10th International Workshop on Charm Physics (CHARM 2020) 31st May – 04 June, 2021

Measurement of open charm production in heavy-ion collisions with ALICE

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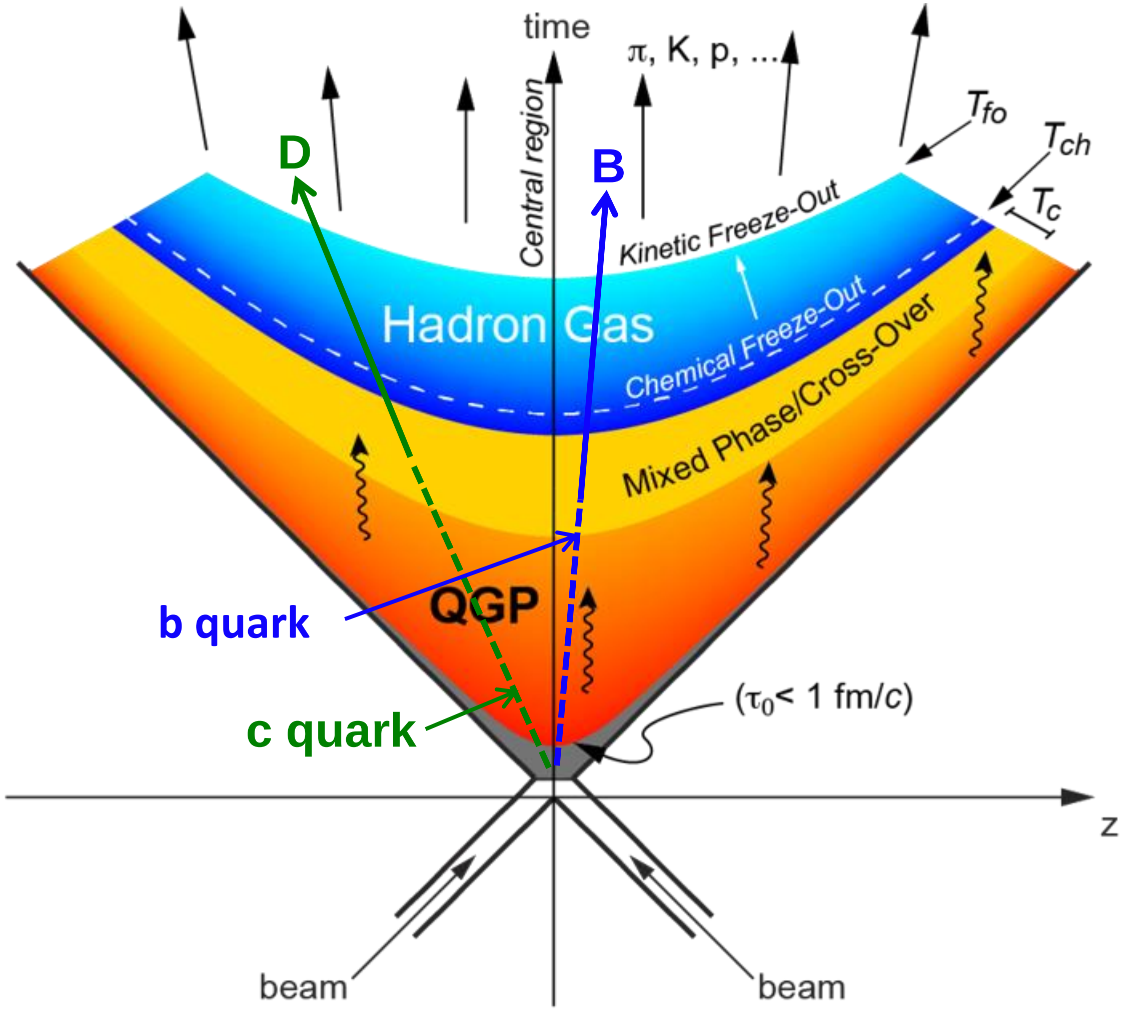
Heavy Quarks as QGP Probes



- ✓ **Heavy-quark mass (charm and beauty) large compared to the scales characterizing the QGP:**

$$m_Q >> \Lambda_{QCD} \text{ and } m_Q >> \tau_{QGP}$$

- ✓ **As consequence:**
  - ✓ Production restricted to initial hard-scattering processes

    Production time of $c\bar{c}(b\bar{b})$ pair at rest:

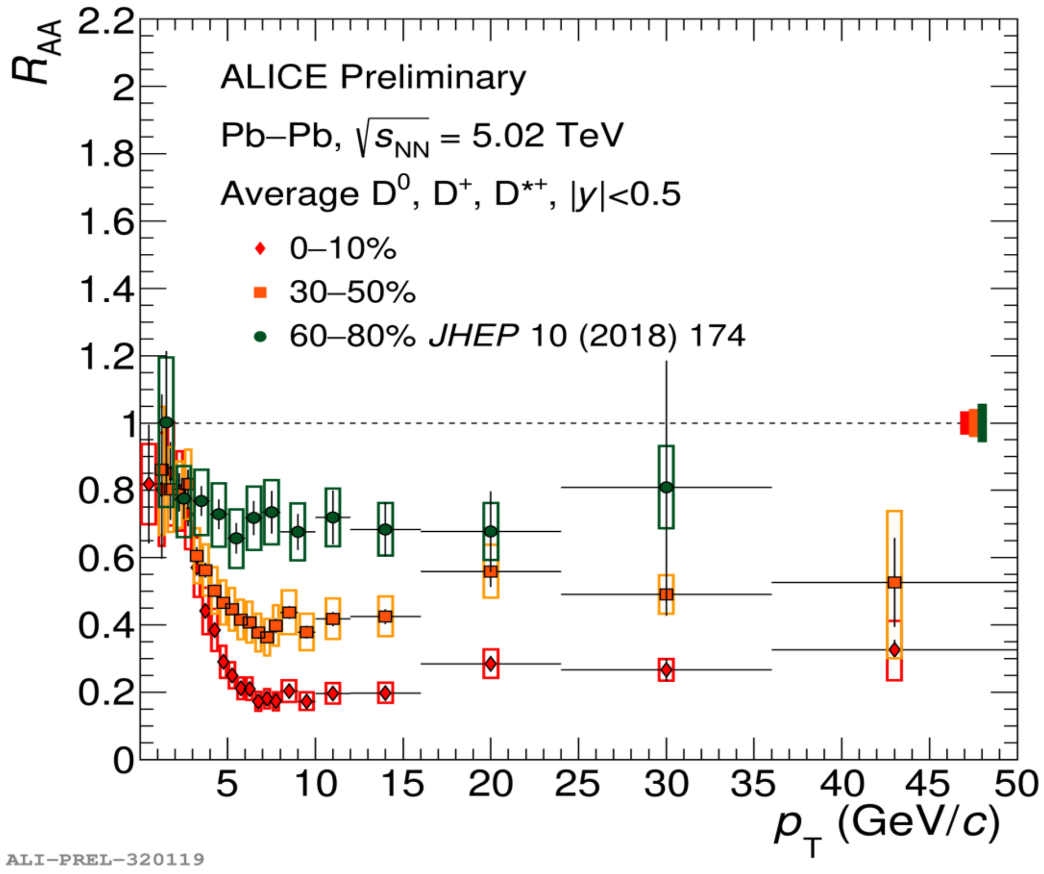
    $\tau_{prod} = \hbar/4m_{c(b)} \simeq 0.1(0.02)$ fm/c < $\tau_{QGP} \simeq 0.1$-1 fm/c

- ✓ **Brownian motion** in the QGP at low momenta ⟹ access to the **spatial diffusion coefficient $2\pi TD_s$**
- ✓ Flavour conserved in strong interactions ⟹ **transported through the full system evolution**
- ✓ Long relaxation time τ_Q comparable with the fireball lifetime (~ few fm/c) ⟹ **reach partial thermalisation**

QGP investigations with HQs:

- ✓ **In-medium energy-loss**: colour-charge and quark-mass dependence
- ✓ HQ participation in the collective expansion, **thermalisation** in the medium

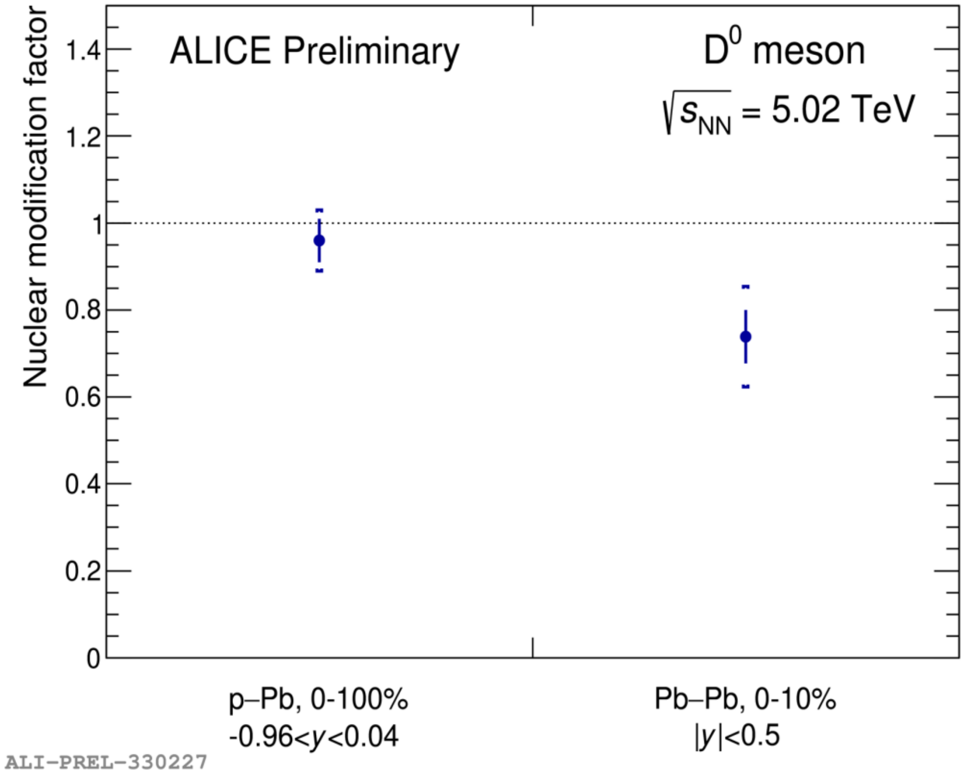
In-medium energy loss: D-meson nuclear modification factor



- ✓ Strong suppression of D mesons in Pb-Pb collisions
- ✓ Increasing suppression with centrality

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

D^0 R_{AA} measured down to $p_T = 0 \rightarrow p_T$-integrated R_{AA}



Hint of p_T-integrated D^0 $R_{AA} < 1$ and R_{pPb} ~1

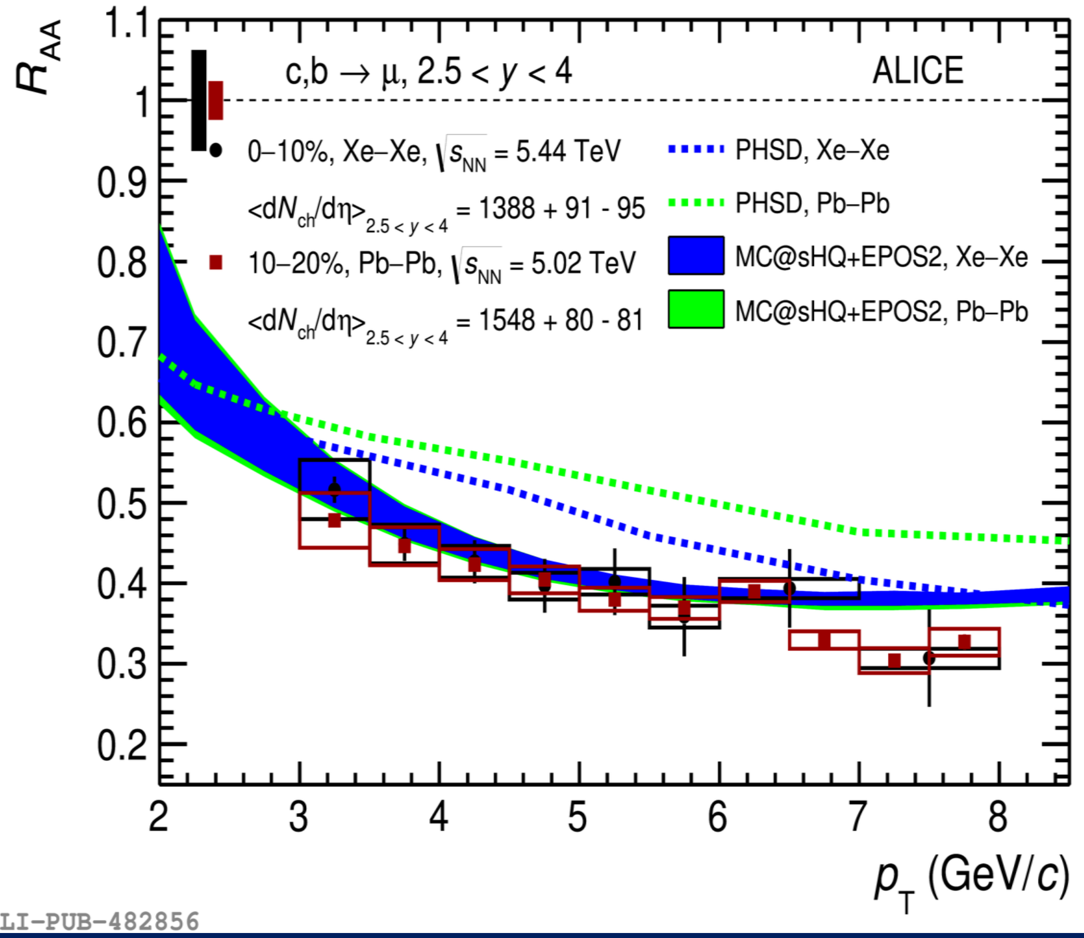
- ✓ Modification of hadronization in Pb-Pb collisions?
- ✓ Larger shadowing in Pb-Pb than in p-Pb

In-medium energy loss: different collision systems

- ✓ Comparison of R_{AA} in different collisions systems $\Rightarrow$ different system size
- ✓ Sensitivity to probe the path-length dependence of the in-medium parton energy loss at different N_{part} or N_{ch} (M. Djordjevic et al, Phys. Rev. C 99, 061902 (2019))

- ✓ Similar heavy-flavour hadron decay muon R_{AA} for 0-10% Xe-Xe and 10-20% Pb-Pb

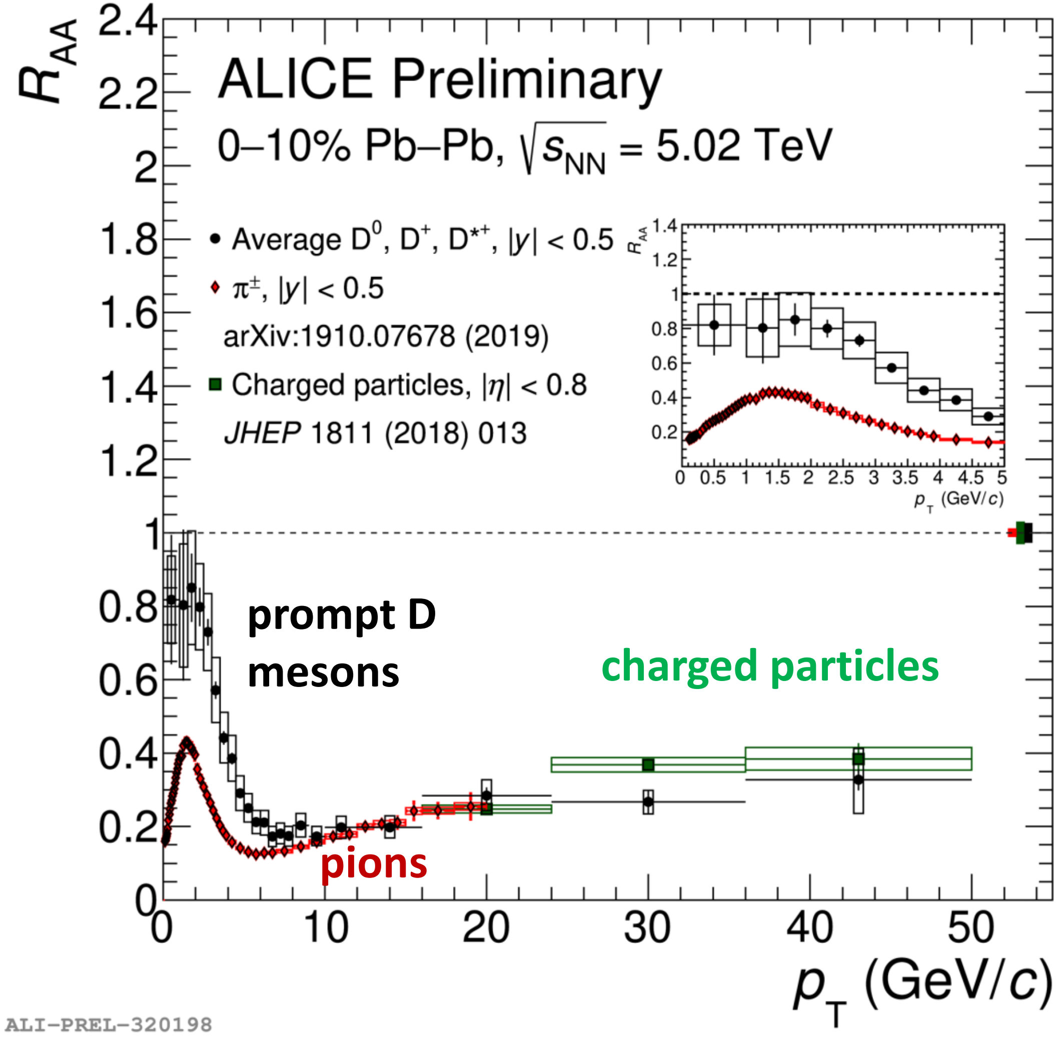
- ✓ Similar results are also observed for charged particles (PLB 788 (2019) 166)
  - ✓ Constrain further model predictions



Xe–Xe : arXiv:2011.06970
PHSD Phys.Rev. C93 no.3 (2016) 034906
MC@sHQ+EPOS2 Phys.Rev. C89 (2014) 014905

In-medium energy loss: light vs heavy quarks

Quark-mass and colour-charge dependence studied comparing **D mesons** and **light hadrons**



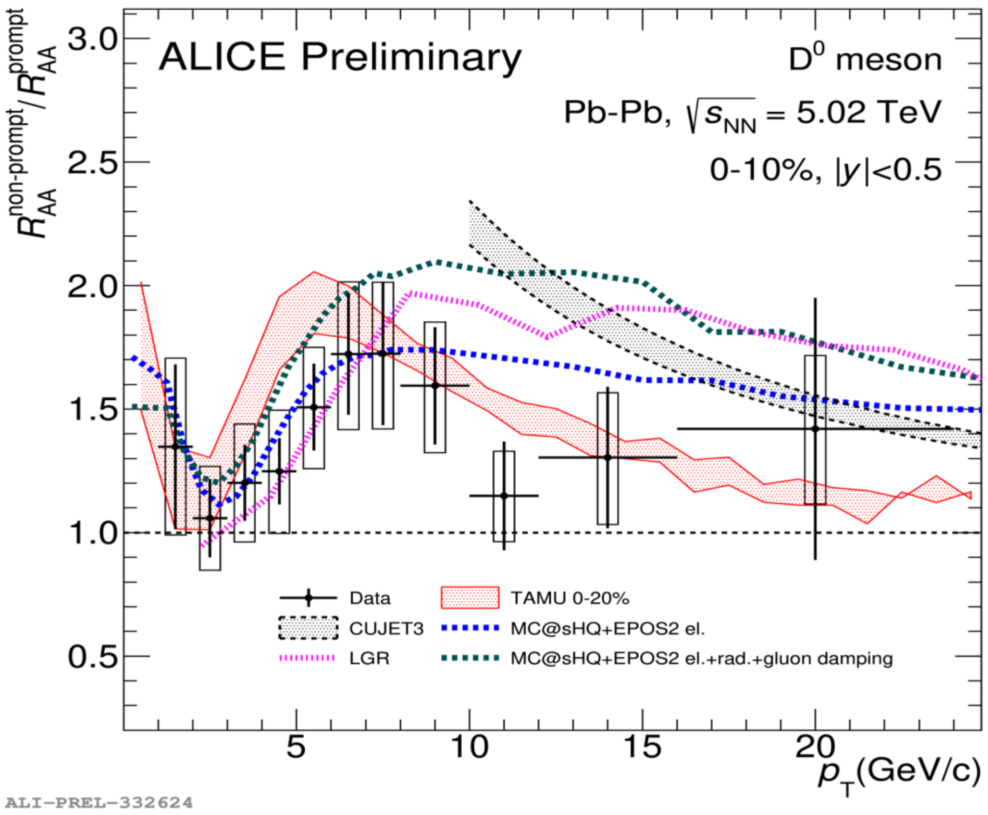
ΔE(ch. part) > ΔE(D) > ΔE(B) → R_{AA}(ch. part) < R_{AA}(D) < R_{AA}(B)

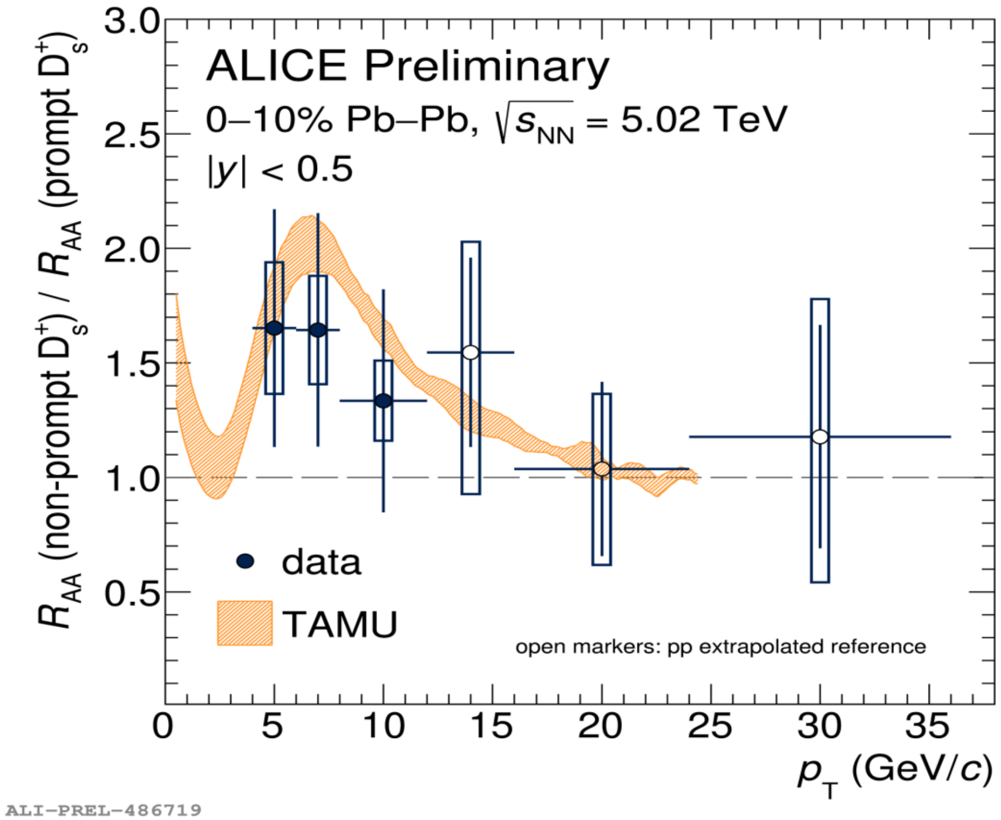
- ✓ **R_{AA}(D) > $R_{AA}(\pi)$ for p_T < 10 GeV/c**
- ✓ **Comparable R_{AA} for p_T > 10 GeV/c**

⟹ Interpretation not straightforward: possible mass and Casimir factor effects, shadowing, interplay between different p_T spectra of charm, light quarks and gluons, and different fragmentation fractions

In-medium energy loss: charm vs beauty

ΔE(ch. part) > ΔE(D) > ΔE(B) → R_{AA}(ch. part) < R_{AA}(D) < R_{AA}(B)



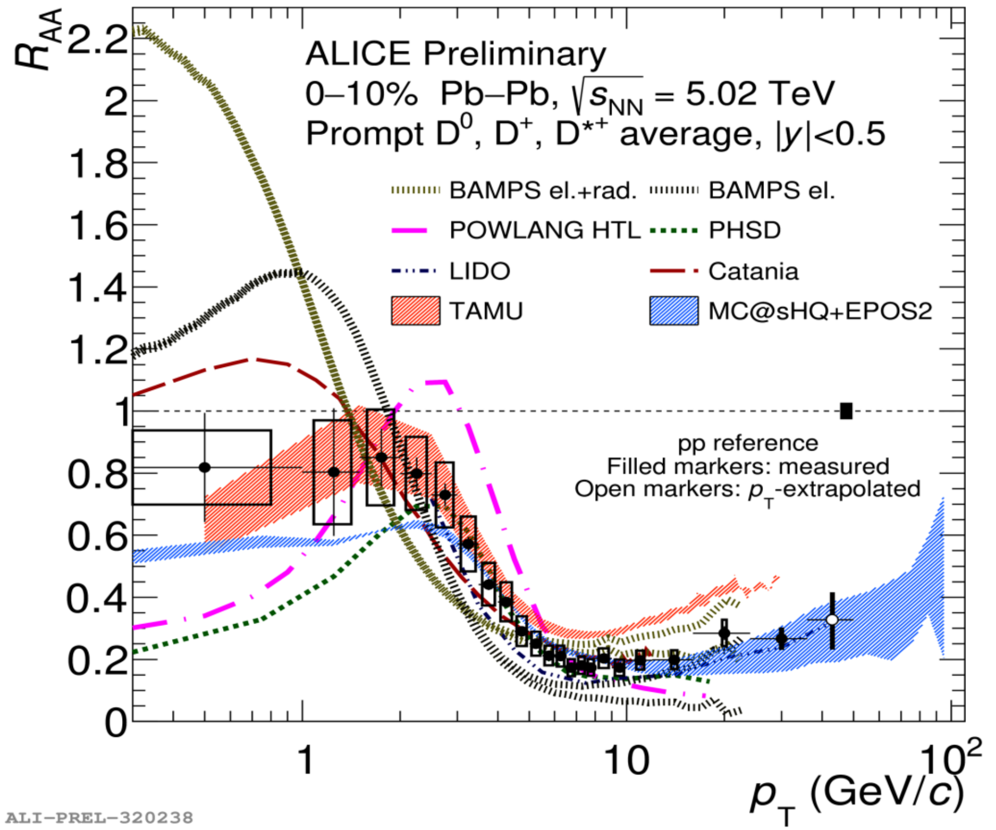


- ✓ Ratio of non-prompt (D^0 and D_s^+) and prompt (D^0 and D_s^+) compared with the models
  - ✓ Interplay of different ingredients
    - ✓ Parton-mass dependence of the energy loss
    - ✓ Dead cone effect: gluon radiation suppressed for small angles ($\vartheta < m/E$)
    - ✓ charm quark coalescence

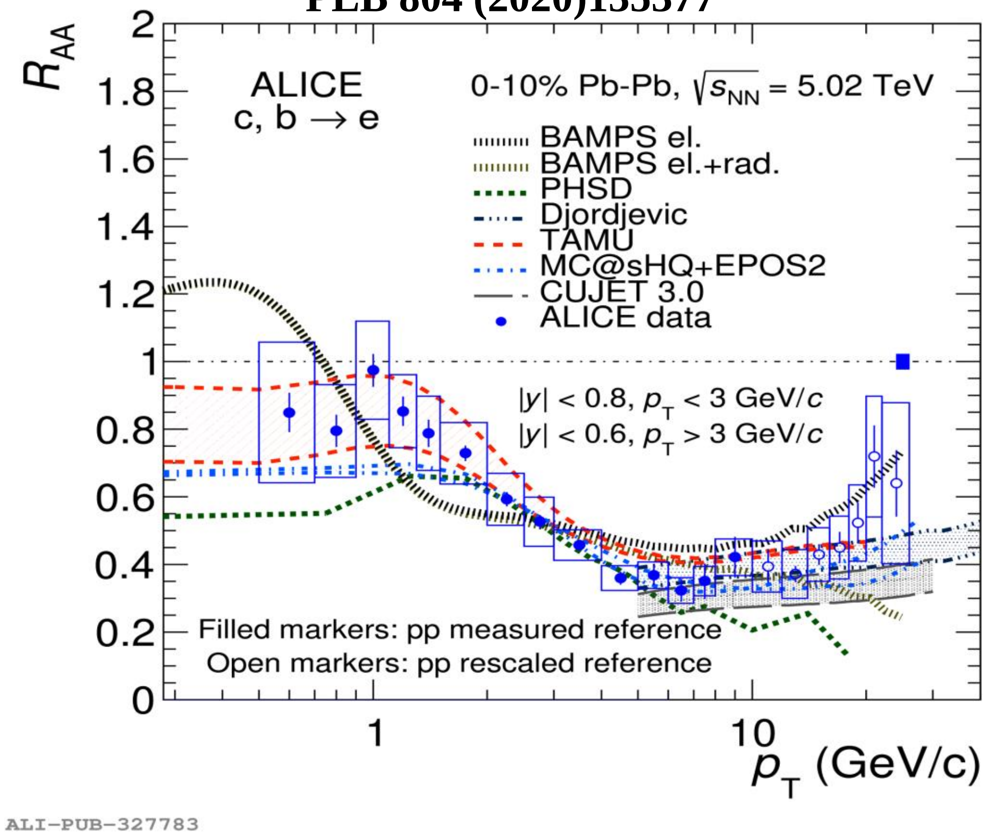
TAMU: PLB 735 445-450 (2014)
CUJET3 Chin.Phys.C 43 no.4, (2019)
LGR EPJC 80 no.12, (2020)
MC@sHQ+EPOS2 Phys.Rev.C 89 014905

Heavy flavour R_{AA} compared with models

Energy loss via **collisional** (dominant at low p_T) and **radiative** (dominant at high p_T) processes



PLB 804 (2020)135377



✓ Interplay of collisional and radiative energy loss + hadronisation via coalescence and fragmentation, hydrodynamic expansion of the medium

TAMU: PLB 735 (2014) 445 POWLANG: EPJC 75 (2015) 121 PHSD: Phys. Rev. C 92 (2015) 014910 MC@sHQ+EPOS: PRC 89 (2014) 014905 LIDO: Phys. Rev. C 98 (2018) 064901 BAMPS: JPG 42 (2015) 115106 DAB-MOD: PRC 96 (2017) 064903 CATANIA: Eur. Phys. J. C78 no. 4, (2018) 348

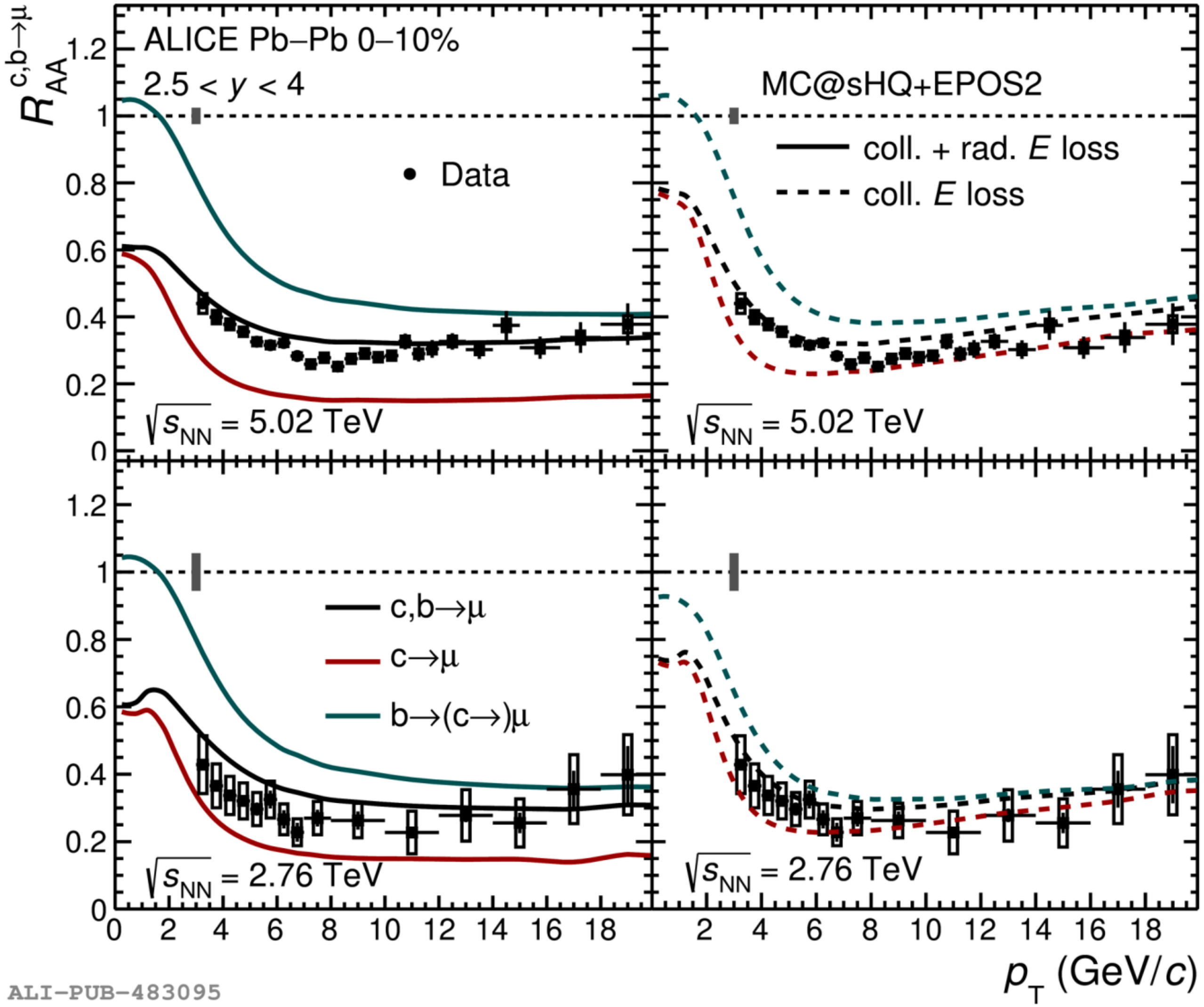
Heavy flavour R_{AA} compared with models

Energy loss via **collisional** (dominant at low p_T) and **radiative** (dominant at high p_T) processes

arXiv:2011.05718

- ✓ R_{AA} of muons from heavy-flavour hadron decays in Pb–Pb collisions at 2.76 TeV and at 5.02 TeV
- ✓ Fairly described by models implementing
  - ✓ Collisional energy loss (dashed line)
  - ✓ Collisional + radiative energy loss (solid line)
- ✓ Compared with predictions of c→μ and b→(c→)μ
  - ✓ At high p_T, the measured R_{AA} is closer to the model for b→(c→)μ than c→μ

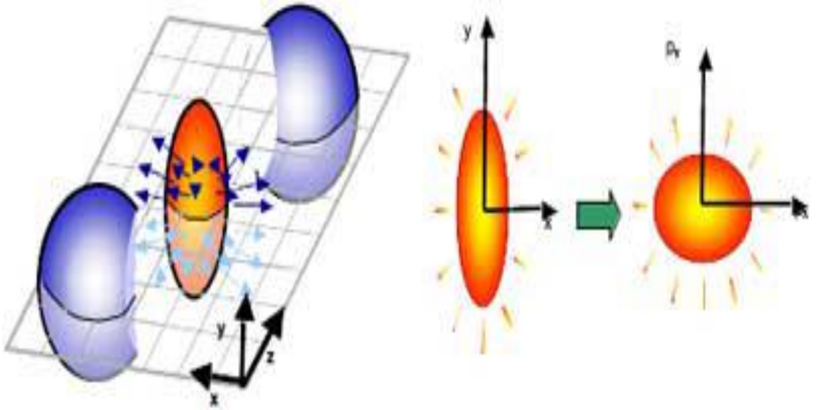
MC@sHQ_EPOS2
Phys. Rev. C 89, 014905
Phys. Rev. C 90, 024907



Azimuthal anisotropies of heavy-flavour particles

- ✓Interaction among medium constituents convert the initial geometrical anisotropy into momentum anisotropy of final-state particles
- ✓Quantified by the **Fourier decomposition of the azimuthal distribution of particle momenta**

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



Quantified as the v_n, Ψ_{RP} is the reaction plane angle

$v_1 \Rightarrow$ direct flow

$v_2 \Rightarrow$ elliptic flow

$v_3 \Rightarrow$ triangular flow

Directed flow (v_1): Probes electromagnetic field in medium

Elliptic flow (v_2):

low p_T: sensitive to the participation in the collective motion and thermalisation of HQ

high p_T: sensitive to path-length dependence of energy loss

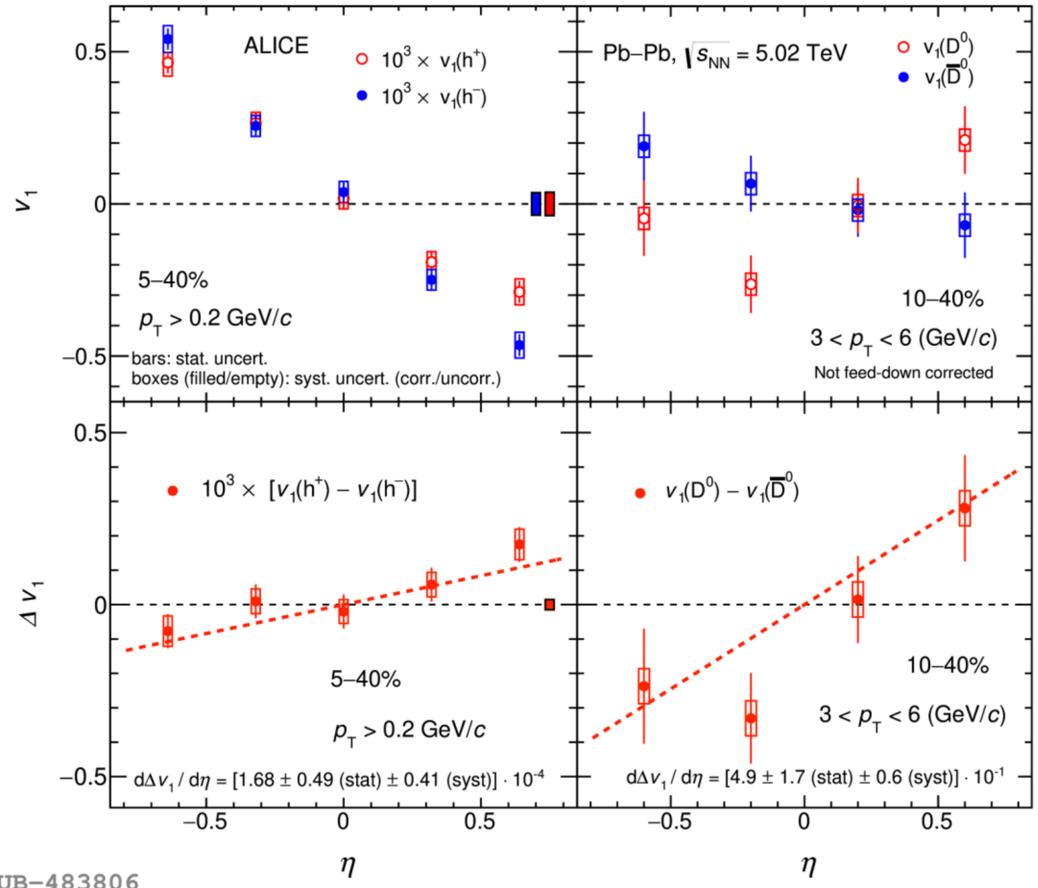
Triangular flow (v_3): Originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region

Both v_2 and v_3 are sensitive to the ratio for shear viscosity to the entropy density η/s

Direct flow (v_1) of heavy-flavour particles

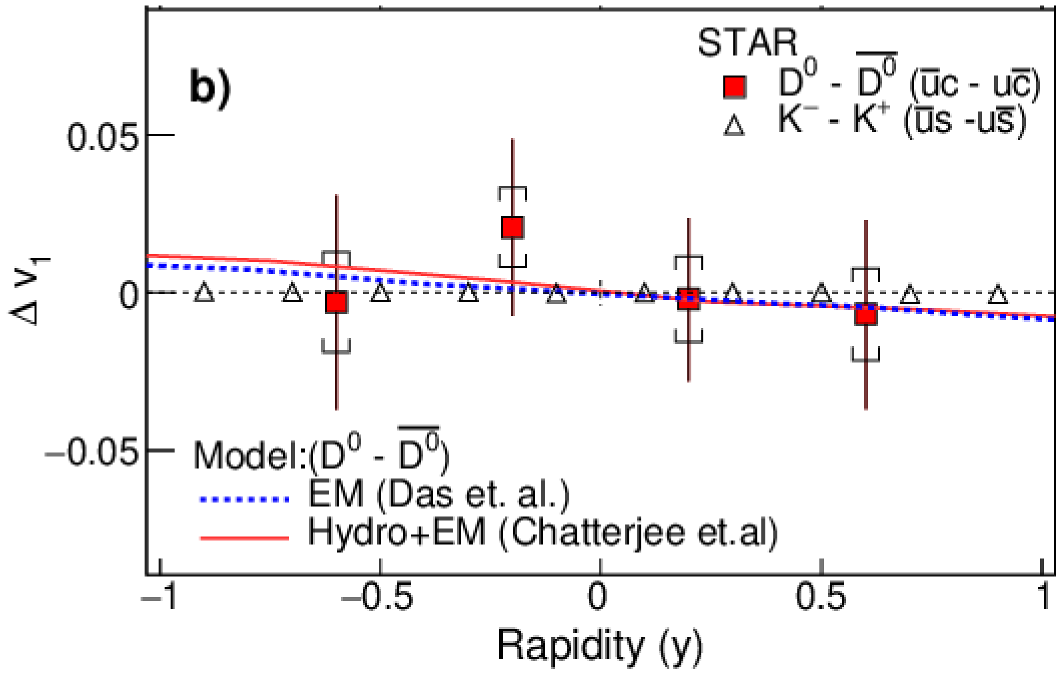
[Phys. Rev. Lett. 125, 022301(2020)]

Charged hadrons **D mesons**



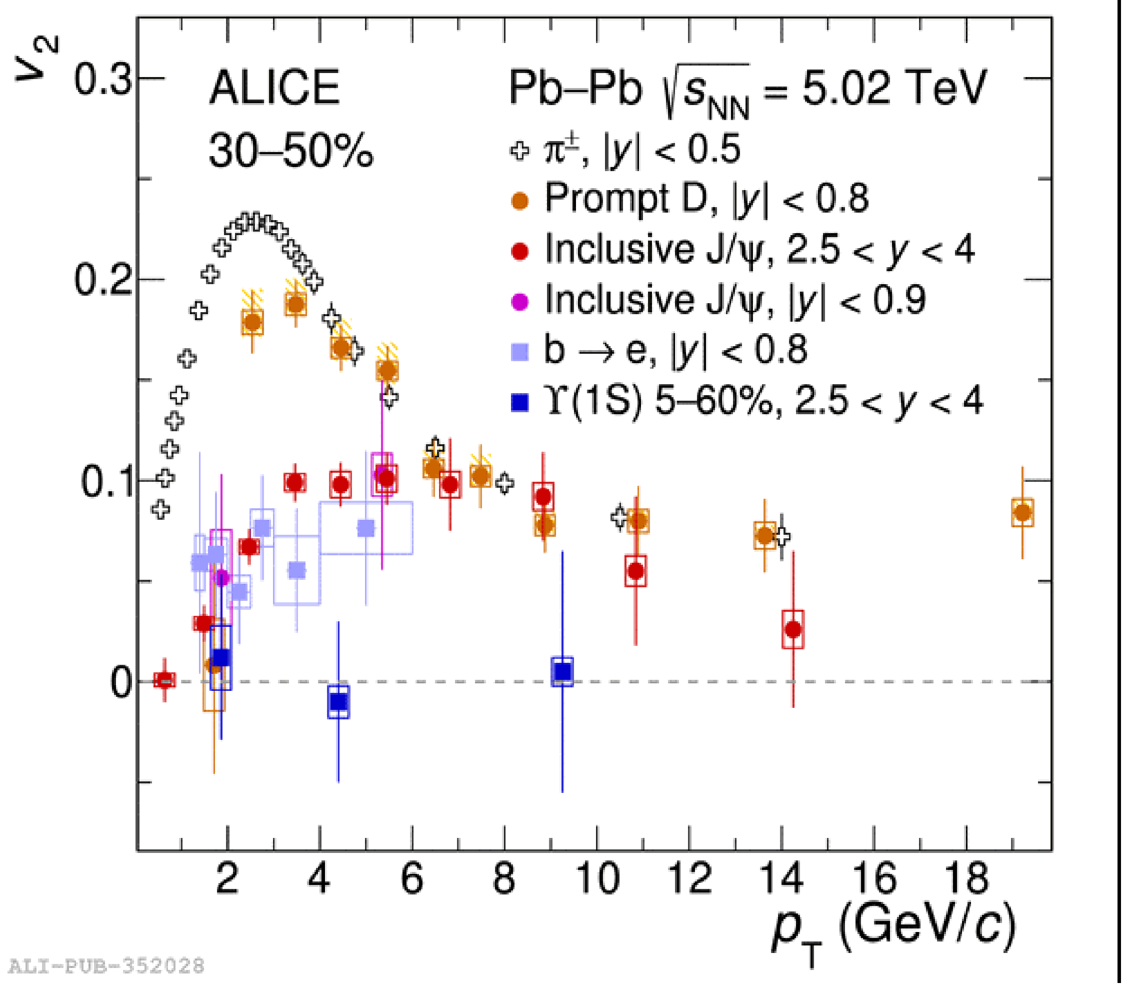
- ✓ Charm quarks are produced early in the collisions ⇒ powerful probes to quantify initial magnetic field
- ✓ Positive slope of $d\Delta v_1/d\eta$ for D^0 and $\overline{D}^0$ indicates the charge separation
- ✓ Similar trend between lighter charged particles and D mesons, but 3 orders of magnitude larger
- ✓ Indication of initial electromagnetic effects

[J. Adam et al, Phys. Rev. Lett. 123, 162301(2019)]



Indication of opposite trend with respect to STAR measurement →Likely due to much stronger magnetic field produced at LHC energies compared to RHIC

Elliptic flow (v_2) of heavy-flavour particles



Pions: JHEP 09 (2018) 006 **Prompt D:** PLB 813 (2021) 136054 **Inclusive J/ψ:** JHEP 10 (2020) **(b→e)** PRL 126, 162001 (2021) **ϒ(1S)**: PRL 123,192301 (2019)

- ✓ Positive v_2 for prompt D mesons
- ✓ Positive v_2 for J/ψ
- ✓ Positive v_2 for b→e (significance 3.75σ)
- ✓ ϒ(1S) v_2 compatible with zero

Looking more in details at different p_T regions:

- For p_T < 3 GeV/c ⇨ **mass ordering**

  $v_2(\Upsilon(1S)) \lesssim v_2(b\rightarrow e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)$

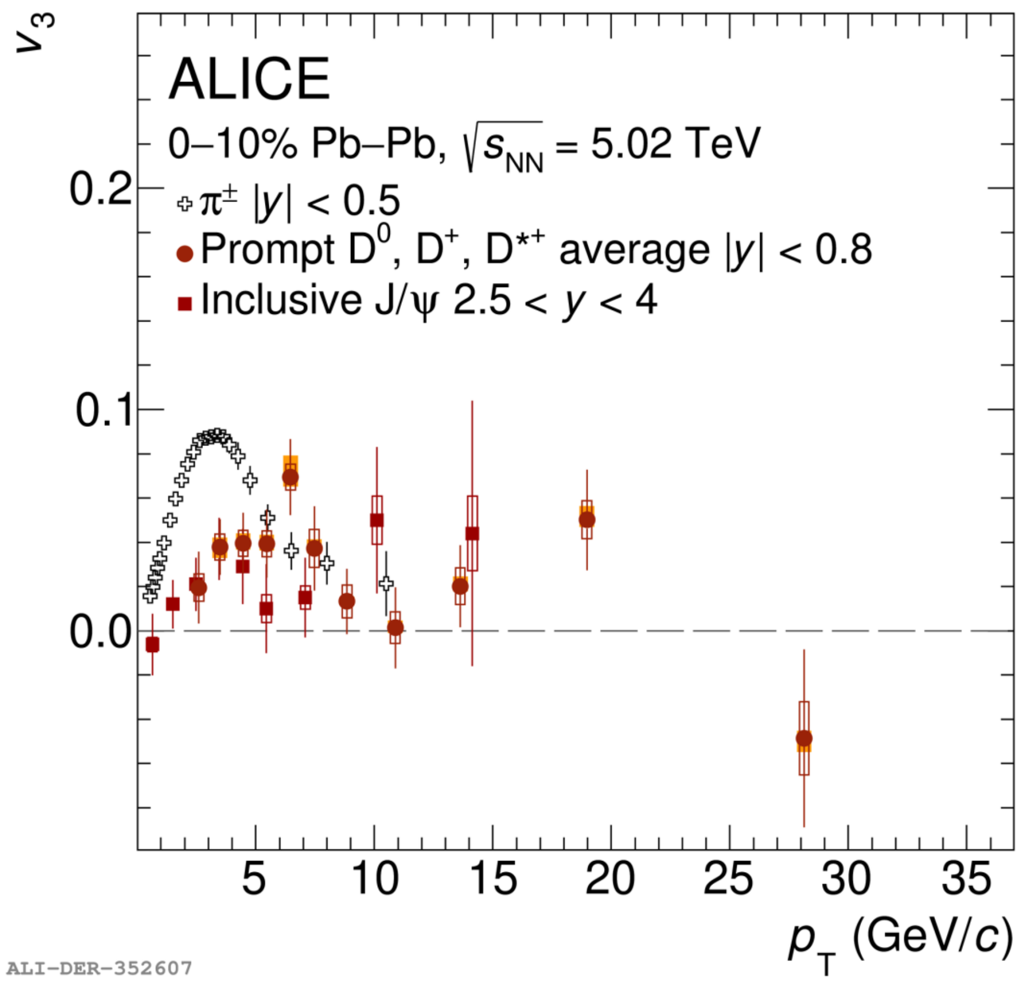
- For 3 < p_T < 6 GeV/c ⇨ **charm quark coalescence with flowing light quarks**

  $v_2(J/\psi) < v_2(D) \sim v_2(\pi)$

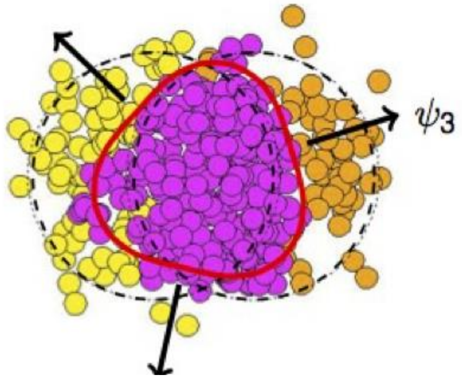
- For p_T > 6 GeV/c ⇨ **consistent with similar path-length dependence of the energy loss for light and heavy quarks**

  $v_2(J/\psi) \sim v_2(D) \sim v_2(\pi)$

Triangular flow (v_3) of heavy-flavour particles



Originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region



For p_T < 5 GeV/c: **$0 < v_3(J/\psi) \sim v_3(D) < v_3(\pi)$**

Charm quarks sensitive to initial state fluctuations

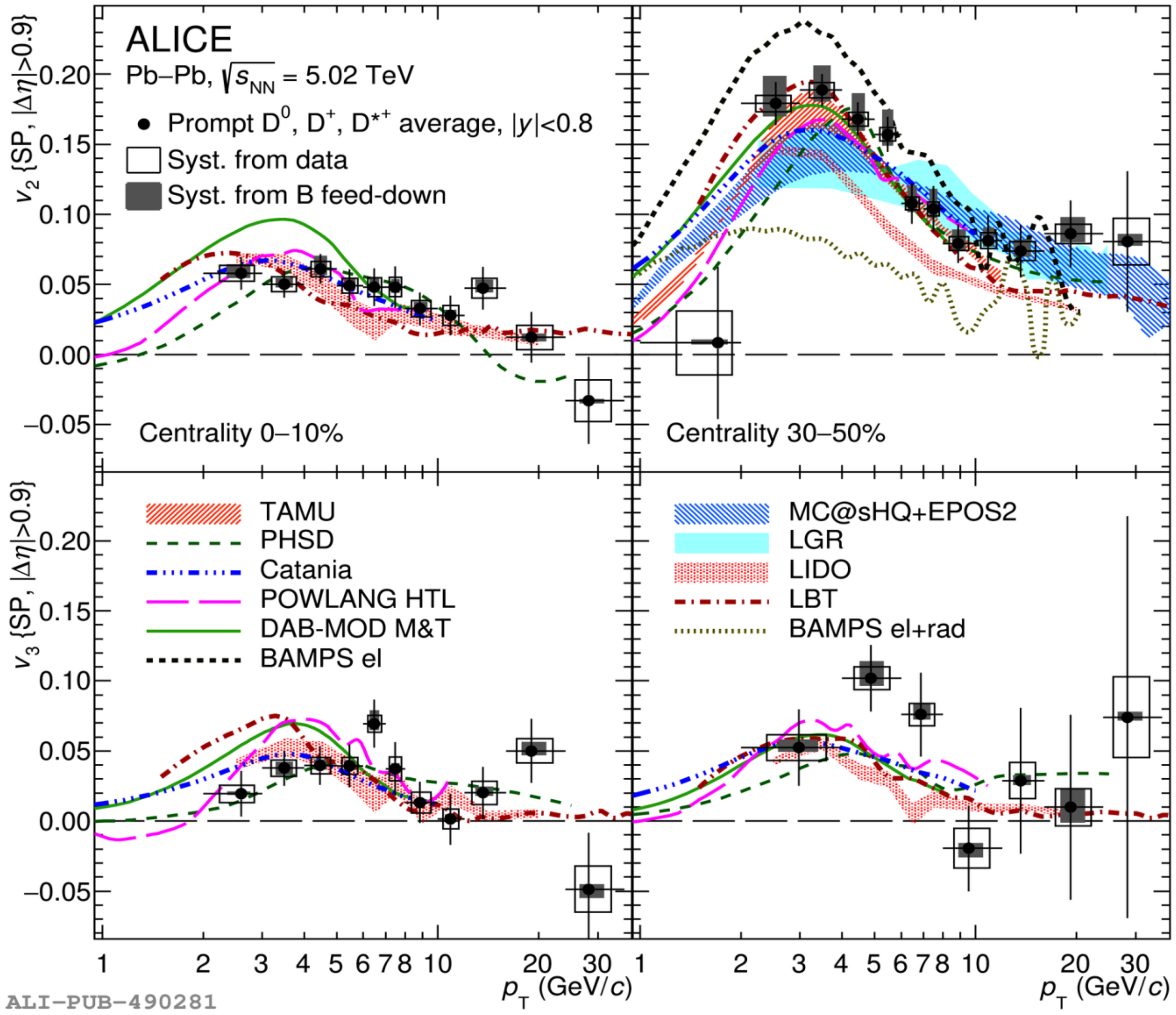
Pions: JHEP 09 (2018) 006

Prompt D: PLB 813 (2021) 136054

Inclusive J/ψ: JHEP 10 (2020)

D meson v_2 and v_3 in transport models

PLB 813 (2021) 136054



All models include hadronisation via quark coalescence and fragmentation fairly describe the measured v_n harmonics

Constrain charm spatial diffusion coefficient:

$\boxed{D_s = (T/m_Q)\tau_Q}$

From models that describe the data with χ^2/ndf<2

$\boxed{1.5 < 2\pi T D_s < 7}$

Leading to the charm thermalisation time:

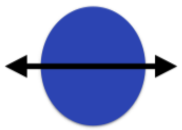
$\boxed{\tau_{charm} = 3\text{-}14 \text{ fm}/c}$

TAMU: PRL 124, 042301 (2020) MC@sHQ+EPOS2: PRC 91, 014904 (2015) LGR: EPJC 80, 7 (2020) 671 LIDO: PRC 98, 064901 (2018) PHSD: PRC 93, 034906 (2016) Catania: PRC 96, 044905 (2017) POWLANG: EPJC 75, 121 (2015) LBT: PLB 777 (2018) 255-259 BAMPS: JPG 42, 115106 (2015) DAB-MOD: PRC 96, 064903 (2017)

Event-shape engineering (ESE)

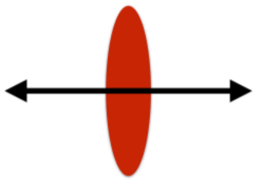
Events classified on the basis of eccentricity according to the magnitude of the second hormonic reduced flow vector q_2

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}, \quad Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \quad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$



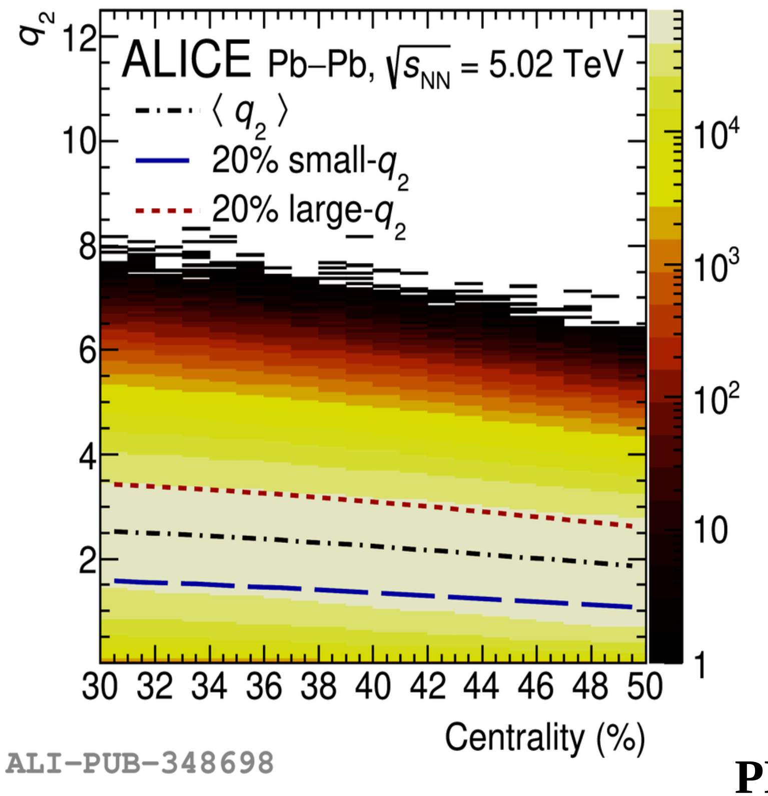
20% smallest q_2

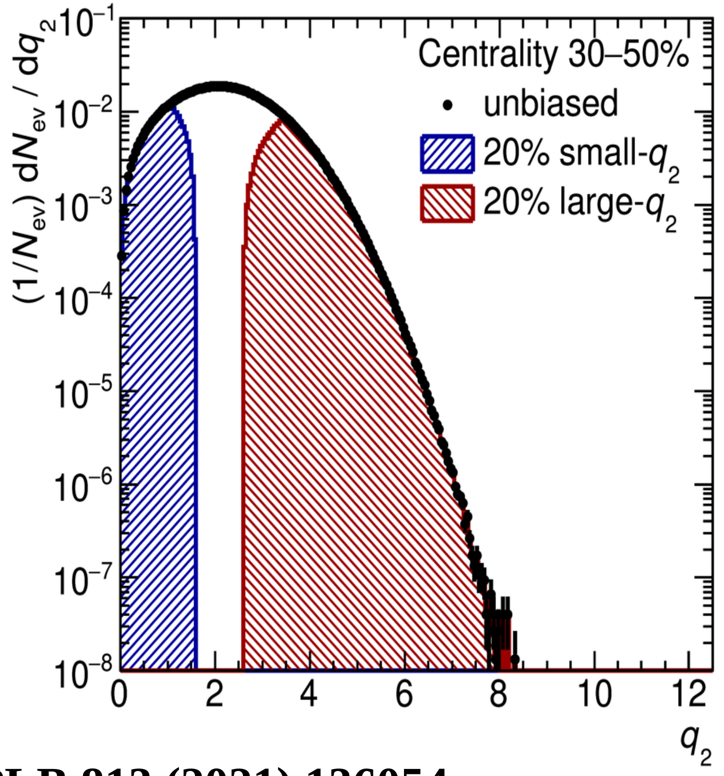
$\langle v_2 \rangle_{\mathrm{small}-q_2} < \langle v_2 \rangle_{\mathrm{unbiased}}$



20% largest q_2

$\langle v_2 \rangle_{\mathrm{large}-q_2} > \langle v_2 \rangle_{\mathrm{unbiased}}$





PLB 813 (2021) 136054

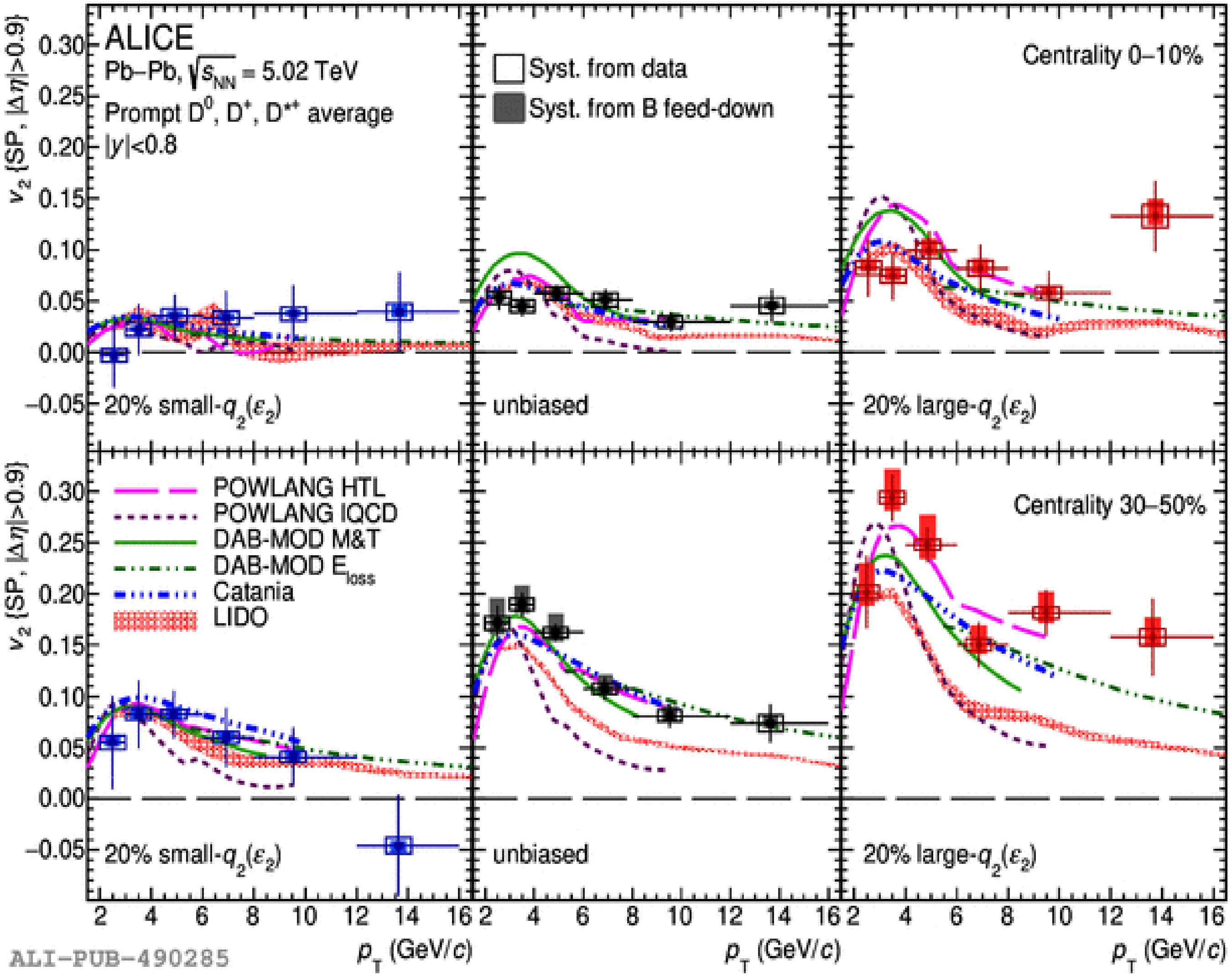
Elliptic flow for different q_2 samples:

✓ correlation between v_2 of D mesons and soft hadrons

✓ event-by-event fluctuations in the initial state

ESE-selected elliptic flow

PLB 813 (2021) 136054



Clear separation between v_2 measured in events with small/large q_2

v_2 (large q_2) > v_2 (unbiased)

v_2 (small q_2) < v_2 (unbiased)

positive correlation between D-meson v_2 and light-hadron v_2

Models based on charm quark transport in a hydrodynamically expanding medium describe the q_2 dependence of the elliptic flow

POWLANG: EPJC 79, 494 (2019)

DAB-MOD M&T: PRC 96 064903 (2017)

LIDO: PRC 98 064901 (2018)

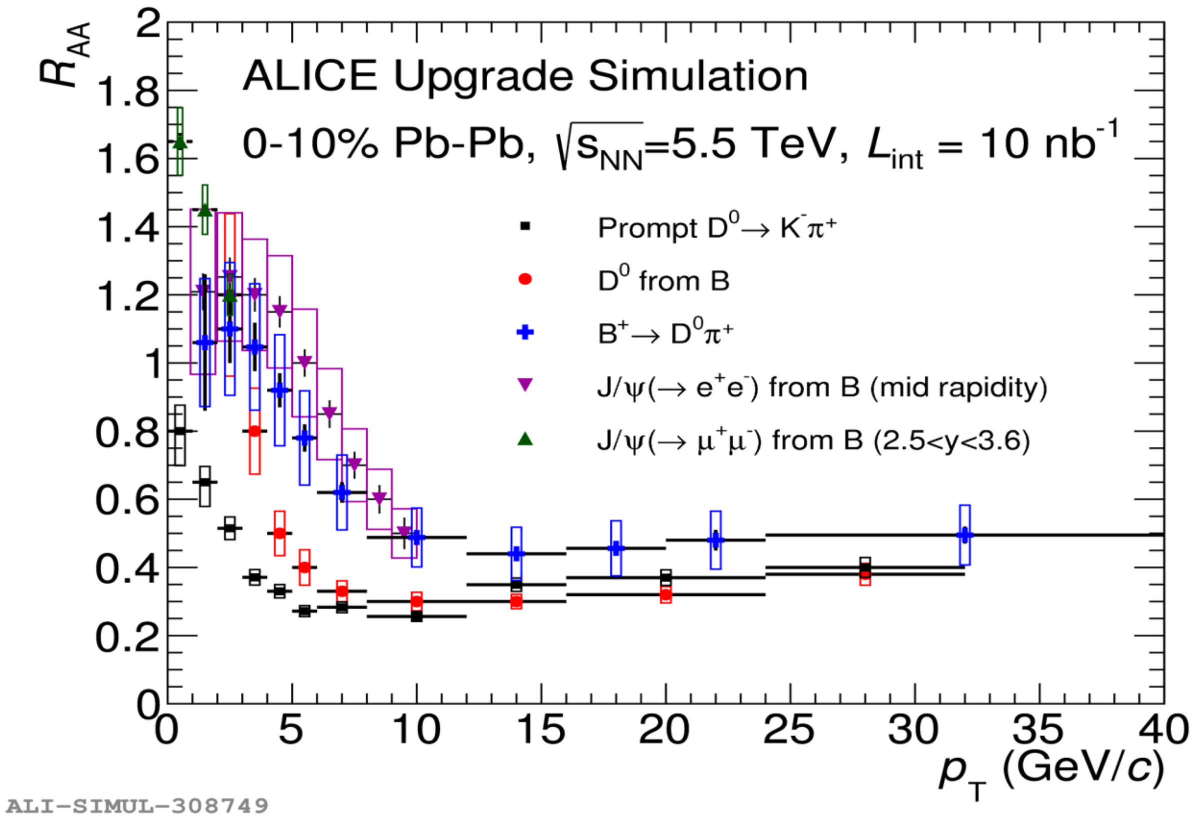
CATANIA: PLB 805 135460 (2020)

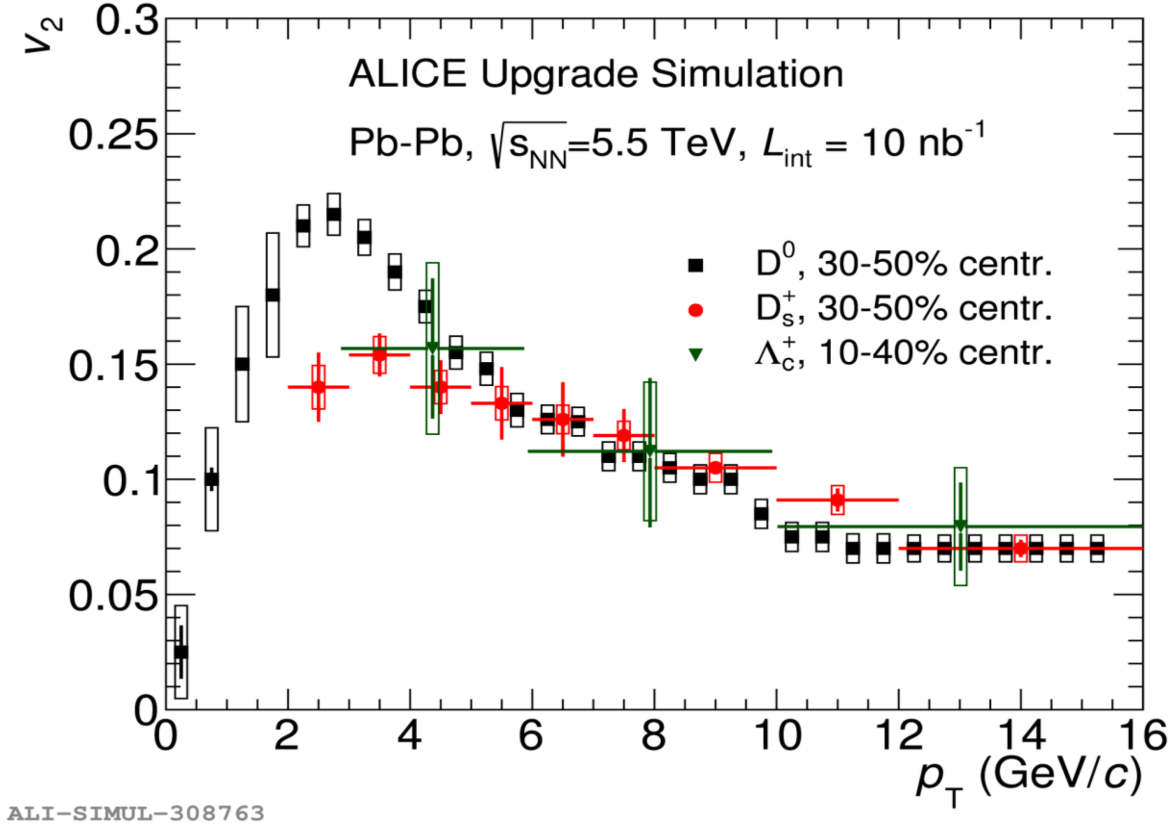
Summary and conclusion

- ✓ **Strong suppression of heavy-flavour production in central Pb-Pb collisions**
  - ✓ **Mass ordering** of the R_{AA} observed at low/intermediate p_T
  - ✓ **R_{AA} described by several models with different implementation of the charm/beauty-quarks energy loss** (+ hadronisation via coalescence and fragmentation, hydrodynamic expansion of the medium)
- ✓ Similar R_{AA} observed in 0-10% Xe-Xe collisions and 10-20% Pb-Pb collisions ➡ **constraints the path-length dependent energy loss**
- ✓ Larger positive slope $d\Delta v_1/d\eta$ for D^0 and $\overline{D}^0$ indicates the presence of **strong initial electromagnetic field**
- ✓ Positive D-meson and J/ψ v_2 and v_3 ➡ **heavy quarks participate in collective expansion of the system**
- ✓ Comparison with models **constraints the charm spatial diffusion** coefficient and the charm quark **thermalisation time** (~ QGP lifetime)
- ✓ Positive v_2 for electrons from beauty hadron decays: also **beauty quarks partially thermalise**?
- ✓ positive correlation between D and light-hadron v_2 in **agreement with transport model predictions**

Future prospectus

- ✓ ALICE will upgrade its detectors and readout systems in view of Run 3 → new Inner Tracking System (ITS2)
- ✓ HF vertexing improved especially at low p_T
- ✓ Precise measurements of charm mesons and baryons
- ✓ Access to measurements of beauty-strange mesons and beauty-baryon production and flow





Thank you for your kind attention!!!