Heavy-flavour flow and event-shape engineering

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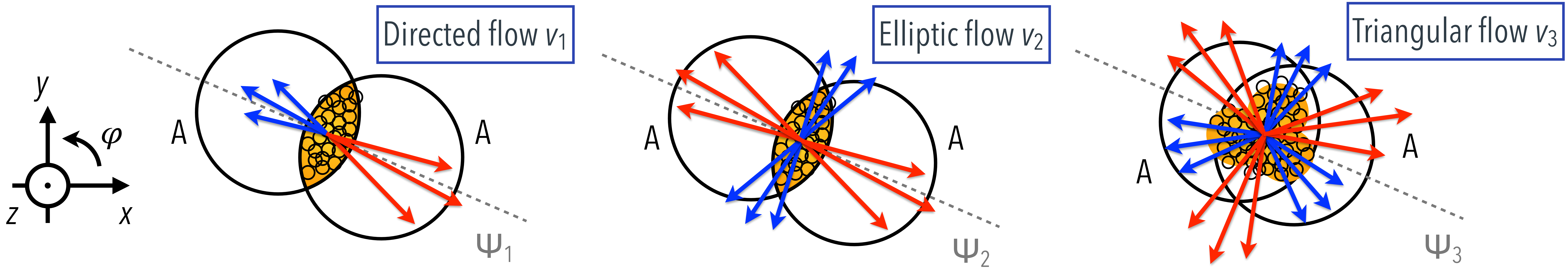
Terzo incontro sulla Fisica degli Ioni Pesanti

Padova | 25–26 November 2021

- A colour-deconfined medium, called *quark–gluon plasma* (QGP) is created in ultrarelativistic heavy-ion collisions
- The initial geometrical anisotropy is transferred to a momentum anisotropy by the pressure gradients

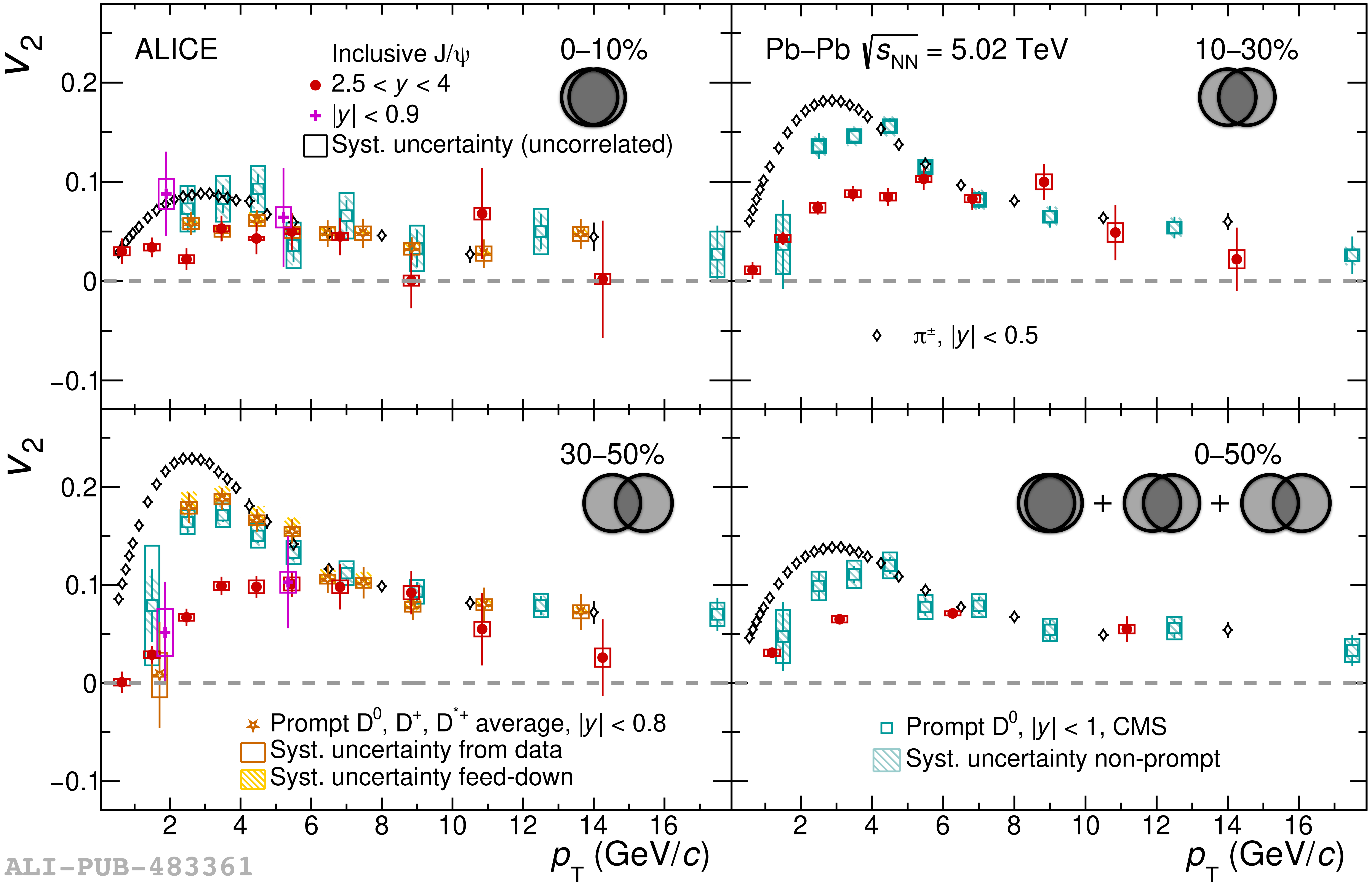
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1+\sum_{i=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right\}$$

$$v_n = \langle\cos[n(\varphi-\Psi_n)]\rangle$$ Flow harmonic coefficients



- Azimuthal anisotropy in HF hadron production
  - ➡ Participation of charm and beauty quarks in the collective motions and their possible thermalisation
  - ➡ Study path-length dependence of in-medium parton energy loss
  - ➡ Sensitivity to initial-state event-by-event fluctuations
  - ➡ Probe strong initial electromagnetic fields in the QGP

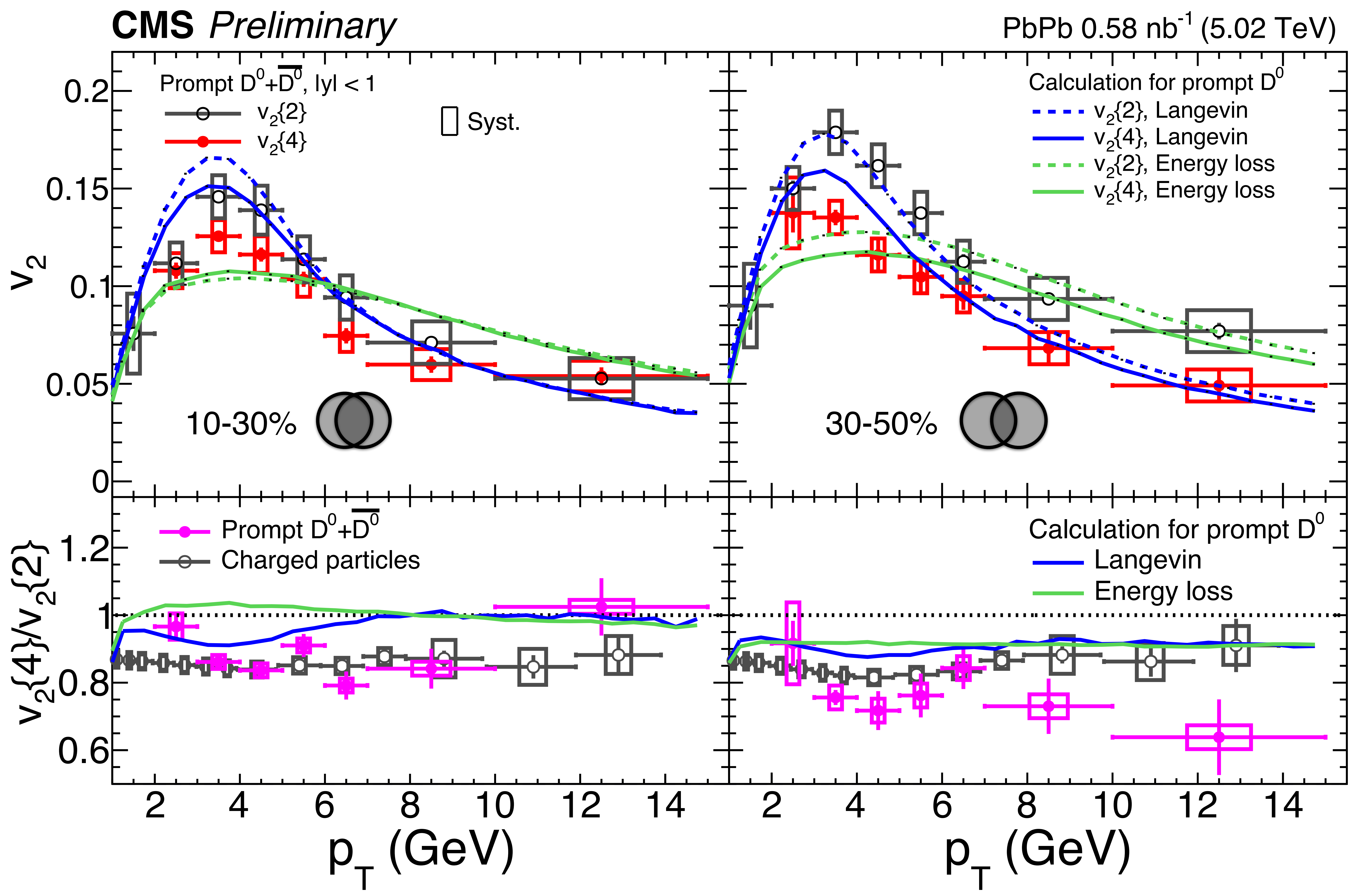
Elliptic flow of open and hidden charm mesons



- Significant v_2 for open and hidden charm mesons → charm participation to collective motions
- p_T < 3–4 GeV/c: mass hierarchy
  - ➡ $v_2(J/\psi) < v_2(D, D^0) < v_2(\pi)$
- 3–4 < p_T < 6–8 GeV/c: coalescence
  - ➡ $v_2(J/\psi) < v_2(D, D^0) = v_2(\pi)$
- p_T > 8 GeV/c: path-length dependence of in-medium energy loss
  - ➡ $v_2(J/\psi) = v_2(D, D^0) = v_2(\pi)$

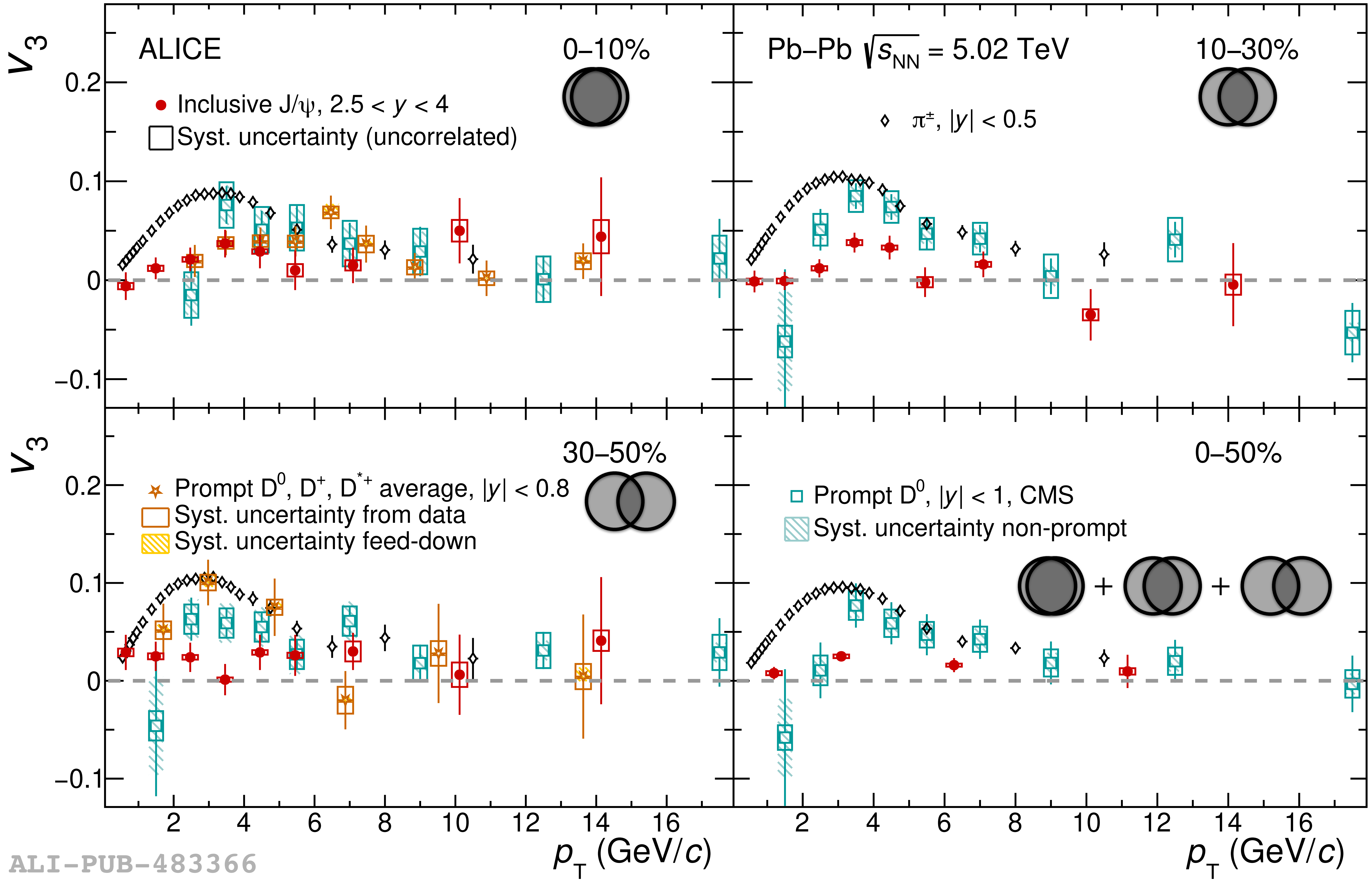
ALICE prompt D: PLB 813 (2021) 136054
ALICE J/ψ forward y: JHEP 10 (2020) 141
ALICE $\pi^{\pm}$: JHEP 09 (2018) 006
CMS prompt D^0: PRL 120 (2018) 202301
ALICE J/ψ mid y: JHEP 10 (2020) 141

D-meson $v_2\{2\}$ vs. $v_2\{4\}$



- D-meson $v_2\{4\}$ smaller than $v_2\{2\}$
  - ➡ Expected in case of event-by-event fluctuations in the flow signal
- Similar effect for charm and light hadrons
- Described by theoretical models based on charm-quark transport in a hydrodynamically expanding QGP

CMS prompt D^0: CMS-PAS-HIN-20-001



- Significant v_3 for open and hidden charm mesons → charm sensitive to initial-state event-by-event fluctuations

- p_T < 3–4 GeV/c: mass hierarchy
  - ➡ $v_3(J/\psi) < v_3(D, D^0) < v_3(\pi)$
- 3–4 < p_T < 6–8 GeV/c: coalescence
  - ➡ $v_3(J/\psi) < v_3(D, D^0) = v_3(\pi)$
- p_T > 8 GeV/c: path-length dependence of in-medium energy loss
  - ➡ $v_3(J/\psi) = v_3(D, D^0) = v_3(\pi)$

ALICE prompt D: PLB 813 (2021) 136054
ALICE J/ψ forward y: JHEP 10 (2020) 141
CMS prompt D^0: PRL 120 (2018) 202301
ALICE $\pi^\pm$: JHEP 09 (2018) 006

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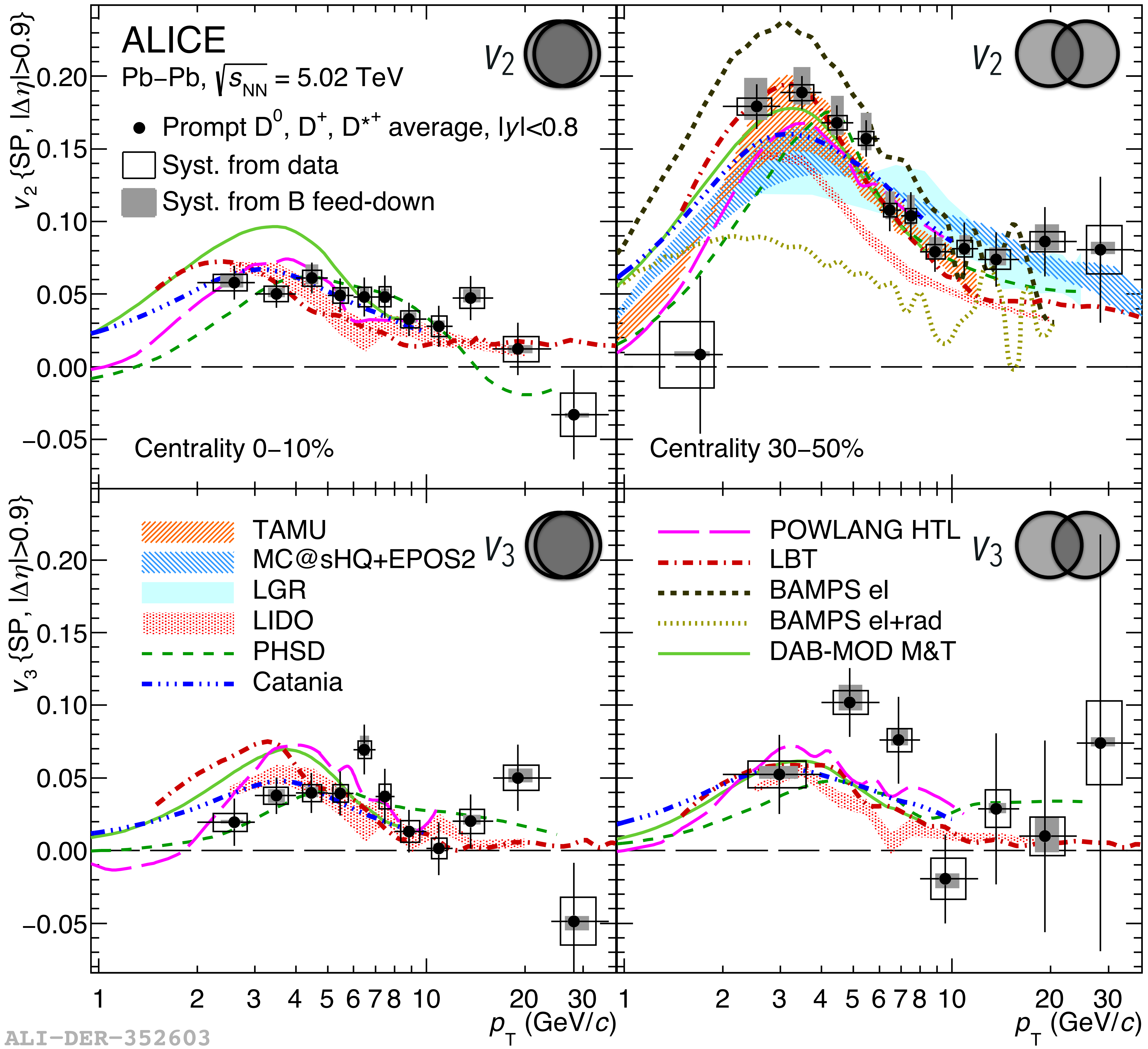
ALICE prompt D: PLB 813 (2021) 136054

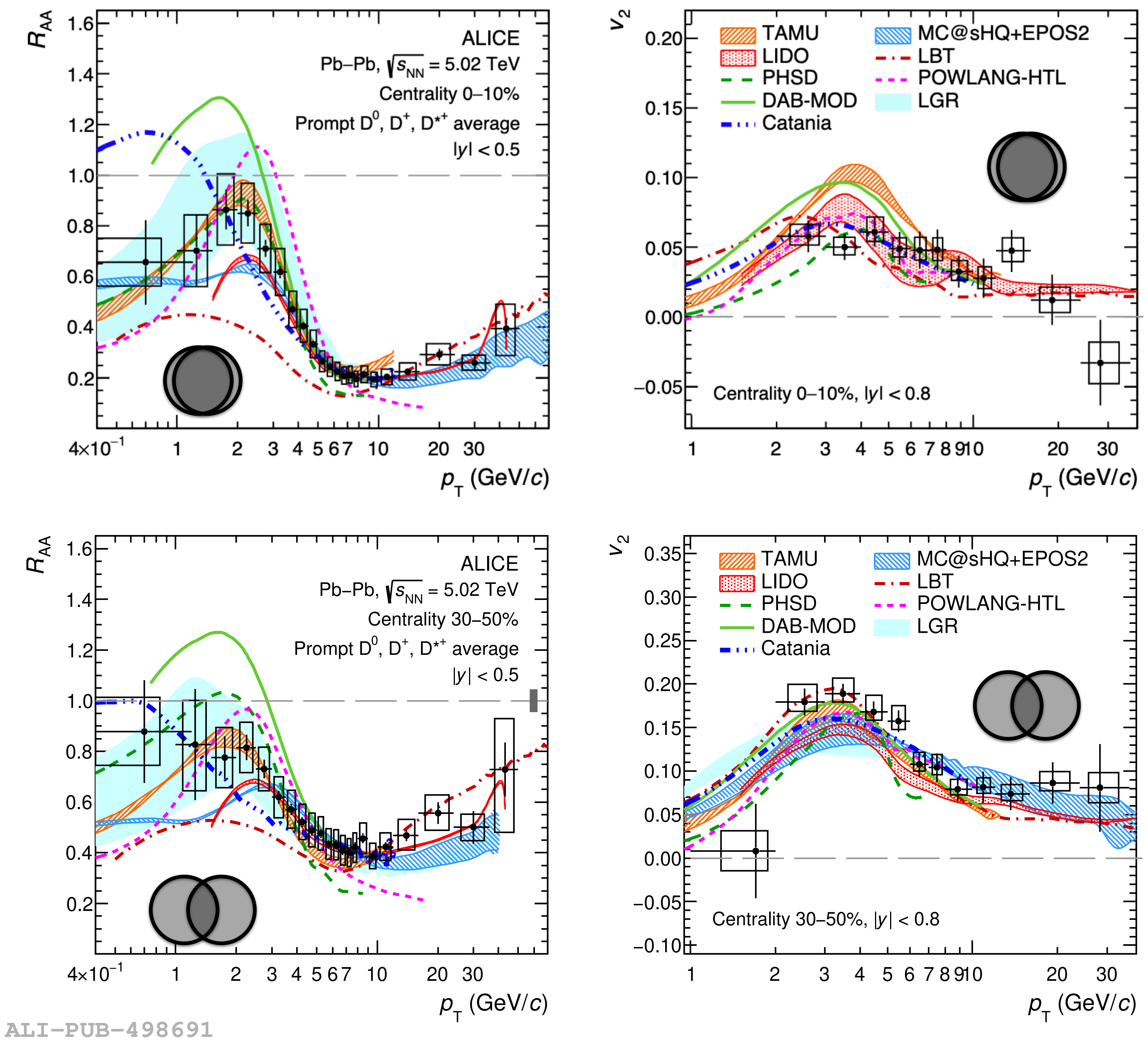


- Transport of charm quarks in an hydrodynamically expanding medium via Boltzmann or Langevin equations
  - ➡ Interactions of charm quark in the medium
    - Low p_T: elastic scatterings contribute to transfer collective motion from light to charm quarks
    - High p_T: path-length dependence of energy loss
  - ➡ Hadronisation of charm quark in the medium
    - Recombination with flowing light quarks enlarges charm-hadron v_2 compared to quark-hadron v_2

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: Eur. Phys. J. C, 80 7 (2020) 671
LIDO: PRC 98 (2018) 064901
PHSD: PRC 93 (2016) 034906
Catania: PLB 805 (2020) 135460
POWLANG: EPJC (2019) 79:494
LBT: PRC 94 (2016) 014909
BAMPS: JPG 42 (2015) 11, 115106
DAB-MOD: PRC 102 (2020) 024906

D-meson azimuthal anisotropy vs. transport models

ALICE prompt D: arXiv:2110.09420



- Transport of charm quarks in an hydrodynamically expanding medium via Boltzmann or Langevin equations
  - diffusion coefficient D_s related to thermalisation time of charm quark

$$\boxed{1.5 < 2\pi D_s T_c < 4.5}$$

for models that describe data with $\chi^2/\mathrm{ndf} < 5$

$$\tau_{\mathrm{charm}} = (m_{\mathrm{charm}}/T) \cdot D_s = 3 - 9\ \mathrm{fm}/c \approx \tau_{\mathrm{QGP}}$$

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
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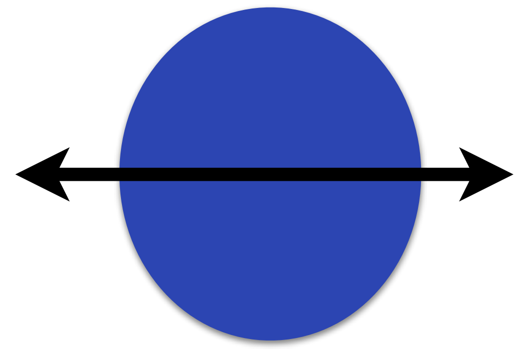
LBT: PRC 94 (2016) 014909
BAMPS: JPG 42 (2015) 11, 115106
DAB-MOD: PRC 102 (2020) 024906

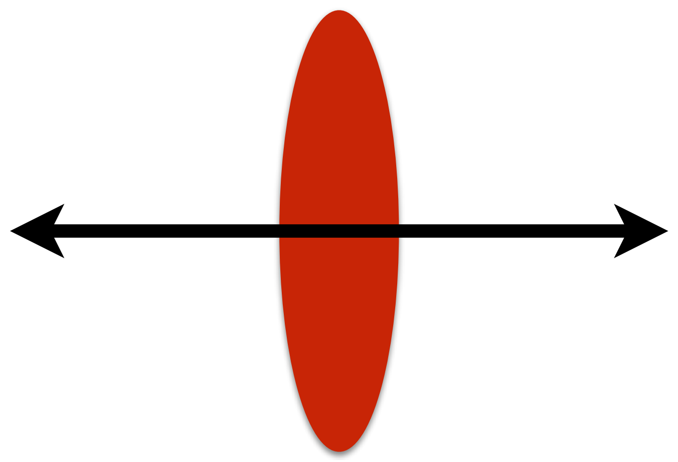
Charm vs. light elliptic flow

- D-meson v_2 studied as a function of average event flow with event-shape engineering technique
  - Positive correlation between heavy and light hadron v_2
  - Sensitivity for charm to event-by-event fluctuations



20% smallest q_2^{TPC}

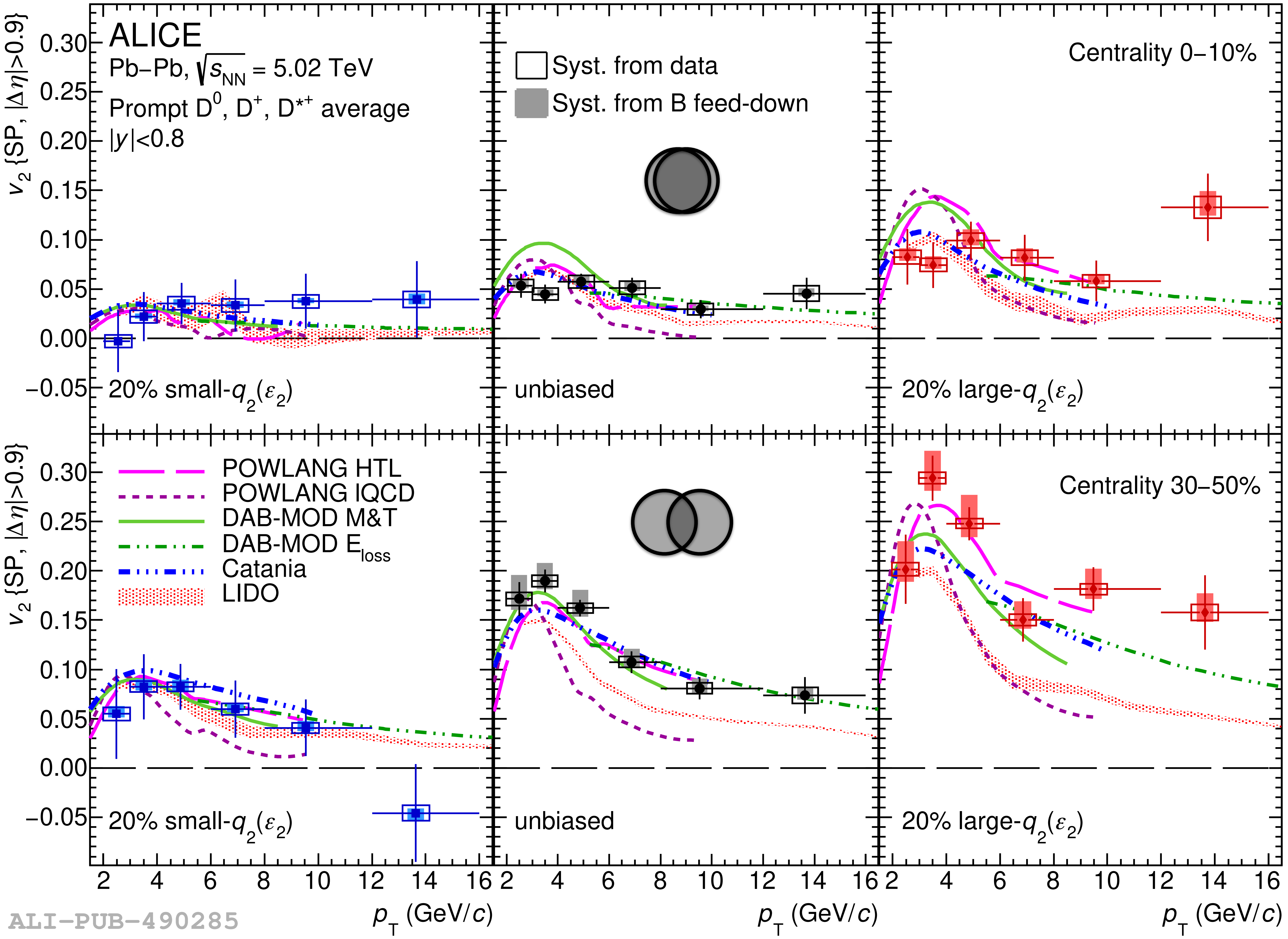
$\langle v_2 \rangle_{\mathrm{small}-q_2} < \langle v_2 \rangle_{\mathrm{unb}}$



20% largest q_2^{TPC}

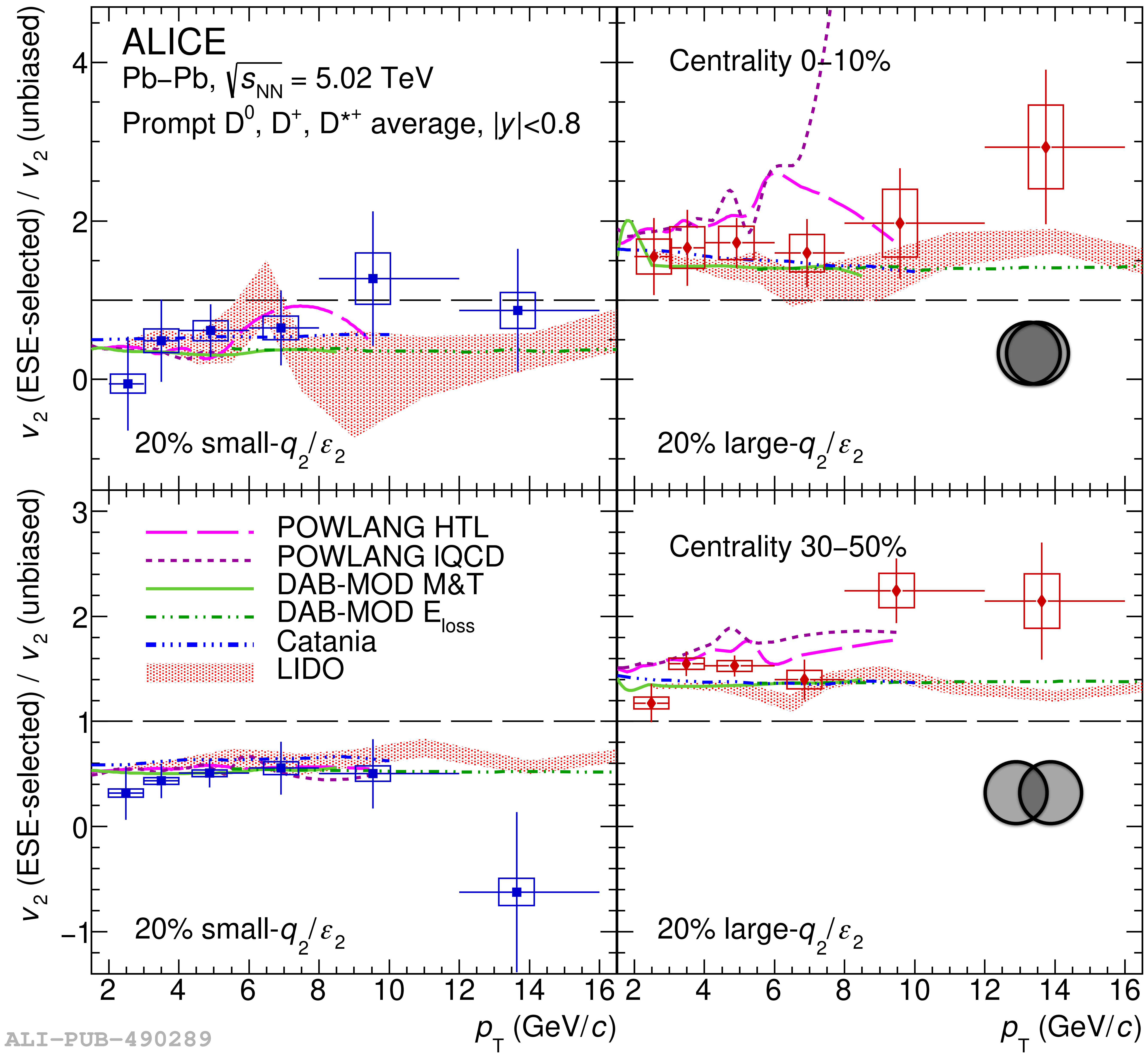
$\langle v_2 \rangle_{\mathrm{large}-q_2} > \langle v_2 \rangle_{\mathrm{unb}}$

ALICE prompt D: PLB 813 (2021) 136054



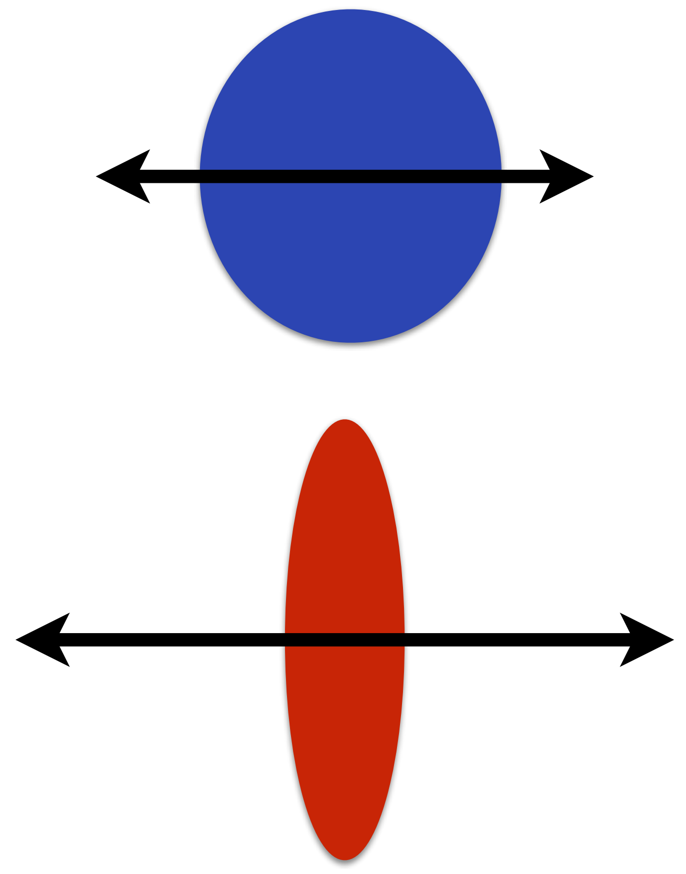
POWLANG: EPJC (2019) 79:494
DAB-MOD: PRC 102 (2020) 024906
Catania: PLB 805 (2020) 135460
LIDO: PRC 98 (2018) 064901

ESE elliptic flow ratios

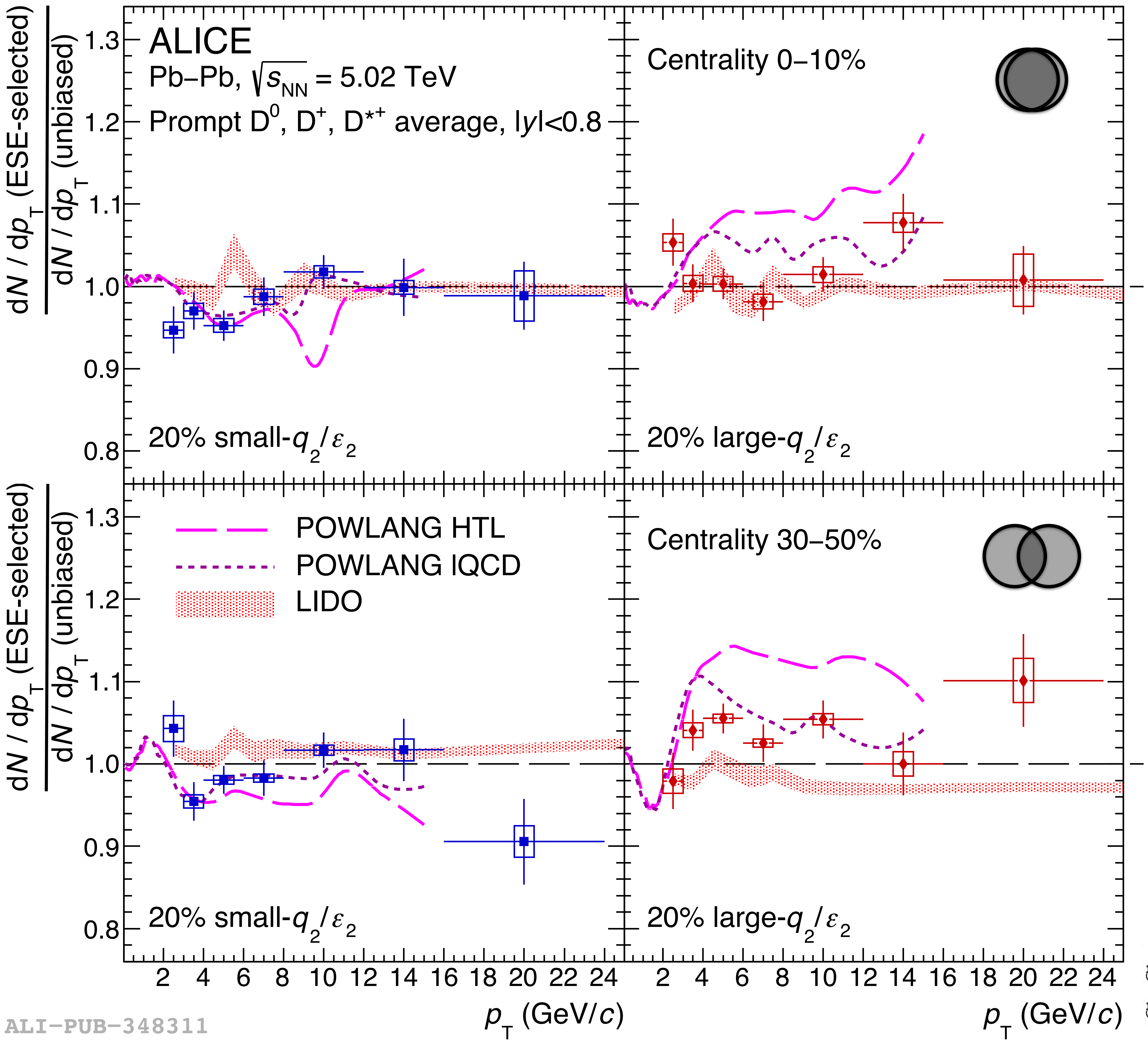


ALICE prompt D: PLB 813 (2021) 136054

- Models based on charm-quark transport in an hydrodynamically expanding medium describe q_2 dependence of D-meson v_2 flow
- Predicted variation of D-meson v_2 in ESE-selected samples with respect to unbiased sample similar for different transport parameters (e.g. POWLANG HTL vs. lQCD)

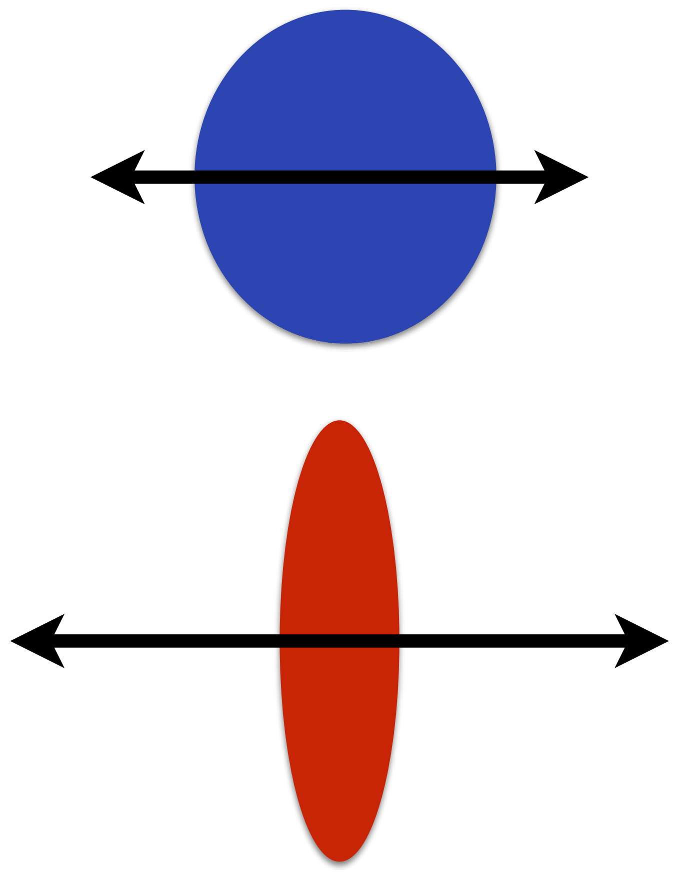


POWLANG: EPJC (2019) 79:494
DAB-MOD: PRC 102 (2020) 024906
Catania: PLB 805 (2020) 135460
LIDO: PRC 98 (2018) 064901



ALICE prompt D: PLB 813 (2021) 136054

- **No significant modification** of the p_{T}-differential production yields of D-mesons in different ESE-selected samples of events



20% smallest q_2^{TPC}

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

20% largest q_2^{TPC}

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

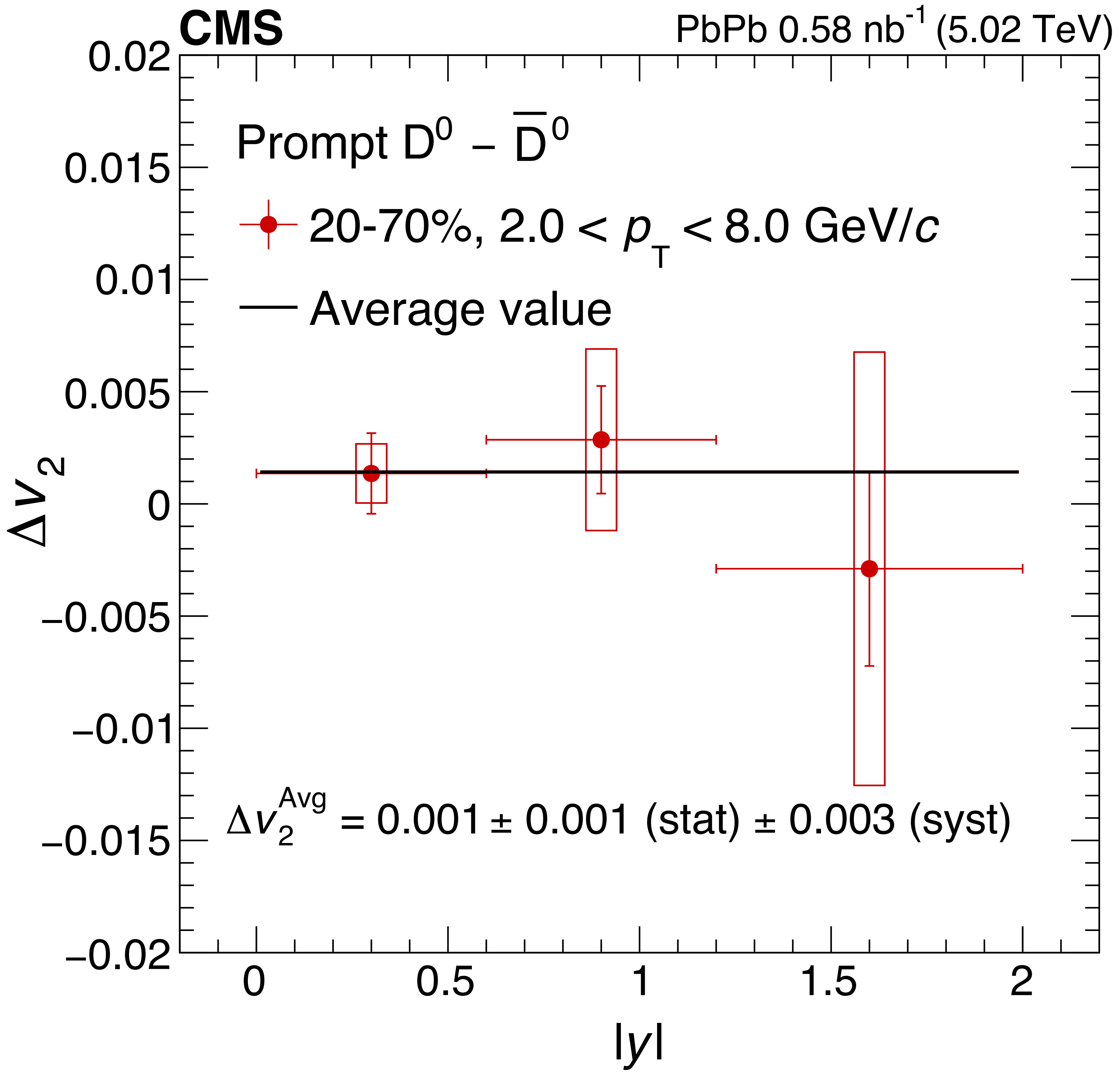
POWLANG: EPJC (2019) 79:494

LIDO: PRC 98 (2018) 064901

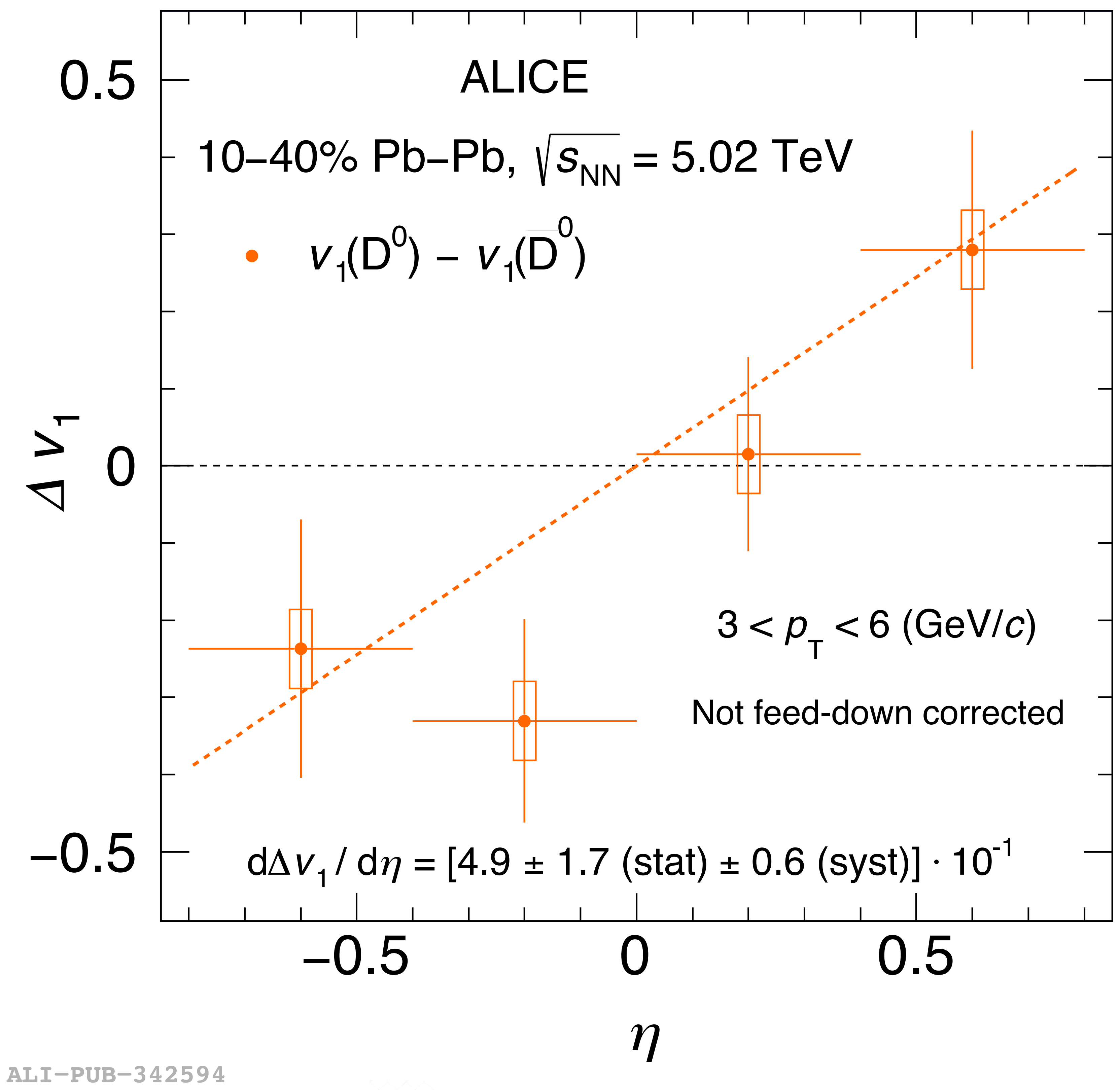
Search for strong electromagnetic fields: charge-dependent D-meson v_n

- Initial strong electric (magnetic) fields are expected to produce a charge dependence in the elliptic (directed) flow
  - ➡ Charm quarks ideal probes due to their early production

U. Gürsoy et al, PRC 98 (2018) 055201
S. K. Das et al, PLB 768 (2017) 260-264
A. Dubla et al, MPA Vol. 35, No. 39 (2020) 2050324



CMS prompt D^0: PLB 816 (2021) 136253

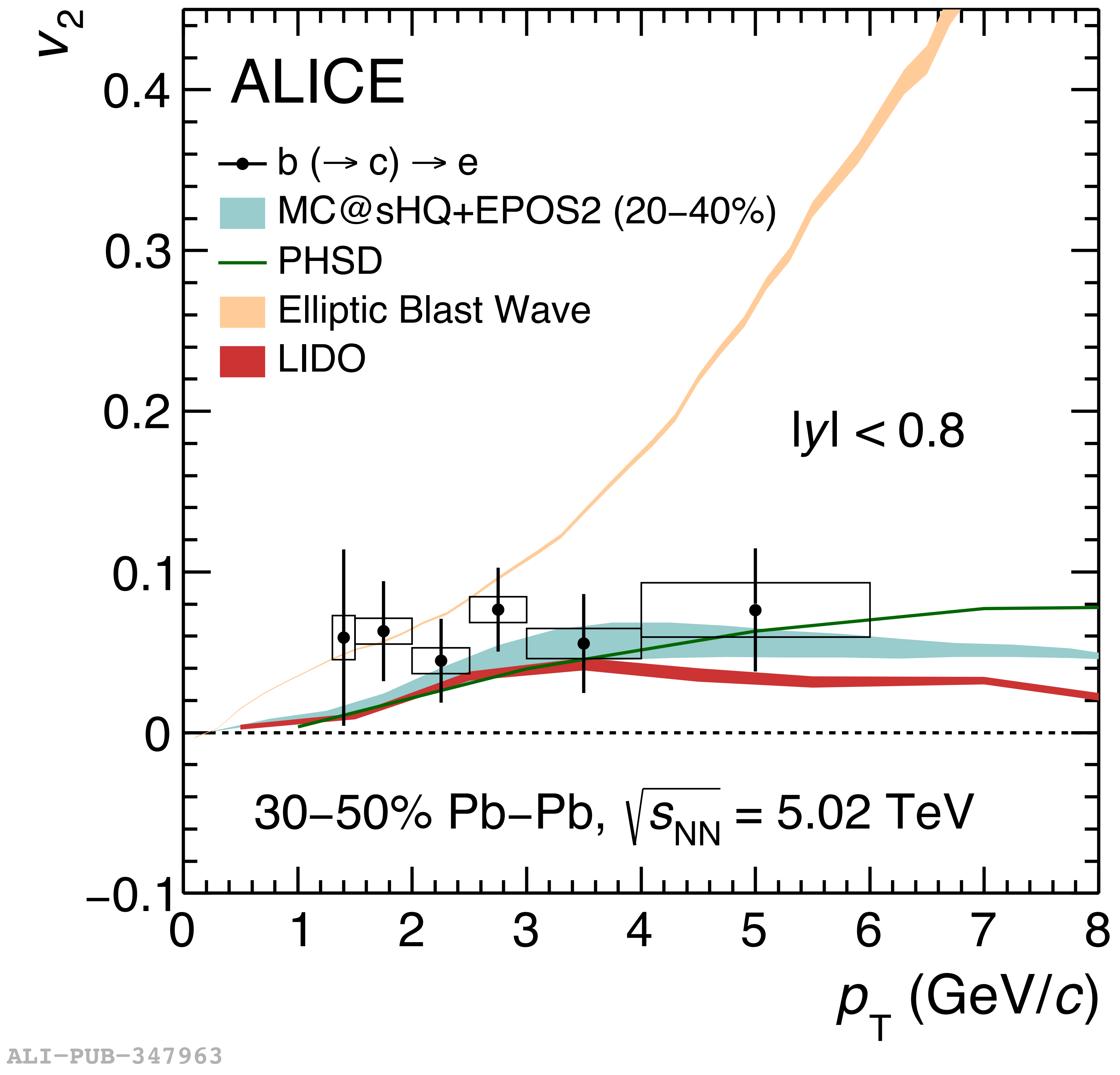


ALICE D^0: PRL 125 (2020) 022301

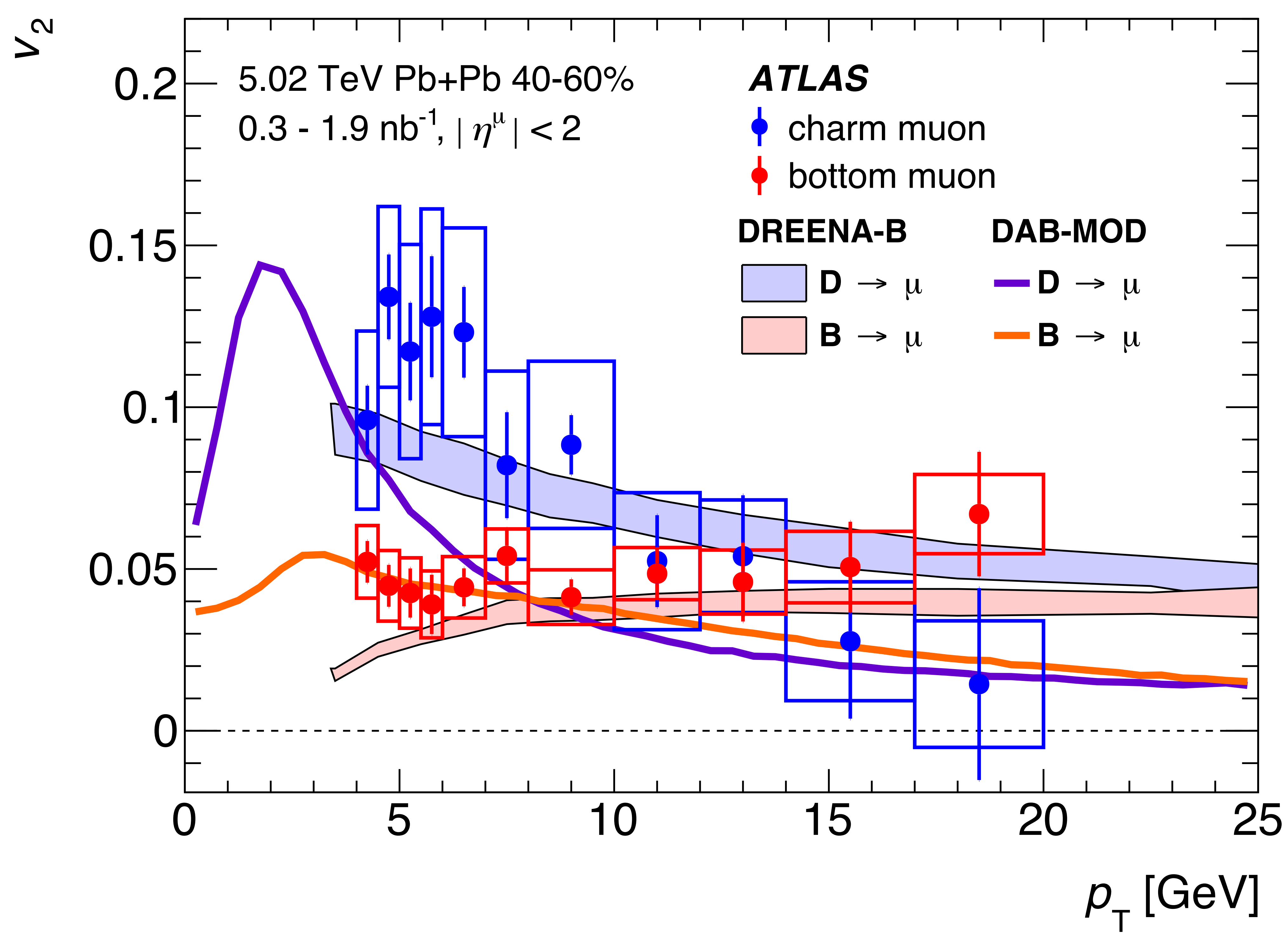
- No indication of charge dependent v_2 as a function of rapidity
- 2.7σ significant indication of y-dependent charge difference for D^0 mesons

Elliptic flow of open-beauty hadrons

ALICE b → e: PRL 126 (2021) 162001



ATLAS c,b → μ: PLB 807 (2020) 135595



Elliptic BW: PRC 101 (2020) 064905
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LIDO: PRC 98 (2018) 064901
PHSD: PRC 93 (2016) 034906
DAB-MOD: PRC 102 (2020) 024906
DREENA-B: PLB 791 (2019) 236-241

- Positive v_2 of leptons from beauty-hadron decays both at low and high p_T
  - ➡ Indication of participation in the collective motions of the system
  - ➡ Lower than charm (larger mass)
  - ➡ Expected contribution from hadronisation via coalescence with light quarks from the medium

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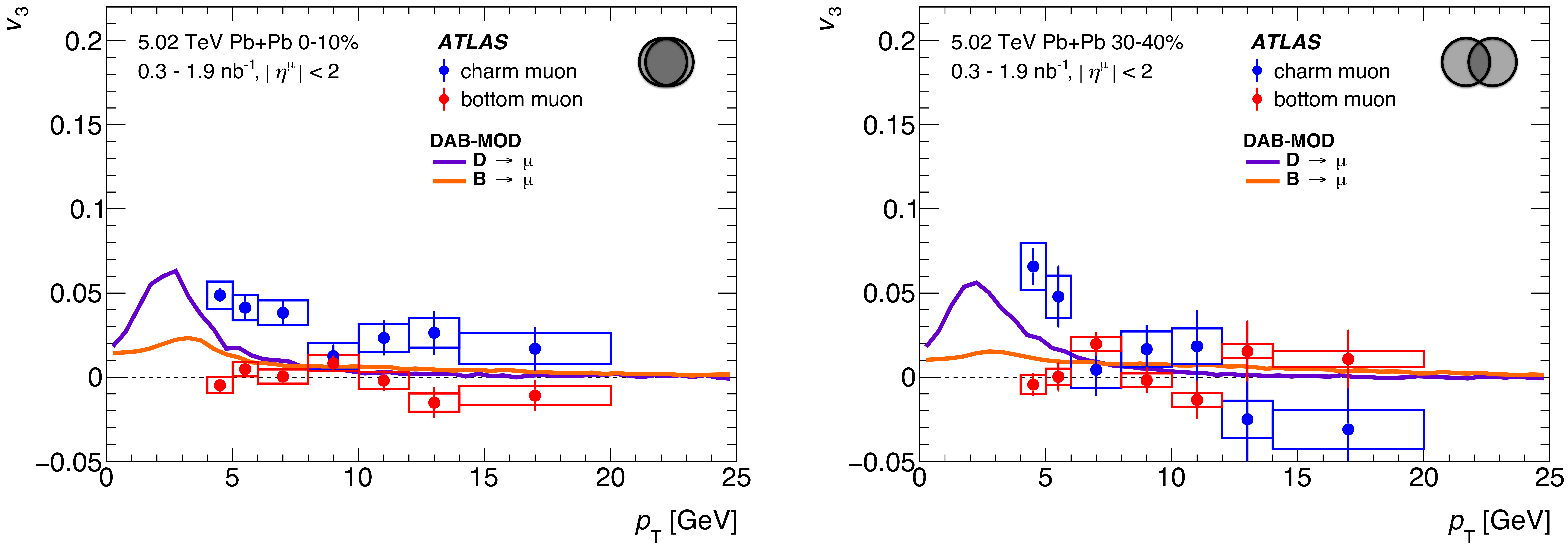
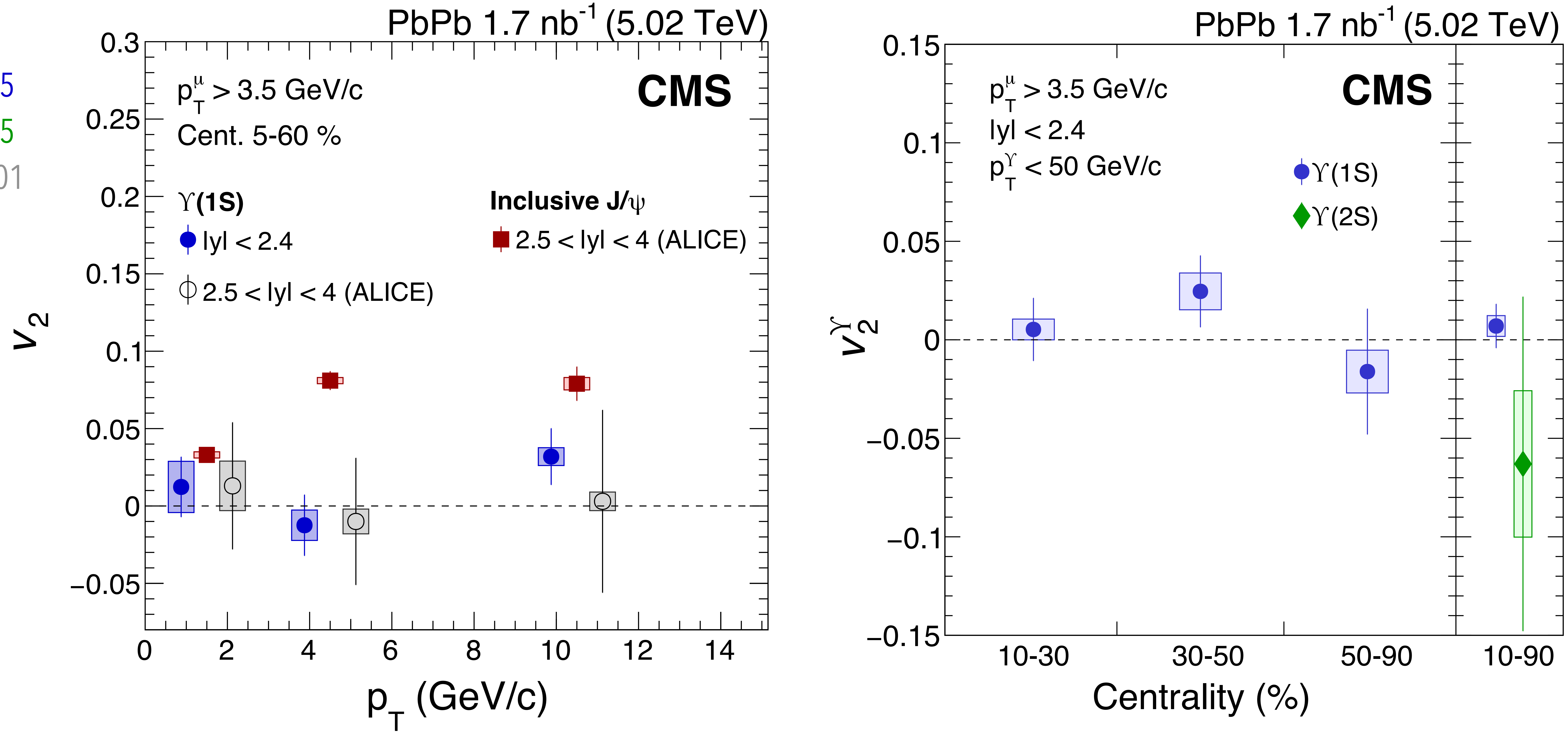
ATLAS c,b → μ: PLB 807 (2020) 135595   DAB-MOD: PRC 102 (2020) 024906



- No indication of positive v_3 of muons from beauty-hadron decays neither in central nor semicentral collisions
  - ➡ Compatible with very low v_3 predicted by DAB-MOD transport model
  - ➡ Lower p_T range important to draw a firm conclusion

Elliptic flow of hidden-beauty mesons

- CMS ϒ(1S): PLB 819 (2021) 136385
- CMS ϒ(2S): PLB 819 (2021) 136385
- ALICE ϒ(1S): PRL 123 (2019) 192301
- ALICE J/ψ: JHEP 10 (2020) 141



- v_2 of ϒ(1S) and ϒ(2S) compatible with zero within large uncertainties in all the p_T and centrality intervals measured
  - ➡ No contribution from coalescence with light quarks from the QGP
  - ➡ Does beauty quark flow?

Summary and conclusions

- Charm-quark flow: positive v_2 and v_3 of open and hidden charm mesons, correlated with light hadrons
  - ➡ Indicate significant degree of thermalisation of charm quarks in the QGP
  - ➡ Indicate sensitivity to initial-state event-by-event fluctuations
  - ➡ Contribution from charm-quark hadronisation via coalescence

- Search for strong early electromagnetic fields in heavy-ions
  - ➡ Electric field: no significant D-meson charge-dependent v_2
  - ➡ Magnetic field: hint of D-meson charge-dependent v_1

- Beauty-quark flow: positive v_2 for open-beauty hadrons, no significant v_2 for bottomonia
  - ➡ Does beauty quark flow?
  - ➡ Only contribution from beauty-quark hadronisation via coalescence?

ADDITIONAL SLIDES

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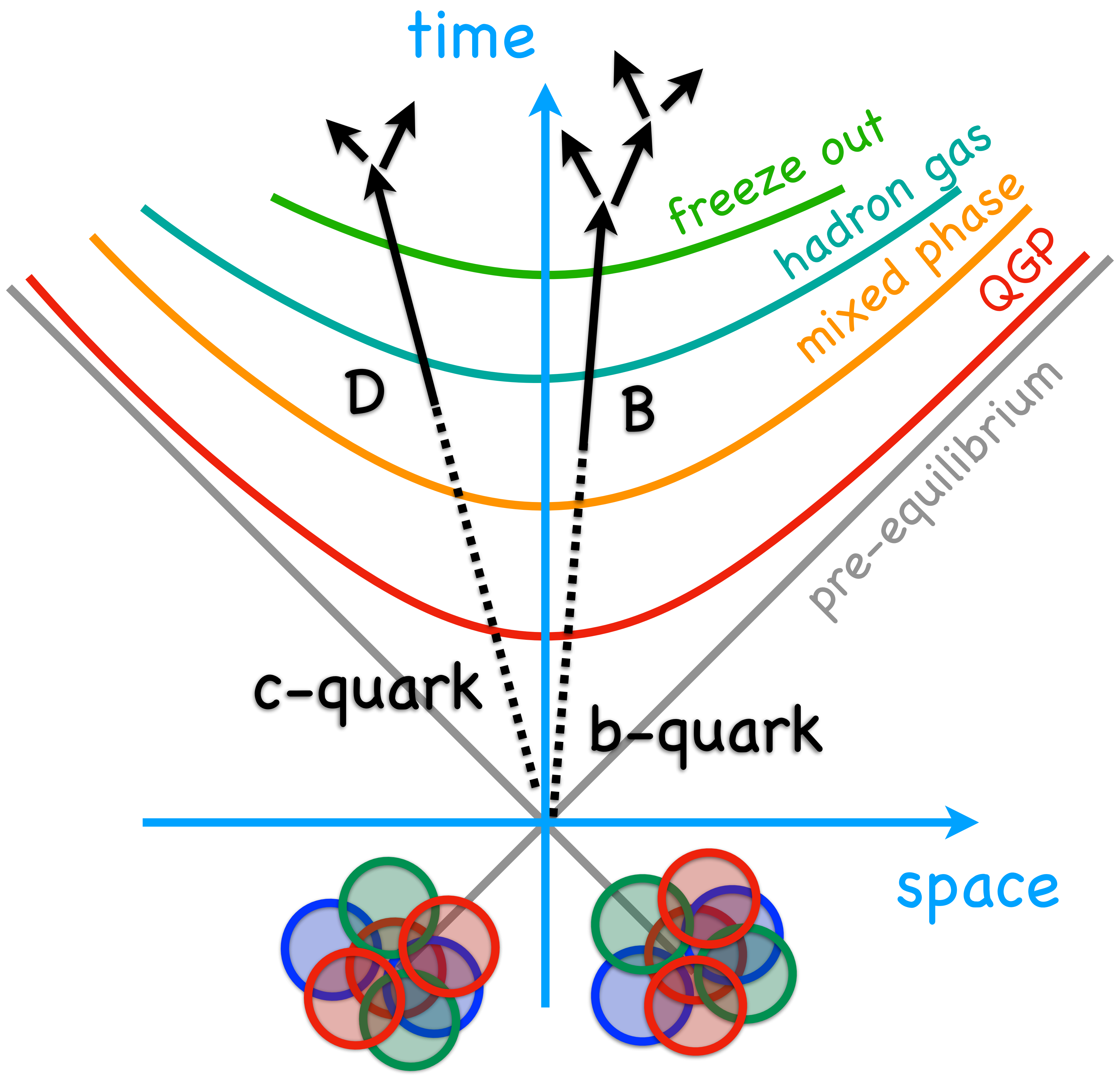

- QCD calculations on lattice predict a phase transition from the ordinary nuclear matter to a colour-deconfined medium, called *quark–gluon plasma* (QGP)
  - ➡ created in ultrarelativistic heavy–ion collisions
  - ➡ very high energy density $\varepsilon > 15$ GeV/fm^3
  - ➡ after a pre-equilibrium phase expands hydrodynamically

- Heavy flavours: produced in shorter time scales than QGP formation time
  - ➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx$ 0.05-0.1 fm/c depending on p_{T}
  - ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) $\approx$ 0.3 fm/c

  } HF experience the full system evolution

PRC 89 (2014) 034906

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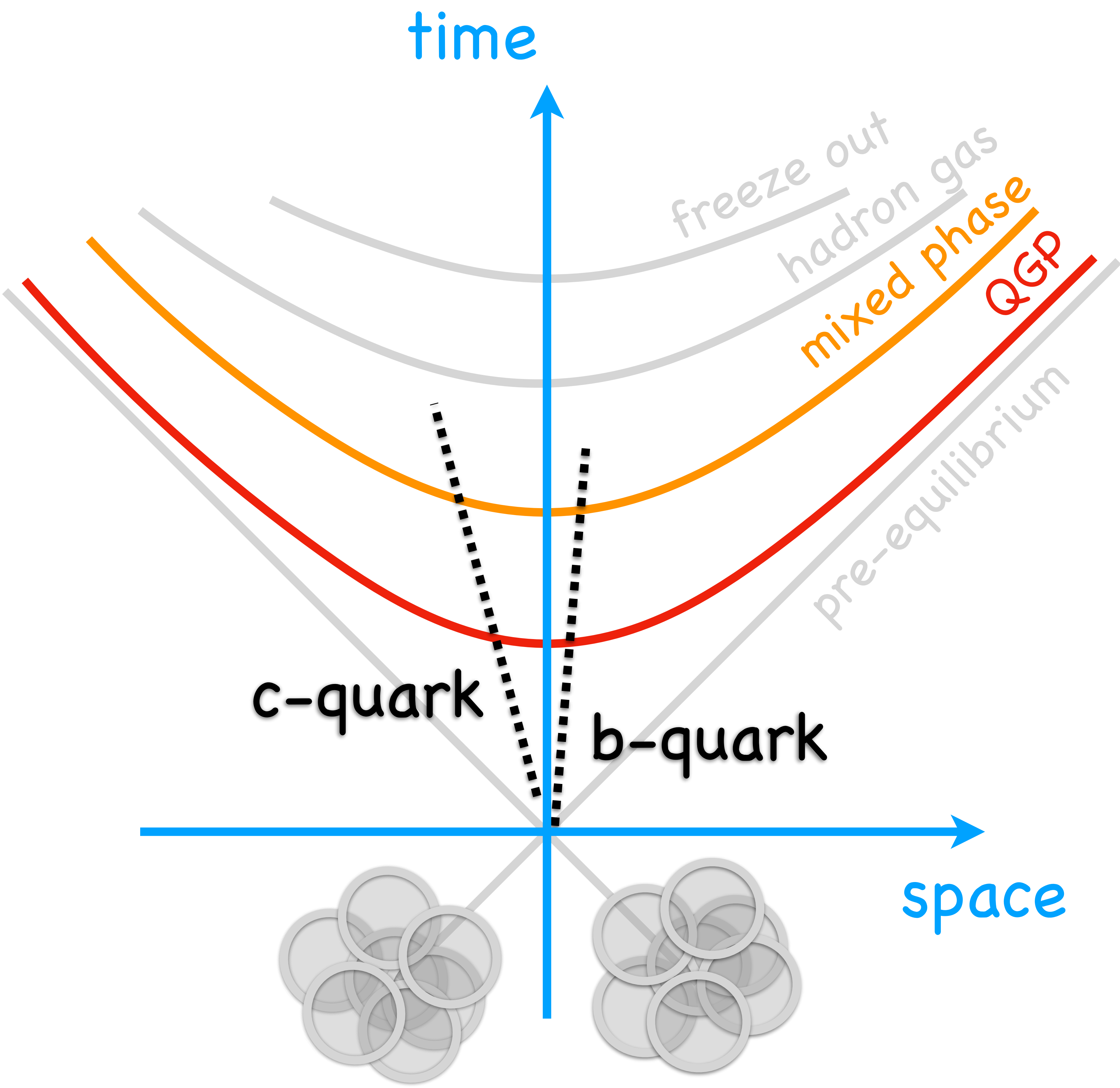
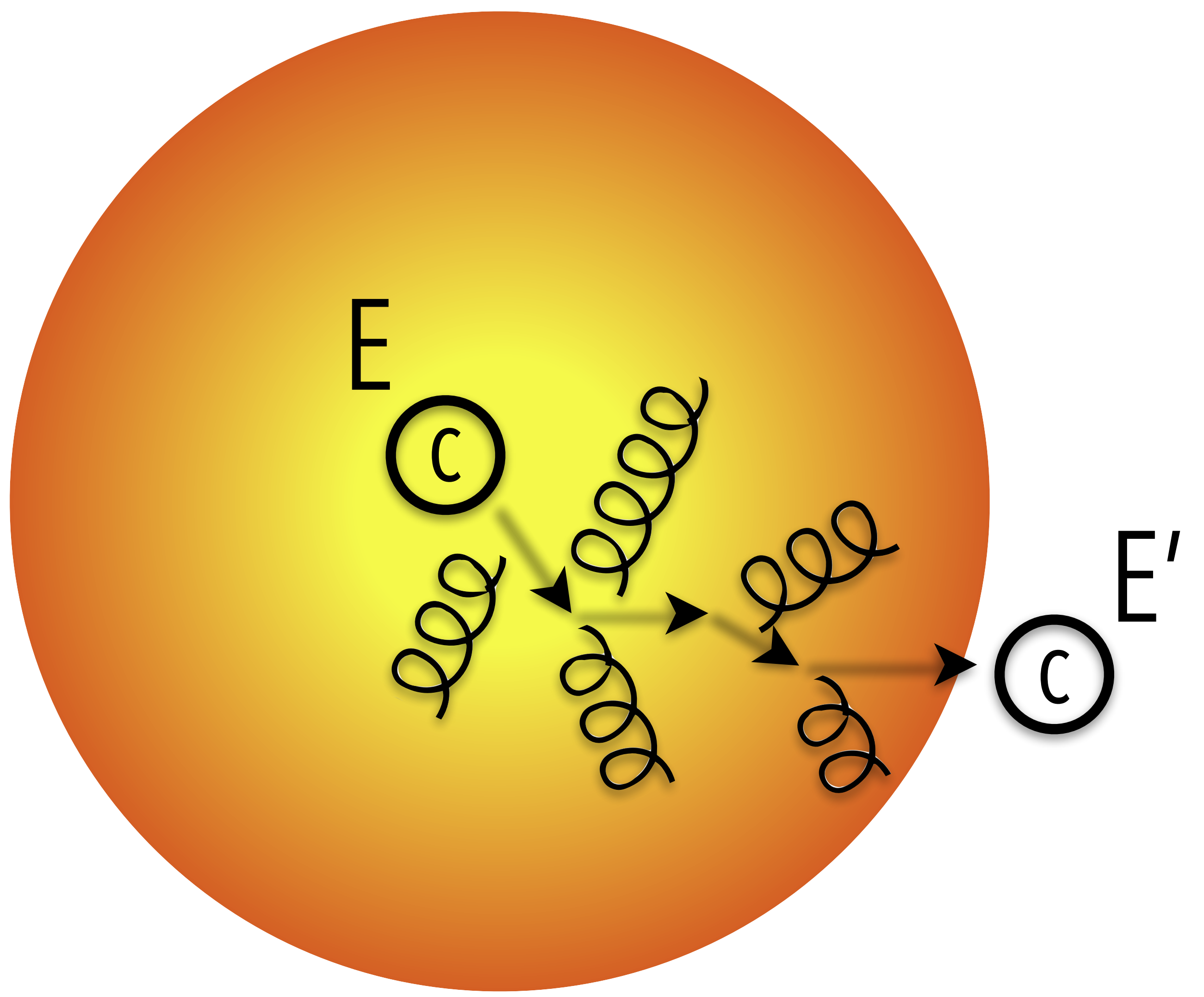


- HF propagate in the QGP with a Brownian motion
  - ➡ interact with medium constituents
  - ➡ loose energy via elastic collisions and radiative processes
  - ➡ heavy-quark thermalisation in the QGP?



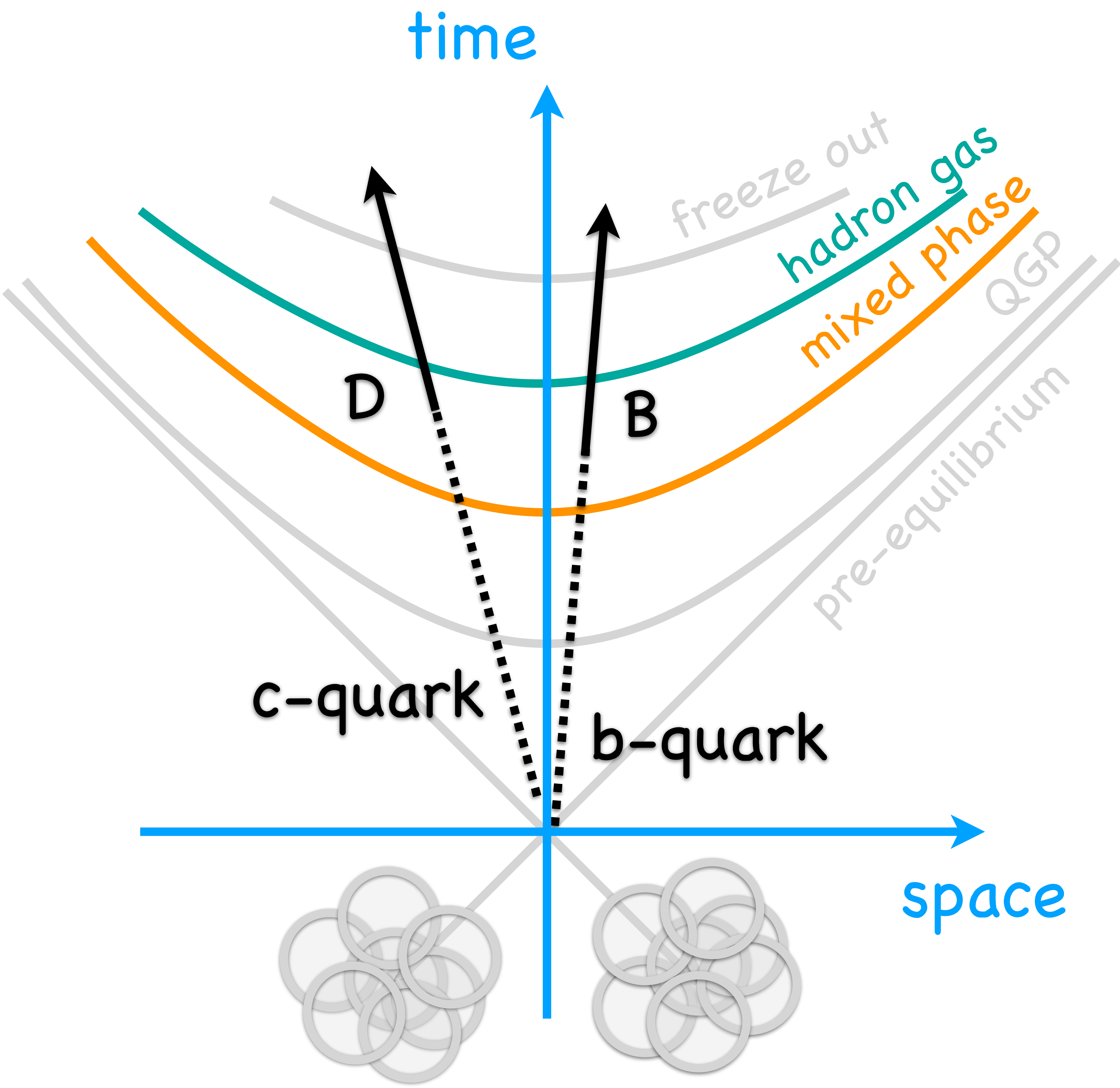
➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx$ 0.05-0.1 fm/c depending on p_{T}

➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) $\approx$ 0.3 fm/c

PRC 89 (2014) 034906

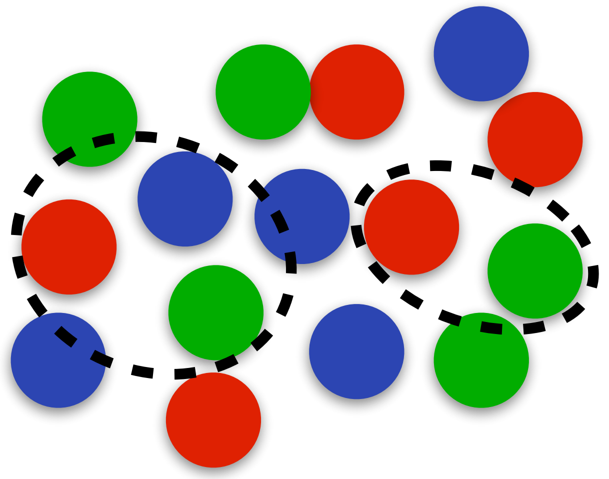
➡ $\tau_{\mathrm{QGP\ lifetime}} \approx$ 10 fm/c

PLB 696 (2011) 328-315



- Competing mechanisms for the HF hadronisation in the QGP

  1. Fragmentation $D_{q\rightarrow h}(z_q, Q^2)$
     - ➡ energy-loss of partons while traversing the QGP modifies fraction of the parton momentum z_q taken by the hadron
       - equal for all hadron species
  2. Coalescence
     - ➡ partons close in phase space can recombine into hadrons
     - ➡ quarks with different mass coalesce if have similar velocities



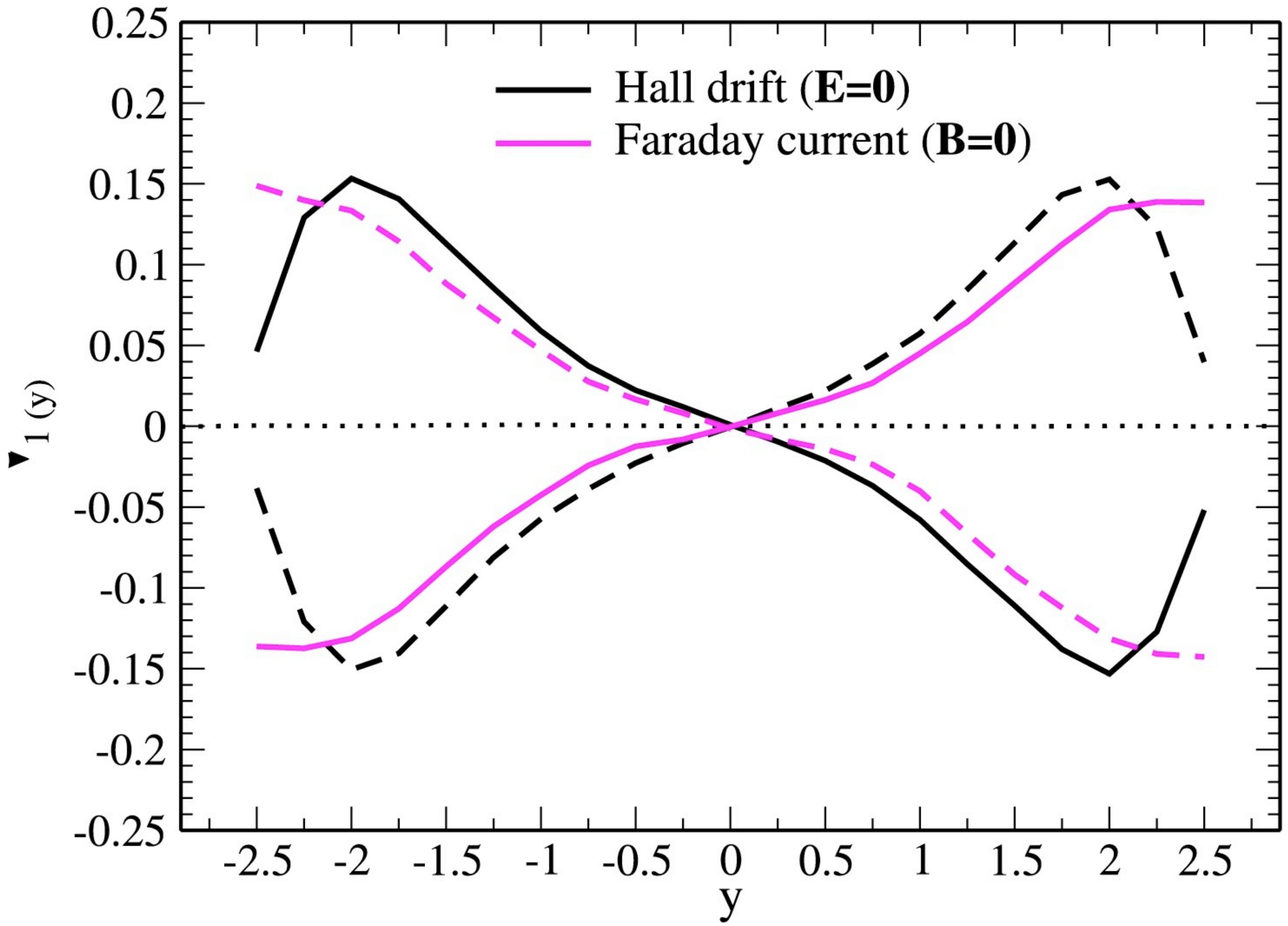
PRL 90 (2003) 202302
PRL 90 (2003) 202303
PRC 67 (2003) 064902
PLB 595 (2004) 202-208

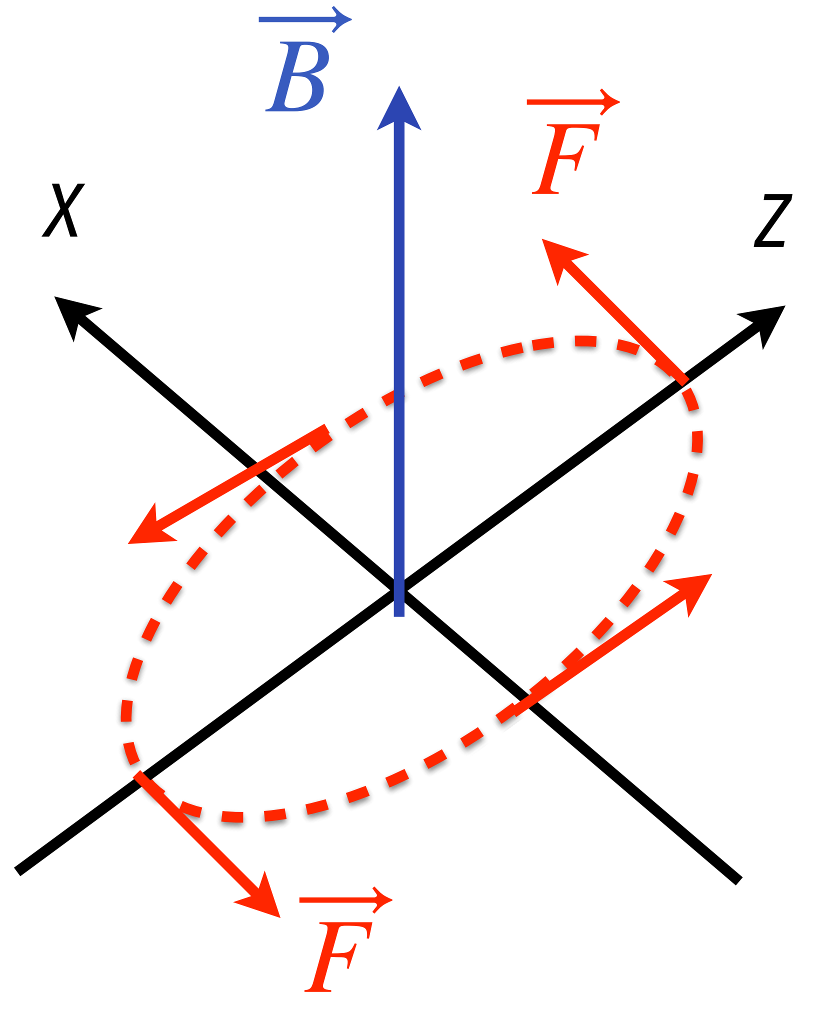
- Statistical hadronisation model
  - ➡ Hadrons emitted from the interaction region in statistical equilibrium at the QGP phase boundary

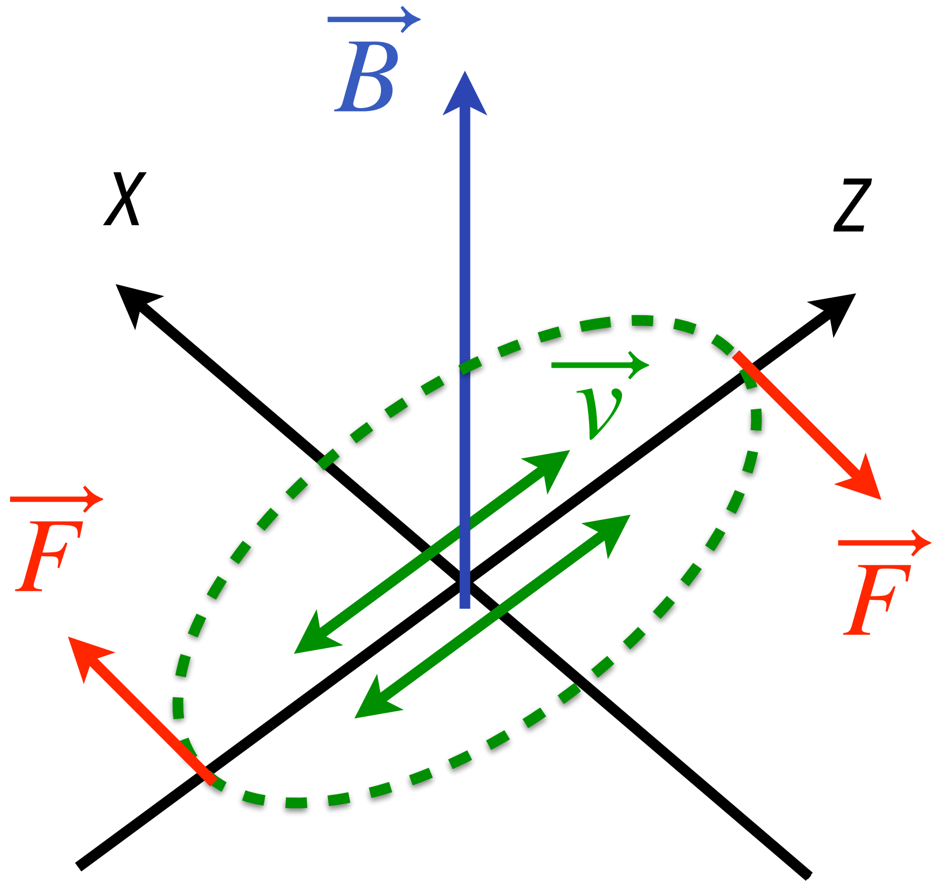
PLB (2008) 659:149-155

Charge-dependent directed flow

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



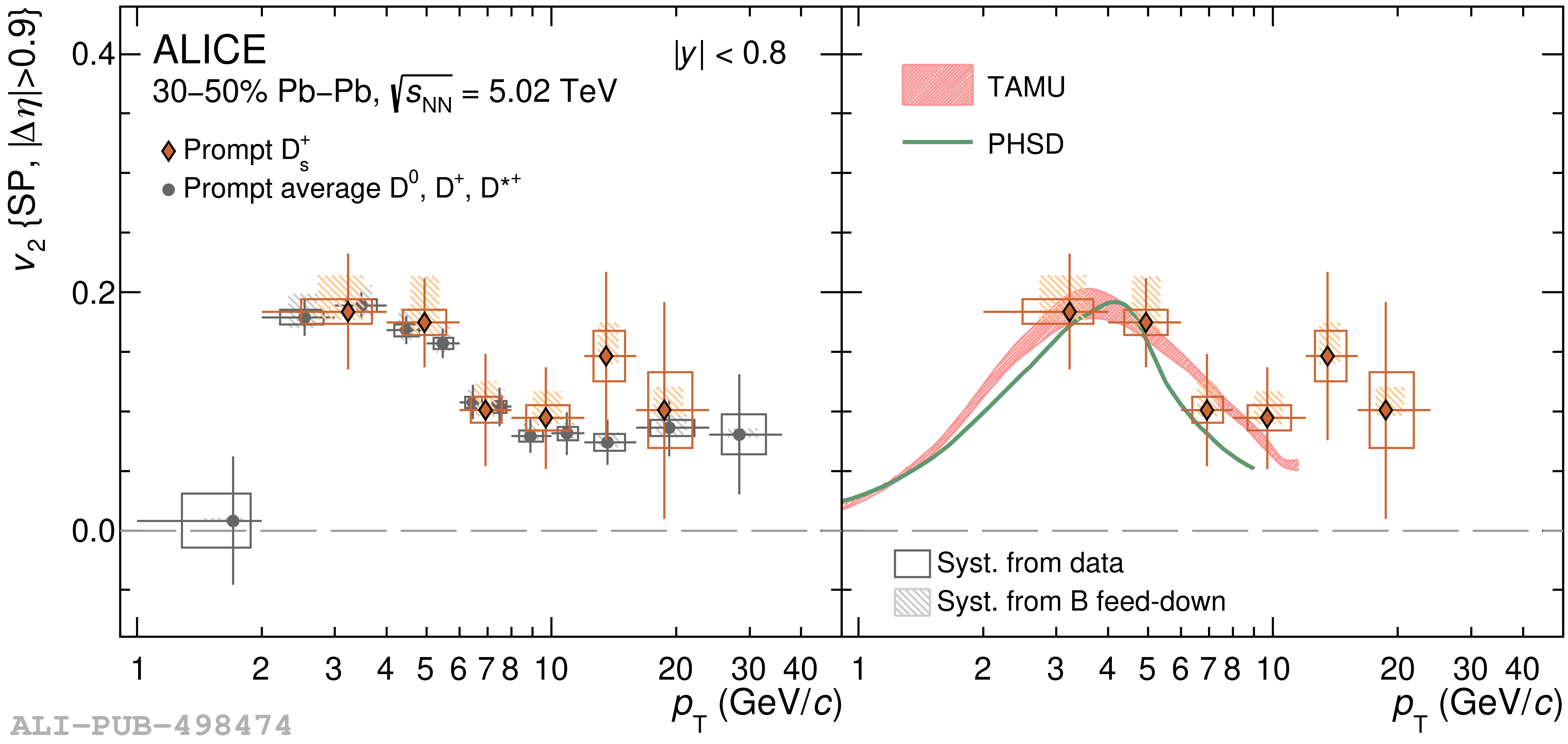




- Originated by two competing effects:
  - ➡ Faraday effect: electric field induced by decreasing $\vec{B}$
  - ➡ Hall effect: Lorentz force induced by moving charges $\vec{F} = q\vec{v} \times \vec{B}$

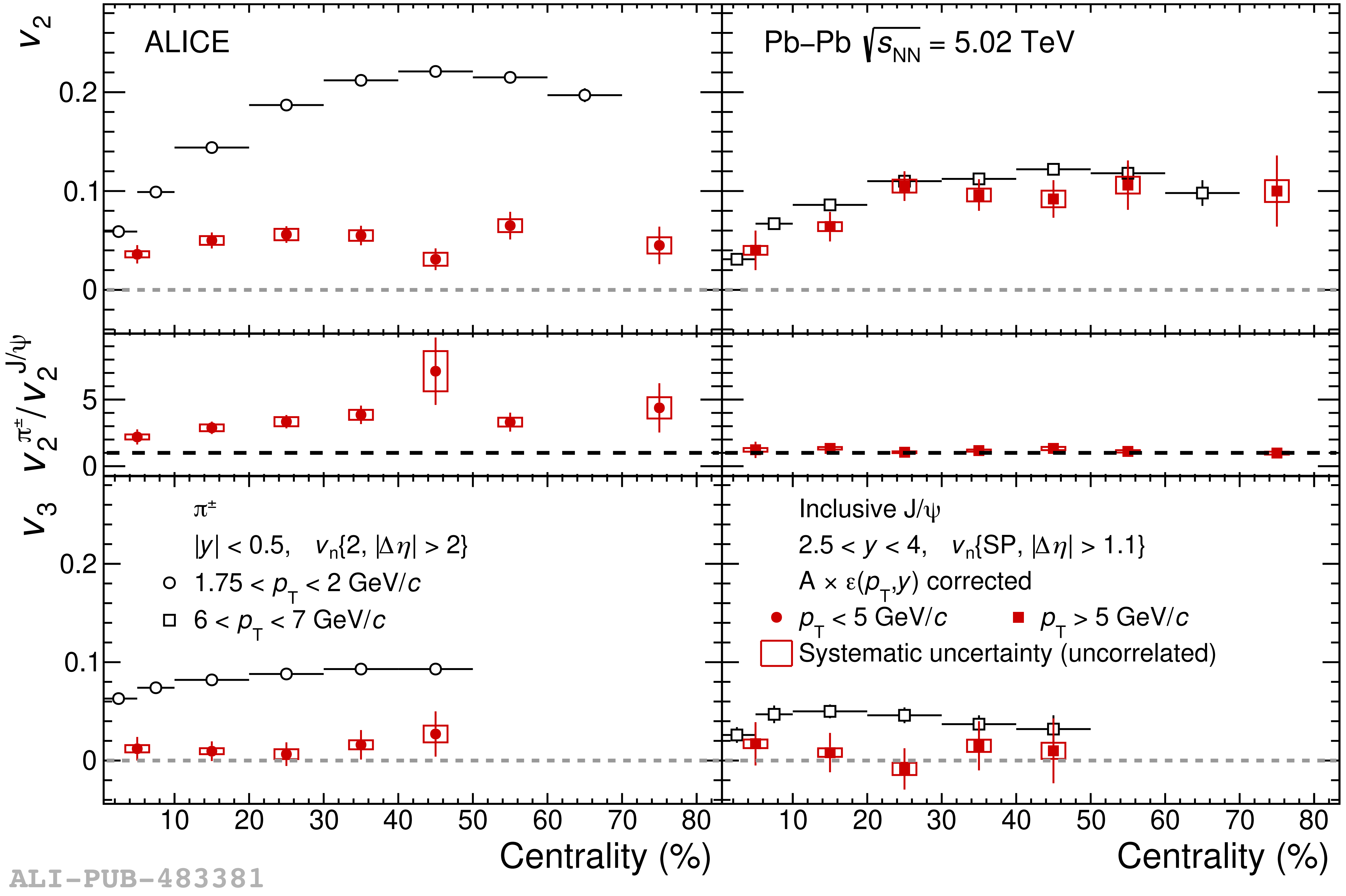
Strange D-meson elliptic flow

- No significant difference between D_s^+ and non-strange D mesons within current uncertainties



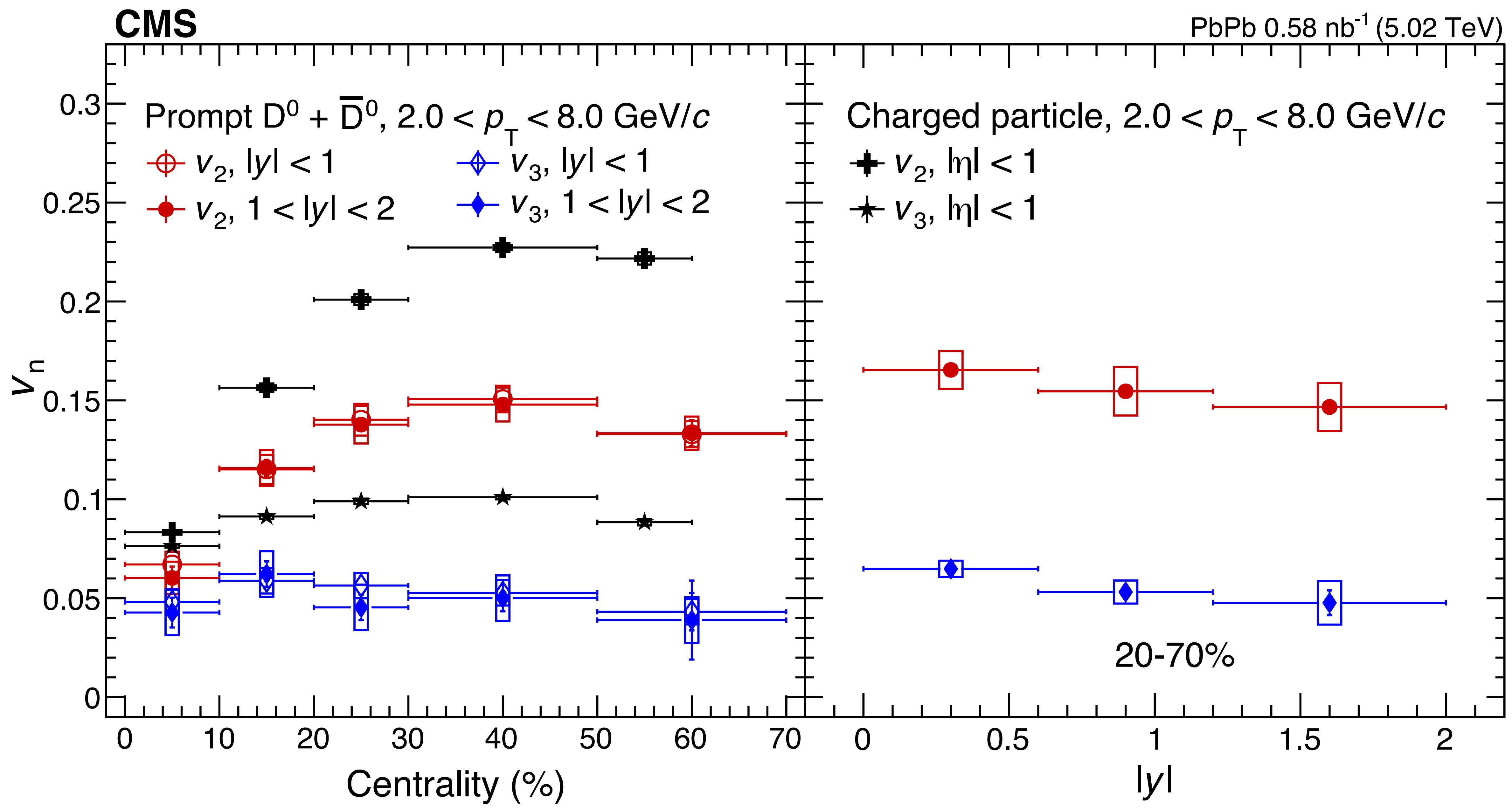
ALICE prompt D: PLB 813 (2021) 136054 ALICE prompt D_s^+: arXiv:2110.10006

Centrality and rapidity dependence of charm meson elliptic flow



ALICE J/ψ: JHEP 10 (2020) 141

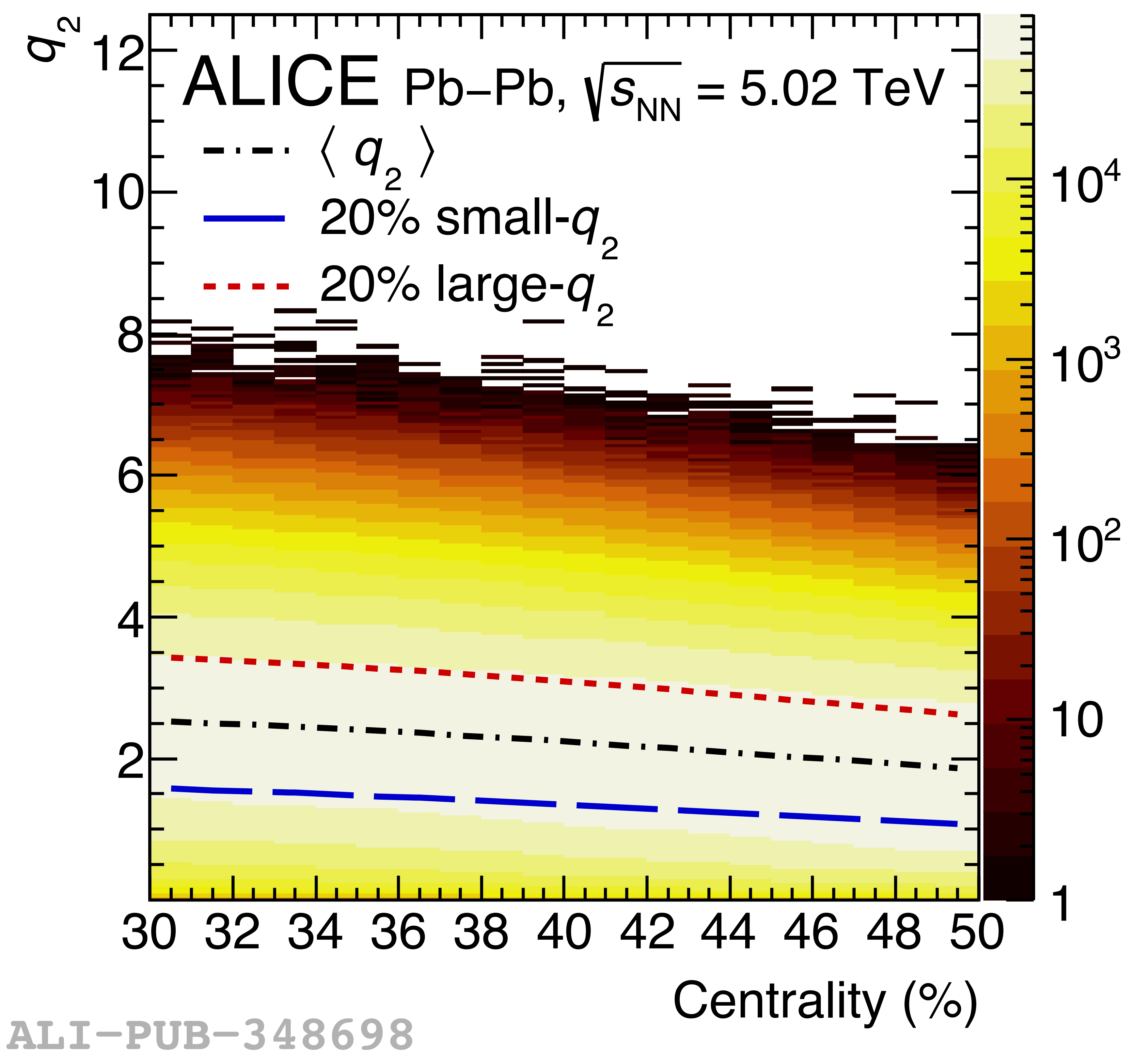
ALICE $\pi^\pm$: JHEP 09 (2018) 006

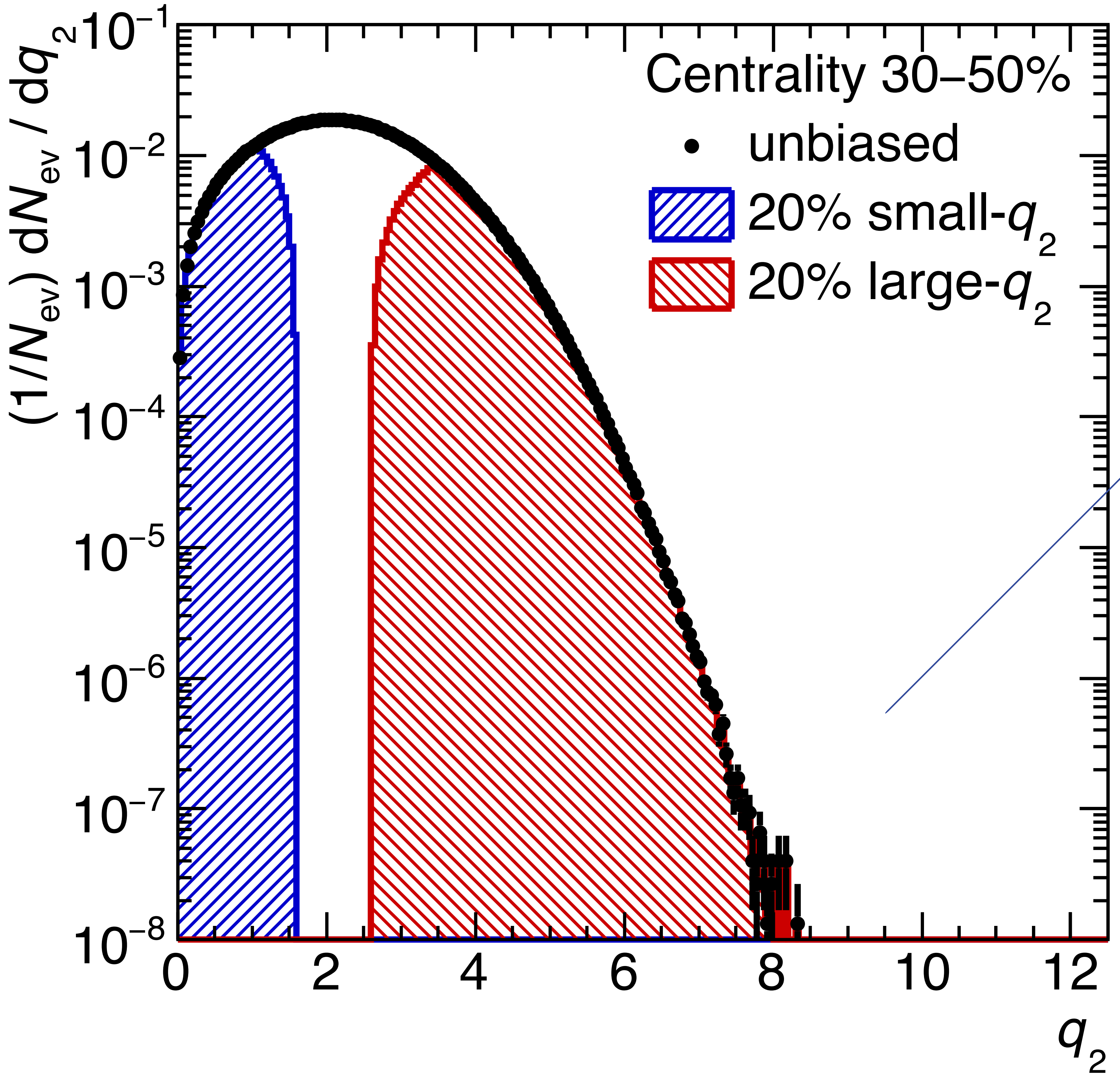


CMS prompt D^0: PLB 816 (2021) 136253

CMS charged particles: PLB 776 (2017) 195

PLB 813 (2021) 136054

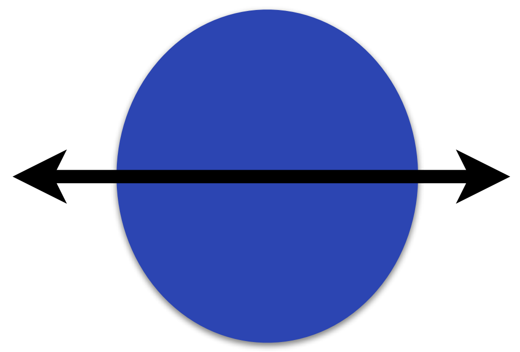




- The event-shape engineering (ESE) technique relies on the classification of events at a certain centrality according to the magnitude of the second-harmonic reduced flow vector:

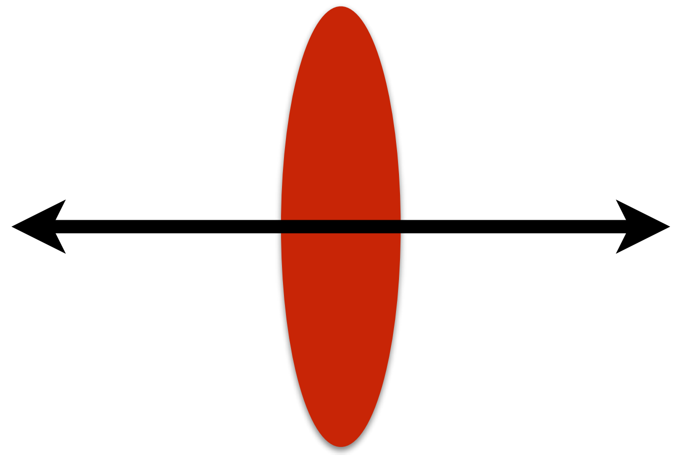
$$q_2 = |\vec{Q}_2|/\sqrt{M}$$

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



20% smallest q_2^{TPC}

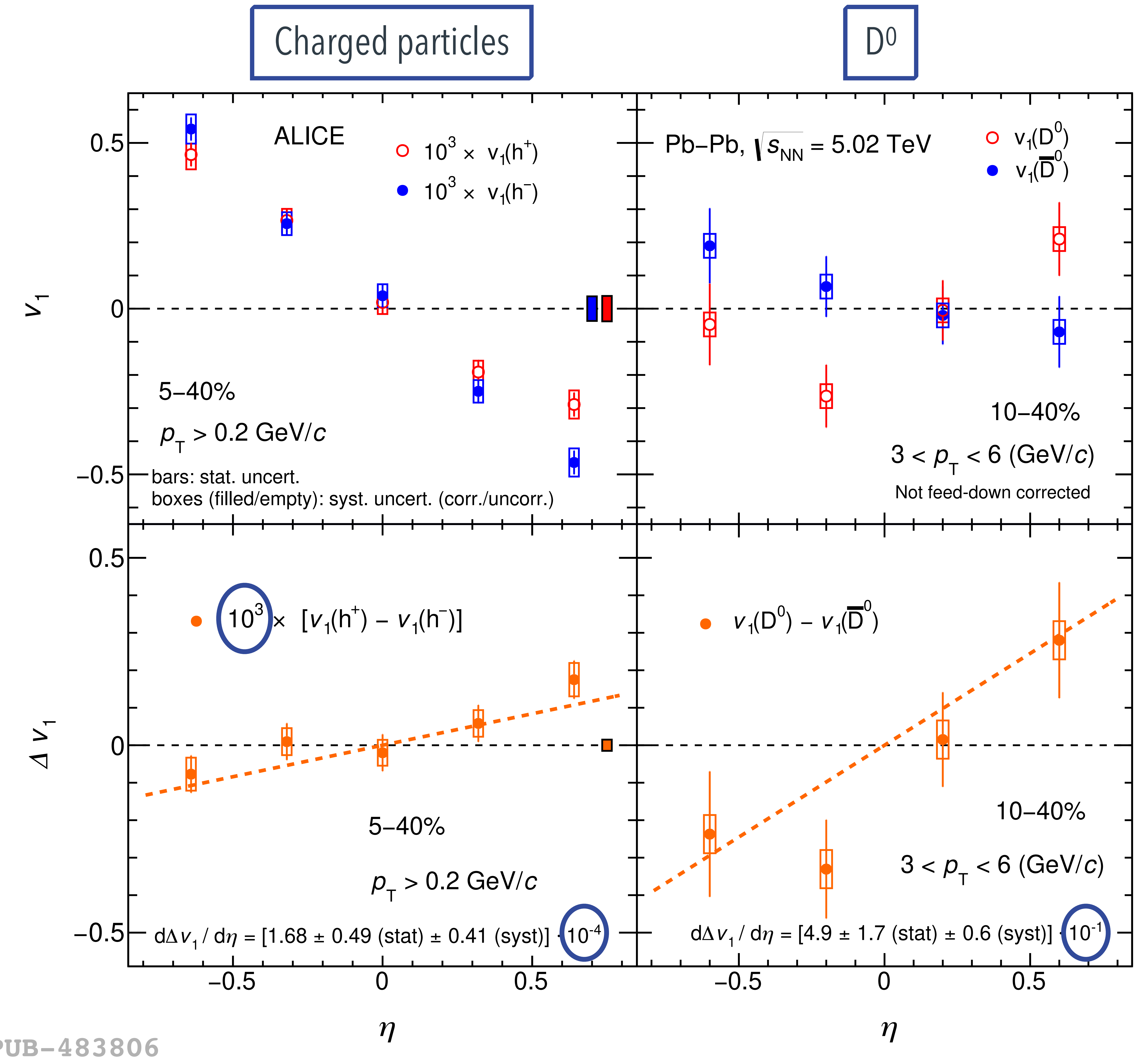
$\langle v_2 \rangle_{small-q_2} < \langle v_2 \rangle_{unb}$



20% largest q_2^{TPC}

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

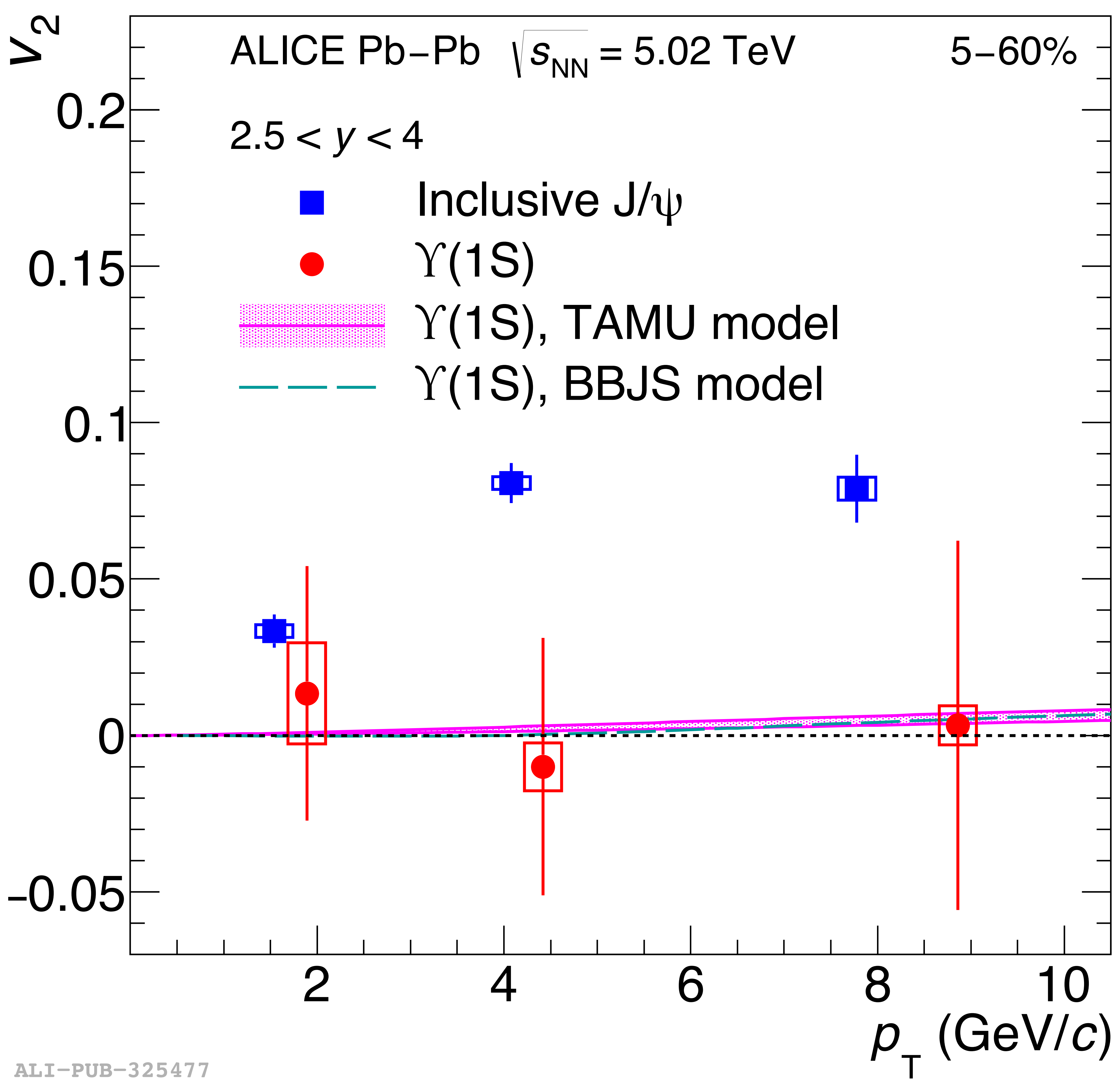
Search for strong magnetic fields: charge-dependent D-meson v_1

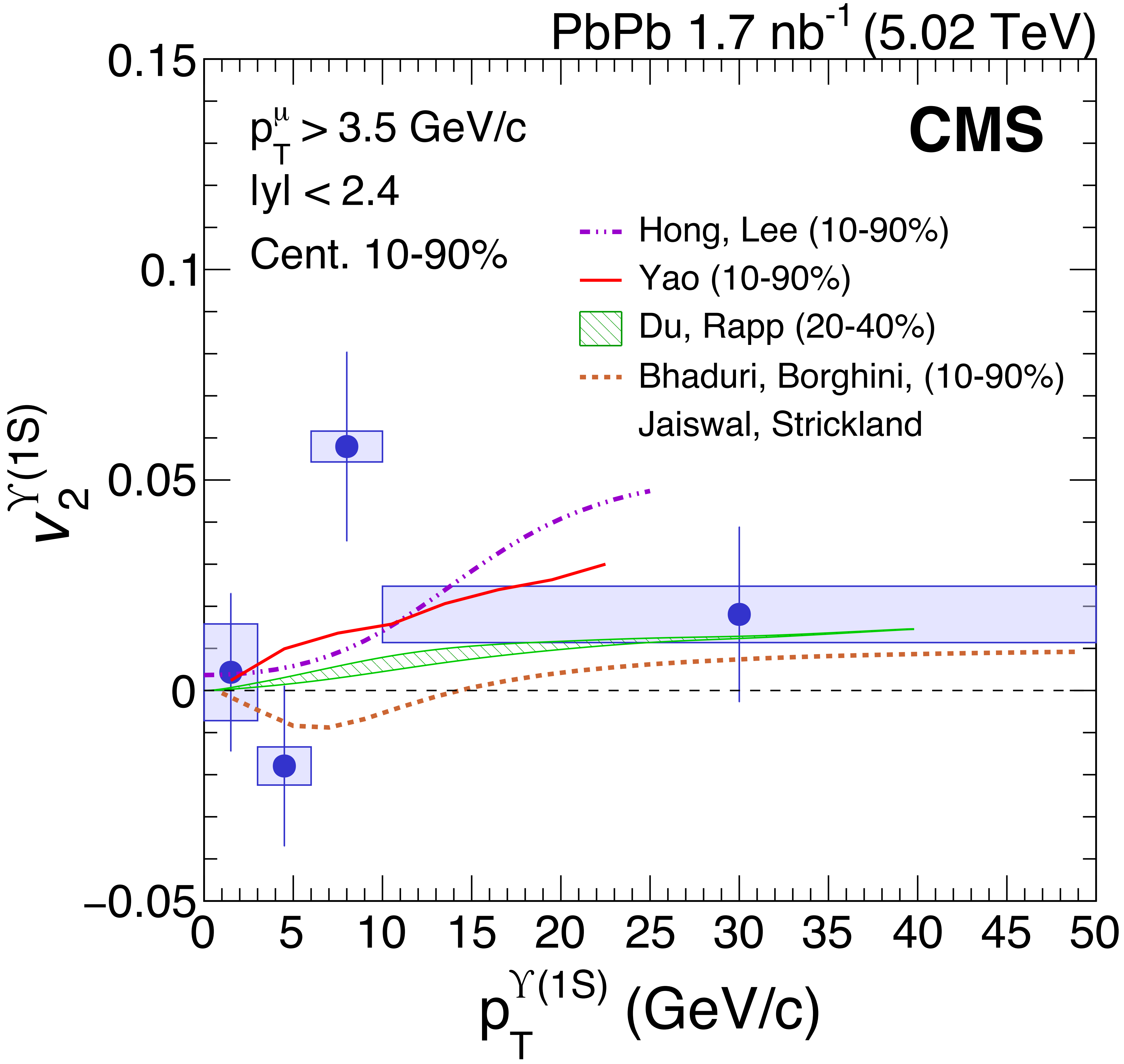


ALICE D0: PRL 125 (2020) 022301

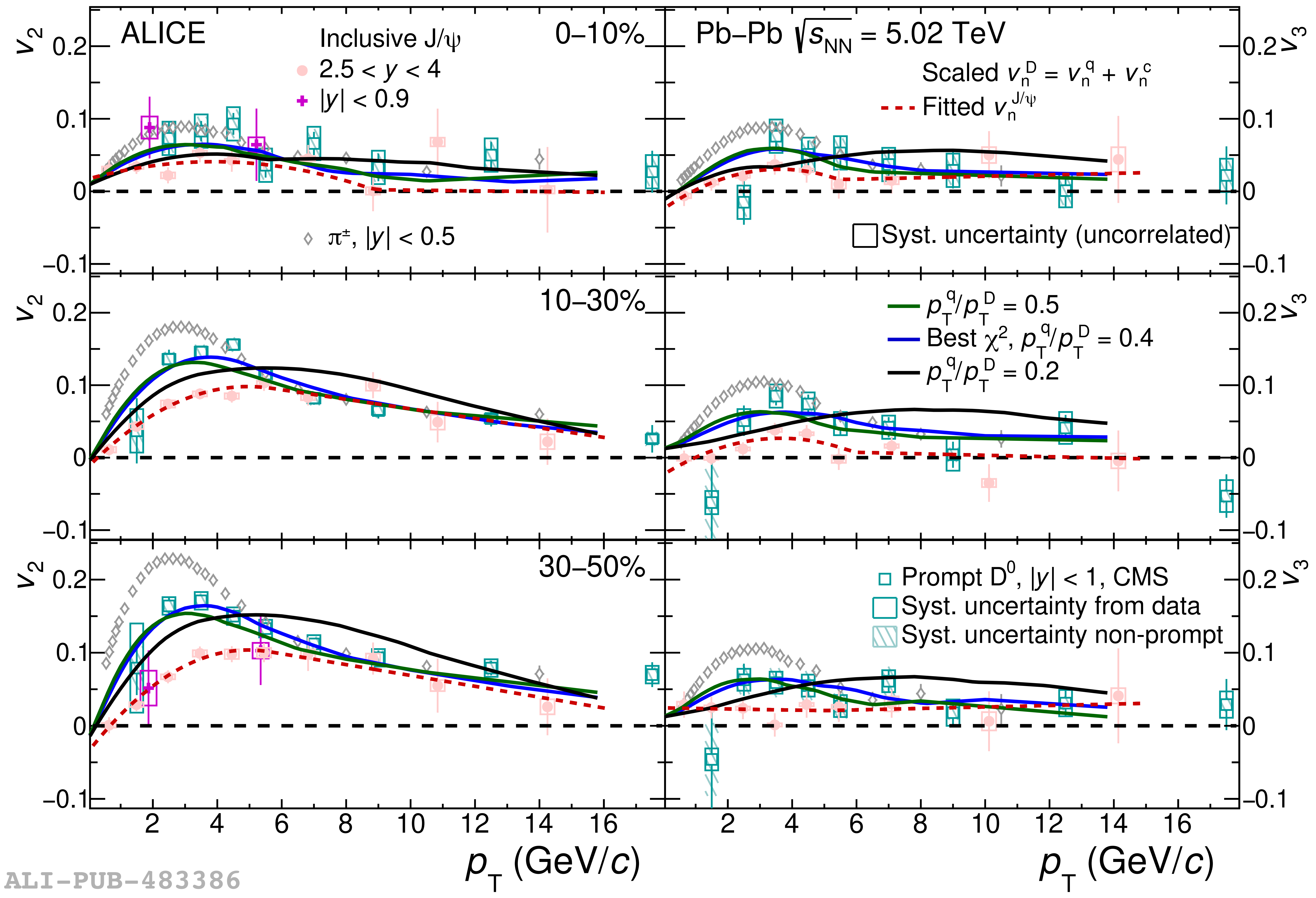
- Charm-quark production time comparable with maximum of magnetic field created in heavy-ion collisions — S. K. Das et al, PLB 768 (2017) 260-264; A. Beraudo et al, arXiv:2102.08064
  - ➡ Charge-dependent directed flow ideal observable to study early magnetic fields
- Indication of *y*-dependent charge difference
  - ➡ Different magnitude for charged particles and D0 mesons
  - ➡ 2.6σ significance for charged particles
  - ➡ 2.7σ significance for D0 mesons

ϒ(1S) elliptic flow vs. transport models





- CMS ϒ(1S): arXiv:2006.07707
- ALICE ϒ(1S): PRL 123 (2019) 192301
- ALICE J/ψ: JHEP 10 (2020) 141
- TAMU: PRC (2017) 96, 054901
- BBJS: PRC 100 (2019) 051901
- Yao: PRD 100 (2019) 014008
- Hong, Lee: PLB 801 (2020) 135147



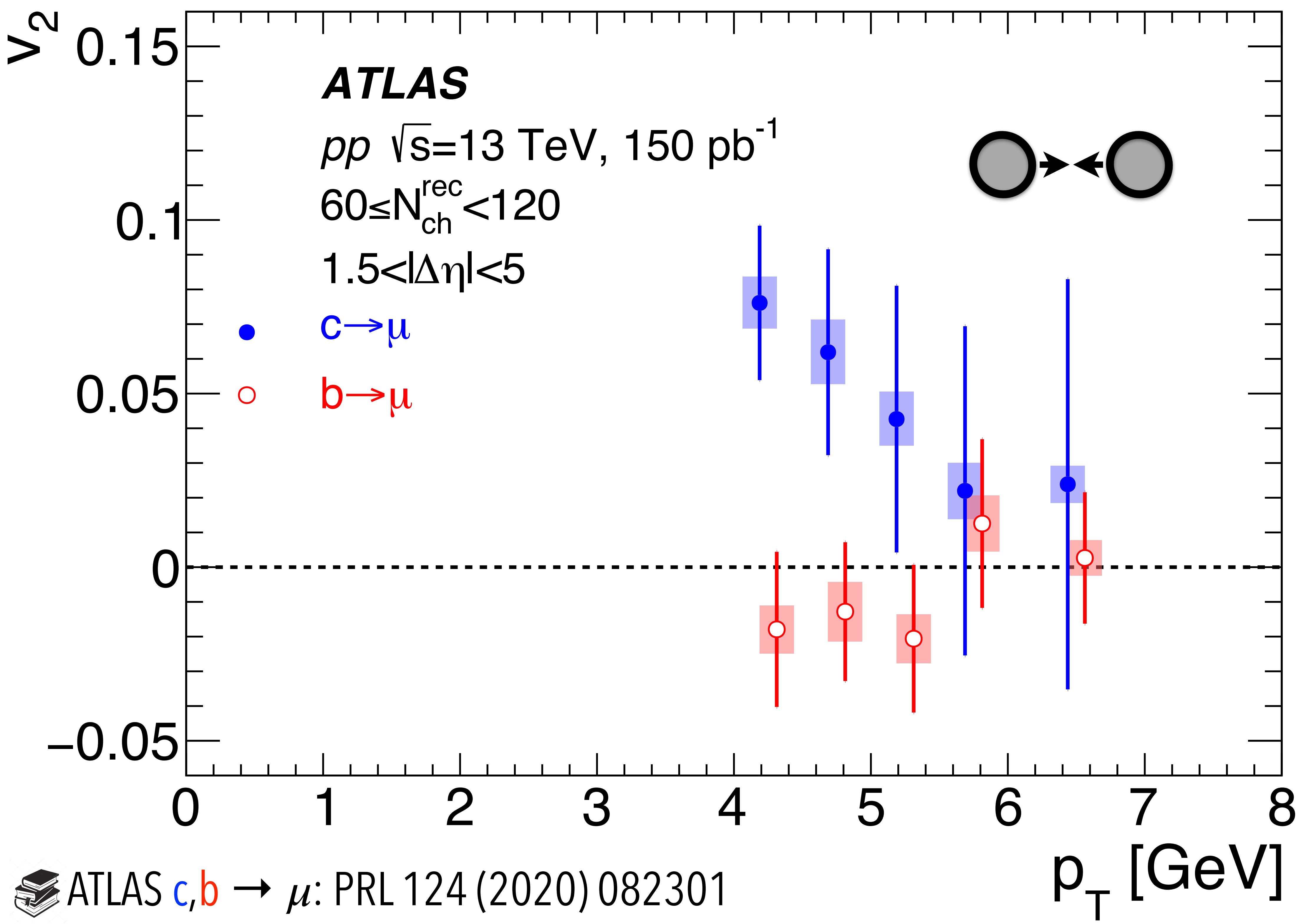
- v_n of D mesons can be obtained as a weighted average of the one of charm and light quarks:

$$v_n^D(p_T^D) = v_n^q(p_T^q) + v_n^c(p_T^c)$$

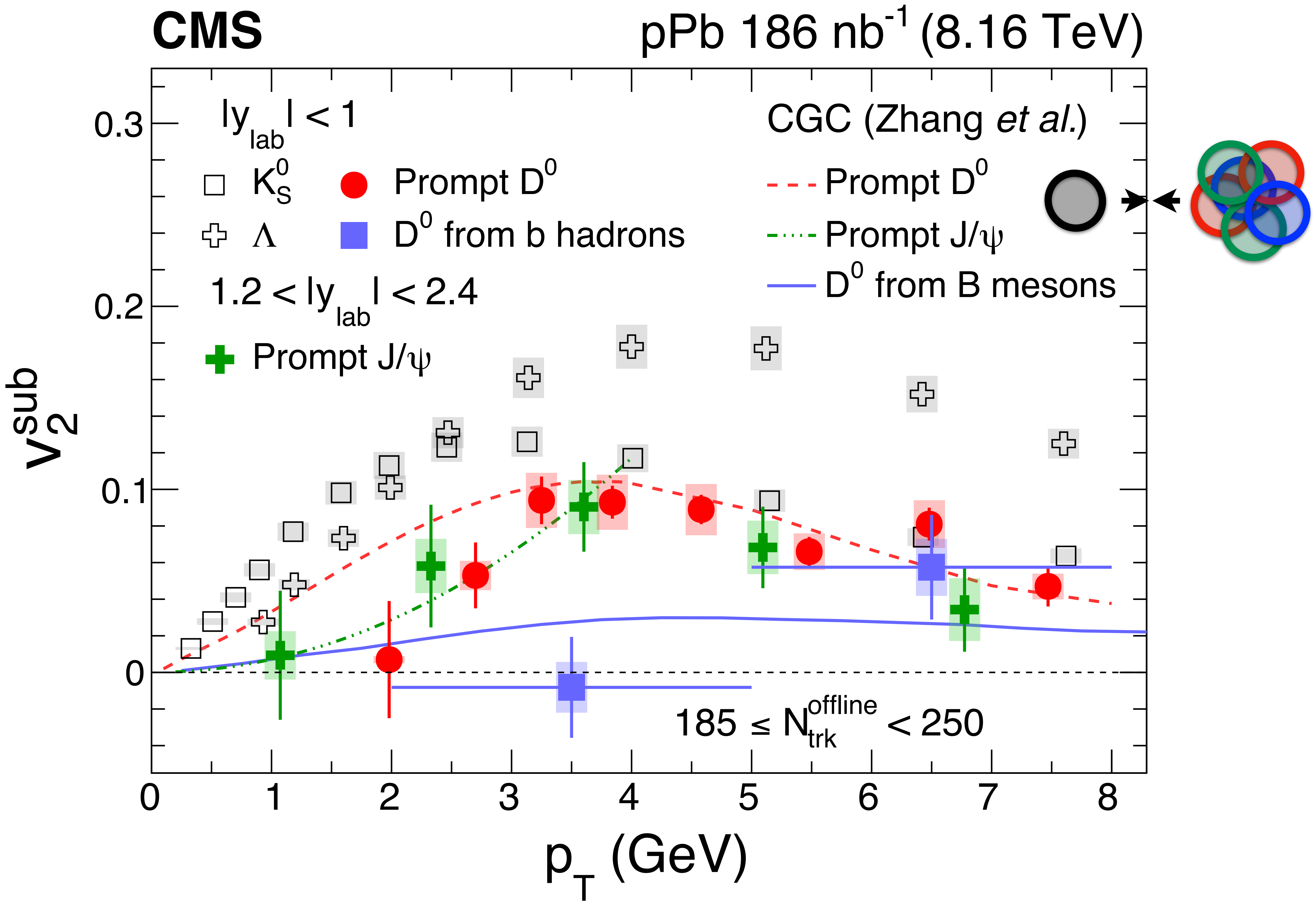
  - ➡ Quark p_T and v_n obtained as half of those of charged pions and J/ψ mesons
  - ➡ Best agreement in case of $p_T^D/p_T^q = 0.4$

ALICE $\pi^{\pm}$: JHEP 09 (2018) 006
CMS prompt D^0: PRL 120 (2018) 202301
ALICE J/ψ forward y: JHEP 10 (2020) 141
ALICE J/ψ mid y: JHEP 10 (2020) 141

Elliptic flow of open-beauty hadrons - small systems



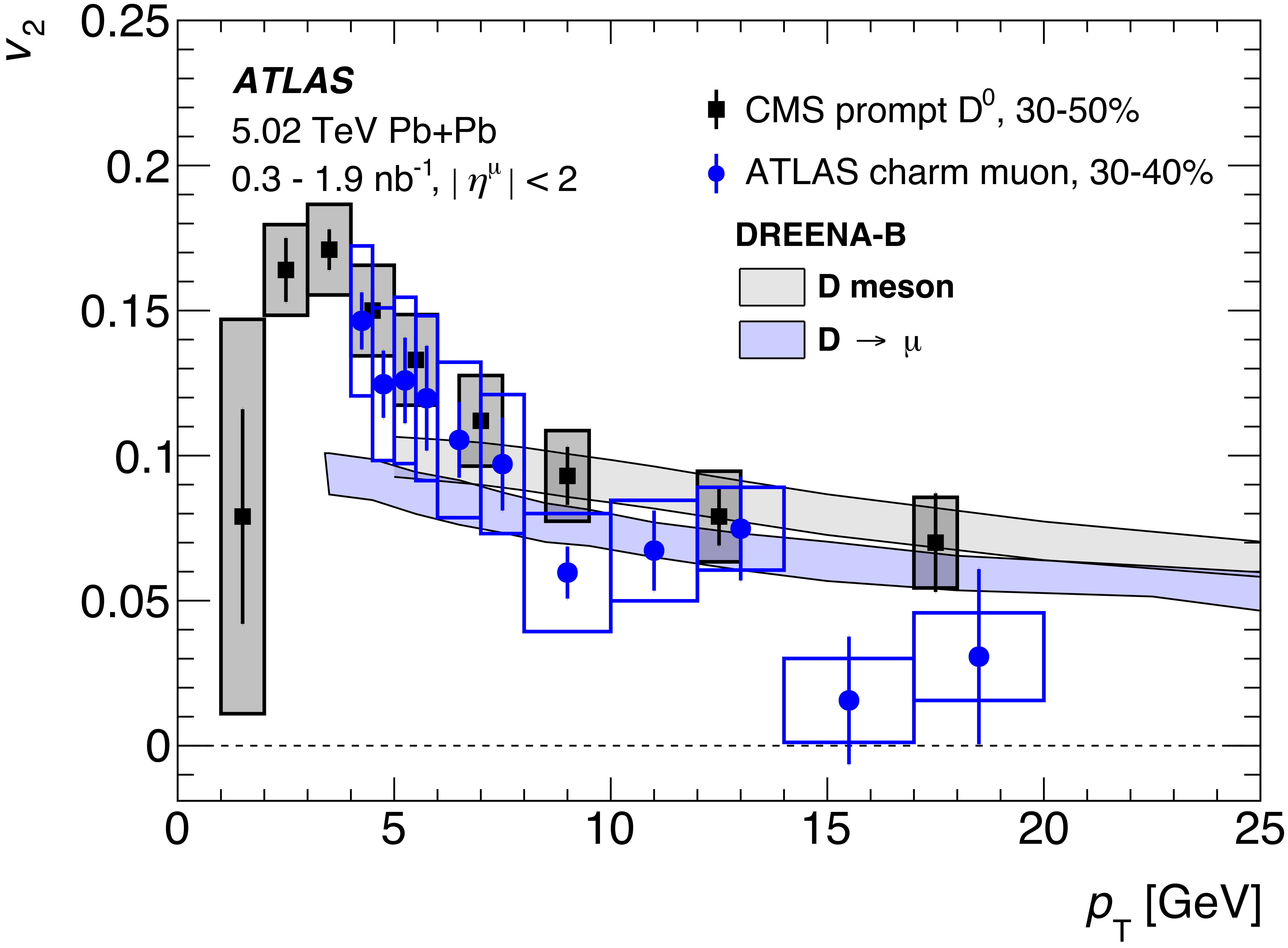
ATLAS c,b → μ: PRL 124 (2020) 082301



CMS c,b → D⁰, c→ J/ψ: PLB 813 (2021) 136036
ALICE J/ψ: PLB 780 (2018) 7-20

- No significant v_2 of muons (D^0) from beauty-hadron decays in pp (pPb) collisions
  - ➡ Is it zero or just very small?
  - ➡ v_2 mainly driven by beauty-quark coalescence in heavy-ion collisions?
  - ➡ For more information about small systems see presentation by Georgios Krintiras on Wed June 9th at 16:00

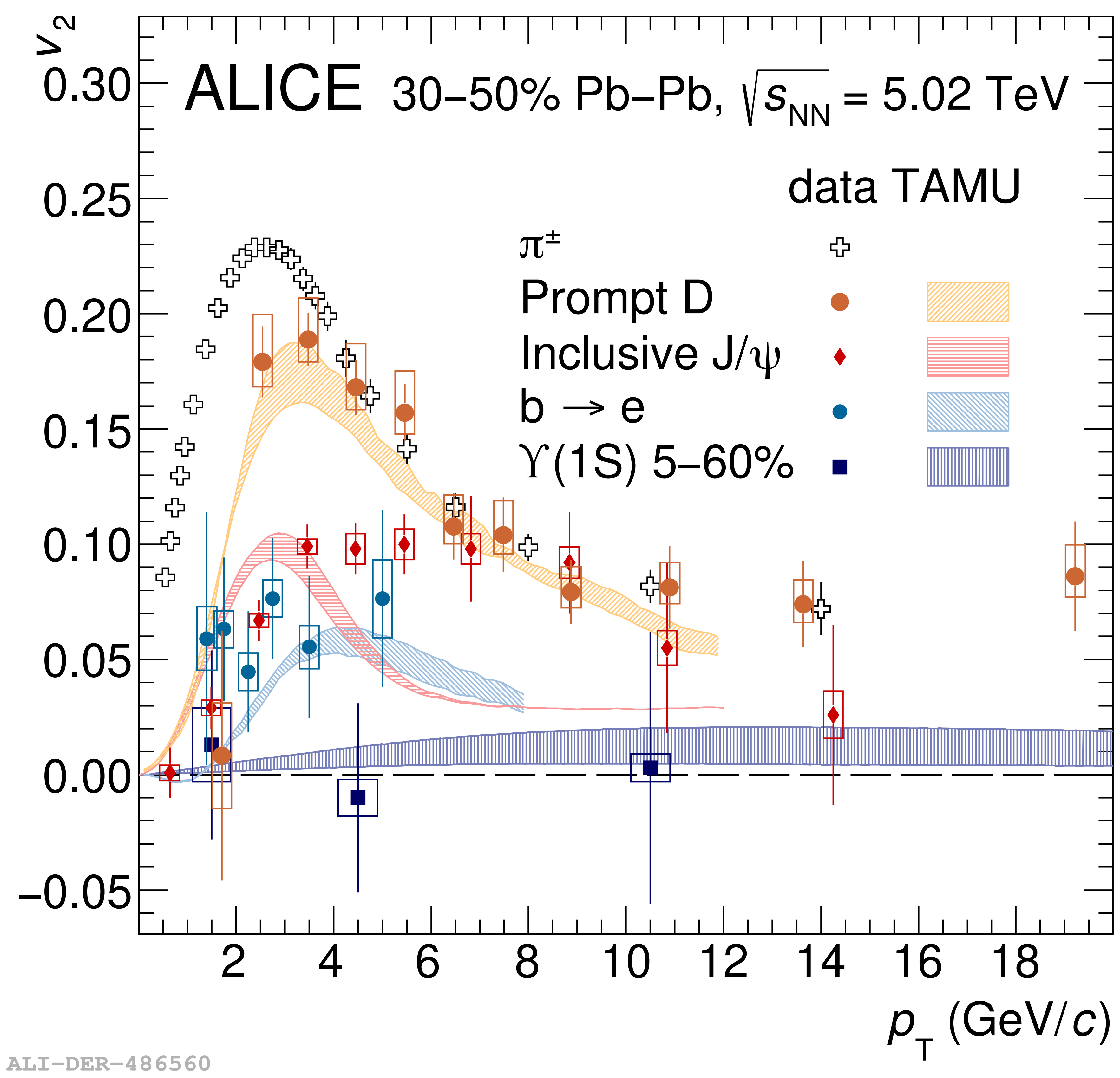
D-meson vs. muons from D-meson decays



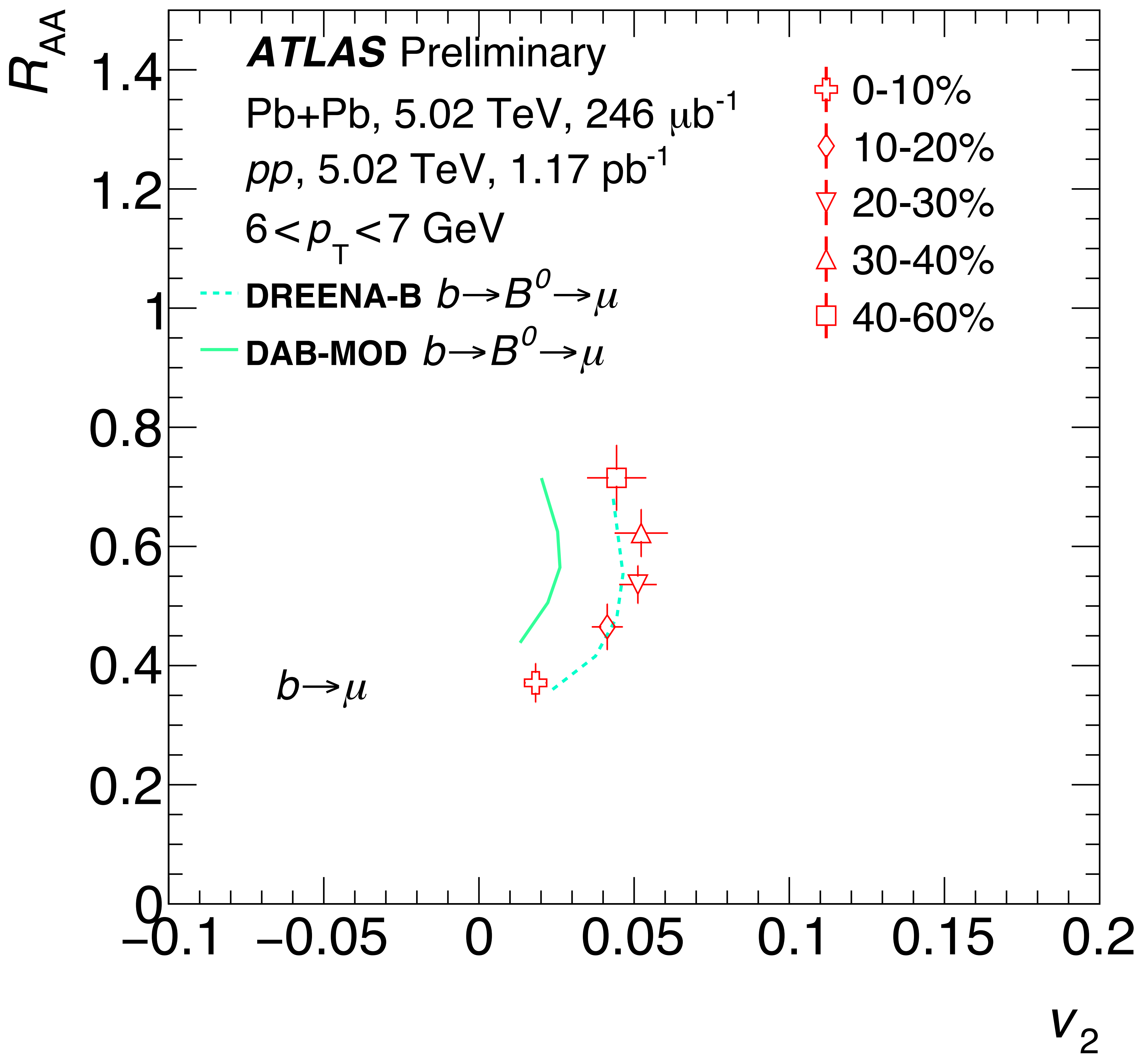
ATLAS c → μ: PLB 807 (2020) 135595

CMS prompt D^0: PRL 120 (2018) 202301

F. Grosa (CERN)
fgrosa@cern.ch



- Precise measurements of different hadron species crucial for setting constraints to models



- Simultaneous description of different observables challenging

ATLAS μ: ATLAS-CONF-2021-020
DAB-MOD: PRC 102 (2020) 024906
DREENA-B: PLB 791 (2019) 236-241

ALICE $\pi^{\pm}$: JHEP 09 (2018) 006
ALICE prompt D: PLB 813 (2021) 136054
ALICE J/ψ: JHEP 10 (2020) 141
ALICE b → e: PRL 126 (2021) 162001
ALICE ϒ(1S): PRL 123 (2019) 192301
TAMU: PRL 124 (2020) 042301, NPA 943 (2015) 147–158, PRC (2017) 96, 054901