



ALICE

LHCP 2014

The Second Annual Conference  
on Large Hadron Collider Physics



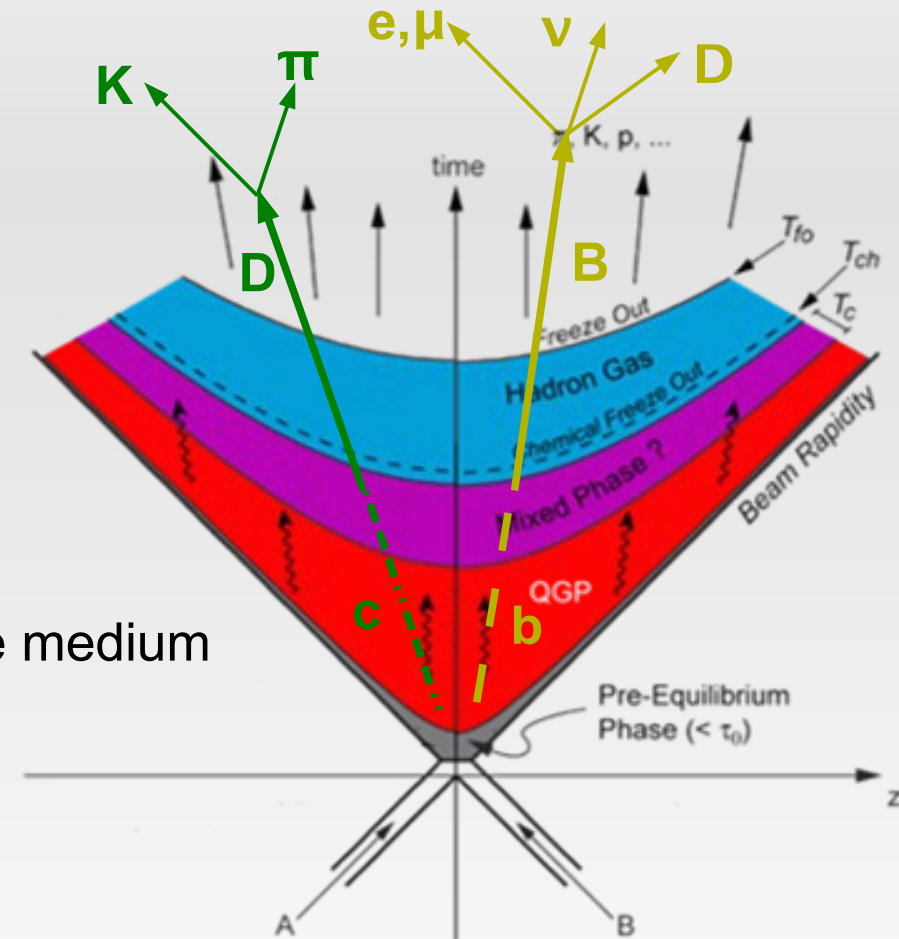
# Measurements of heavy-flavour production and azimuthal anisotropy in Pb-Pb collisions with the ALICE detector

- D mesons via hadronic decay channels
- Electrons from heavy-flavour hadron decays
- Muons from heavy-flavour hadron decays

Andrea Dubla (Utrecht University)  
for the ALICE Collaboration

## Why heavy flavours in Pb-Pb?

- **Charm and beauty** quarks are produced in hard scattering processes (large  $Q^2$ ) in the early stage of the collision
- They experience the full evolution of the system → sensitive probes of the properties of the hot and dense QCD matter (QGP)
- Expected to **lose energy** while traversing the medium
- Do heavy quarks participate in the **collective expansion** of the medium?
- **perturbative QCD** describes the **cross sections** measured in pp collisions. (talk Elena Bruna: HF1 11.39)



# ALICE detector

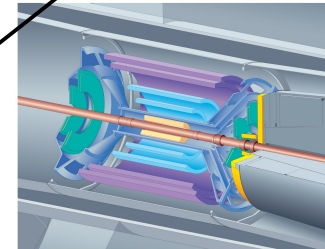


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**EMCal:** trigger,  
electron ID

**ITS:** tracking,  
vertexing and PID via  
 $dE/dx$

**VZERO:** trigger,  
centrality and event  
plane determination

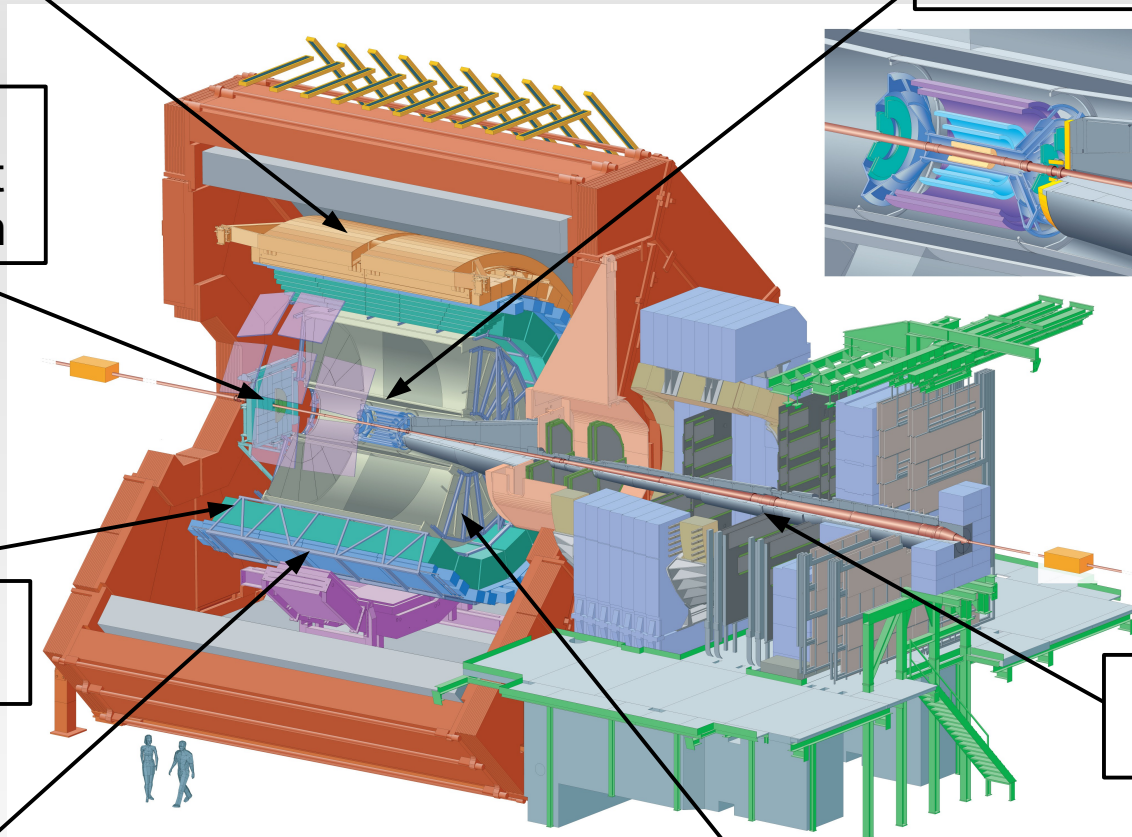


**TRD:** tracking,  
electron ID

**Forward muon  
spectrometer**

**TOF:** PID via time of  
flight

**TPC:** tracking, PID  
via  $dE/dx$ , event  
plane determination

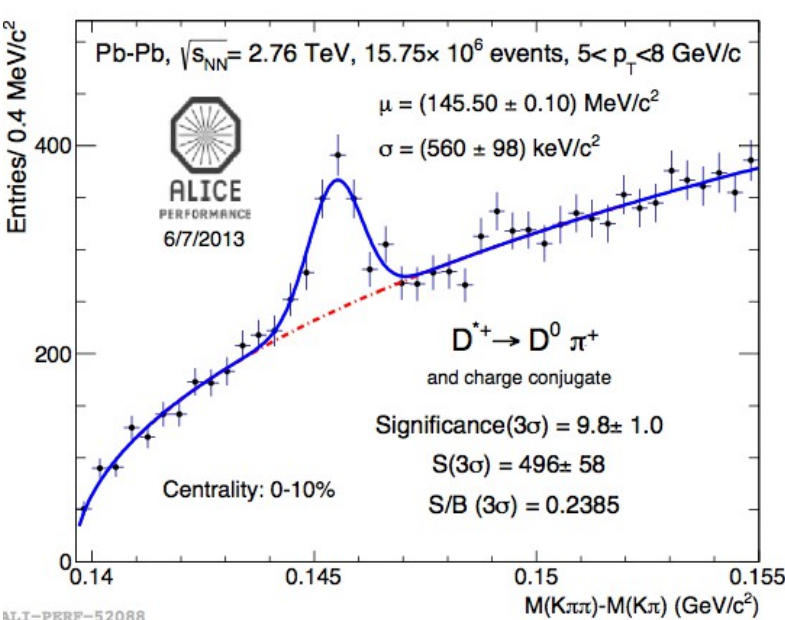
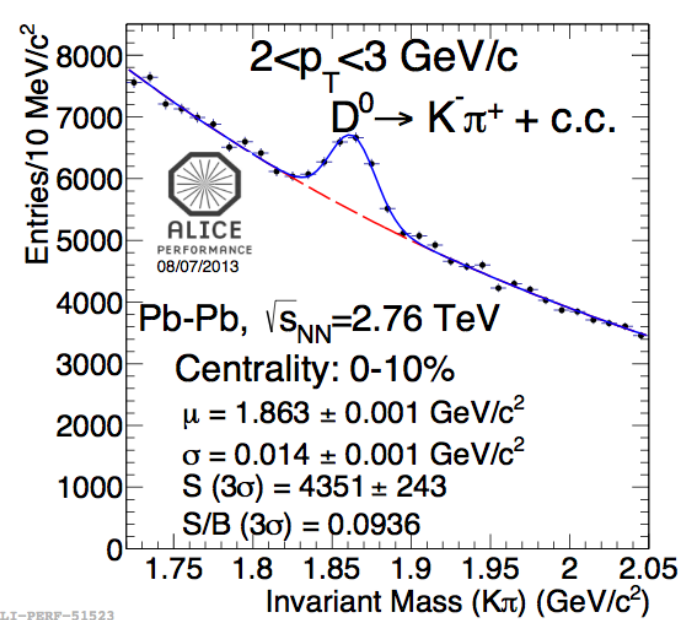
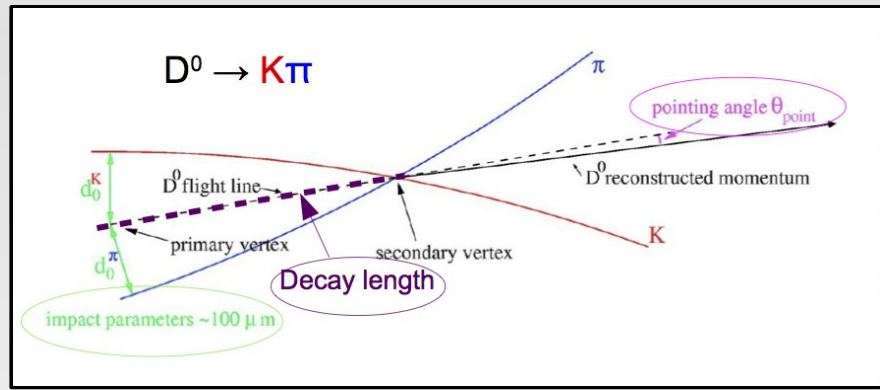


# D mesons via hadronic decay channels



- Analysis based on reconstruction of decay vertex topologies displaced from the primary vertex
- TPC and TOF used to identify  $\pi$  and K to reduce the combinatorial background.
- Signal extraction through invariant mass analysis.

$D^0 \rightarrow K^- \pi^+$	$c\tau = 123 \mu\text{m}$	$BR = 3.88\%$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$c\tau = 312 \mu\text{m}$	$BR = 9.13\%$
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$		$BR = 2.63\%$
$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$	$c\tau = 150 \mu\text{m}$	$BR = 2.28\%$

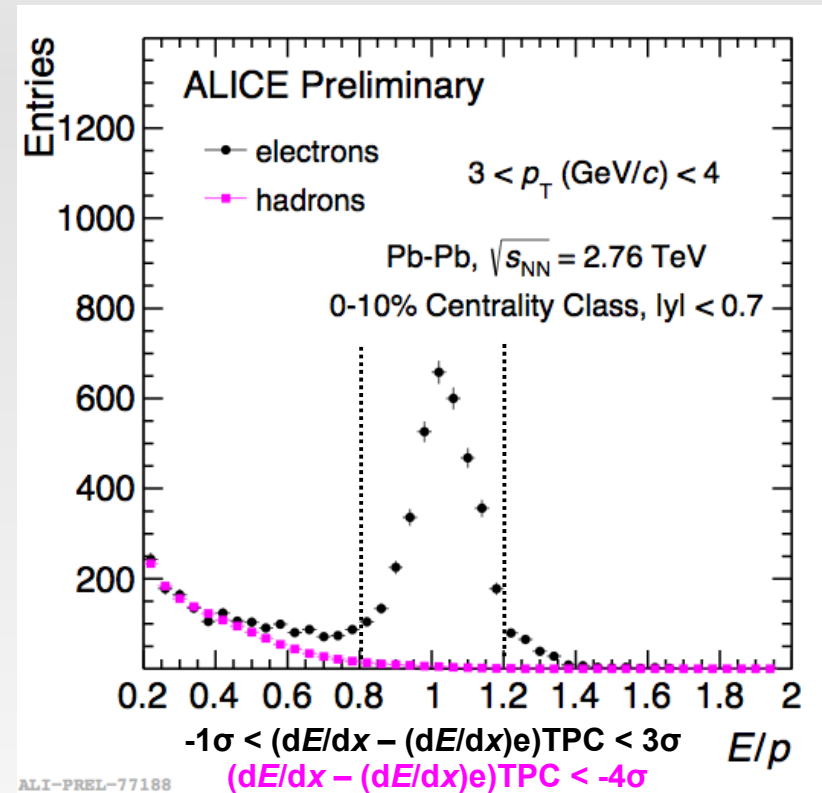
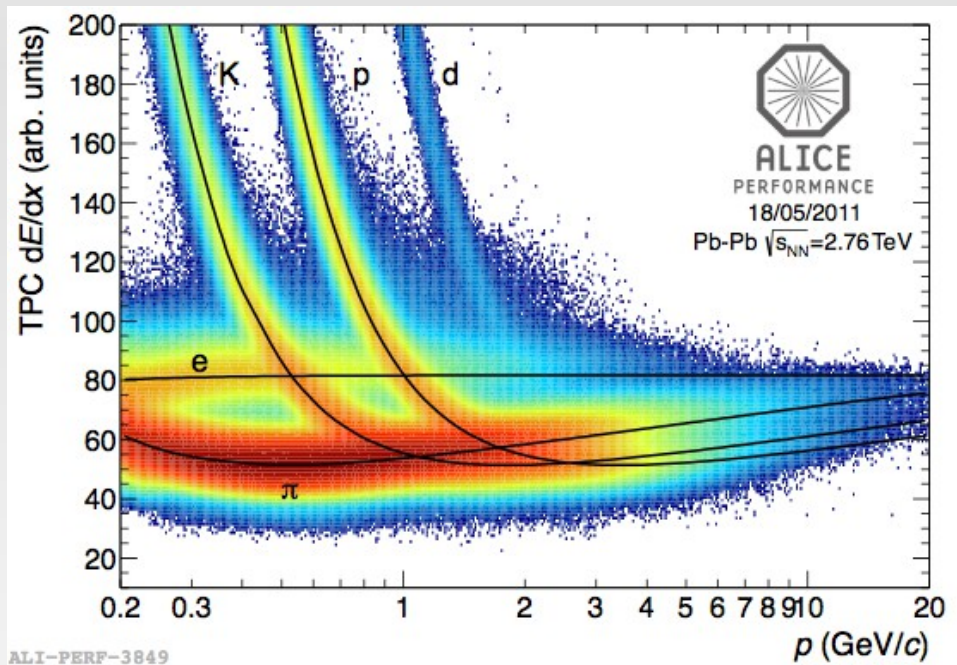


$|y| < 0.5$

# Electrons from heavy-flavour hadron decays



- **Low- $p_T$**  electrons ( $p_T < 3 \text{ GeV}/c$ ): PID via TPC  $dE/dx$  complemented with TOF and/or ITS.
- **High- $p_T$**  electrons ( $p_T > 3 \text{ GeV}/c$ ): PID using TPC, EMCal and/or TRD.



## Main background sources:

- $\gamma$  conversions
- $\pi^0$  and  $\eta$  Dalitz decays

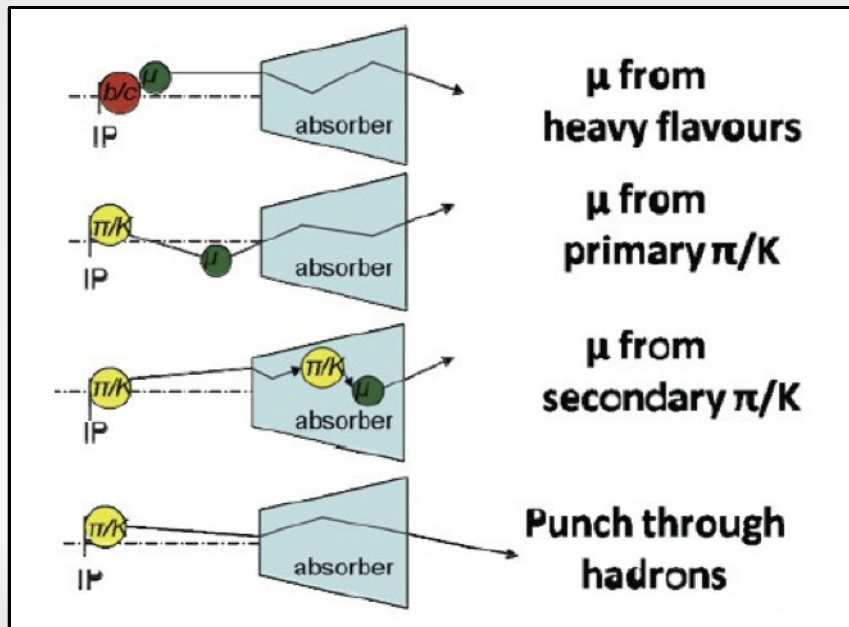
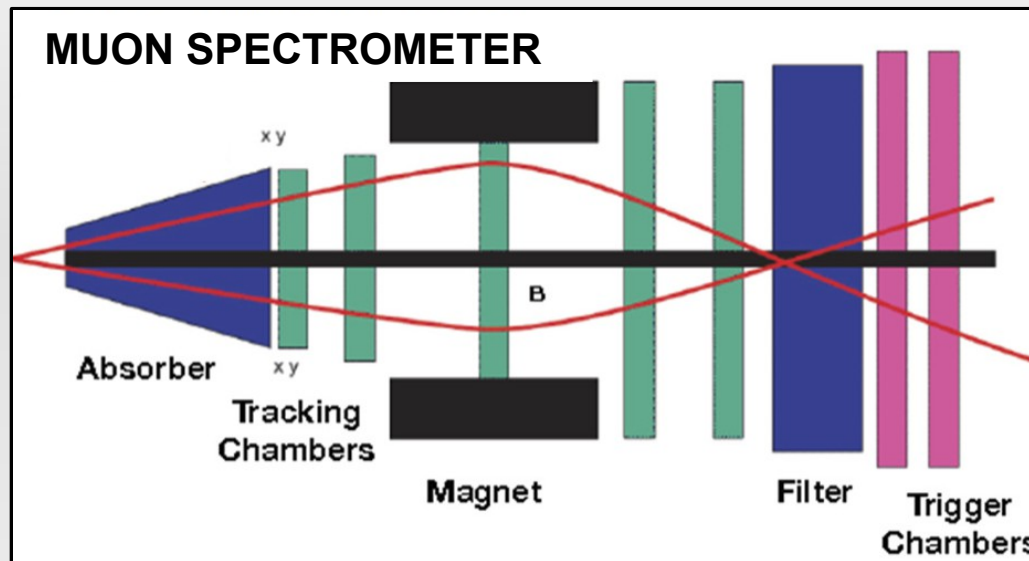
$|y| < 0.7$

## Background subtraction:

- Measured: Invariant mass method ( $e^+e^-$  pairs)
- Calculated: Cocktail method based on data.

# Muons from heavy-flavour hadron decays

$$2.5 < y < 4$$



## Track selection:

- Acceptance and geometrical cuts
  - Muon trigger matching:  
reject the hadrons that cross the absorber.
  - Tracks → point back to the vertex:  
Remove beam-gas interaction and particles produced in the absorber
- Remaining main background:**  
→  $\mu$  from primary  $\pi$  and K decays.

# Study in-medium energy loss: $R_{AA}$

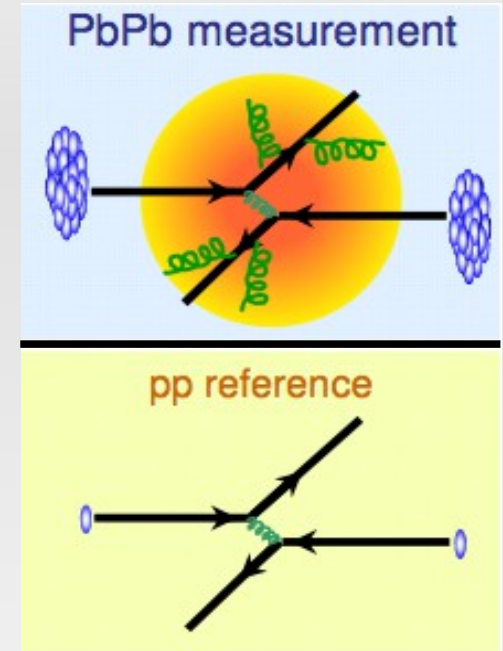


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Production of hard probes (heavy quarks, jets...) in A-A expected to scale with the number of nucleon-nucleon collisions  $N_{\text{coll}}$  (**binary scaling**)

→ **Observable**: nuclear modification factor

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$



- If no nuclear effects are present →  $R_{AA} = 1$  (binary scaling)
- In-medium parton energy loss via **radiative** (gluon emission) and **collisional** processes depending on:

- color charge
- quark mass (dead cone effect)
- path length and medium density

→  $R_{AA} \neq 1$

⇒  $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$   
Need to compare  $R_{AA}^\pi, R_{AA}^D, R_{AA}^B$

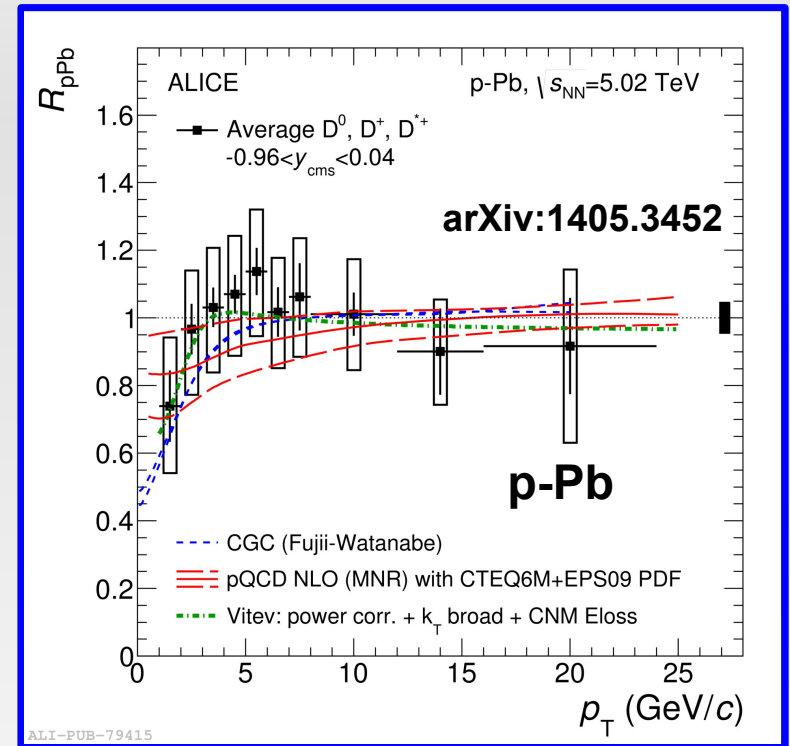
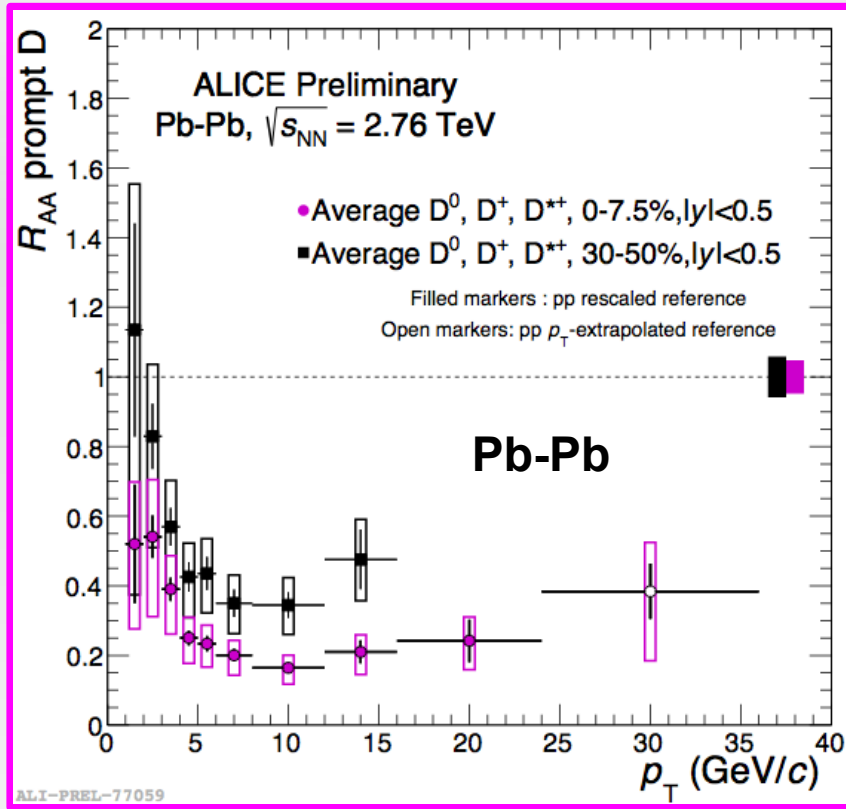
Dokshitzer and Kharzeev, PLB 519 (2001) 199  
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

# D-meson nuclear modification factor



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M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295  
 K. Eskola, H. Paukkunen and C. Salgado, JHEP 04 (2009) 065  
 K. J. Eskola, H. Paukkunen and C.A. Salgado, JHEP 0904 (2009) 065  
 Fujii - Watanabe, arXiv:1308.1258



## ✓ ALICE observed:

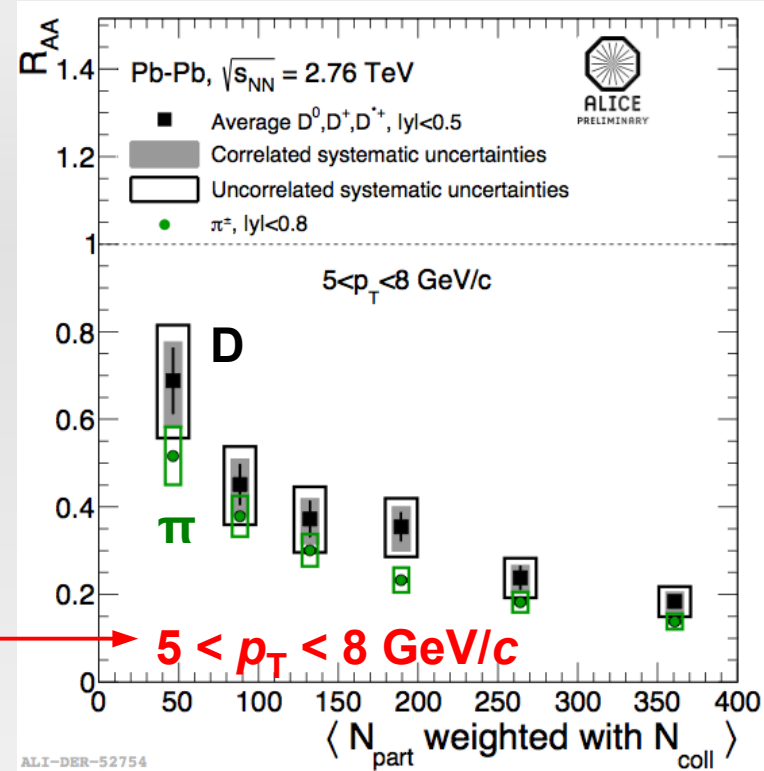
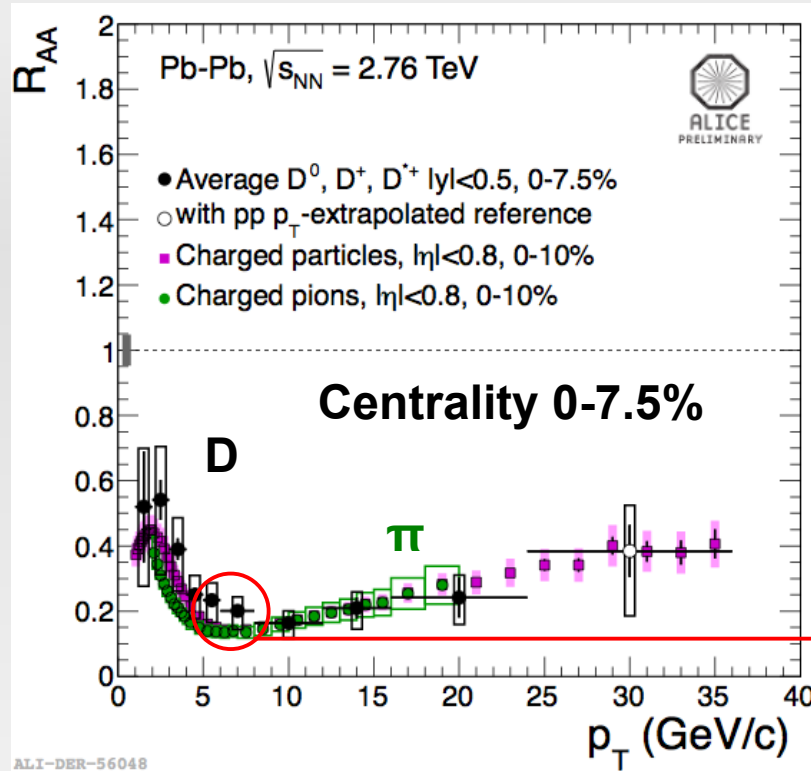
- **Large suppression** of D mesons at high- $p_T$  in **Pb-Pb** collisions → final state effect due to charm quark in-medium energy loss → larger suppression in more central collisions
- **$R_{pPb}$  consistent with unity** → no strong modification of D meson spectra in p-Pb relative to pp collisions.
- Models implementing Cold Nuclear Matter (CNM) effects (shadowing/saturation, CNM energy loss) describe the p-Pb data within uncertainties



# D-meson and pion $R_{AA}$



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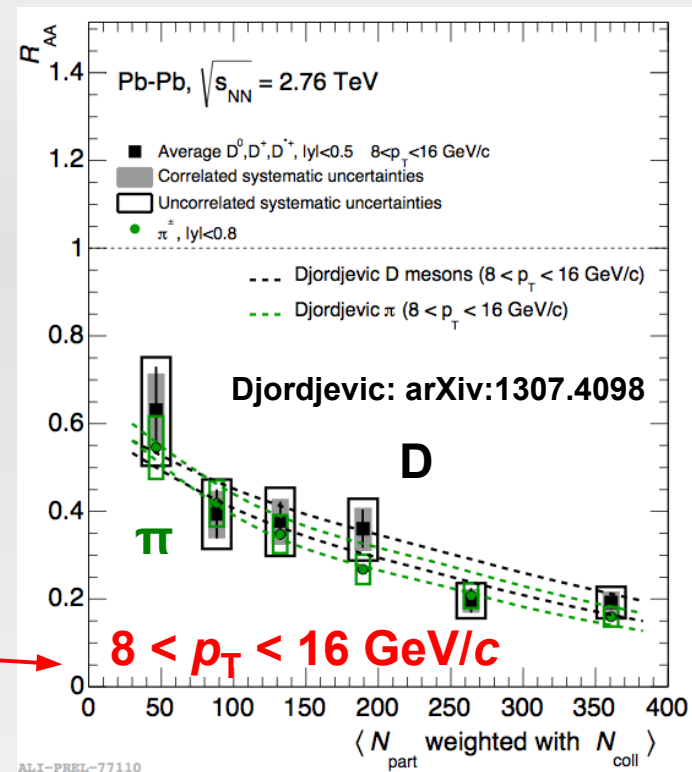
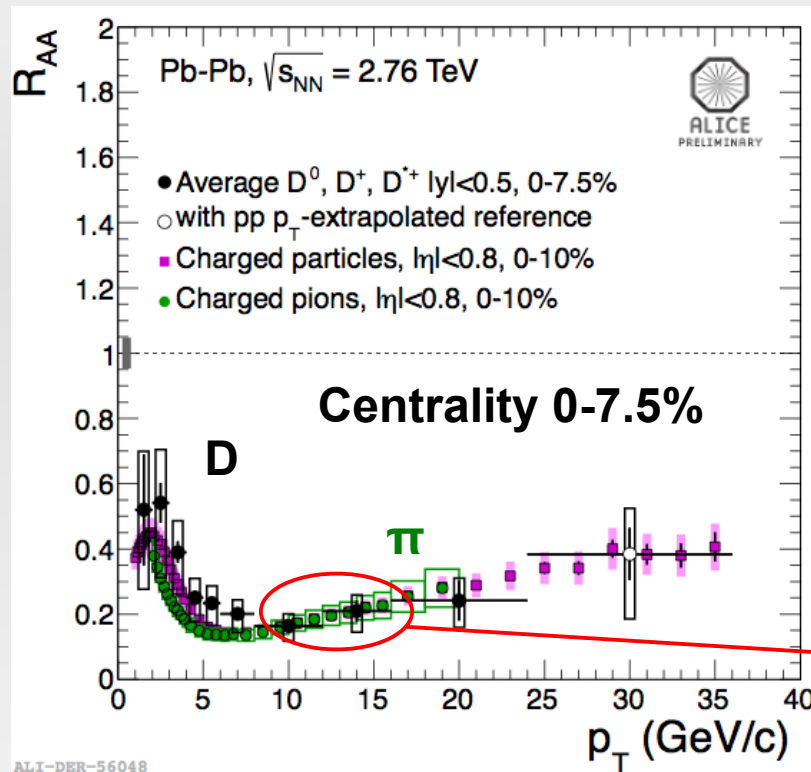


- Expected hierarchy in the energy loss :  $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$  ?  $\rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
- D meson and  $\pi$   $R_{AA}$  as a function of  $p_T$  and  $N_{part}$  compatible with uncertainties.

# D-meson and pion $R_{AA}$



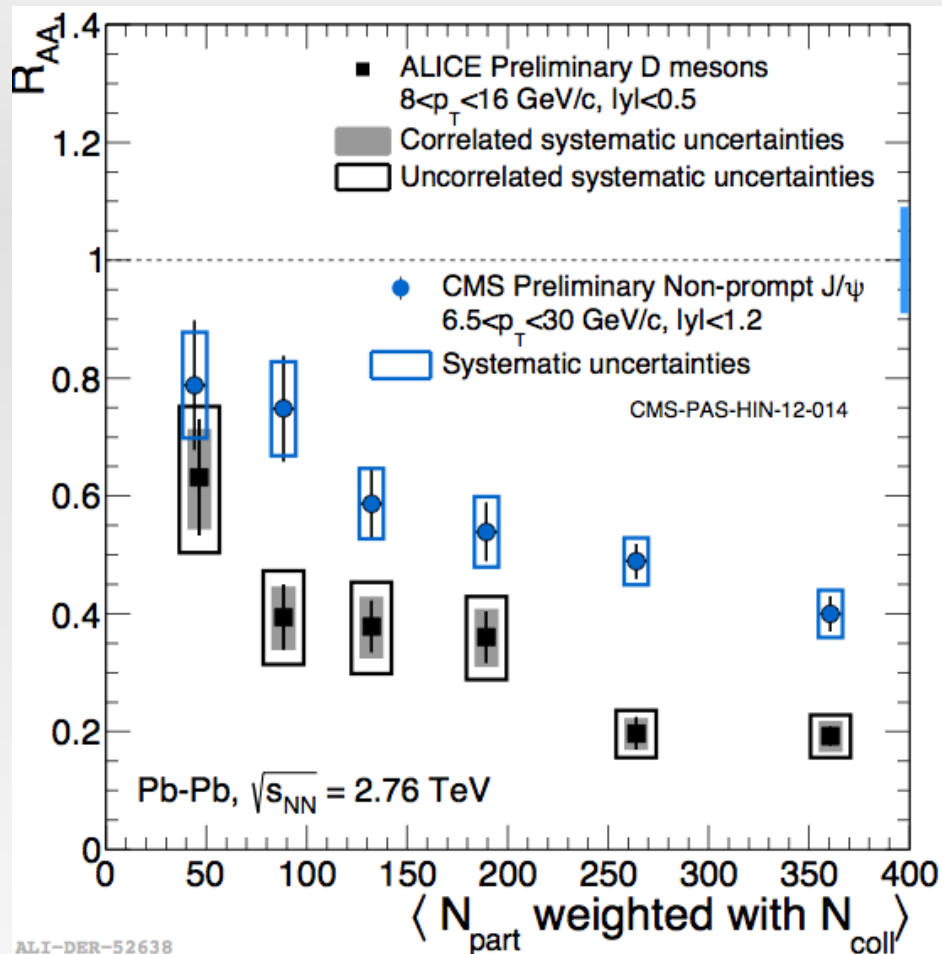
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- Expected hierarchy in the energy loss :  $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$  ?  $\rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
- D meson and  $\pi$   $R_{AA}$  as a function of  $p_T$  and  $N_{part}$  compatible with uncertainties.
- Consistency between  $R_{AA}(D)$  and  $R_{AA}(\pi)$  described by models taking into account:
  - $\rightarrow \Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  - $\rightarrow$  different shape of the  $p_T$  spectra
  - $\rightarrow$  different fragmentation function

# D-meson and J/ψ ← B

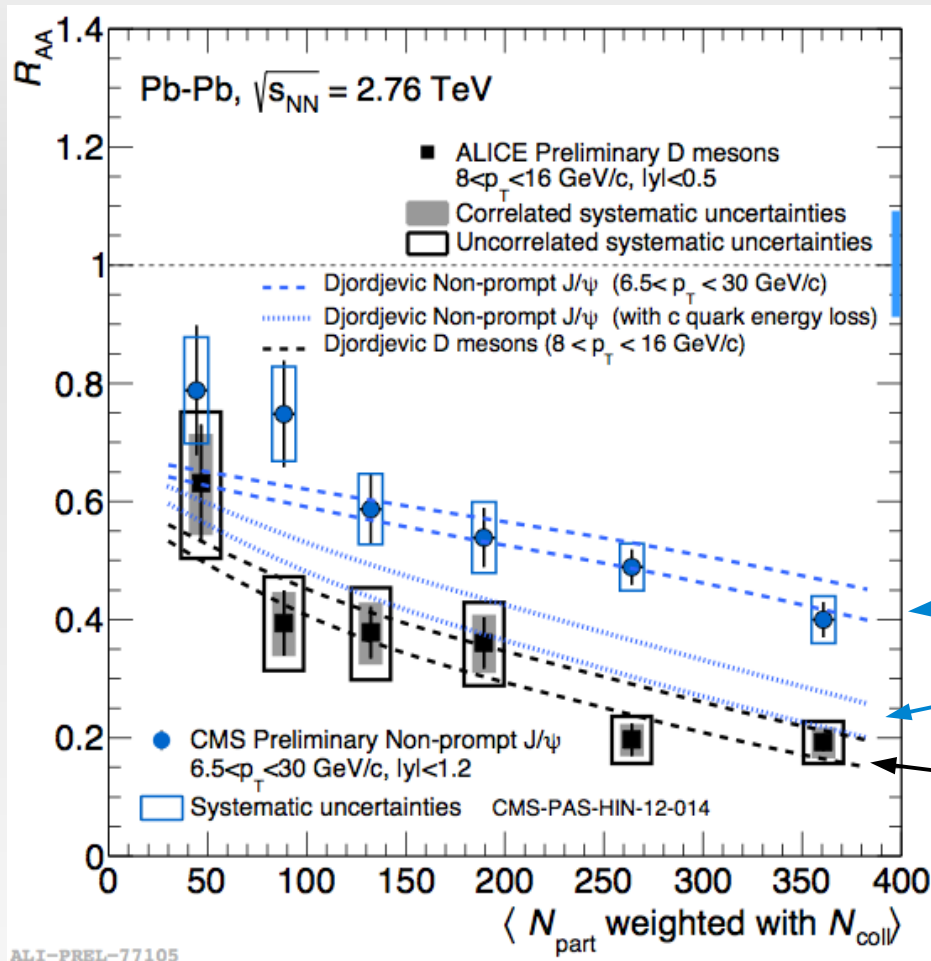
## $R_{AA}$ vs centrality



- Similar  $\langle p_T \rangle$  ( $\sim 10$  GeV/c) for D and B mesons (J/ψ ← B)
- Rapidity range slightly different.
- Indication of  $R_{AA}(D) < R_{AA}(B)$  in central events

# D-meson and J/ψ ← B

## $R_{AA}$ vs centrality



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- Rapidity range slightly different.
- **Indication of  $R_{AA}(D) < R_{AA}(B)$  in central events**

✓ **Djordjevic**: non-prompt J/ψ  $R_{AA}$  considering for energy loss

- b quark mass }  
 - c quark mass }

To test the mass dependence

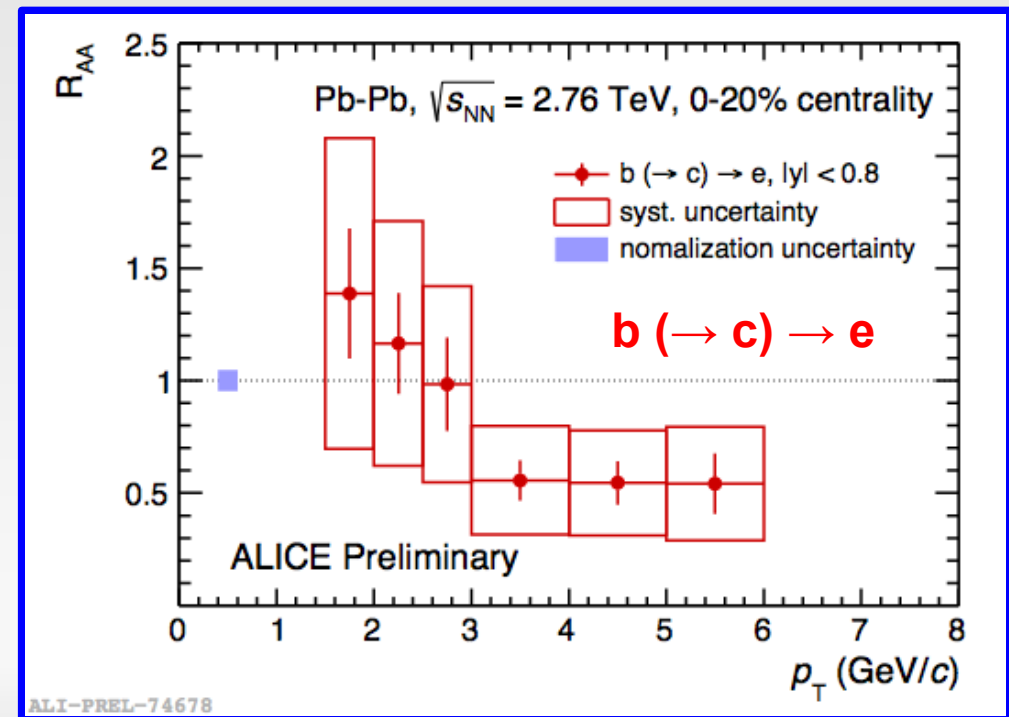
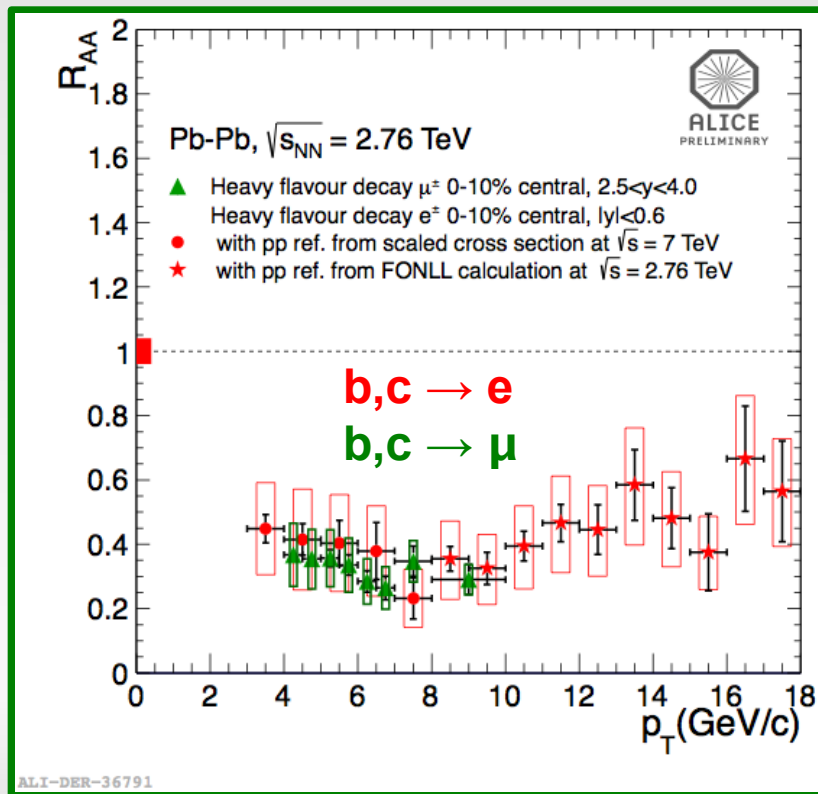
✓ **Djordjevic**: D-meson  $R_{AA}$

Djordjevic: arXiv:1307.4098

- pQCD model including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt J/ψ  $R_{AA}$  similar to that observed
- Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).

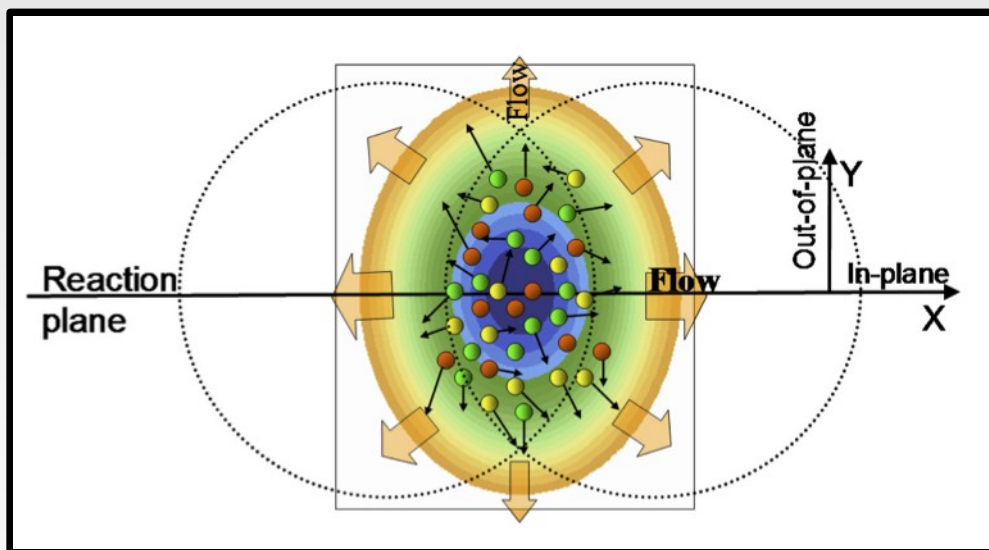
# $R_{AA}$ of heavy-flavour decay leptons

- Heavy-flavour decay electron  $R_{AA}$  at mid-rapidity ( $|y| < 0.6$ ) **compatible** with that of heavy-flavour decay muons at forward rapidity ( $2.5 < y < 4$ )  
→ large suppression observed in central collision.
- First  $R_{AA}$  measurement of beauty-decay electrons:  
→ Separation of charm and beauty contributions based on fits to the electron impact parameter distribution  
→  $R_{AA} < 1$  for  $p_T > 3$  GeV/c (confirms that also b quarks lose energy in the medium)



# Collectivity: Elliptic flow $v_2$

- Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**.  
→ light particle  $v_2$  is described by hydrodynamics.
- In addition, path-length dependent energy loss induces an asymmetry in momentum space.  
→ Longer path length: larger energy loss
- **Observable: elliptic flow  $v_2 = 2^{\text{nd}}$  Fourier coefficient of the particle azimuthal distribution.**



$$E \frac{d^3 N}{d^3 \mathbf{p}} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})] \right)$$

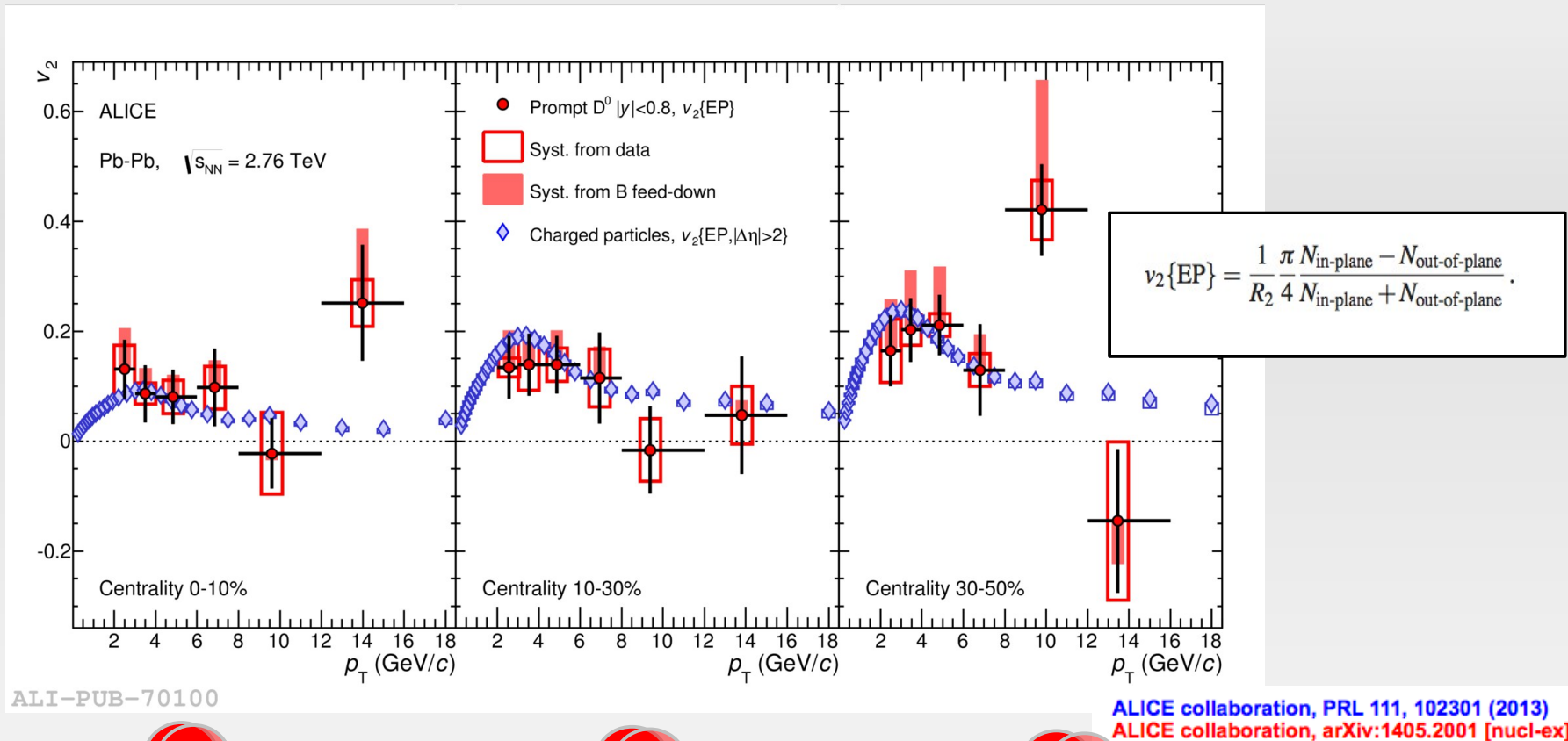
$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle$$

**Heavy-flavour  $v_2$  measurements probe:**

→ **Low/intermediate  $p_T$** : collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination).

→ **High  $p_T$** : path-length dependence of heavy-quark energy loss.

# D-meson elliptic flow



Positive  $v_2^D$  observed ( $5\sigma$  effect for  $2 < p_T < 6$  GeV/c in 30-50% centrality class)  
 Hint for an increase of D meson  $v_2$  from central to semi-peripheral collisions

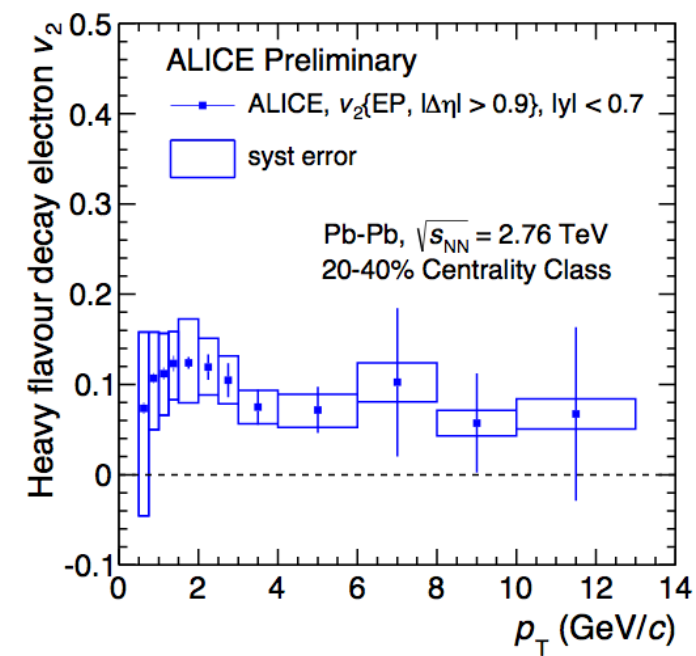
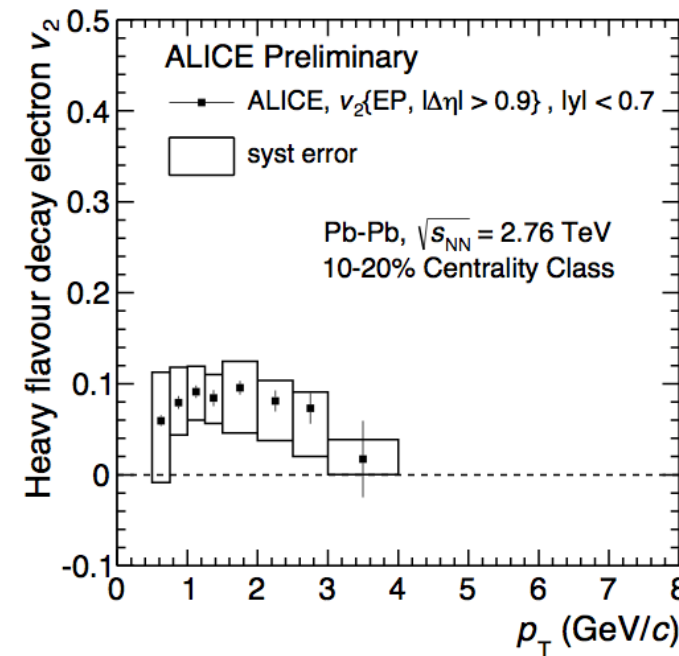
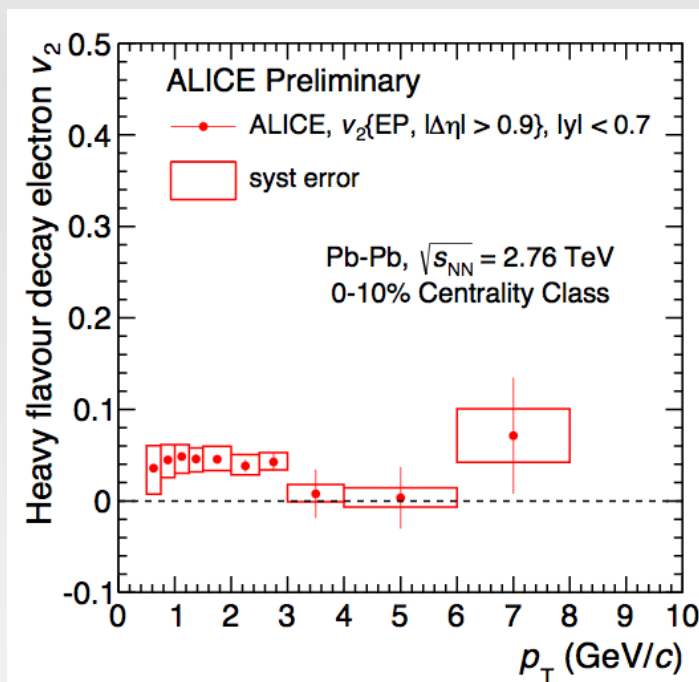
D-meson  $v_2$  similar to charged-particle  $v_2$

Confirms significant interaction of charm quarks with the medium.  
 Suggests collective motion of low- $p_T$  charm quark in the expanding fireball

# Electrons from heavy-flavour hadron decays



$$v_2^{HFE} = \frac{(1 + R_{SB})v_2^{incl} - v_2^{back}}{R_{SB}}$$



Positive  $v_2^{HFE}$  observed ( $3\sigma$  effect in  $2 < p_T < 3$  GeV/c in 20-40% centrality class)

Hint for an increase of  $v_2^{HFE}$  from central to semi-peripheral collisions

Confirms significant interaction of heavy quarks with the medium

Suggests collective motion of low- $p_T$  heavy quarks (mainly charm) in the expanding fireball<sub>16</sub>

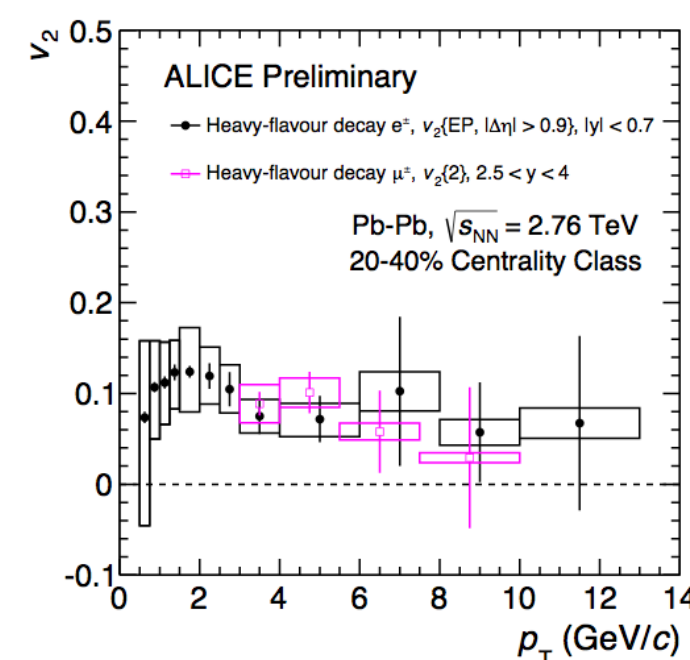
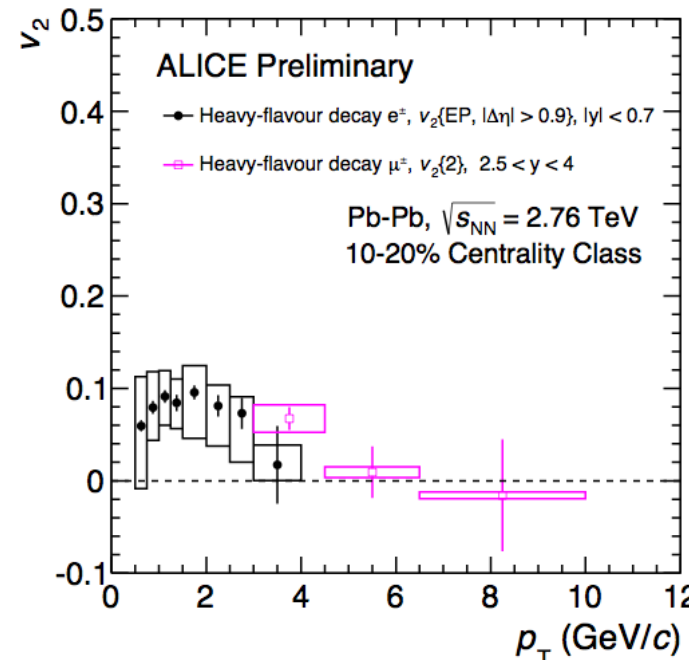
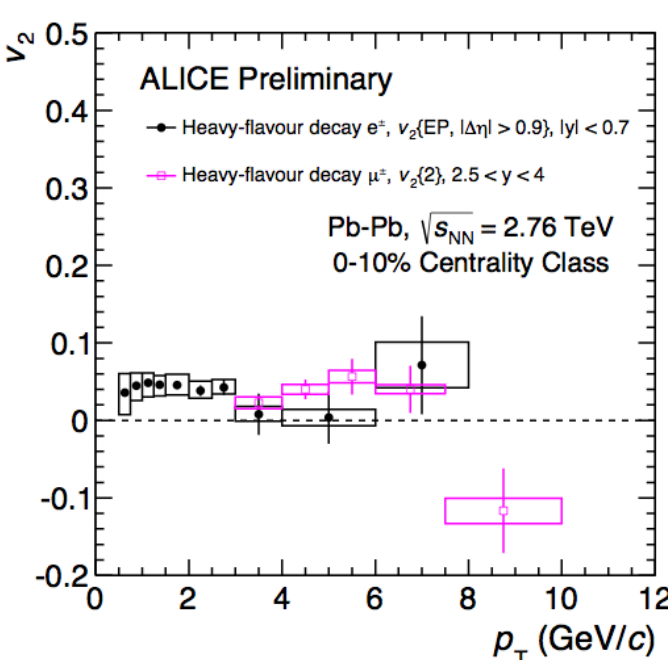


# Leptons from heavy-flavour hadron decays



HF decay muons  
 $2.5 < y < 4$

HF decay electrons  
 $|y| < 0.7$



$v_2$  of heavy-flavour decay **electrons** (at mid-rapidity) and **muons** (at forward rapidity) are similar in the different centrality classes.

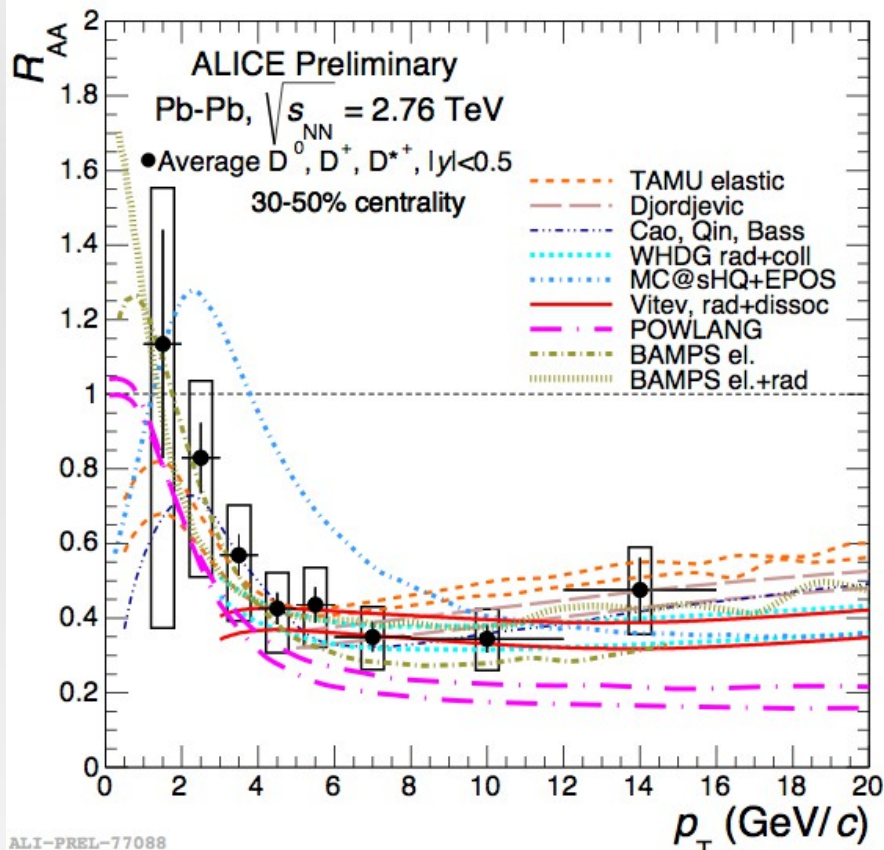
Exhibit positive  $v_2$  with similar centrality dependence as observed for D mesons

Confirm significant interaction of heavy quarks with the medium

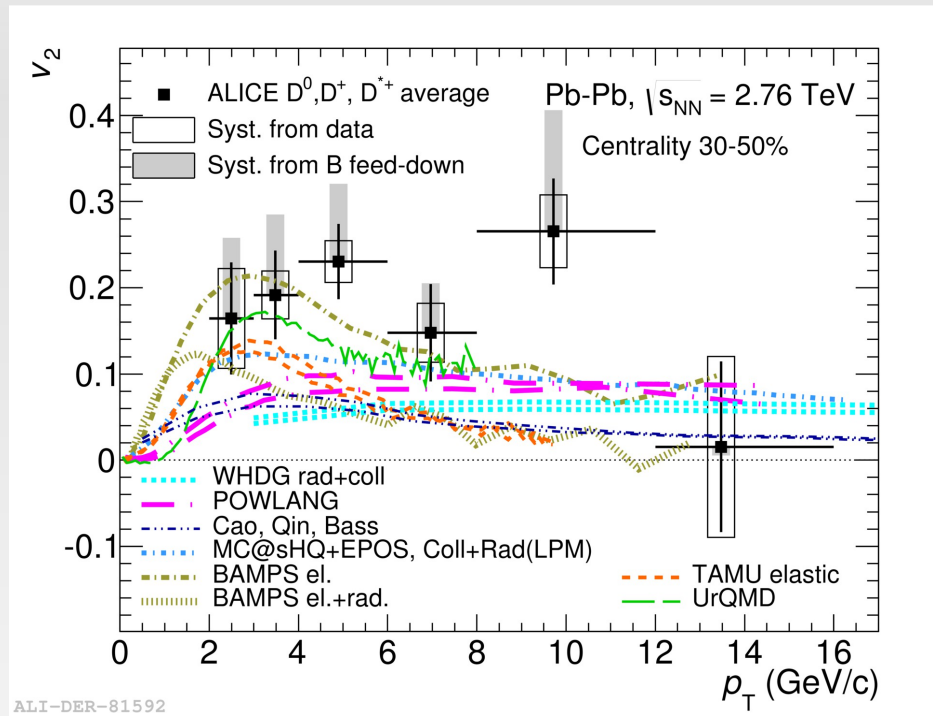
# Model predictions: D-meson $R_{AA}$ and $v_2$



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- POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; - TAMU: arXiv:1401.3817;  
 - MC@HQ+EPOS: PRC 89 (2014) 014905; - WHDG: Nucl. Phys. A 872 (2011) 256;  
 - BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph]; - UrQMD: arXiv:1211.6912[hep-ph];  
 J.Phys. Conf. Ser. 426 (2013) 012032; - Cao,Quin, Bass: PRC 88 (2013);  
 - Vitev.: PRC 80 (2009) 054902; - Djordjevic: arXiv:1307.4098



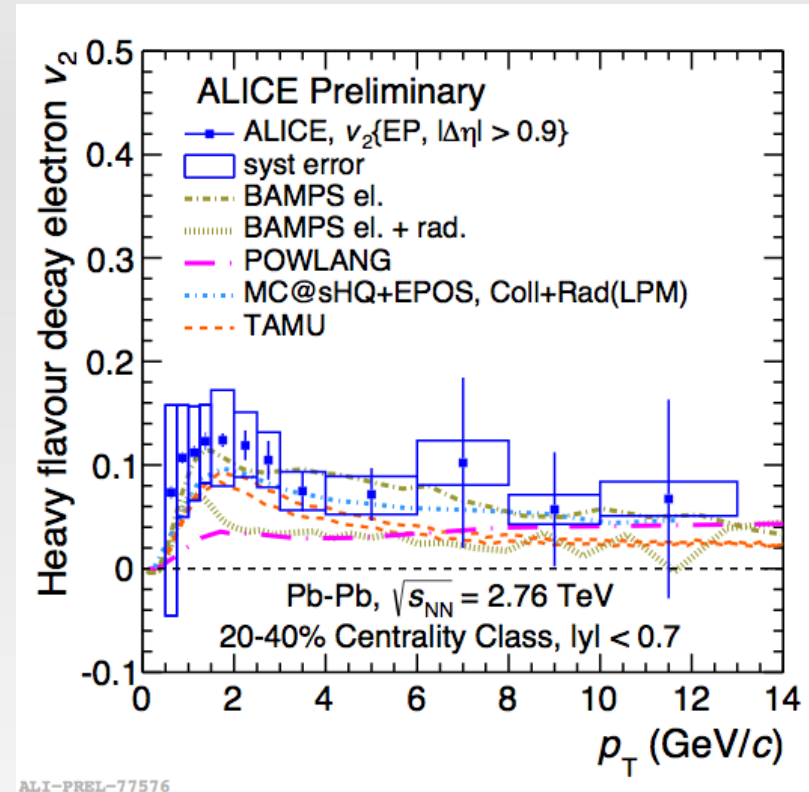
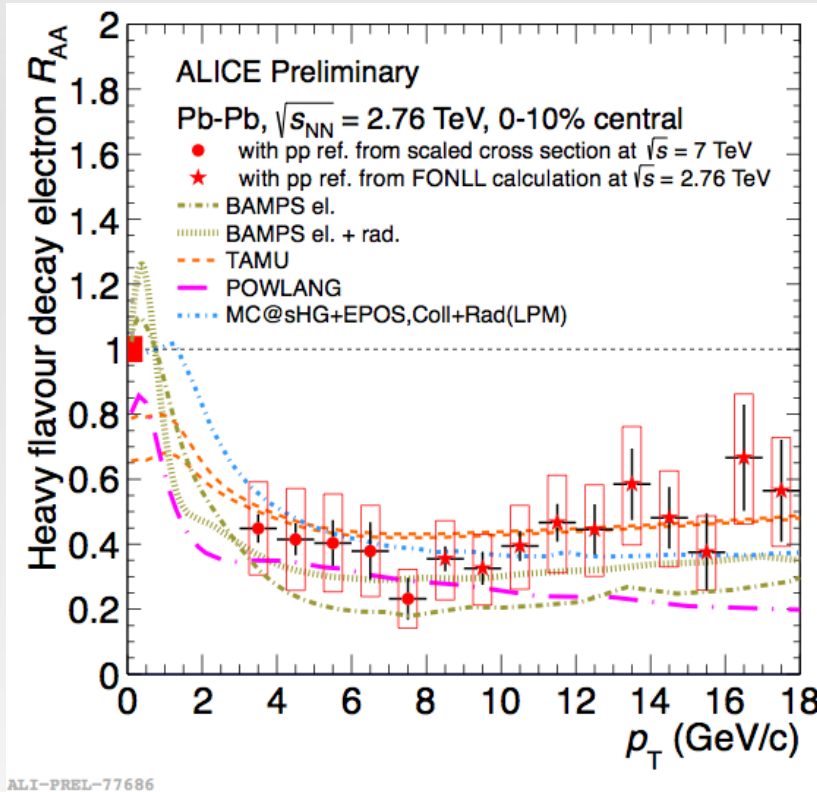
arXiv: 1405.2001; PRL 111, 102301 (2013)

- models including in-medium energy loss can describe qualitatively the measured strong suppression ( $R_{AA} < 1$ ) of the yield at high  $p_T$  and the anisotropy ( $v_2 > 0$ )
- simultaneous description of  $R_{AA}$  and  $v_2$  is challenging for models.
- $v_2^D$  and  $R_{AA}^D$  measurements together start to provide constraints for models

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# Model predictions: HFE $R_{AA}$ and $v_2$

– POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; – TAMU: arXiv:1401.3817;  
 – MC@HQ+EPOS: PRC 89 (2014) 014905;  
 – BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];



- Similar picture from the comparison of  $R_{AA}$  and  $v_2$  to models as for the D mesons.
  - Models of in-medium parton energy loss can describe reasonably well heavy-flavour decay electrons and D mesons at midrapidity
- $v_2^{\text{HFE}}$  and  $R_{AA}^{\text{HFE}}$  measurements together start to provide constraints for models

# Conclusion



- Strong **suppression** of **heavy-flavour** yield at high  $p_T$ :
  - Semi-leptonic inclusive decays
  - D-mesons
- Larger suppression for **D mesons** with respect to **B mesons** (non-prompt J/ψ by CMS)
  - Described by theoretical models implementing **mass-dependent** energy loss
- Hint for  $R_{AA} < 1$  also for **electrons from beauty-hadron** decays for  $p_T > 3$  GeV/c.
  
- A **non-zero elliptic flow** of heavy flavours was measured in **semi-central** collisions.
- Hint for an **increase** of heavy-flavour  $v_2$  from **central to peripheral collisions**.
  - Suggests collective motion of low- $p_T$  heavy quarks (mainly charm).
  
- Comparison of **different observables** ( $R_{AA}$ ,  $v_2$ ) to theory starts to constrain the **energy-loss models**.

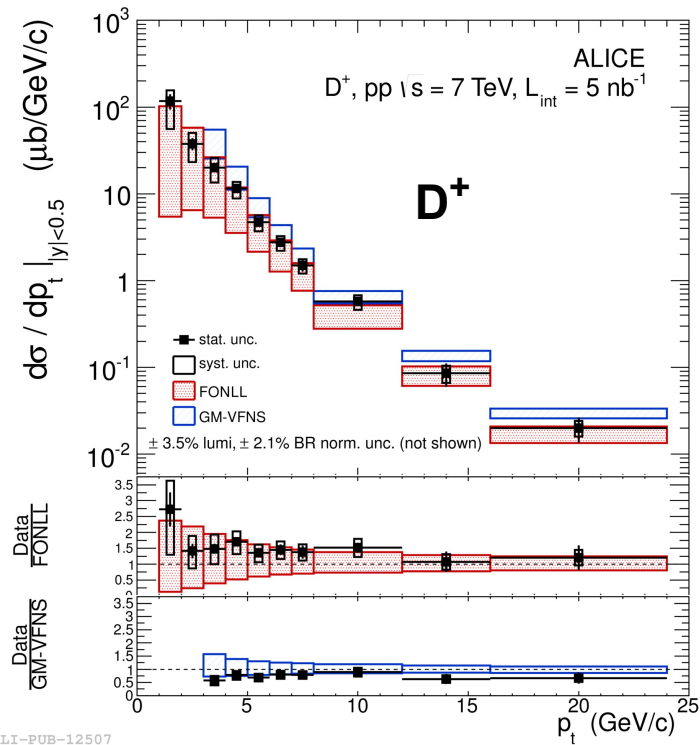


# BACKUP

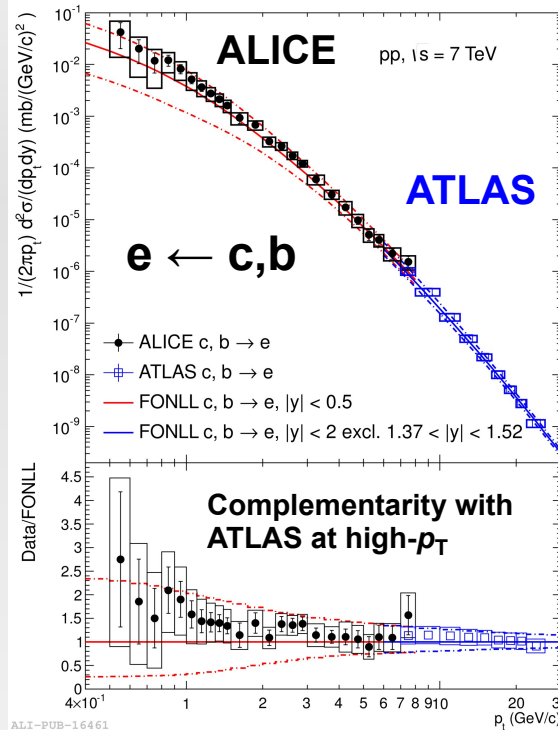
# $p_T$ -differential cross section



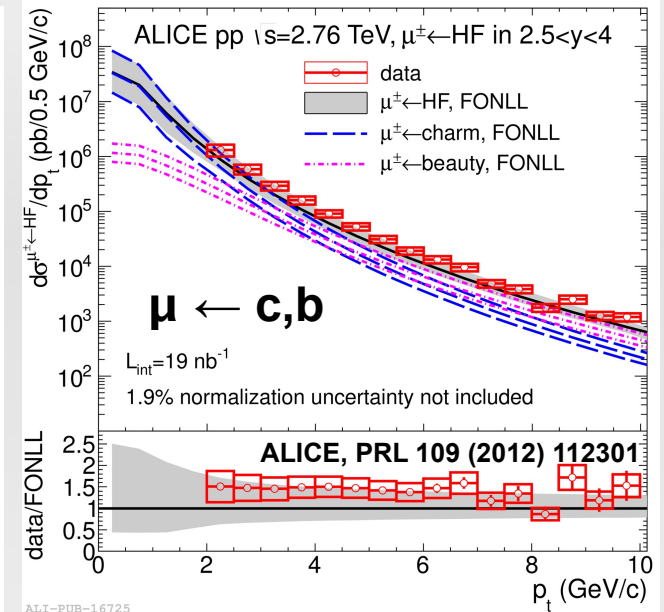
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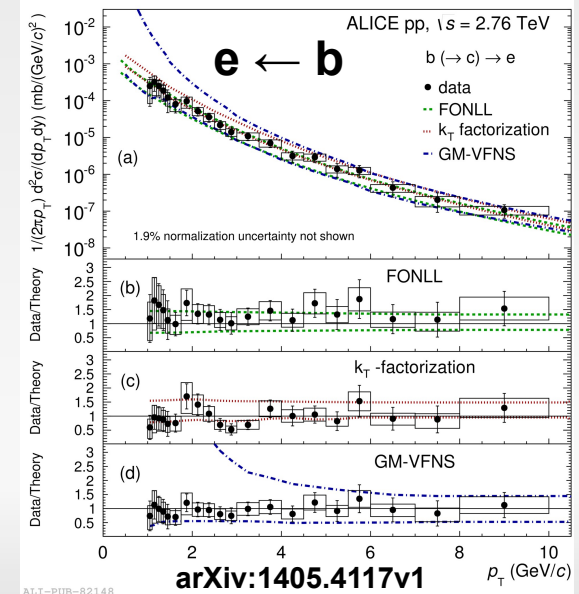
ALICE, JHEP 1201 (2012)



(ATLAS) PLB 707 (2012) 438  
 (ALICE) Phys. Rev. D86 (2012) 112007



ALI-PUB-16725



ALI-PUB-82148

Charm cross-section on the upper side of the FONLL uncertainty band, as at lower  $\sqrt{s}$

Heavy-flavour  $p_T$ -differential cross sections well described by pQCD calculations at both energies (7 and 2.76 TeV)

# Nuclear modification factor: $D_s^+$

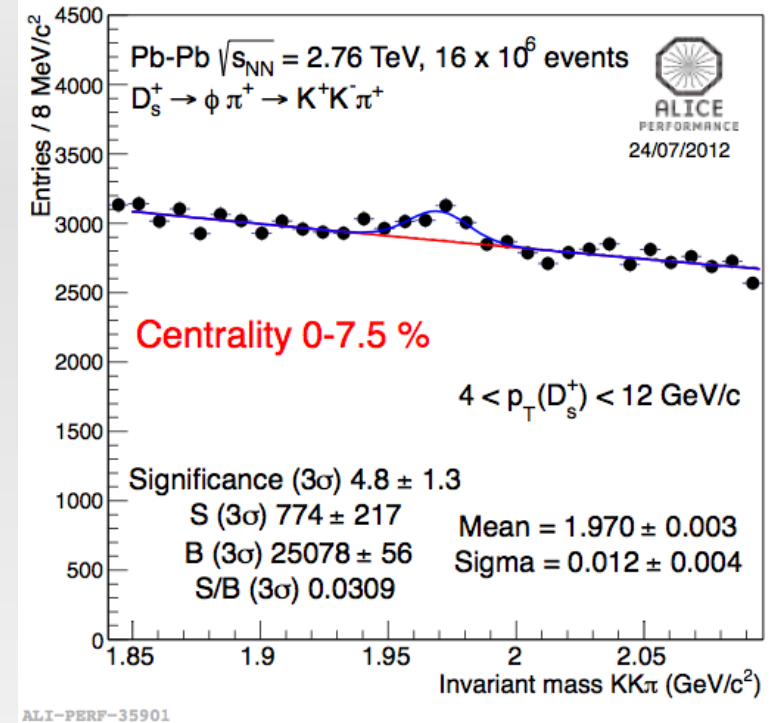
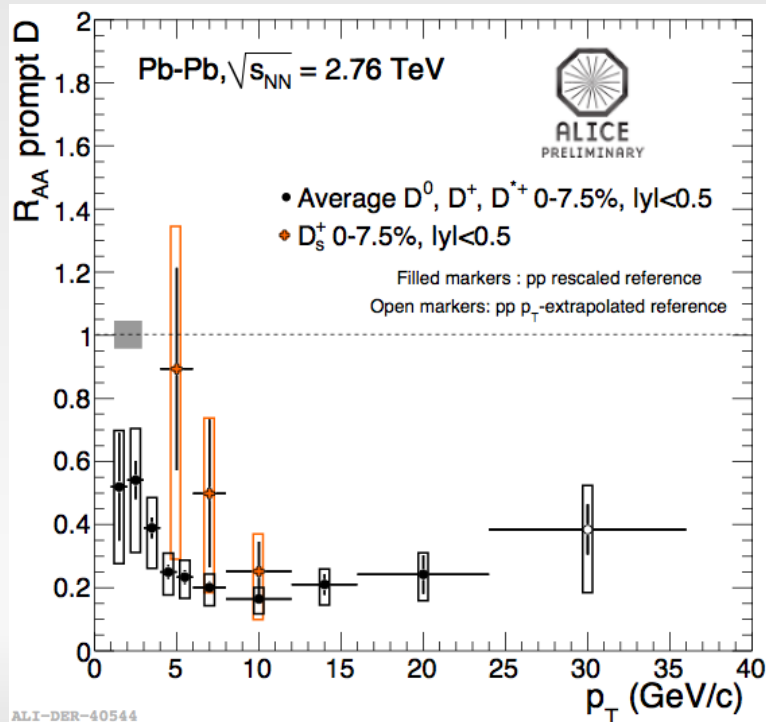


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$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

Kuznetsova, Rafelski EPJ C 51 (2007) 113  
 He et al. PRL 110 (2013) 112301  
 Andronic et al. PLB 659 (2008) 149

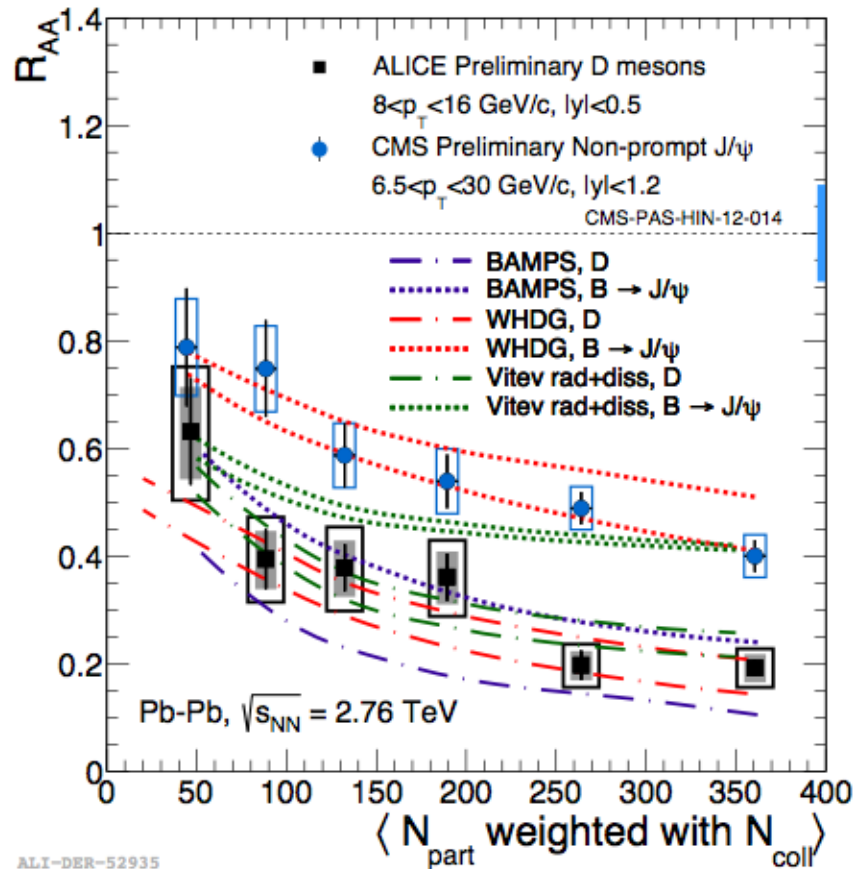
- First measurement of  $D_s^+$  in AA collisions.
- **Expectation:** enhancement of the strange/non-strange D meson yield at intermediate  $p_T$ , if charm hadronizes via recombination in the medium, due to enhanced strangeness abundance






- **Strong  $D_s^+$  suppression** (similar to other D meson) for  $8 < p_T < 12$  GeV/c.
  - $R_{AA}$  seems to increase ( $\rightarrow$  less suppression) at low  $p_T$ .
- $\rightarrow$  Current data do not allow a conclusive comparison to other D mesons within uncertainties.

# D meson and J/ψ ← B

## $R_{AA}$ vs centrality



- ✓ **BAMPS**: collisional energy loss in an expanding medium.
- ✓ **WHDG**: collisional and radiative energy loss in an anisotropic medium.
- ✓ **Vitev et al.**: radiative energy loss + D meson in-medium formation and dissociation.

 **BAMPS**: JPG 38 (2011)124152  
 **WHDG**: Nucl. Phys. A 784 (2007) 426  
 **Vitev et al.**: PRC 80 (2009) 054902

© Models including a mass-dependent energy loss predict a difference between the D-meson and non-prompt J/ψ similar to that observed.

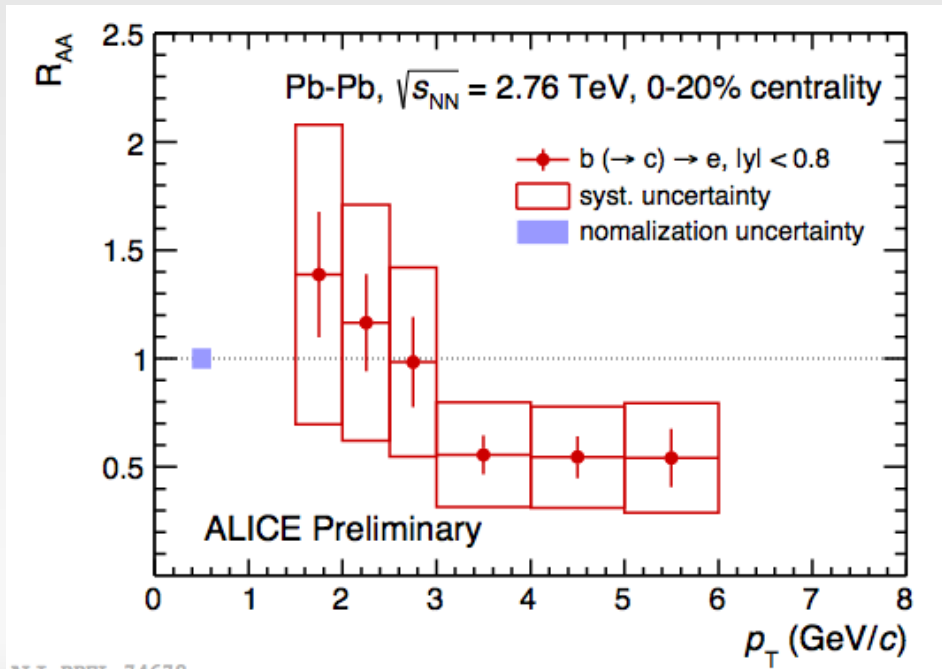
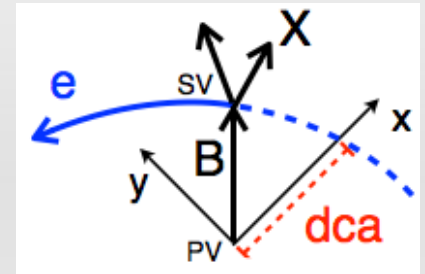


# Beauty-decay electron $R_{AA}$

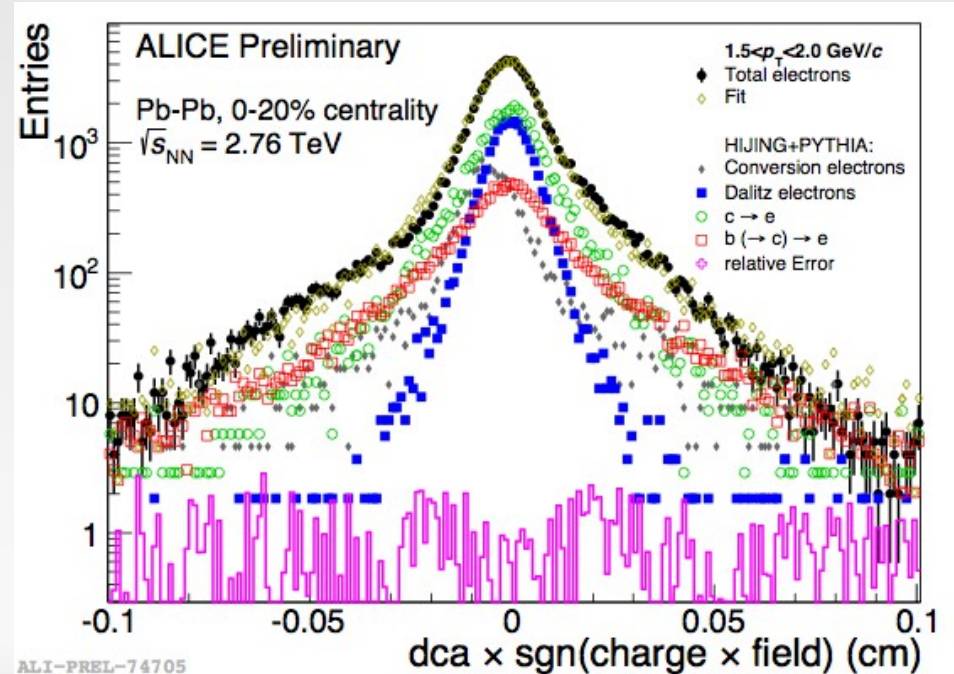


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- Analysis based on the electron impact parameter distribution.
- First  $R_{AA}$  measurement of beauty-decay electron:
  - $R_{AA} < 1$  for  $p_T > 3$  GeV/c



ALI-PREL-74678



ALI-PREL-74705

# D-Meson elliptic flow:



ALICE

- Event plane method  
(TPC  $0 < \eta < 0.8$  or VZERO event plane)

- Extraction of the D-meson yield in- and out-of-plane

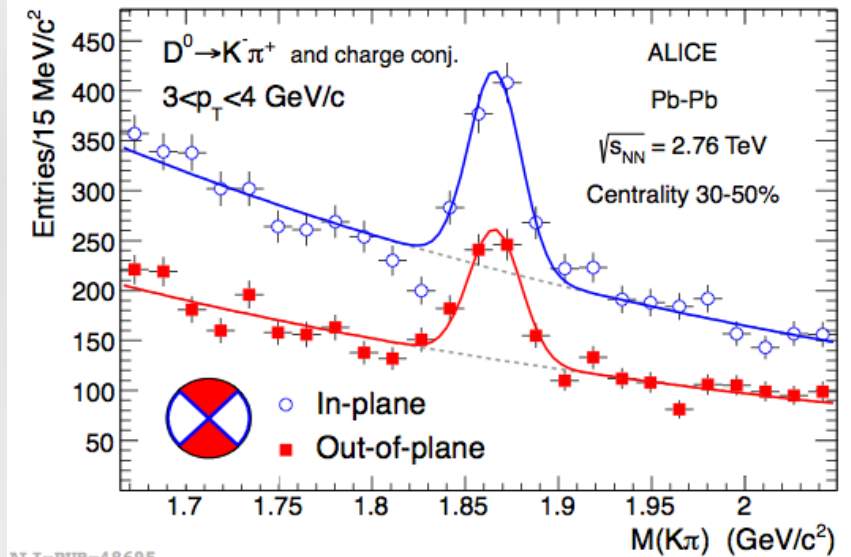
$$v_2\{\text{EP}\} = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

Consistent between the three D-meson species

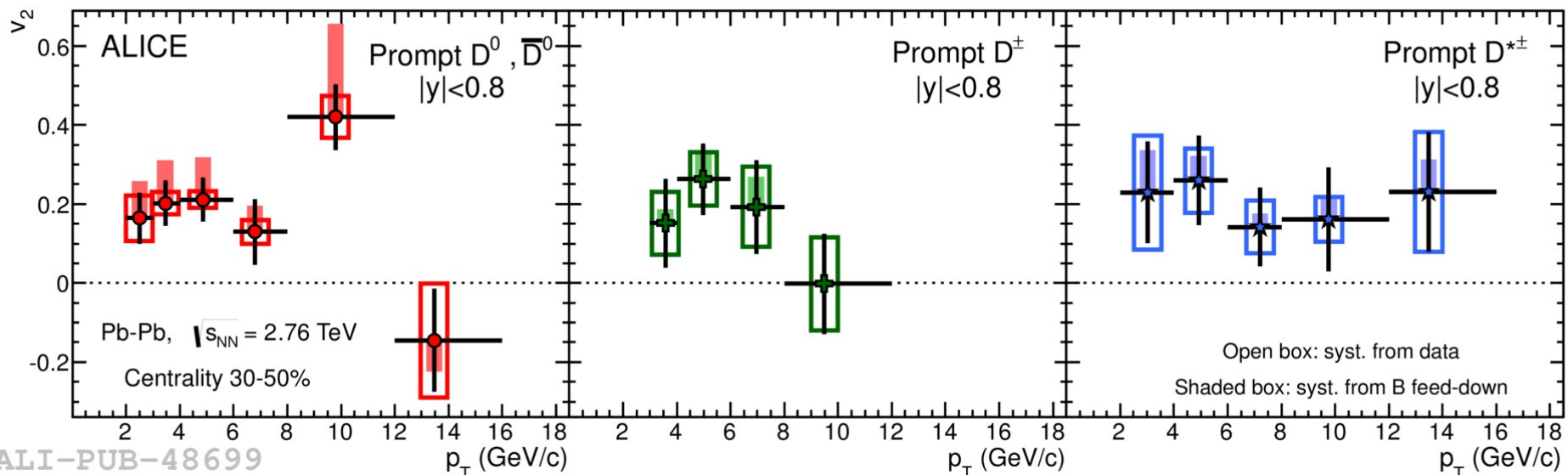
**Positive D-meson  $v_2$  ( $v_2^D$ ) observed**

5.7 $\sigma$  effect for  $D^0, D^+, D^*$  averaged for  $2 < p_T < 6$  GeV/c in 30-50% centrality

ALICE collaboration, PRL 111, 102301 (2013)  
ALICE collaboration, arXiv:1405.2001 [nucl-ex]



ALI-PUB-48695



ALI-PUB-48699

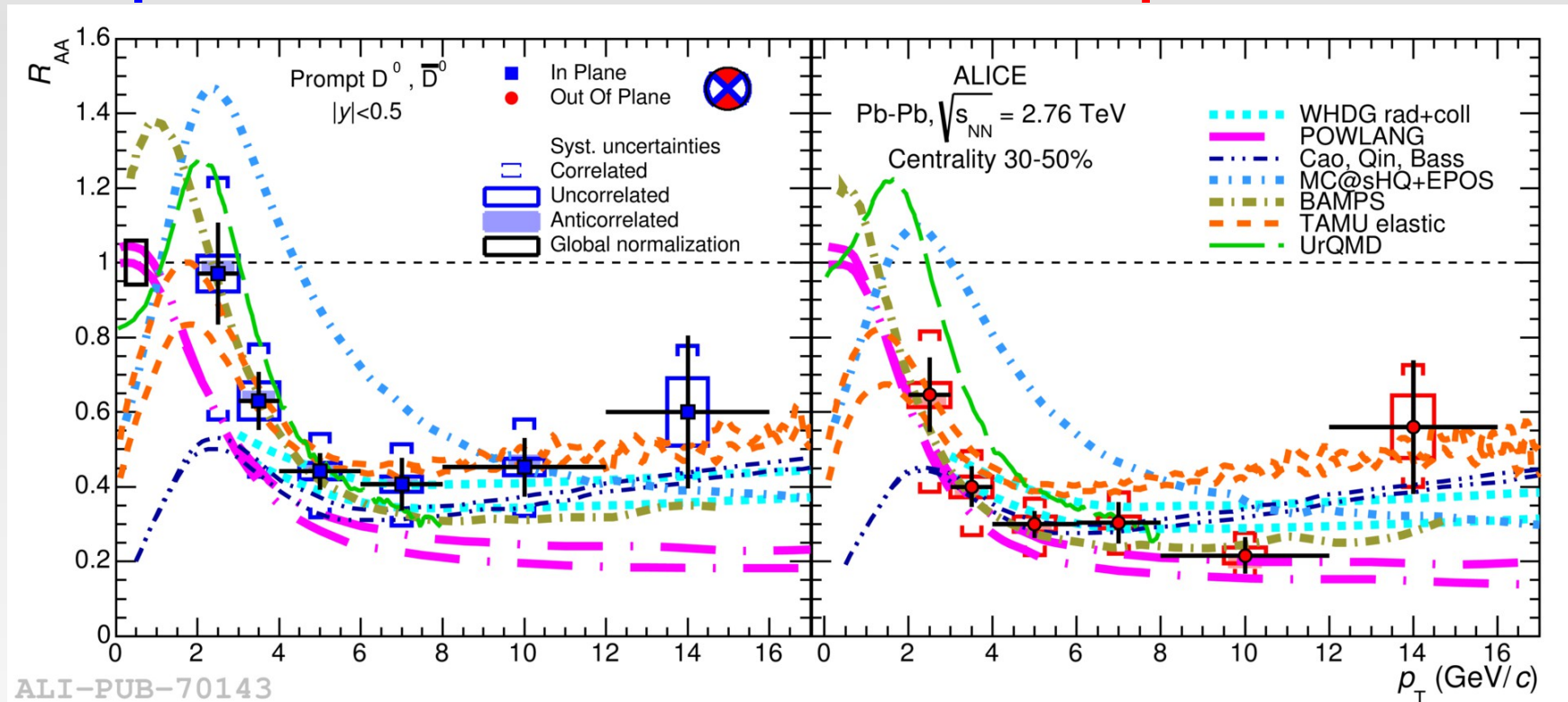
# Model predictions: D meson $R_{AA}$ and $v_2$



- POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; - TAMU: arXiv:1401.3817;  
 - MC@HQ+EPOS: PRC 89 (2014) 014905; - WHDG: Nucl. Phys. A 872 (2011) 256;  
 - BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph]; - UrQMD: arXiv:1211.6912[hep-ph];  
 J.Phys. Conf. Ser. 426 (2013) 012032; - Cao,Quin, Bass: PRC 88 (2013);

In-plane

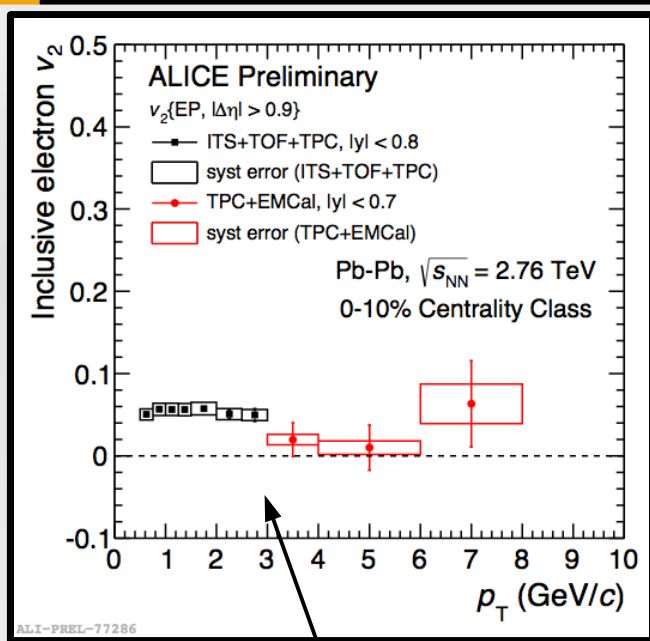
Out-of-plane



$R_{AA}$  measured in-plane and out-of-plane, sensitive to  
 - path length dependence of parton energy loss at high  $p_T$   
 - collectivity at low  $p_T$

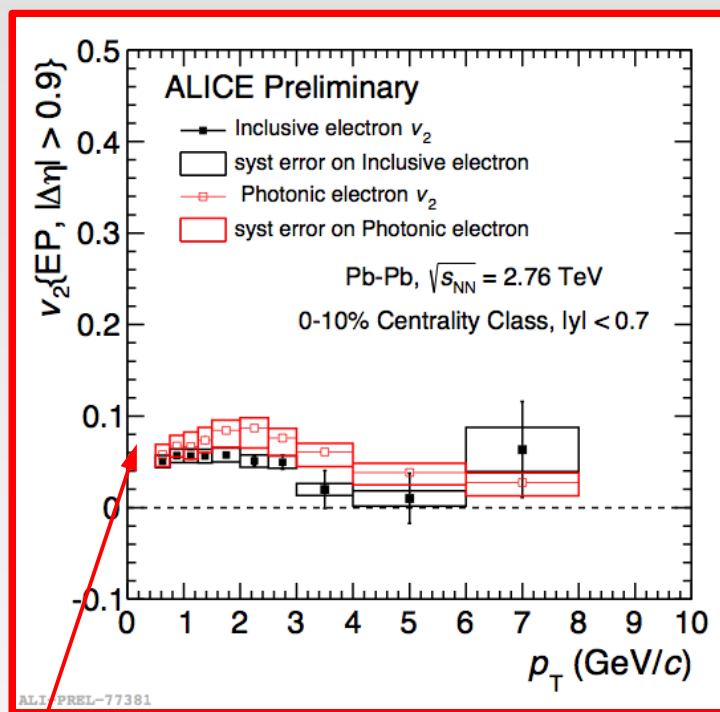
arXiv: 1405.2001; *PRL* 111, 102301 (2013)

# Electron from heavy flavour hadron decays



•  $v_2^{\text{incl}e}$  of inclusive electrons : **measured** with the event plane method using VZERO

- $v_2^{\text{back}e}$  of background electrons
  - Electrons from  $\gamma$  conversion
  - Electrons from  $\pi^0$  Dalitz decay

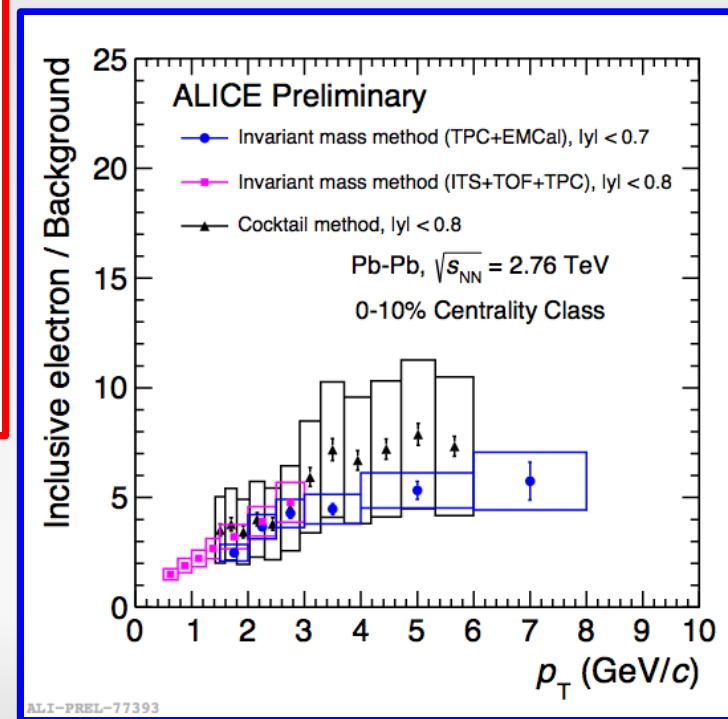


- $p_T < 1.5$  GeV/c: **measured** Invariant mass method ( $e^+e^-$  pairs) **New**
- $p_T > 1.5$  GeV/c: **estimated** Cocktail method based on data ( $\pi^0, \pi^\pm, \text{direct } \gamma$ )

- Signal to background ratio  $R_{SB}$ : **New**
- New results (ITS-TPC-TOF/TPC-EMCal): **Measured** via the invariant mass method
- Previous results (TPC-TOF analysis): **Estimated** via the cocktail method

$$1 + R_{SB} = \frac{N^{\text{Inclusive } e^\pm}}{N^{\text{Background } e^\pm}}$$

$$v_2^{\text{HFE}} = \frac{(1 + R_{SB})v_2^{\text{incl}} - v_2^{\text{back}}}{R_{SB}}$$



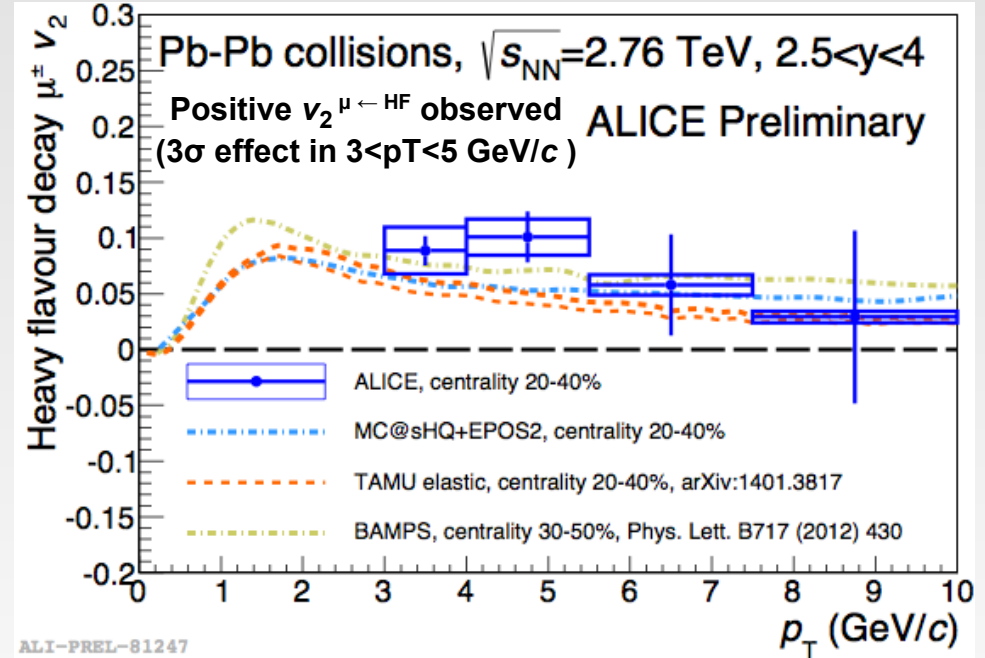
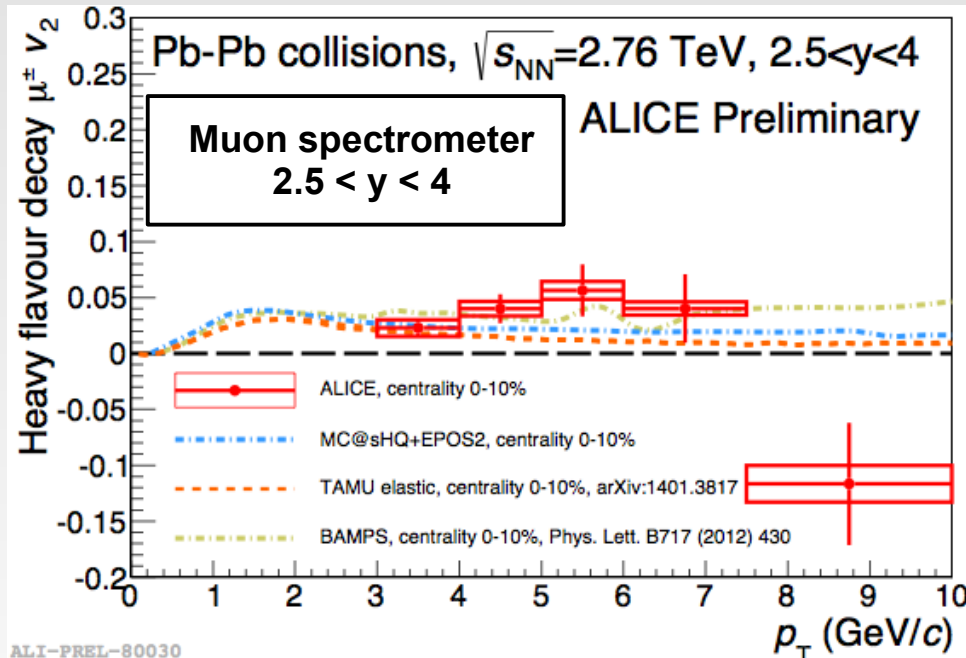
# Muon from heavy flavour hadron decays



ALICE

- Measured  $v_2^{\text{incl } \mu}$  of inclusive muon
- Estimate  $f_{\text{decay } \mu}$  and  $v_2^{\text{decay } \mu}$ 
  - $f_{\text{decay } \mu} \sim 15\% (5\%)$  at  $p_T = 3 (10)$  GeV/c based on extrapolation of P/K spectra at mid-rapidity
  - $v_2^{\text{decay } \mu}$  cocktail method based on data

$$v_2^{\mu \leftarrow \text{HF}} = \frac{v_2^{\text{incl } \mu} - f_{\text{decay } \mu} v_2^{\text{decay } \mu}}{1 - f_{\text{decay } \mu}}$$



Measured positive  $v_2^{\mu \leftarrow \text{HF}}$  at forward rapidity ( $2.5 < y < 4$ )

Hint for an increase with the centrality of  $v_2^{\mu \leftarrow \text{HF}}$

Indication of re-scattering of heavy quarks in the hot and dense medium

# Model prediction: HFM $R_{AA}$ and $v_2$



- **Large suppression** in the most central collisions (factor 3-4).
  - Measured **positive  $v_2^{\mu \leftarrow HF}$**  at forward rapidity in 20-40% centrality class.
- Models of in-medium parton energy loss can describe reasonably well HFM at forward rapidity and D mesons and HFE at midrapidity
- Indication of significant re-scattering of heavy quarks in the hot and dense medium.

Muon spectrometer  
 $2.5 < y < 4$

