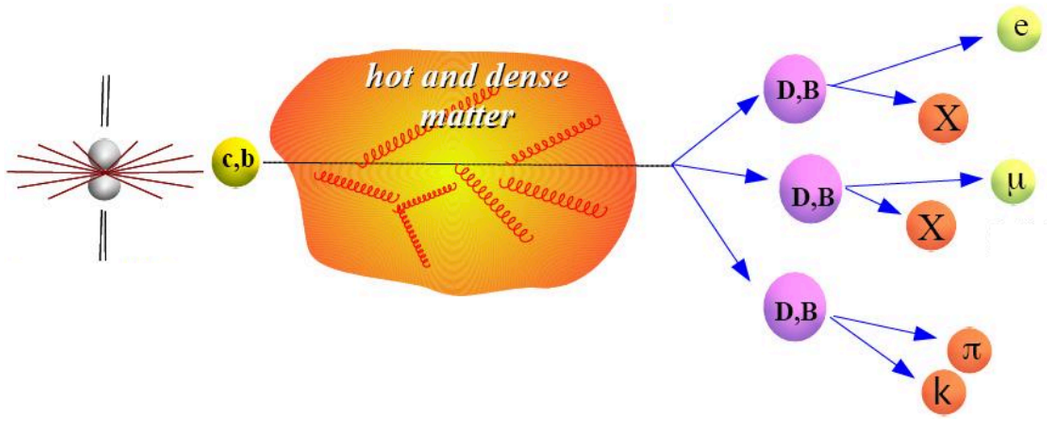
Overview of recent open heavy-flavour results with ALICE at the LHC

Xiaoming Zhang

- **Introduction**
- **R_{AA} and v_2 of open heavy-flavour particles**
- **Collectivity in smaller systems**
- **Charmed baryon production**
- **Open heavy flavour jets**

Introduction

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



Total charm cross section in A–A collisions is expected to scale w. r. t. the number of binary collisions in pp-like collisions

S. Radhakrishnan at QM'18

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%** **STAR Preliminary**

- 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 ≫ Λ_{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

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

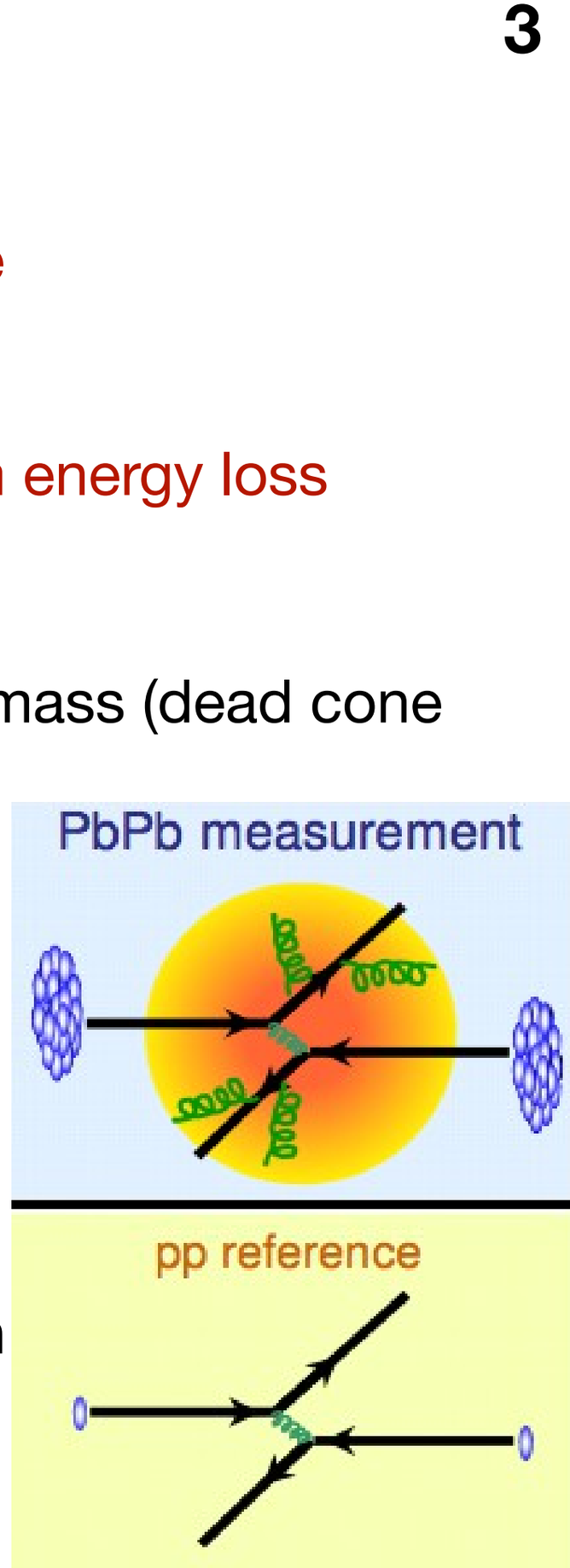
QCD medium

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) ?



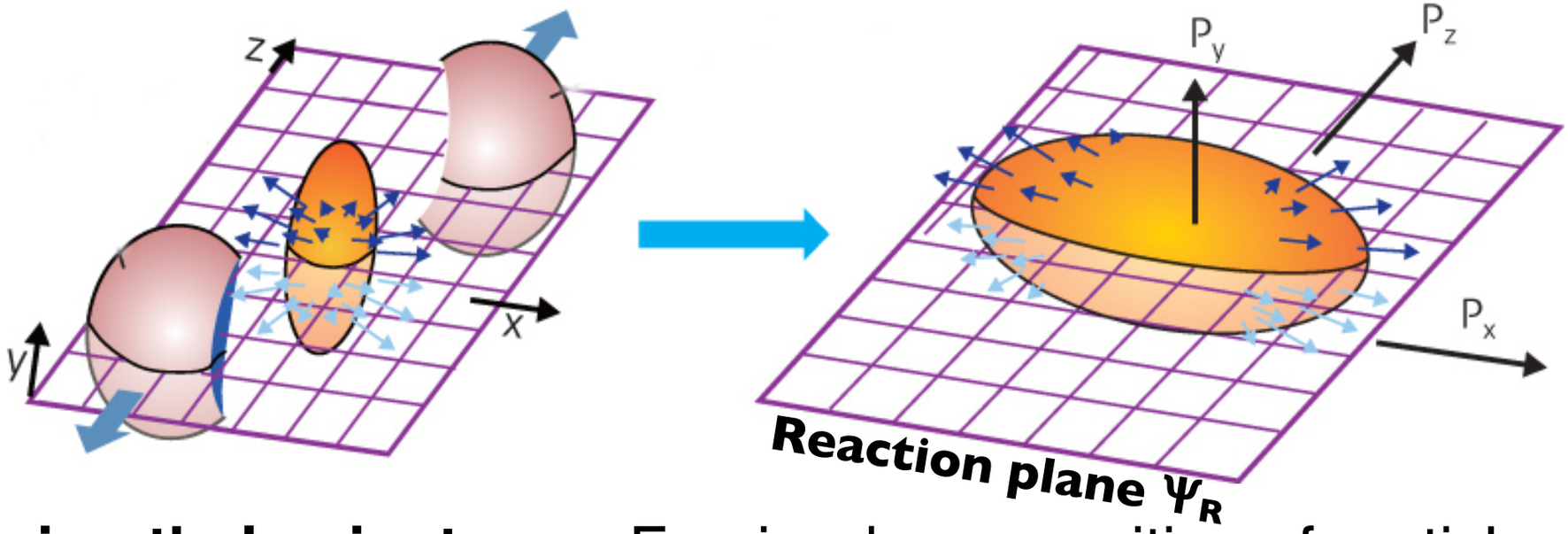
Medium modification of heavy-flavour hadron formation

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

Introduction

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

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



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

Introduction

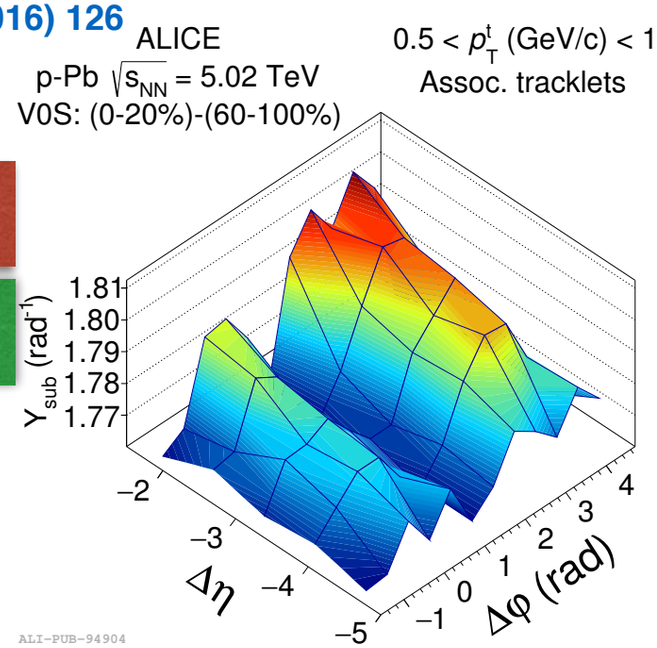
Open heavy-quark correlations and jets

- Complementary to open heavy-flavour measurements
- Possible modification of heavy-quark fragmentation
- Flavour dependence of the jet quenching / redistribution of the lost energy

Smaller systems: pp and p–Pb collisions

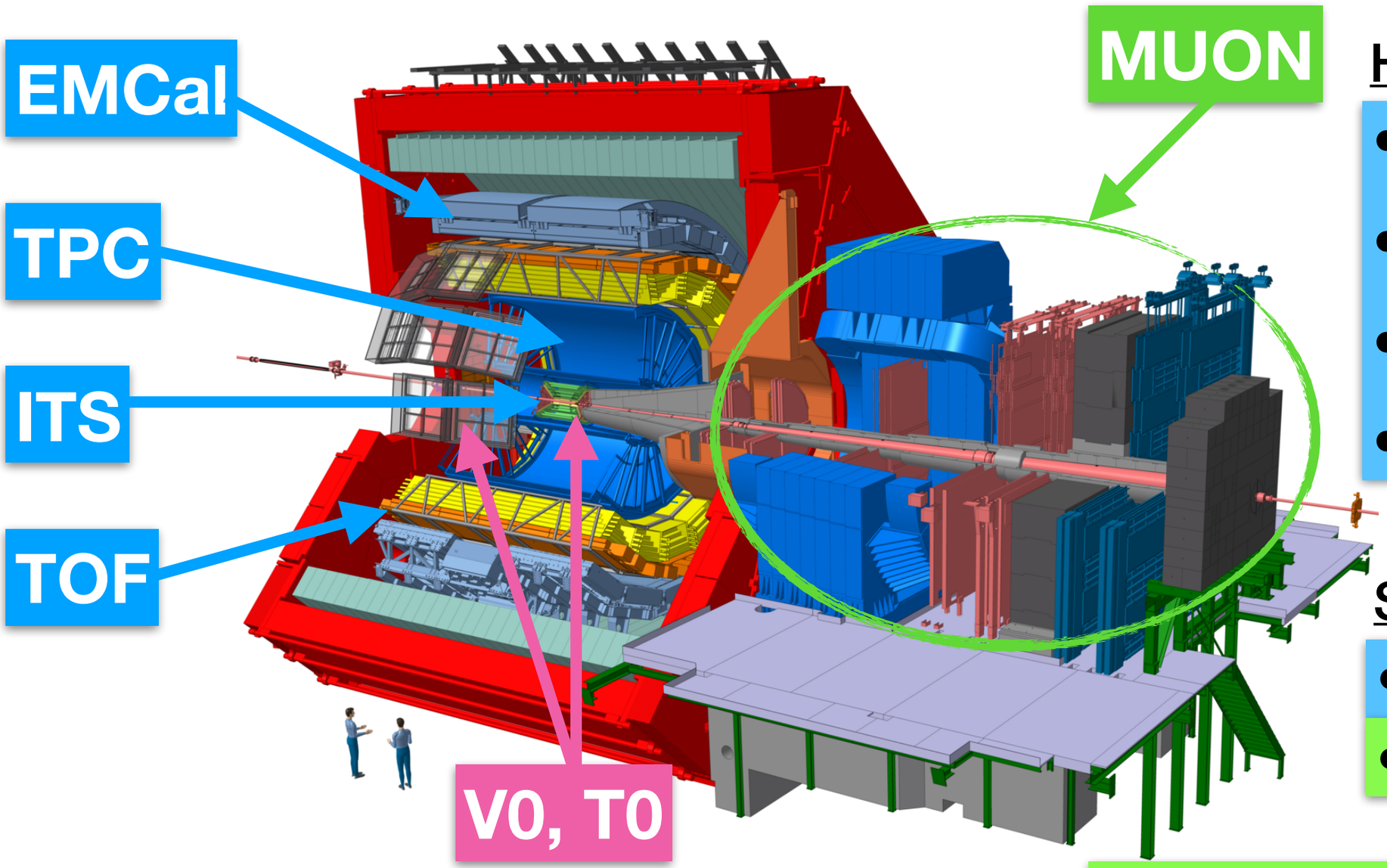
- Control experiments
  - ➡ Important to test pQCD calculations
  - ➡ Provide a necessary baseline for heavy-ion studies
  - ➡ Understanding of Cold Nuclear Matter (CNM) effects

ALICE, Phys. Lett. B753 (2016) 126



- New collectivity-like effects observed at high multiplicity in smaller systems
  - ➡ Insight into Multiple-Parton-Interaction (MPI) phenomena
  - ➡ Understand the interplay of soft and hard processes

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)

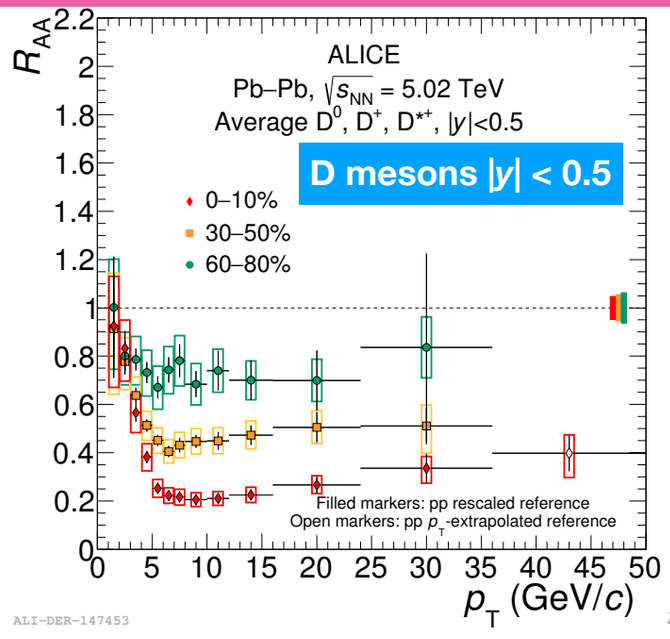
- Muon trigger, tracking, PID

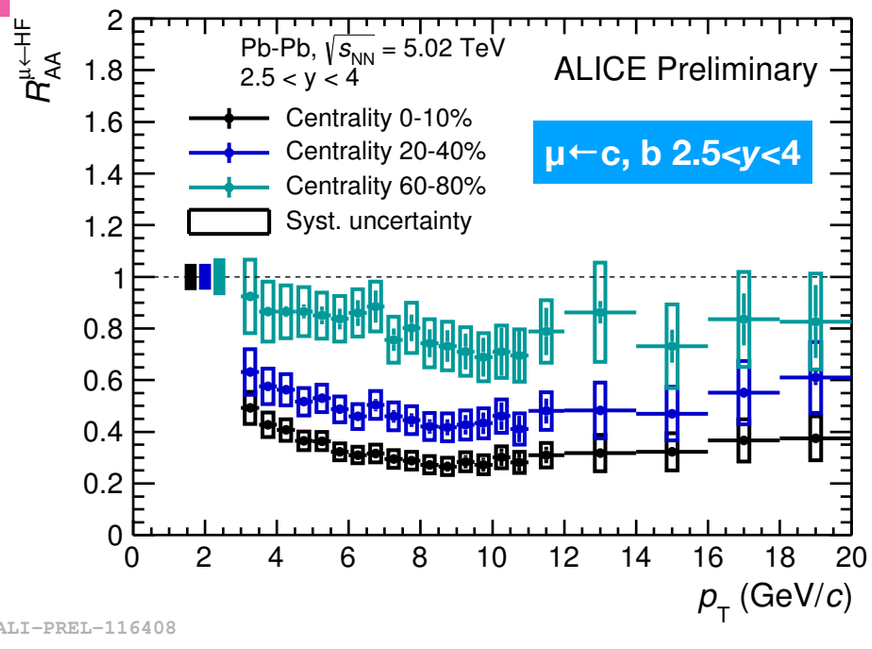
Smaller detectors: V0, T0, ZDC

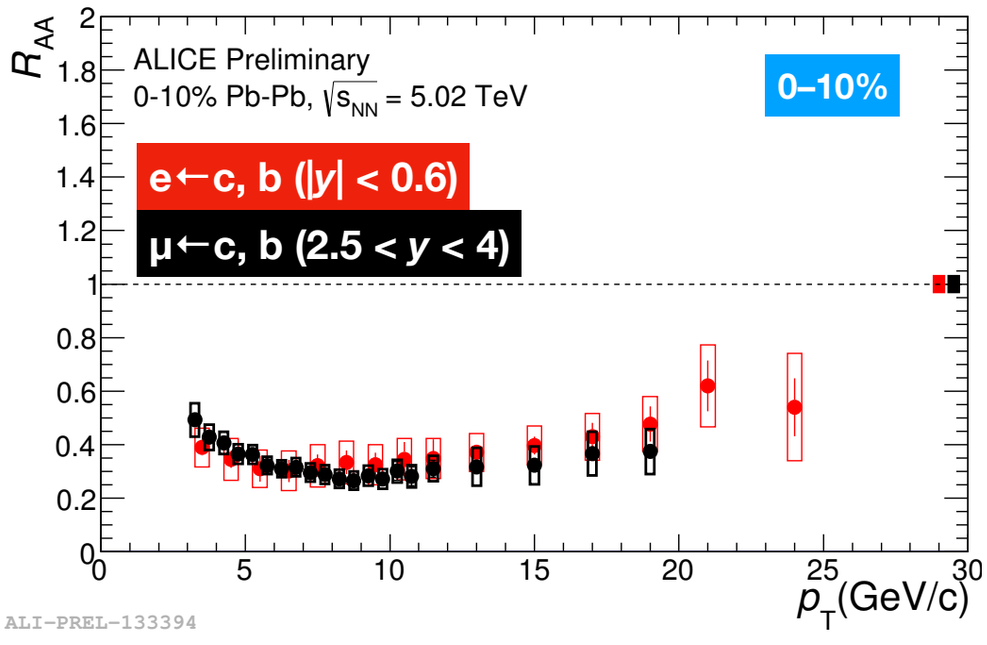
- Event trigger, characterization

Nuclear modification factor

ALICE JHEP 10 (2018) 174







- Increasing suppression from peripheral to central collisions
- R_{AA} of HFe at mid-rapidity is consistent with HFm at forward rapidity

➡ Heavy quarks undergone significant interactions in a wide rapidity window in the most central Pb–Pb collisions

➡ Confirmed the RUN-I measurements

Nuclear modification factor

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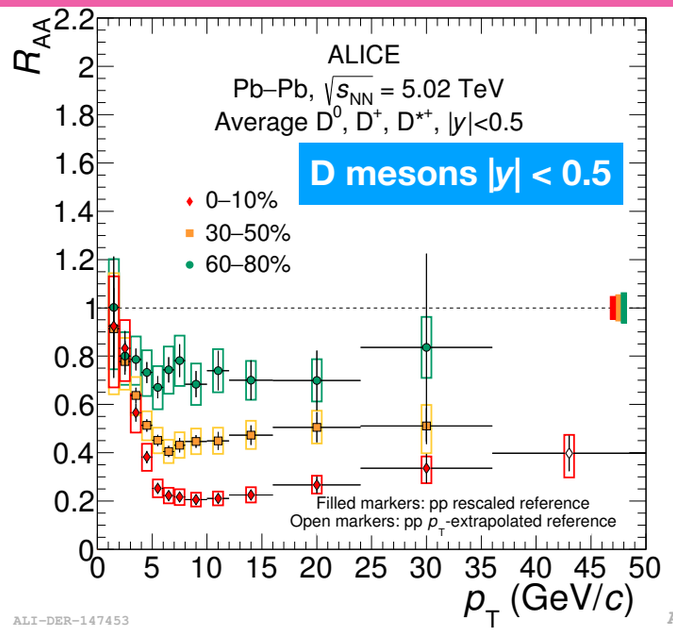

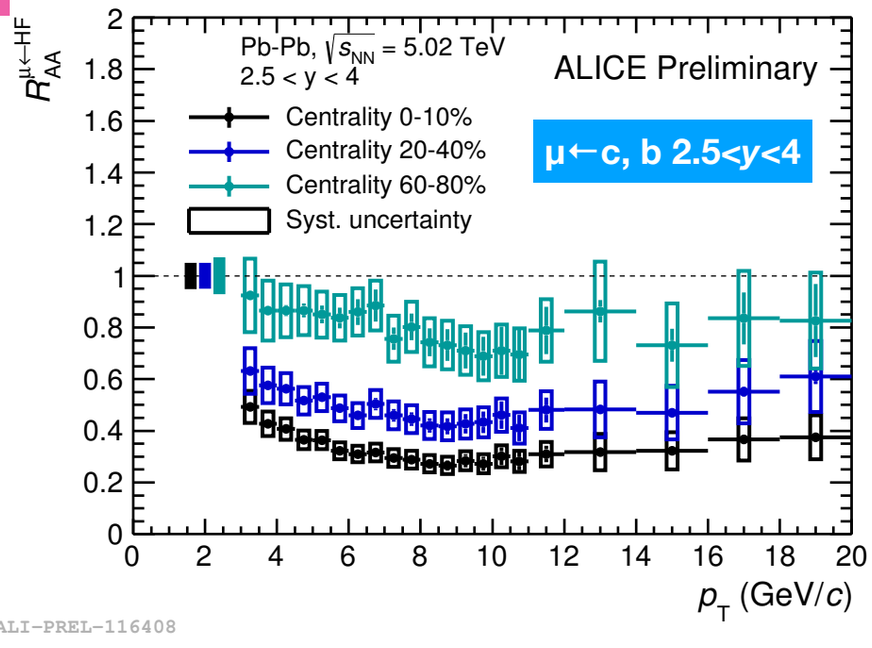

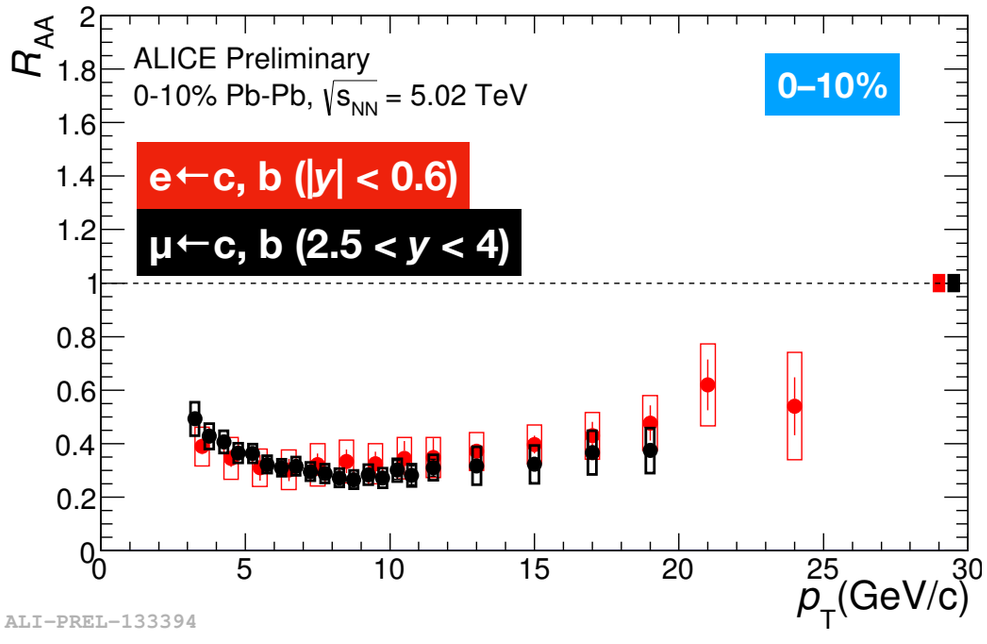

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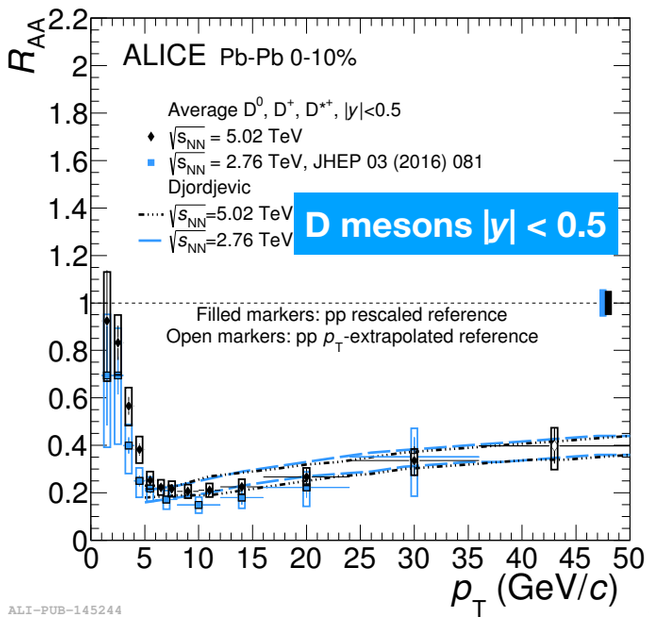
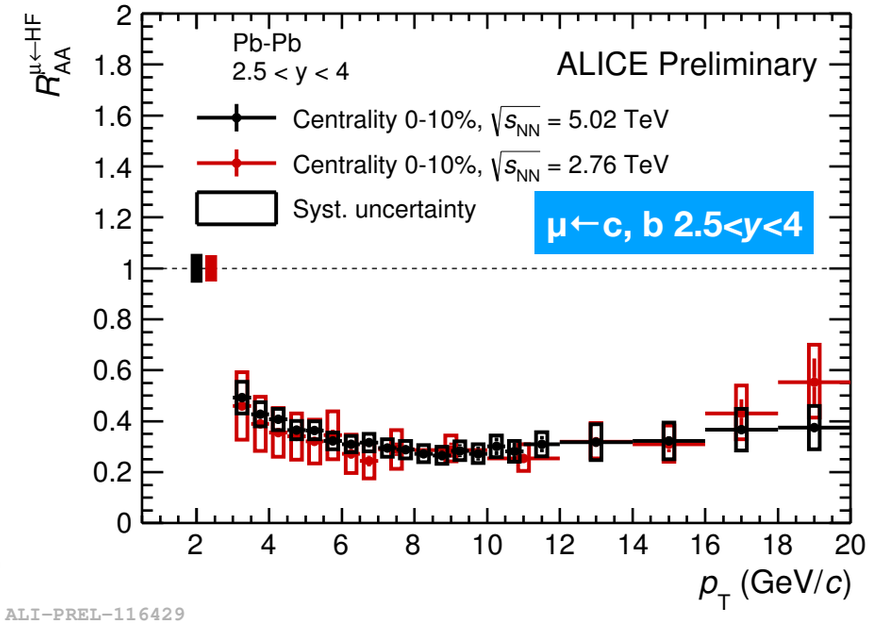
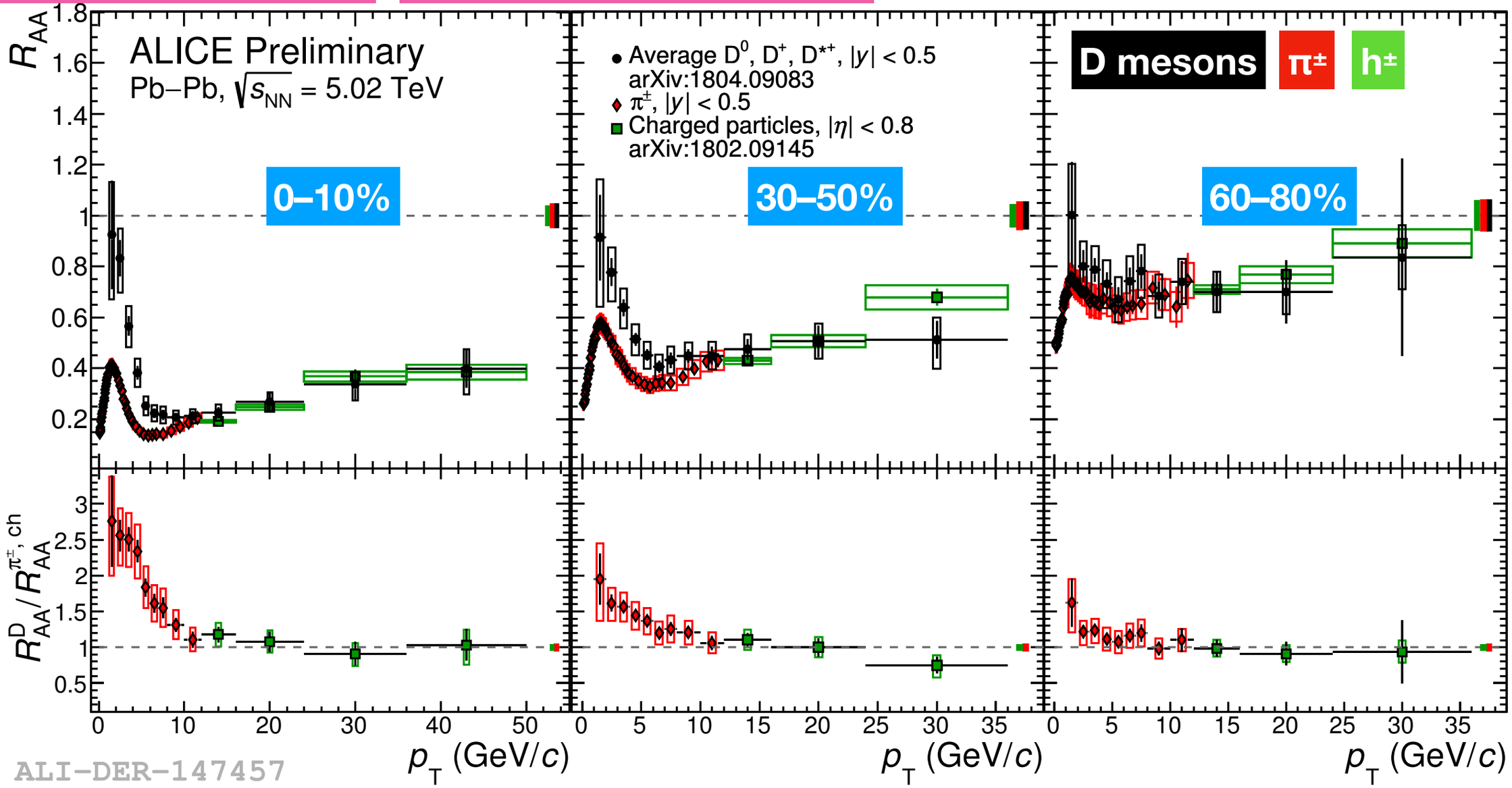




- Similar suppression at 5.02 TeV and 2.76 TeV
- Counterbalance between an increased medium temperature / density and harder quark p_T spectra

D meson R_{AA} vs. light-hadron R_{AA}

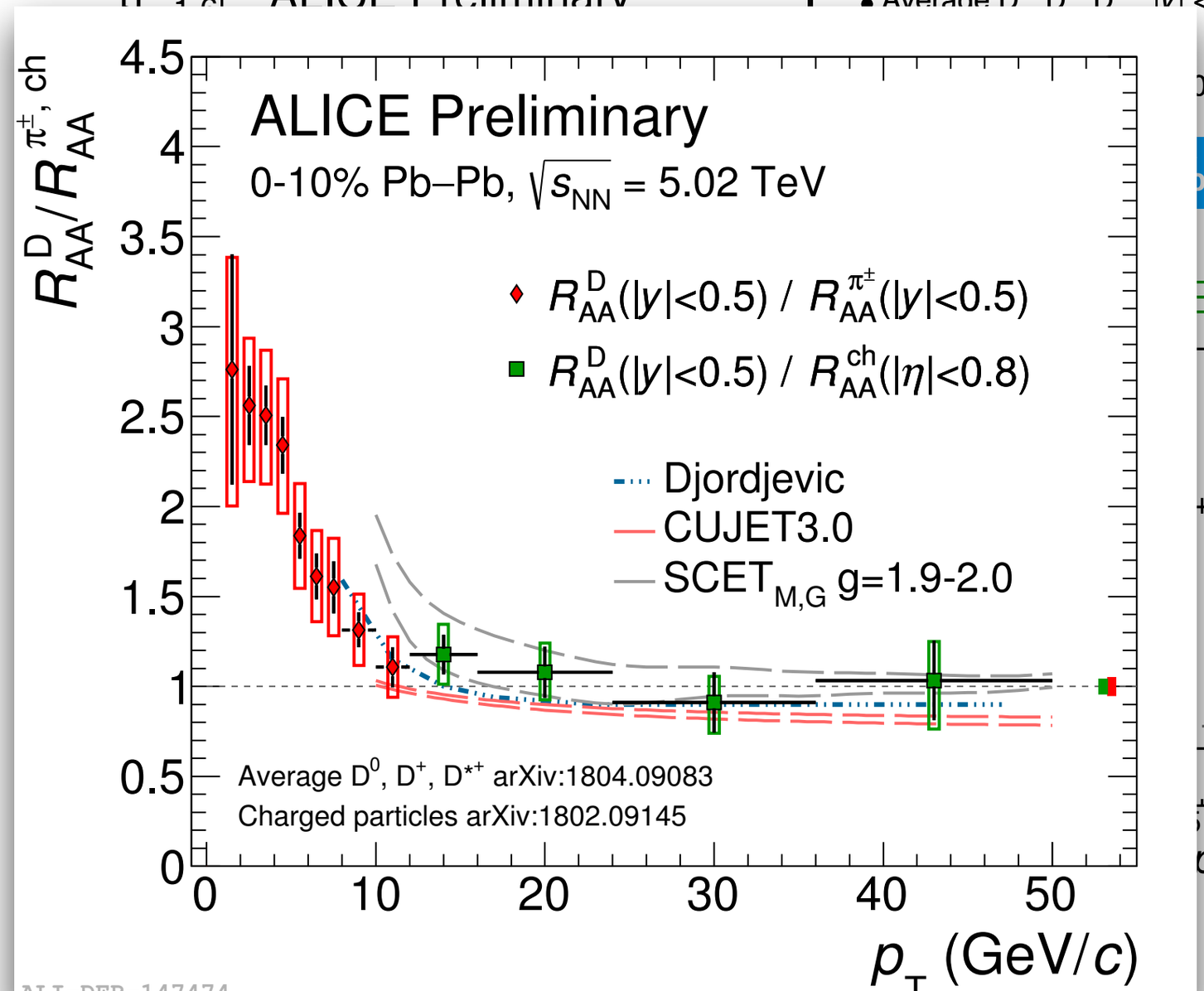
ALICE JHEP 10 (2018) 174 ALICE JHEP 11 (2018) 013



- R_{AA}(D) > R_{AA}(π±) for p_T < 8 GeV/c in central and semi-central collisions
- R_{AA}(D) ≃ R_{AA}(π±) ≃ R_{AA}(h±) in peripheral collisions and for p_T > 8 GeV/c in central and semi-central collisions

D meson R_{AA} vs. light-hadron R_{AA}

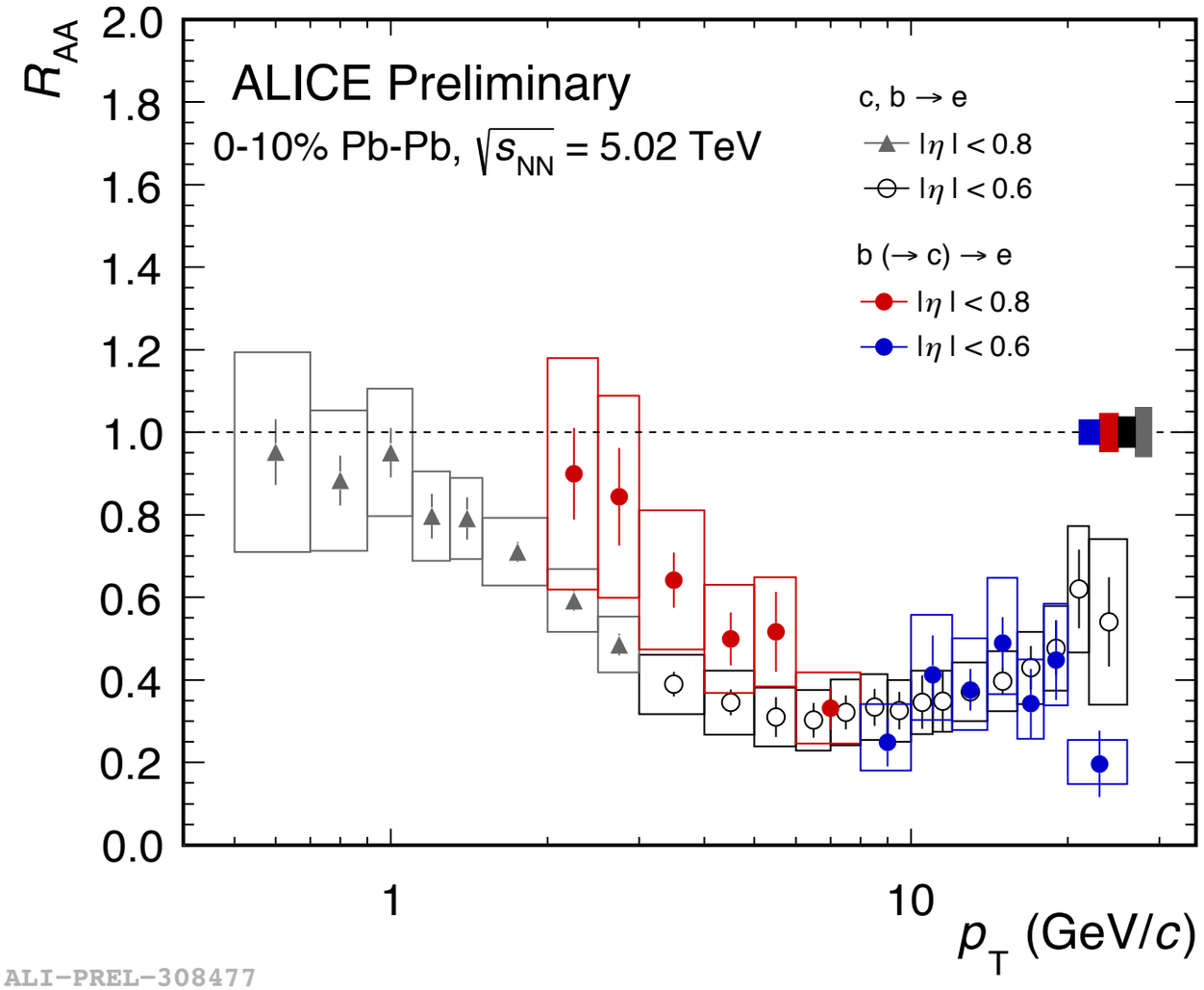
ALICE JHEP 10 (2018) 174 **ALICE JHEP 11 (2018) 013**



- Double ratio at low p_T
  - ➡ N_{coll} vs N_{part} scaling
  - ➡ Different fragmentation and initial spectrum shapes
  - ➡ Possible mass and Casimir factor effects
  - ➡ Different coalescence and radial flow…
  - ➡ Expected by models

- R_{AA}(D) ≃ R_{AA}(π±) ≃ R_{AA}(h±) in peripheral collisions and for p_T > 8 GeV/c in central and semi-central collisions

R_{AA}(e←b) vs. R_{AA}(e←c, b)



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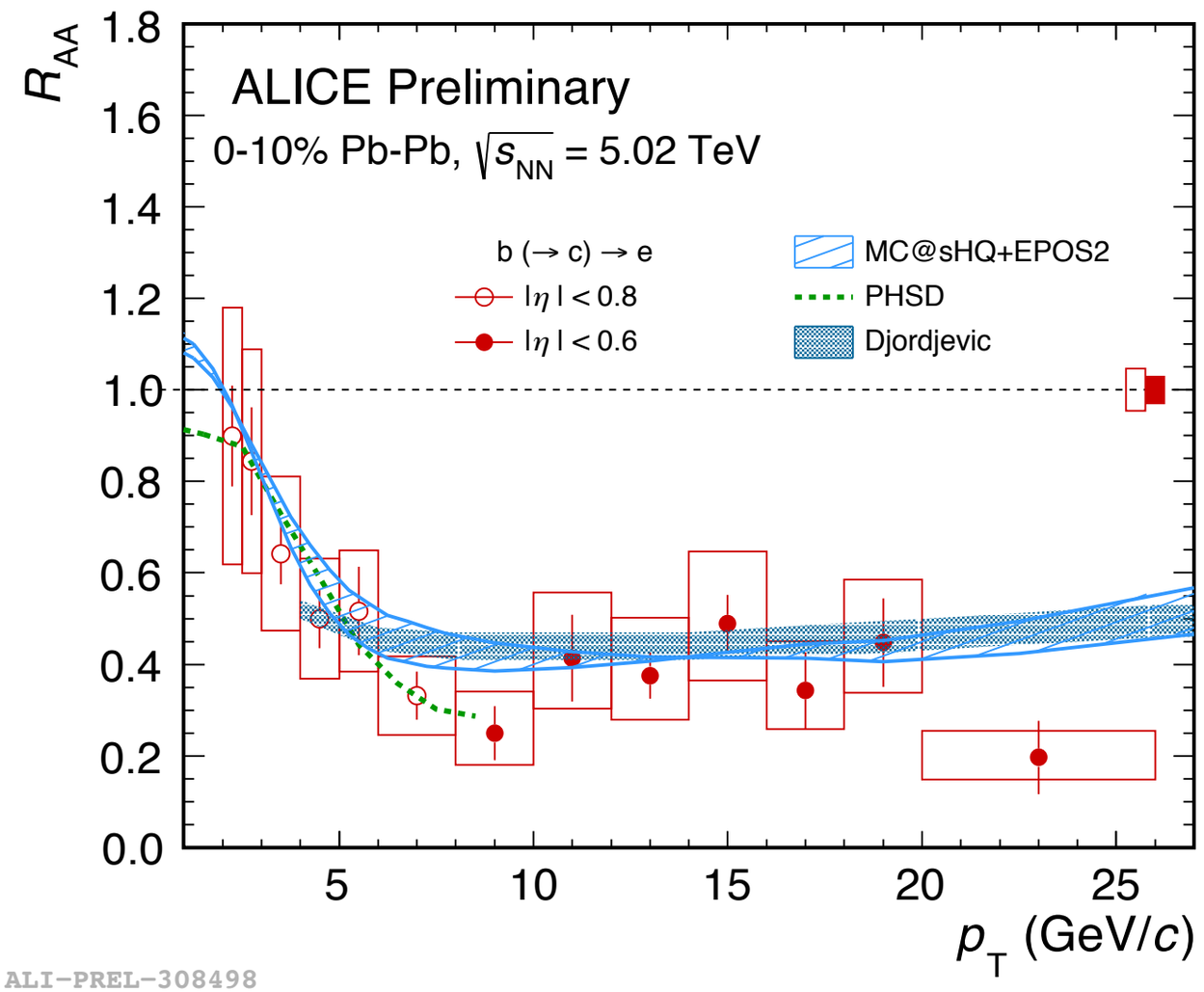
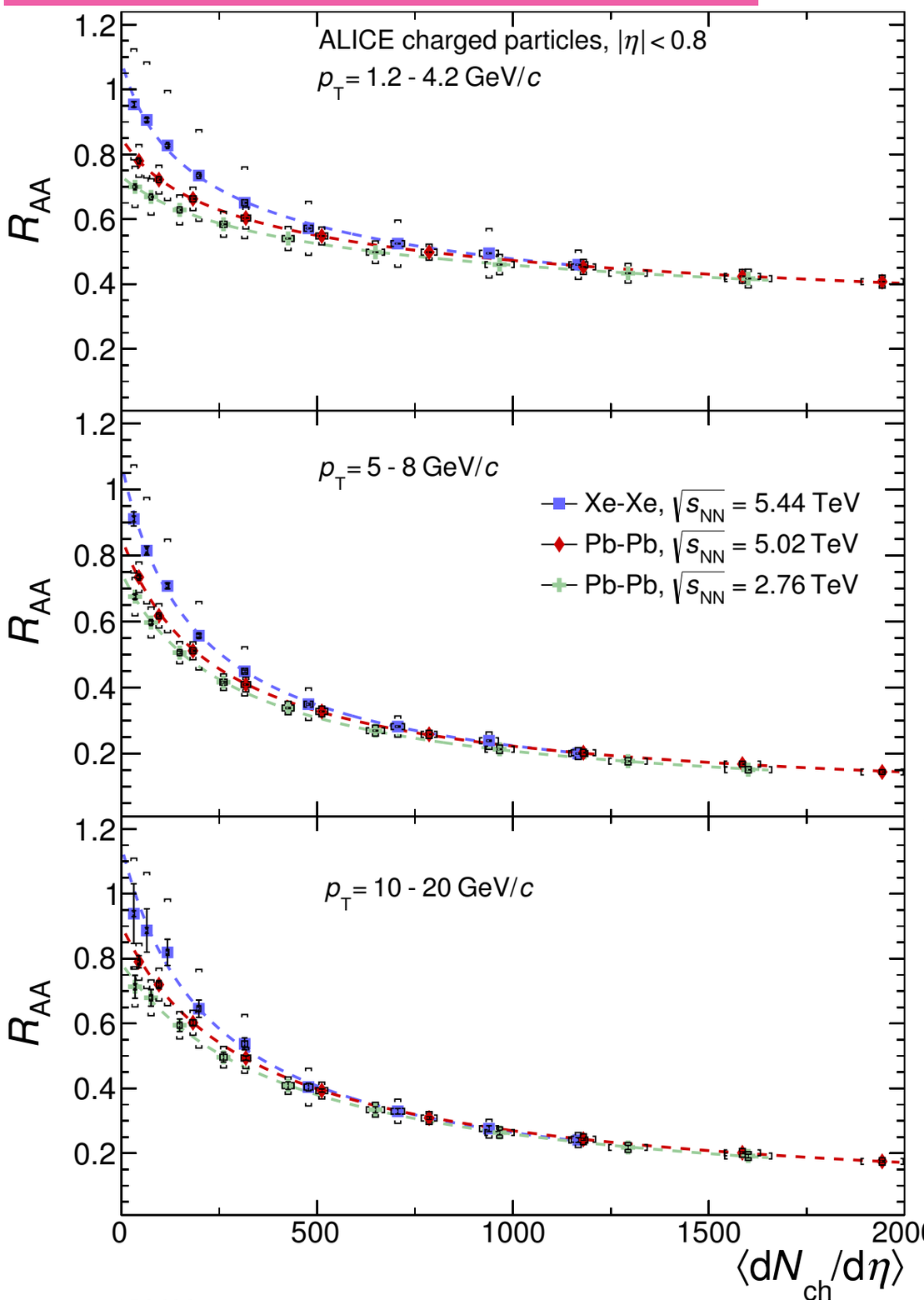


ALI-PREL-308498

- Hint of a smaller suppression for beauty-decay electrons for p_T < 6 GeV/c
- Data is reproduced by models within uncertainties, implementing quark mass dependent energy loss

Xe–Xe vs. Pb–Pb collisions

ALICE Phys. Lett. B788 (2019) 166



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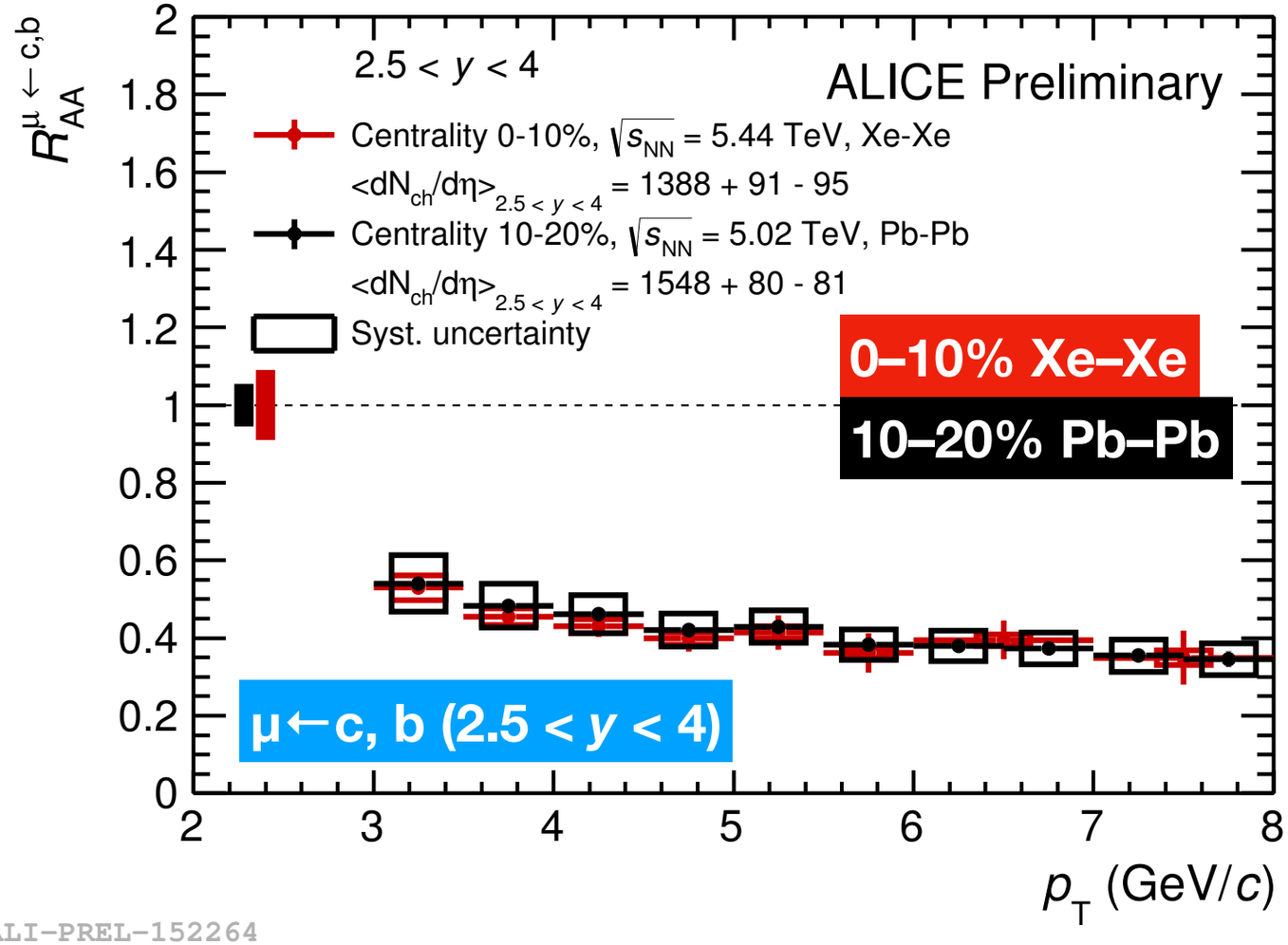
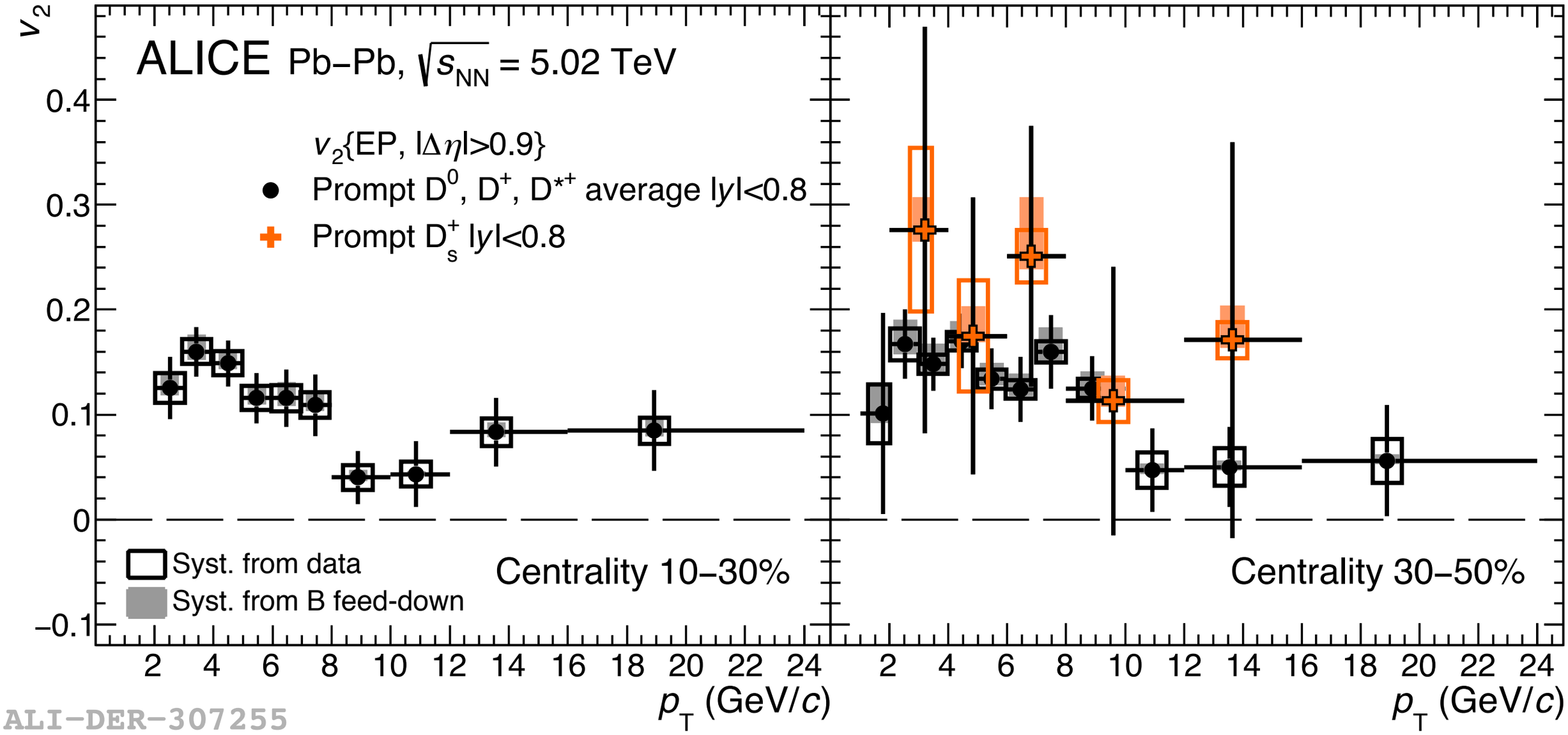


ALI-PREL-152264

- Similar R_{AA} observed with similar $\langle dN_{ch}/d\eta \rangle$ and N_{par}
- Possible interplay of geometry and path-length dependence [arXiv:1805.04030]

Elliptic flow of open heavy flavours

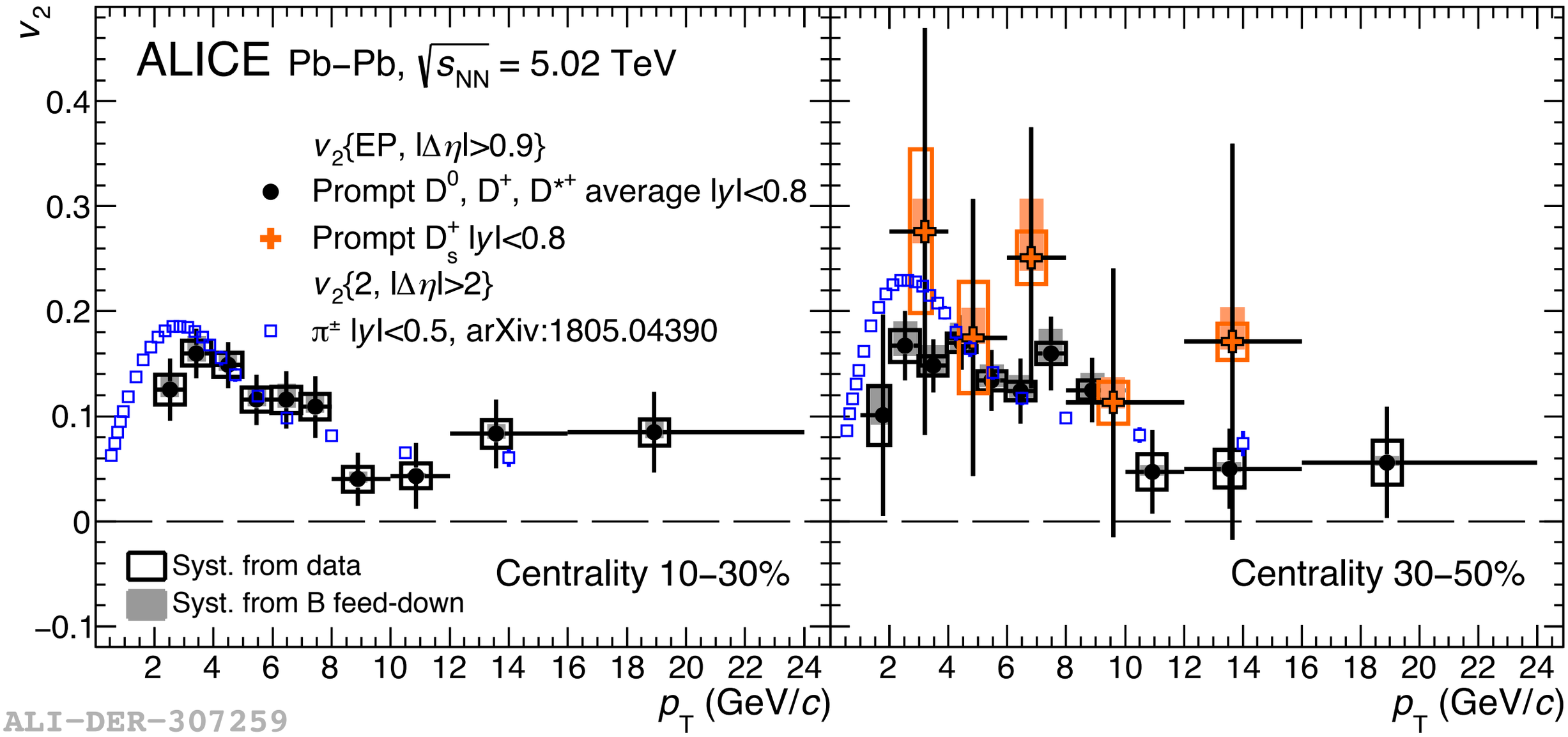
ALICE *Phys. Rev. Lett.* 120 (2018) 102301 | ALICE arXiv:1809.09371



- Positive v_2 of D mesons for p_T in 2 – 8 GeV/c in semi-central collisions
- v_2 of D_s compatible with non-strange D-mesons within uncertainties

Elliptic flow of open heavy flavours

ALICE *Phys. Rev. Lett.* 120 (2018) 102301 | ALICE arXiv:1809.09371 | ALICE JHEP 09 (2018) 006



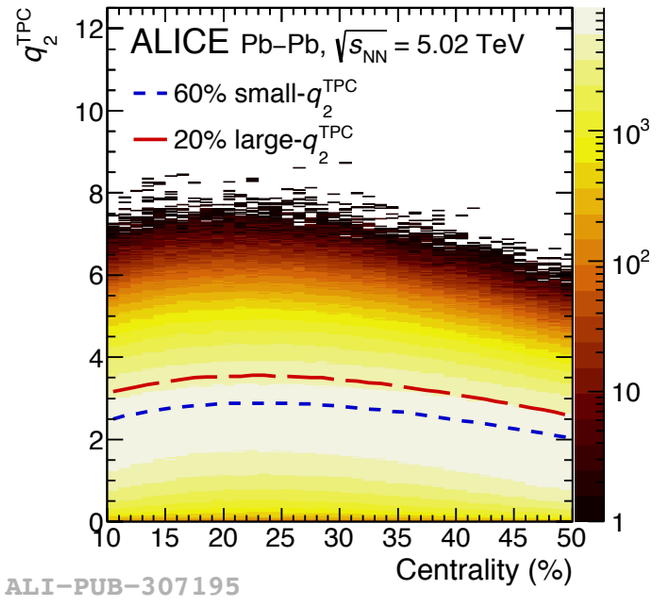
- Positive v_2 of D mesons for p_T in 2 – 8 GeV/c in semi-central collisions
- v_2 of D_s compatible with non-strange D-mesons within uncertainties
- v_2(D) ≃ v_2(π±) for p_T > 4 GeV/c, hint of v_2(D) < v_2(π±) for p_T < 4 GeV/c

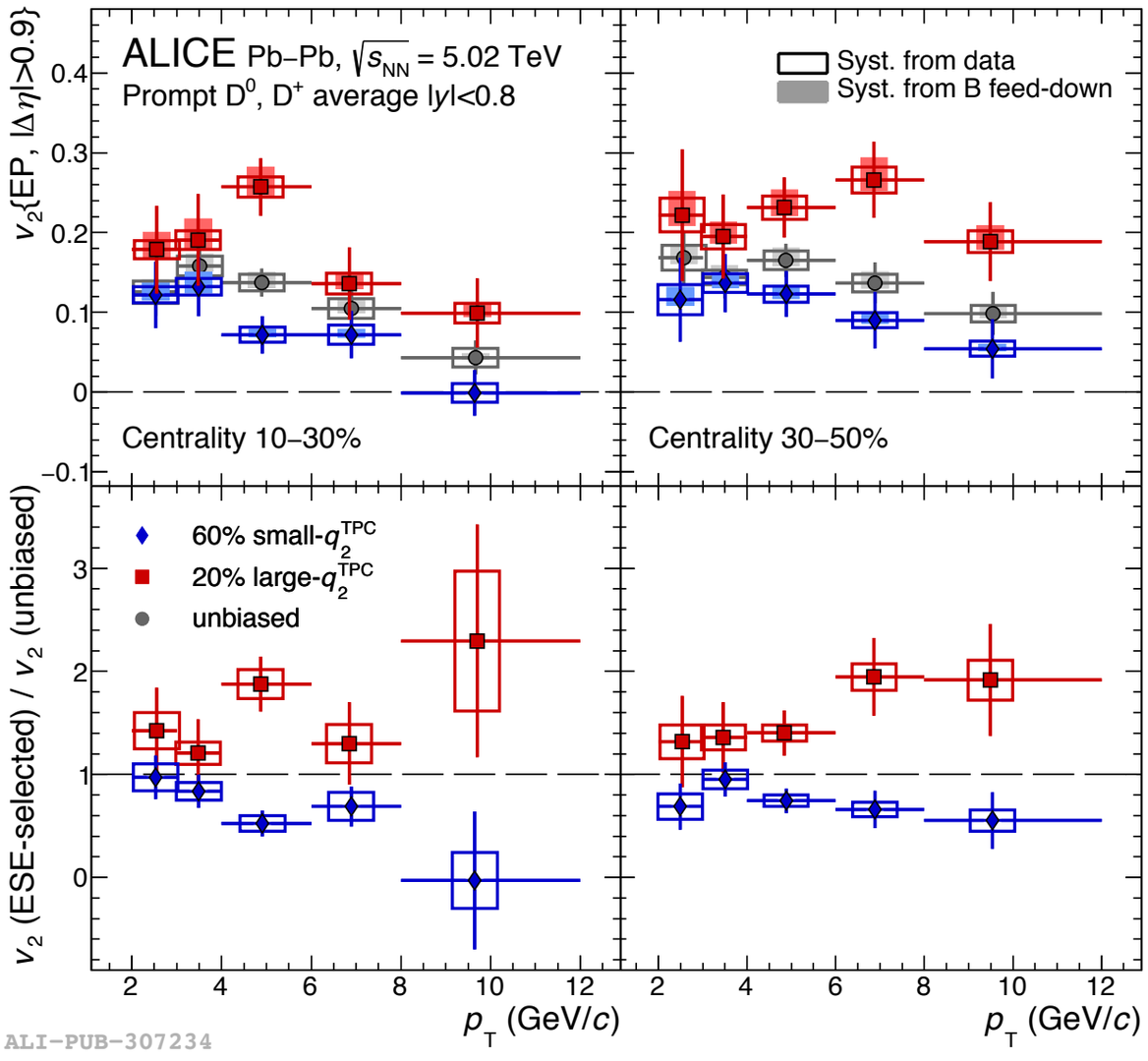
Event-shape engineering

- 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





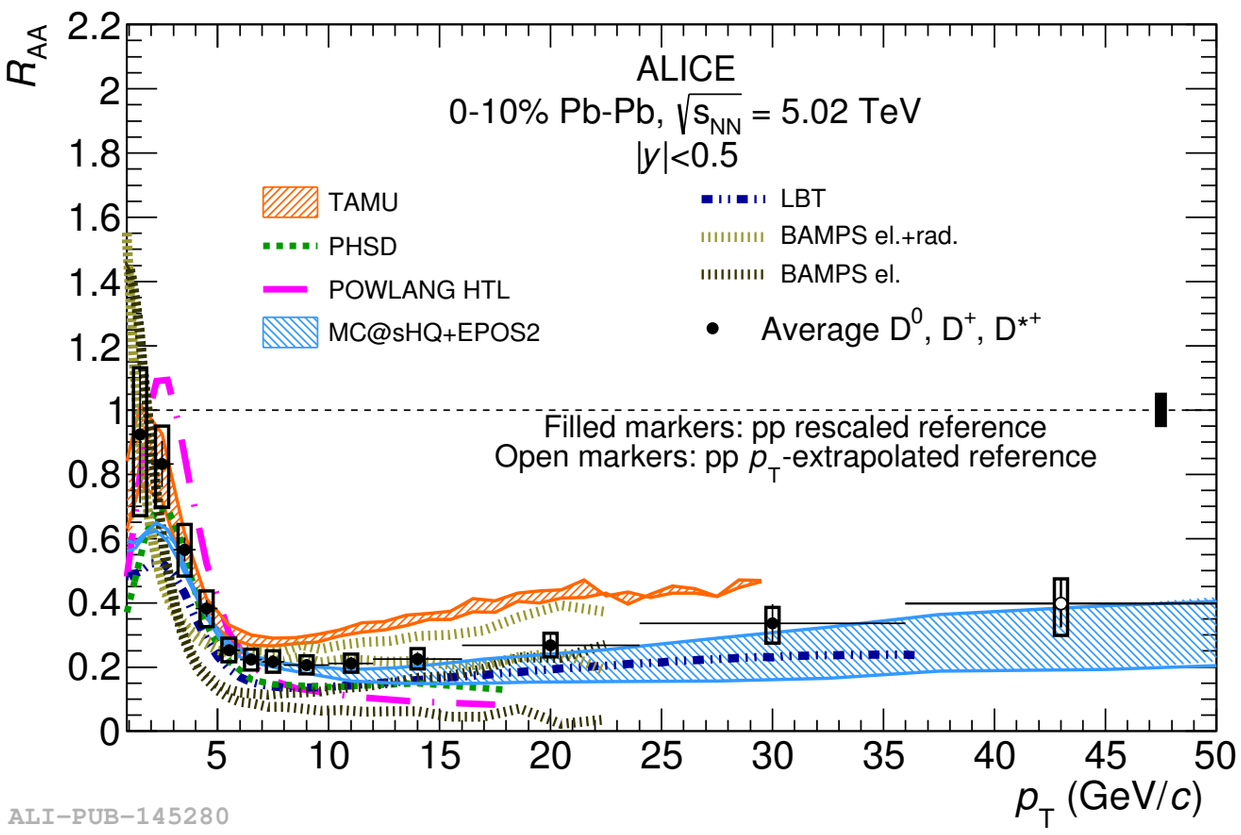
- Significant separation of D-meson v_2 in events with large and small q_2

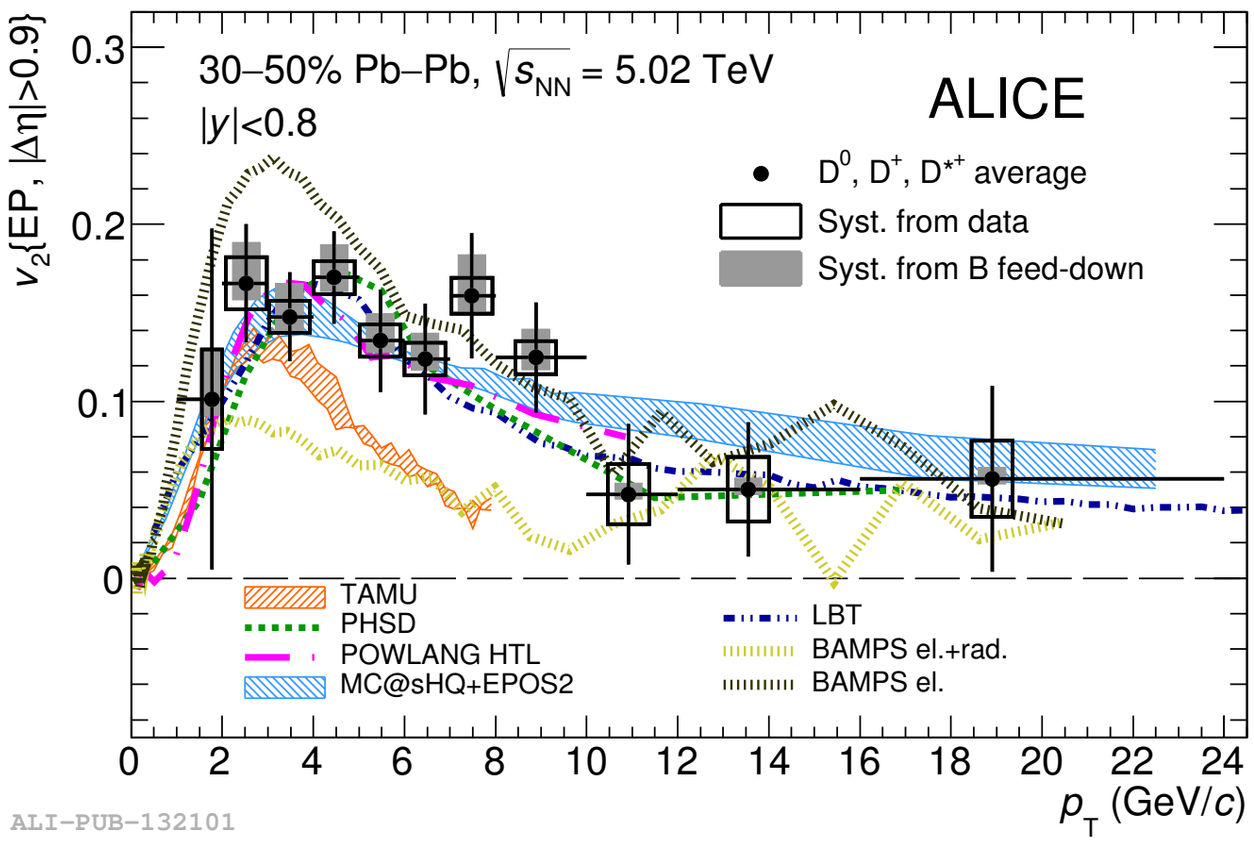
➡ Charm quarks sensitive to the light-hadron bulk collectivity and event-by-event initial condition fluctuations

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

ALICE arXiv:1809.09371

R_{AA} and v_2 of D mesons vs. models





- ALICE LHC RUN-II: improved data precision w. r. t. RUN-I and provided important constraints on models
- Models in which charm quarks pick up collective flow via recombination or subsequent elastic collisions in expanding medium better describe both R_{AA} and v_2 at low p_T (LBT, MC@sHQ, PHSD, POWLANG)

➡ Recombination and collisional energy loss: important for heavy quarks

➡ Charm quark diffusion coefficient at the LHC: (1.5 – 7) / $2\pi T_c$

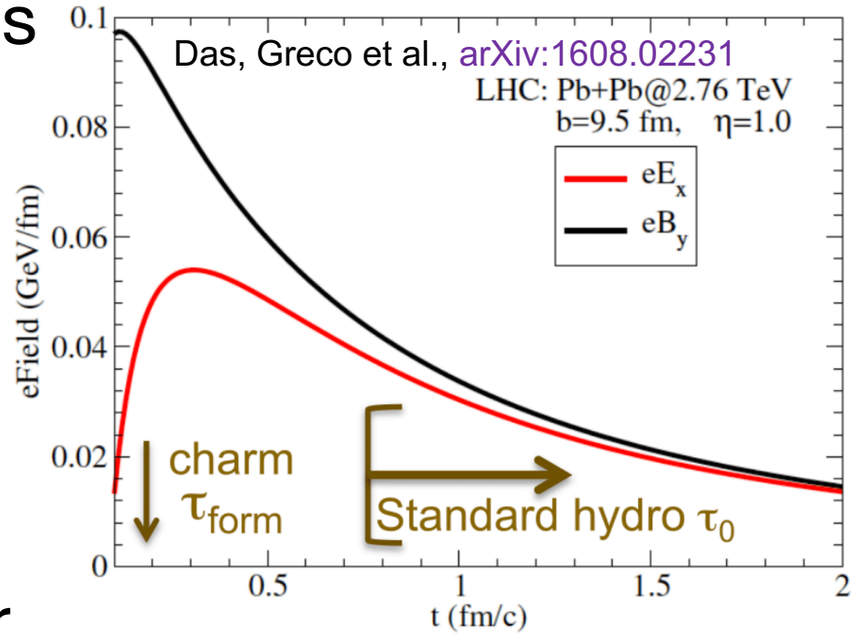
Directed flow of open charm

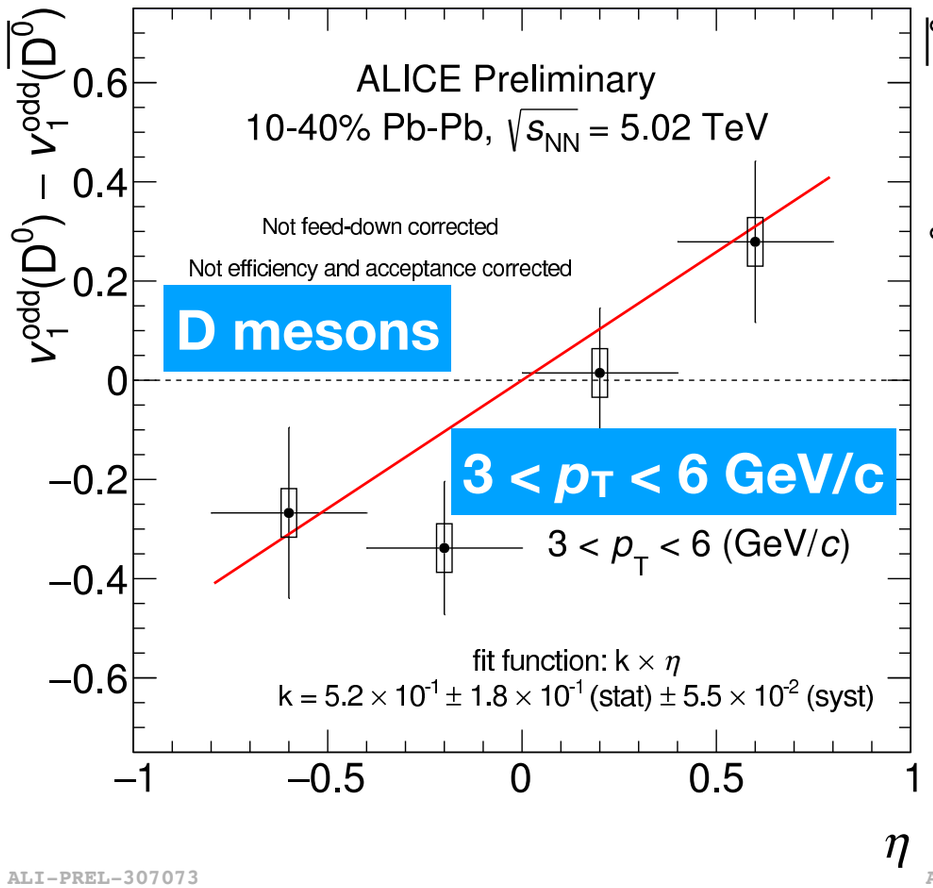
- Sensitive to the early time EM fields in the collisions

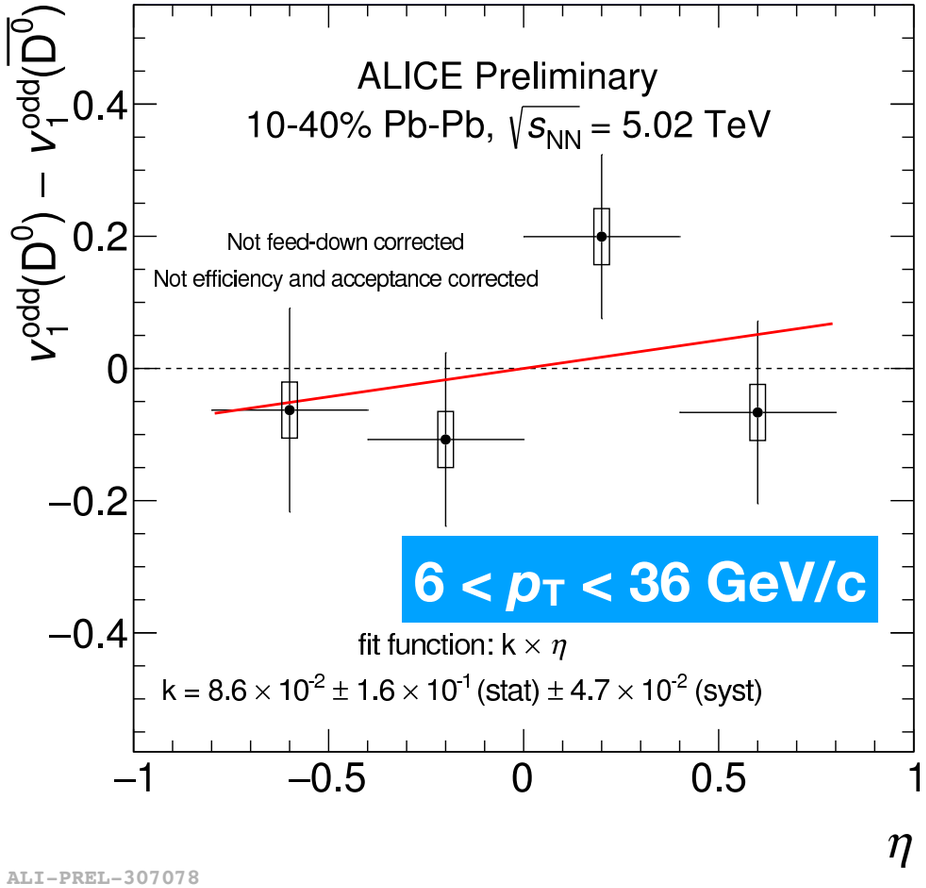
➡ Provide constraint for CME related physics

- Charm dragged by tilted bulk: production points are shifted from the bulk at $y \neq 0$ — larger v_1 for D mesons than for light flavours

➡ Probe the longitudinal profile of the initial matter







Hint of positive slope with a significance of 2.7σ at low p_T

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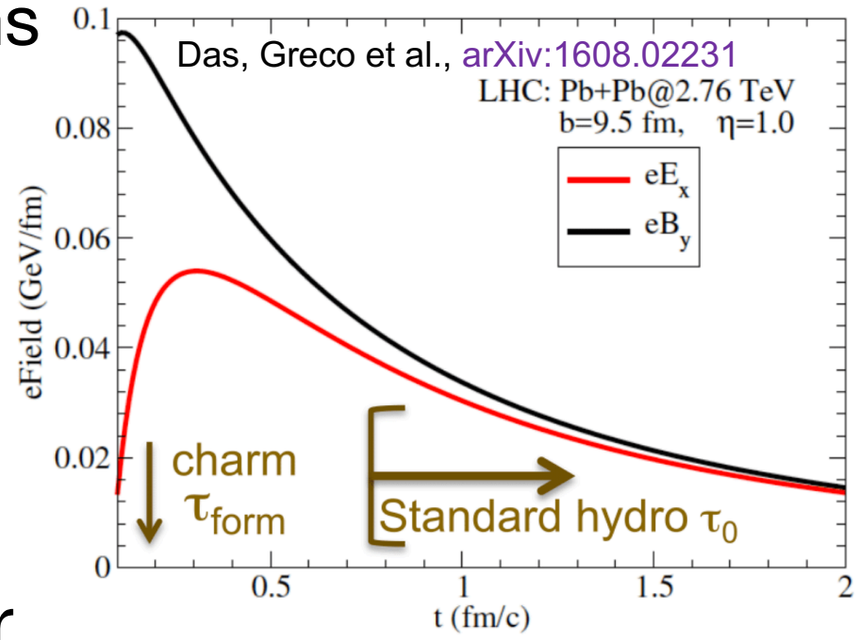

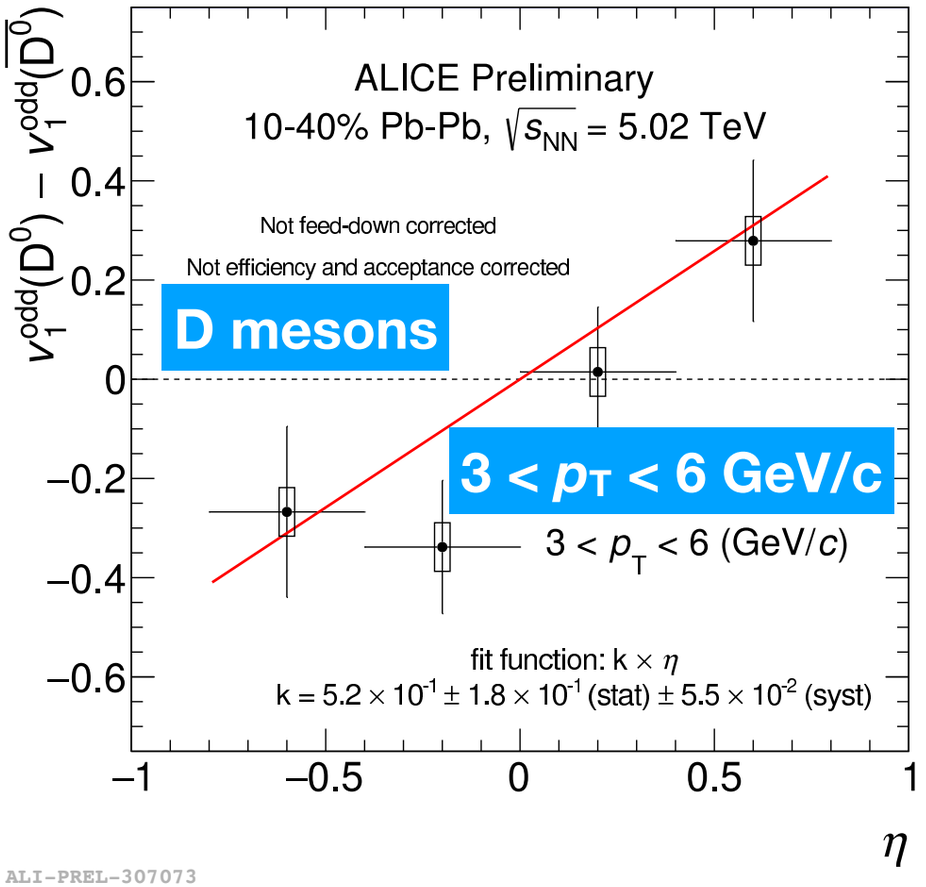

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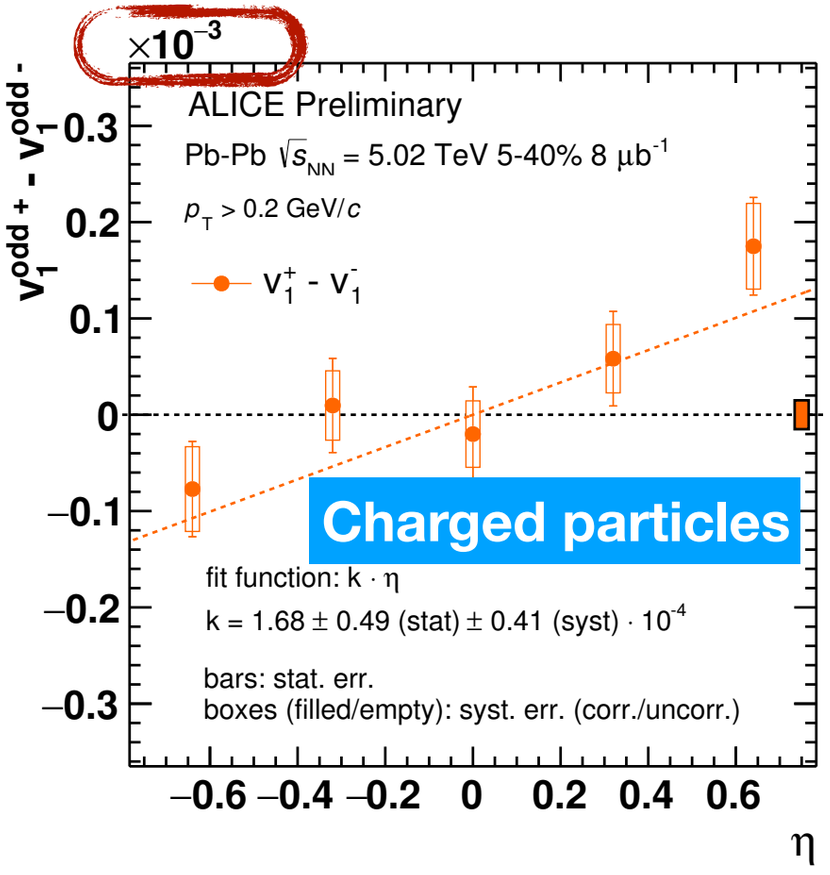


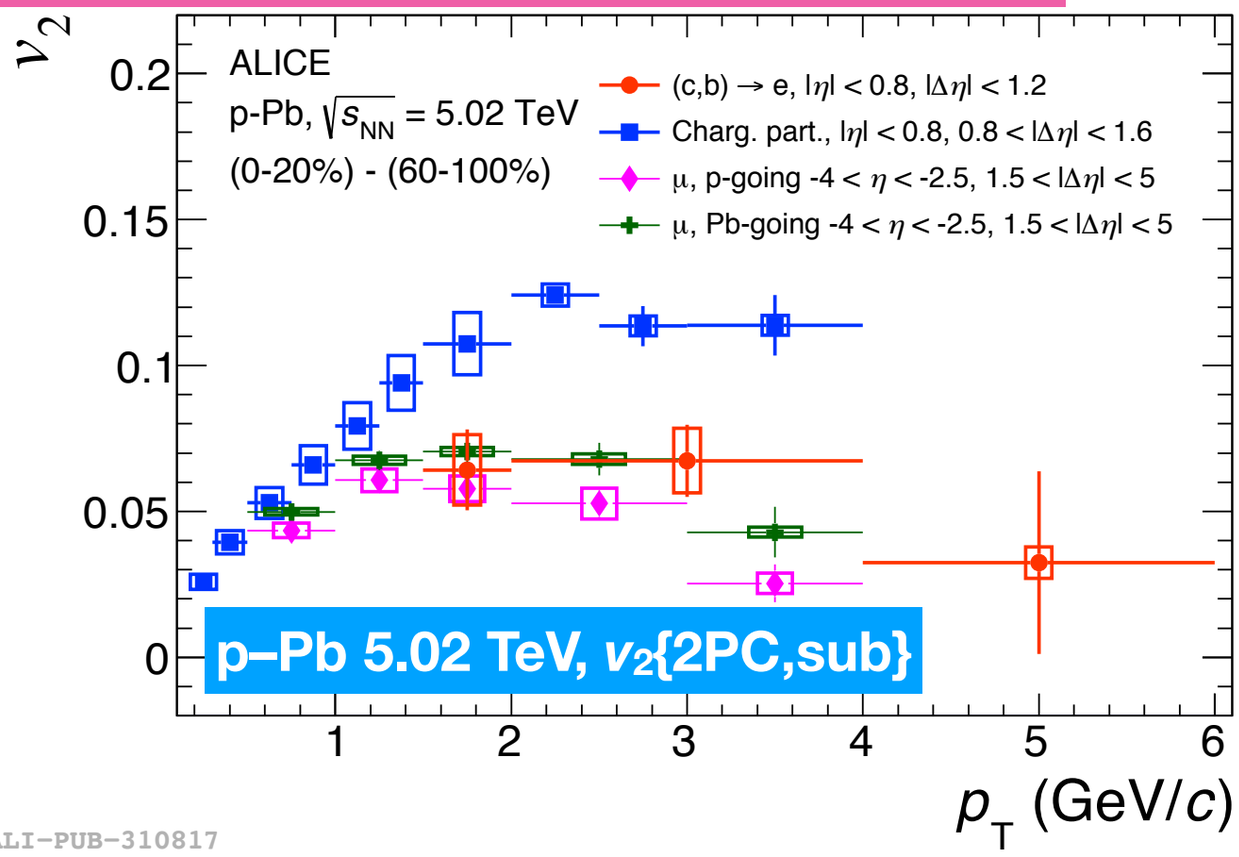
ALI-PREL-129689

Hint of positive slope with a significance of 2.7σ at low p_T

Similar trend observed for charged particles, but different magnitude

HF-decay lepton v_2 in p–Pb collisions

ALICE Phys. Rev. Lett. 122 (2019) 072301



- Positive HFe v_2 in 1.5 < p_T < 4 GeV/c (>5σ) in high multiplicity events
  - ➡ Possible lower than v_2 of charged particles at intermediate-p_T
  - ➡ Similar to inclusive muons at large rapidity

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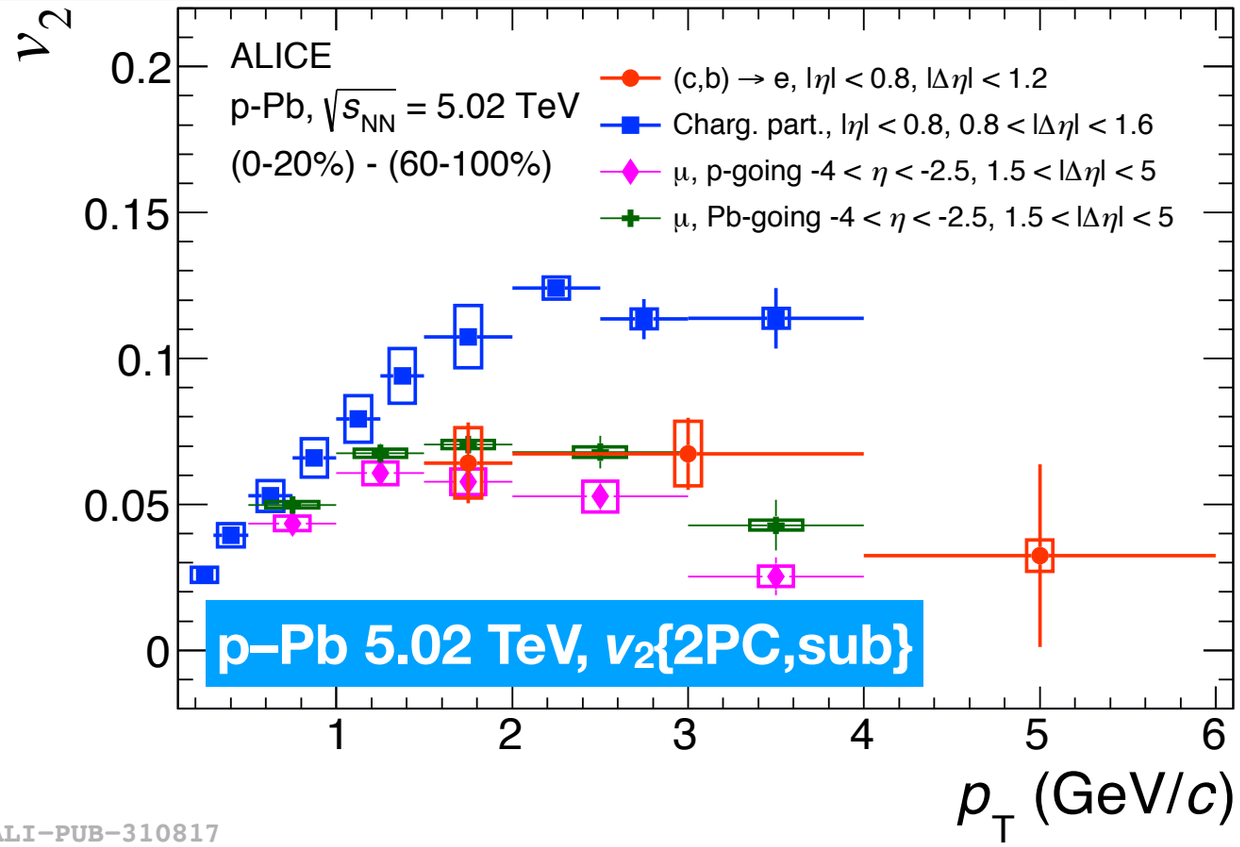
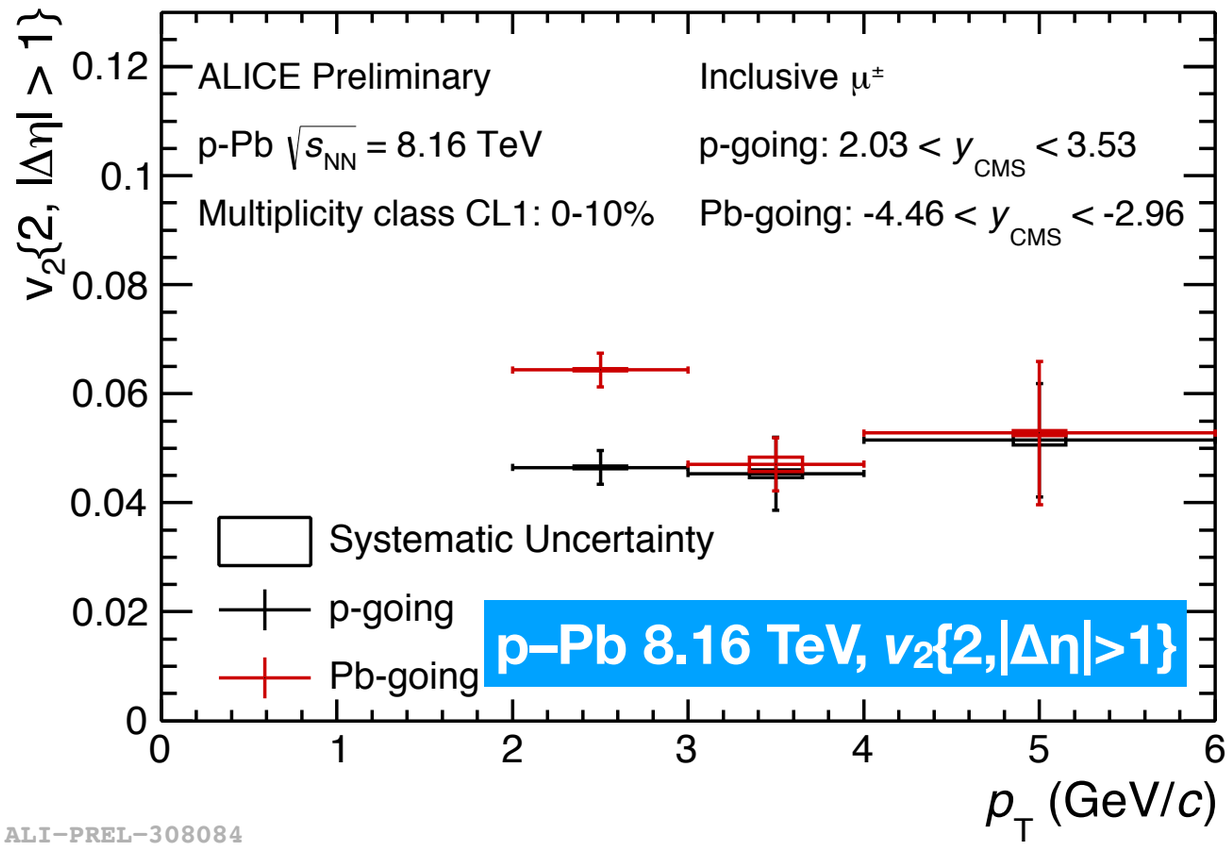
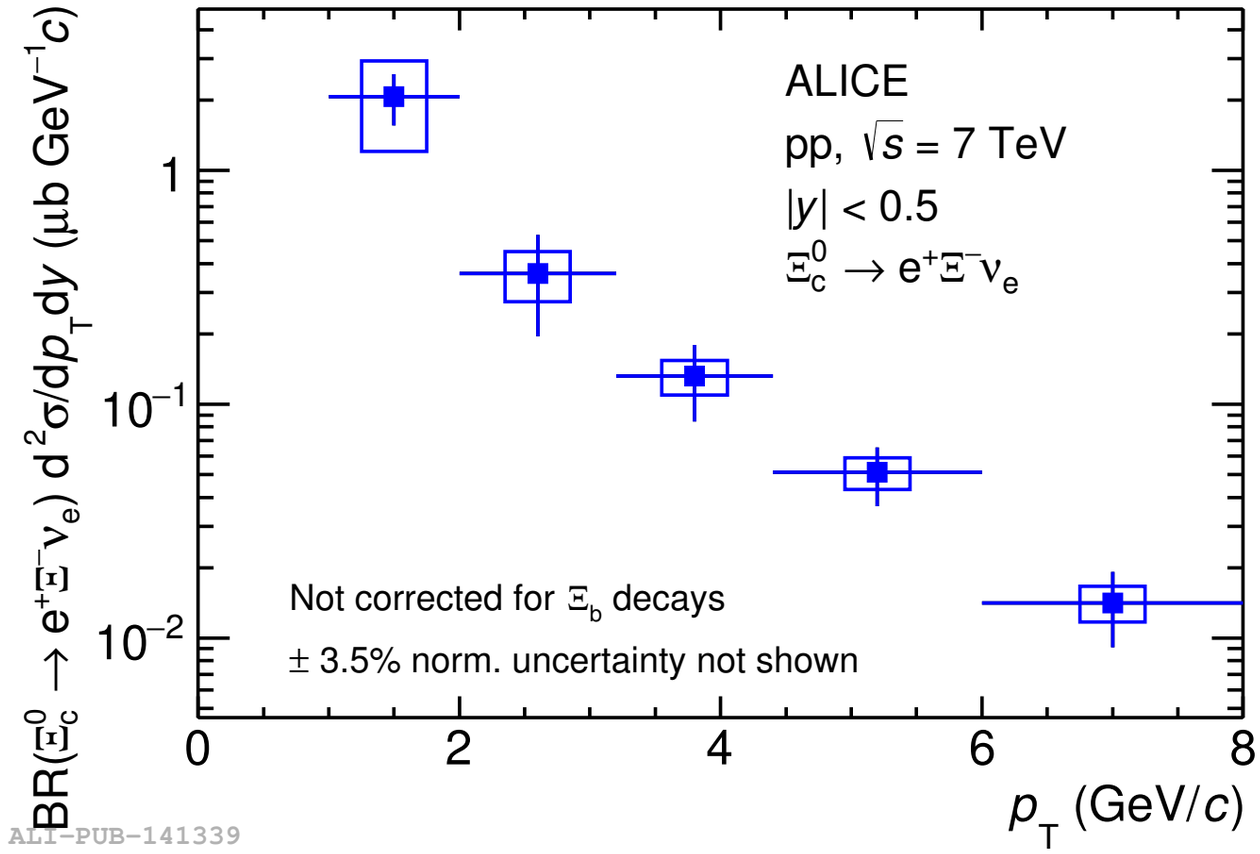


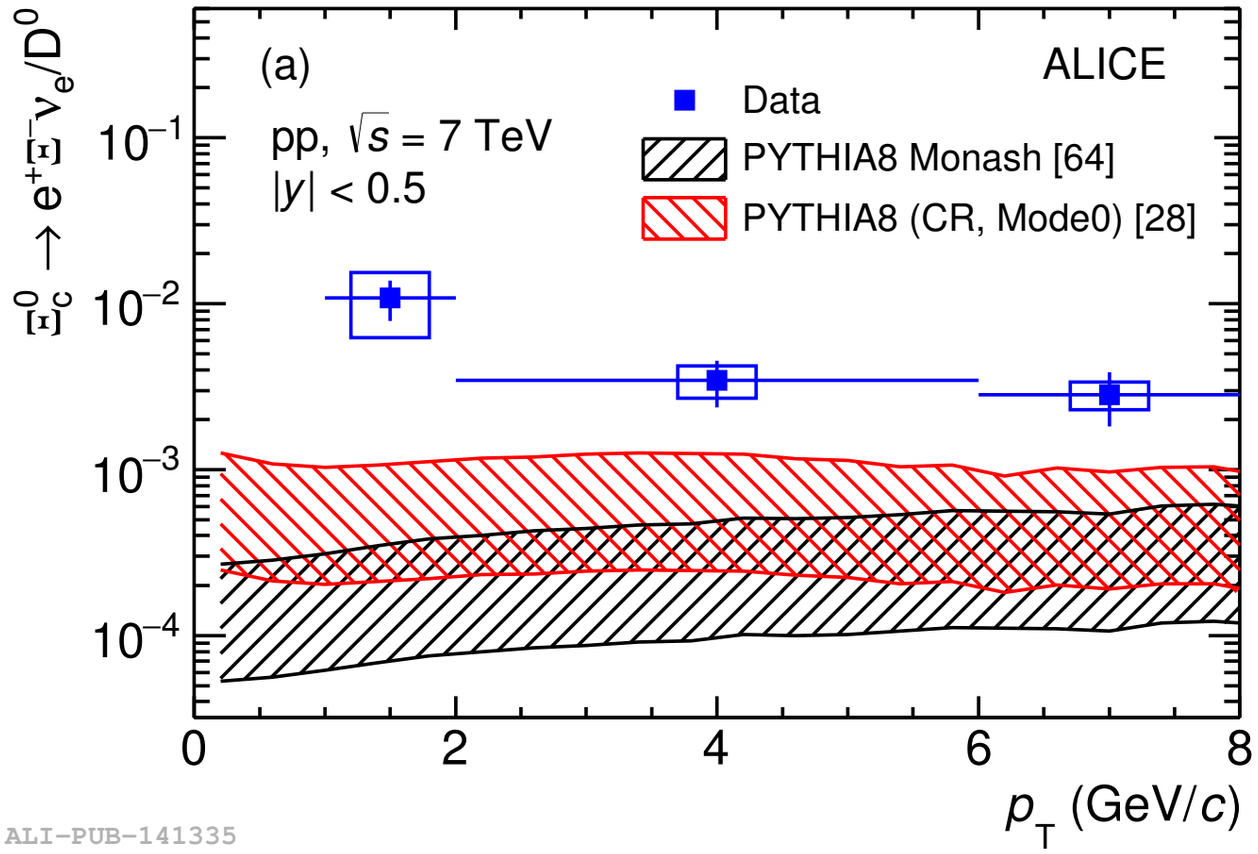


- Positive HFe v_2 in $1.5 < p_T < 4$ GeV/c (>5σ) in high multiplicity events
  - ➡ Possible lower than v_2 of charged particles at intermediate-p_T
  - ➡ Similar to inclusive muons at large rapidity
- New: inclusive muon v_2 at 8.16 TeV, Q-cumulants with 2-particle correlations
  - ➡ Positive v_2 in $2 < p_T < 6$ GeV/c (>3σ) —HFm components dominated

Ξ_c production in pp collisions

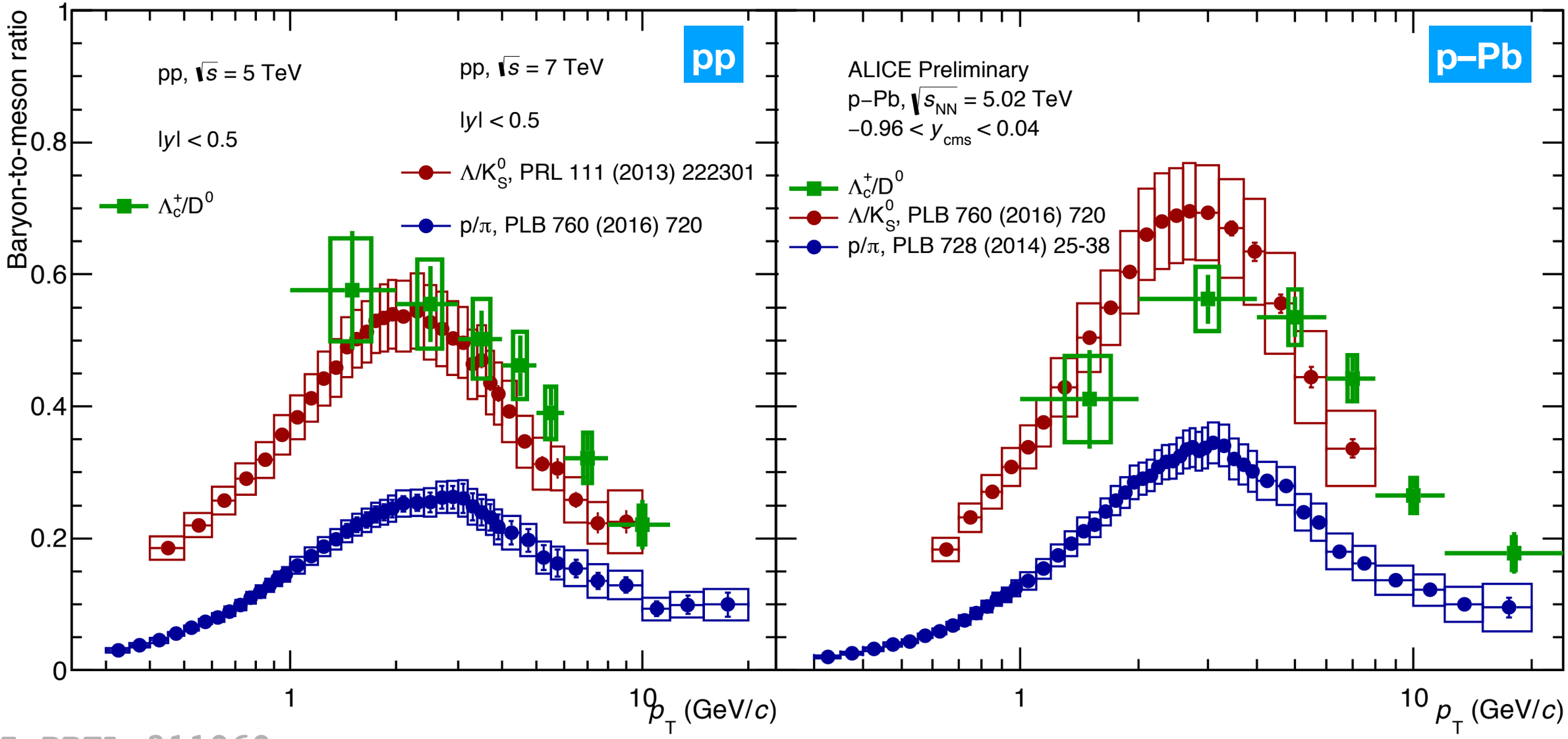
ALICE *Phys. Lett.* B781 (2018) 8





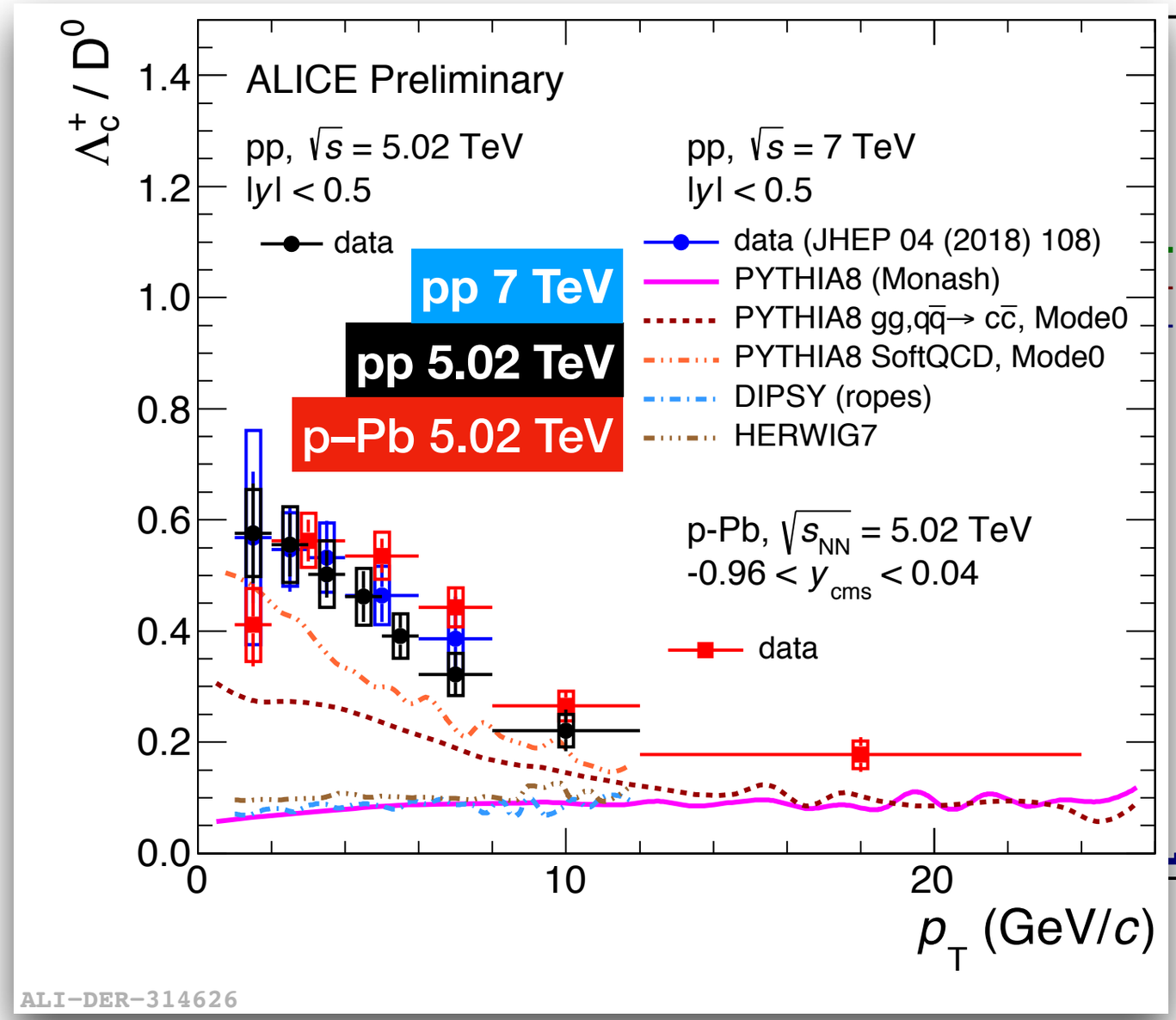
- $\Xi_c(\rightarrow e\Xi^-\nu_e)$ / D^0 ratio higher than theoretical predictions
  - ➡ PYTHIA8 with enhanced color reconnection mechanisms closer to data
  - ➡ $\mathrm{BR}(\Xi_c \rightarrow e\Xi^-\nu_e)$ unknown, high uncertainty bands in theoretical predictions

Λ_c / D^0 ratio in smaller systems



- Decreasing trend from p_T = 4 GeV/c observed in pp and p-Pb collisions
- Similar trend to baryon-to-meson ratio in the light-flavour sector

Λ_c / D^0 ratio in smaller systems



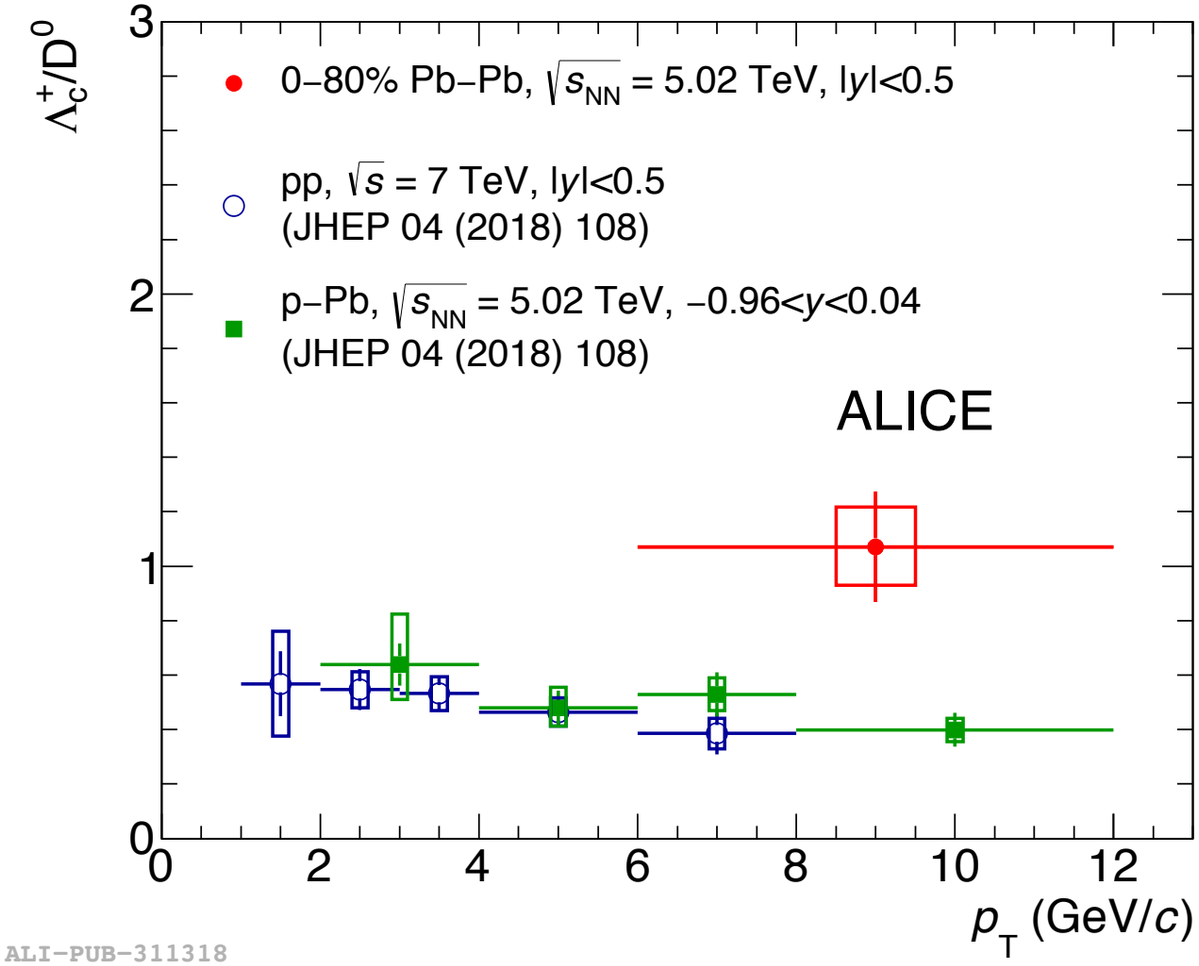
- p–Pb results agree with pp within uncertainties
- All models underestimate the data

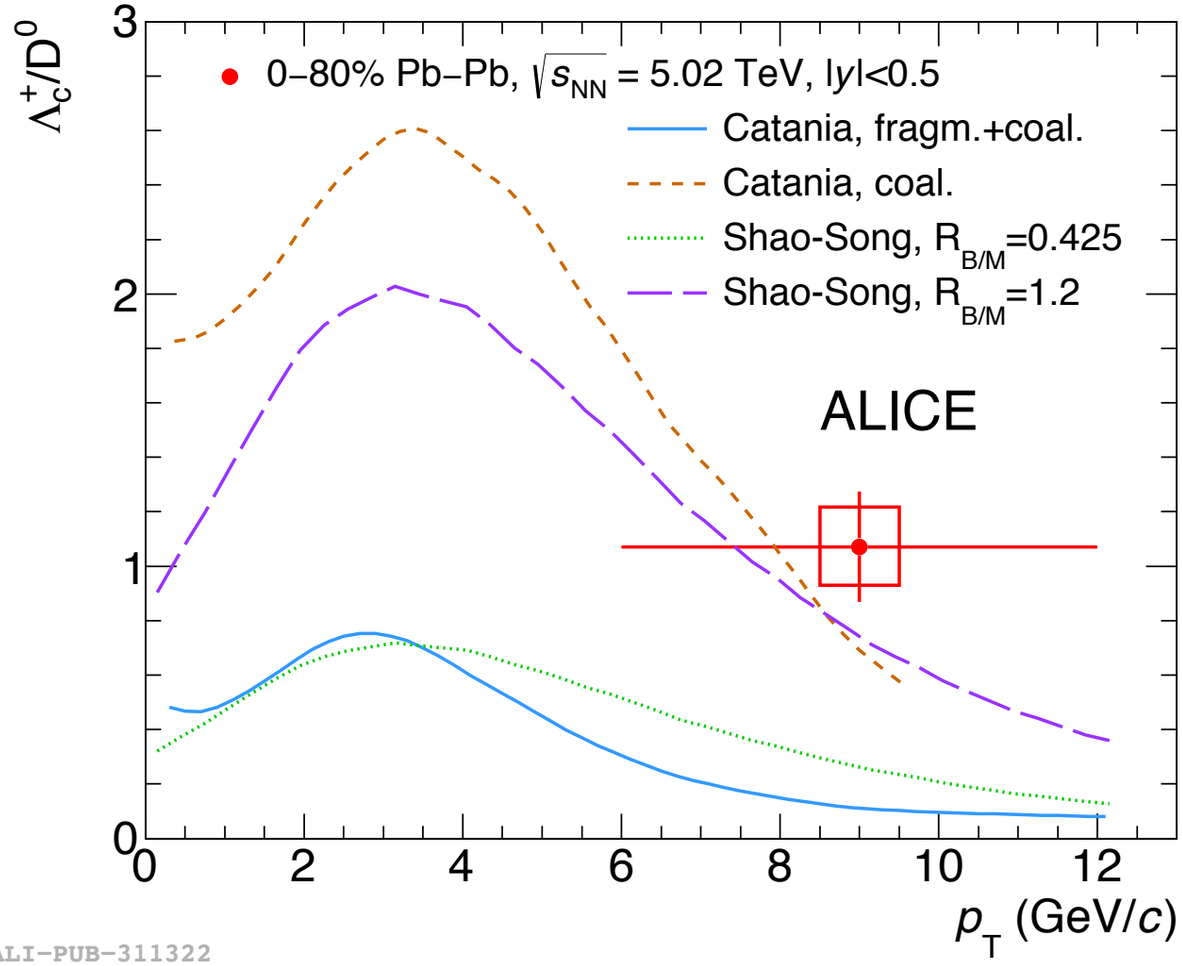
➡ PYTHIA8 with enhanced color reconnection mode closer to data

- Decreasing trend from p_T = 4 GeV/c observed in pp and p-Pb collisions
- Similar trend to baryon-to-meson ratio in the light-flavour sector

Λ_c production in Pb–Pb collisions

ALICE arXiv:1809.10922





- First measurement in Pb–Pb at the LHC
- Λ_c / D^0 ratio in Pb–Pb: higher than (>2σ) pp and p–Pb collisions

➡ Described by model calculations including only coalescence

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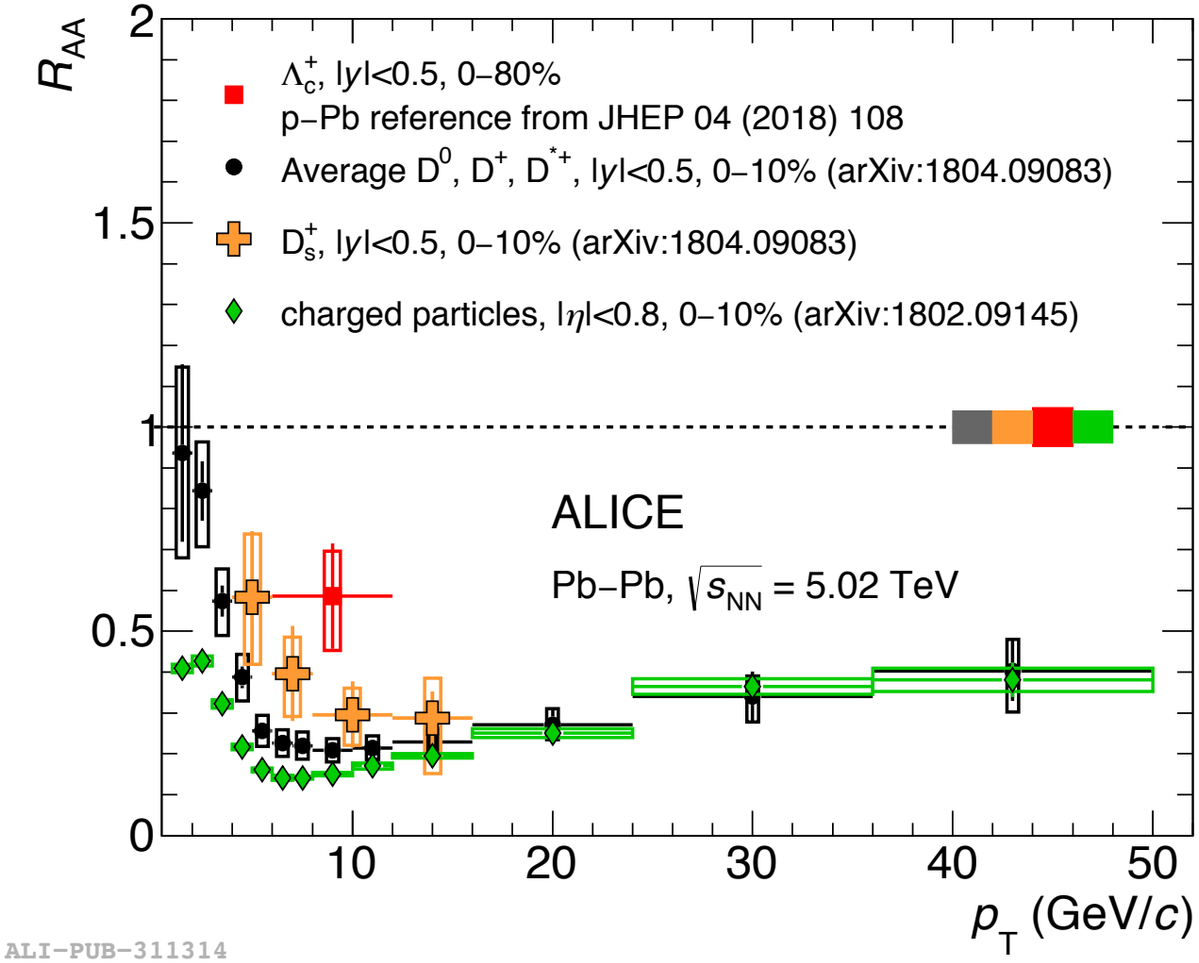
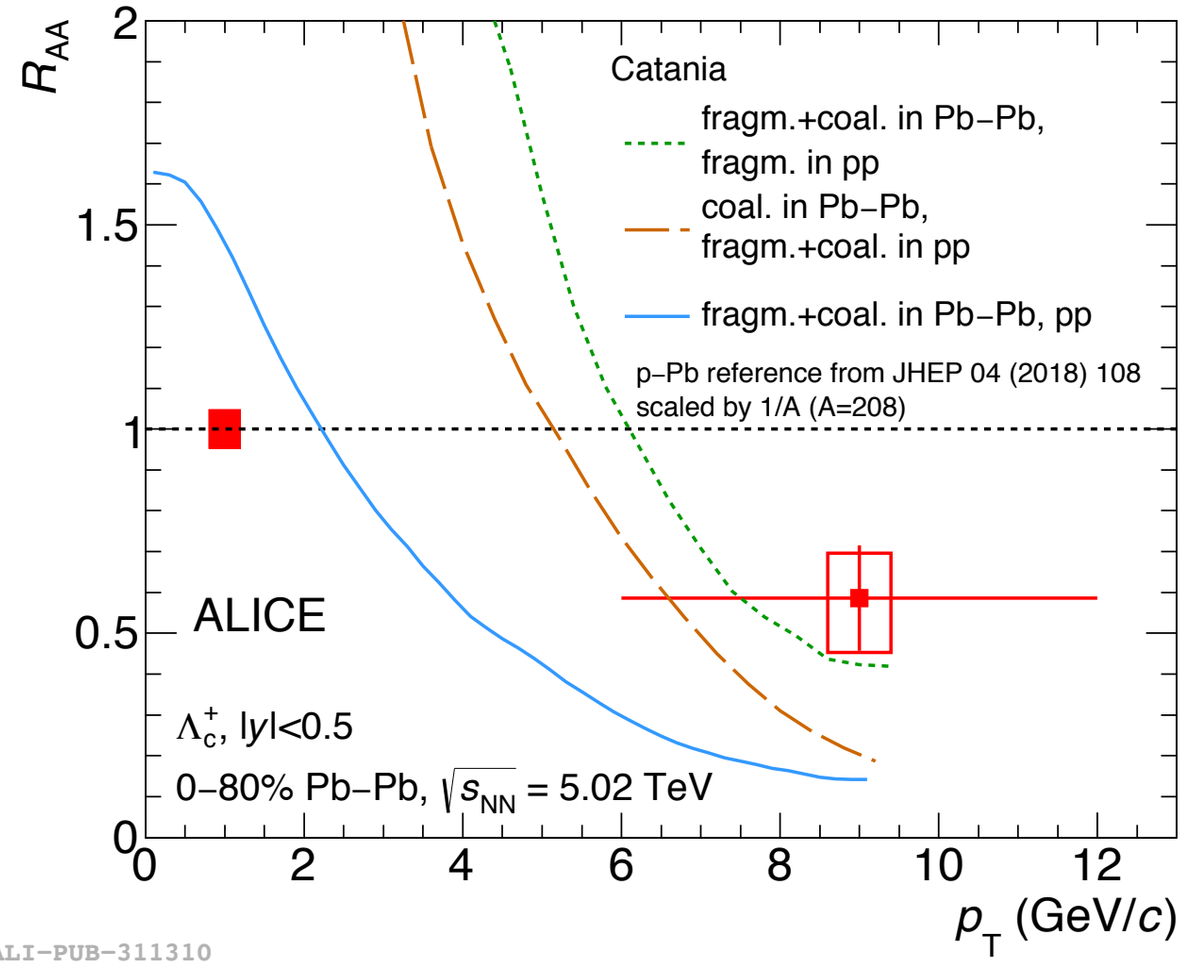
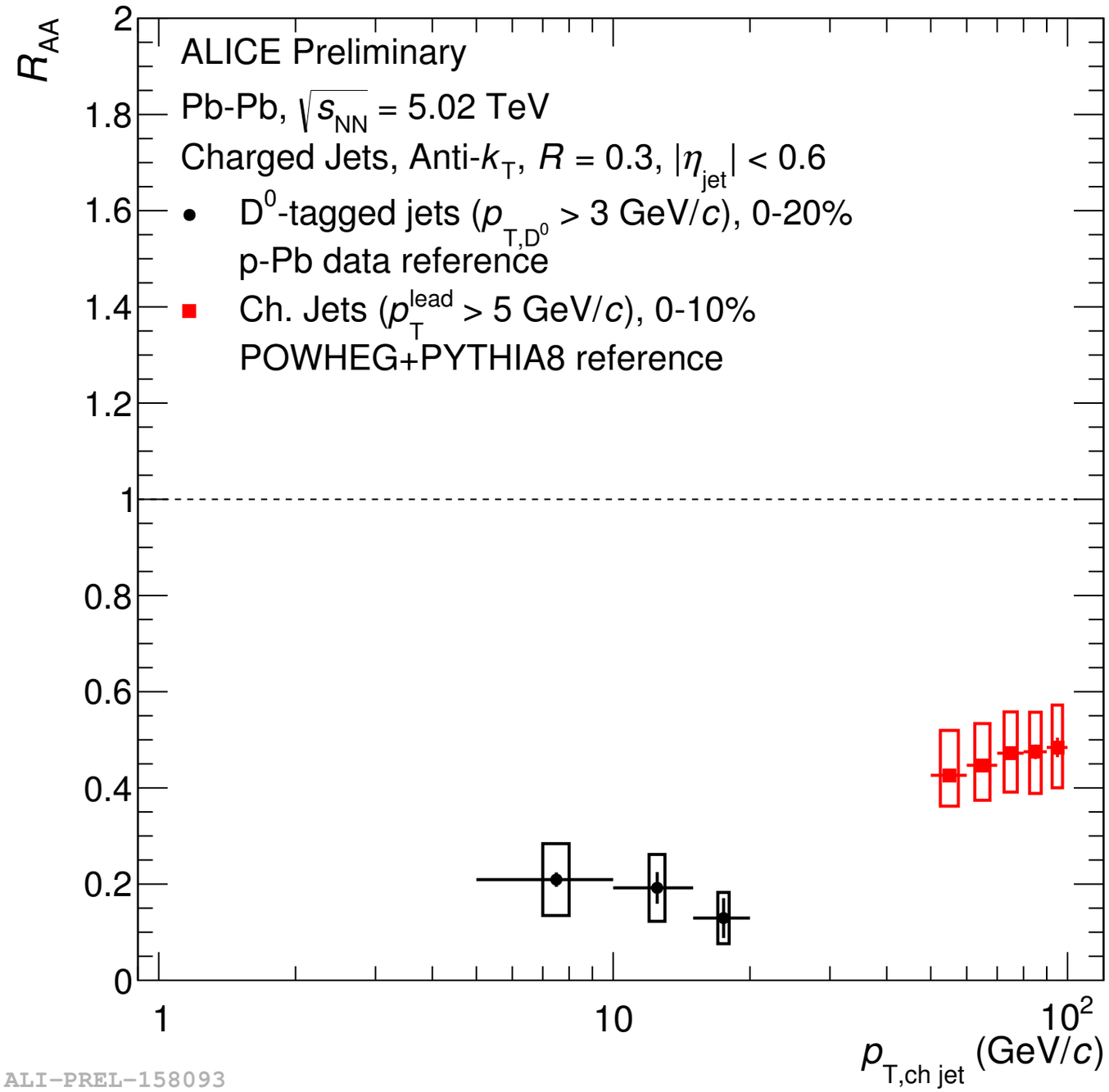




- First measurement in Pb–Pb at the LHC
- Hint of $R_{AA}(\Lambda_c) > R_{AA}(D_s) > R_{AA}$(non-strange D) > $R_{AA}(h^{\pm})$

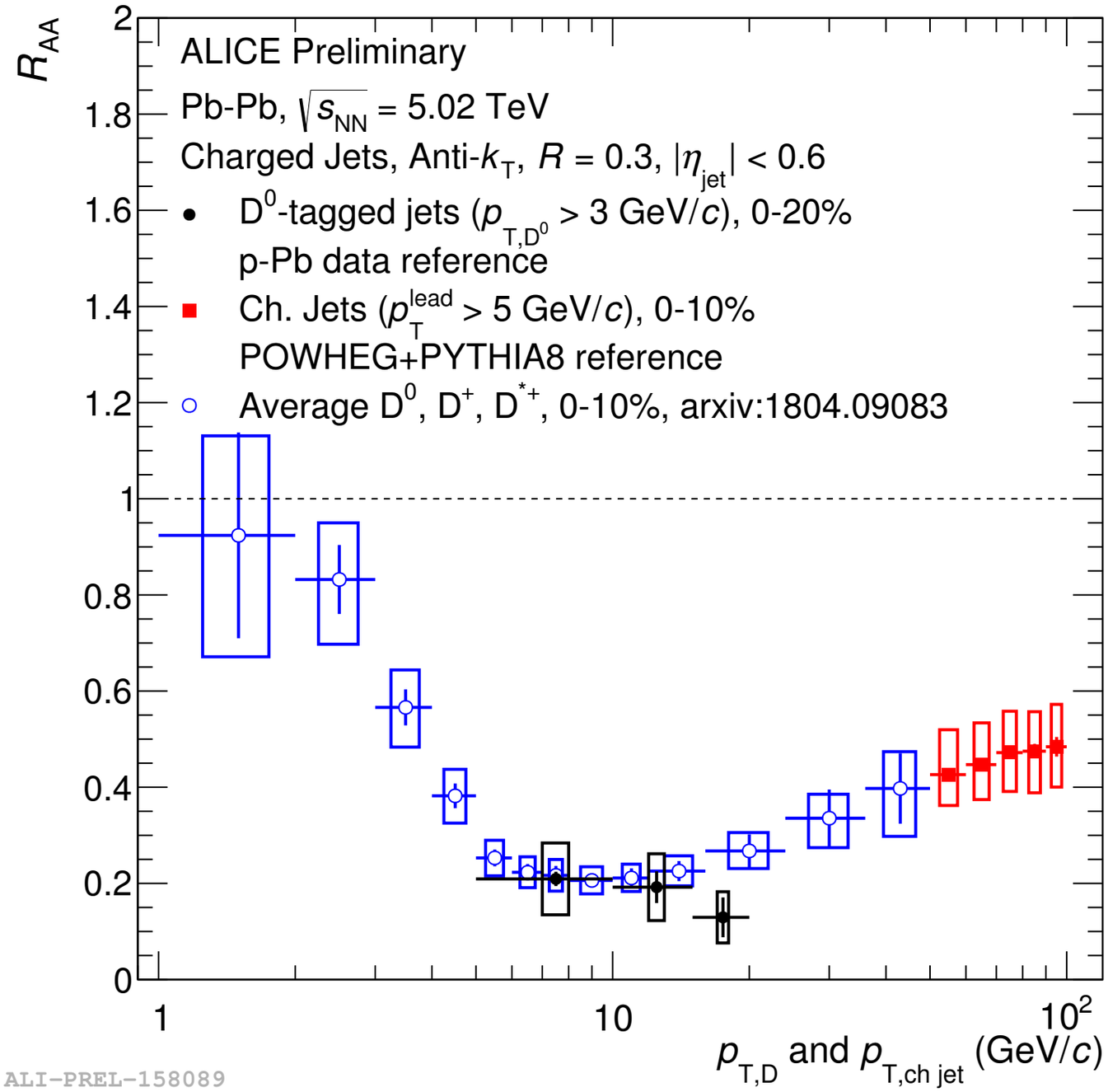
➡ A significant fraction of charm quarks hadronize via coalescence

D^0-tagged jets R_{AA} in Pb–Pb collisions



- Strong suppression of D^0-tagged jets in the most 10% central Pb–Pb collisions
- Hint of more suppression of low p_T D^0-tagged jets than inclusive jets at higher p_T
- D^0-tagged jets: more quark-seeded jets compared to inclusive jets

D^0-tagged jets R_{AA} in Pb–Pb collisions



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- D^0-tagged jets: more quark-seeded jets compared to inclusive jets
- Similar suppression of D^0-jets and D mesons

- New constraint on understanding charm quark in-medium energy loss

Conclusion

R_{AA} and v_2 of open heavy-flavour particles

- ALICE LHC RUN-II: improved data precision w. r. t. RUN-I
- Recombination and collisional energy loss: important for heavy quarks

Collectivity in smaller systems: positive v_2 in high multiplicity events

Charmed baryon production

- PYTHIA8 with enhanced color reconnection closer to data in smaller syst.
- Λ_c production in Pb–Pb: first measurement at the LHC

➡ Described by model calculations including only coalescence

➡ Suggests a significant fraction of charm hadronize via coalescence

Open heavy flavor tagged jets: similar suppression of D^0-jets and D mesons

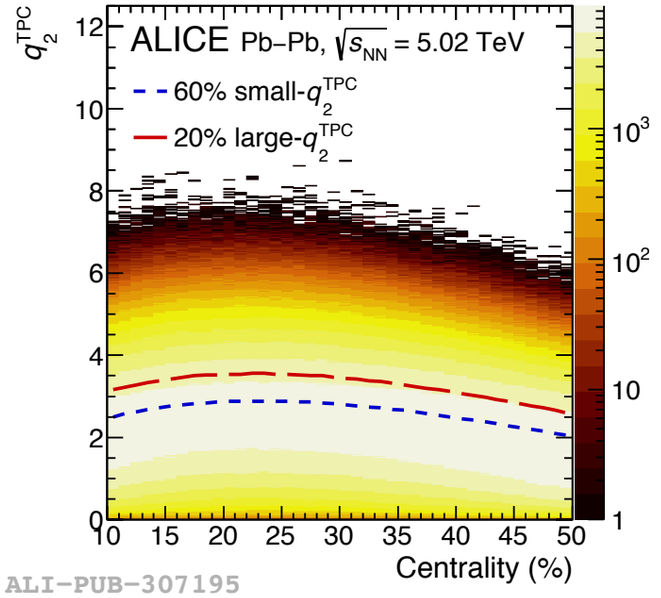
Thanks!

Backup

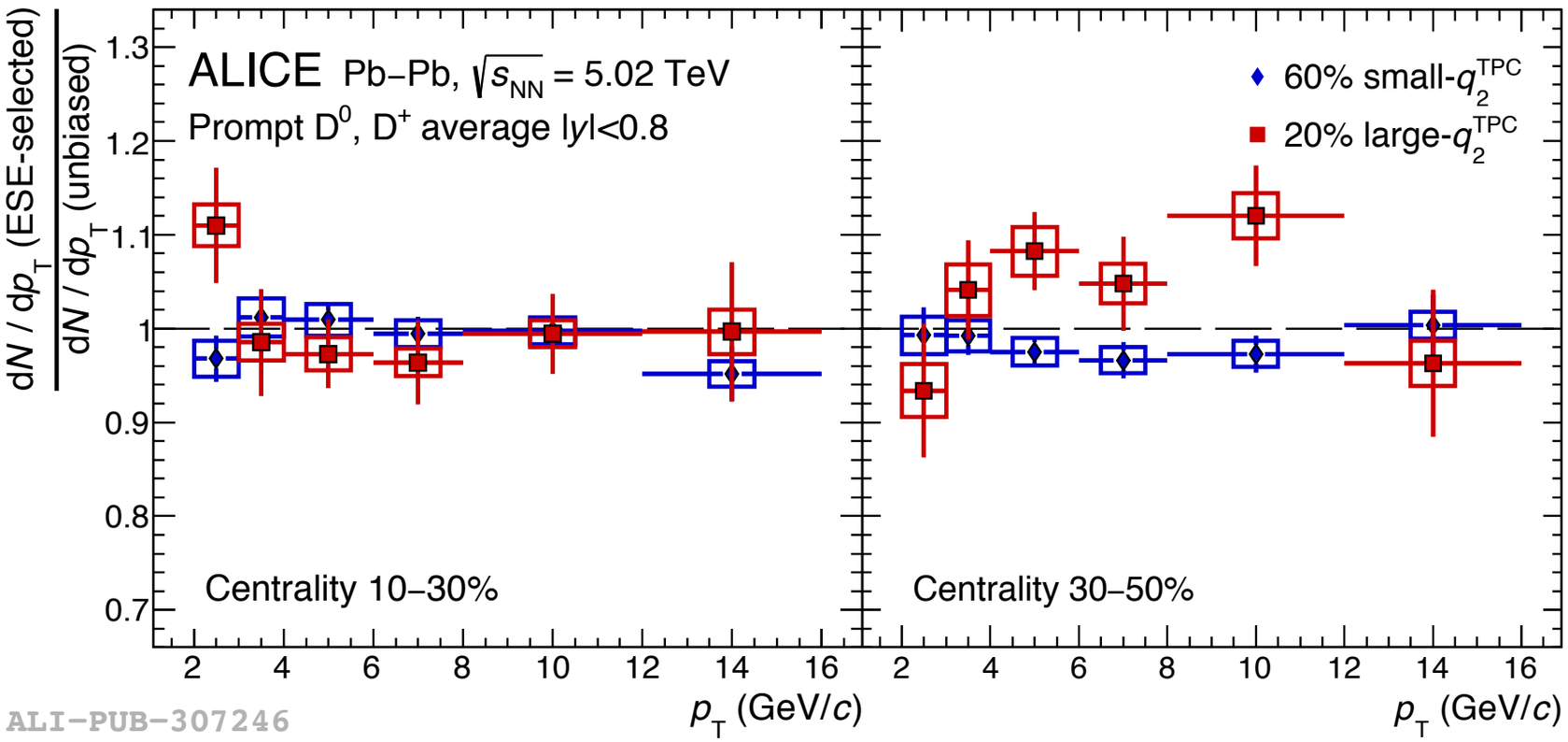
Event-shape engineering

- 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



ALICE arXiv:1809.09371

- dN/dp_T(ESE) / dN/dp_T(unbiased) compatible with unity within errors
- Promising observable to study interplay between elliptic flow and radial flow (at low/intermediate p_T) and and in-medium energy (at high p_T)