Nuclear Modification Factor and Elliptic Flow of Open Heavy Flavours in Pb–Pb Collisions with ALICE at the LHC

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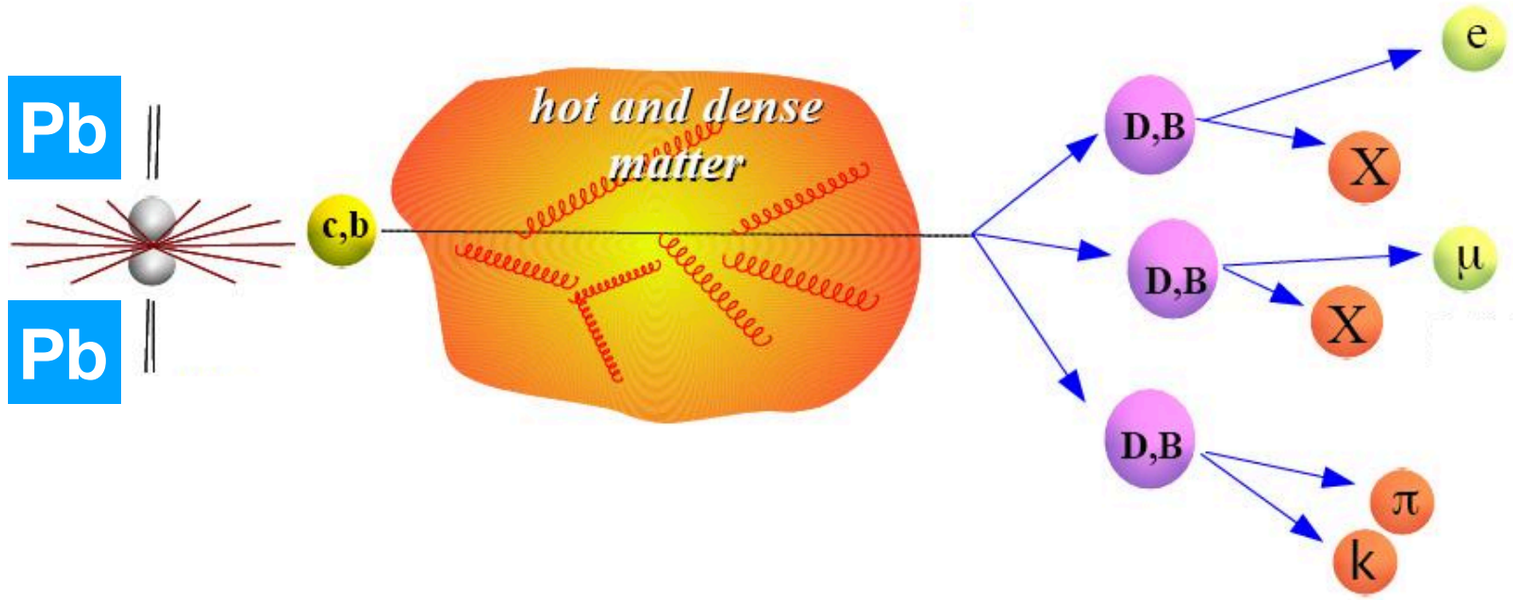
- **Introduction**
- **ALICE apparatus**
- **Nuclear modification factor of open heavy flavours**
- **Collectivity of open heavy flavours**
- **Conclusion**

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



- Produced in initial hard scatterings (high Q^2) at the early stage of heavy-ion collisions: $\tau_{c/b}$ ~0.01 — 0.1 fm/c < τ_{QGP} (~0.3 fm/c)
- Production cross section calculable with pQCD (m_c, $m_b \gg \Lambda_{QCD}$)
- Experience the entire evolution of the QCD medium — probe transport properties of the deconfined medium

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

Nuclear modification factor (R_{AA}): heavy quark in-medium energy loss

- Elastic (radiative) vs. inelastic (collisional) processes
- Radiative energy loss: color charge (Casimir factor) and mass (dead cone effect) dependence

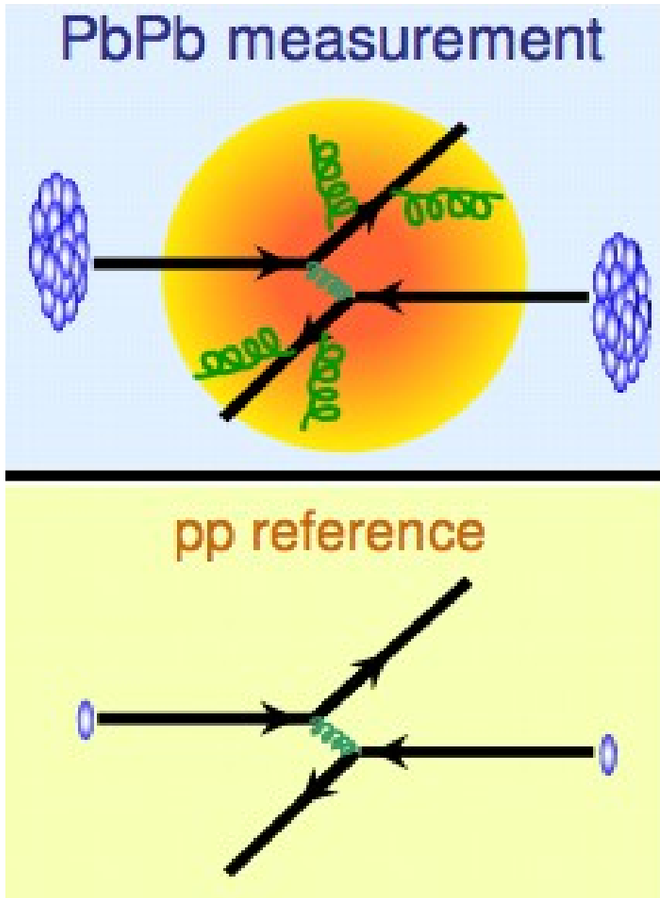
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

QCD medium / QCD vacuum

- R_{AA} = 1, if no medium modification

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

➡ R_{AA}(light hadron) < R_{AA}(D) < R_{AA}(B) ?



Medium modification of heavy-flavour hadron formation

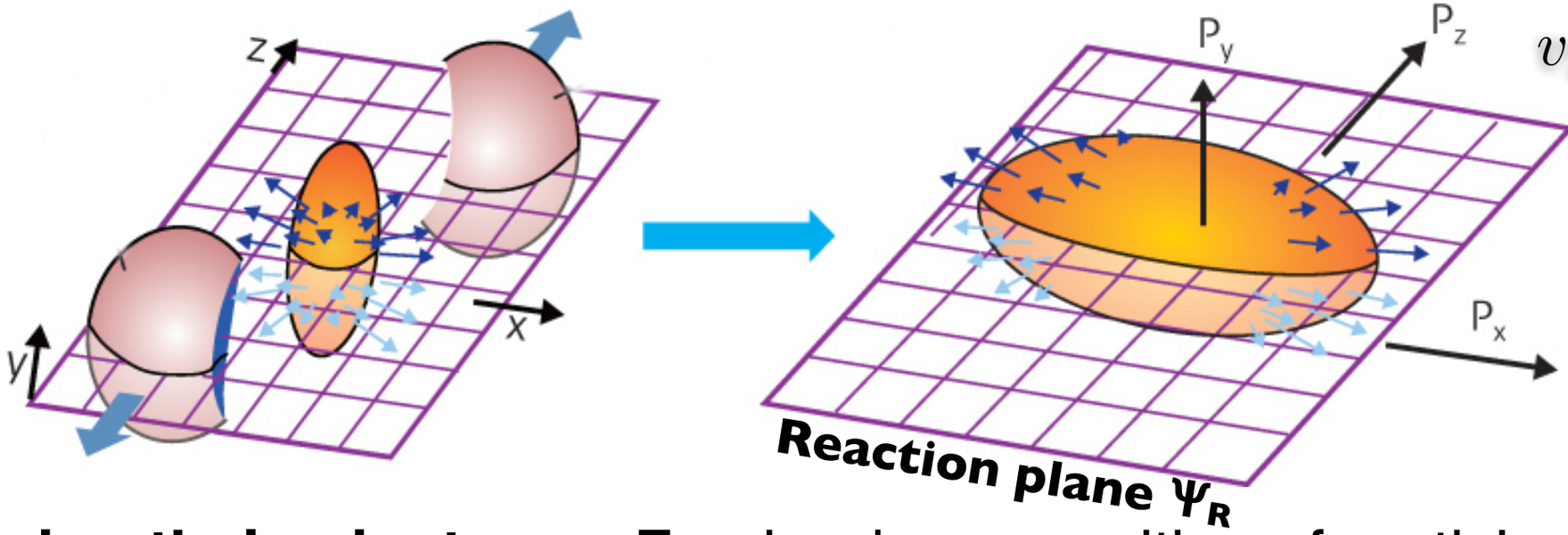
- Hadronization via quark coalescence which may modify the D_s^+ /non-strange D ratio

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

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

$$v_2 = <\cos 2(\varphi-\Psi_{\mathrm{R}})>$$



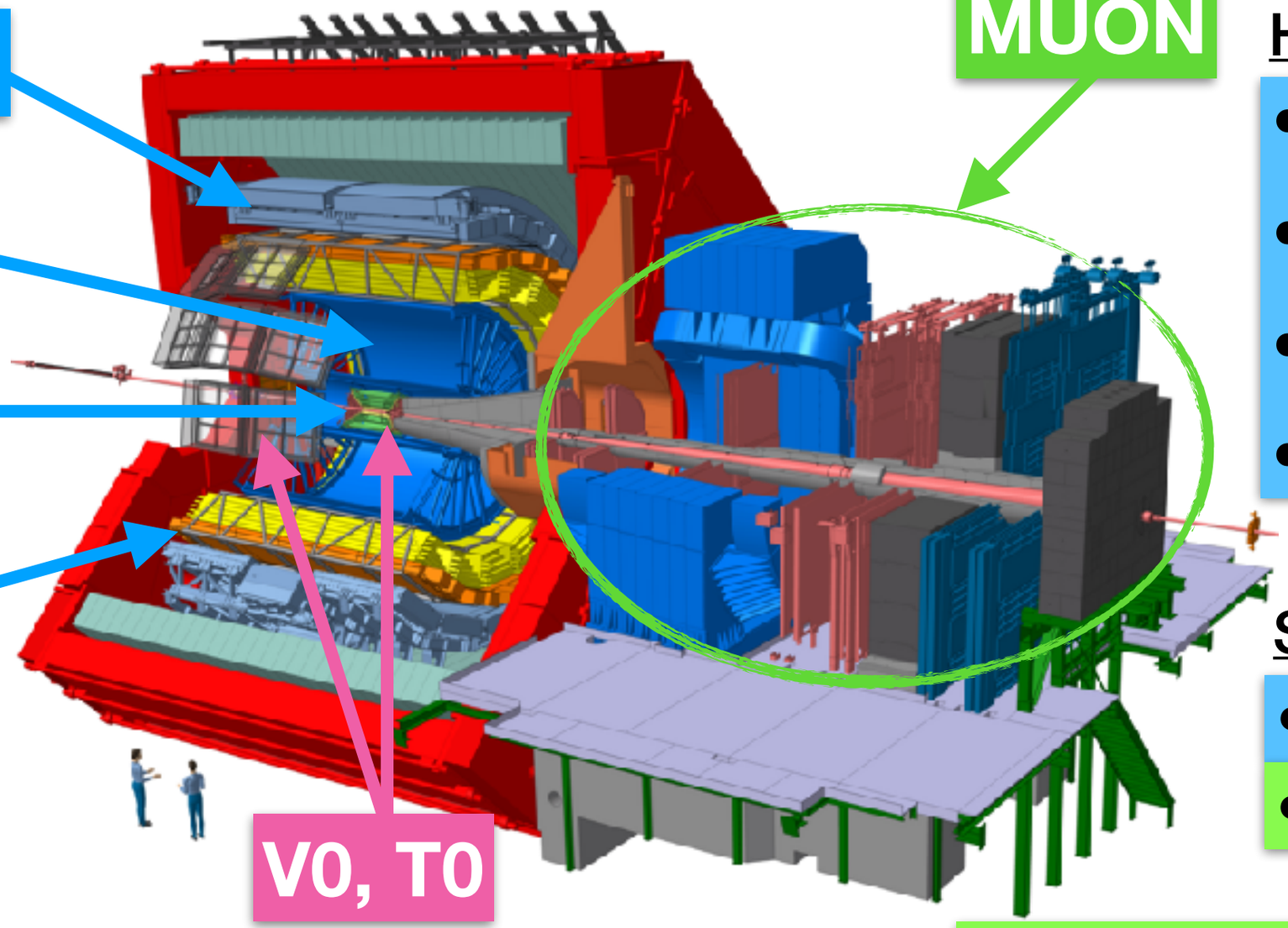
Azimuthal anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP})

- Elliptic flow (v_2): coefficient of second order harmonic

  ➡ Low and intermediate p_T: collective motion and possible heavy-quark thermalization in the QCD medium

  ➡ High p_T: path-length dependence of heavy-quark in-medium energy loss

ALICE apparatus



Hadronic decays:

- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D^{*+} \rightarrow D^0\pi^+$
- $D^+_s \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

Semi-leptonic decays:

- D, B→e+X
- D, B→μ+X

Mid-rapidity (|η|<0.9)

- ITS, TPC, TOF: vertexing, tracking, PID
- EMCal: high-p_T electron trigger, PID

Forward MUON (-4<η<-2.5)

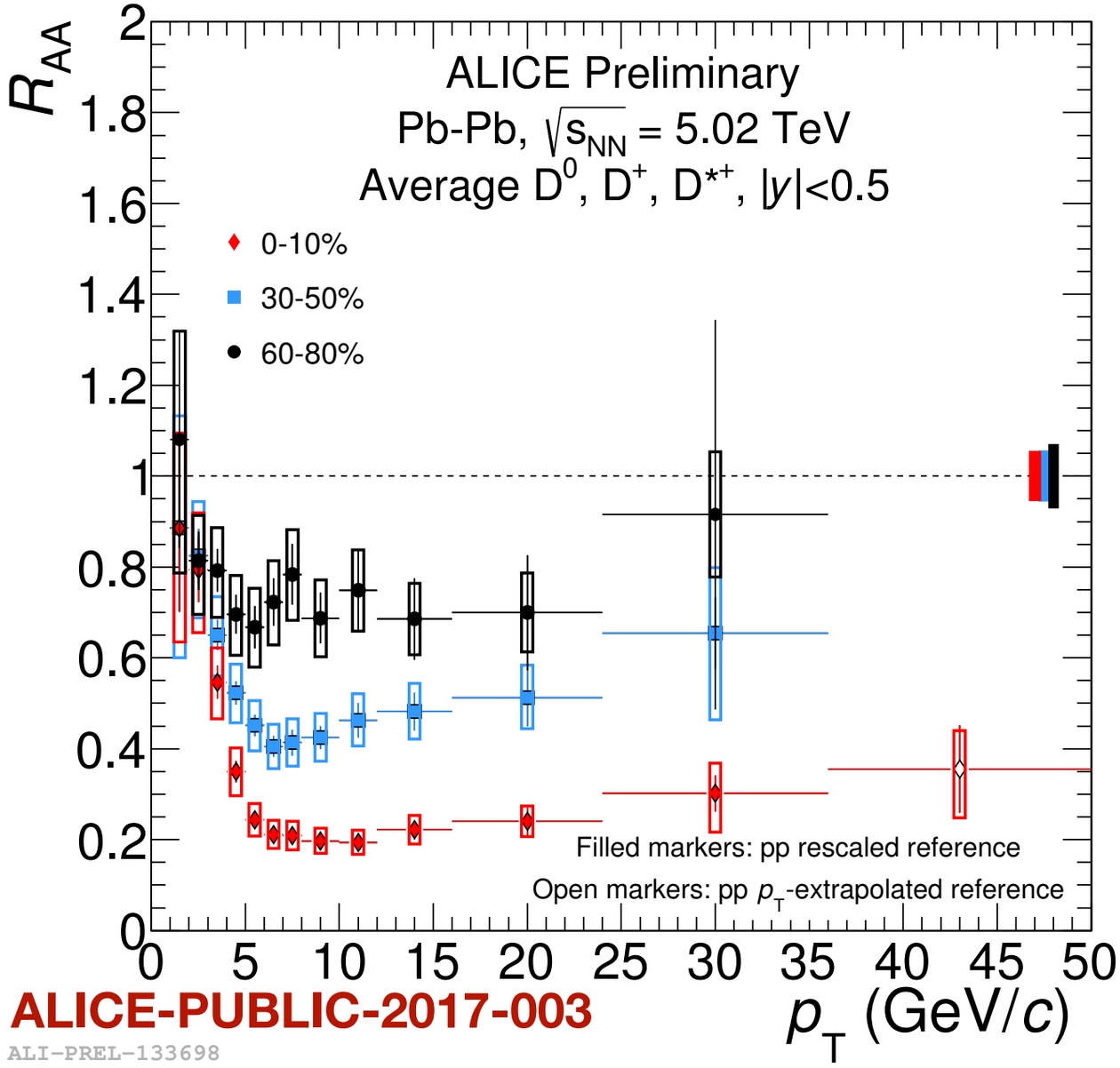
- Muon trigger, tracking, PID

Smaller detectors: V0, T0, ZDC

- Event trigger, characterization

R_{AA} of D mesons

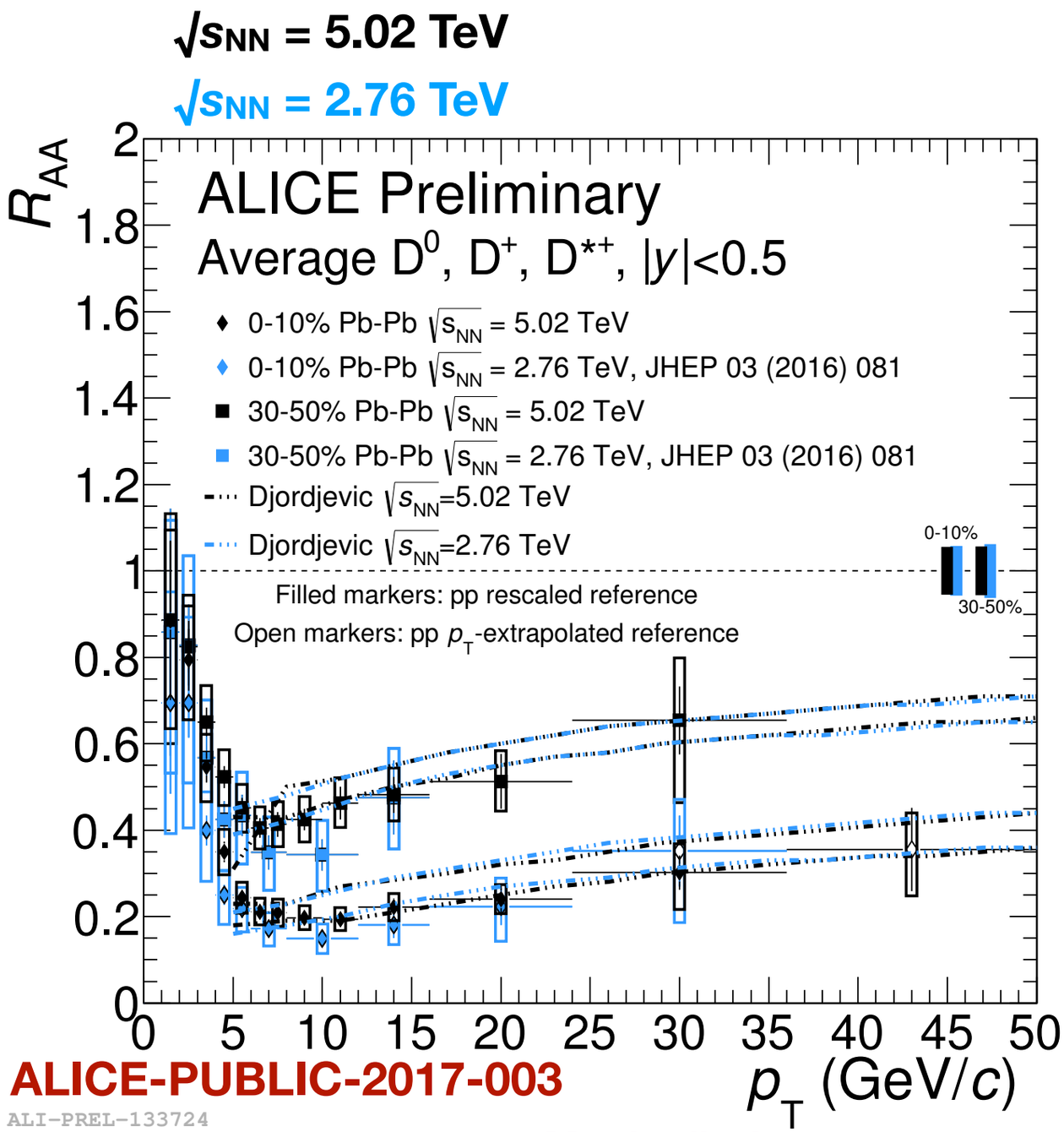
New: 0–10%, 60–80%



- Suppression of D-meson R_{AA} in Pb–Pb collisions at 5.02 TeV exhibits a strong increase towards more central collisions

➡ Strong suppression reaching a factor of about five in the 10% most central collisions

R_{AA} of D mesons



- Suppression of D-meson R_{AA} in Pb–Pb collisions at 5.02 TeV exhibits a strong increase towards more central collisions

➡ Strong suppression reaching a factor of about five in the 10% most central collisions

- The measurements are compatible in Pb–Pb collisions at 5.02 TeV and 2.76 TeV

➡ Predicted by models considering the variation of the medium density and the charm quark p_T distribution at the two energies

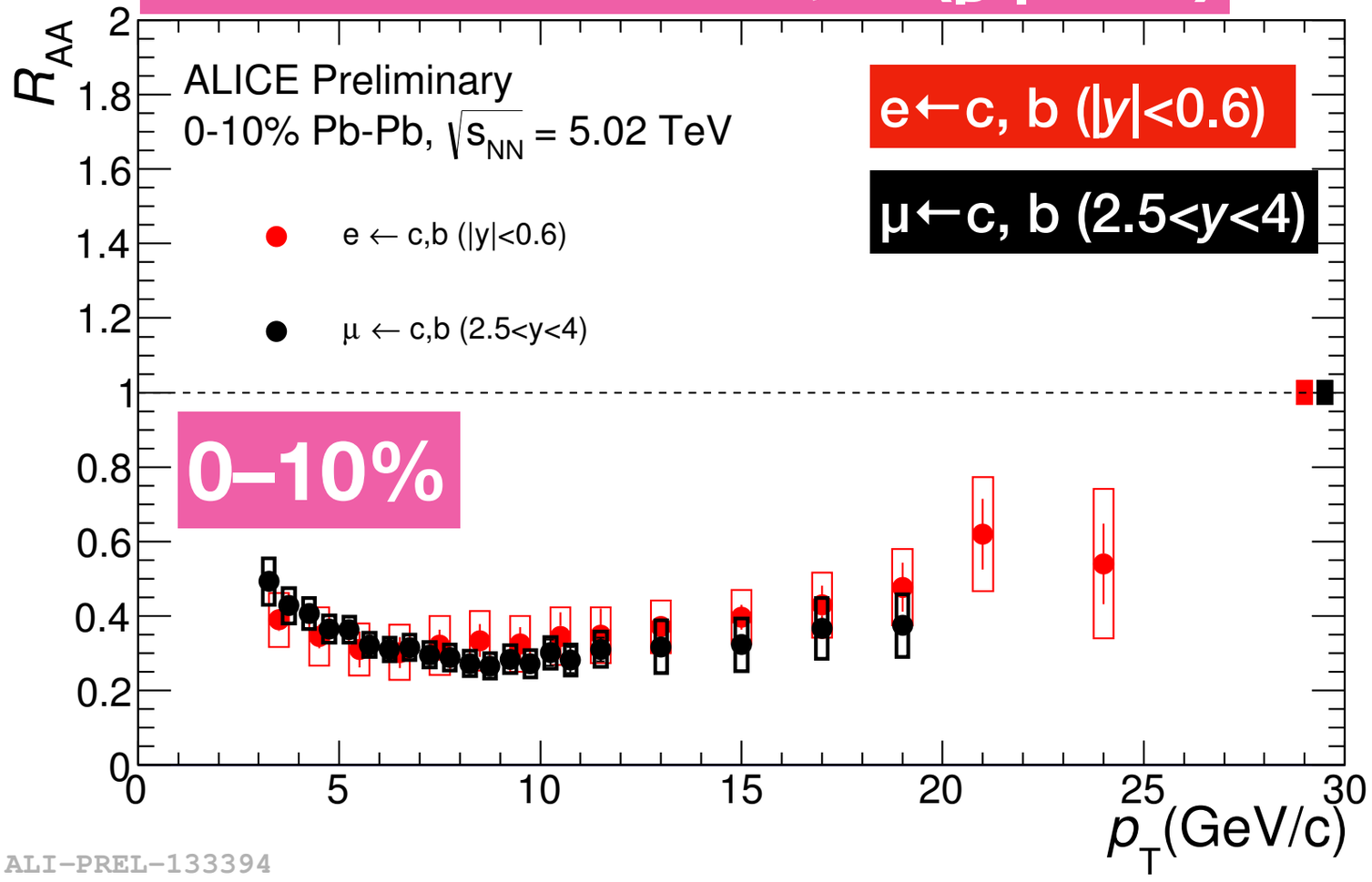
M. Djordjevic

Phys. Rev. Lett. 112 (2014) 042302

Phys. Rev. C92 (2015) 024918

R_{AA} of heavy-flavour decay leptons

New: R_{AA} of e←c, b (|y|<0.6)

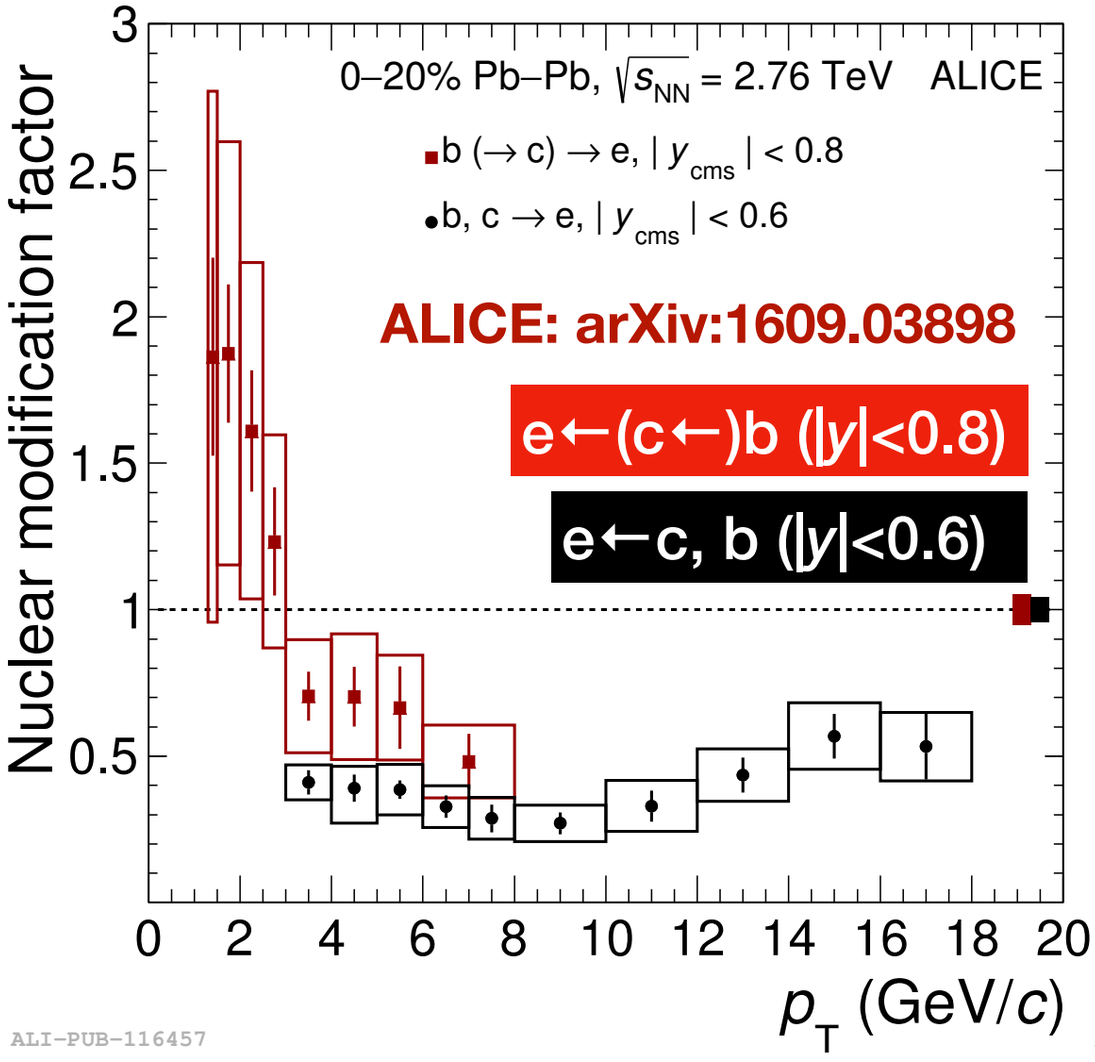


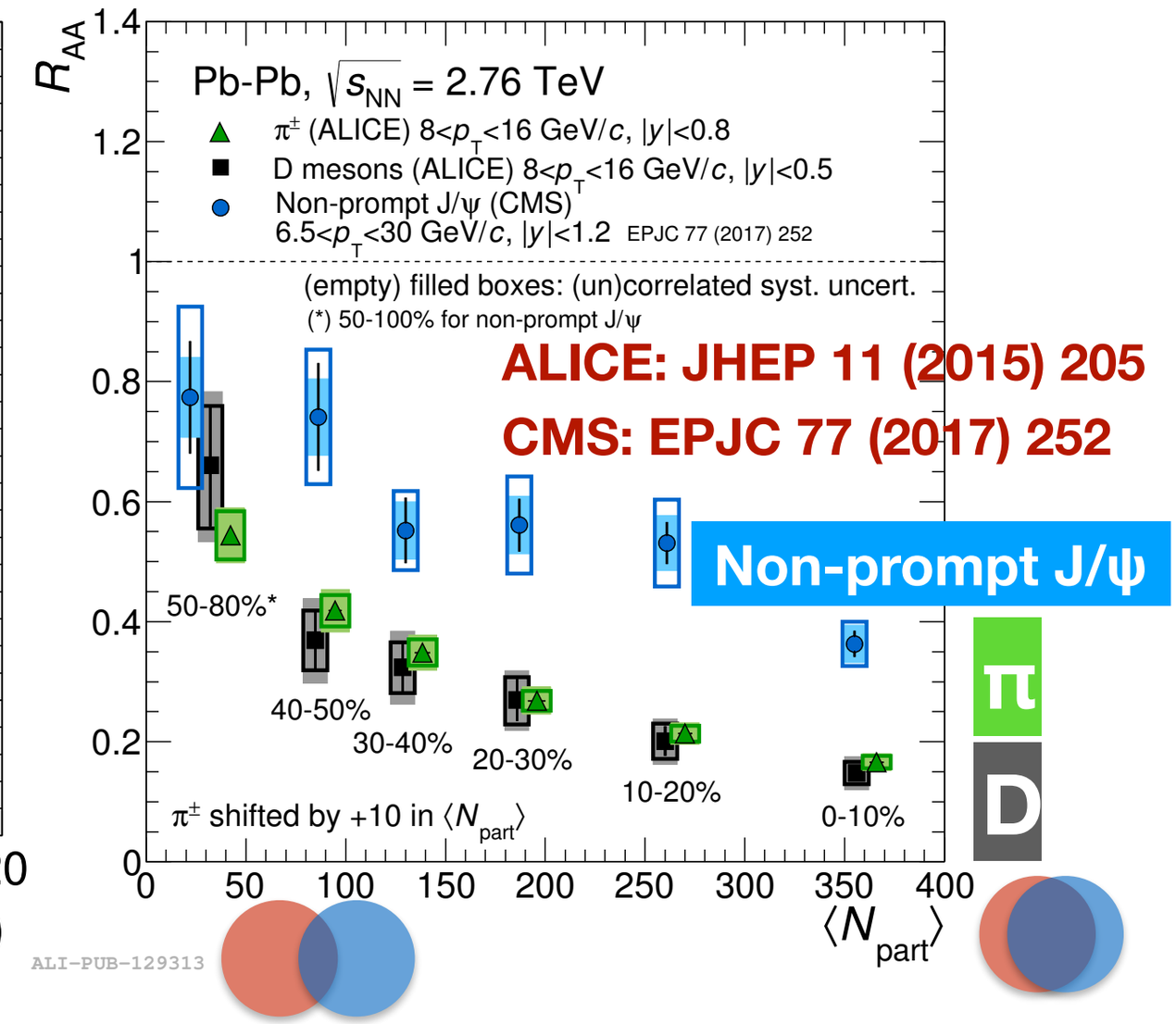
- Strong suppression in most 10% central collisions for heavy-flavour decay electrons at mid-rapidity (|y|<0.6) and heavy-flavour decay muons at forward rapidity (2.5<y<4)
- p_T > 5–6 GeV/c: dominated by beauty decay leptons

- Suppression of heavy-flavour decay muons is compatible with heavy-flavour decay electrons within uncertainties

➡ Indication that heavy quarks suffered strong interactions in the QCD medium in a wide rapidity range

R_{AA}: color-charge and mass dependence



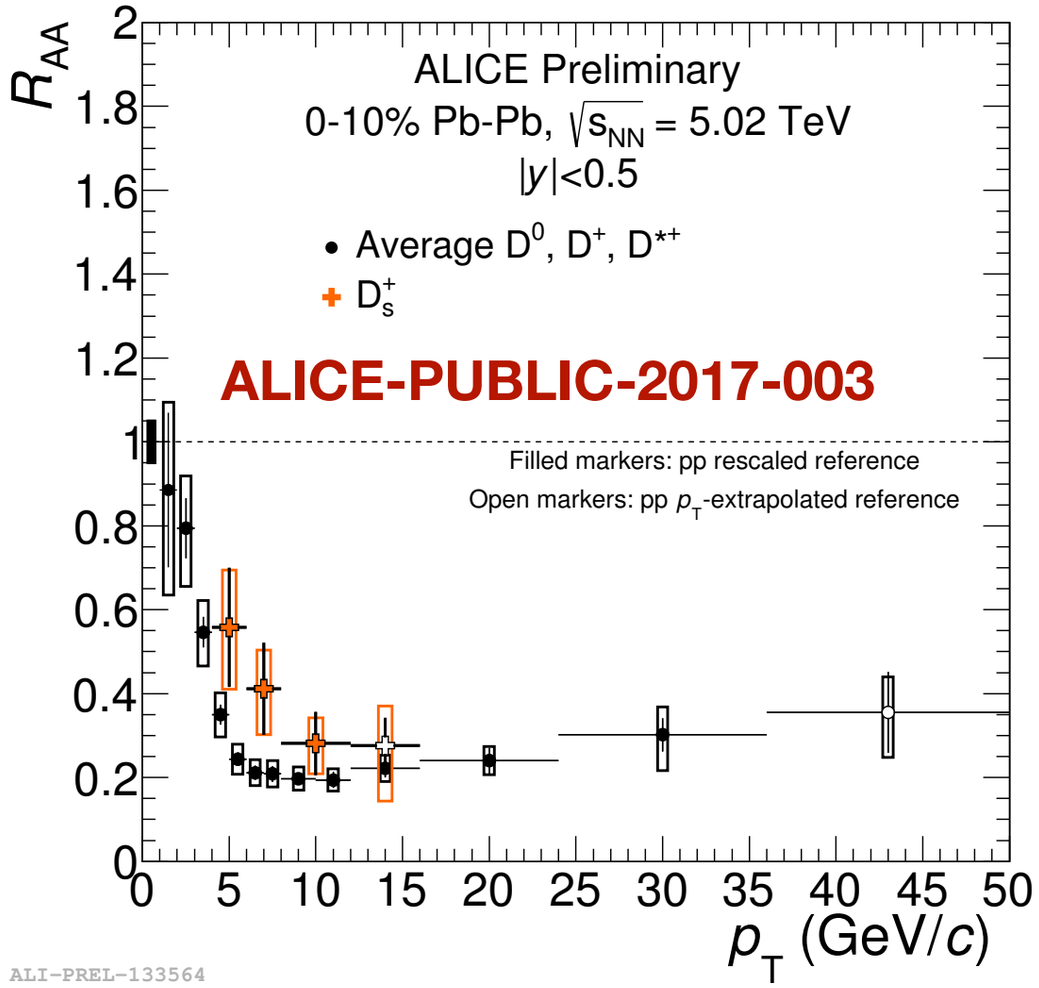


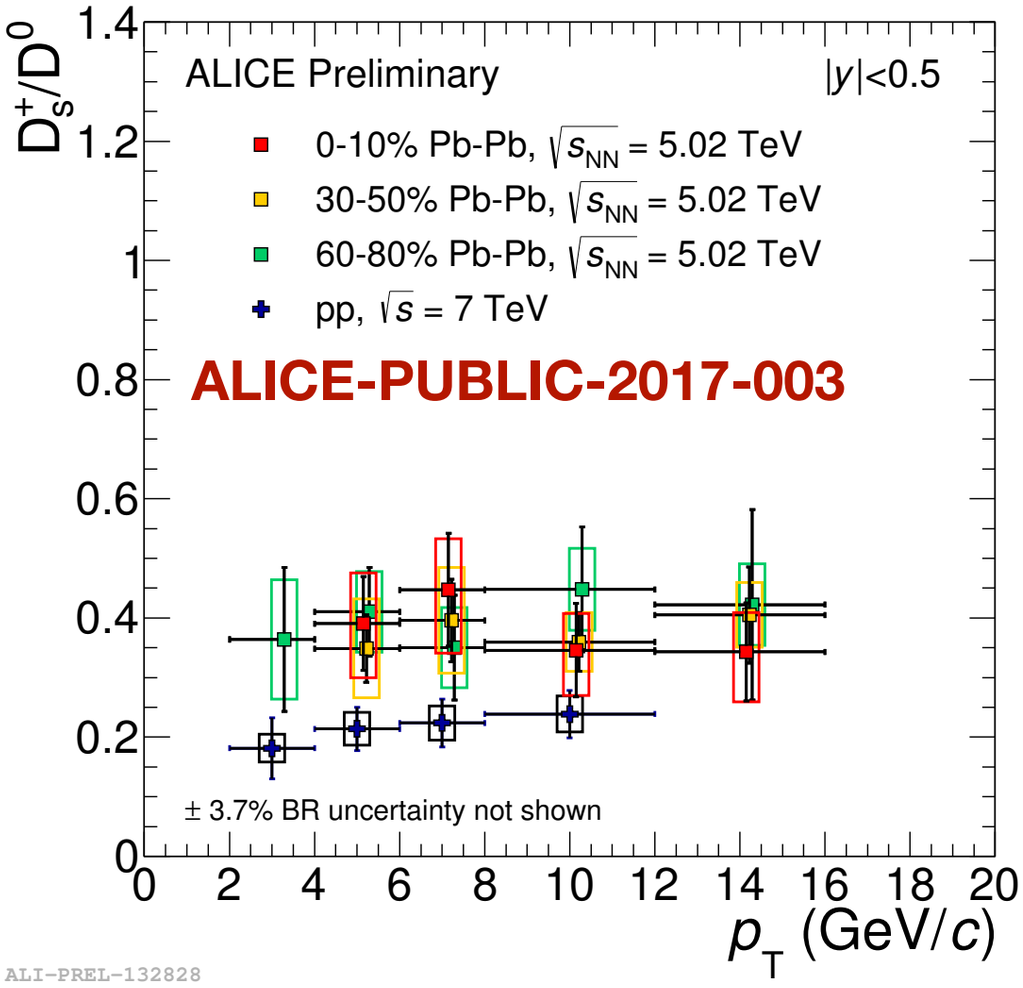
- Hint of R_{AA}(e←b)>R_{AA}(e←b, c) in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- R_{AA} of D mesons systematically smaller than non-prompt J/ψ at high p_T

➡ Indication of mass-dependent suppression for charm and beauty

- R_{AA}(D) ~ R_{AA}(π) — different parton p_T distribution and fragmentation

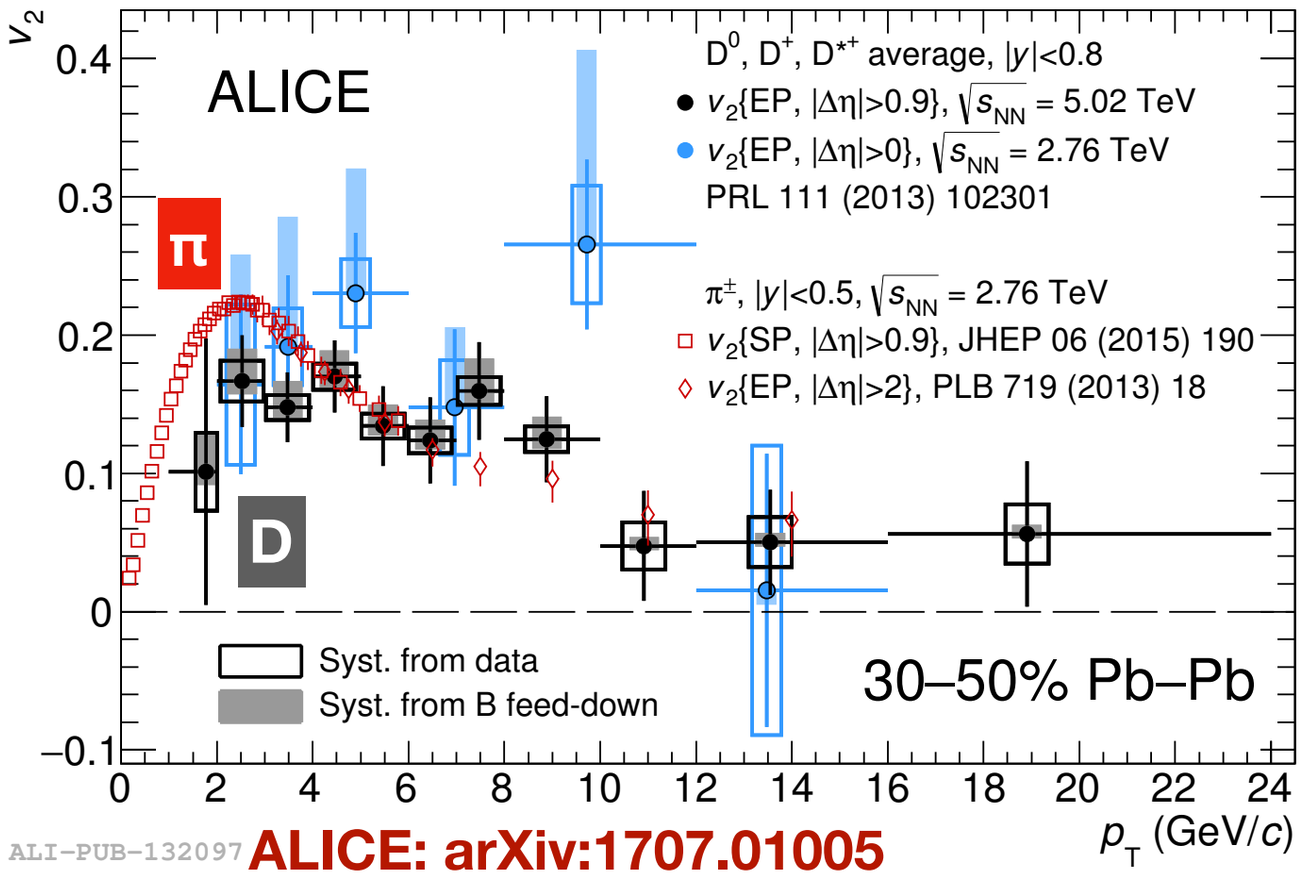
D_s production in Pb–Pb collisions



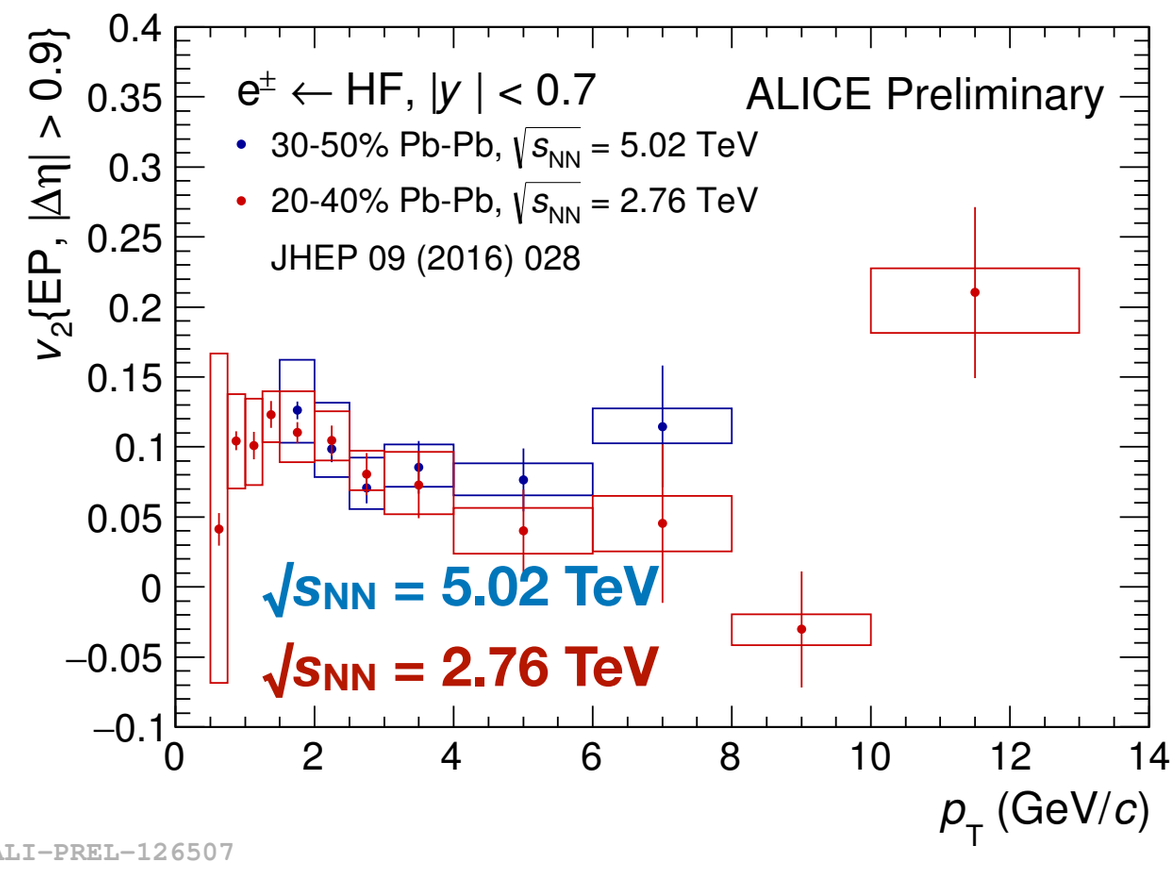


- Hint of $R_{AA}(D_s) > R_{AA}(D)$ in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (still large uncertainty to draw conclusion)
- Hint for a higher D_s / D^0 ratio in Pb–Pb collisions compared to pp collisions, no centrality dependence with current uncertainties
- More statistics needed to draw conclusions on contribution from coalescence on D_s hadronization

Elliptic Flow of Open Heavy Flavours

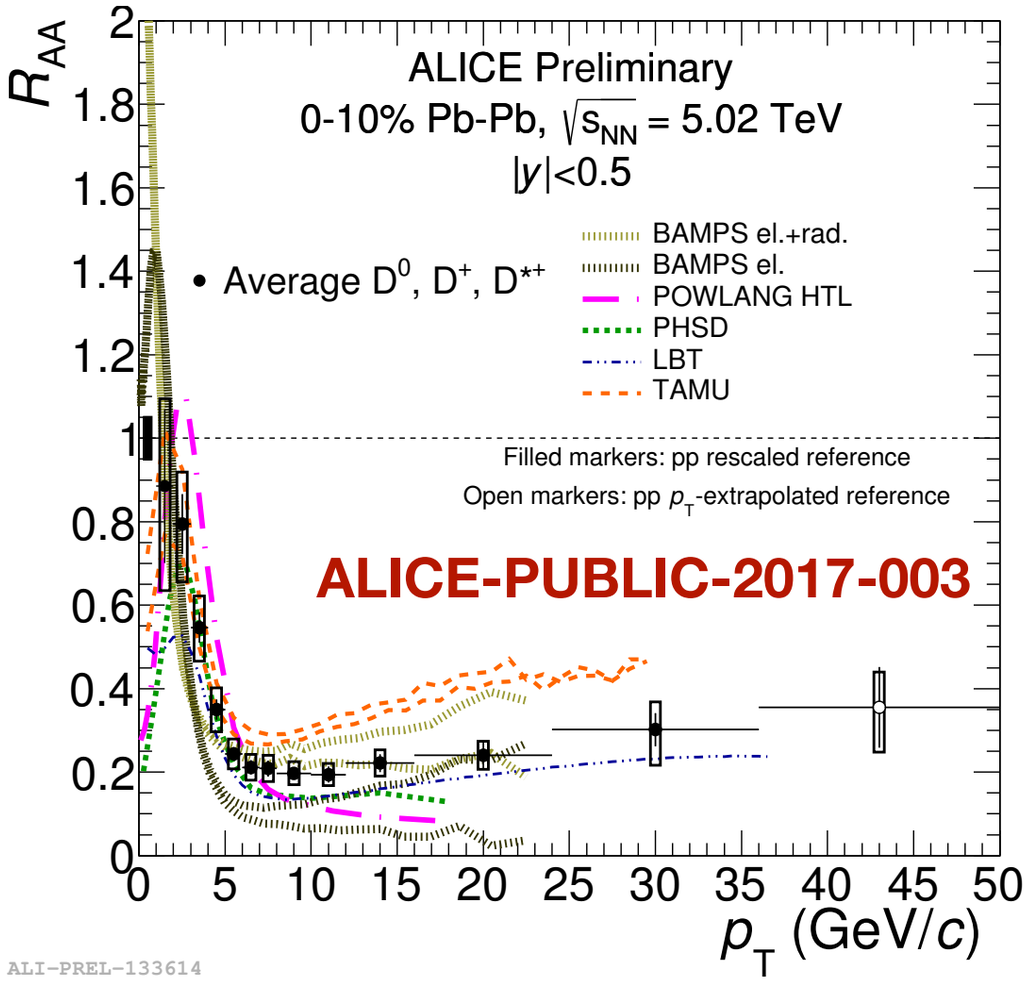


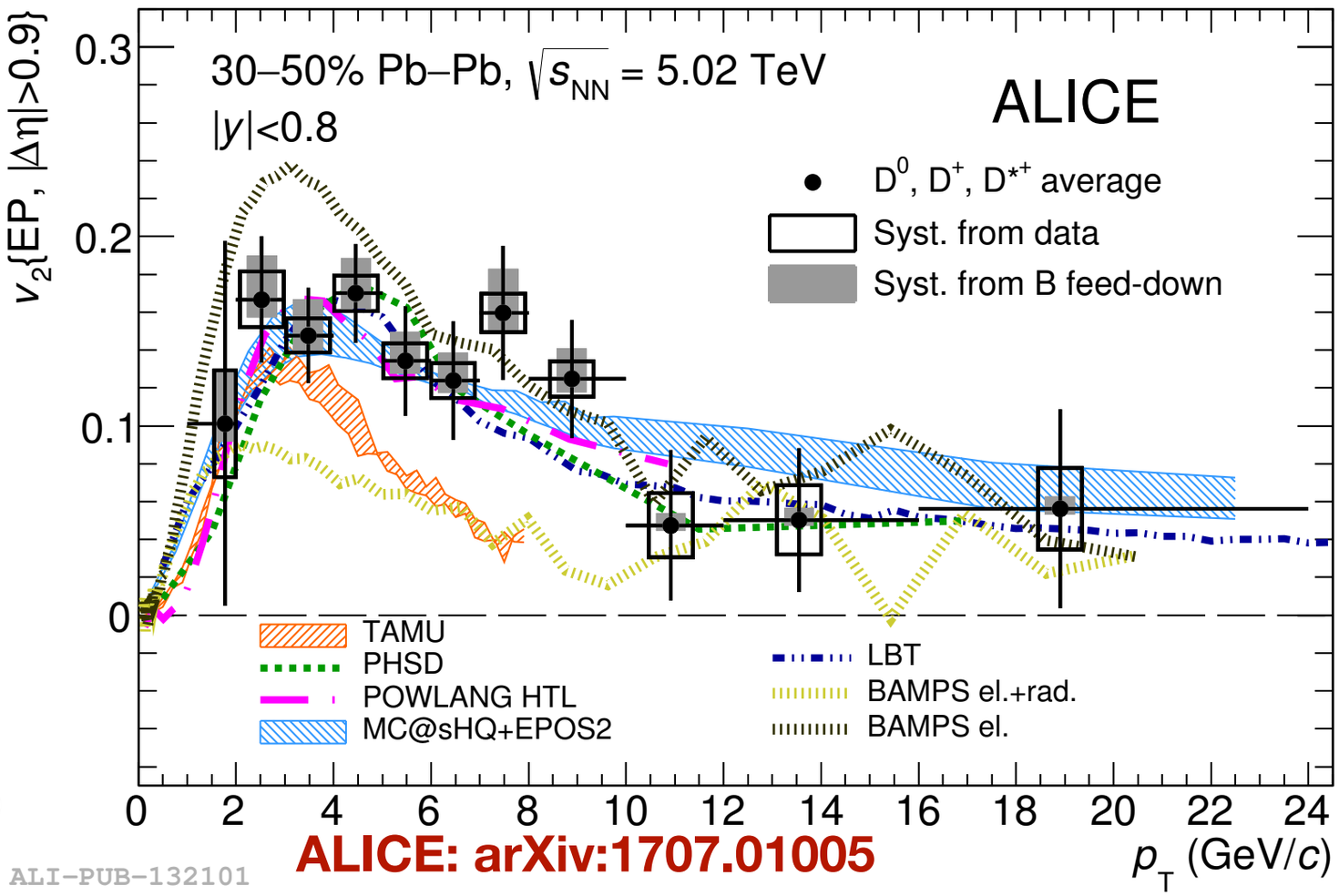
ALICE: arXiv:1707.01005



- Positive v_2 of open heavy flavours at intermediate p_T in semi-central Pb–Pb collisions — indication of collective motion of low-p_T charm quarks in the QCD medium
- v_2 of D mesons: compatible with $\pi^{\pm}$ at high p_T — constraint on path-length dependence of parton in-medium energy loss
- v_2 of open heavy flavours — no energy dependence

R_{AA} vs. v_2: model comparisons





- Experimental results with improved precision compared to RUN-I

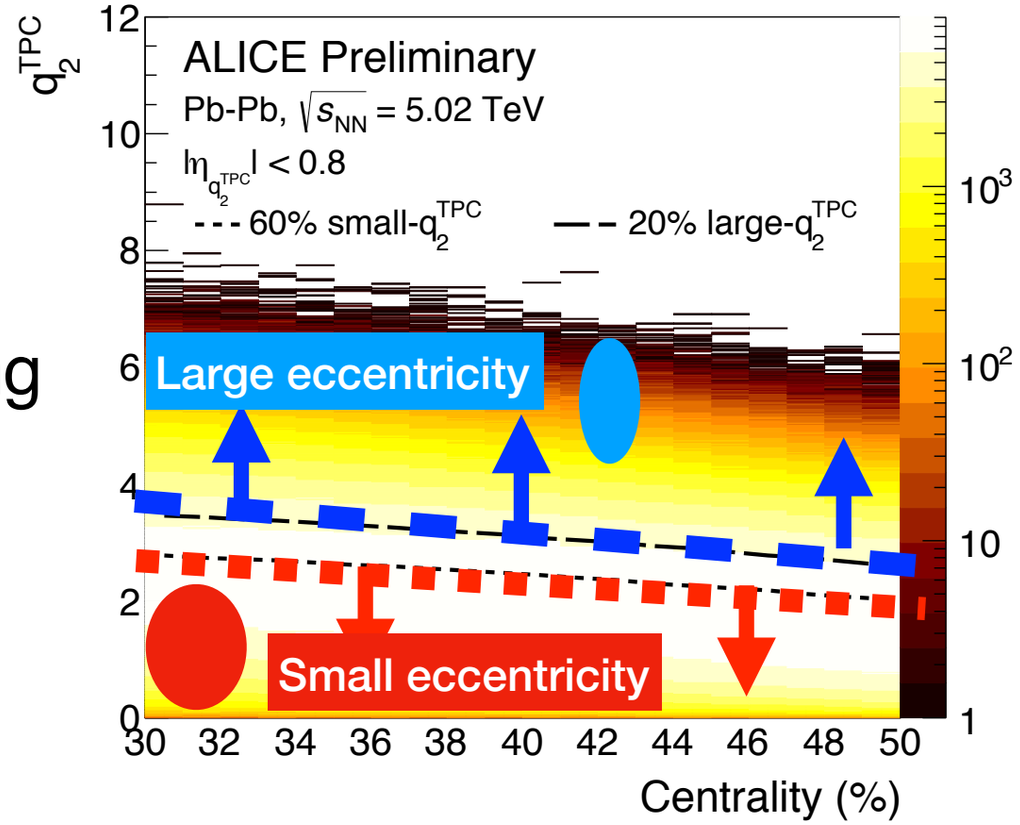
➡ Set constraints to models able to predict simultaneously quenching (R_{AA}) and collectivity (v_2) of heavy quarks in the QCD medium

Event-shape engineering

- Event eccentricity quantified by q_2:

➡ $\langle (q_2)^2 \rangle \approx 1 + \langle M\text{-}1 \rangle \langle (v_2)^2 \rangle$

- Opportunity to study the charm-quark coupling to the light-hadron bulk by measuring v_2 at different q_2 values

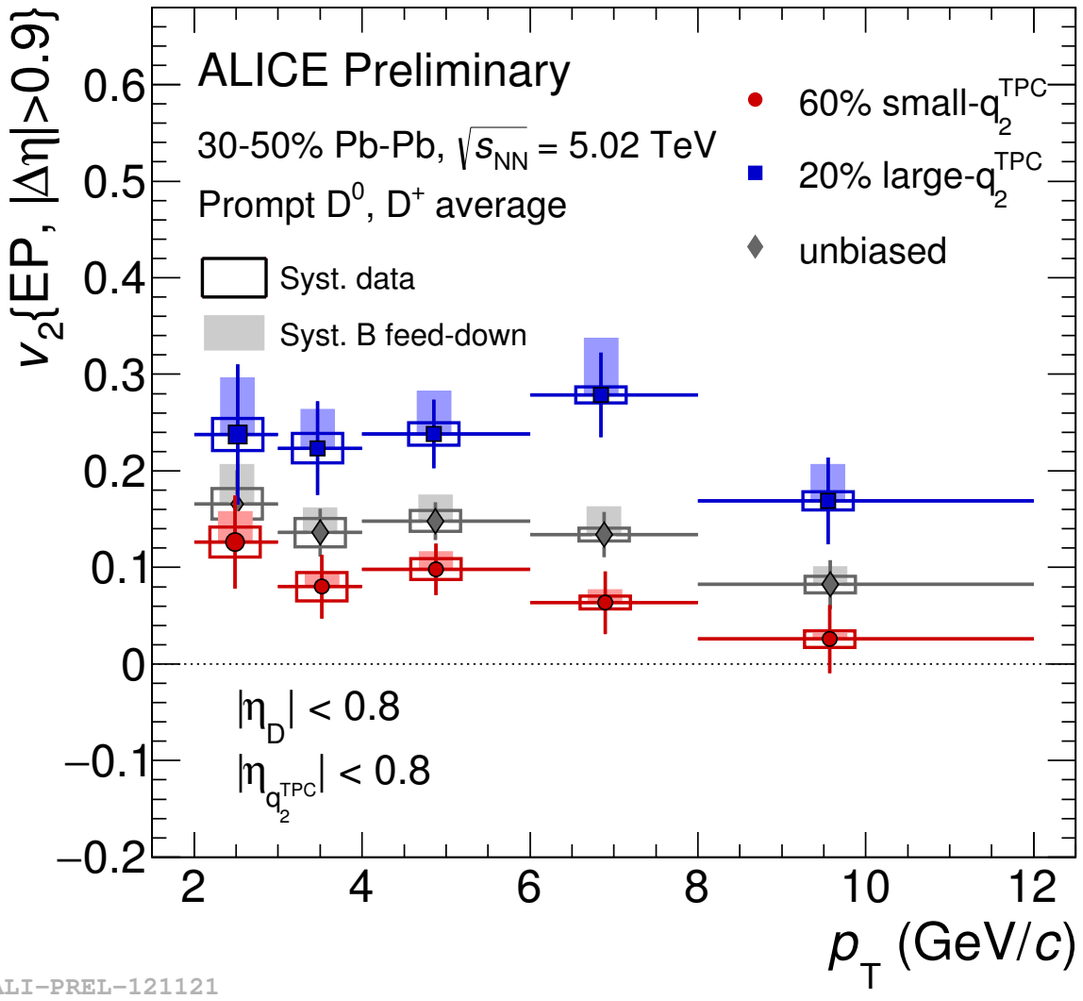


ALI-PREL-121008

- Significant separation of D-meson v_2 in events with large and small q_2

➡ Charm quarks sensitive to the light-hadron bulk collectivity and event-by-event initial condition fluctuations

Autocorrelation and non-flow effects between q_2 determination and D-meson reconstruction are present



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Conclusion

- R_{AA} of D mesons and heavy-flavour decay leptons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV — significant suppression for 10% most central collisions

  ➡ No energy and rapidity dependence

  ➡ Indication of mass dependence suppression for charm and beauty

  ➡ More statistics needed to draw conclusion on coalescence contributions

- Significant elliptic flow of open heavy flavours in semi-central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

  ➡ Strong interaction of heavy quarks with the QCD medium

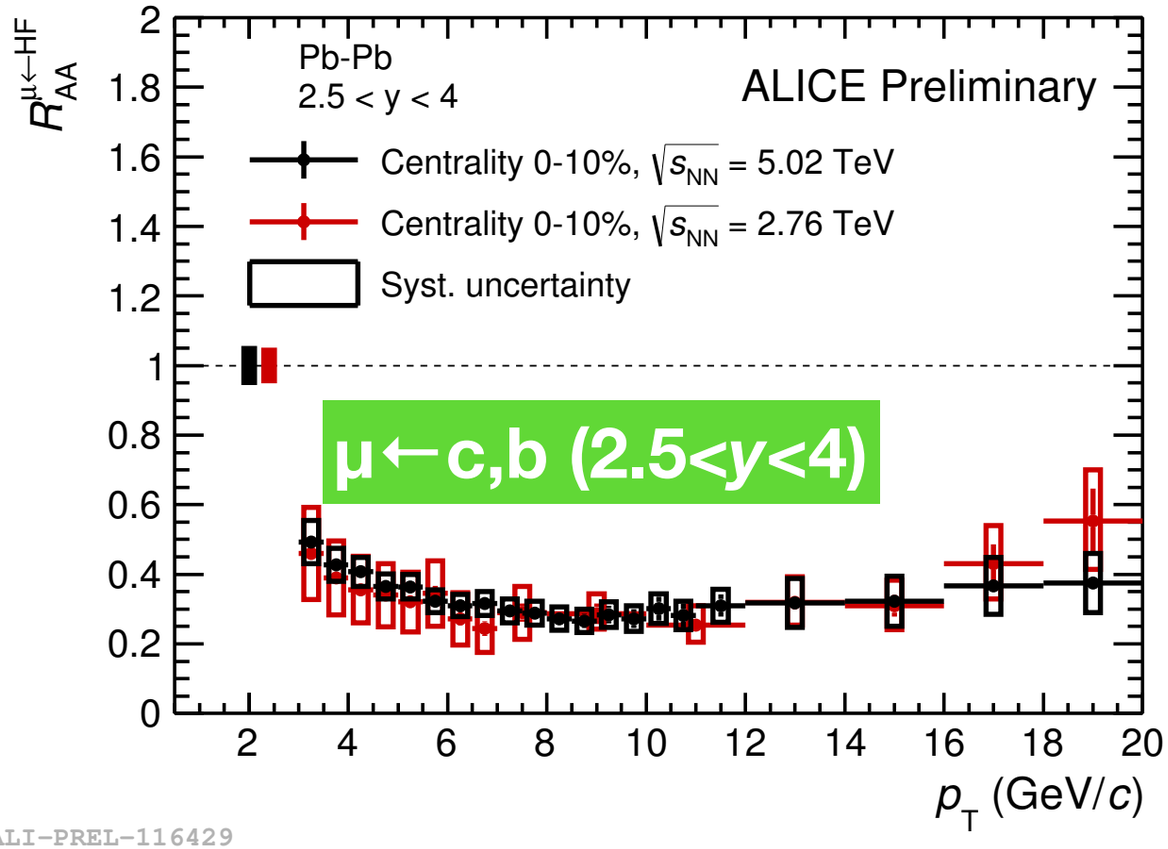
  ➡ Set constraints to models able to calculate both quenching (R_{AA}) and collectivity (v_2) of open heavy flavours

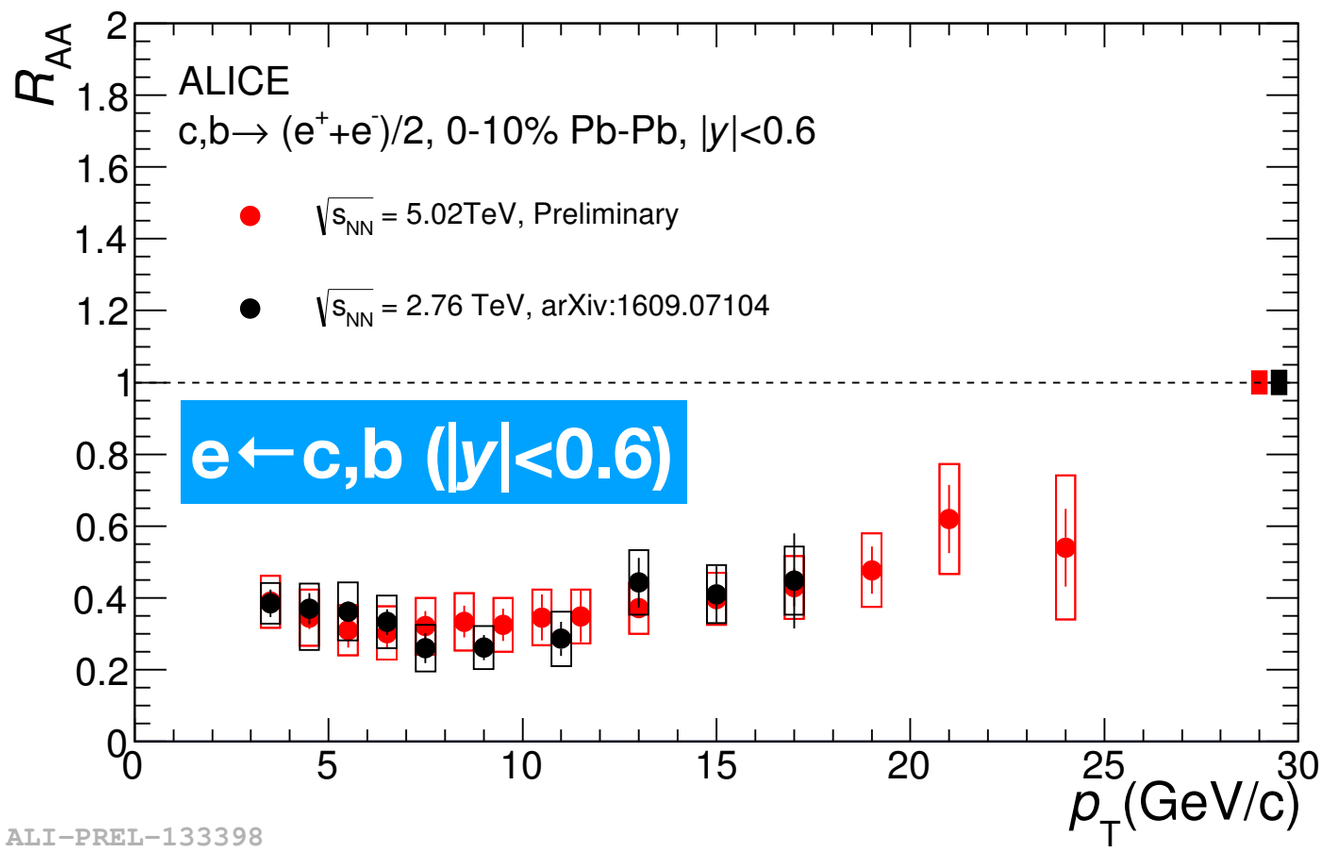
- D^0 and D^+ v_2 with event-shape engineering technique

  ➡ Charm quark may be sensitive to the light-hadron bulk collectivity and event-by-event initial fluctuations

Backup

R_{AA} of Heavy-flavour decay Leptons





- Strong suppression is observed in central Pb–Pb collisions for heavy-flavour decay electrons at mid-rapidity ($|y|<0.6$) and heavy-flavour decay muons at forward rapidity ($2.5<y<4$)
- Uncertainties are reduced at 5.02 TeV w. r. t. 2.76 TeV, measurements are expended to higher p_T in semi-electronic channel
- Results are consistent within errors in two energies

Open heavy flavours in Pb–Pb Collisions

Overview of models for HQ energy loss or transport in the medium (J. Phys. G 9 43 (2016) 093002)

Model	Heavy-quark production	nPDFs	Medium modelling	Quark-medium interactions	Hadroni-zation	Hadron phase
			Transport models			
BAMPS [28, 38, 76]	MC@NLO	No	Boltzmann parton 3+1D	Boltzmann pQCD coll+rad	frag	no
Cao *et al*/Duke [83, 84, 212]	MC@NLO	EPS09	Hydro 2+1D viscous	Langevin coll +pQCD rad	frag+ reco	yes
MC@sHQ+EPOS [45, 73, 74]	FONLL	EPS09	Hydro 3+1D (EPOS)	Boltzmann pQCD coll+rad	frag+ reco	no
PHSD [40, 51]	PYTHIA* tuned to FONLL	EPS09	off-shell parton transport	off-shell trans DQPM coll	frag+ reco	yes
POWLANG [36, 48, 124]	POWHEG	EPS09	Hydro 2+1D viscous	Langevin pQCD coll	string-reco	no
TAMU [65, 77, 126]	FONLL	EPS09	Hydro 2+1D ideal	Langevin T-mat coll	frag+ reco	yes
			Energy-loss models			
AdS/CFT (HG) [313, 314]	FONLL	No	Glauber no hydro	AdS/CFT drag	frag	no
CUJET 3.0 [232, 233]	FONLL	No	Hydro 2+1D viscous	rad+coll	frag	no
Djordjevic *et al* [315, 316]	FONLL	No	Glauber no hydro	rad+coll+ magn. mass	frag	no
Vitev *et al* [72, 317]	non-zero mass VFNS	No	Glauber+ 1D Bjor-ken exp	rad+ in-med dissoc	frag	no
WHDG [86, 230]	FONLL	No	Glauber no hydro	rad+coll	frag	no