Heavy Flavor Results at QM12

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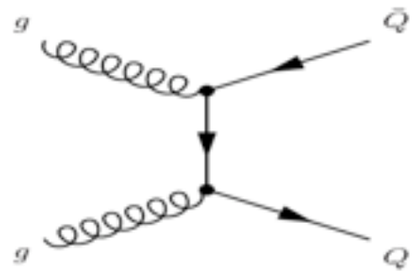
QGP France - Etretat - September 2012

Disclaimer: biased view towards
LHC, ALICE, friends,...
Strongly based on my QMtalk

Outline

- Introduction
- Results
  - Flash of cross sections in pp 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

Why measuring Heavy Flavor ?



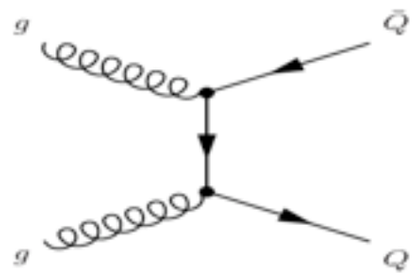
[Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493...]

Why measuring Heavy Flavor ?

Why charm and beauty ?

- Production in hard partonic collisions ⇨ ⇨ pp data
  - Production time $\tau_p \sim 1/m_Q \sim 0.05 - 0.15$ fm/c

    ⇨ **Tool to test pQCD calculations**



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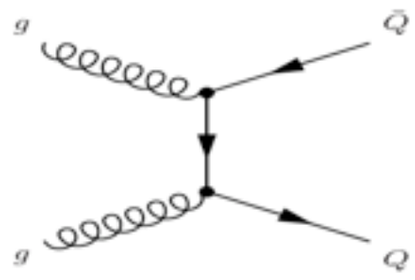

- Nuclear environment influence: p-A collisions ⇨ ⇨ d-Au, p-Pb data in Jan. 2013
  - Shadowing (PDF modifications in nuclei) and Gluon saturation

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

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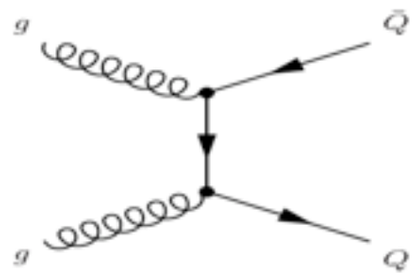

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    ⇨ **Tool to study high density small-x gluons**

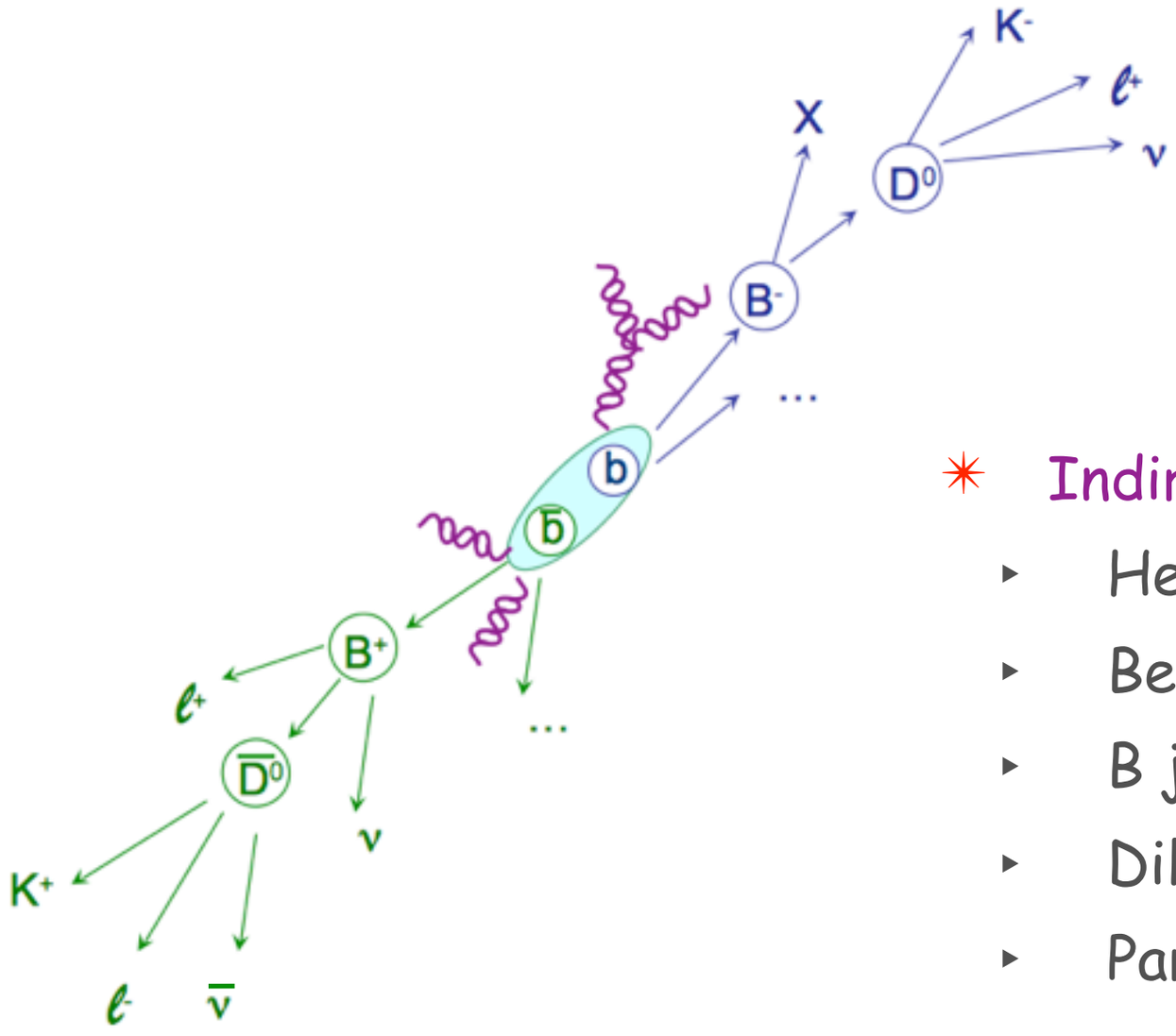
- Effects in a QGP: A-B collisions ⇨ ⇨ Au-Au, Pb-Pb
  - Thermalisation in the QGP (low p_T)
    - Medium transport properties ⇨ dN/dp_T, R_{AA}, v_2
  - Energy loss in the QGP (high p_T)
    - Medium density and size ⇨ dN/dp_T, R_{AA}, v_2
    - Color charge (Casimir factor) : $\Delta E_{u,d,s} < \Delta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

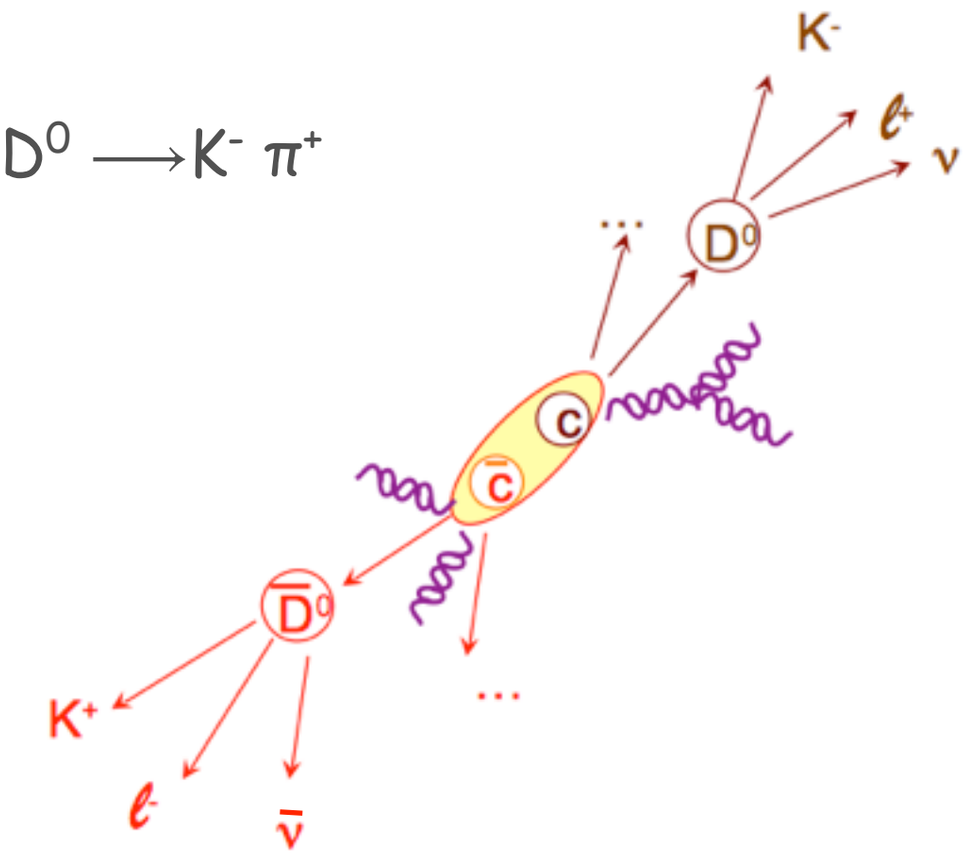
    ⇨ **Probe of the QCD medium**

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

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

… 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…

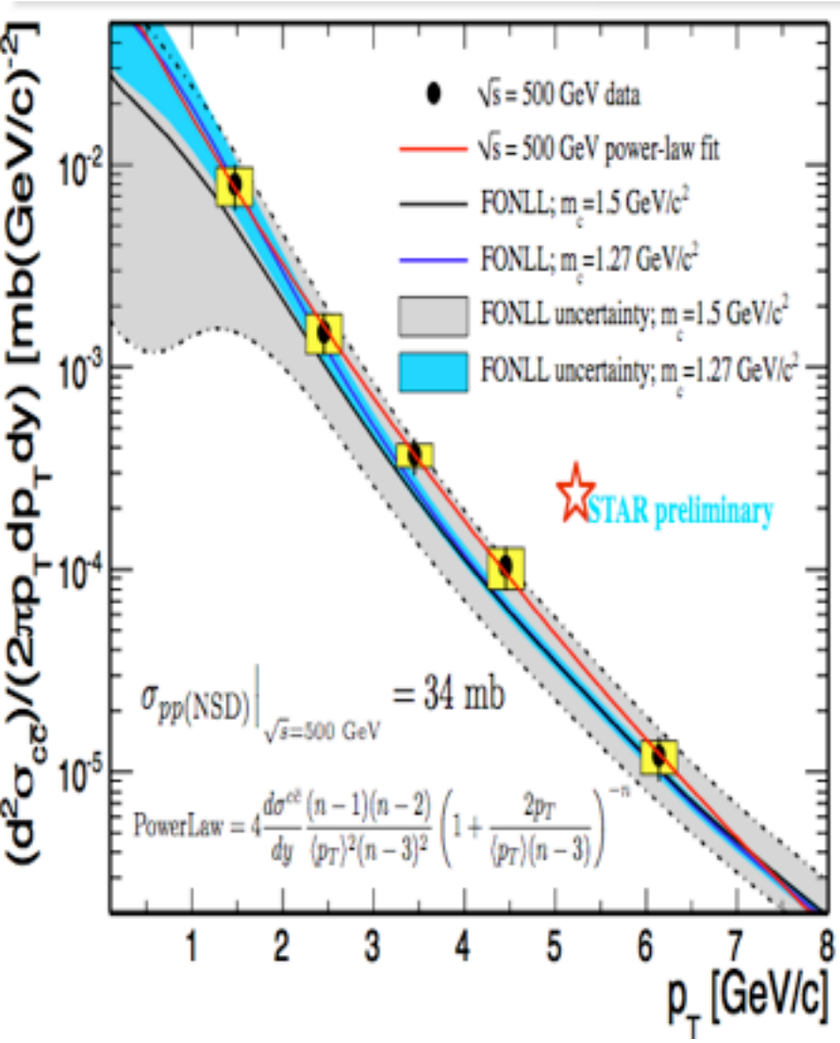
	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF electrons	✔	✔	✔			
B-decay electrons	✔					
HF muons			✔	✔	✔	
D^0, D^+, D^{*+}		✔	✔			
D_s^+			✔			
$B \rightarrow J/\psi$					✔	
B hadrons						
B jets					✔	

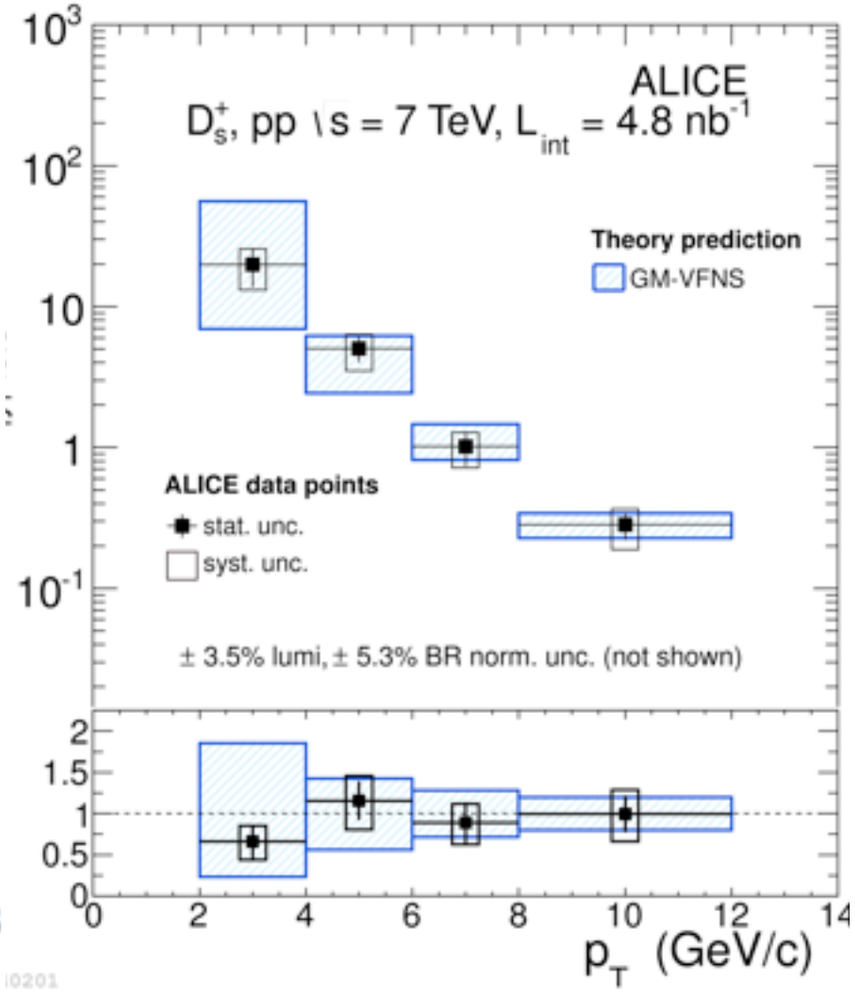
Proton-proton Results

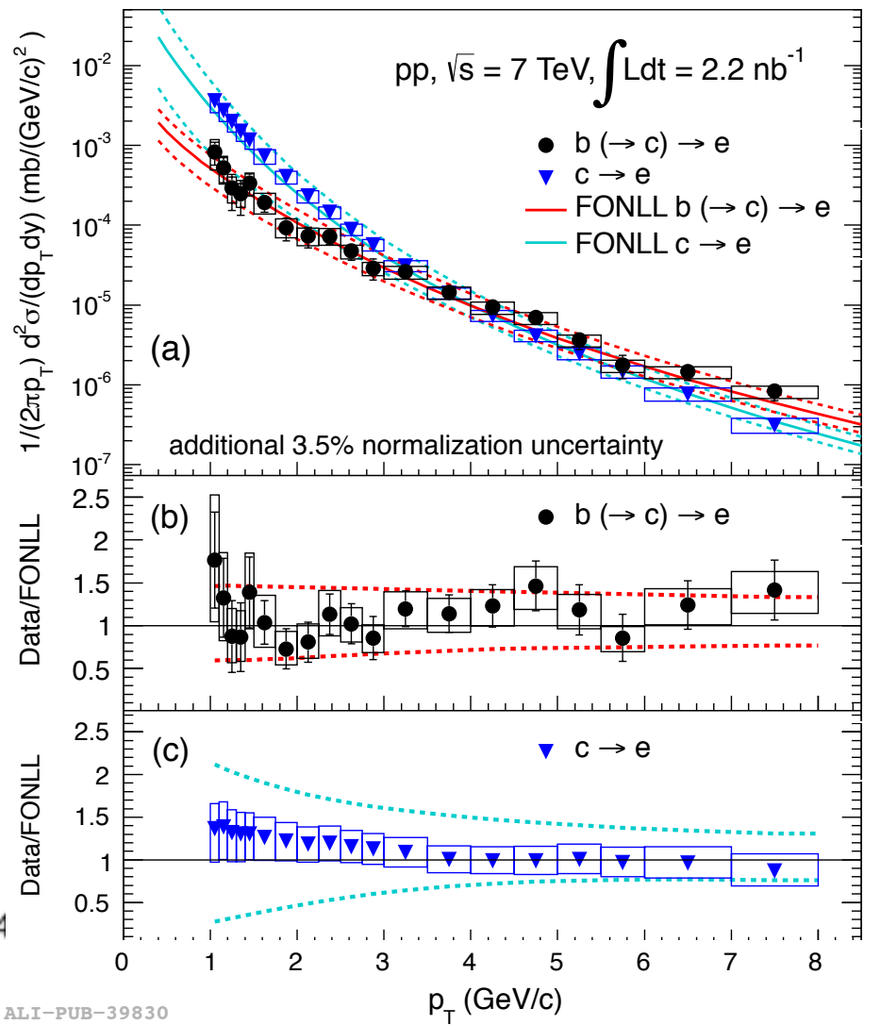
Bunch of pp measurements

[ALICE Coll. arXiv:1208.1948 (2012)]

[ALICE Coll. arXiv:1208.1902 (2012)]





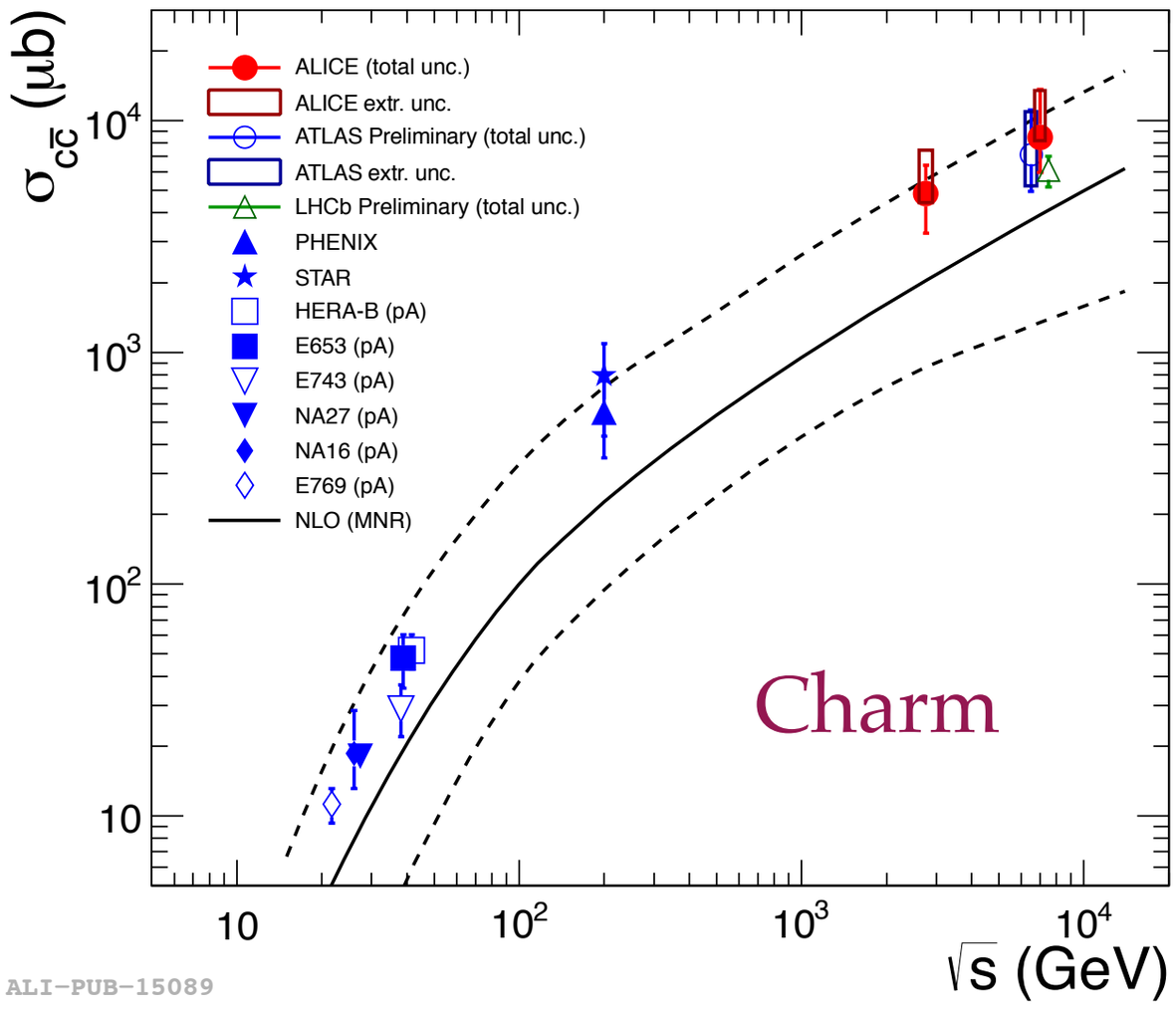


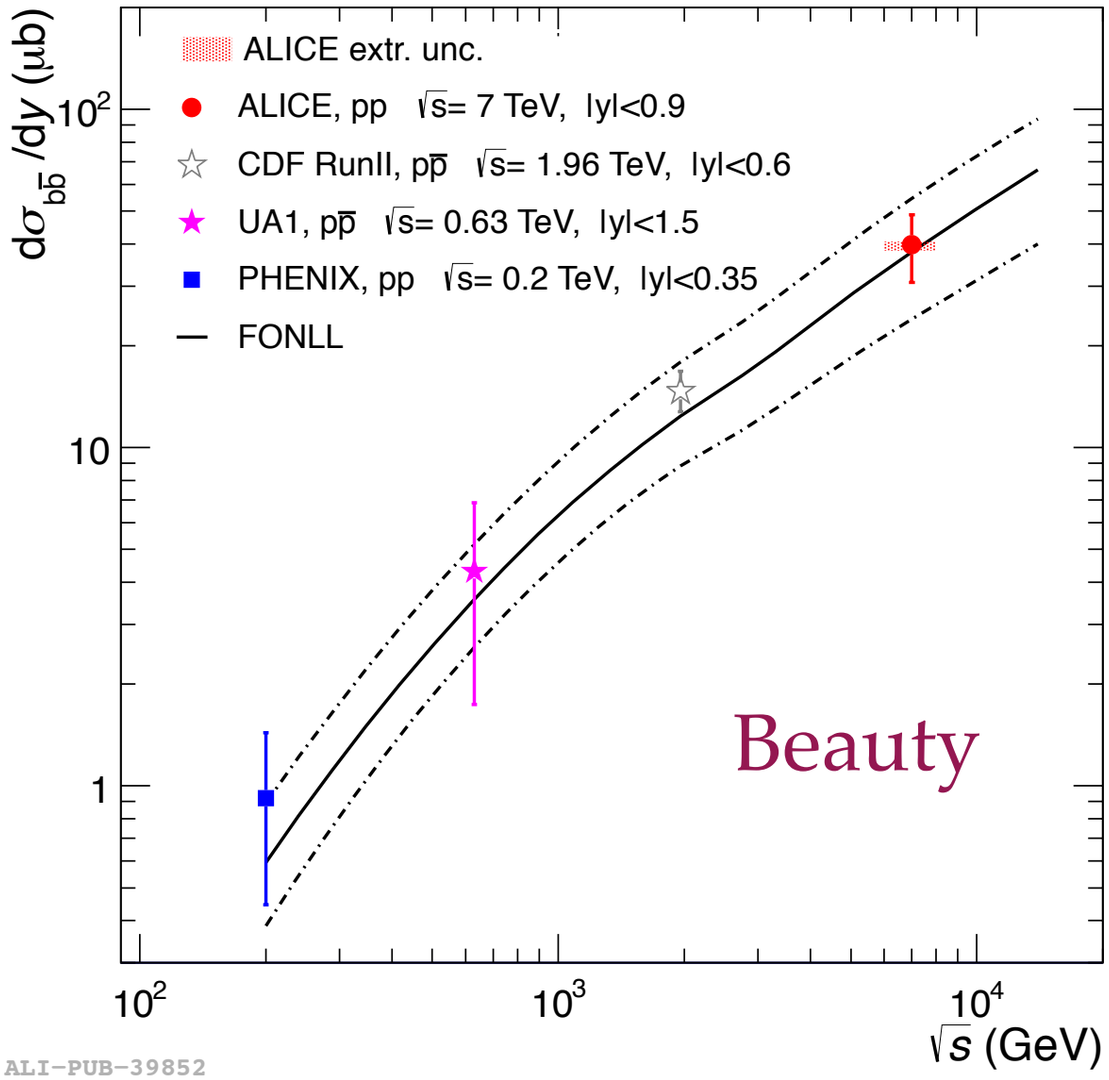
STAR D^0 & D^{*+}, √s=500 GeV | **ALICE D_s^+, √s=7 TeV** | **ALICE B decay e, √s=7 TeV**

- Cross sections in pp coll. at 200 GeV, 500 GeV, 2.76 TeV & 7 TeV
- ... no time to talk about it today !

Charm & Beauty Cross Sections

[ALICE Coll. JHEP 07 (2012) 191]





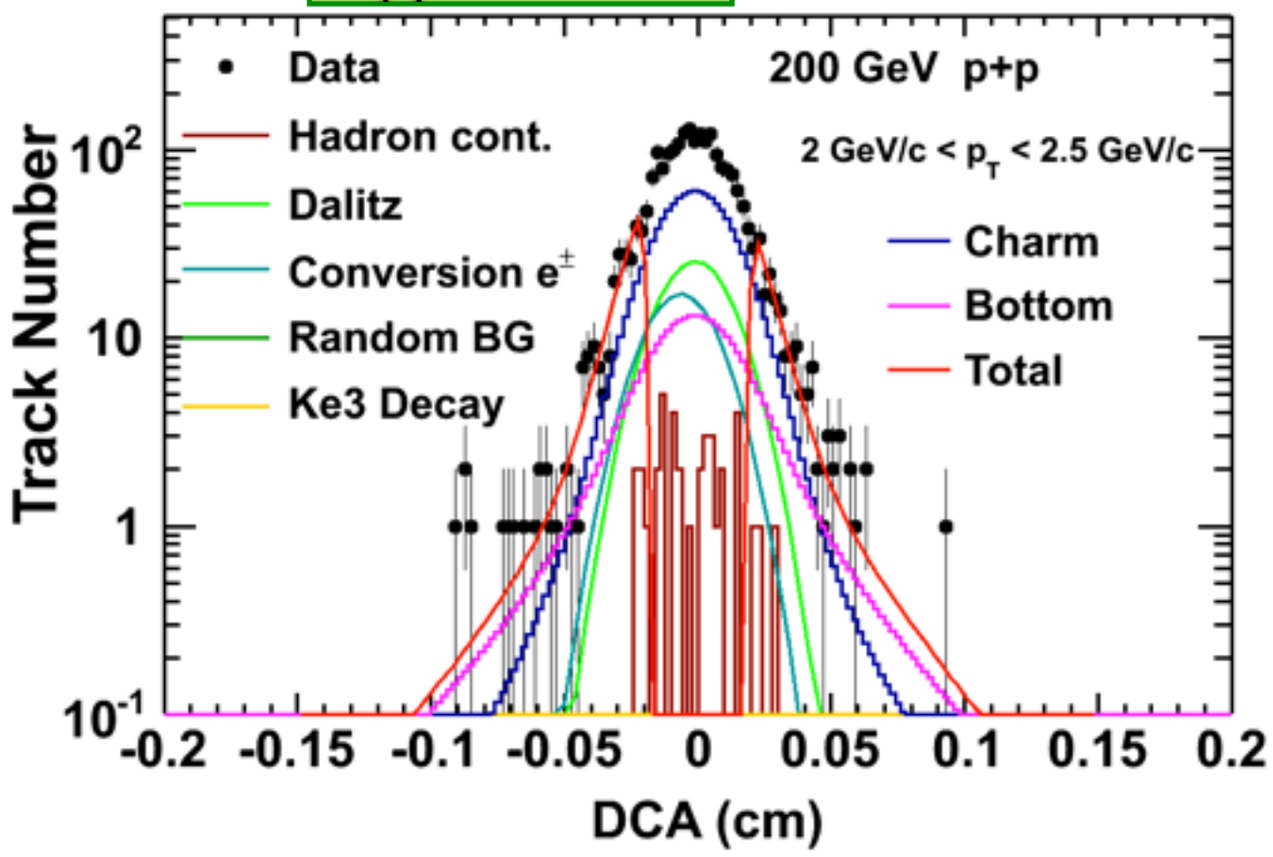
- **Their cross section evolution with √s is well described by pQCD.**
- ~560 μb × 950 collisions / 42mb ~ 13 cc pairs in 0-10% AuAu at 200 GeV
- ~5 mb × 1500 collisions / 65mb ~ 115 cc pairs in 0-10% PbPb at 2.76 TeV

Pb-Pb & Au-Au Results

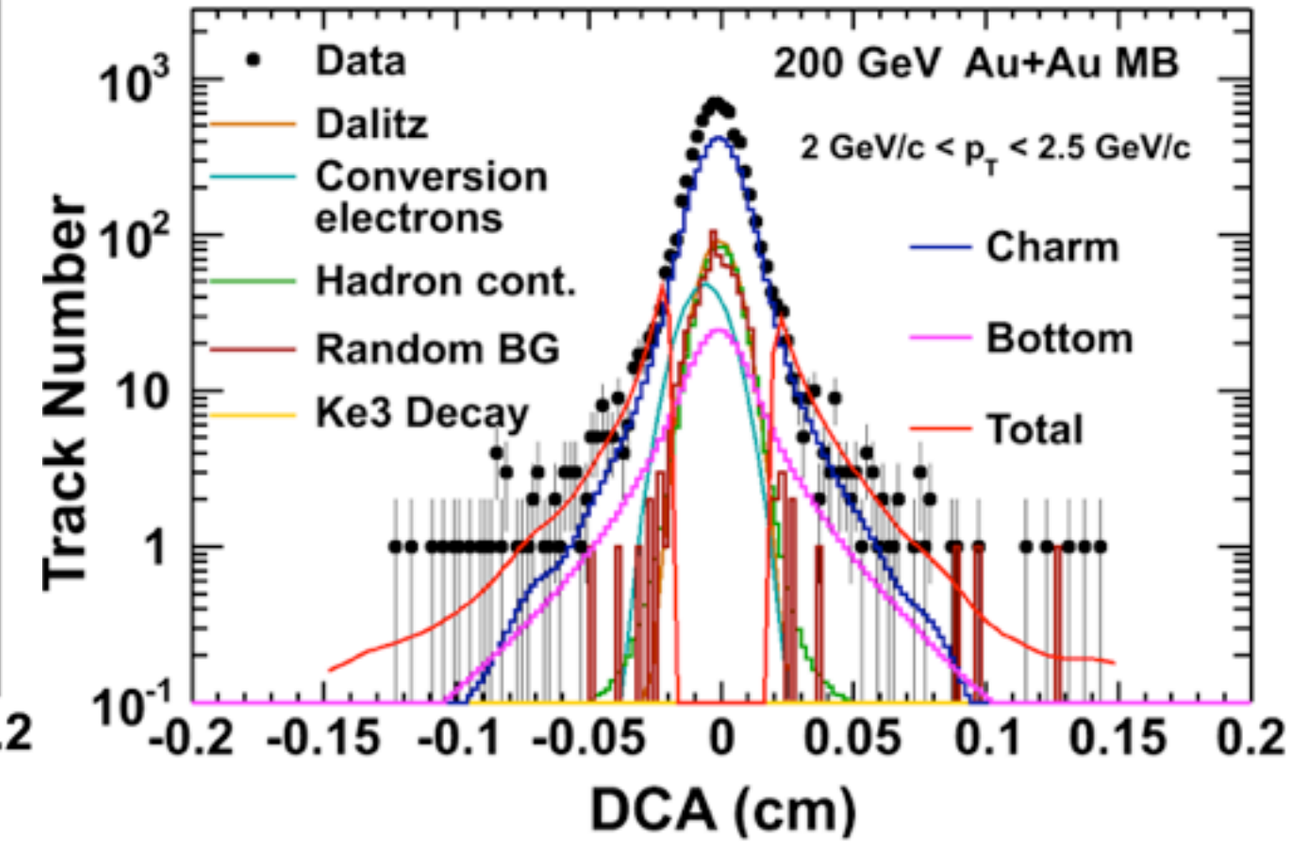
$\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 200$ GeV

PHENIX, Separating Charm & Beauty

pp 200 GeV



AuAu 200 GeV

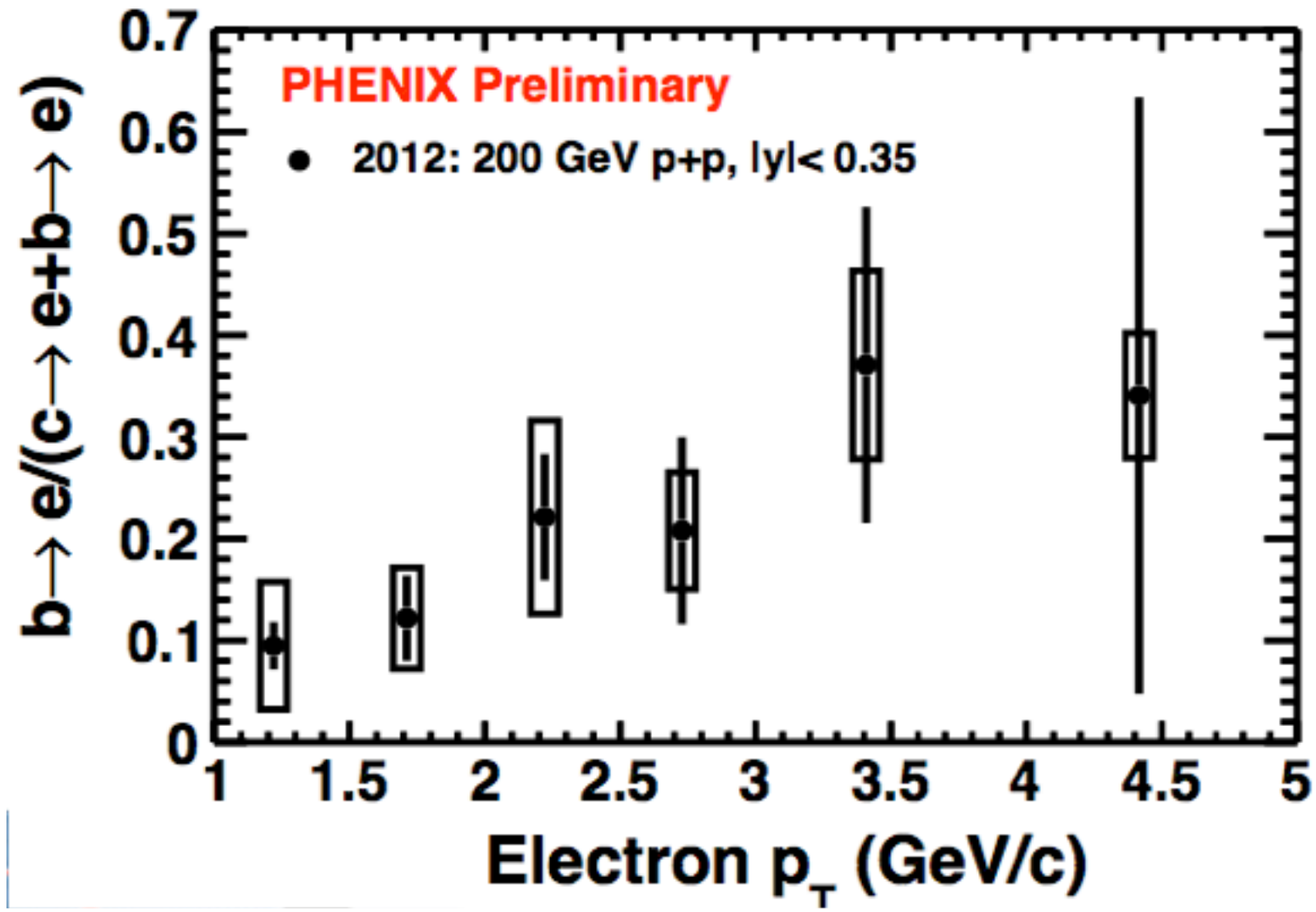


Rosati, Nouicer, QM12

- 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 in pp

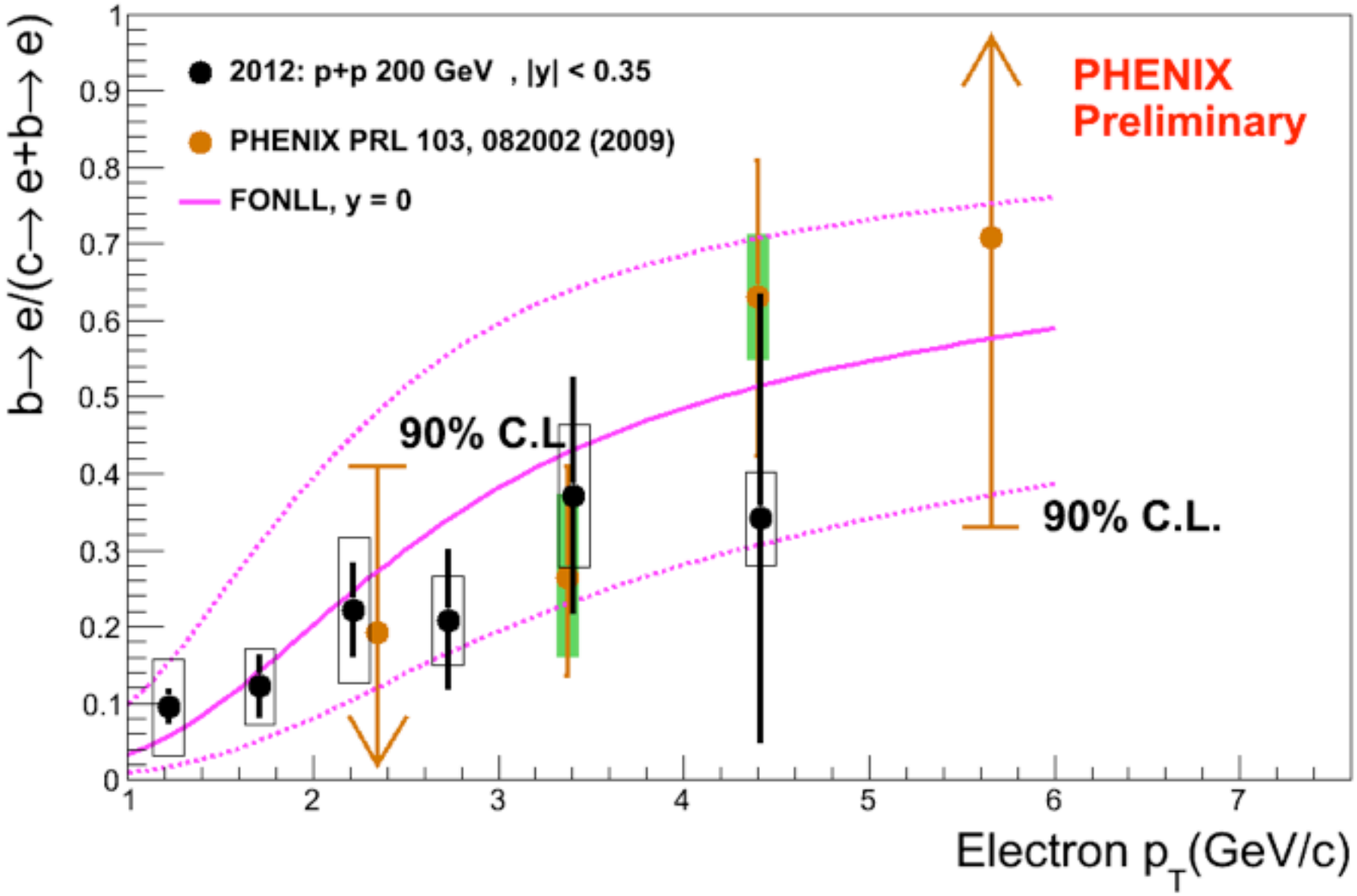
pp 200 GeV



Rosati, Nouicer, QM12

PHENIX, Charm & Beauty HF in pp

pp 200 GeV



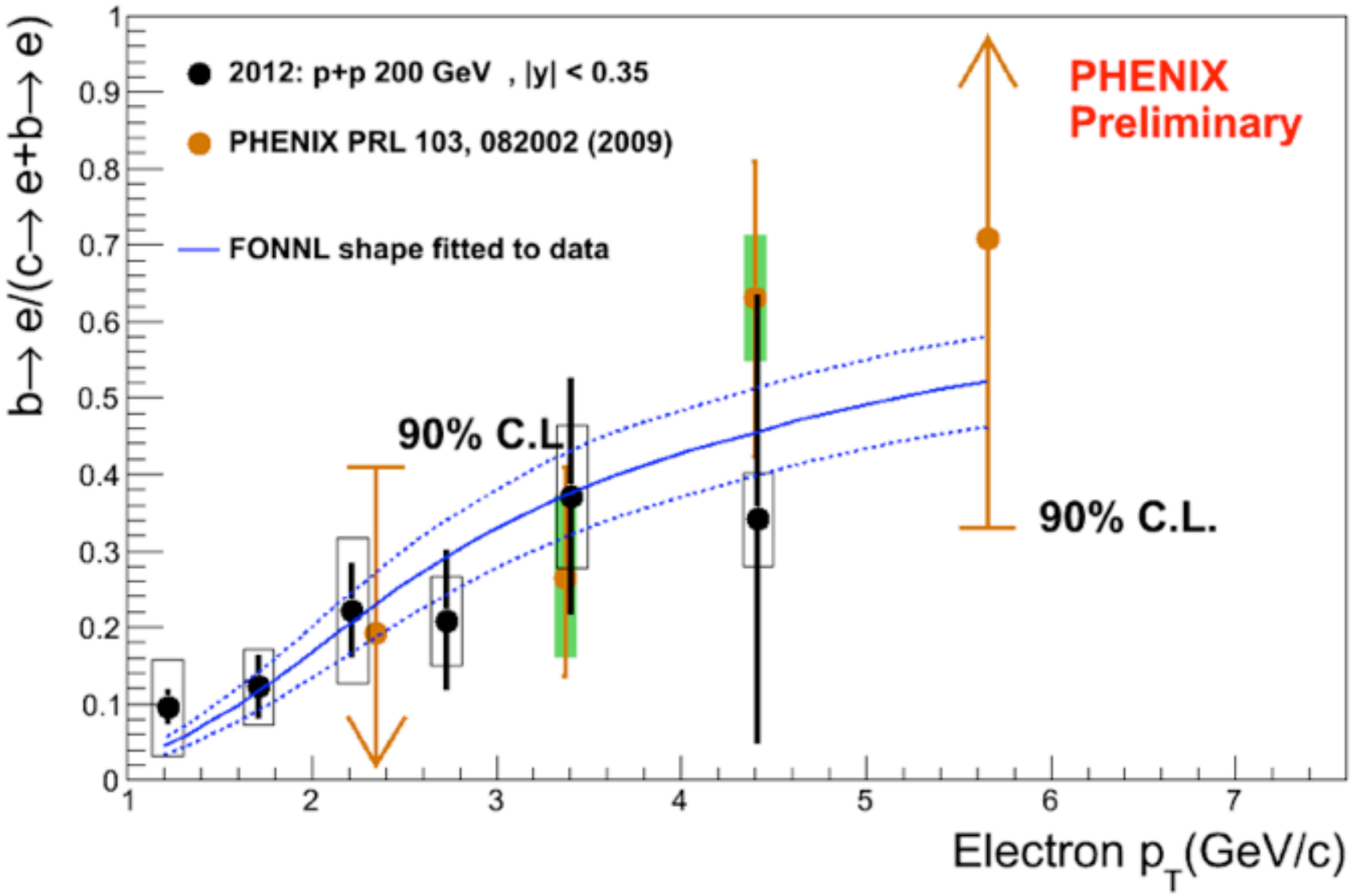
➡ Results consistent with PHENIX previous publication

➡ FONLL describes the b/(b+c) ratio

Rosati, Nouicer, QM12

PHENIX, Charm & Beauty HF in pp

pp 200 GeV



➡ Results consistent with PHENIX previous publication

➡ FONLL describes the b/(b+c) ratio

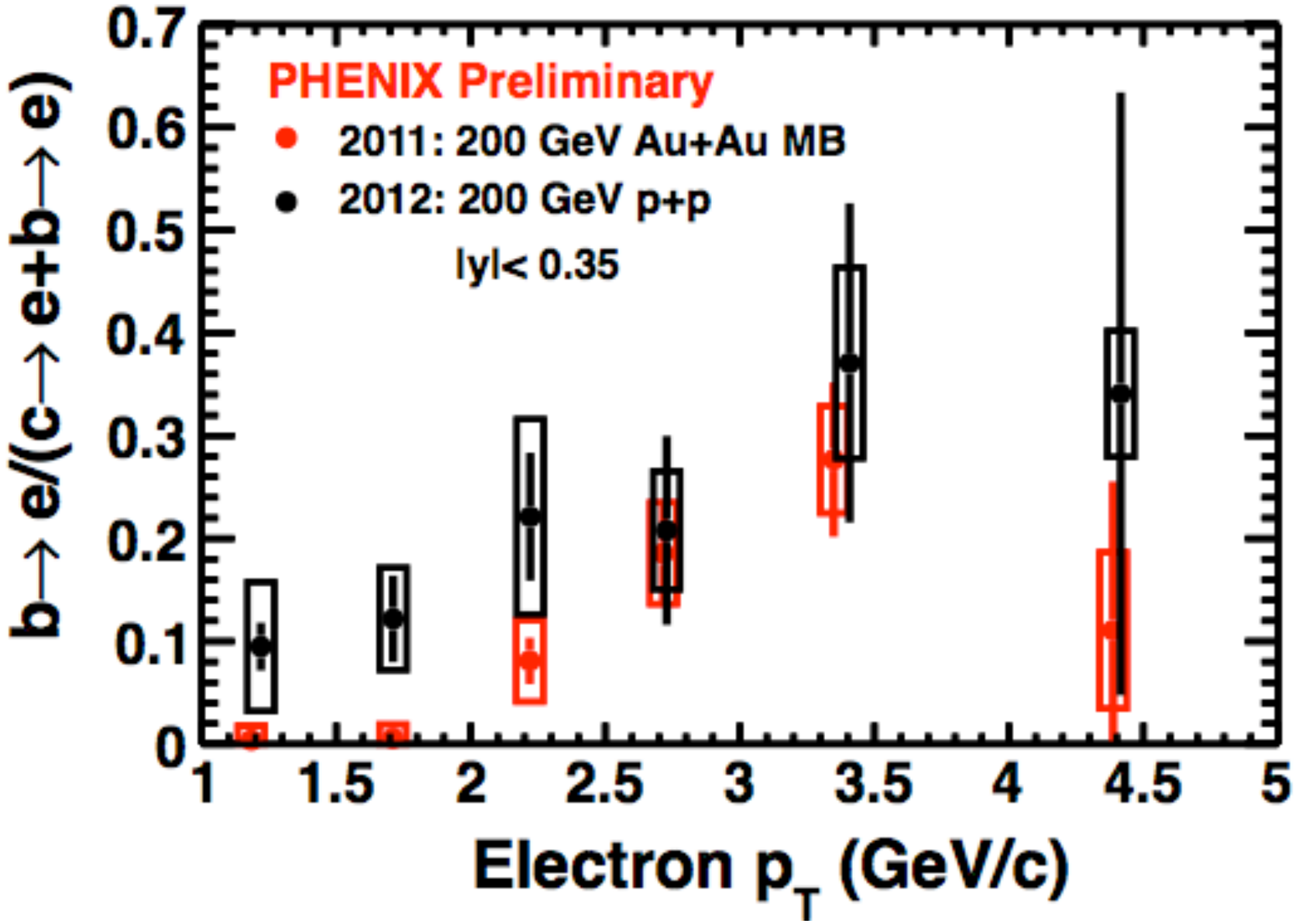
✳ Use fit of the FONLL shape to data to define a pp reference ?!

Rosati, Nouicer, QM12

PHENIX, Charm & Beauty HF

pp 200 GeV

AuAu 200 GeV



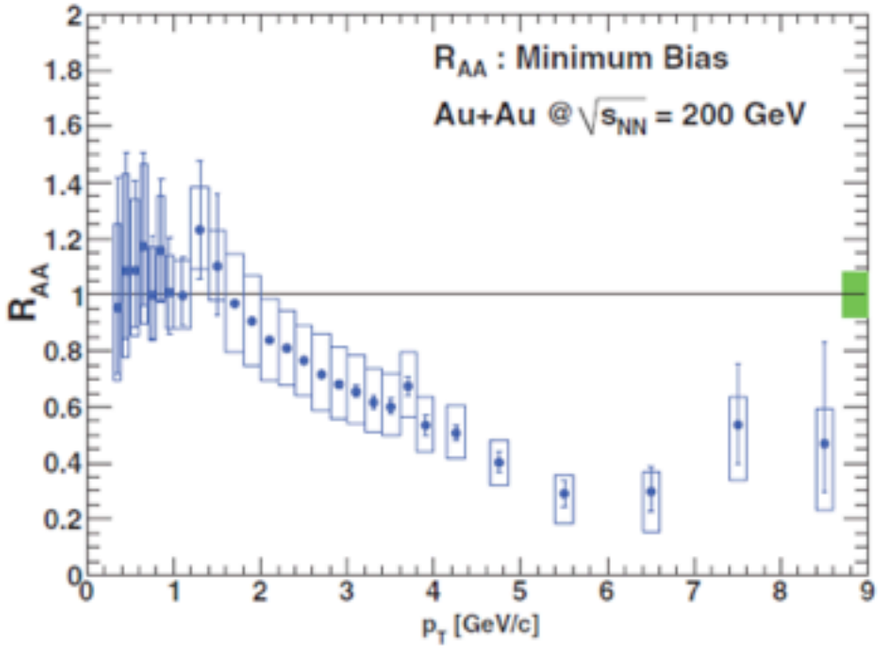
Dixit Marzia "Bottom in *Au+Au* appears more suppressed" ?

Rosati, Nouicer, QM12

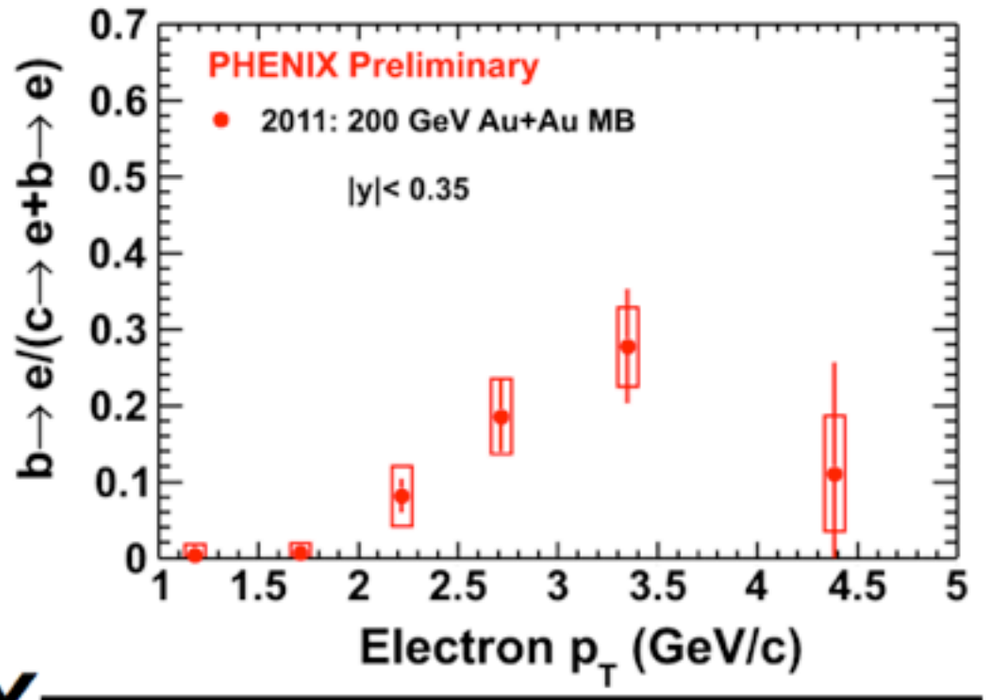
PHENIX, Beauty decay Electron R_{AA}

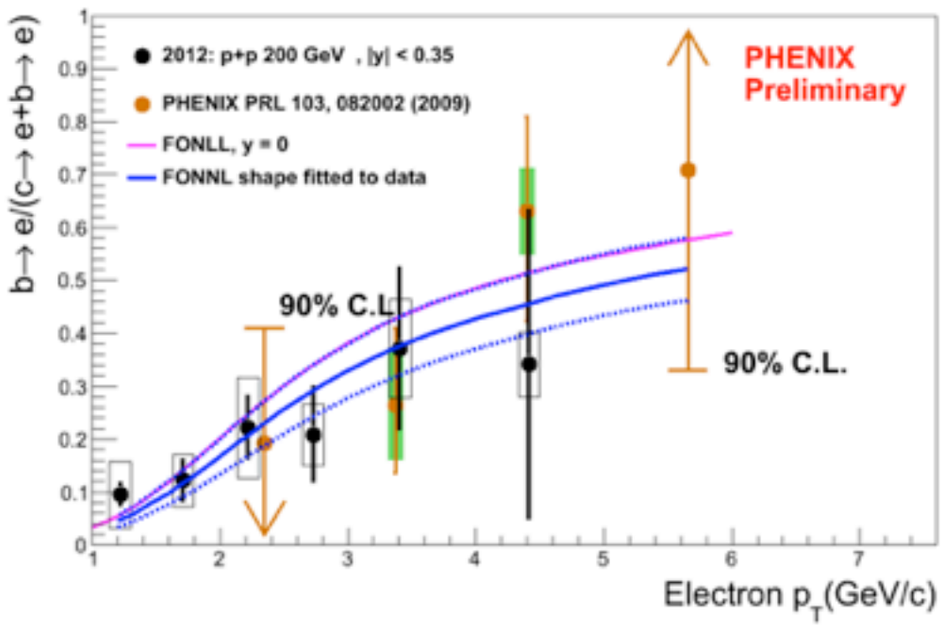
$$R_{AA}^{b\to e} = R_{AA}^{b+c\to e}\frac{\left(\frac{b\to e}{b+c\to e}\right)^{AA}}{\left(\frac{b\to e}{b+c\to e}\right)^{pp}}$$

R_{AA} (b→e) =



X

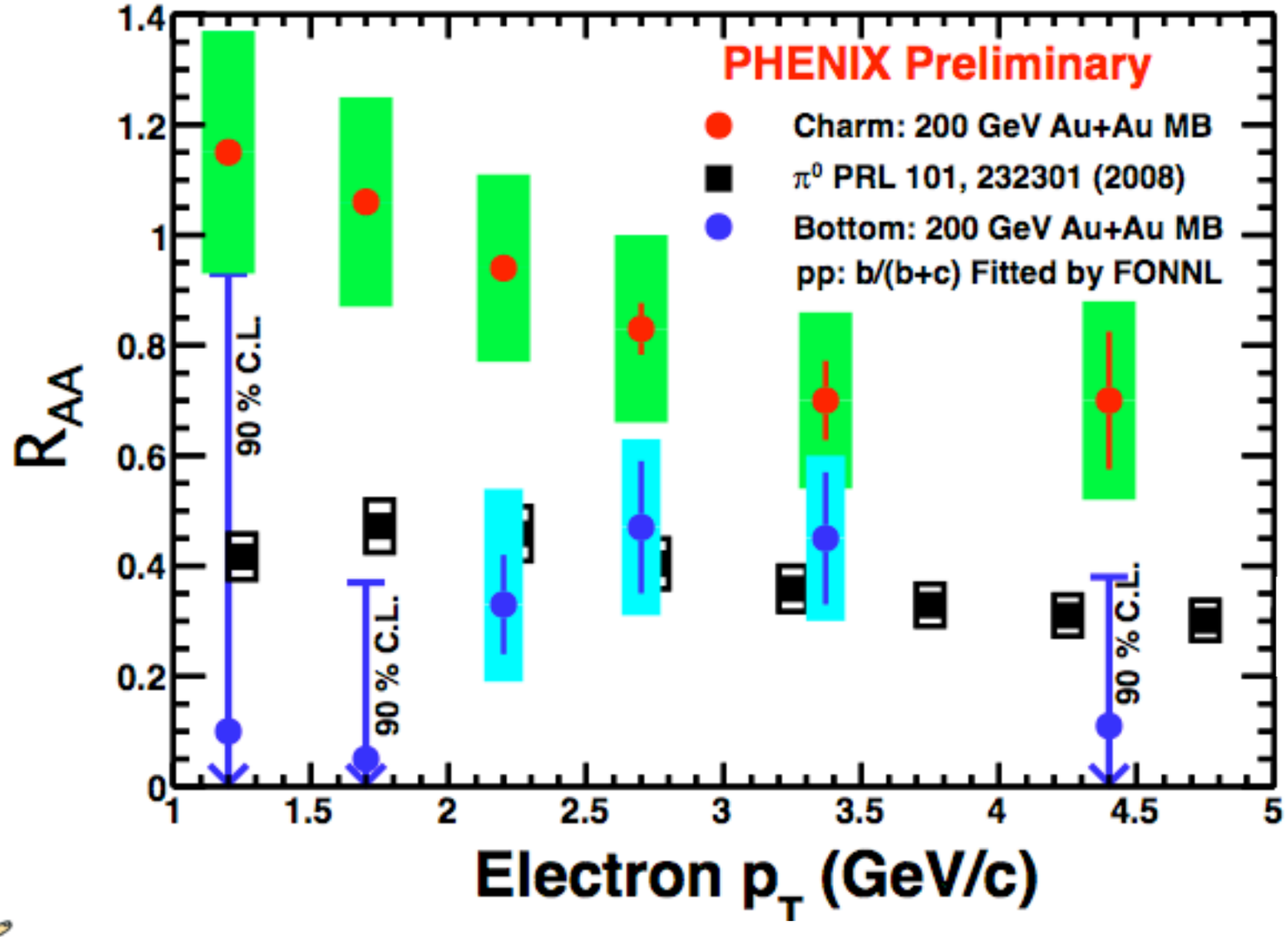




$$R_{AA}^{c\to e} = R_{AA}^{b+c\to e}\frac{1-\left(\frac{b\to e}{b+c\to e}\right)^{AA}}{1-\left(\frac{b\to e}{b+c\to e}\right)^{pp}}$$

PHENIX, Charm & Beauty HF R_{AA}

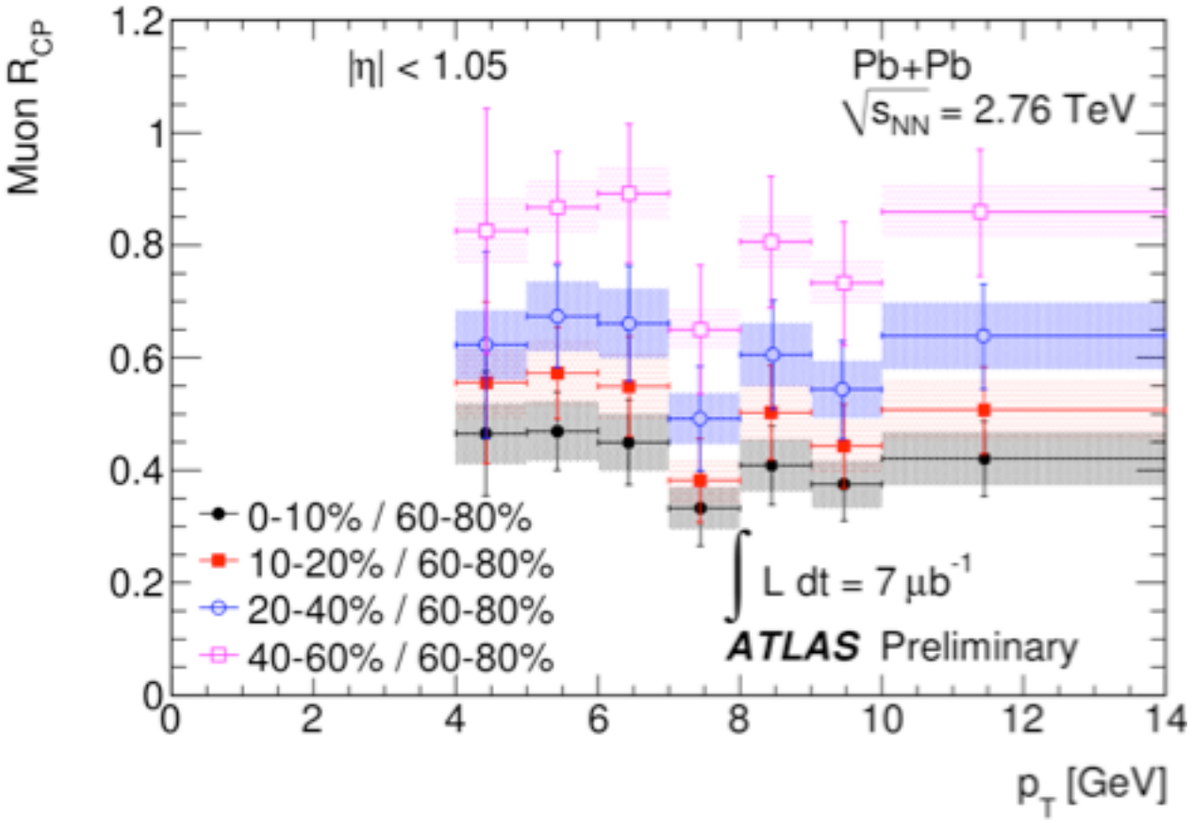
AuAu 200 GeV

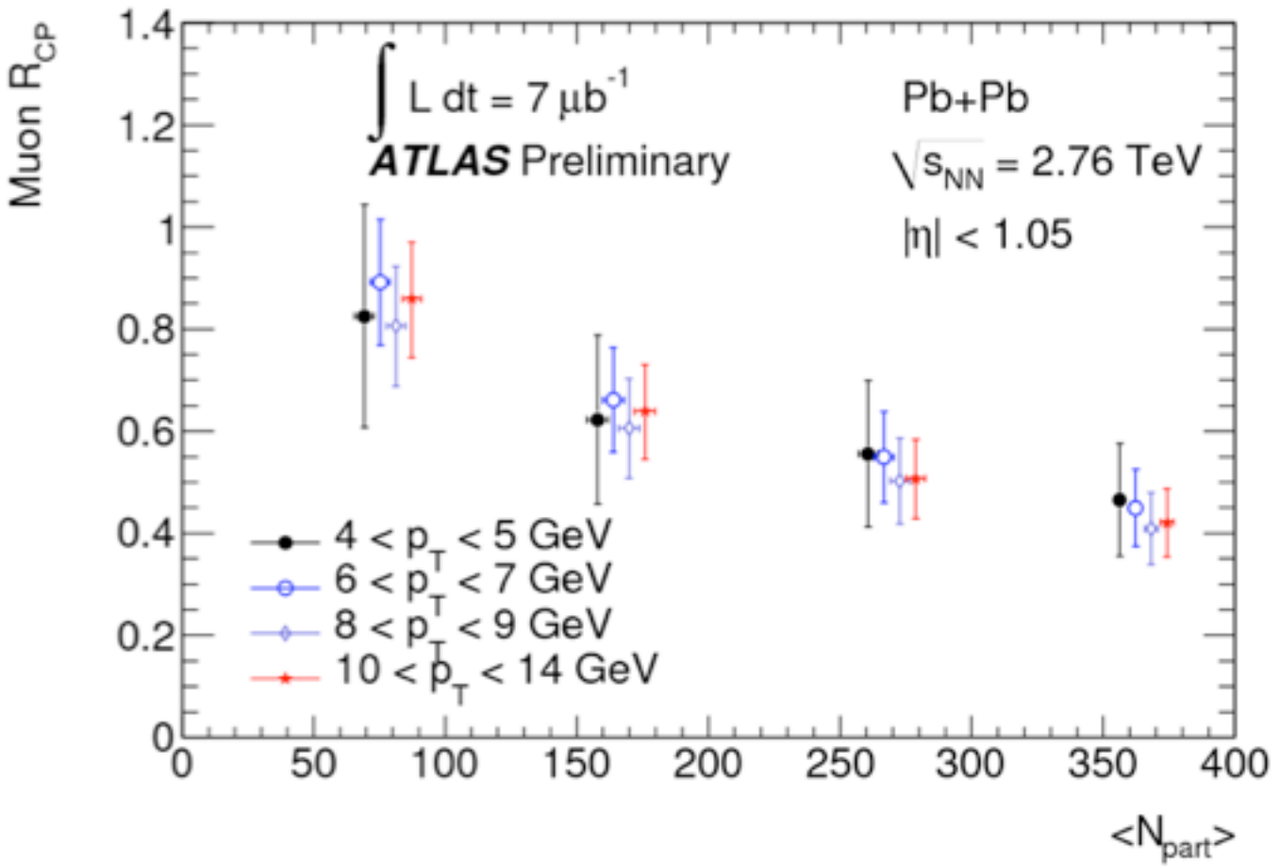


Dixit Marzia "Bottom in Au+Au appears more suppressed" ?

Rosati, Nouicer, QM12

ATLAS, HF muons





- Heavy flavor muon fraction evaluated studying the momentum lost passing through the calorimeter and the angular deflection in the inner detector
- **Central to peripheral ratio, R_{CP}:**
  - **Systematic suppression with centrality**
  - **No pt dependence**

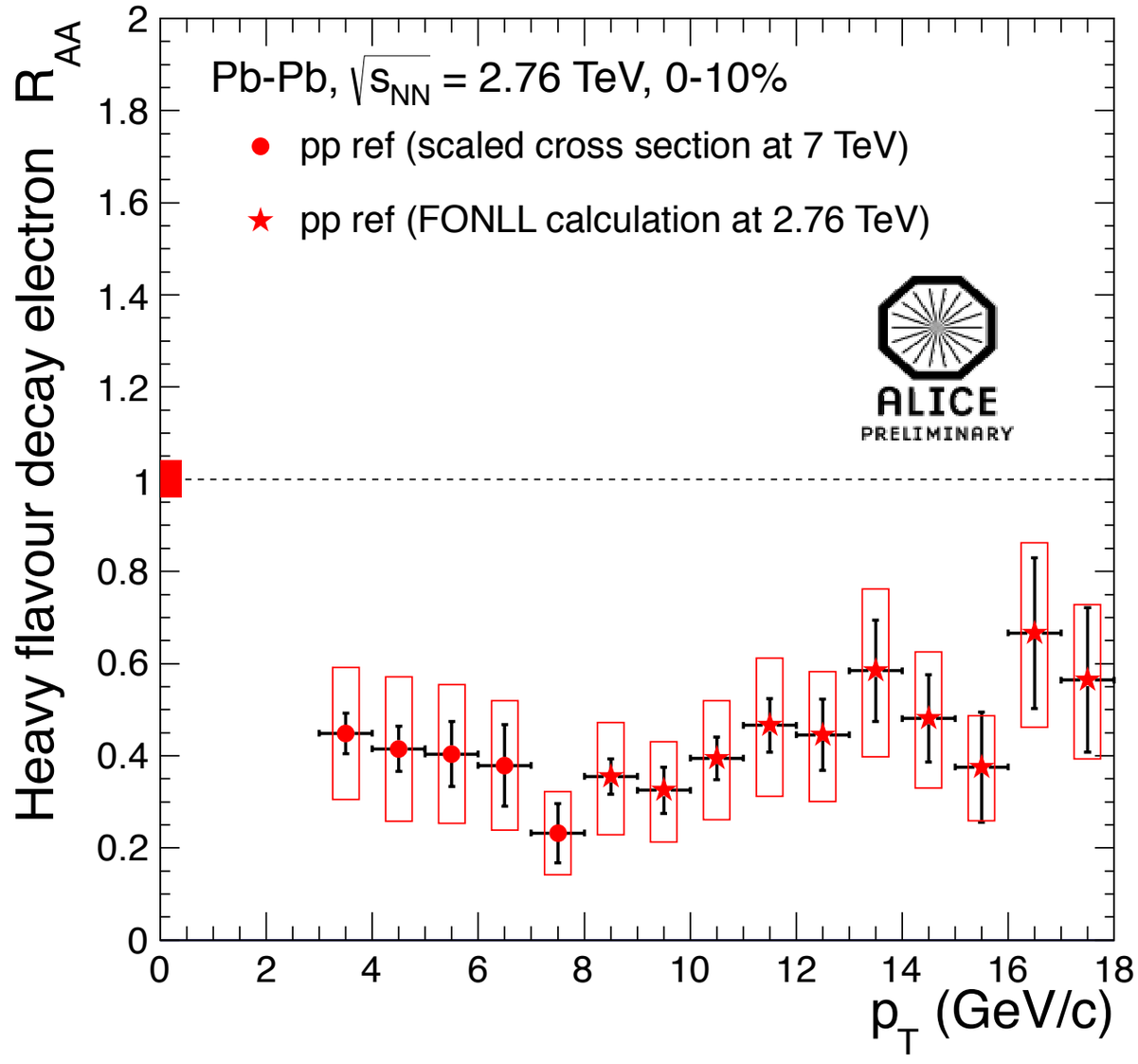
PbPb 2.76 TeV

Milov, Perepelitsa, QM12

ALICE, HF Electrons, 0-10%

PbPb 2.76 TeV

- Electron identification: TPC+EMCAL
- Subtract background electrons from the inclusive electrons
- Background electrons:
  - π^0 + Dalitz($\pi^{\pm}$,η) + γ-conversions via invariant mass analysis
  - Plus J/ψ cocktail based on pp data with ($0.2 < R_{AA}(J/\psi) < 0.8$)
- pp reference:
  7 TeV pp data scaled to 2.76TeV
  + FONLL at high p_T



[ALICE Coll., arXiv:1205.5423 (2012)]

➡ **Clear suppression for $3<p_T<18$ GeV/c**

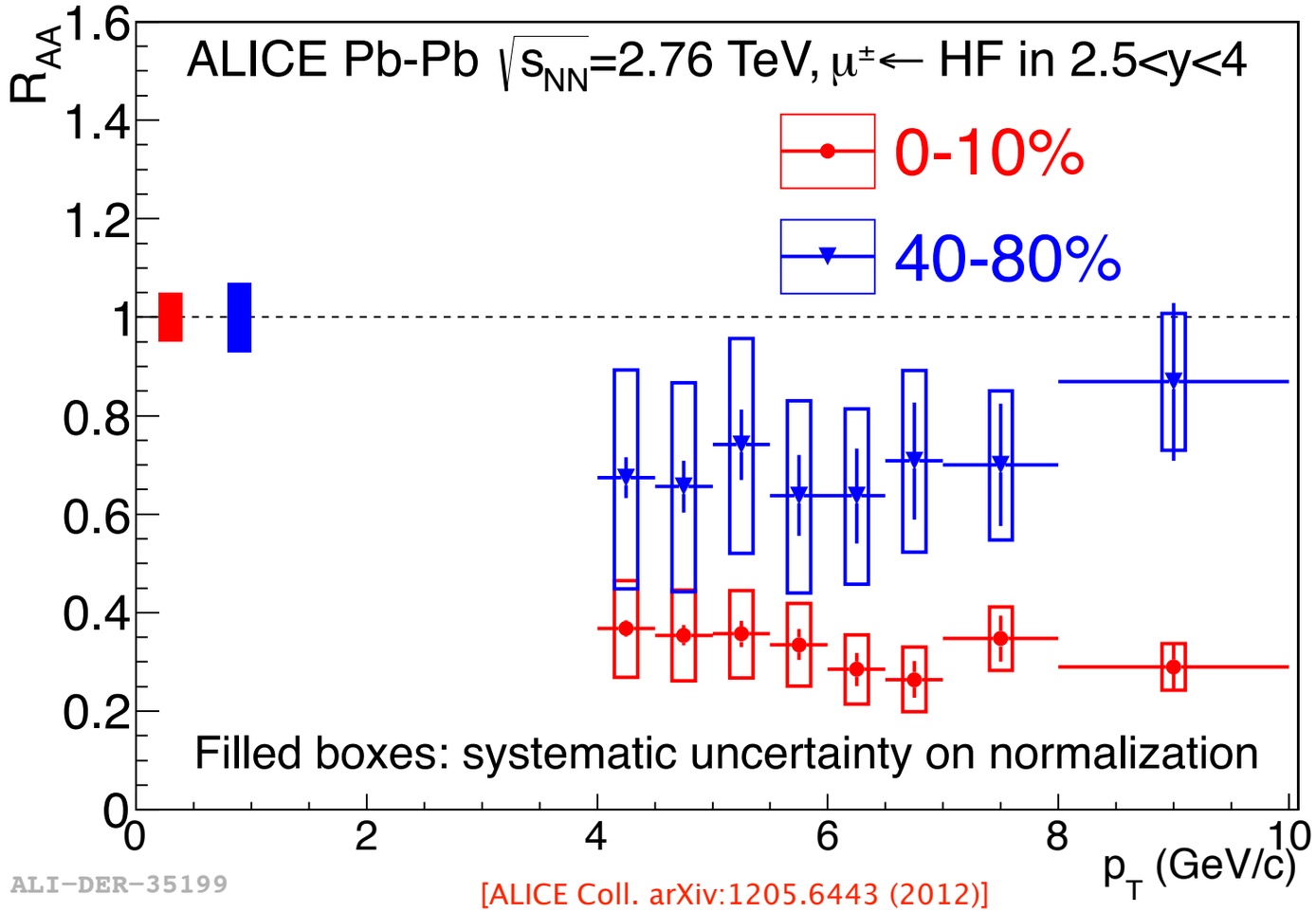
- **Amounts to a factor of 1.5-3 for $3<p_T<10$ GeV/c**

ZCdV, Sakai, QM12

ALICE, HF Muons, 0-10%

PbPb 2.76 TeV

- Subtract background muons from π, K decays
- Background muons: π, K extrapolated from mid-rapidity measurements. Consider $R_{AA}^{\pi}(y=0)$, $R_{AA}^{K}(y=0)$, and let vary $0 < R_{AA}^{\pi,K}(y\text{-forward}) < 2\ R_{AA}^{\pi,K}(y=0)$
- pp reference: pp data at 2.76 TeV



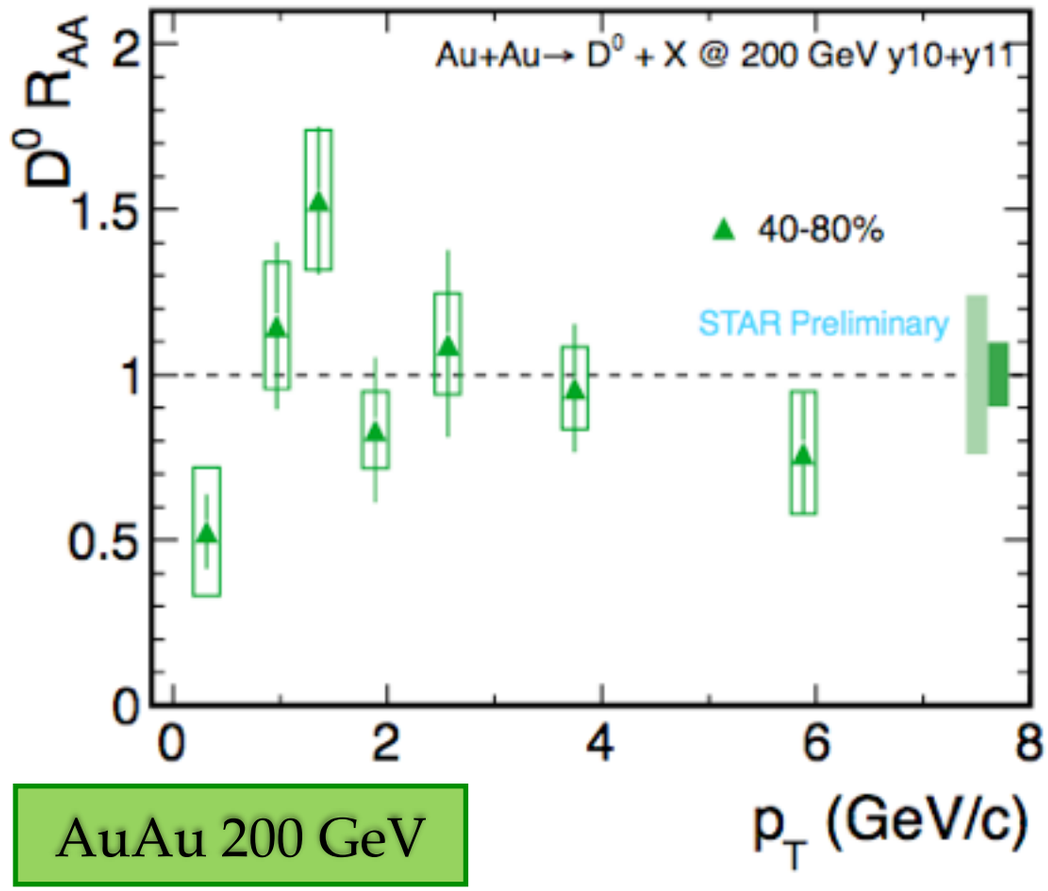
[ALICE Coll. arXiv:1205.6443 (2012)]

Xiaoming, later today

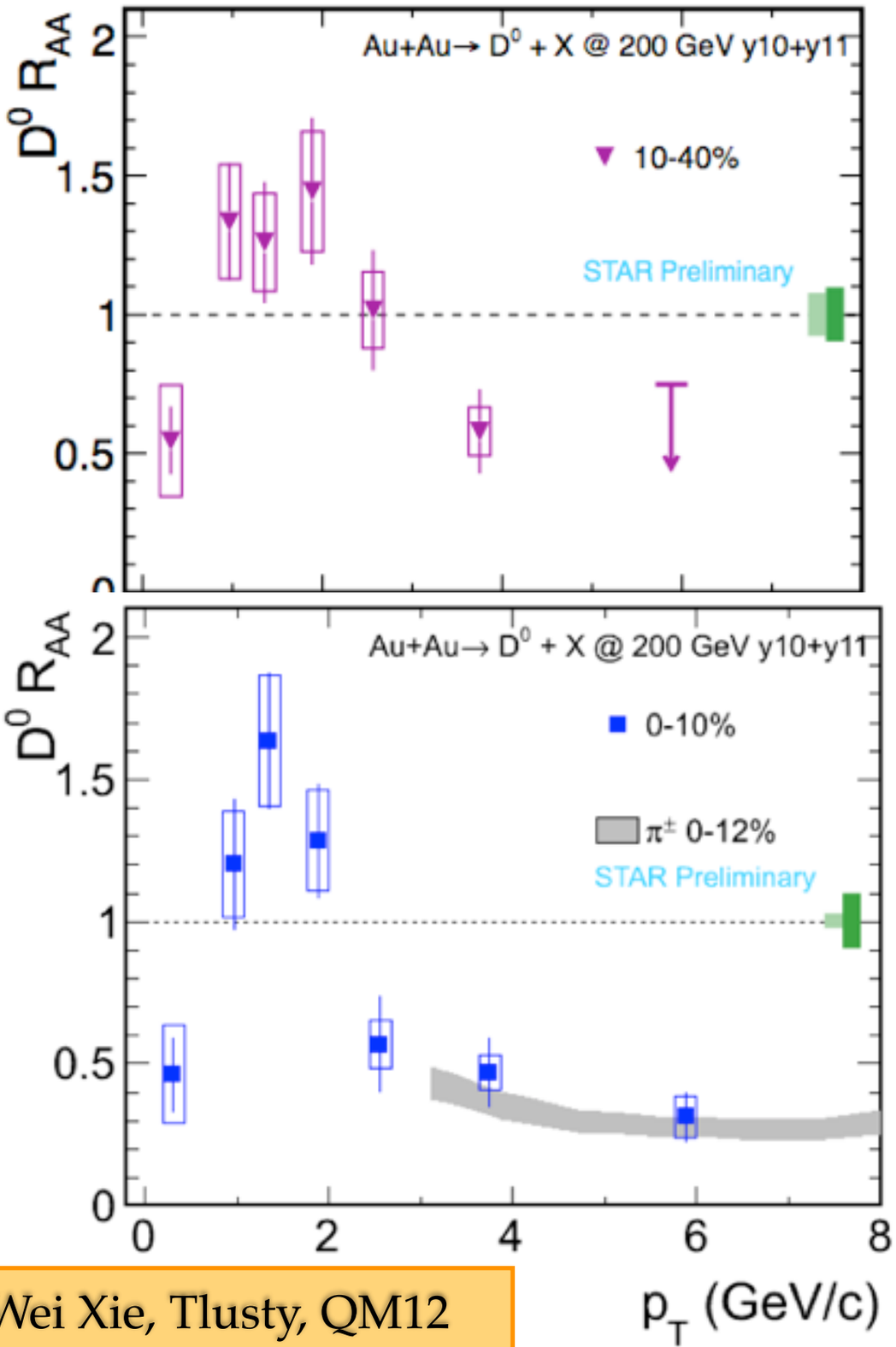
ZCdV, Zhang, QM12

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

STAR, Inclusive D^0 meson R_{AA}



AuAu 200 GeV

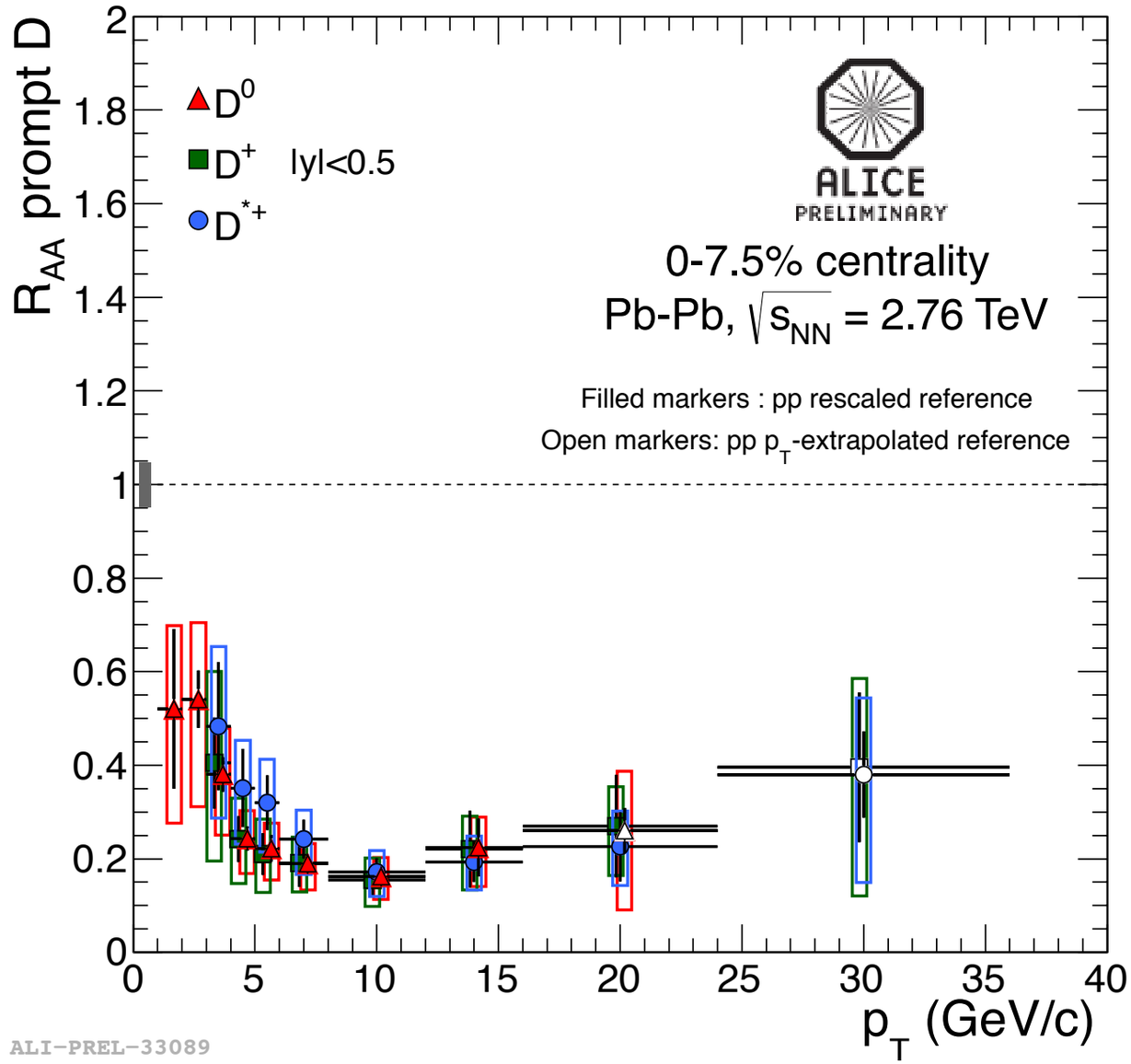


Wei Xie, Tlusty, QM12

- 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^{*+} mesons, 0-7.5%

- Reconstruction of secondary decay vertices with ITS + TPC-TOF for K/π PID
- **Prompt D mesons** = inclusive D mesons – D mesons from B decays
- pQCD-based subtraction of D from B decays, with the constrain $1/3 < R_{AA}(\text{DfromB})/R_{AA}(\text{D}) < 3$
- pp reference: 7 TeV data scaled to 2.76 TeV + high p_T-pQCD-extrapolation



PbPb 2.76 TeV

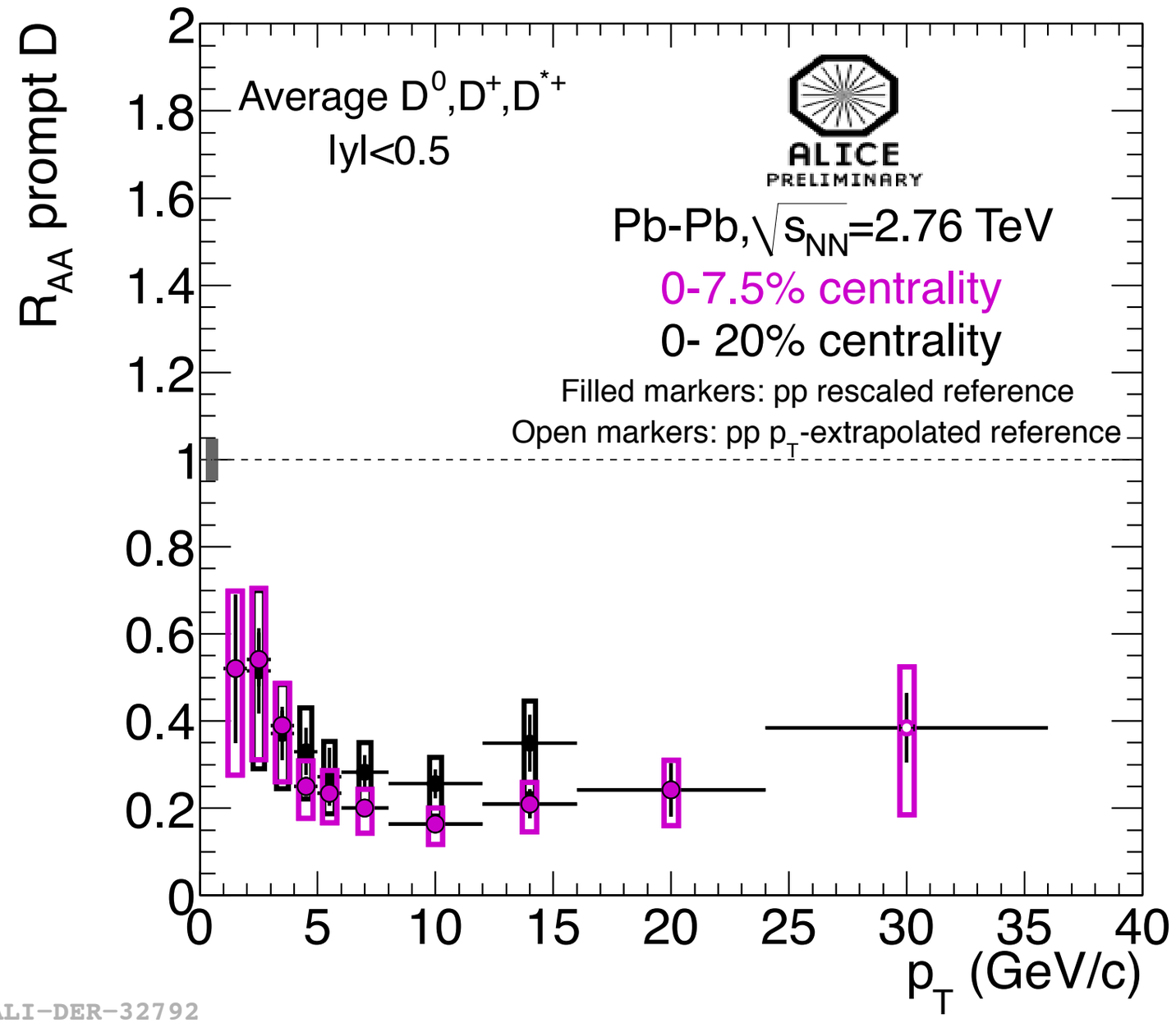
ZCdV, Grelli, QM12

[ALICE Coll. arXiv:1203.2160 (2012)]

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

PbPb 2.76 TeV

ZCdV, Grelli, QM12



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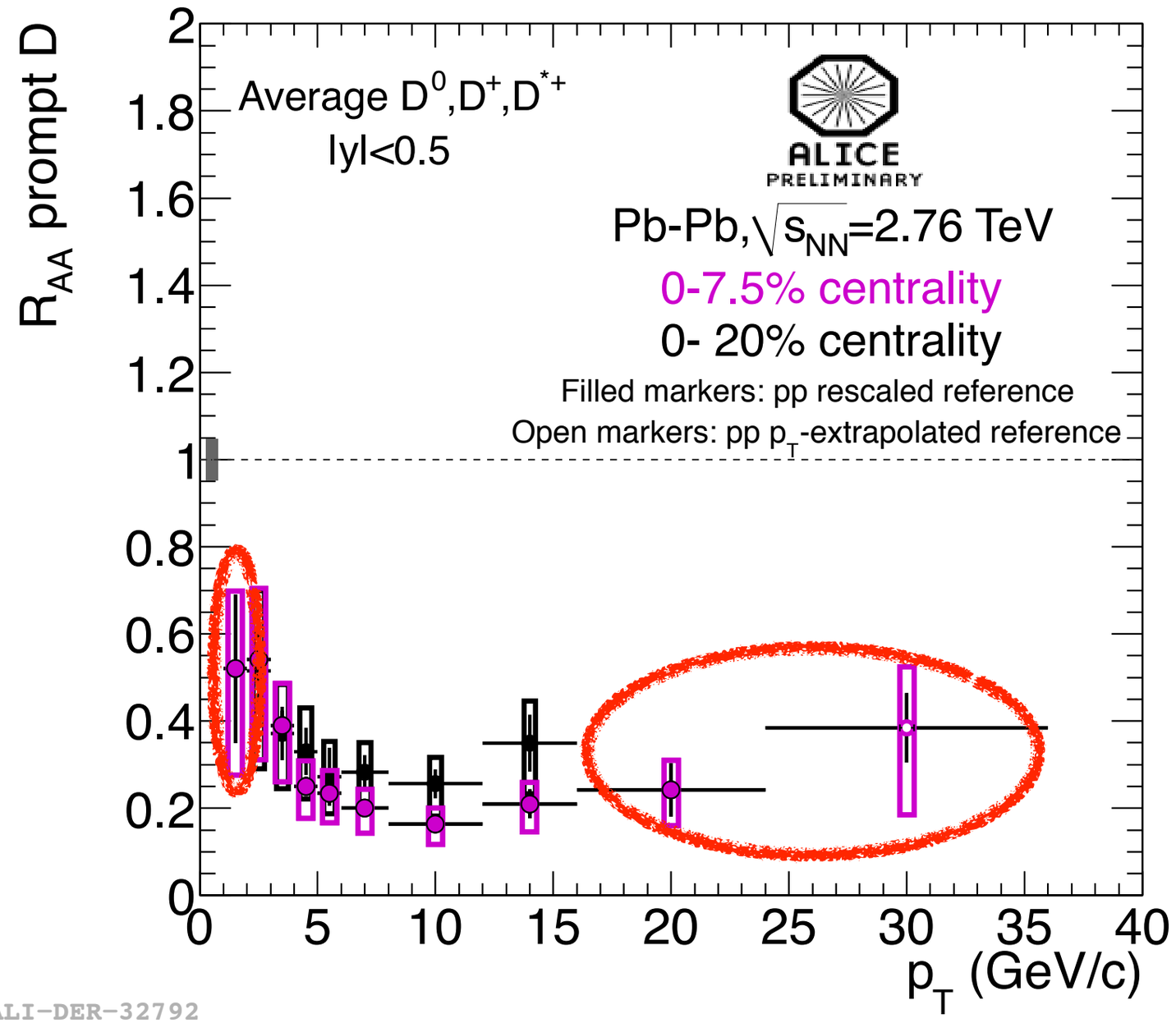
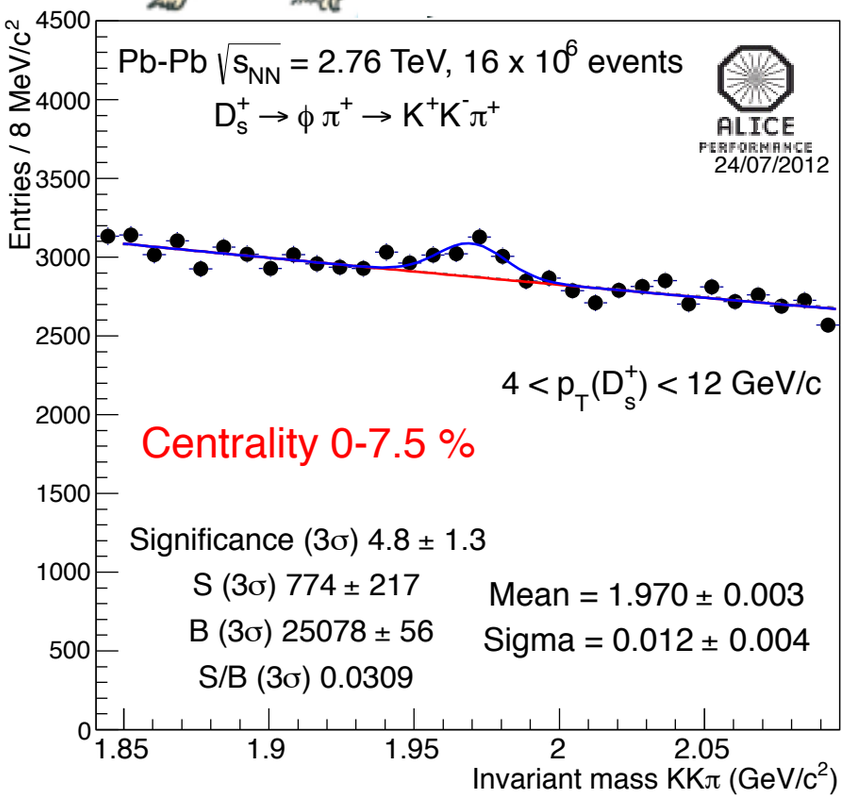


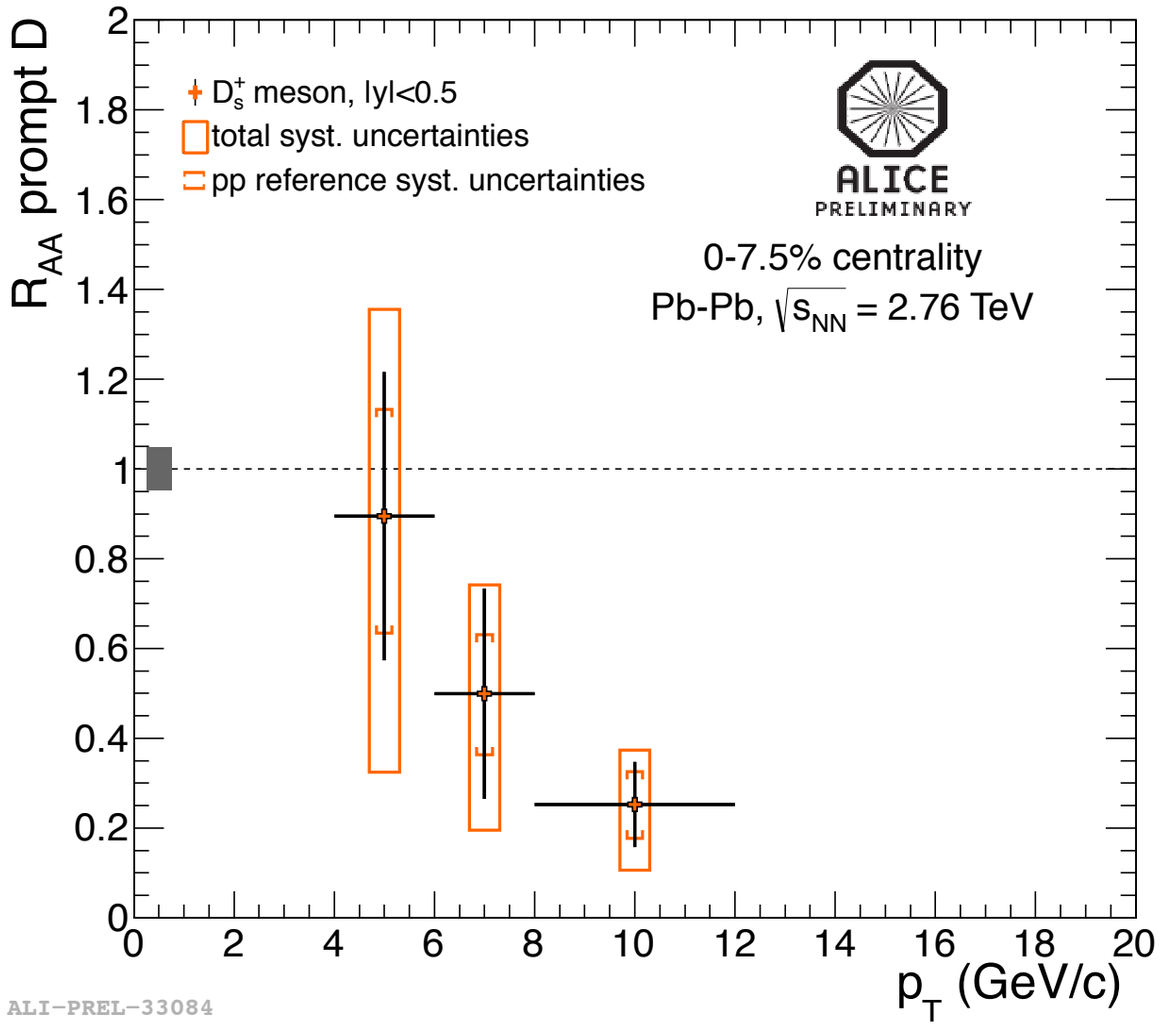
[ALICE Coll. arXiv:1203.2160 (2012)]

- Extended measurement to $1<p_T<36$ GeV/c
- Suppression by up to a factor of 5 at p_T ~10 GeV/c in 0-7.5%

ALICE, First D_s^+ measurement, 0-7.5%

- Expectation: relative enhancement of the strange/non-strange D mesons at intermediate p_T - charm in-medium hadronization ?





- **First measurement of prompt D_s^+ dN/dp_T and R_{AA}**
- **Suppression by a factor of 3-5 for p_T~8-12 GeV/c**
- **Similar to that of the D^0, D^+, D^{*+}**

PbPb 2.76 TeV

ZCdV, Innocenti, QM12

[I. Kuznetsova, J. Rafelski, Eur.Phys.J.C51:113-133 (2007)] [M. He, et al, arXiv:1204.4442] [A. Andronic, et al, arXiv:0708.1488v3]

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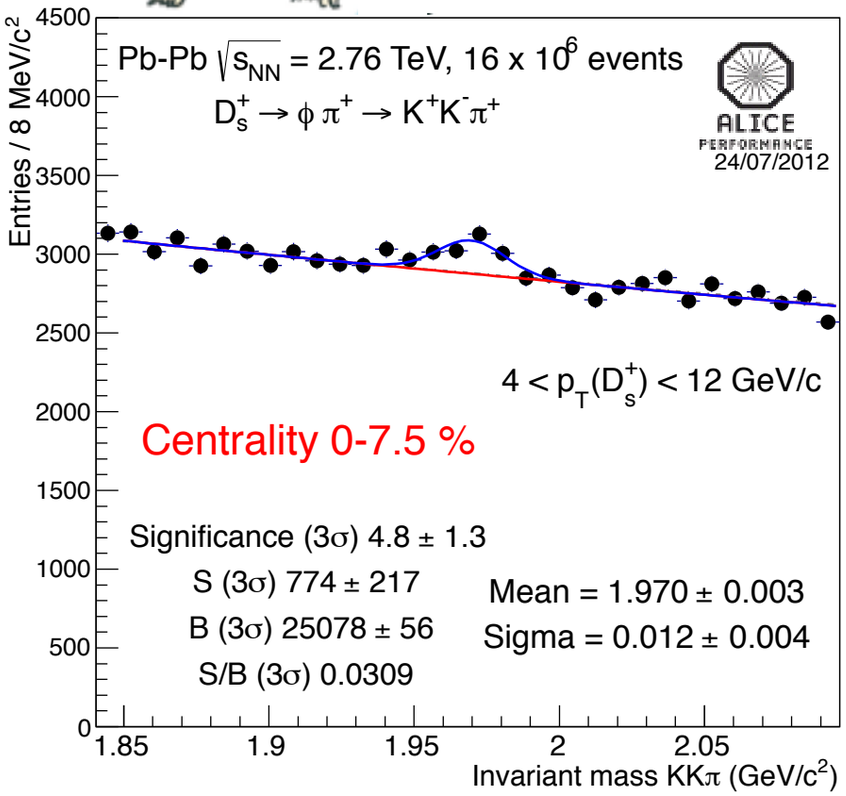

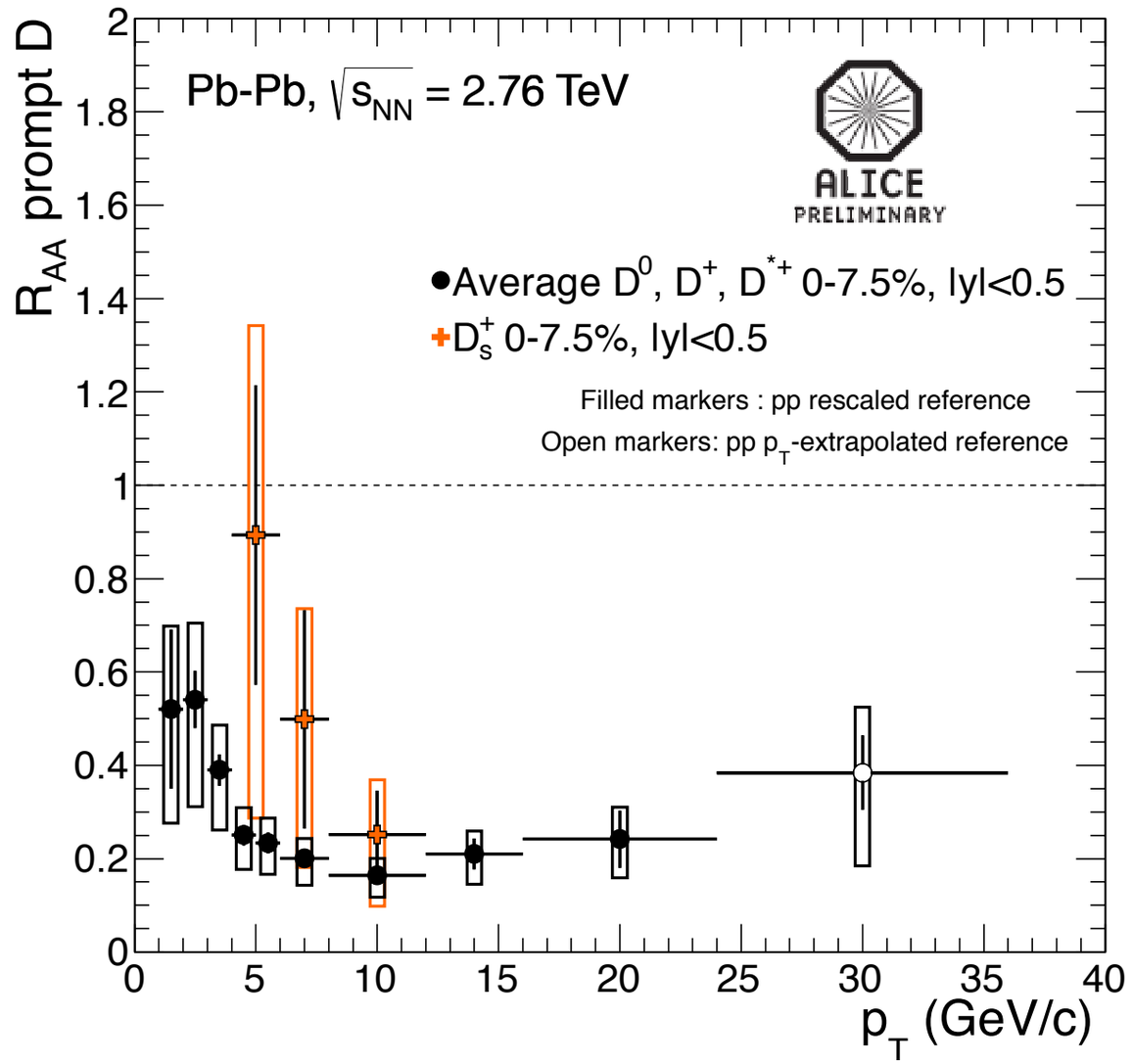

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ZCdV, Innocenti, QM12

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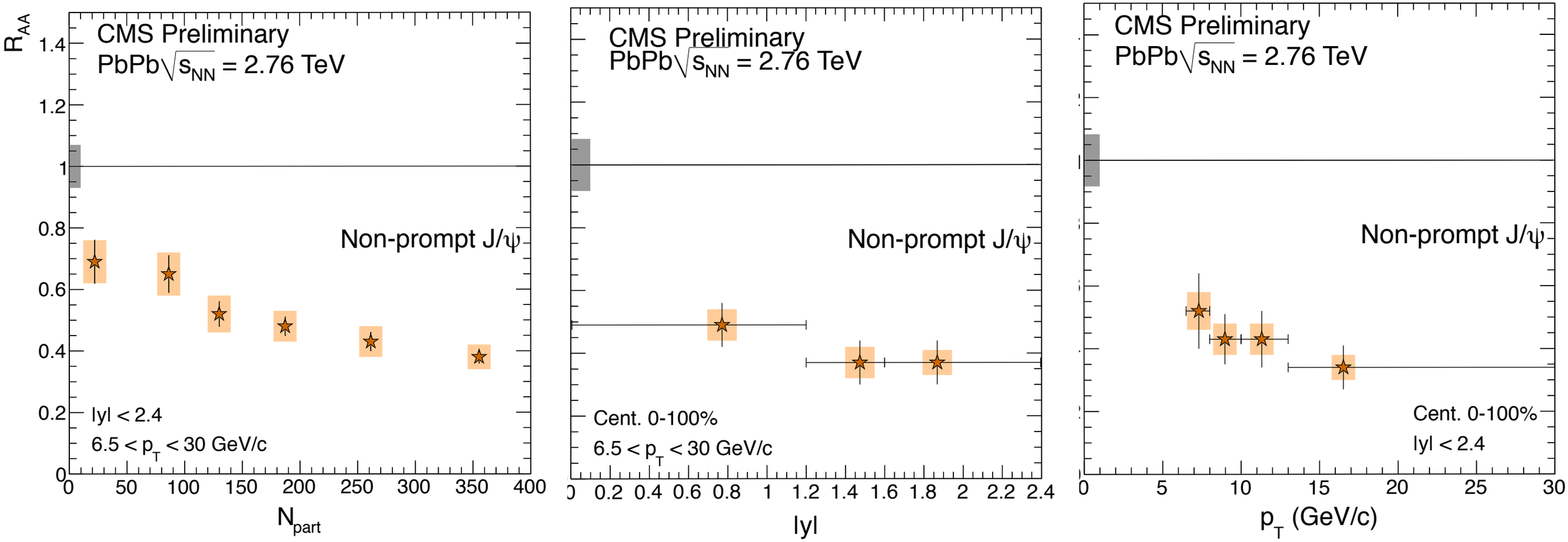
CMS, Non-Prompt J/ψ



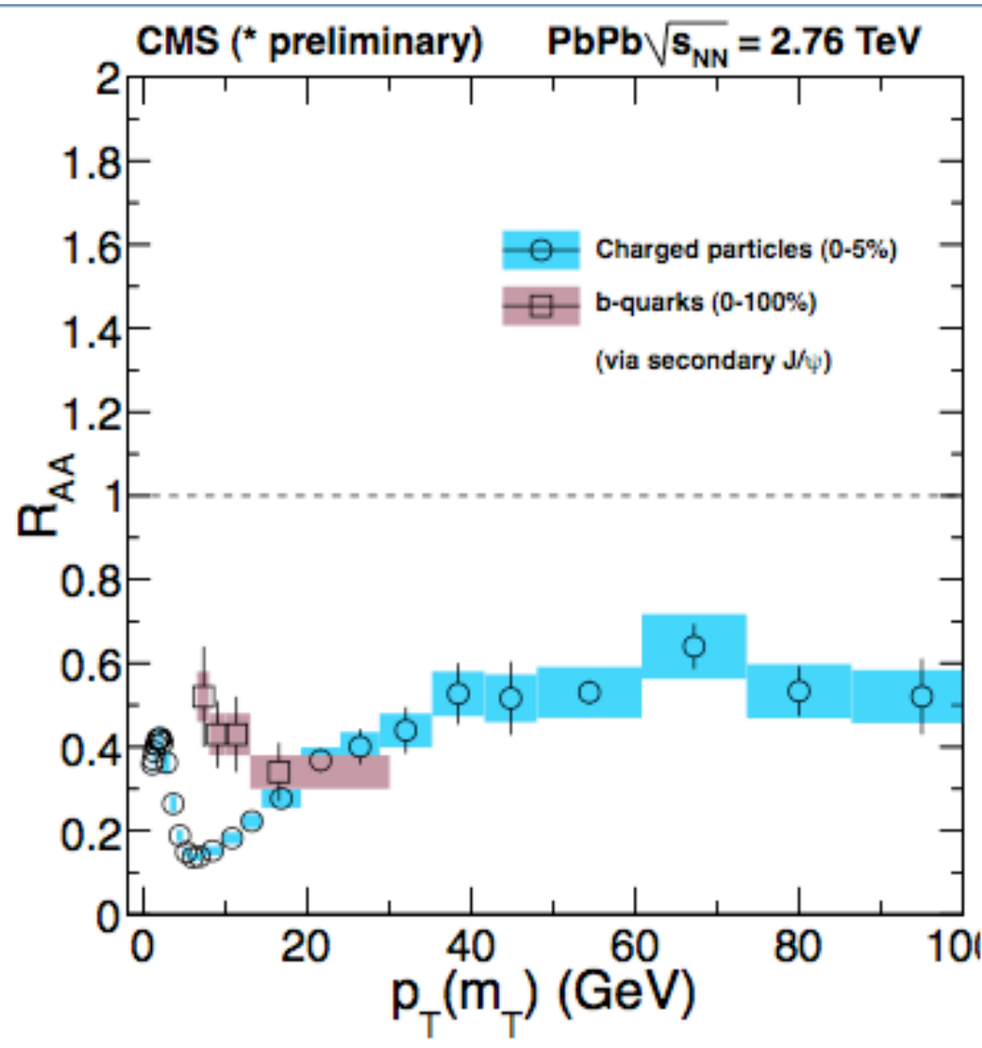
- Centrality dependence of B→J/ψ R_{AA}
  - 50-100%: factor ~1.4
  - 0-5%: factor ~2.5
- Hint of less suppression at mid-rapidity
- Hint of larger suppression at higher pt

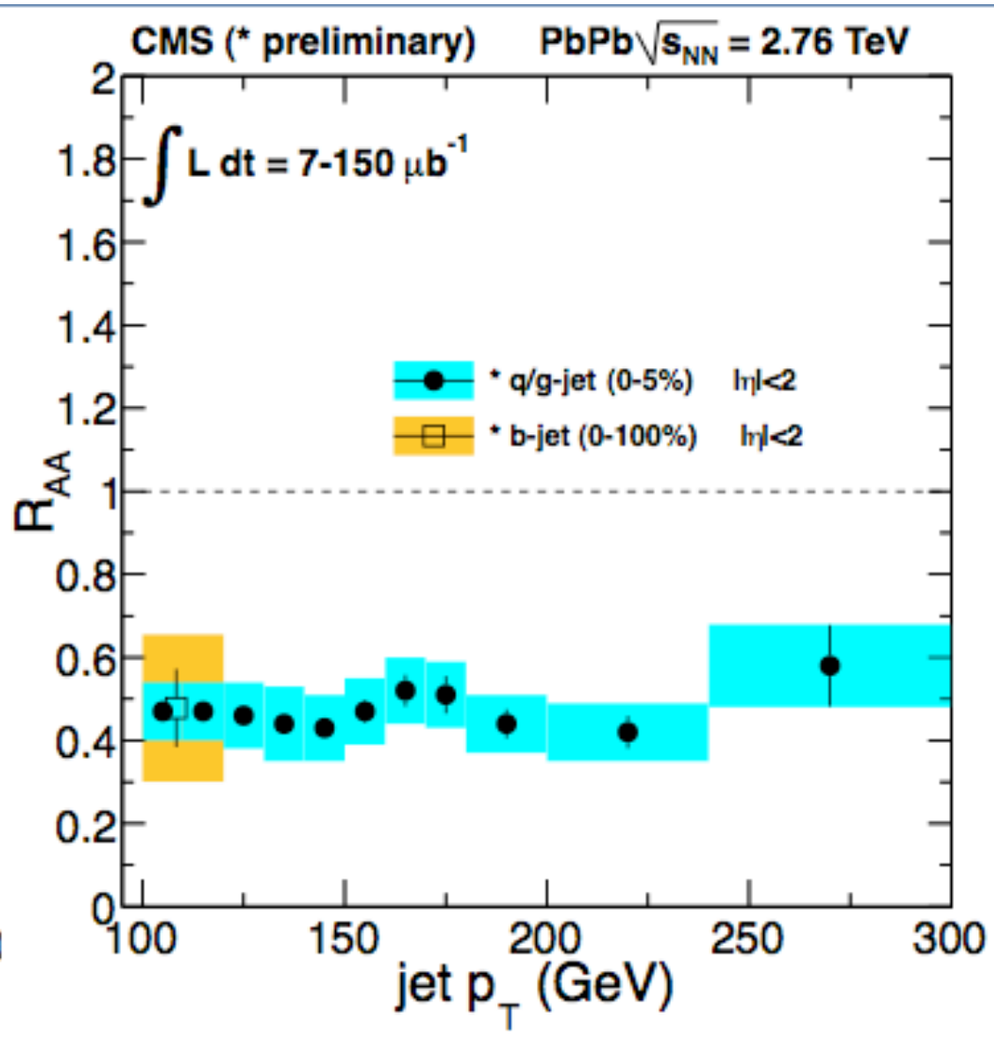
PbPb 2.76 TeV

Camelia's talk today

Mironov, Jo, QM12

CMS, Beauty Jets





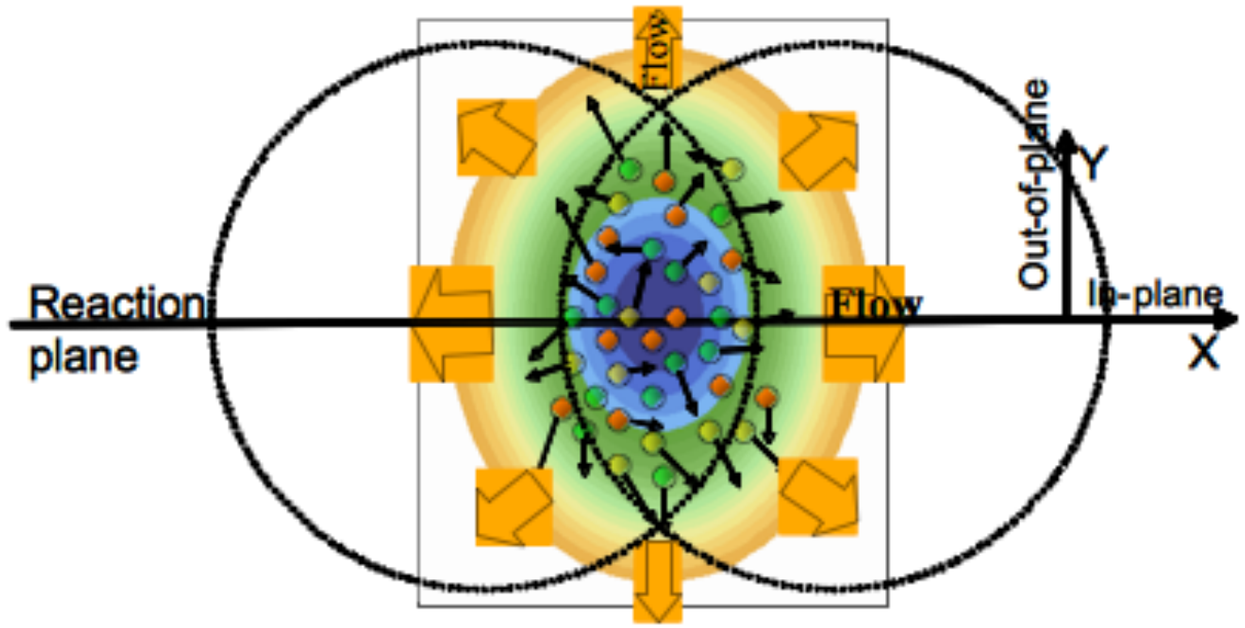
- At low-p_T: different suppression pattern than light
- At high-p_T: b and light similar suppression

EPJC 72 (2012) 1945

PbPb 2.76 TeV | Mironov, QM12 | Camelia's talk today

Azimuthal Anisotropy

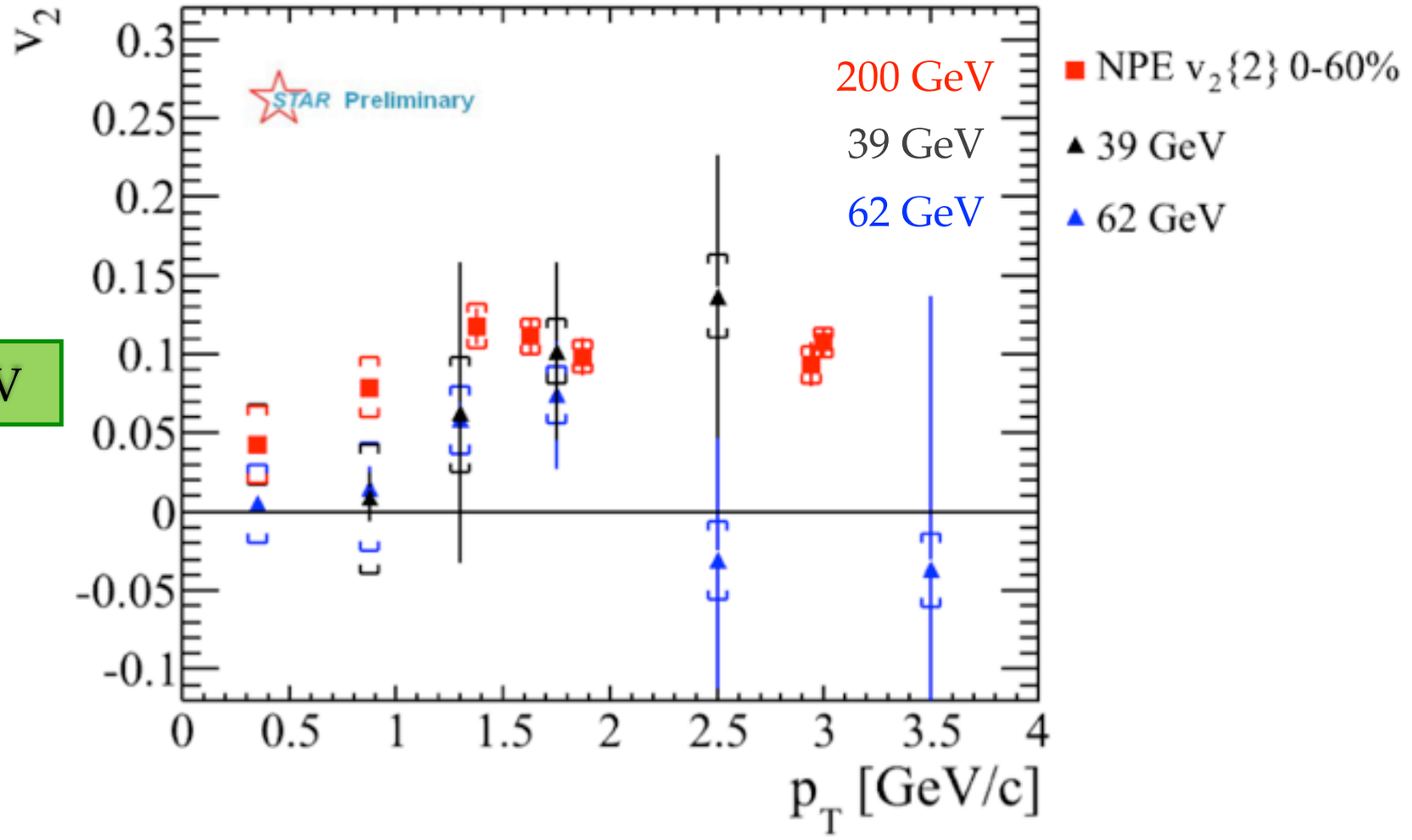
- Heavy flavor is suppressed up to high p_T... Azimuthal dependence ?
- Address path length dependence of HQ energy loss at high p_T ?
- Collective motion (flow) at low p_T ?



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

STAR, Heavy Flavor v_2, 0-60%

AuAu 200GeV



- Non Photonic electron v_2 :
  - At 39 and 62 GeV consistent with zero within uncertainties
  - **At 200 GeV, v_2 >0 for pt > 3 GeV/c**
- **D^0 v_2 consistent, within large uncertainties, with NPE v_2 and charged hadron v_2**

Wei Xie, Tlusty, QM12

STAR, Heavy Flavor v_2, 0-60%

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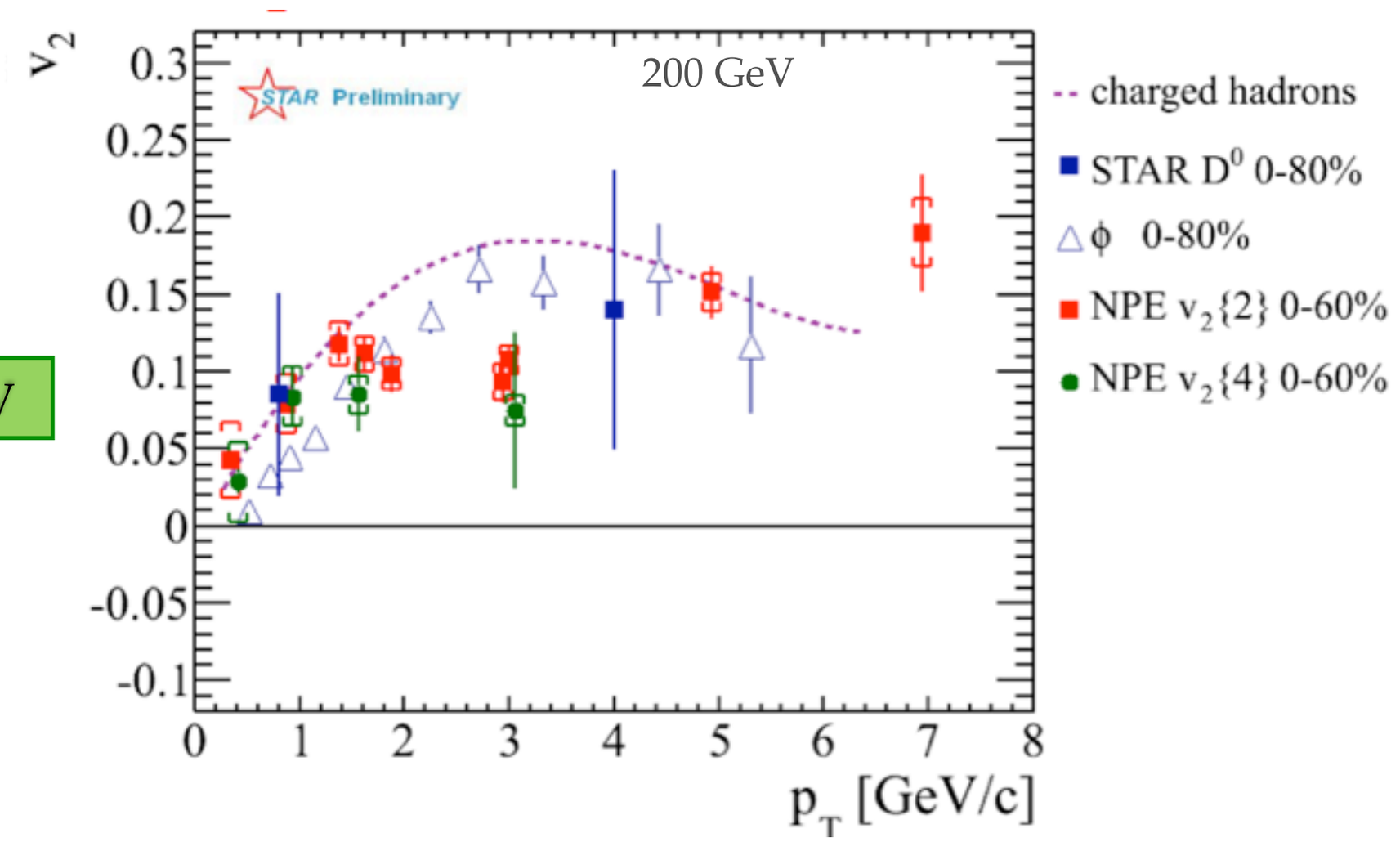

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Wei Xie, Tlusty, QM12

ALICE, HF Electron v_2, 20-40%

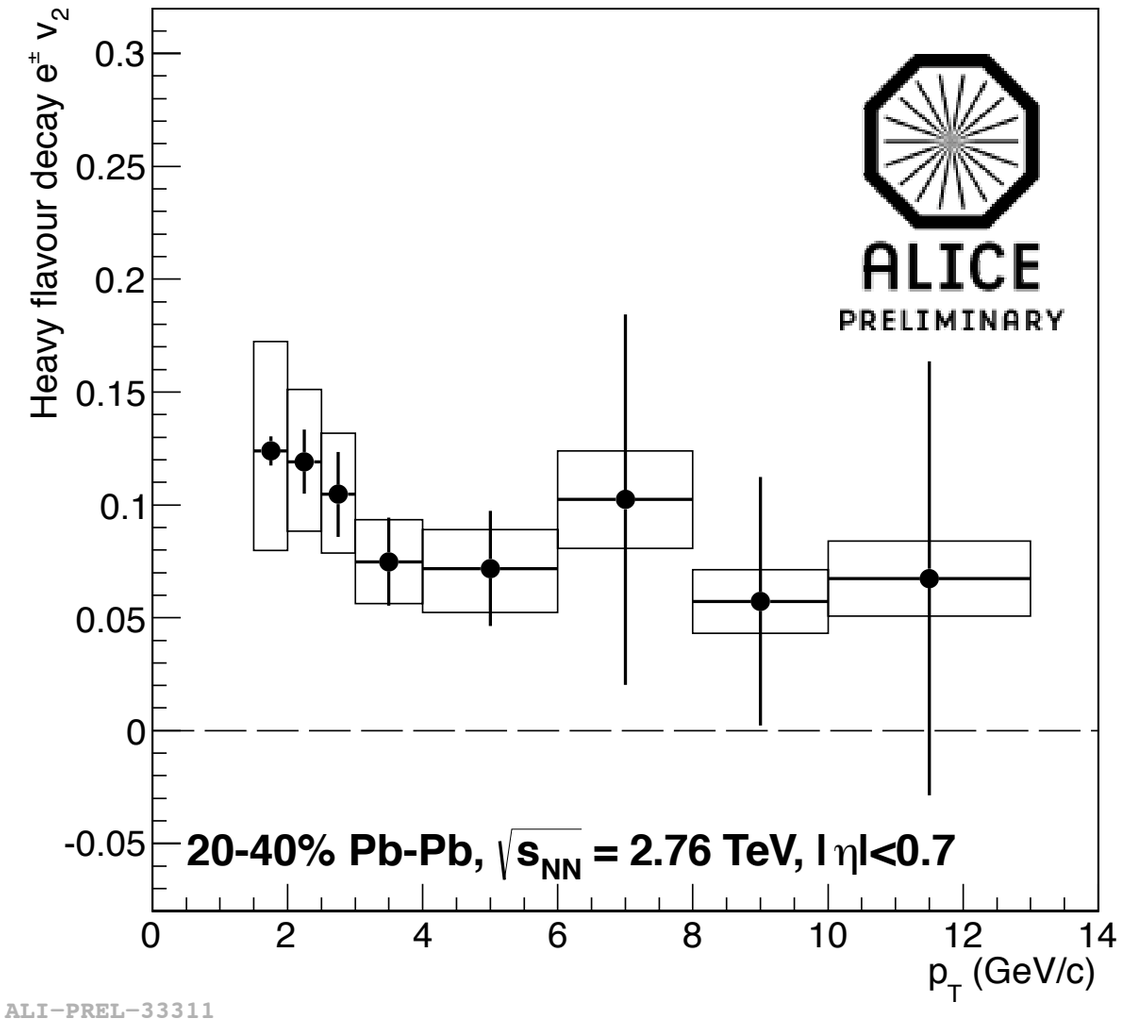
PbPb 2.76 TeV

- v_2 measured with the event plane (EP) method

$$v_2^{\mathrm{HFe}} = \frac{(1+\alpha)\, v_2^{\mathrm{e\ inclusive}} - v_2^{\mathrm{e\ background}}}{\alpha}$$

$$\alpha = N^{\mathrm{HFe}} / N^{\mathrm{e\ background}}$$

- Background electrons: π^0 + Dalitz($\pi^{\pm}$,η) + γ-conversions via cocktail with their measured v_2



➡ **Heavy flavor electron $v_2>0$ at low p_T (>3σ effect in $2<p_T<3$ GeV/c)**

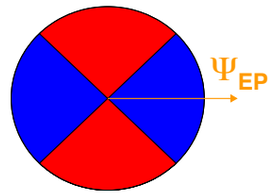
ZCdV, Sakai, QM12

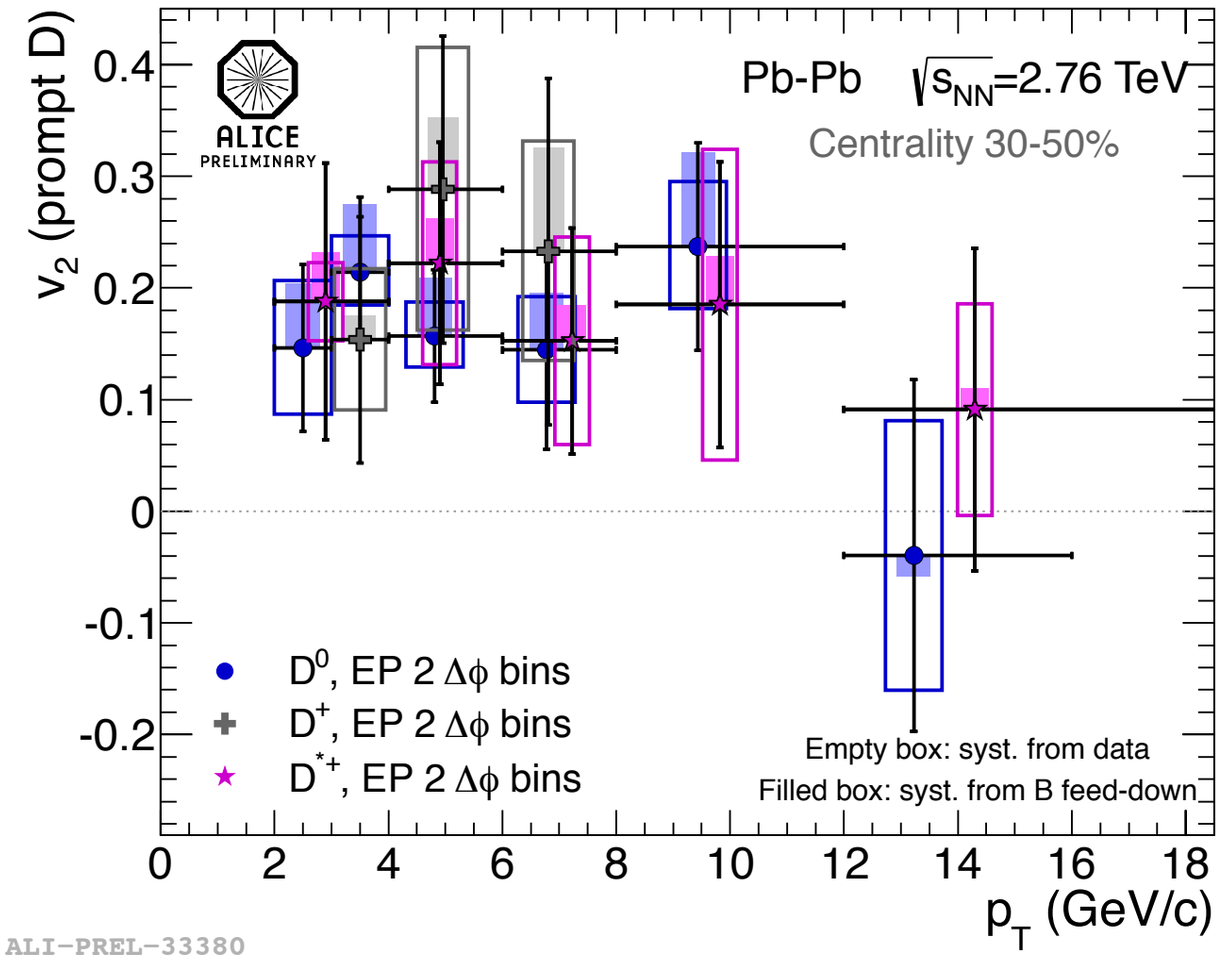
ALICE, D meson v_2

- Data: 2011 Pb-Pb run, MB + centrality triggers
- v_2 measured with the event plane method

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

R_2 : event plane resolution





PbPb 2.76 TeV

ZCdV, Caffarri, QM12

- 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)

ALICE, D meson v_2

- Data: 2011 Pb-Pb run, MB + centrality triggers
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$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$

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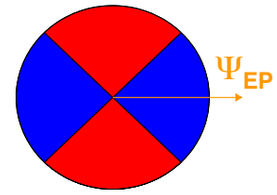
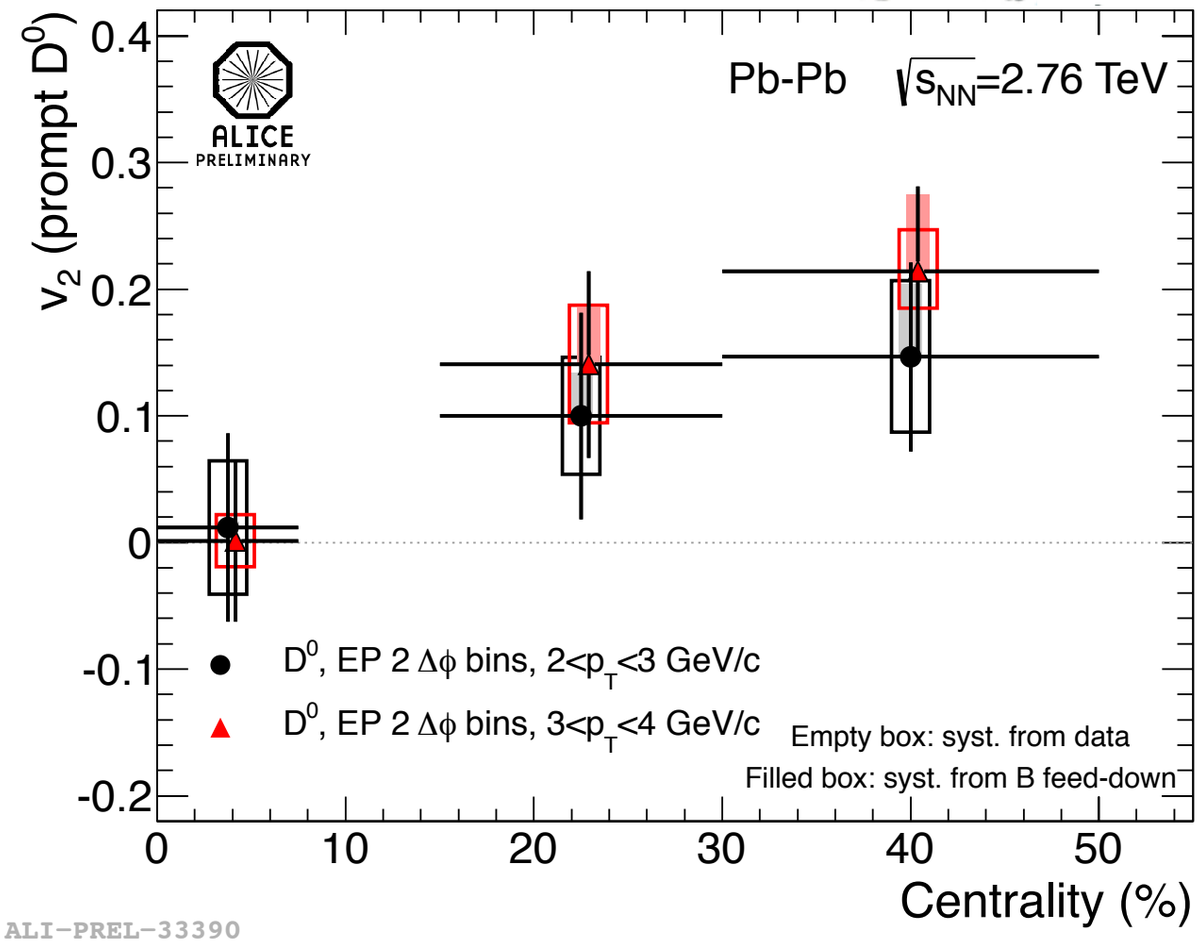


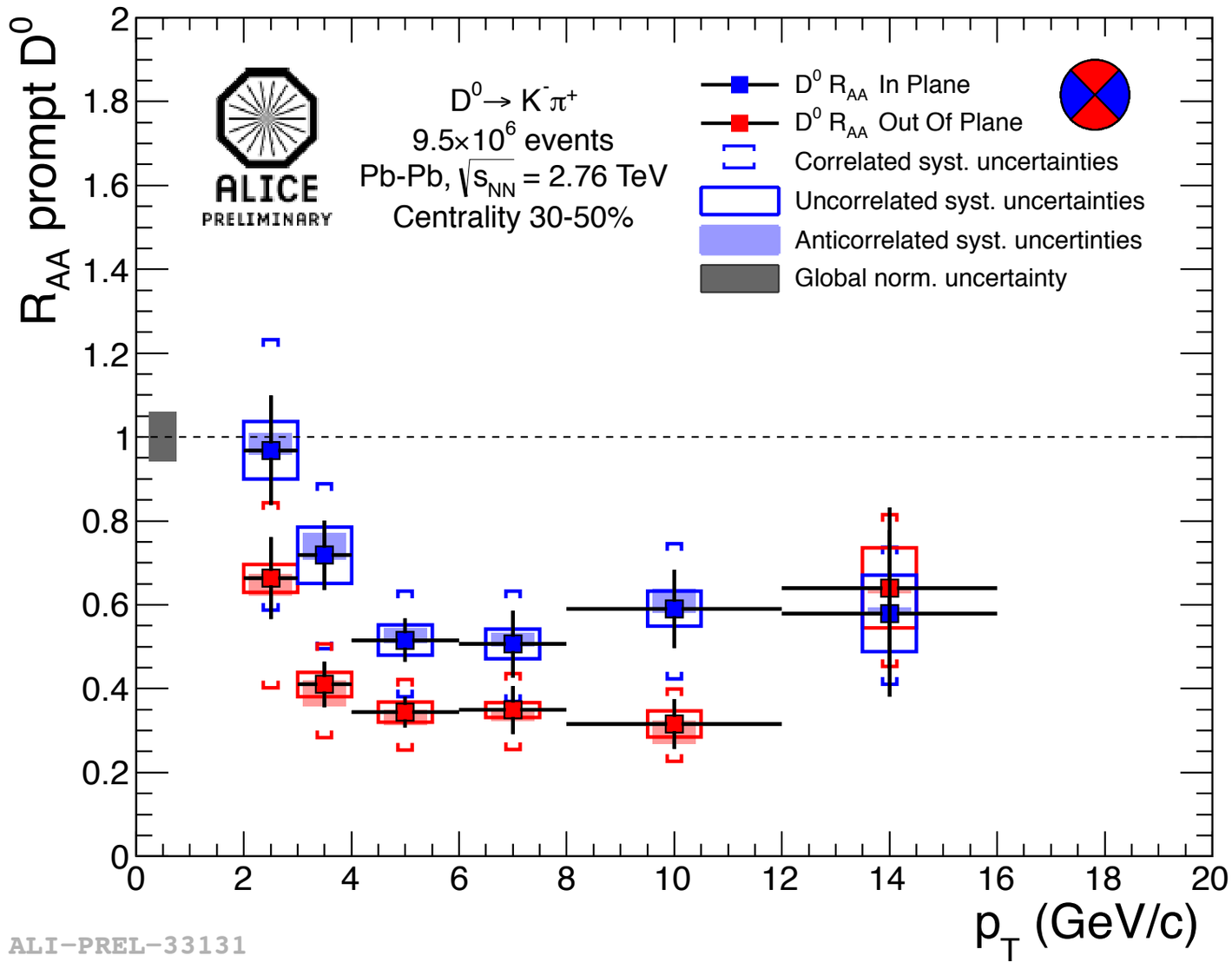


PbPb 2.76 TeV

ZCdV, Caffarri, QM12

- 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)
- Hint of centrality dependence at low p_T

ALICE, D⁰ RAA vs Event Plane, 30-50%



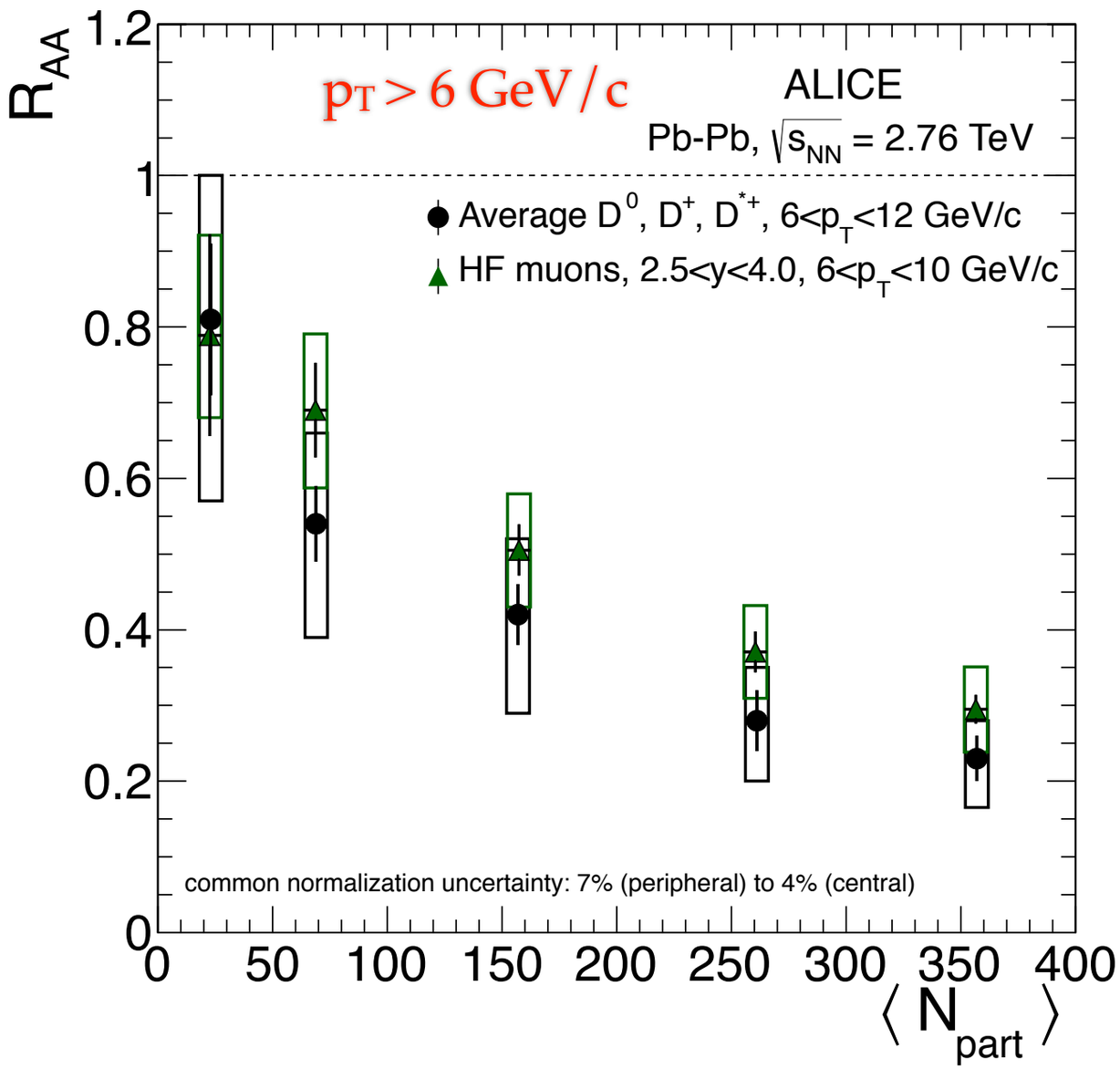
PbPb 2.76 TeV

ZCdV, Caffarri, QM12

- 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

Comparison with data and models

LHC, R_{AA} Centrality Dependence

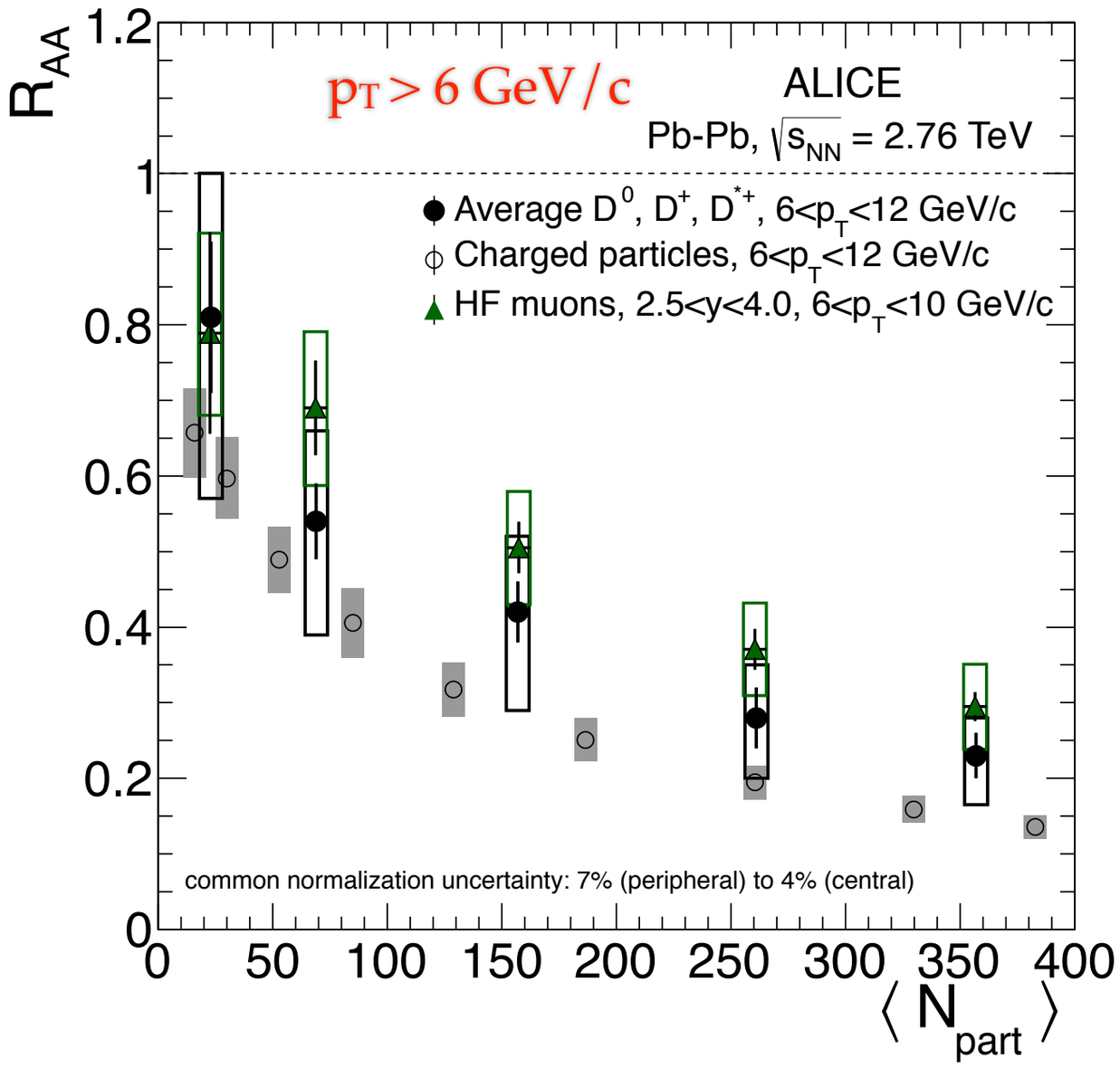


PbPb 2.76 TeV

[ALICE Coll. arXiv:1203.2160 (2012)]
[ALICE Coll. arXiv:1205.6443 (2012)]

➡ **D mesons and HF muon R_{AA} at high-p_T show a similar centrality trend**

LHC, R_{AA} Centrality Dependence

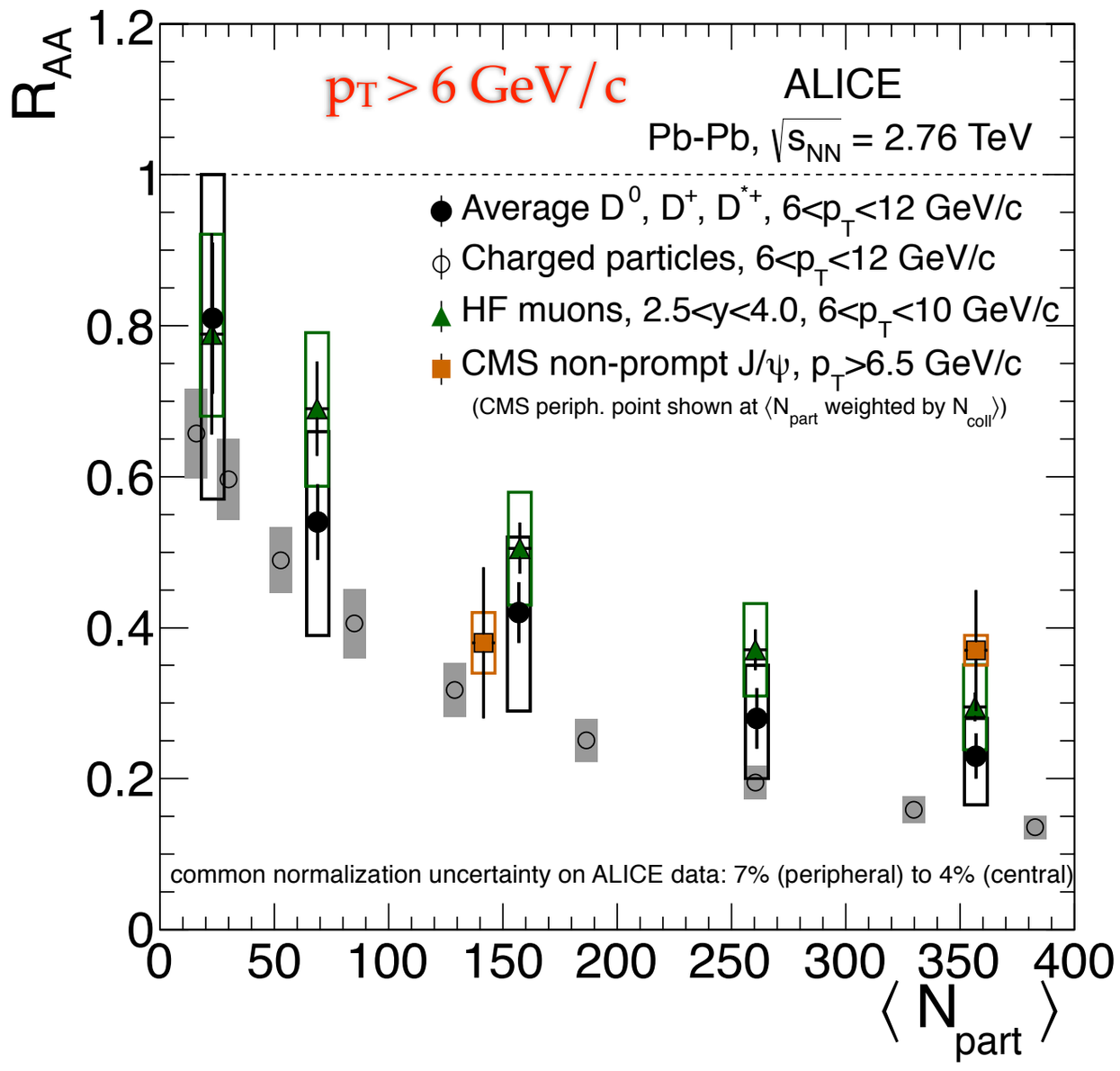


PbPb 2.76 TeV

[ALICE Coll. arXiv:1203.2160 (2012)]
[ALICE Coll. arXiv:1205.6443 (2012)]

- **D mesons** and **HF muon** R_{AA} at high-p_T show a similar centrality trend
- Data not conclusive on **charged particles** R_{AA} < **D mesons** R_{AA}

LHC, R_{AA} Centrality Dependence



PbPb 2.76 TeV

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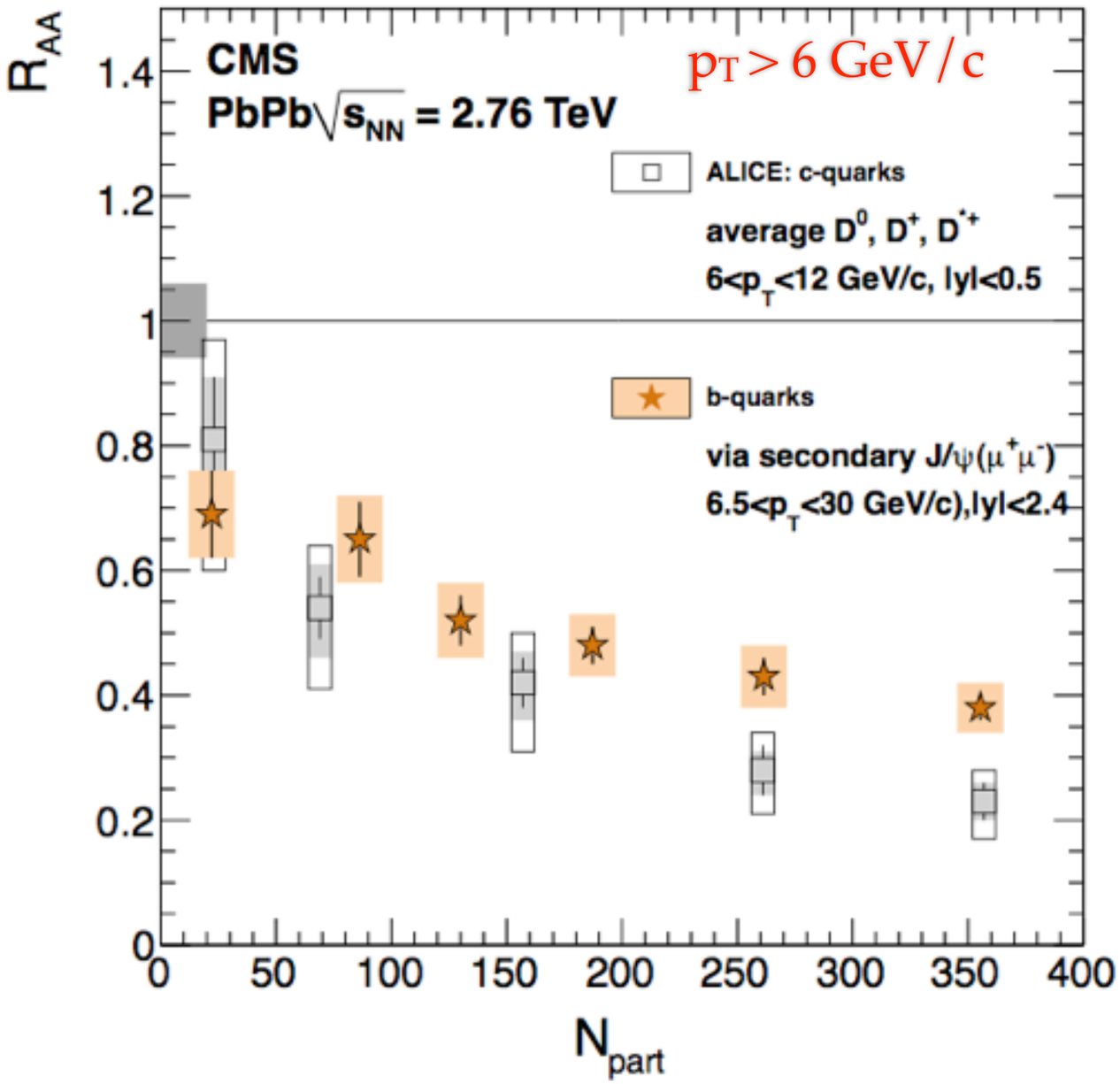
[CMS Coll., JHEP 05 (2012) 063]

- D mesons and HF muon R_{AA} at high-p_T show a similar centrality trend
- Data not conclusive on charged particles R_{AA} < D mesons R_{AA}
- Non-prompt J/ψ (CMS) consistent with HF muon R_{AA}

LHC, R_{AA} Centrality Dependence

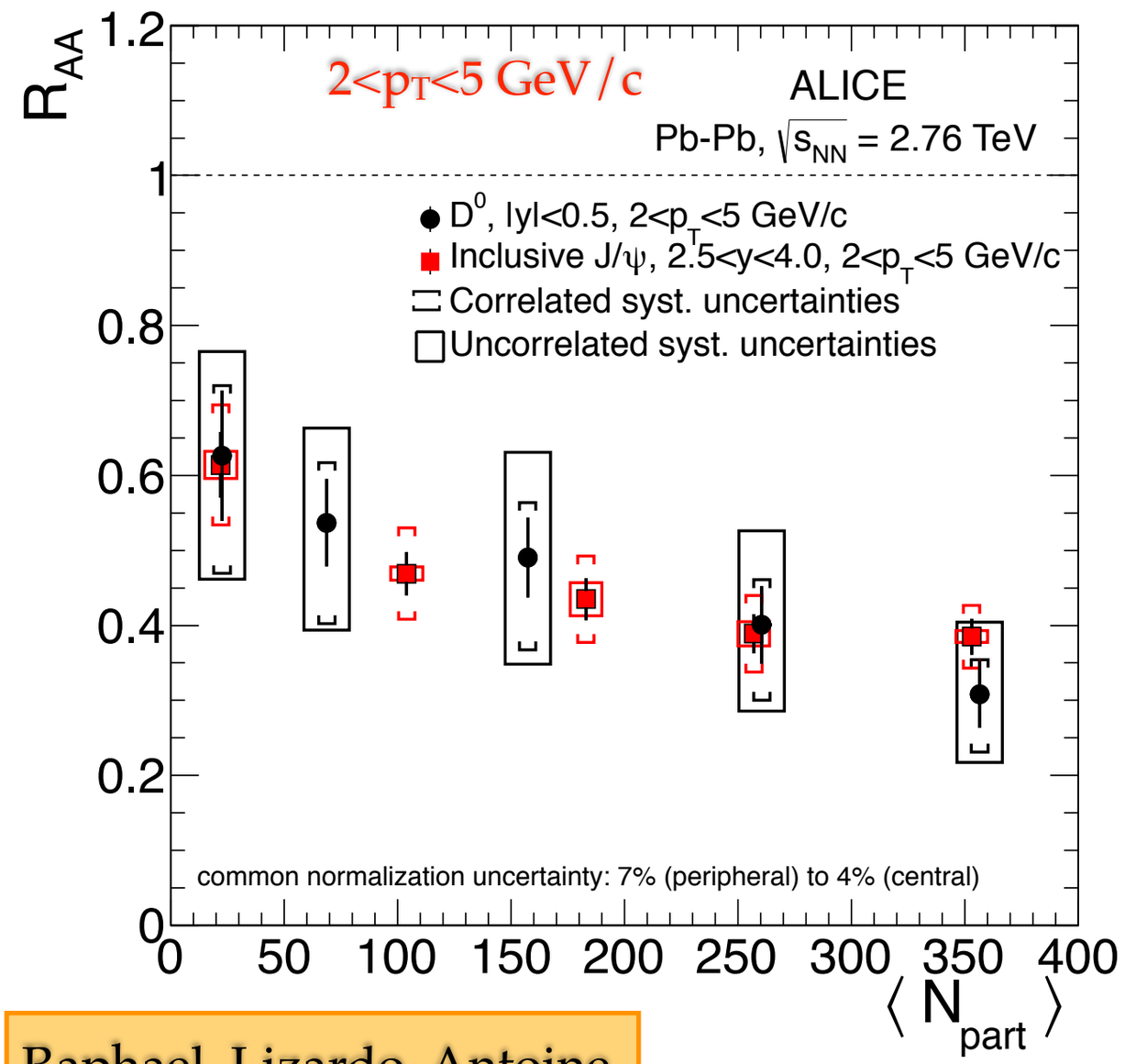


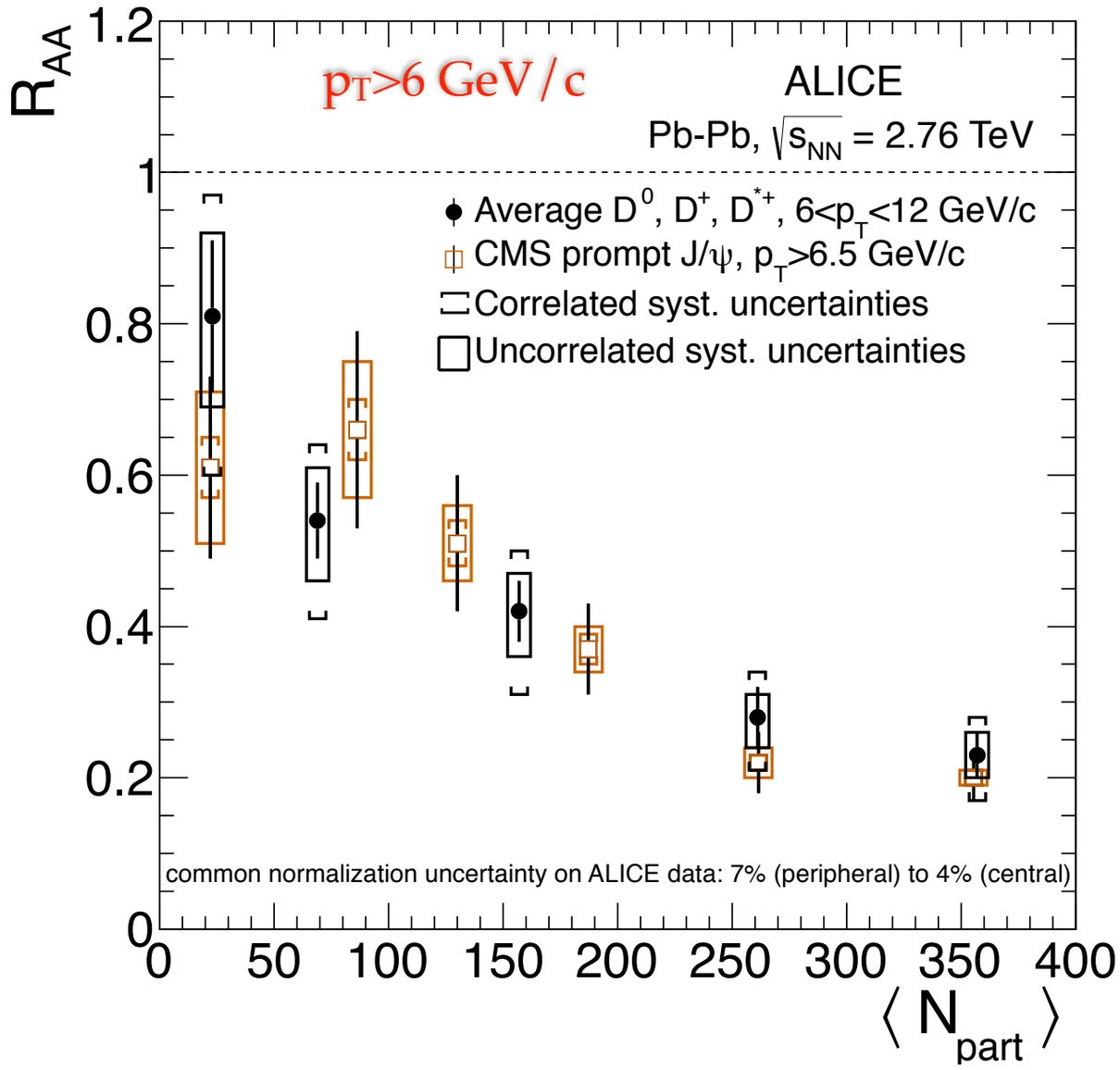
PbPb 2.76 TeV

Camelia's today talk

➡ 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.

LHC, R_{AA} of Open and Hidden Charm





Raphael, Lizardo, Antoine, Torsten today talk

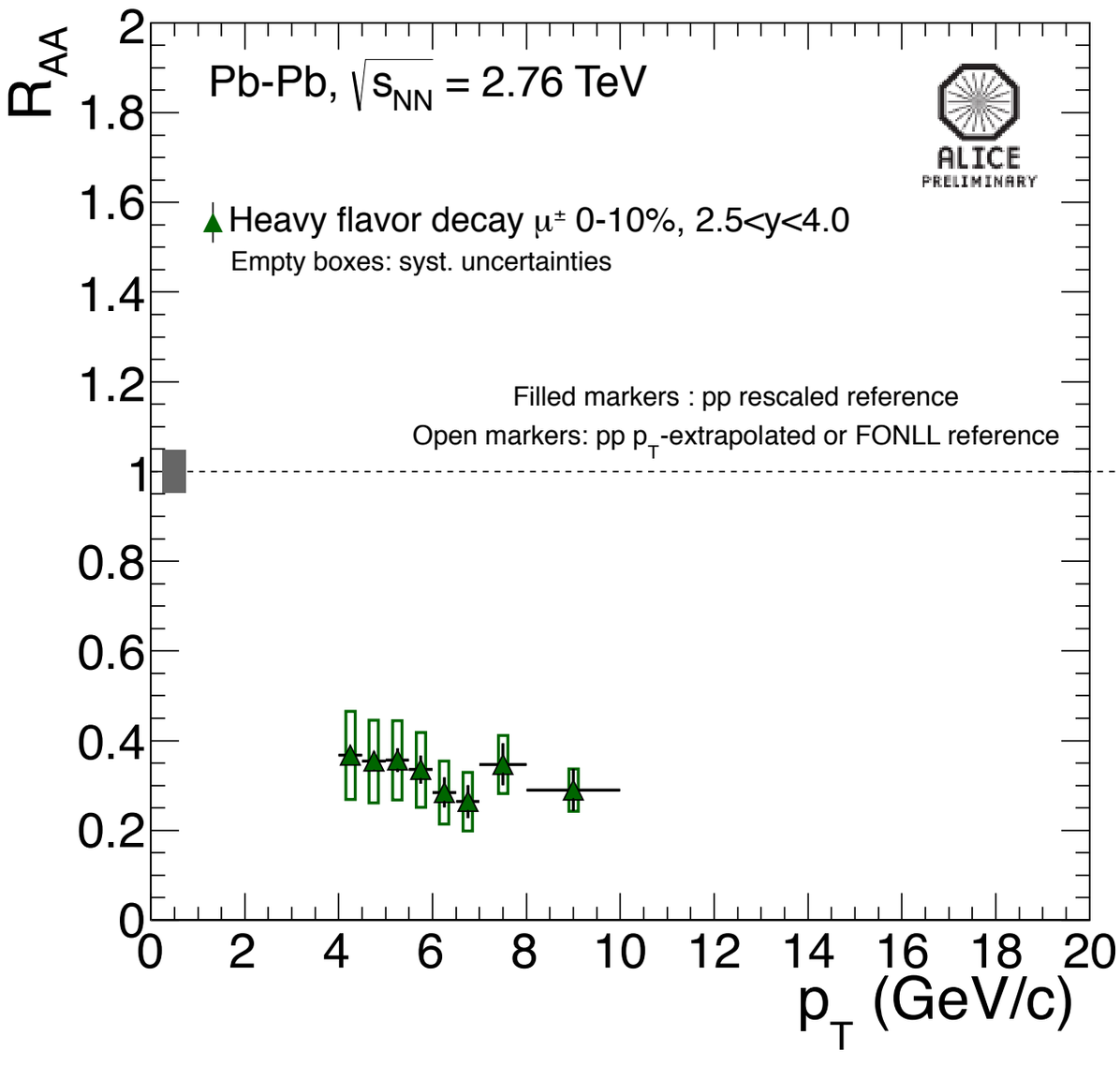
[ALICE Coll. arXiv:1203.2160 (2012)] [CMS Coll., JHEP 05 (2012) 063]

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)

LHC, R_{AA} p_T Dependence

PbPb 2.76 TeV

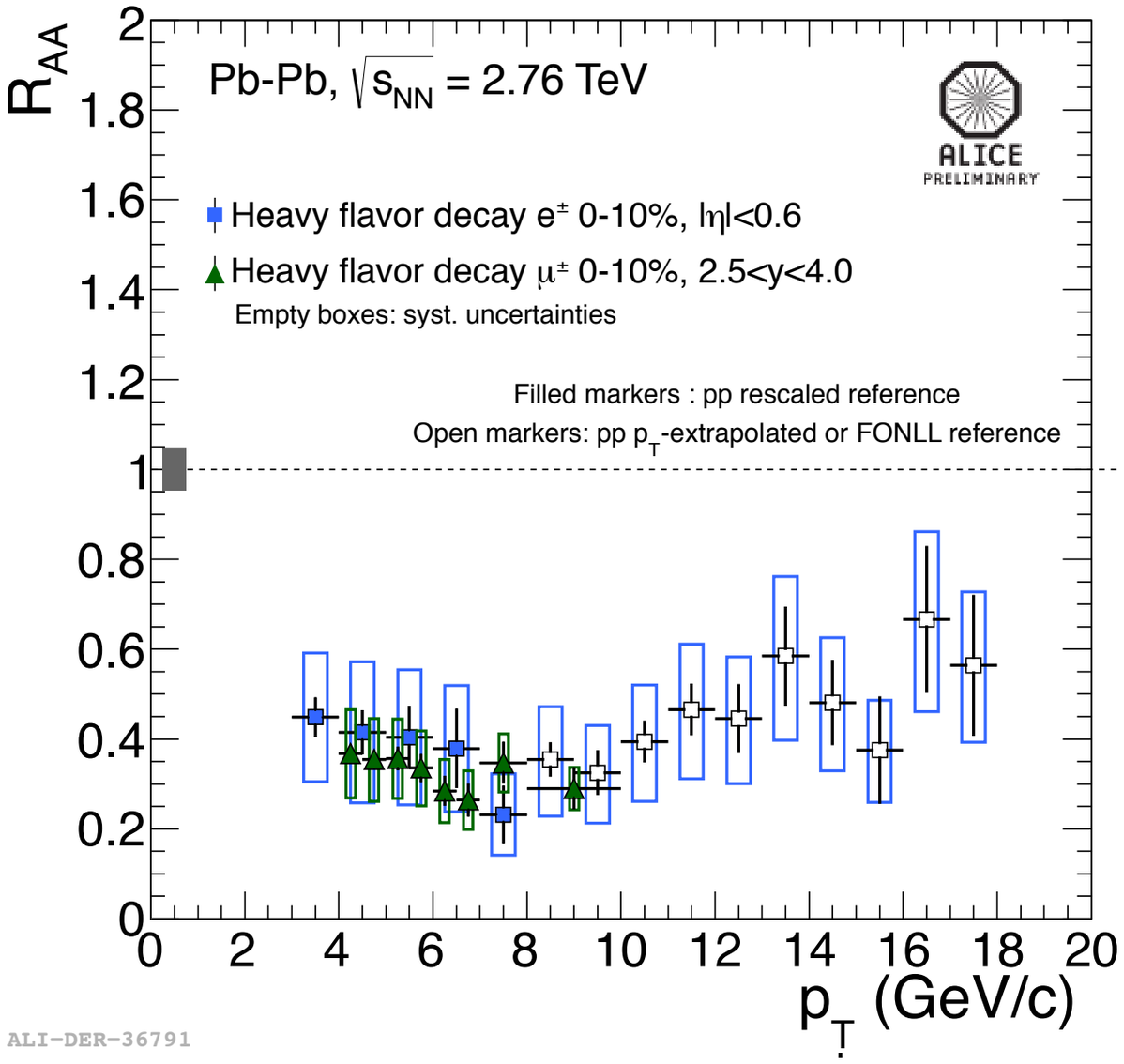


➡ Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%

[ALICE Coll. arXiv:1205.6443 (2012)]

LHC, R_{AA} p_T Dependence

PbPb 2.76 TeV



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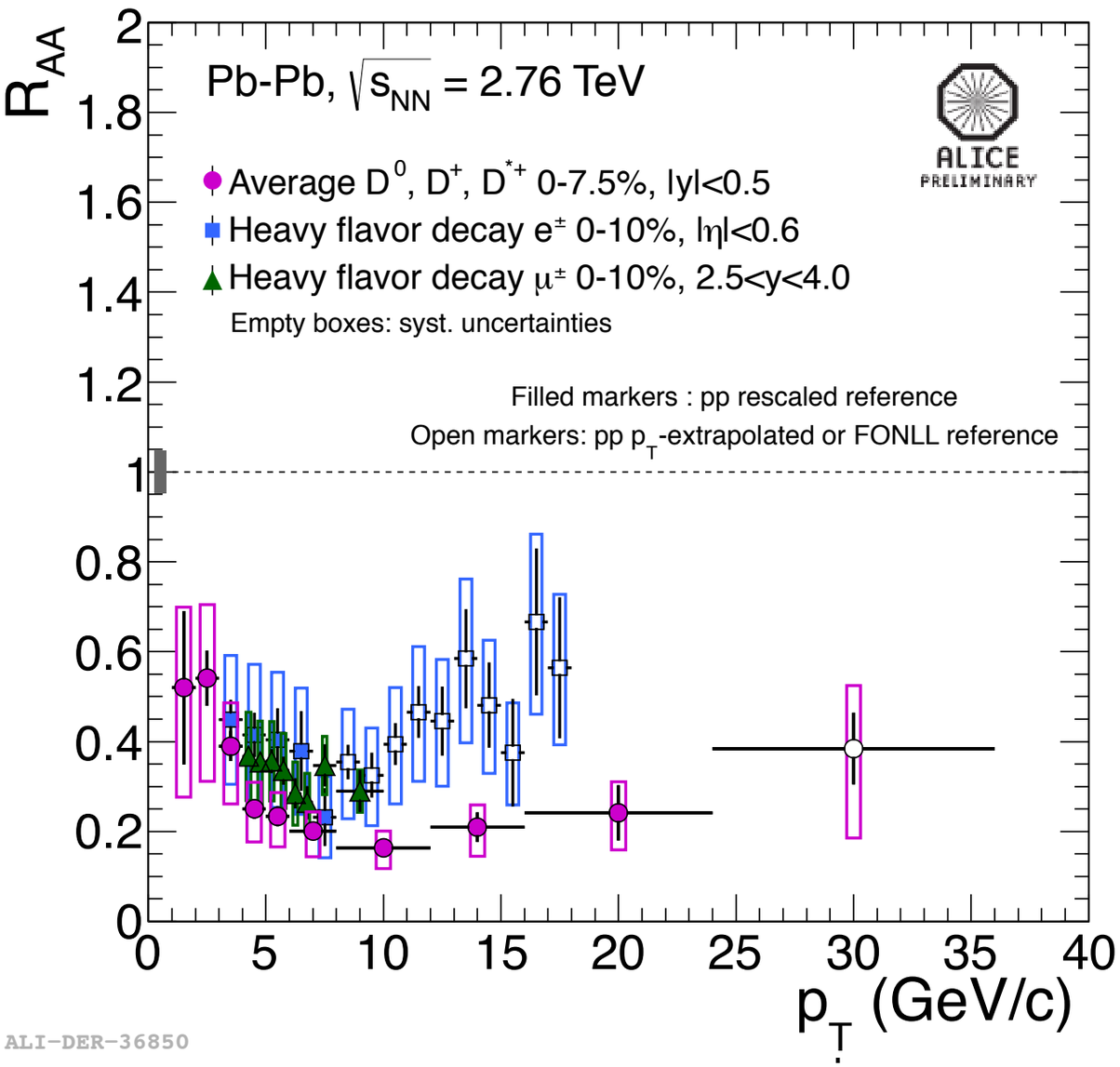
LHC, R_{AA} p_T Dependence

PbPb 2.76 TeV

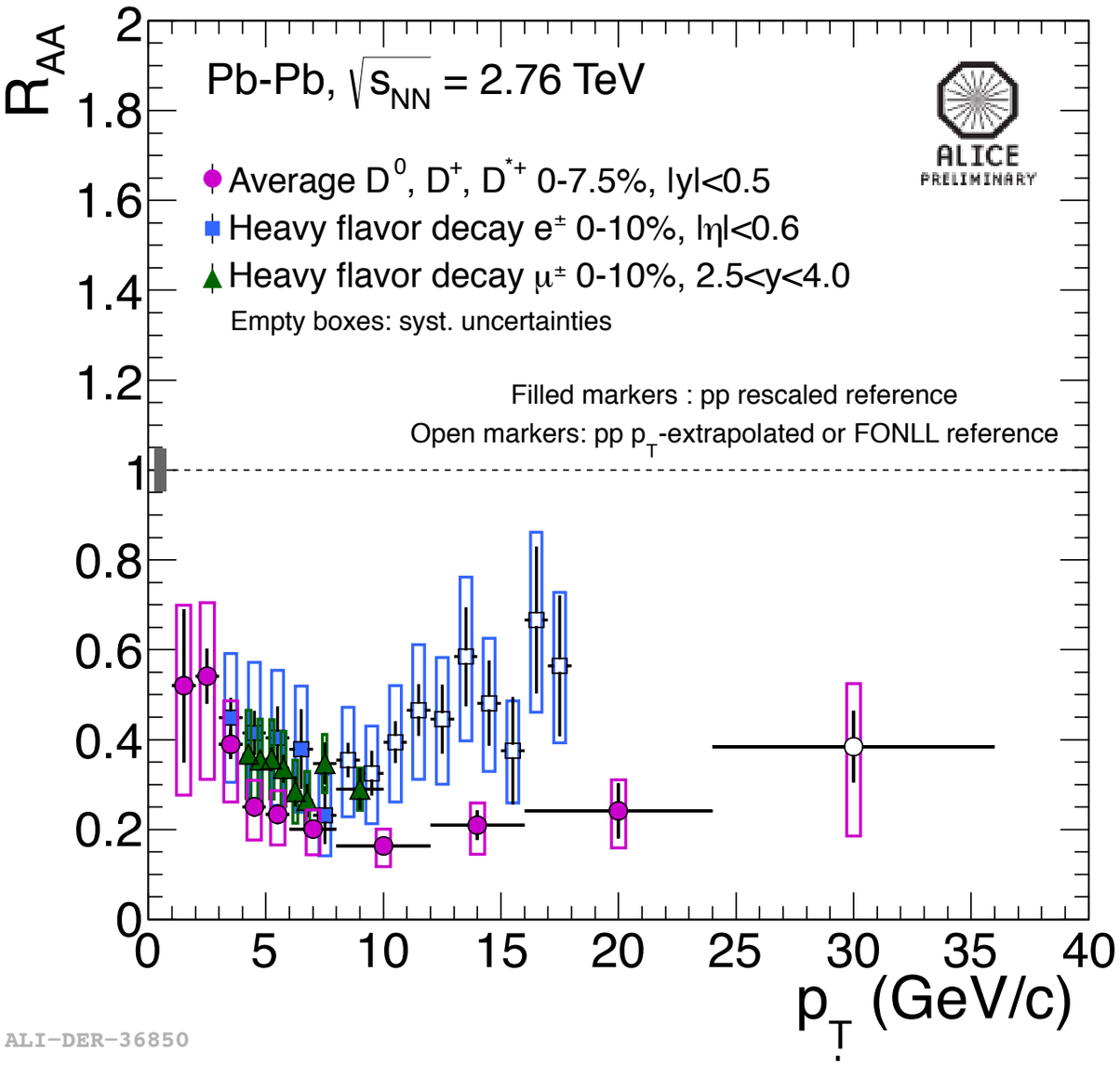


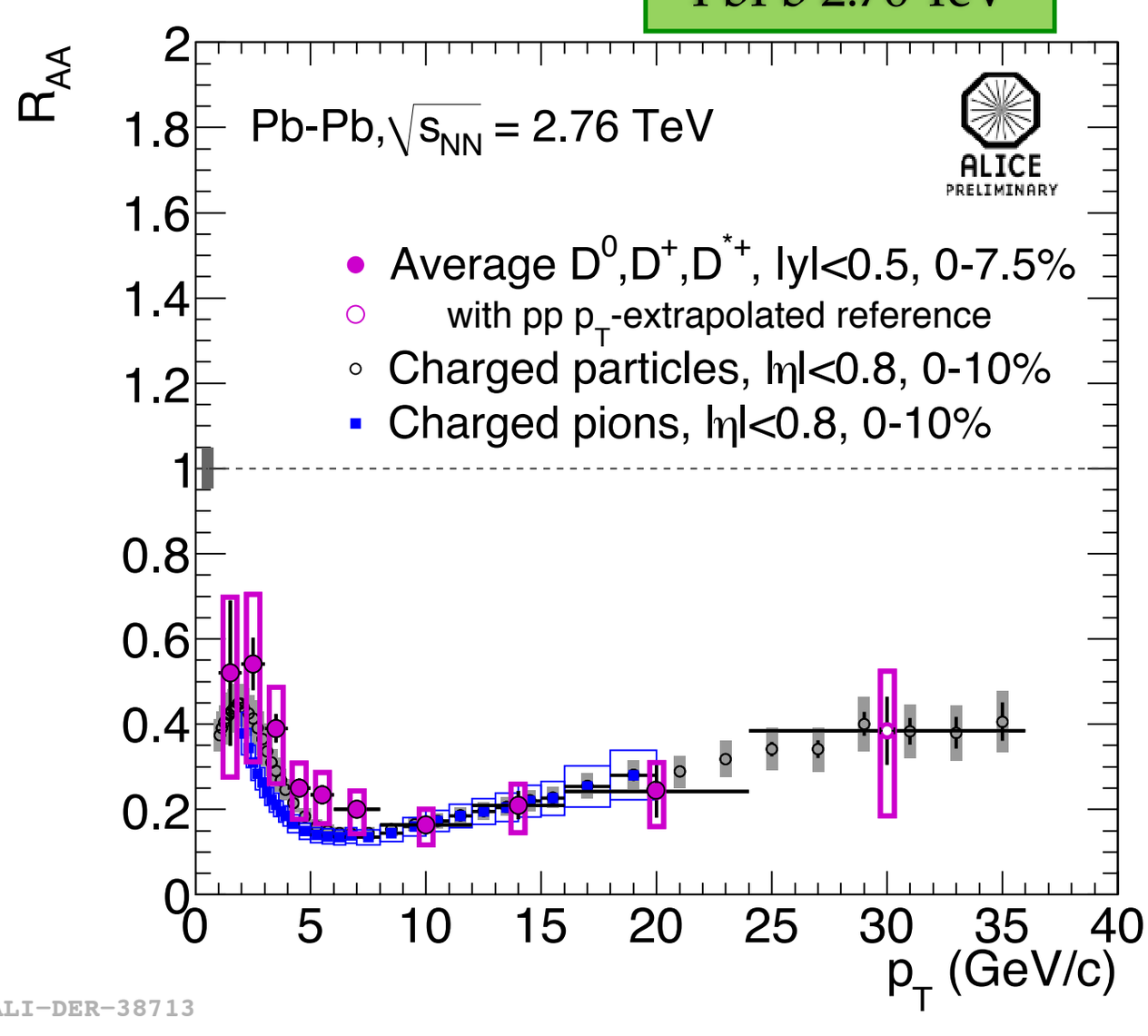
- Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%
- they are also comparable with D mesons R_{AA} (|y|<0.5) in 0-7.5% considering the semileptonic decay kinematics ($p_T^e \sim 0.5\ p_T^B$ at high p_T)
- D R_{AA} shows a similar trend as charged particles and $\pi^{\pm}$ in 0-10%

[ALICE Coll. arXiv:1205.6443 (2012)]

LHC, R_{AA} p_T Dependence

PbPb 2.76 TeV





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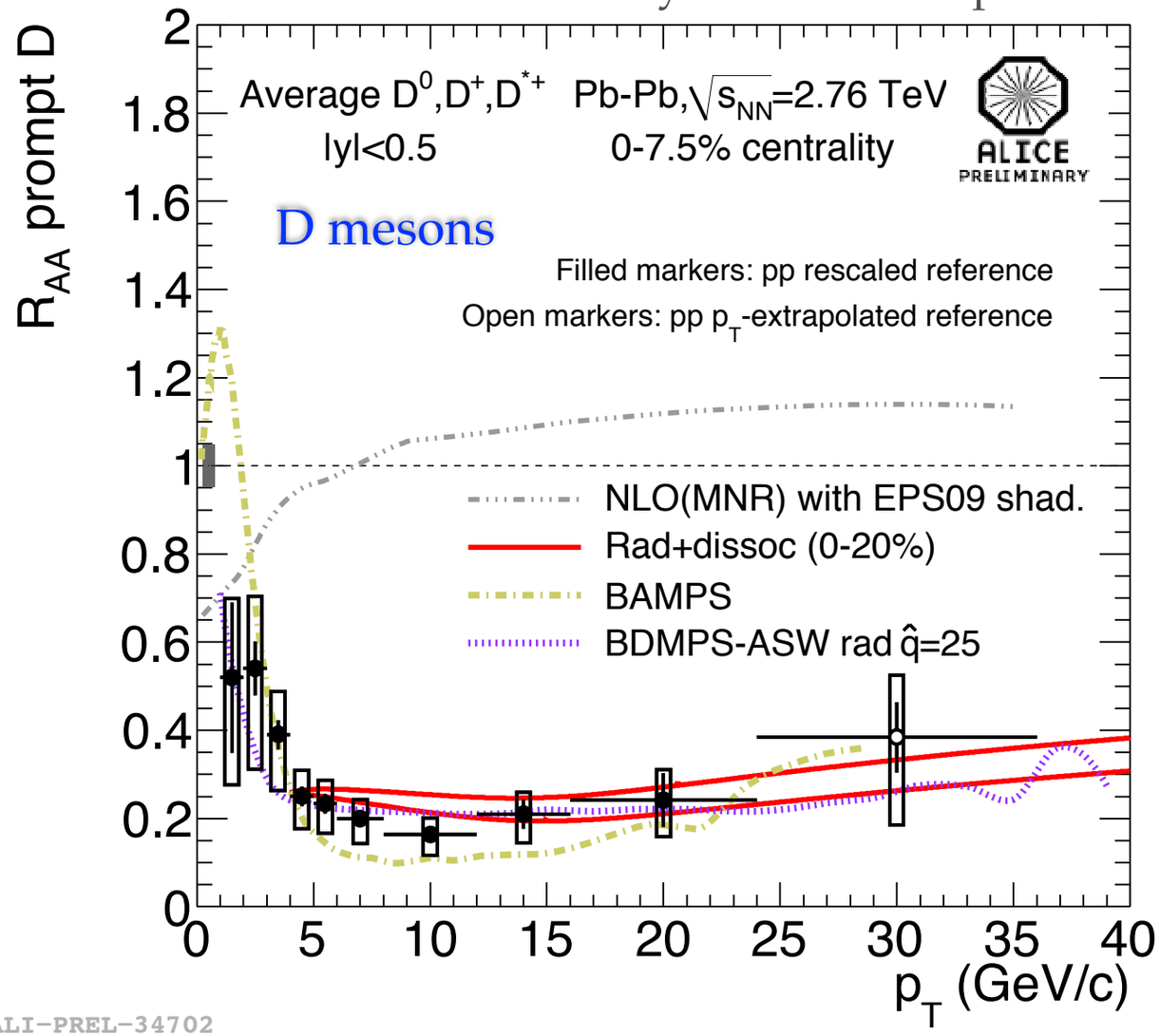
- D R_{AA} shows a similar trend as charged particles and $\pi^{\pm}$ in 0-10%

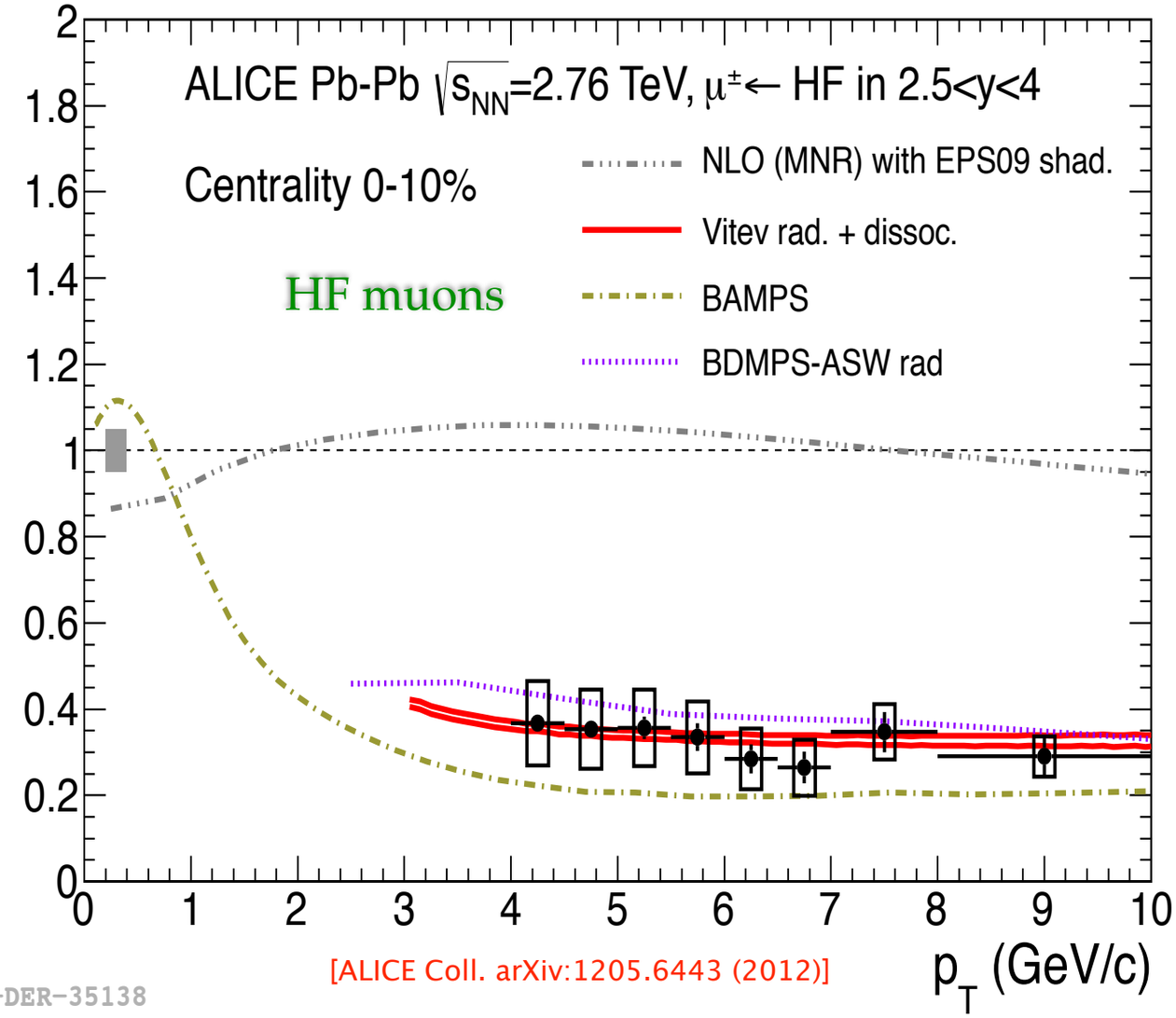
[ALICE Coll. arXiv:1205.6443 (2012)]

Models Description of R_{AA}

PbPb 2.76 TeV

Note: Only models with predictions for HF muon and D mesons are shown.

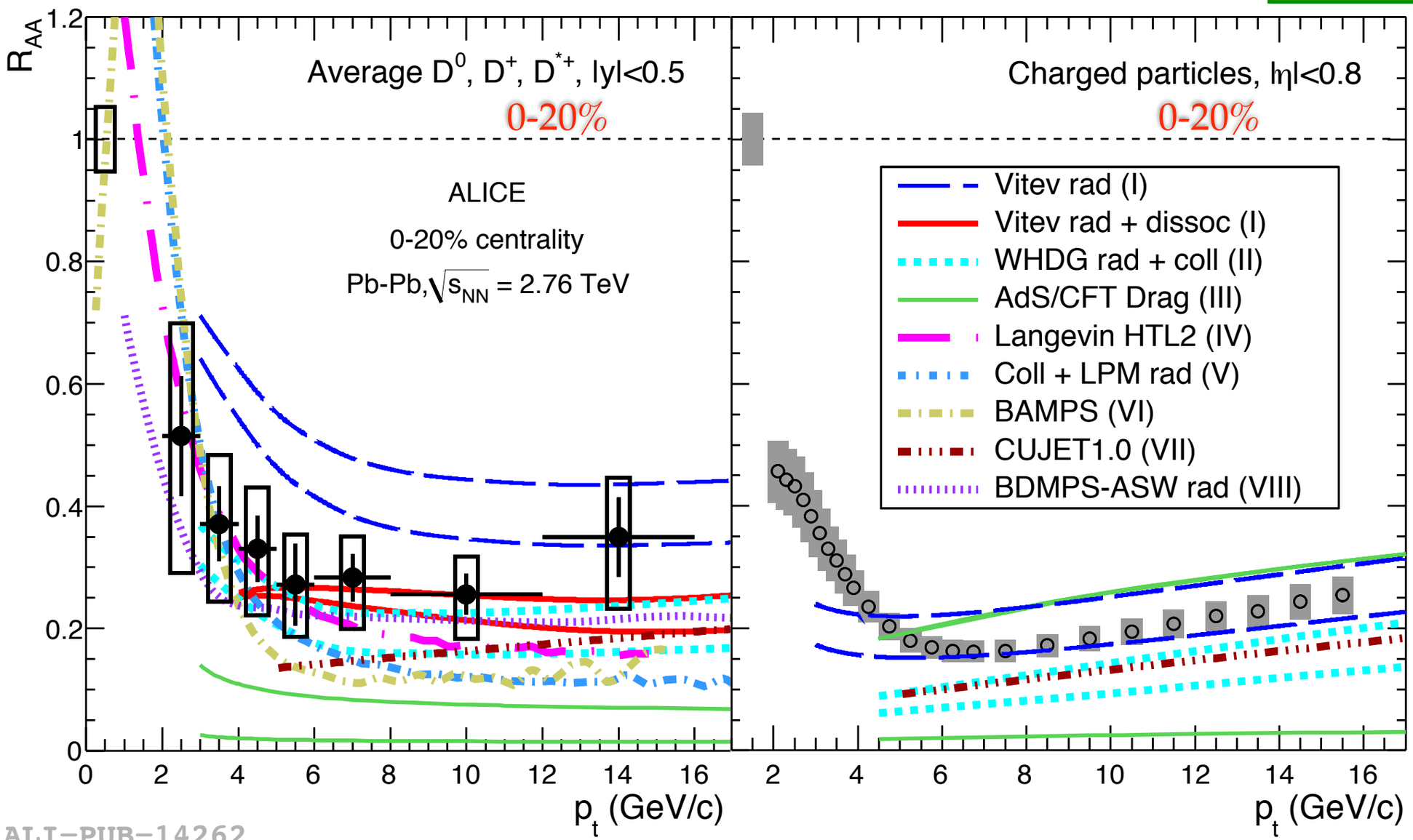




- HF decay μ & D mesons R_{AA} suppression in the most central collisions can not be explained by shadowing alone for p_T>4 GeV/c
  - ⇨ likely a final state effect
  - ⇨ need pPb data to quantify initial state effects
- Models describe reasonably well both HF decay μ and D mesons R_{AA}

Models Description of R_{AA}

D mesons | Charged particles | PbPb 2.76 TeV



[ALICE Coll. arXiv:1203.2160 (2012)]

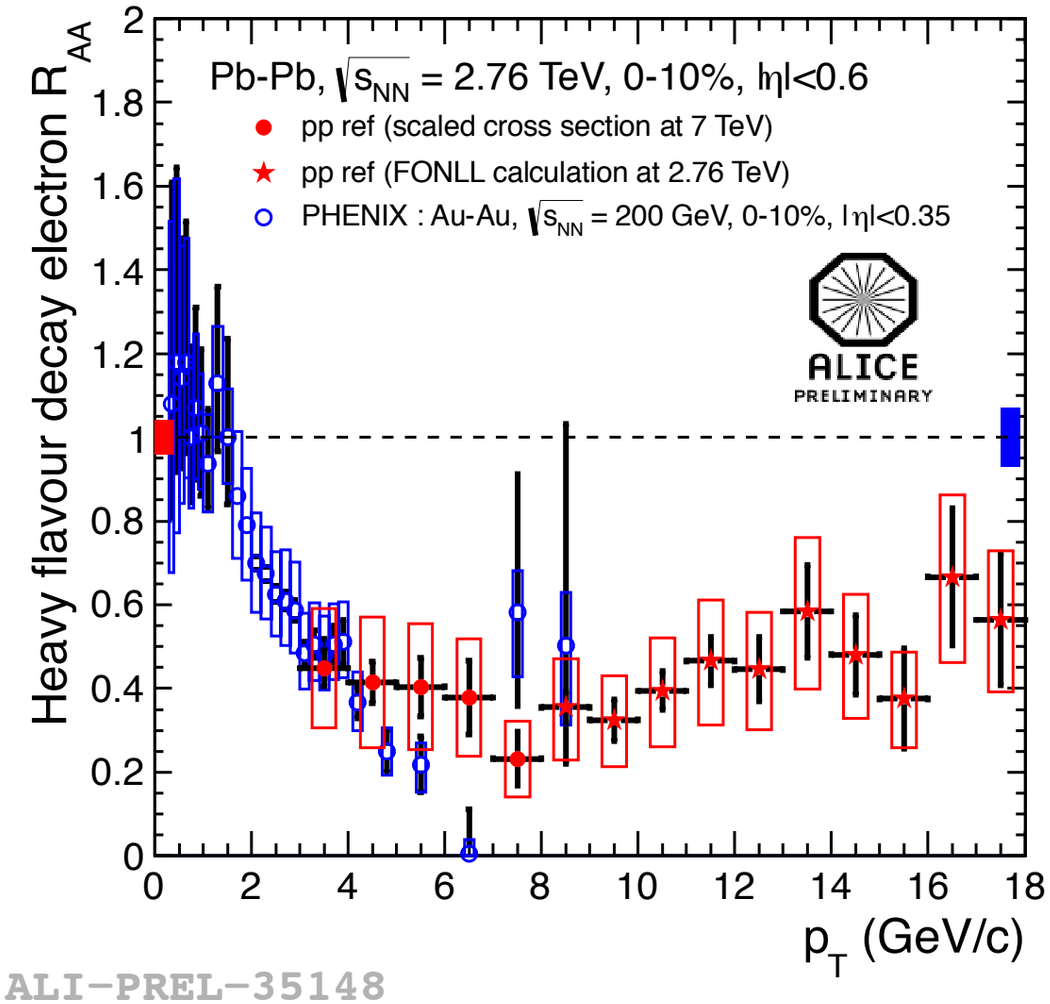
➡ **Models predict reasonably well both charged particles and D mesons R_{AA}**

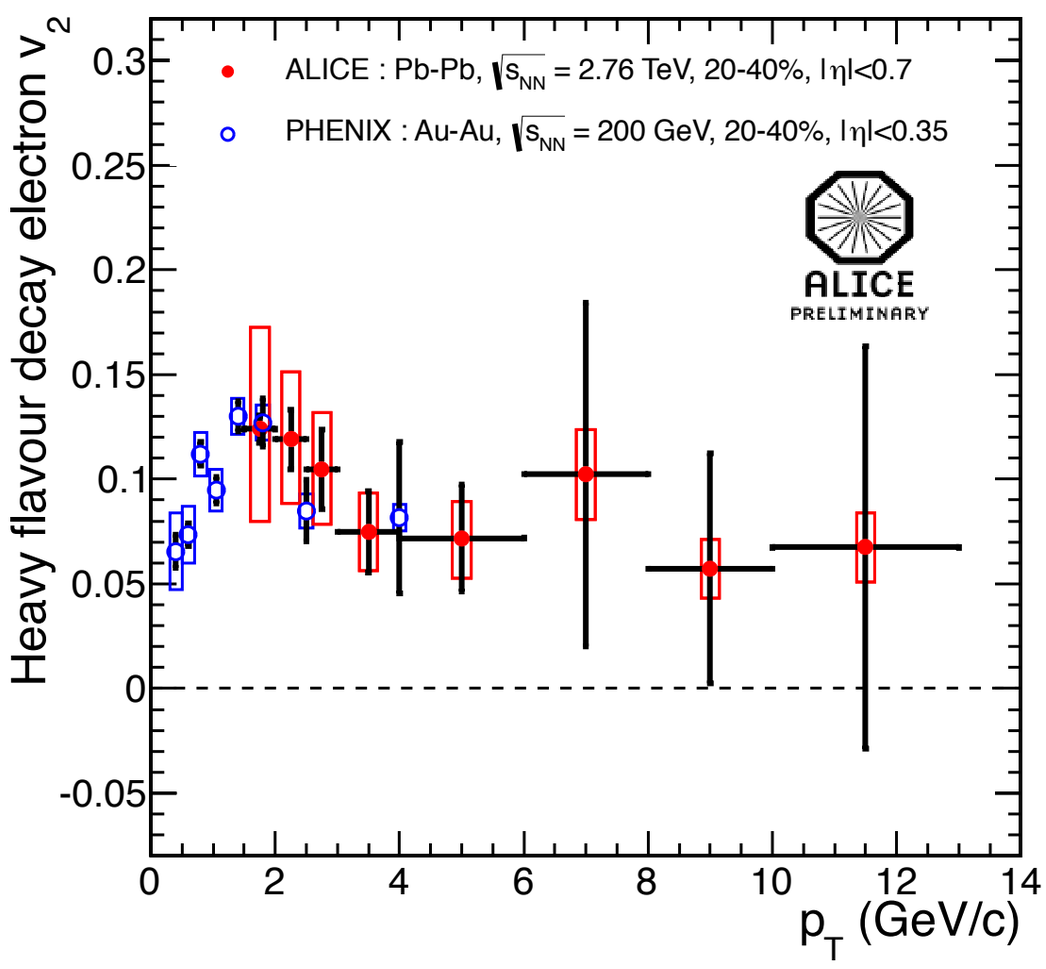
✳ AdS/CFT drag coefficients underestimate the charm R_{AA} and have limited predictive power for the light flavor R_{AA}.

HFE R_{AA} AND v_2 AT RHIC AND LHC

AuAu 200 GeV

PbPb 2.76 TeV





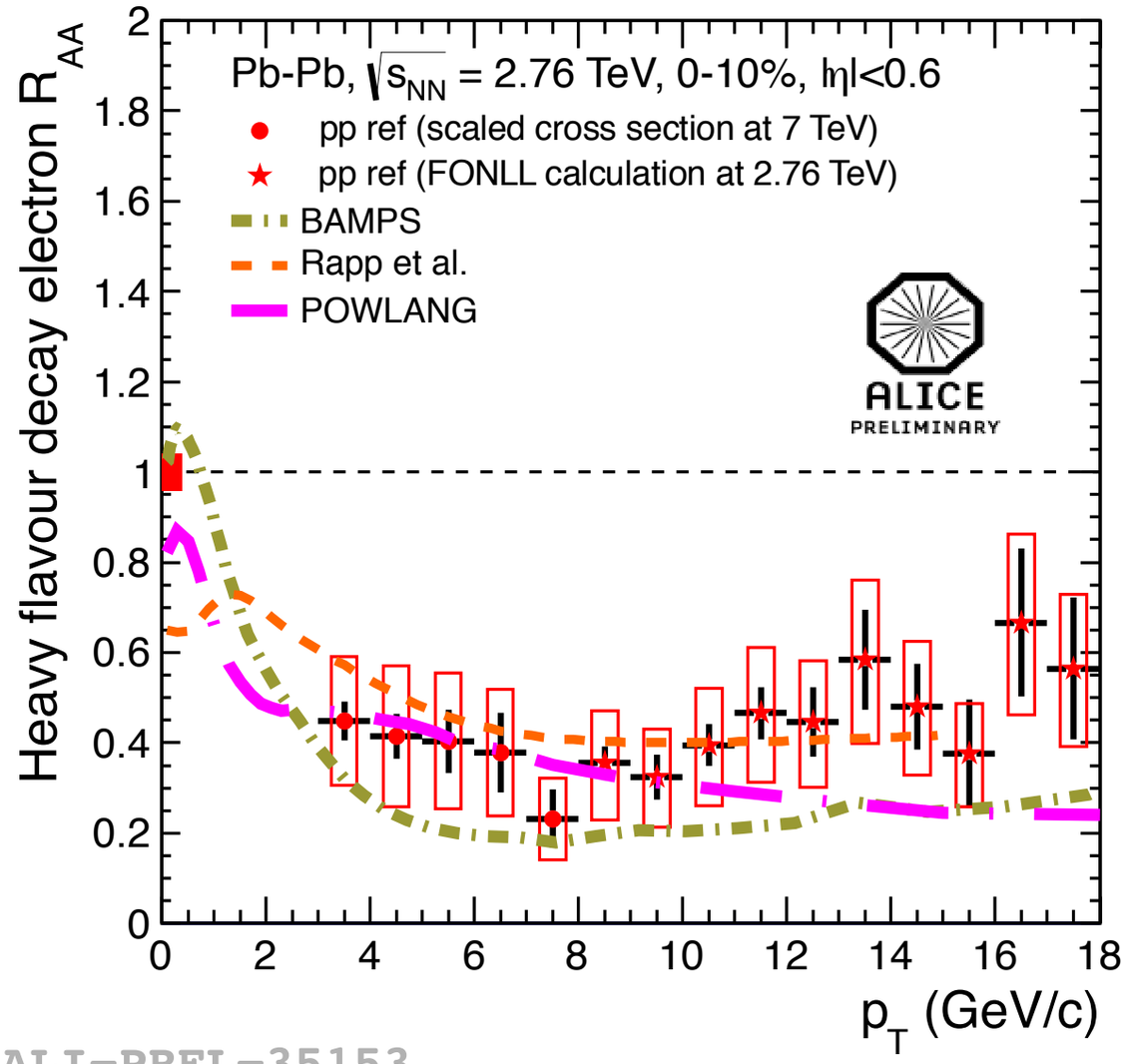
ALI-PREL-35148

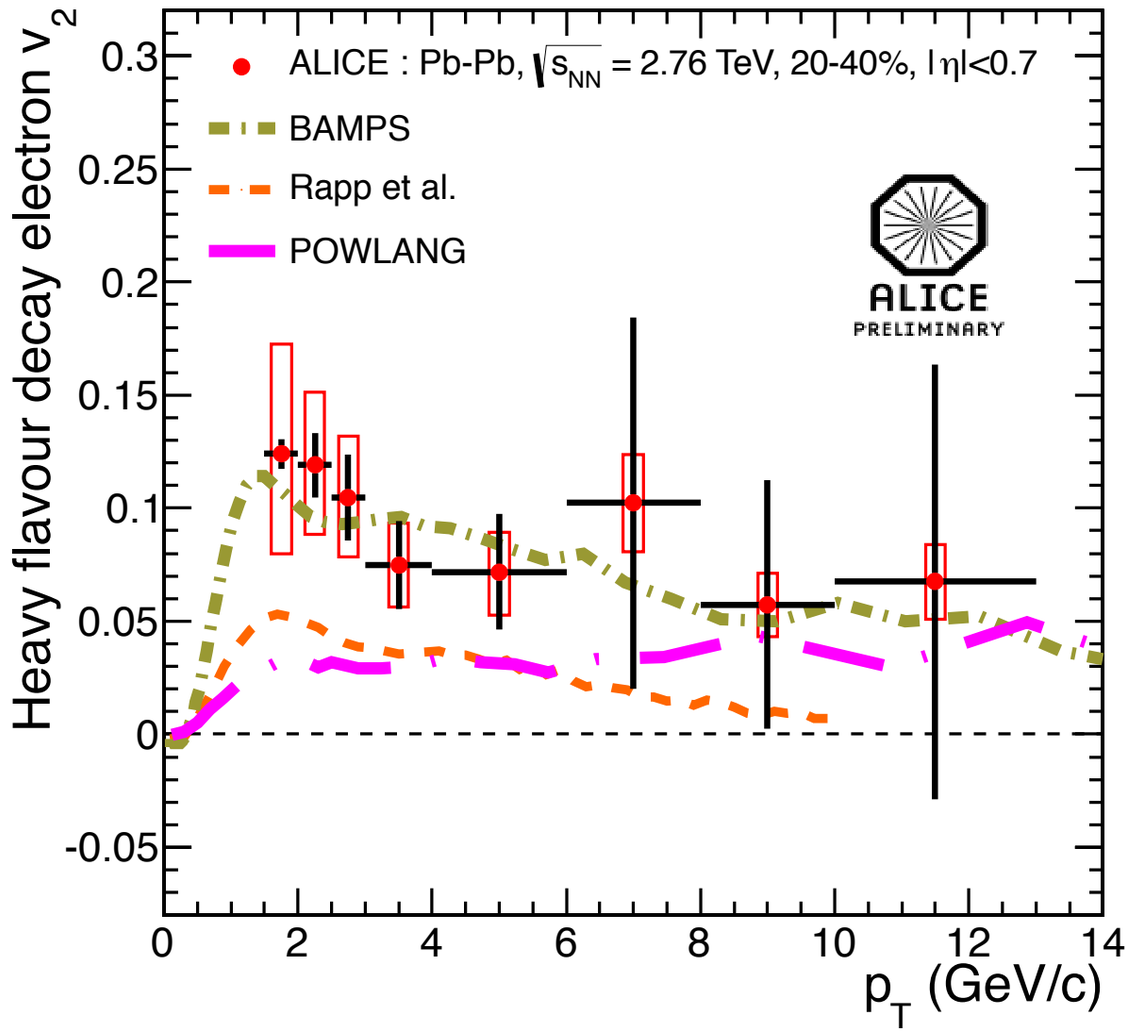
➡ **Similar magnitude of heavy flavor electron R_{AA} ($3<p_T<9$ GeV/c) and v_2 ($1.5<p_T<4$ GeV/c) at $\sqrt{s_{NN}}$=200GeV (PHENIX) and $\sqrt{s_{NN}}$=2.76TeV (ALICE)**

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

Heavy Flavor electron R_{AA} & v_2

PbPb 2.76 TeV

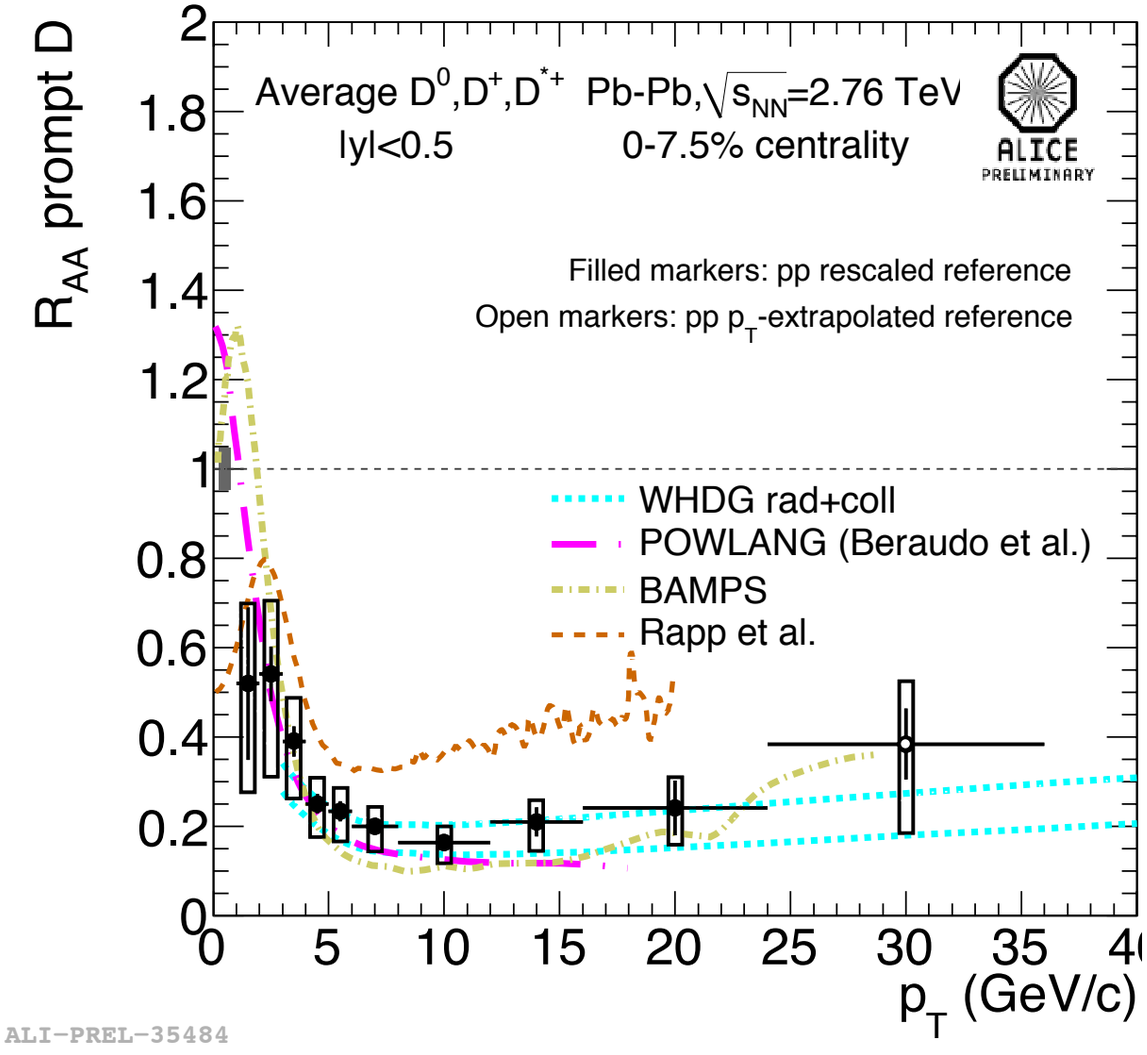




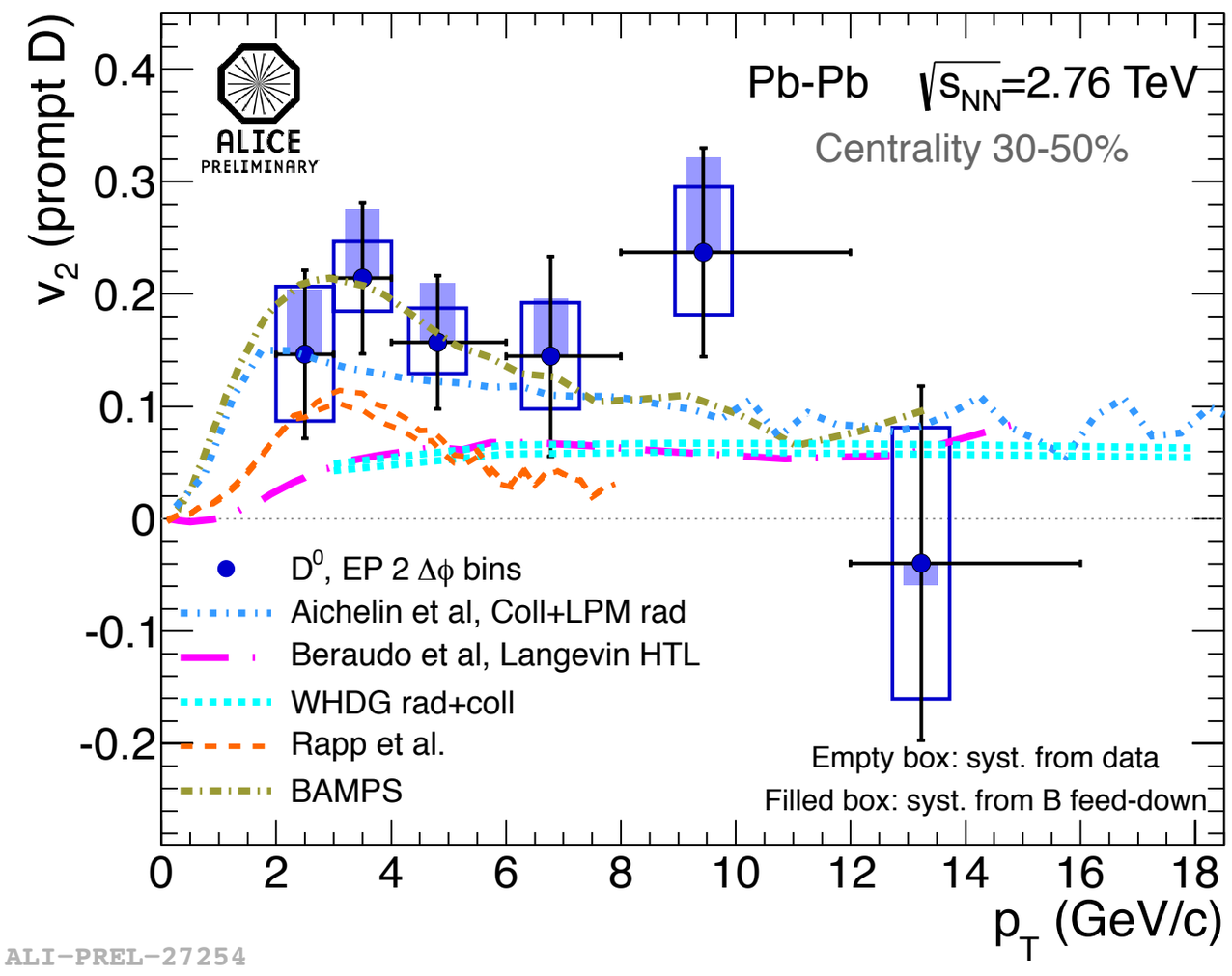
ALI-PREL-35153

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

D meson R_{AA} & v_2



ALI-PREL-35484



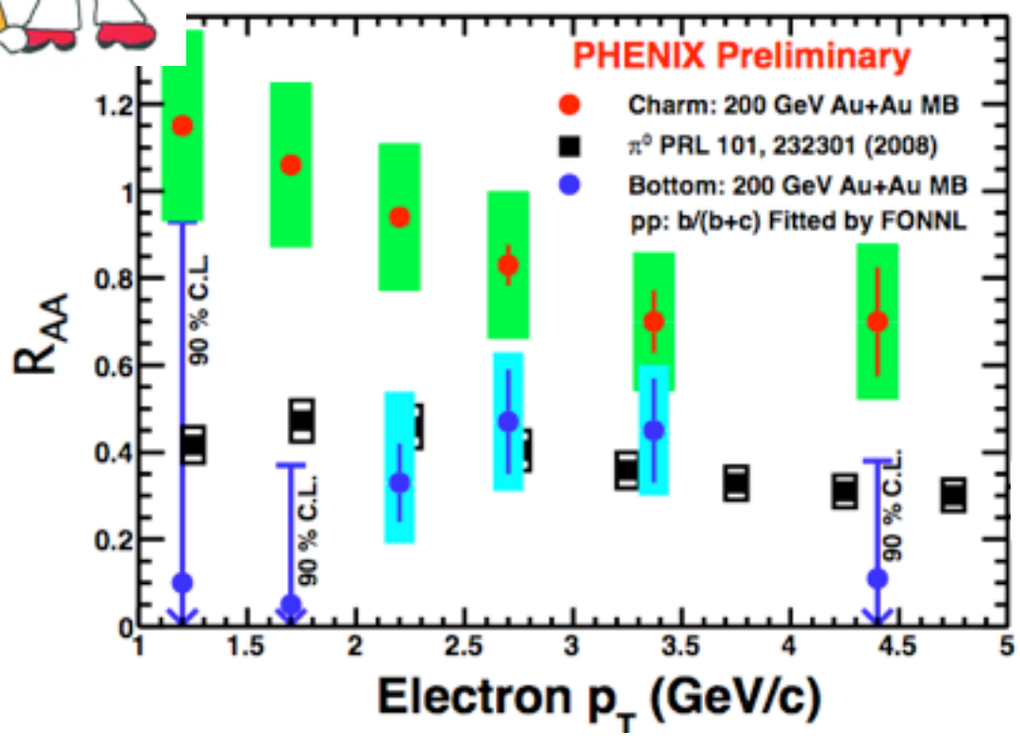
ALI-PREL-27254

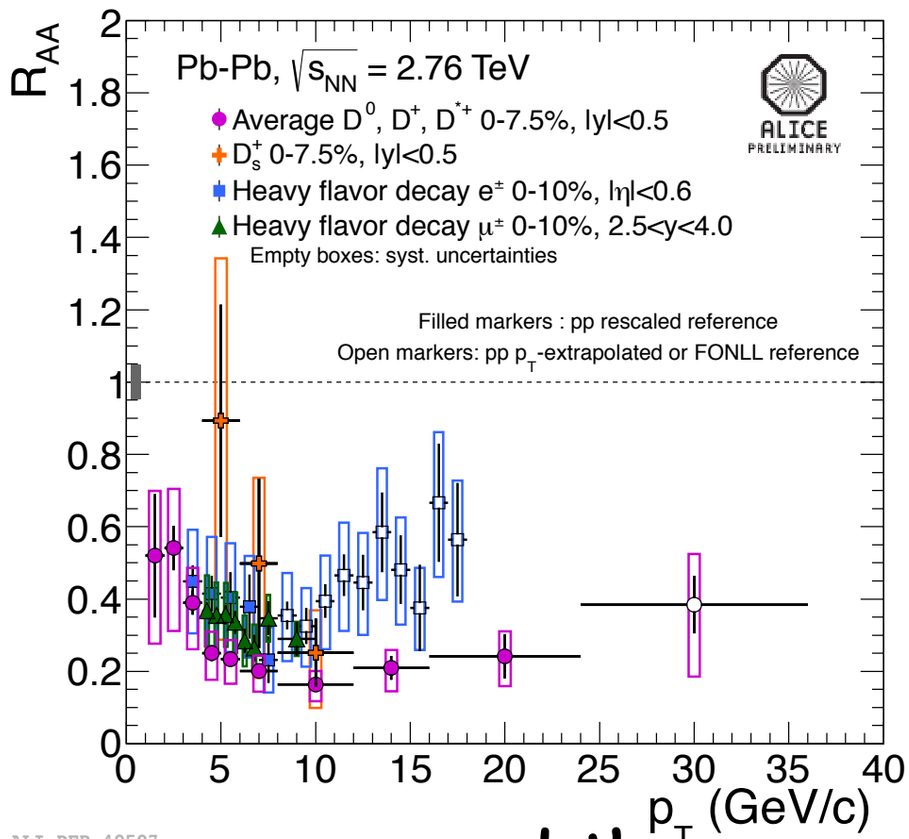
PbPb 2.76 TeV

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

In sum...

Summary

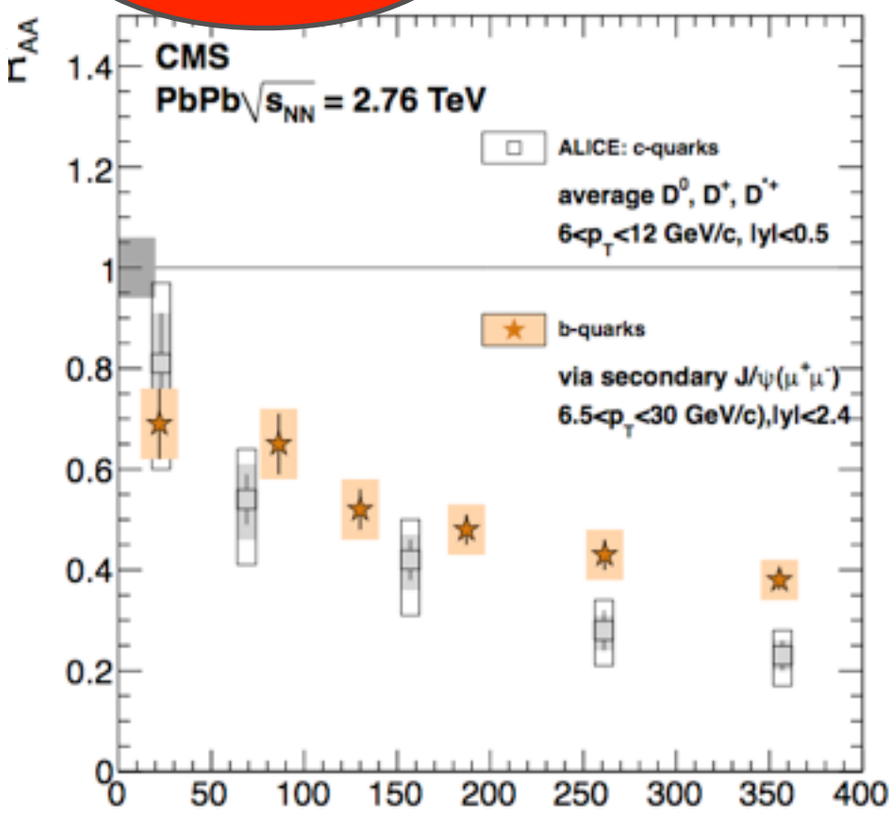


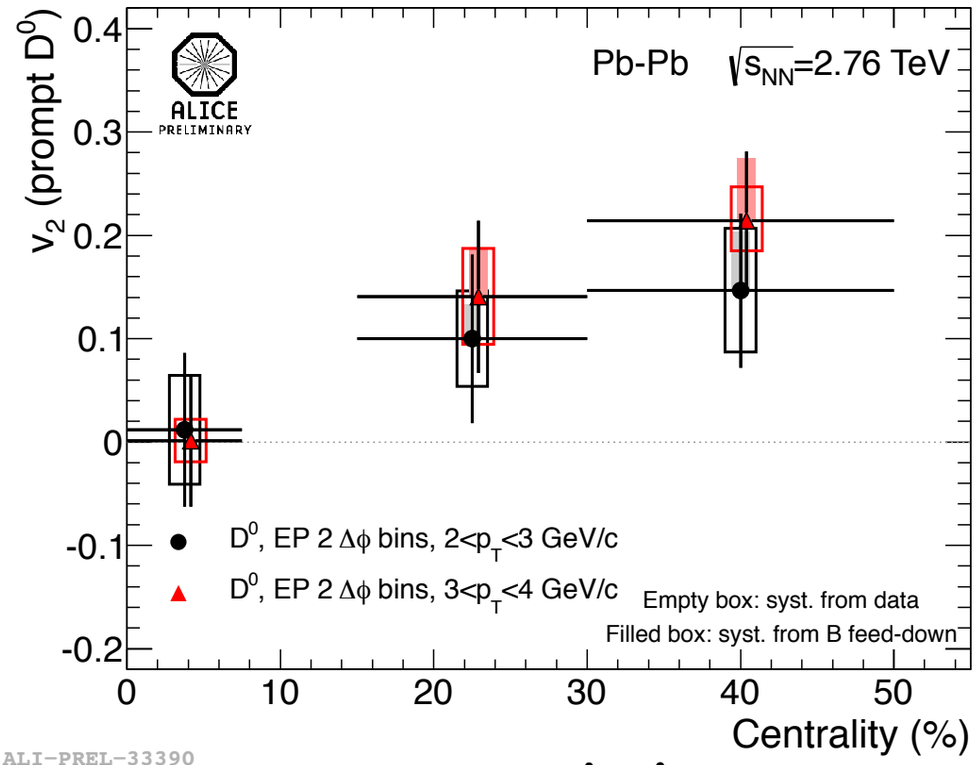


- PHENIX, AuAu 200 GeV: b→e seem more suppressed than c→e
- STAR, AuAu 200 GeV: inclusive D are suppressed at high pt
- ALICE+CMS, PbPb 2.76 TeV:
  - Charged particles and pions have a similar p_T and centrality trend than prompt D meson R_{AA}
  - Non-prompt J/ψ seem more suppressed than charged particles
  - $v_2>0$ for HFe (D mesons) at $2<p_T<3$ GeV/c ($2<p_T<6$ GeV/c)
  - Hint of v_2 centrality dependence at low p_T (D^0)
- HQ energy loss models reproduce reasonably well heavy flavor R_{AA} measurements. Challenging simultaneous description of R_{AA} and v_2

In sum...

Summary





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Backup

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