ALICE Heavy Flavor Measurements

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Heavy Ion Meeting - 24th of October 2013

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

ALICE

Executive Summary

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  - An exhaustive review
  - About analysis details

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  - (short) Introduction
  - (biased) Highlights
  - pPb and PbPb data (+ 2 pp slides)

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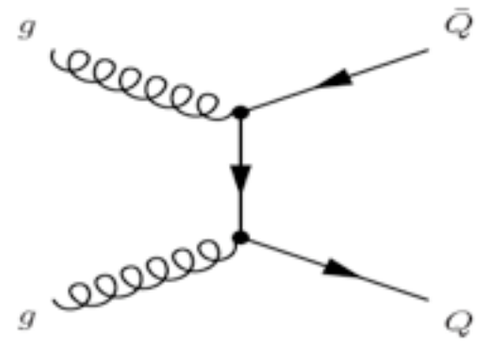
- This will be about:
  - (short) Introduction
  - (biased) Highlights
  - pPb and PbPb data (+ 2 pp slides)

- The keywords:
  - Charm, beauty
  - Electrons, muons, D^0, D^+, D^{*+}, D_s^+ mesons (+ non-prompt J/ψ as extra)
  - Nuclear modification factor
  - Azimuthal anisotropy
  - Models

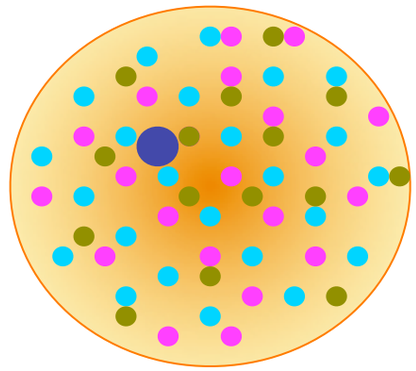
Introduction

Heavy Quarks as QGP Probes

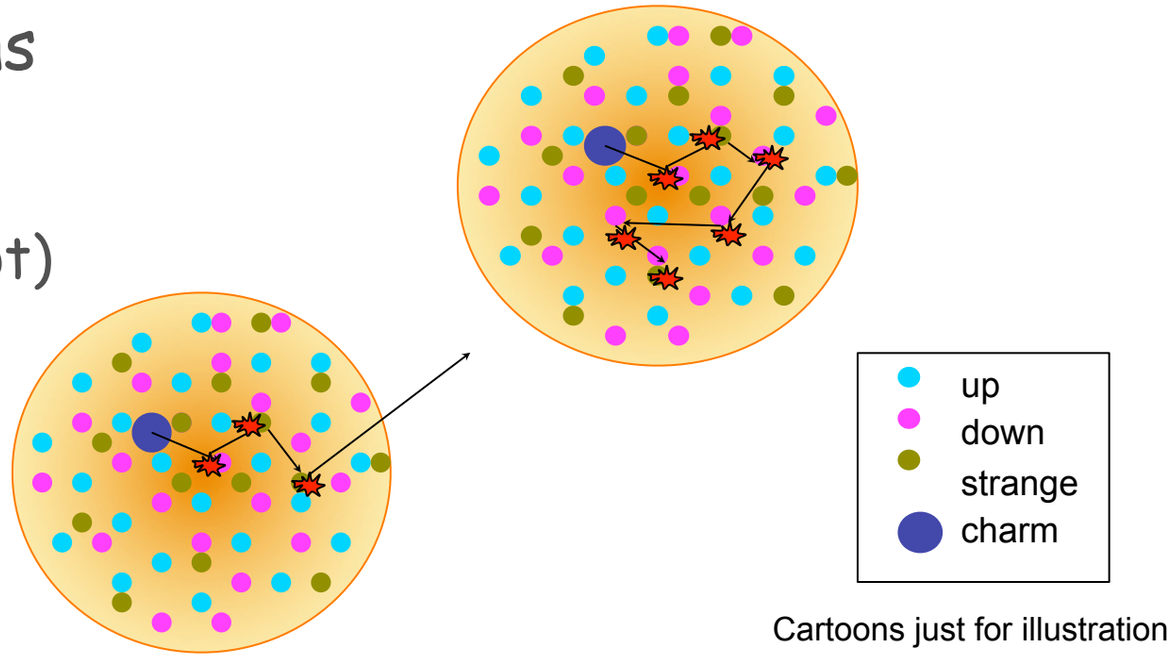
- Production in nucleon-nucleon collisions
  - Production time $\tau_p \sim 0.05 - 0.15$ fm/c
  - ➡ **Tool to test pQCD calculations**



- 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**

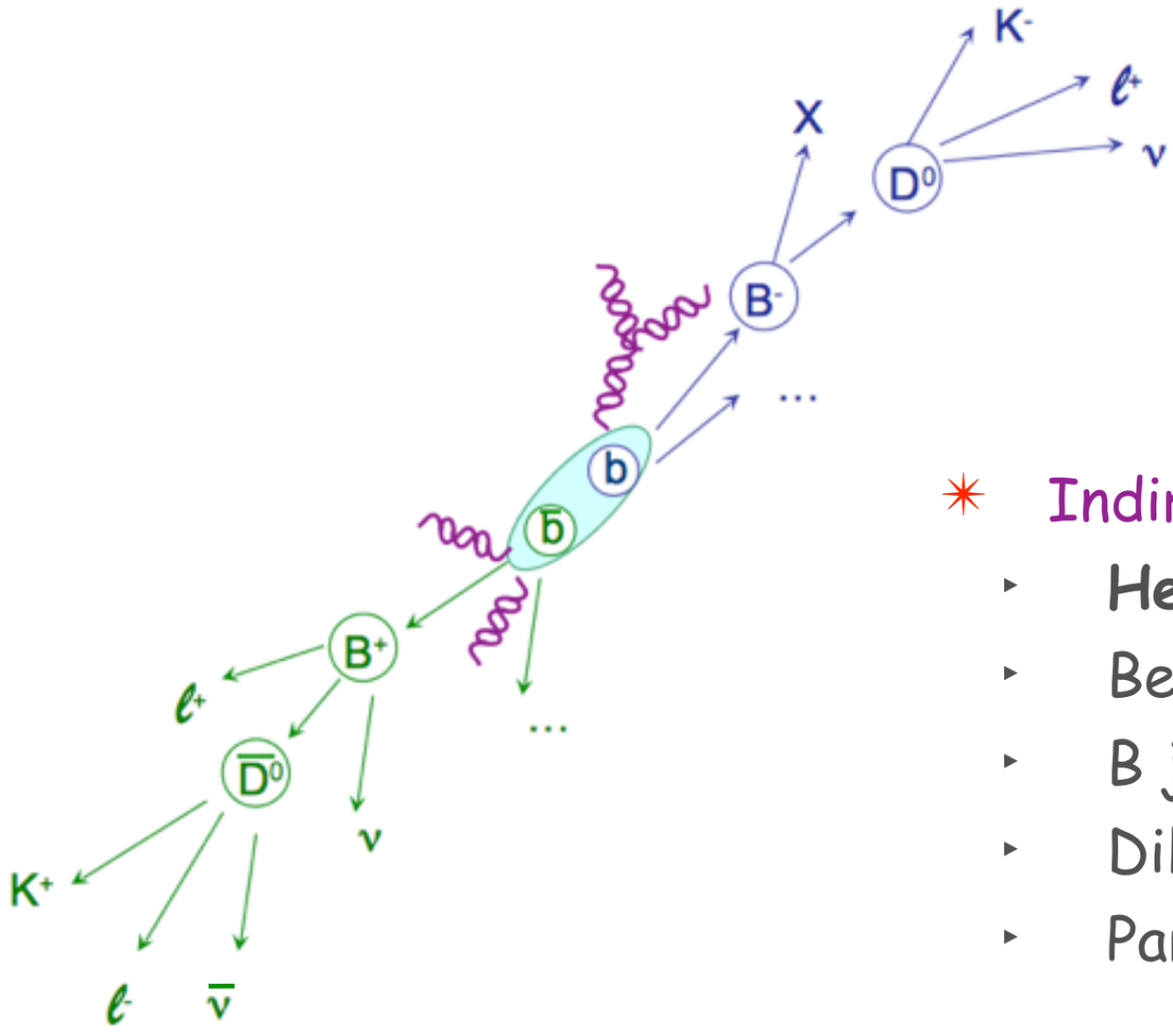


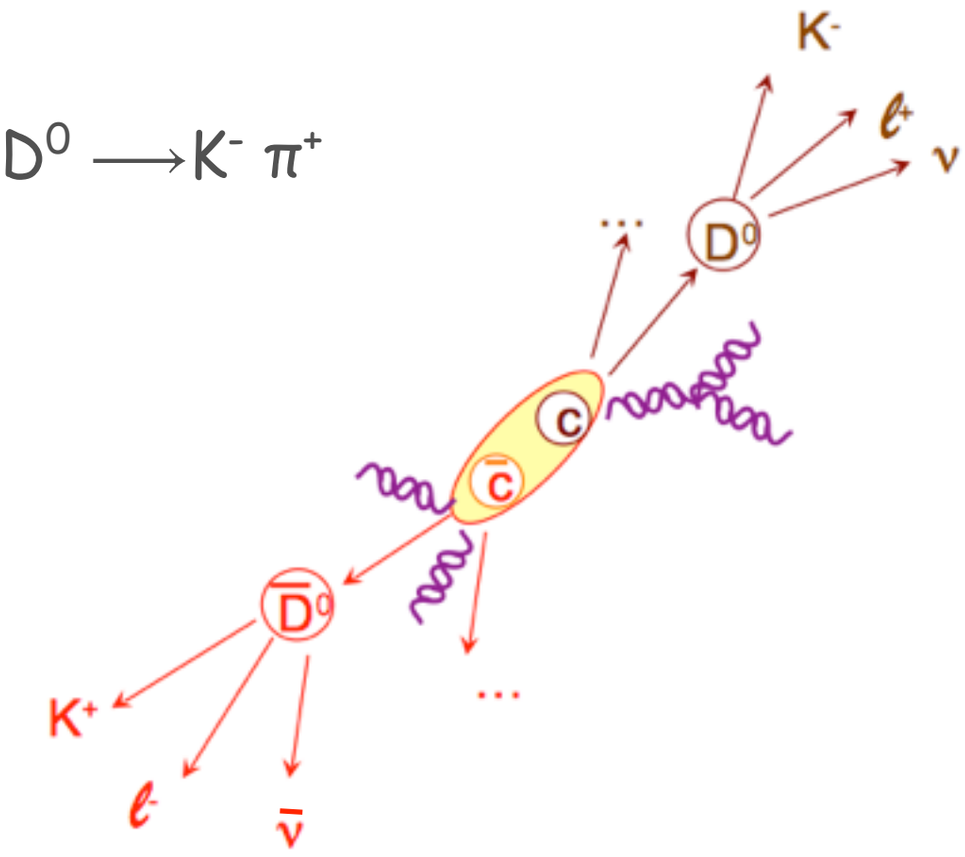
Cartoons just for illustration

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

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					✔	

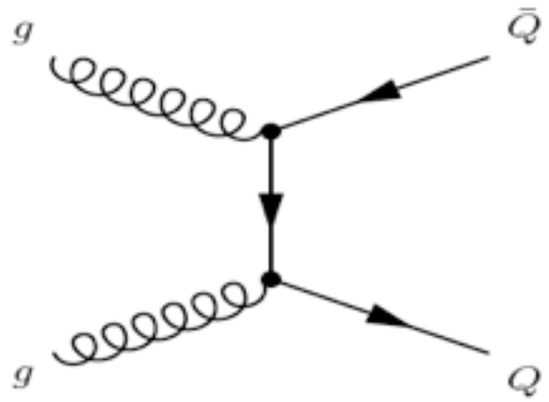
Proton-proton Results

$\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7 TeV

Production in hard partonic collisions

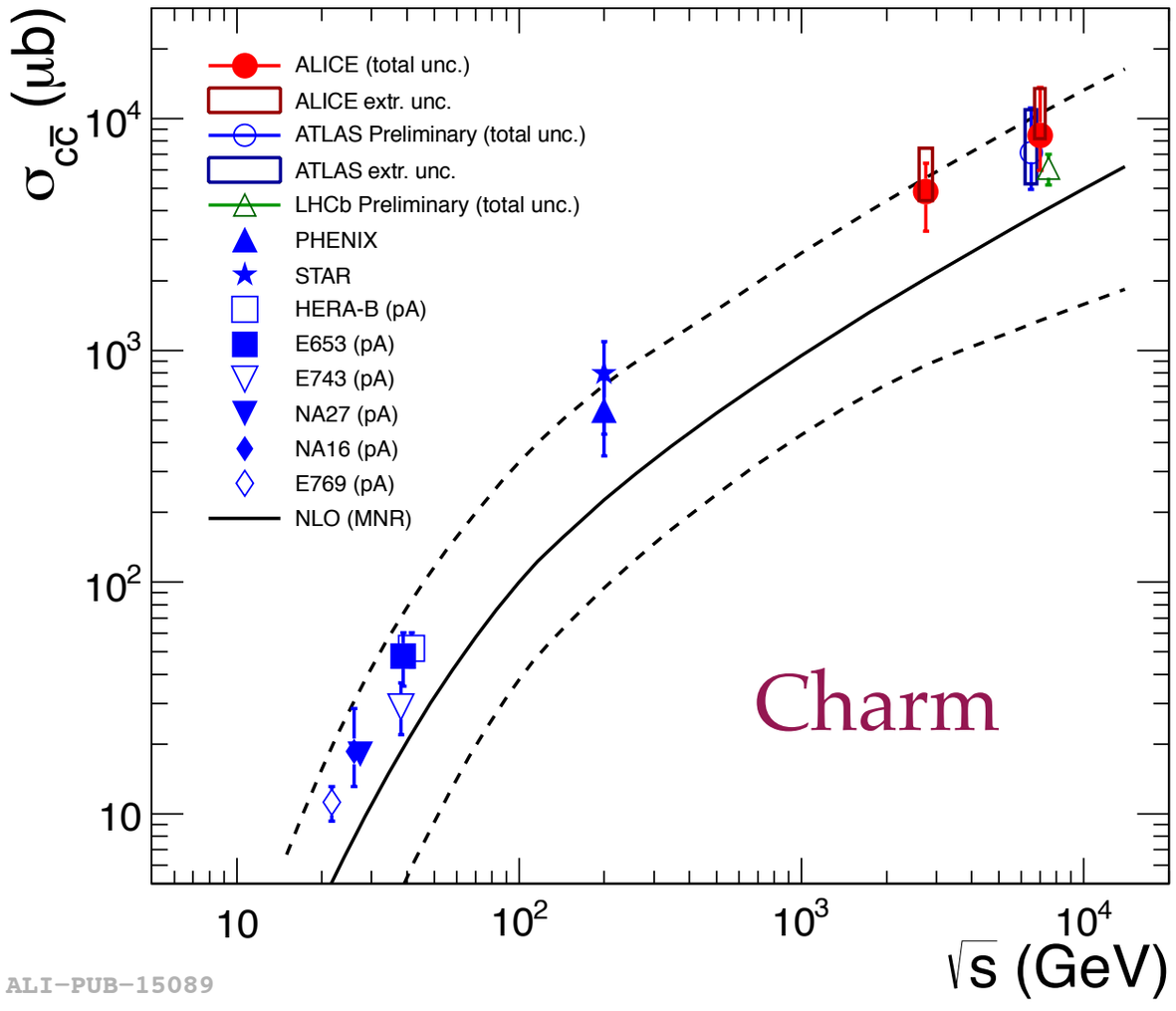
- Production time $\tau_p \sim 1/m_Q \sim 0.05$ - 0.15 fm/c

  ⇨ **Tool to test pQCD calculations**

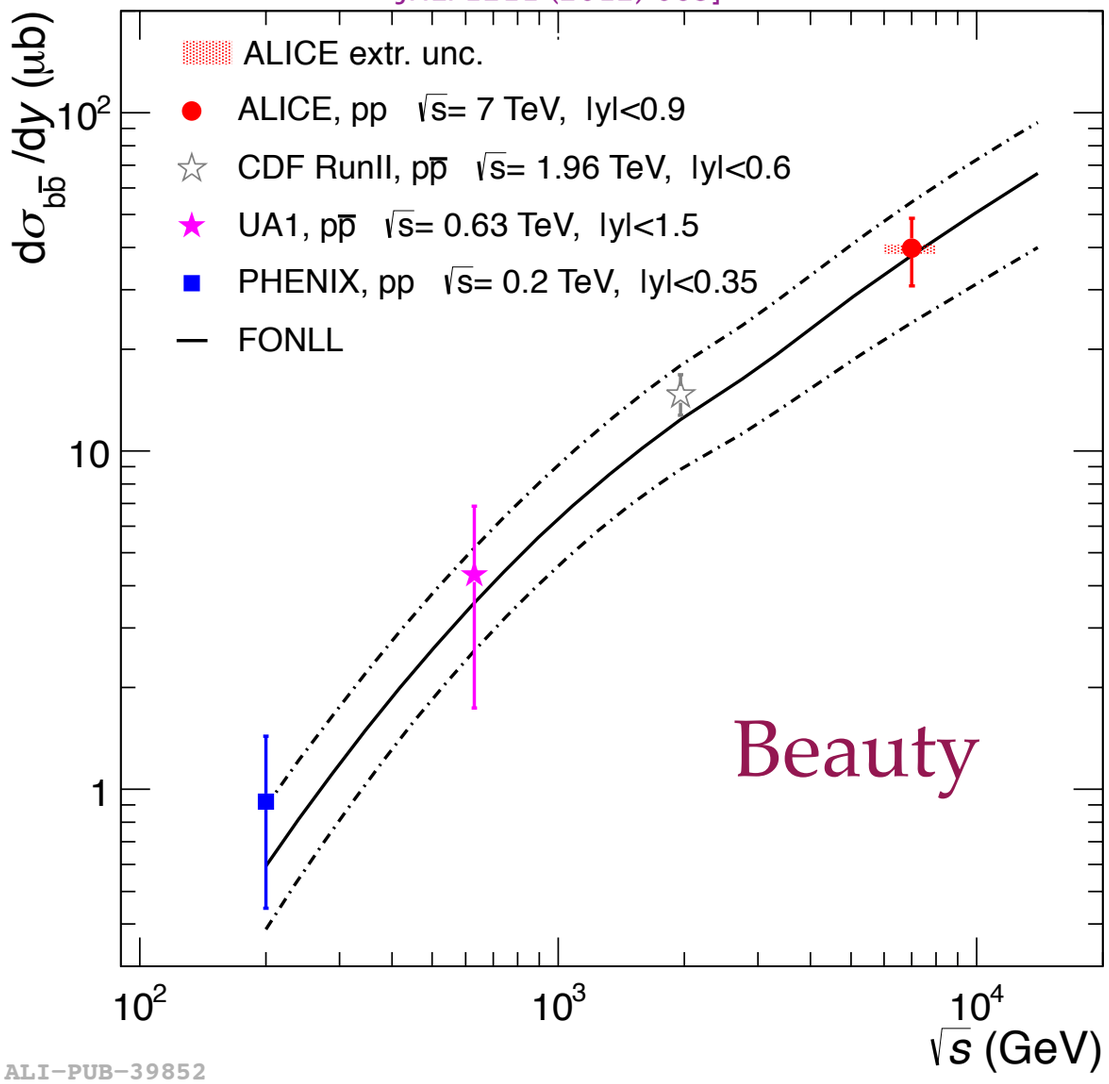


Charm & Beauty Cross Sections

[ALICE Coll. JHEP 07 (2012) 191]

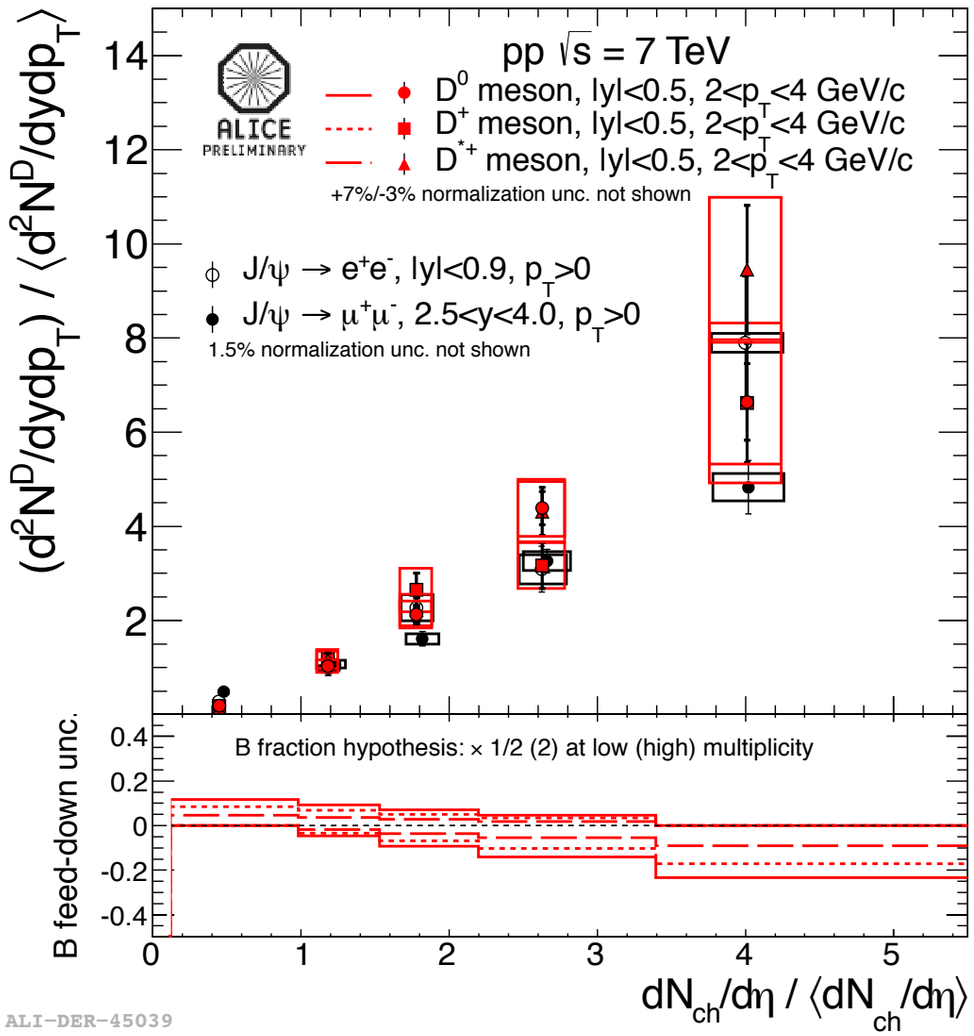


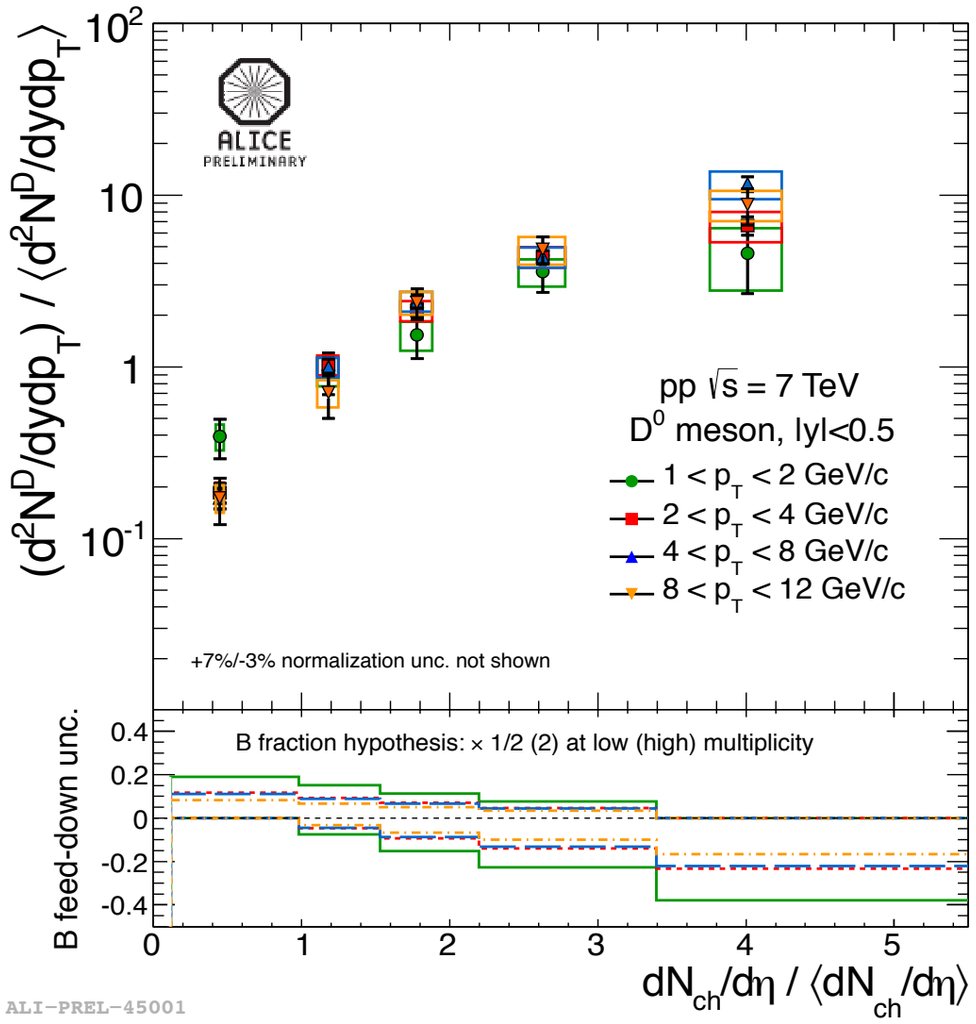
[ALICE Coll. arXiv: 1208.1902 (2012), JHEP1211 (2012) 065]



- **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

Charm(onia) Multiplicity Dependence





- 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).]

p-Pb Results

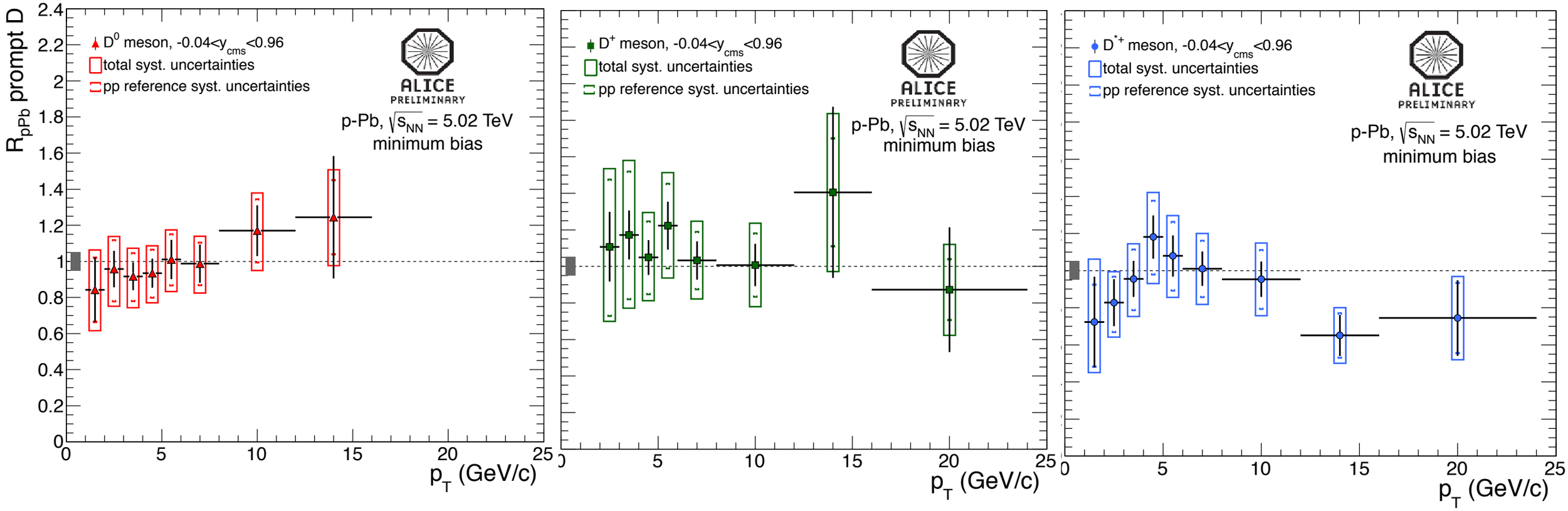
$\sqrt{s_{NN}} = 5.02$ TeV

Effects in a nuclear medium: A-B collisions ⇨ ⇨ d-Au, p-Pb

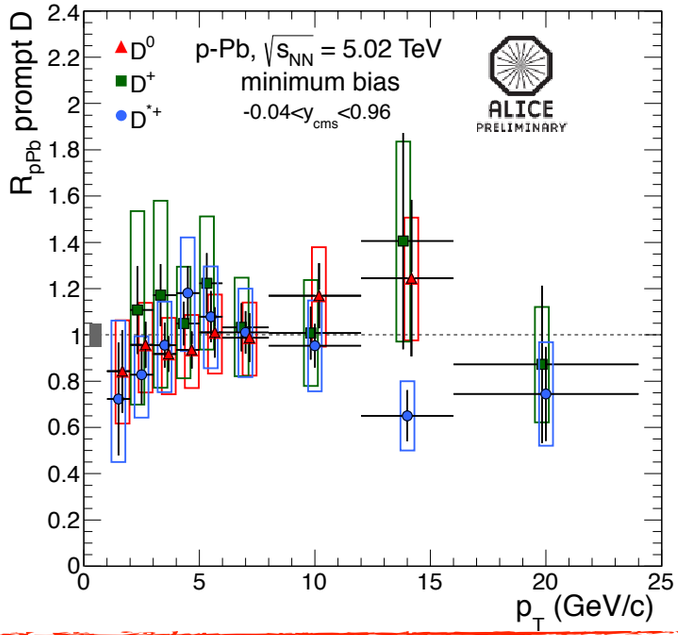
- Shadowing ⇨ dN/dp_T, R_{AB}
  - Impact parameter dependence of nPDFs ? ⇨ look at the variation with b
- Saturation ⇨ dN/dp_T, R_{AB}

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

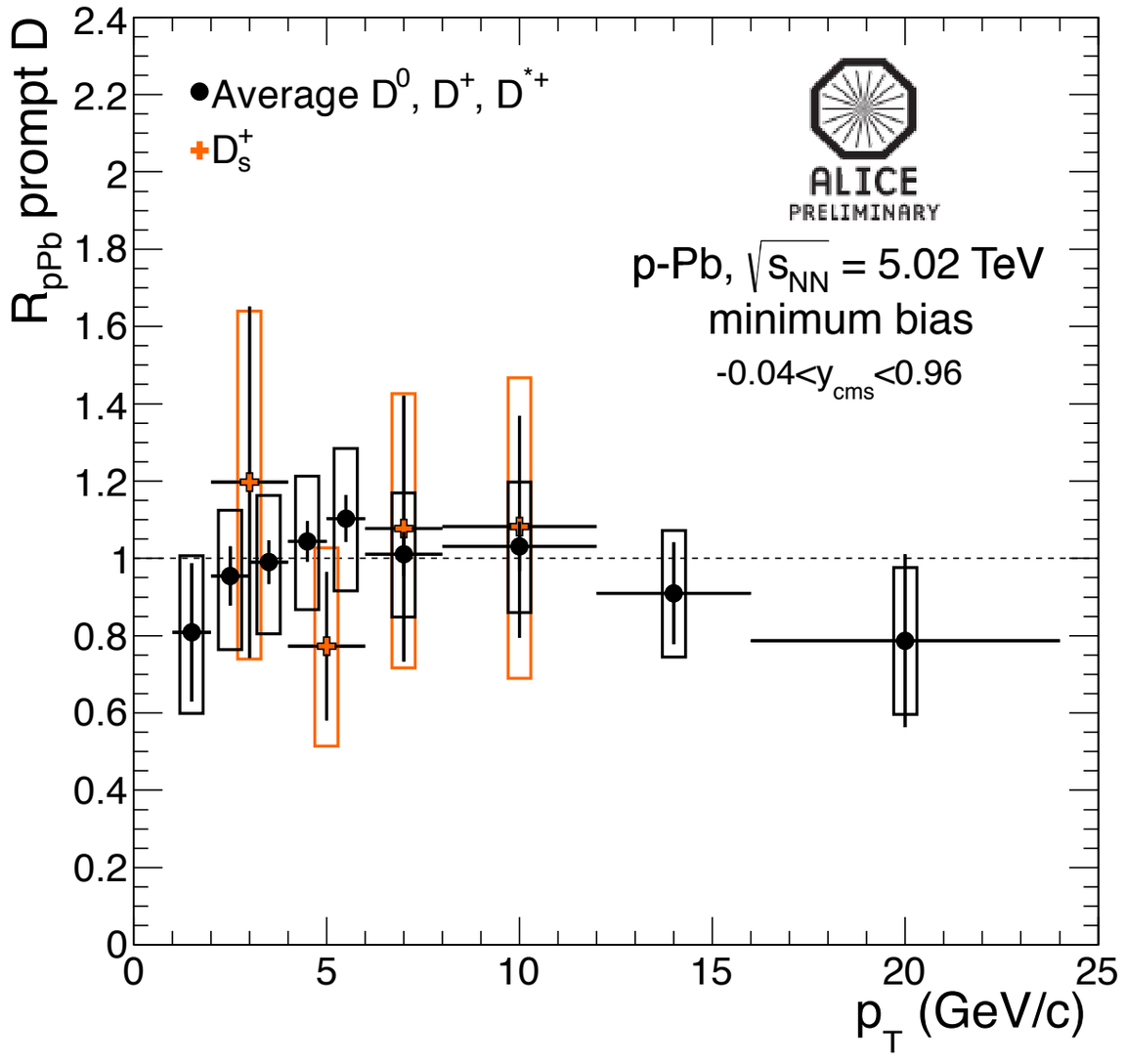
Prompt D^0, D^+, D^{*+} mesons



- Compatible D^0, D^+, D^{*+} results
- R_{pPb} compatible with unity in the whole p_T range

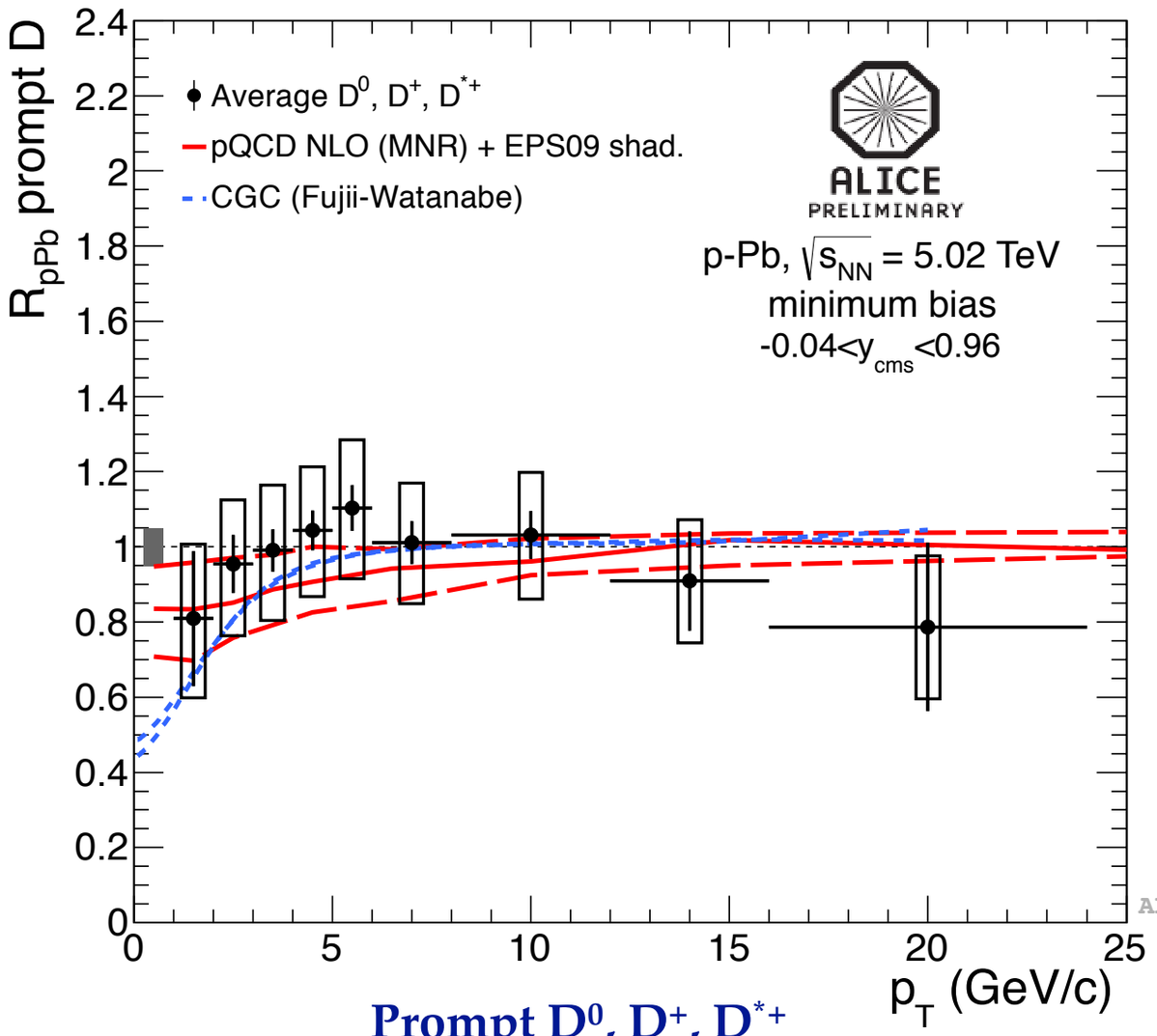


Prompt D^0, D^+, D^{*+}, D_s^+ mesons

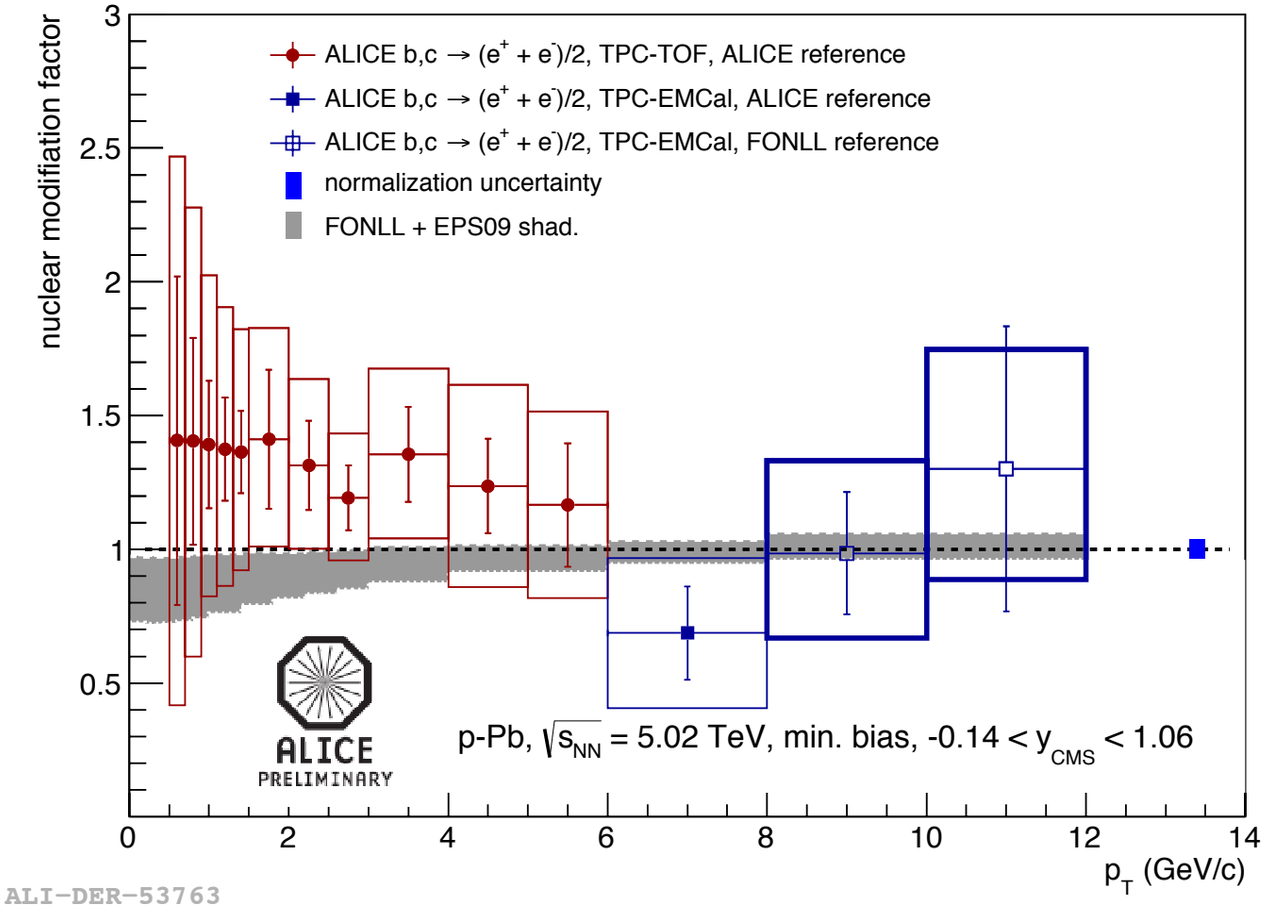


- R_{pPb} compatible with unity in the whole p_T range
- First measurement of prompt D_s^+ in p-Pb collisions
- D_s^+ pattern similar to that of the D^0, D^+, D^{*+}

R_{PPB} vs P_T Compared to Models



Prompt D^0, D^+, D^{*+}



Heavy flavor electrons

ALI-DER-53763

- Good agreement with MNR calculations with EPS09 shadowing
- Also well described by CGC predictions
- Nuclear effects expected to be small for high pt in PbPb collisions

Pb-Pb Results

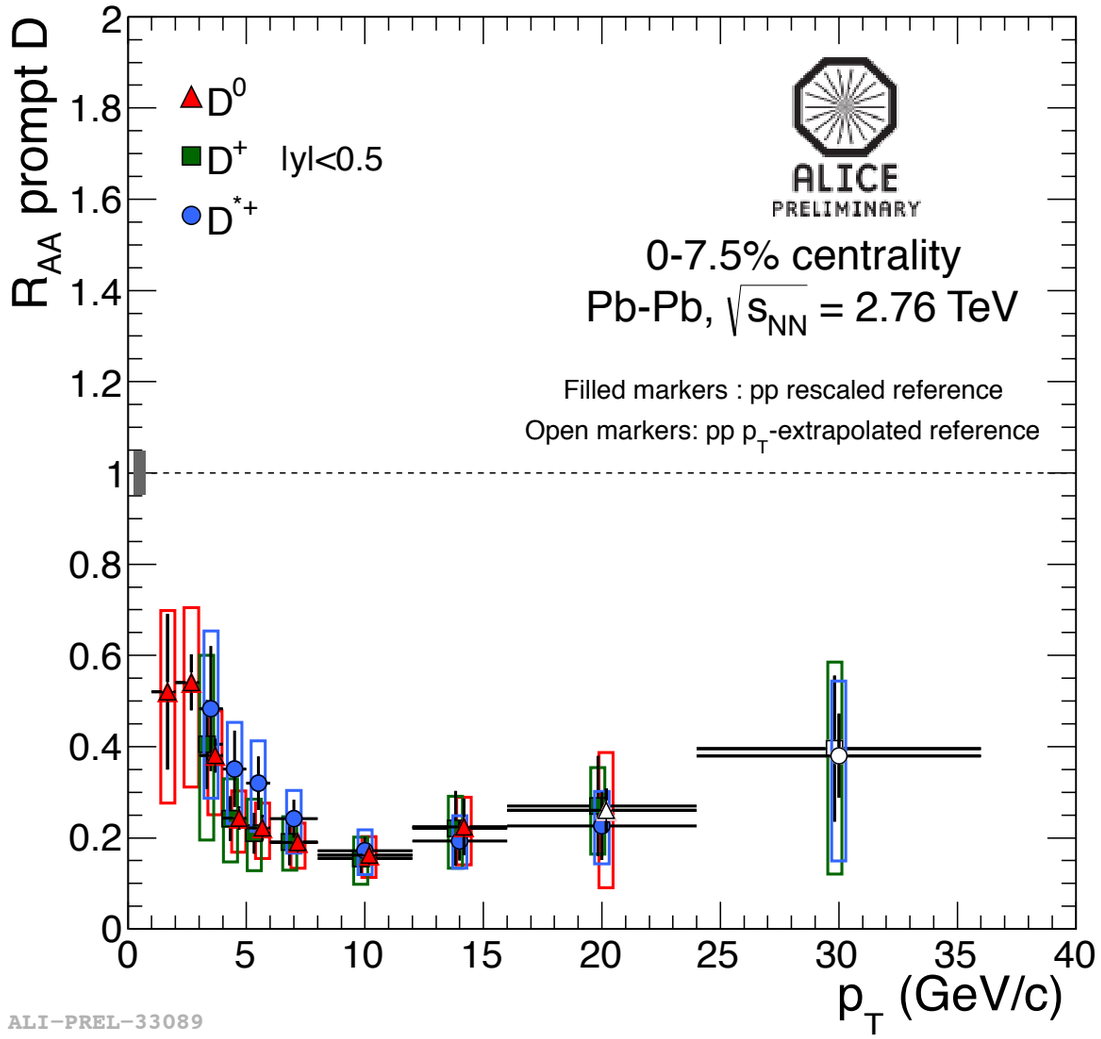
$\sqrt{s_{NN}} = 2.76$ TeV

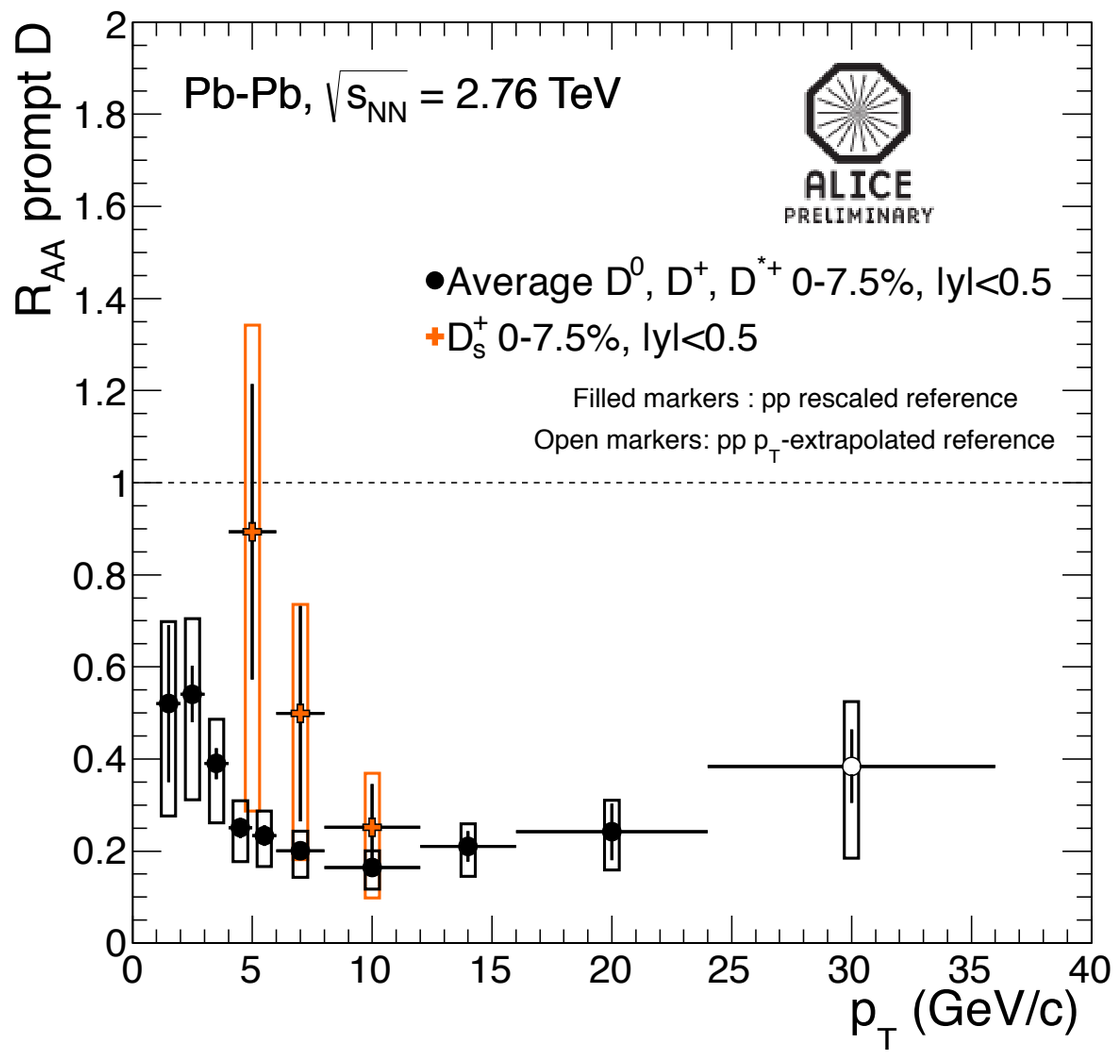
Effects in a QGP: A-B collisions ⇨ ⇨ Au-Au, Pb-Pb

- 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**

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



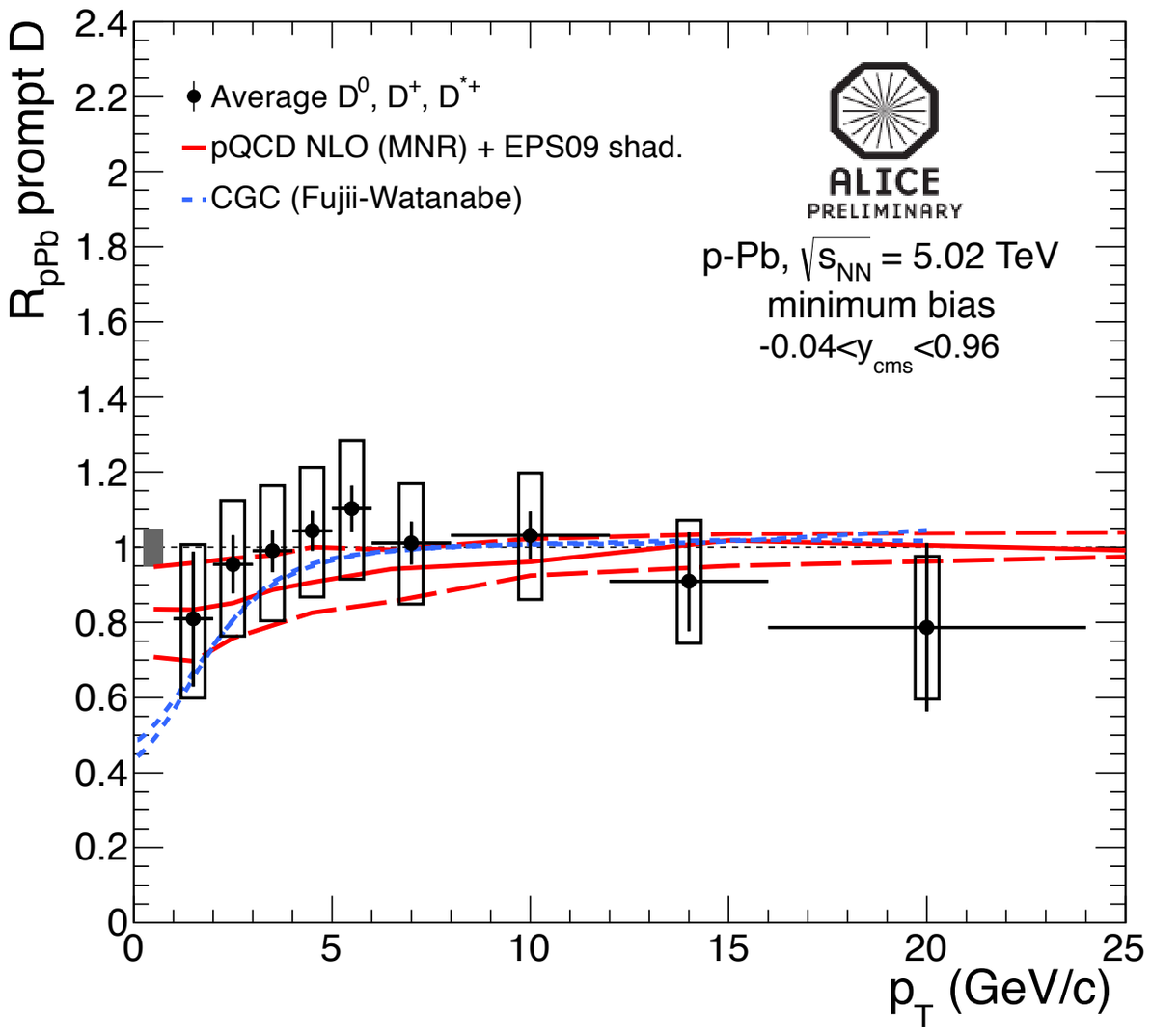


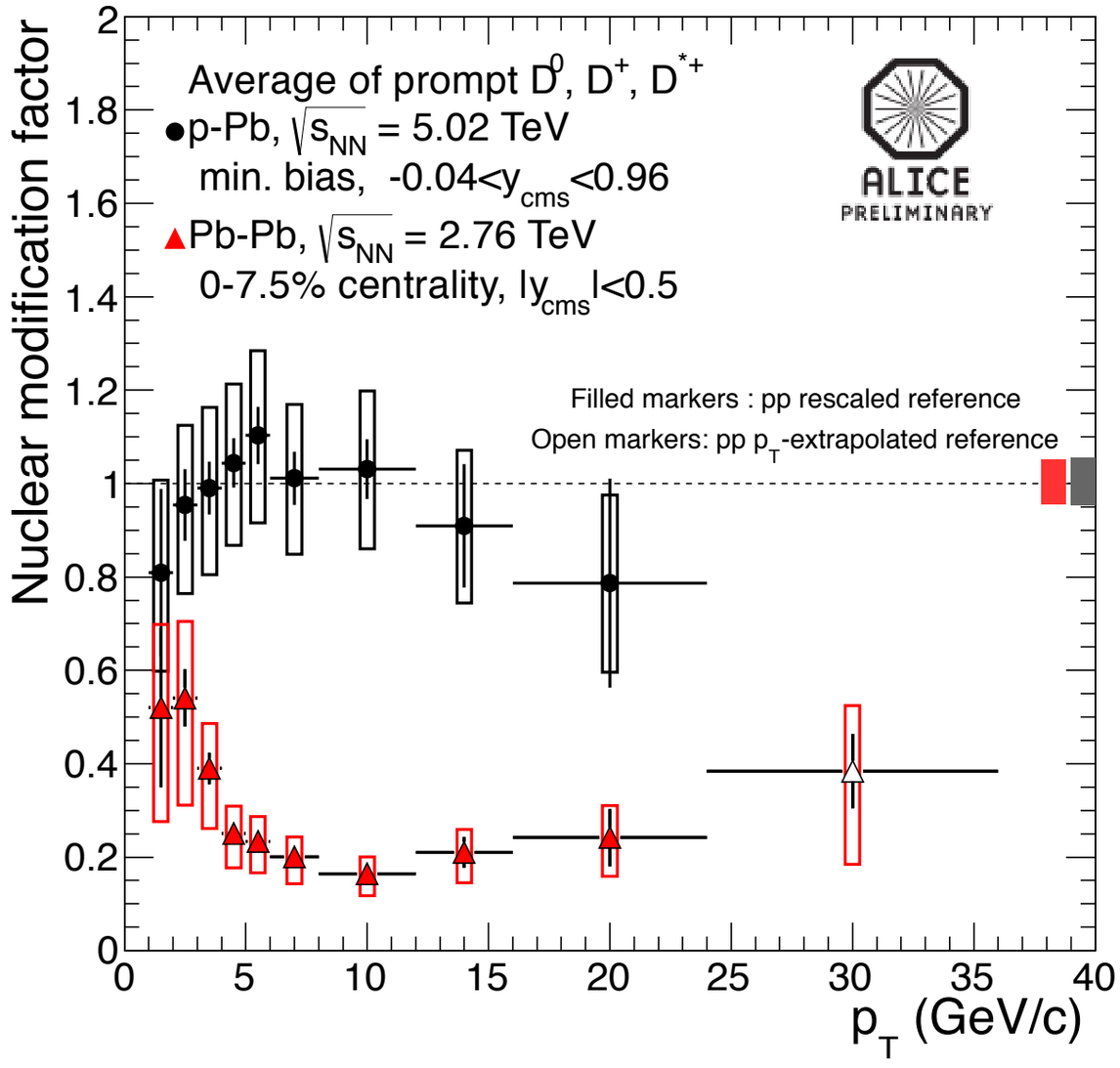
- **Suppression by up to a factor of 5 at p_T ~10 GeV/c in 0-7.5%**
- **First measurement of prompt D_s^+ in heavy ion collisions**
- **D_s^+ suppression similar to that of the D^0, D^+, D^{*+}**

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

[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]

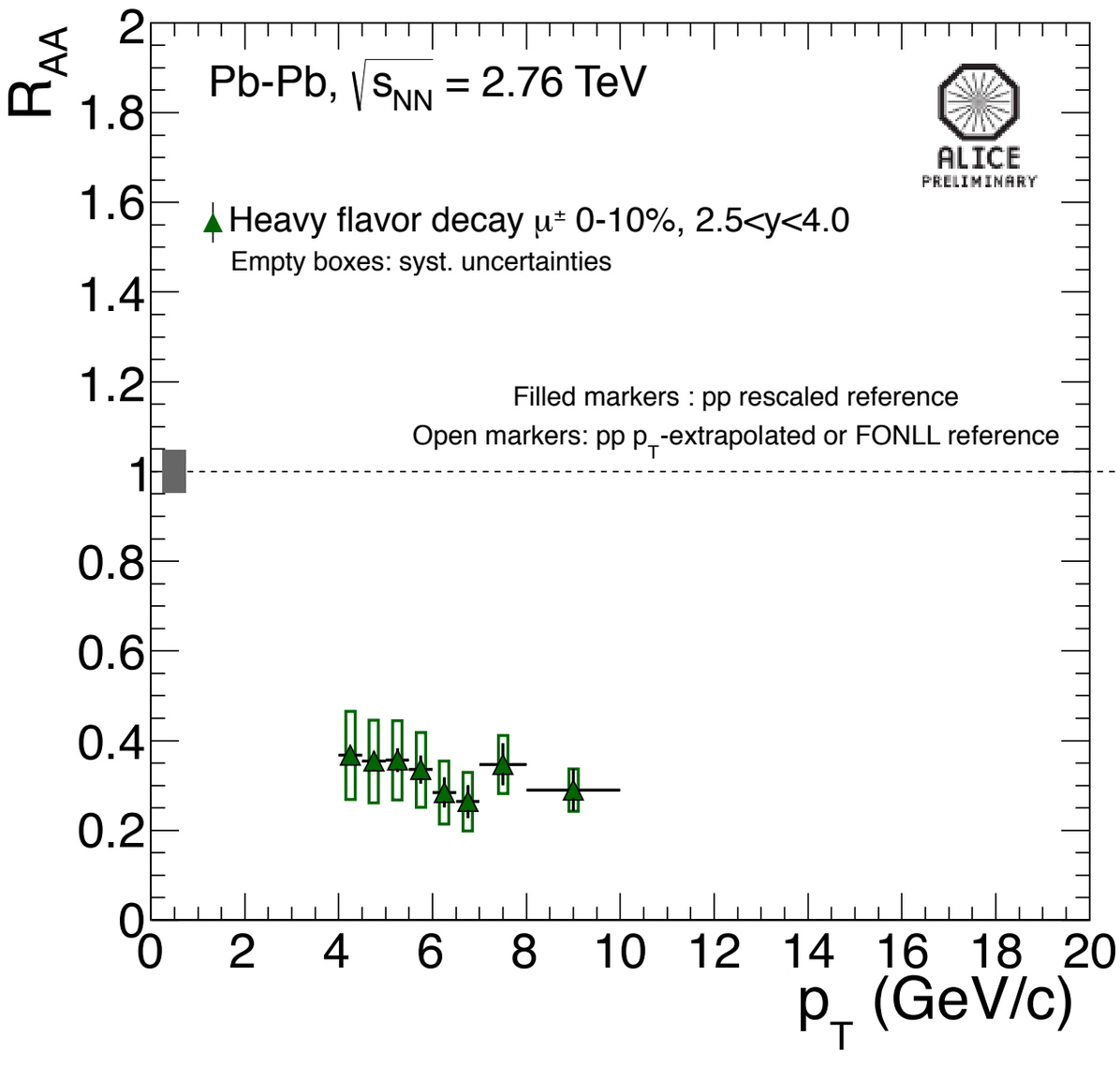
D Mesons in PPb and PbPb





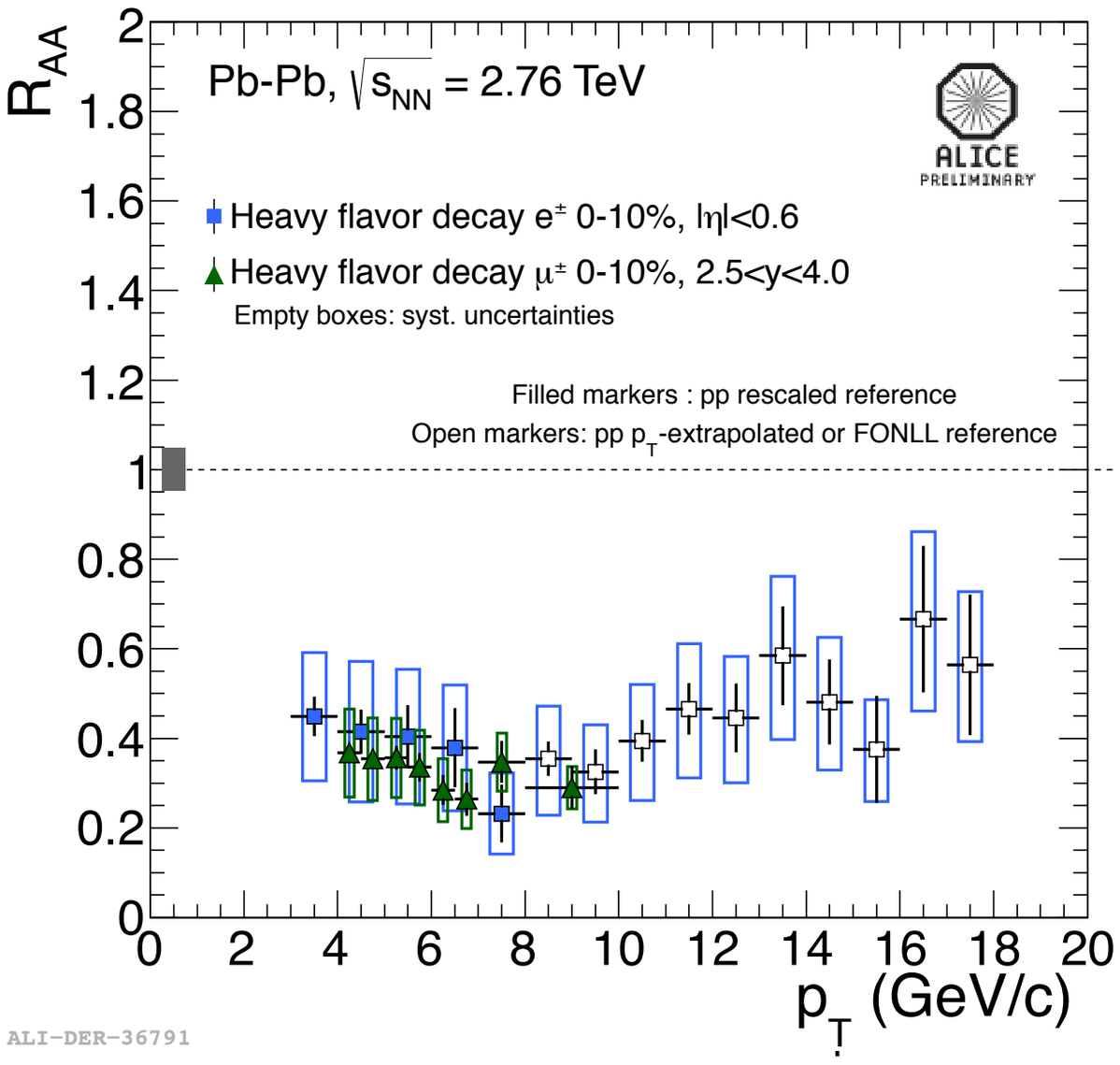
- The suppression at moderate to high-p_T can not be explained by shadowing/saturation alone.
- The suppression is a final state effect

LHC R_{AA} p_T dependence I



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

LHC R_{AA} p_T dependence I



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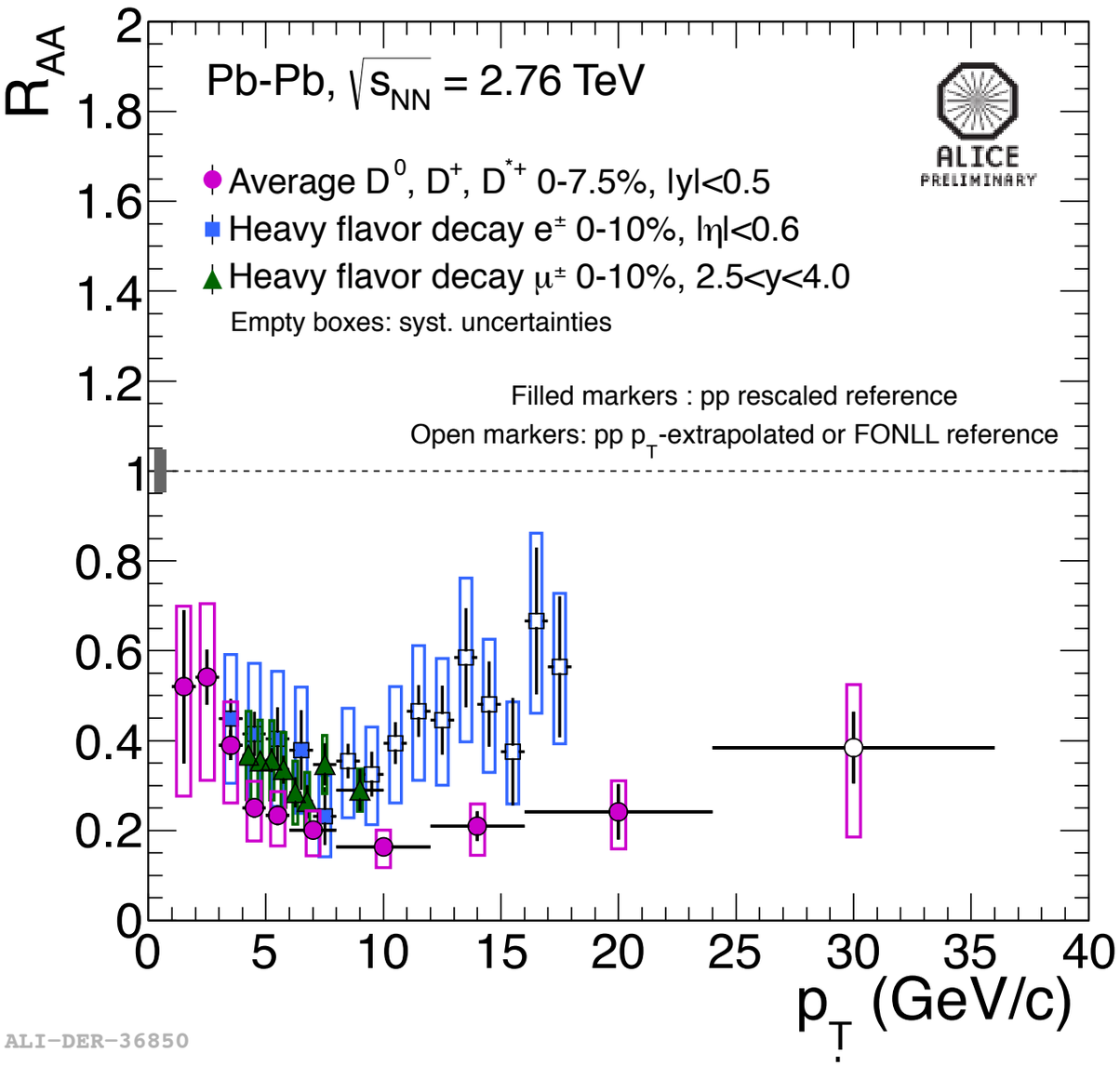
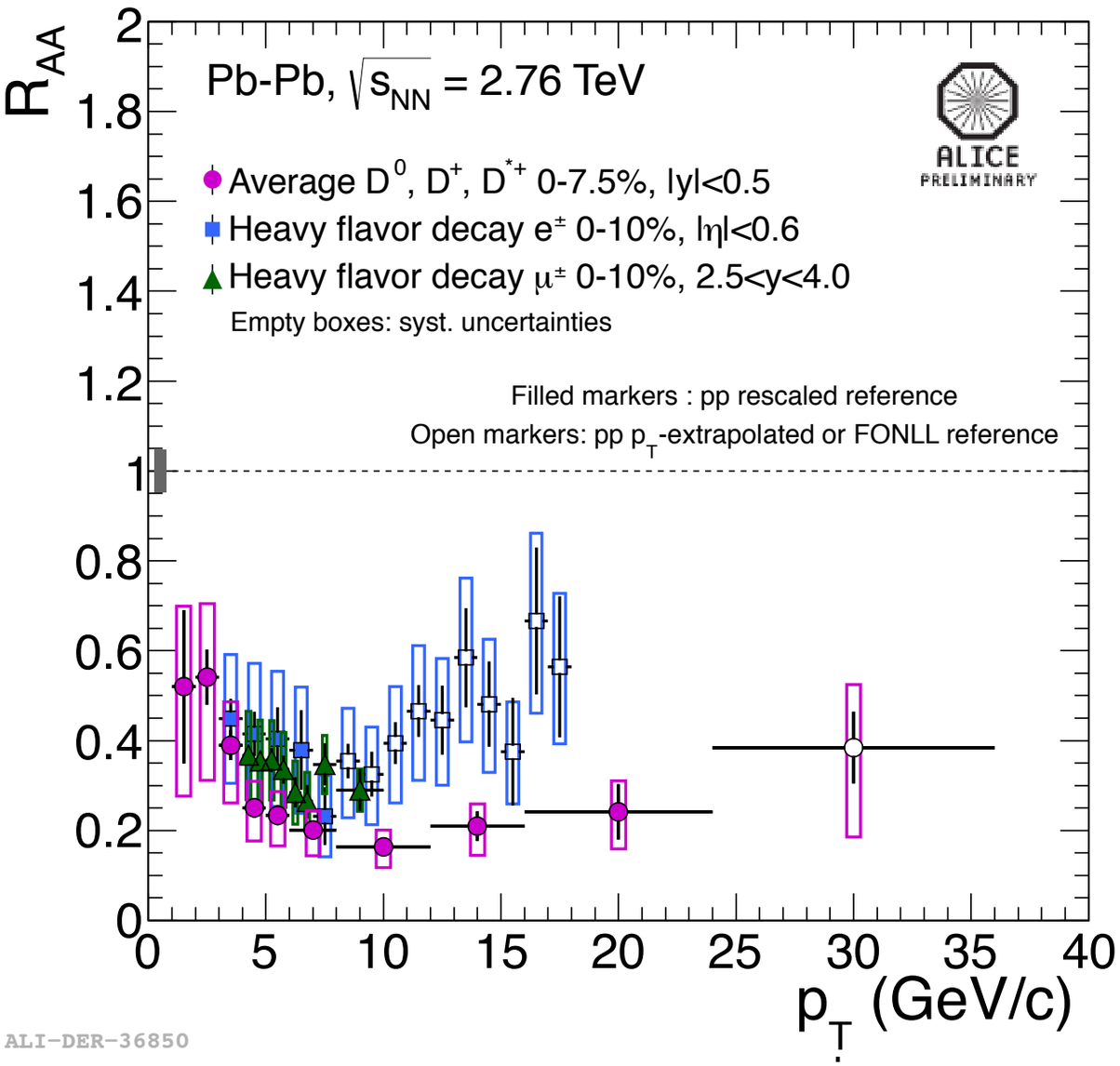
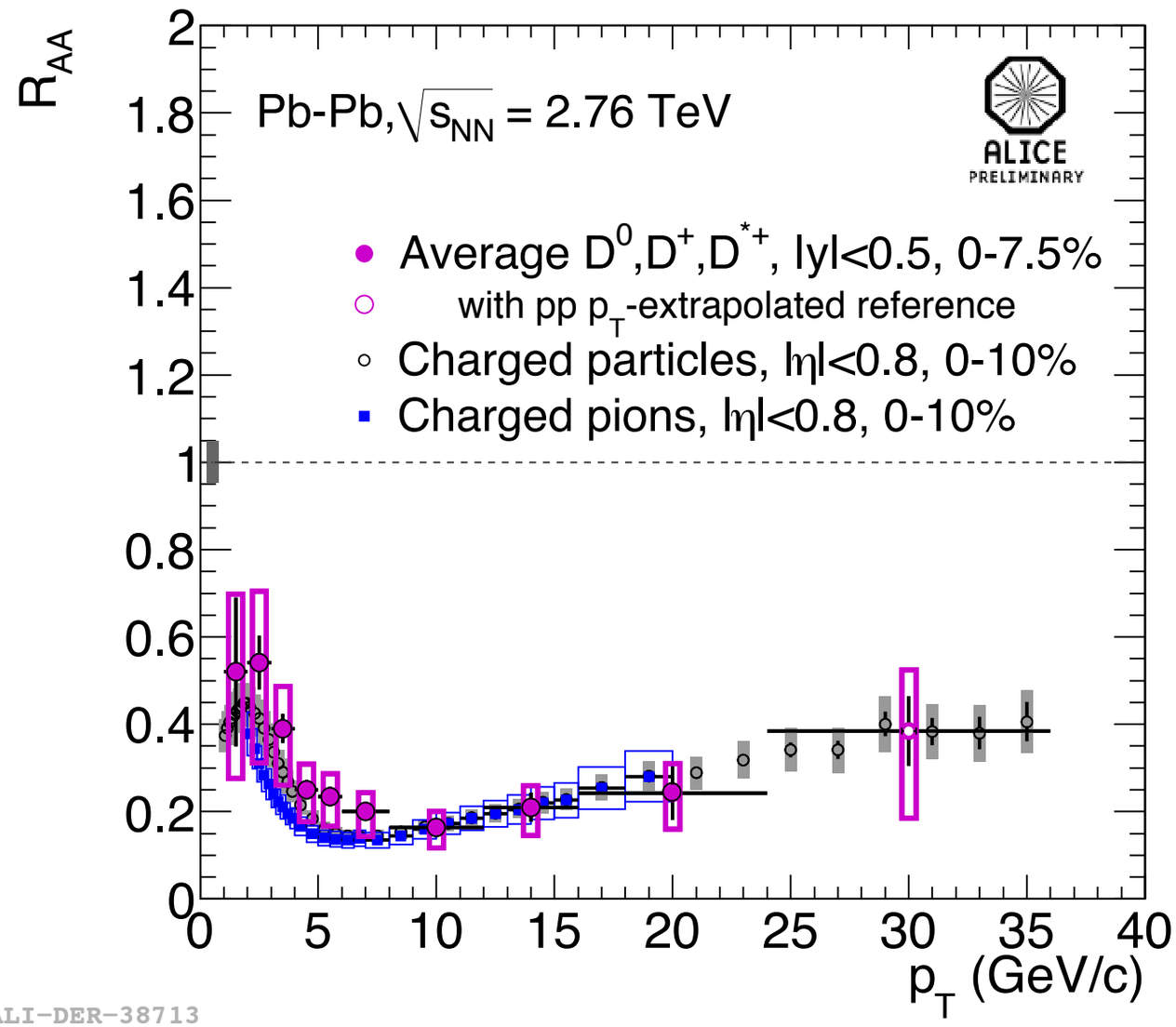


- Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%
- they are also comparable with D mesons R_{AA} (|y|<0.5) in 0-7.5% considering the semileptonic decay kinematics ($p_T^e \sim 0.5\ p_T^B$ at high p_T)
- D R_{AA} shows a similar trend as charged particles and $\pi^{\pm}$ in 0-10%

LHC R_{AA} p_T dependence I





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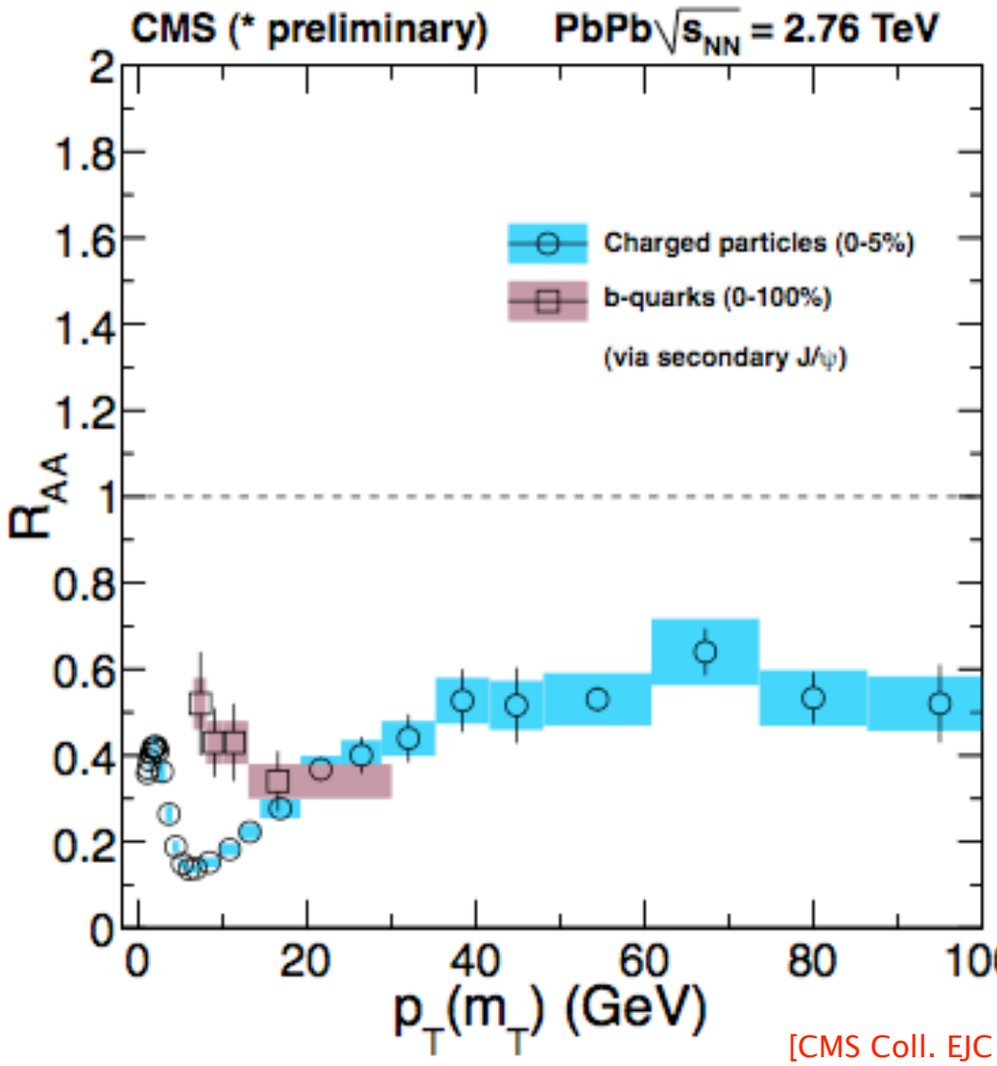
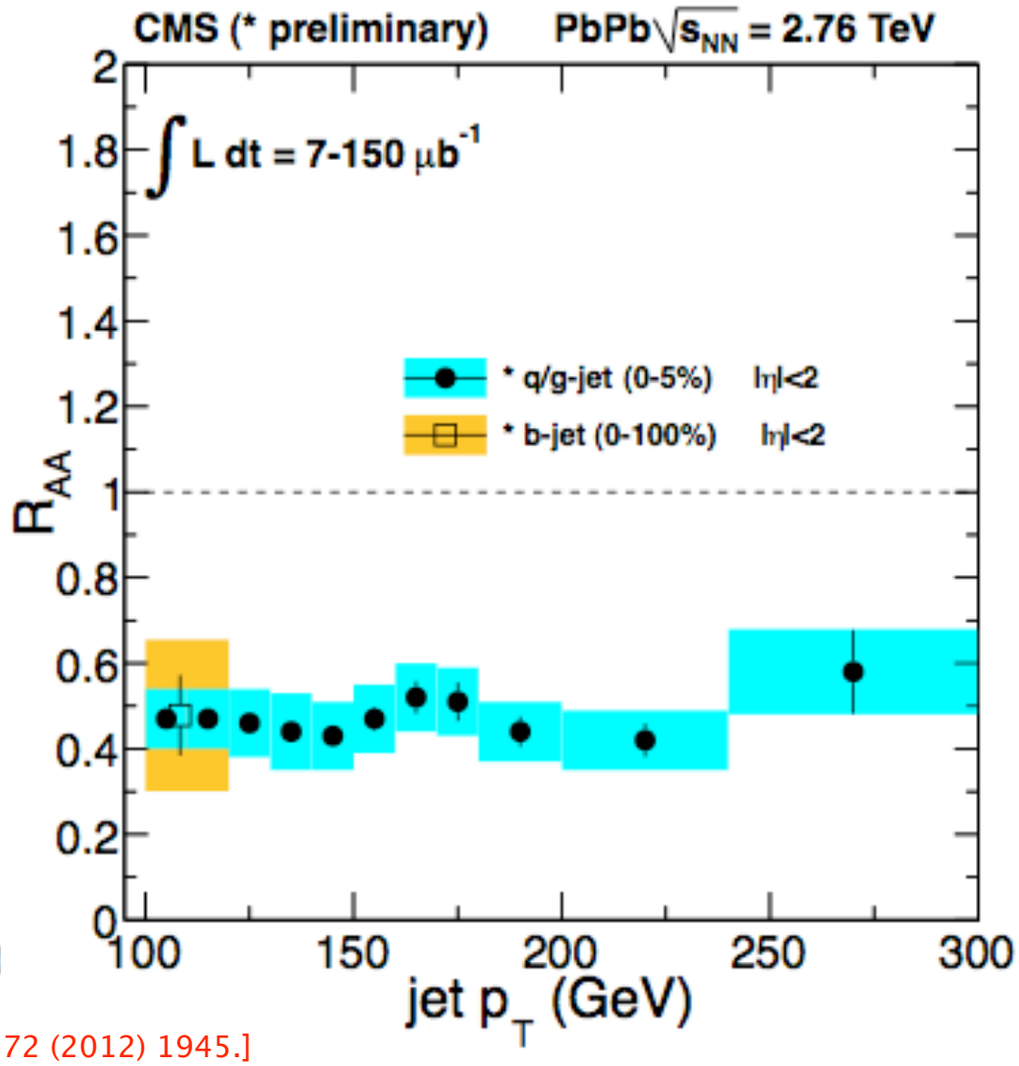
LHC R_{AA} P_T DEPENDENCE II

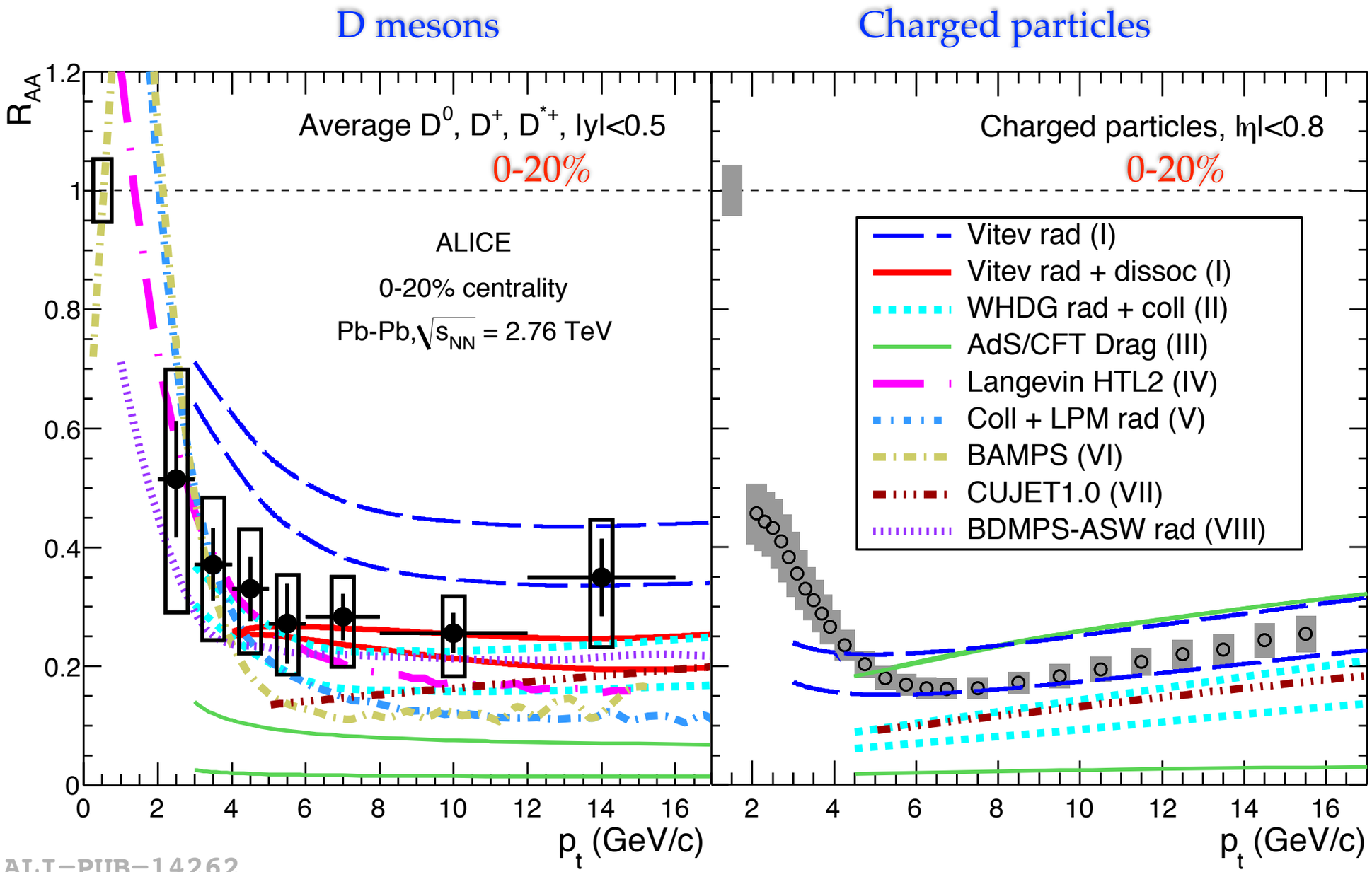




[CMS Coll. EJC 72 (2012) 1945.]

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

R_{AA} vs P_T

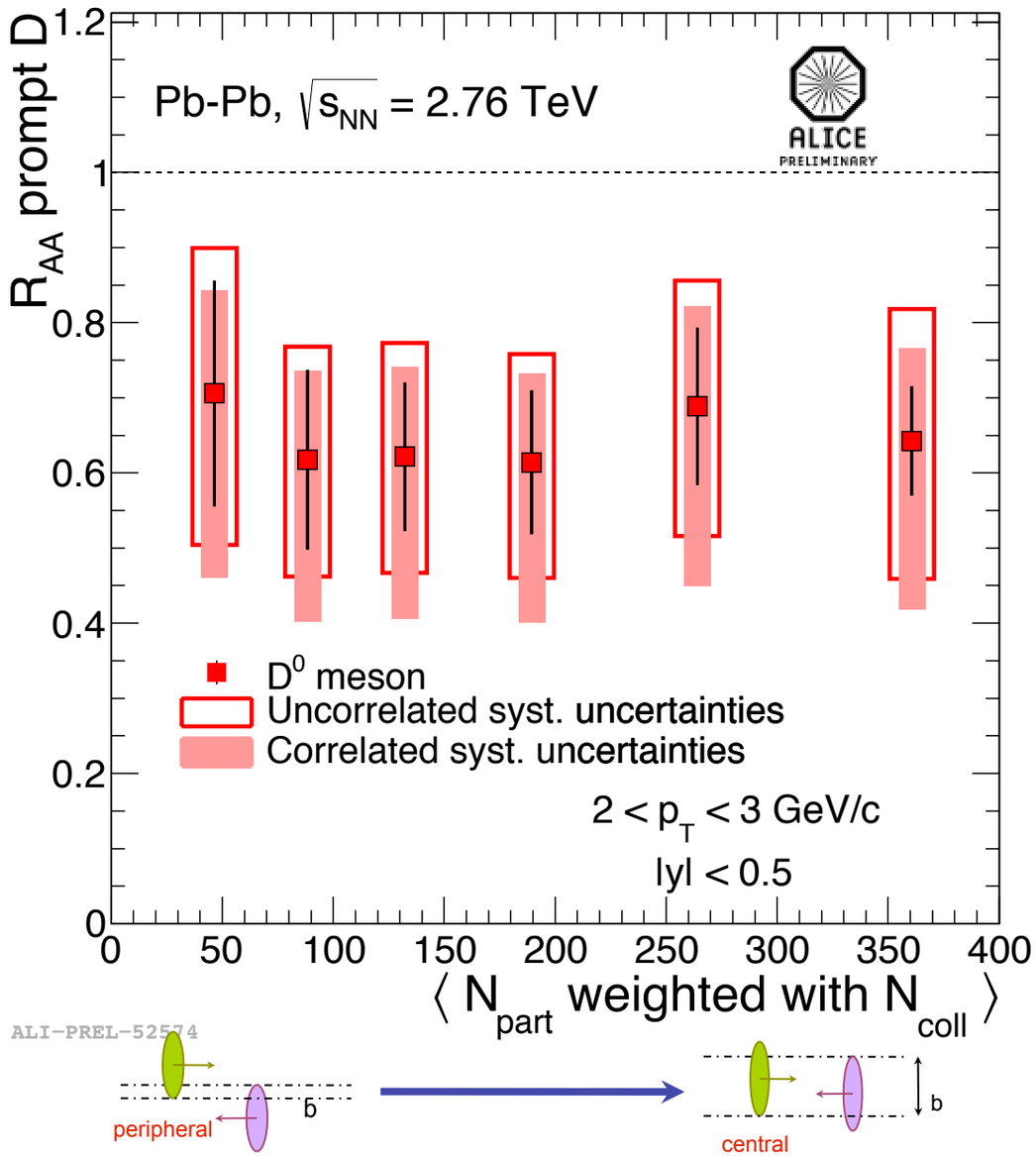


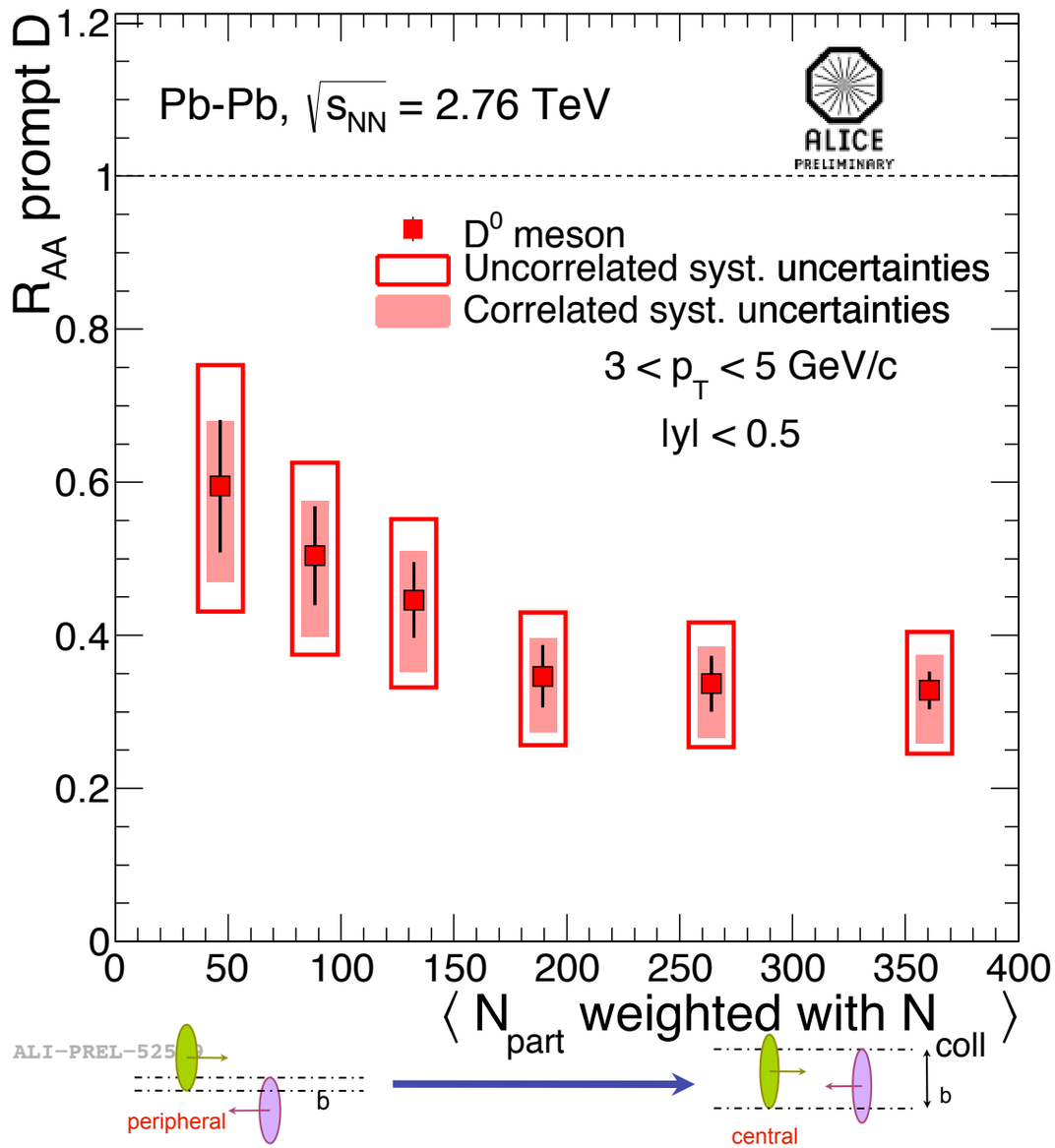
[ALICE Coll. JHEP 09 (2012) 112, arXiv:1203.2160 (2012)]

➡ **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}.

Charm R_{AA} vs N_{part} at low p_T



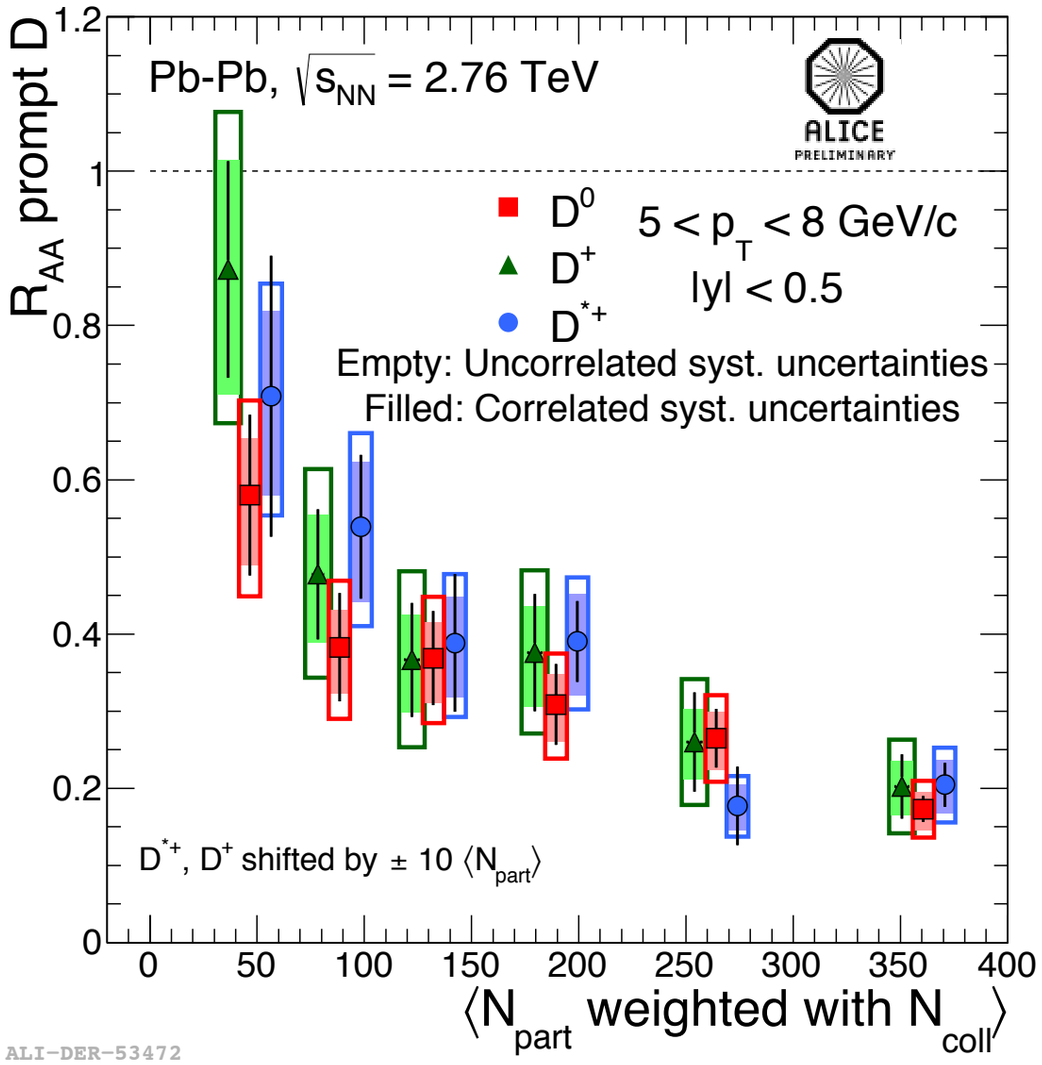


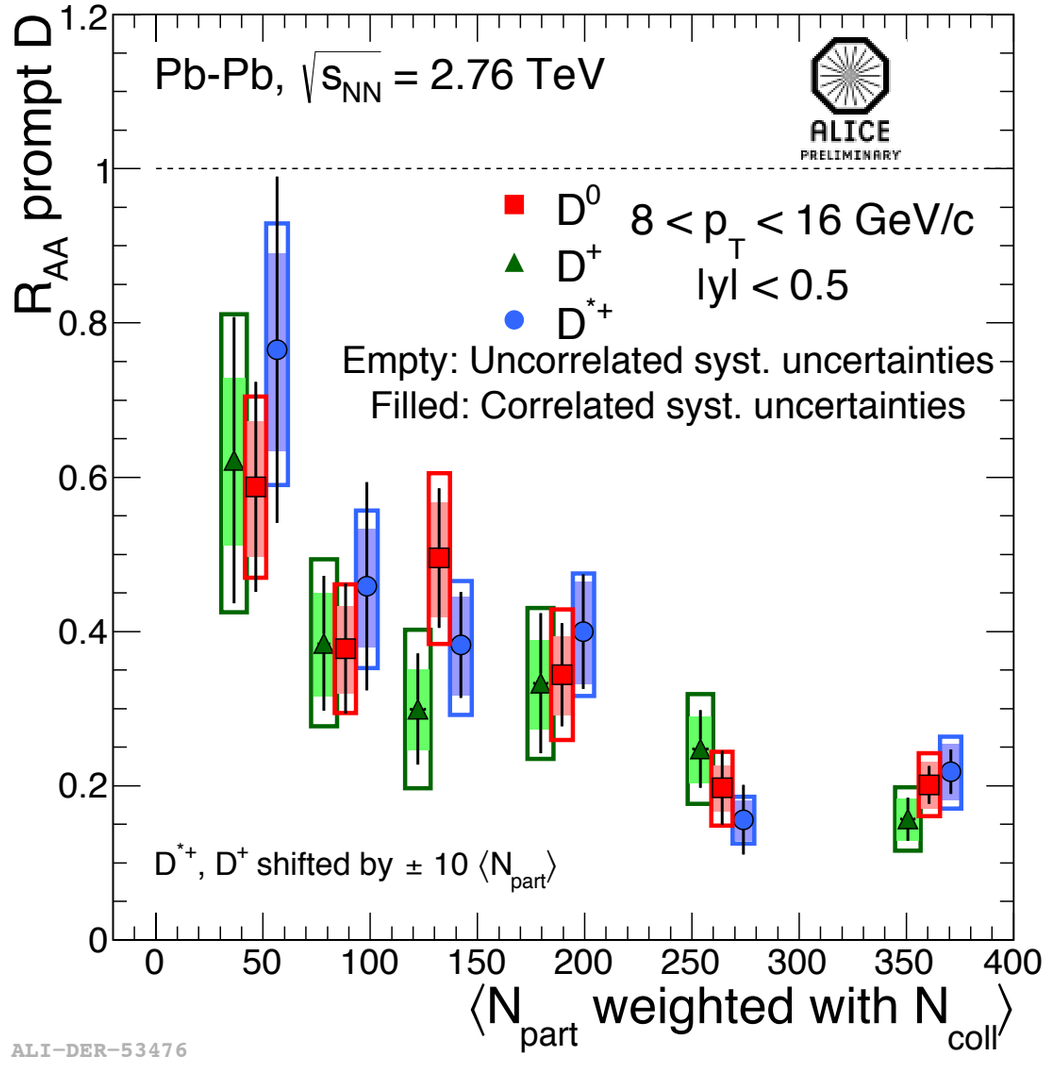
➡ **Different suppression pattern in the 2-3 and 3-5 GeV/c p_T intervals**

Systematic uncertainties:

- correlated in centrality classes: normalization, pp reference cross section
- uncorrelated: dominated by data systematics (i.e. cut variation efficiencies) and B feed-down ($R_{AA}^{\text{feed-down}}/R_{AA}^{\text{Prompt}}$ might depend on N_{part}).

Charm R_{AA} vs N_{part} at High p_T





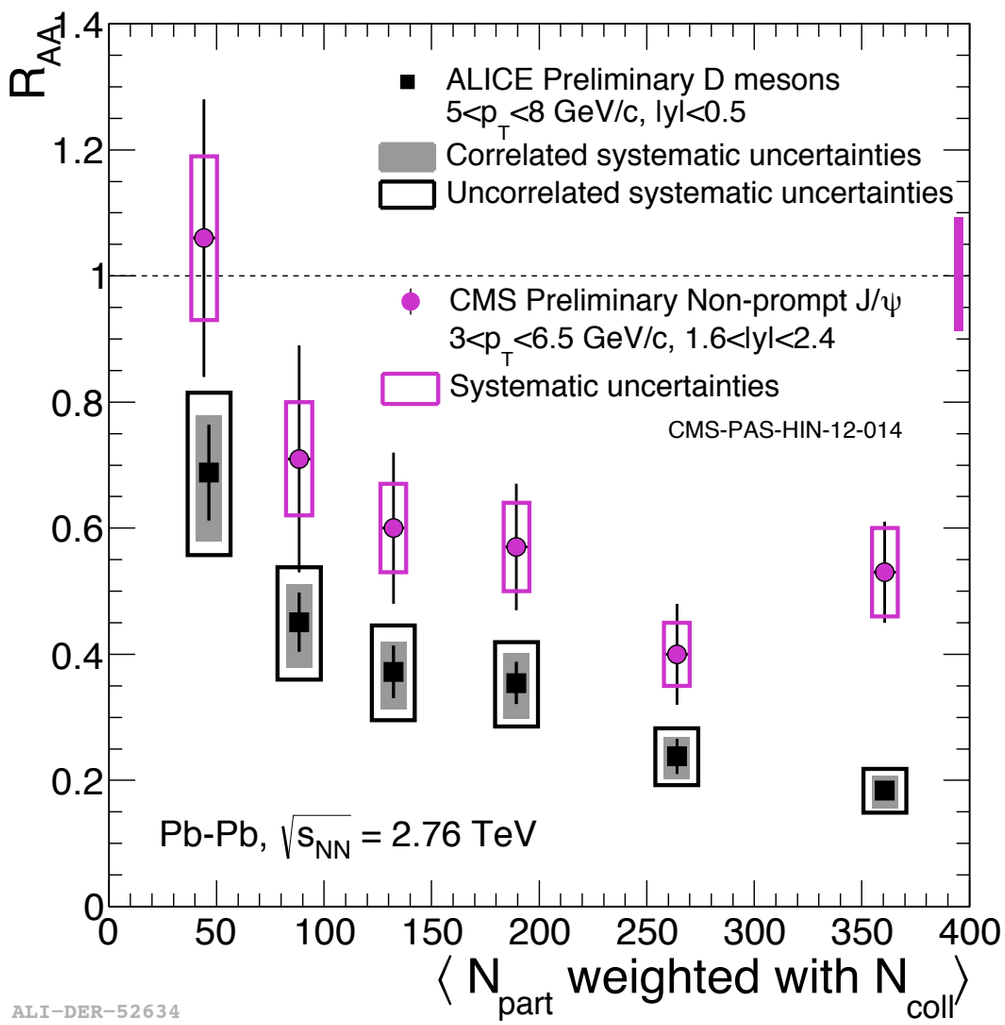
➡ **D^0, D^+, D^{*+} suppression increases in more central collisions in the 5-8 and 8-16 GeV/c p_T ranges**

Systematic uncertainties:

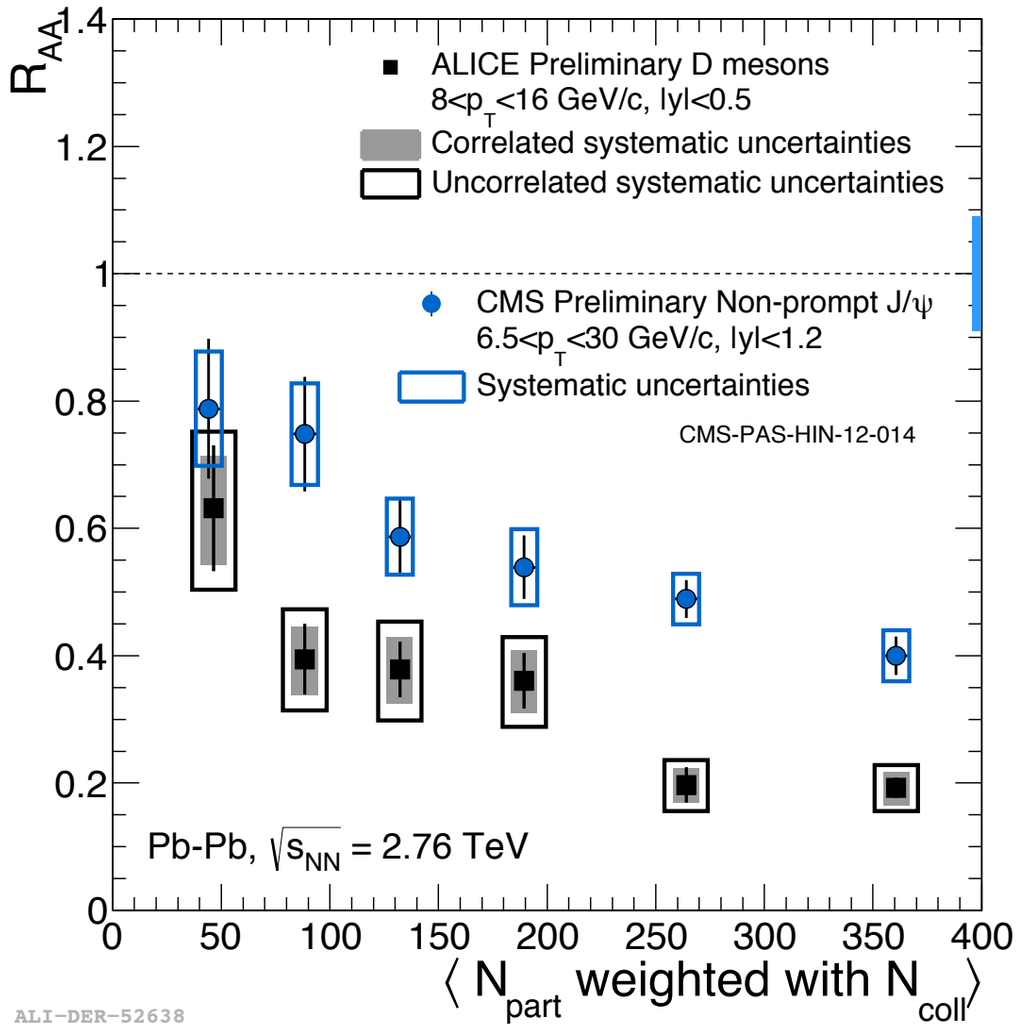
- correlated in centrality classes: normalization, pp reference cross section
- uncorrelated: dominated by data systematics (i.e. cut variation efficiencies) and B feed-down ($R_{AA}^{feed\text{-}down}/R_{AA}^{Prompt}$ might depend on N_{part}).

Comparison D and non-Prompt J/ψ

D, $|y|<0.5$, $5<p_T<8$ GeV/c
J/ψ, $1.6<|y|<2.4$, $3<p_T<6.5$ GeV/c



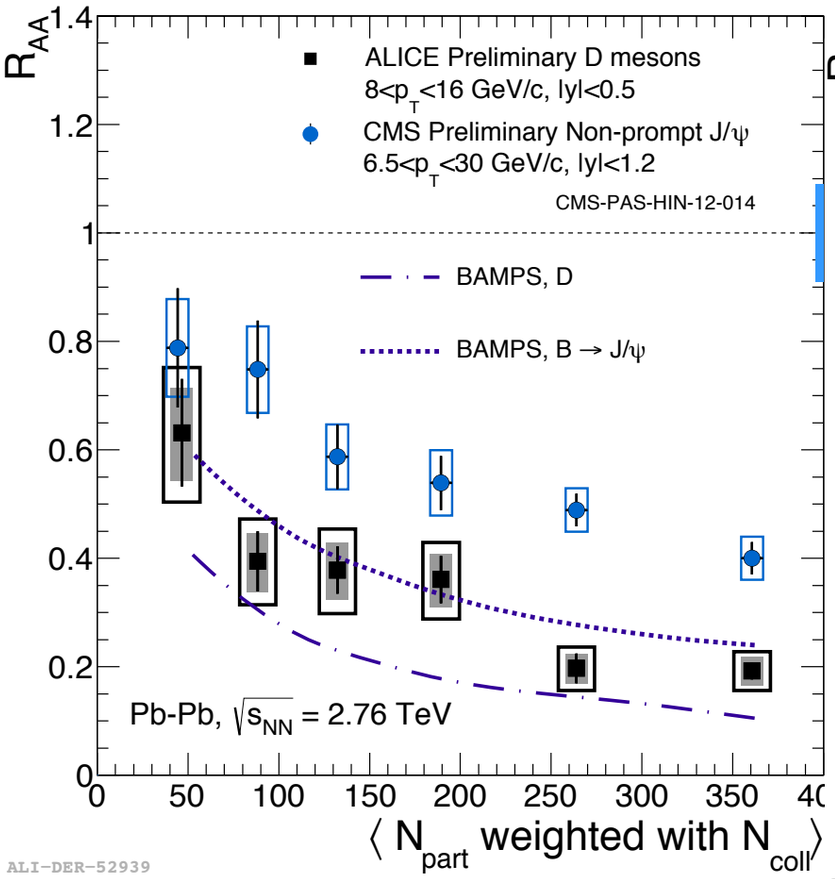
D, $|y|<0.5$, $8<p_T<16$ GeV/c
J/ψ, $|y|<1.2$, $6.5<p_T<30$ GeV/c

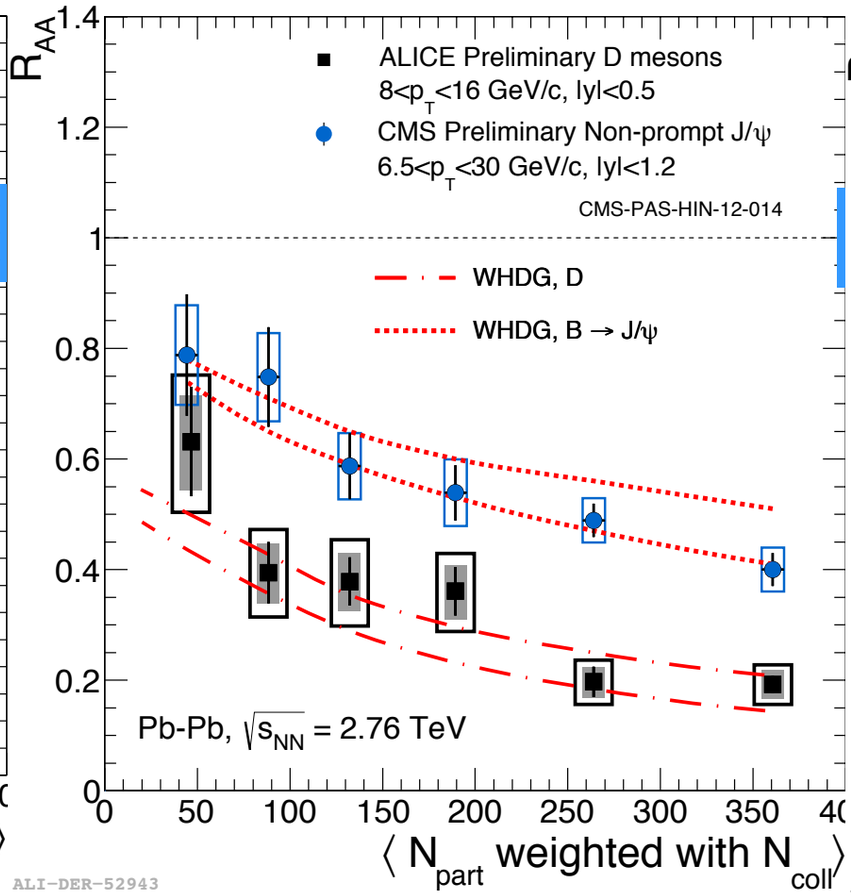


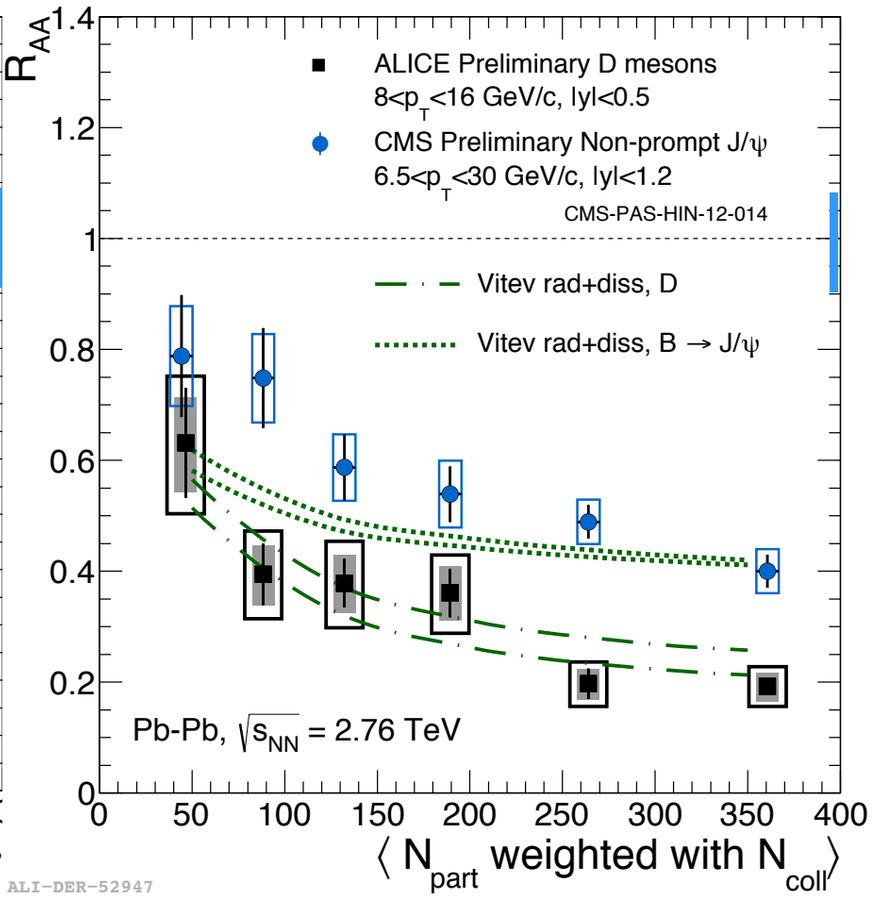
➡ **Indication of smaller suppression of beauty than charm in the most central collisions**

P_T interval chosen to have similar $\langle p_T \rangle$ for D and B mesons.
D meson $\langle p_T \rangle$~10.5 GeV/c (interval 8-16 GeV/c)
EvtGen simulations indicate that $\langle p_T(B) \rangle$ from non-prompt J/ψ is of 11.5 GeV/c (range 6.5-30 GeV/c)

Comparison D and non-Prompt J/ψ







BAMPS - collisional energy loss in an expanding medium

It tends to predict larger suppression for both D mesons and non-prompt J/ψ.

WHDG - collisional + radiative energy loss in anisotropic medium

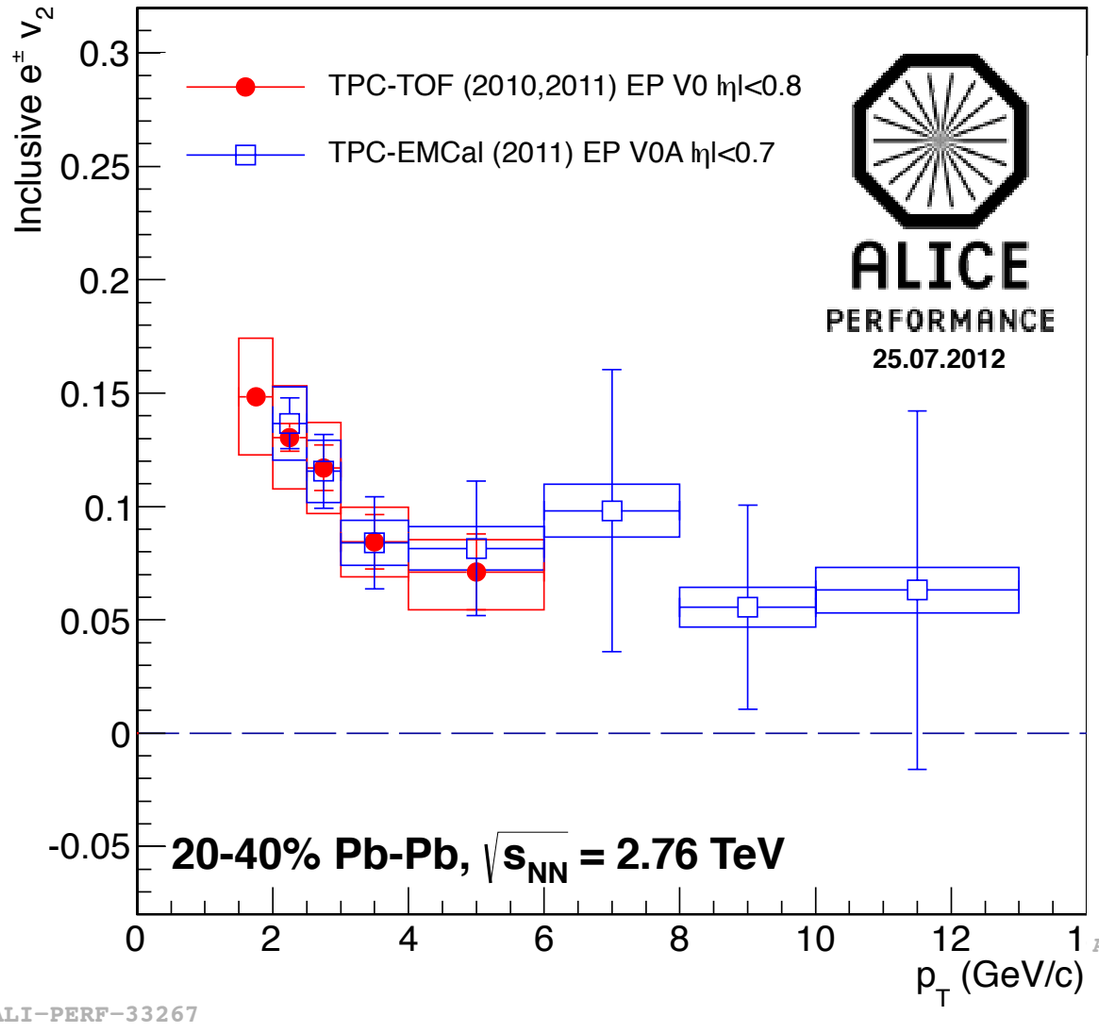
Good agreement with both measurements.

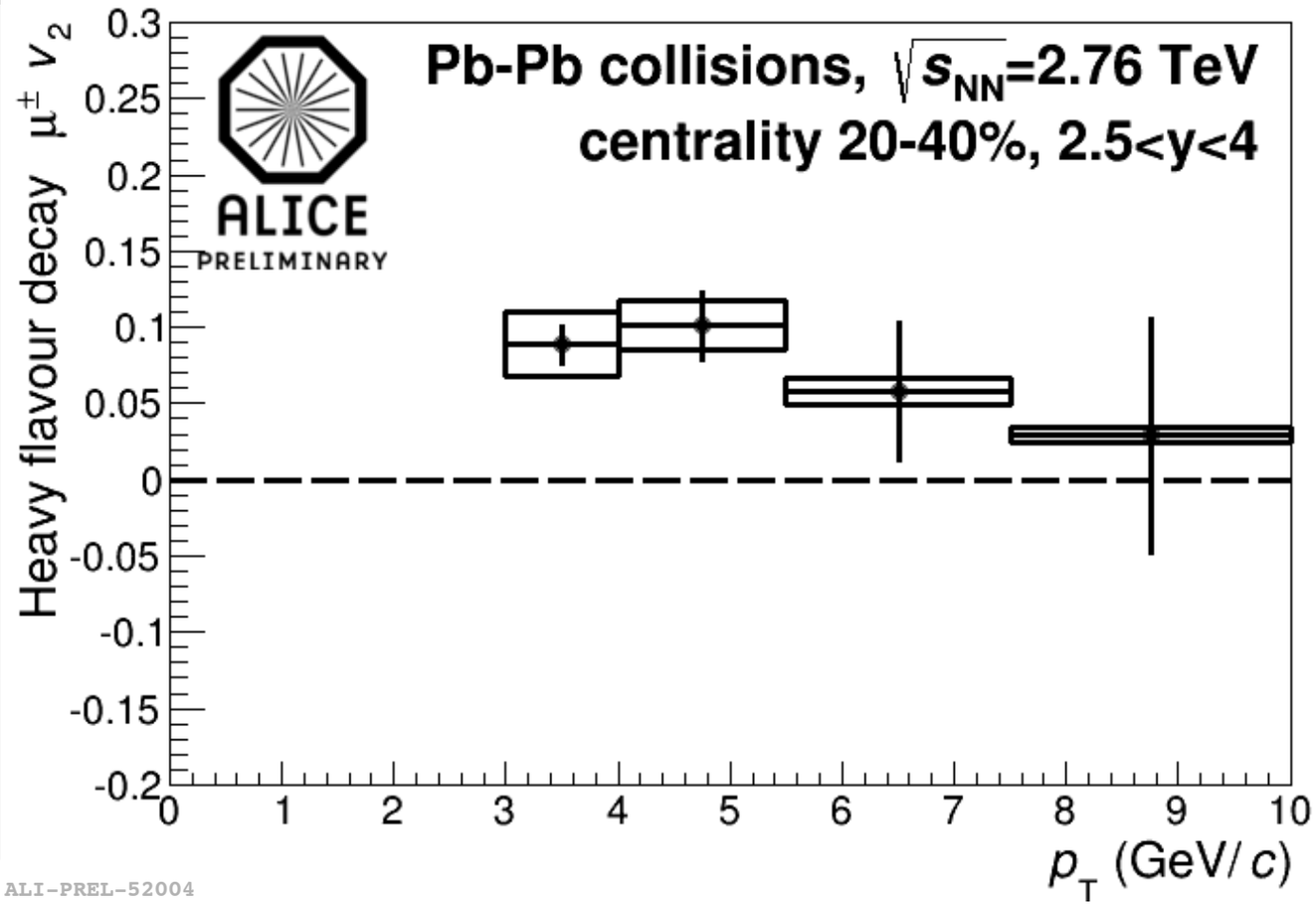
Vitev – radiative + dissociation

Relative good description, but underestimates non-prompt J/ψ for peripheral classes.

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
[Vitev: R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C80 (2009) 054902; Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713 (2012) 224]

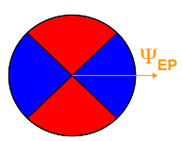
HF LEPTON v2





- Heavy flavor electron v_2>0 at low p_T (>3σ effect in 2<p_T<3 GeV/c)
- Heavy flavor muon v_2>0 at low p_T (>3σ effect in 3<p_T<5 GeV/c)

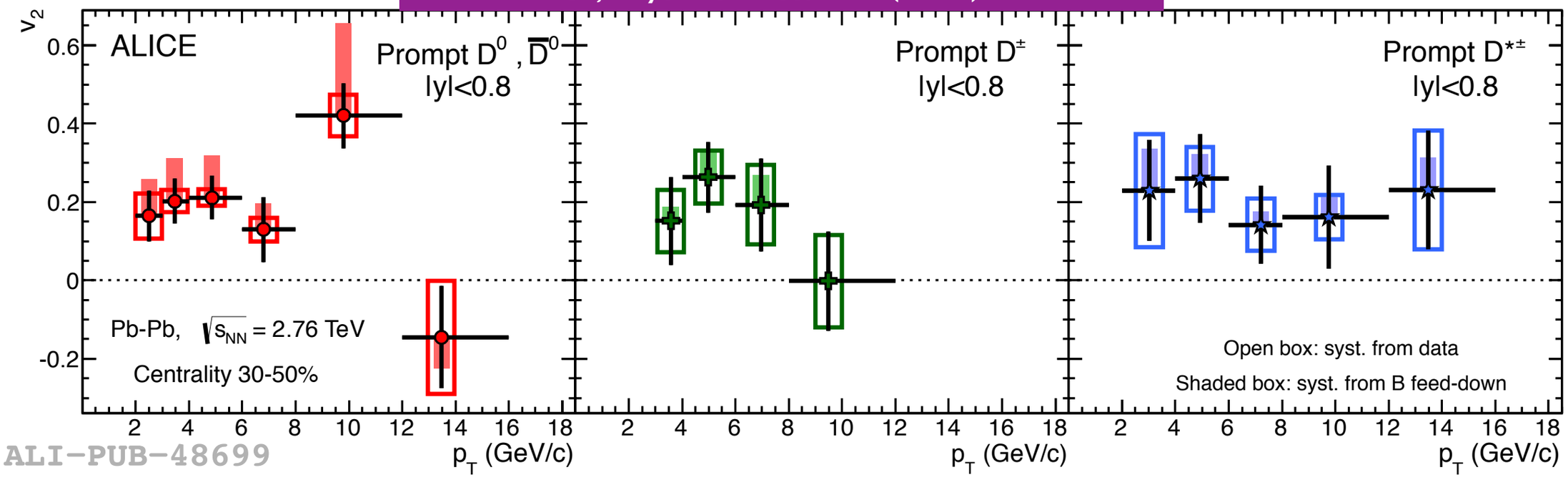
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$



R_2 : event plane resolution

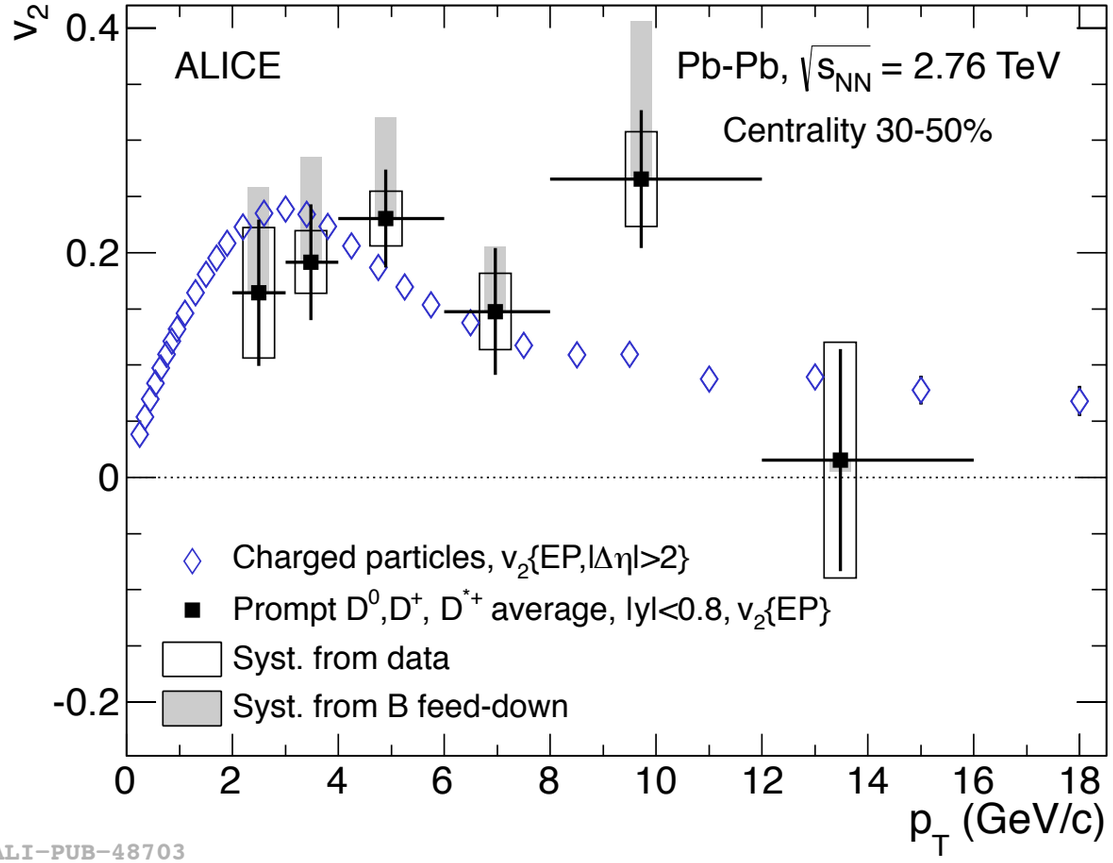
D meson v_2 in 30-50% PbPb Collisions

ALICE, Phys. Rev. Lett. 111 (2013) 102301



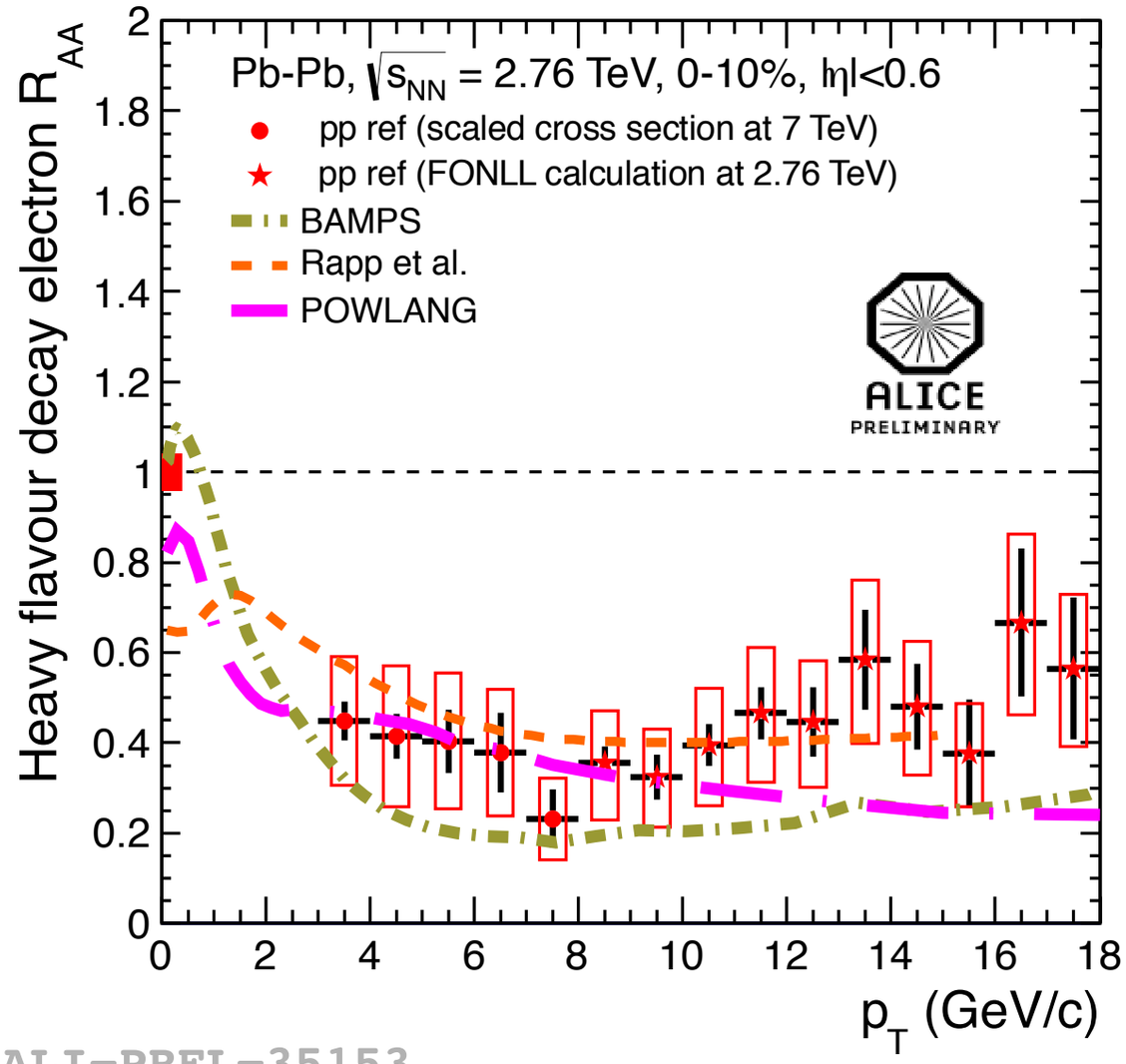
ALI-PUB-48699

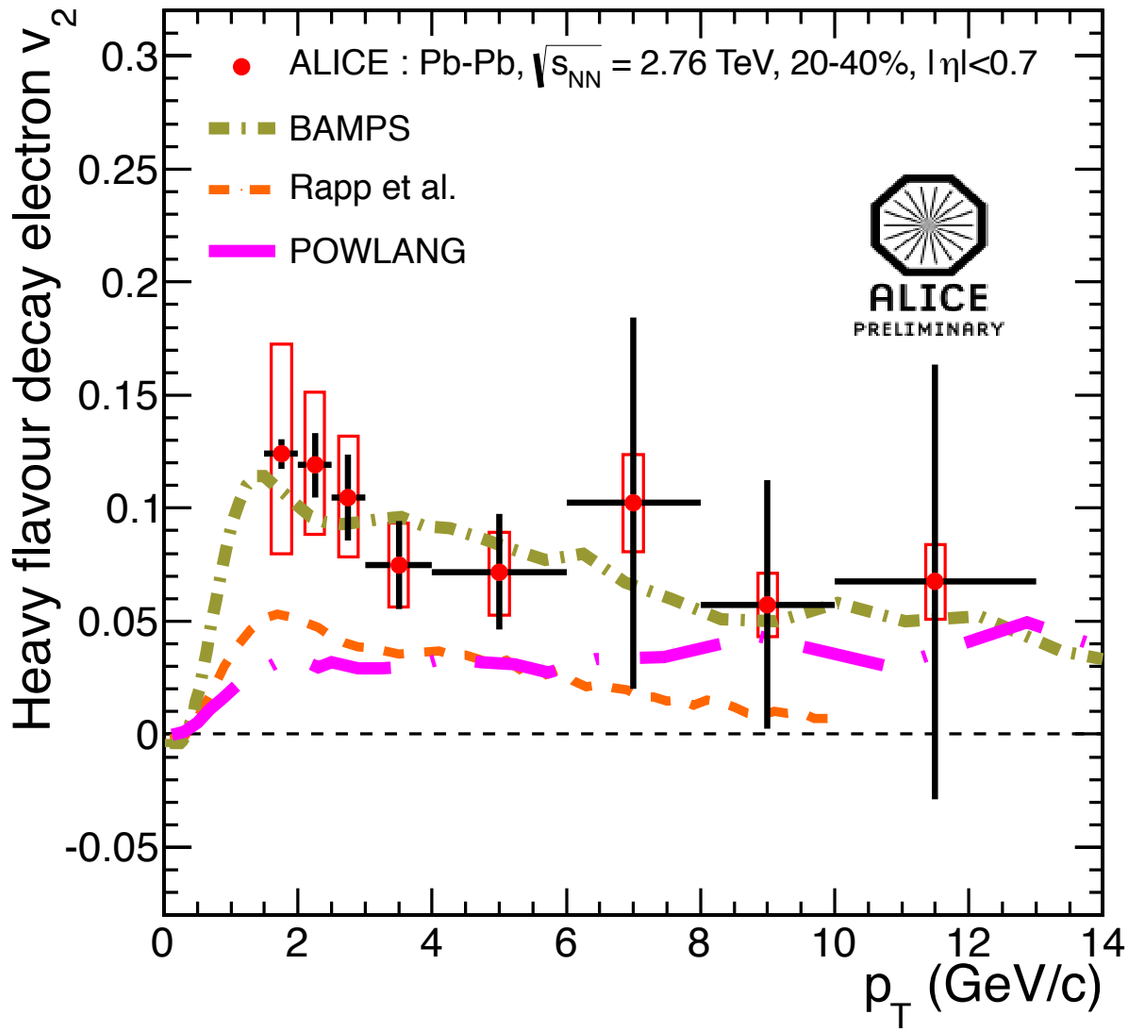
- Consistency among D meson species (D^0,D^+,D^{*+})
- D meson v_2 > 0 (~5σ effect in $2<p_T<6$ GeV/c)
- D meson v_2 similar to that of light particles: hint for collective motion of charm quarks at low p_T



ALI-PUB-48703

Heavy Flavor electron R_{AA} & v_2



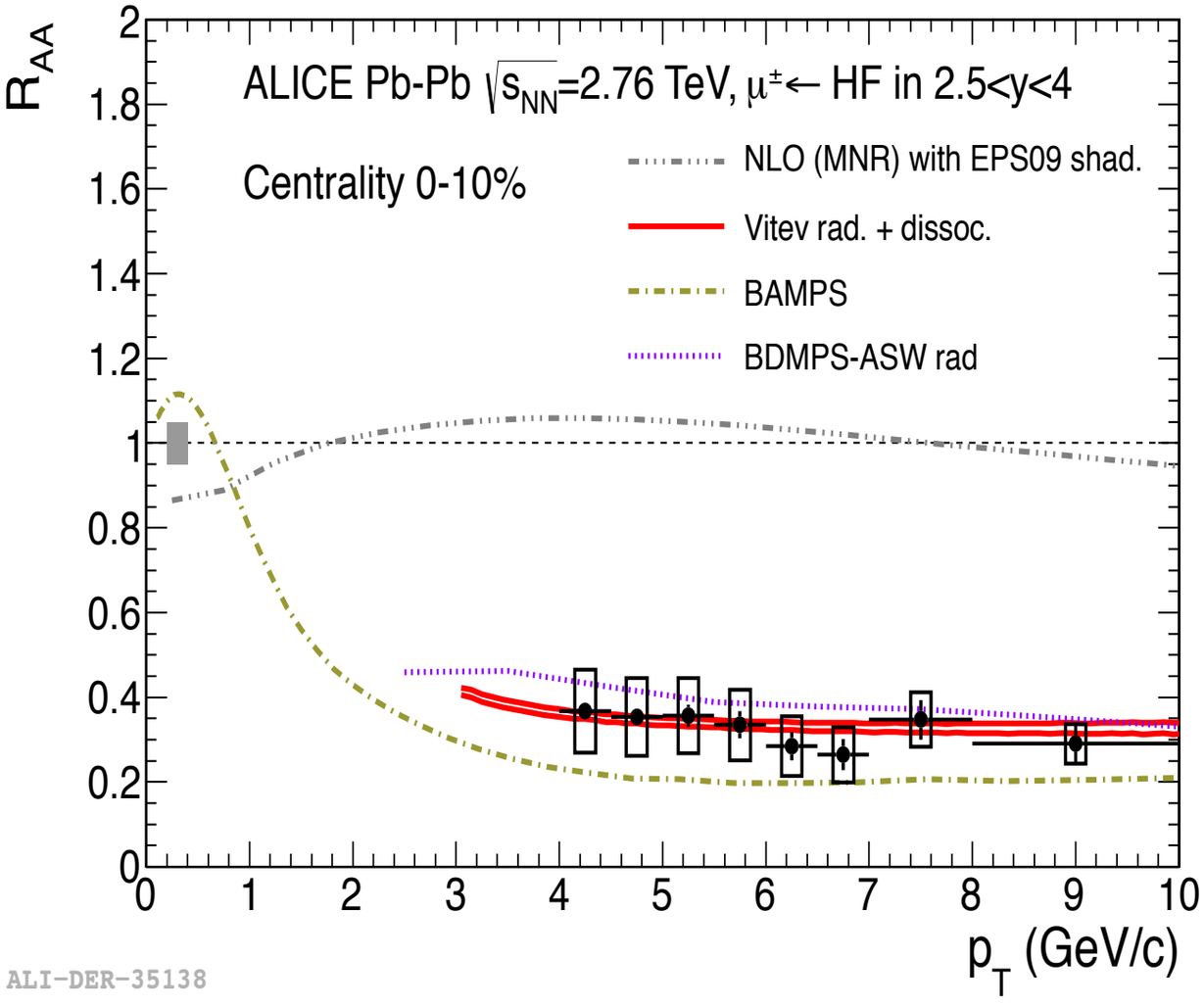


ALI-PREL-35153

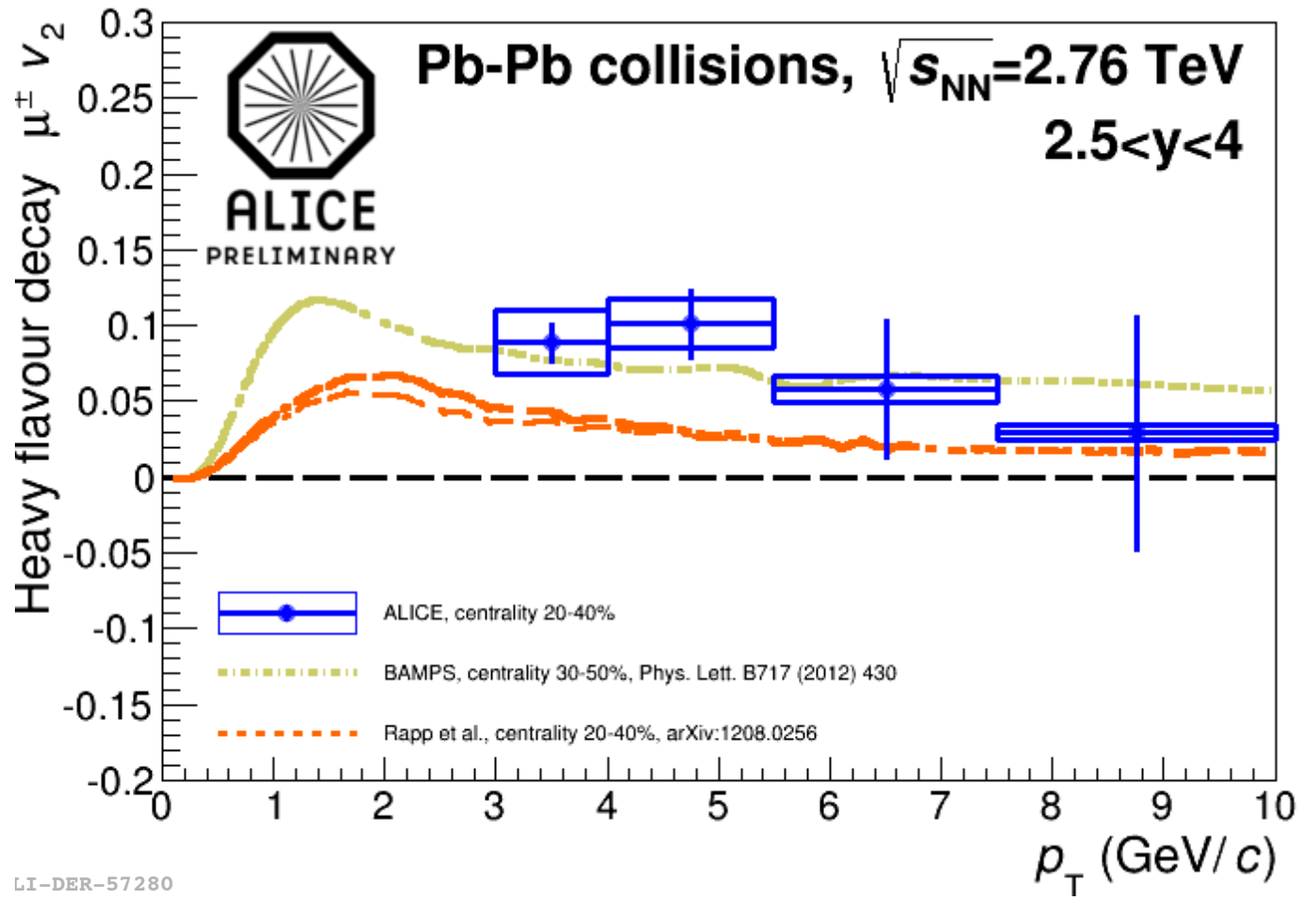
➡ **The simultaneous description of HFe R_{AA} and v_2 is challenging**

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]

Heavy Flavor Muon R_{AA} & v_2



ALI-DER-35138

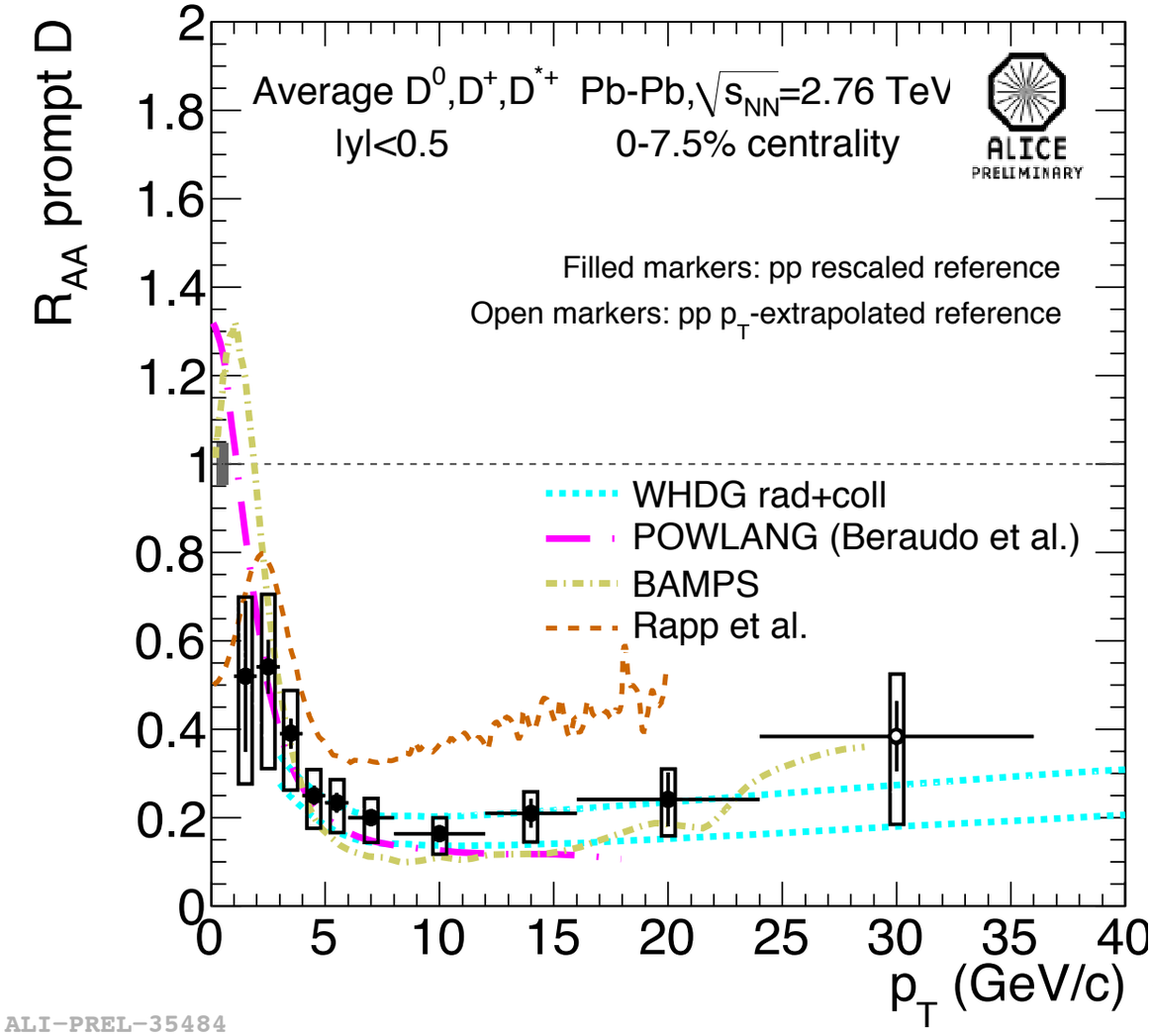


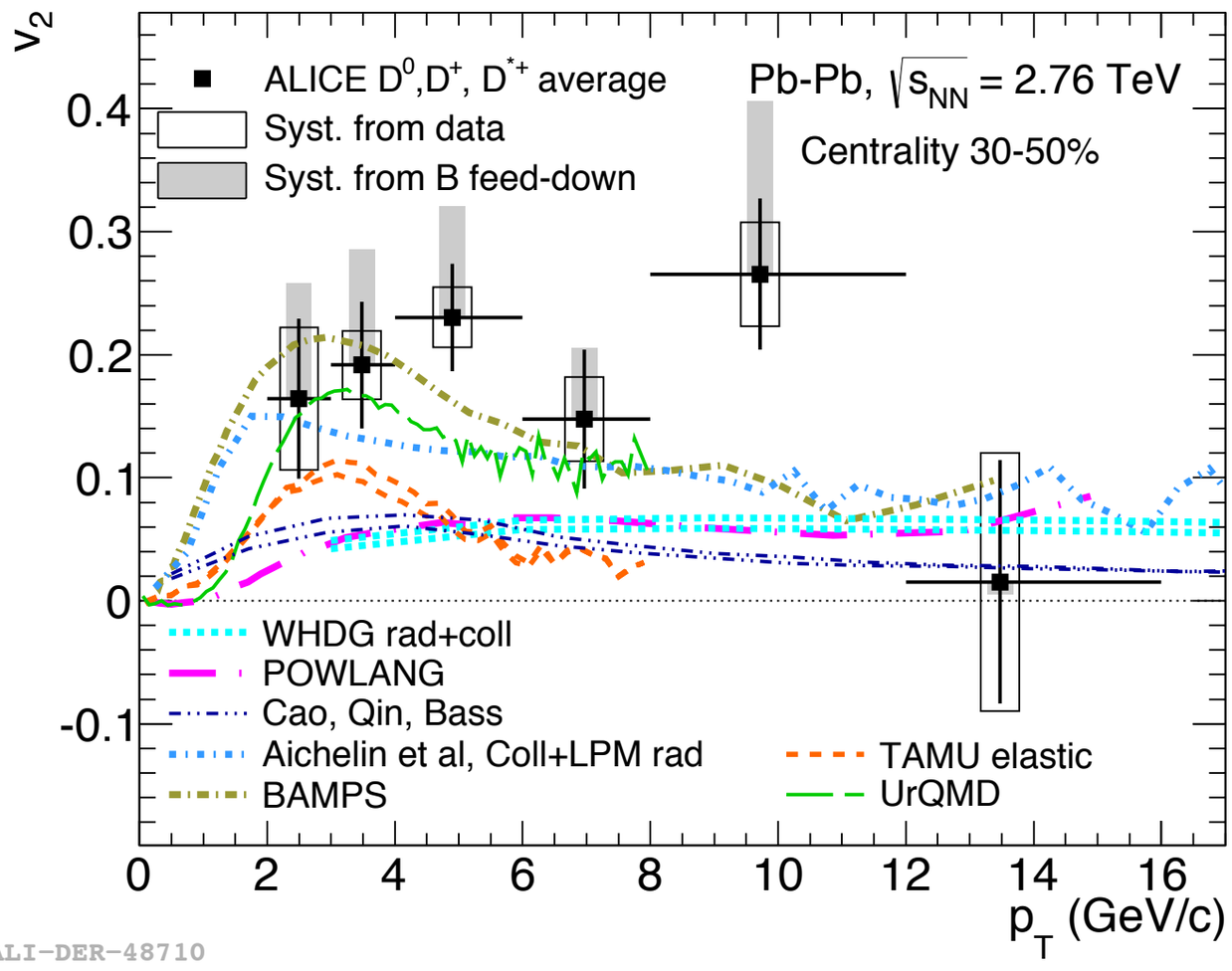
LI-DER-57280

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

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]

D Meson R_{AA} & v_2



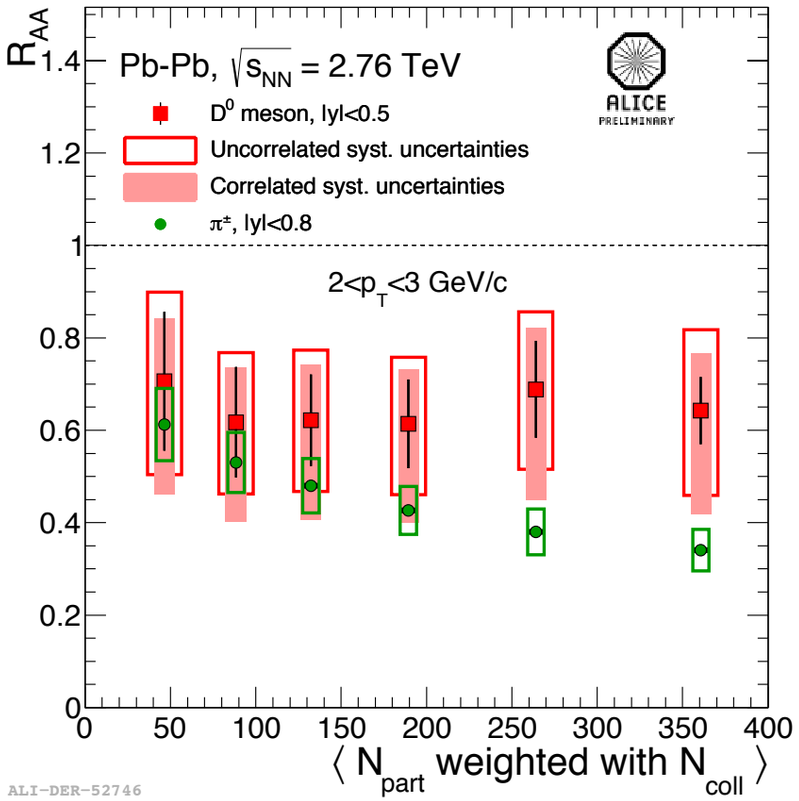


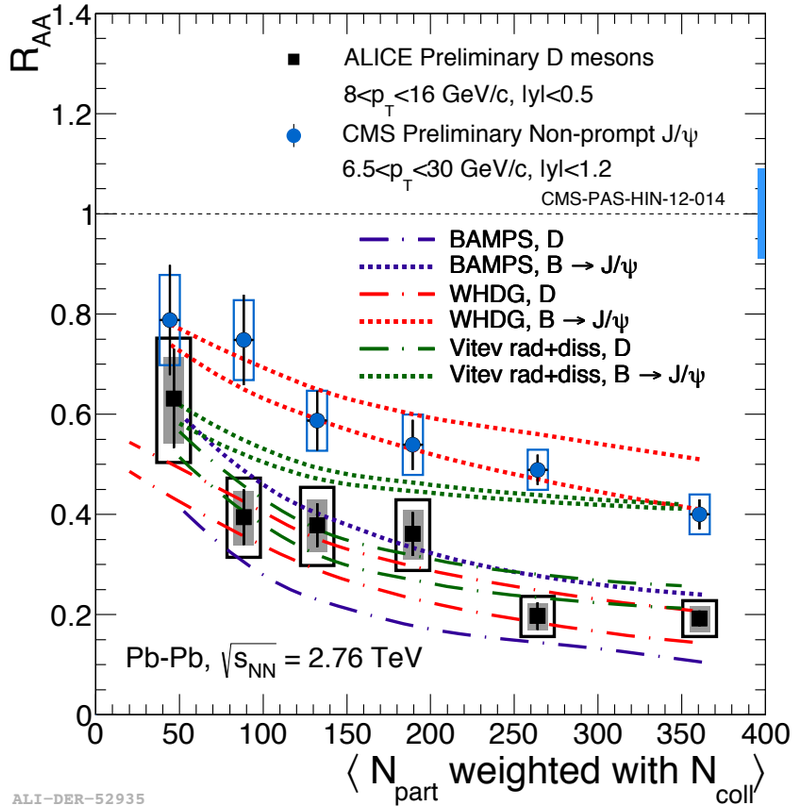
➡ **The simultaneous description of D mesons R_{AA} and v_2 is challenging**

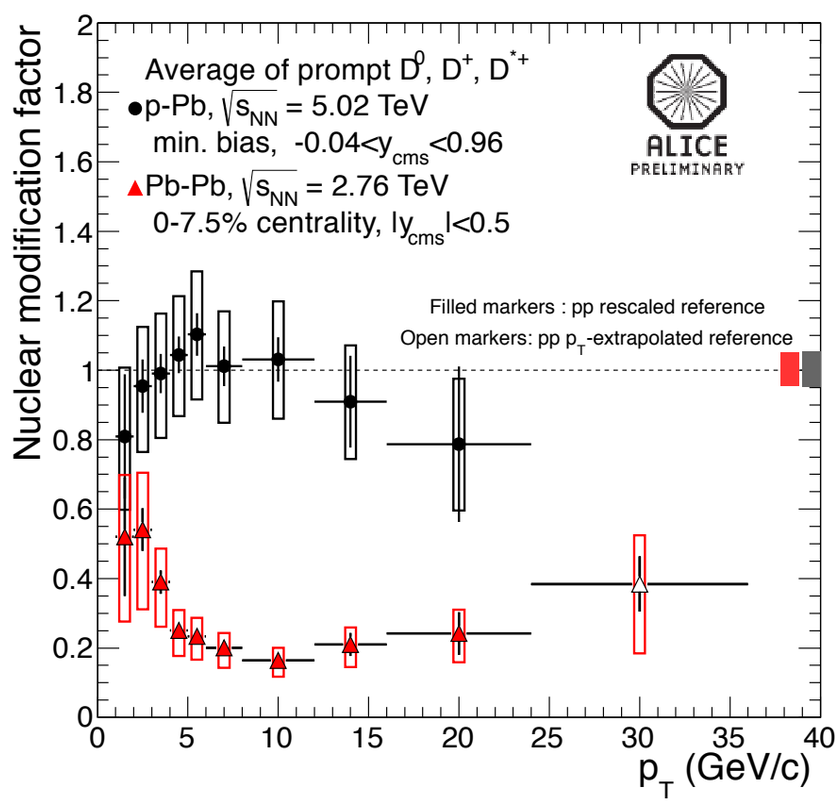
[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]
[UrQMD: arXiv:1211.6912, J. Phys. Conf. Ser. 426, 012032 (2013)]
[TAMU: Phys. Rev. C 86 (2012) 014903]
[WHDG: J. Phys. G 38 (2011) 124114]
[Aichelin et al., Phys. Rev. C 79 (2009) 044906, J. Phys. G 37 (2010) 094019]

Summary

- 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 D's in central events
- This suppression can not be explained by only CNM for p_T>4 GeV/c
- Azimuthal anisotropy of HFe, HFm and charmed mesons is observed
  - v_2>0 for p_T ~ 3 GeV/c at LHC,
    hint of collective motion of charm quarks at low p_T
- HQ energy loss models reproduce reasonably well heavy flavor R_{AA} measurements. Challenging simultaneous description of R_{AA} and v_2.



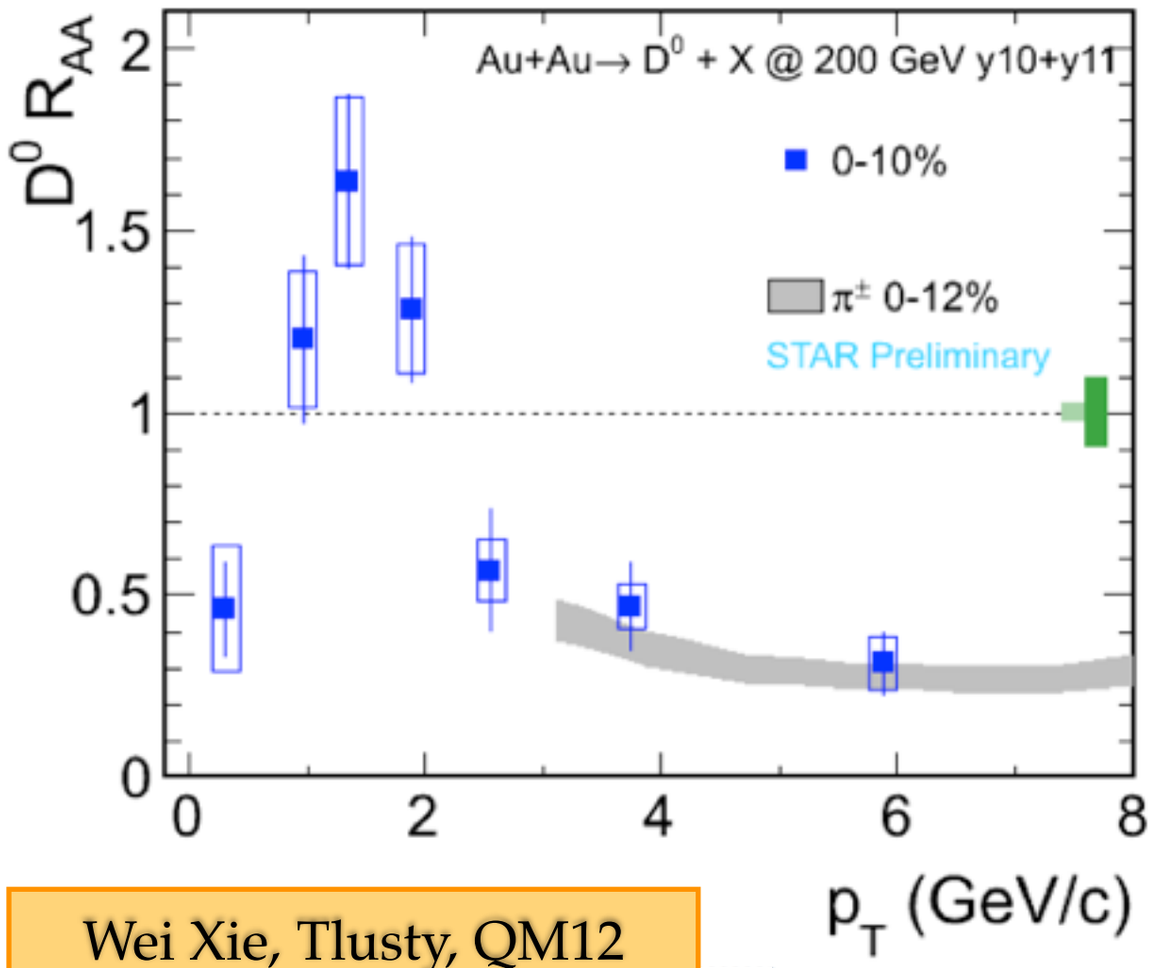




Backup

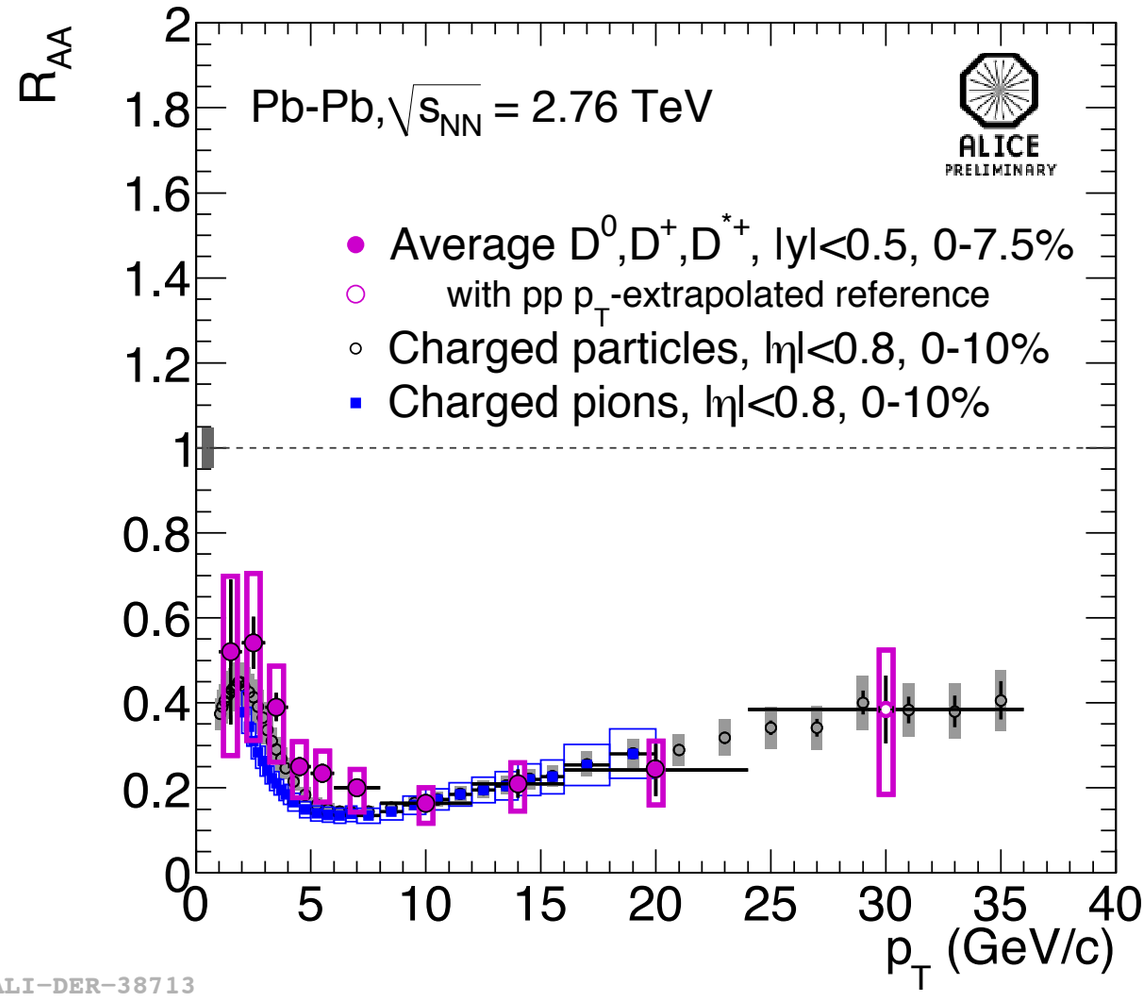
D MESON R_{AA} AT RHIC AND LHC

AuAu 200 GeV



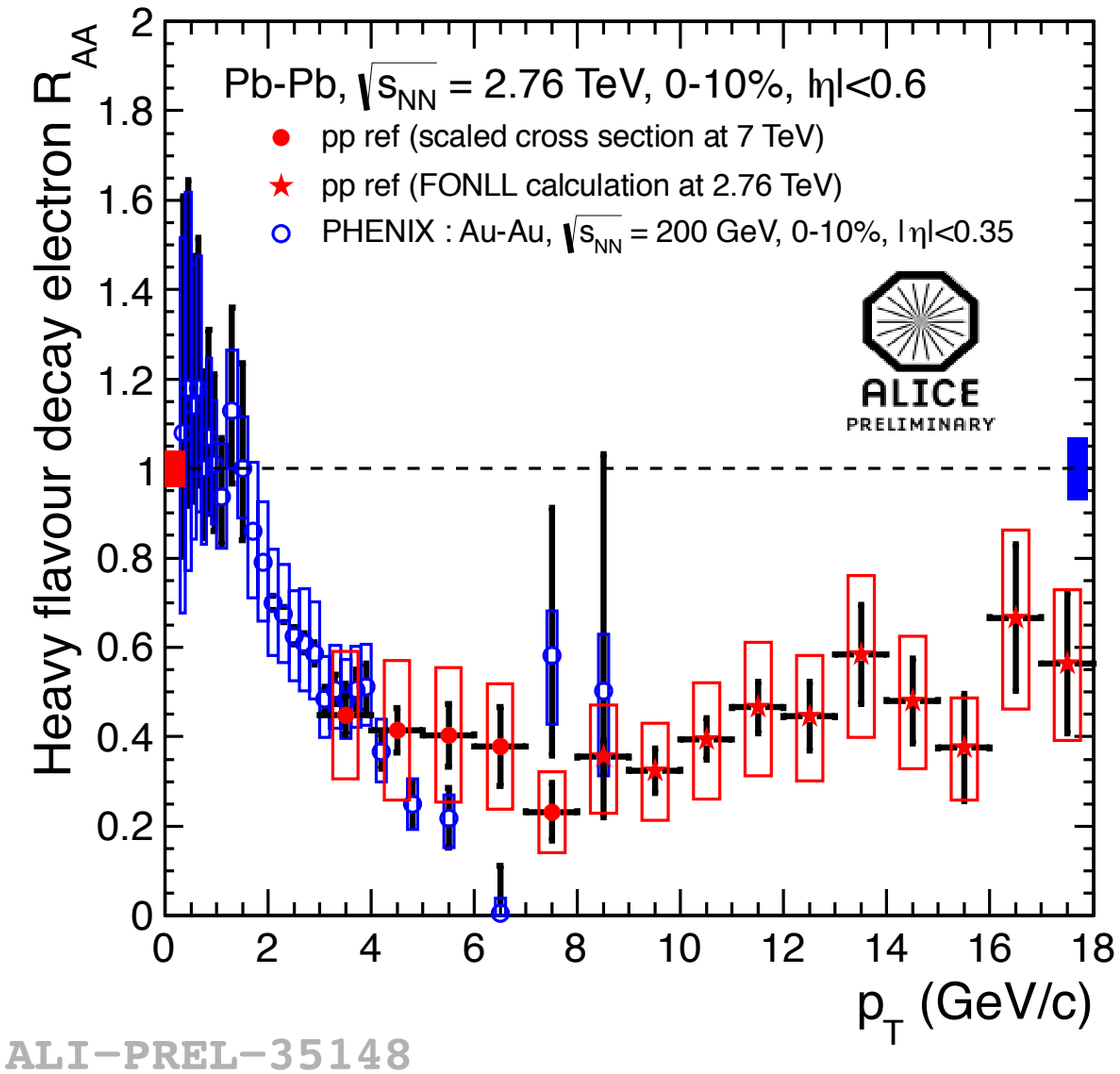
Wei Xie, Tlusty, QM12

PbPb 2.76 TeV



- Inclusive D^0 mesons (c+b)
- Prompt D^0 mesons (c)

HFE R_{AA} AT RHIC AND LHC



AuAu 200 GeV

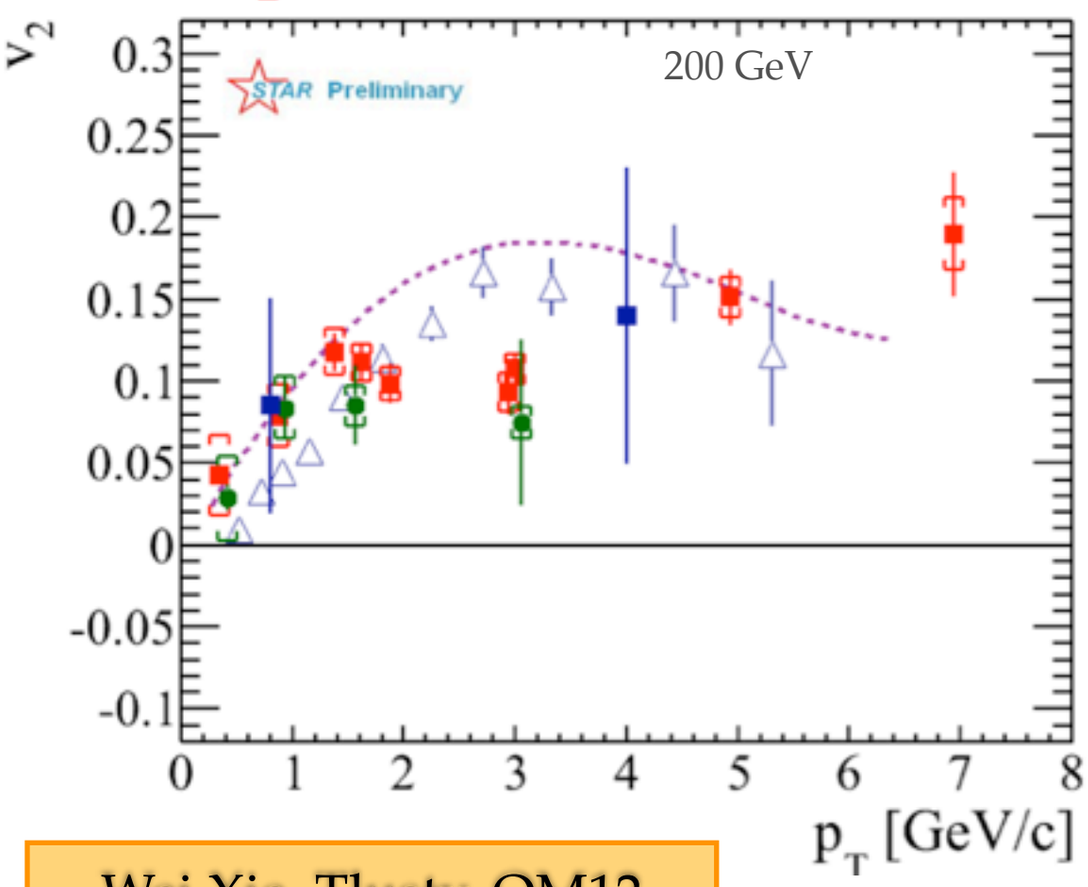
PbPb 2.76 TeV

[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)**

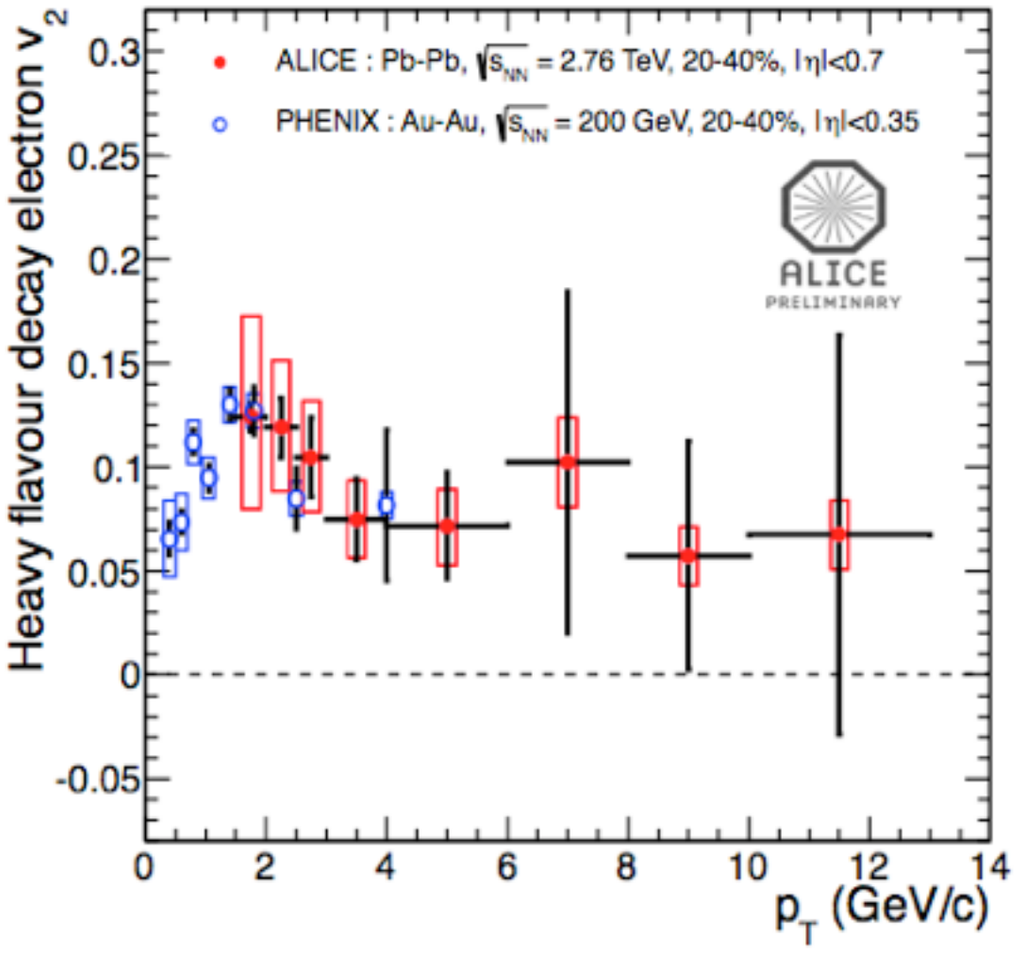
✳ Caveat: c/b contribution to the HF electron spectra may differ at RHIC and LHC

Heavy Flavor Electron v_2 vs energy



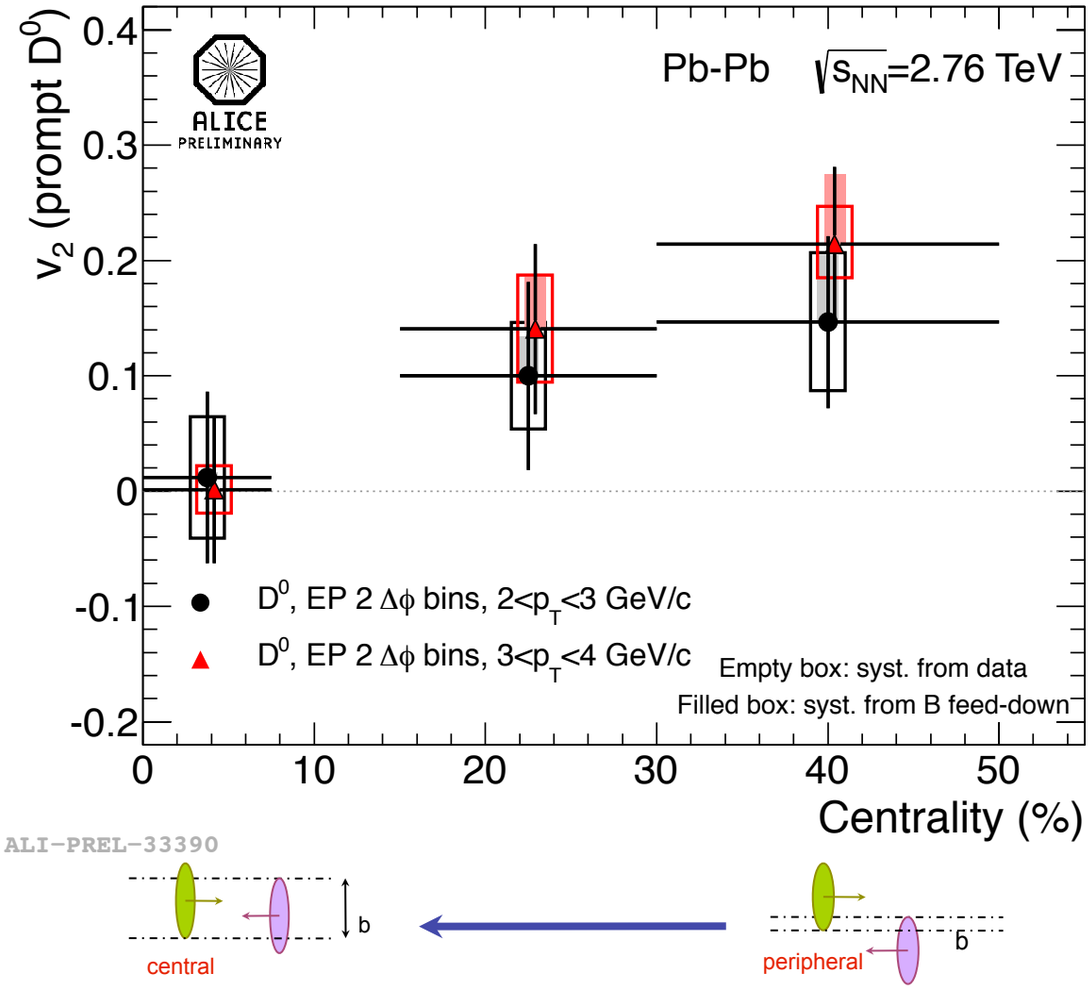
Wei Xie, Tlusty, QM12

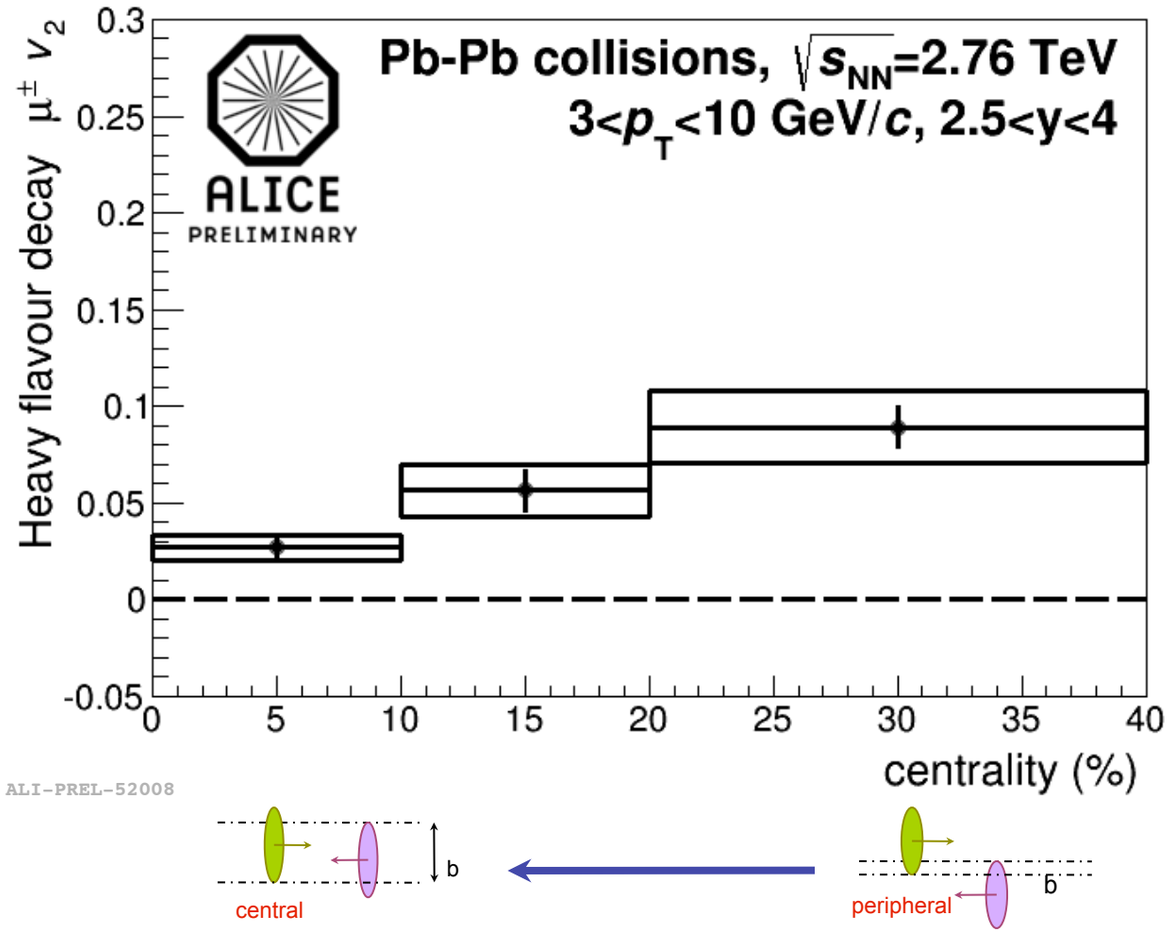
AuAu 200GeV



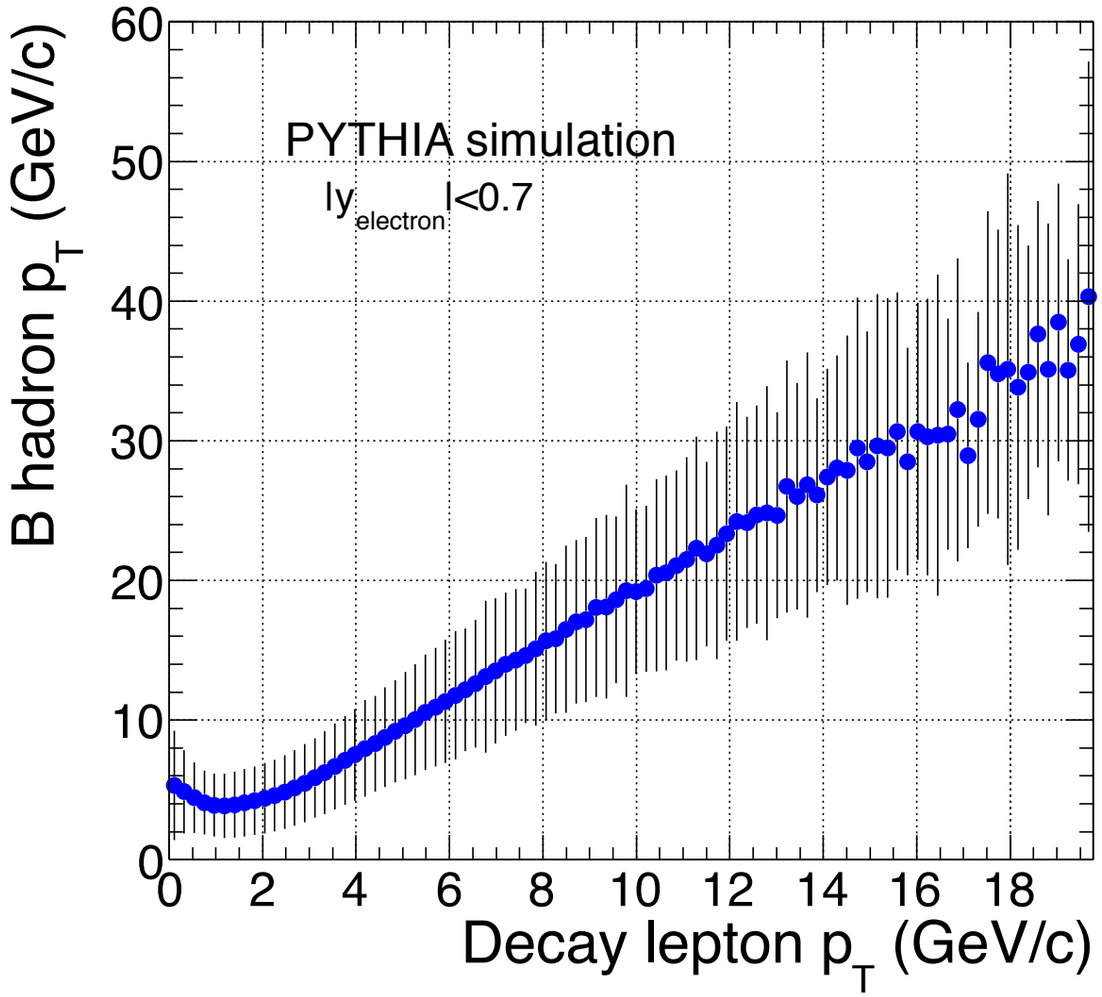
- Non-photonic / HF electron v_2 :
  - At 39 and 62 GeV consistent with zero within uncertainties
  - **At 200 GeV, $v_2>0$ for $p_T > 3$ GeV/c**
  - **At 2.76 TeV, $v_2>0$ at low p_T (>3σ effect in $2<p_T<3$ GeV/c)**

v_2 CENTRALITY DEPENDENCE





➡ **Hint of centrality dependence of heavy flavor v_2 at LHC**


PYTHIA simulation
|y_electron|<0.7
B hadron p_T (GeV/c)
Decay lepton p_T (GeV/c)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18