Measurements of the suppression and anisotropy of heavy-flavour particles in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with ALICE

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

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for the ALICE Collaboration

Physics motivation

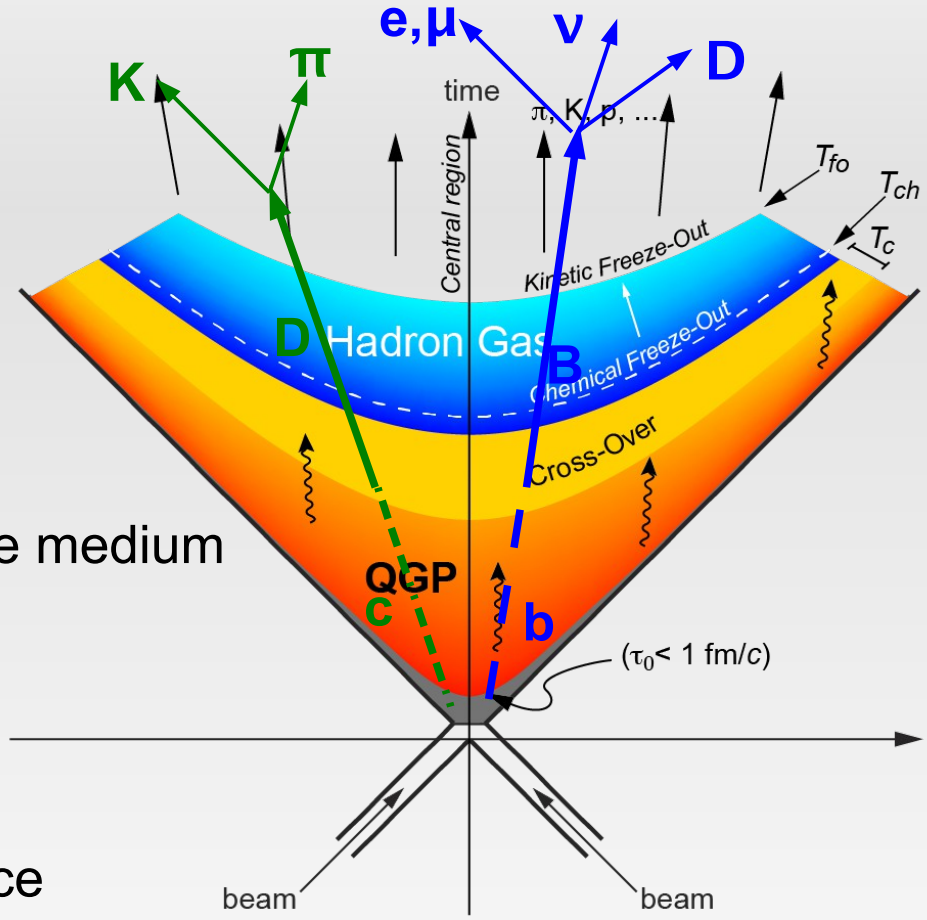
→ **Charm and beauty** quarks are produced in hard scattering processes (large Q^2) in the early stage of the collision

→ 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?

→ **Hadronization**: fragmentation vs coalescence



→ **Need reference measurements in pp and p-Pb collisions**

→ **Perturbative QCD** describes the **cross sections** measured in pp collisions.

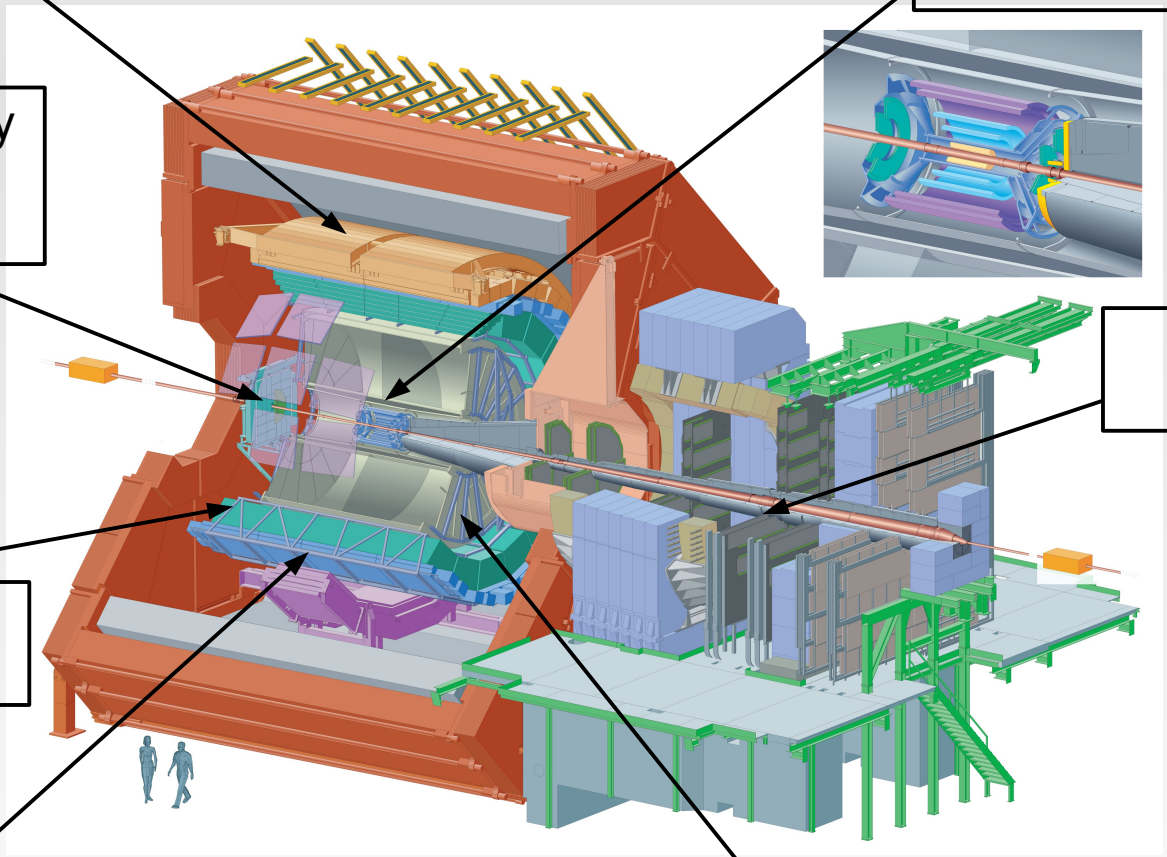
(talk Grazia Luparello: Saturday 24th – 8:30)

ALICE detector

EMCal: trigger, electron ID

ITS: tracking, vertexing and PID via d*E*/d*x*

V0: trigger, centrality and event plane determination



Forward muon spectrometer

TRD: tracking, electron ID

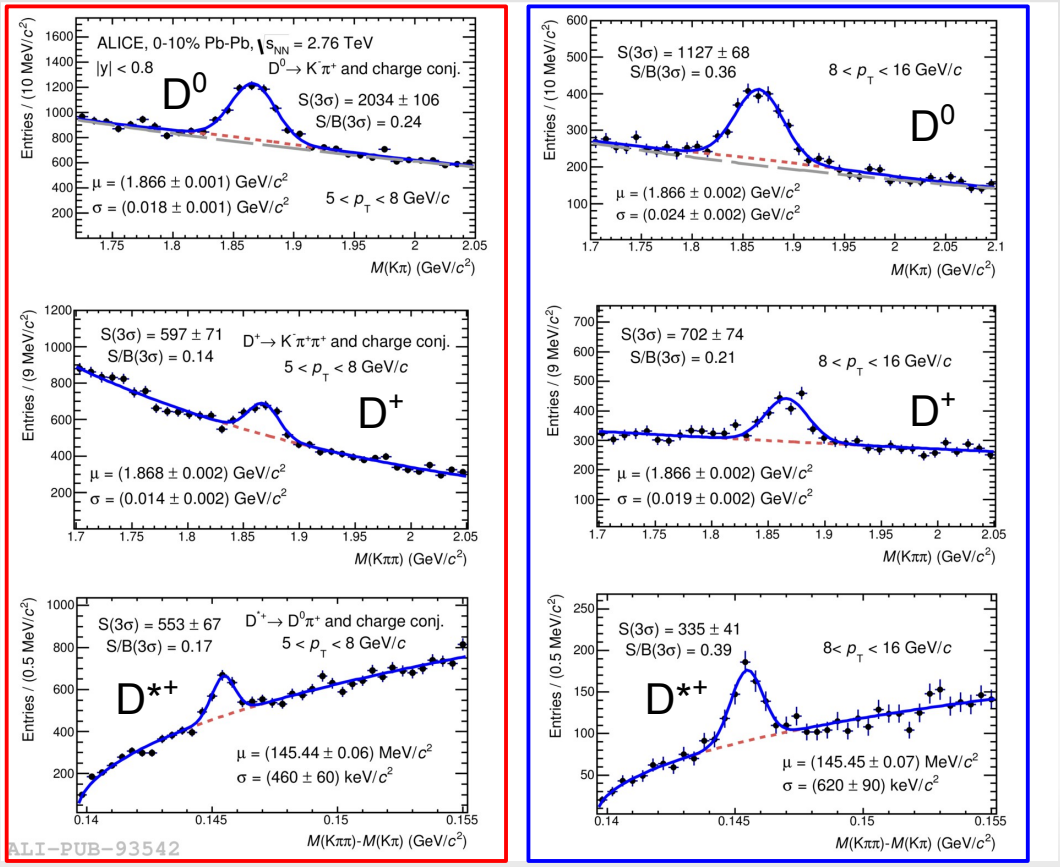
TOF: PID via time of flight

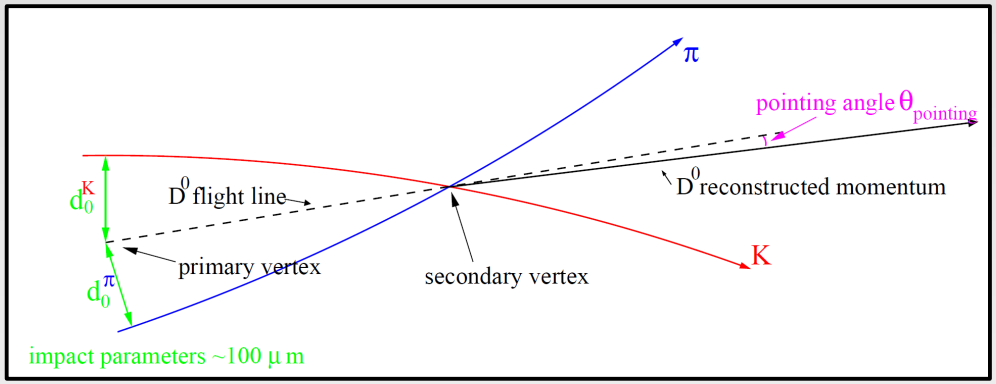
TPC: tracking, PID via d*E*/d*x*, event plane determination

D mesons via hadronic decay channels

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

$5 < p_T < 8$ GeV/c | **$8 < p_T < 16$ GeV/c**





$D^0 \rightarrow K^-\pi^+$	$c\tau \sim 123$ μm	BR~3.88%
$D^+ \rightarrow K^-\pi^+\pi^+$	$c\tau \sim 312$ μm	BR~9.13%
$D^{*+} \rightarrow D^0\pi^+$		BR~67.7%
$D_s^+ \rightarrow \phi\,\pi^+ \rightarrow K^-K^+\pi^+$	$c\tau \sim 150$ μm	BR~2.28%

$|y| < 0.8$

JHEP 03 (2016) 081

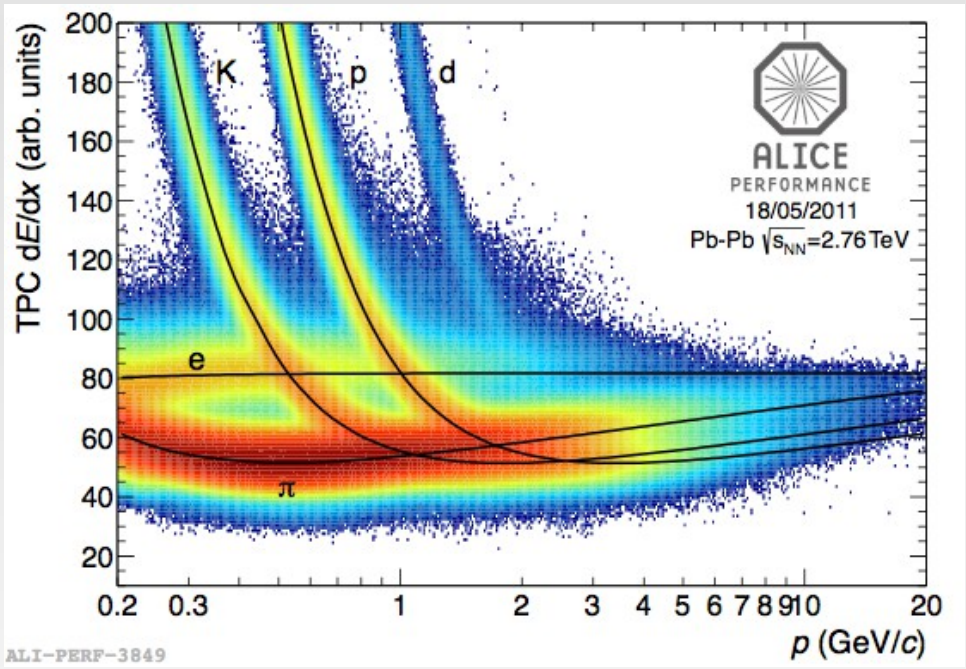
Electrons from heavy-flavour hadron decays

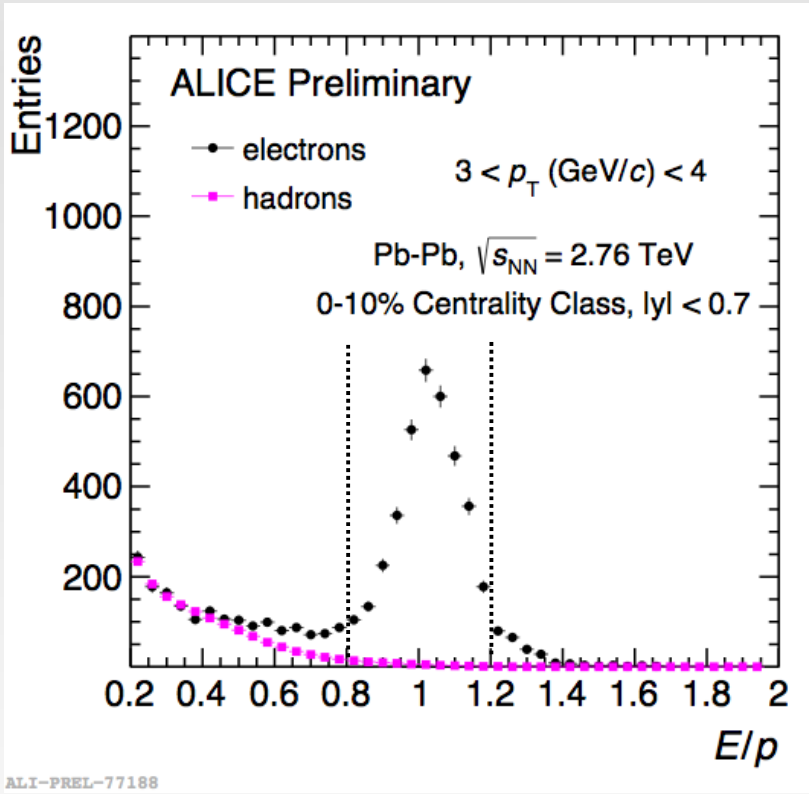
– **Low-p_T** electrons (p_T < 3 GeV/c): PID via TPC dE/dx complemented with TOF and ITS

– **High-p_T** electrons (p_T > 3 GeV/c): PID using TPC, EMCal

$-1\sigma < (\text{TPC } dE/dx - \langle \text{TPC } dE/dx \rangle_e)\text{TPC} < 3\sigma$

$(\text{TPC } dE/dx - \langle \text{TPC } dE/dx \rangle_e)\text{TPC} < -4\sigma$





Main background sources:

– direct and decay γ conversions

– π^0 and η Dalitz decays

|y| < 0.7

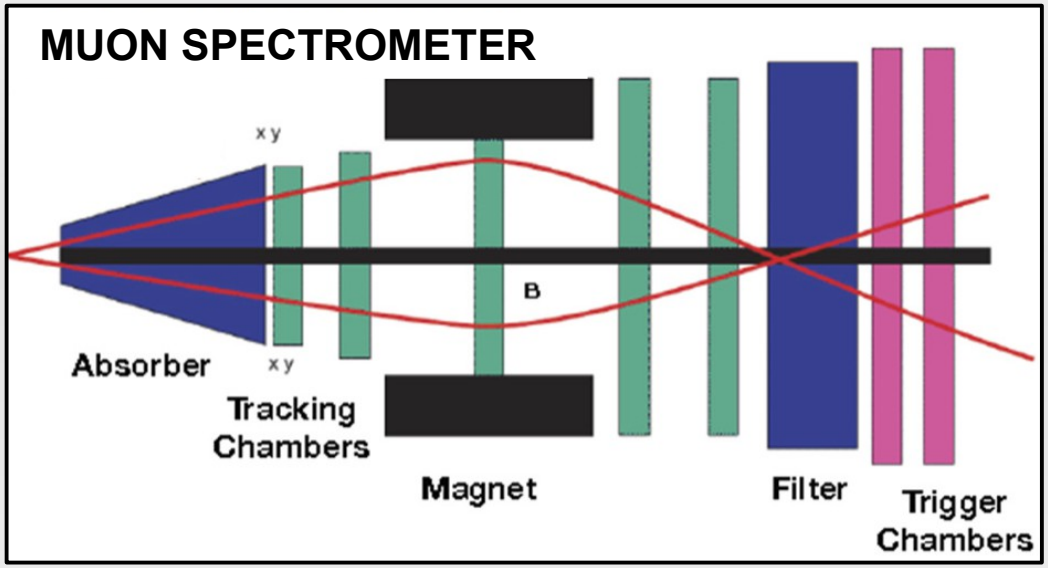
Background subtraction:

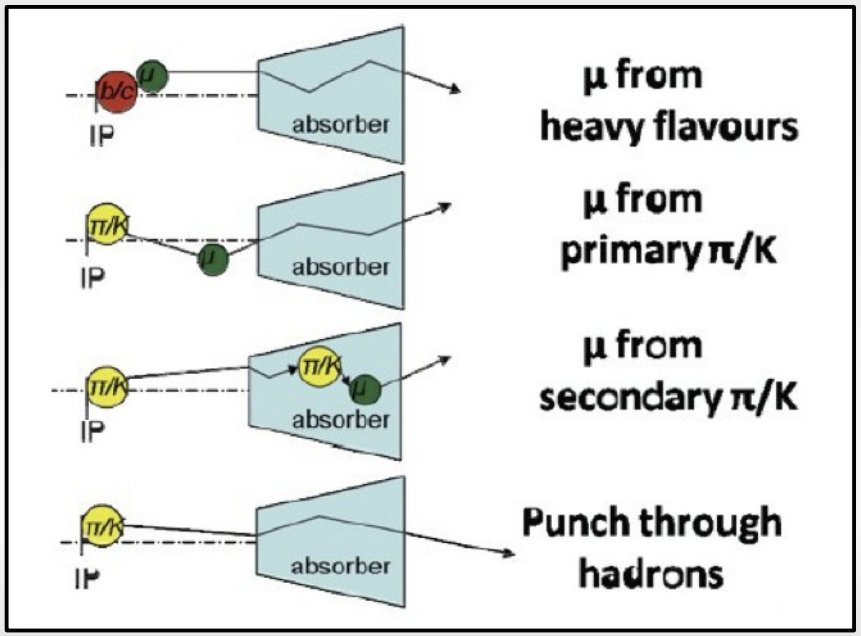
– Measured: invariant mass method (e^+e^- pairs)

– Calculated: cocktail method based on data.

Muons from heavy-flavour hadron decays

$-4 < \eta < -2.5$





Track selection:

– Acceptance and geometrical cuts

– Muon trigger matching:

reject the hadrons that cross the absorber

– Select tracks pointing back to the vertex:

Remove tracks from beam-gas interactions

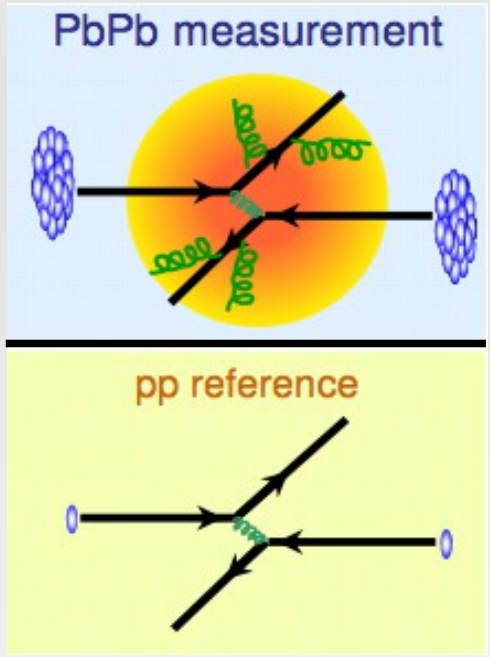
Remaining main background:

– μ from primary π and K decays (subtracted with MC-tuned cocktail)

– μ from W/Z/γ* decays at high p_T

Study in-medium energy loss

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



- **Observable**: nuclear modification factor

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

- 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

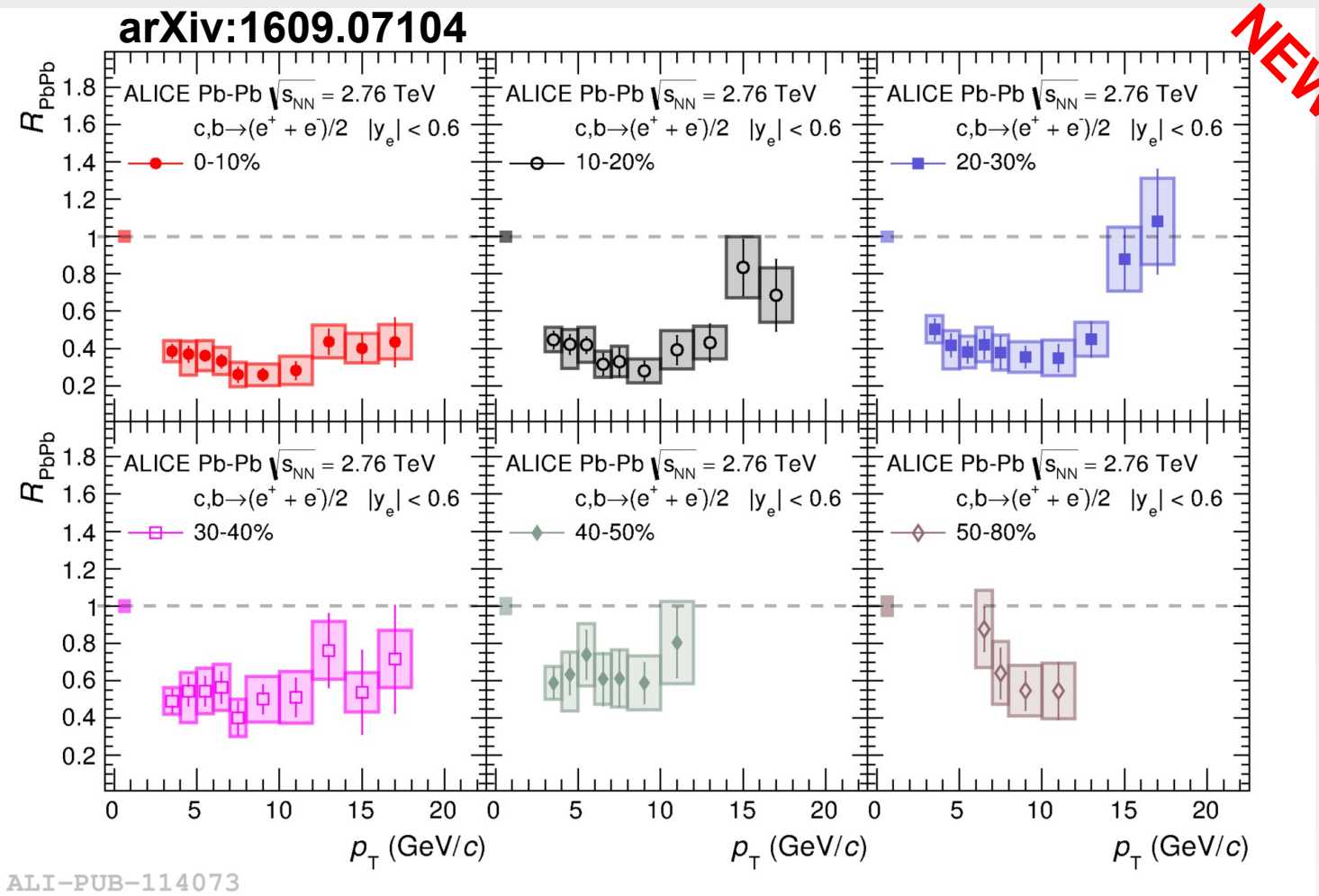
→ $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Need to compare R_{AA}^{π}, R_{AA}^{D}, R_{AA}^{B}

? → $R_{AA} \neq 1$

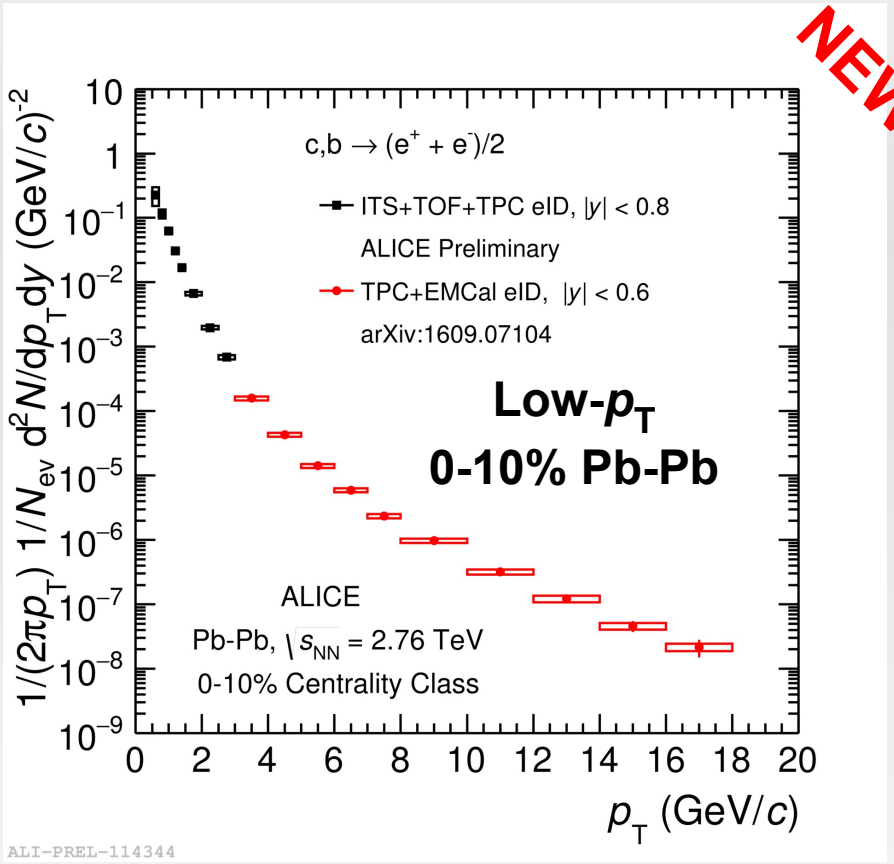
Dokshitzer and Kharzeev, PLB 519 (2001) 199
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

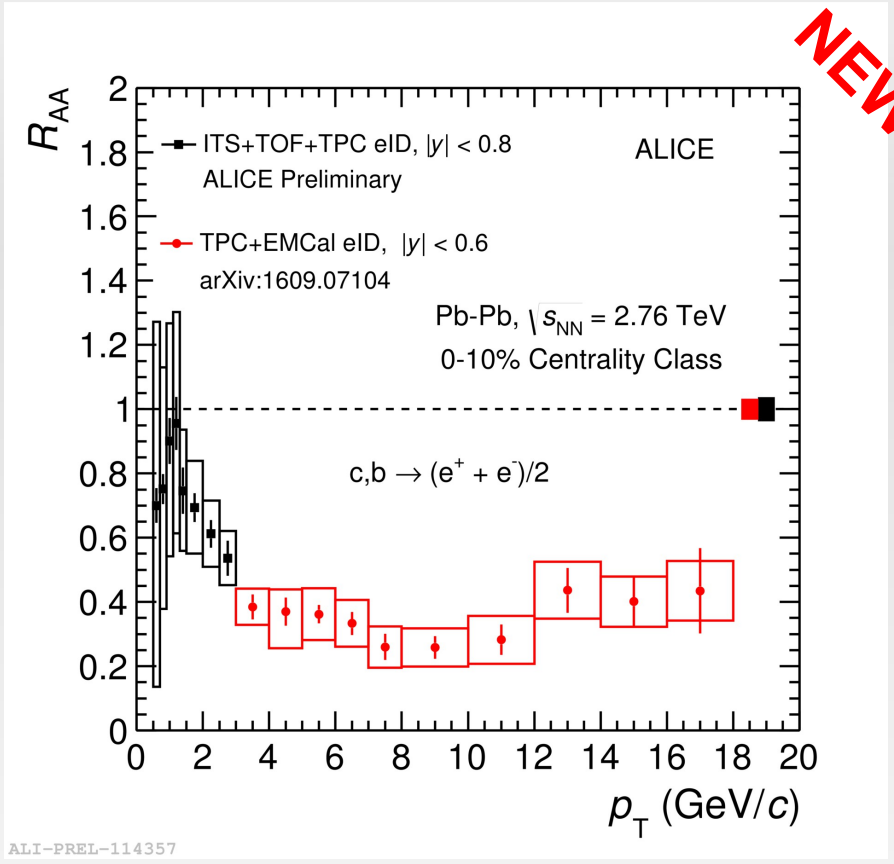
Heavy-flavour decay electron nuclear modification factor



New high p_T R_{AA} measurements in several Pb-Pb centrality classes show stronger suppression in the 10% most central collisions respect to semi-central collisions. Stronger energy loss in central collisions due to the increase of medium density

Heavy-flavour decay electron nuclear modification factor





New R_{AA} measurements in 0-10% central Pb-Pb collisions are extended down to p_T = 0.5 GeV/c

→ **low-p_T** measurements **crucial** in all systems to **test binary scaling** of total $c\bar{c}$ cross section

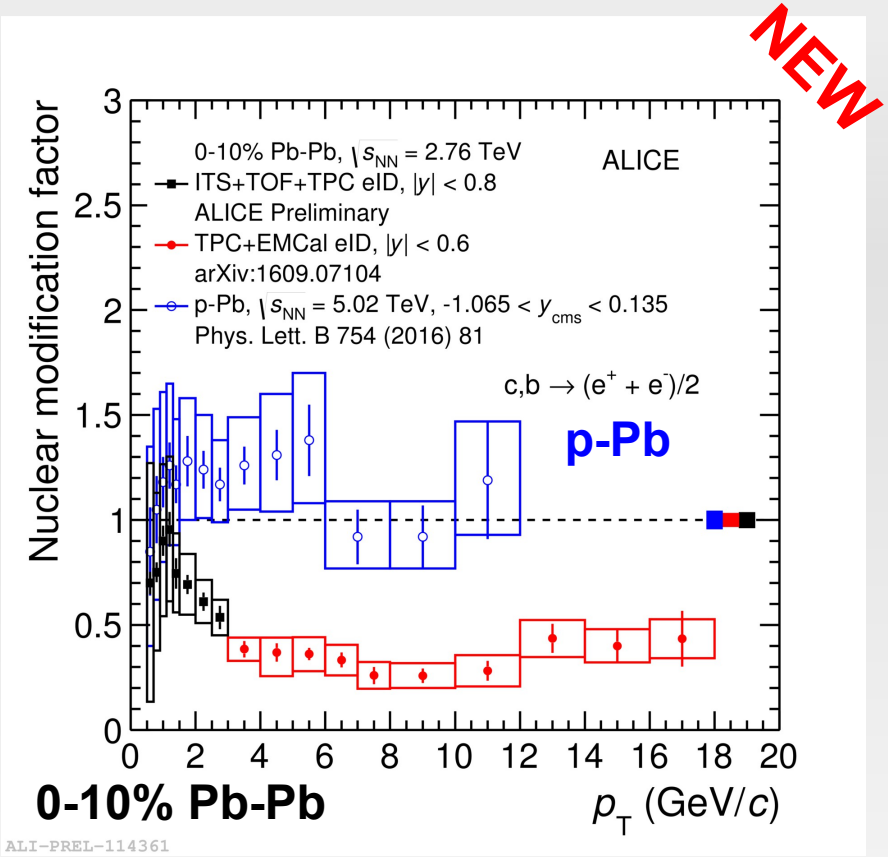
→ systematic uncertainty dominated by the pp reference at the same collision energy

(Phys. Rev. D 91 (2015) 012001)

→ Suppression compatible with the one observed in the muon decay channel

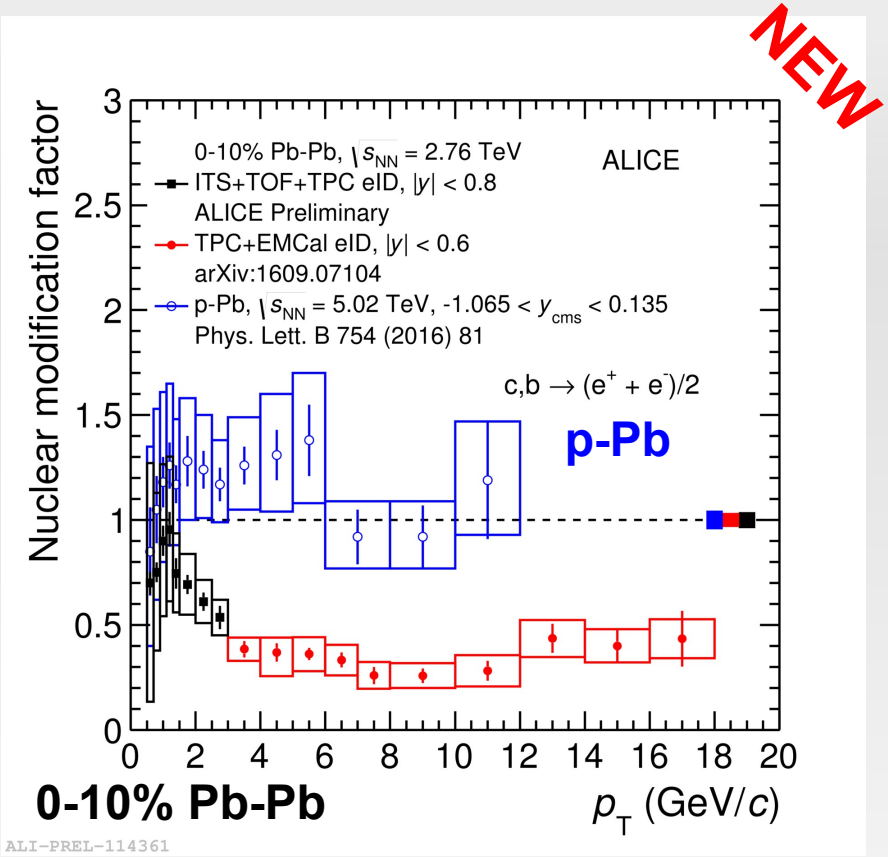
(talk Zuman Zhang: Sunday 25th – 10:40)

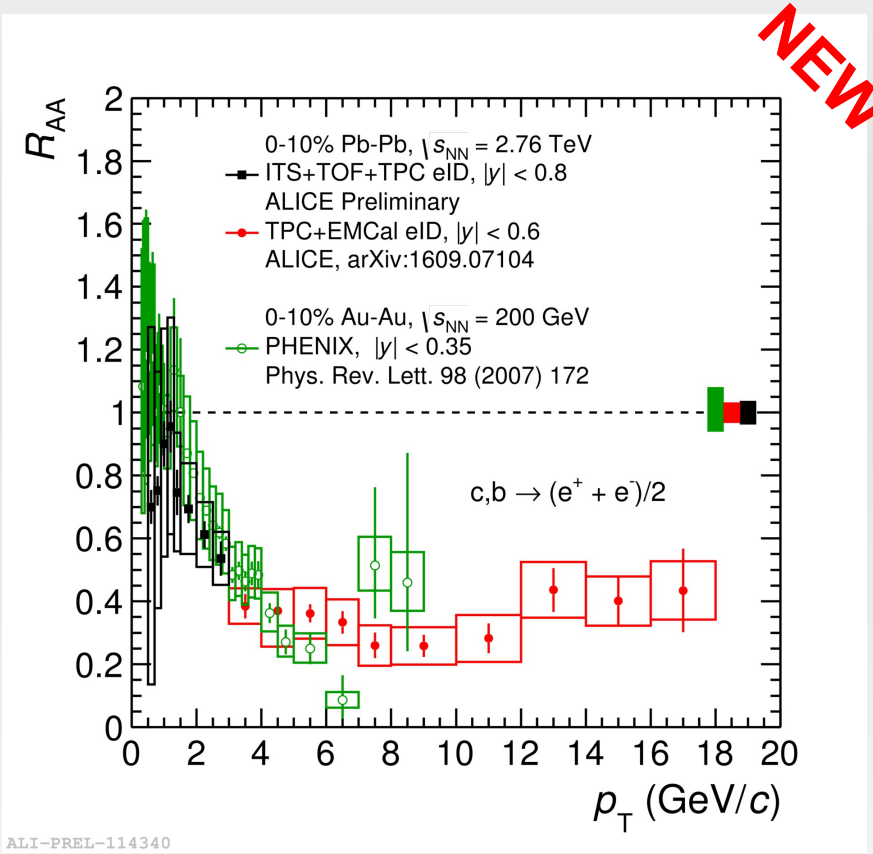
Heavy-flavour decay electron nuclear modification factor



- R_{pPb} **consistent with unity (PLB 754 (2016) 81)** → no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- **Large suppression** at high p_T in **Pb-Pb** collisions
  → **final-state effect** due to heavy quarks in-medium energy loss

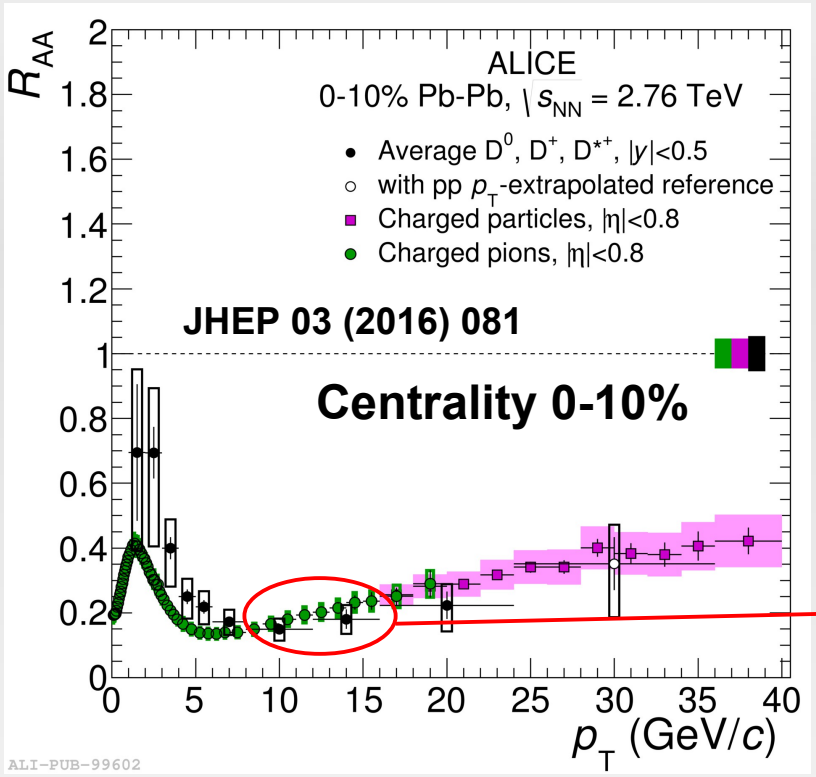
Heavy-flavour decay electron nuclear modification factor

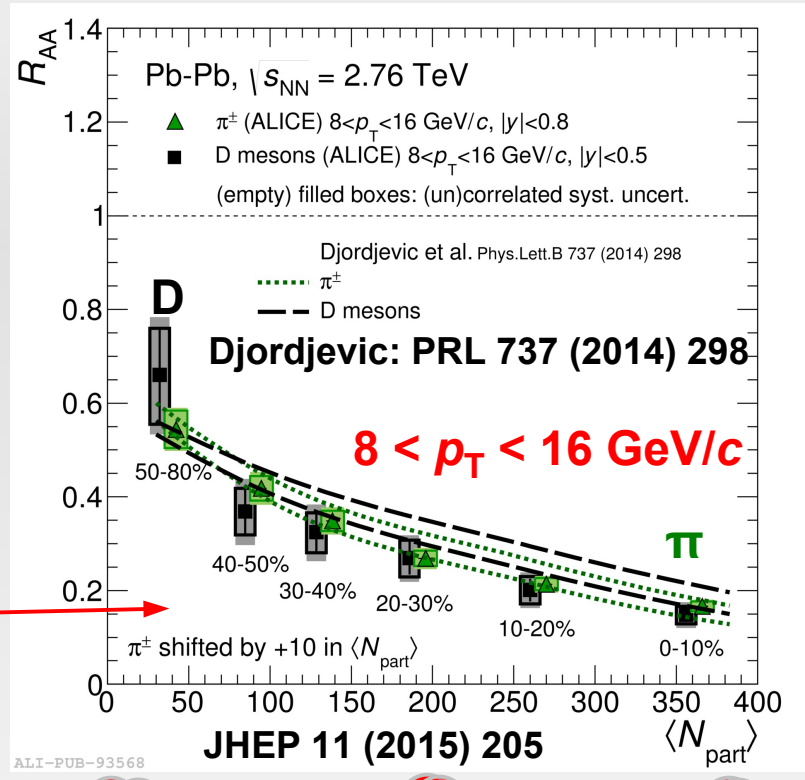




- R_{pPb} **consistent with unity (PLB 754 (2016) 81)** → no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- **Large suppression** at high p_T in **Pb-Pb** collisions
  → **final-state effect** due to heavy quarks in-medium energy loss
- R_{AA} compatible within uncertainties with **PHENIX (PRL 98, (2007) 172)** at low p_T

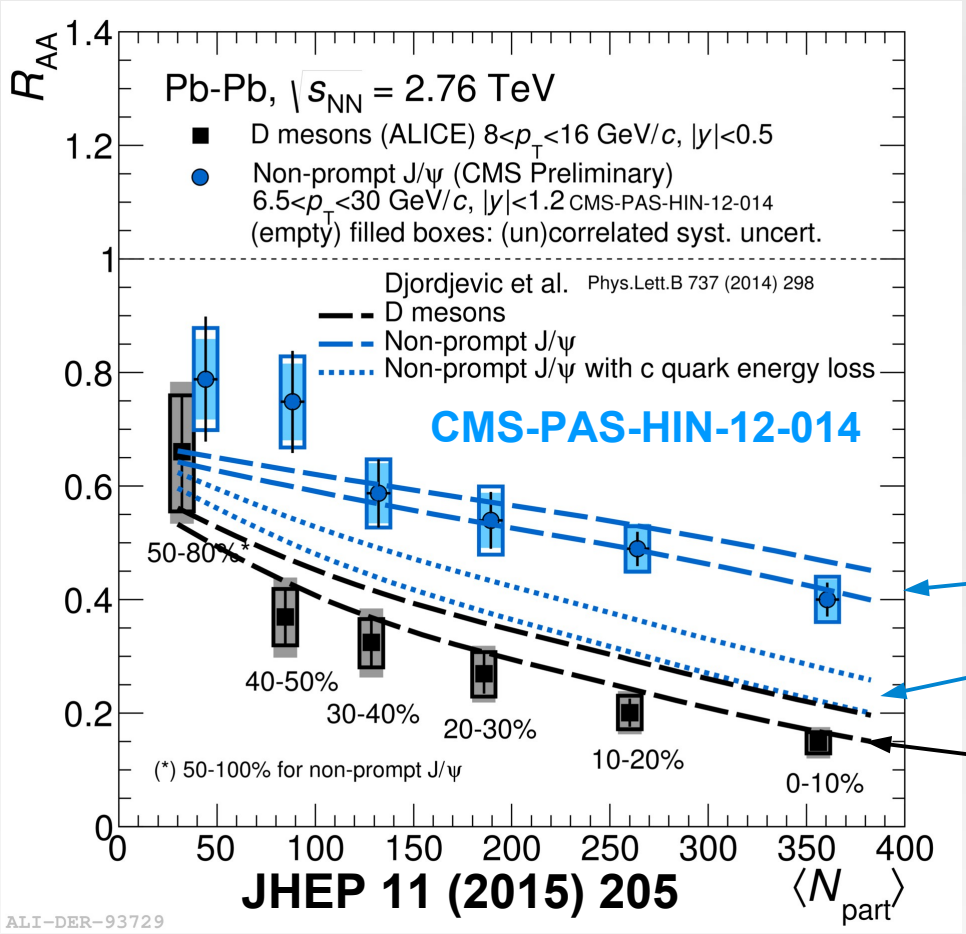
D-meson and pion nuclear modification factor





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

D-meson and J/ψ ← B R_{AA} vs centrality



– Similar <p_T> (~10 GeV/c) for D and B mesons (J/ψ ← B) from CMS
– Rapidity range slightly different
– **Indication of R_{AA}(D) < R_{AA}(J/ψ ← B)** in central events at high p_T

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

– b quark mass
– c quark mass

Testing the mass dependence

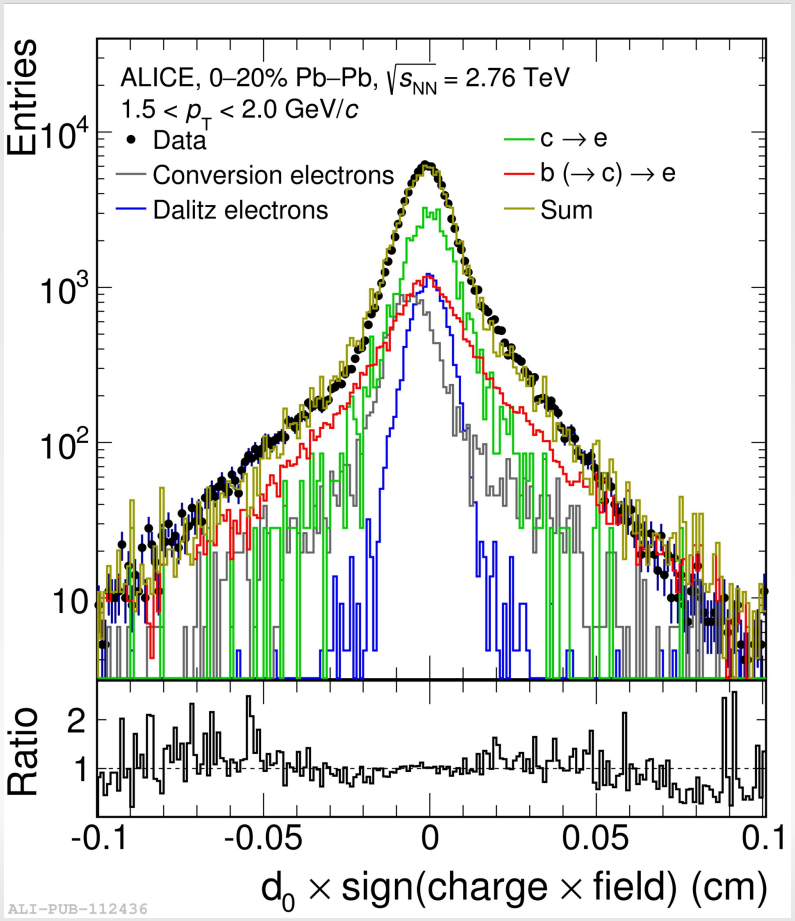
✔ **Djordjevic**: D-meson R_{AA} **PRL 737 (2014) 298**

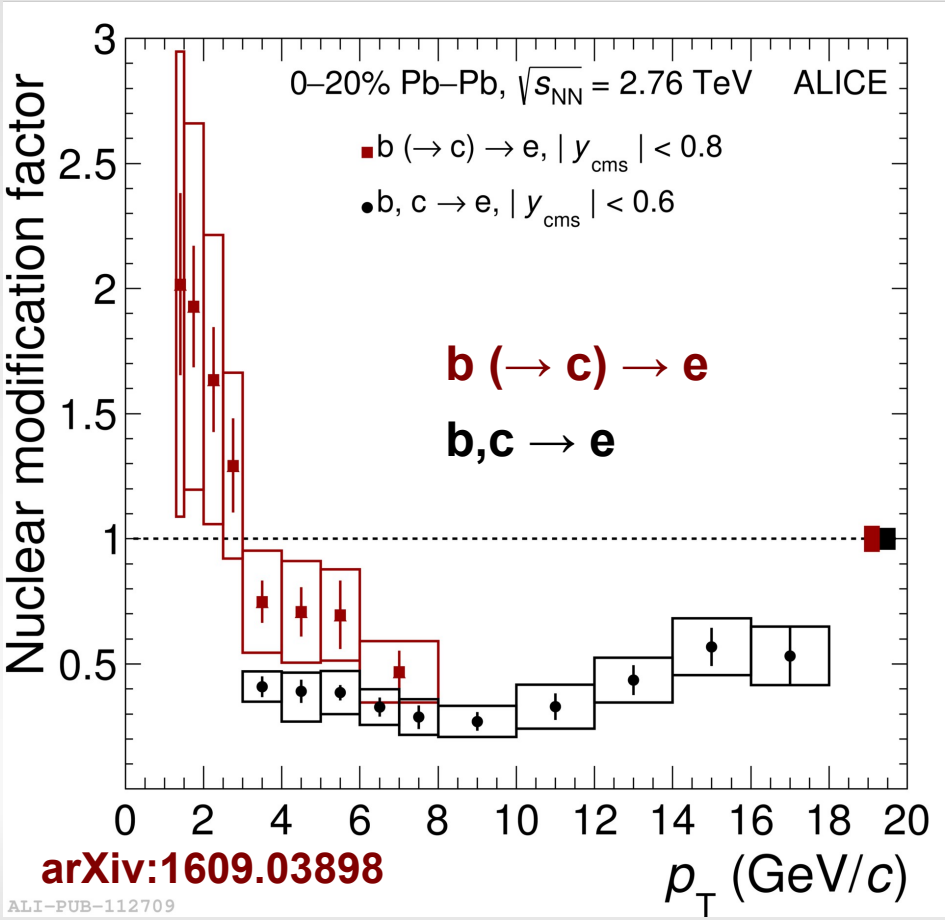
– **pQCD model including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt J/ψ R_{AA} similar to that observed**
– Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.)

Beauty-decay electron R_{AA}

– Analysis based on the electron impact parameter distribution.

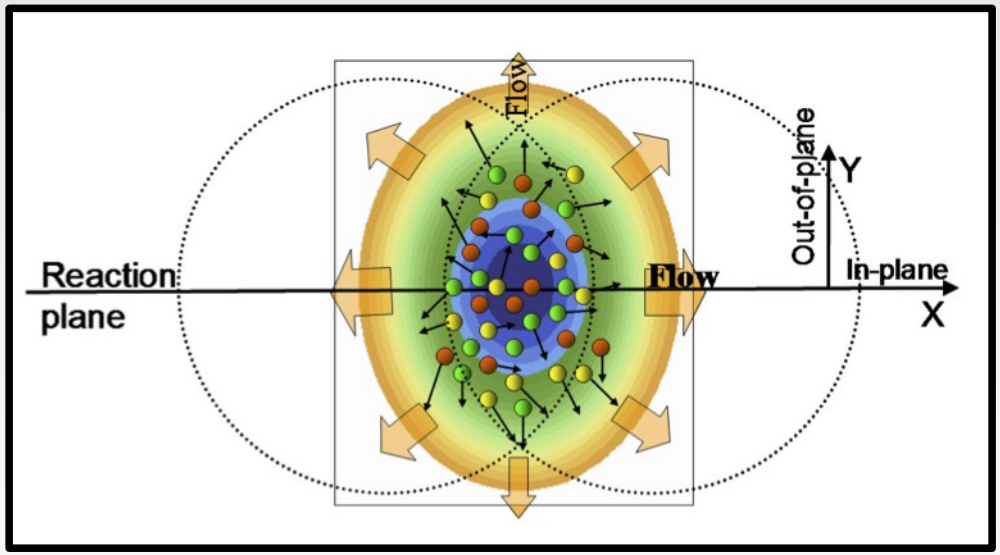
– First R_{AA} measurement of beauty-decay electron:
→ $R_{AA} < 1$ for $p_T > 3$ GeV/c
→ consistent with the picture of **mass-dependent radiative and collisional energy loss**





Collectivity: azimuthal anisotropy

- Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**
- In addition, path-length dependent energy loss induces an asymmetry in momentum space
- **Observable**: **elliptic flow v_2 =** 2nd Fourier coefficient of the particle azimuthal distribution



$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\Psi_\mathrm{RP})]\right)$$

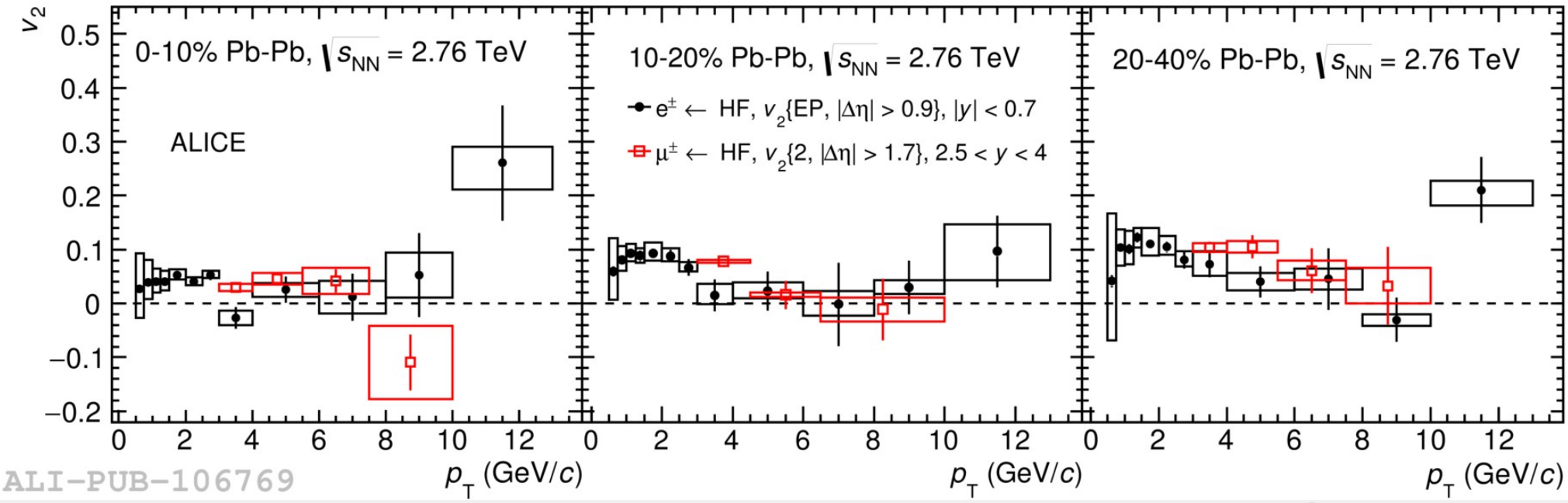
Heavy-flavour v_2 measurements probe:

- **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

Leptons from heavy-flavour hadron decays

HF-decay muons
$-4 < \eta < -2.5$
PLB 753, (2016) 41

HF-decay electrons
$|y| < 0.7$
arXiv:1606.00321

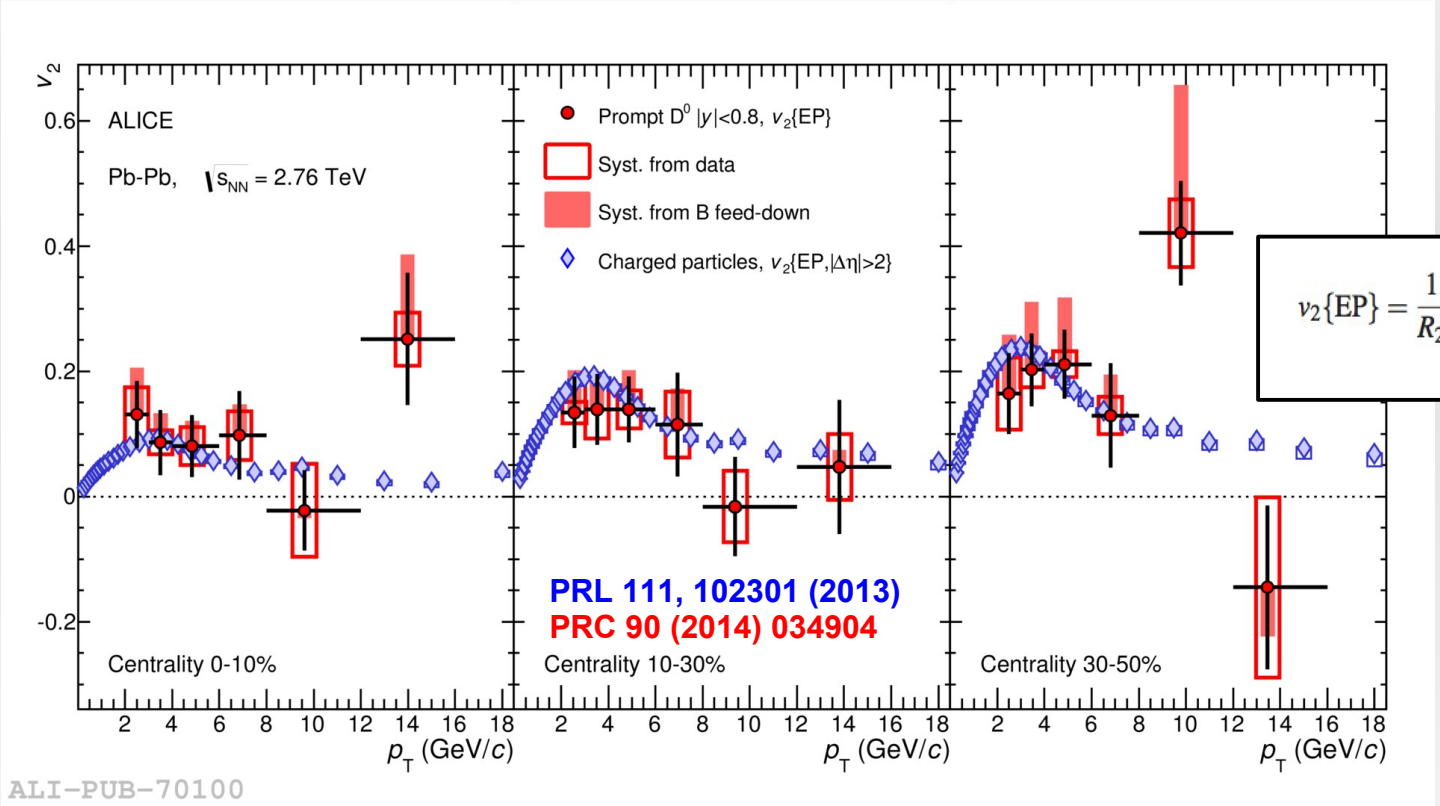


v_2 of heavy-flavour decay **electrons** (at mid-rapidity) and **muons** (at forward rapidity) are similar in the different centrality classes. Positive v_2 observed → 5.9σ effect for $2 < p_T < 2.5$ GeV/c in 20-40% centrality class for the heavy-flavour decay electrons.

Hint for an increase of v_2 from central to semi-central collisions as observed for D mesons

Suggests collective motion of low-p_T charm quarks in the expanding fireball

D-meson elliptic flow



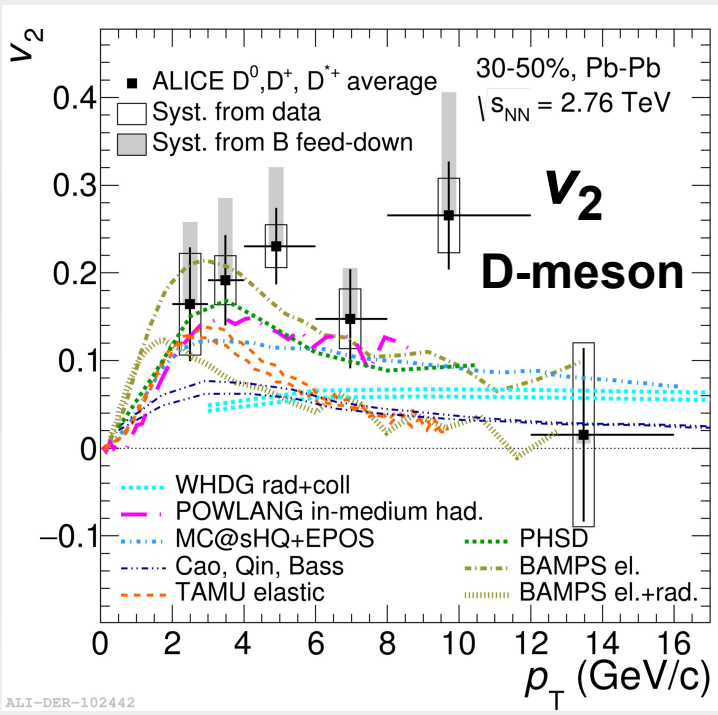
$$v_2\{\mathrm{EP}\} = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}.$$

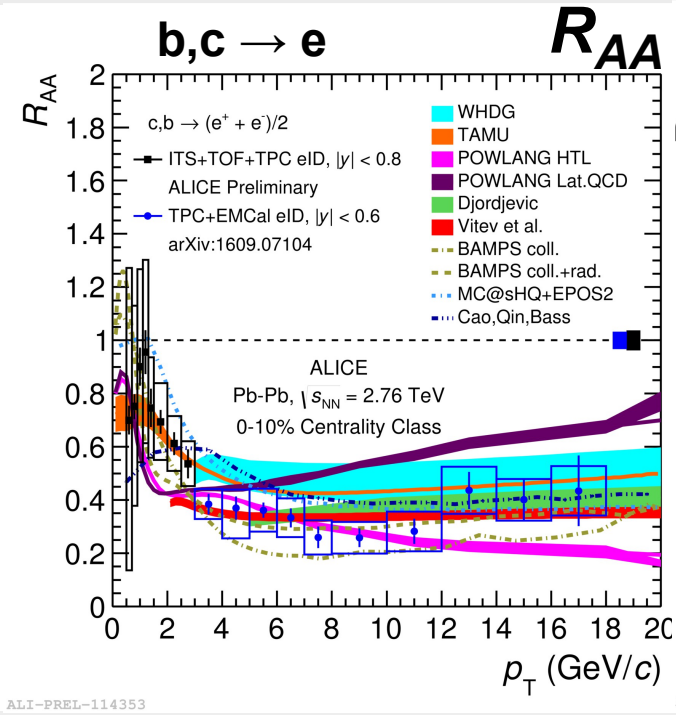
Positive v_2(D) observed (5σ effect for $2 < p_T < 6$ GeV/c in 30-50% centrality class)

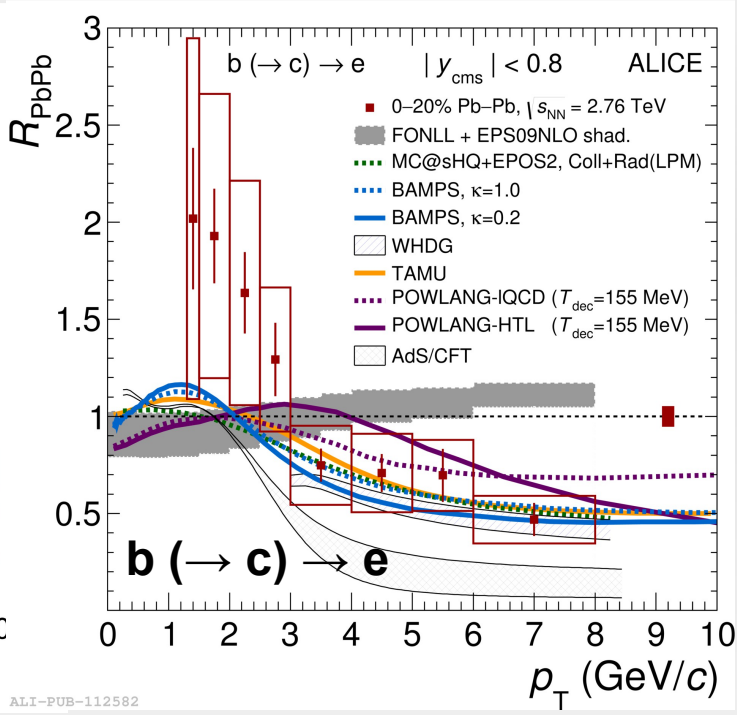
D-meson v_2 similar to **charged-particle v_2**

Confirms significant interaction of charm quarks with the medium

Model predictions: R_{AA} and v_2







– v_2 and R_{AA} measurements for different heavy-flavour decay channels together start to provide constraints for models

– POWLANG: EPJ C 75 (2015) 121;
– 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: PRL 737 (2014) 298

Conclusion

→ Strong **suppression** of **heavy-flavour** yields at high p_T → **final-state effect**
- D mesons at central rapidity
- Semi-leptonic decays at central and forward rapidity

→ Larger suppression for **D mesons** with respect to **B mesons** (non-prompt J/ψ by CMS) at high p_T
- Described by theoretical models implementing **mass-dependent** energy loss

→ Hint for $R_{AA} < 1$ for beauty decay electrons at high p_T

→ A **non-zero elliptic flow** of heavy flavours was measured in **semi-central** collisions

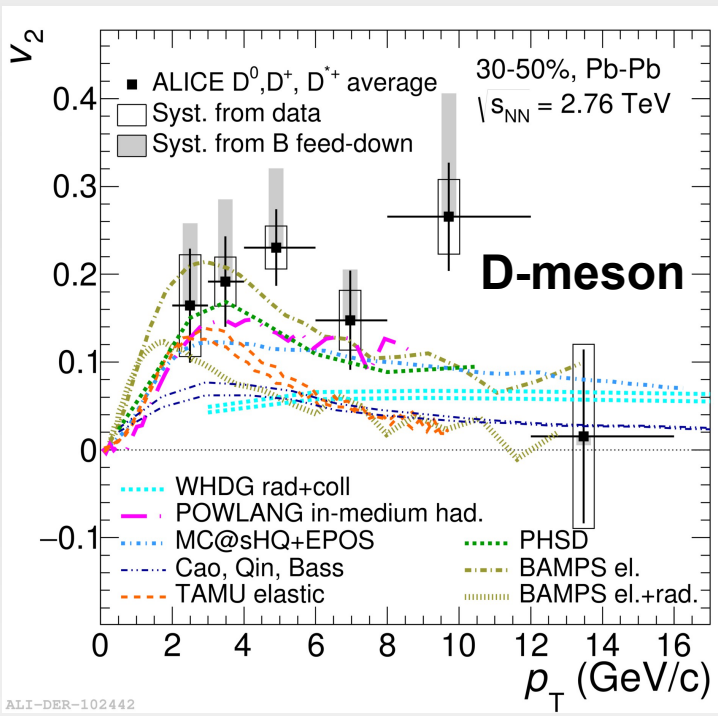
→ Hint for an **increase** of heavy-flavour v_2 from **central to semi-central collisions**
- D-meson elliptic flow similar to charged-particle v_2
- 5.9σ effect in 20-40% centrality class for the heavy-flavour decay electrons

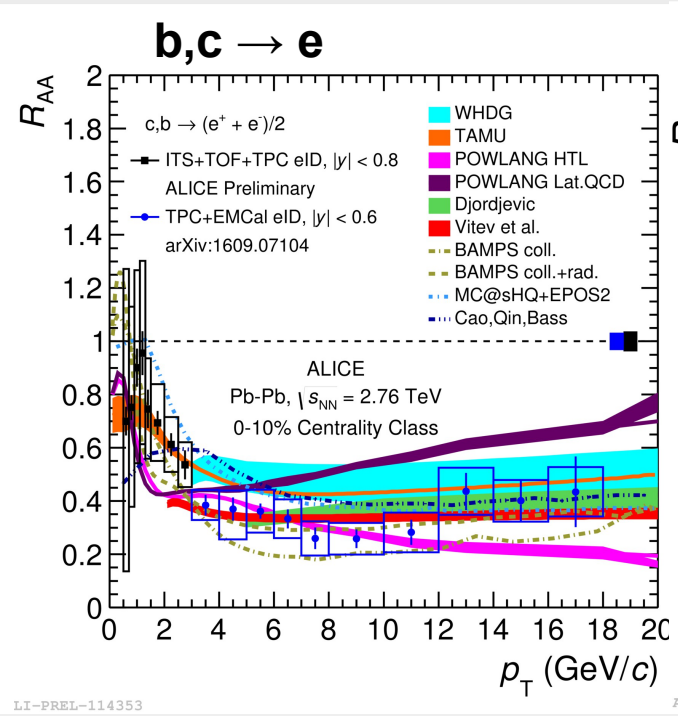
→ Suggests collective motion of low-p_T heavy quarks (mainly charm)

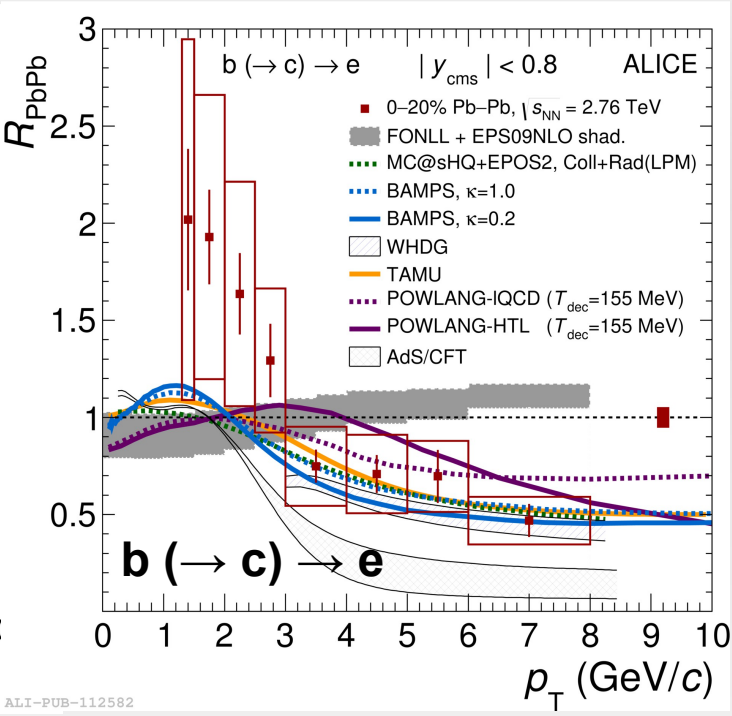
→ Comparison of **different observables** (R_{AA}, v_2) with theory starts to constrain the **energy-loss and hadronization models**

BACKUP

Model predictions: R_{AA} and v_2







– v_2 and R_{AA} measurements for different heavy-flavour decay channels together start to provide constraints for models.

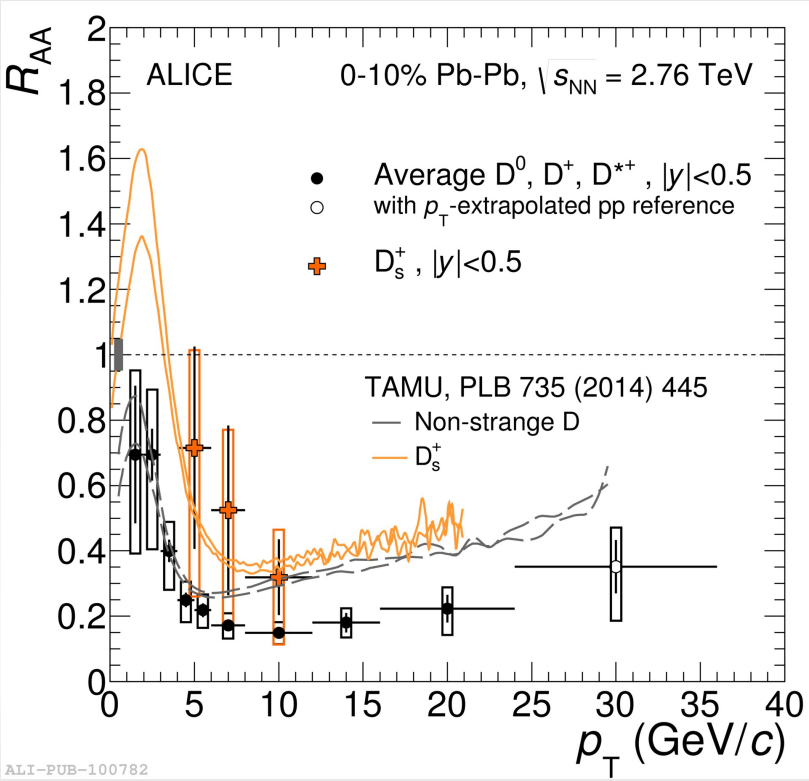
→ Both collisional and radiative energy loss mechanisms and an expanding medium seem to be needed to describe v_2 and R_{AA} for most of the model.

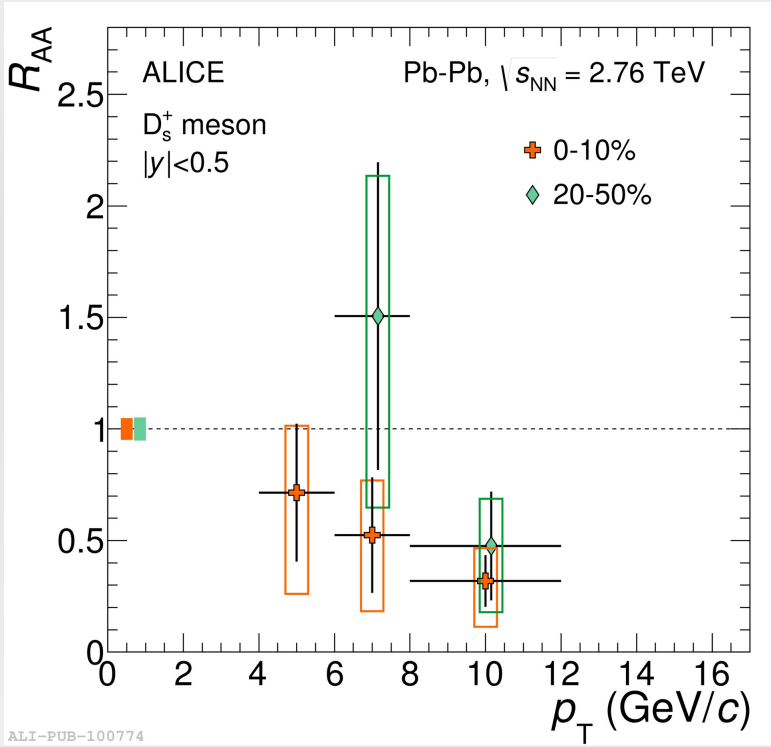
→ Role of recombination of heavy quark in the medium seems to help in describing v_2

Nuclear modification factor: D_s^+

- Measurement of D_s^+ production in Pb-Pb collisions
- **Expectation**: enhancement of the **strange** over **non-strange** D-meson yield at intermediate p_T if charm hadronizes via recombination in the medium, due to enhanced strangeness abundance

JHEP 03 (2016) 082

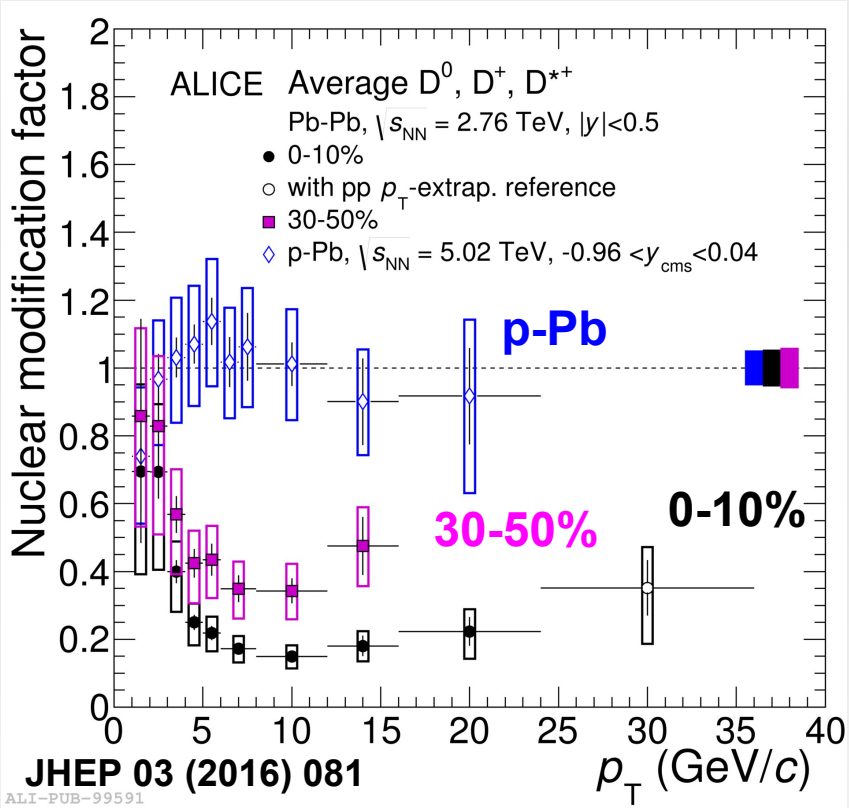


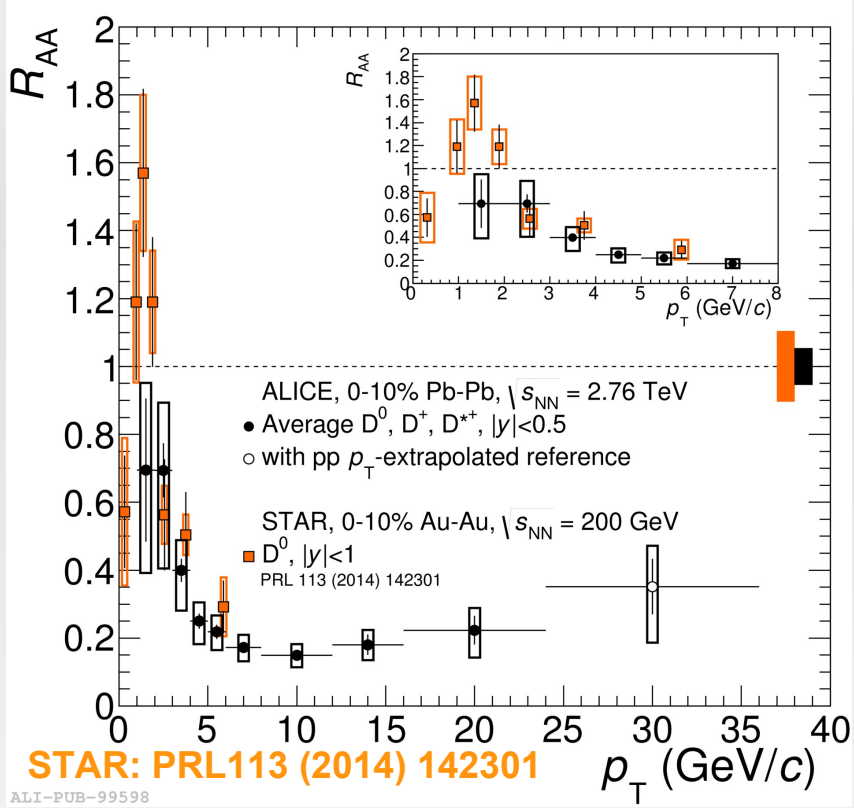


- Strong D_s^+ **suppression** in **central collisions** (similar to other D-meson) for $8 < p_T < 12$ GeV/c
  - Hint of less suppression for $p_T < 8$ GeV/c

TAMU: PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149
Kuznetsova, Rafelski EPJ C51 (2007) 113

D-meson nuclear modification factor





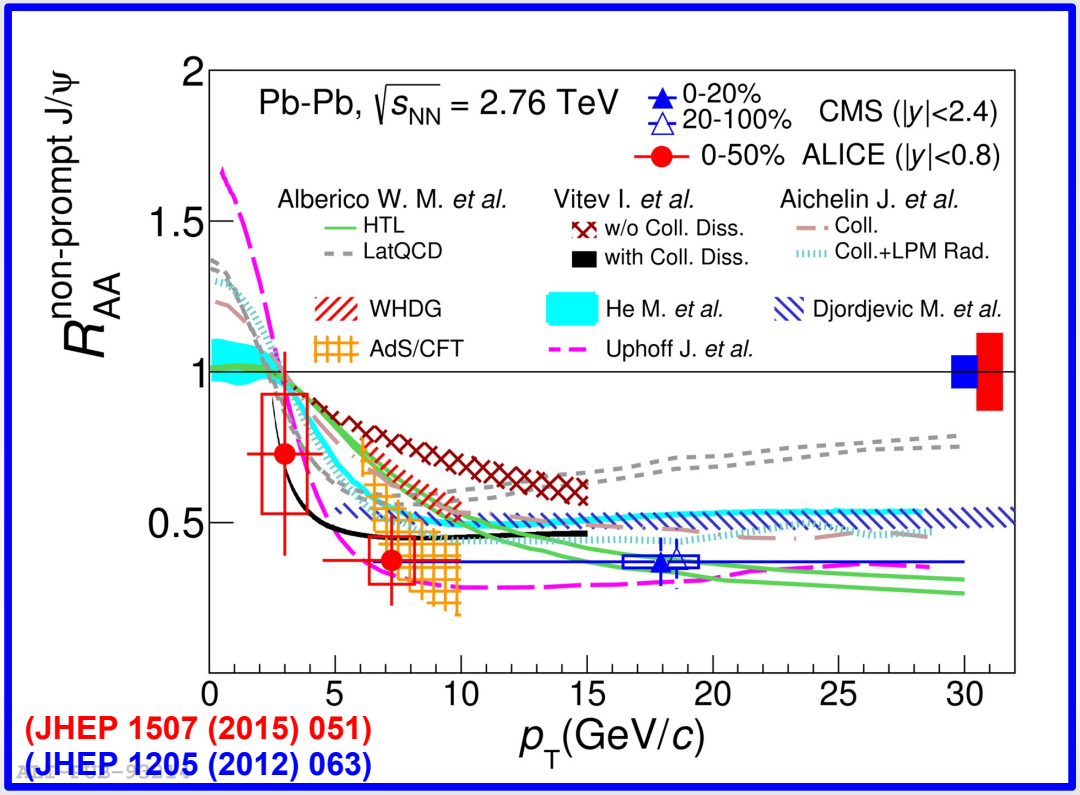
- R_{pPb} **consistent with unity (PRL 113 (2014) 232301)** → no strong modification of D-meson spectra in p-Pb collisions relative to pp collisions
- **Large suppression** of D-mesons at high p_T in **Pb-Pb** collisions → larger suppression in the 10% most central collisions → **final-state effect** due to charm quark in-medium energy loss
- **D-meson R_{AA}** compatible within uncertainties with **D^0 R_{AA} by STAR** for p_T > 2 GeV/c
  → low-p_T measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section

R_{AA} of beauty decay electrons and J/ψ ← B

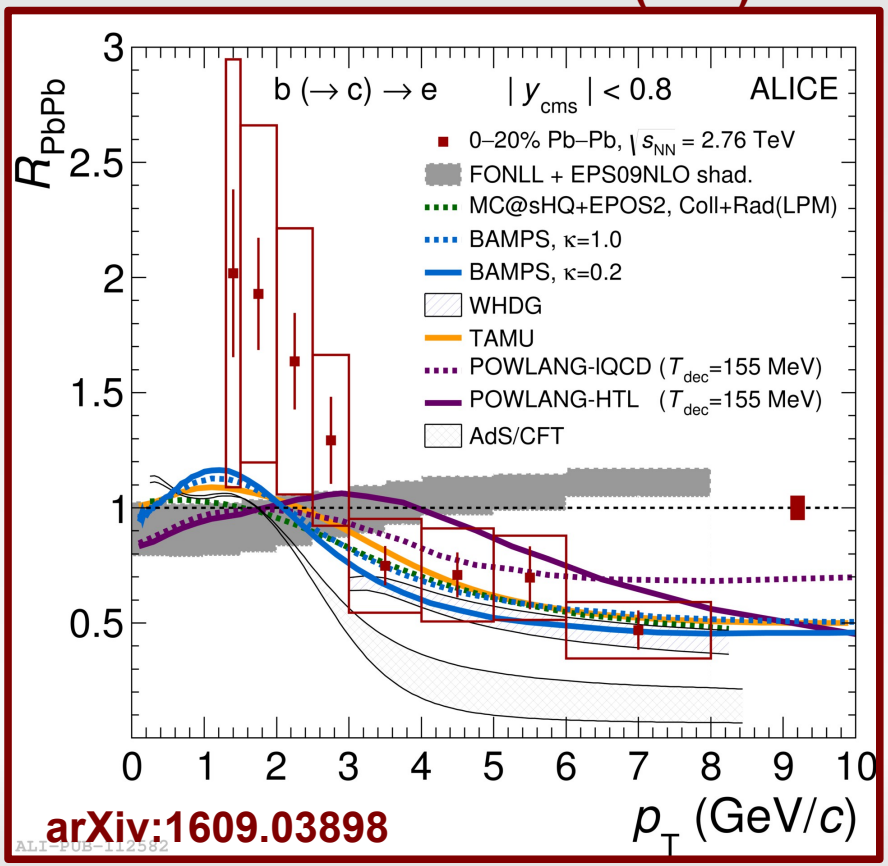
– **Indication of suppression R_{AA}(J/Ψ ← B)** in central events at high p_T

– **R_{AA} measurement of beauty:**
→ Hint for R_{AA} < 1 for beauty-decay electrons in p_T > 3 GeV/c

– models including in-medium energy loss can describe qualitatively the measured suppression



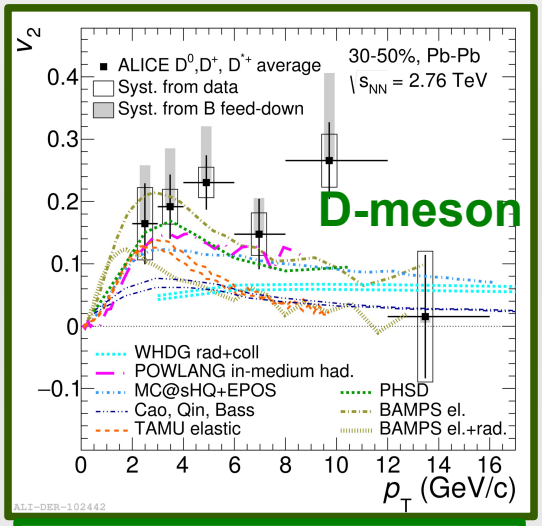
b (→ c) → e

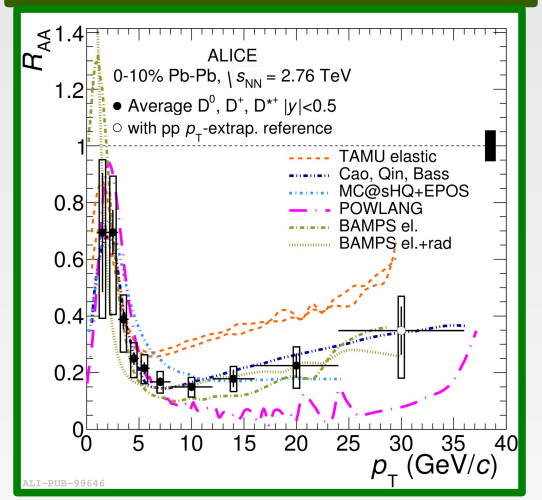


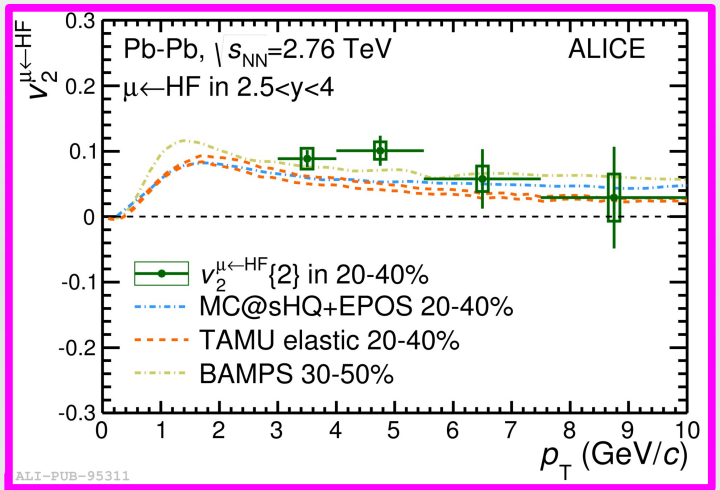
Model predictions: R_{AA} and v_2

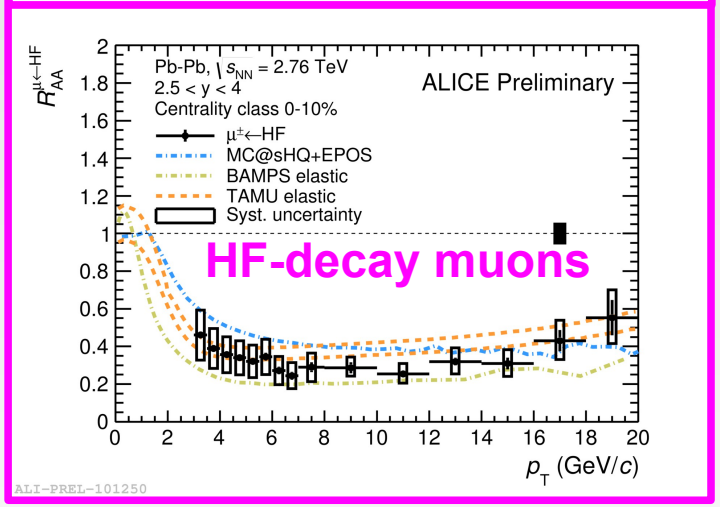
v_2

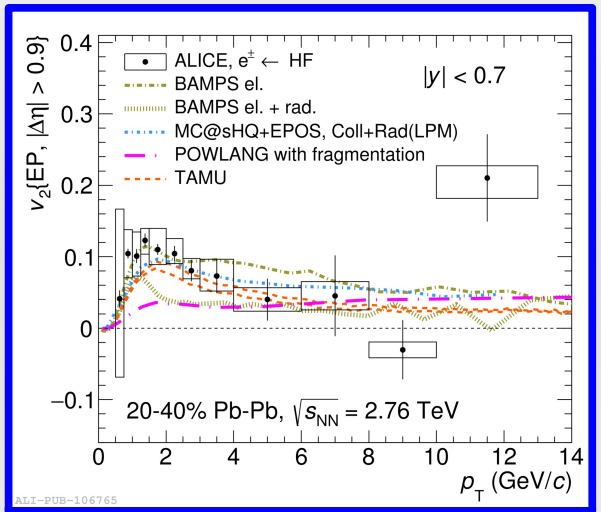
R_{AA}

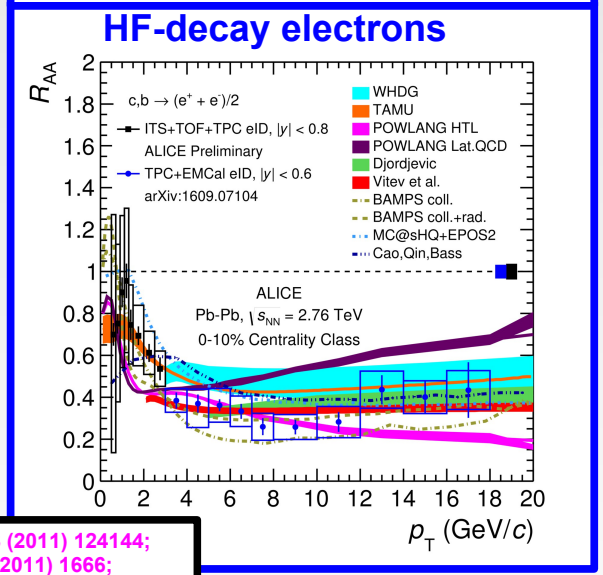








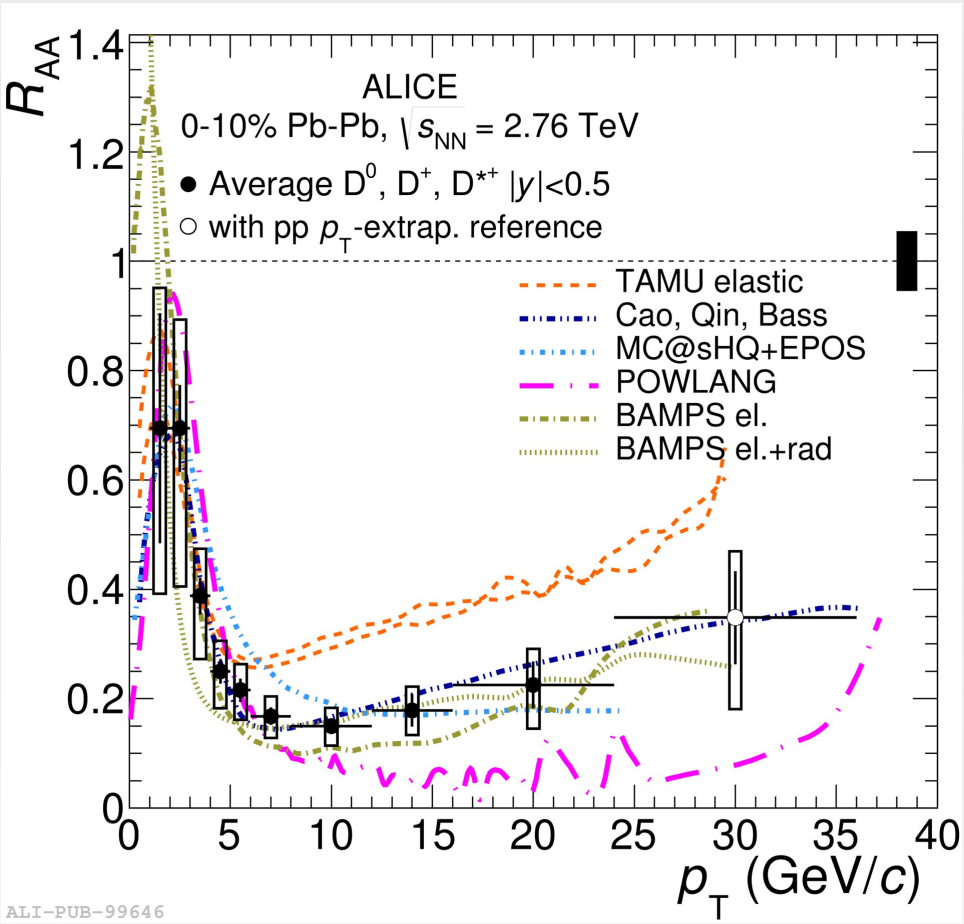


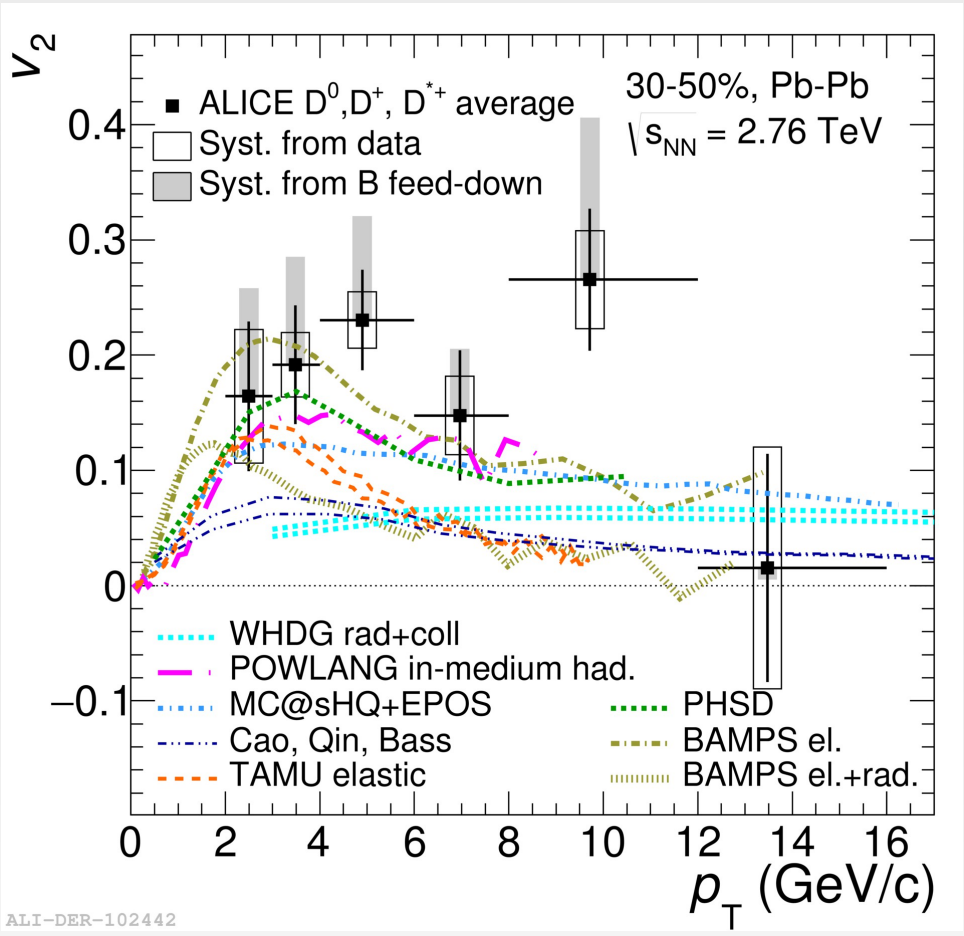


- v_2 and R_{AA} measurements together start to provide constraints for models

– 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: PRL 737 (2014) 298

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

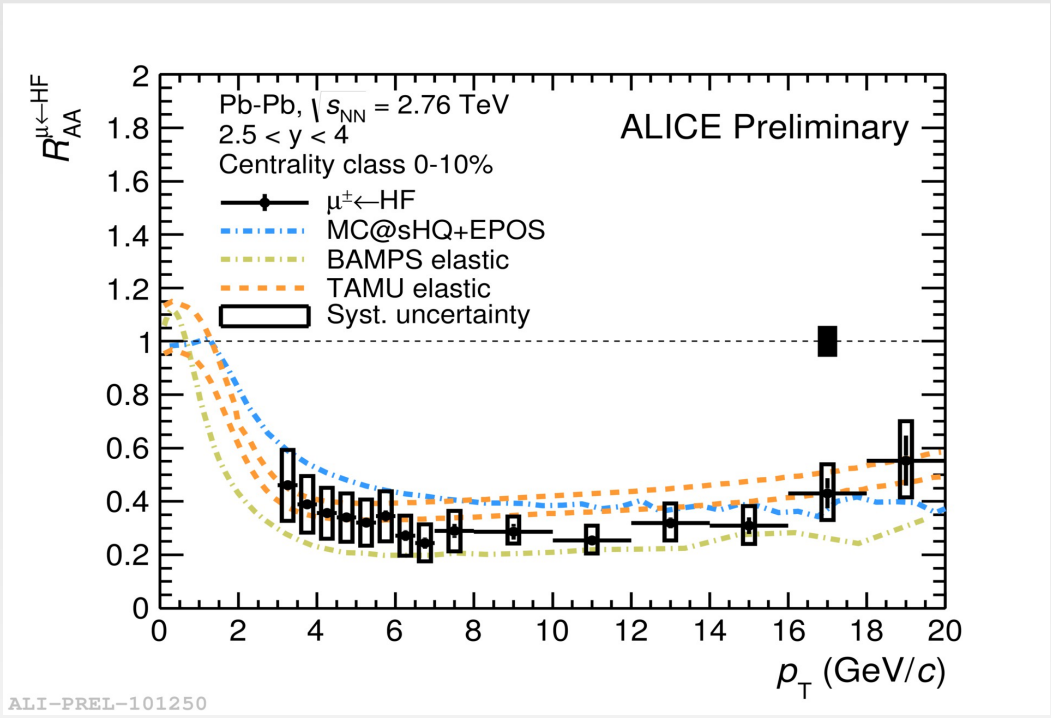


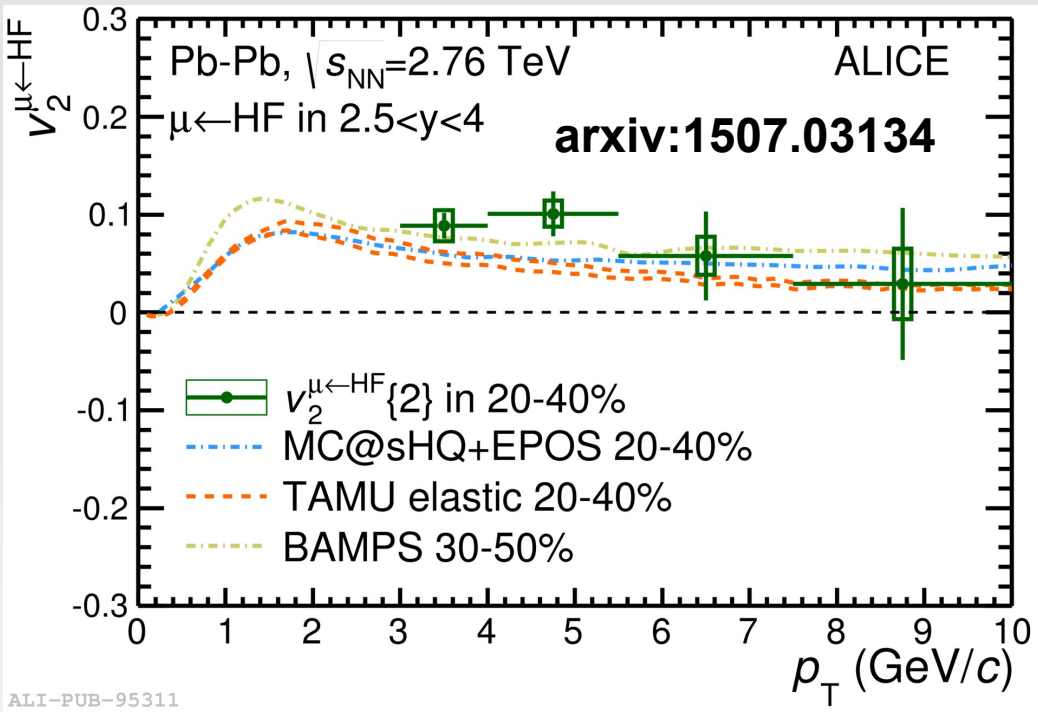


- models including in-medium energy loss can describe qualitatively the measured strong suppression (R_{AA} < 1) of the yield at high p_T and the anisotropy (v_2 > 0)
- v_2^D and R_{AA}^D measurements together start to provide constraints for models

Model predictions: HFM R_{AA} and v_2

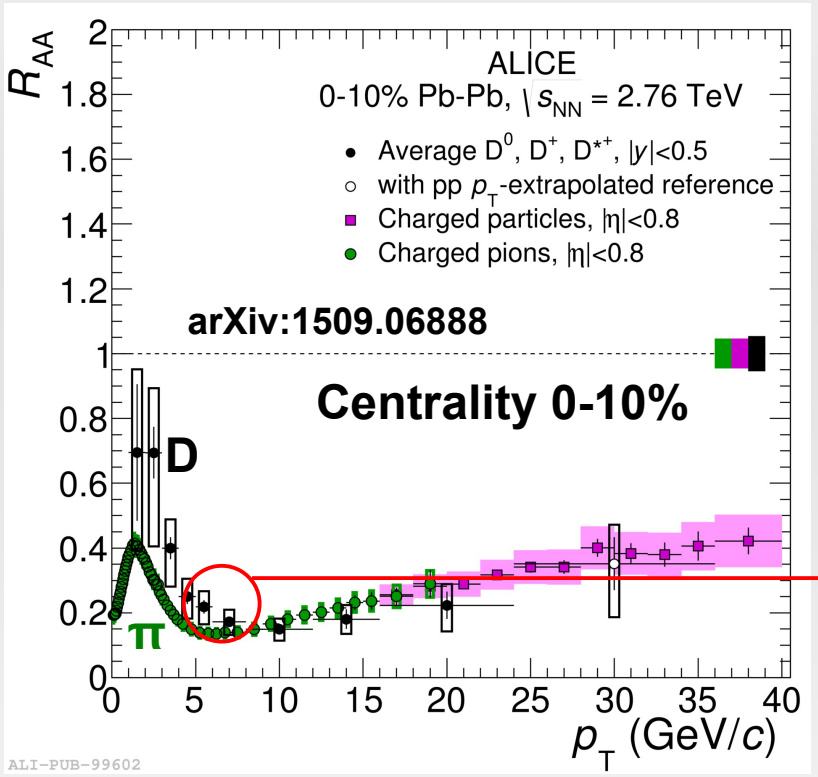
– TAMU: arXiv:1401.3817;
– MC@HQ+EPOS: PRC 89 (2014) 014905;
– BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];

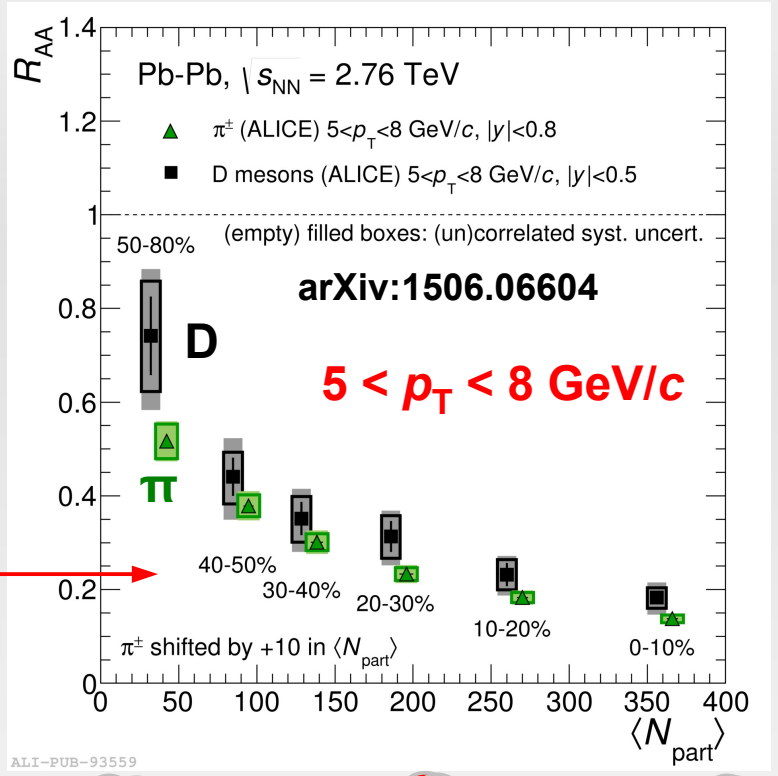




- Similar picture from the comparison of R_{AA} and v_2 to models as for other heavy-flavour measurements.
  → Models of in-medium parton energy loss can describe reasonably well heavy-flavour decay muons at forward rapidity.
- v_2^{HFM} and R_{AA}^{HFM} measurements together start to provide constraints for models

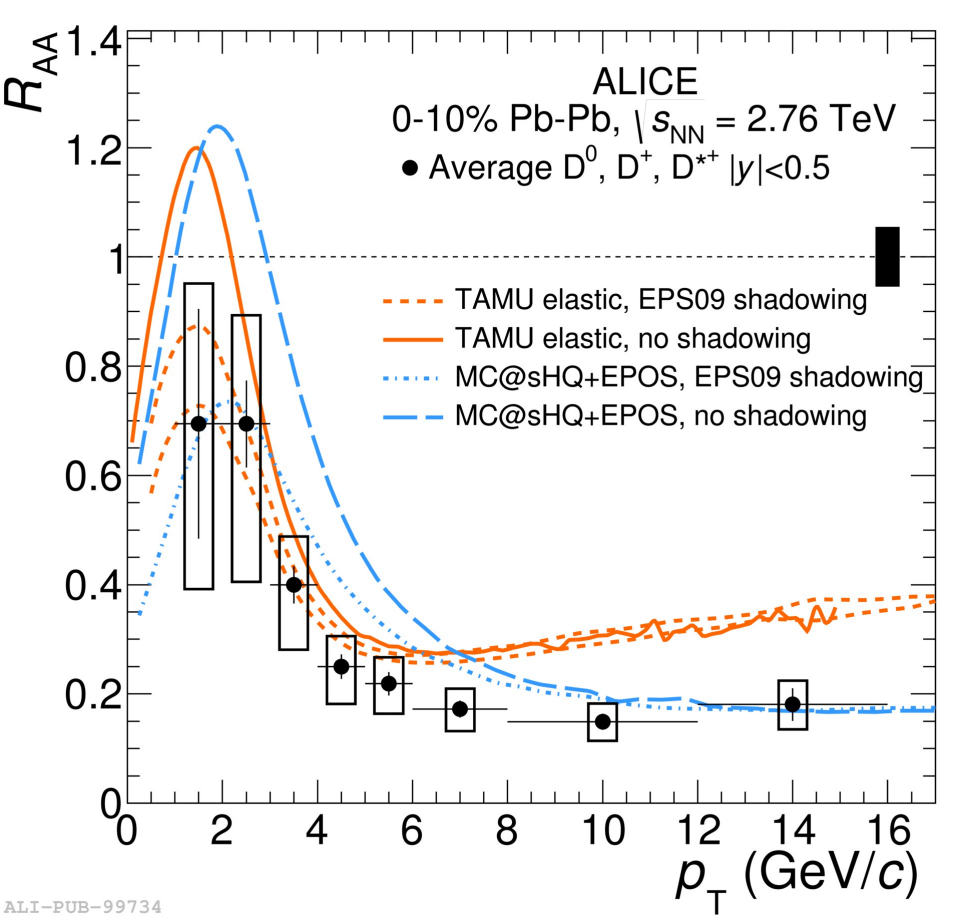
D-meson and pion R_{AA}





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

D-meson and pion R_{AA}



Centrality 0-10%

arXiv:1509.06888

MC@sHQ+EPOS2: PRC 89 (2014) 014905

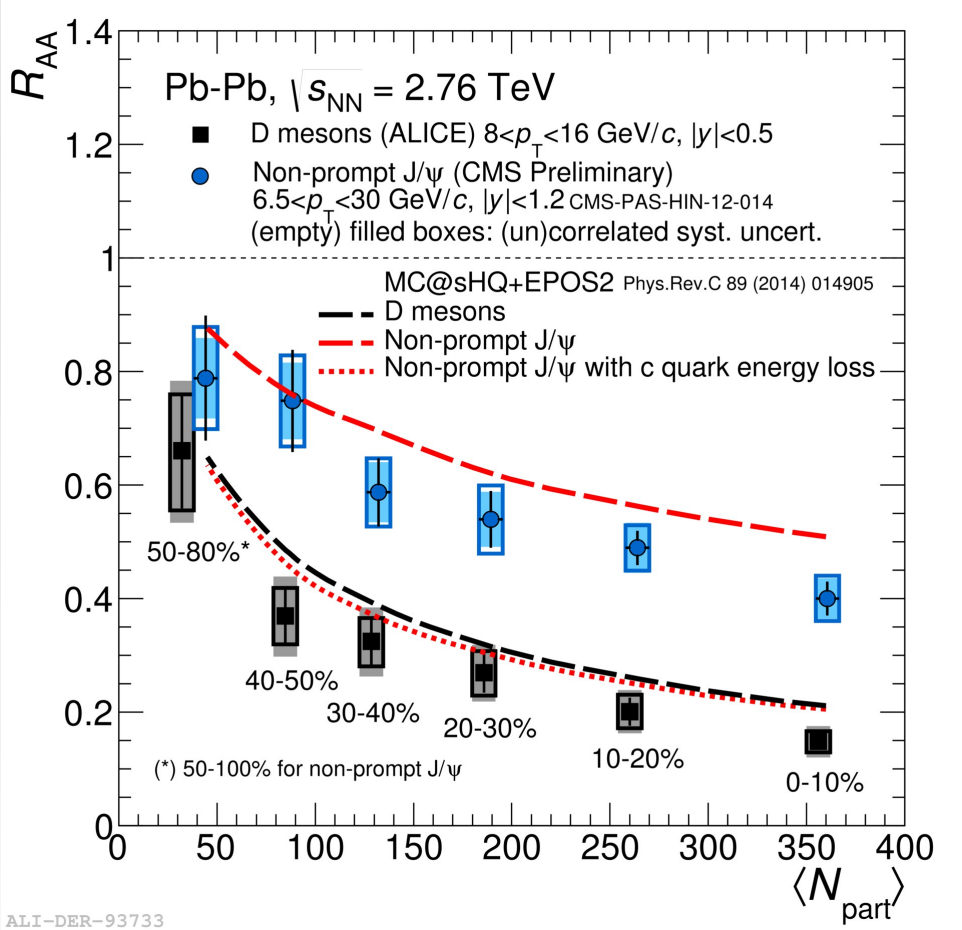
TAMU: PLB 735 (2014) 445

→ low-p_T measurements better described by model including nuclear shadowing (EPS09)

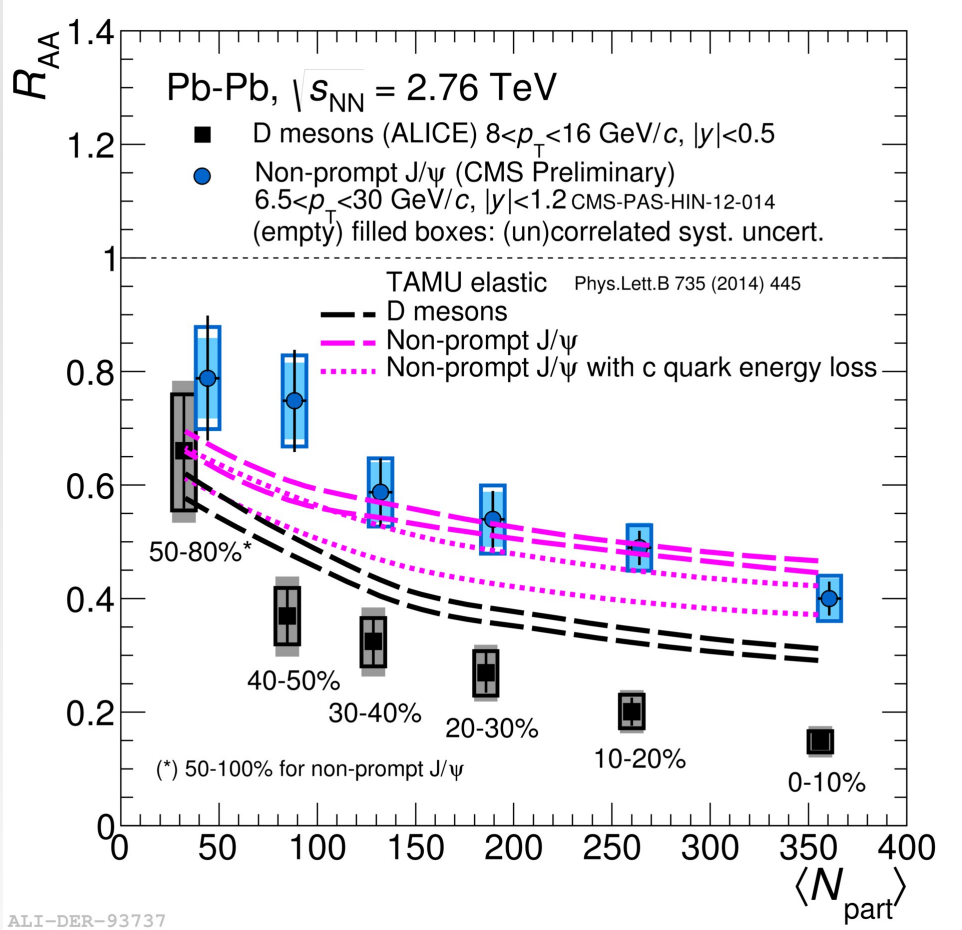
→ low-p_T measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section

D meson and J/ψ ← B
R_{AA} vs centrality

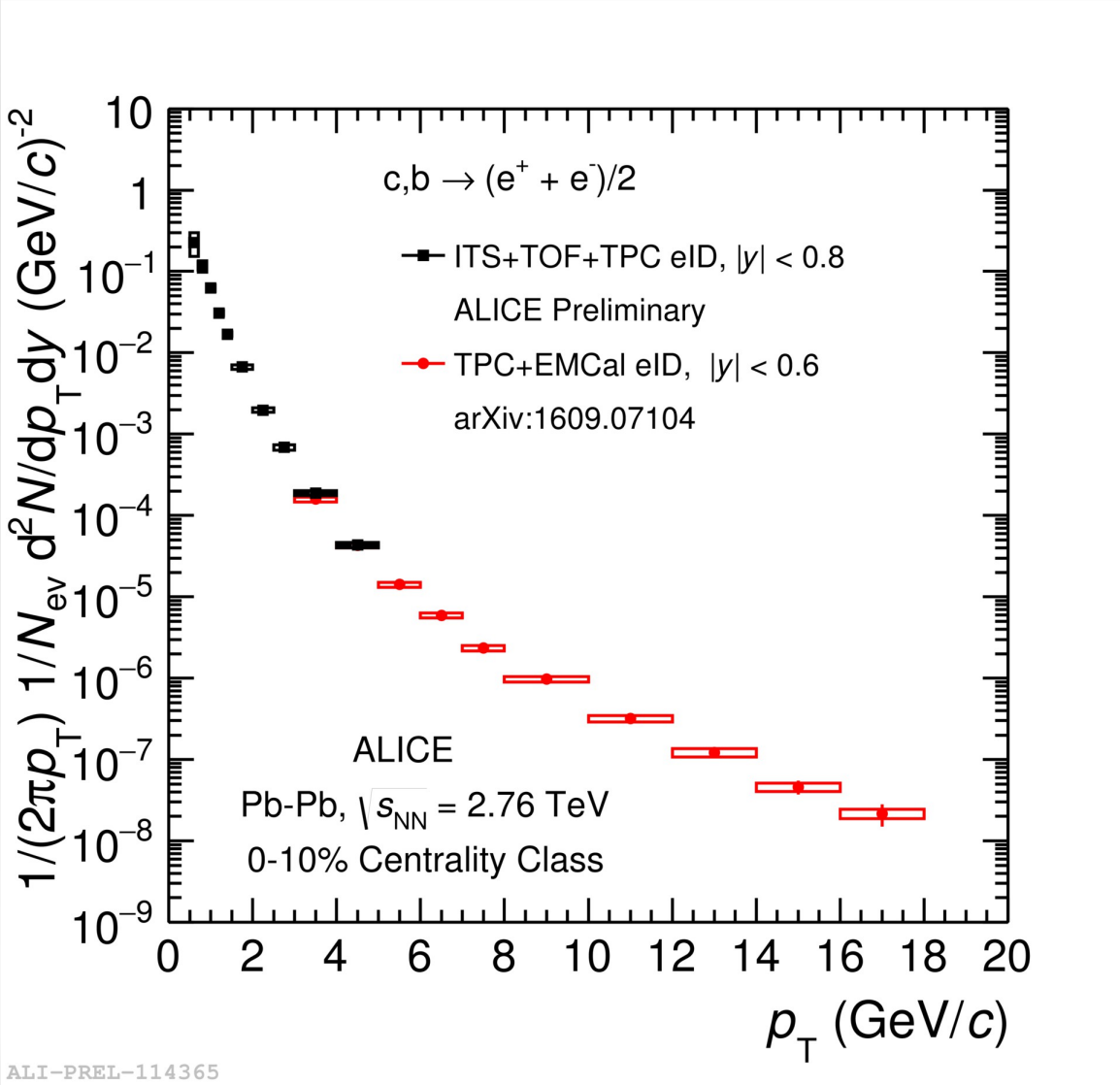
MC@sHQ+EPOS2: PRC 89 (2014) 014905



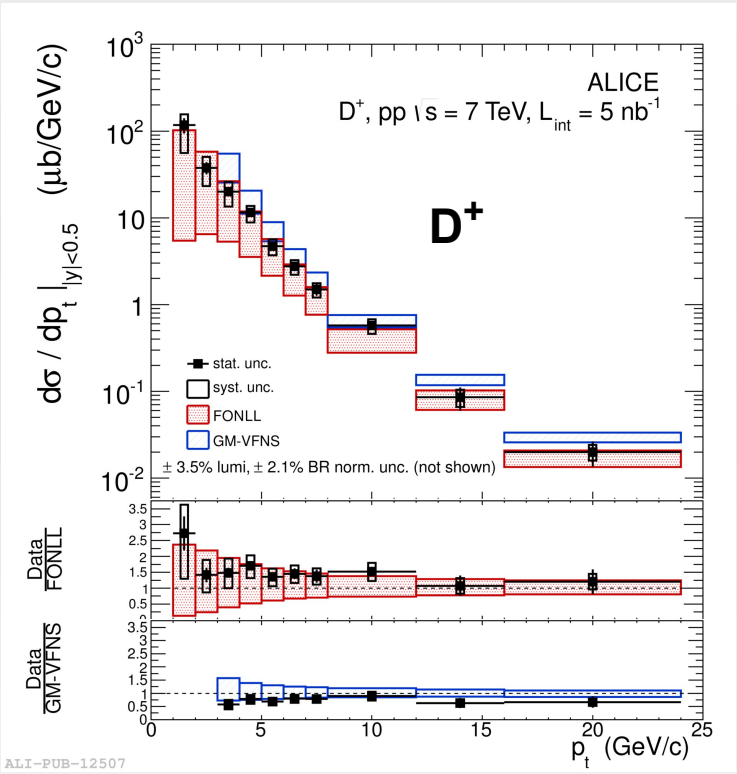
TAMU: PLB 735 (2014) 445



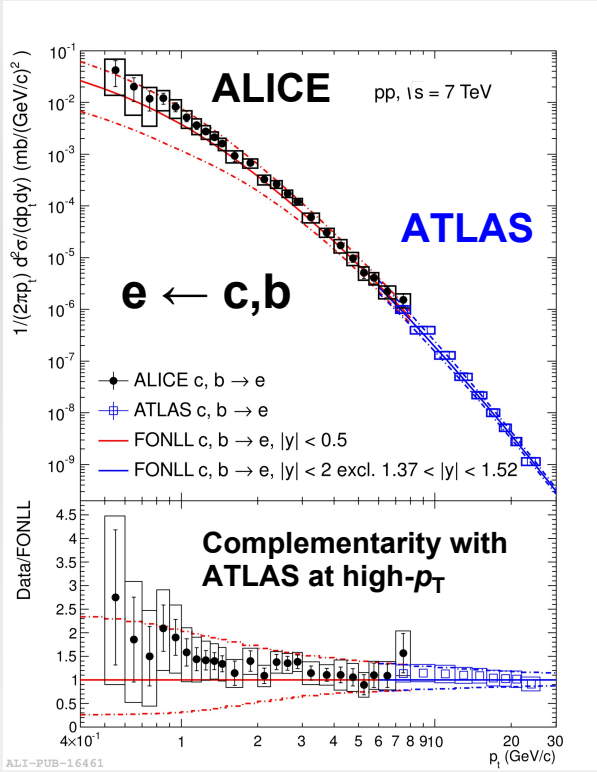
→ Models including mass dependence energy loss predict a difference between D-meson and non-promt J/ψ similar to that observed.


c,b → (e⁺ + e⁻)/2
ITS+TOF+TPC eID, |y| < 0.8
ALICE Preliminary
TPC+EMCal eID, |y| < 0.6
arXiv:1609.07104
ALICE
Pb-Pb, √sNN = 2.76 TeV
0-10% Centrality Class
1/(2πpT) 1/Nev d²N/dpT dy (GeV/c)⁻²
pT (GeV/c)
ALI-PREL-114365

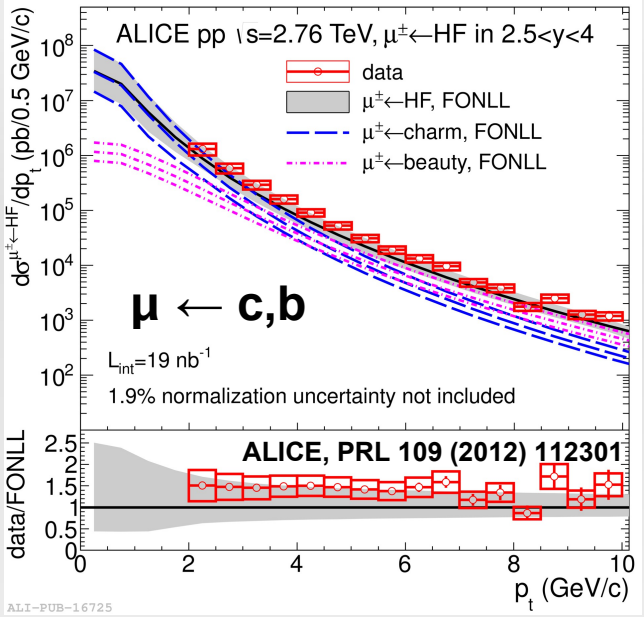
p_T-differential cross section

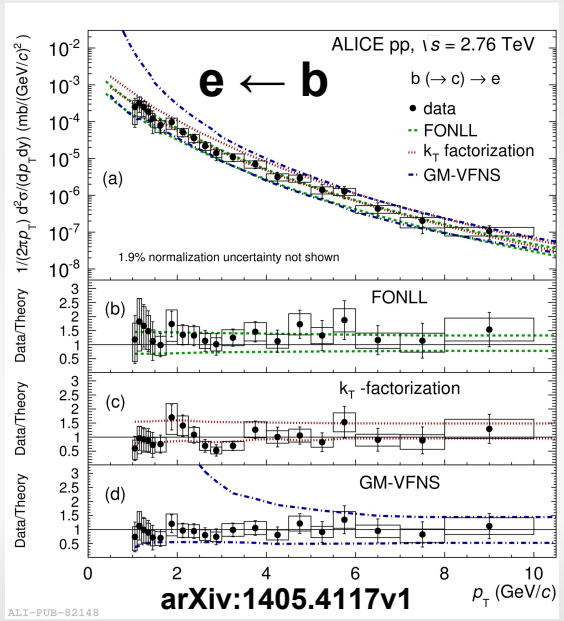


ALICE, JHEP 1201 (2012)



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





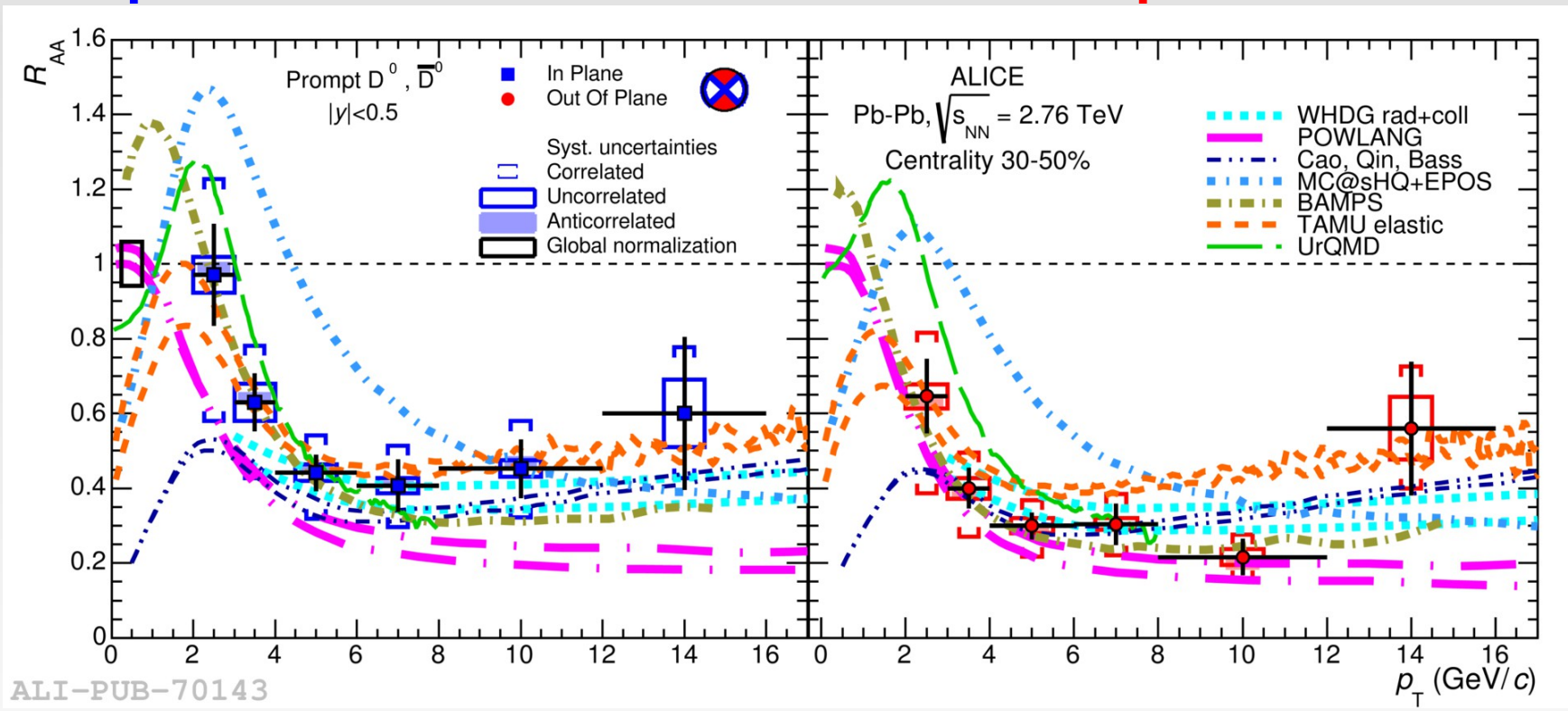
FONLL: JHEP 9805 (1998) 007
GM-VFNS: PRL 96 (2006) 012001
***k*$_T$ Fact: PRD 62 (2000) 071502**

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

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**



arXiv: 1405.2001; PRL 111, 102301 (2013)

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

D-Meson elliptic flow:

- Event plane method (TPC $0<\eta<0.8$ or VZERO event plane)
- Extraction of the D-meson yield in- and out-of-plane

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

Consistent between the three D-meson species

Positive D-meson v_2 (v_2^D) observed

5.7σ 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]