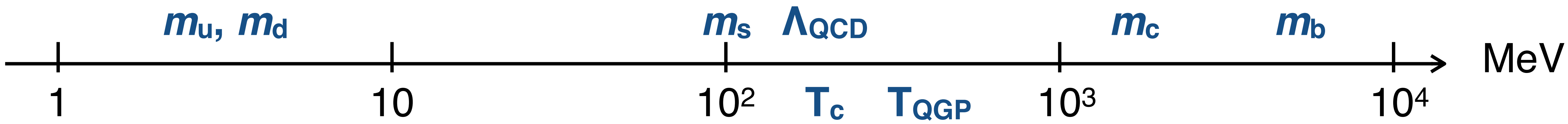
2018 European Nuclear Physics Conference

Heavy-flavour production measurements in heavy-ion collisions with ALICE at the LHC

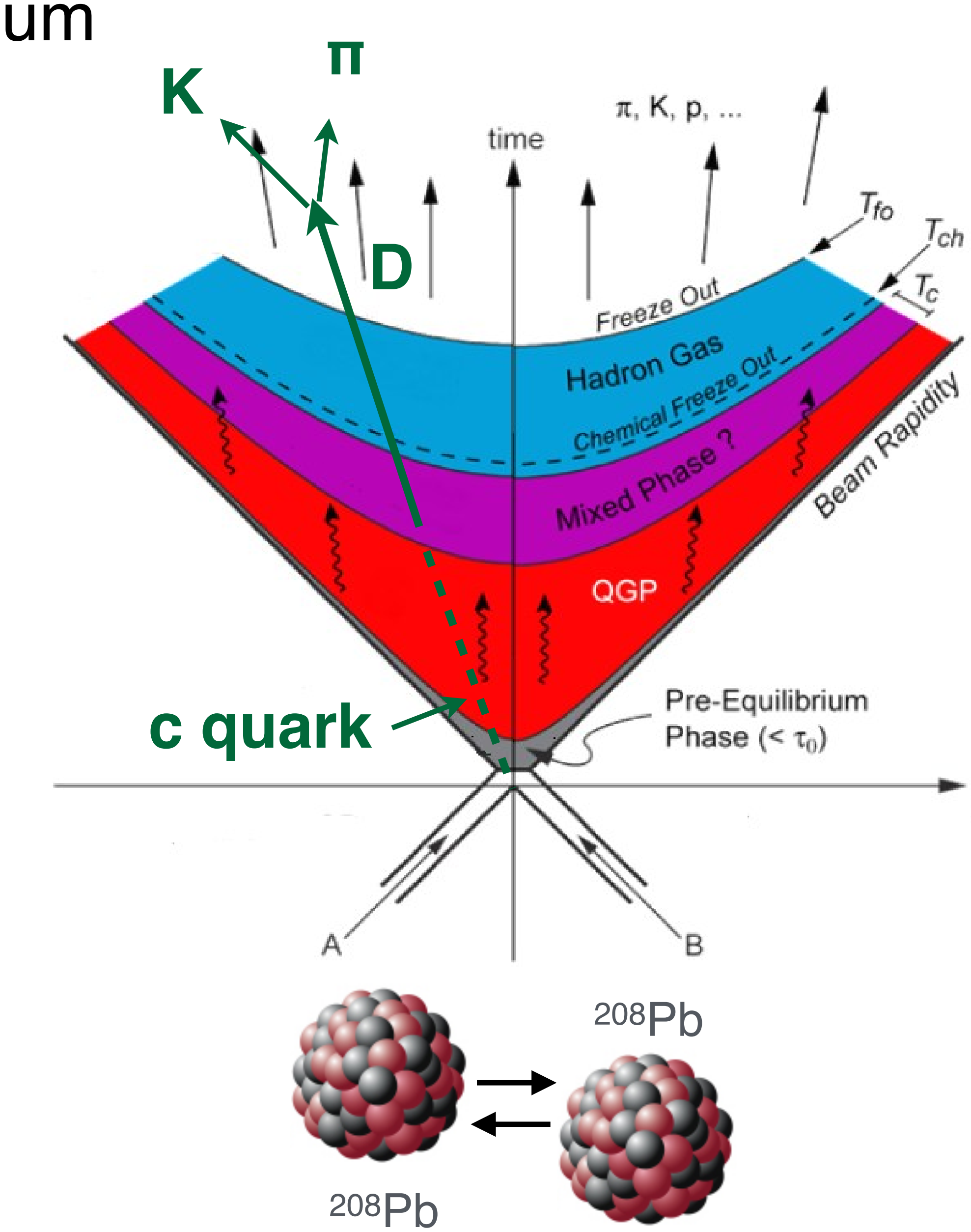
A. Festanti
CERN
On behalf of the ALICE Collaboration

ALICE

Probing QGP with heavy quarks



- Early production in hard-scattering processes with high Q^2 (m_c, m_b >> T_{QGP})
- Production cross section calculable with pQCD (m_c, m_b >> Λ_{QCD})
- Experience the entire evolution of the medium
- Strongly interacting with QGP



Probing QGP with heavy quarks

m_u, m_d — m_s — Λ_{QCD} — m_c — m_b

1 — 10 — 10^2 — T_c — T_{QGP} — 10^3 — 10^4 MeV

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- Experience the entire evolution of the medium
- Strongly interacting with QGP

- **energy loss via radiative and collisional processes**
  - path length and medium density
  - color charge (Casimir factor)
  - quark mass (dead cone effect)

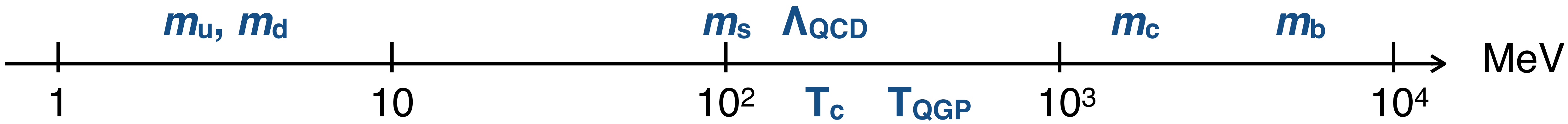
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Observable: nuclear modification factor

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

No modification → R_{AA}=1
Energy loss → R_{AA}<1 at high p_T

Probing QGP with heavy quarks



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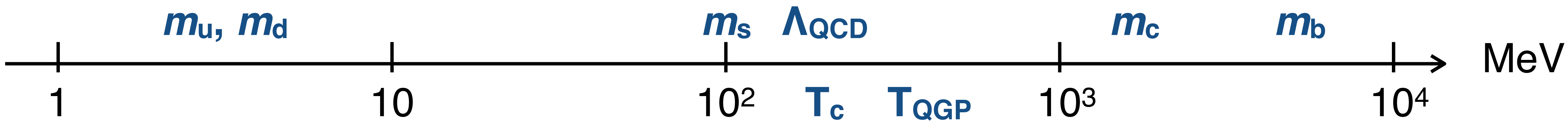
  - **energy loss via radiative and collisional processes**
  - **medium modification to heavy-flavour hadron formation**
    - hadronisation via quark coalescence

Probing QGP with heavy quarks



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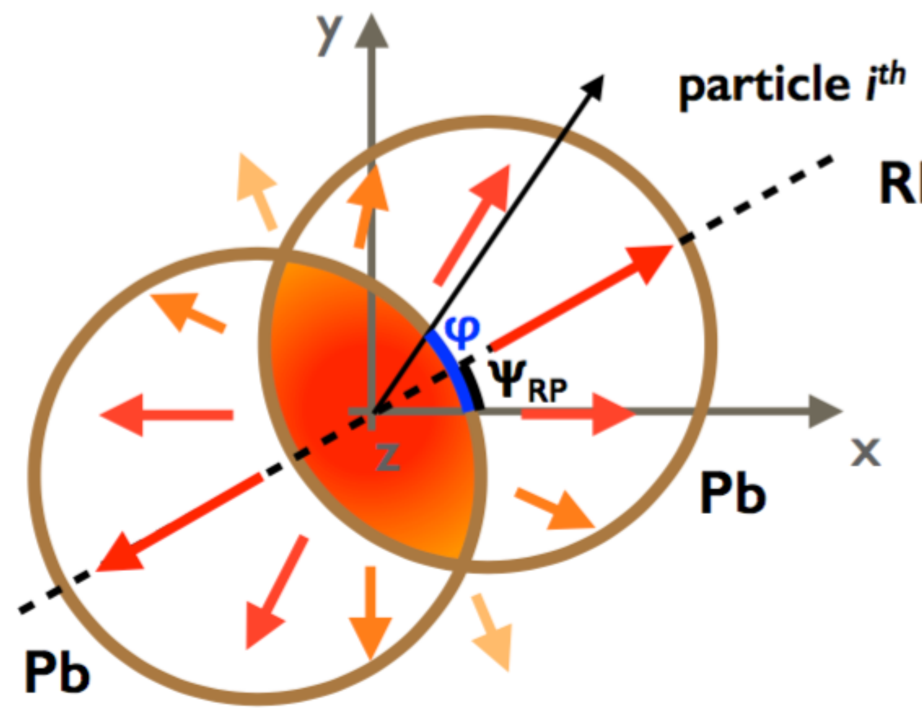
- Experience the entire evolution of the medium
- Strongly interacting with QGP
  - **energy loss via radiative and collisional processes**
  - **medium modification to heavy-flavour hadron formation**
  - **participation in the collective motion**
    - azimuthal anisotropy of produced particles

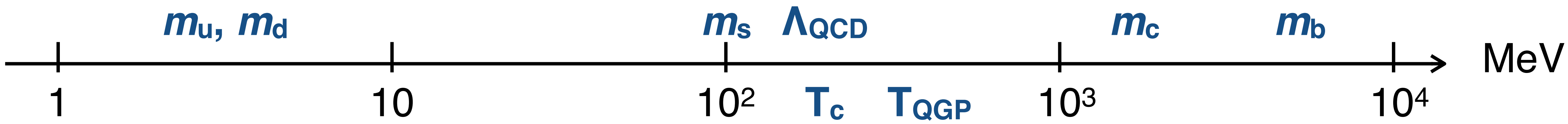


Observable: elliptic flow v_2

$$\boxed{v_2 = \langle \cos 2(\varphi - \psi_2) \rangle}$$

Second coefficient of the Fourier expansion of the azimuthal distribution of D w.r.t. to reaction plane angle (Ψ_{RP})

Probing QGP with heavy quarks



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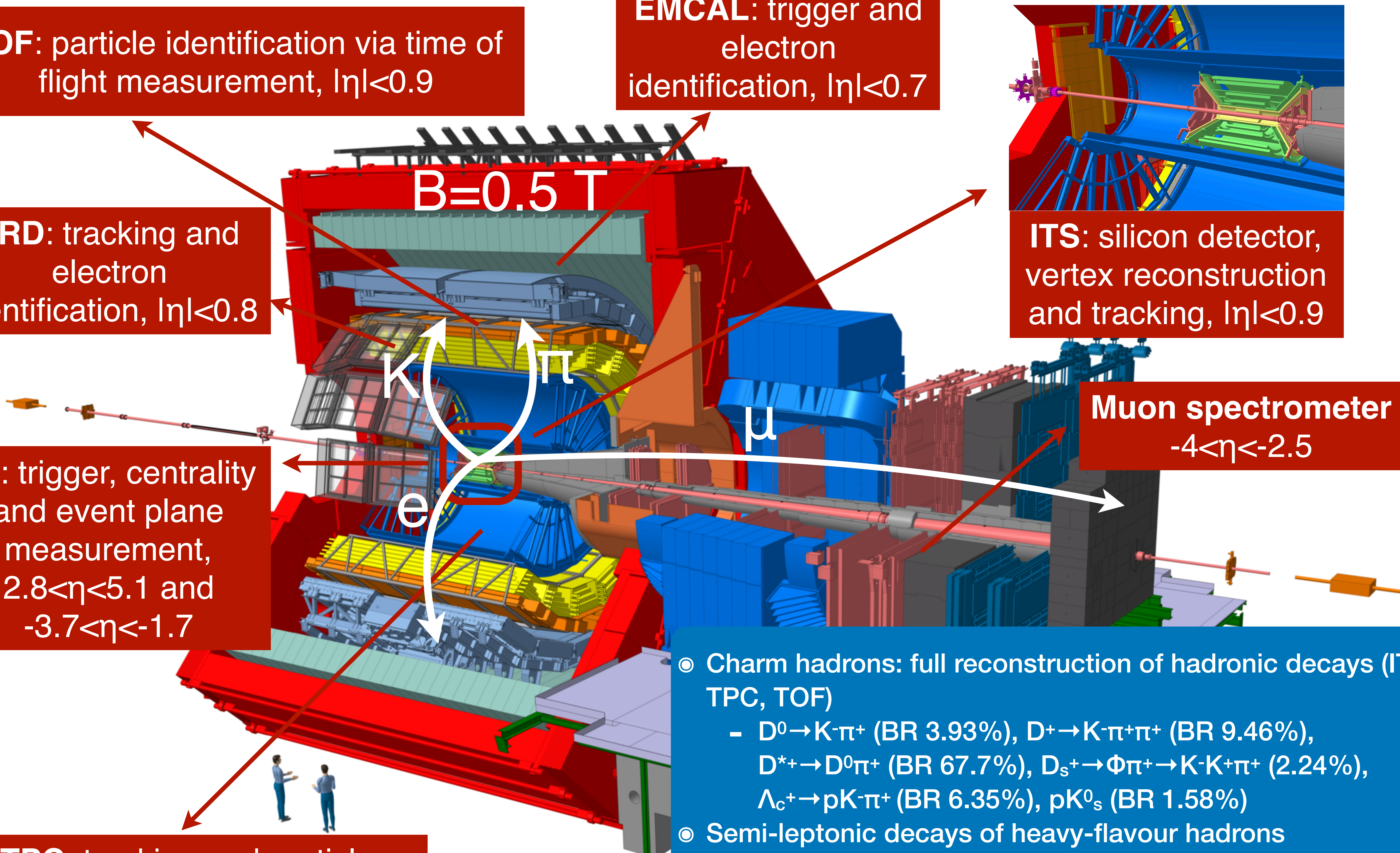
- Production cross section calculable with pQCD (m_c, m_b >> Λ_{QCD})
- Experience the entire evolution of the medium
- Strongly interacting with QGP
  - **energy loss via radiative and collisional processes**
  - **medium modification to heavy-flavour hadron formation**
  - **participation in the collective motion**
- Cold Nuclear Matter (CNM) effects (not due to QGP formation) can modify heavy-flavour production in nuclear collisions: studied in p-Pb collisions

Observable: nuclear modification factor

$$\boxed{R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{A \times \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}}$$

ALICE Experiment



TOF: particle identification via time of flight measurement, $|\eta|<0.9$

EMCAL: trigger and electron identification, $|\eta|<0.7$

ITS: silicon detector, vertex reconstruction and tracking, $|\eta|<0.9$

TRD: tracking and electron identification, $|\eta|<0.8$

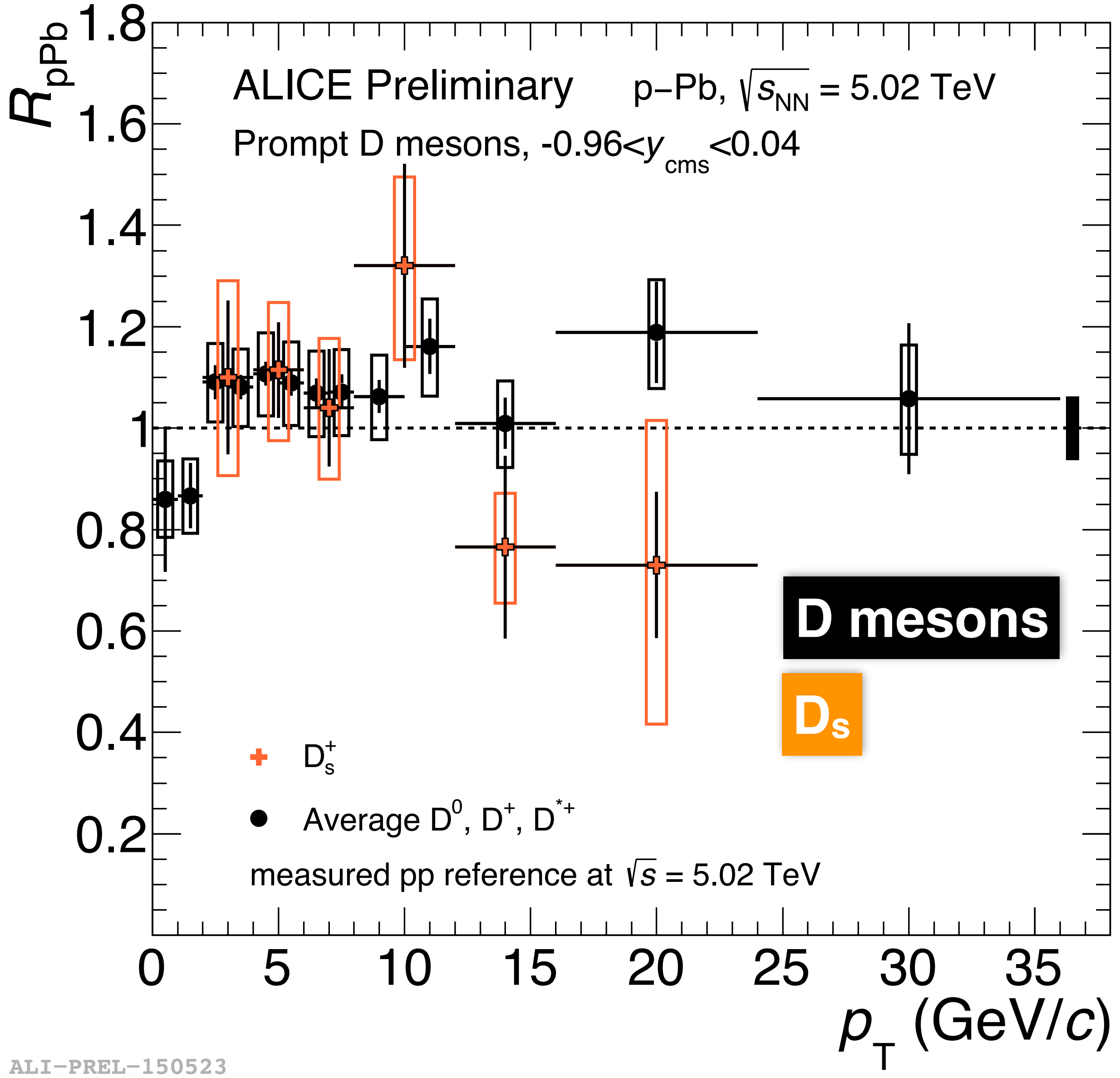
Muon spectrometer $-4<\eta<-2.5$

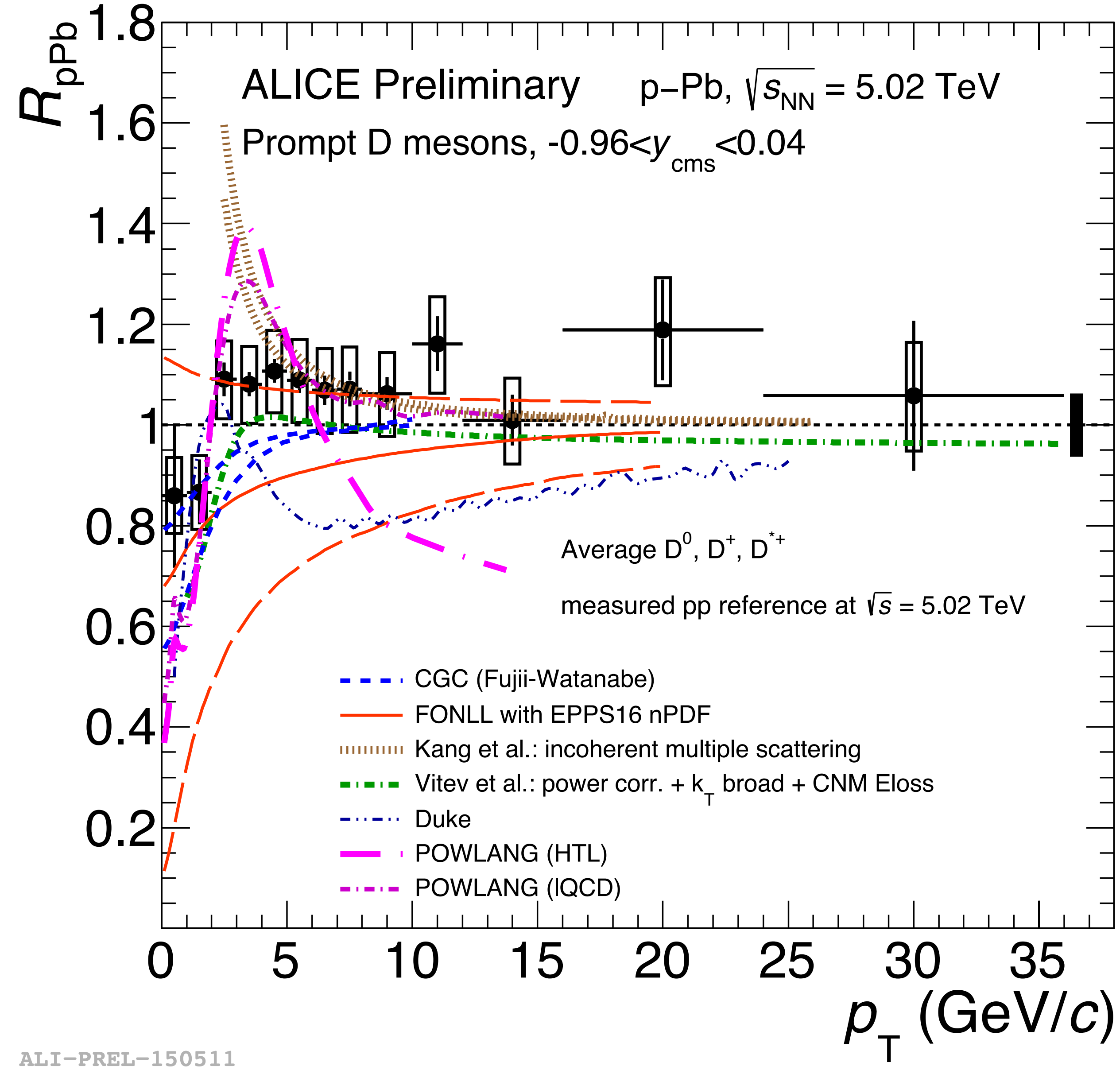
V0: trigger, centrality and event plane measurement, $2.8<\eta<5.1$ and $-3.7<\eta<-1.7$

TPC: tracking and particle identification via dE/dx, $|\eta|<0.9$

- Charm hadrons: full reconstruction of hadronic decays (ITS, TPC, TOF)
  - $D^0 \rightarrow K^-\pi^+$ (BR 3.93%), $D^+ \rightarrow K^-\pi^+\pi^+$ (BR 9.46%), $D^{*+} \rightarrow D^0\pi^+$ (BR 67.7%), $D_s^+ \rightarrow \Phi\pi^+ \rightarrow K^-K^+\pi^+$ (2.24%), $\Lambda_c^+ \rightarrow pK^-\pi^+$ (BR 6.35%), pK^0_s (BR 1.58%)
- Semi-leptonic decays of heavy-flavour hadrons
  - $b,c \rightarrow e^\pm X$ (BR~10%) (TPC, TOF, EMCAL)
  - $b,c \rightarrow \mu^\pm X$ (BR~10%) (Muon spectrometer)

D-meson production in p-Pb collisions

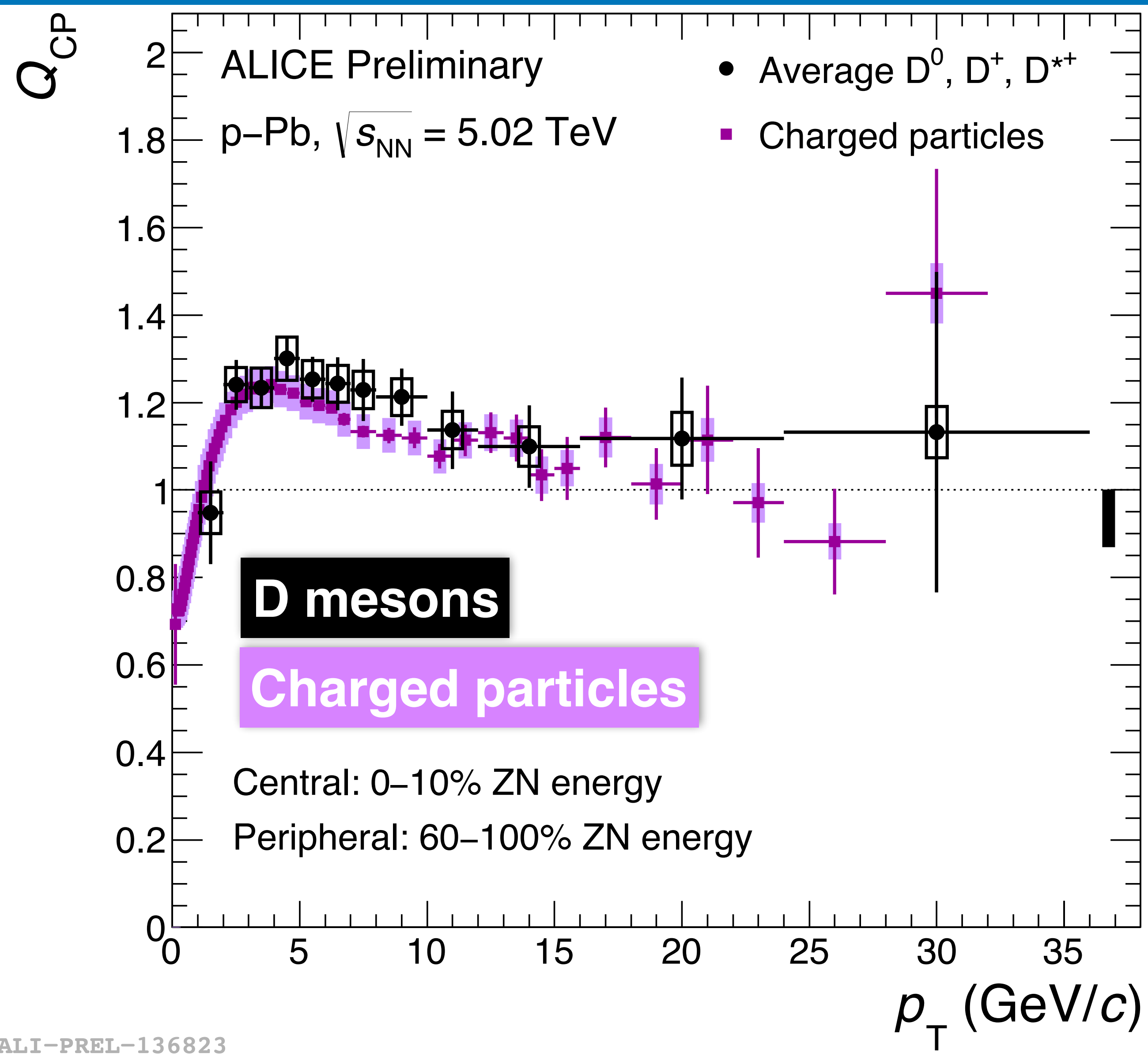


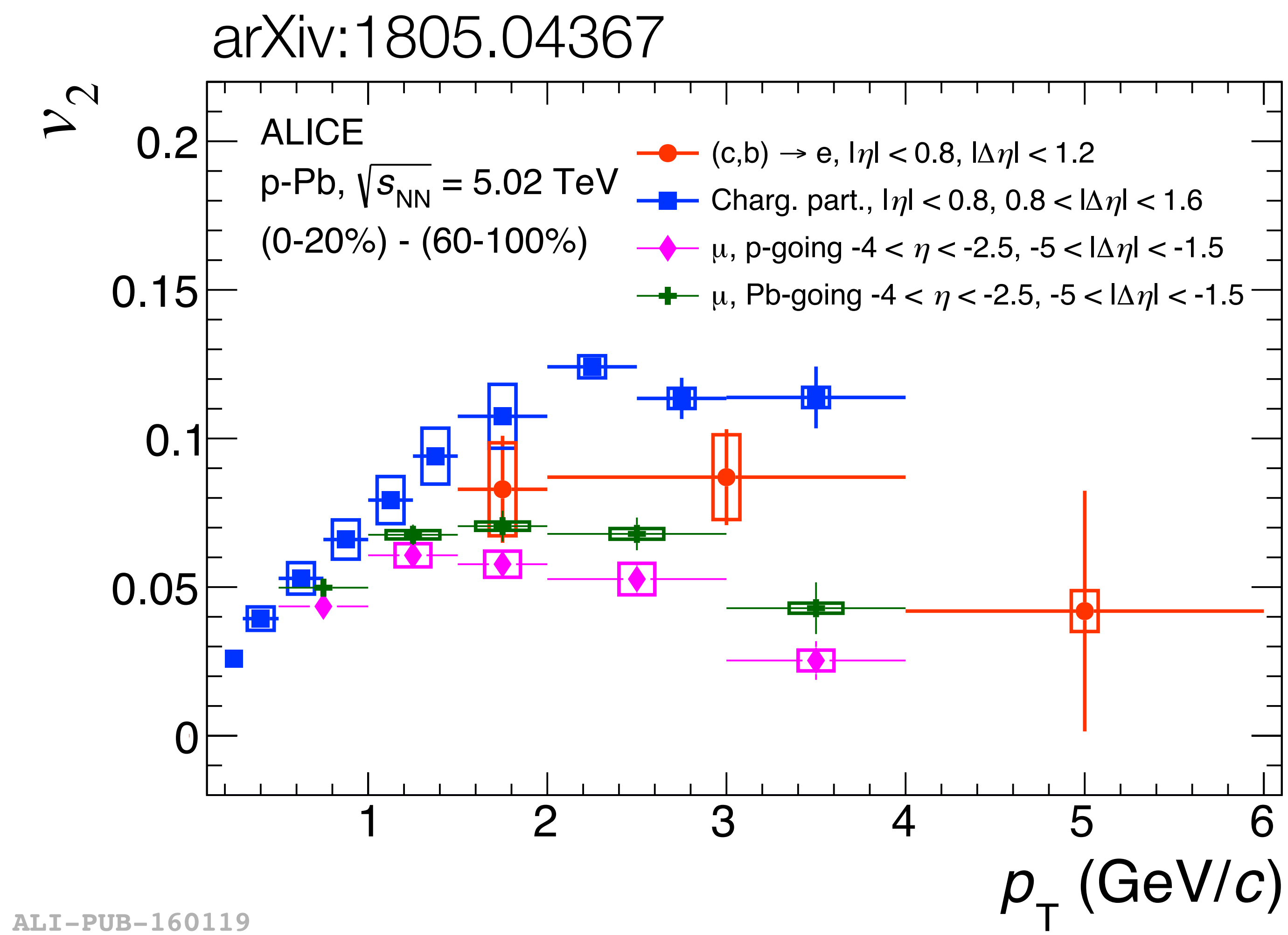


- **D-meson R_{pPb} consistent with unity** within uncertainties in minimum bias p-Pb collisions
- **D_s** R_{pPb} **compatible** with **non-strange D-**meson R_{pPb}

- Models including
  - CNM effects only are compatible with data
  - Incoherent multiple scattering describes data for $p_T > 5$ GeV/c
  - Including QGP formation describe data at low/intermediate p_T

Multiplicity-differential studies in p-Pb collisions



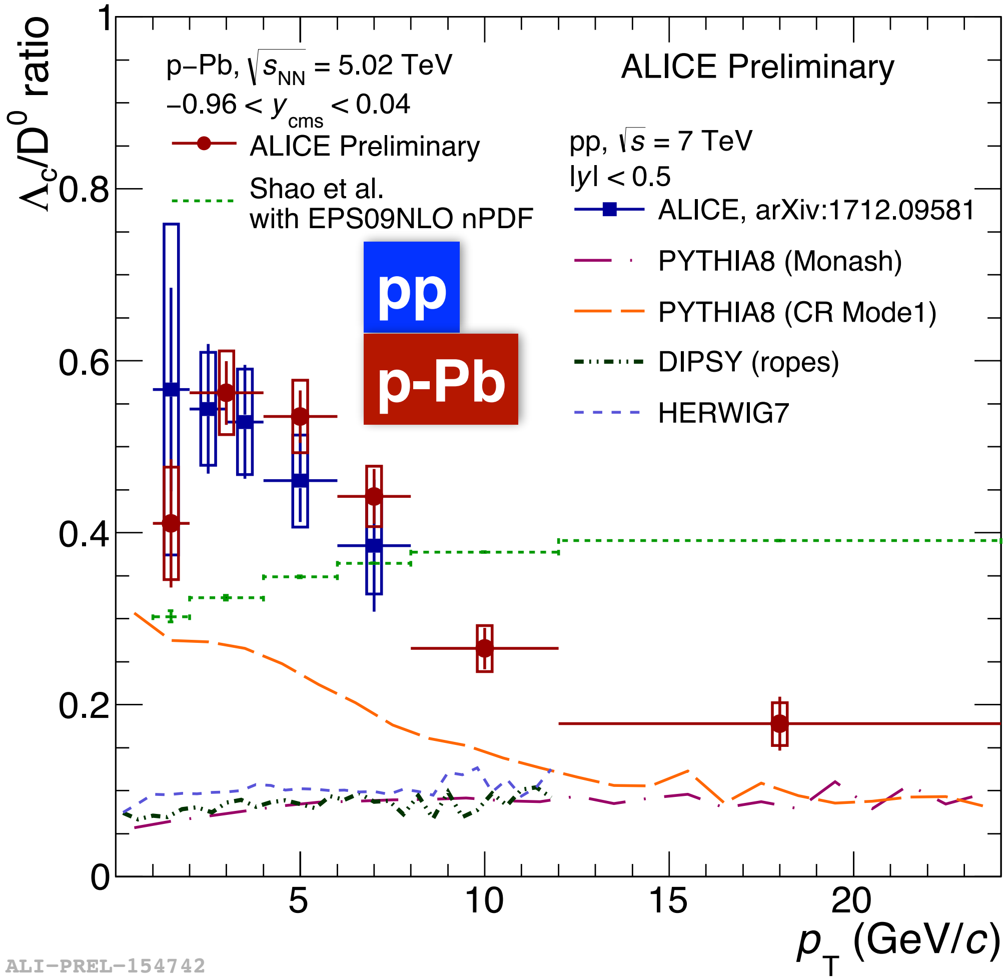


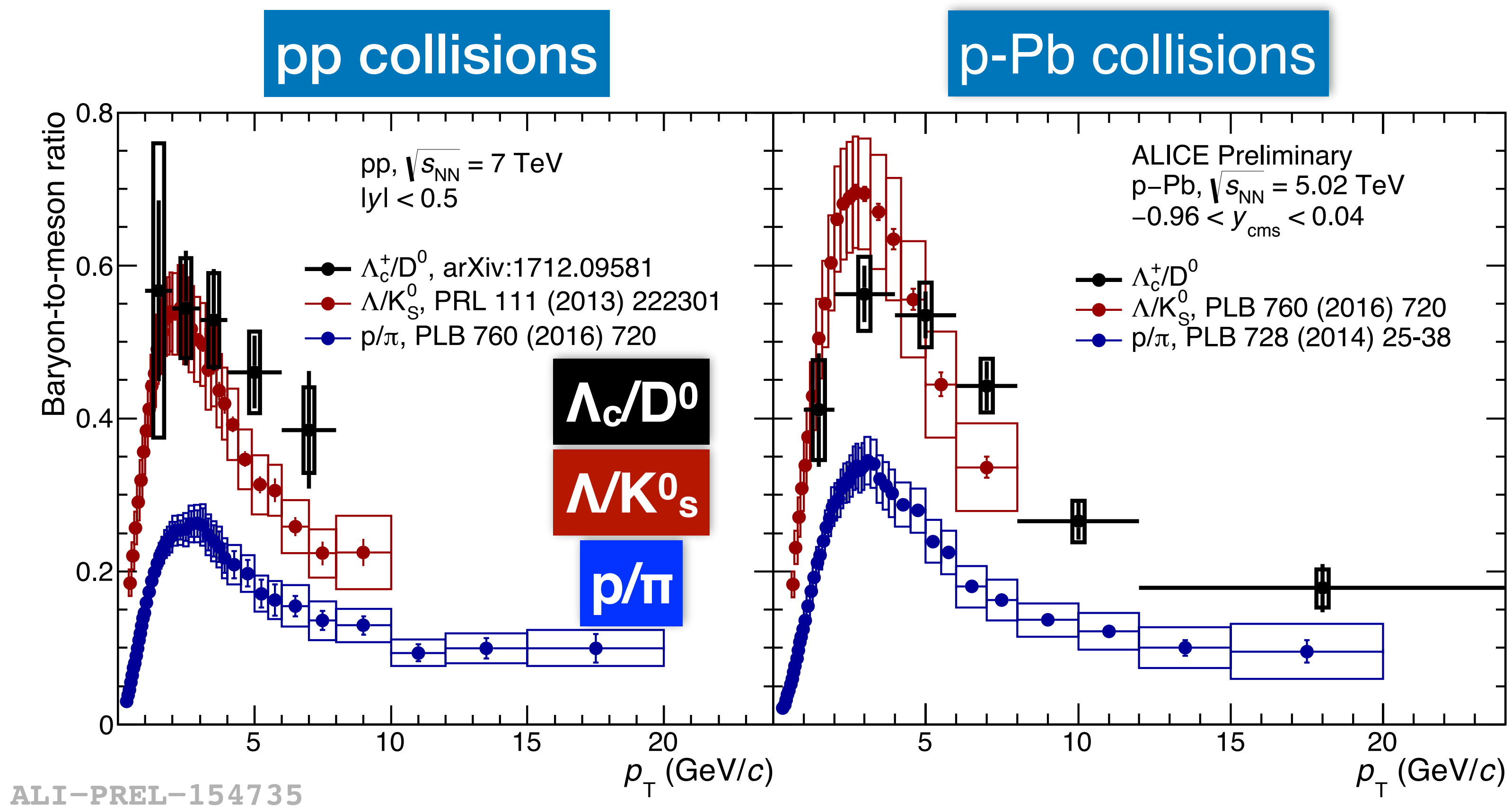
- **Hint of central-to-peripheral ratio larger than 1** in $3 < p_T < 8$ GeV/c for D mesons (1.5σ significance)
- Similar trend as observed for charged particles

- v_2(c,b→e)>0 with 5.1σ significance in $1.5 < p_T^e < 4$ GeV/c
- Qualitatively similar effect as observed for charged particles and inclusive muons

Collective effects in p-Pb collisions? Initial- or final-state effects?

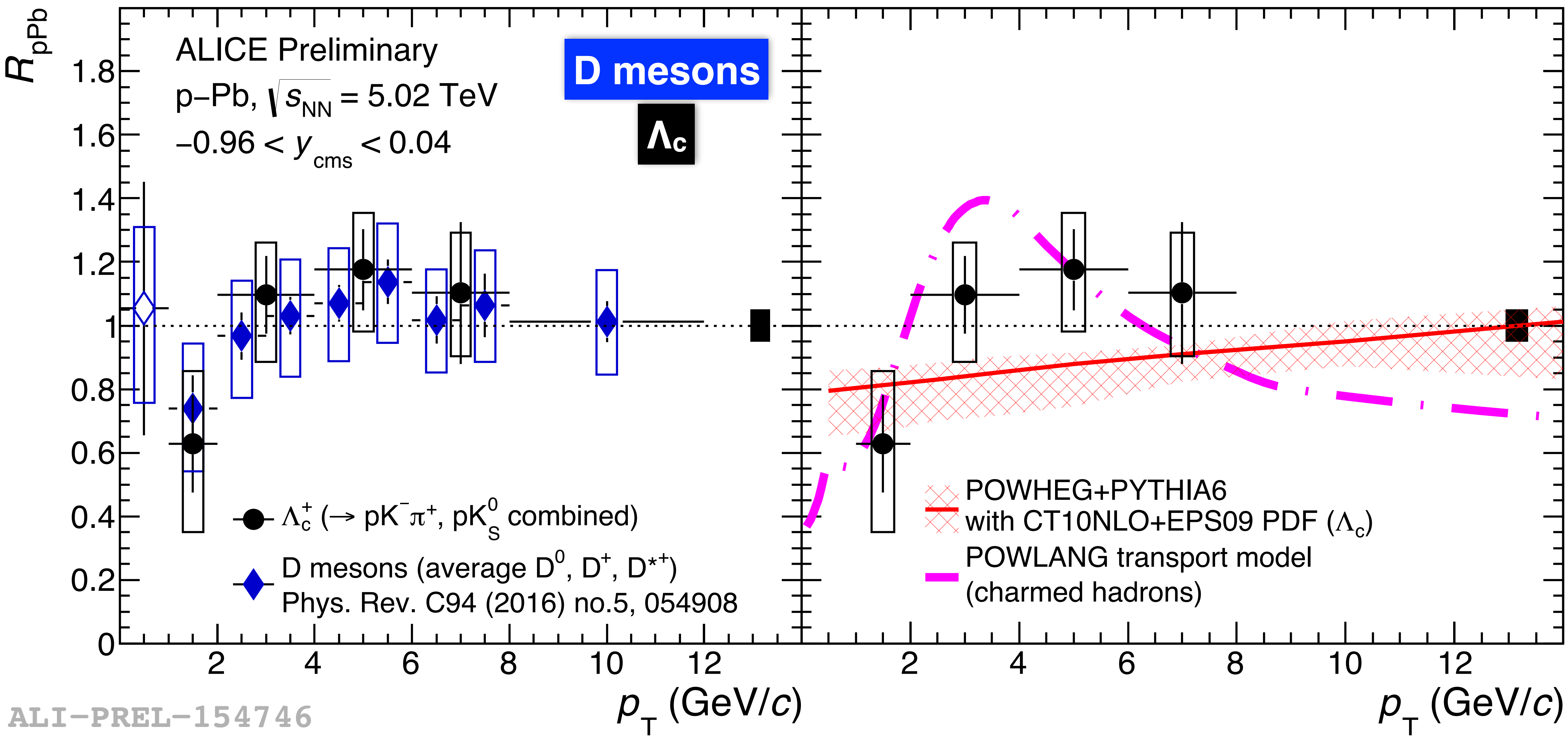
Λ_c/D^0 in pp and p-Pb collisions





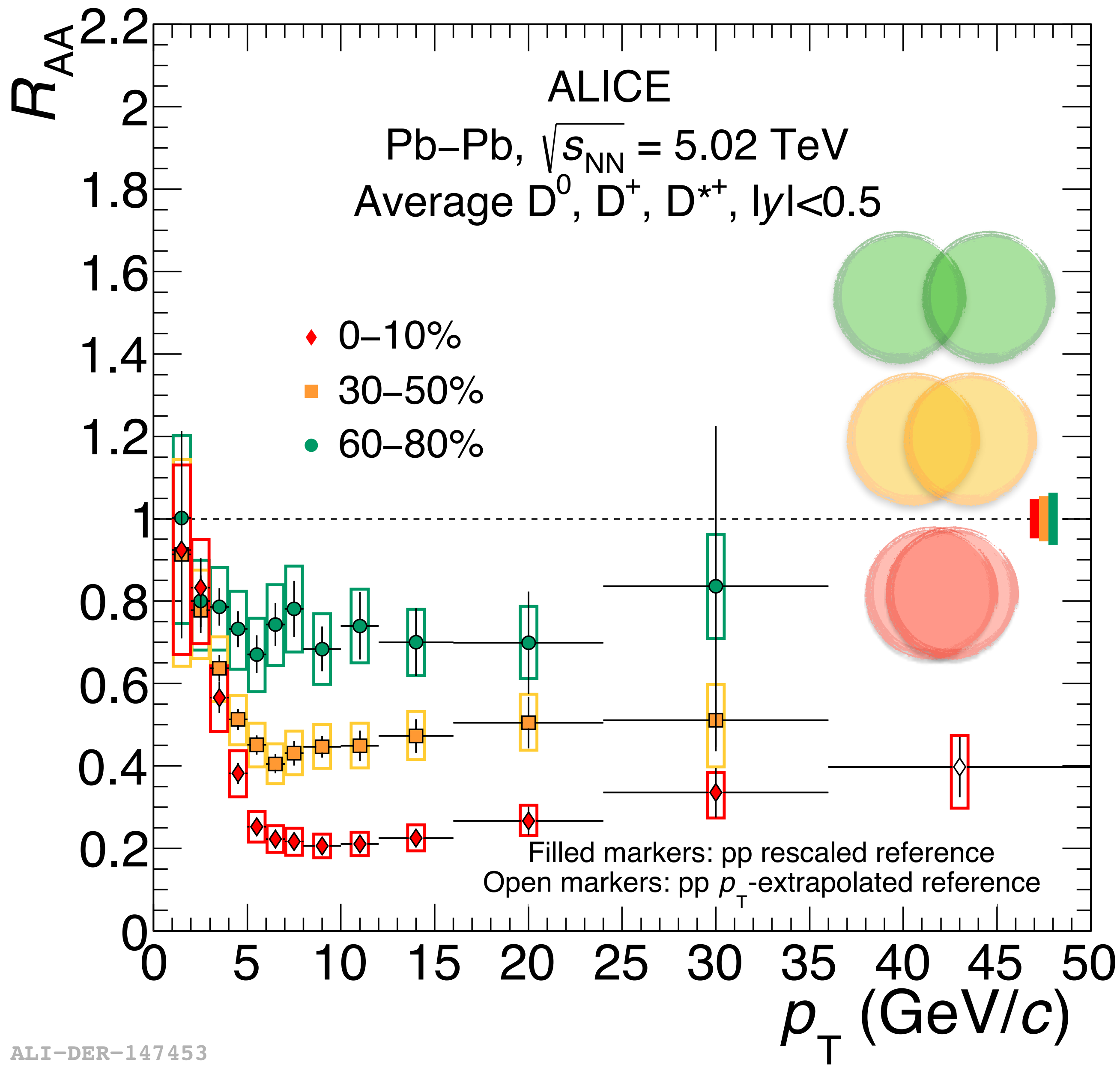
- Λ_c/D^0 compatible within uncertainties in pp and p-Pb collisions
- Λ_c/D^0 **higher than expectations from MC** (PYTHIA8 with enhanced colour reconnection is closer to data)
- Decreasing trend of Λ_c/D^0 for $p_T > 4$ GeV/c is observed in p-Pb collisions
  - **Similar trend as a function of p_T as the light-flavour baryon-to-meson ratio**

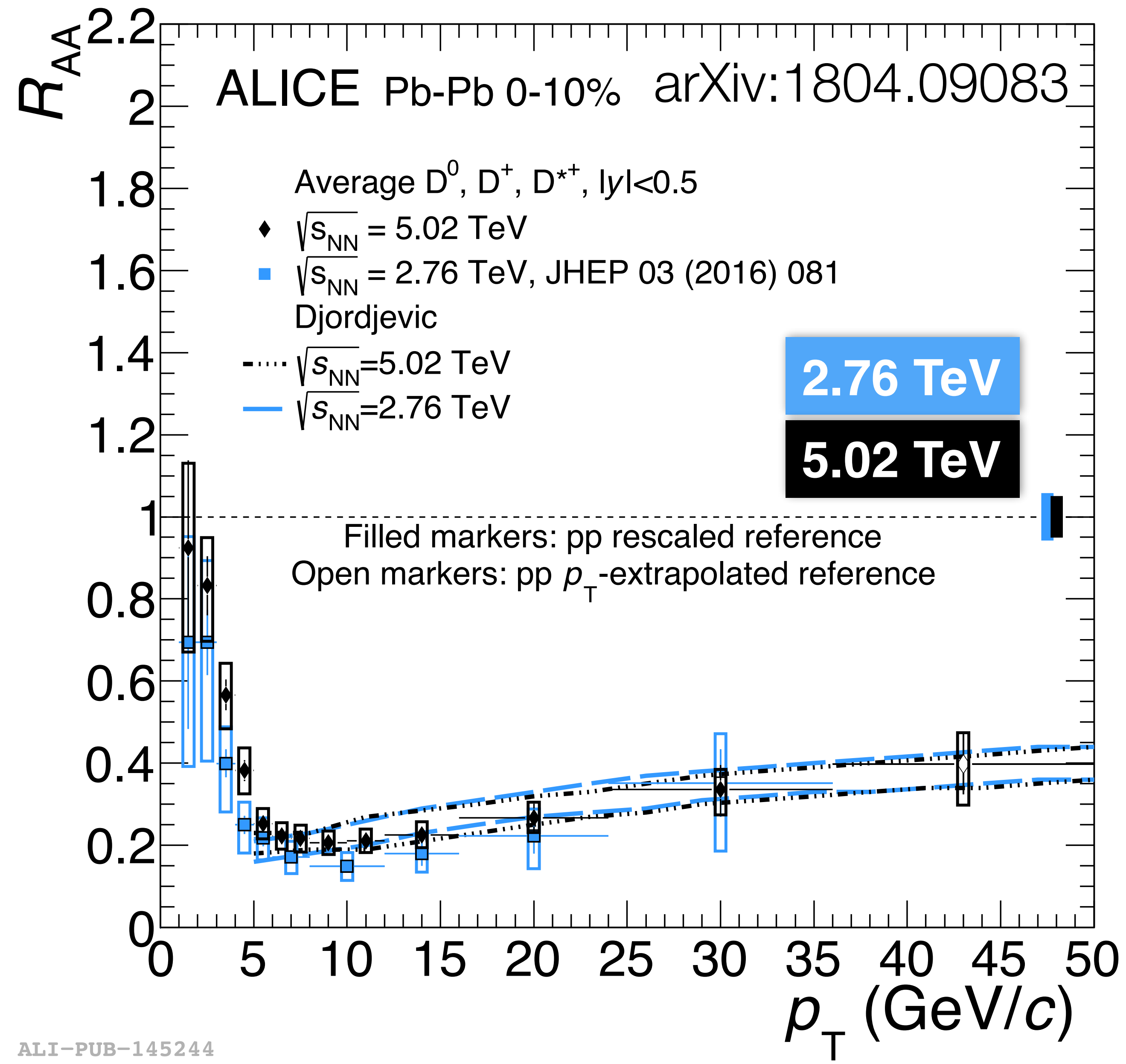
Λ_c R_{pPb}



- **Λ_c R_{pPb} consistent with unity**, D-meson R_{pPb} and models within uncertainties
  - CNM effects: POWHEG+PYTHIA with CT10NLO+EPS09 PDFs
  - Hot medium effects: POWLANG with “small-size” QGP formation + collisional energy loss

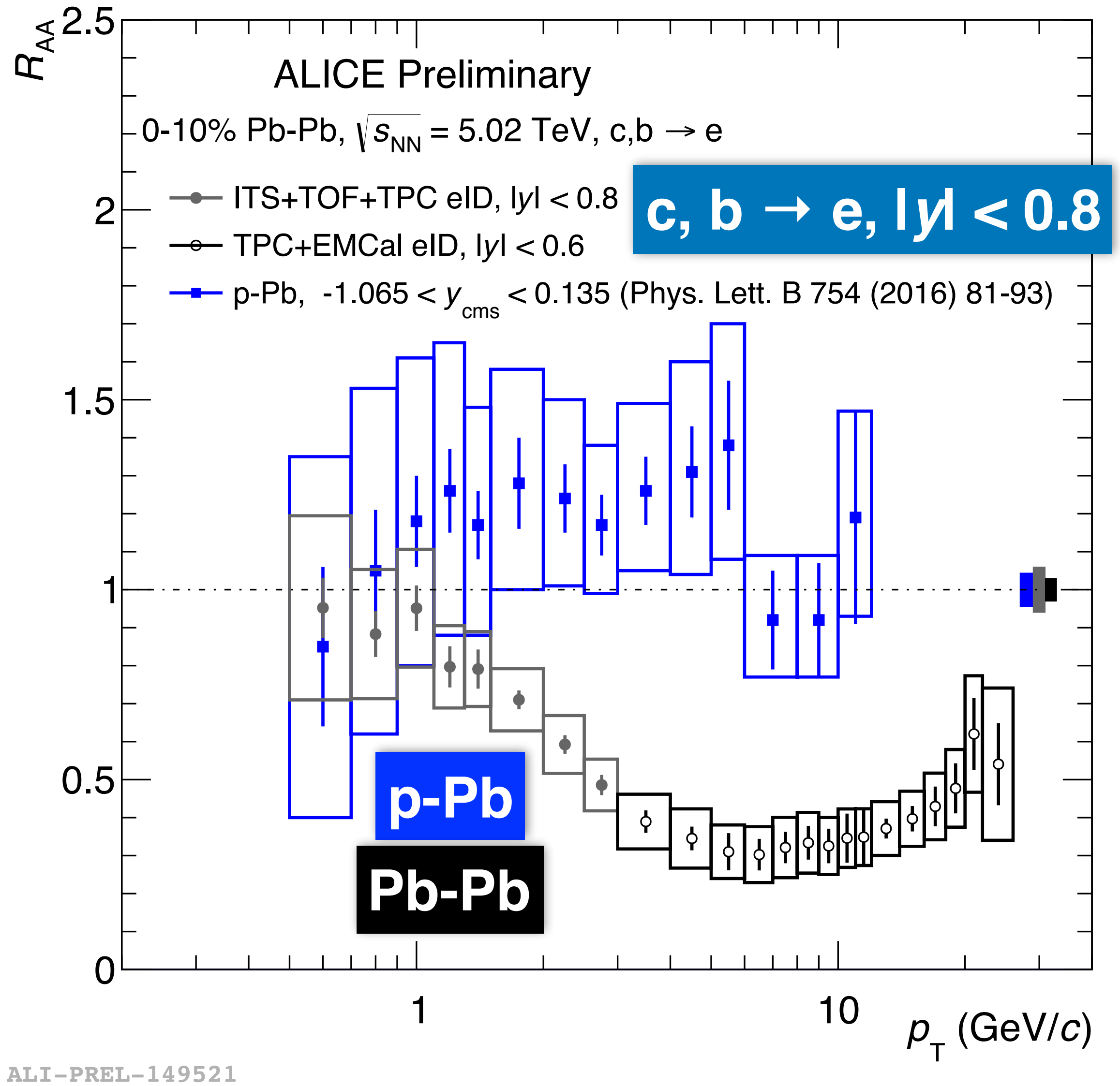
D-meson R_{AA}

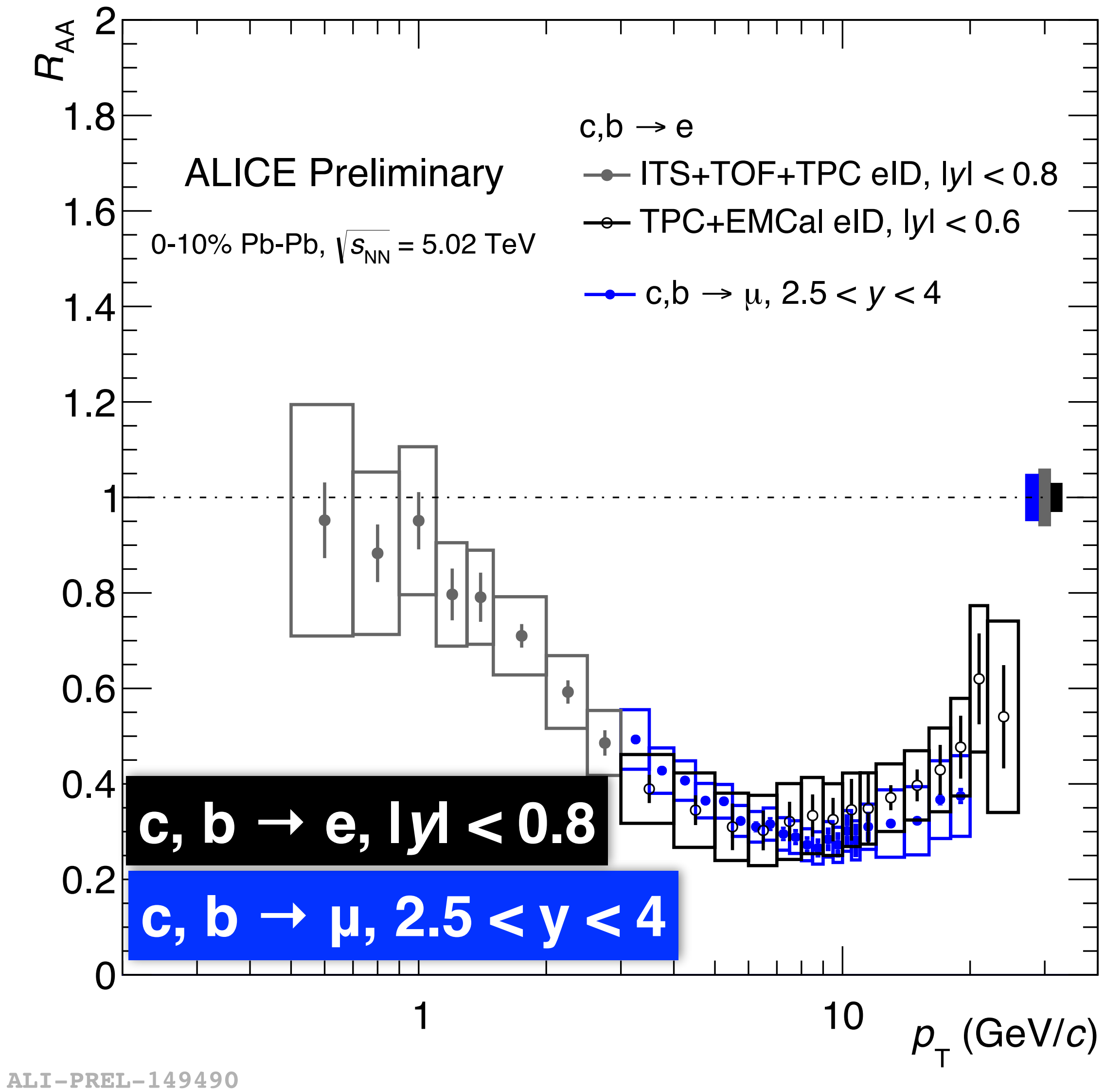




- **Strong suppression** at high p_T of non-strange D mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV increasing with centrality
  - **Evidence of strong charm quark energy loss in the medium**
- Similar suppression at $\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s_{NN}}$ = 5.02 TeV
  - **Interplay between harder spectra and denser medium**

Heavy-flavour hadron decay electron R_{AA}

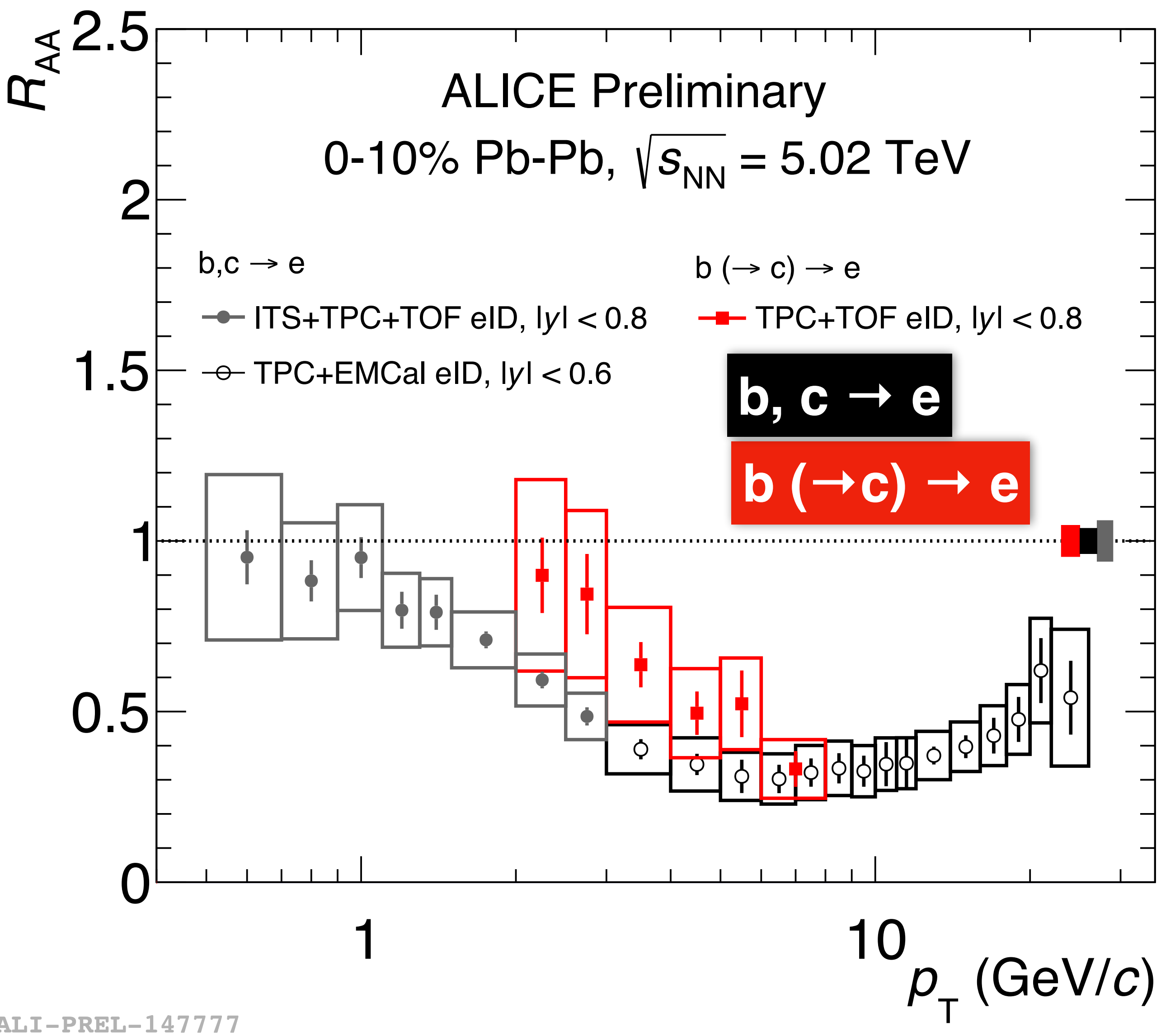


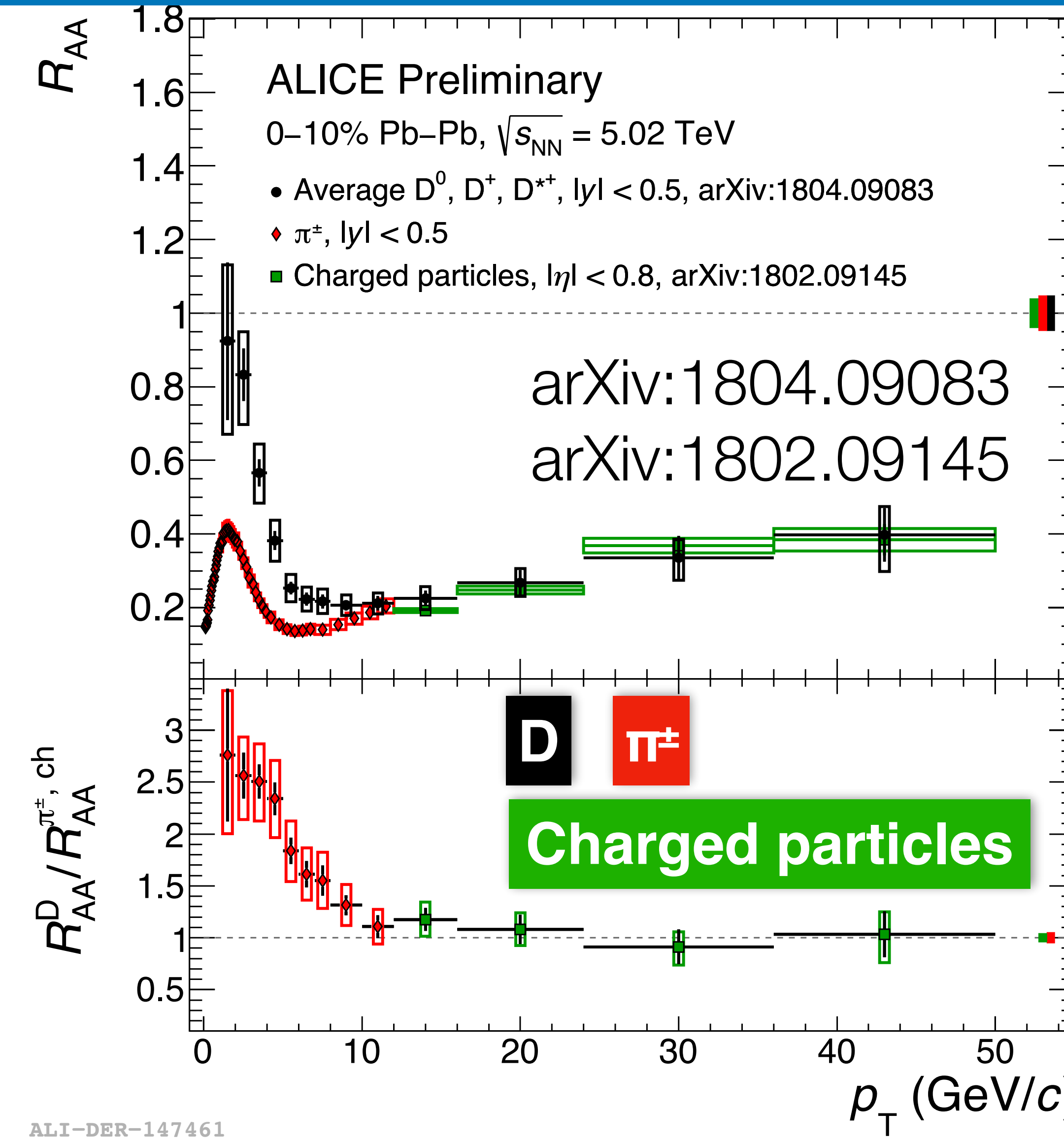


- Strong suppression of heavy-flavour hadron decay electron R_{AA} at high p_T in central Pb-Pb collisions
- Nuclear modification factor measured in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compatible with unity
- Similar suppression observed for muons from heavy-flavour hadron decays at forward rapidity

Suppression in Pb-Pb collisions due to charm and beauty in-medium interaction

HF electrons, D-meson and charged-particle R_{AA}

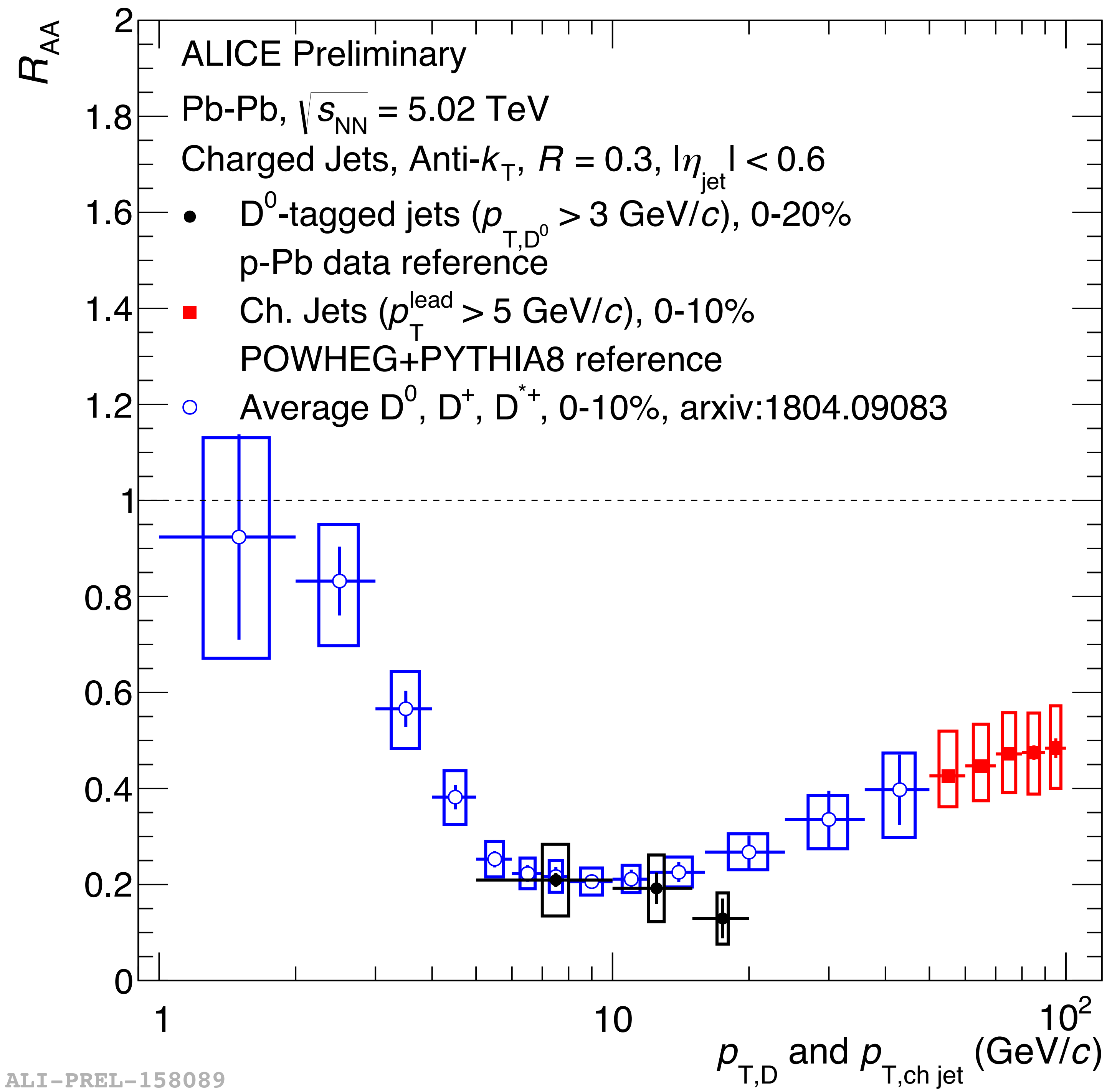




- Hint of smaller suppression of beauty-decay electrons than that of heavy flavour hadron decay electron in central Pb-Pb collisions
- Expected from models implementing **mass-dependent parton energy loss**

- Similar D, $\pi^{\pm}$ and ch.-particle R_{AA} for $p_T > 10$ GeV/c
- D-meson R_{AA} larger than that of $\pi^{\pm}$ at low p_T
  - **N_{part} vs N_{coll} scaling** at low p_T, different **fragmentation** and **initial spectra shapes, coalescence** and **radial flow** to be considered in addition to **mass** and **Casimir factor effects**

D-tagged jets R_{AA}

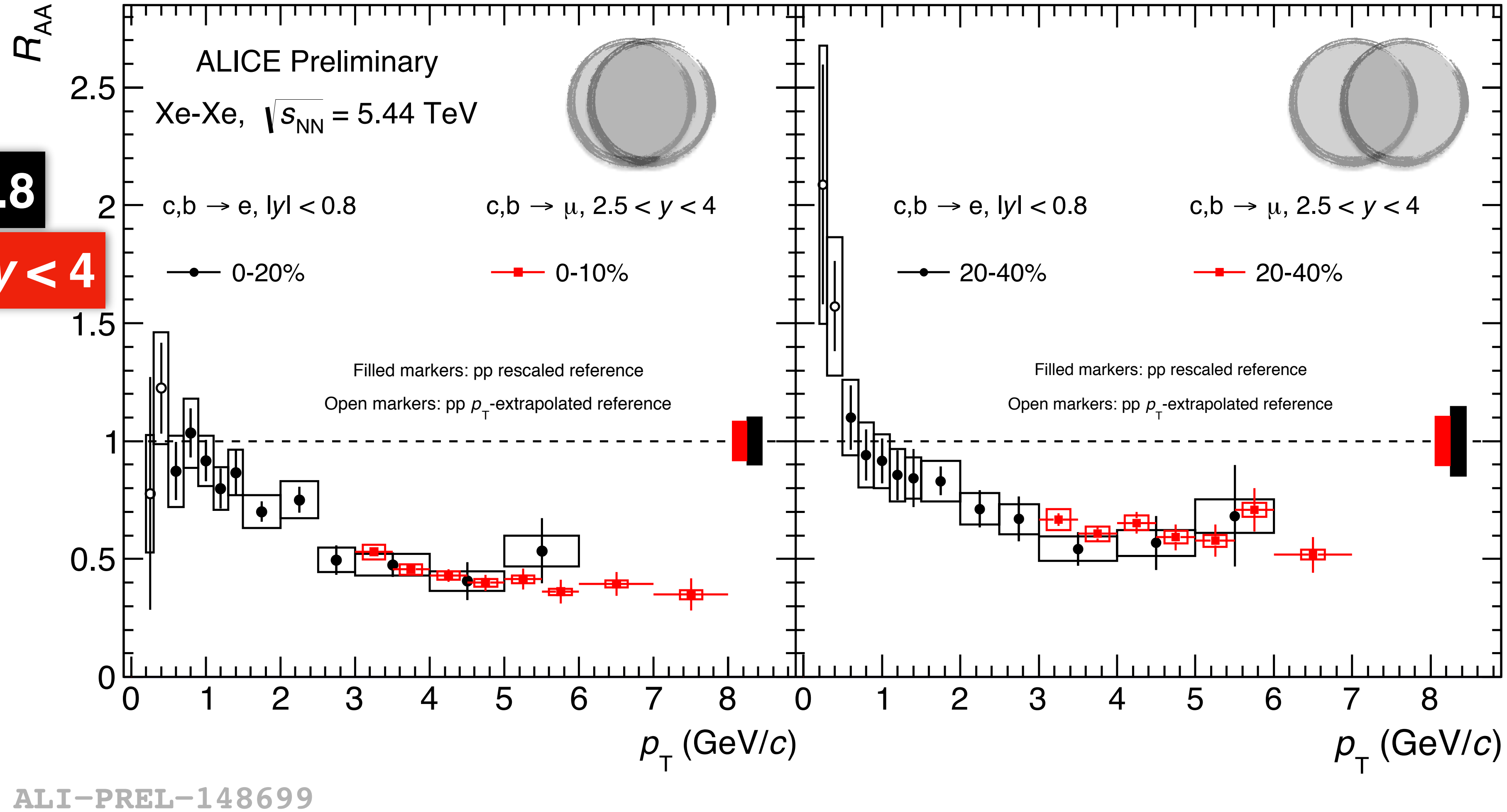


- First measurement of **D-tagged jets in Pb-Pb collisions**
- **Strong suppression of the D^0-tagged jets in central Pb-Pb** collisions
  - Hint of more suppression of low p_T D^0-jets than inclusive jets at higher p_T
  - **Similar to D-meson R_{AA}**
- D^0-jets: more quark-seeded jets compared to inclusive jets
- Important to study the impact of collisional energy loss for heavy-flavour jets

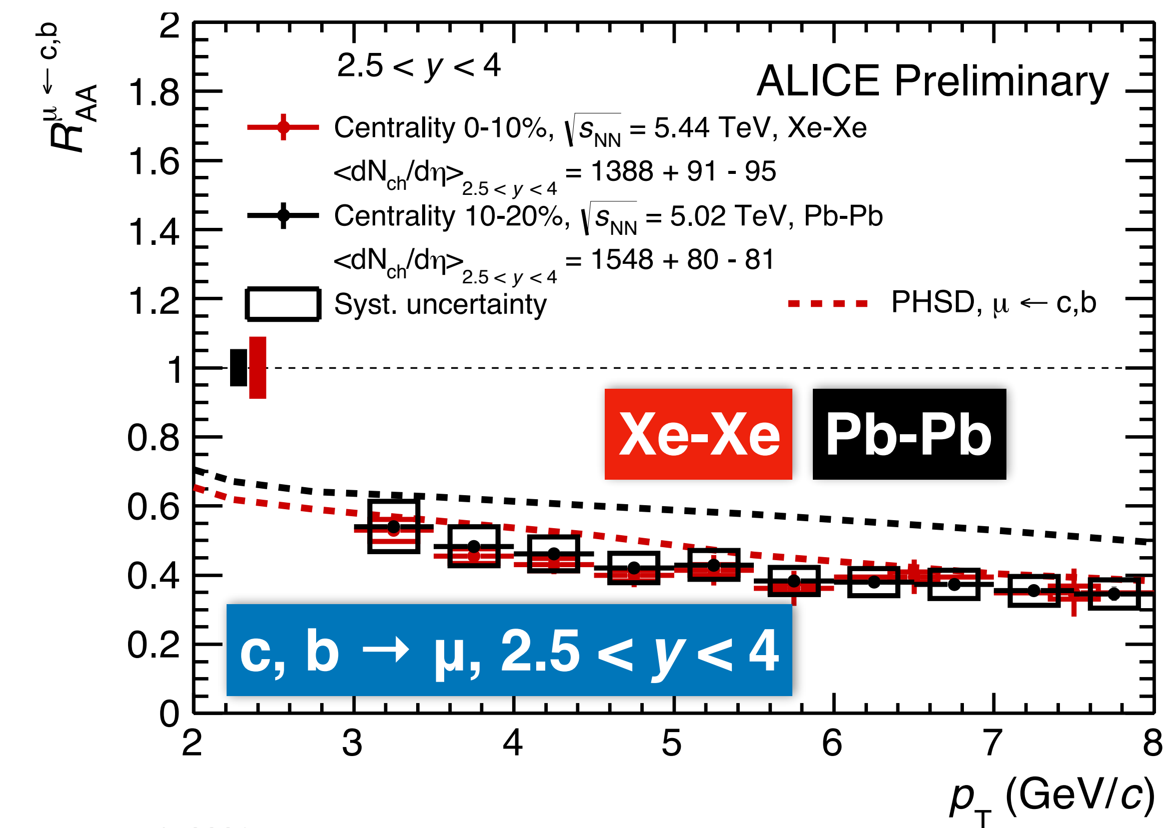
Heavy-flavour hadron decay electron and muon R_{AA} in Xe-Xe

c, b → e, |y| < 0.8

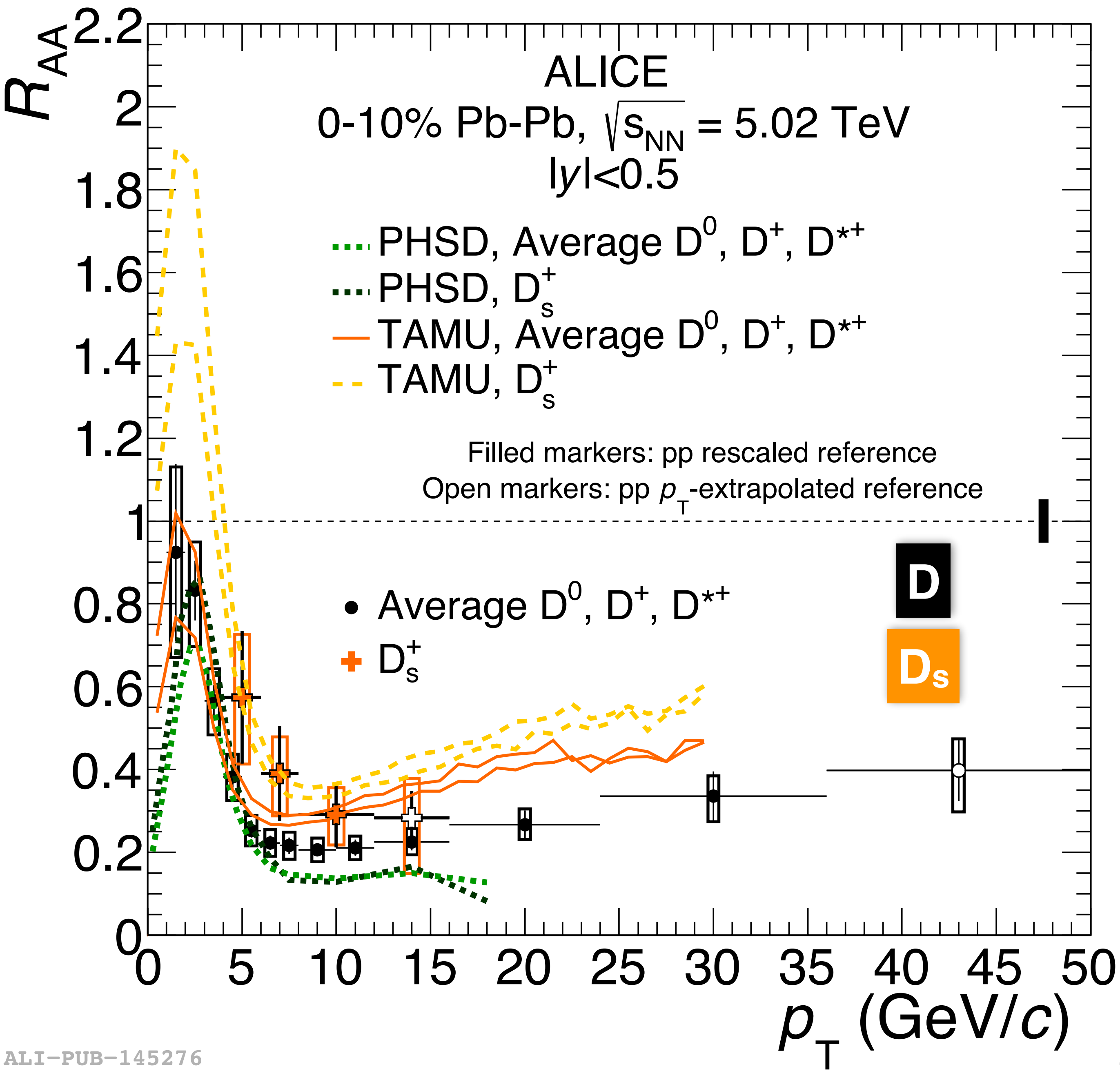
c, b → μ, 2.5 < y < 4

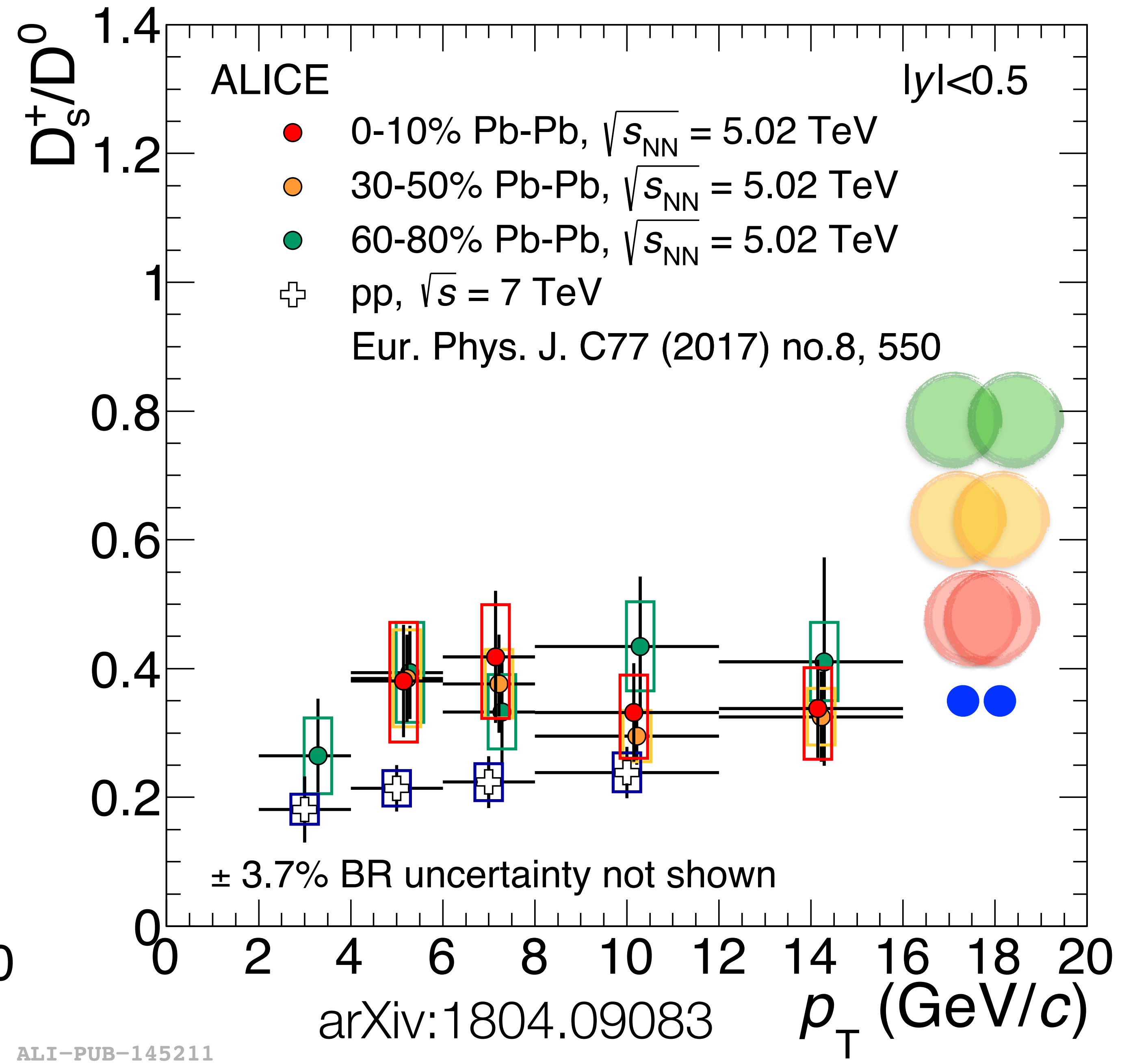


- **Similar suppression** of heavy-flavour hadron decay **electron** and **muon R_{AA}** measured in **Xe-Xe** collisions at $\sqrt{s_{NN}}$ = 5.44 TeV
- Comparison of **Pb-Pb and Xe-Xe** results at different multiplicities to probe **path-length dependence of energy loss**



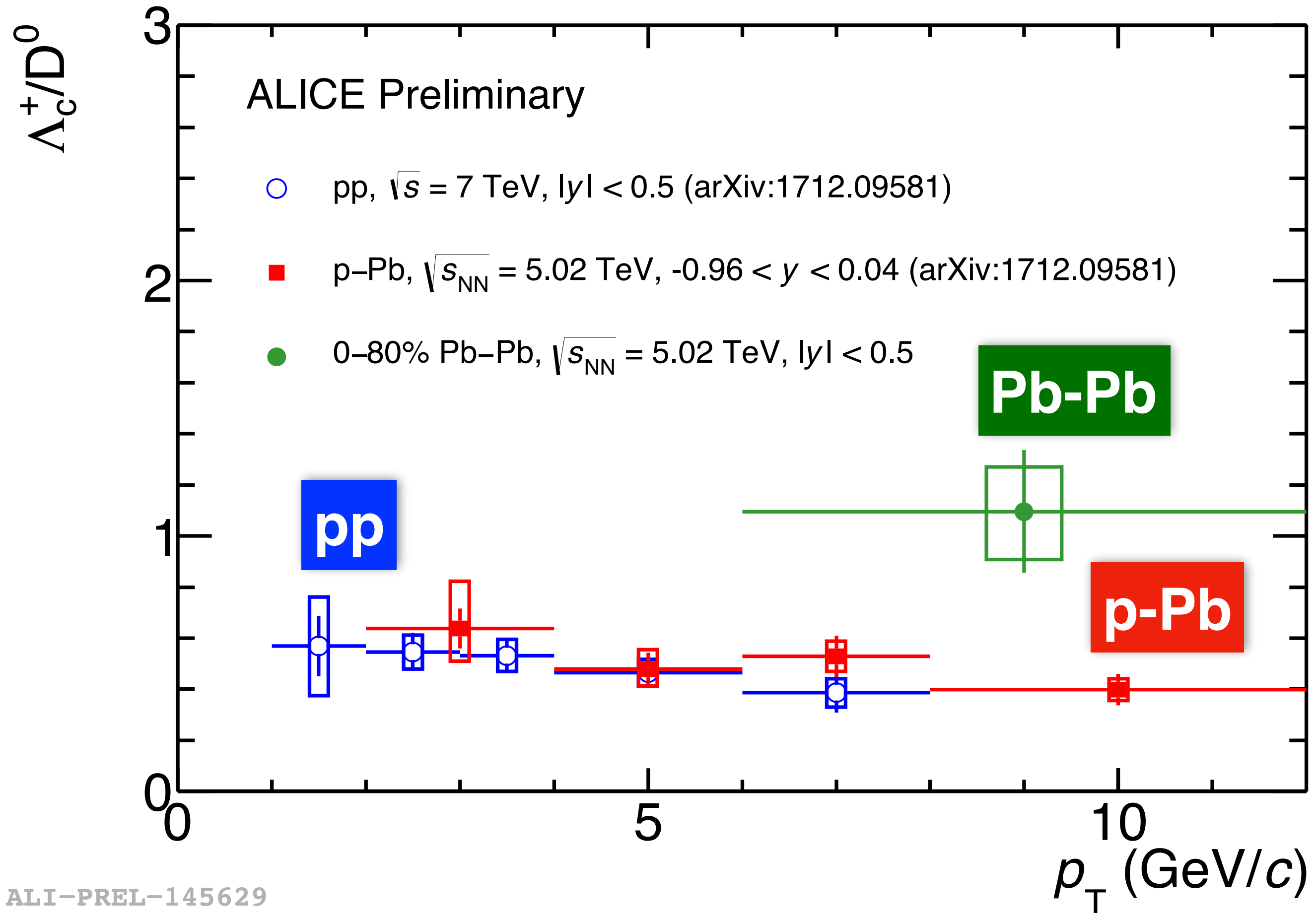
D_s R_{AA} and D_s/D^0 ratio

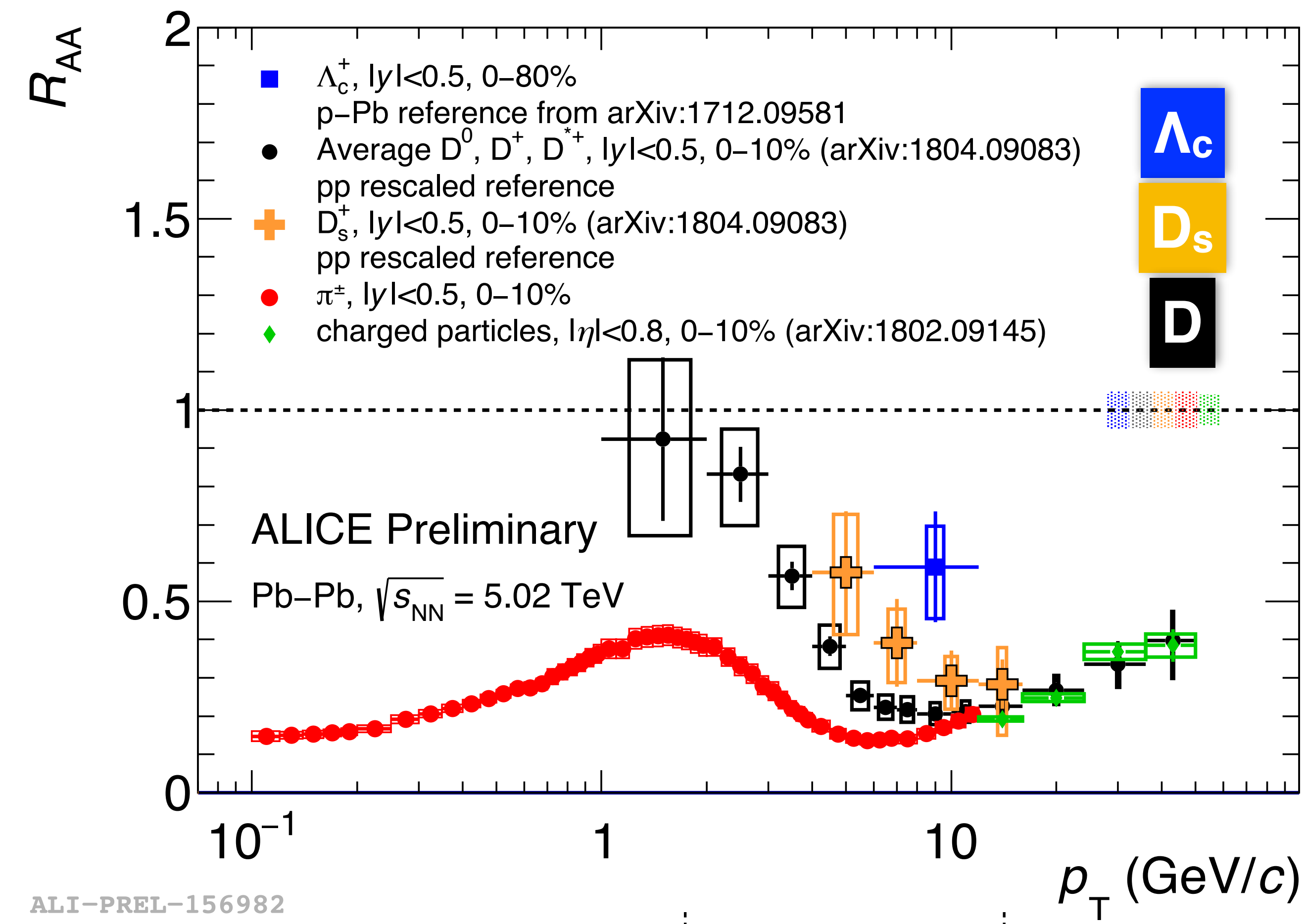




- **Hint of enhanced D_s production in comparison to non-strange D** mesons in **Pb-Pb** collisions → expected from models
  - **Coalescence + strangeness enhancement effect?**
- No evidence for a centrality dependence of the D^0/D_s ratio within uncertainties

Λc production in Pb-Pb collisions





Model	System	Λ_c/D^0
Oh et. al.	Central Au-Au, 200 GeV	~0.35 p_T = 6 GeV/c
Ghosh et al.	RHIC and LHC	0.15-0.2 p_T = 9 GeV/c
Das et al.	0-20% Pb-Pb, 5.5 TeV	~0.2 p_T = 9 GeV/c
Plumari et al.	0-20% Pb-Pb, 2.76 TeV	0.1-0.2 p_T = 8 GeV/c

- **Enhancement** of the **Λ_c/D^0** ratio in **Pb-Pb** collisions with respect to **pp and p-Pb** collisions
  - Models tend to underestimate the experimental results
- **Hint** of larger Λ_c R_{AA} in 0-80% than D-meson R_{AA} in 0-10%
  - **Ordering of charm hadron R_{AA} is consistent with recombination expectations**

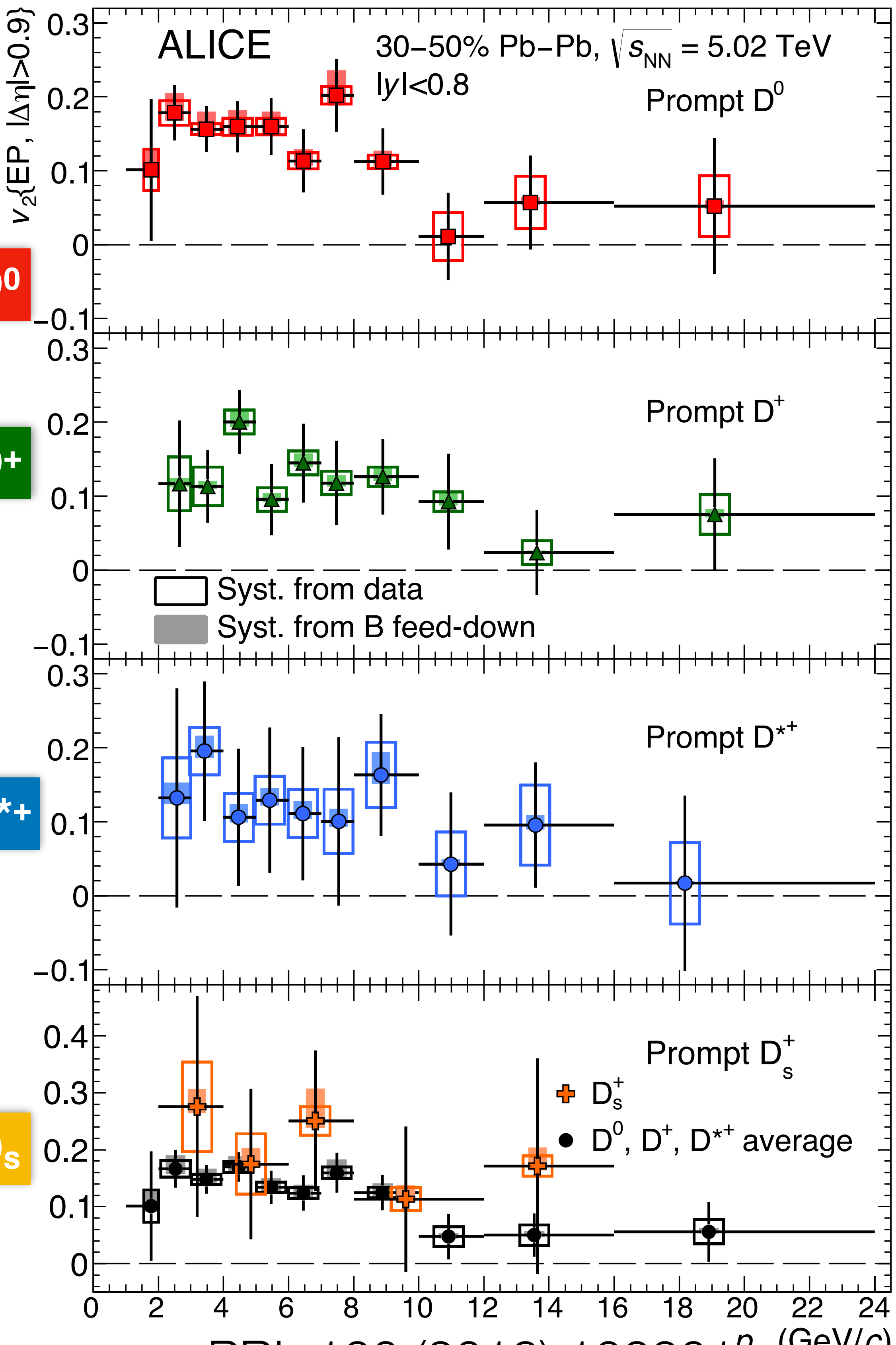
D-meson v_2

D⁰

D+

D*+

Ds



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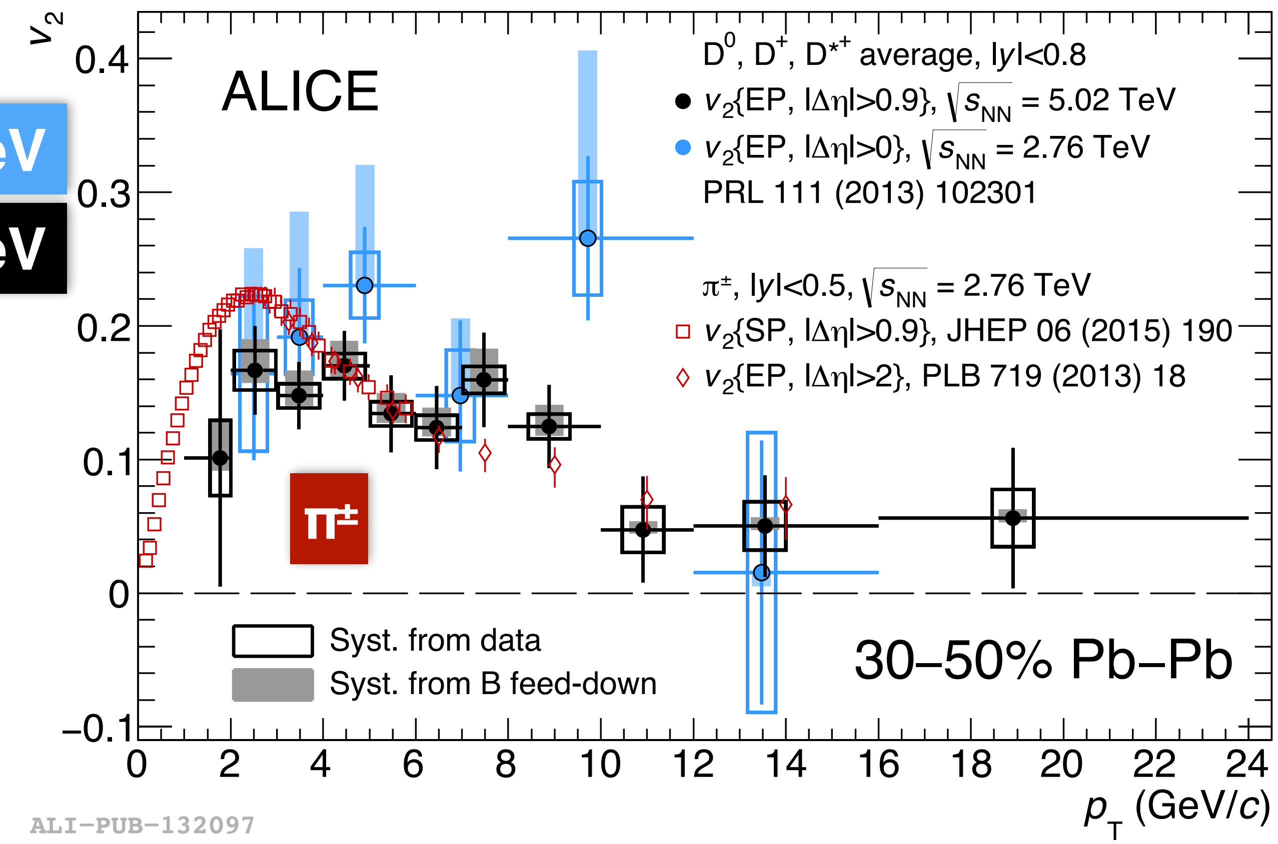
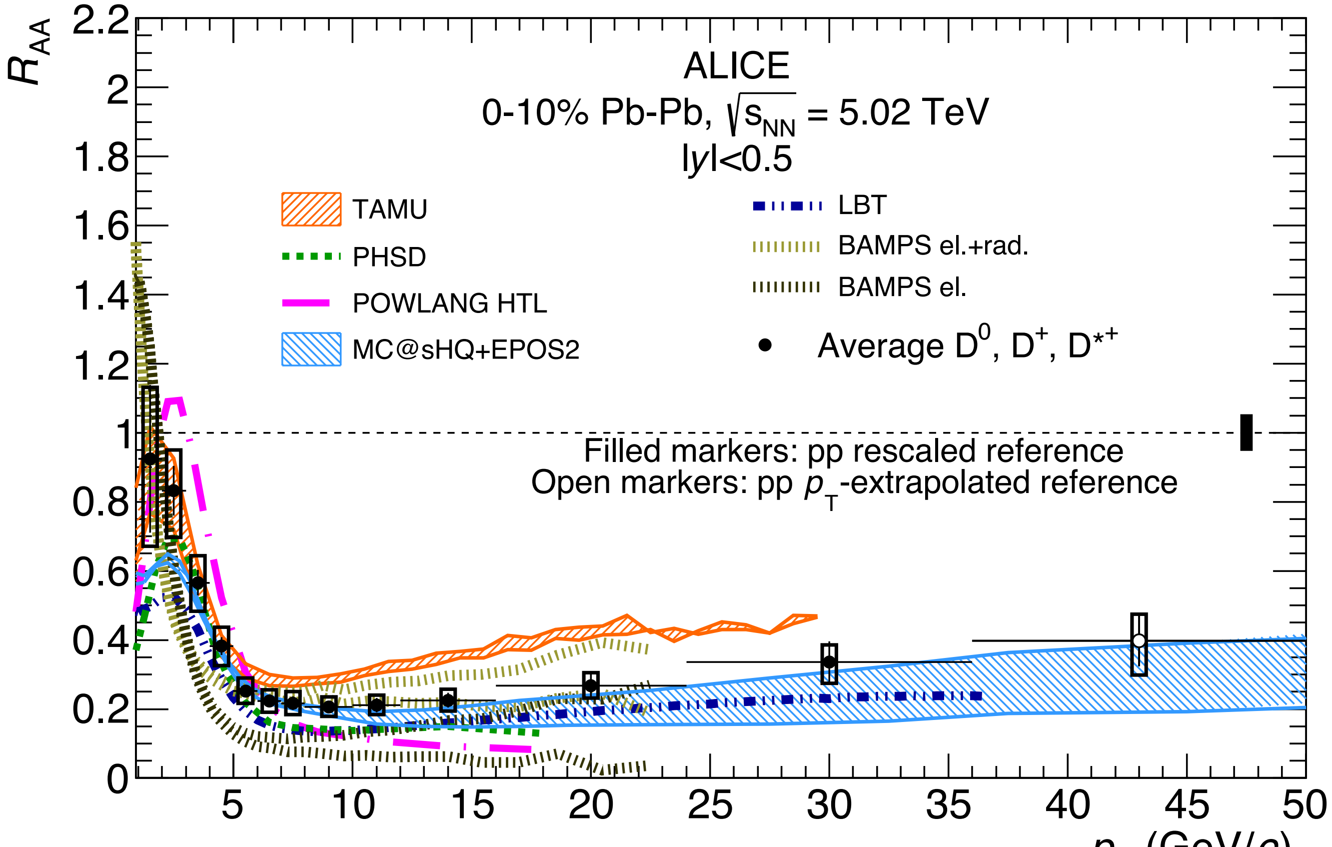
2.76 TeV

5.02 TeV

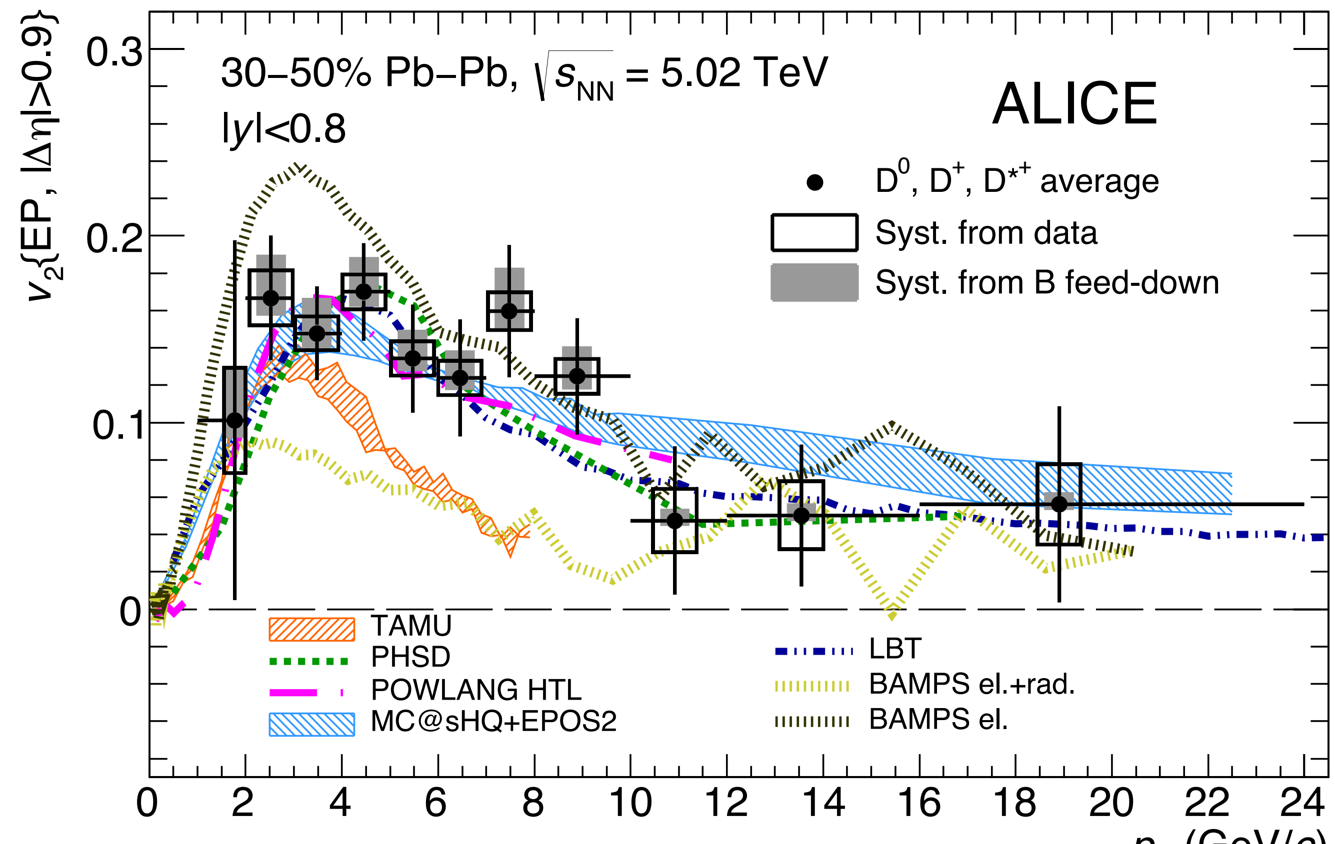


- **Positive D-meson v_2** in $2 < p_T < 10$ GeV/c
  - Charm quark is sensitive to the medium collective flow
- First measurement of the **D_s v_2**
  - Compatible with that of non-strange D mesons
- Compatible D-meson v_2 at $\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s}$ = 5.02 TeV
- Similar D-meson and charged-pion v_2
  - Hint of larger pion v_2 for $p_T < 4$ GeV/c

Comparison to models



arXiv:1804.09083



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- Models including **charm quark recombination** and **elastic collisions in an expanding medium** better describe both v_2 and R_{AA} at low p_T (LBT, MC@sHQ, PHSD, POWLANG)
- R_{AA} and v_2 together provide important constraints to models and help to extract information about **medium properties**
  - models that reasonably describe the data: $\mathbf{1.5 < 2\pi T D_s(T) < 7}$ at $T_c \rightarrow$ $\boldsymbol{\tau_{charm} = 3\text{-}14\ \mathrm{fm}/c}$

Summary

p-Pb collisions

- R_{pPb} **compatible with unity** and described by models including nPDFs
- **Hint of D-meson $R_{\mathrm{CP}} > 0$** at low p_{T} and **non-zero v_2 for HFe** in high multiplicity events → Collective effects? Initial- or final-state effects?
- **Λ_c/D^0 in pp and p-Pb** higher than MC predictions

Pb-Pb collisions

- **Strong R_{AA} suppression at high p_{T}** in central collisons → final-state effects
- **D_s/D**: hint of **enhancement in Pb-Pb** with respect to pp → **coalescence + strangeness enhancement ?**
- **Λ_c/D^0: hint of enhancement** with respect to pp and p-Pb
- **Positive** D-meson **v_2 → strong coupling of charm quark with the medium**

Future goals

- **Upgrades of ALICE** and **large statistics** during **LHC Run3-4**
  - D-meson R_{AA} and v_2 with **improved precision** and **extended p_{T}** reach
  - Precise **charm-baryon** measurements
  - Access **beauty-hadron** measurements

Backup

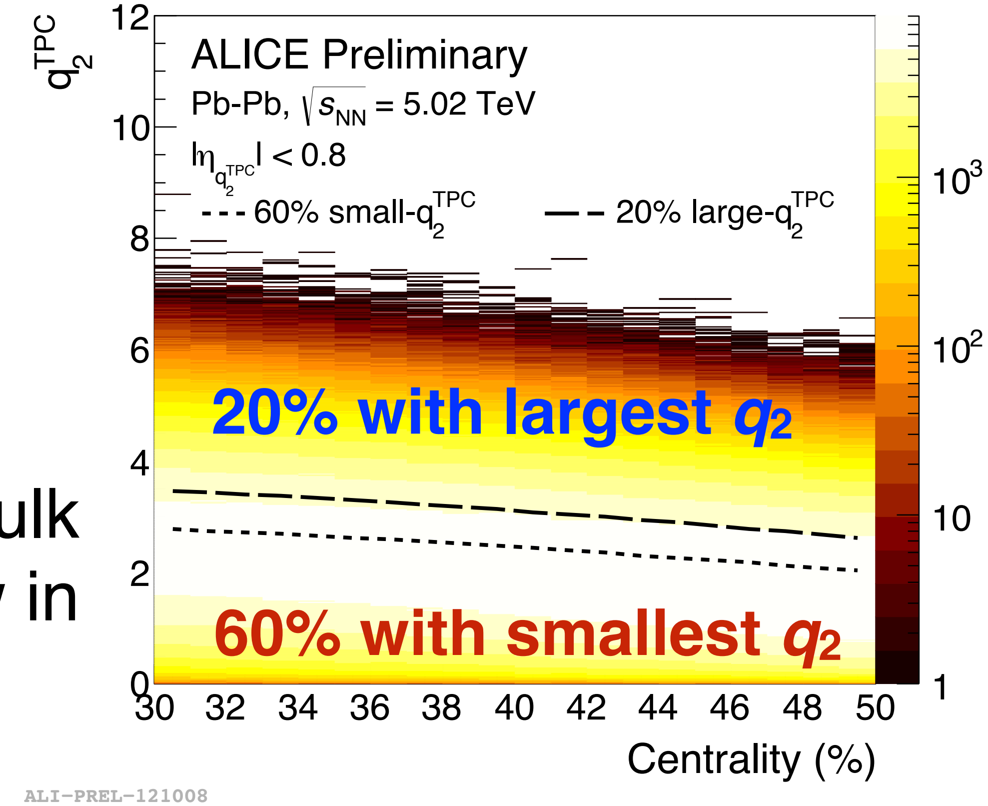
Event-shape engineering analysis

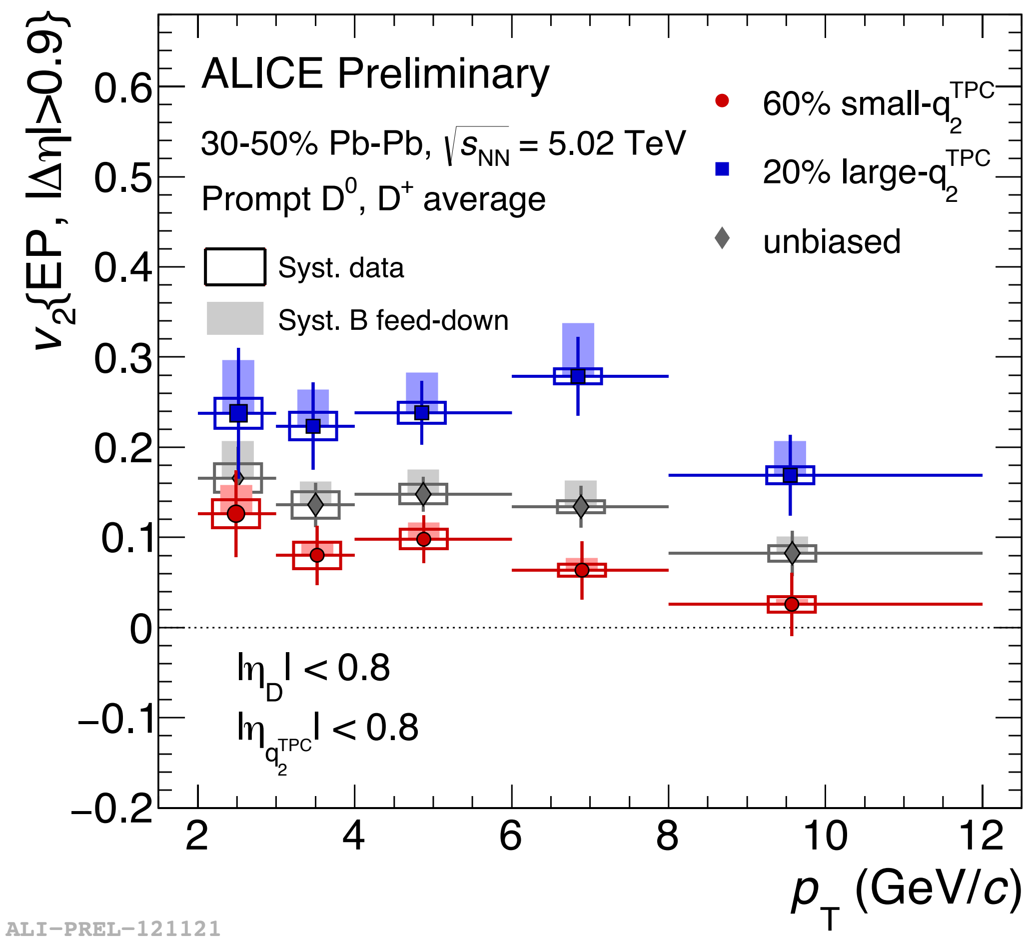
- Event eccentricity quantified by the second-harmonic reduced flow vector q_2

$$\langle q_2^2 \rangle \simeq 1 + \langle (M - 1) \rangle \langle (v_2^2 + \delta_2) \rangle$$ non-flow effects

- q_2 depends on multiplicity and strength of the flow

- Opportunity to study the coupling of c quarks to the bulk of light quarks by measuring the D-meson elliptic flow in events with different q_2 values





- Separation of D-meson v_2 in events with large and small q_2
- **D-meson v_2** is **correlated to light hadron flow** and it is sensitive to event-by-event initial conditions fluctuations
- Non flow contributions not completely removed