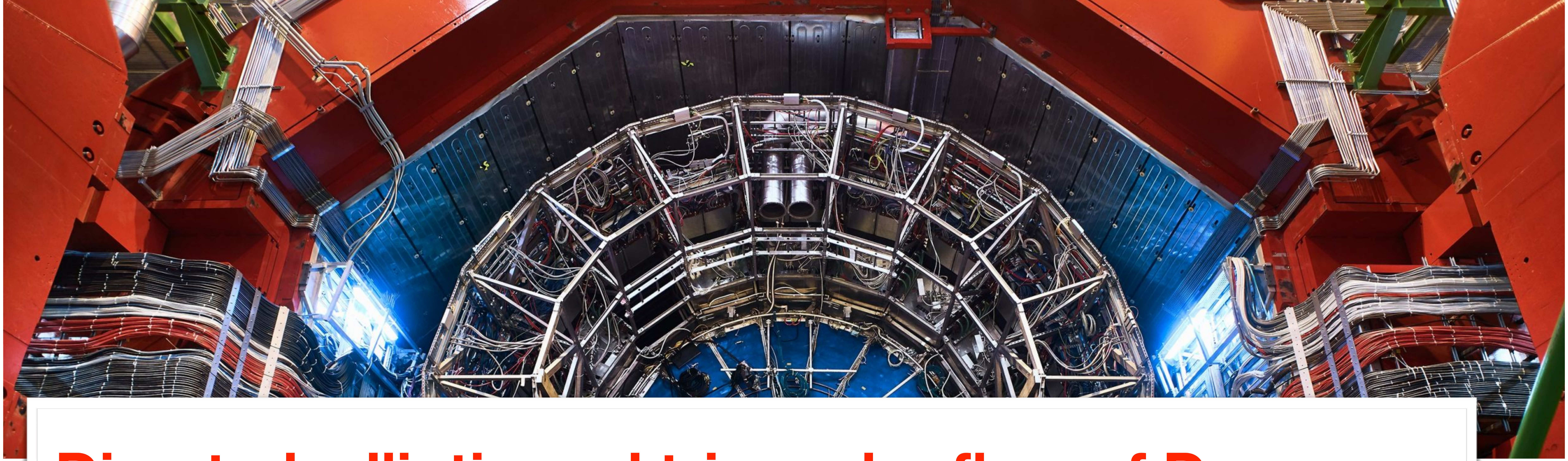

Directed, elliptic and triangular flow of D mesons in ALICE

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IS2021
The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

INFN

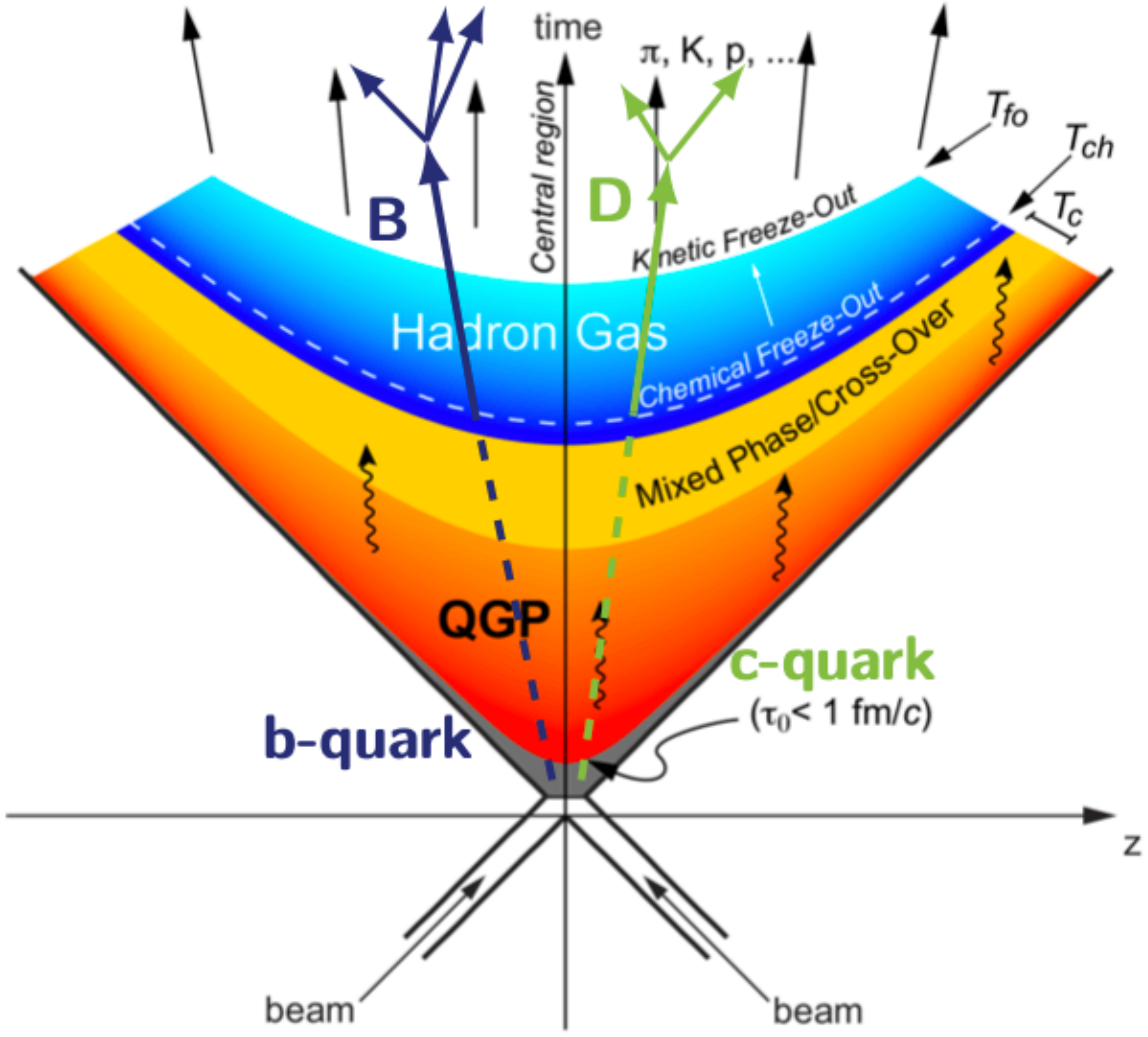
ALICE

Why heavy-quark azimuthal anisotropies?

- **Heavy-flavour-quark production restricted to the initial hard-scattering processes** because of their large masses

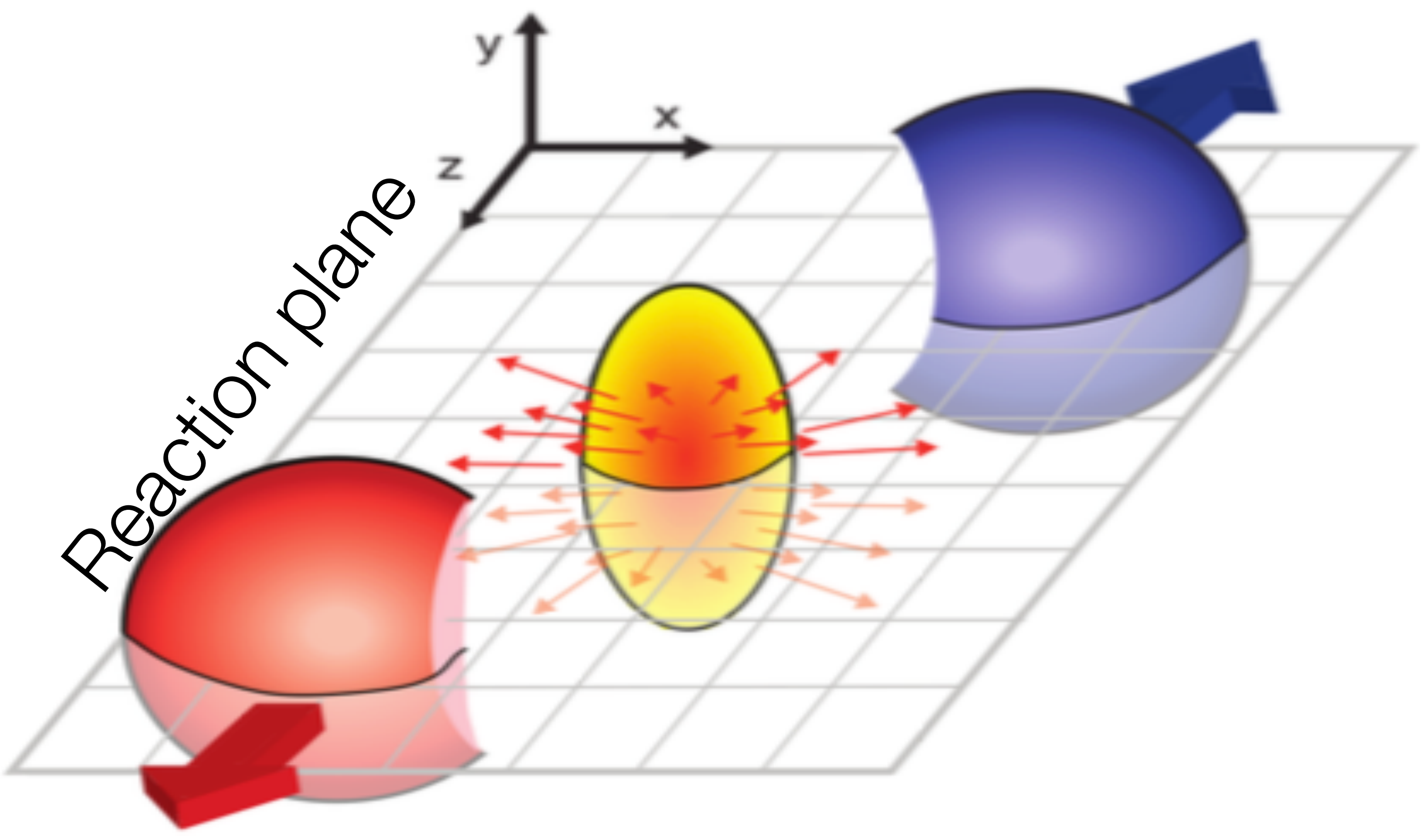
  Production time of $c\bar{c}(b\bar{b})$ pair at rest:
  $\tau_{prod} = \hbar/4m_{c(b)} \simeq 0.1(0.02)$ fm/c < $\tau_{QGP} \simeq 0.1\text{-}1$ fm/c

- **Probe the entire space-time evolution of the system** and **interact with the medium constituents** via elastic and inelastic processes



Azimuthal anisotropies allow the investigation of:
➡ the initial conditions of the system
➡ the interaction and coupling of heavy quarks with the medium

Elliptic and triangular flow



- **Initial spatial anisotropy transferred into final anisotropy in momentum via collective interactions**
- Expressed via the Fourier decomposition of the azimuthal distribution of particle momenta

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

Flow coefficients

$$v_n = \langle \cos(n(\varphi - \Psi_n))\rangle$$

n^{th} symmetry plane

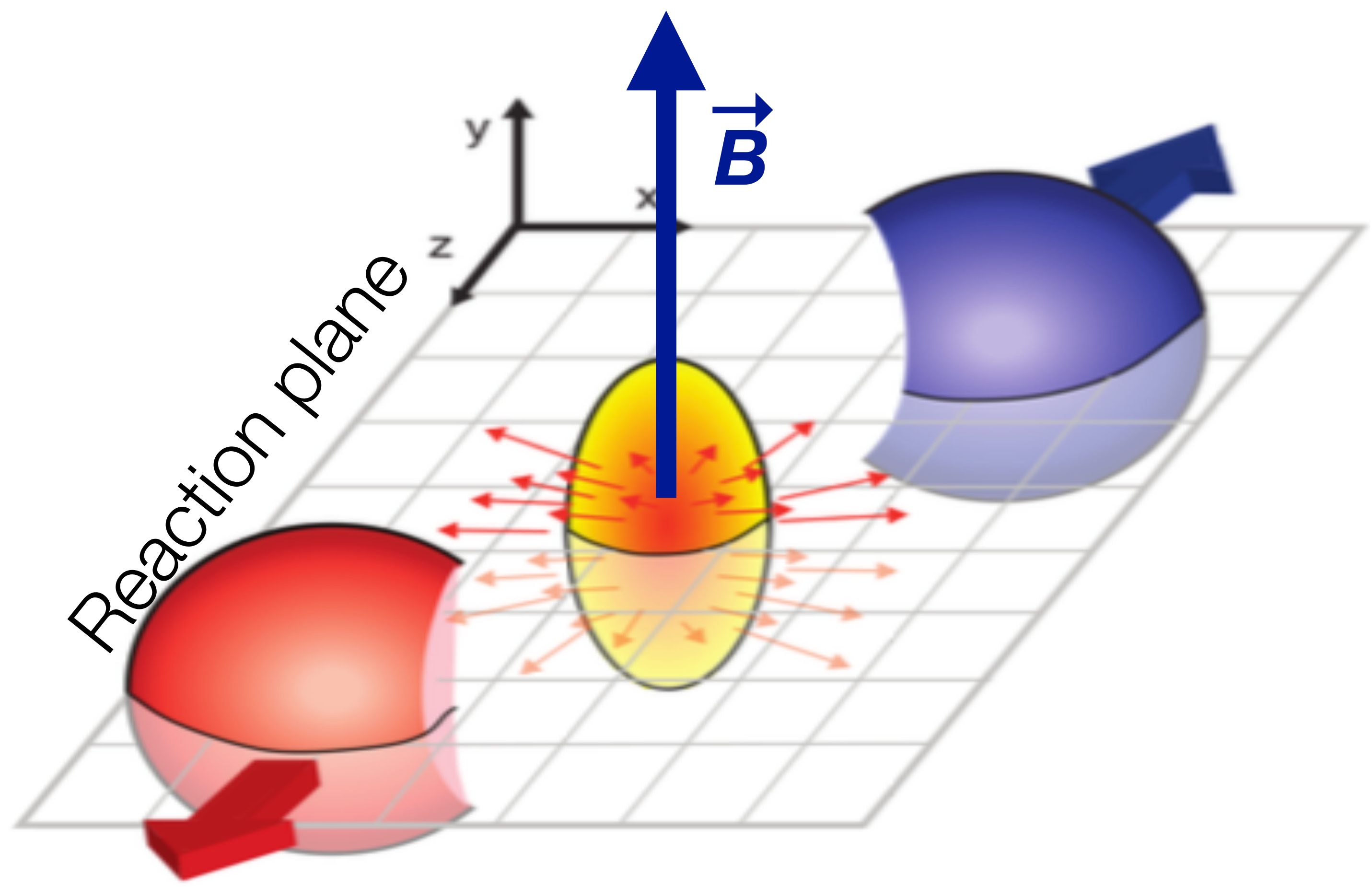
Elliptic flow (v_2):

- Originate from asymmetry between in-plane and out-of-plane direction
- HQ participation in the collective motion and **thermalisation** (at low p_T)
- **Path-length dependence of energy loss** (at high p_T)

Triangular flow (v_3):

- Originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region
- Sensitive to the ratio of shear viscosity to the entropy density η/s

Charge-dependent directed flow (v_1)

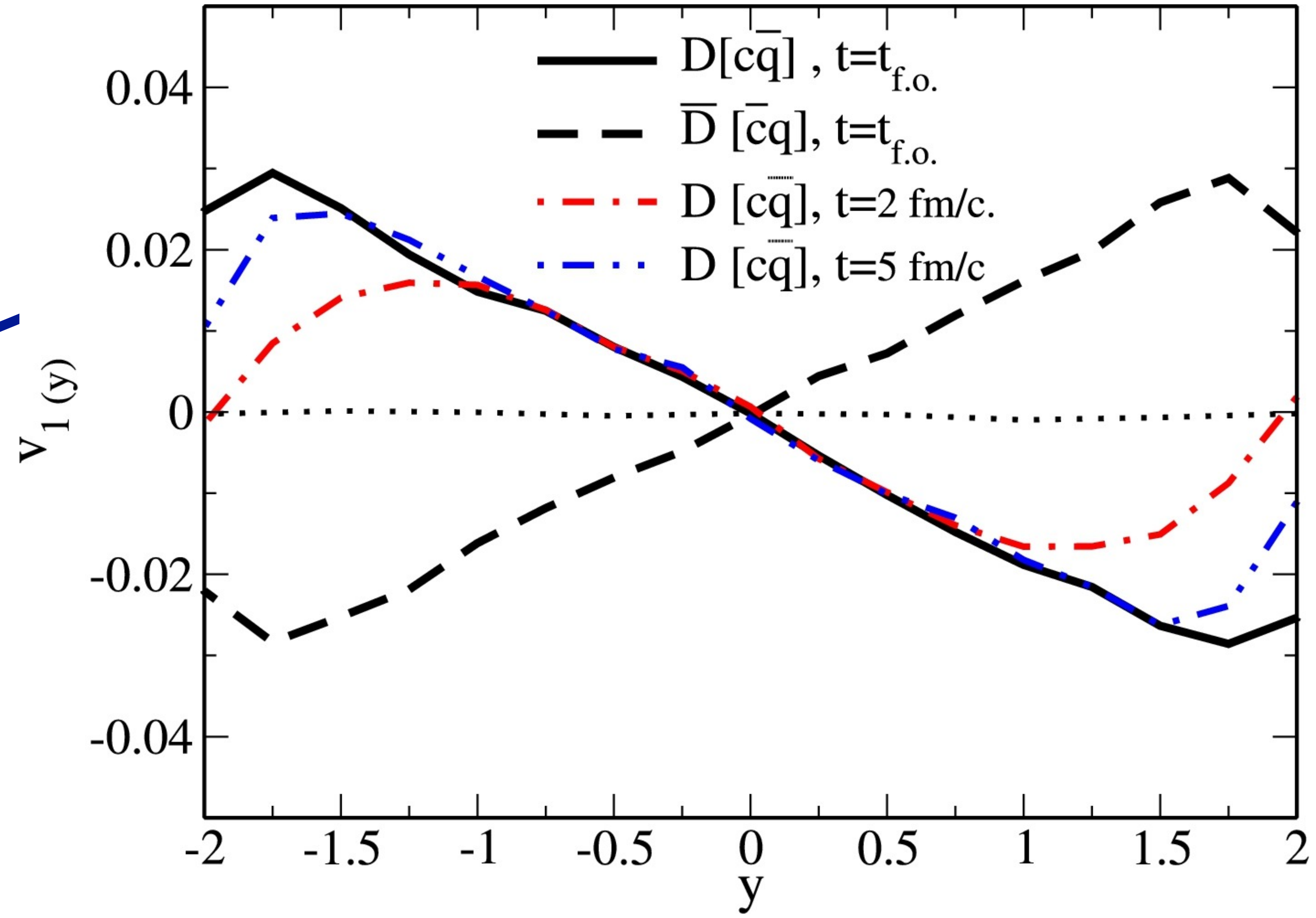


- **Strong magnetic field (~10¹⁸ G)** generated by the movement of spectator protons → quickly decreases (~1 fm/c) as the spectators fly away

- **Charm quarks are ideal probes** of the properties of this **magnetic field**
  - charm quarks produced when the magnetic field is maximum
  - kinetic relaxation time of charm similar to the QGP lifetime

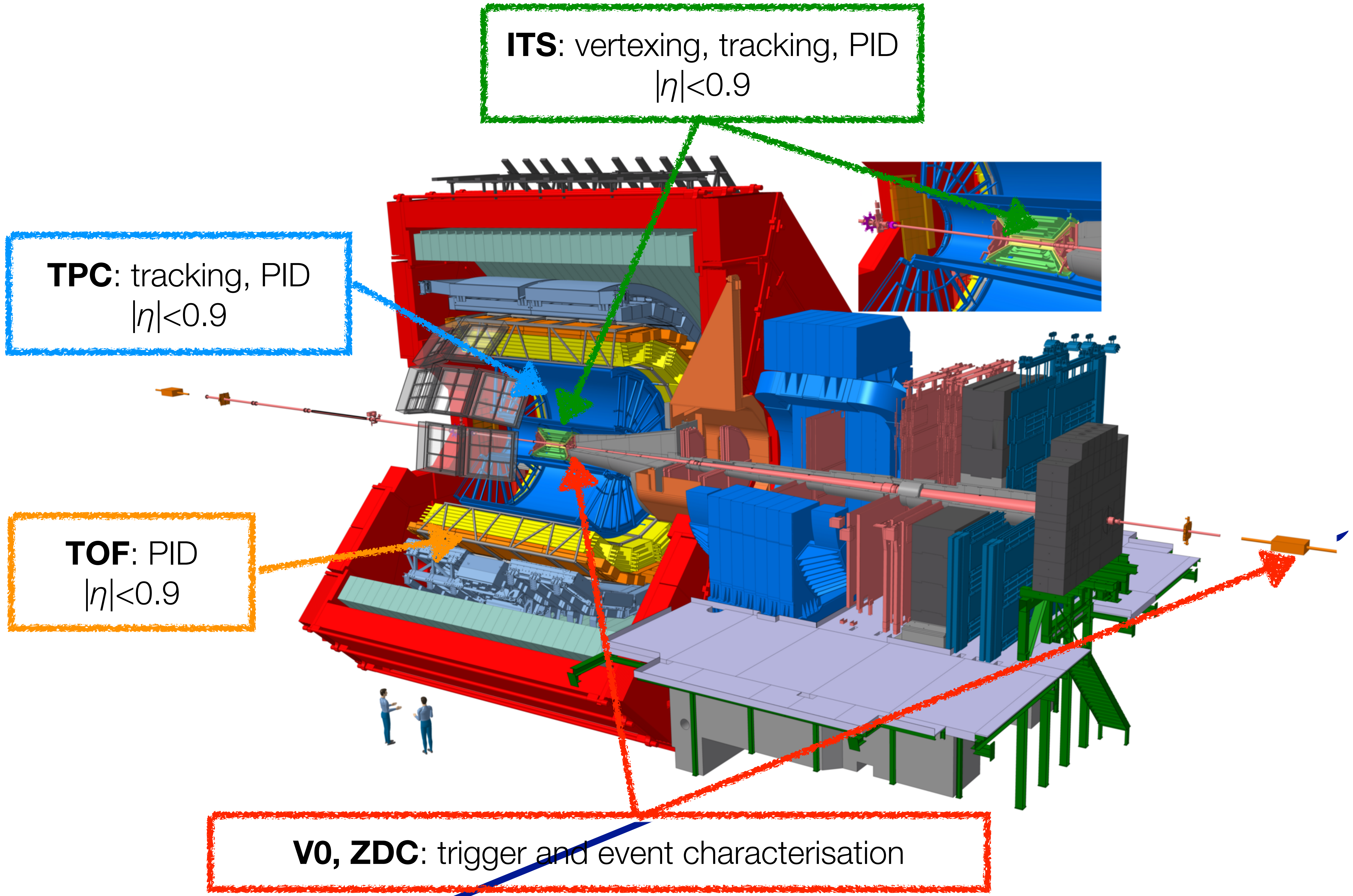
- **Theory predictions:**
  - larger direct flow of charm quarks compared to light quarks
  - opposite trend of $v_1(D^0)$ and $v_1(\bar{D}^0)$ vs η due to the magnetic field

S. Chatterjee, P. Bozek: PRL 120 (2018) 19, 192301; PLB 798 (2019) 134955
Y. Sun *et al.*: arXiv:2004.09880
L. Oliva *et al.*: arXiv:2009.11066



S. K. Das *et al.*, PLB 768 (2017) 260-264

ALICE layout



Fully reconstructed D mesons in hadronic decays

$D^0 \rightarrow K^-\pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \Phi\, \pi^+ \rightarrow K^-K^+\pi^+$

Data sample

Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

2015 dataset

$\mathscr{L}_{int}$(MB) ~ 13 μb^{-1} $\rightarrow v_1$

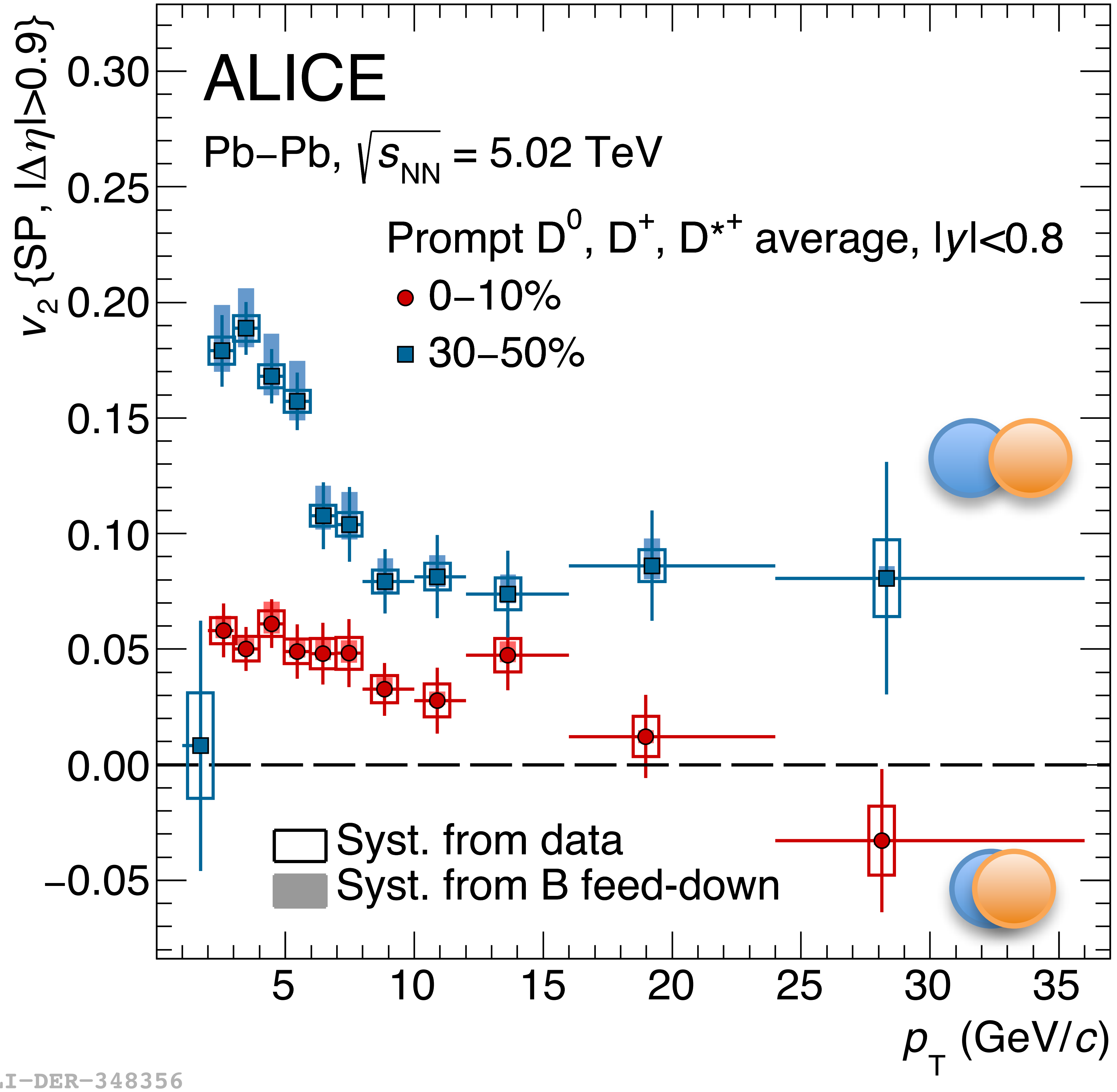
2018 dataset

$\mathscr{L}_{int}$(0-10%) ~ 130 μb^{-1} $\rightarrow v_2$ & v_3

$\mathscr{L}_{int}$(30-50%) ~ 56 μb^{-1} $\rightarrow v_2$ & v_3

D-meson v_2

PLB 813 (2021) 136054

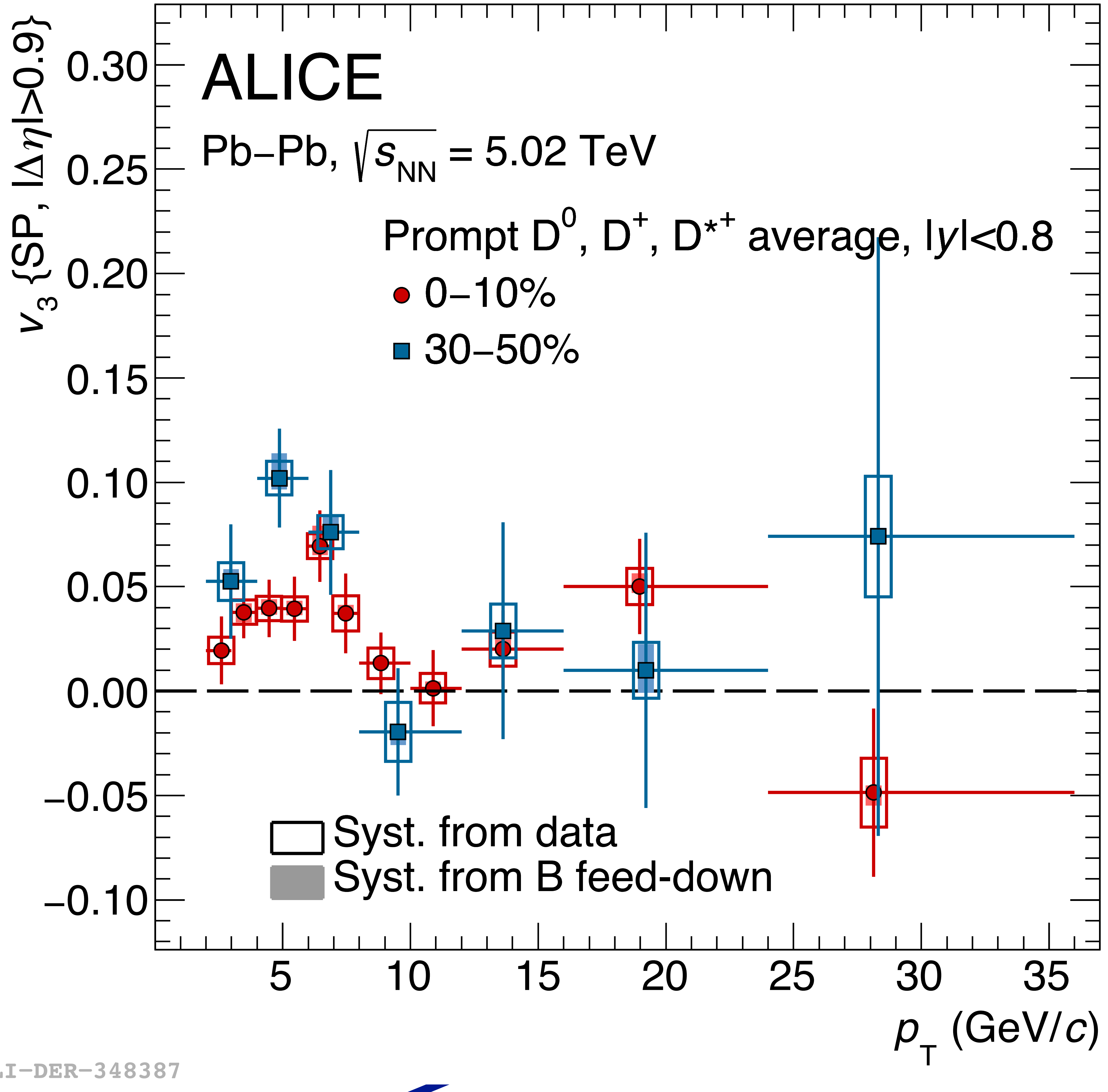


ALI−DER−348356

- ➡ **Positive v_2** for non-strange D mesons at $p_T > 2$ GeV/*c* in **0-10%** and **30-50%** centrality classes
- ➡ Increase from central to semi-central reflecting the increasing eccentricity of the interaction region

D-meson v_3

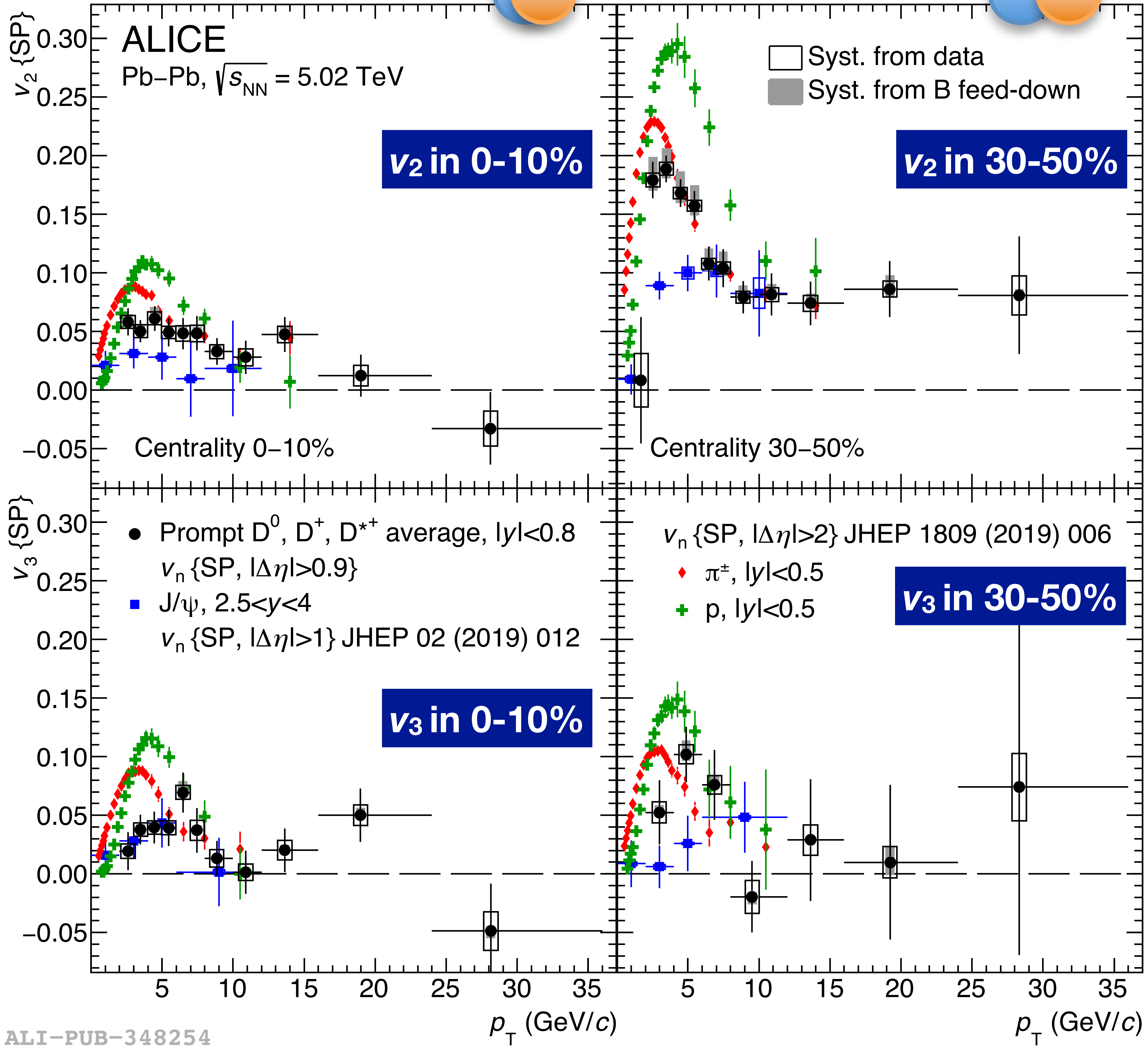
PLB 813 (2021) 136054



➡ **Positive v_3** for non-strange D mesons at $2 < p_T < 8$ GeV/c in **0-10%** and **30-50%** centrality classes

➡ Compatible within uncertainties in the two centrality classes as observed for light hadrons

Heavy-hadrons vs light-hadrons v_2 and v_3



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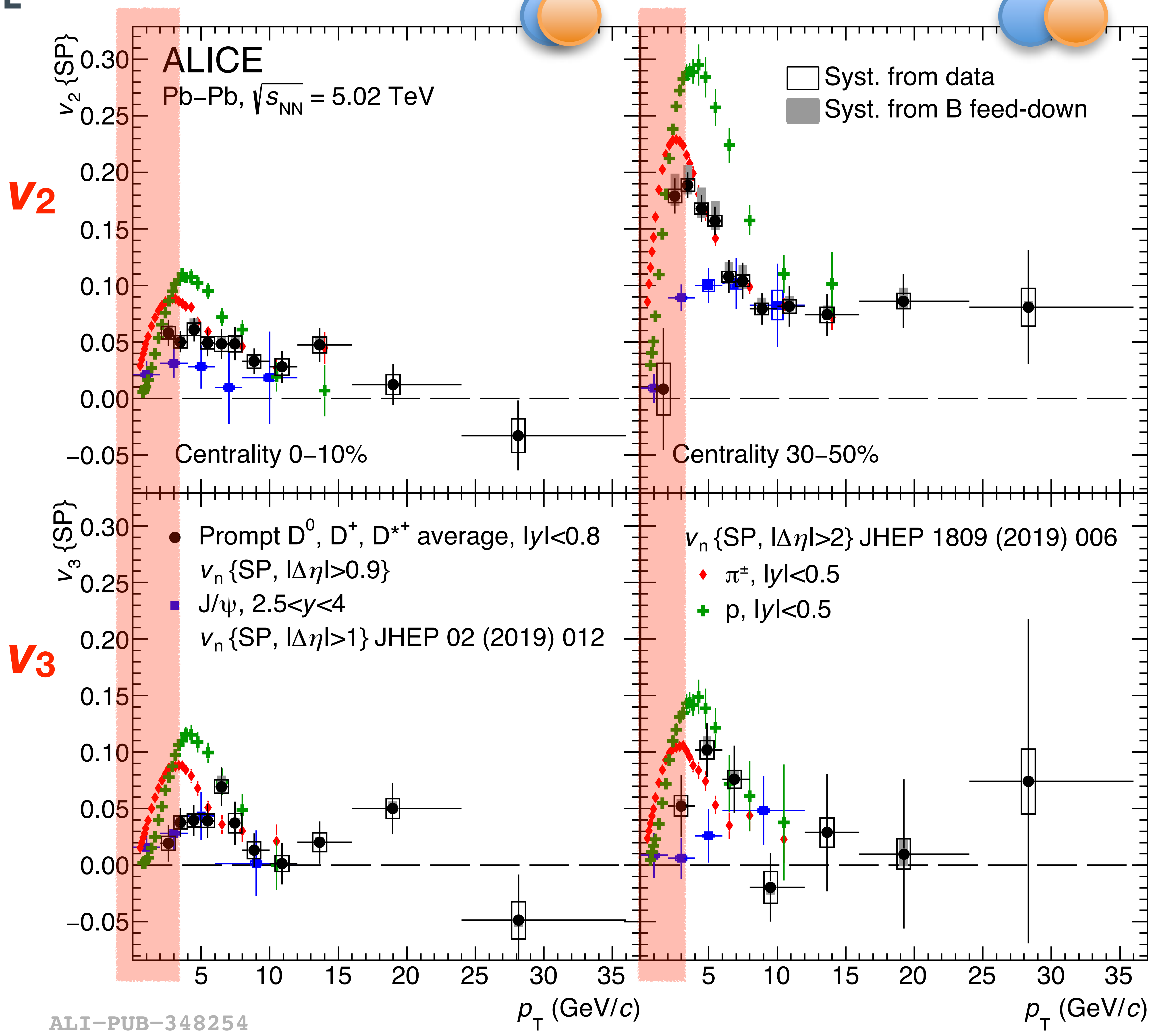
Heavy-hadrons vs light-hadrons v_2 and v_3



- p_T < 3 GeV/c → mass ordering

  $v_n(J/\psi) < v_n(D) < v_n(p) < v_n(\pi)$

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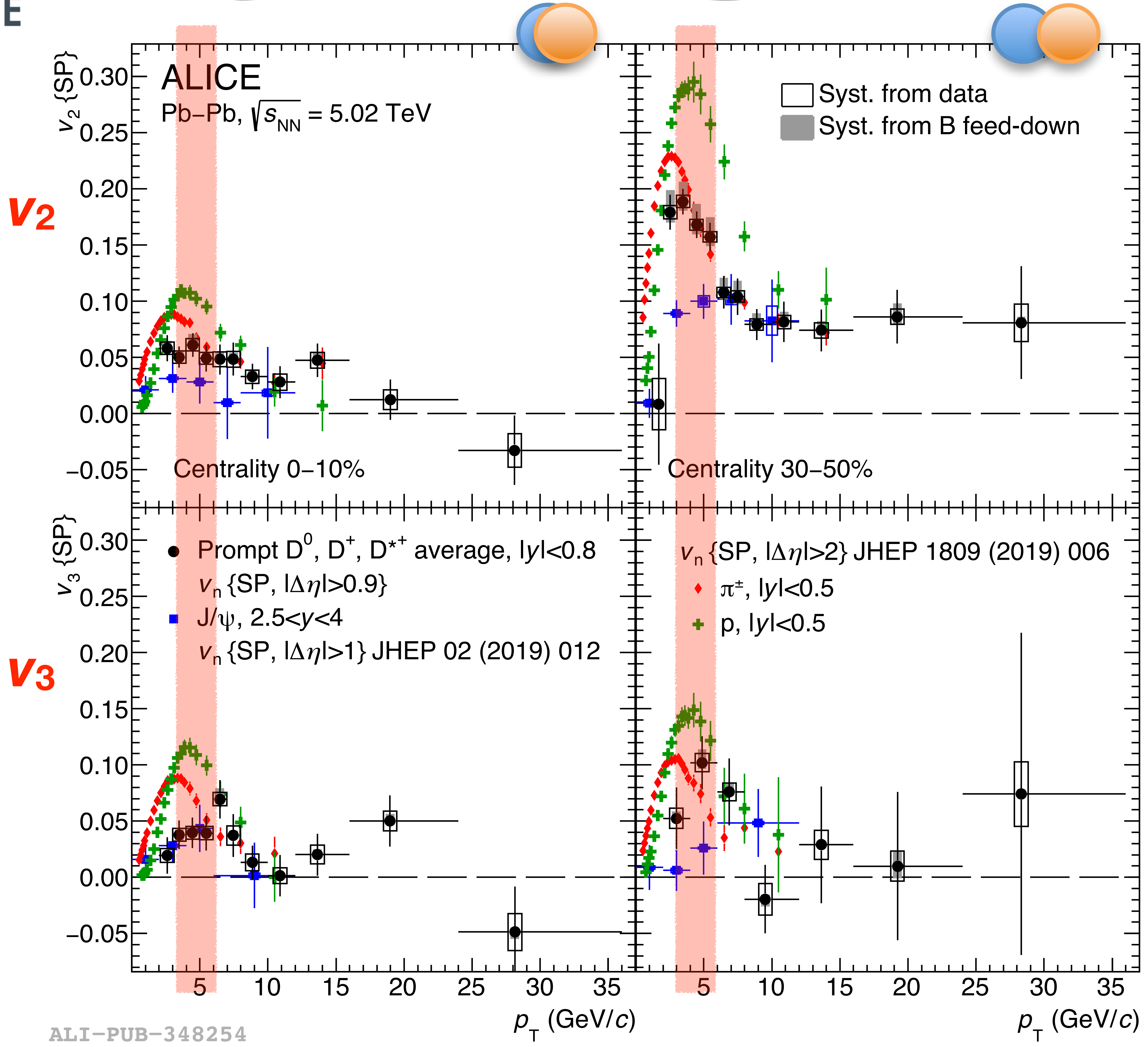
Heavy-hadrons vs light-hadrons v_2 and v_3



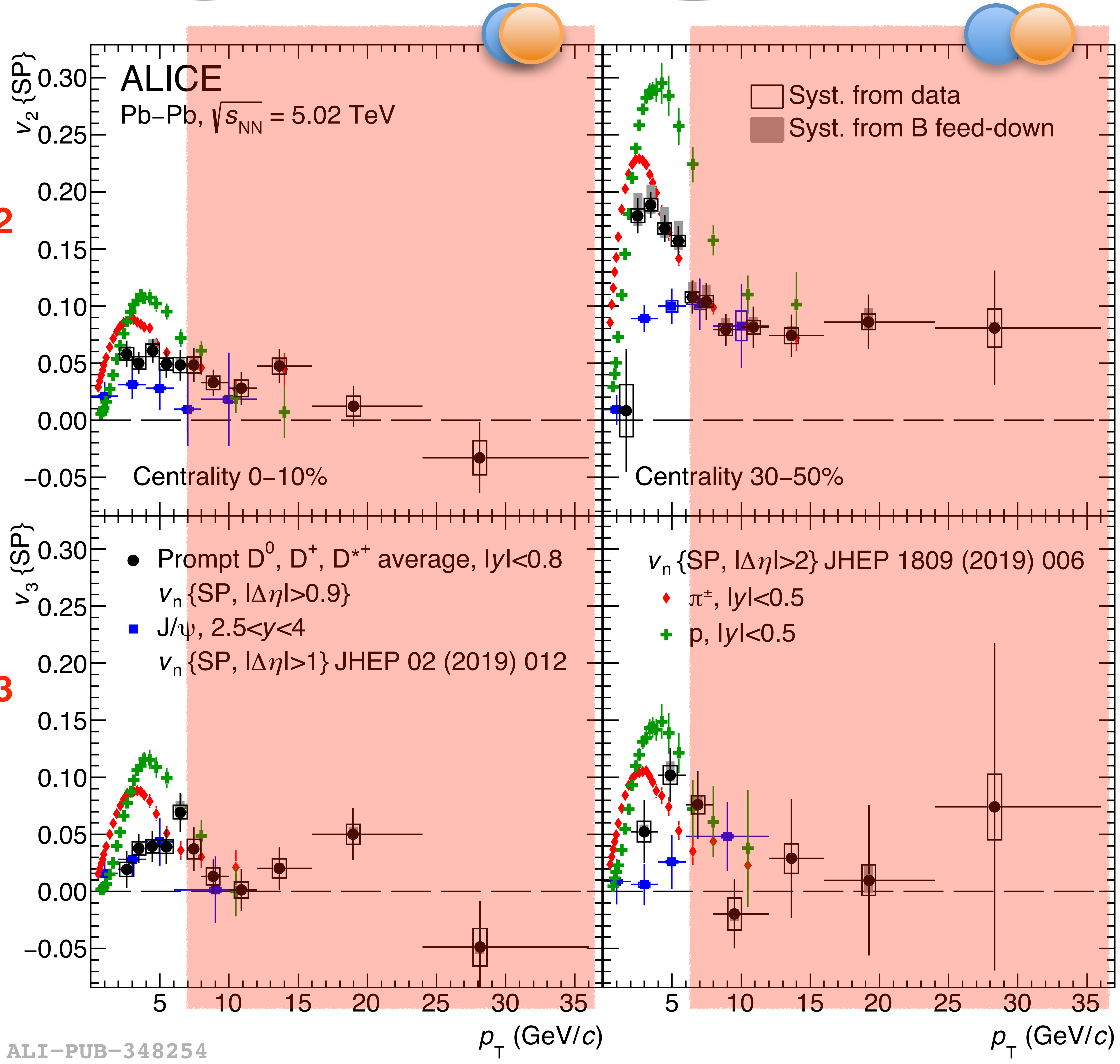
- $p_T < 3$ GeV/c → mass ordering
  $v_n(J/\psi) < v_n(D) < v_n(p) < v_n(\pi)$
- $3 < p_T <$ 6-8 GeV/c → charm quark coalescence with flowing light quarks
  $v_n(J/\psi) < v_n(D) \sim v_n(\pi) < v_n(p)$

PLB 813 (2021) 136054

Heavy-hadrons vs light-hadrons v_2 and v_3

v_2

v_3



- p_T < 3 GeV/c → mass ordering

  $v_n(J/\psi) < v_n(D) < v_n(p) < v_n(\pi)$

- 3 < p_T < 6-8 GeV/c → charm quark coalescence with flowing light quarks

  $v_n(J/\psi) < v_n(D) \sim v_n(\pi) < v_n(p)$

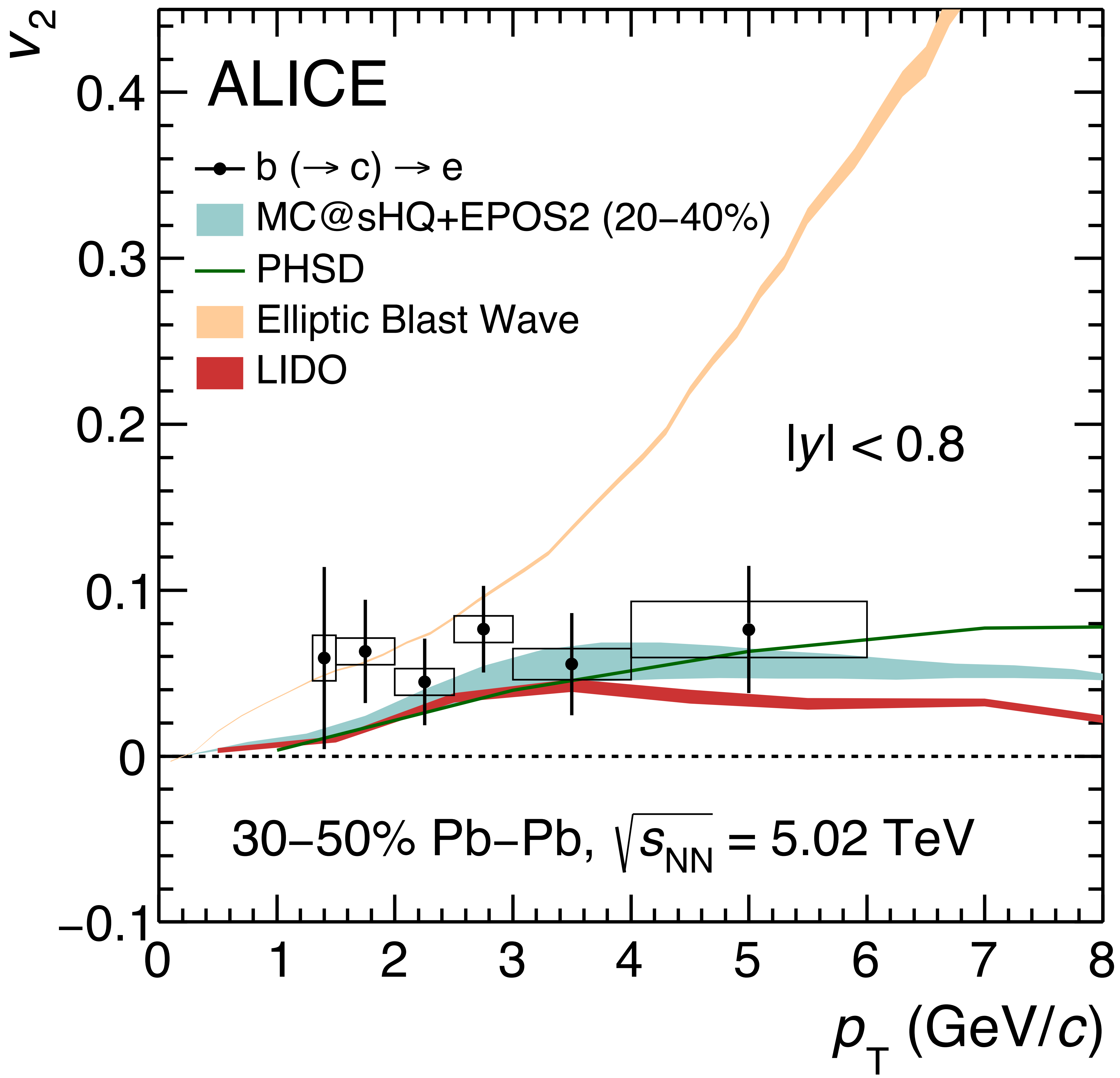
- p_T > 8 GeV/c → similar path-length dependence of the energy loss for light and heavy quarks

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

PLB 813 (2021) 136054

Elliptic flow of electrons from beauty-hadron decays

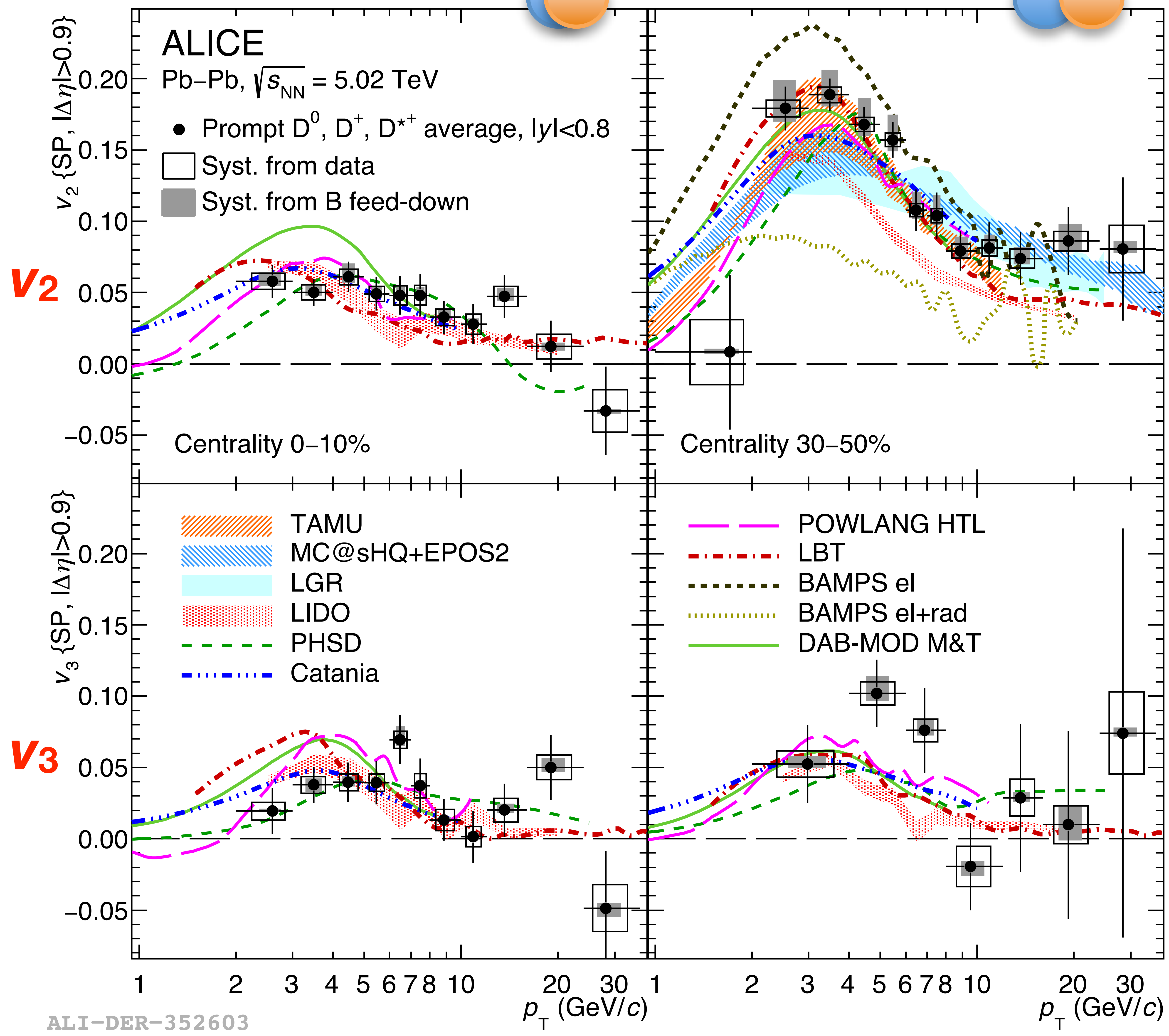
arXiv:2005.11130



ALI-PUB-347963

- **Positive v_2 for b→e (significance 3.75σ)**
- **Smaller than the v_2 of the D mesons**

D-meson v_2 and v_3 in transport models



All models include:

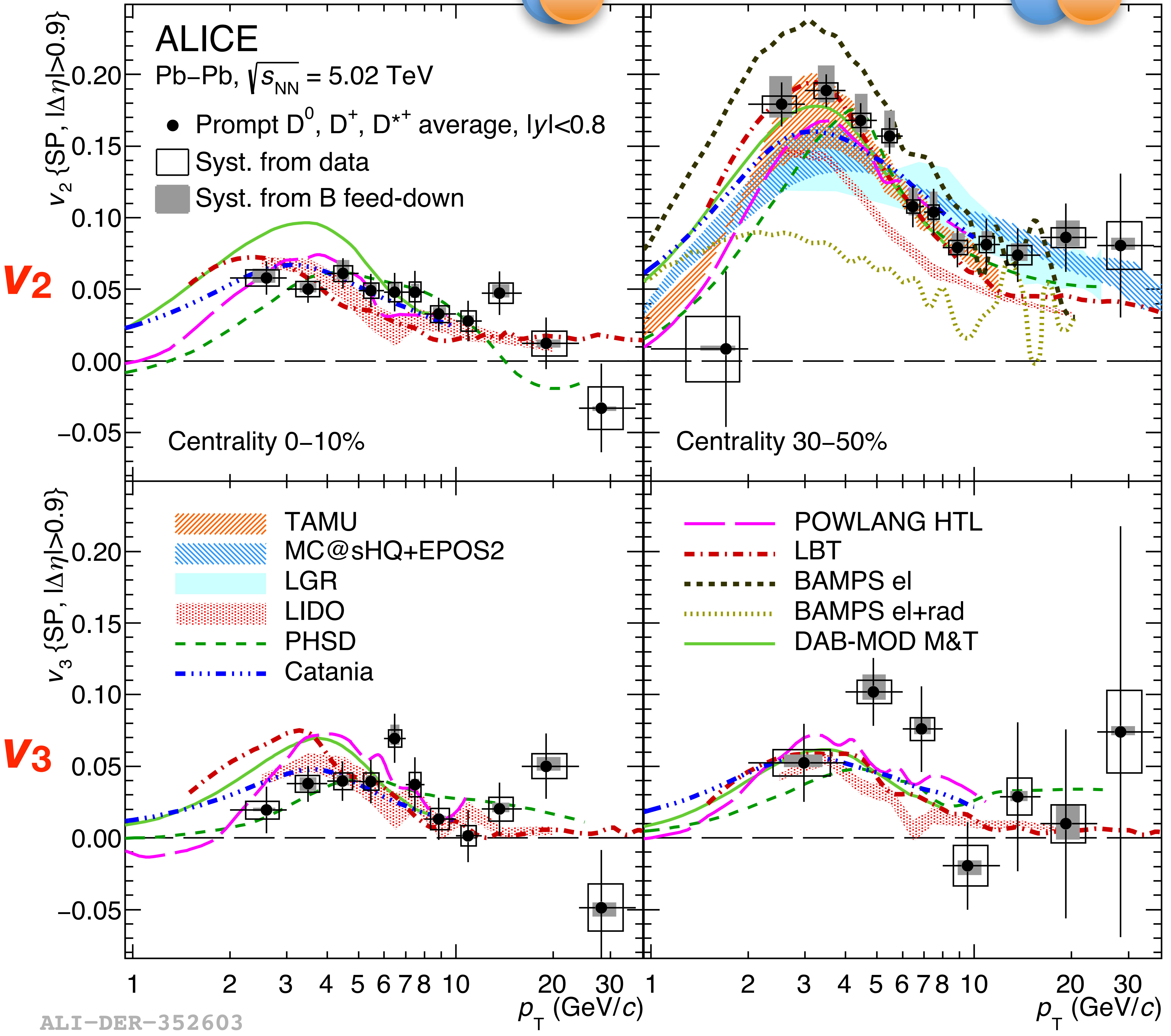
- ✓transport of charm quarks in a hydrodynamical expanding medium
- ✓charm-quark energy loss (collisional and/or radiative)
- ✓hadronisation via quark coalescence and fragmentation (except BAMPS)

Models predicting v_3 also include initial-state event-by-event fluctuations

PLB 813 (2021) 136054

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)

D-meson v_2 and v_3 in transport models



All models include:

- ✓transport of charm quarks in a hydrodynamical expanding medium
- ✓charm-quark energy loss (collisional and/or radiative)
- ✓hadronisation via quark coalescence and fragmentation (except BAMPS)

Models predicting v_3 also include initial-state event-by-event fluctuations

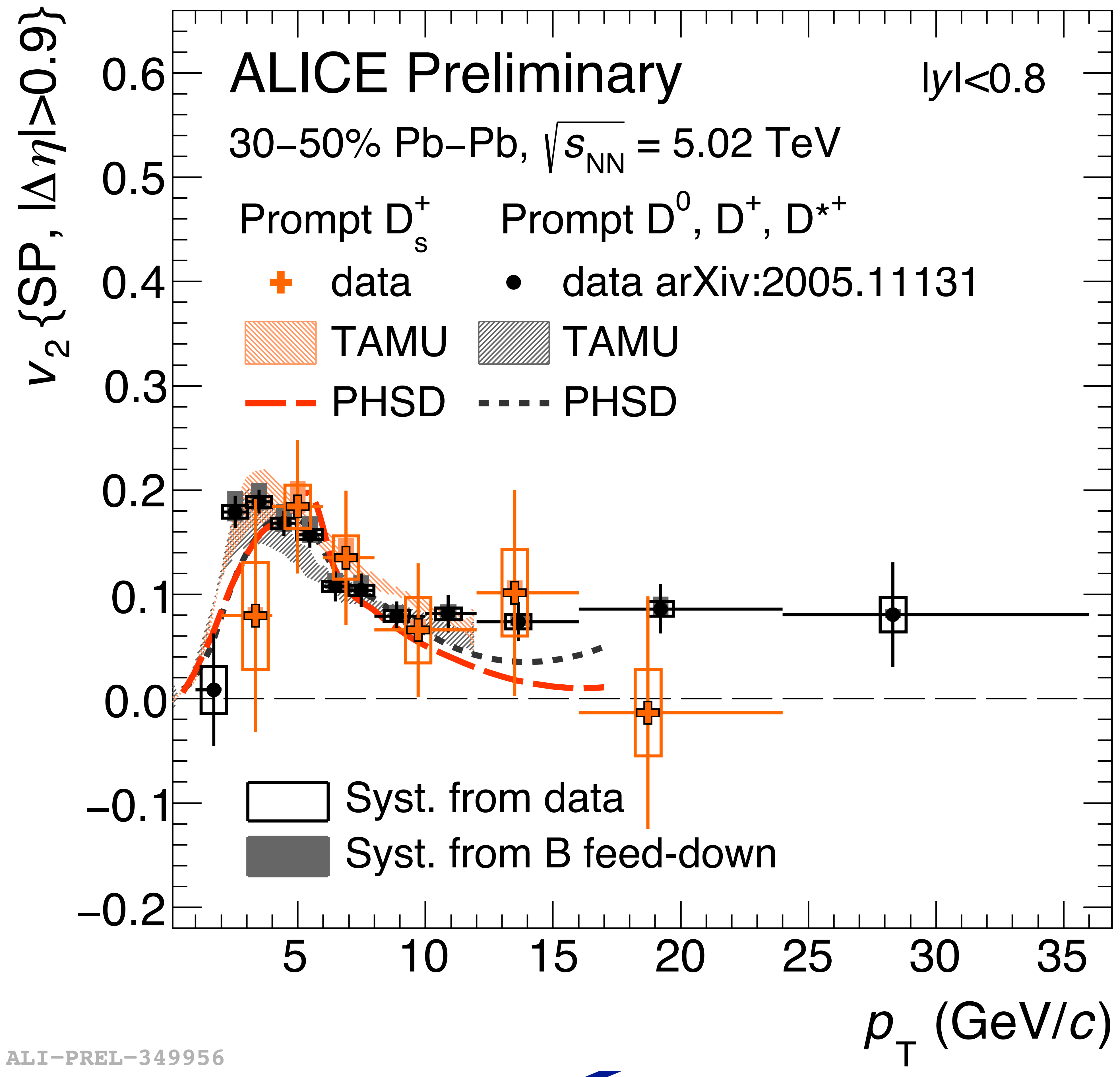
Constrain charm spatial diffusion coefficient:
$1.5 < 2\pi T D_s < 7$ at $T = T_c$
for models that describe the data with χ^2/ndf < 2

➡**charm thermalisation time**: **τ_{charm} = 3-14 fm/c**

PRL 120 (2018) 102301

PLB 813 (2021) 136054

D_s^+-meson v_2

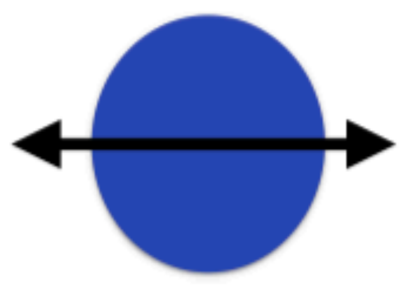


- ➡ $v_2(D_s^+)$ ~ $v_2(D)$ within large uncertainties
- ➡ Hadronisation via quark recombination included in both TAMU and PHSD models
- ➡ Good agreement between data and models

Event-shape engineering (ESE)

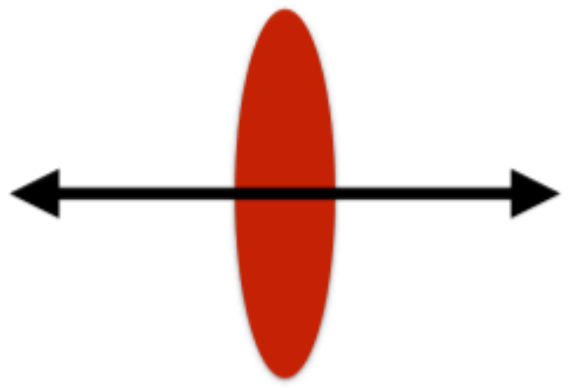
- **Events classified on the basis of the eccentricity,** according to the magnitude of the second harmonic reduced flow vector q_2

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



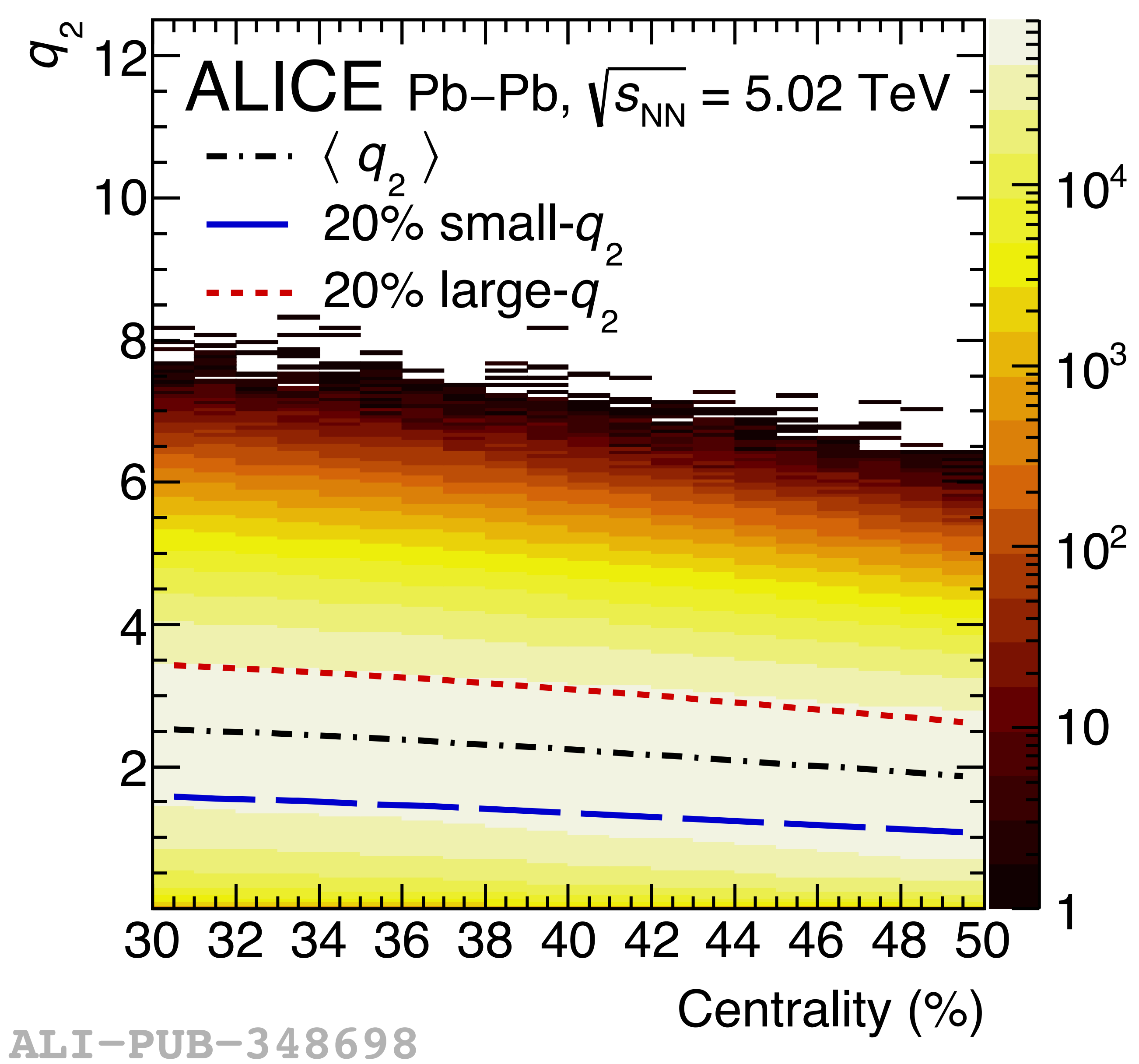
20% smallest q_2

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

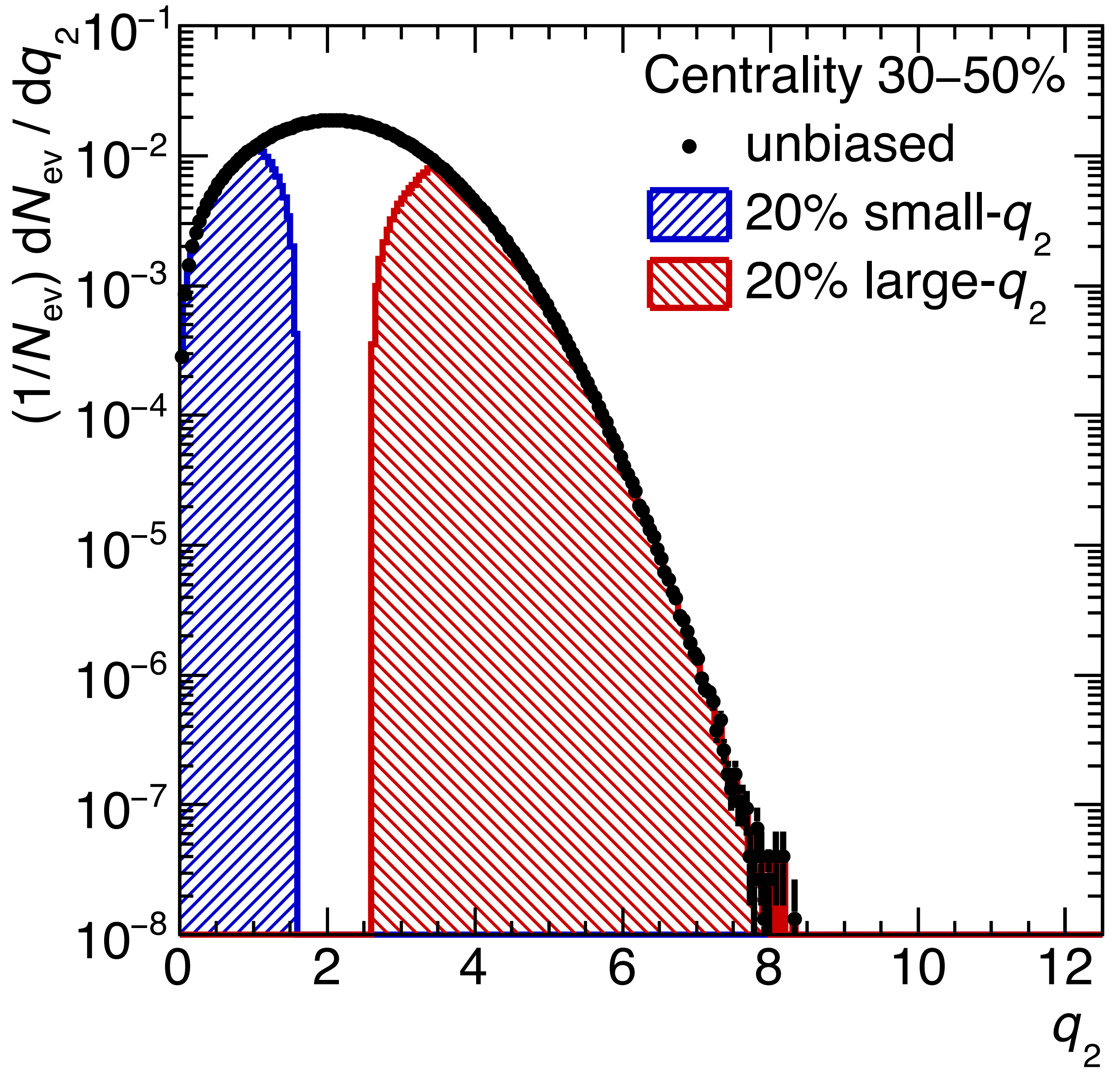


20% largest q_2

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



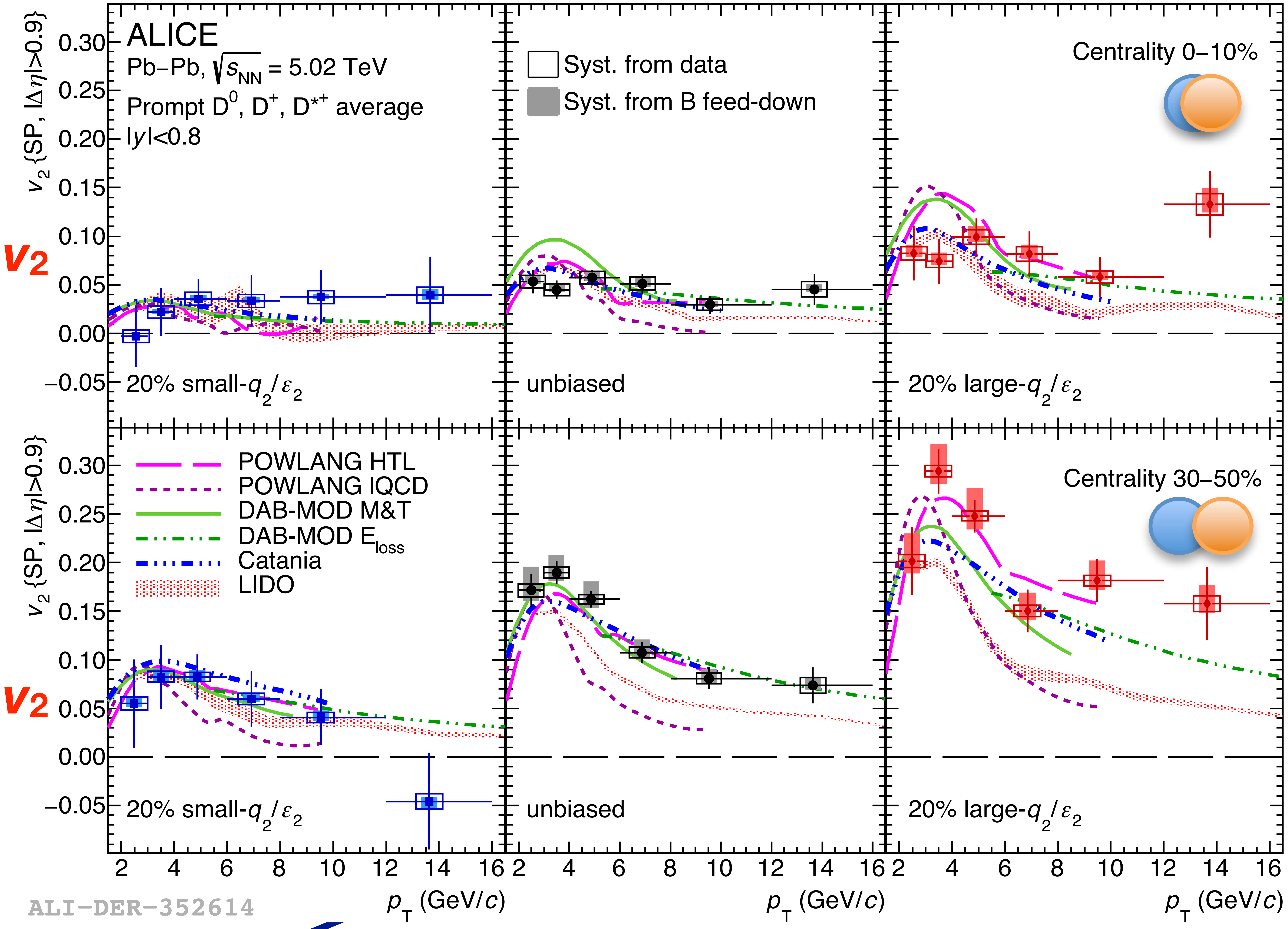
ALI-PUB-348698



PLB 813 (2021) 136054

Useful to study the interplay between anisotropic flow of heavy quarks and that of the bulk

ESE-selected elliptic flow



PLB 813 (2021) 136054

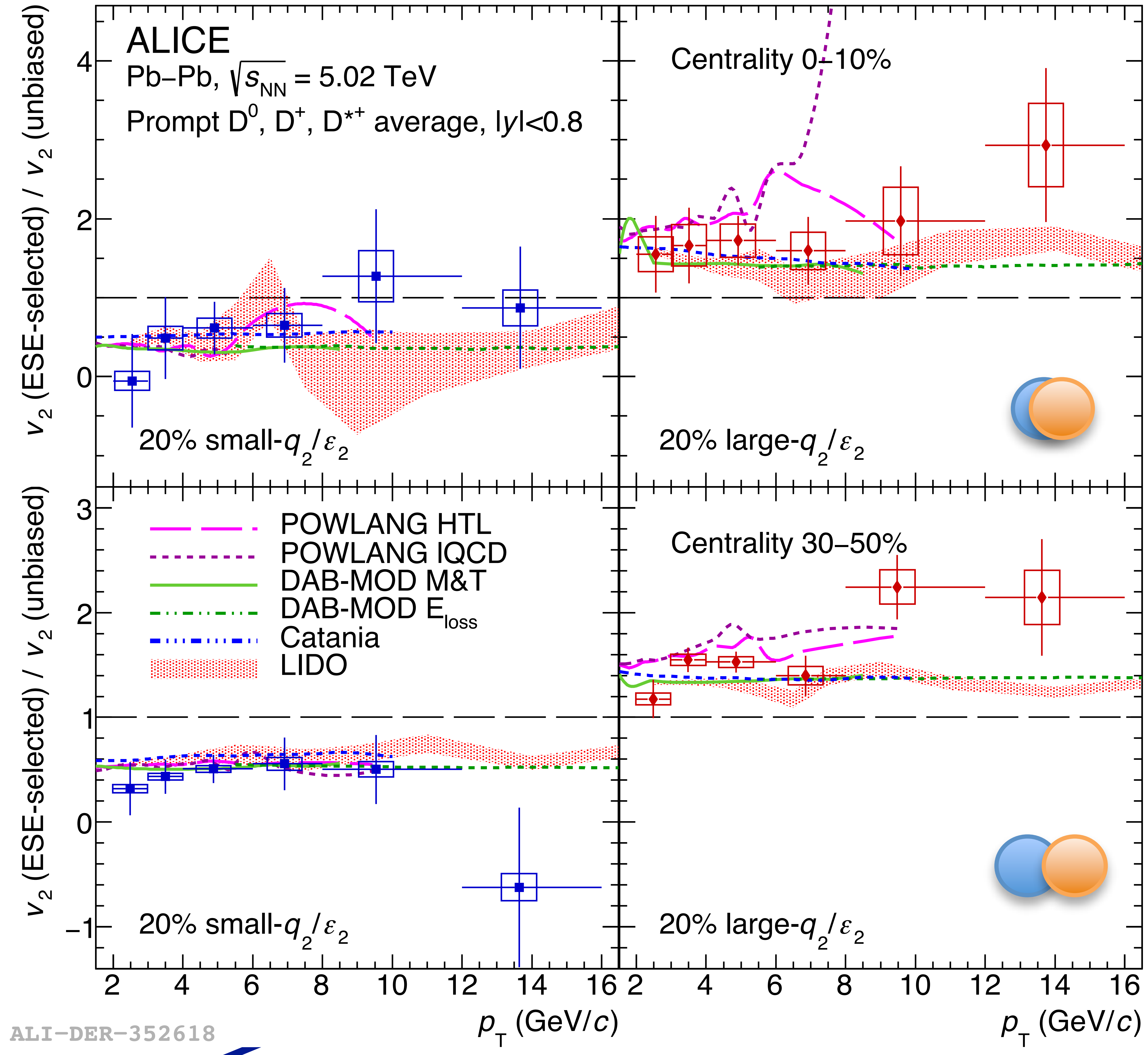
➡ Clear separation between v_2 measured in events with small/large q_2:

- ➡ **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

ESE-selected elliptic flow



➡ **Ratio v_2(ESE-selected sample) to v_2(unbiased) ~ 0.5** in both 0-10% and 30-50% centrality classes

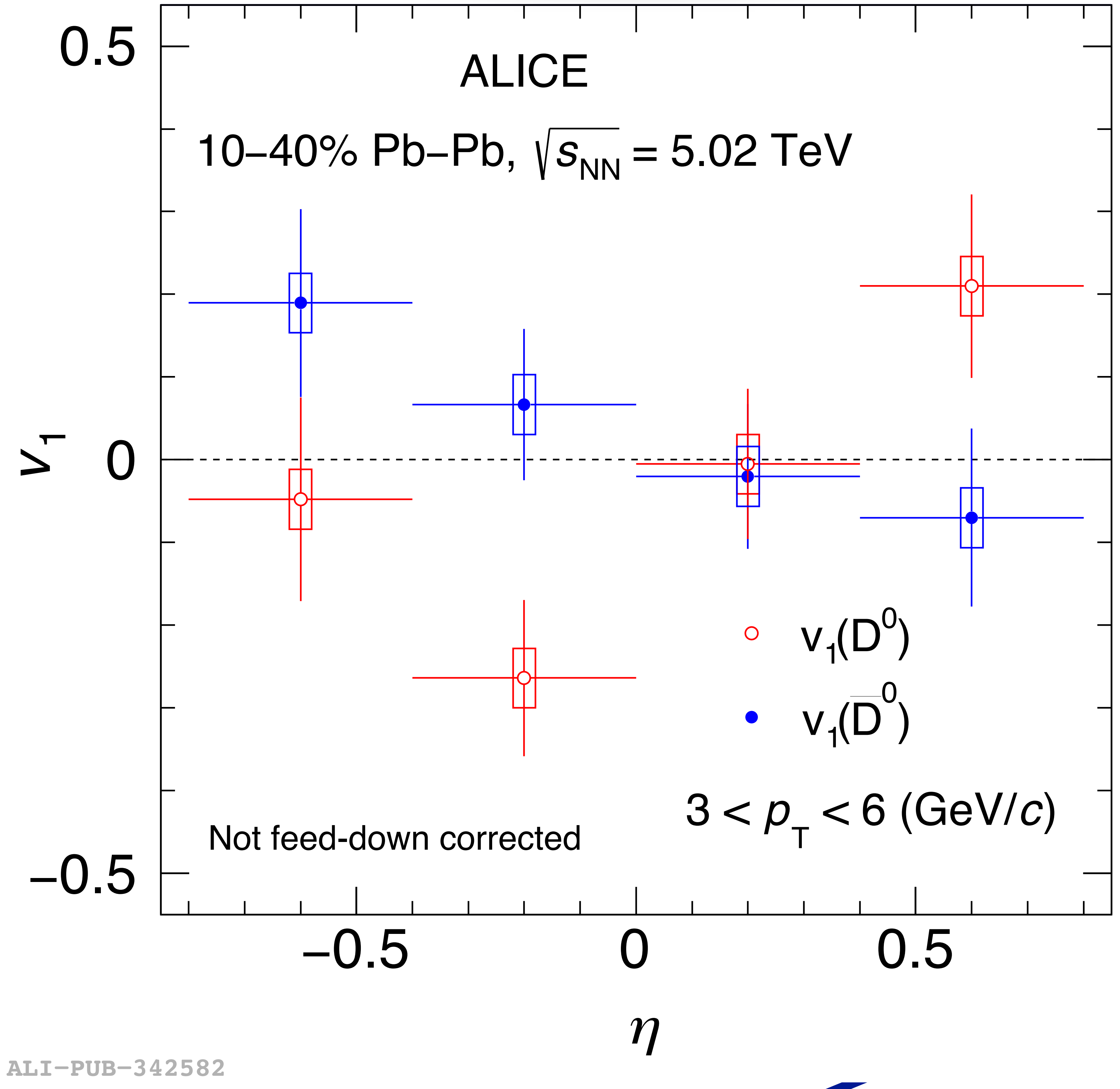
➡ **Different implementations of the same model give similar predictions**
→the effect of the ESE selection is more related to the initial geometry and the underlying hydrodynamic expansion rather than to the dynamic evolution of the heavy quarks in the medium

PLB 813 (2021) 136054

D-meson v_1

PRL 125, 022301 (2020)

D^0 and $\bar{D}^0$



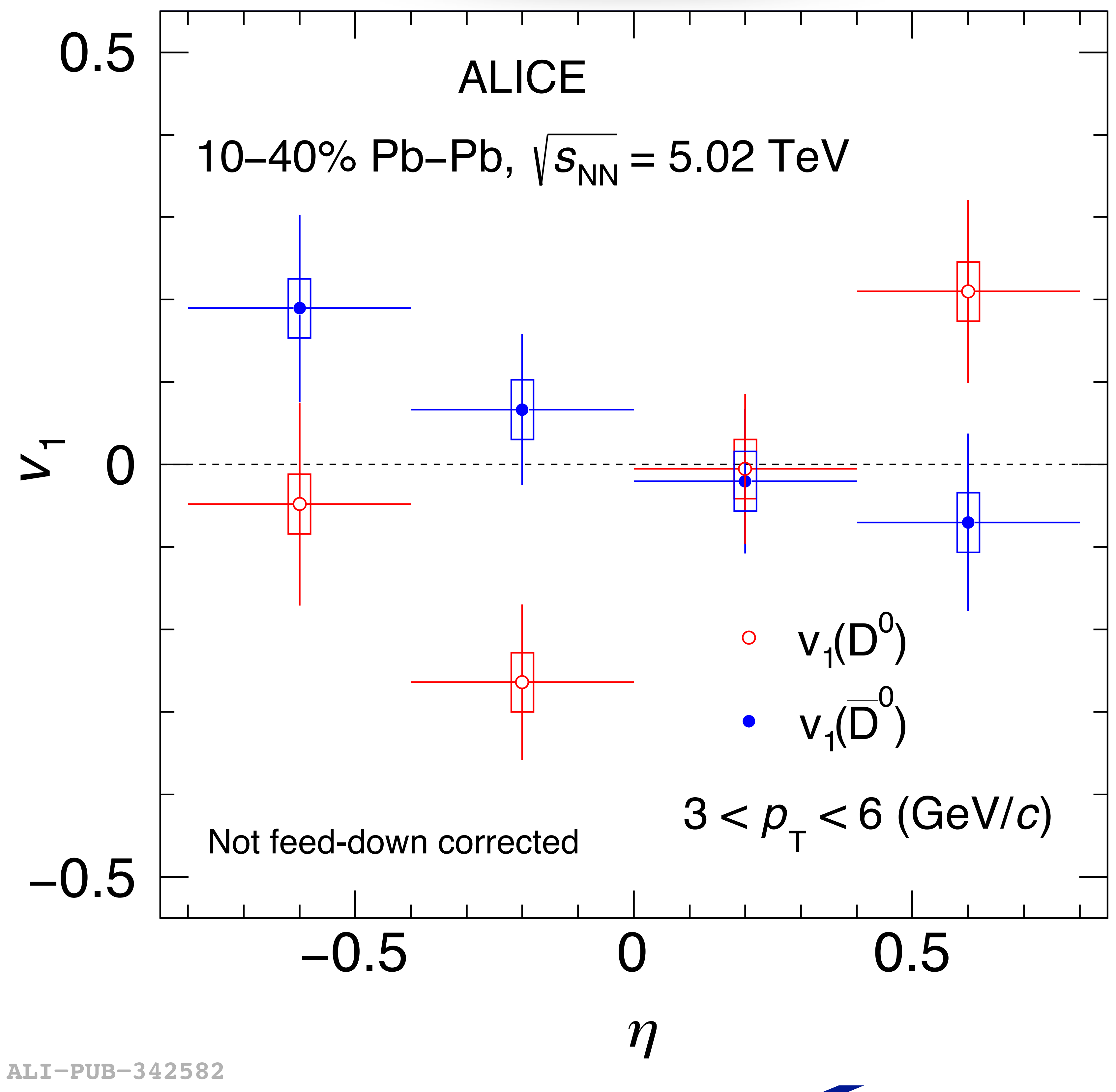
➡ Hint of **opposite trend of $v_1(D^0)$** and **$v_1(\bar{D}^0)$** as a function of η

➡ Measured slopes have opposite signs wrt theory expectations

D-meson v_1

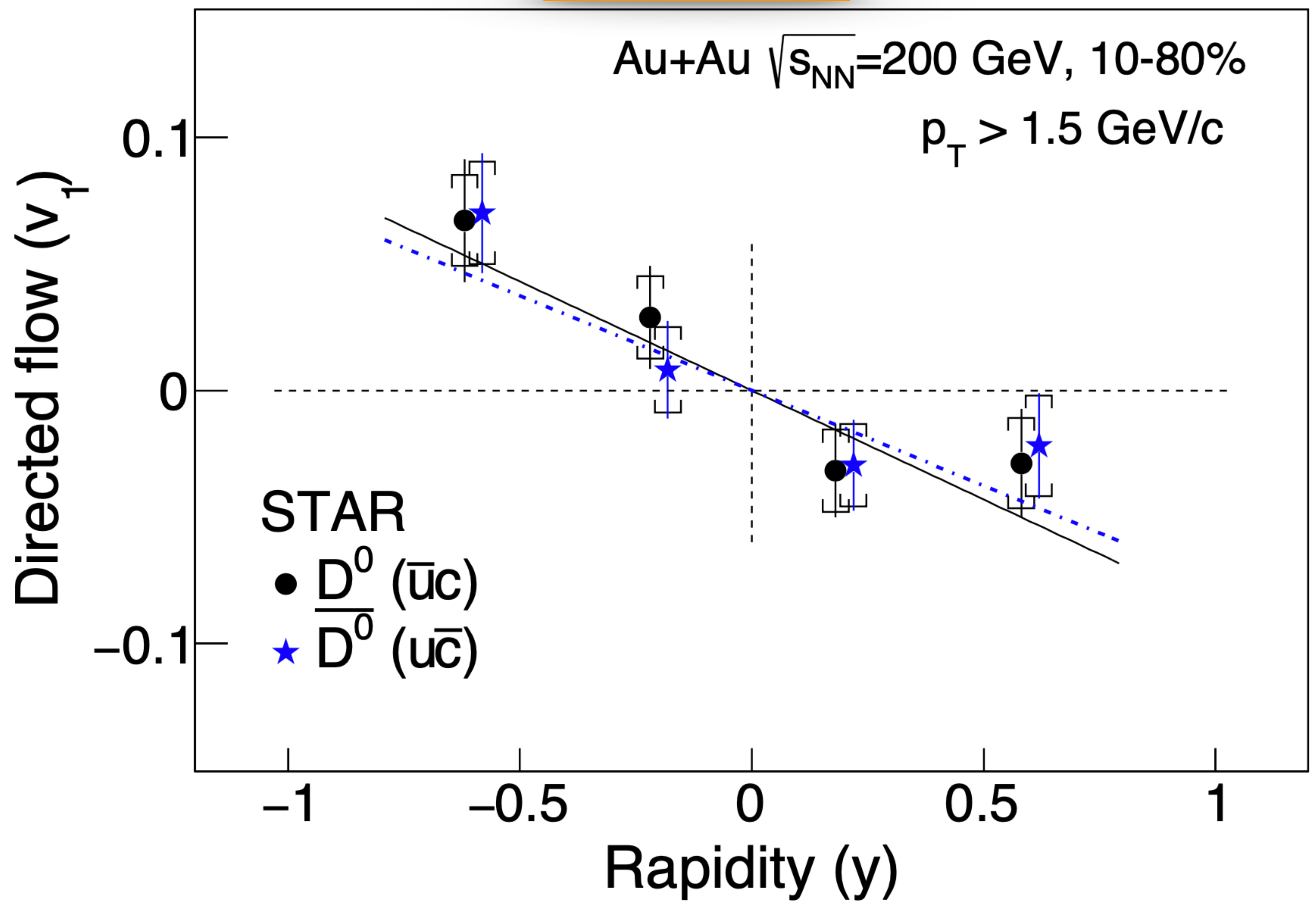
PRL 125, 022301 (2020)

D⁰ and $\bar{D}^0$ **@ LHC**



- ➡ Hint of **opposite trend of $v_1(D^0)$** and **$v_1(\bar{D}^0)$** as a function of η
- ➡ Measured slopes have opposite signs wrt theory expectations
- ➡ At RHIC: Negative slopes for both D^0 and $\bar{D}^0$ as a function of rapidity

D⁰ and $\bar{D}^0$ **@ RHIC**

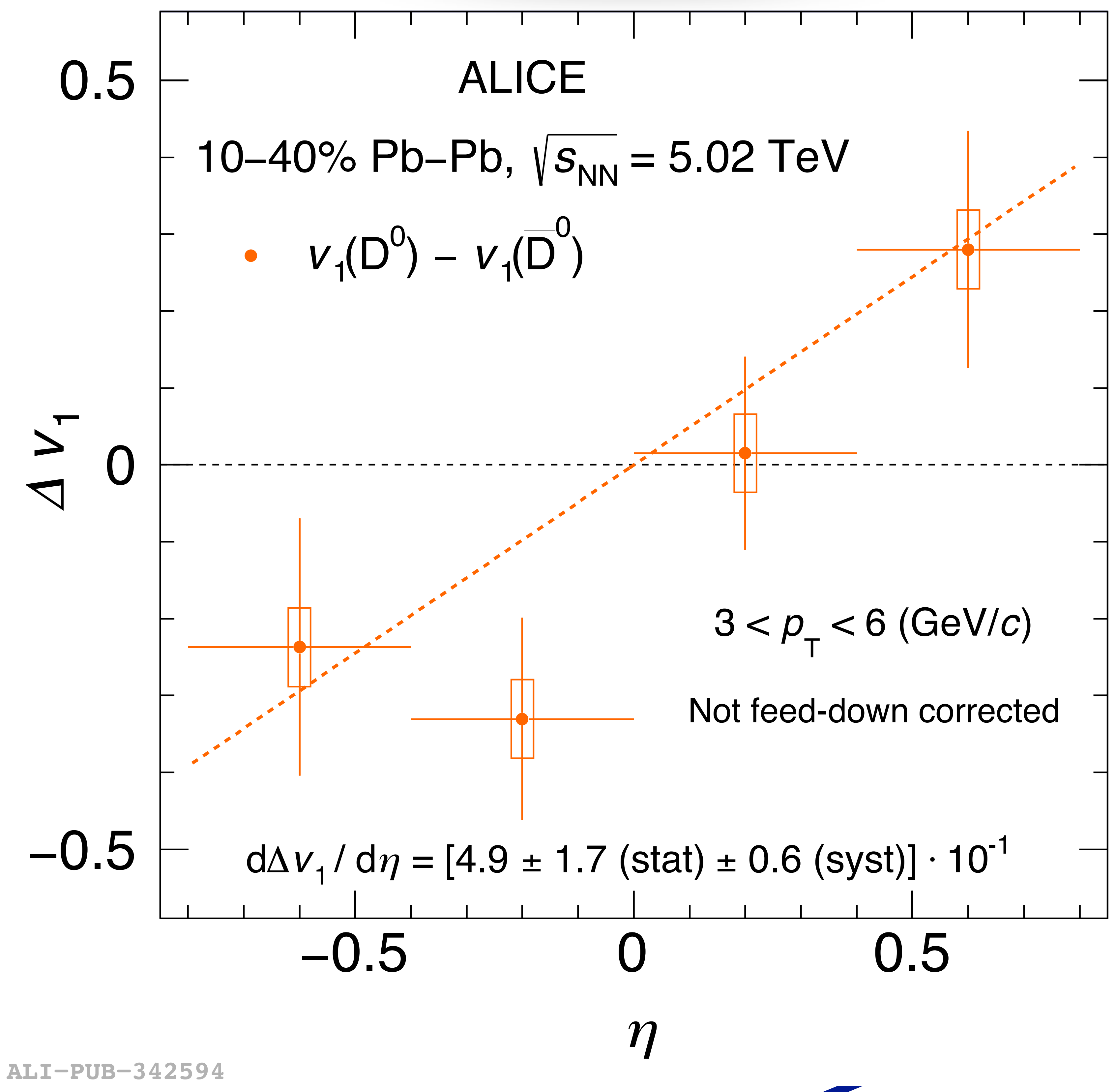


STAR, PRL 123, 162301 (2019)

D-meson Δv_1

PRL 125, 022301 (2020)

D^0 and $\bar{D}^0$



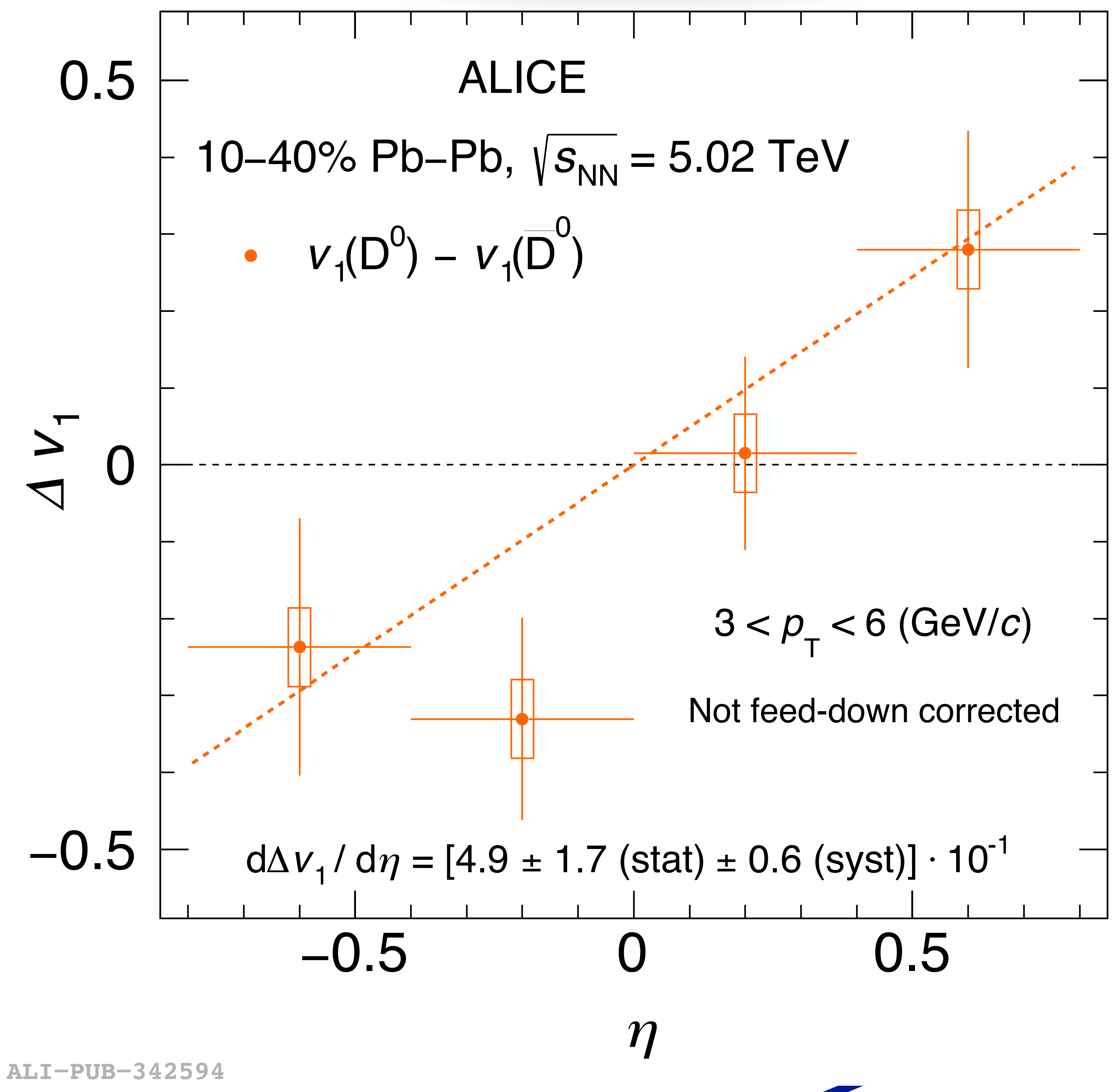
Δv_1 vs η fitted with a linear function:

➡hint of a **positive slope** with a **2.7σ significance**

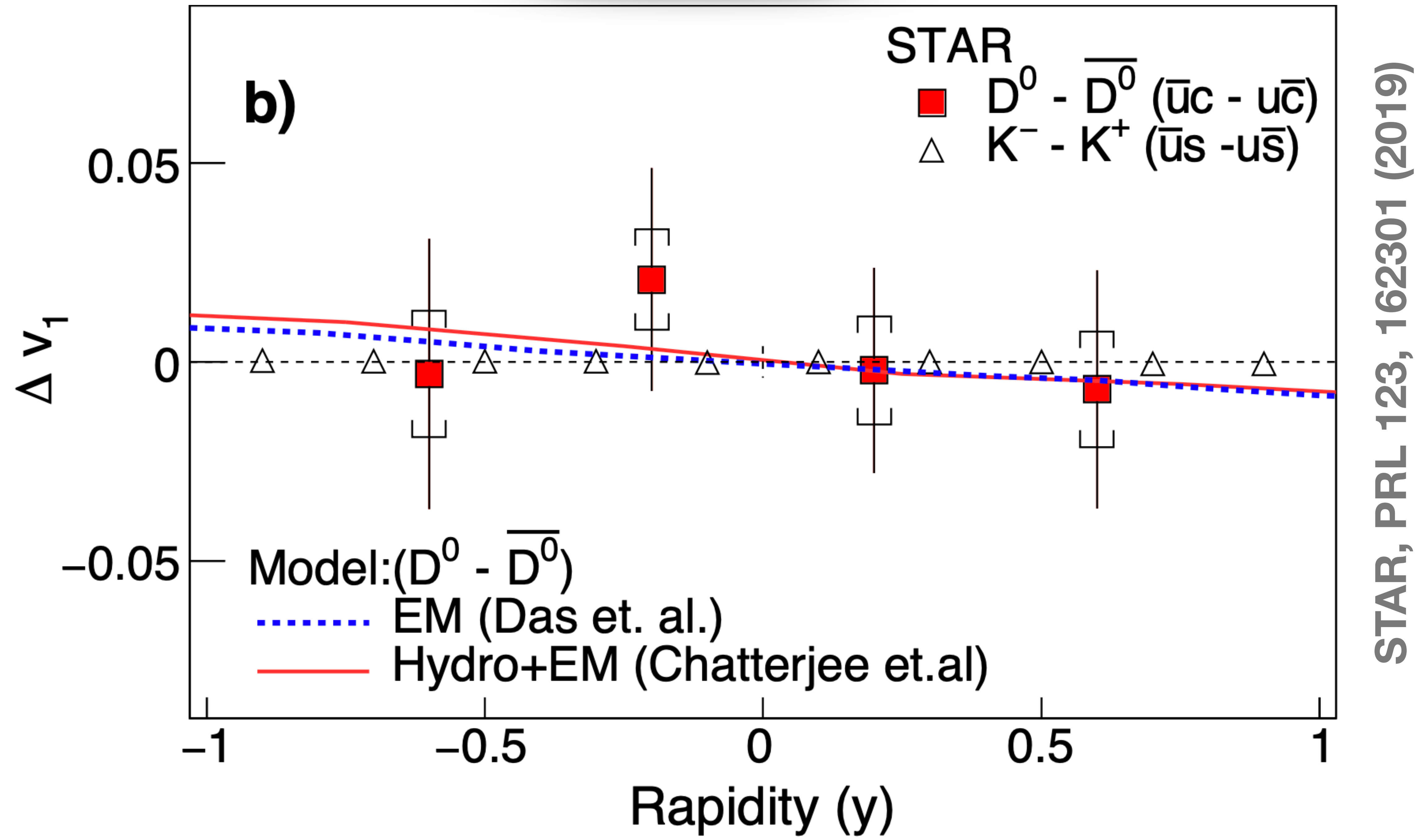
D-meson Δv_1

PRL 125, 022301 (2020)

D^0 and $\bar{D}^0$ @ LHC



D^0 and $\bar{D}^0$ @ RHIC



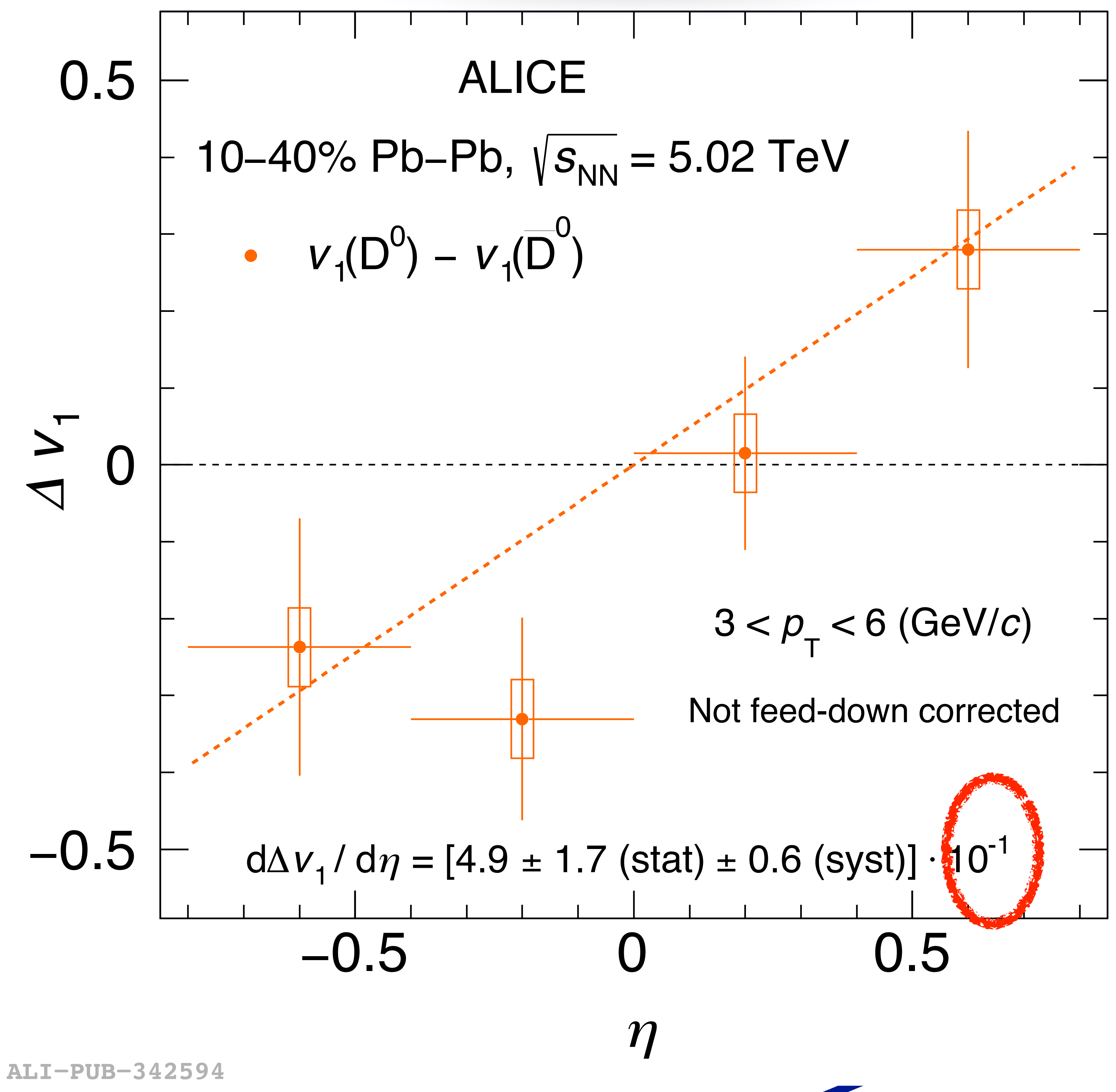
Δv_1 vs η fitted with a linear function:
➡hint of a **positive slope** with a **2.7σ significance**

At RHIC: **Δv_1 vs y compatible with 0**
(expected effect smaller than precision achieved)

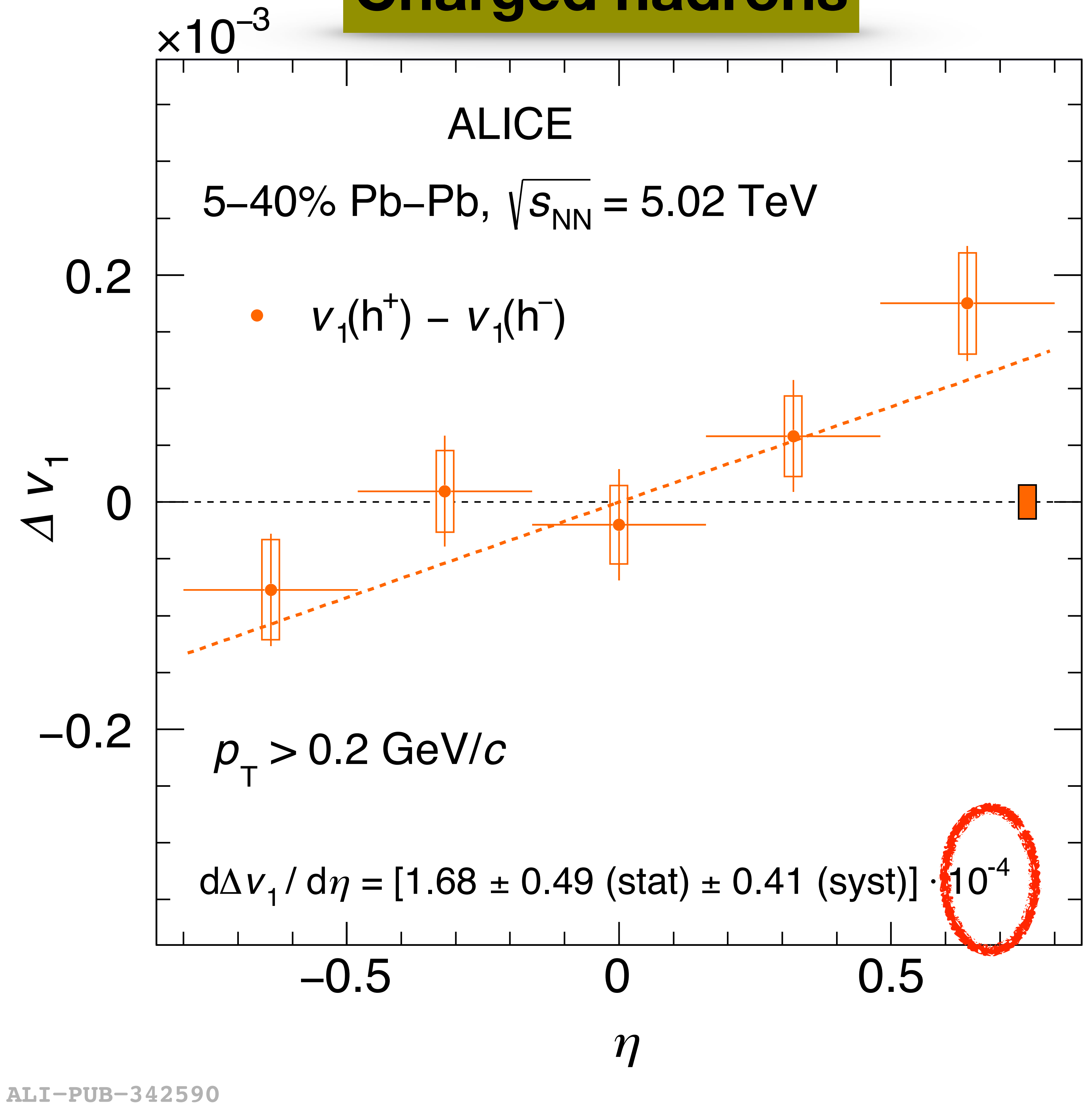
D-meson Δv_1: comparison with charged hadrons

PRL 125, 022301 (2020)

D^0 and $\bar{D}^0$



Charged hadrons



Δv_1 vs η fitted with a linear function:
➡ hint of a **positive slope** with a **2.7σ significance**

➡ **Similar trend** observed **for charged particles,** but **different in magnitude**

Conclusions

D meson azimuthal anisotropies measured in Pb–Pb collisions at 5.02 TeV

➡**Elliptic and triangular flow measurement**:

✓D-meson v_2 and v_3 > 0: participation of charm quarks in the collective expansion of the system

✓Constrain charm spatial diffusion coefficient: **1.5 < 2π*TD*$_s$ < 7**

➡**ESE measurement**:

✓Correlation between the anisotropic flow of charm quarks and bulk matter in agreement with transport model calculations

➡**Direct flow measurement**:

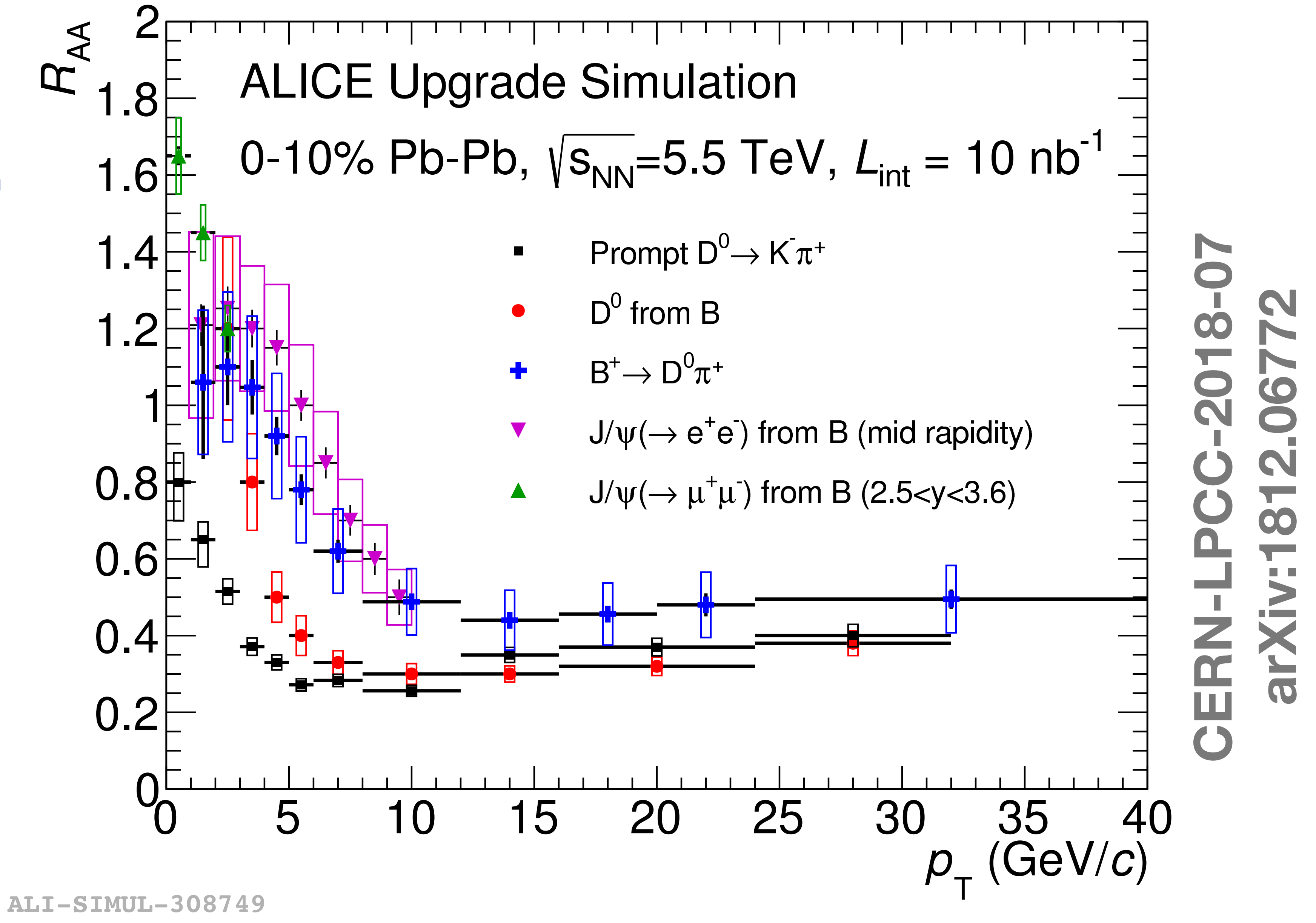
✓Positive slope of $d\Delta v_1/d\eta$

Wide ALICE upgrade program for LHC Run 3 and 4:

➡Investigate deeper the low p_T regime

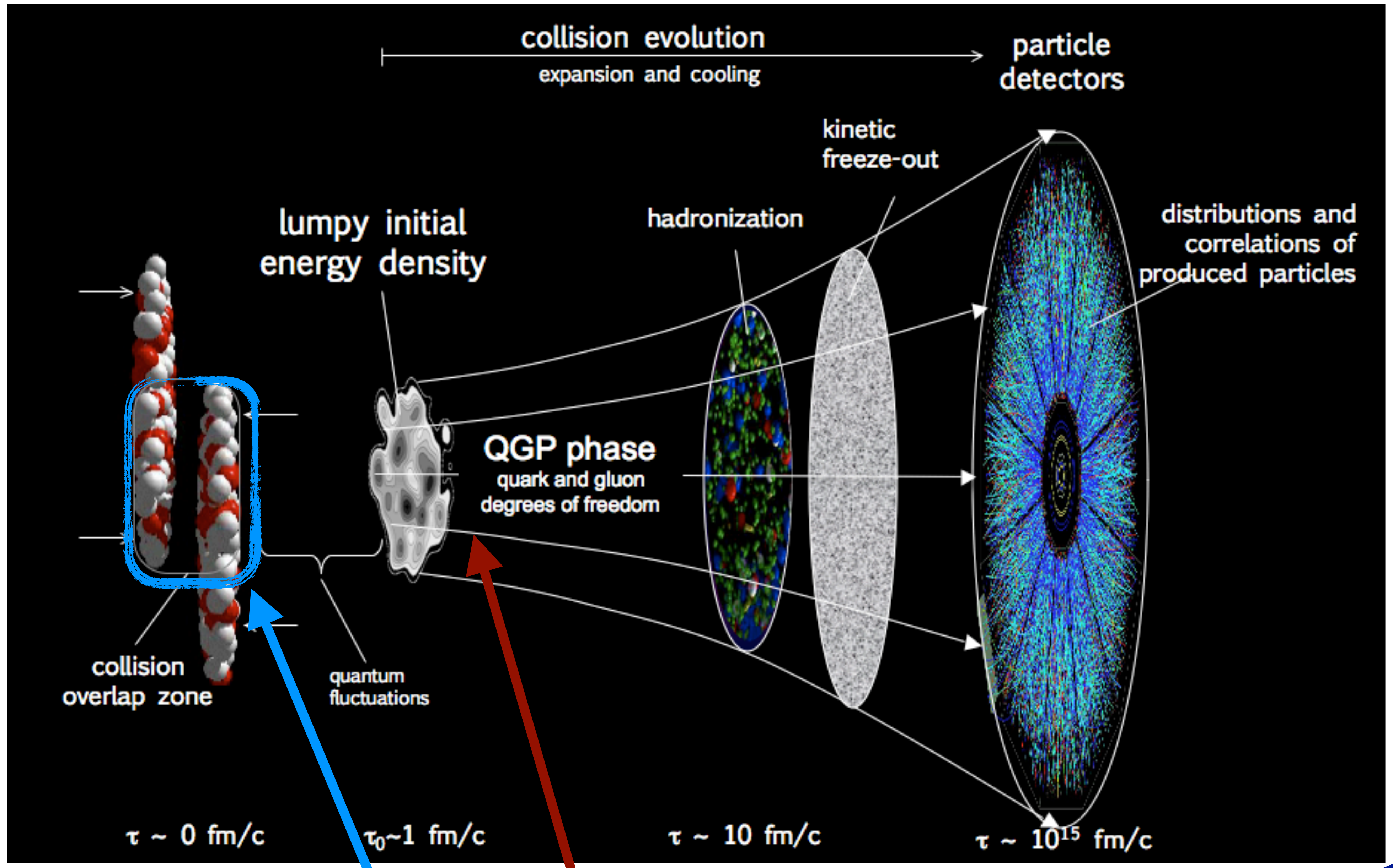
➡Precise measurements of charm mesons and baryons

➡Access to measurements of beauty-strange mesons and beauty-baryon production and flow



Back-up slides

Nuclear collisions and QGP expansion



Conditions similar to the Universe ~10 μs after the Big Bang

Collision overlap zone:
Full overlap -> **"central"** collisions
Non-complete overlap -> **"peripheral"** collisions

- **Pre-thermal processes**
scattering of incoming quarks and gluons

- **Thermalisation** (t~1 fm/*c* = $3*10^{-24}$ s)
Equilibrium is established

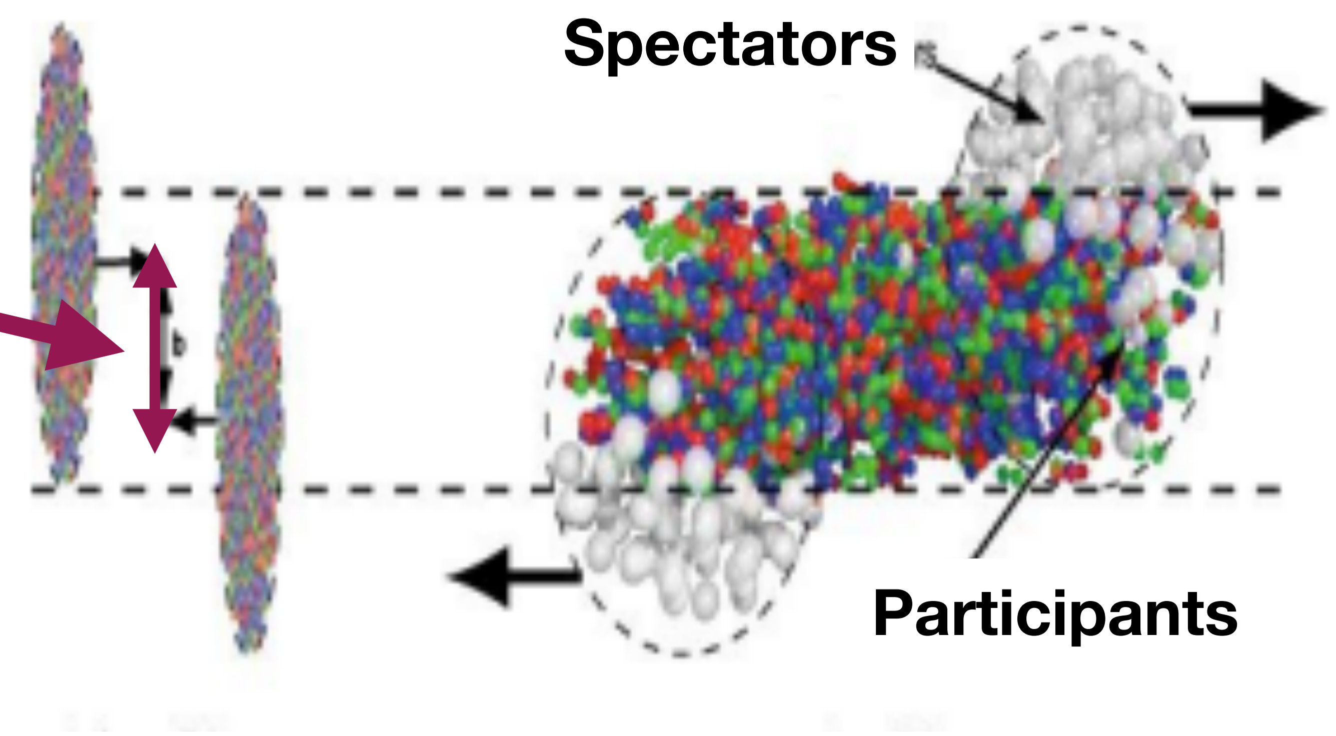
- **QGP expansion and cooling** (t~10 fm/*c*)
Described by an almost perfect fluid dynamics

- **Hadronisation, Chemical freeze-out**
Inelastic interactions cease, particle abundances frozen

- **Kinetic freeze-out**
Elastic interactions cease, particle dynamics (spectra) frozen

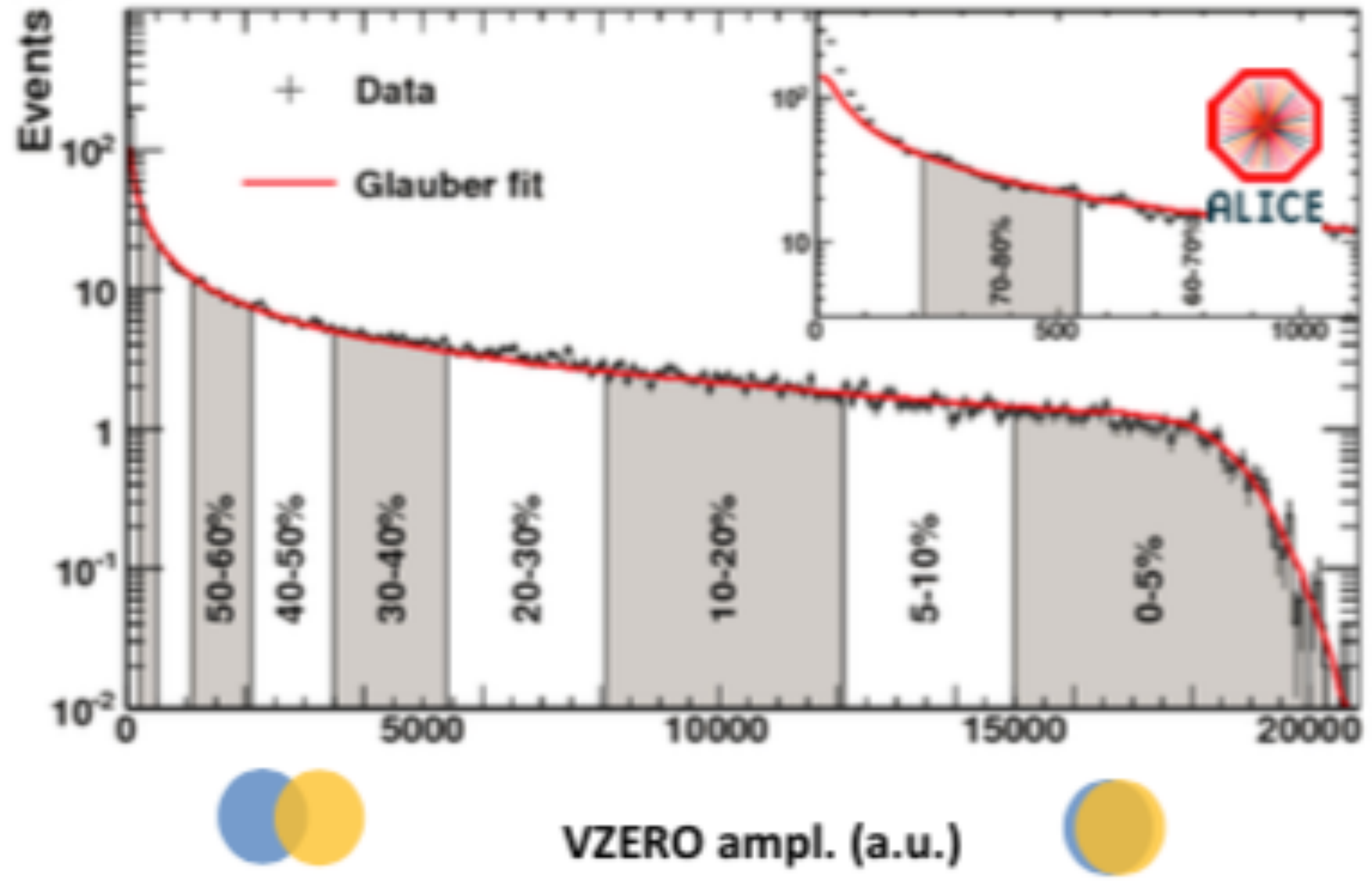
Centrality in AA collisions

- Ions are large, R~7 fm, collisions occur with random impact parameter that cannot be directly measured
- **Higher centrality -> hotter QGP**

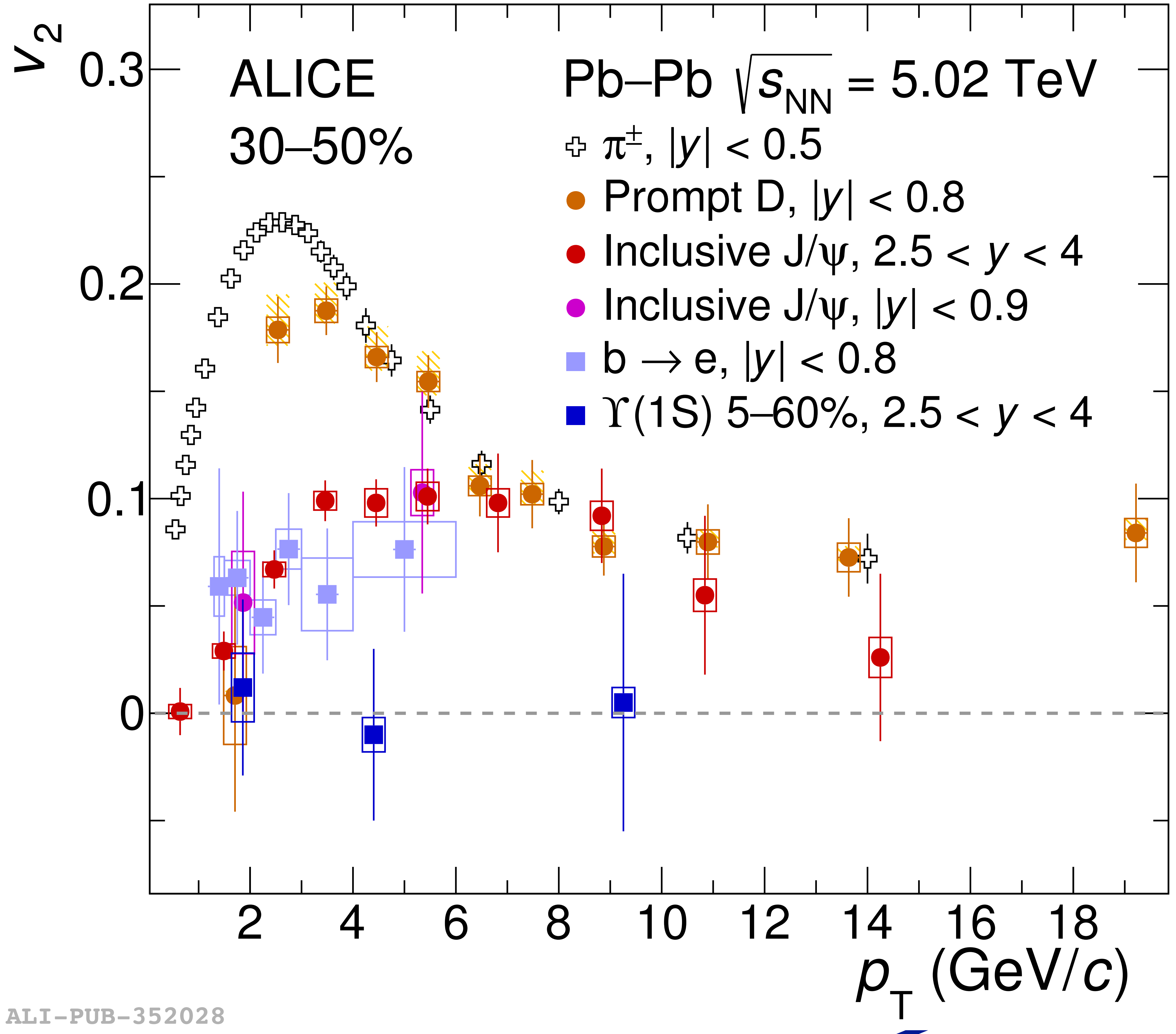


Before collision **After collision**

- The impact parameter has to be estimated based on measured quantities: e.g. N_{ch} , E_T , ZDC…
- Glauber model: connects centrality to a number of binary collisions (N_{coll}) and participants (N_{part})



Elliptic flow of heavy-flavour particles



JHEP 09 (2018) 006 (pions)
arXiv:2005.11131 (D mesons)
arXiv:2005.14518 (J/ψ)
arXiv:2005.11130 (b→e)
PRL 123 (2019)192301 (ϒ(1S))

✦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(ϒ(1S))≲v_2(b→e)~v_2(J/ψ) < v_2(D) <v_2(π)
- For $3 < p_T < 6$ GeV/c ➡ **charm quark coalescence with flowing light quarks**
  v_2(J/ψ)< v_2(D)~v_2(π)
- For $p_T > 6$ GeV/c: ➡ **consistent with similar path-length dependence of the energy loss for light and heavy quarks**
  v_2(J/ψ)~ v_2(D)~v_2(π)