

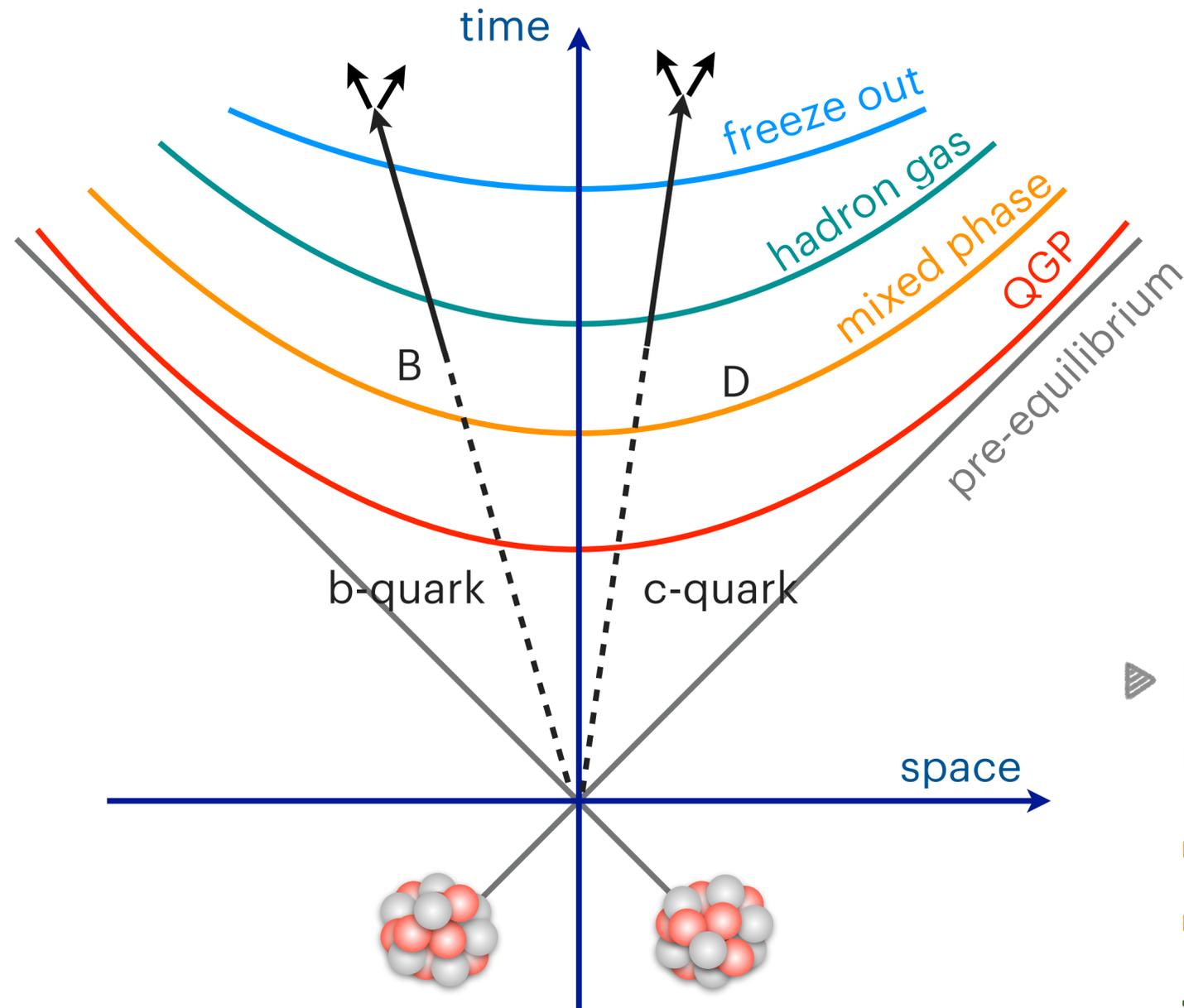
# Collectivity in small and large systems with heavy-flavour observables with ALICE



**Stefano Trogolo**  
University of Houston  
on behalf of the ALICE Collaboration



Initial Stages 2023 - Copenhagen, 21<sup>st</sup> June 2023



- ▶ In ultra relativistic heavy-ion collisions → **colour-deconfined medium**, called **quark-gluon plasma (QGP)**
  - ➔ predicted by lattice calculations
  - ➔ high energy density  $\epsilon > 15 \text{ GeV}/\text{fm}^3$
  - ➔ **hydrodynamic expansion** after a pre-equilibrium phase

 S. Borsanyi et al., PLB 370 (2014) 99

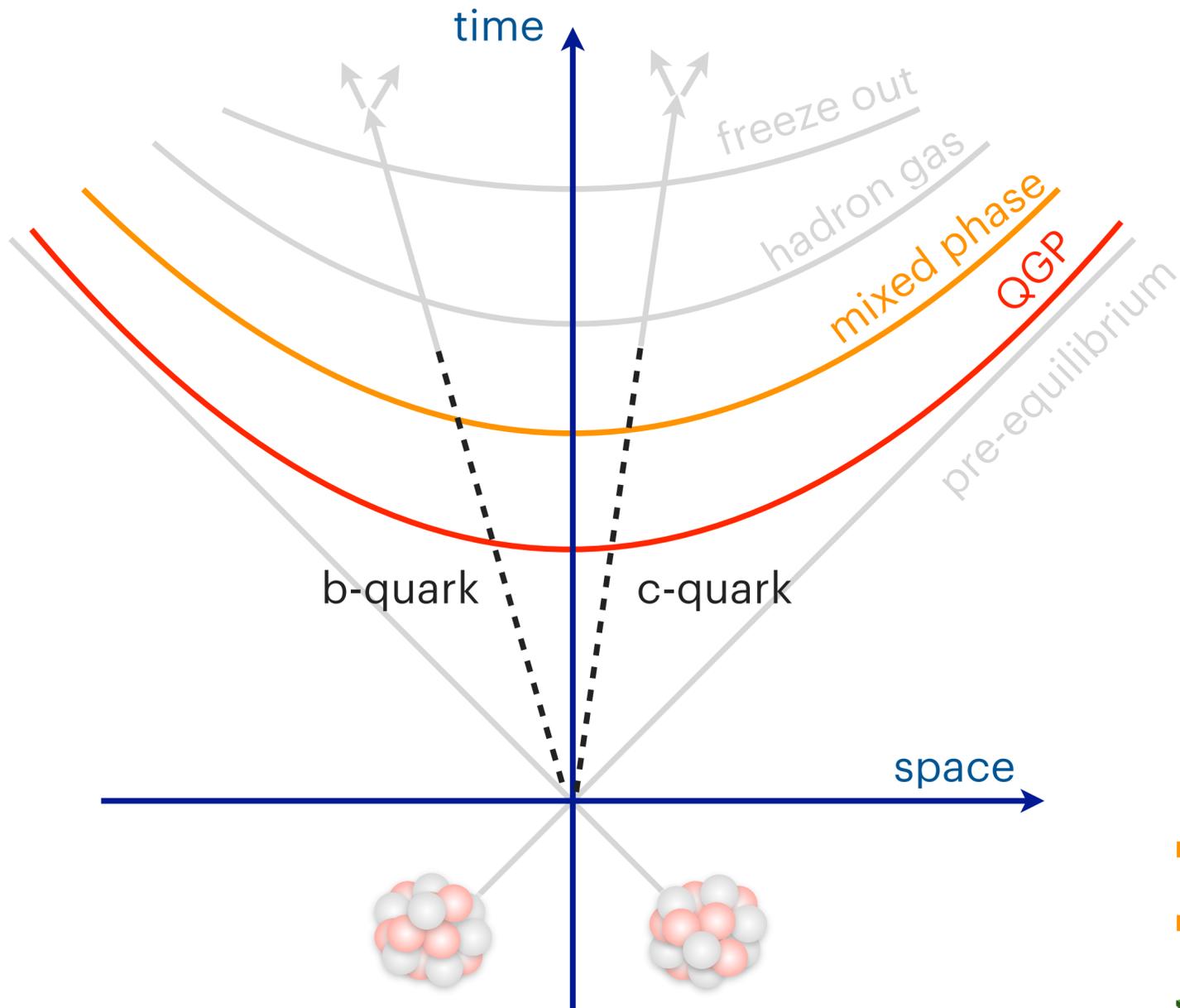
- ▶ Heavy flavours produced in **hard-scattering processes** in the early stages of the collision

➔  $\tau_{\text{HF}} \approx \hbar/m \approx 0.05\text{-}0.1 \text{ fm}/c$

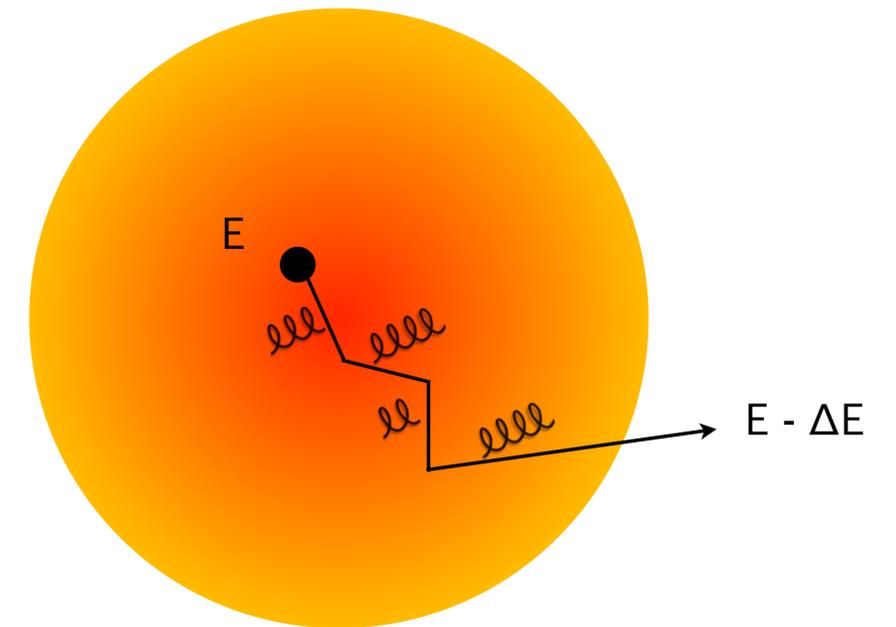
➔  $\tau_{\text{QGP form (LHC)}} \approx 0.3 \text{ fm}/c$

→ experience the **full system evolution**

 F.M. Liu et al., PRC 89, 034906 (2014)



- ▶ Heavy quarks **interact** with QGP constituents
- ▶ energy loss via **elastic collisions** and/or **radiative processes**
- ▶ low- $p_T$  heavy-quarks **thermalisation** in the medium?



▶  $\tau_{HF} \approx \hbar/m \approx 0.05-0.1 \text{ fm}/c$

▶  $\tau_{QGP \text{ form}} (\text{LHC}) \approx 0.3 \text{ fm}/c$

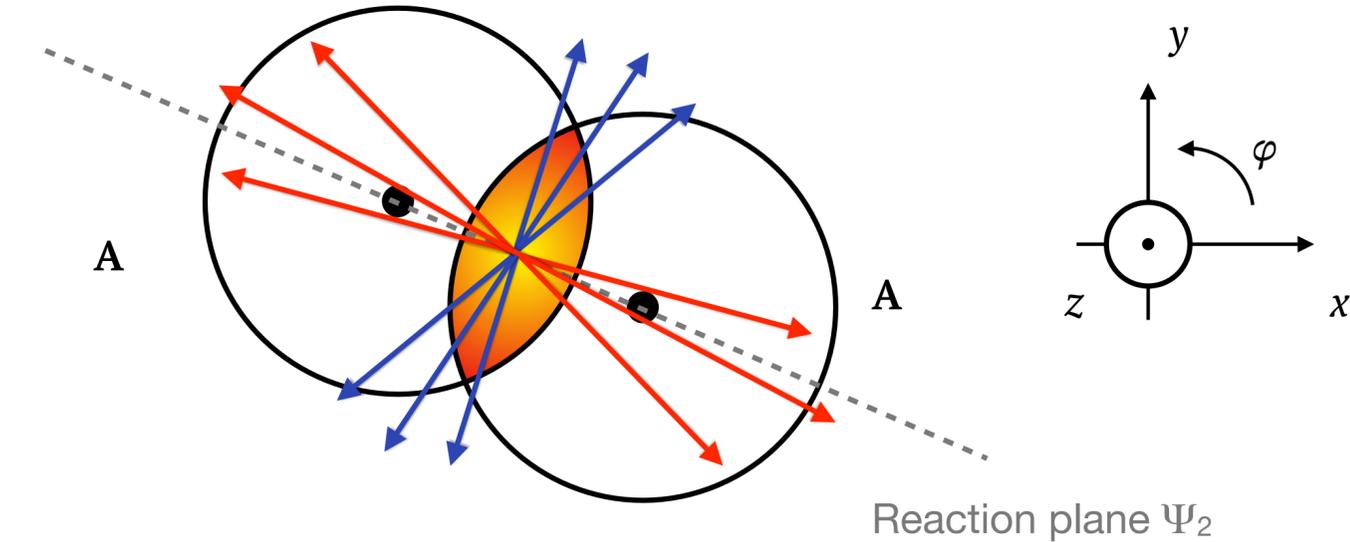
📖 F.M. Liu et al., PRC 89, 034906 (2014)

▶  $\tau_{QGP \text{ lifetime}} \approx 10 \text{ fm}/c$

📖 ALICE, PLB 696 (2011) 328-337

- ▶ The interaction region has an **initial geometrical anisotropy**
- ▶ The initial geometrical anisotropy is transformed into a **momentum anisotropy by the pressure gradients**

$$E \frac{d^3N}{dp_T} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right\}$$



$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

second harmonic coefficient  
**elliptic flow**

 S. Voloshin et al., Z.Phys.C 70 (1996) 665-672

 J.-Y.Ollitrault, NPA 590 (1995) 561c-564c

 A. M. Poskanzer et al., PRC 58 (1998) 1671-1678

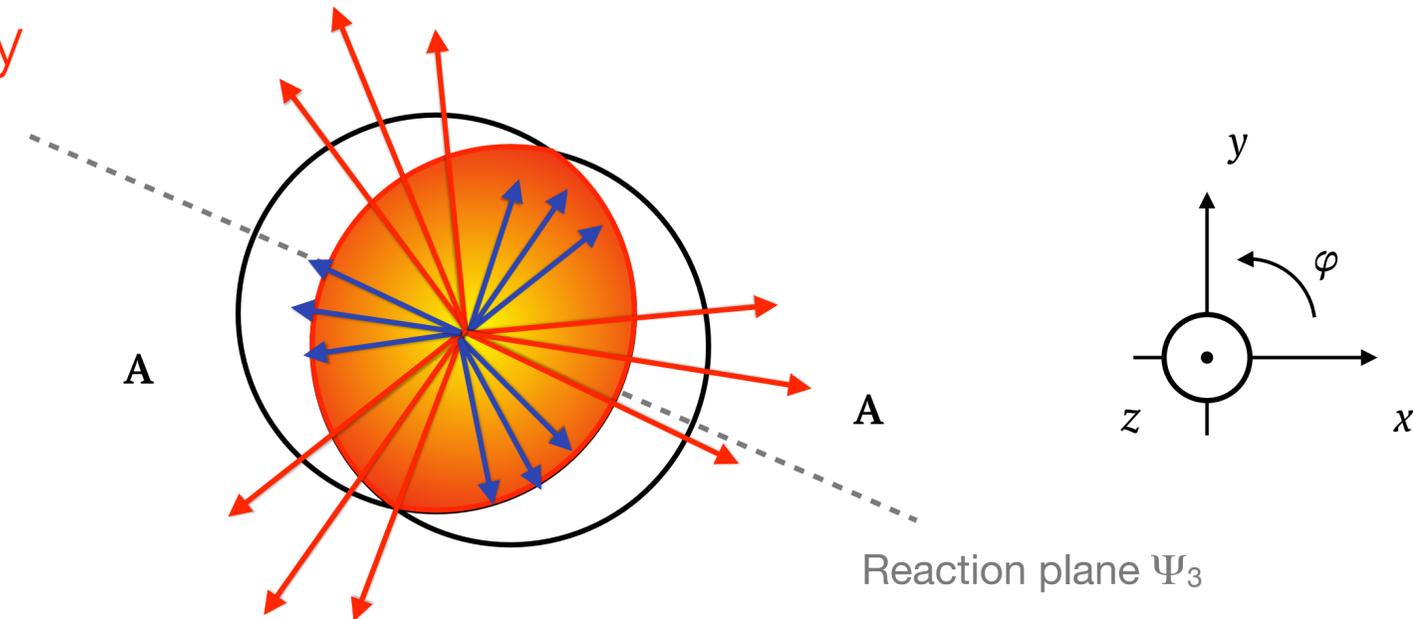
- ▶ Elliptic flow ( $v_2$ ): **asymmetry** between the **in-plane** and **out-of-plane** directions
  - ➔ low  $p_T$ : participation in **collective motion** and **thermalization** of heavy quarks
  - ➔ high  $p_T$ : **path-length** dependence of energy loss

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$$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$$

third harmonic coefficient  
**triangular flow**

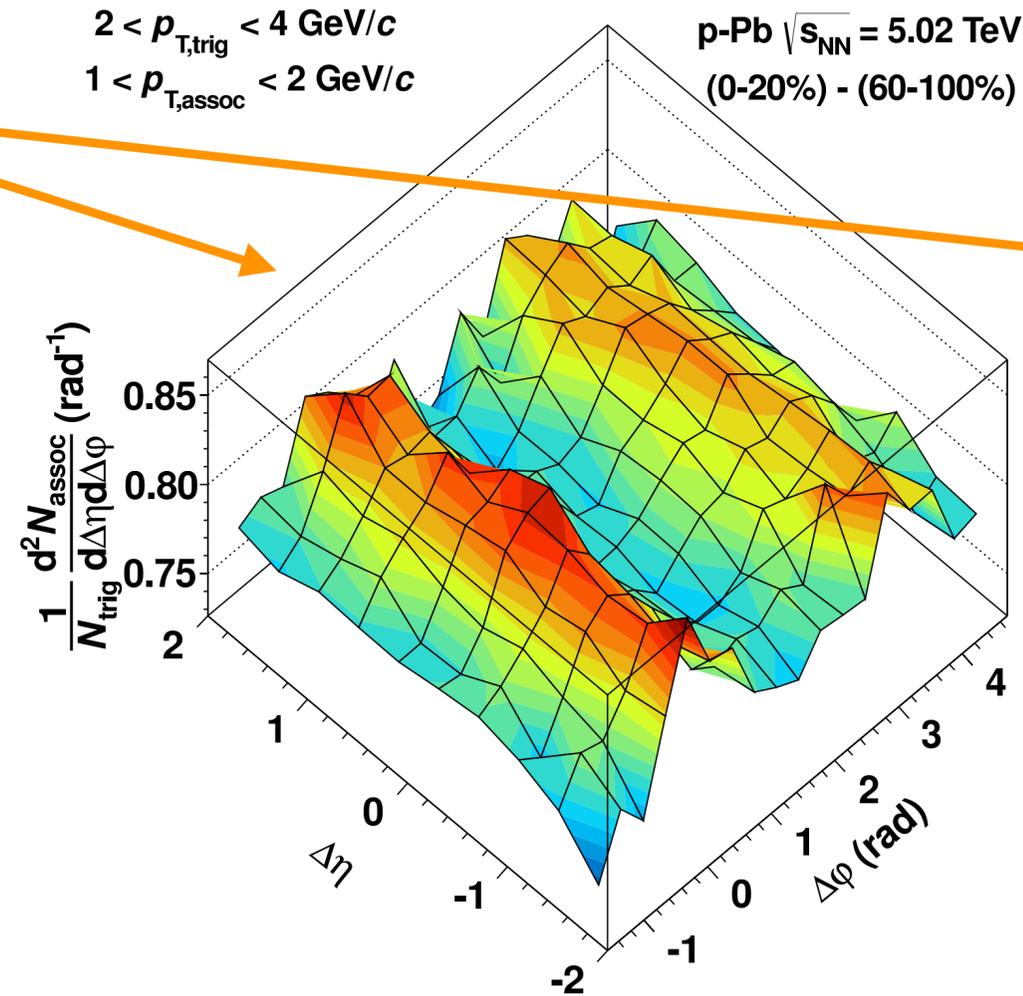


 S. Voloshin et al., Z.Phys.C 70 (1996) 665-672  
 J.-Y.Ollitrault, NPA 590 (1995) 561c-564c  
 A. M. Poskanzer et al., PRC 58 (1998) 1671-1678

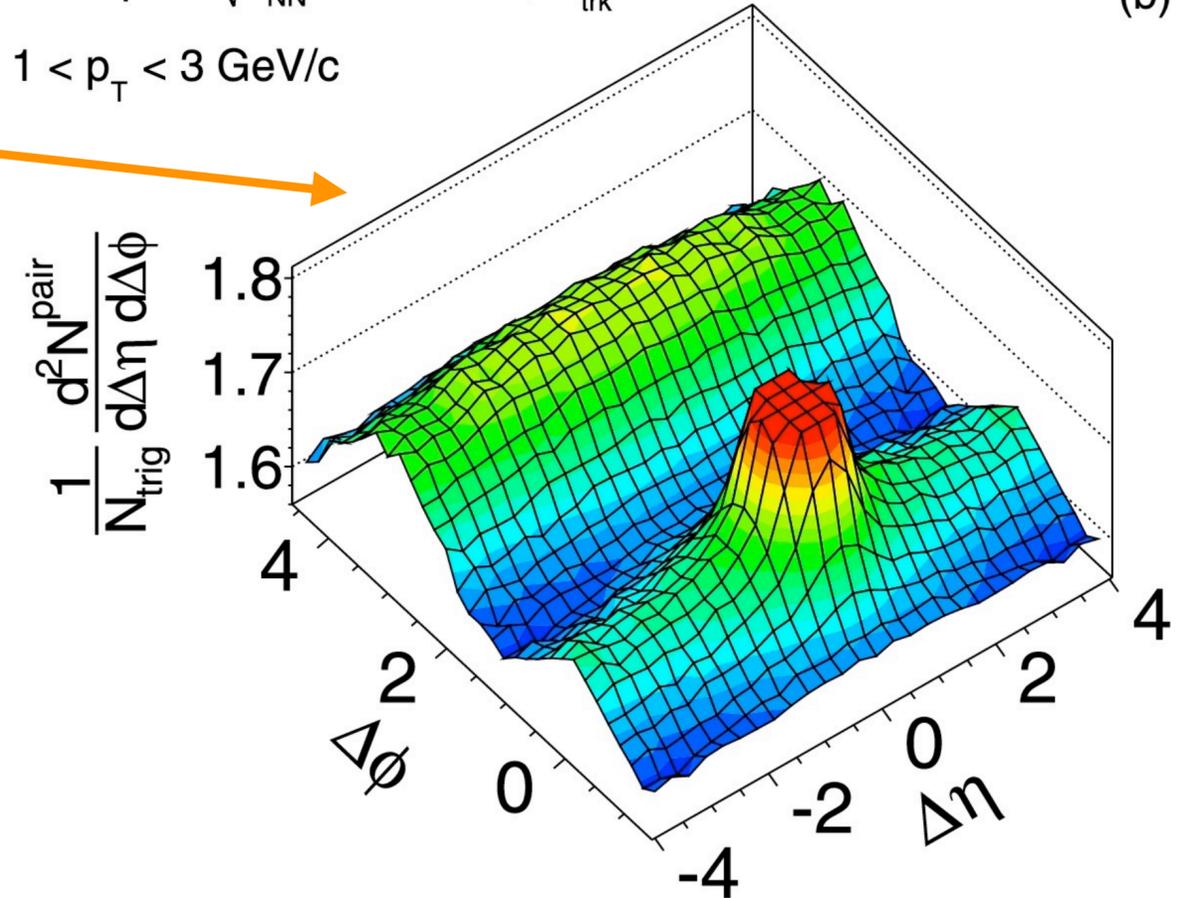
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  - ➔ high  $p_T$ : **path-length** dependence of energy loss
- ▶ Triangular flow ( $v_3$ ): event-by-event **fluctuations** in the **initial distributions** of nucleons and gluons in the overlap region
  - ➔ sensitive to the ratio of the shear viscosity to the entropy density,  $\eta/s$

► In heavy-ion collisions, **long-range correlations** → result of hydrodynamic expansion of the QGP

Observation of **long-range correlations** in **high-multiplicity** events of **small collision systems** (i.e. pp, p-Pb) more than ten years ago



CMS pPb  $\sqrt{s_{NN}} = 5.02$  TeV,  $N_{trk}^{offline} \geq 110$   
 $1 < p_T < 3$  GeV/c



ALICE, PLB 719 (2013) 29

CMS, PLB 718 (2013) 795

► Positive **elliptic flow** measured in **p-A** and **pp** collisions by several experiments so far

➔ origin is still largely debated

➔ measurements of **elliptic flow** in small system → shed light on azimuthal anisotropies in small systems

## Time Projection Chamber

- ▶ Track reconstruction
- ▶ Particle identification via specific energy loss

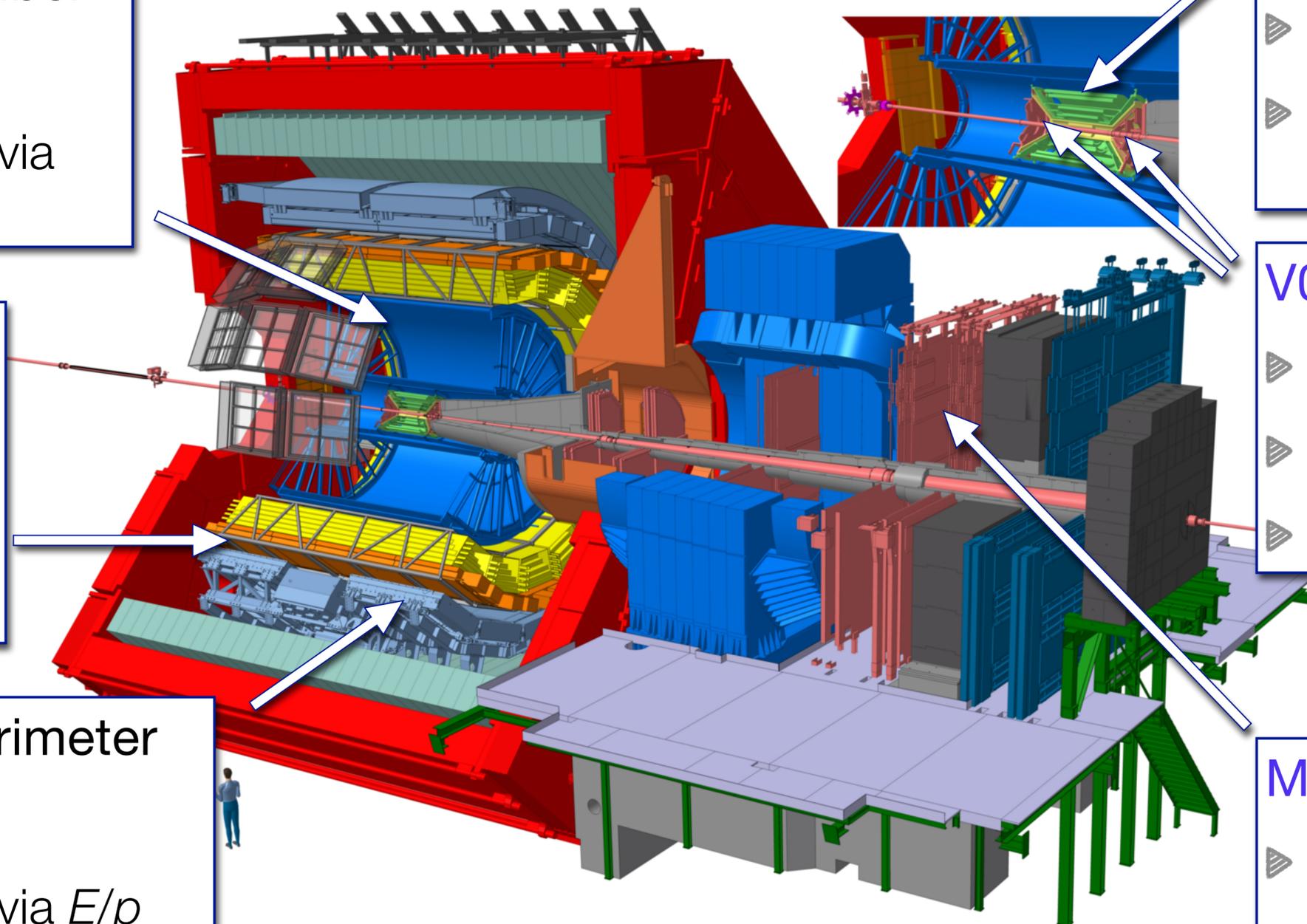
## Time-Of-Flight detector

- ▶ Particle identification via the time-of-flight measurement

## ElectroMagnetic Calorimeter

- ▶ Trigger
- ▶ Particle identification via  $E/p$  measurement

Central barrel coverage  $|\eta| < 0.9$



## Inner Tracking System

- ▶ Track reconstruction
- ▶ Primary and decay vertex reconstruction

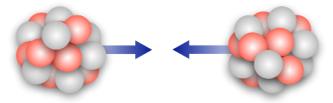
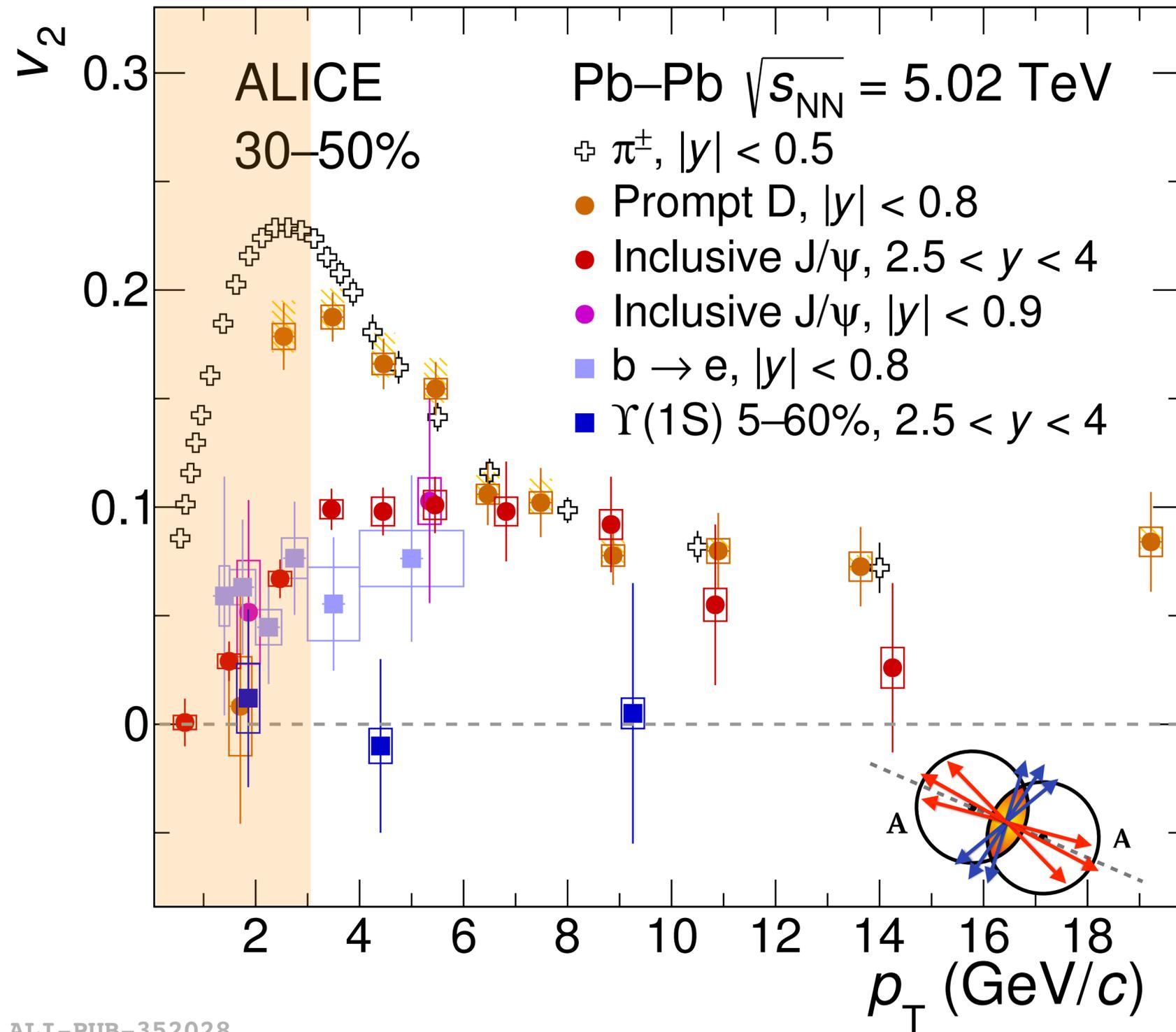
## V0 detector

- ▶ Trigger
- ▶ Centrality determination
- ▶ Event plane estimation

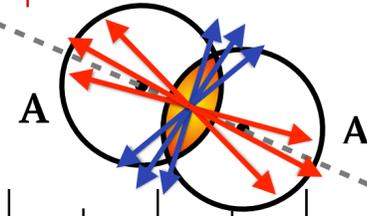
## Muon spectrometer

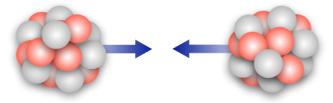
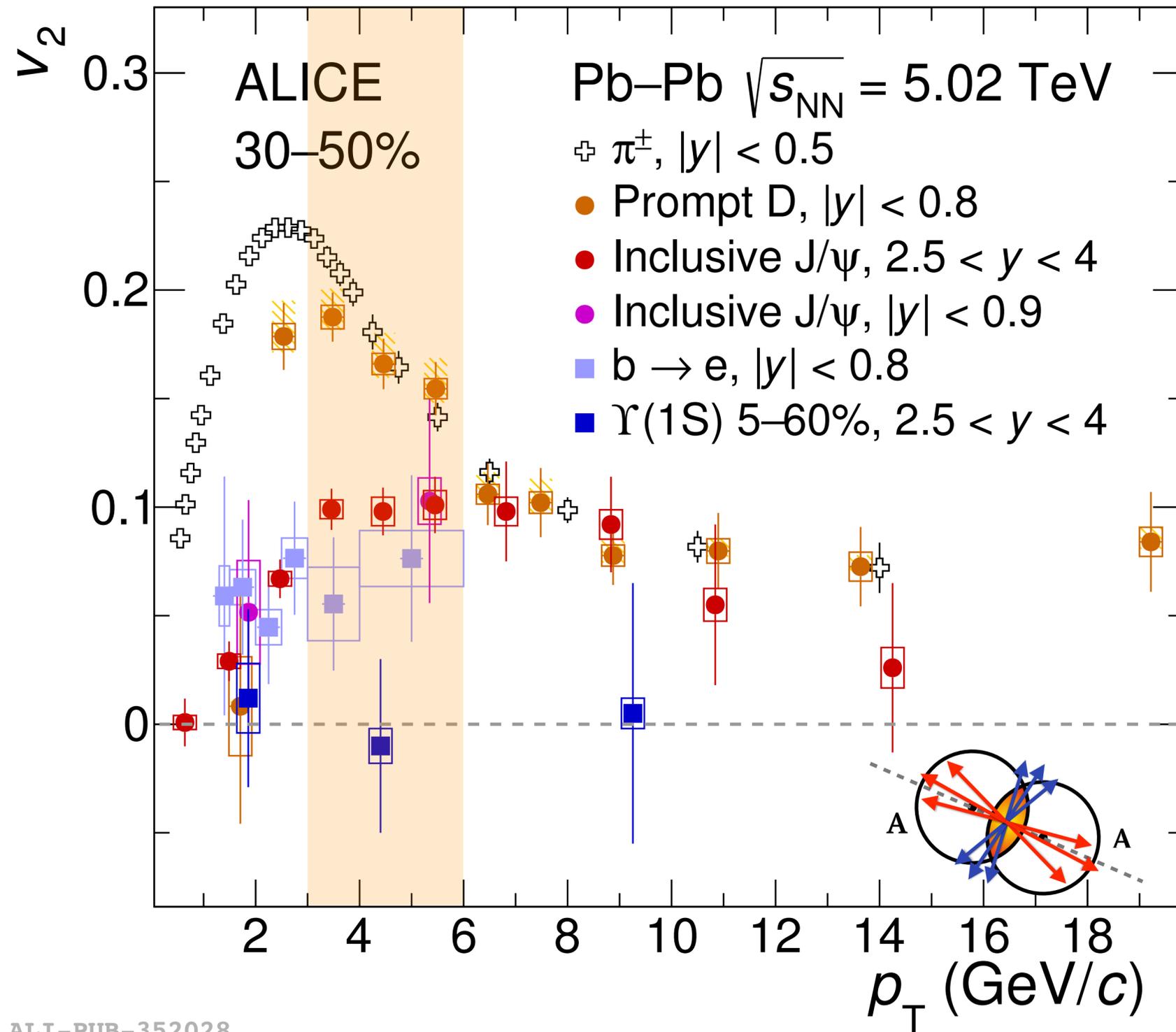
- ▶ Muon trigger and reconstruction

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

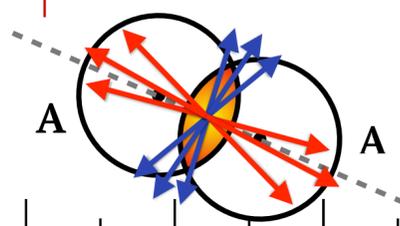


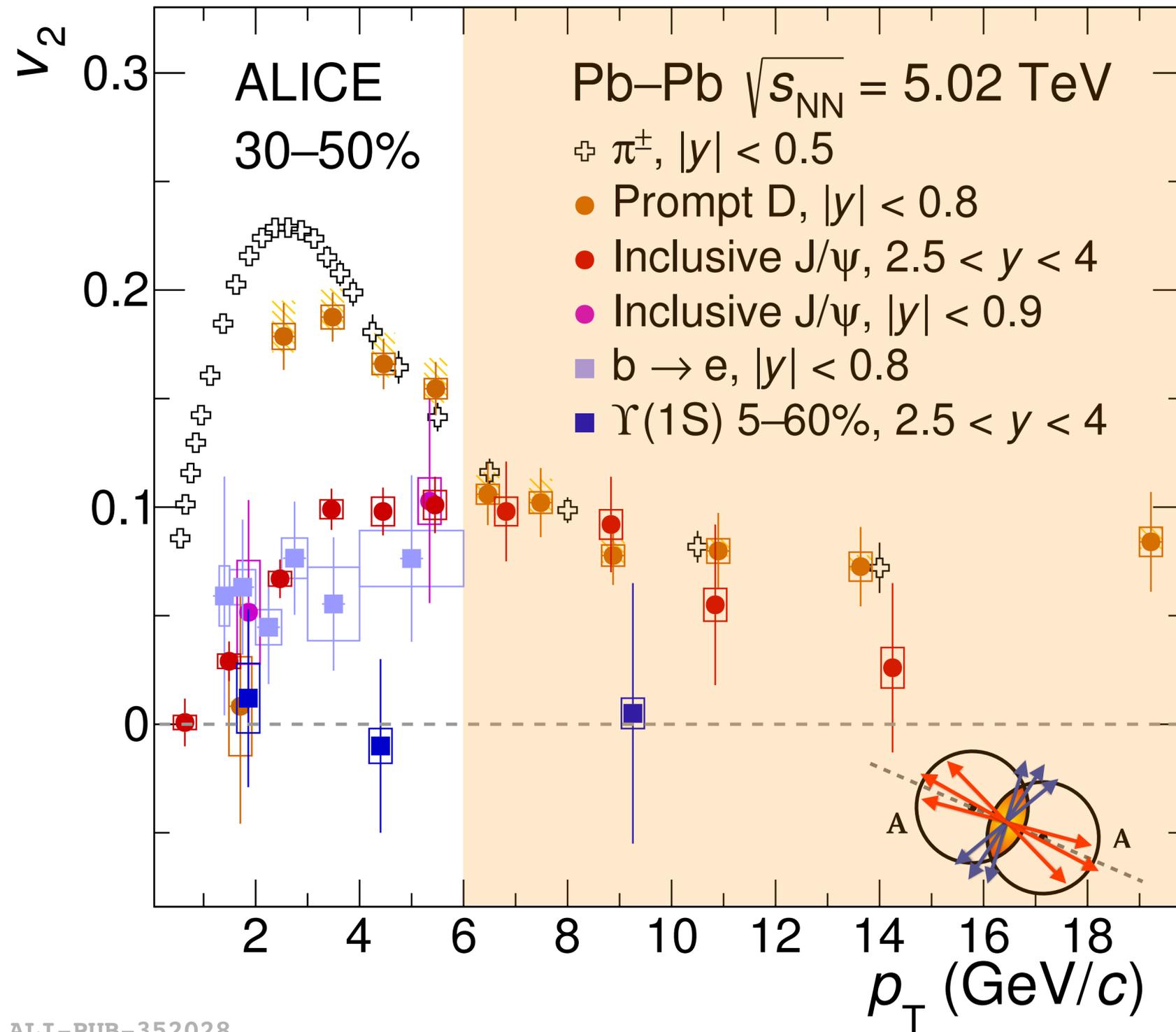
- ▶ Positive  $v_2$  for open/hidden charm and  $e \leftarrow b$
- ▶  $p_T < 3$  GeV/c: **thermalisation** of heavy quarks
- ▶  $v_2(\Upsilon) \approx v_2(e \leftarrow b) \approx v_2(J/\psi) < v_2(D) < v_2(\pi)$



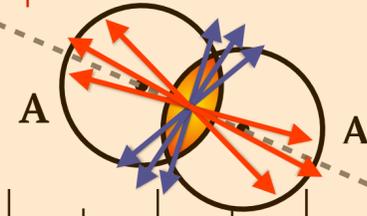
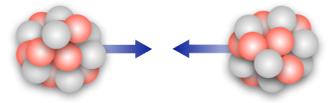


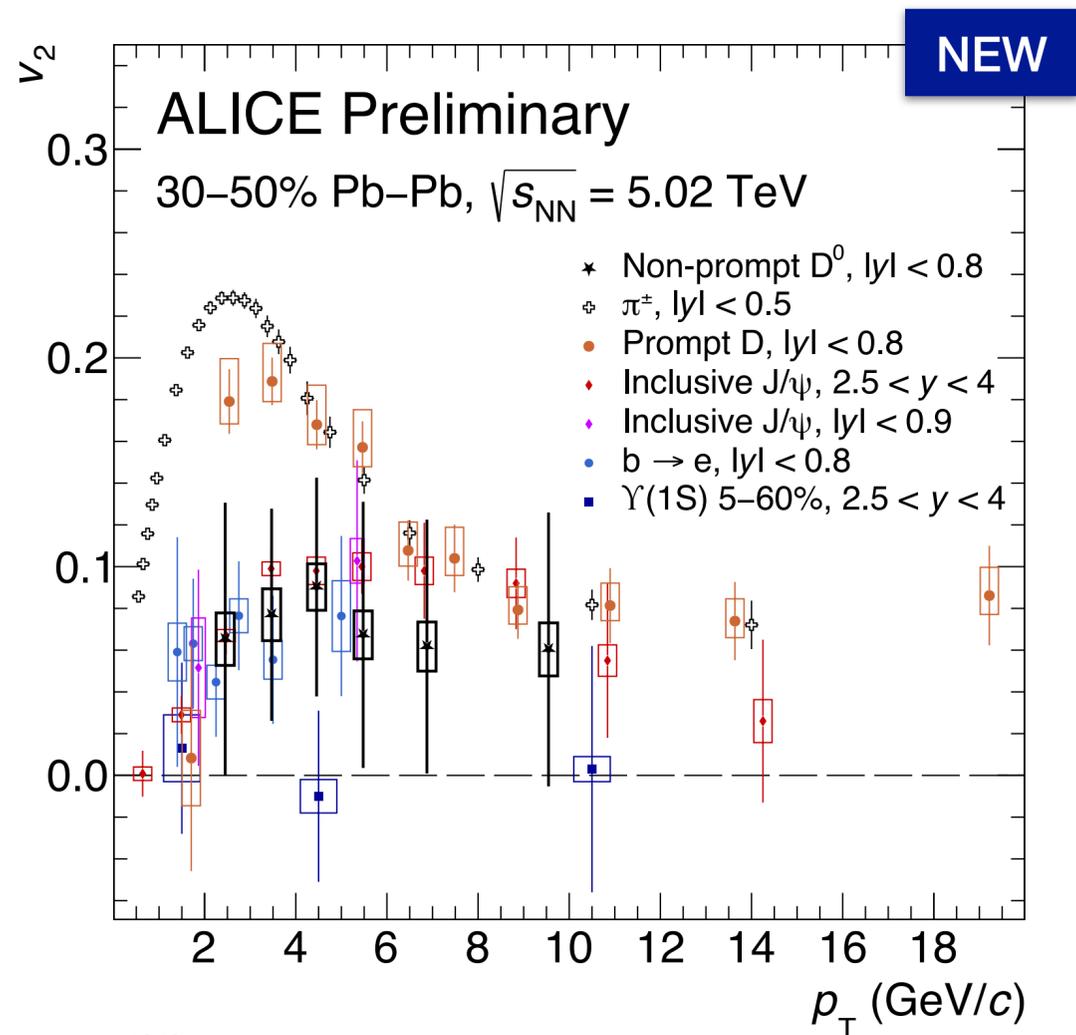
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- ▶  $3 < p_T < 6$  GeV/c: contribution from hadronisation via **coalescence with flowing light quarks**
  - ➔  $v_2(J/\psi) < v_2(D) \approx v_2(\pi)$
  - ➔  $v_2(\Upsilon) < v_2(e \leftarrow b)$



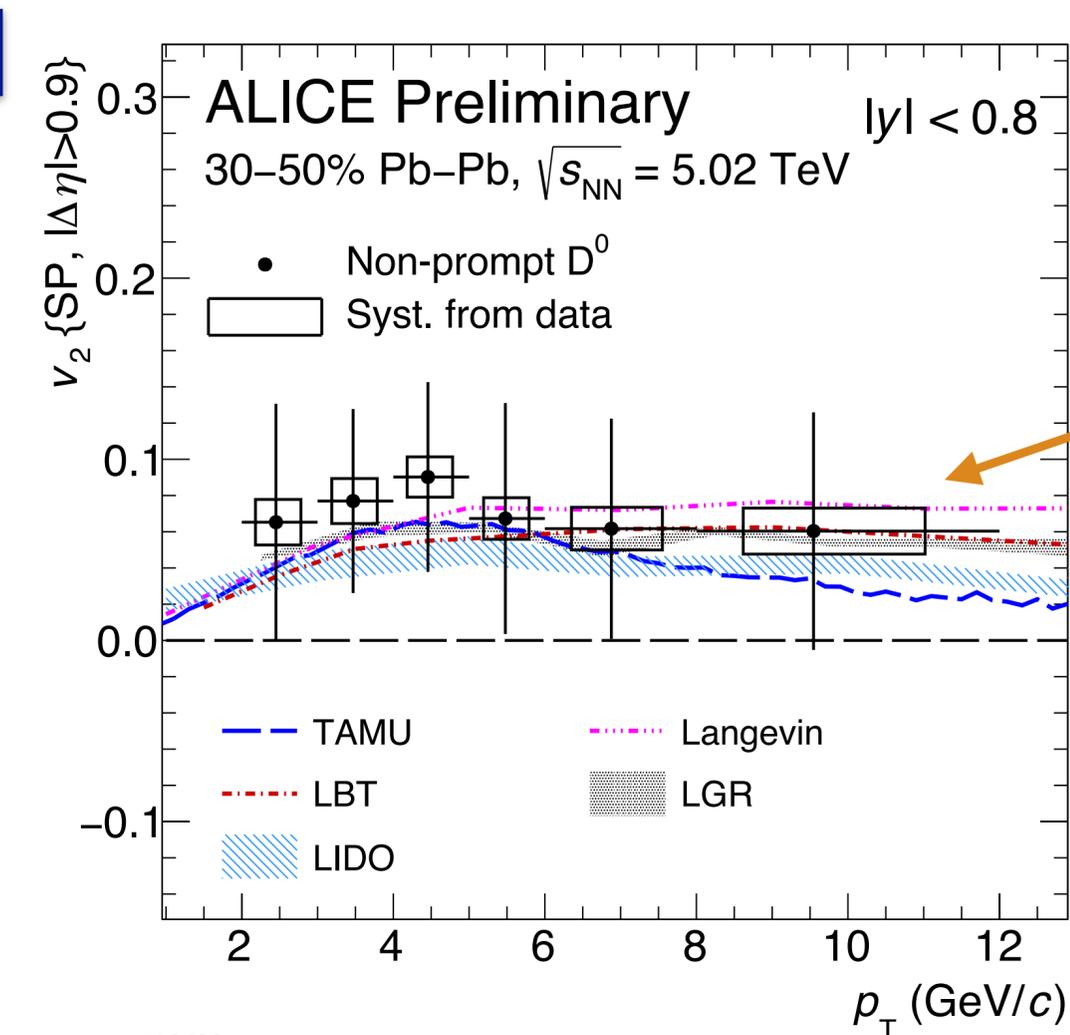


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  - ▶  $v_2(\Upsilon) < v_2(e \leftarrow b)$
- ▶  $p_T > 6$  GeV/c: **path-length** dependence of **in-medium energy loss**
  - ▶  $v_2(\mathbf{J}/\psi) \approx v_2(\mathbf{D}) \approx v_2(\pi)$
- ▶ Bottomonium  $v_2$  compatible with zero

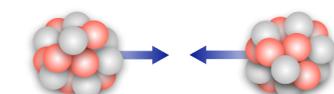




ALI-PREL-502687



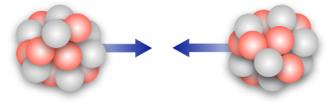
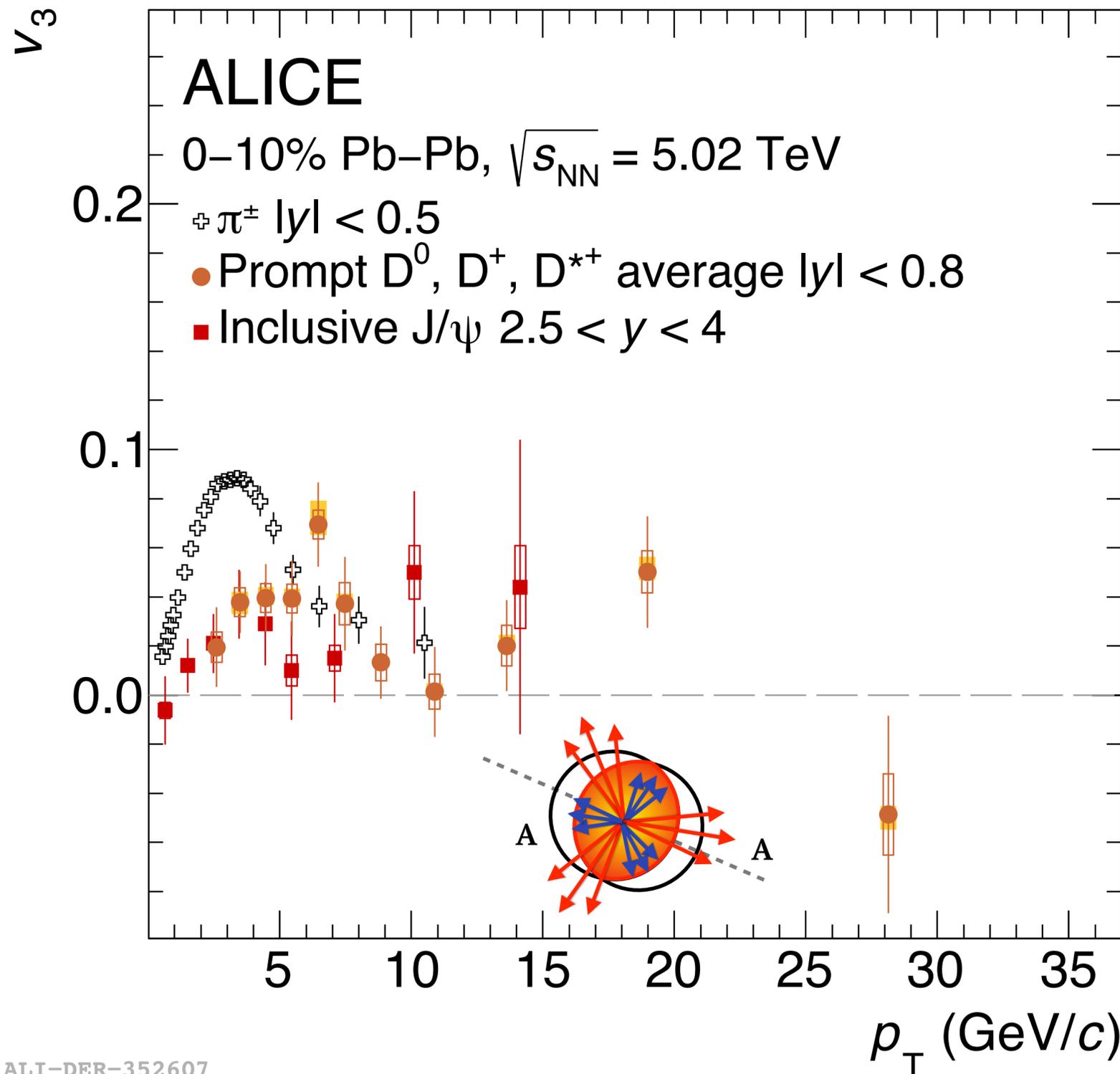
ALI-PREL-502682



Non-prompt  $D^0$   $v_2$  measured using **Machine Learning** technique  
 → multi-classification BDT algorithm to separate prompt and non-prompt

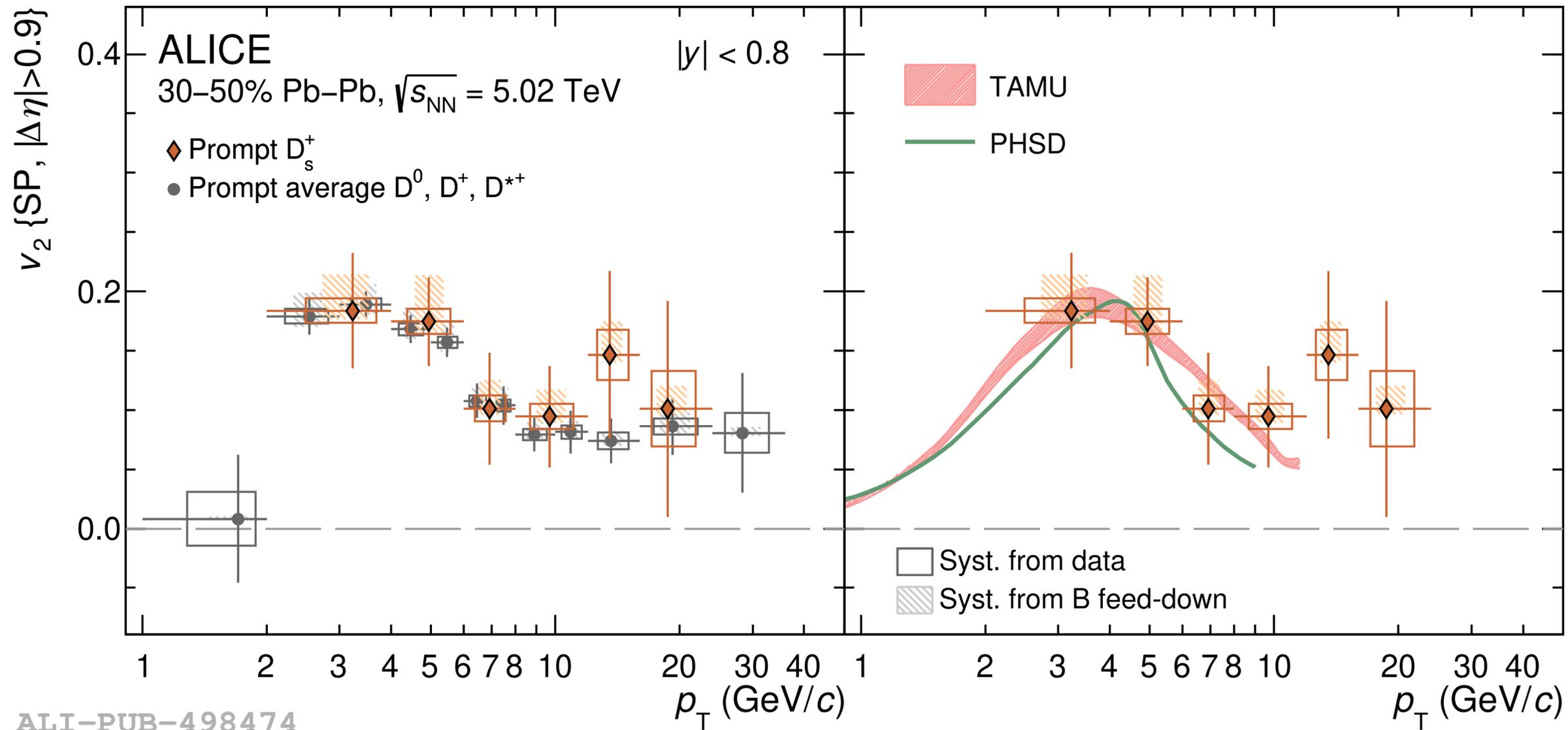
TAMU: PRL 124, 042301 (2020)  
 PHSD: PRC 92, 014910 (2015)

- ▶ Positive non-prompt  $D^0$   $v_2$  observed in  $2 < p_T < 12$  GeV/c in semicentral collisions
  - ➔ lower than prompt  $D^0$  and compatible with  $e \leftarrow b$  elliptic flow results
- ▶ Results described by predictions from models including hadronization via **coalescence** in addition to **fragmentation**

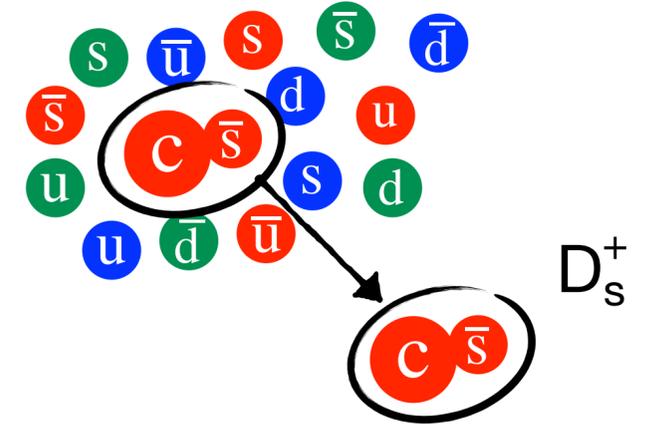


- ▶ Positive  $v_3$  for open/hidden charm
- ▶  $p_T < 4$  GeV/c: **thermalisation** of heavy quarks
  - ➔ mass ordering observed
  - ➔  $v_3(J/\psi) \approx v_3(D) \rightarrow$  **interplay** of anisotropic and radial flow
- ▶  $4 < p_T < 8$  GeV/c: heavy-quark hadronisation via **coalescence with flowing light quarks**
- ▶  $p_T > 8$  GeV/c: **path-length** dependence of **in-medium energy loss**



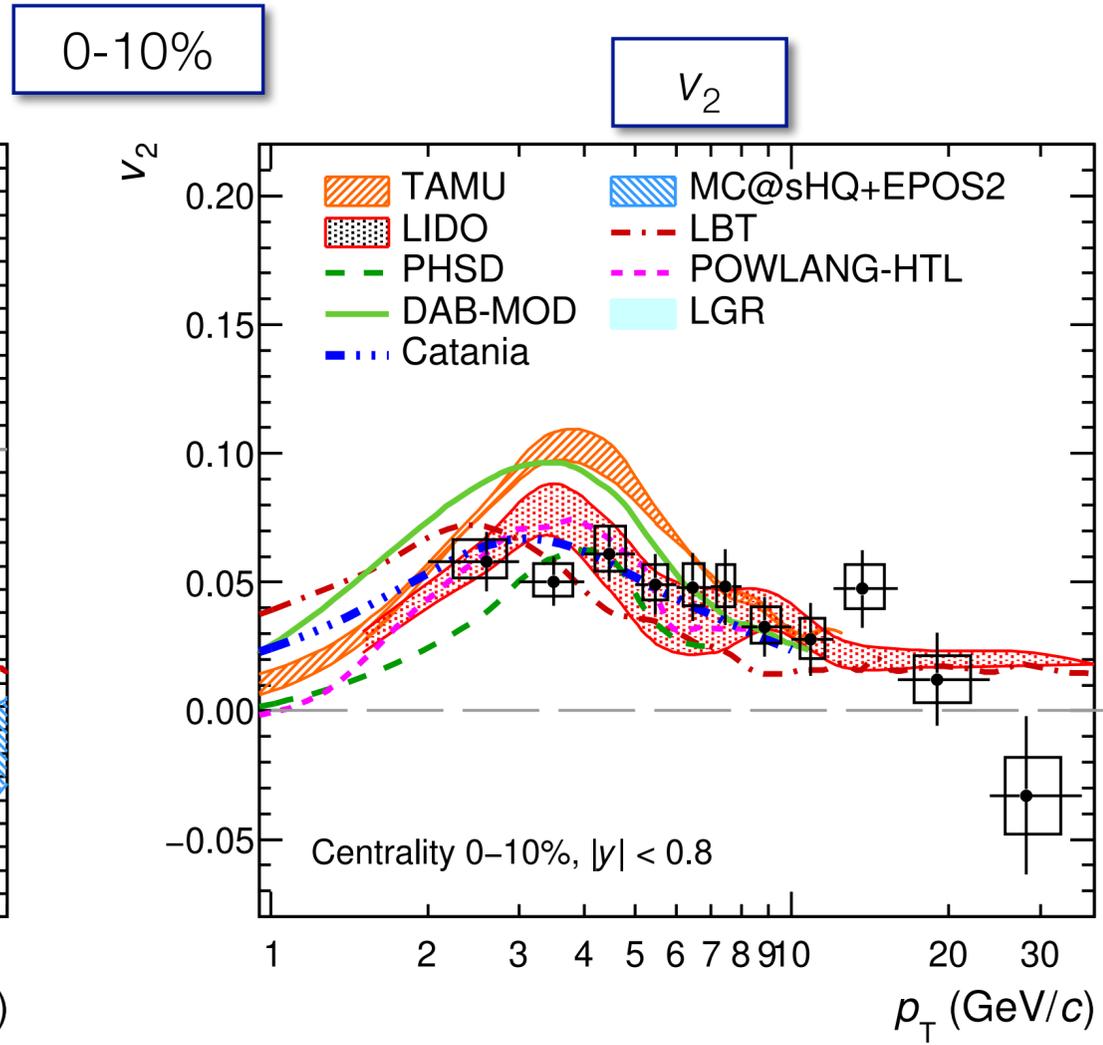
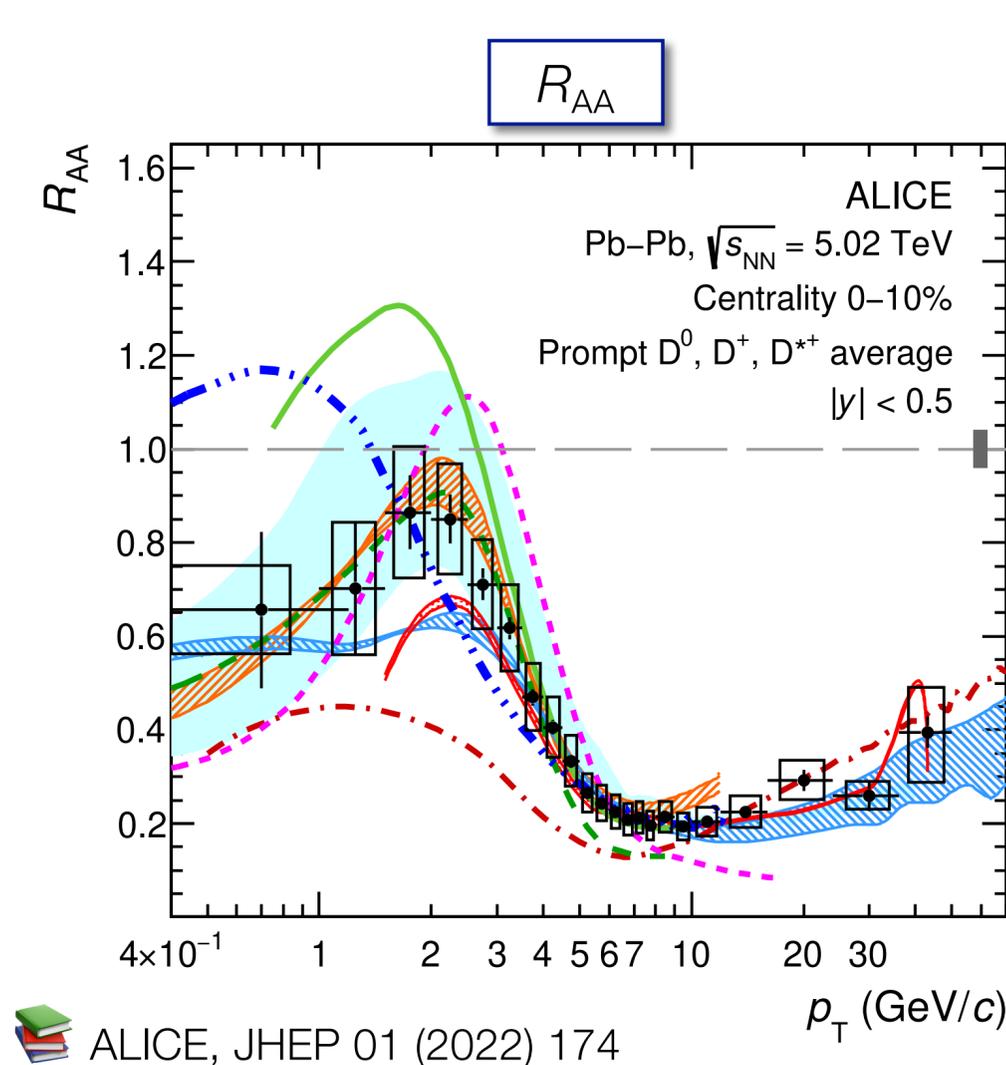


■ ALICE, PLB 827 (2022) 136986  
■ TAMU: PRL 124, 042301 (2020)  
■ PHSD: PRC 92, 014910 (2015)



- ▶ Positive  $D_s^+$   $v_2$  observed in  $2 < p_T < 8$  GeV/c in semicentral collisions with significance of  $6.4\sigma$
- ▶ Compatible with predictions from models including **charm-quark coalescence with flowing strange quarks**

- ▶ The low- $p_T$  region provides insight into the heavy quark interactions with the medium
- ▶ Comparison of  $R_{AA}$  with transport models:
  - ➔ some models **only collisional**, other **coll.+rad.**
  - ➔ all models include hadronisation via **frag.+reco.**
  - ➔ agreement for  $6 < p_T < 10$  GeV/c

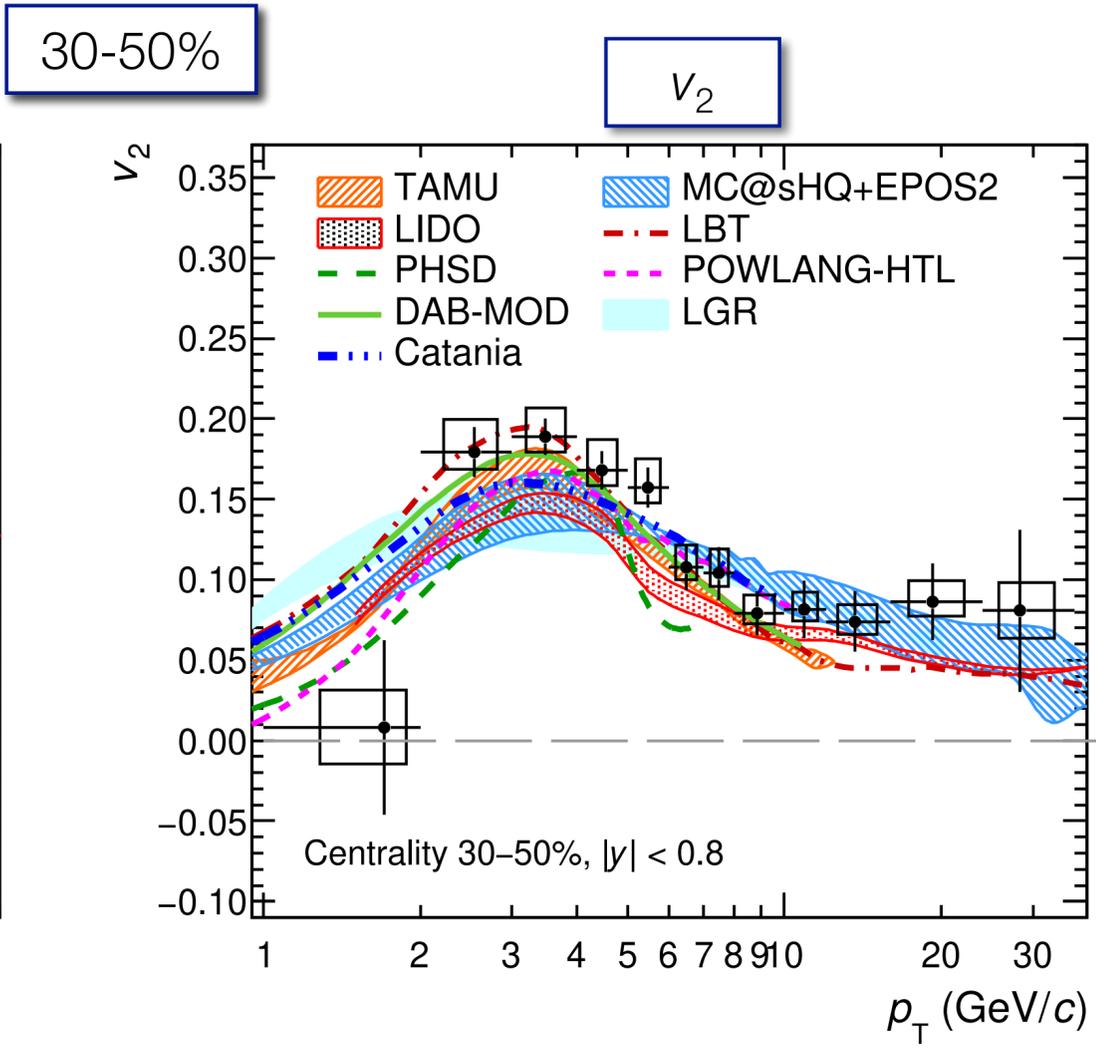
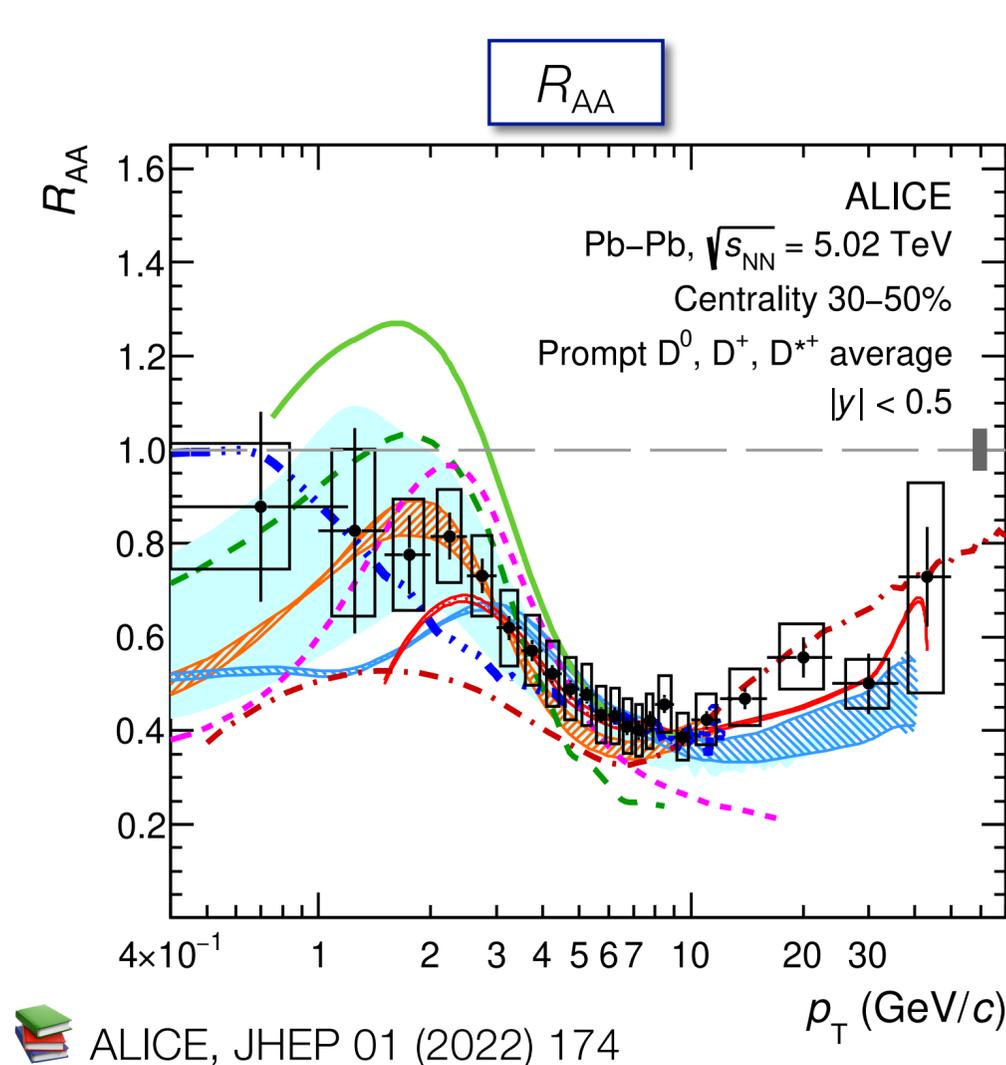


- ▶ For  $p_T < 5$  GeV/c sensitivity not only to charm-quark interaction with the medium
  - ➔ shadowing
  - ➔ bulk evolution of the medium

- TAMU: PRL 124, 042301 (2020)
- PHSD: PRC 93, 034906 (2016)
- POWLANG: EPJC 75, 121 (2015)
- CATANIA: PRC 96, 044905 (2017)

- MC@sHQ+EPOS: PRC 91, 014904 (2015)
- LIDO: PRC 98 064901 (2018)
- LBT: PLB 777 (2018) 255-259
- LGR: EPJC, 80 7 (2020) 671
- DAB-MOD M&T: PRC 96 064903 (2017)

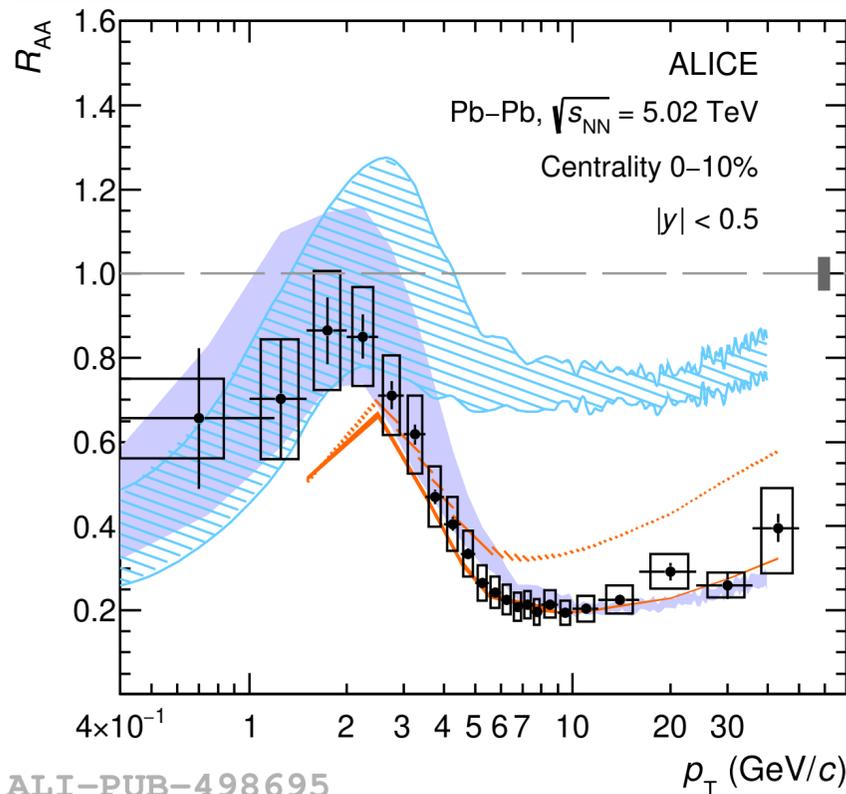
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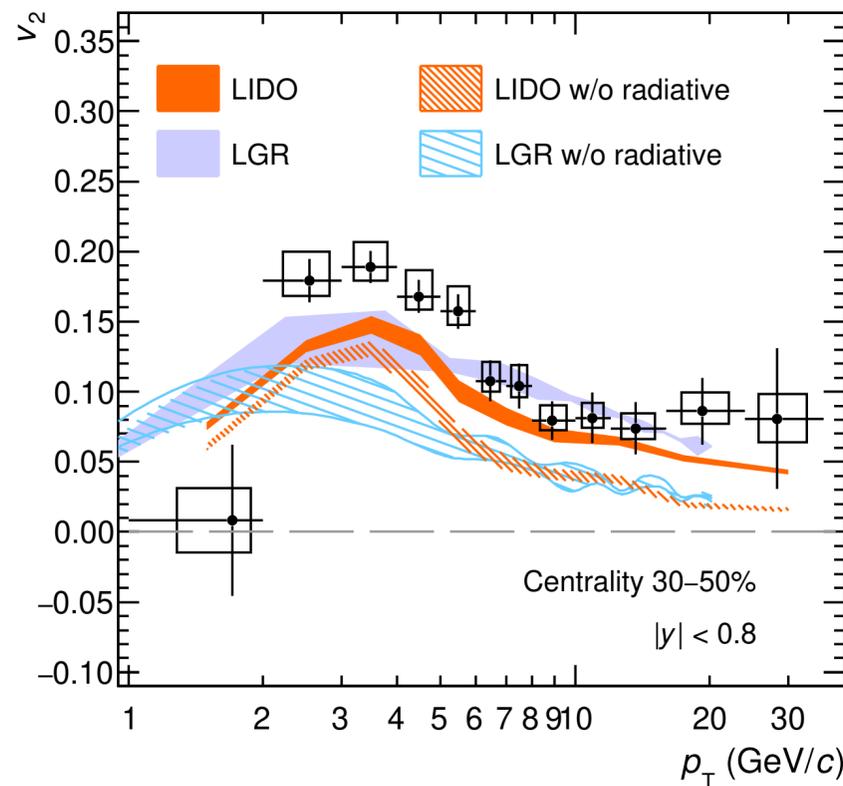
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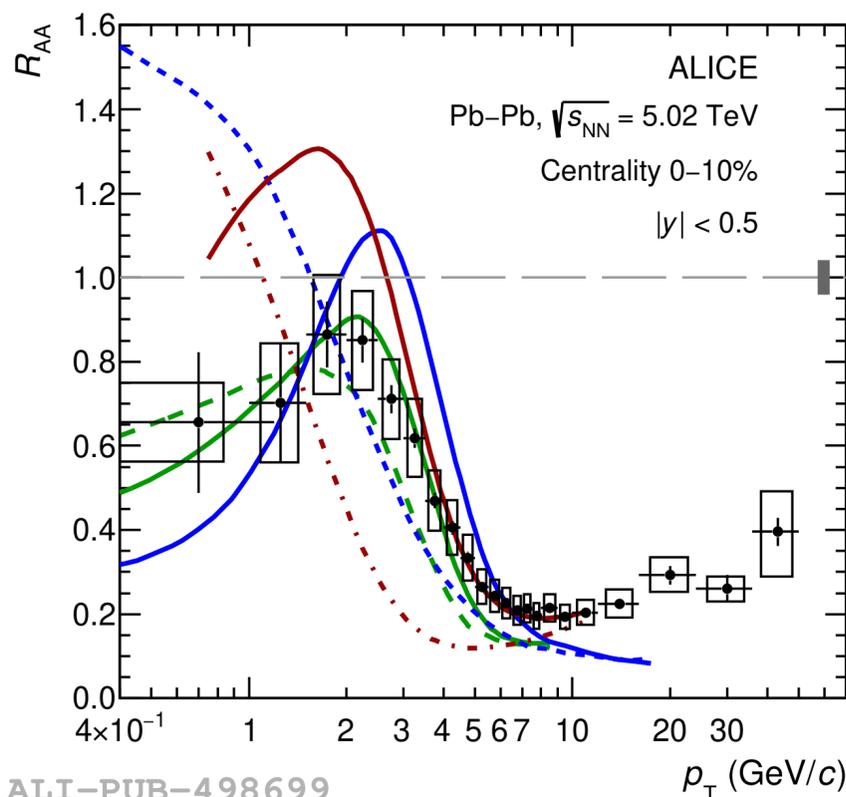
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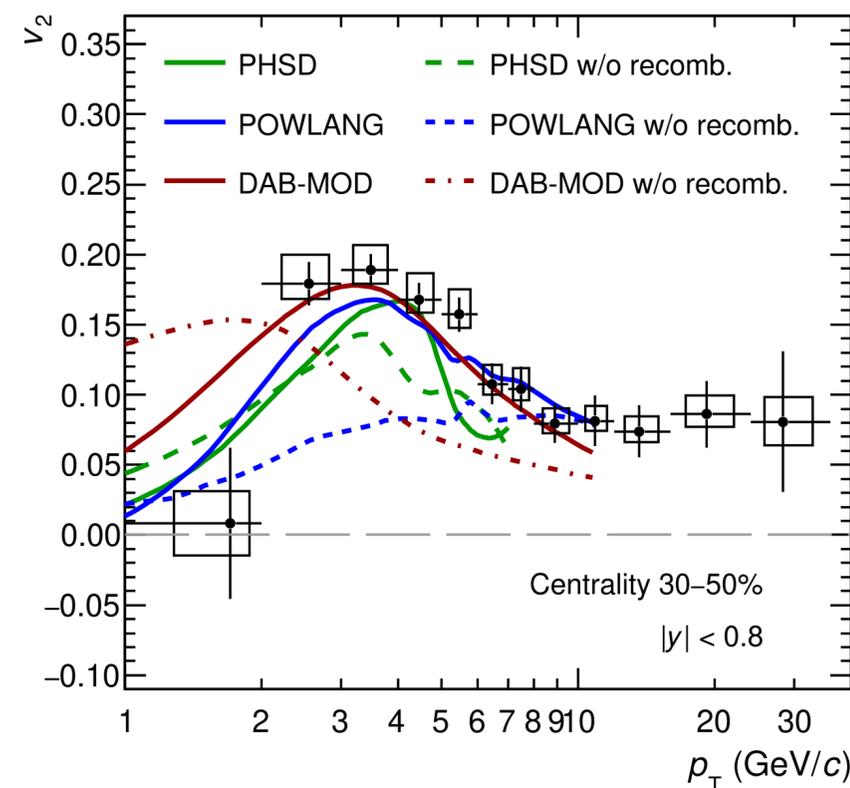
- ▶ Spatial diffusion coefficient is not the only key ingredient
- ▶ Collisional vs. radiative energy loss
  - ➔ only collisional processes underestimate the energy loss
  - ➔ predict too high  $R_{AA}$  and low  $v_2$

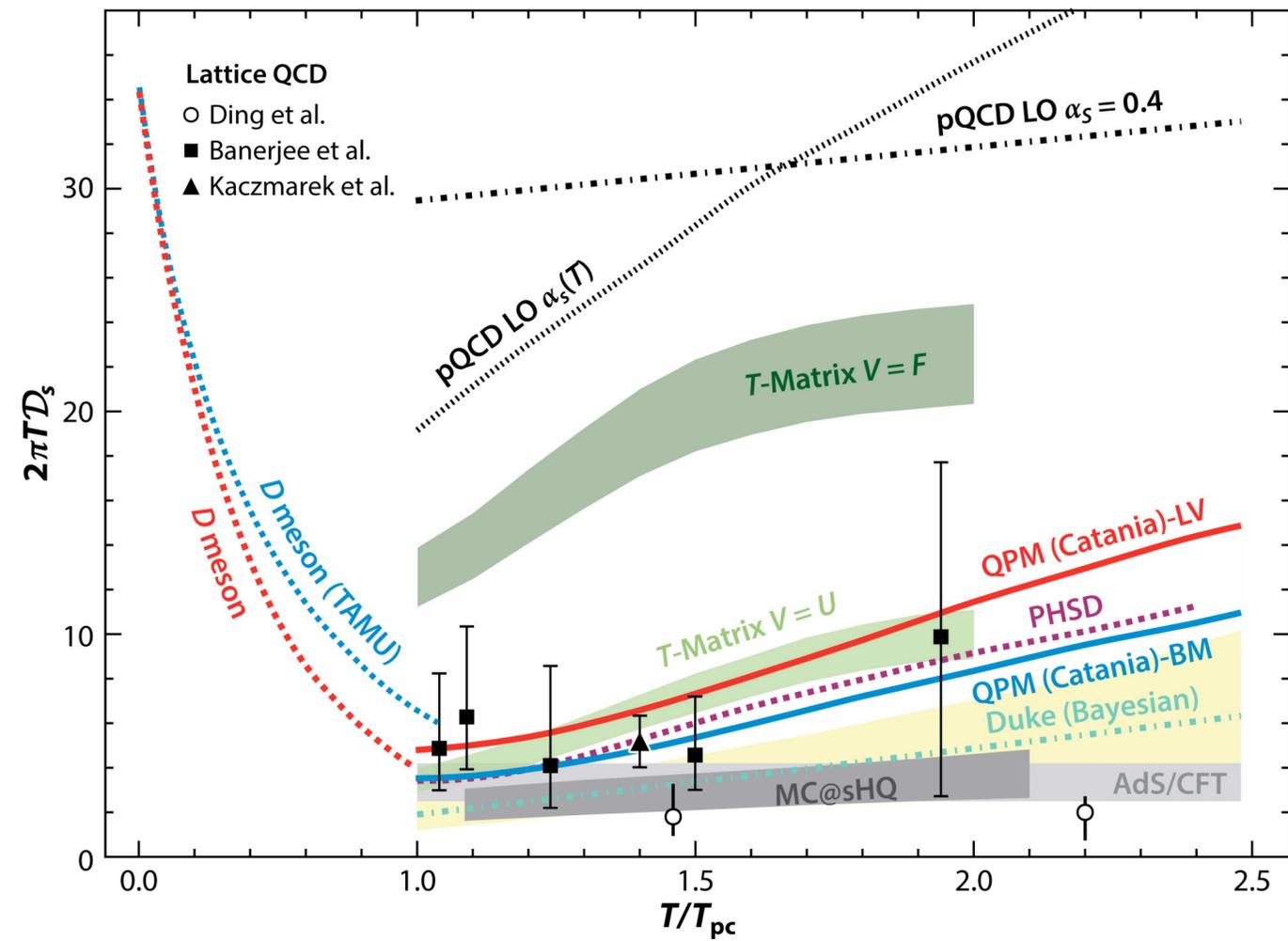
ALICE, JHEP 01 (2022) 174

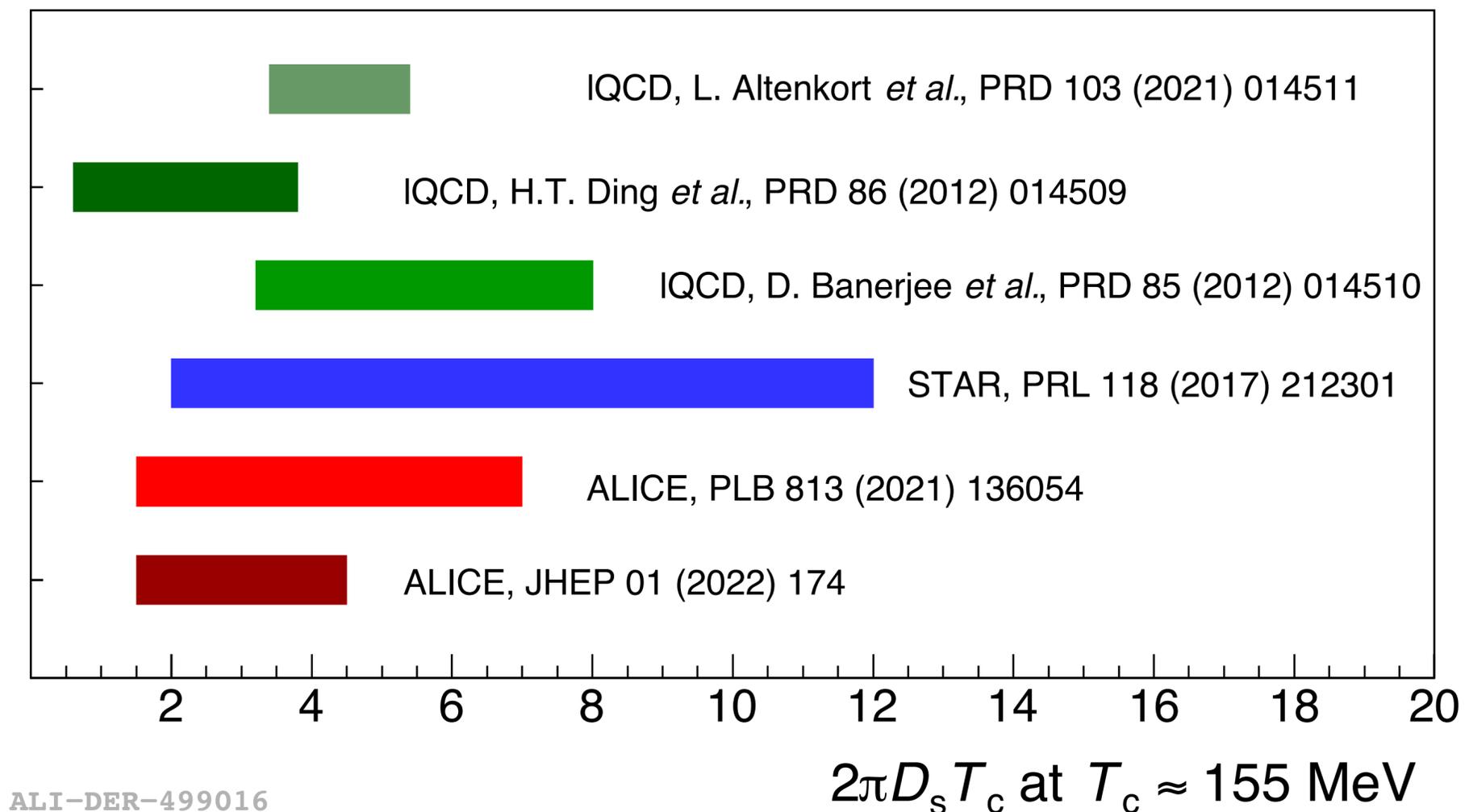
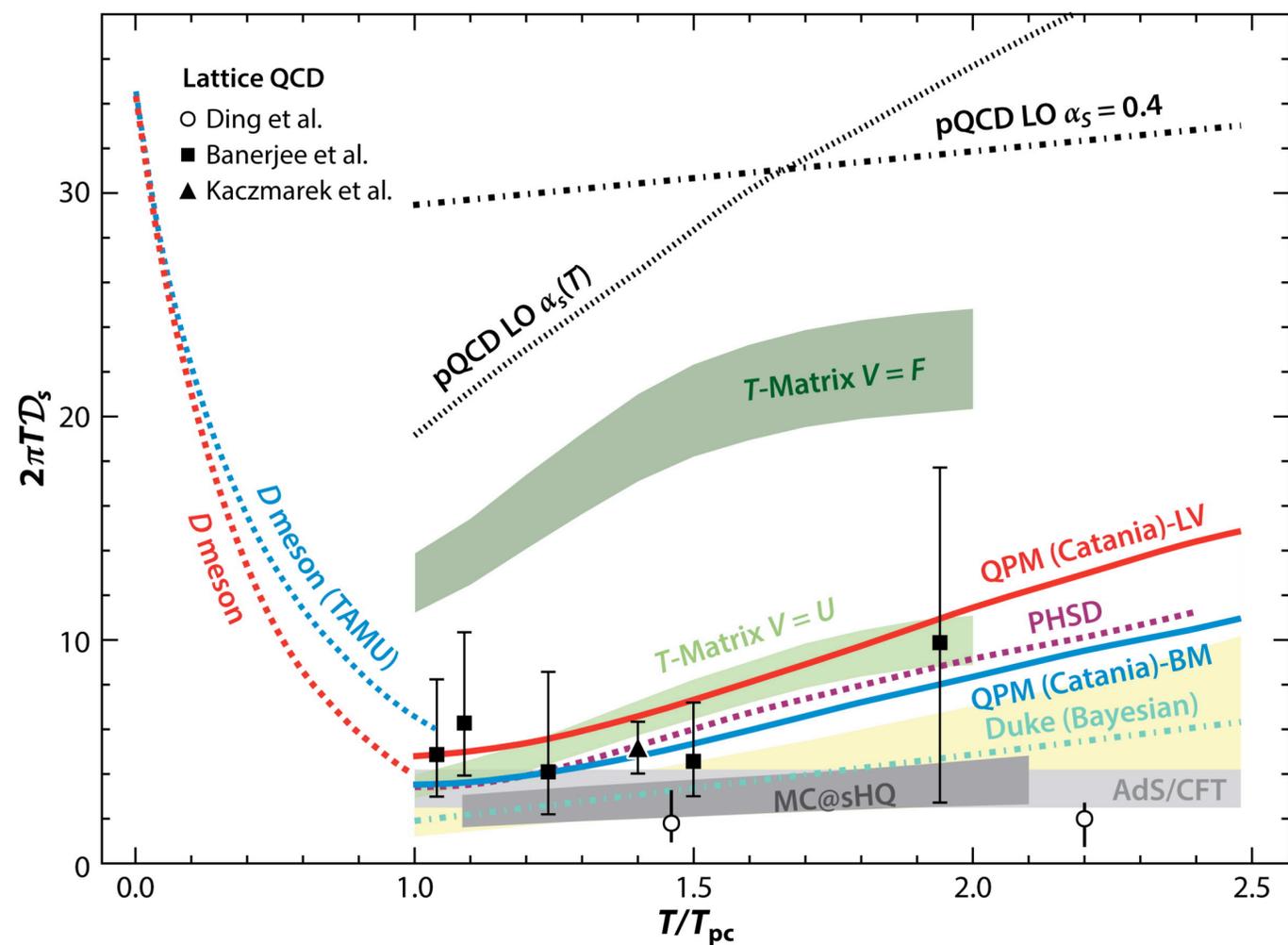
- ▶ Relation between  $p_{charm}$  and  $p_D$  is different for fragmentation and recombination
  - ➔ recombination  $\rightarrow p_D > p_{charm}$  and D meson inherits also the flow of light quark



ALI-PUB-498699







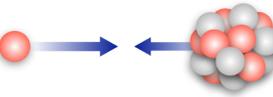
ALI-DER-499016

$2\pi D_s T_c$  at  $T_c \approx 155$  MeV

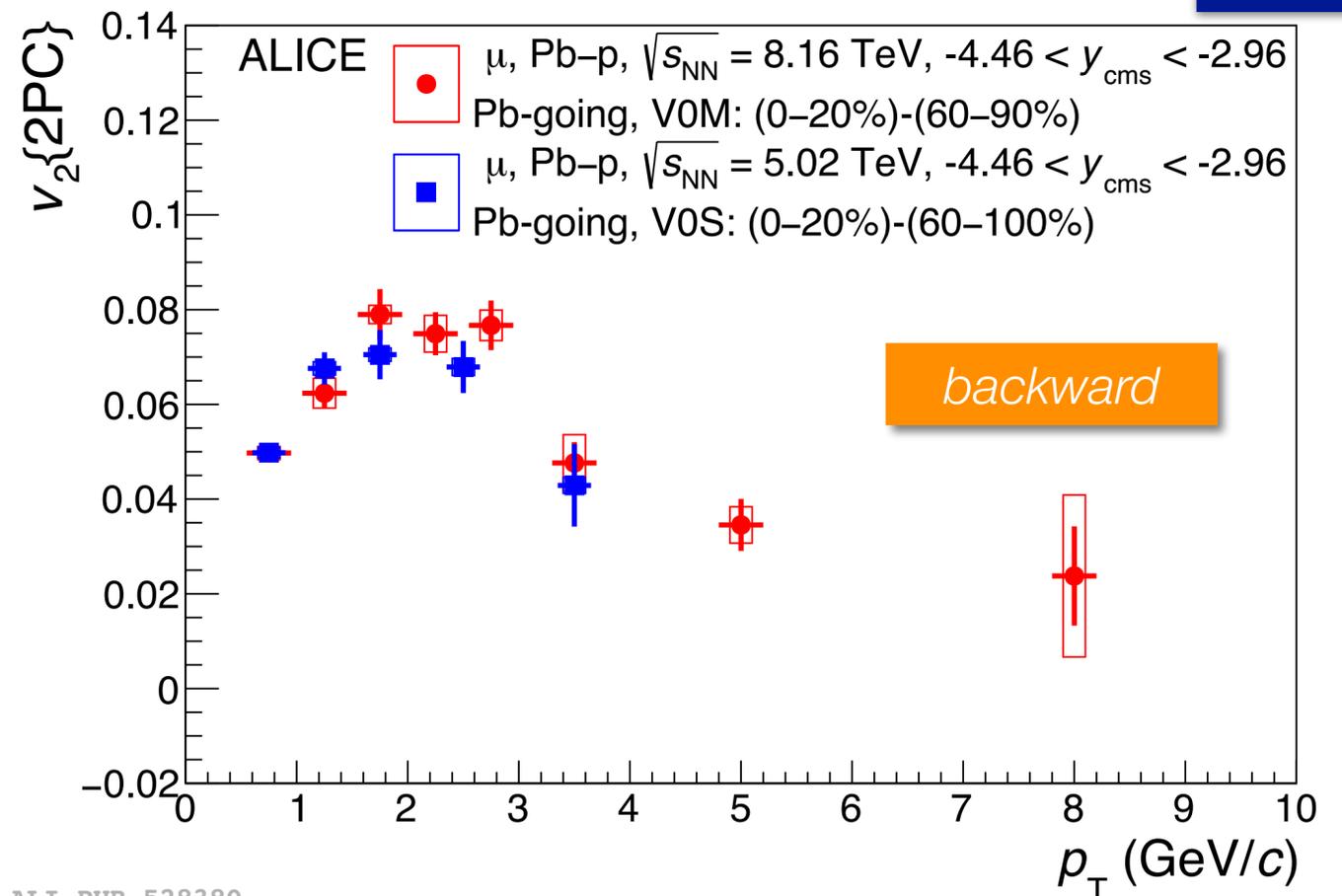
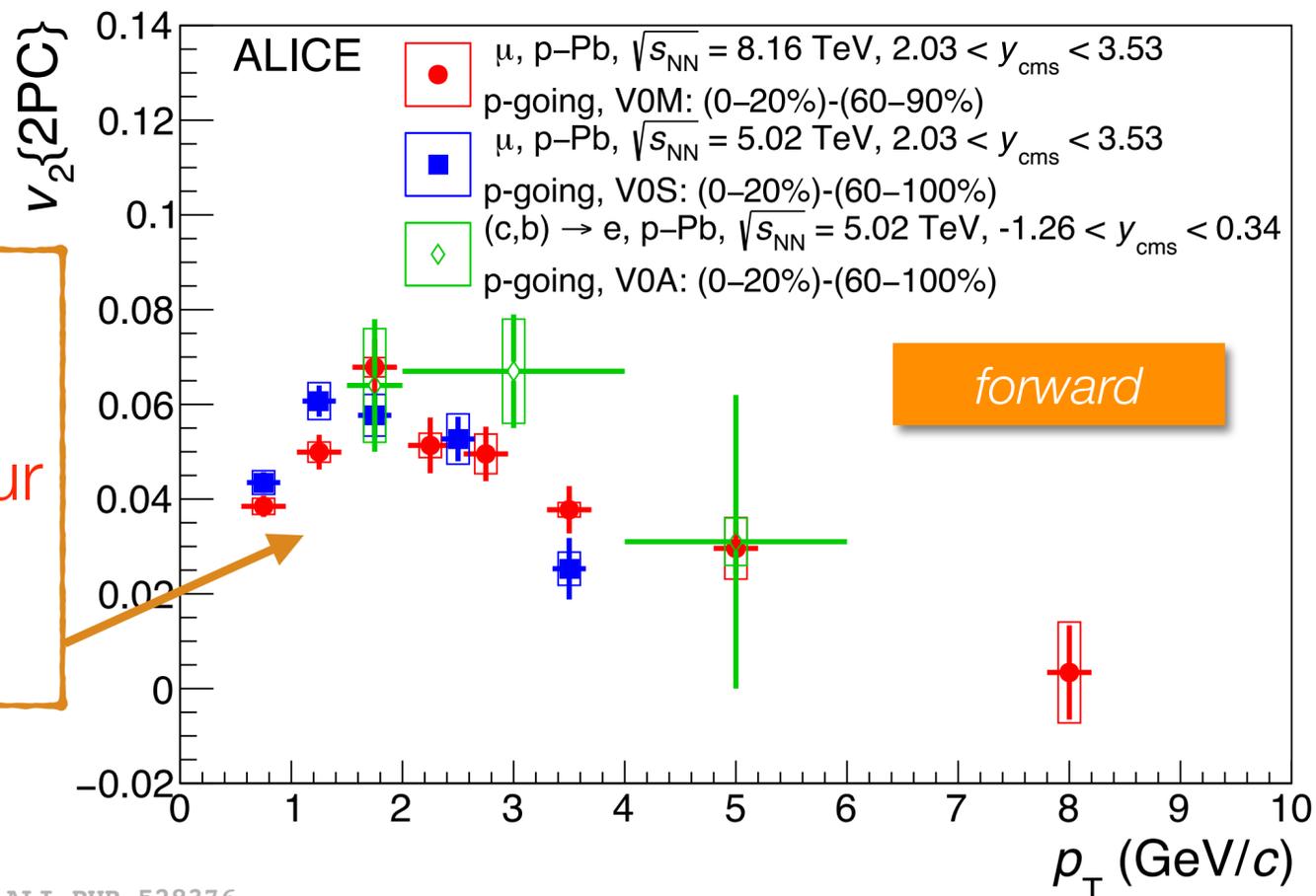
- ▶ Data-to-model agreement (i.e.  $\chi^2$  analysis) for both the  $R_{AA}$  and flow
- ▶ constrain diffusion coefficient  $D_s$  ( $\propto$  relaxation time)  $\rightarrow 1.5 < 2\pi D_s T_c < 4.5$ 
  - ▶  $\tau_{\text{charm}} \approx 3-8$  fm/c
  - ▶  $\tau_{\text{QGP lifetime}} \approx 10$  fm/c

# Muons azimuthal anisotropies in p-Pb

- ▶ Measurement of inclusive muon  $v_2$  in p-Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV
  - ➔ positive  $v_2$  at forward and backward rapidity
- ▶ From comparison with previous results:
  - ➔ no significant energy dependence → agreement between 5.02 TeV and 8.16 TeV
  - ➔ compatible with  $e \leftarrow c, b$   $v_2$  in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV

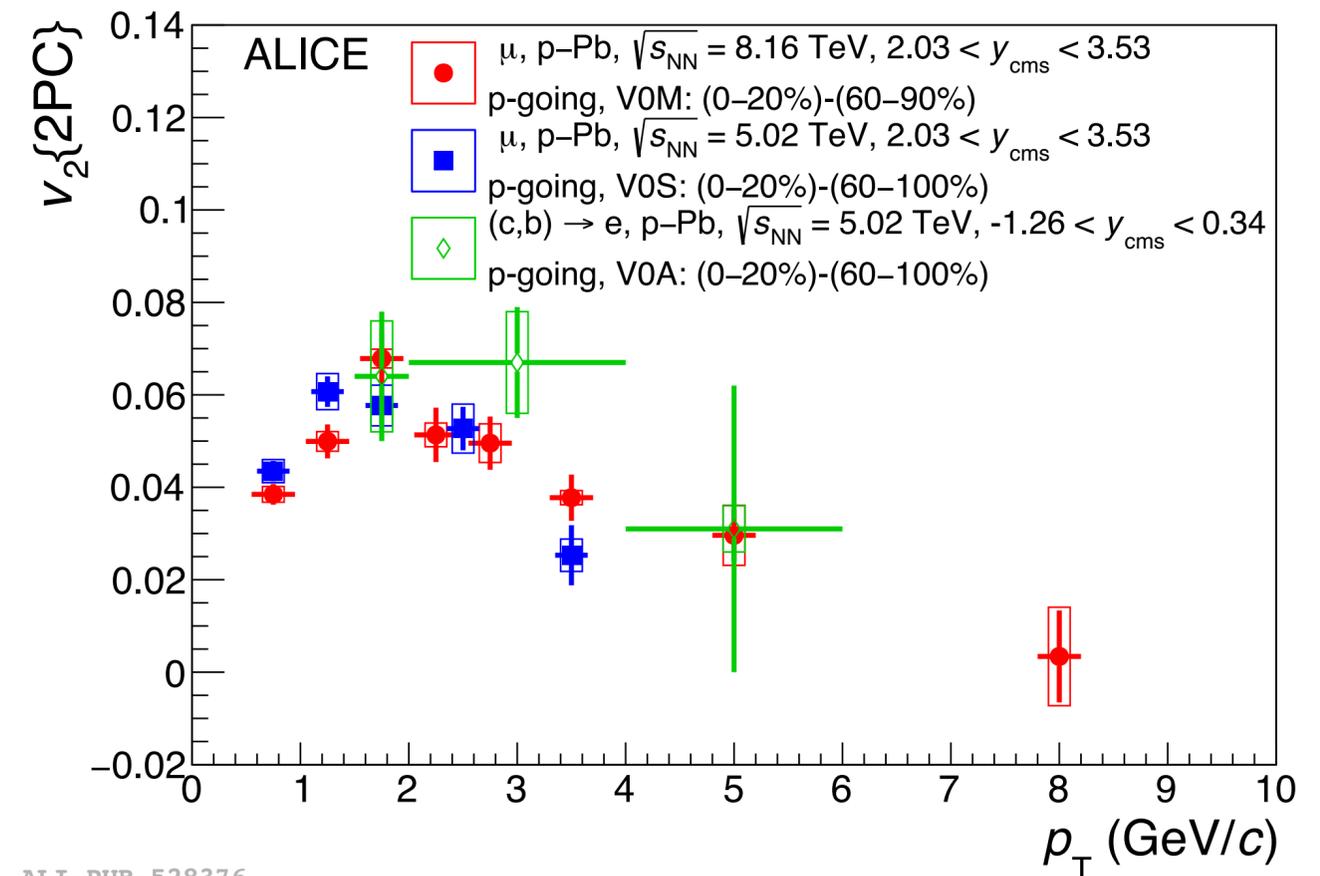
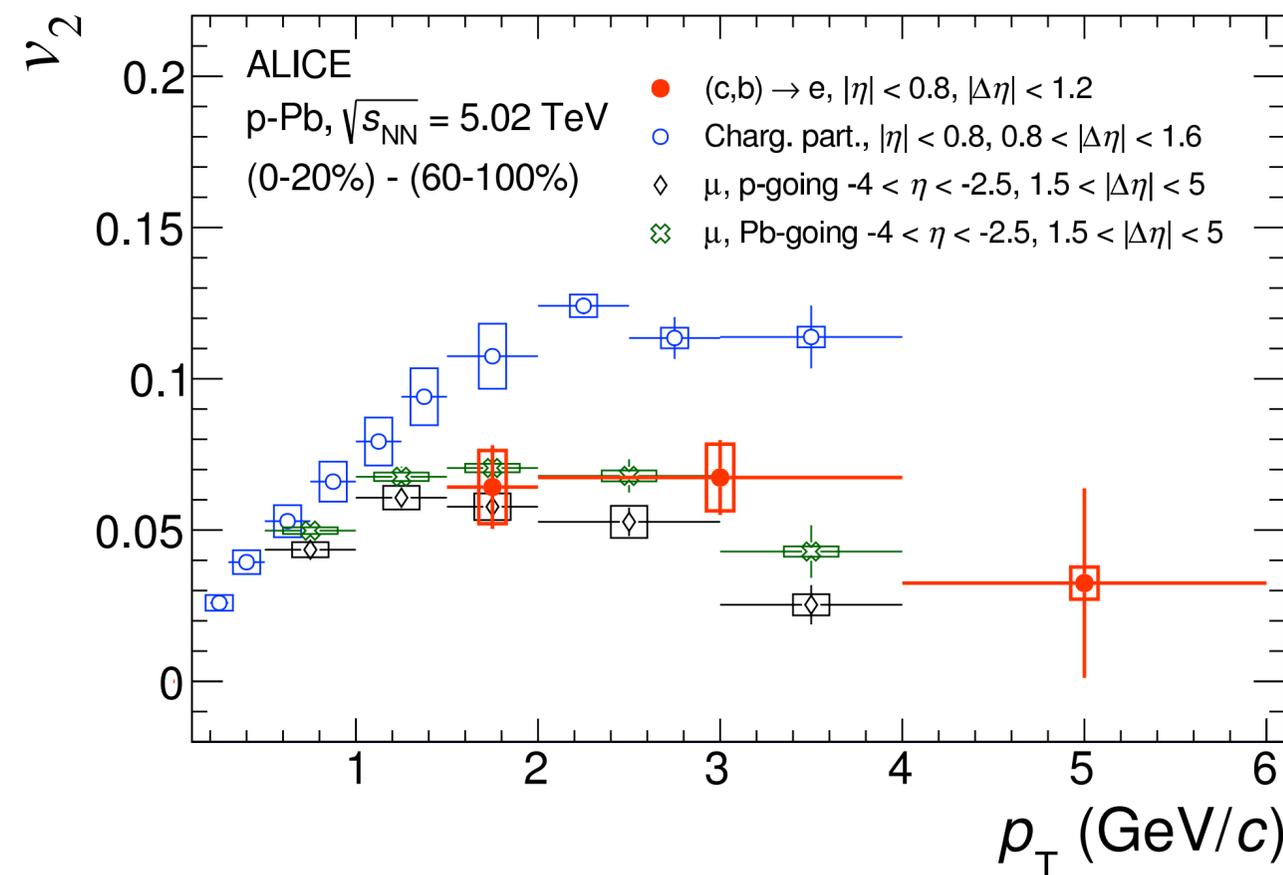


NEW



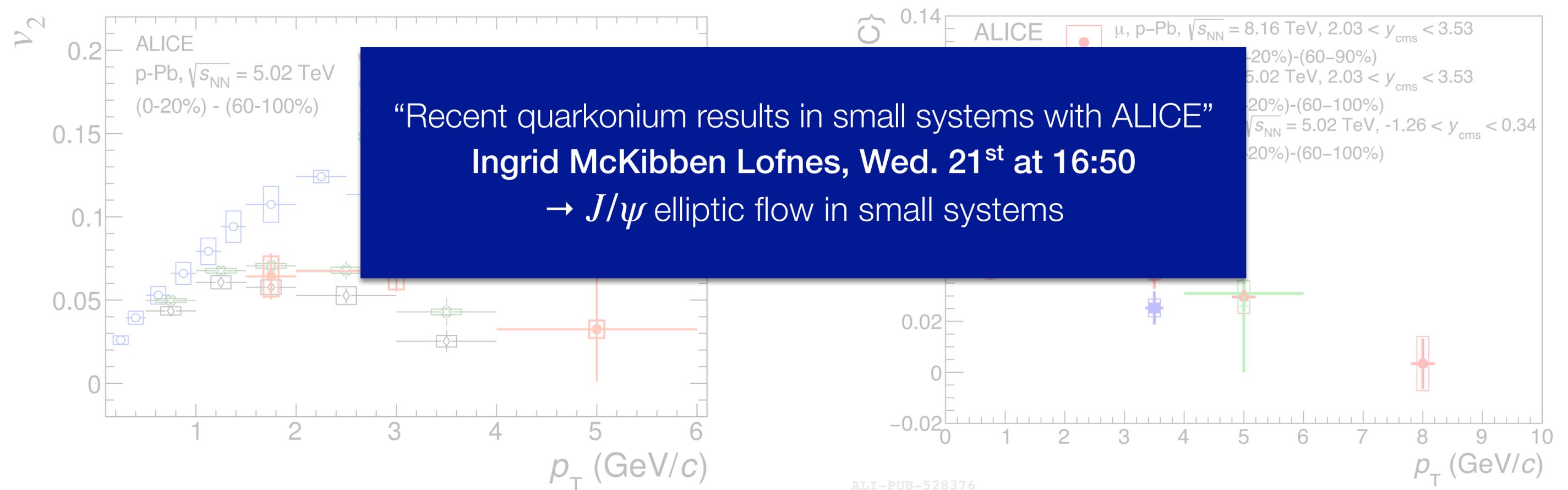
Larger contribution from light-flavour hadrons at low  $p_T$

- ▶ Comparison with light-flavour hadron  $v_2$  in p-Pb
  - ➔ direct comparison not straightforward → different rapidities and particle-to-parton  $p_T$  scale and muon contamination at low  $p_T$
  - ➔ **charged particles  $v_2$**  higher than electrons and muons  $v_2$
  - ➔ ordering (light vs. heavy) as observed in Pb-Pb collisions



ALI-PUB-528376

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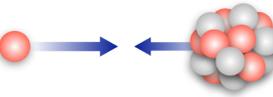


► Measurement of inclusive muon  $v_2$  in p-Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV

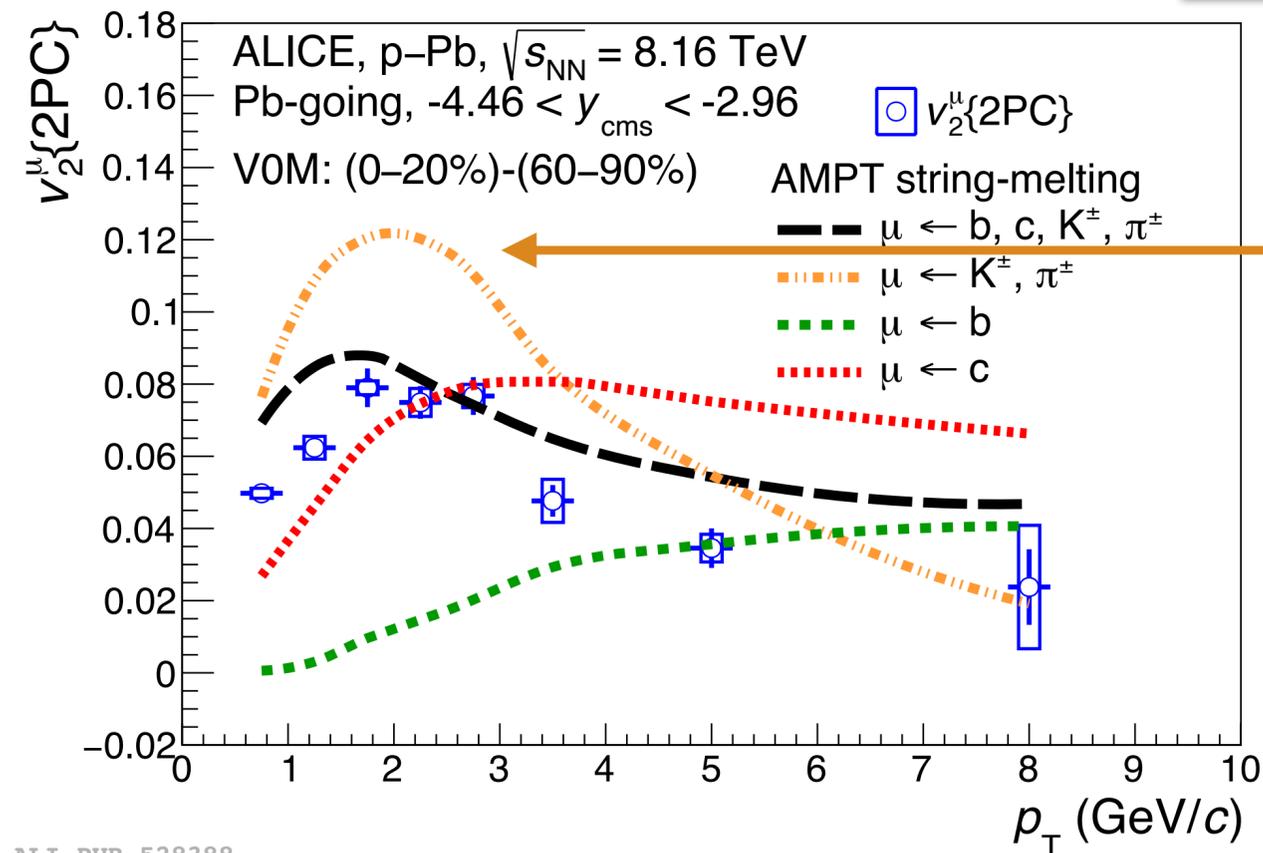
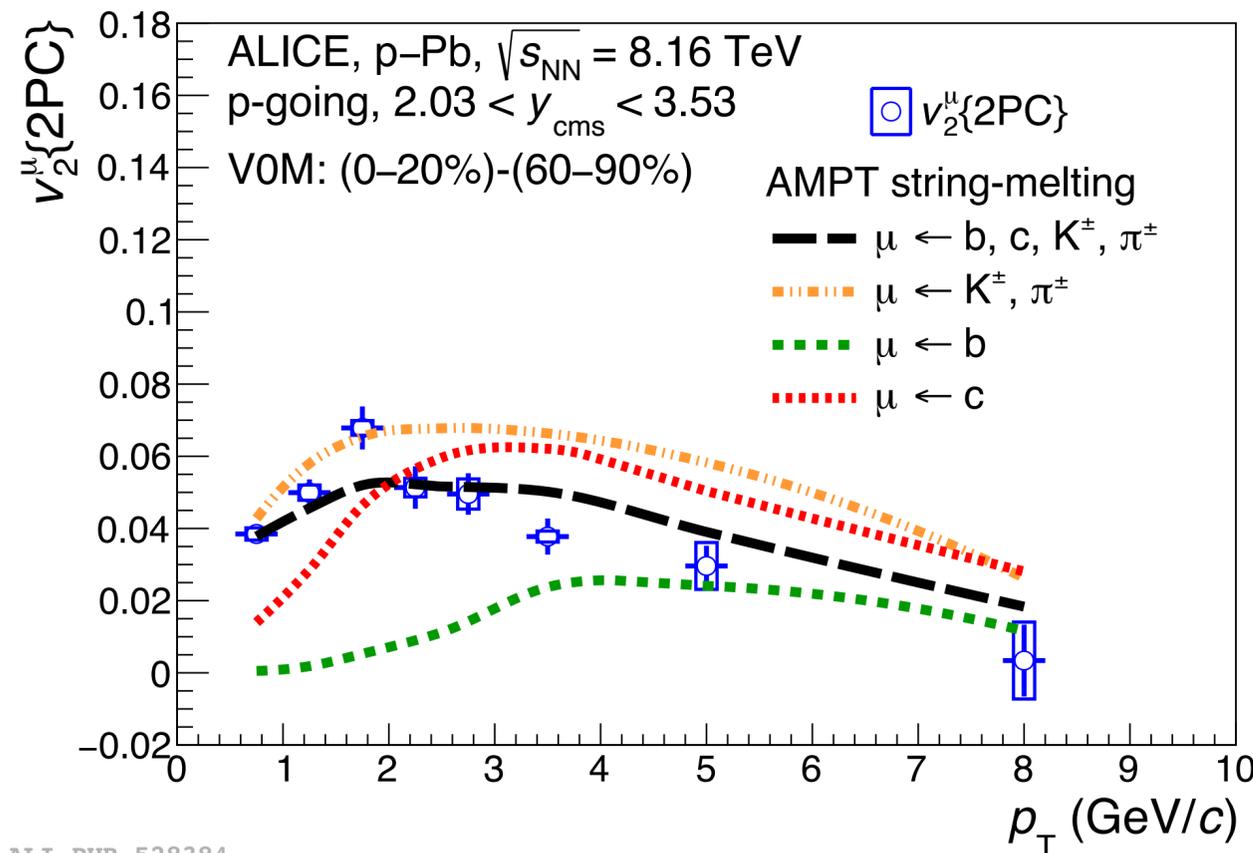
→ positive  $v_2$  at forward and backward rapidity

► From comparison with models:

→ AMPT in agreement with the measured  $v_2$  → larger at backward w.r.t. forward rapidity



NEW



Larger contribution from light-flavour hadrons at low  $p_T$

# Muons azimuthal anisotropies in p-Pb

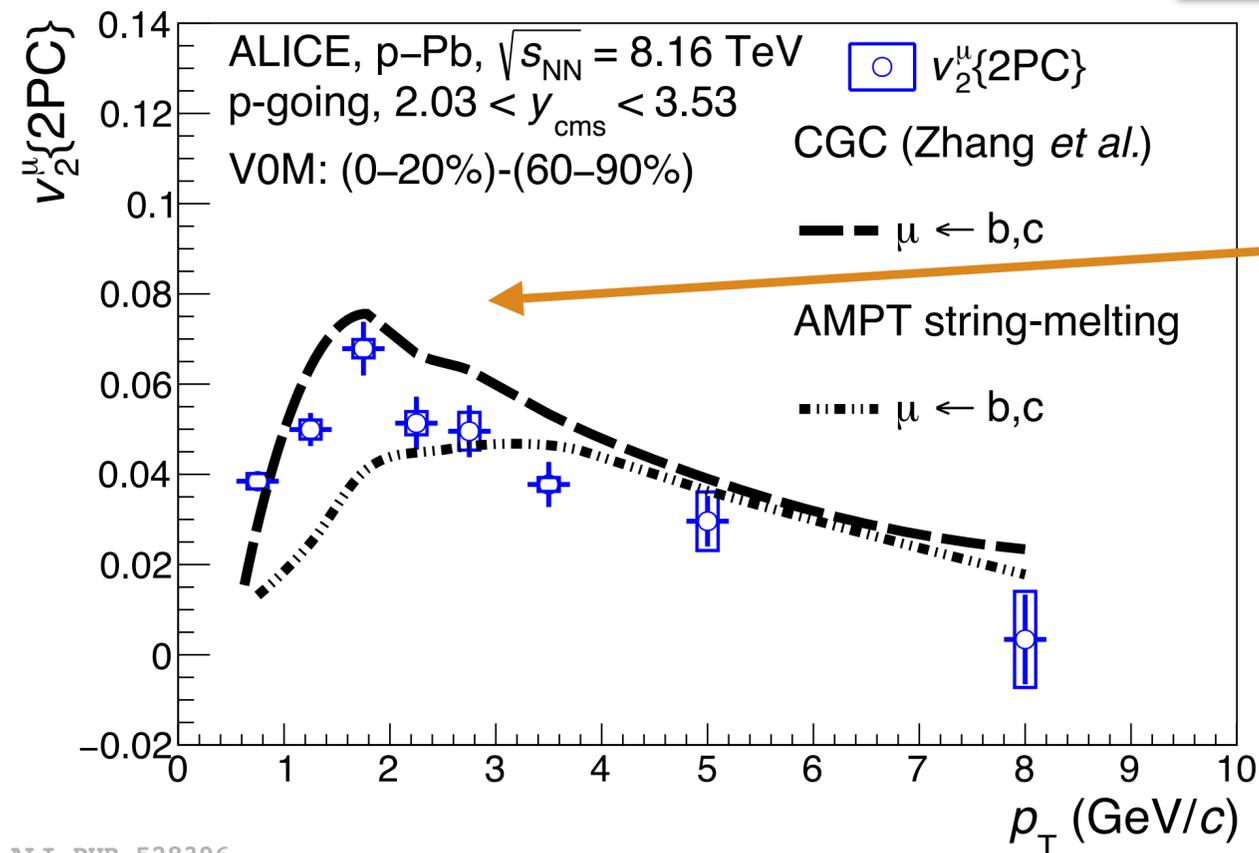
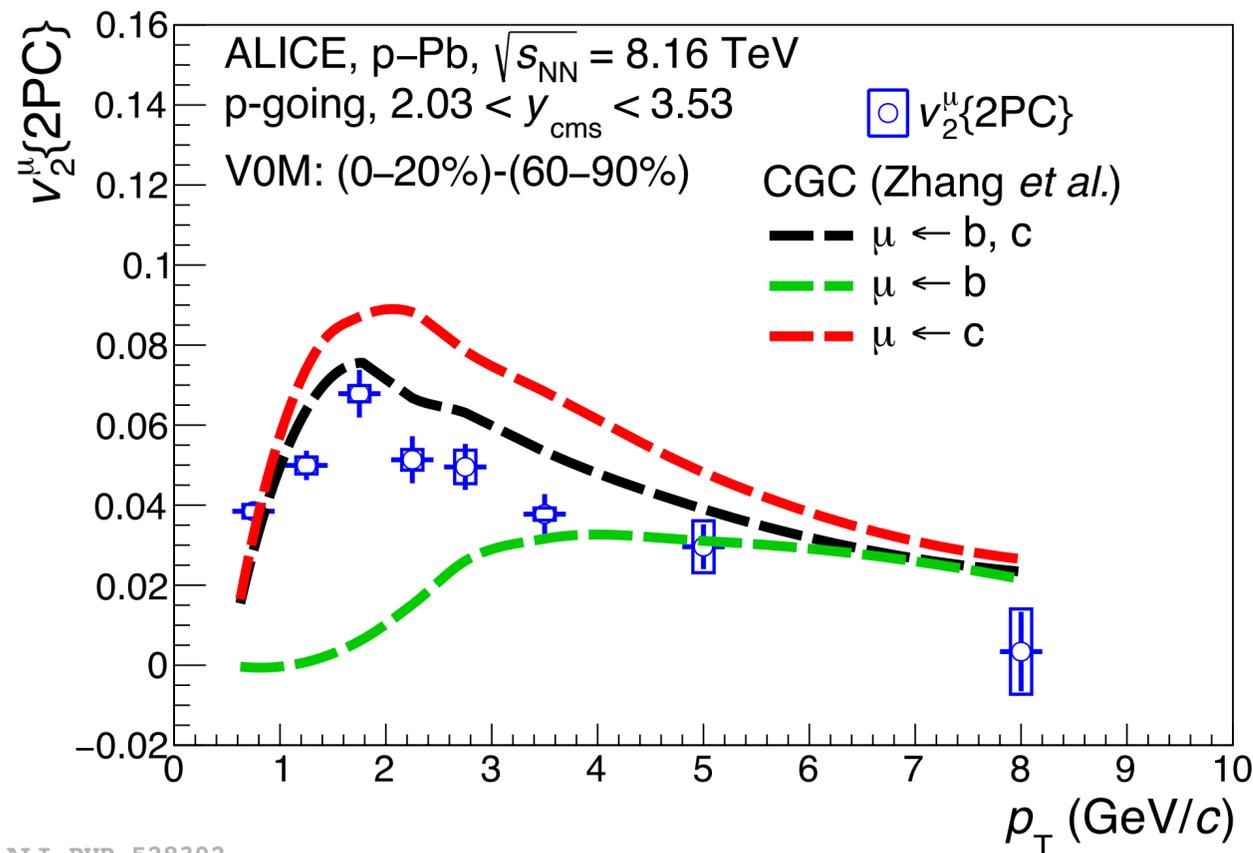
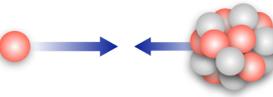
▶ Measurement of inclusive muon  $v_2$  in p-Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV

→ positive  $v_2$  at forward and backward rapidity

▶ From comparison with models:

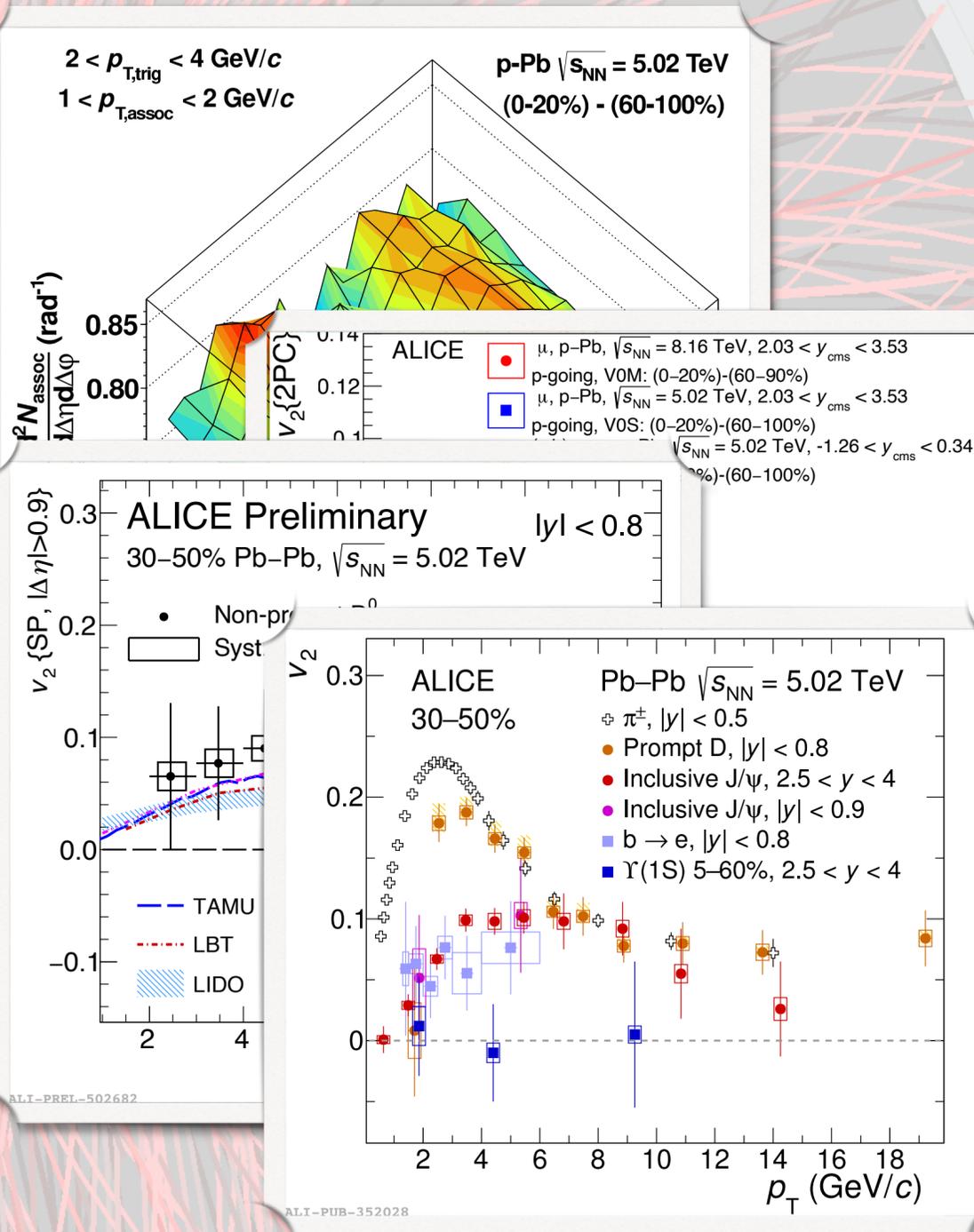
→ AMPT in agreement with the measured  $v_2$  → larger at backward w.r.t. forward rapidity

→ CGC-based calculations reproduce the measurement for  $p_T > 2$  GeV/c

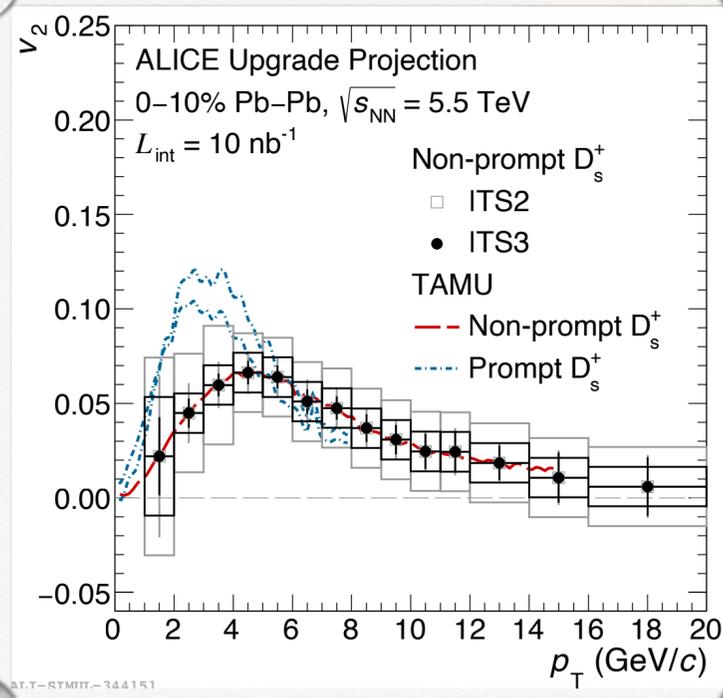
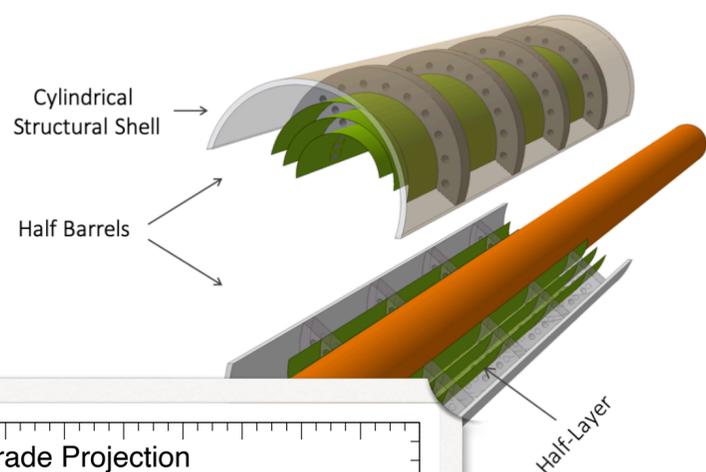
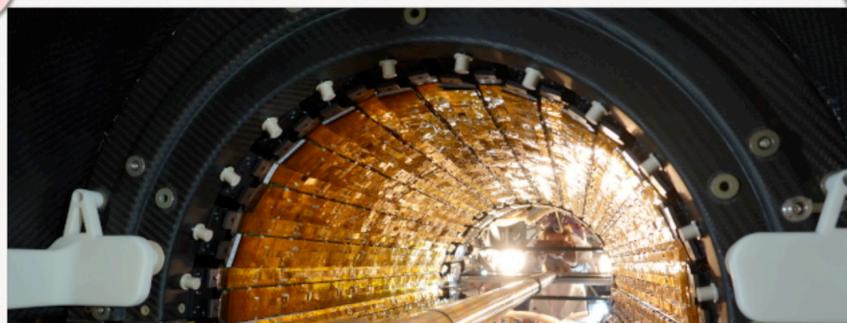


NEW

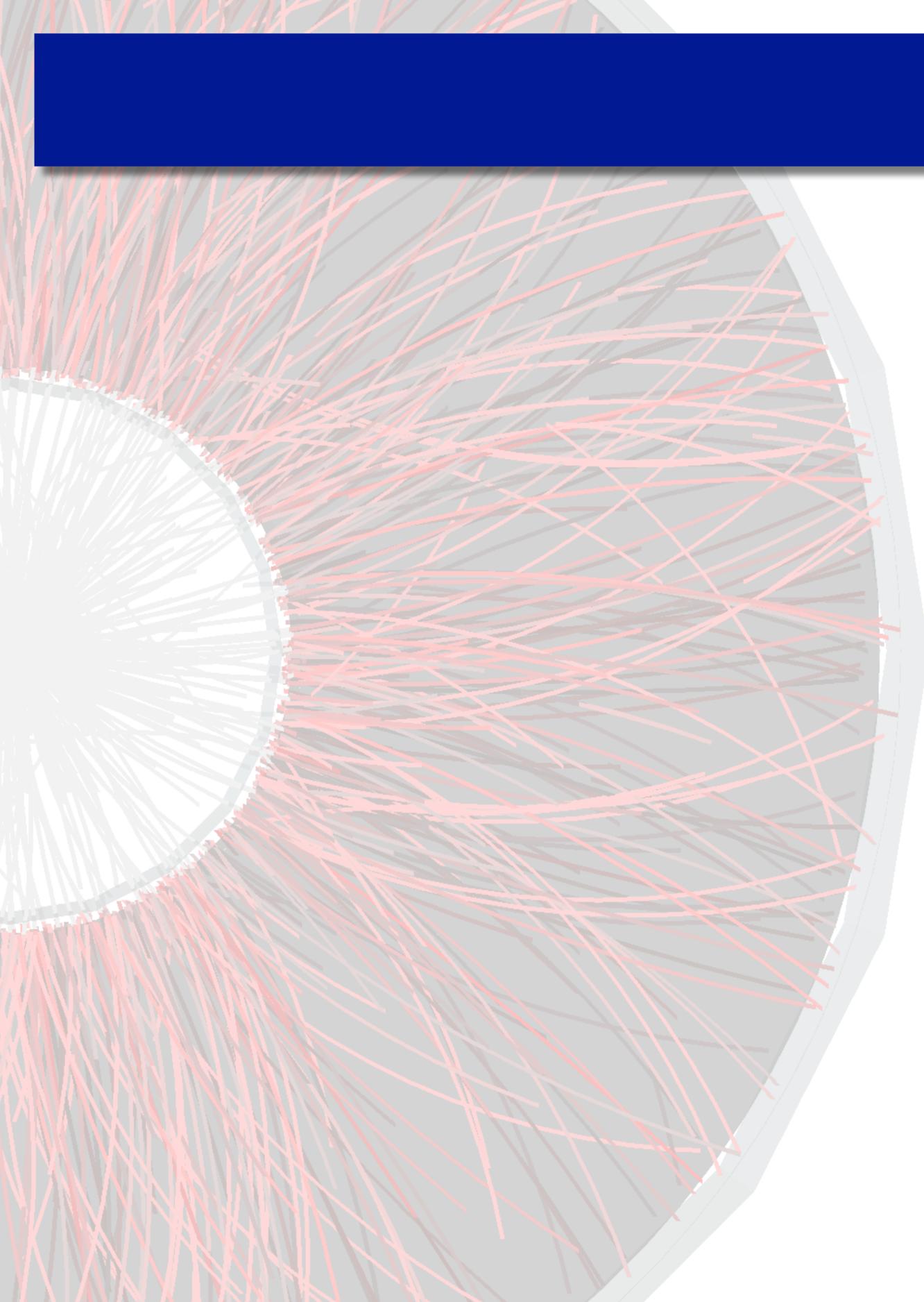
CGC predicts larger flow at low  $p_T$   
 → does not include contribution from light-flavour hadrons



- ▶ ALICE performed precise heavy-flavour hadron measurements exploiting Run 2 data sample
  - ➔ improved measurement in the charm sector
  - ➔ further measurements addressing beauty  $v_2$
  - ➔ confirmation of collectivity in high-multiplicity collisions in small systems
  
- ▶ Lessons learnt so far:
  - ➔ charm quark **interacts with the medium constituents** via **collisional** and **radiative** processes in Pb-Pb collisions
  - ➔ charm quarks are **thermalised** with medium → collective motion
  - ➔ **beauty** quark **less thermalised** than charm quark in the QGP
  - ➔ heavy quarks reveal a **collective-like behaviour** in **high-multiplicity** p-Pb collisions.

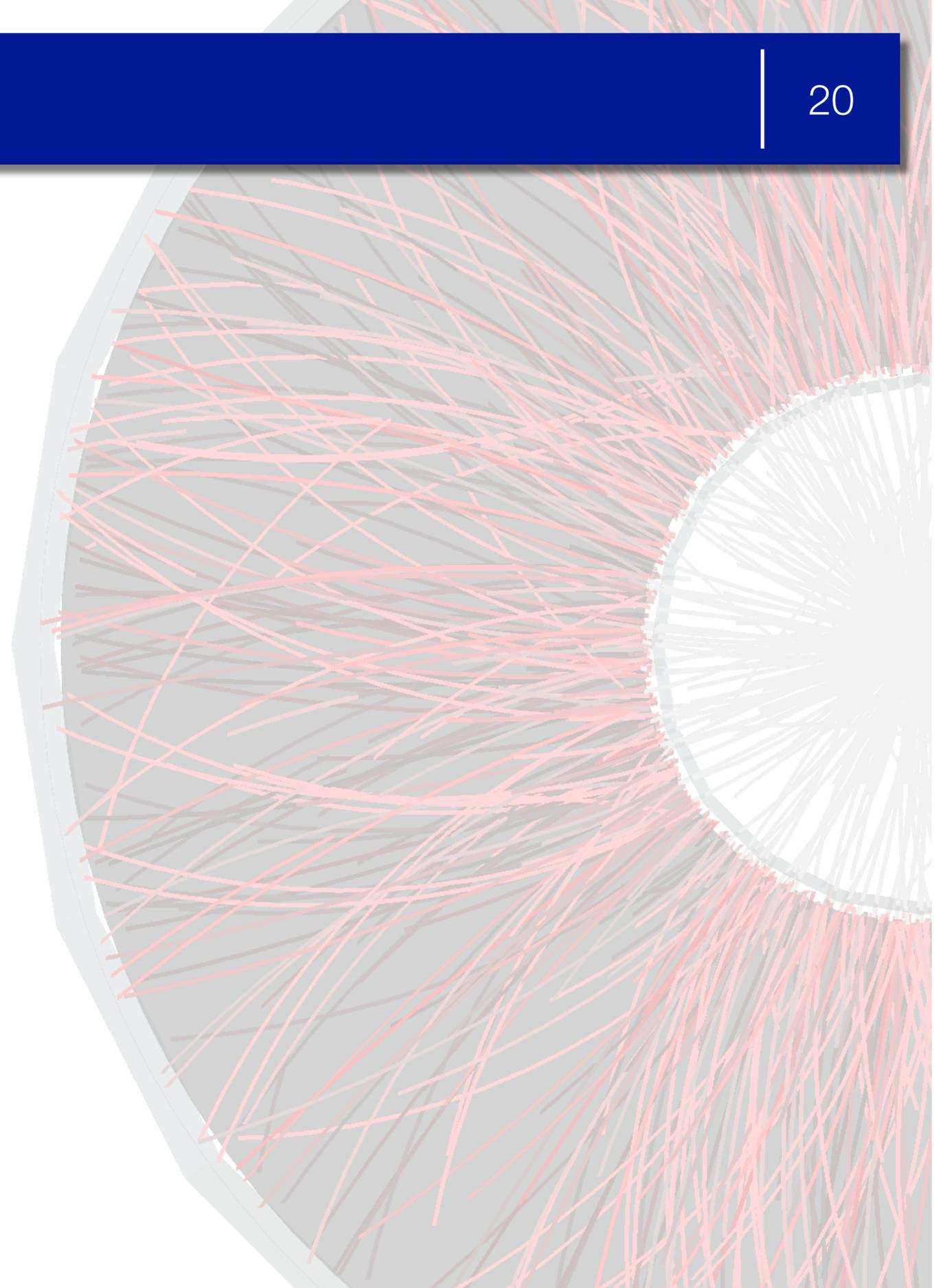


- ▶ LHC Run 3 and ALICE is preparing **upgrades** for **Run 4**
  - ➔ **increase collected luminosity** in all collision systems by more than one order of magnitude
  - ➔ upgrade of many detectors and new silicon **Inner Tracking System**
    - ➔ Run 3: **ITS2 (installed in 2021)**  TDR: CERN-LHCC-2013-024
    - ➔ Run 4: **ITS3 (TDR in preparation)**, curved wafer-scale ultra-thin silicon sensors  LoI: CERN-LHCC-2019-018
  - ➔ crucial for heavy-flavour hadron measurements
  
- ▶ New and more precise heavy-flavour hadron measurements down to low  $p_T$ 
  - ➔ precise measurements of charm mesons and baryons
  - ➔ possibility to measure **beauty-strange meson**, **beauty-baryon production**, and **azimuthal anisotropies**

An abstract graphic on the left side of the slide. It features a circular structure with a grey outer ring and a white inner core. The interior is filled with a dense network of thin, red lines that radiate from the center and cross each other, creating a complex, web-like pattern. The overall appearance is reminiscent of a biological structure like a retina or a neural network.

**Thank you for  
your attention!**

# Additional material



► Full reconstruction **via hadronic decays**:

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K_S^0$

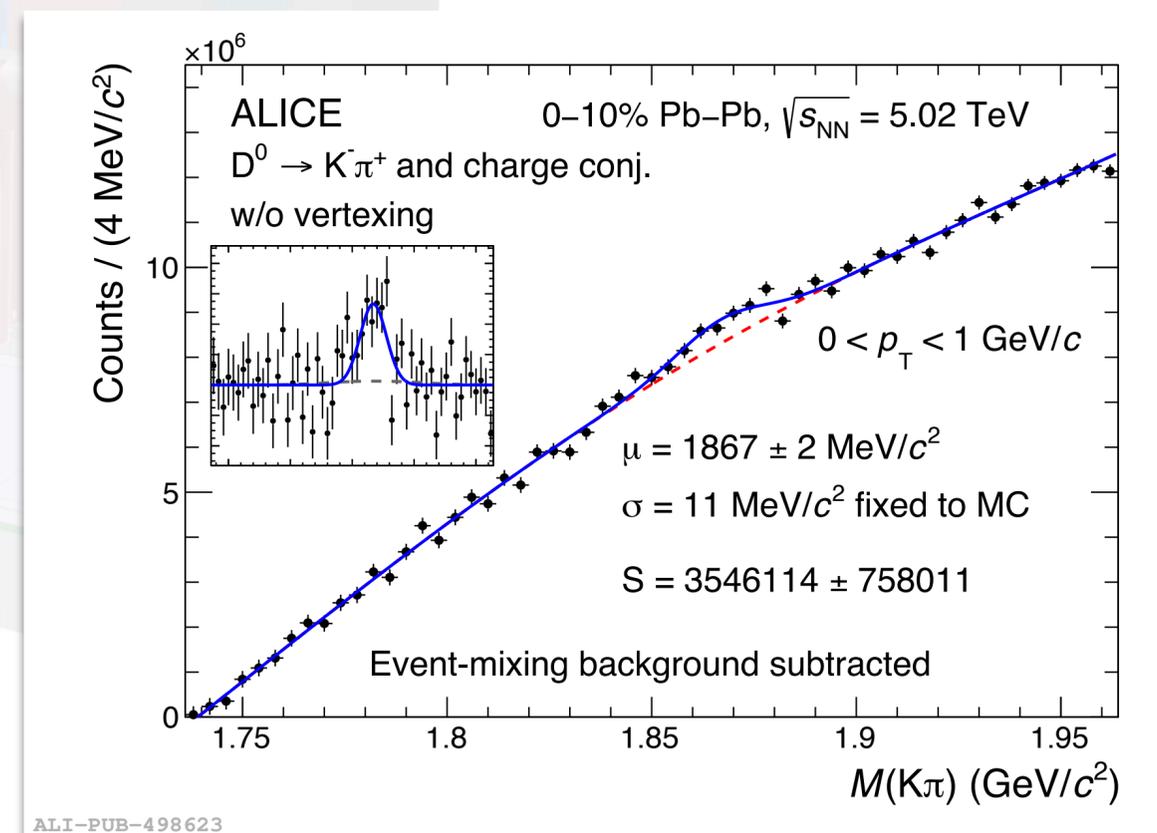
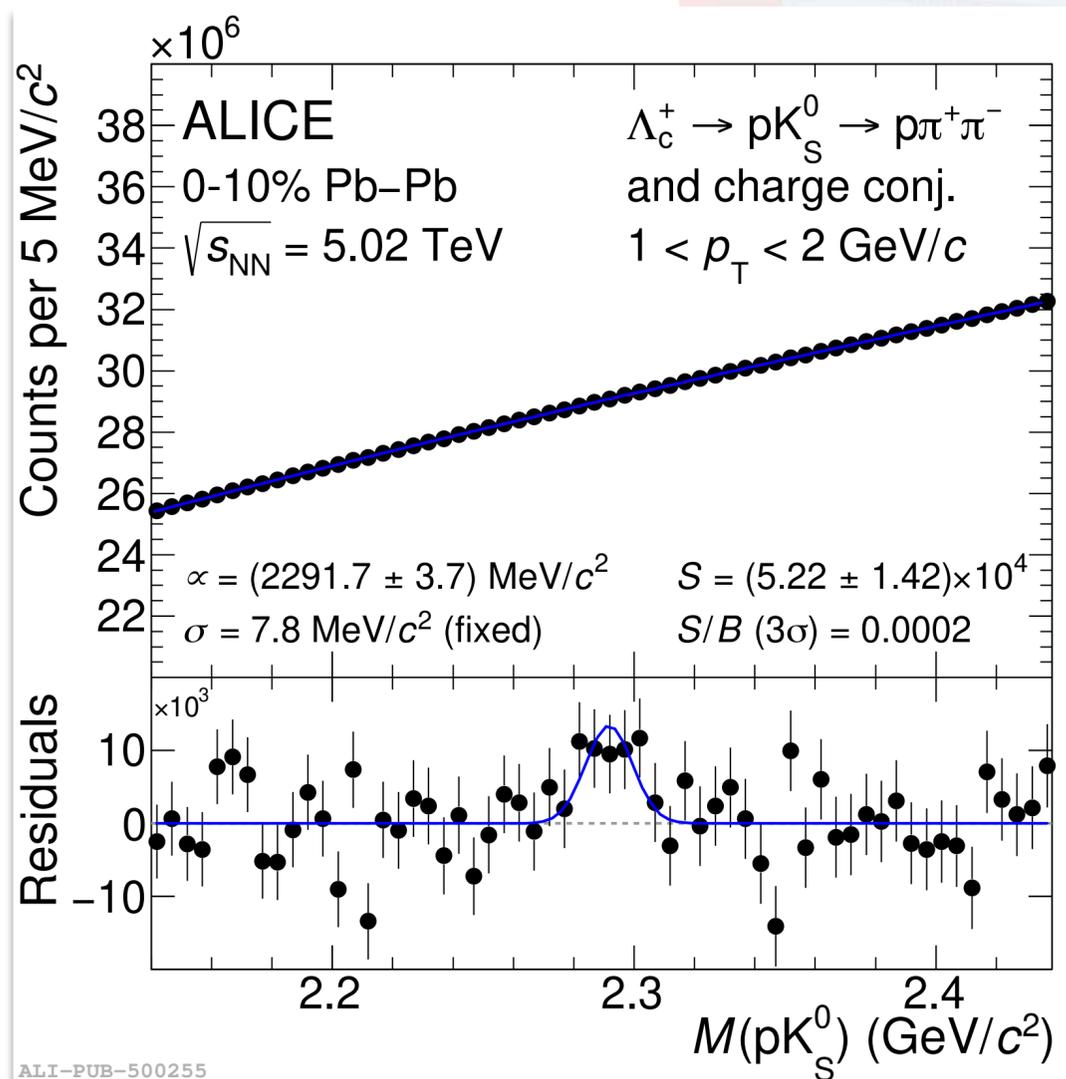
► Exploring:

- displaced **decay-vertex topology selections**
- **particle identification** of decay tracks

► Low- $p_T$   $D^0$  analysis uses only:

- **particle identification**
- **event-mixing** background subtraction

► Invariant-mass analysis



► Partial reconstruction **via semileptonic decays:**

➔  $c, b \rightarrow e^\pm X$

➔  $c, b \rightarrow \mu^\pm X$

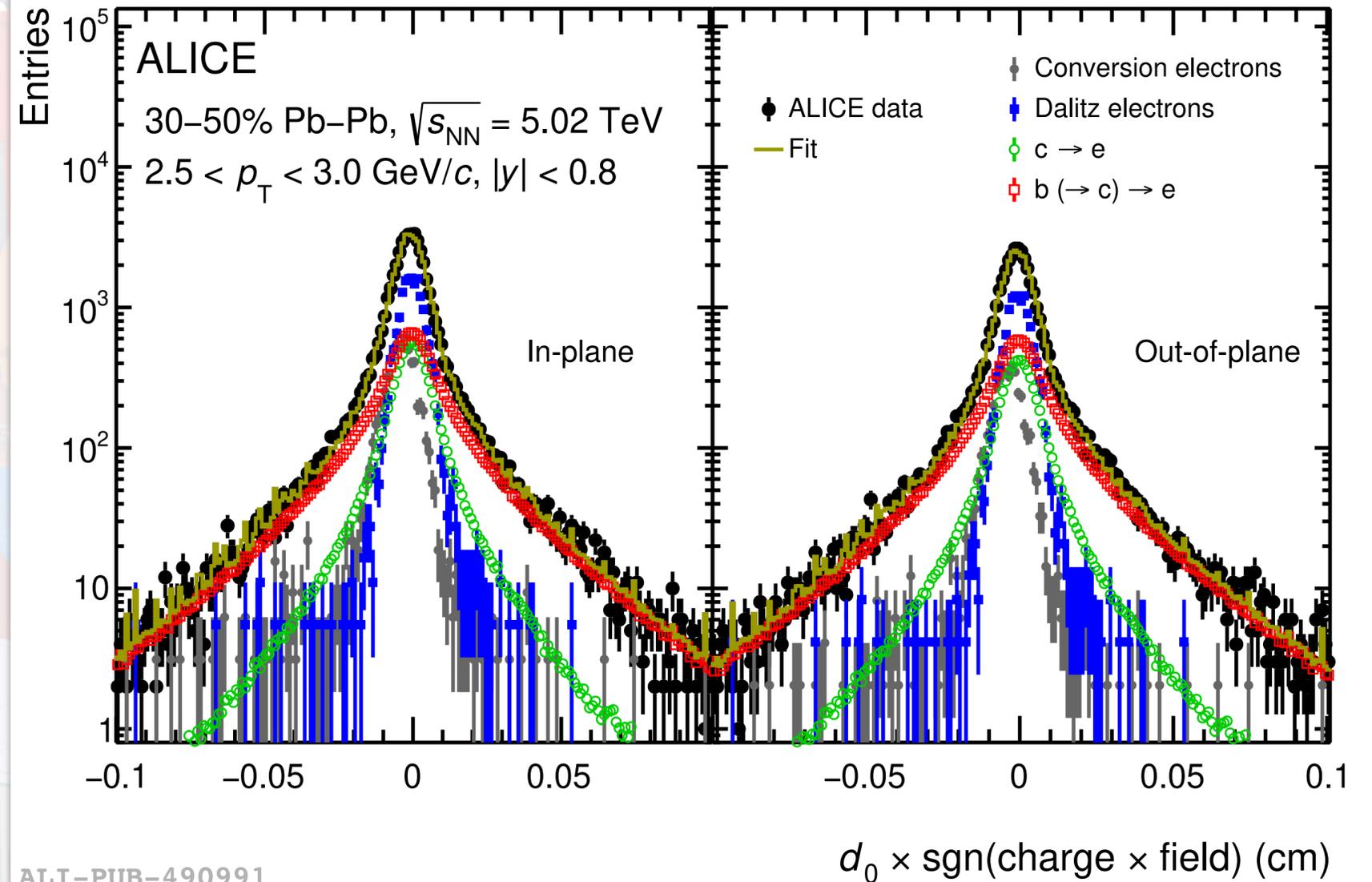
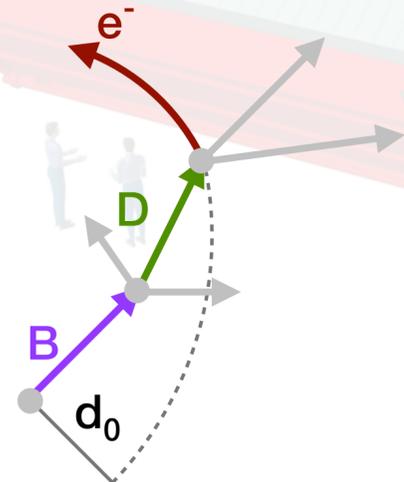
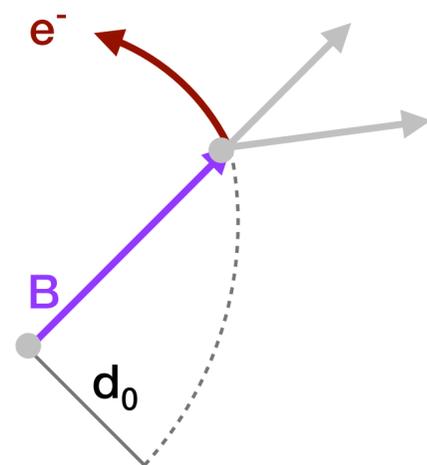
► Exploring:

➔ identification of  $e^\pm$  at mid rapidity

➔ tracking of  $\mu^\pm$  at forward rapidity

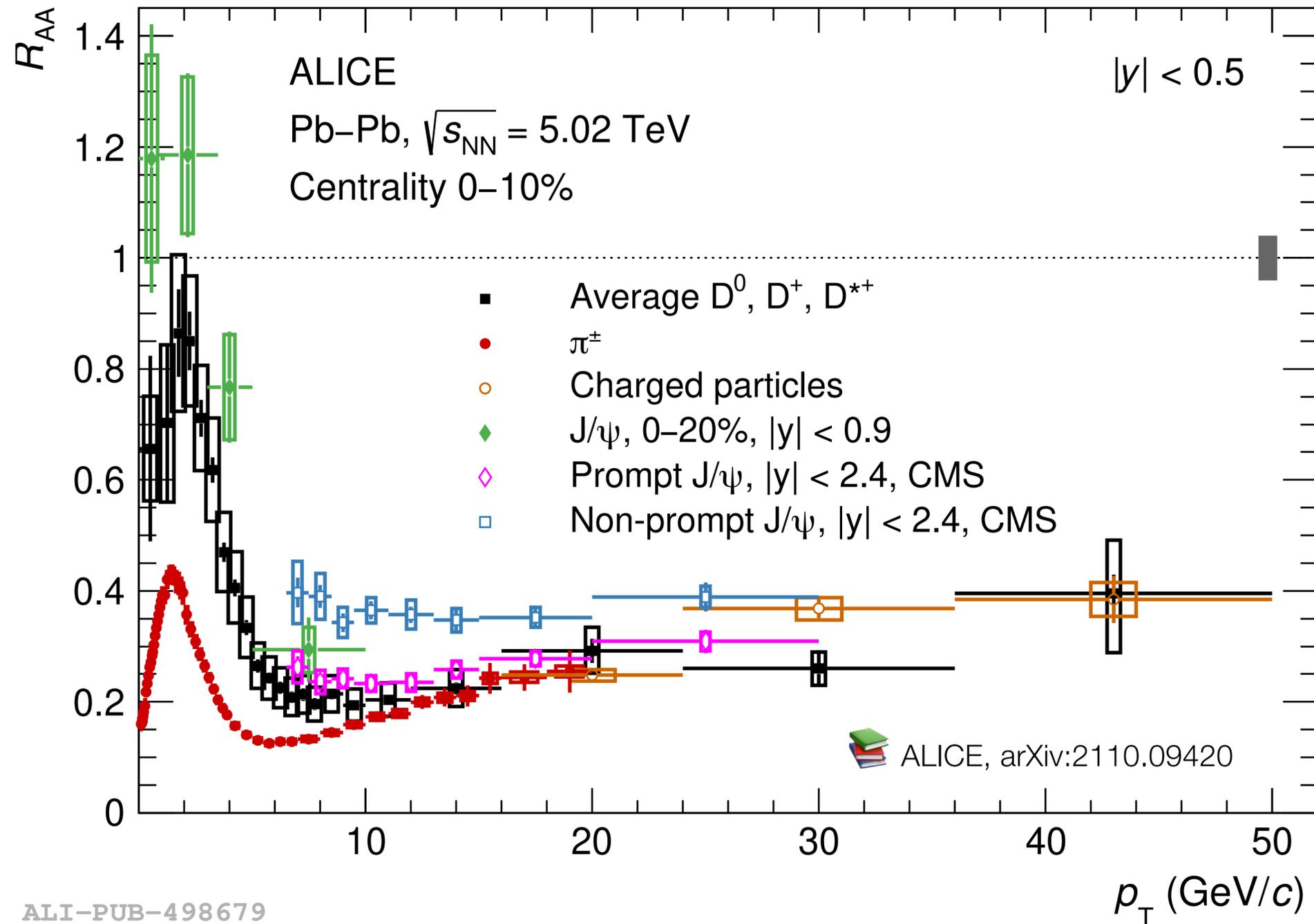
➔ subtraction of **hadron contamination** and **non-HF leptons**

➔ separation of **charm** and **beauty electrons** via **impact parameter  $d_0$**



ALI-PUB-490991

ALICE, PRL 126, 162001 (2021)



## Charm vs. light quarks

- ▶ low  $p_T$ :  $R_{AA}(D) > R_{AA}(\pi)$ 
  - ➔ several concurring effects (i.e. soft production of pion, radial flow, hadronisation mechanism)
- ▶ high  $p_T$ :  $R_{AA}(D) \cong R_{AA}(\pi)$ 
  - ➔ harder  $p_T$  distribution and frag. function of charm quark w.r.t. light quarks and gluons

ALI-PUB-498679

 $\pi^\pm$ , PRC 101 (2020) 044907

 incl.  $J/\psi$ , ALICE, PLB 805 (2020) 135434

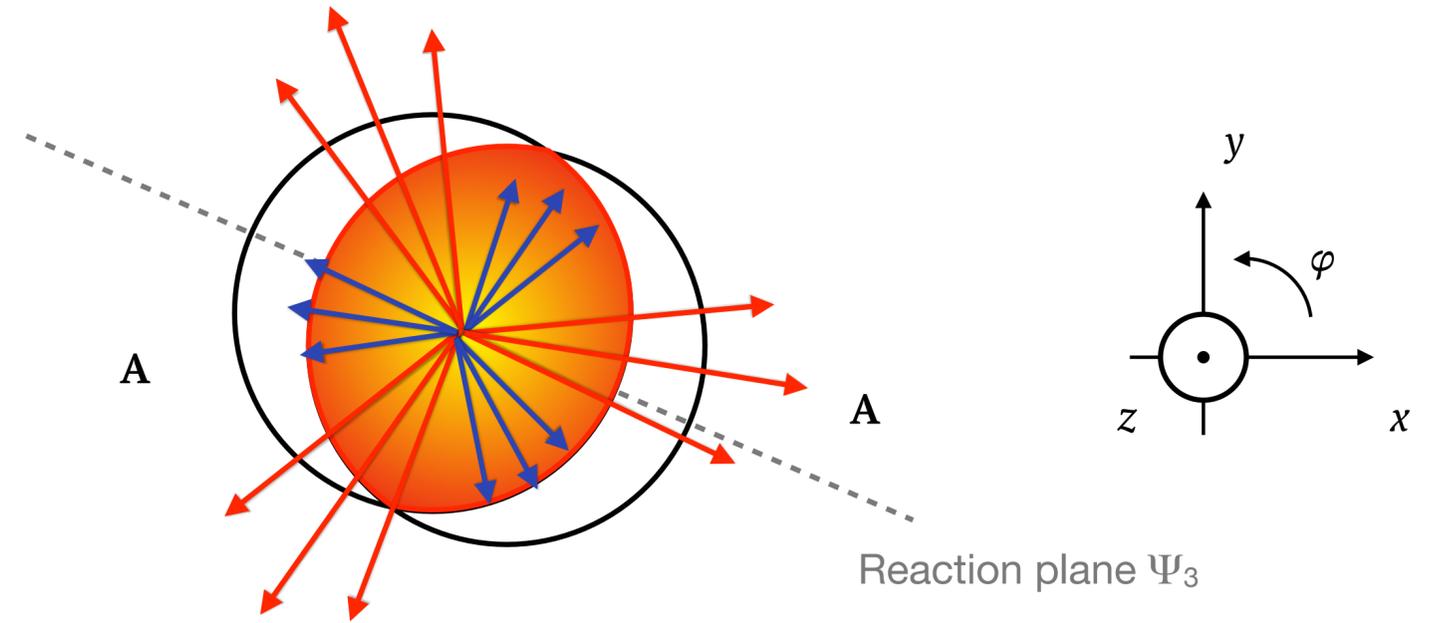
ch. particles, JHEP 11 (2018) 013

 prompt and non-prompt  $J/\psi$ , CMS, EPJC 78 (2018) 509

$$E \frac{d^3N}{dp_T} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left\{ 1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right\}$$

$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$  second harmonic coeff.  
**elliptic flow**

$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$  third harmonic coeff.  
**triangular flow**



## Event-shape engineering (ESE) <sup>[2]</sup>

technique that allows us to study various observables (e.g.  $v_n$ , yields,...) in classes of events corresponding to the **same centrality**, but **different eccentricity**

eccentricity  $\varepsilon$



$$\langle q_n^2 \rangle \simeq 1 + \langle (M - 1) \rangle \langle (v_n^2 + \delta_n) \rangle$$

small  $\varepsilon \rightarrow$  small  $q_n$

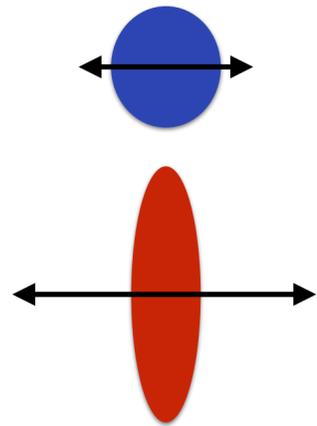
large  $\varepsilon \rightarrow$  large  $q_n$

[2] J. Schukraft, A. Timmins, S. Voloshin, Phys. Lett. B 719, 394 (2013)

- **Classification** of events at a certain centrality according to the **magnitude of the  $n^{\text{th}}$ -harmonic reduced flow vector**:

$$q_2 = |\vec{Q}_2| / \sqrt{M}$$

$$\vec{Q}_2 = \sum_{j=1}^M e^{i2\varphi_j}$$



20% smallest  $q_2^{\text{TPC}}$

$$\langle v_2 \rangle_{\text{small-}q_2} < \langle v_2 \rangle_{\text{unb}}$$

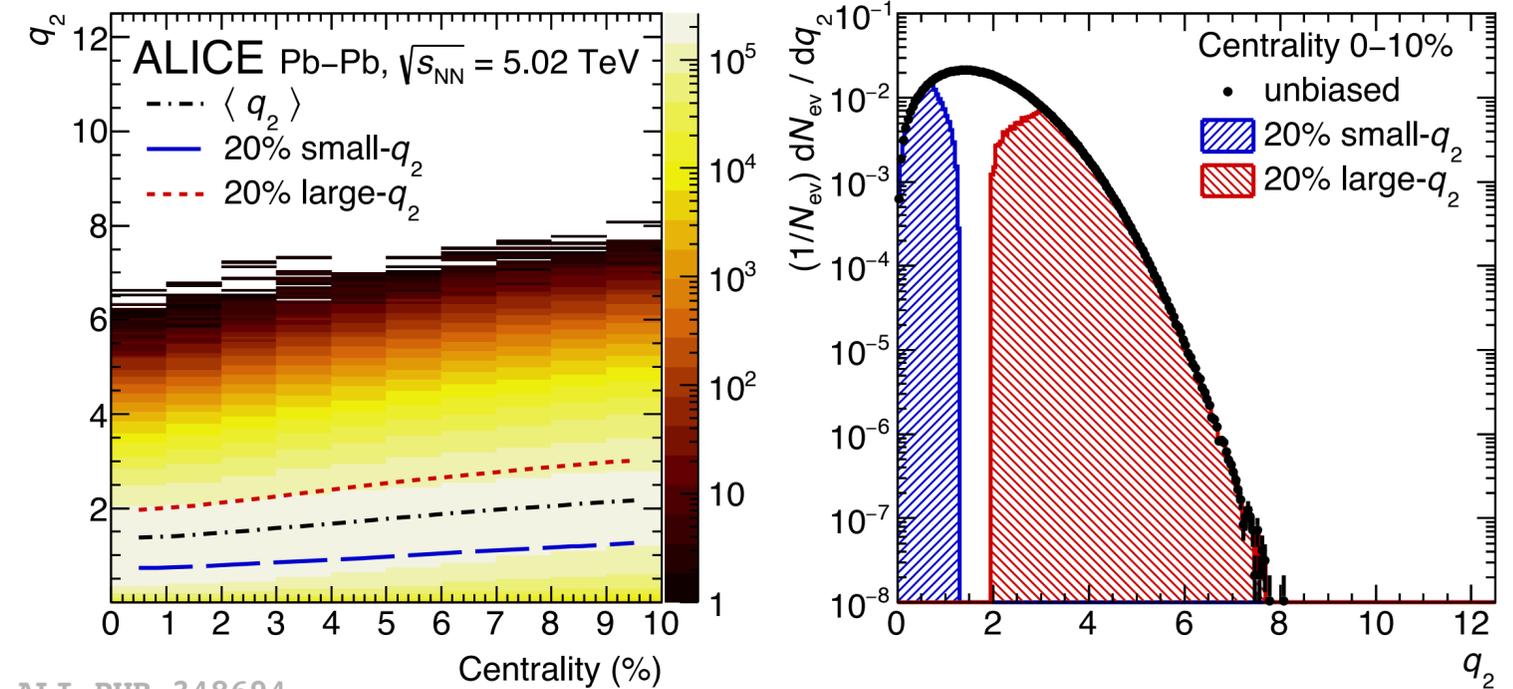
20% largest  $q_2^{\text{TPC}}$

$$\langle v_2 \rangle_{\text{large-}q_2} > \langle v_2 \rangle_{\text{unb}}$$

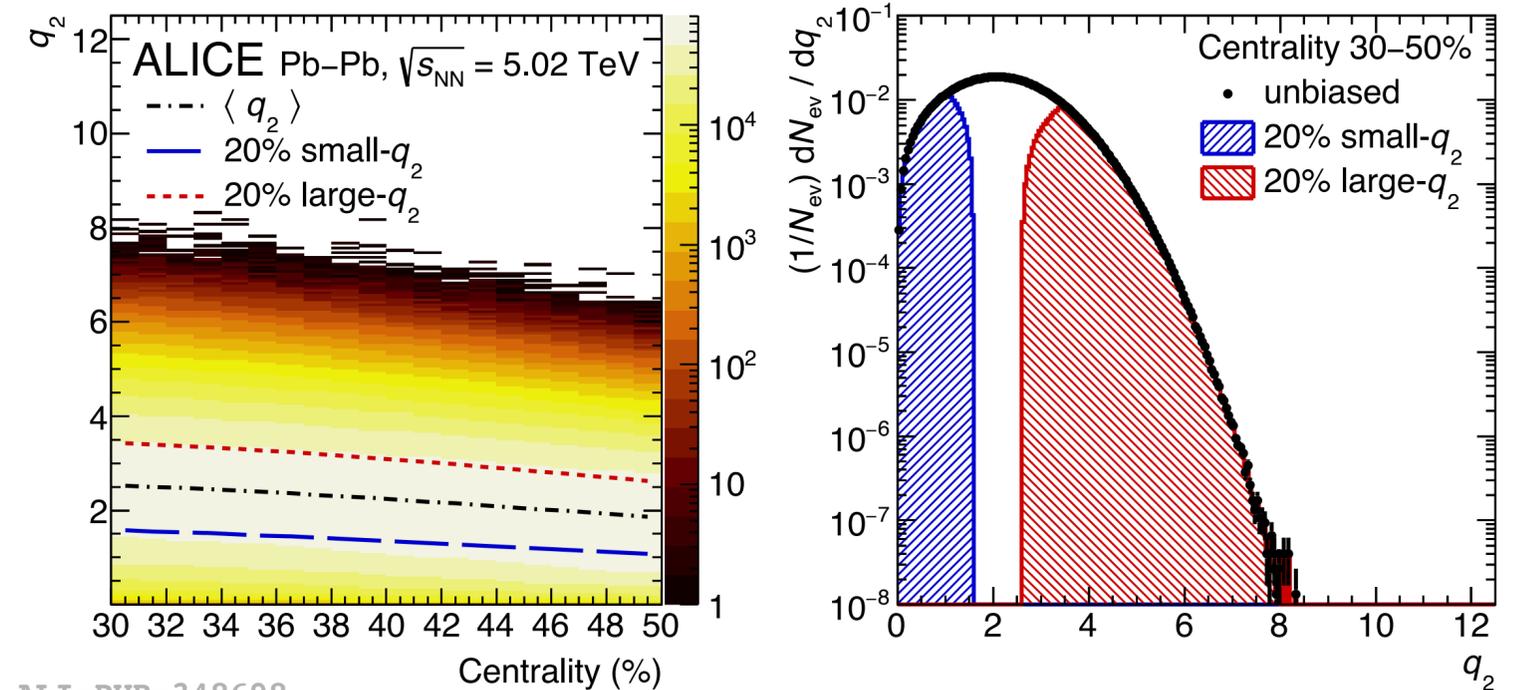
- **Elliptic flow** for different  $q_2$  samples:

➔ correlation between  $v_2$  of **D mesons** and **soft hadrons**

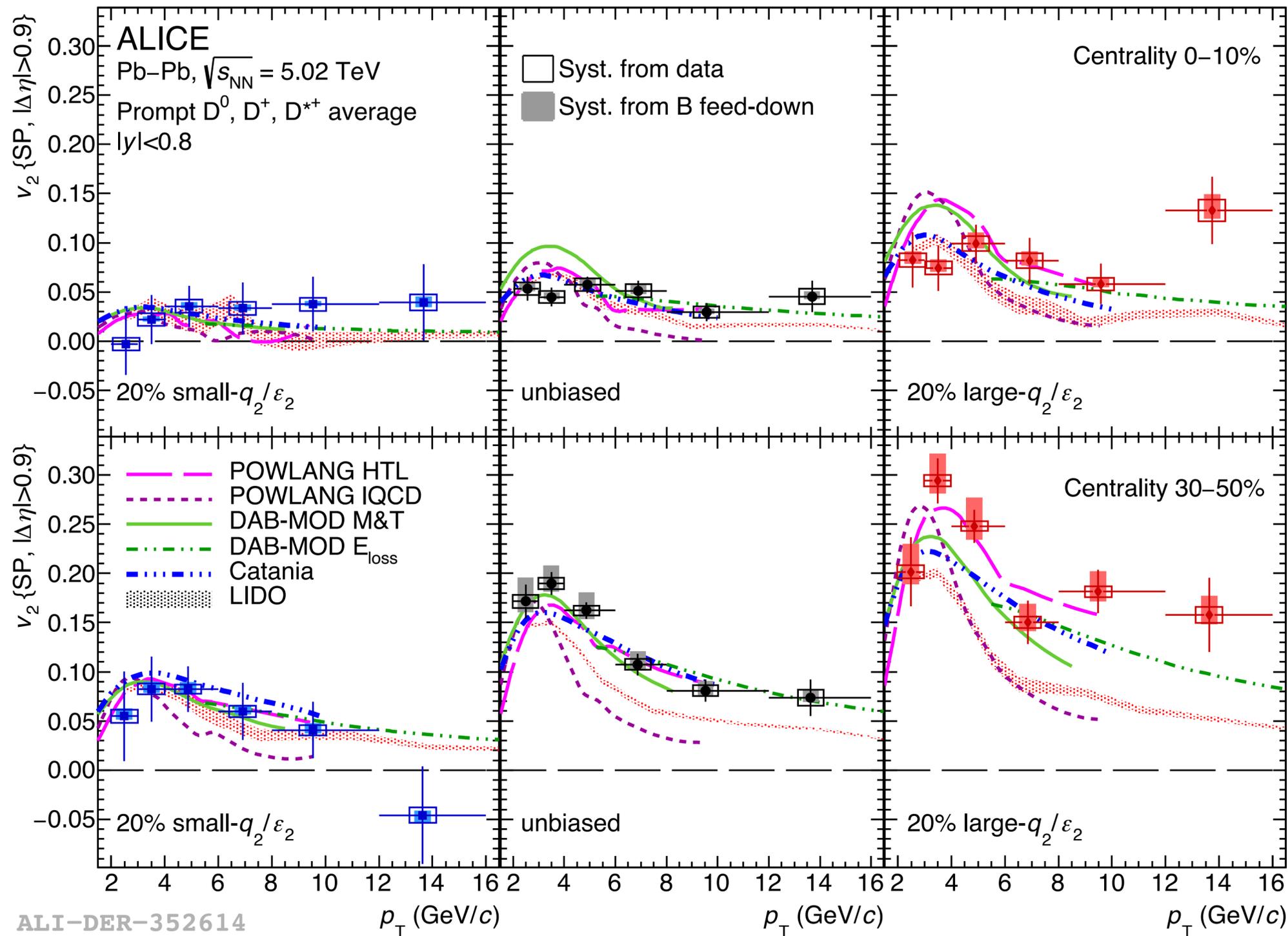
➔ event-by-event **fluctuations** in the **initial state**



ALI-PUB-348694



ALI-PUB-348698



- ▶ D-meson  $v_2$  in ESE-selected sample in **0-10%** and **30-50%** centrality class
- ▶ Results point to a **positive correlation** between **D-meson  $v_2$**  and **light-hadron  $v_2$**
- ▶ Models based on **charm-quark transport** in an hydrodynamically expanding medium reasonably describe the  **$q_2$  dependence of elliptic flow**

ALI-DER-352614



ALICE, PLB 813 (2021) 136054



POWLANG: EPJC 79, 494 (2019)



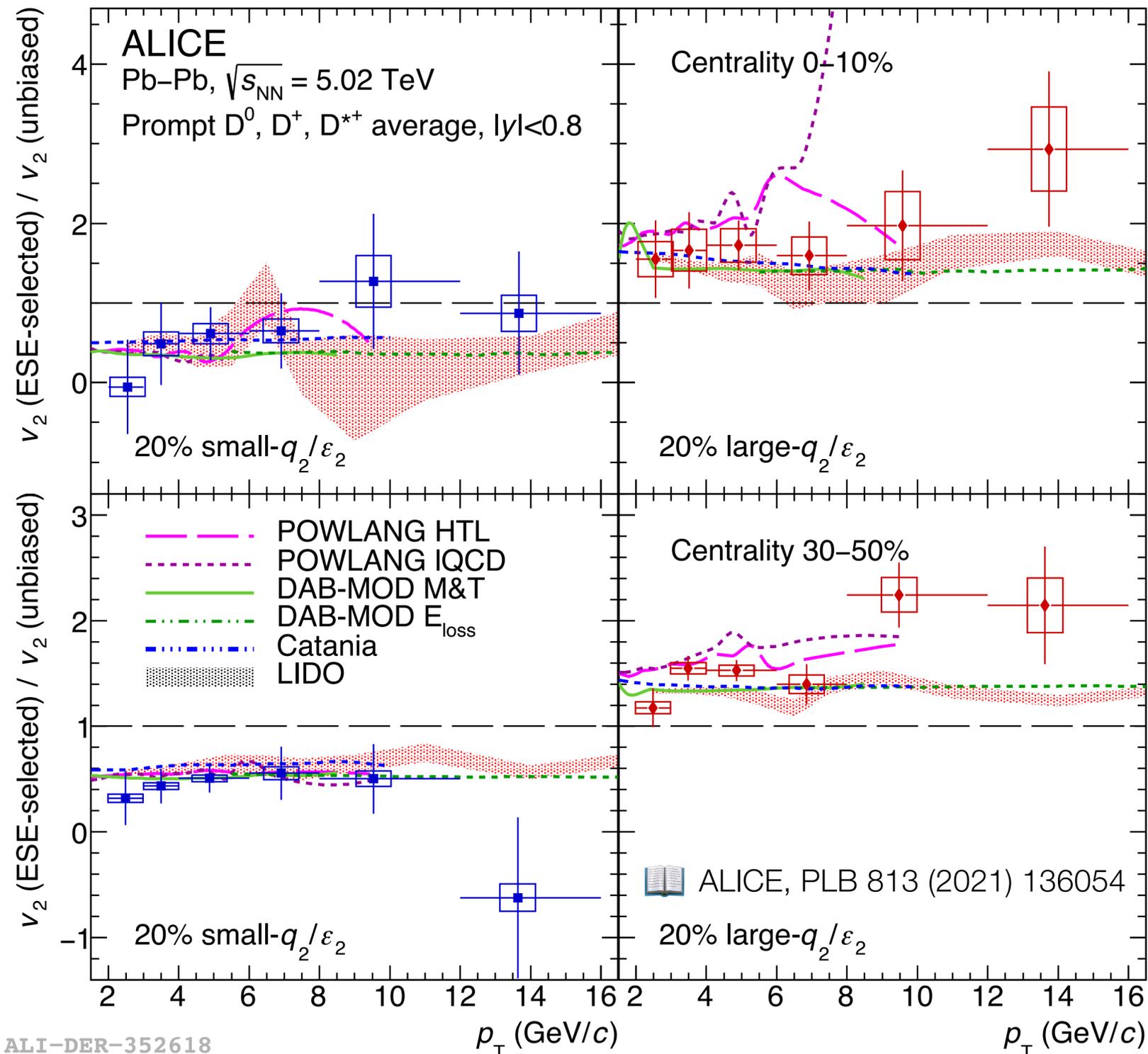
DAB-MOD M&T: PRC 96 064903 (2017)



LIDO: PRC 98 064901 (2018)



CATANIA: PLB 805 135460 (2020)

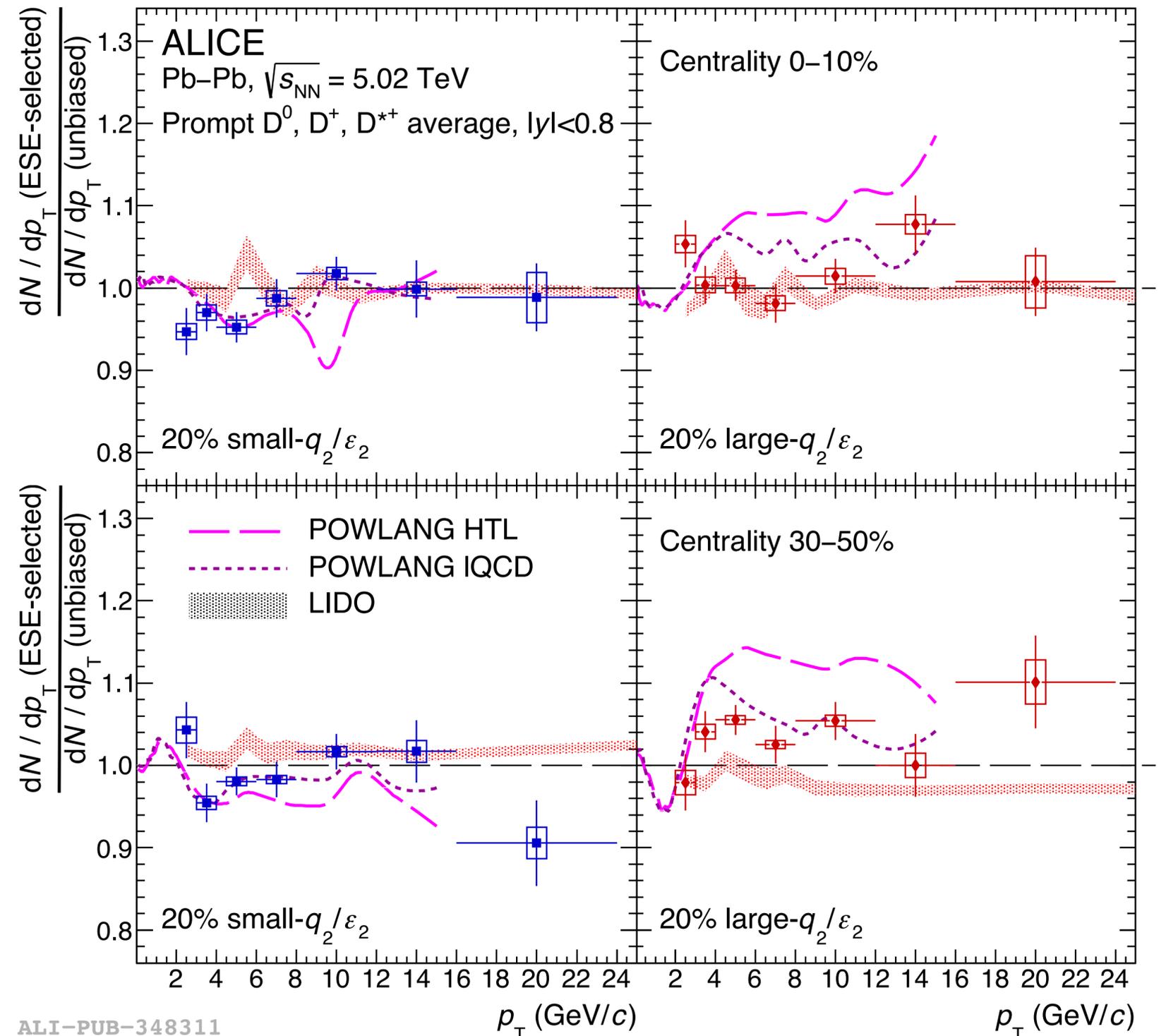


- ▶ **Ratio**  $v_2(\text{ESE-selected})$  to  $v_2(\text{unbiased})$ 
  - ➔  $v_2$  (large- $q_2$ /small- $q_2$ )  $\cong v_2$  (unbiased) of **about 50%** in both 0-10% and 30-50% centrality
  - ➔ similar **trend** observed for **light-hadron**
  
- ▶ Comparison with **charm-quark transport** models
  - ➔ **different implementations** of the same models give **similar predictions**

POWLANG: EPJC 79, 494 (2019)  
 DAB-MOD M&T: PRC 96 064903 (2017)

LIDO: PRC 98 064901 (2018)  
 CATANIA: PLB 805 135460 (2020)

- ▶ D-meson yield ratios in ESE-selected sample
  - ➔ investigate interplay **between elliptic flow and radial flow** (at low/intermediate  $p_T$ ) **and in-medium energy loss** (high  $p_T$ )
- ▶  $dN/dp_T$  (ESE)/ $dN/dp_T$  (unbiased) **compatible with the unity** within the uncertainties in both centrality classes
  - ➔ indication of no significant modification of the  $p_T$  distribution
  - ➔ more firm conclusions with larger data sample



ALI-PUB-348311