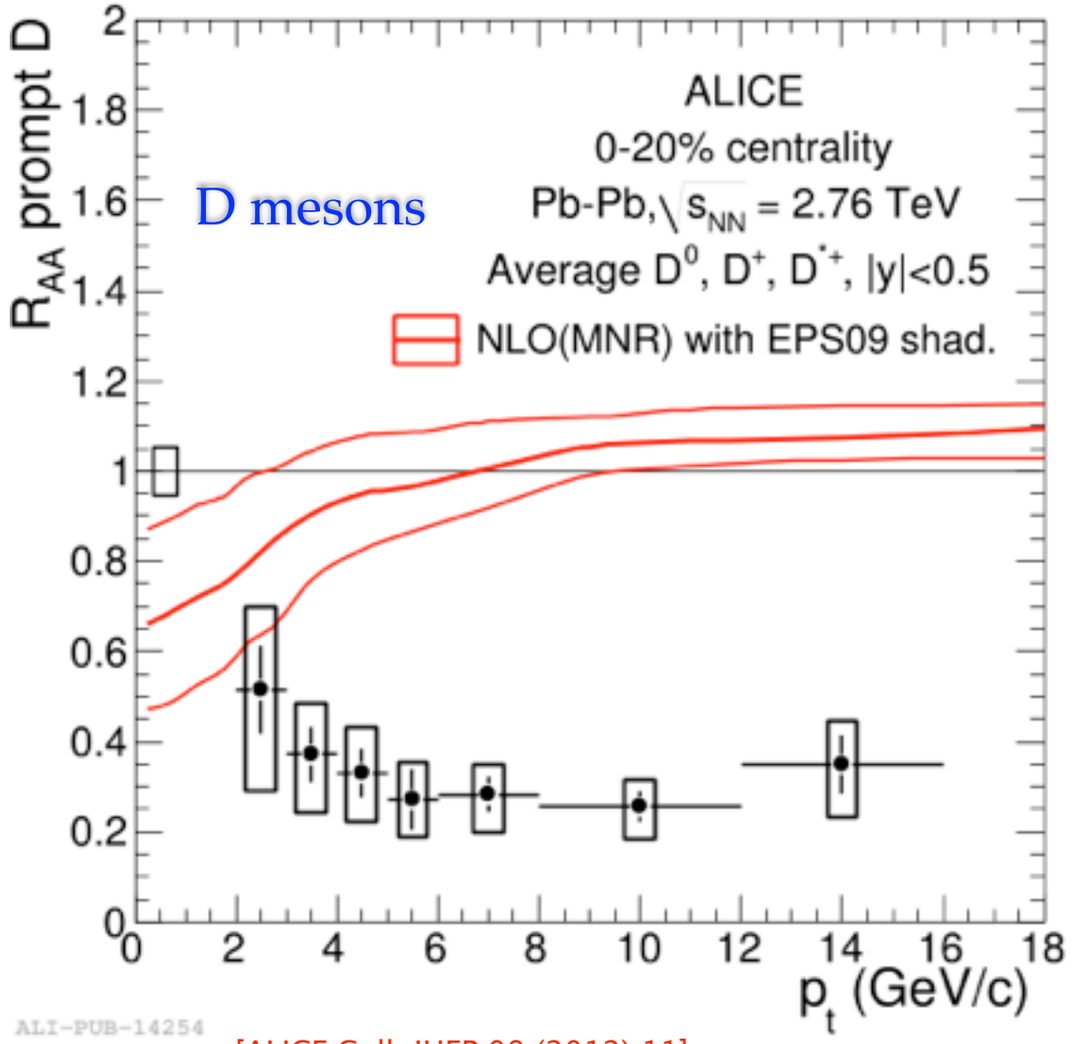
Mironov. QM12

[ALICE Coll. JHEP 09 (2012) 11]

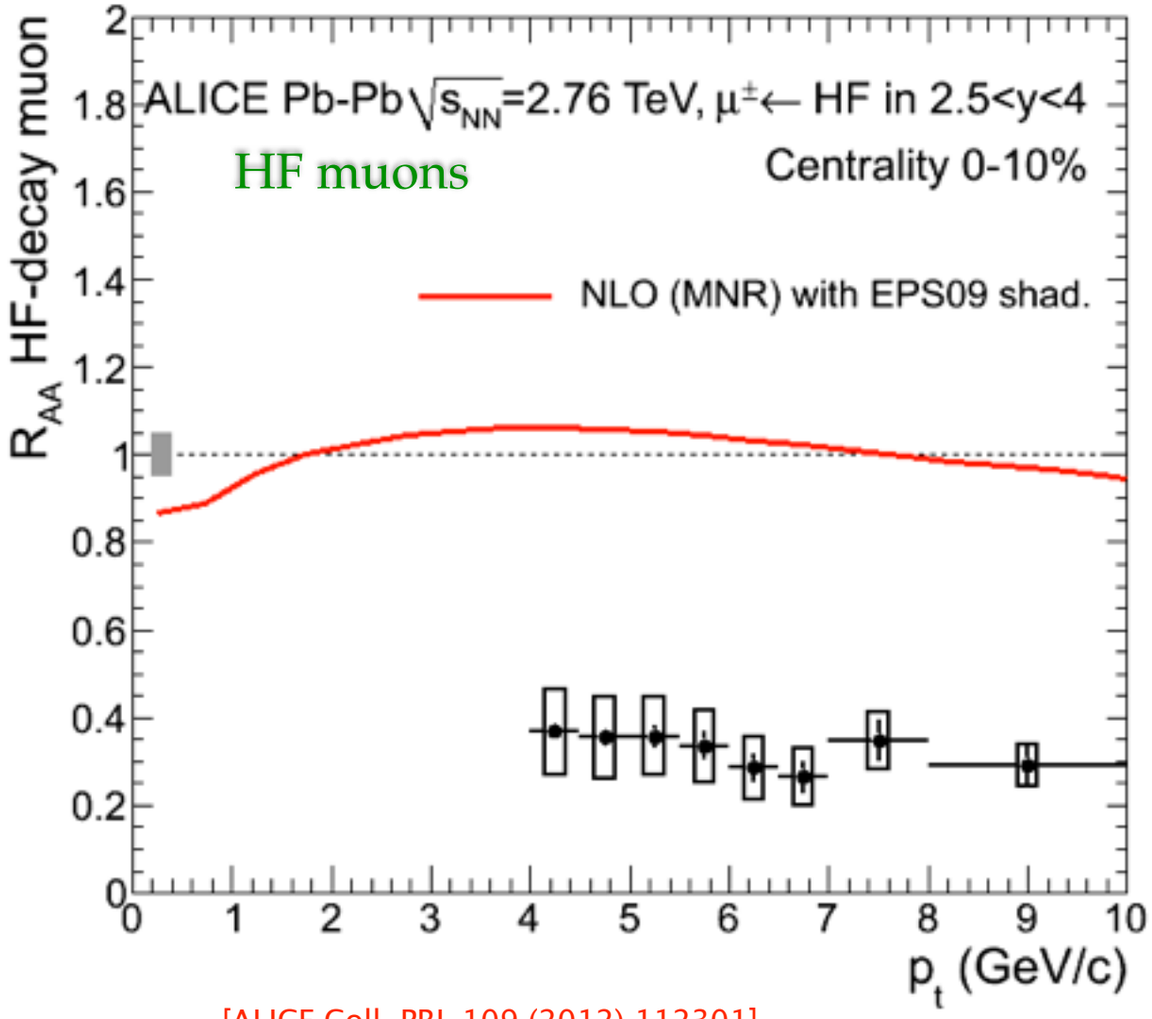
➡ In central collisions, for pt>6 GeV/c, non-prompt J/ψ (CMS) seem less suppressed than prompt D mesons, albeit the difference on the b/c average pt.

Cold Nuclear Matter & HF R_{AA}

PbPb 2.76 TeV



[ALICE Coll. JHEP 09 (2012) 11]

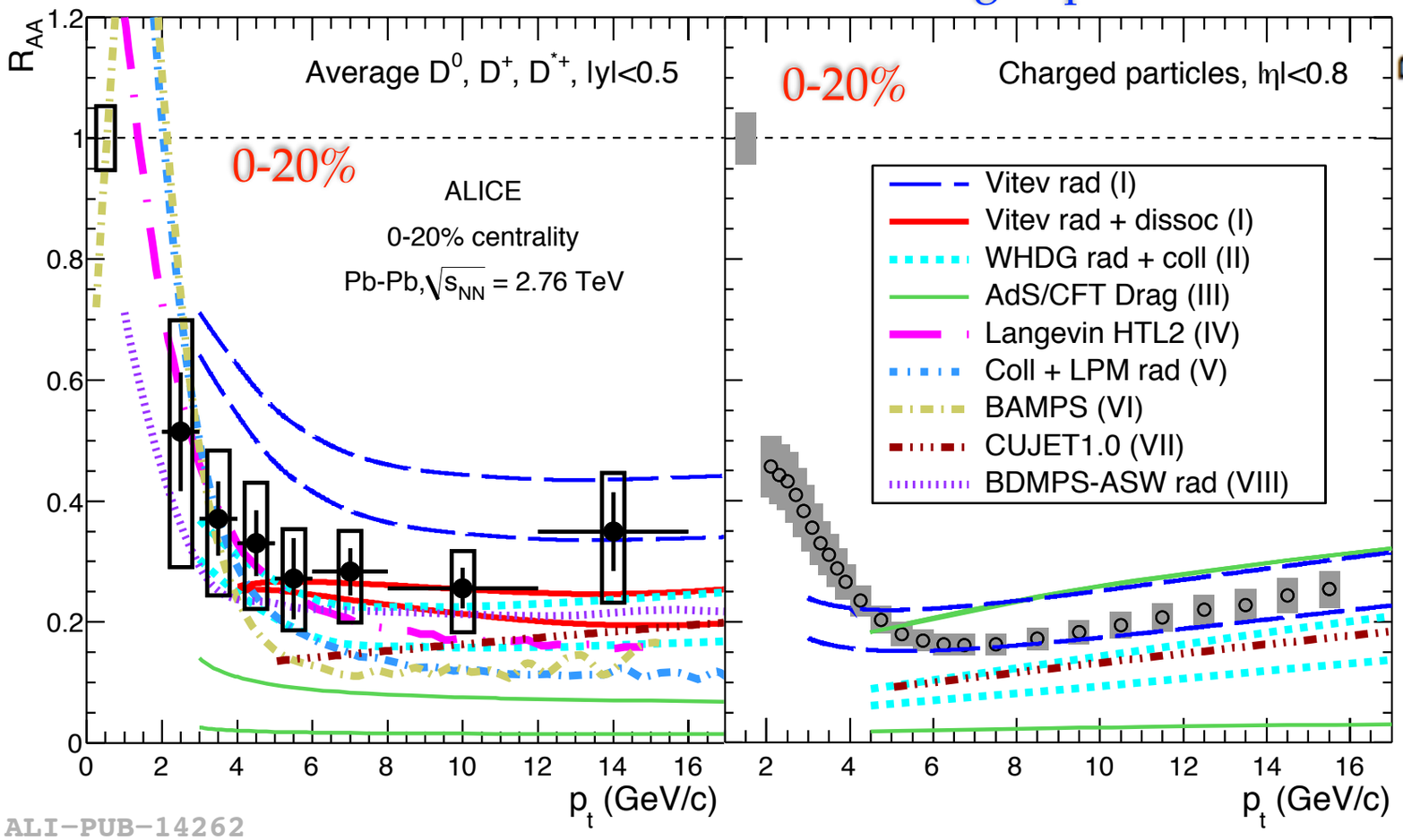


[ALICE Coll. PRL 109 (2012) 112301]

➡ HF decay μ & D mesons R_{AA} suppression in the most central collisions can not be explained by shadowing alone for p_T>4 GeV/c
⇨ likely a final state effect
⇨ need pPb data to quantify initial state effects

Models Description of R_{AA}

D mesons

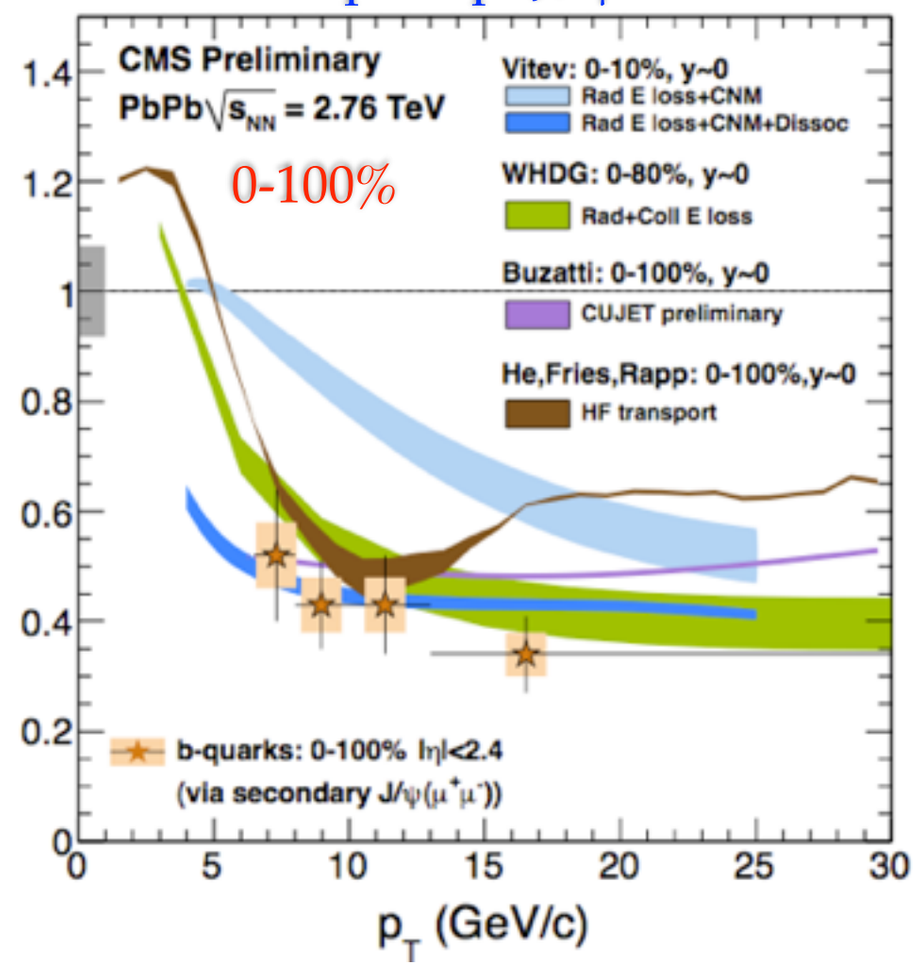


[ALICE Coll. JHEP 09 (2012) 11]

Charged particles

[ALICE Coll. arXiv: 1208.2711 (2012)]

Non-prompt J/ψ



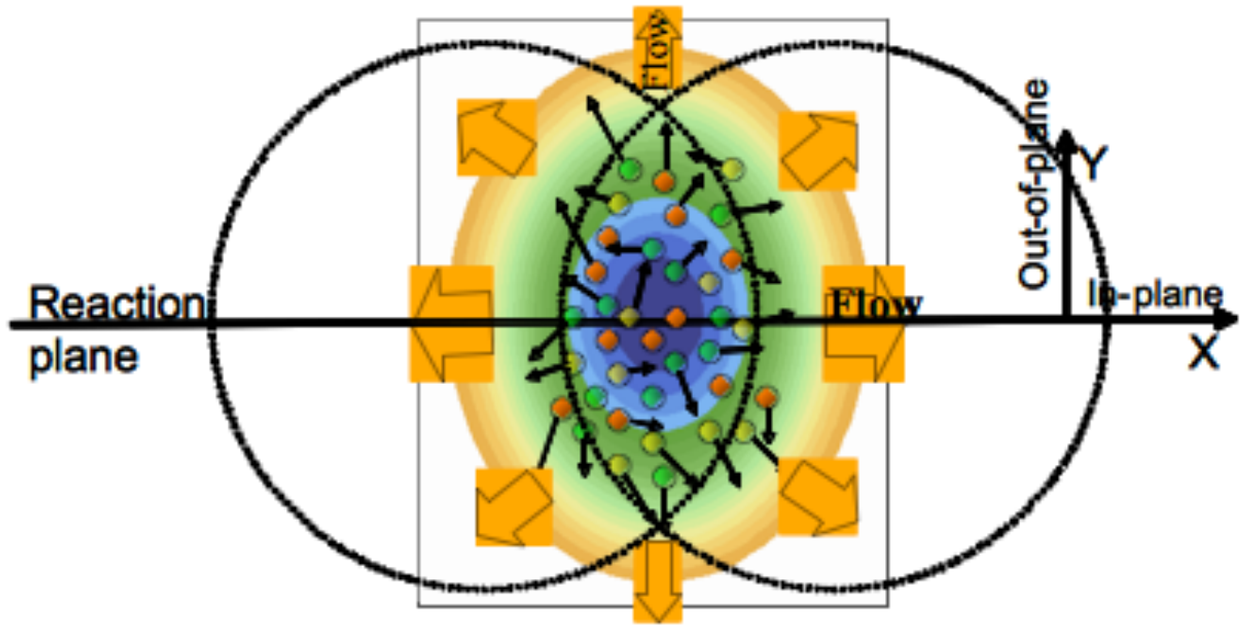
[CMS Coll. QM12]

PbPb 2.76 TeV

➡ **Models predict quantitatively well both light, charm and beauty R_{AA}**

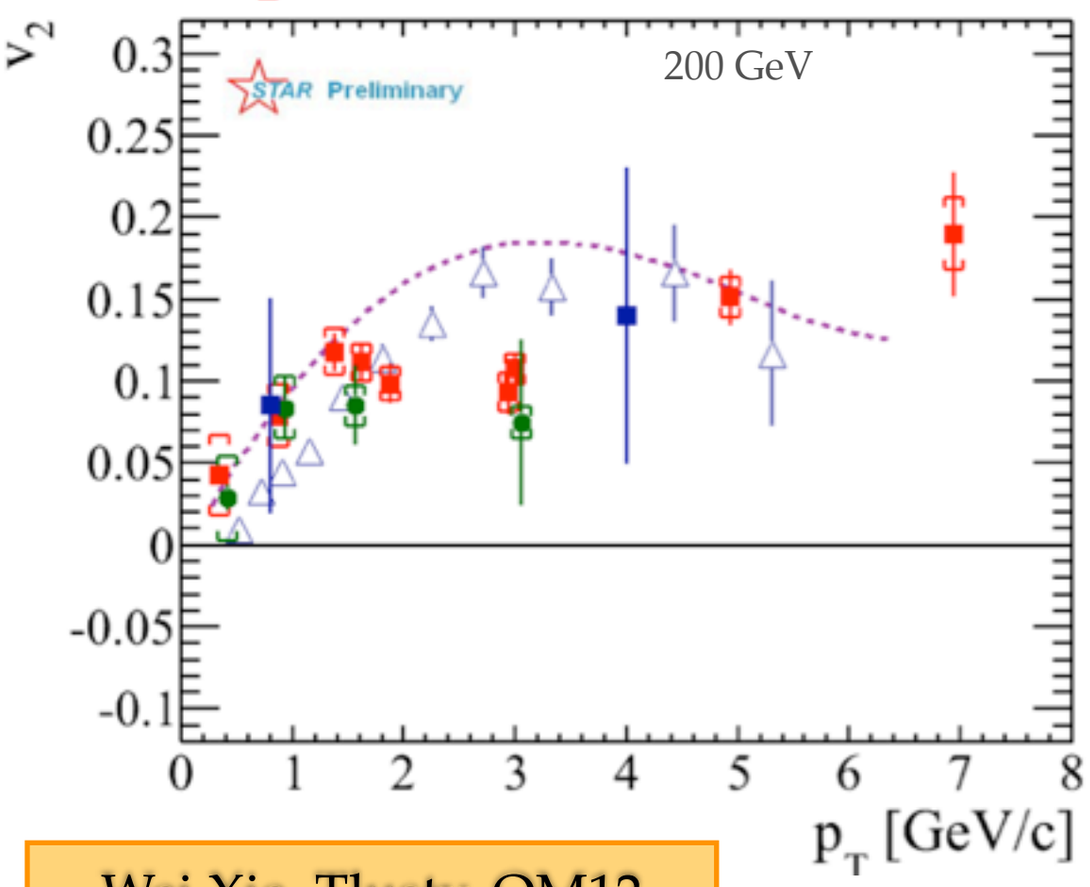
Azimuthal Anisotropy

- Heavy flavor is suppressed up to high p_T... Azimuthal dependence ?
- Address path length dependence of HQ energy loss at high p_T ?
- Collective motion (flow) at low p_T ?

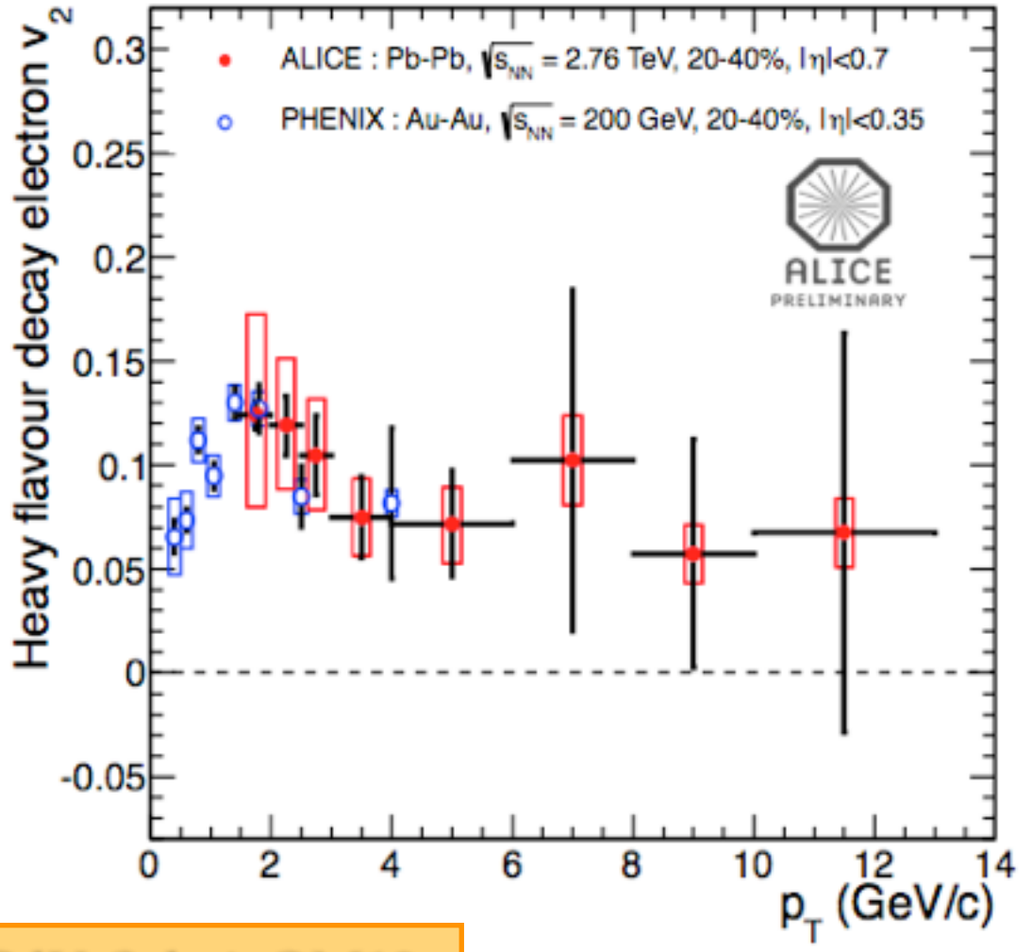


$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

Heavy Flavor Electron v_2



Wei Xie, Tlusty, QM12



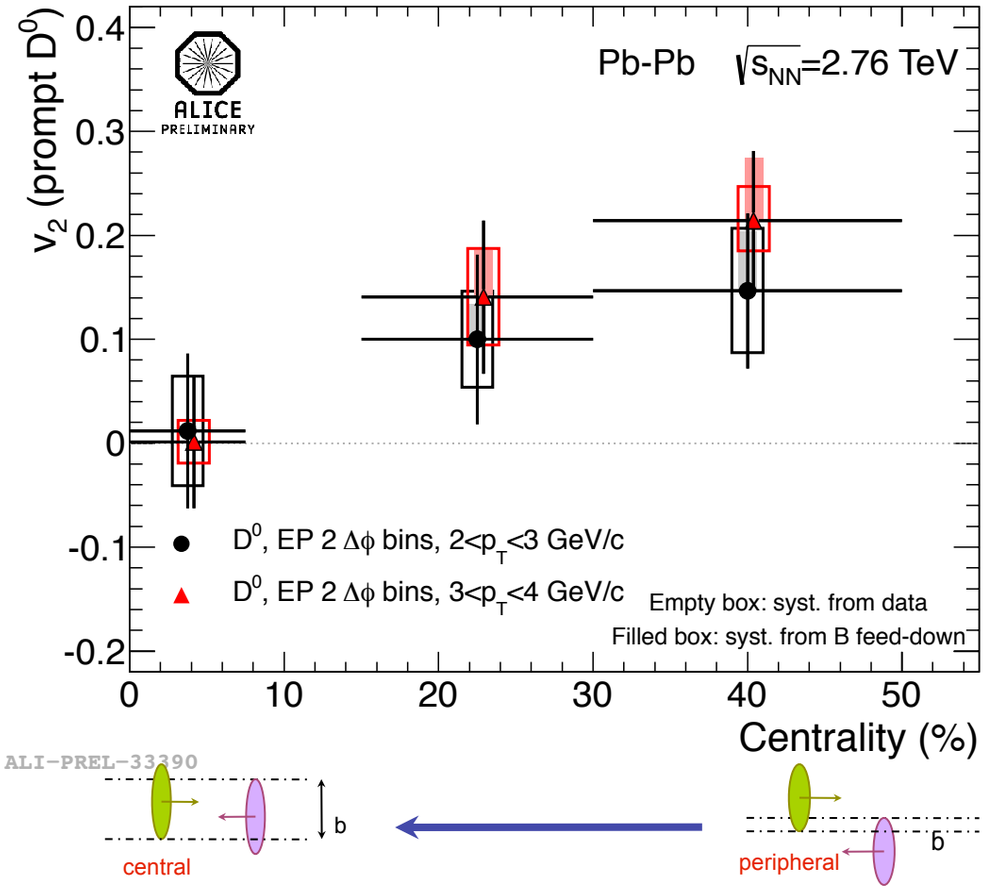
ZCdV, Sakai, QM12

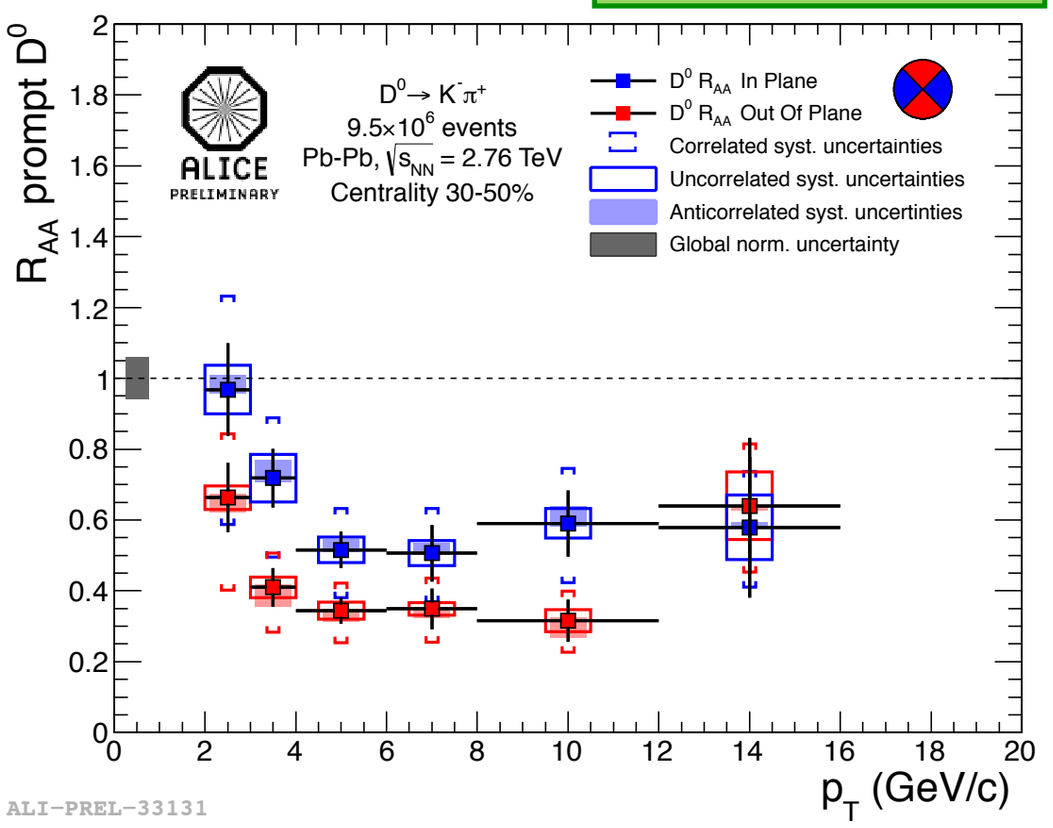
AuAu 200GeV

- Non-photonic / HF electron v_2 :
  - At 39 and 62 GeV consistent with zero within uncertainties
  - **At 200 GeV, v_2>0 for p_T > 3 GeV/c**
  - **At 2.76 TeV, v_2>0 at low p_T (>3σ effect in 2<p_T<3 GeV/c)**

Further Insight at LHC ?

PbPb 2.76 TeV

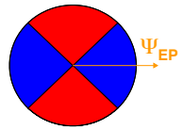




- Indication of non-zero D meson v_2 (3σ effect in 2<p_T<6 GeV/c)
- Hint of centrality dependence at low p_T
- Larger suppression **OutOfPlane** than **InPlane** up to p_T~10 GeV/c
  - might indicate elliptic flow at low p_T
  - might indicate longer path length at high p_T

ZCdV, Caffarri, QM12

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$

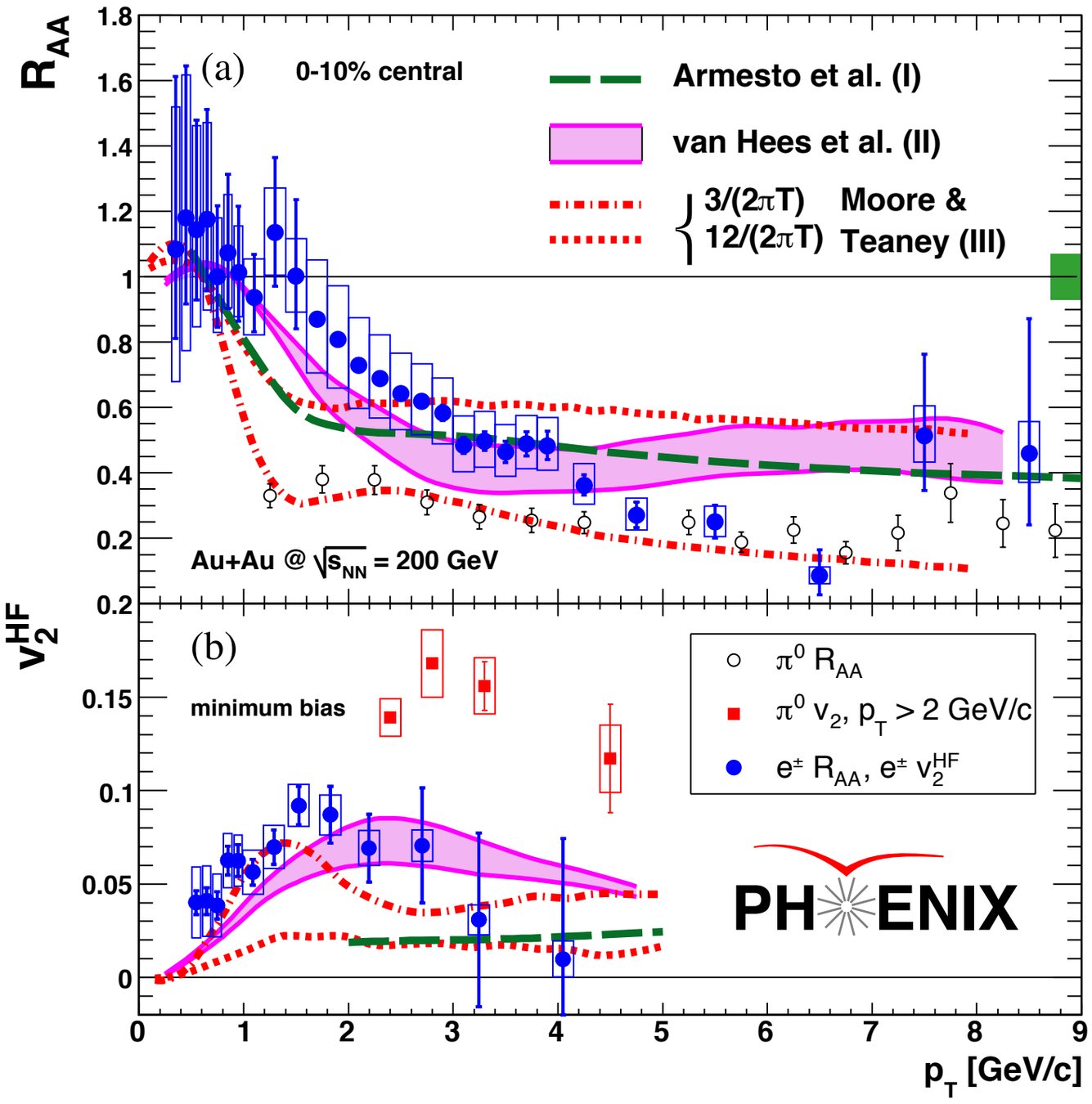


R_2 : event plane resolution

R_{AA} & v_2 comparison to models

HF electron R_{AA} & v_2 at RHIC

AuAu 200 GeV



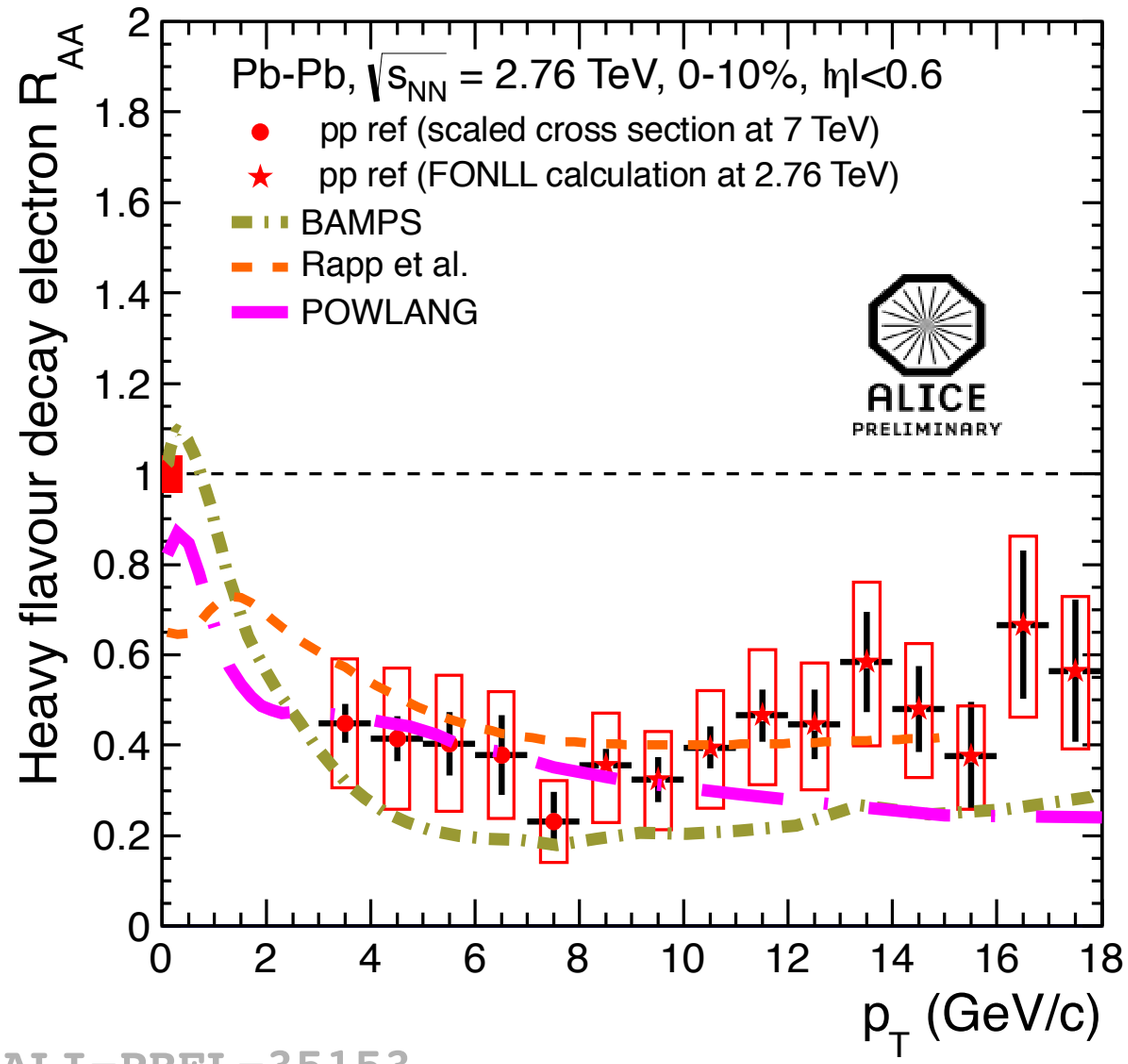
➡ The simultaneous description of HFe R_{AA} and v_2 is challenging

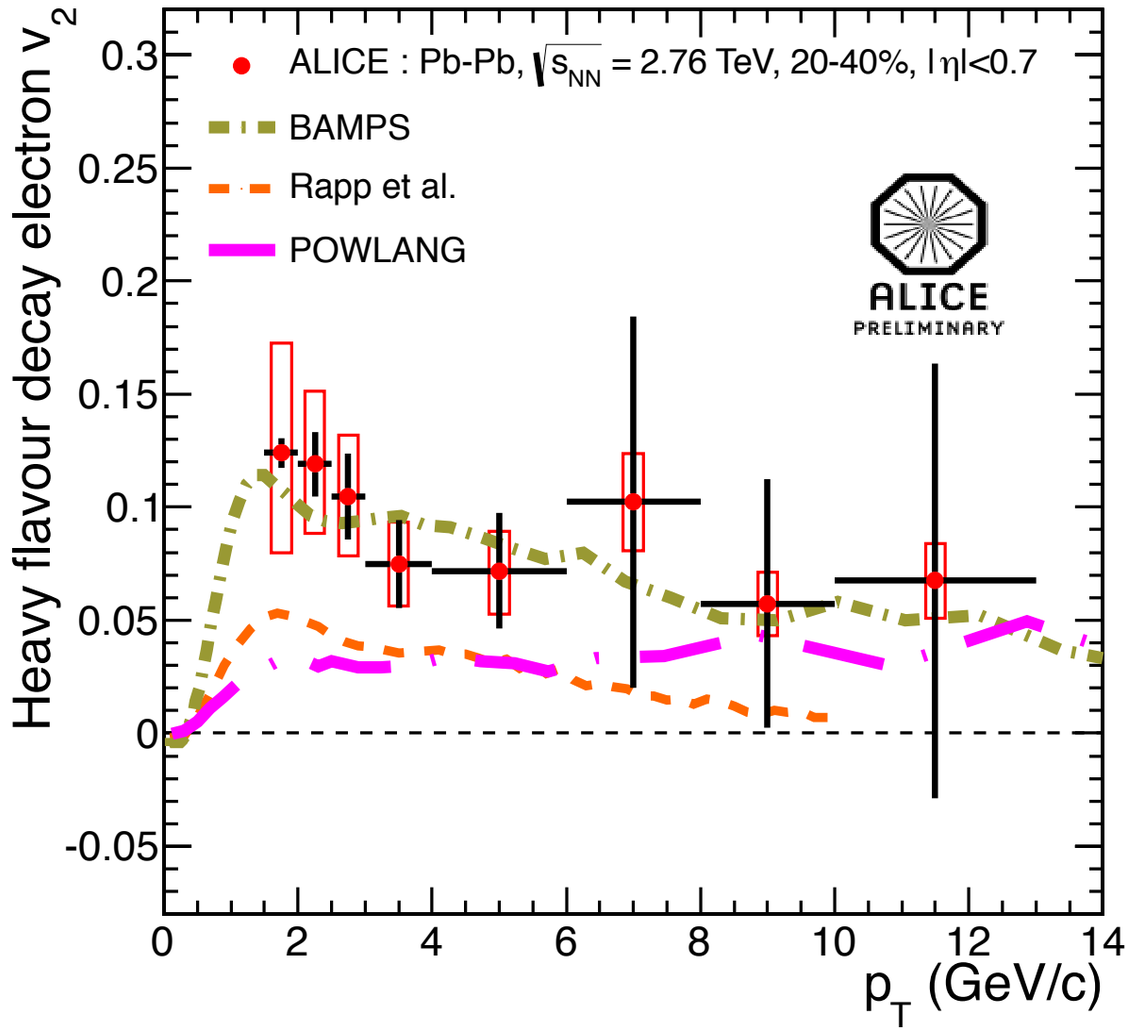
[PHENIX, P.R.L.98 (2007) 172301]
[Armesto et al, P.L.B 637, 362 (2006)]

[H.van de Hees et al, P.R.C 73, 034913 (2006)]
[G.D.Moore et al, P.R.C 71, 064904 (2005)]

HF electron R_{AA} & v_2 at LHC

PbPb 2.76 TeV

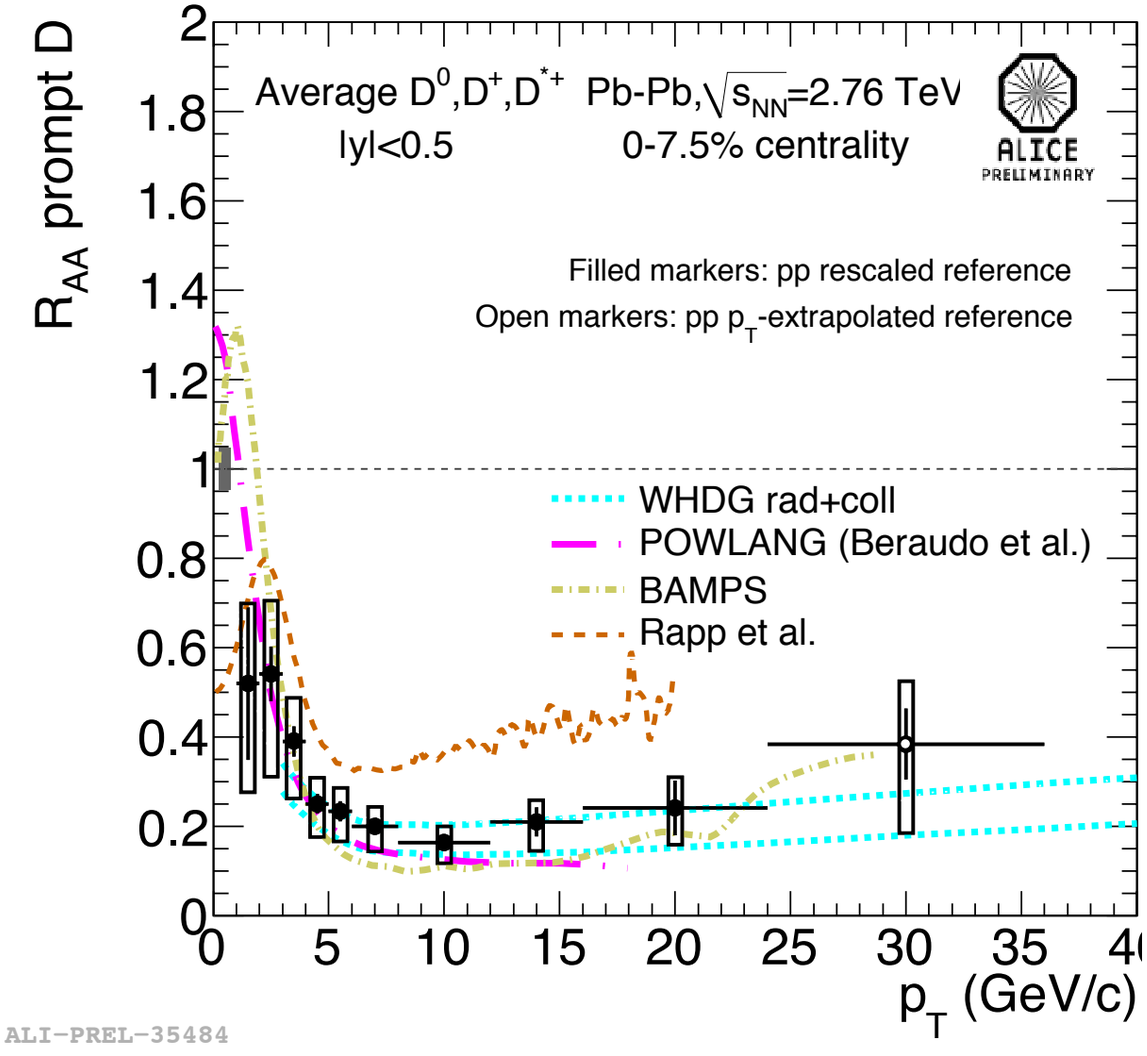


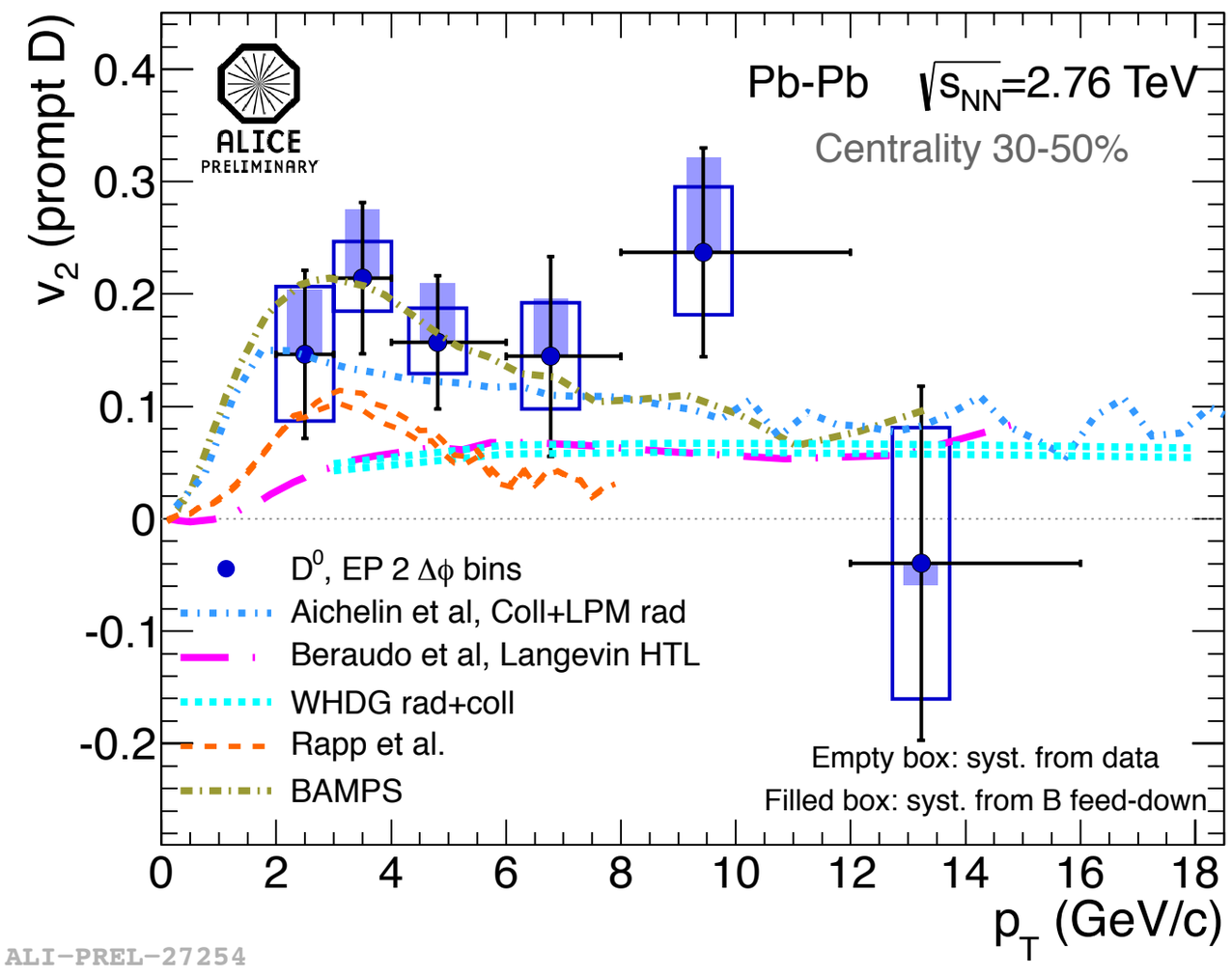


ALI-PREL-35153

➡ **The simultaneous description of HFe R_{AA} and v_2 is challenging**

D meson R_{AA} & v_2 at LHC

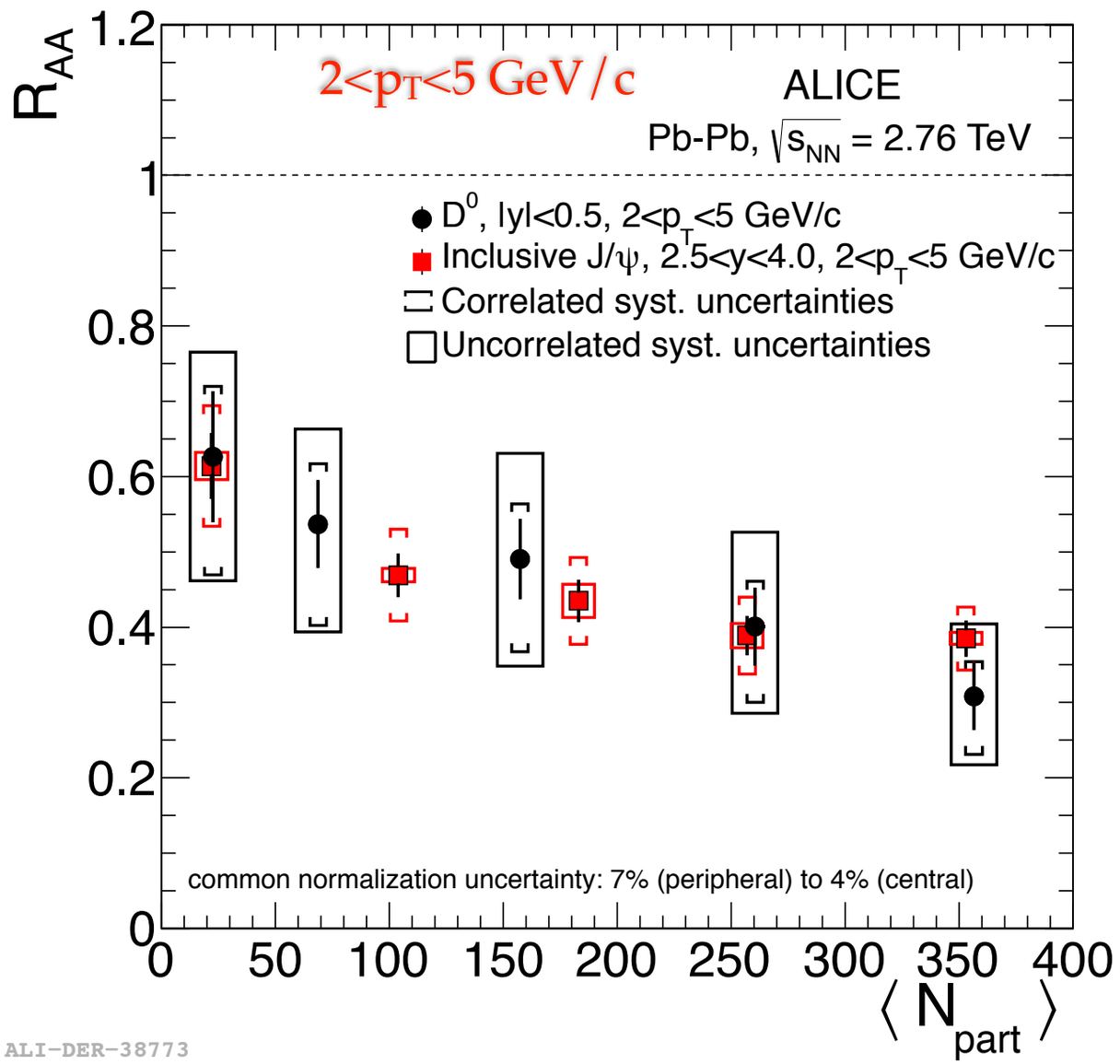


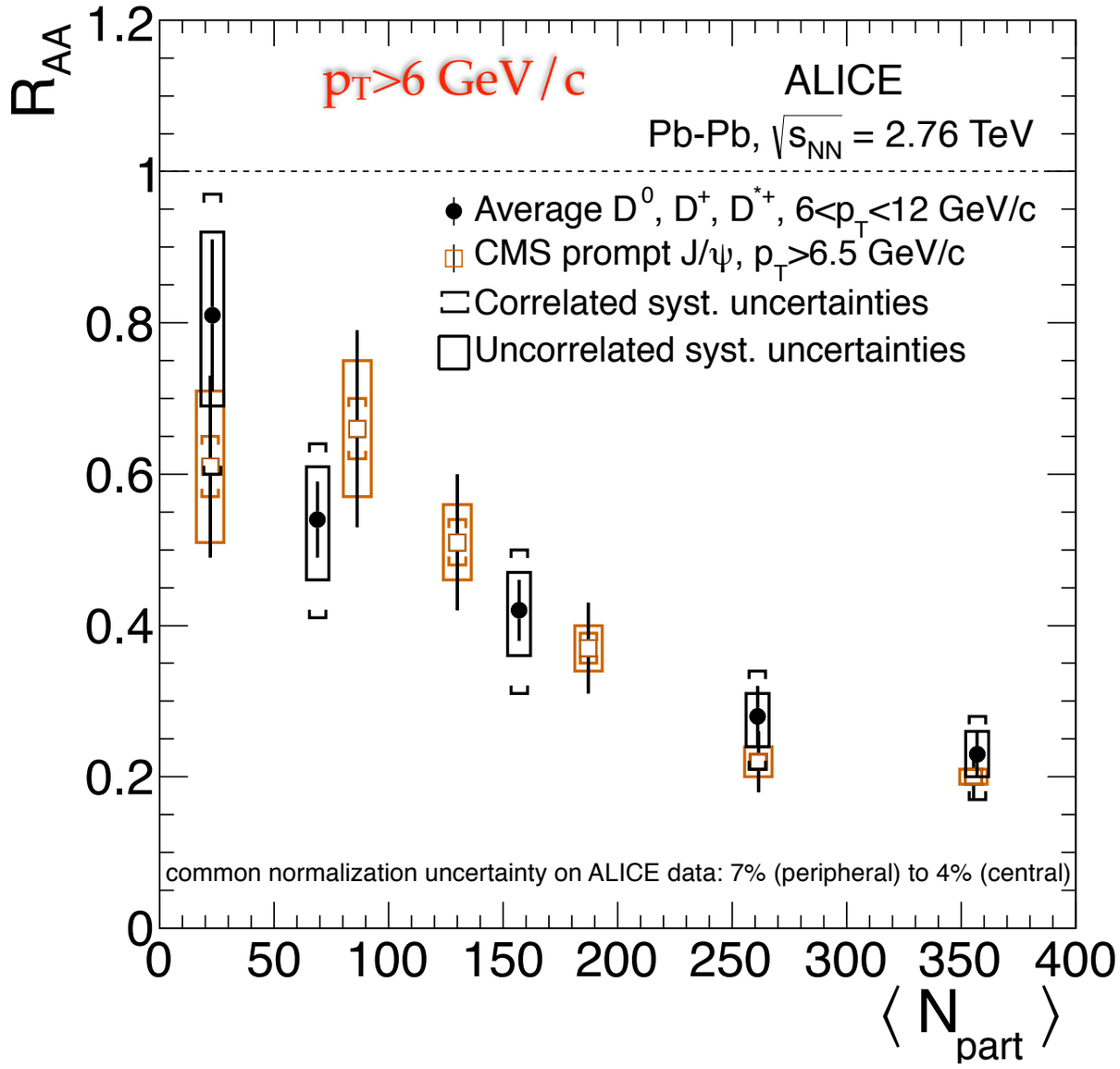


PbPb 2.76 TeV

➡ **The simultaneous description of D mesons R_{AA} and v_2 is challenging**

LHC, R_{AA} of Open and Hidden Charm





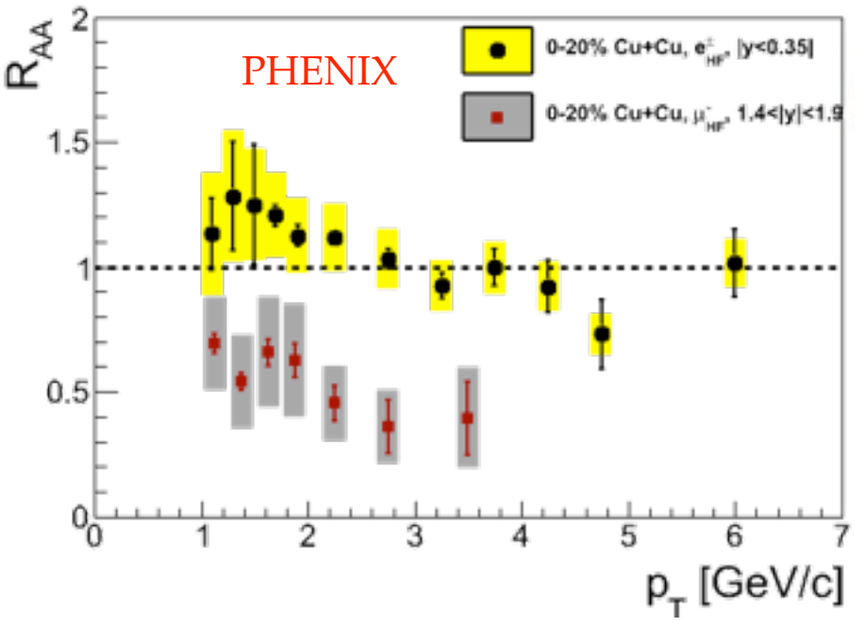
ALI-DER-38773

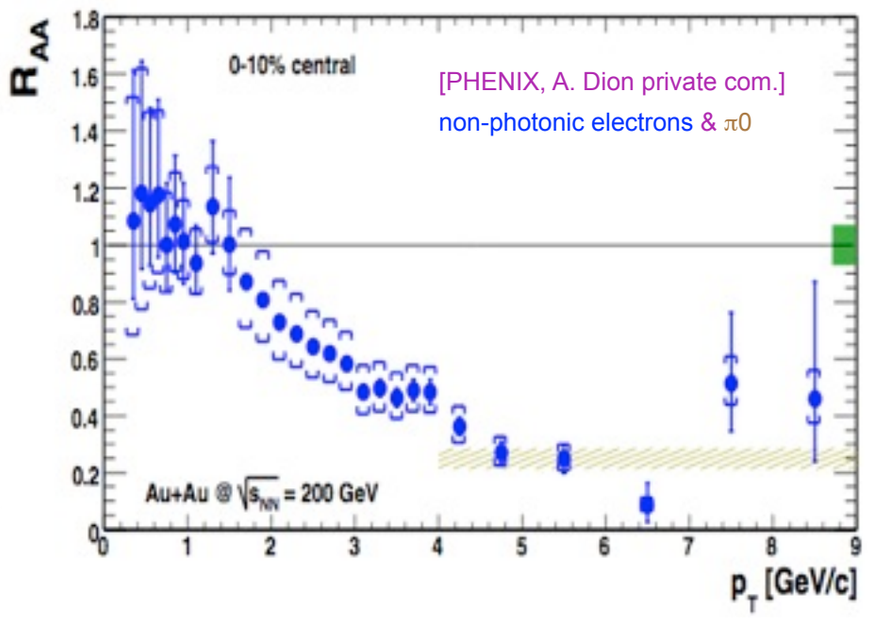
[ALICE Coll. arXiv:1203.2160 (2012)] [CMS Coll., JHEP 05 (2012) 063]

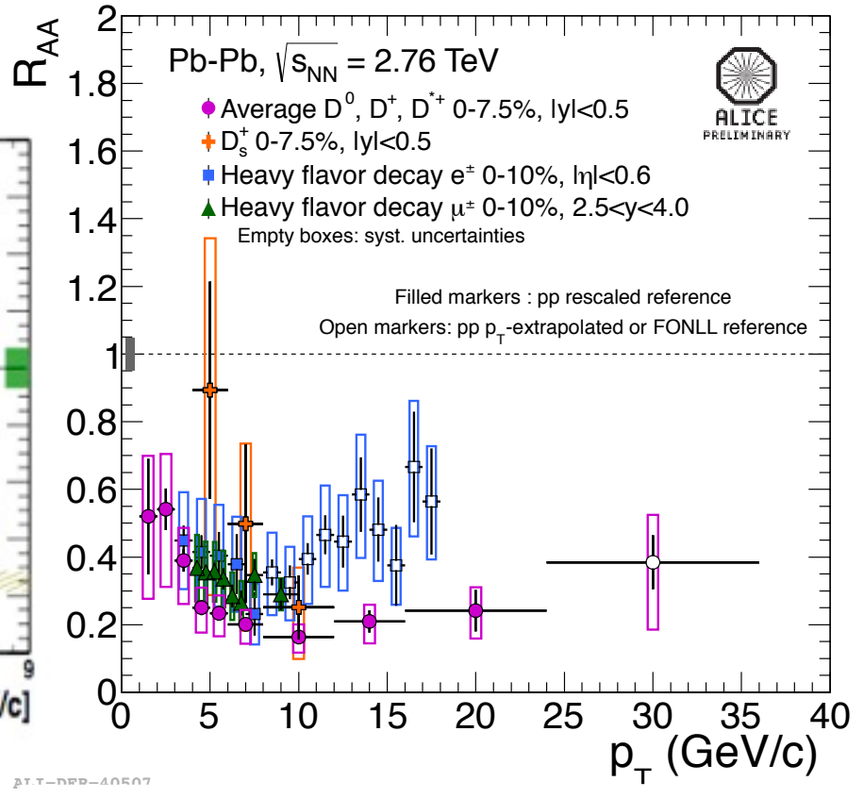
PbPb 2.76 TeV

- ➡ Similar trend of D mesons and J/ψ at low and high p_T
  - 2<p_T<5 GeV/c D (|y|<0.5) vs inclusive J/ψ (ALICE, 2.5<y<4.0)
  - $p_T \gtrsim 6$ GeV/c D (|y|<0.5) vs prompt J/ψ (CMS, |y|<2.4)

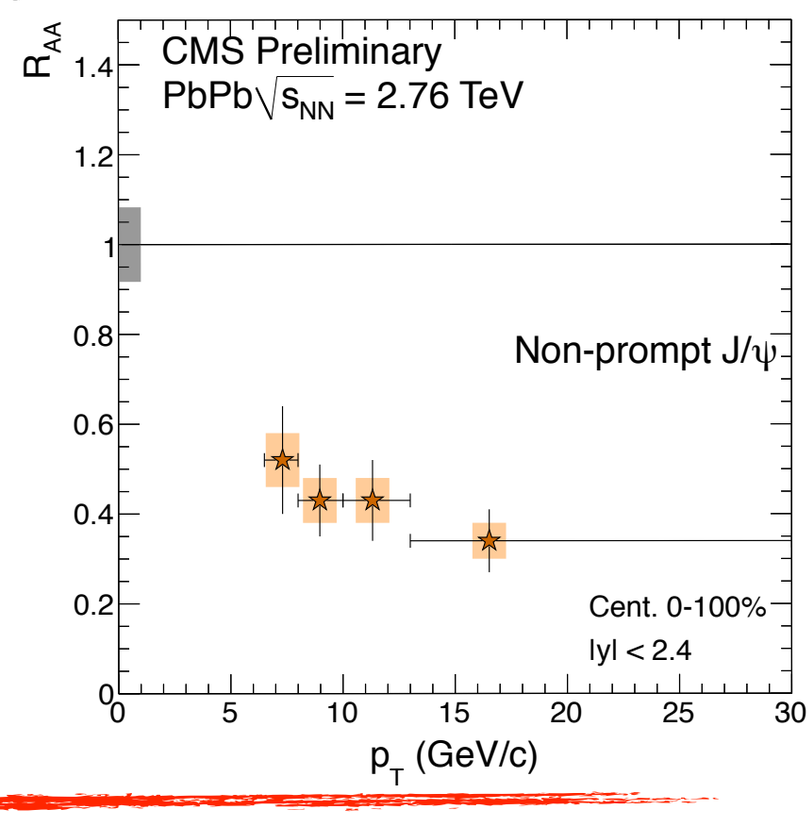
Summary I





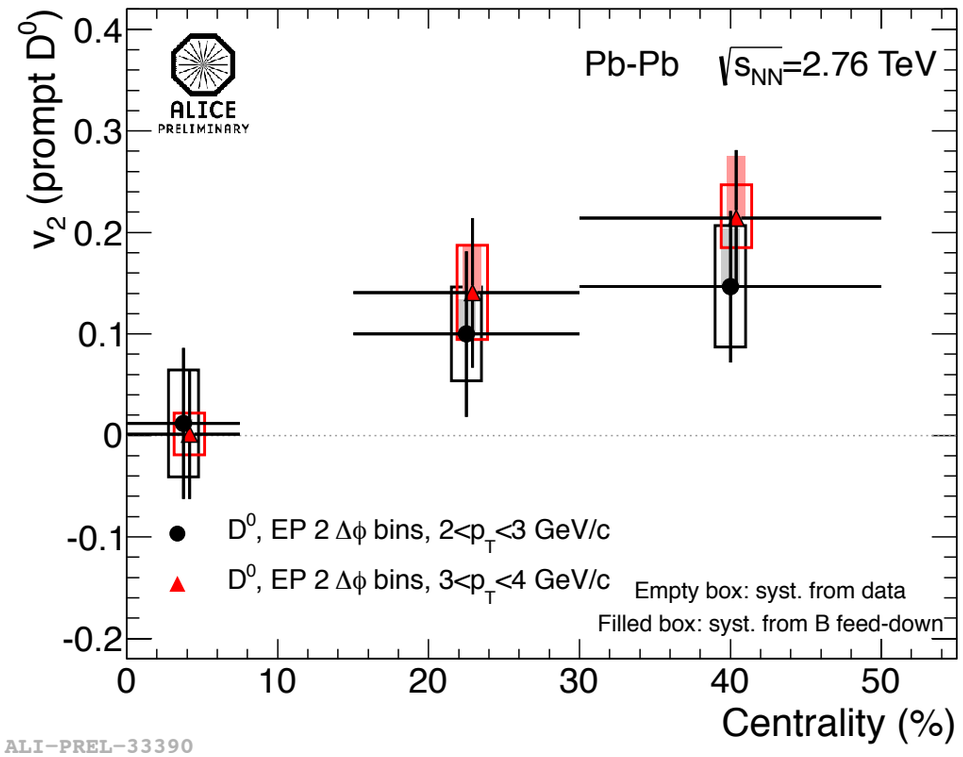


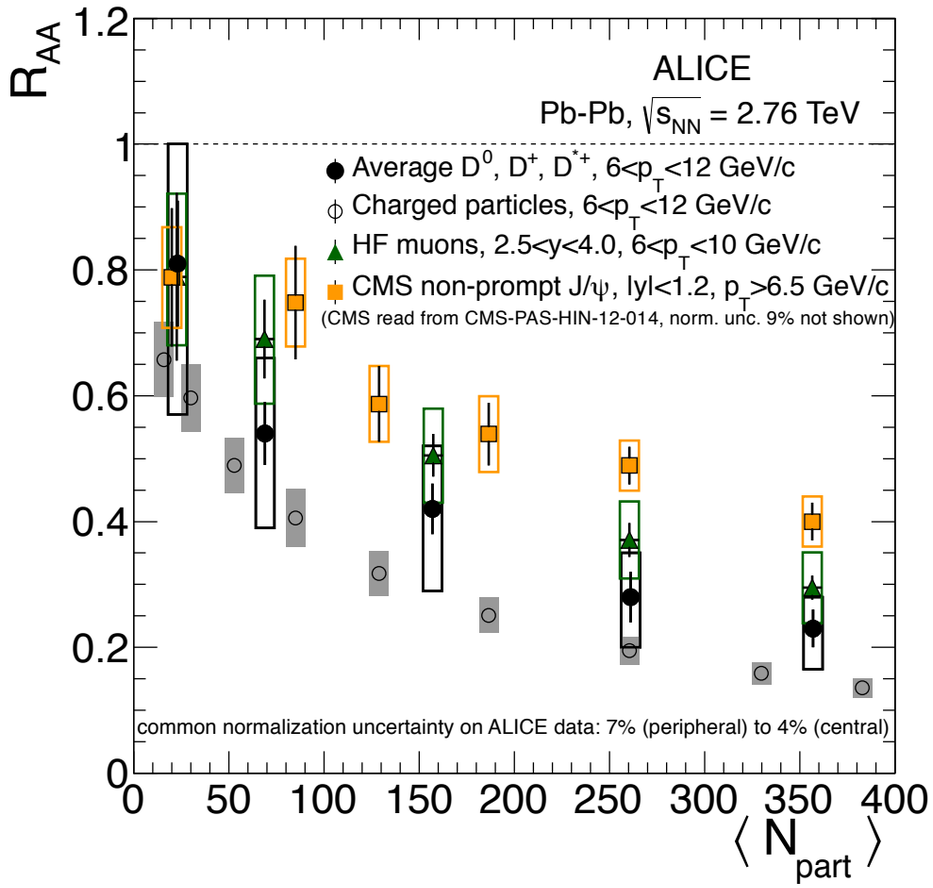
- HF data in pA and CuCu collisions at 200 GeV
  - presents no suppression within uncertainties,
  - but an un-expected further suppression at forward rapidity,
  - need more, and precise, measurements
- Heavy flavor production is suppressed in the most central collisions
  - Both at RHIC and LHC



In sum...

Summary II





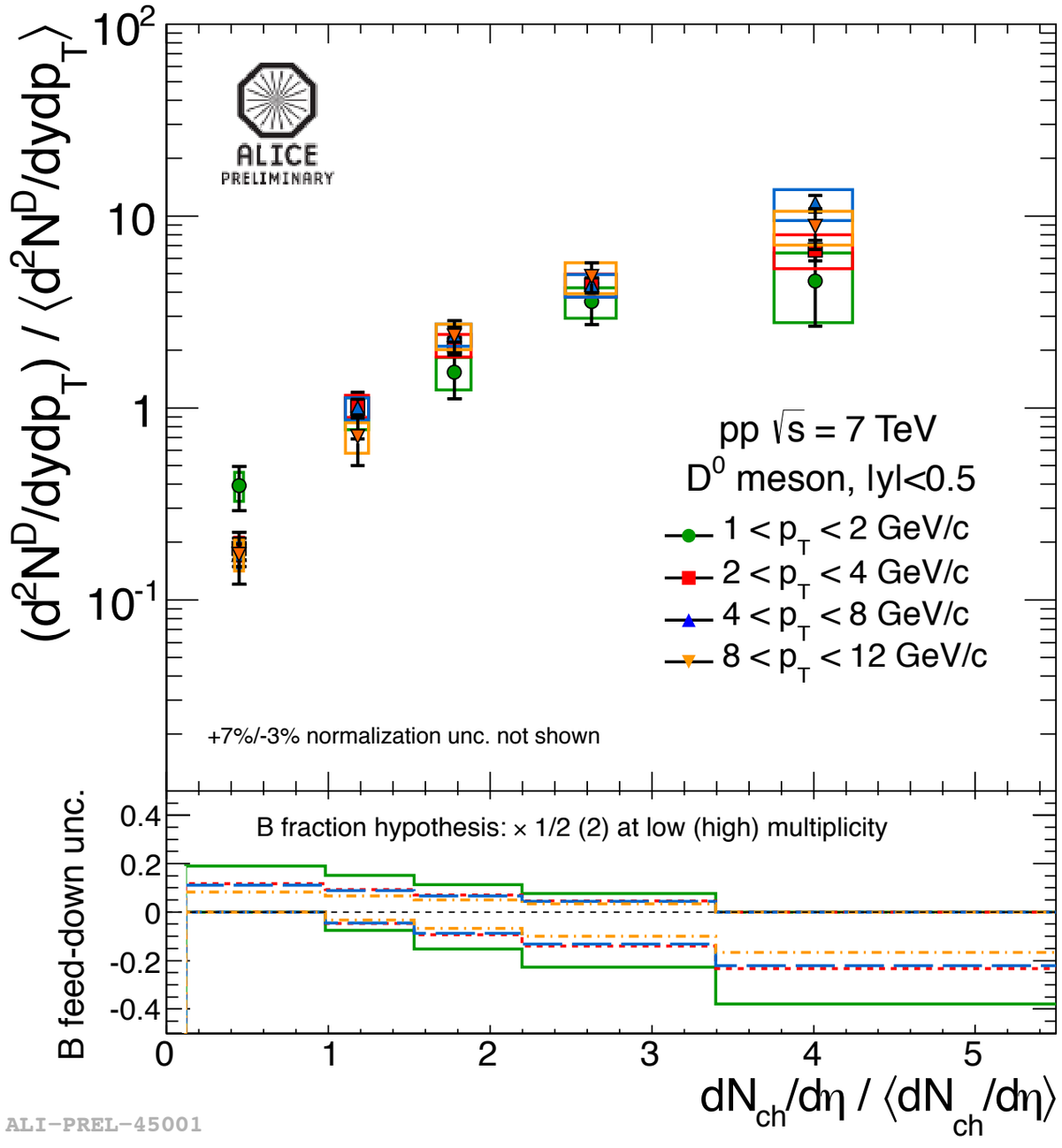
- Heavy flavor production is suppressed in the most central collisions
  - Light particles have a similar p_T and centrality trend than charm R_{AA}
  - Non-prompt J/ψ seem less suppressed than charged particles
- Azimuthal anisotropy of HFe and charm observed
  - v_2>0 both for p_T ~ 3 GeV/c at RHIC and at the LHC
  - Hint of v_2 centrality dependence at low p_T (D^0, ALICE)
- HQ energy loss models reproduce reasonably well heavy flavor R_{AA} measurements. Challenging simultaneous description of R_{AA} and v_2.

Thanks for your attention !

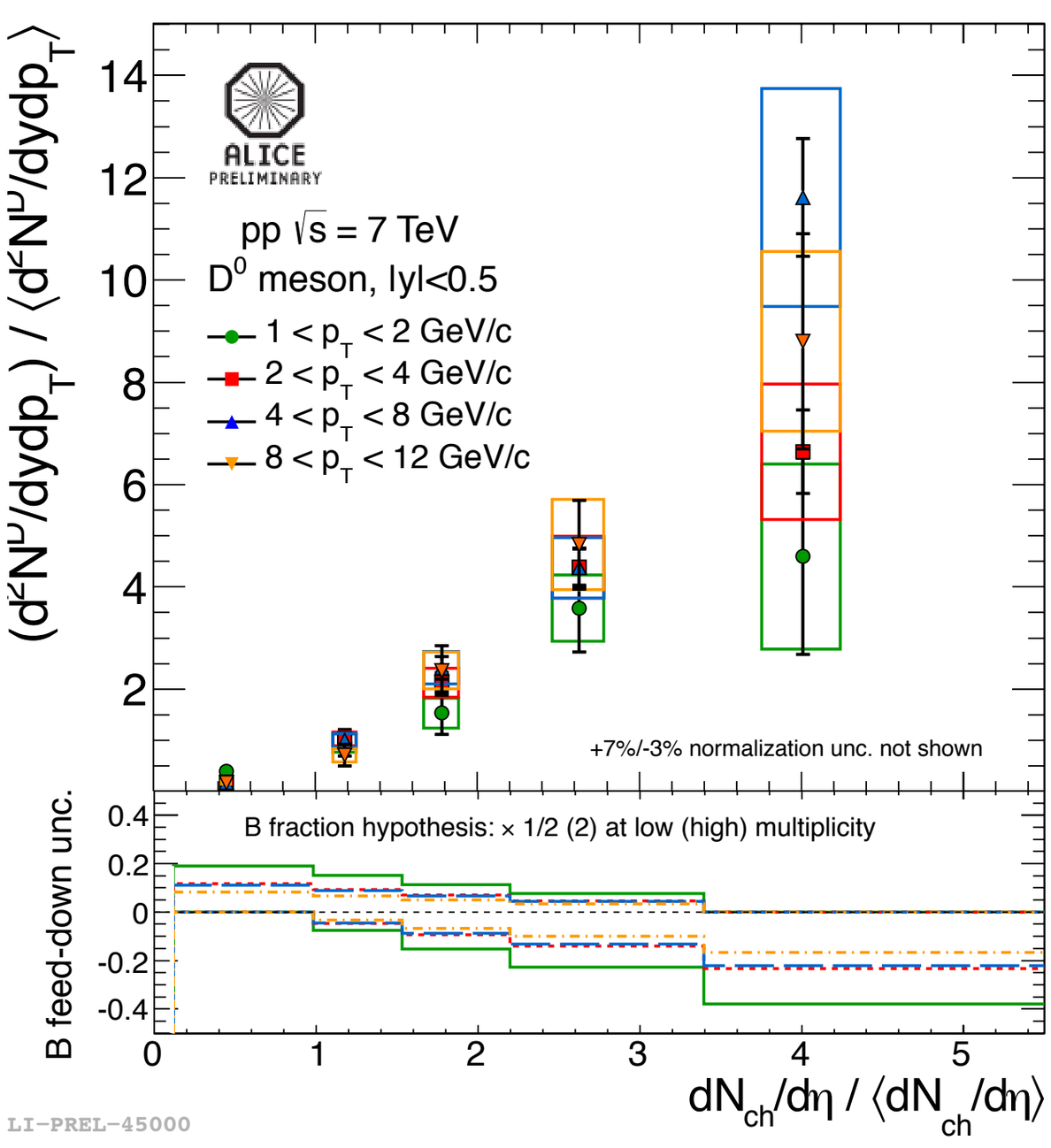
Special thanks to the organizers for the invitation
and to A. Dainese for the help

Backup

D0 Multiplicity & pt Dependence

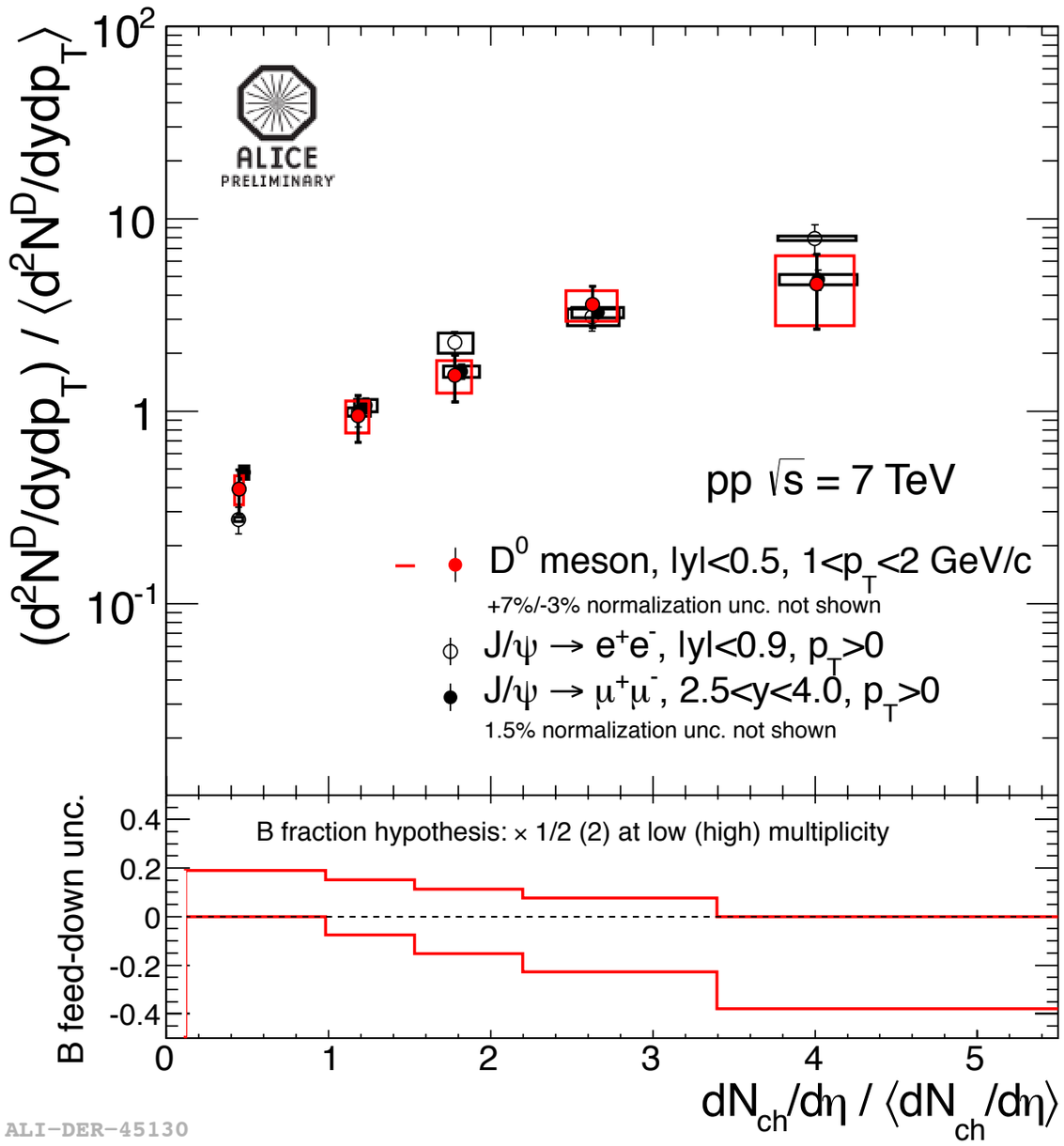


ALI-PREL-45001

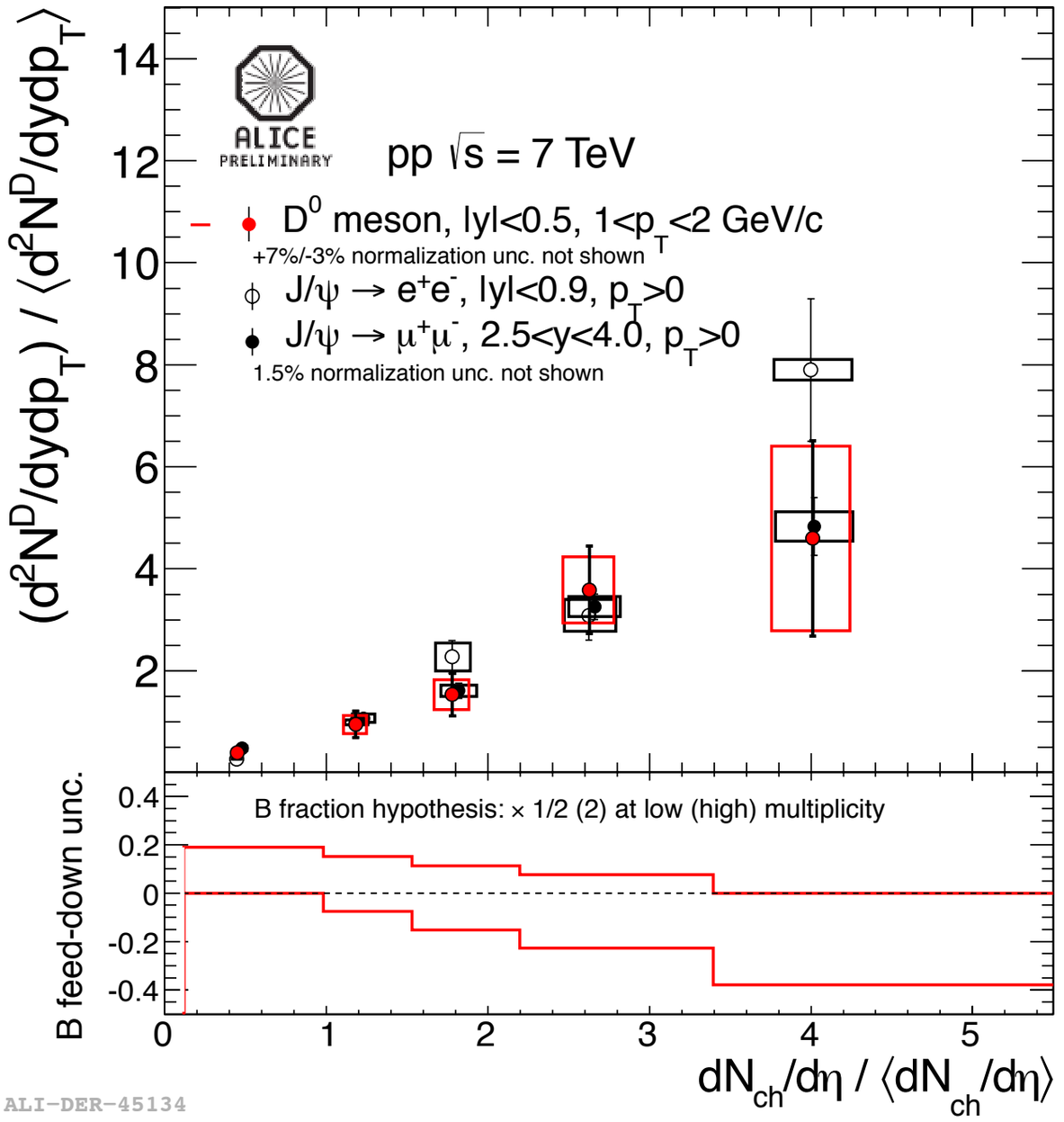


LI-PREL-45000

HF Multiplicity Dependence

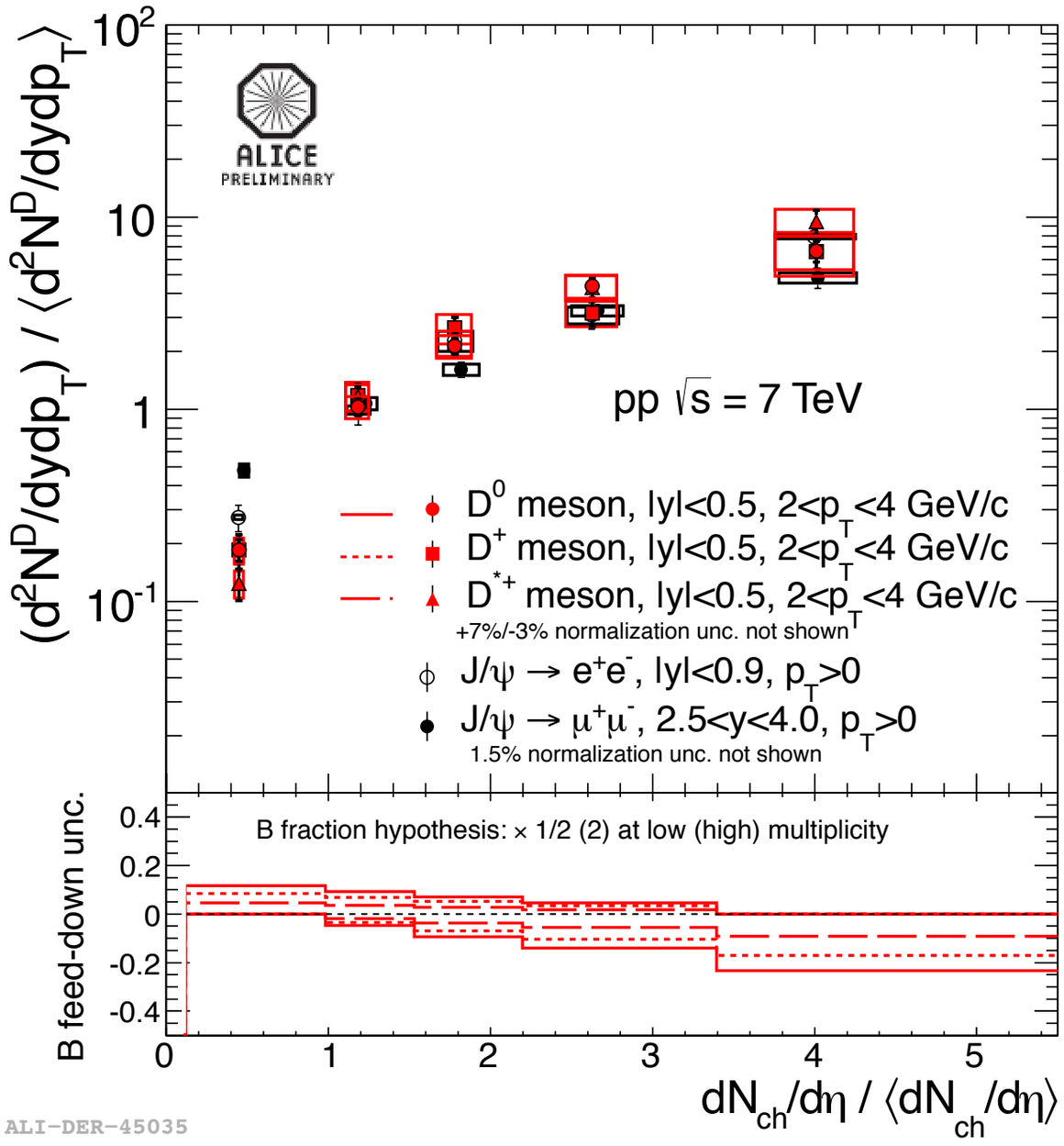


ALI-DER-45130

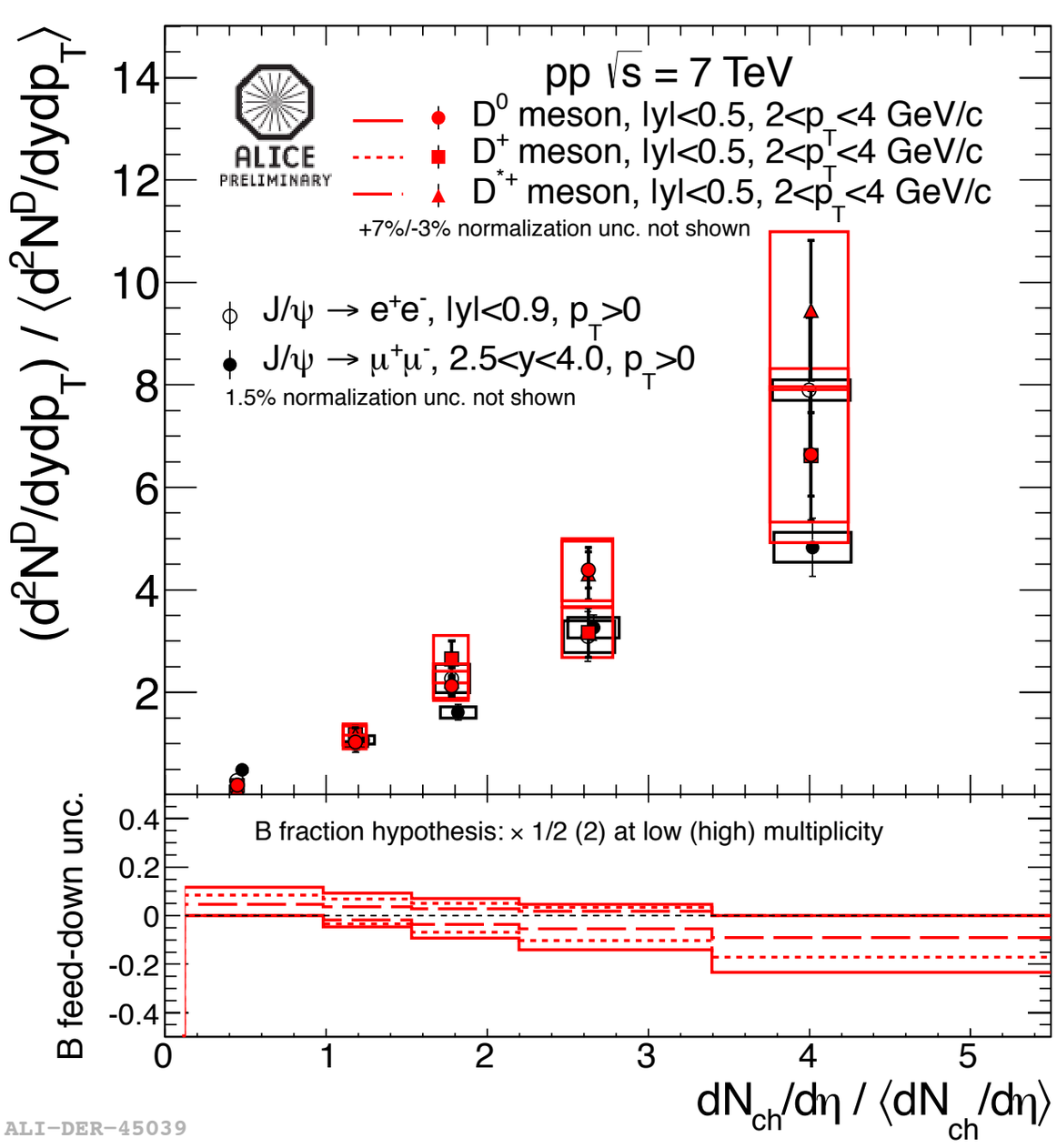


ALI-DER-45134

HF Multiplicity Dependence

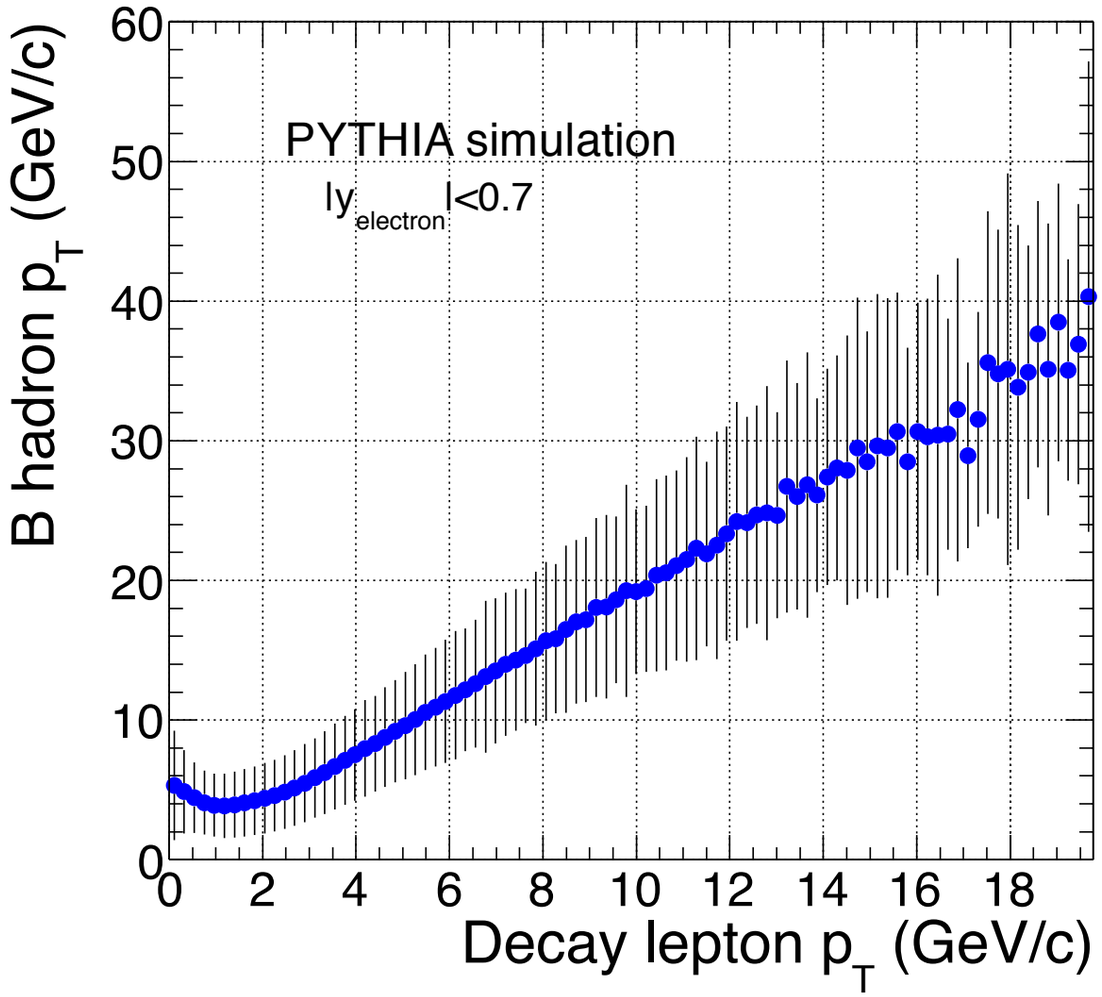


ALI-DER-45035



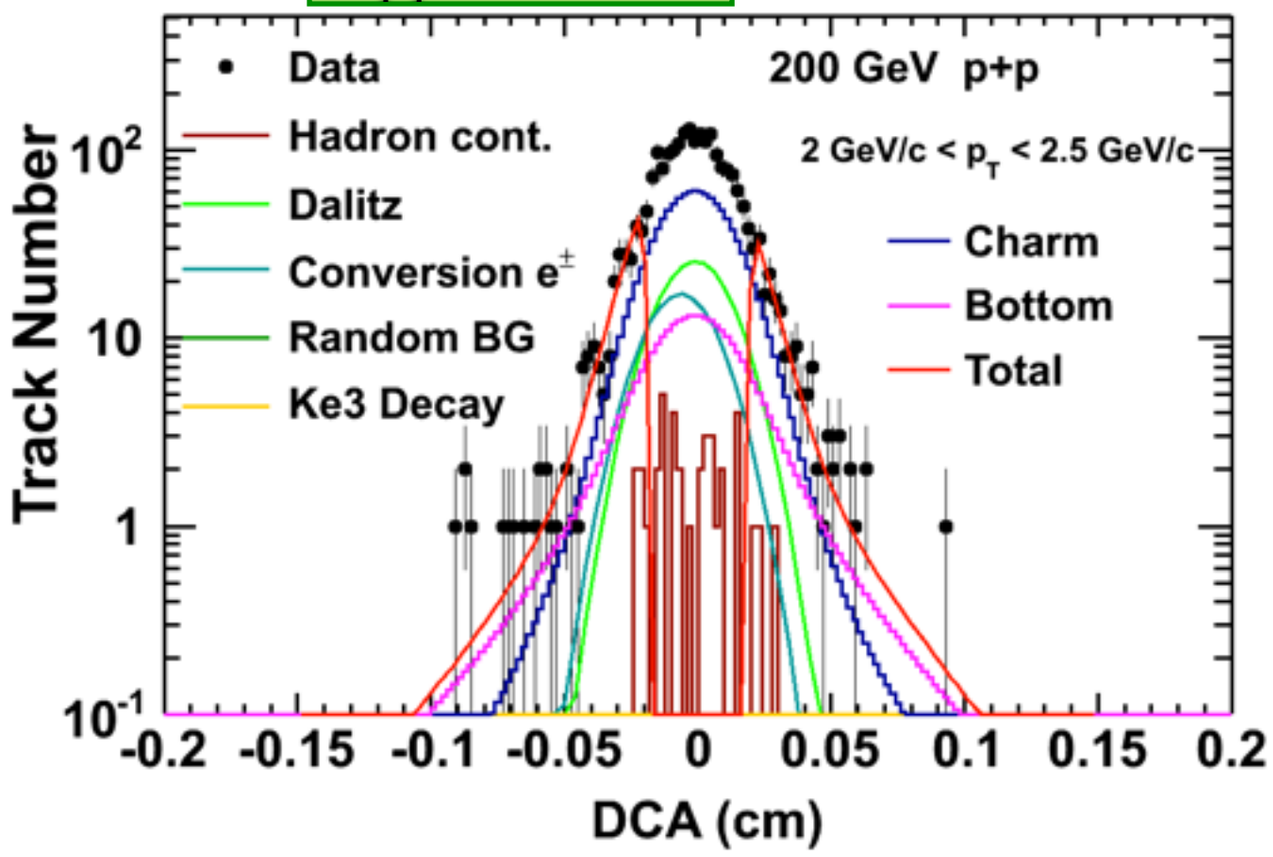
ALI-DER-45039

Correlation of pT(B) & pT(D) vs PT(lepton)

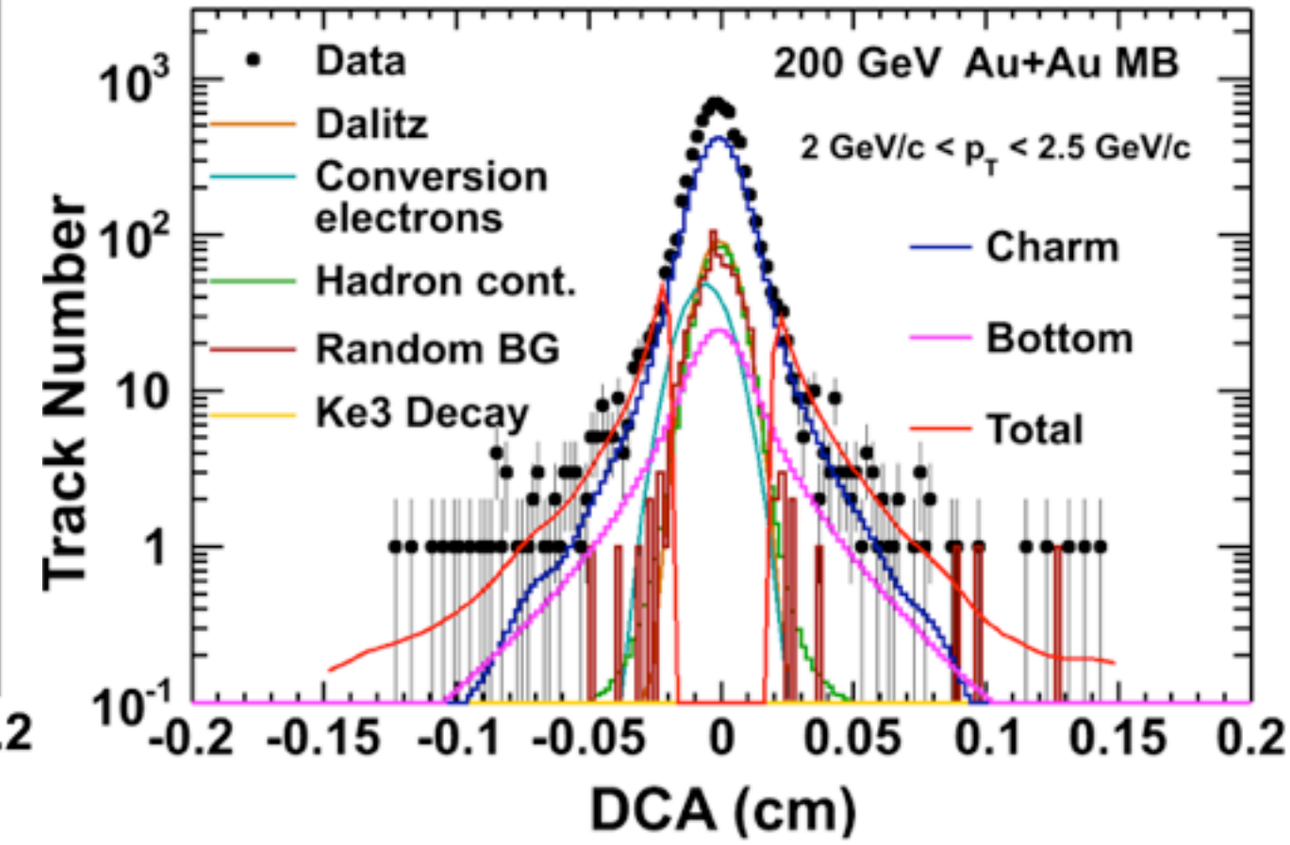


PHENIX, Separating Charm & Beauty

pp 200 GeV



AuAu 200 GeV



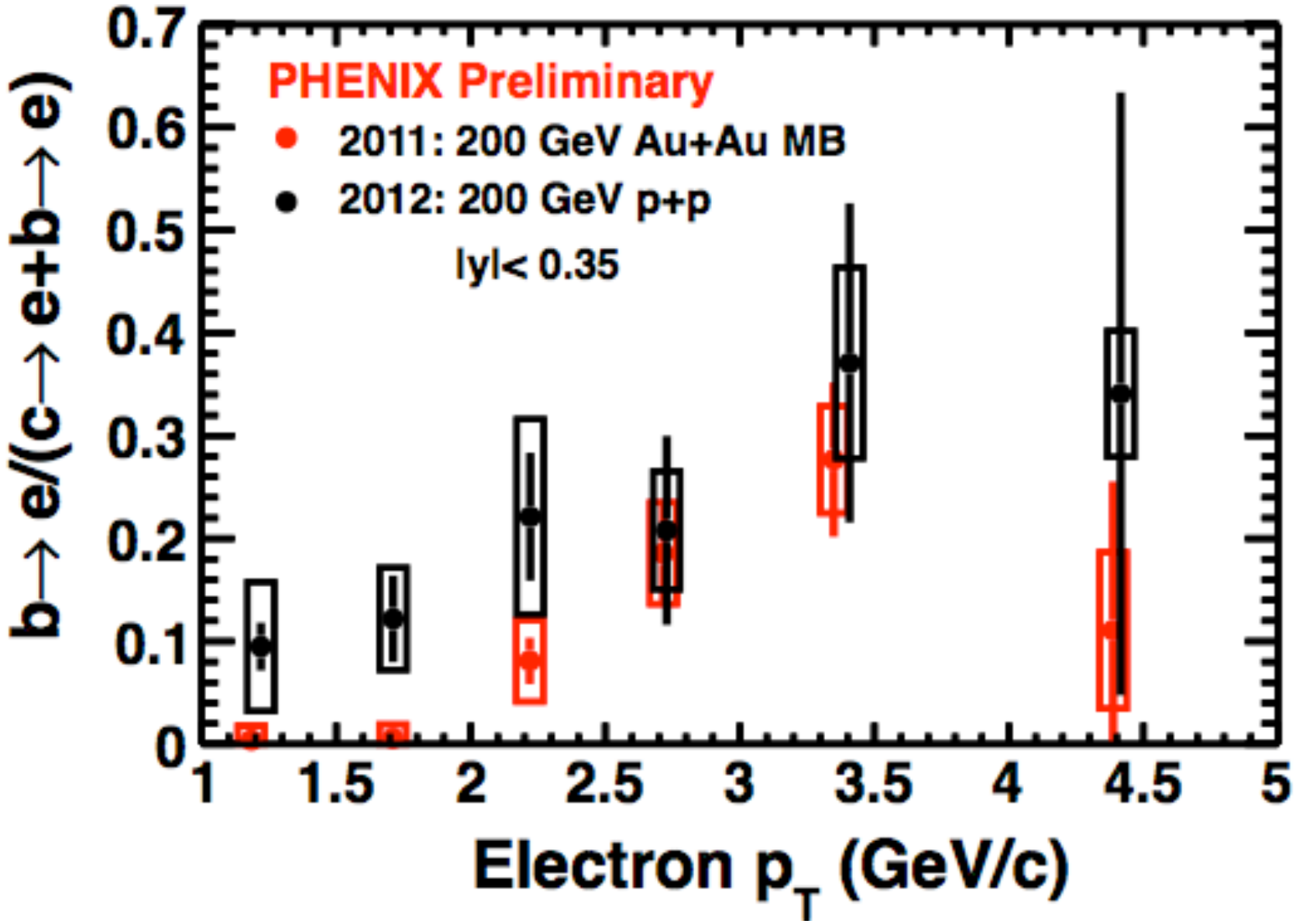
Rosati, Nouicer, QM12

- Identify electrons
- **Fit the electron DCA distribution of inclusive electrons in pt bins and extract the charm and beauty fractions**
  - Rely on MC templates of the different contributions
  - Photonic contribution evaluated with:
    a) cocktail method, b) conversion tagging in the VTX

PHENIX, Charm & Beauty HF

pp 200 GeV

AuAu 200 GeV

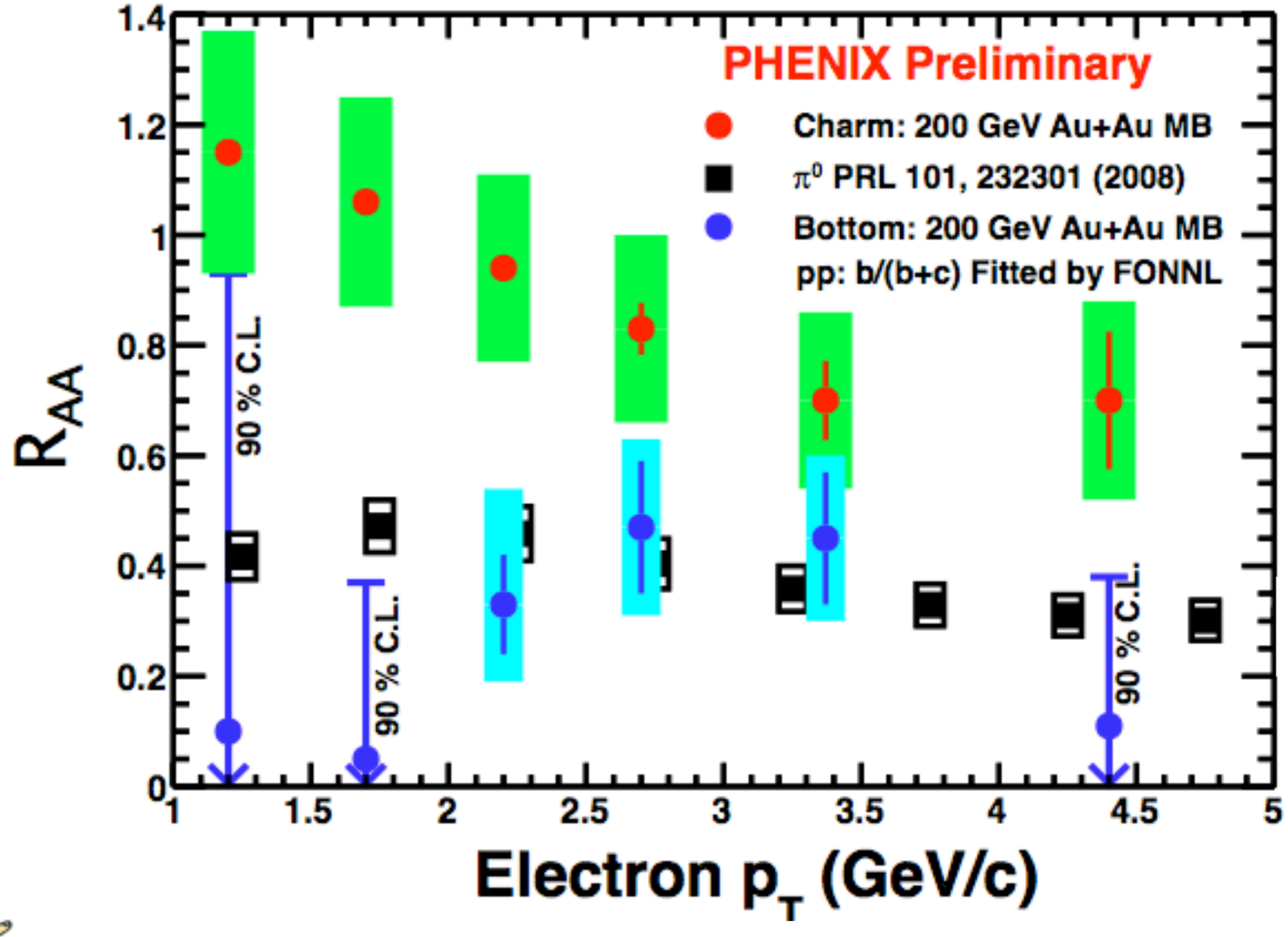


Dixit Marzia "Bottom in *Au+Au* appears more suppressed" ?

Rosati, Nouicer, QM12

PHENIX, Charm & Beauty HF R_{AA}

AuAu 200 GeV

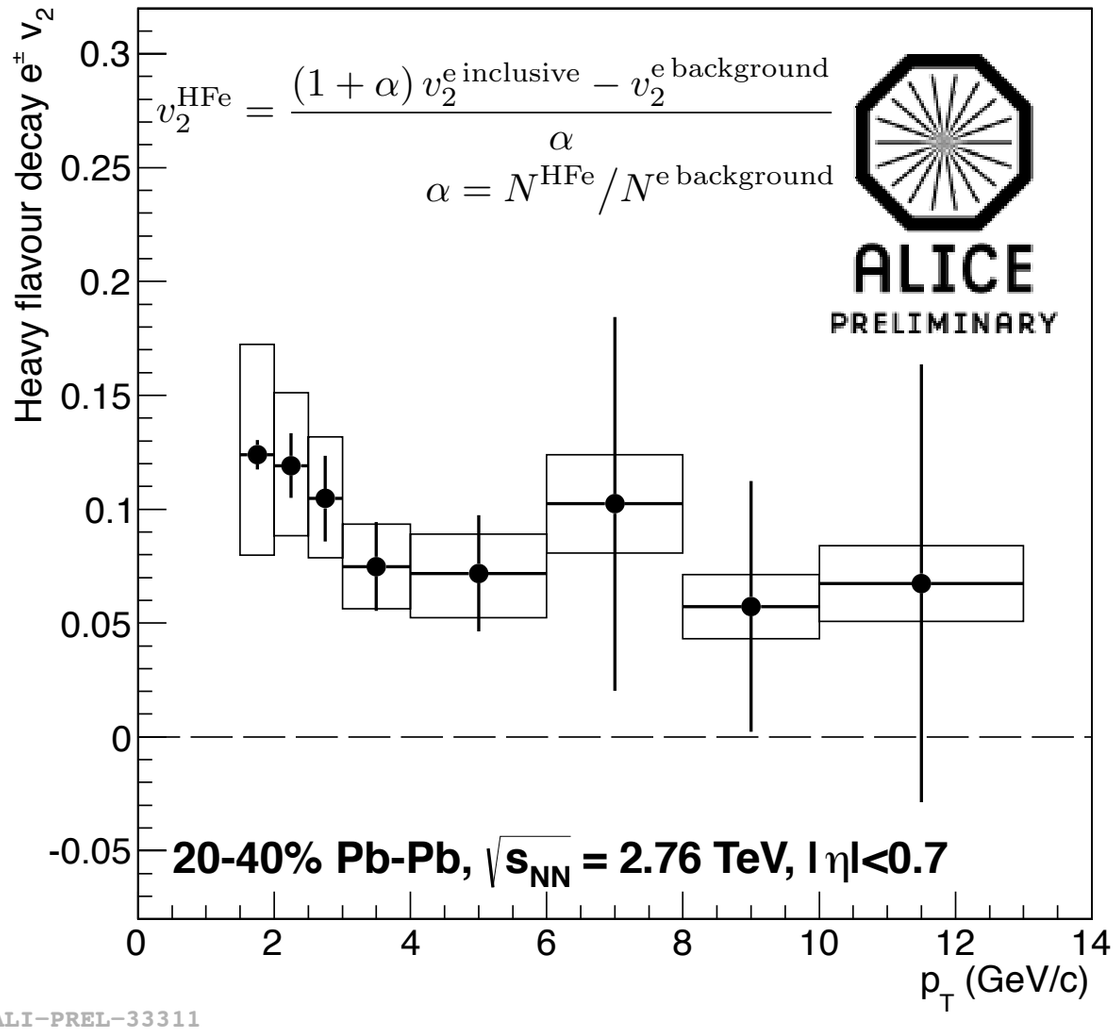


Dixit Marzia "Bottom in Au+Au appears more suppressed" ?

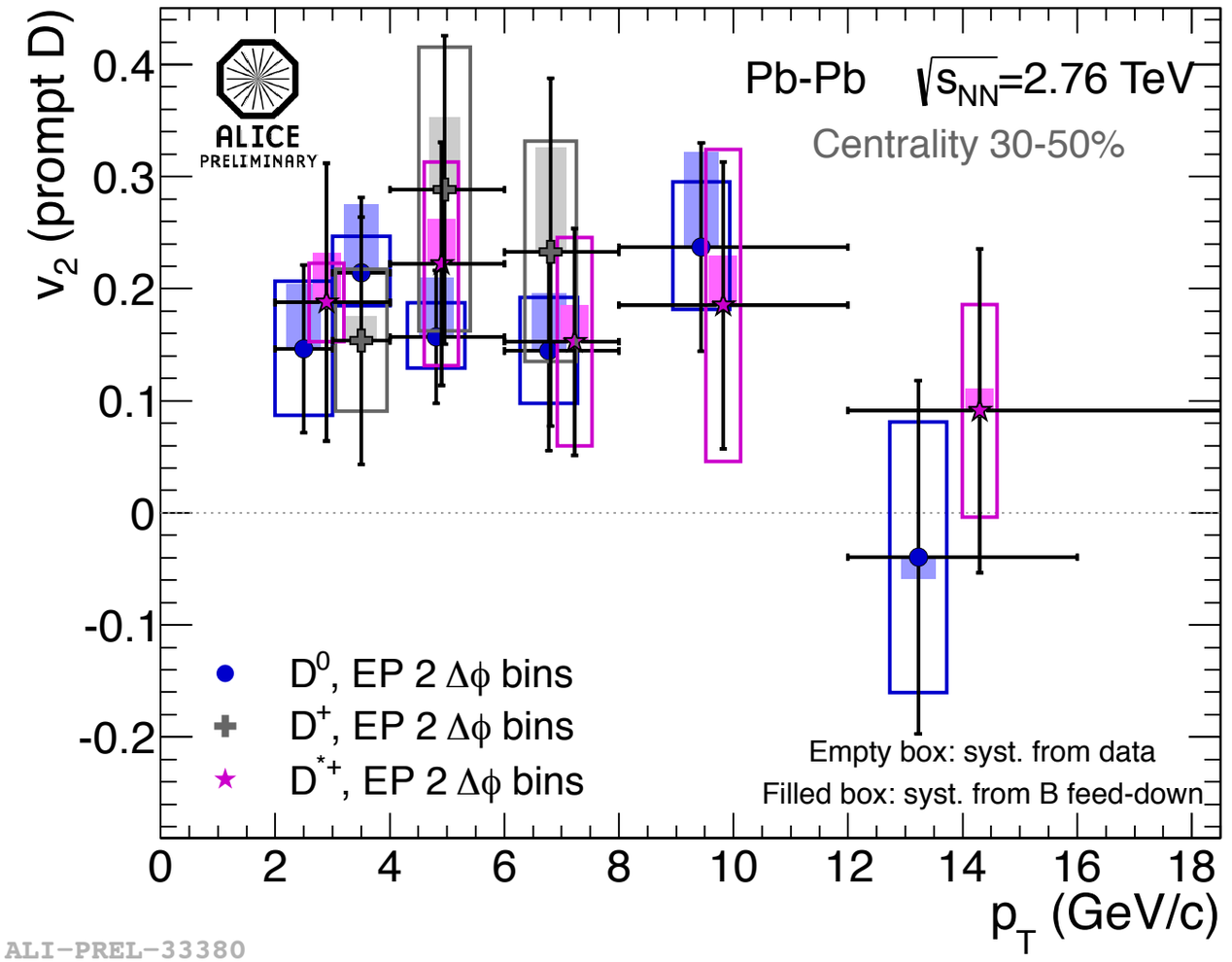
Rosati, Nouicer, QM12

ALICE, HF v_2

PbPb 2.76 TeV



ALI-PREL-33311



ALI-PREL-33380

- Heavy flavor electron v2>0 at low pT (>3σ effect in 2<pT<3 GeV/c)
- Consistency among D meson species (D^0,D^+,D^{*+})
- Indication of non-zero D meson v_2 (3σ effect in 2<p_T<6 GeV/c)

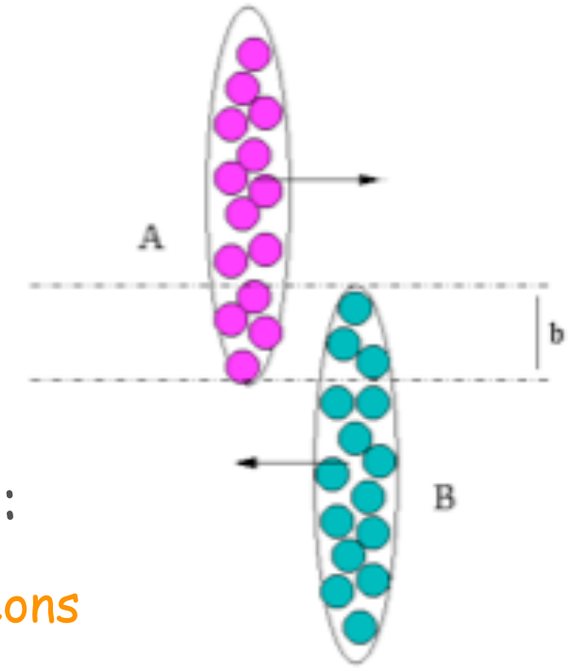
ZCdV, Sakai, QM12

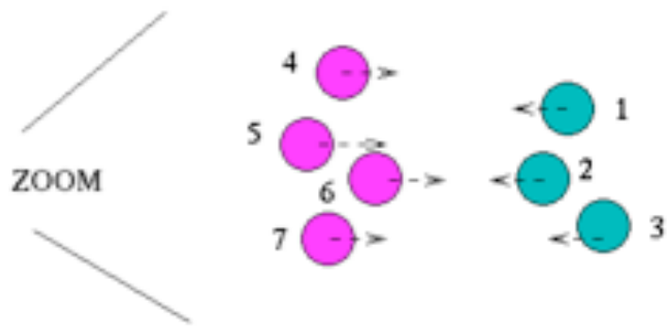
Centrality, the Glauber Model

- Glauber model : geometrical picture of the collision
  - The nucleons are distributed following a known density distribution function ρ(r) (Wood-Saxon), as a function of their radius, usually measured experimentally;
  - The nucleons travel in straight-line trajectories and their trajectory does not change while passing through the nucleus;
  - The nucleons interact with a nucleon-nucleon inelastic cross section, $\sigma_{NN}(\sqrt{s_{NN}})$, measured in pp collisions, where $\sqrt{s_{NN}}$ is the energy available in the nucleon-nucleon (NN) center of mass. At 2.76TeV σ_{NN}=64±5 mb.

$$\rho(r) = \frac{\rho_0}{1+\exp(\frac{r-R}{a})},$$

$$R = 1.19\,A^{\frac{1}{3}} - \frac{1.61}{A^{\frac{1}{3}}}(\text{fm}),$$





- Characteristic parameters:
  - Number of participant nucleons
  - Number of colliding nucleons

Npart = 7, Ncoll = 8