# Searching Collective-like Effects for Heavy-Flavour in Small Systems with ALICE

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Indian Institute of Technology Indore

14th International Workshop on Multiple Parton Interactions at the LHC
[MPI@LHC],
20-24 Nov 2023,
University of Manchester, United Kingdom

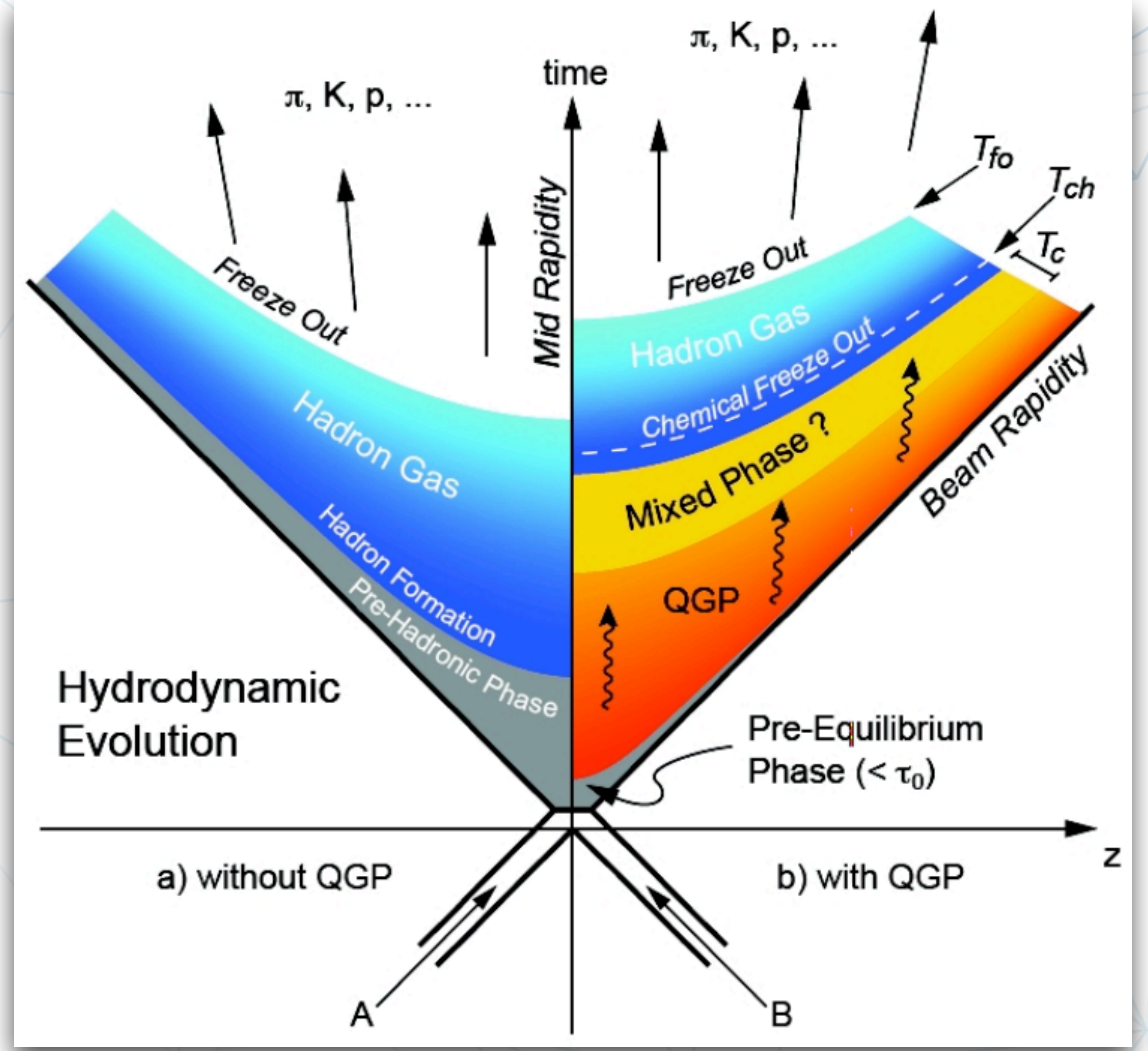
# Motivation : Heavy-Flavours

* Charm and beauty quarks : produced via hard scatterings in heavy-ion collisions

**CHARM**
$m_c = 1.3\ \mathrm{GeV}/c^2$

**BEAUTY**
$m_b = 4.2\ \mathrm{GeV}/c^2$

* Why are they studied in collisions of small systems?



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Produced at early stages →
Experience full evolution of the system

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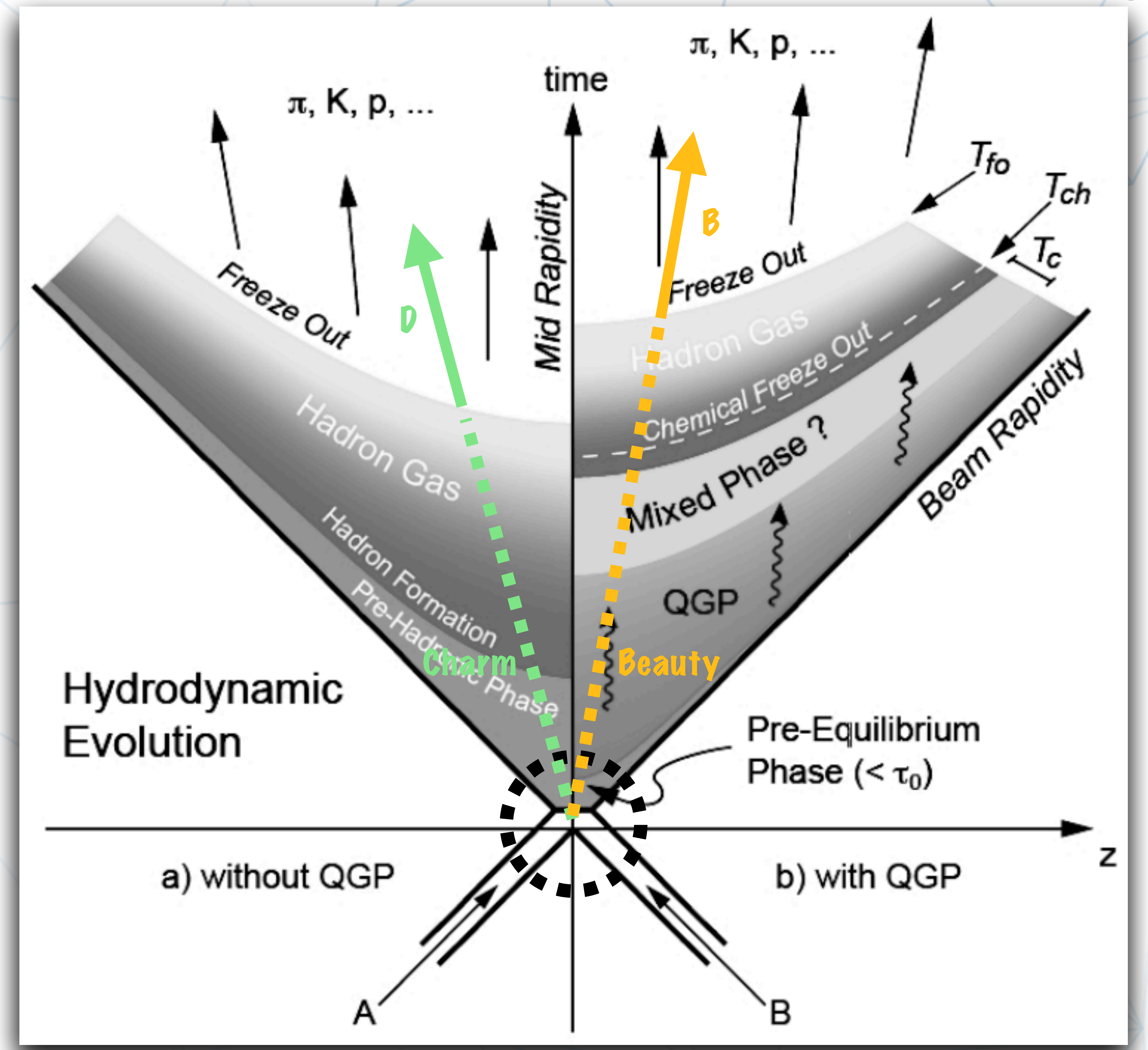

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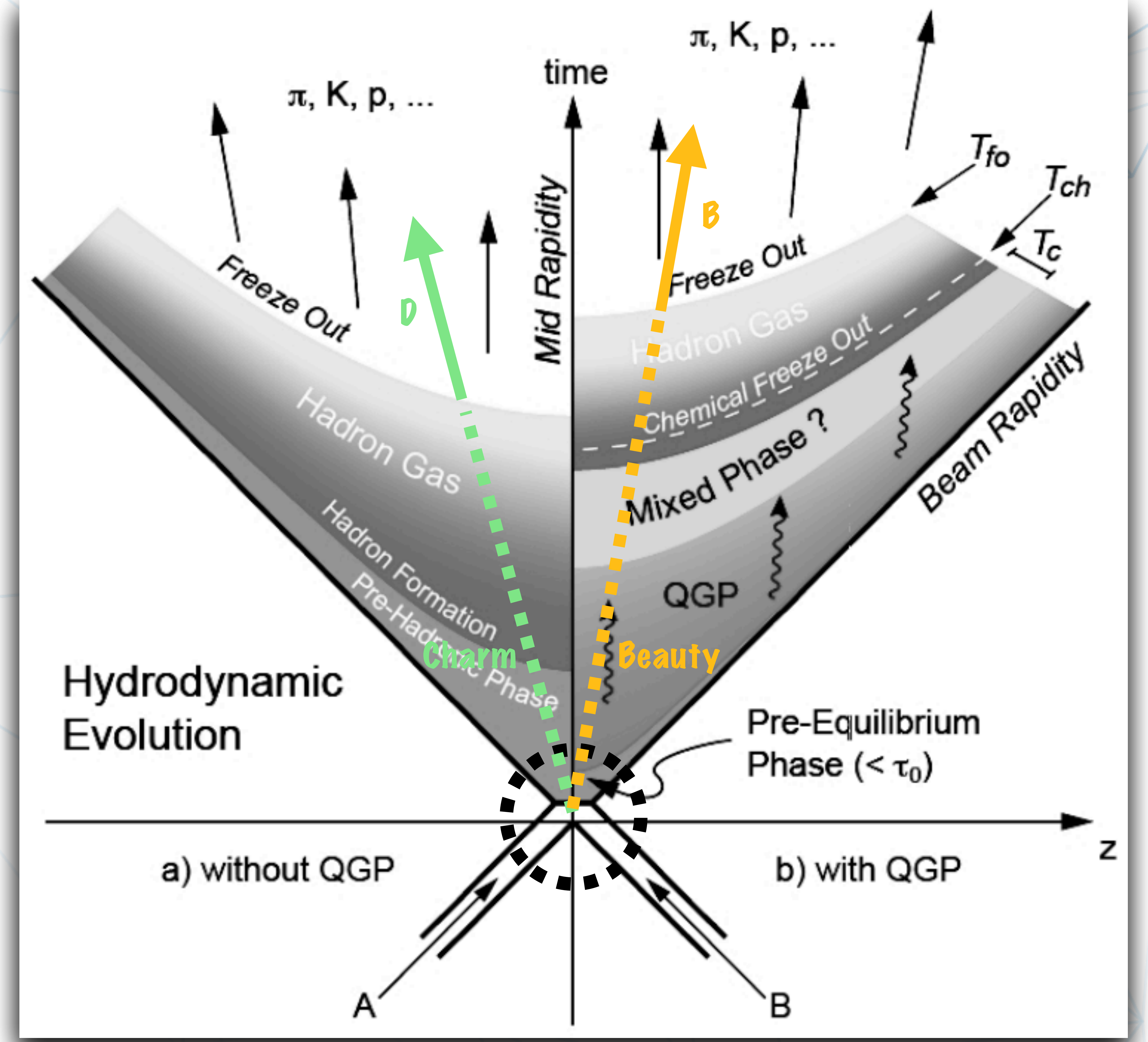
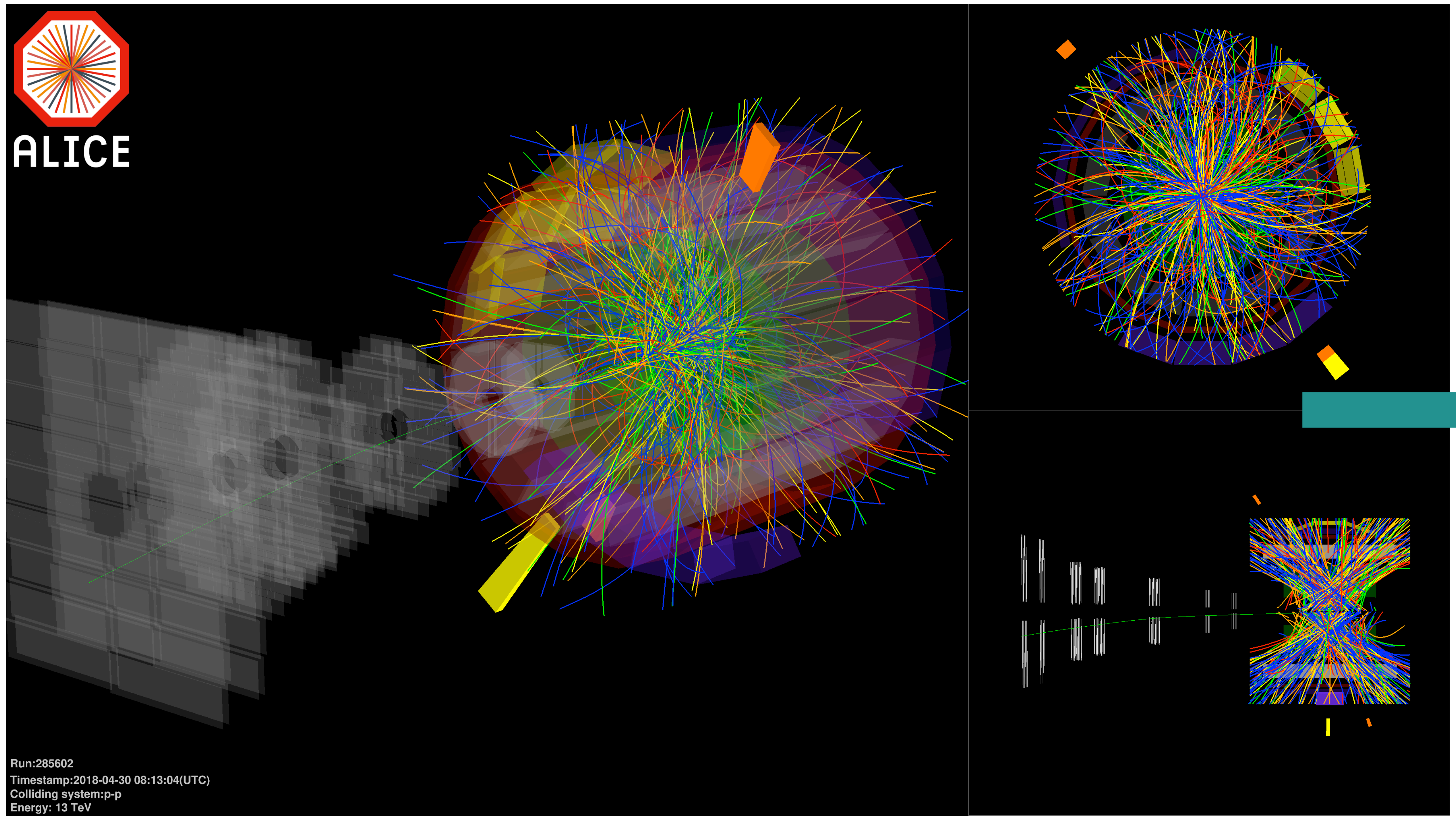
Baseline for p—Pb and Pb—Pb measurements

Test of pQCD calculations

Cold Nuclear Matter (CNM) effects in heavy-flavour yields



# Motivation : Small Systems

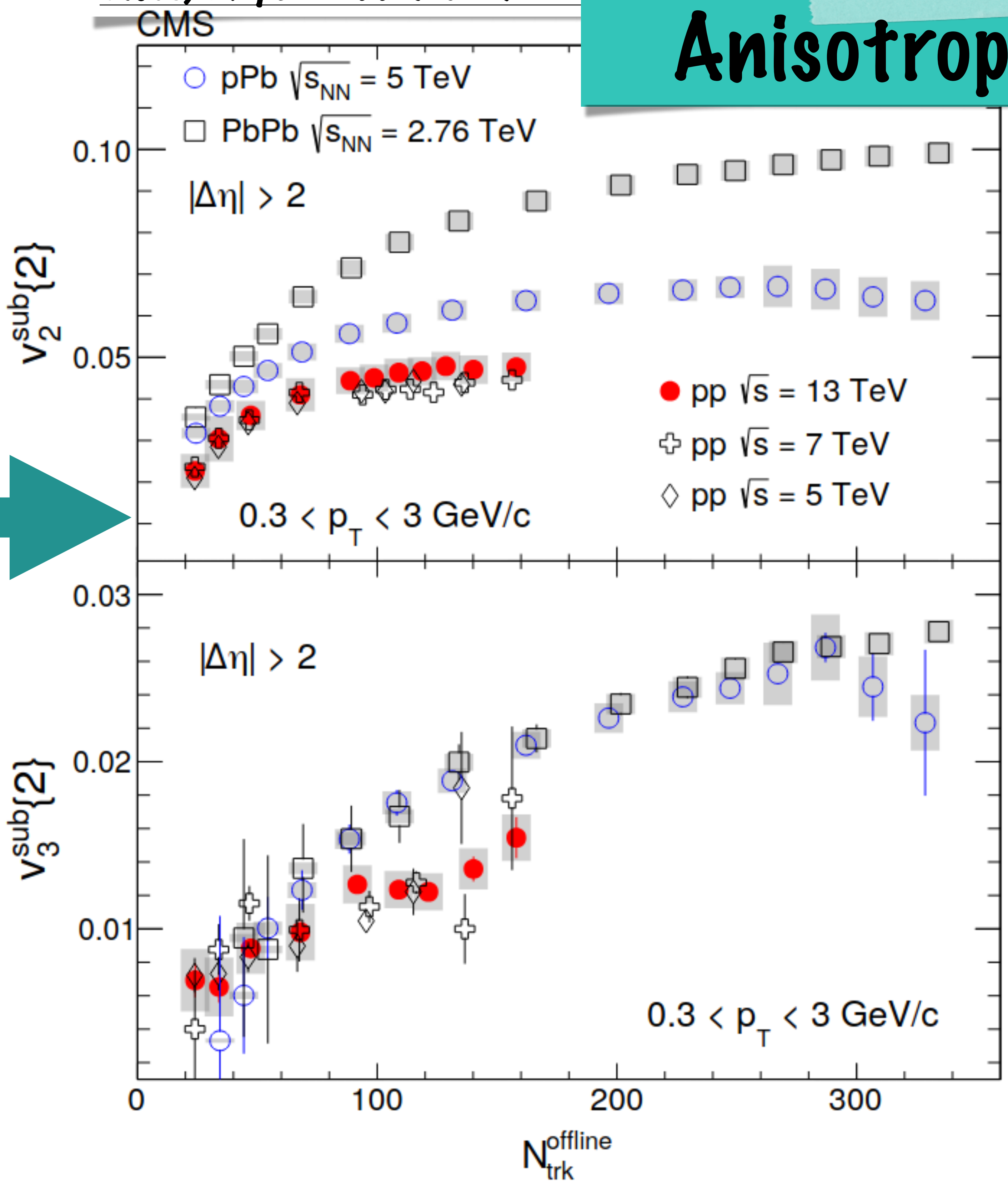



ALICE-EVENTDISPLAY-2018-002

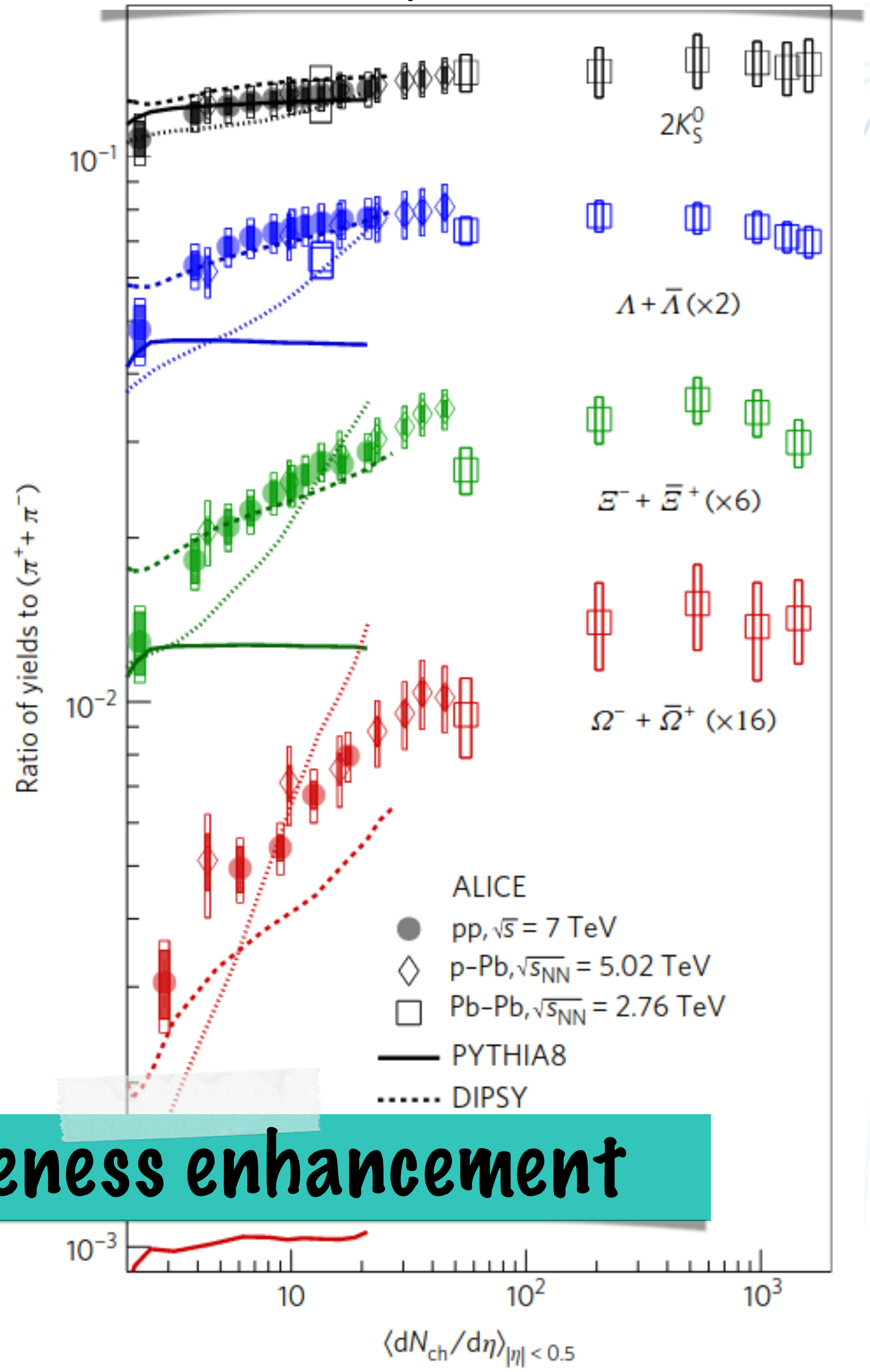
High multiplicity pp, p—Pb collisions show similar signatures to those observed in heavy-ion collisions

CMS, Phys. Lett. B 765 (2017) 193

**Anisotropic flow**




ALICE, Nature Physics 13 (2017) 535-539




**Strangeness enhancement**

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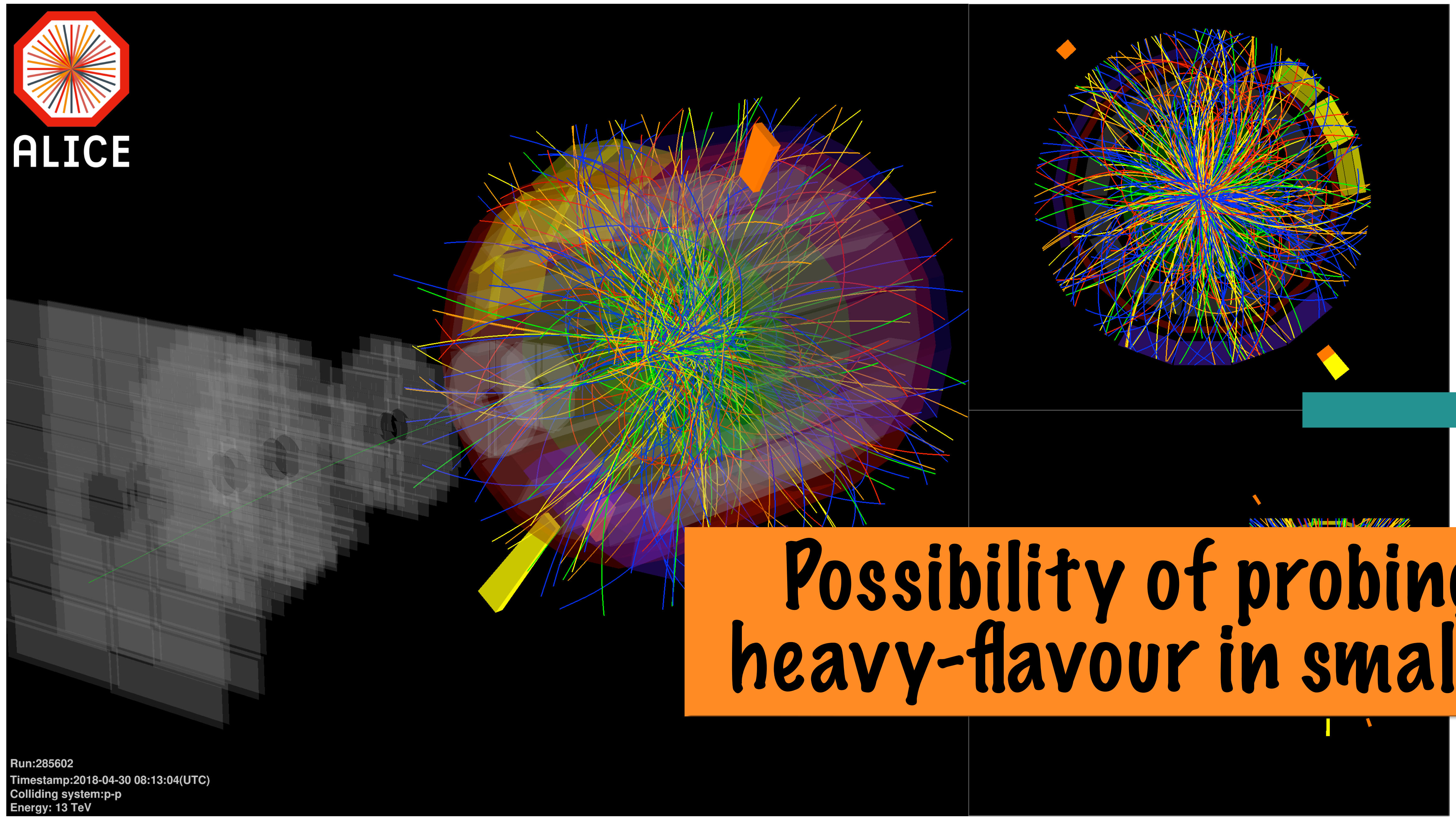


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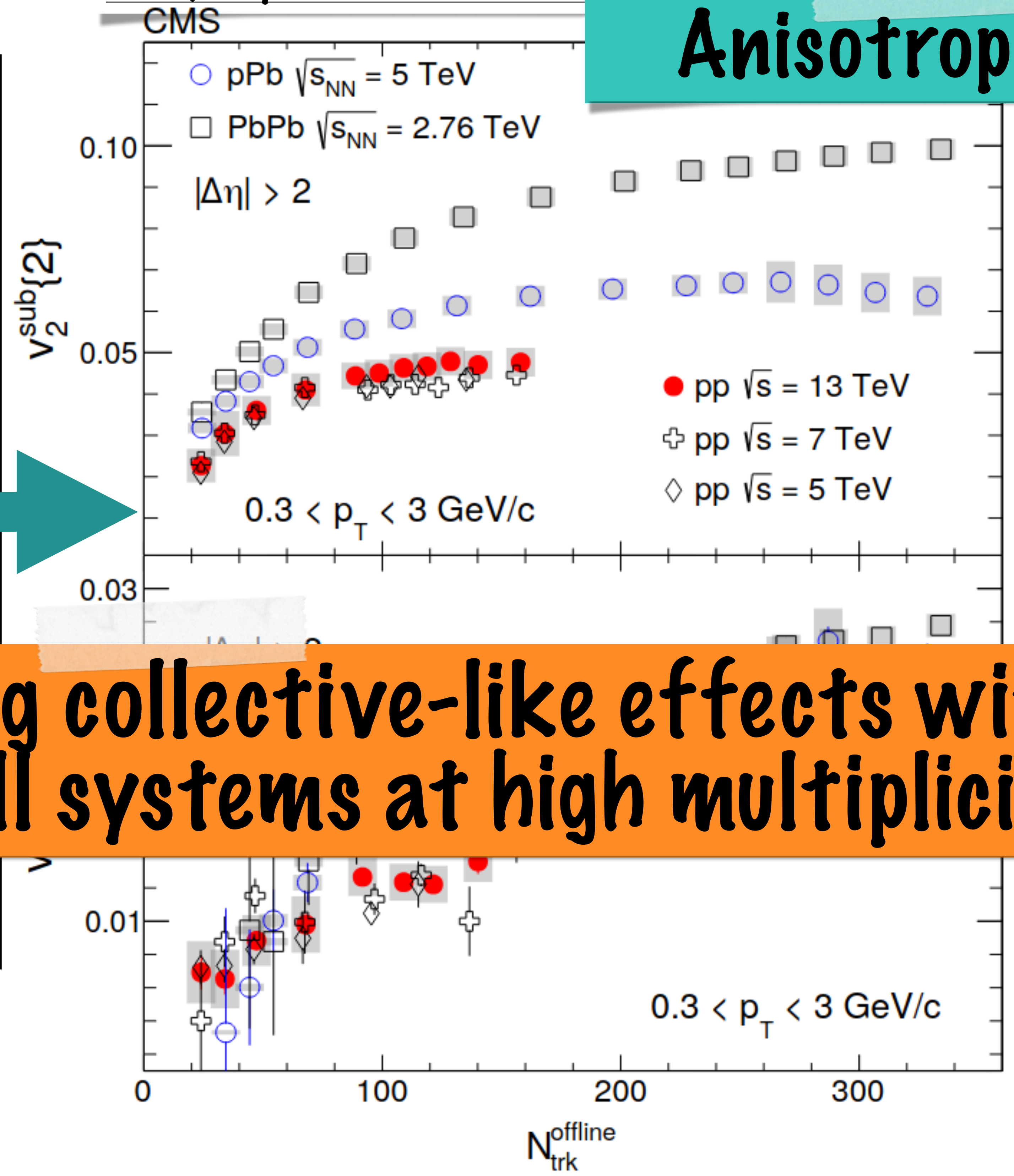


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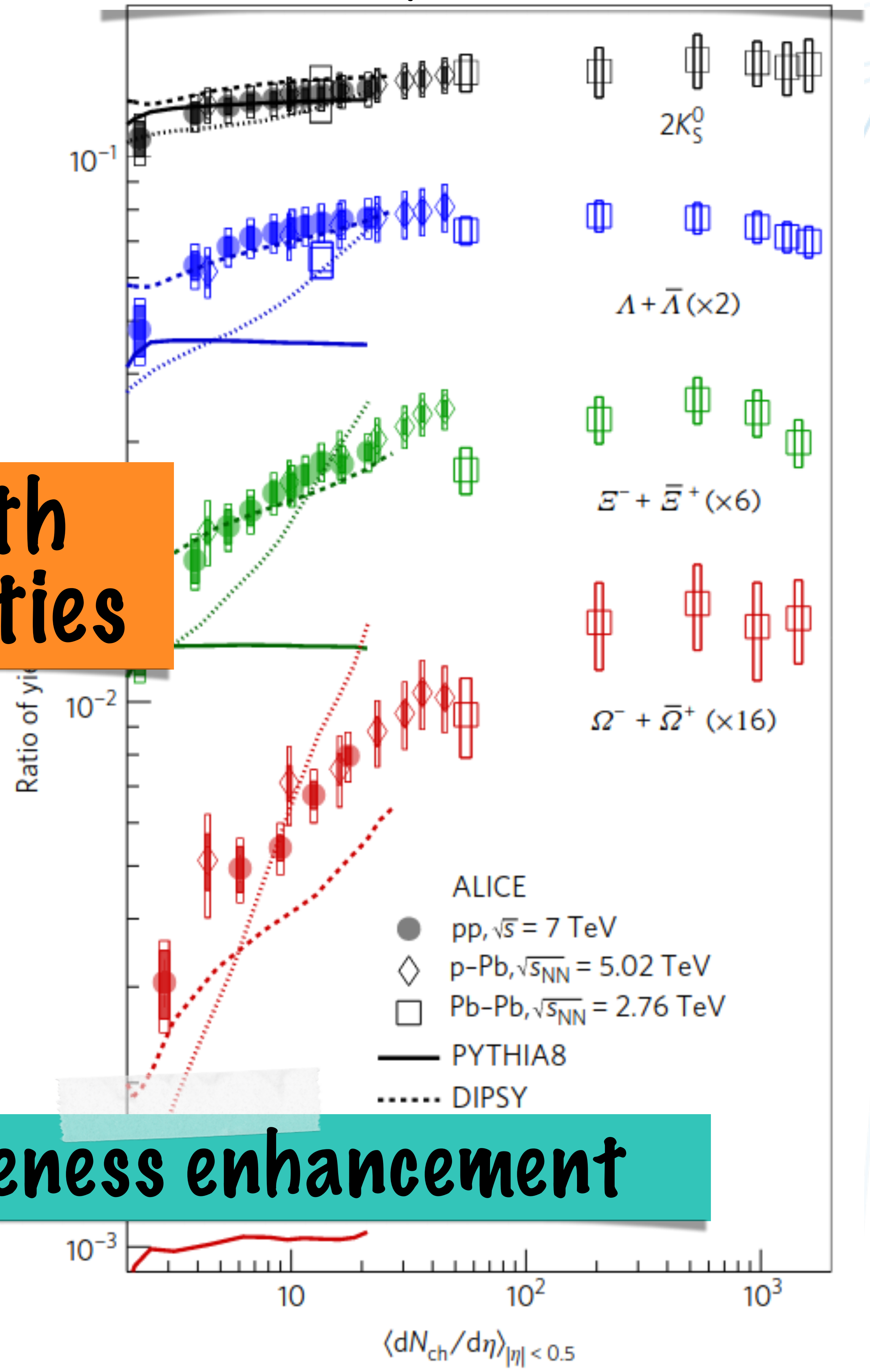
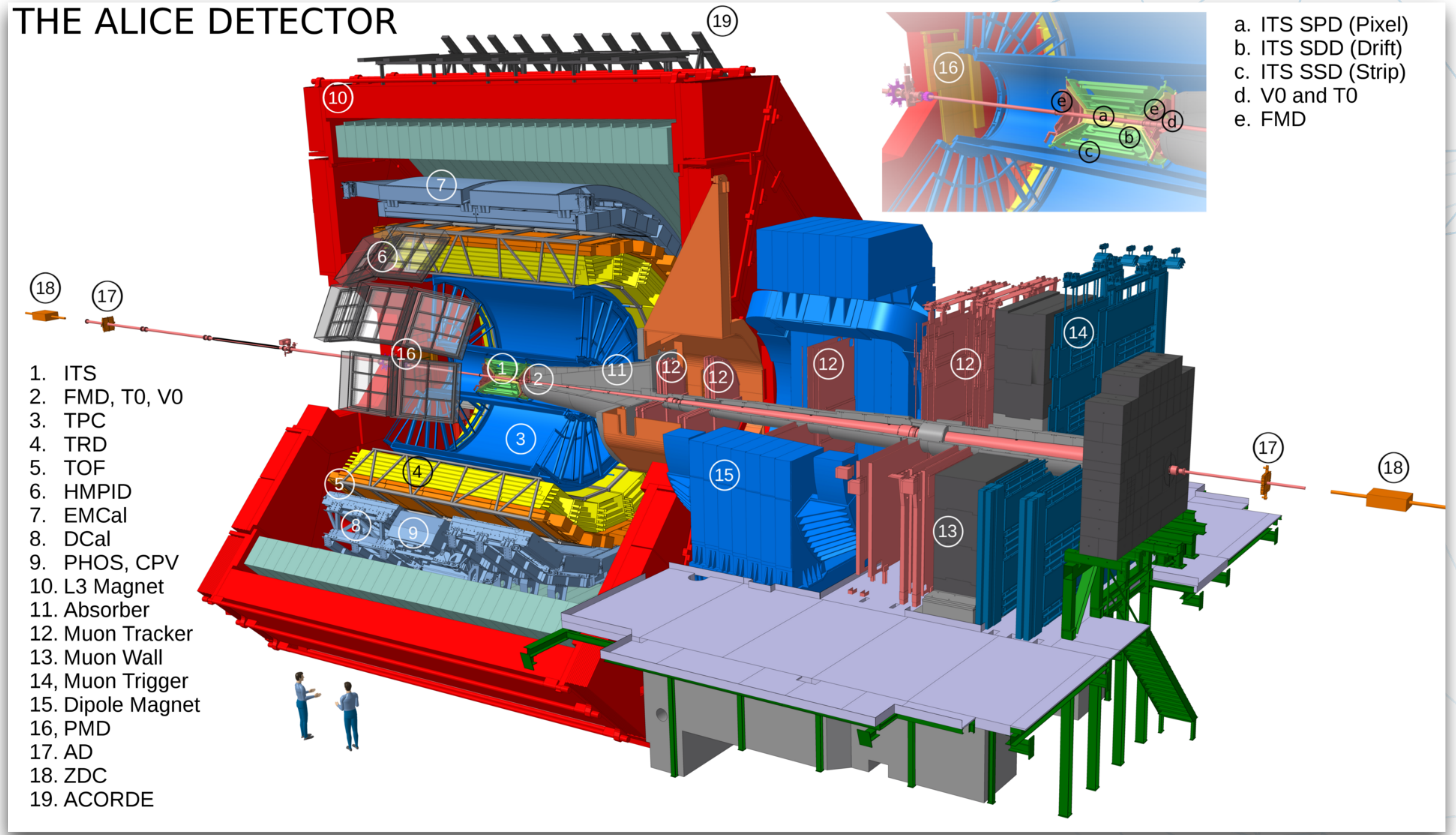



**Possibility of probing collective-like effects with heavy-flavour in small systems at high multiplicities**

**Strangeness enhancement**

# The ALICE Detector - Run 2



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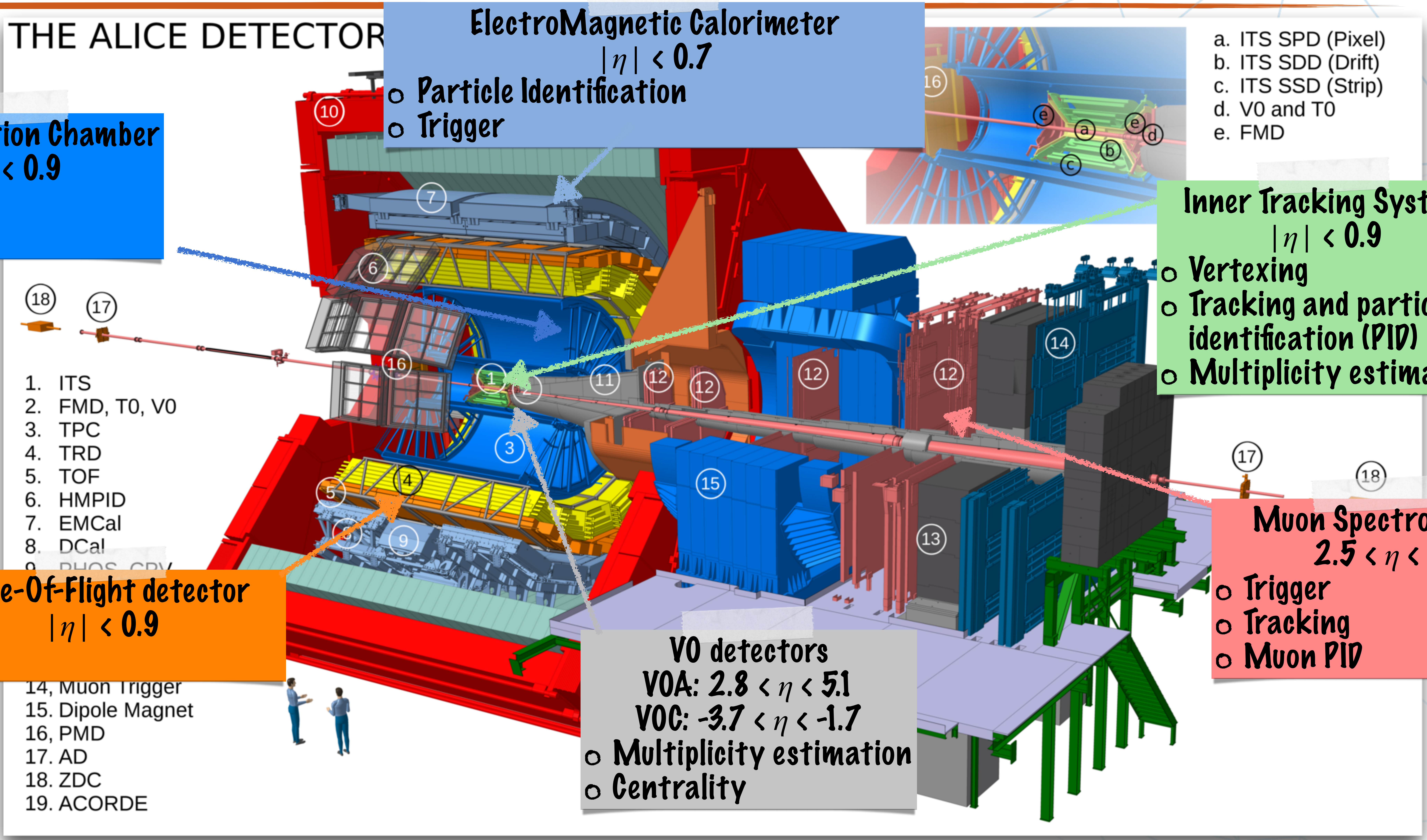



**Time Projection Chamber**
$|\eta| < 0.9$
- Tracking
- PID

**ElectroMagnetic Calorimeter**
$|\eta| < 0.7$
- Particle Identification
- Trigger

**Inner Tracking System**
$|\eta| < 0.9$
- Vertexing
- Tracking and particle identification (PID)
- Multiplicity estimation

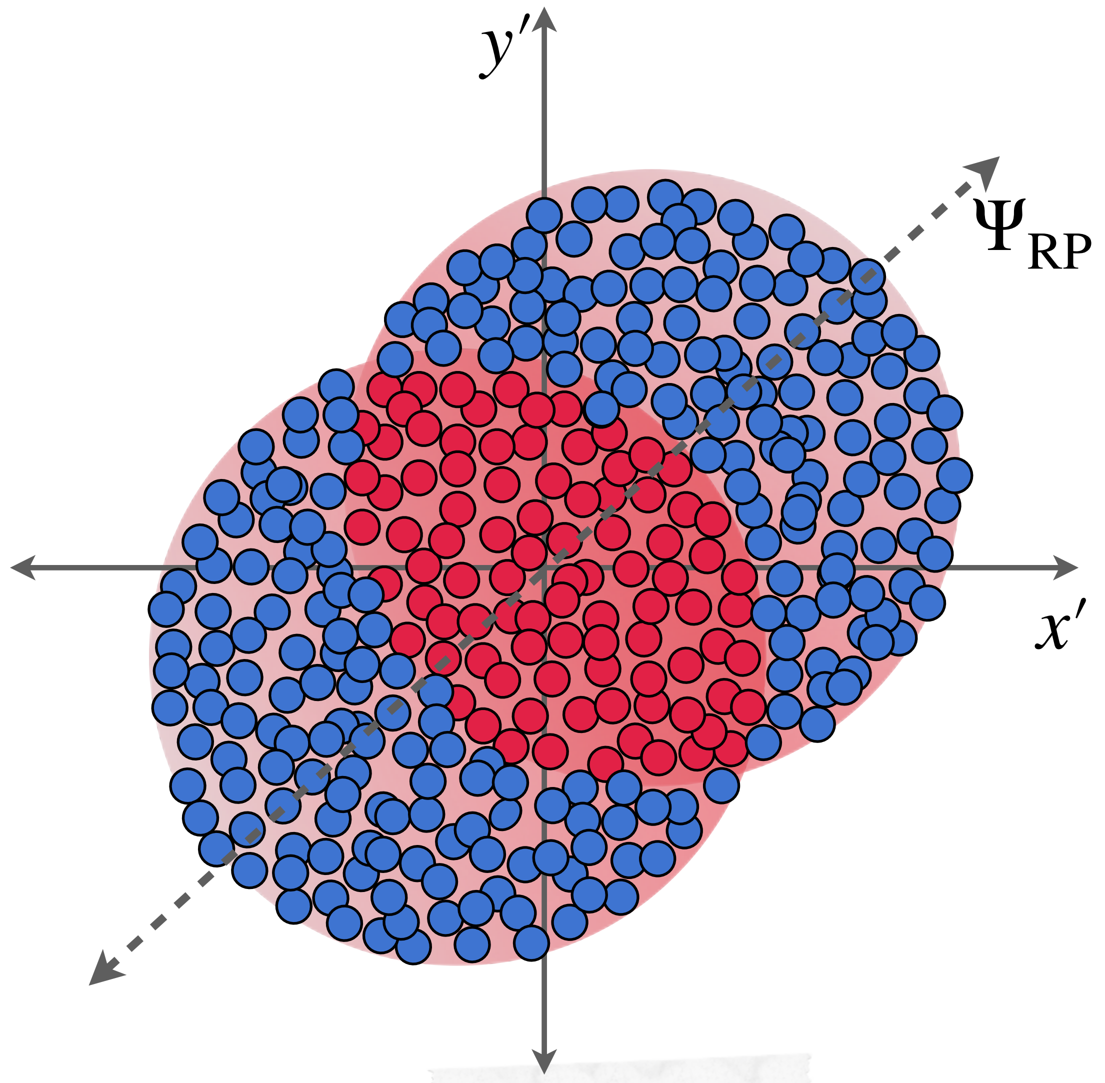
**Time-Of-Flight detector**
$|\eta| < 0.9$
- PID

**V0 detectors**
V0A: $2.8 < \eta < 5.1$
V0C: $-3.7 < \eta < -1.7$
- Multiplicity estimation
- Centrality

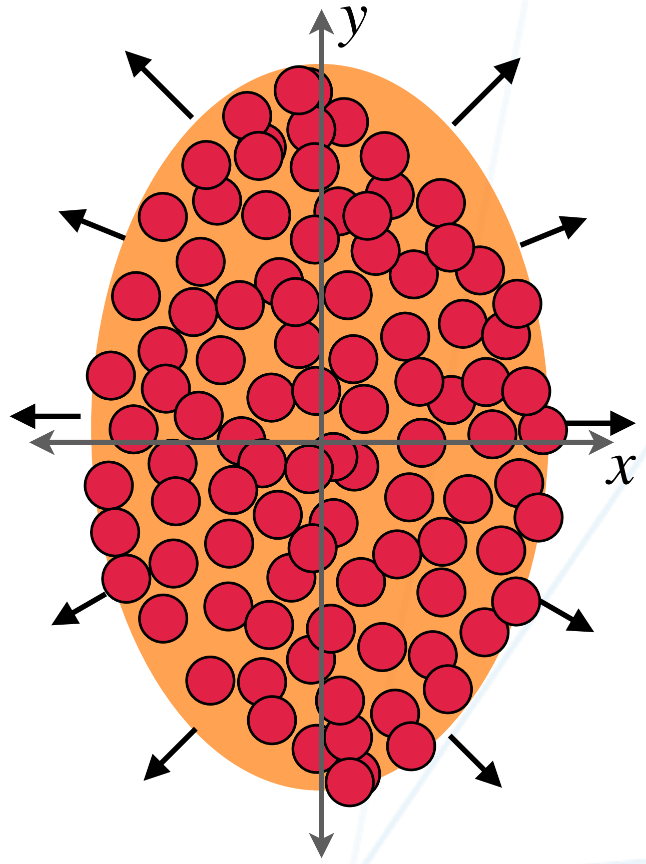
**Muon Spectrometer**
$2.5 < \eta < 4$
- Trigger
- Tracking
- Muon PID

# Heavy-Flavour Elliptic Flow

* In small systems , two-particle correlations are used to extract the azimuthal anisotropy of the collision

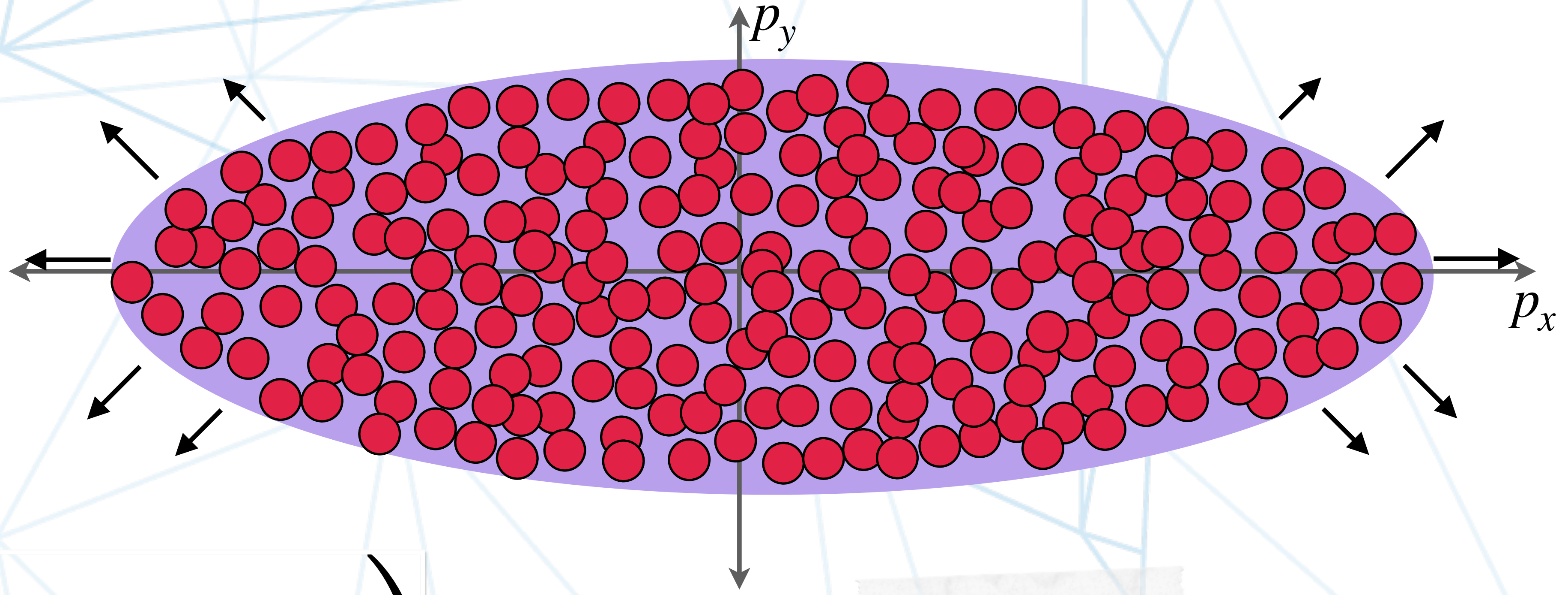



$\Psi_{RP}$ → Reaction Plane angle (between beam axis and centres of the nuclei)




Spatial anisotropy

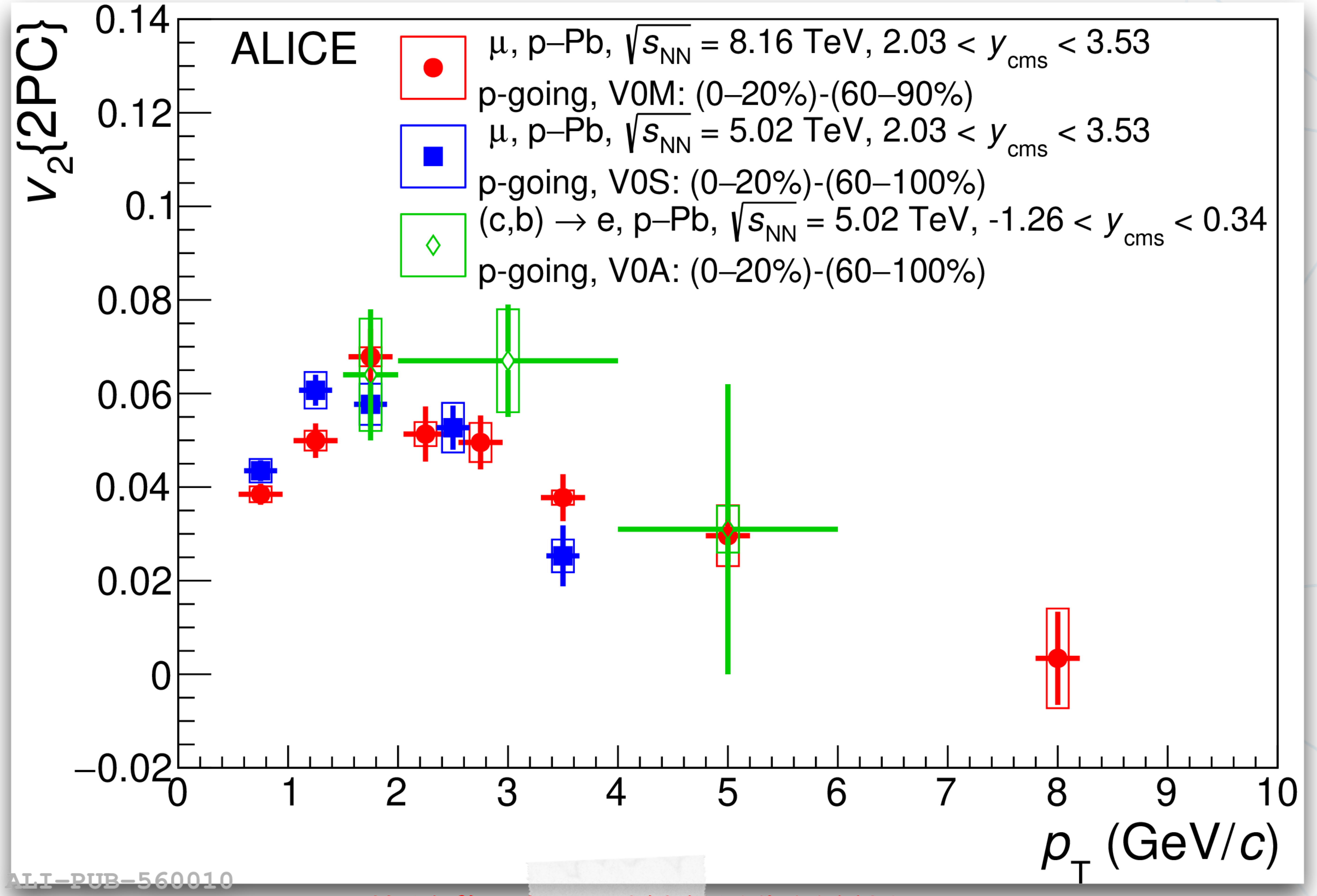
$$v_2(p_T) = \langle \cos[2(\phi - \Psi_2)] \rangle$$




Momentum anisotropy

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

# Heavy-Flavour Elliptic Flow



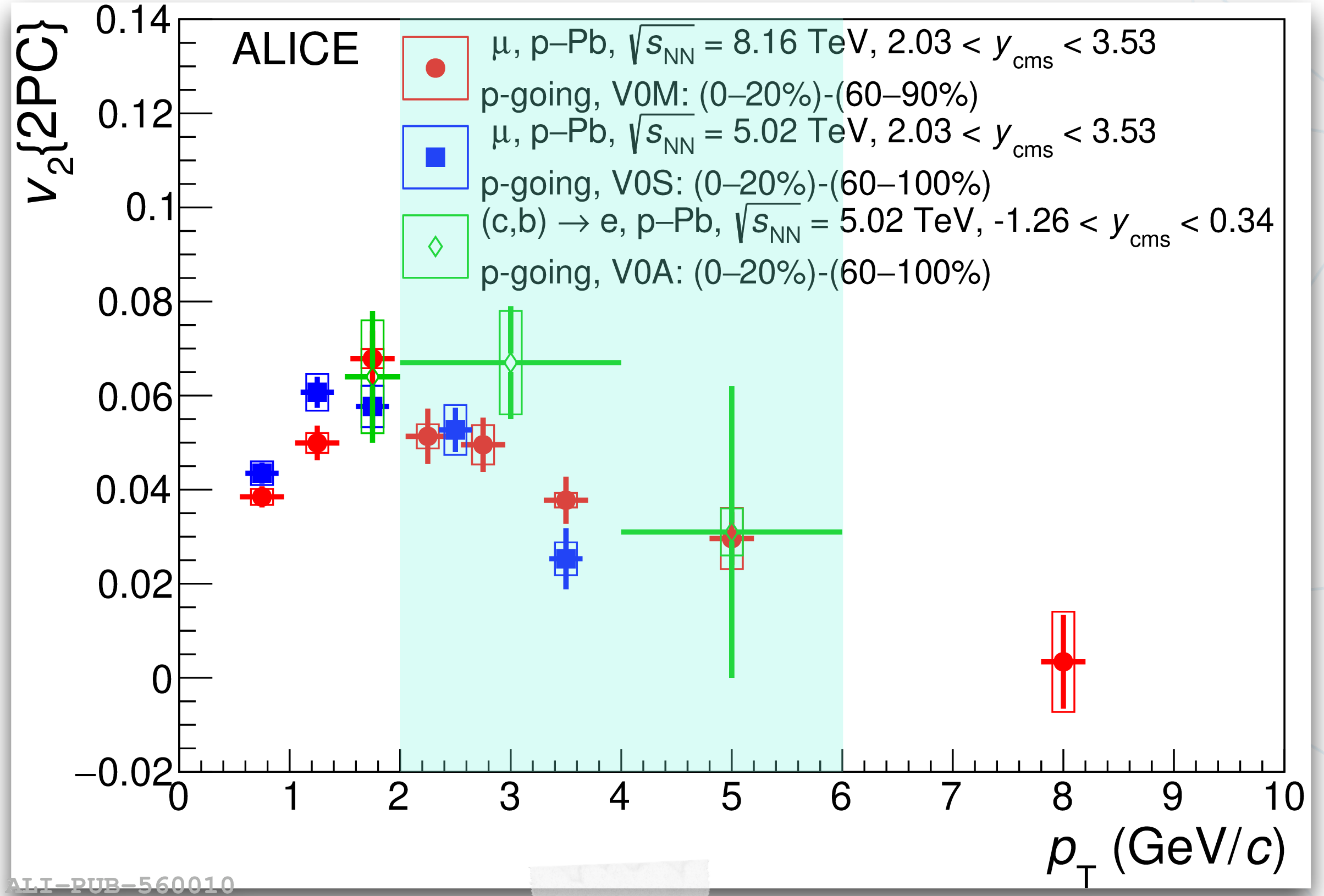

Positive $v_2$ of inclusive muons in p—Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV⌘ →

Collectivity in small systems?

Compatible with $v_2$ of inclusive muons⌘ and electrons from heavy flavour hadron decays⌘ in p—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV


⌘ALICE, Phys. Lett. B 846 (2023), 137782
⌘ALICE, Phys. Lett. B 753 (2016) 2016, 126139
⌘ALICE, Phys. Rev. Lett. 122, (2019), 072301

# Heavy-Flavour Elliptic Flow

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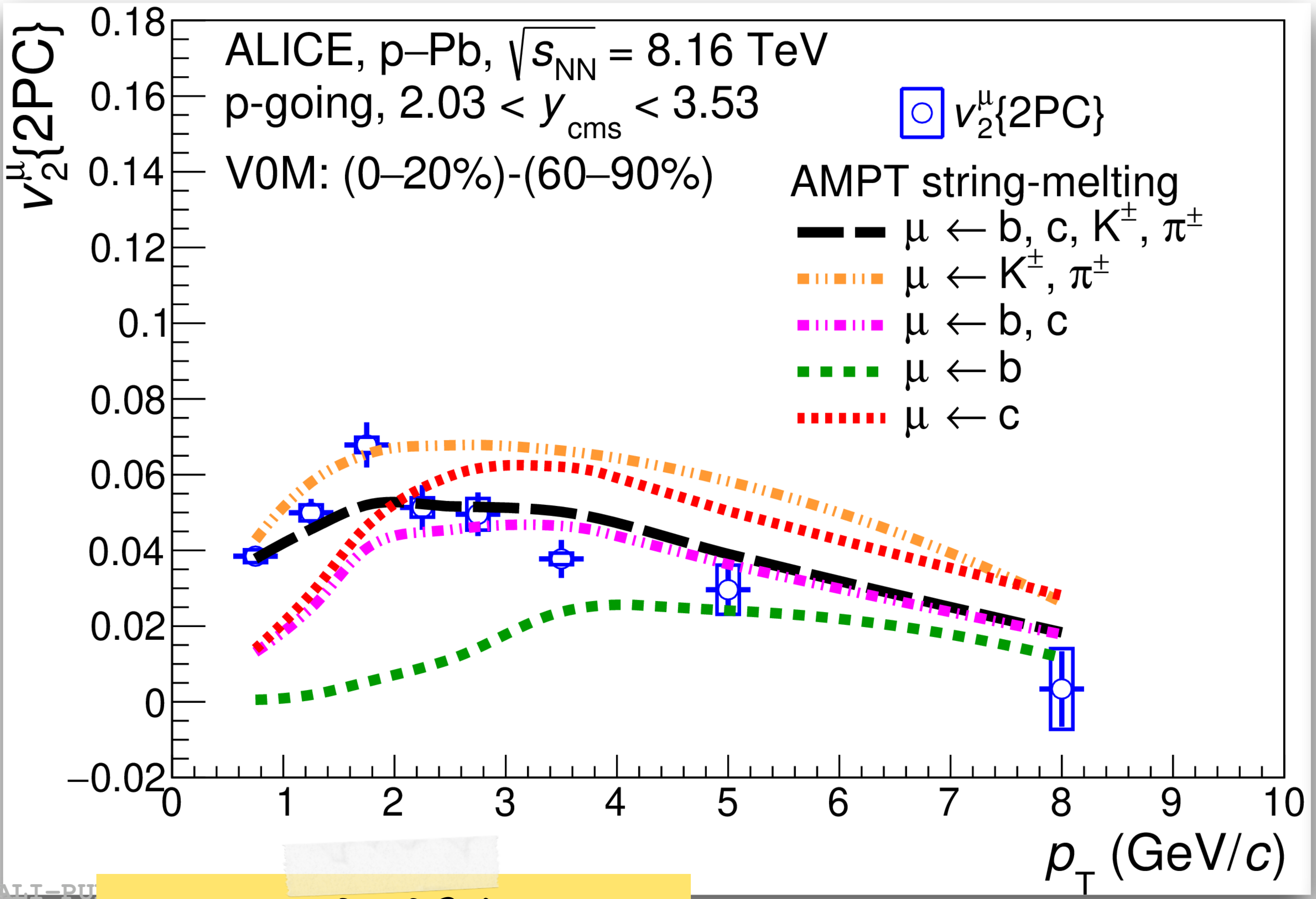
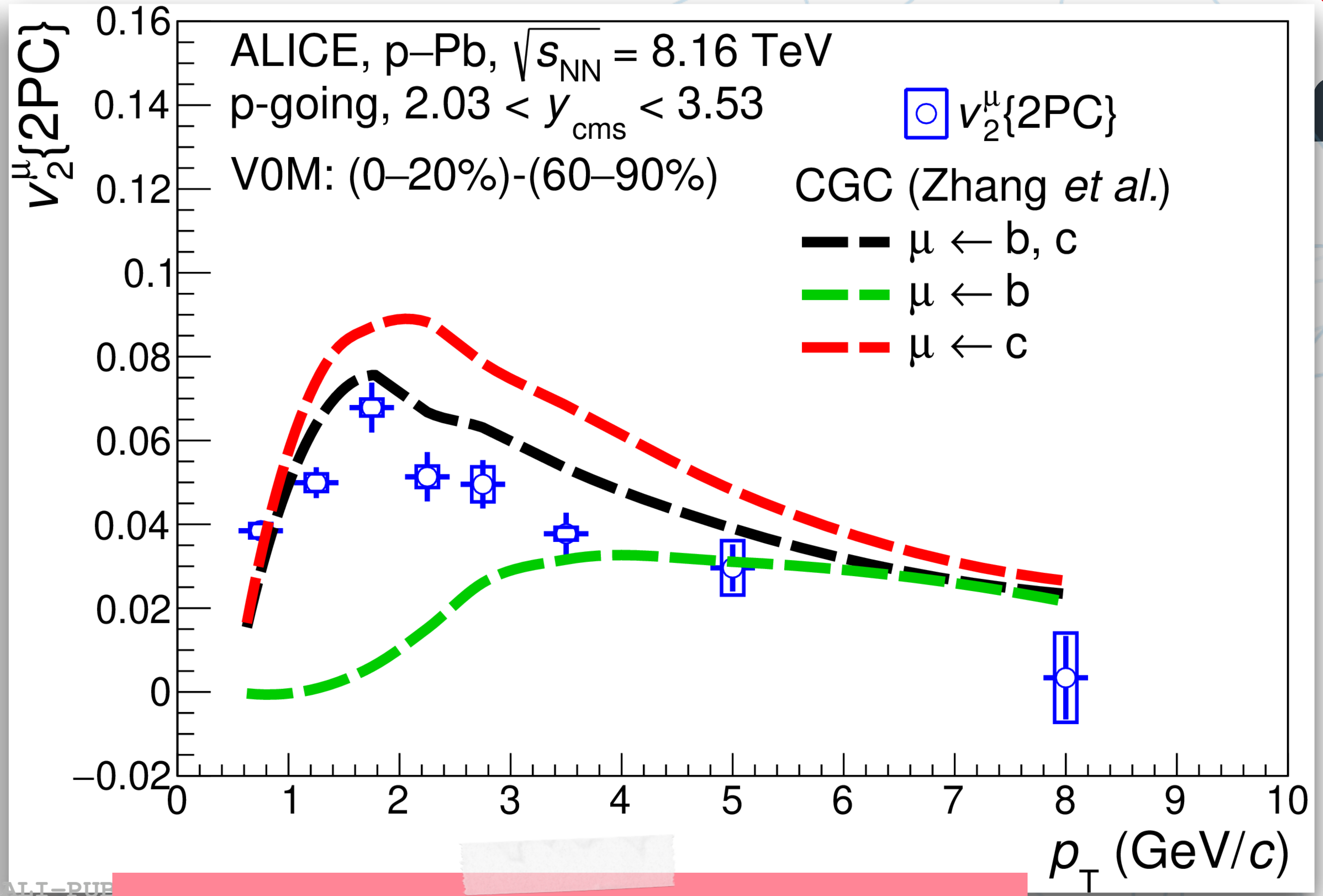
Positive $v_2$ of inclusive muons in p—Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV⌘ → Collectivity in small systems?

$2 < p_T < 6$ GeV/c → Significance upto $12\sigma$ !

Compatible with $v_2$ of inclusive muons⌘ and electrons from heavy flavour hadron decays⌘ in p—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

# Heavy-Flavour Elliptic Flow




$v_2$ in AMPT⌘ →

**Flow explained by the anisotropic parton escape mechanism**

Color Glass Condensate (CGC)⌘ →

**qualitative agreement with data⌘**


⌘ALICE, Phys. Lett. B 846 (2023), 137782

⌘Li et. al, Phys. Rev. C, 99 (2019), 044911

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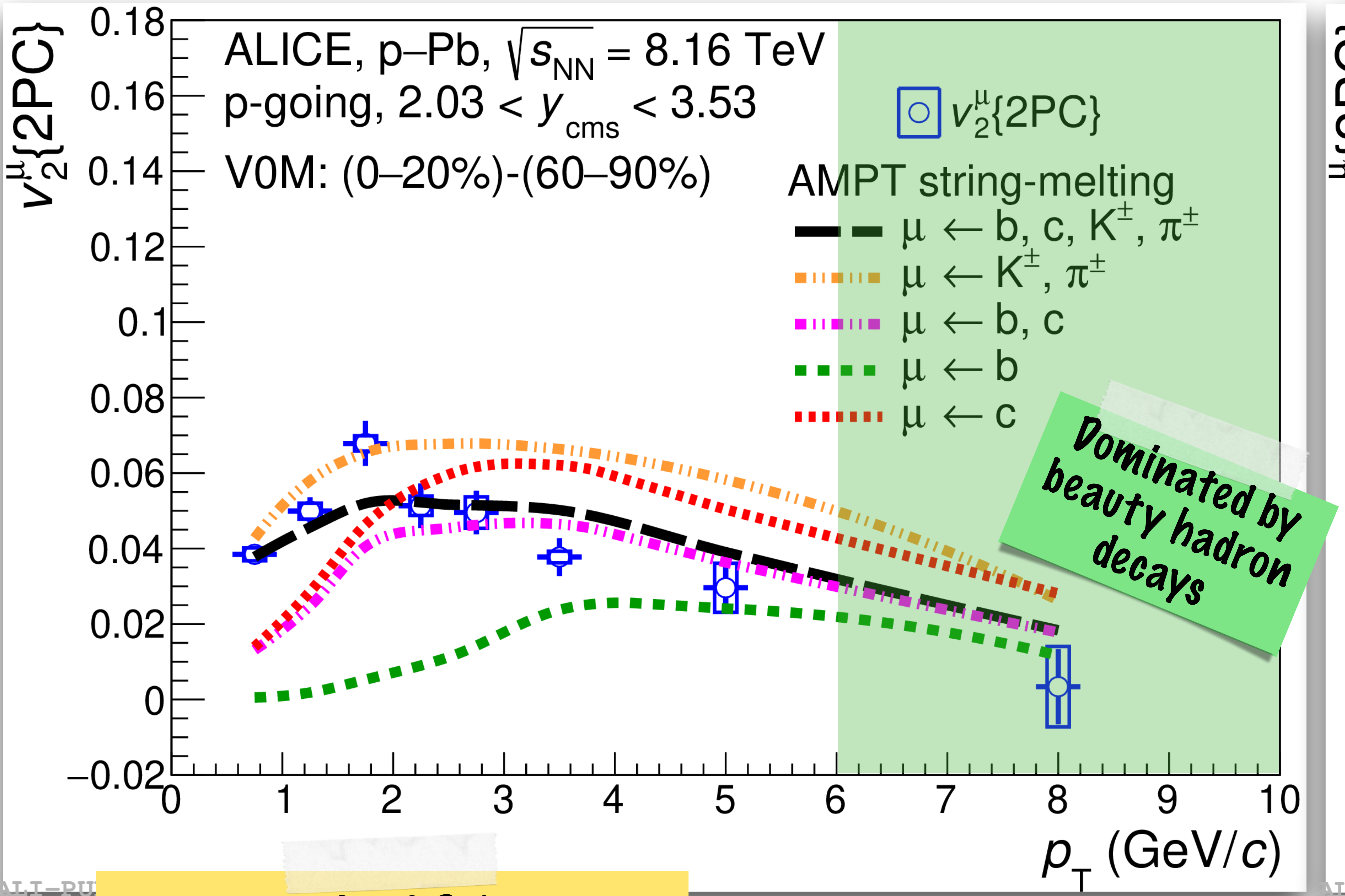
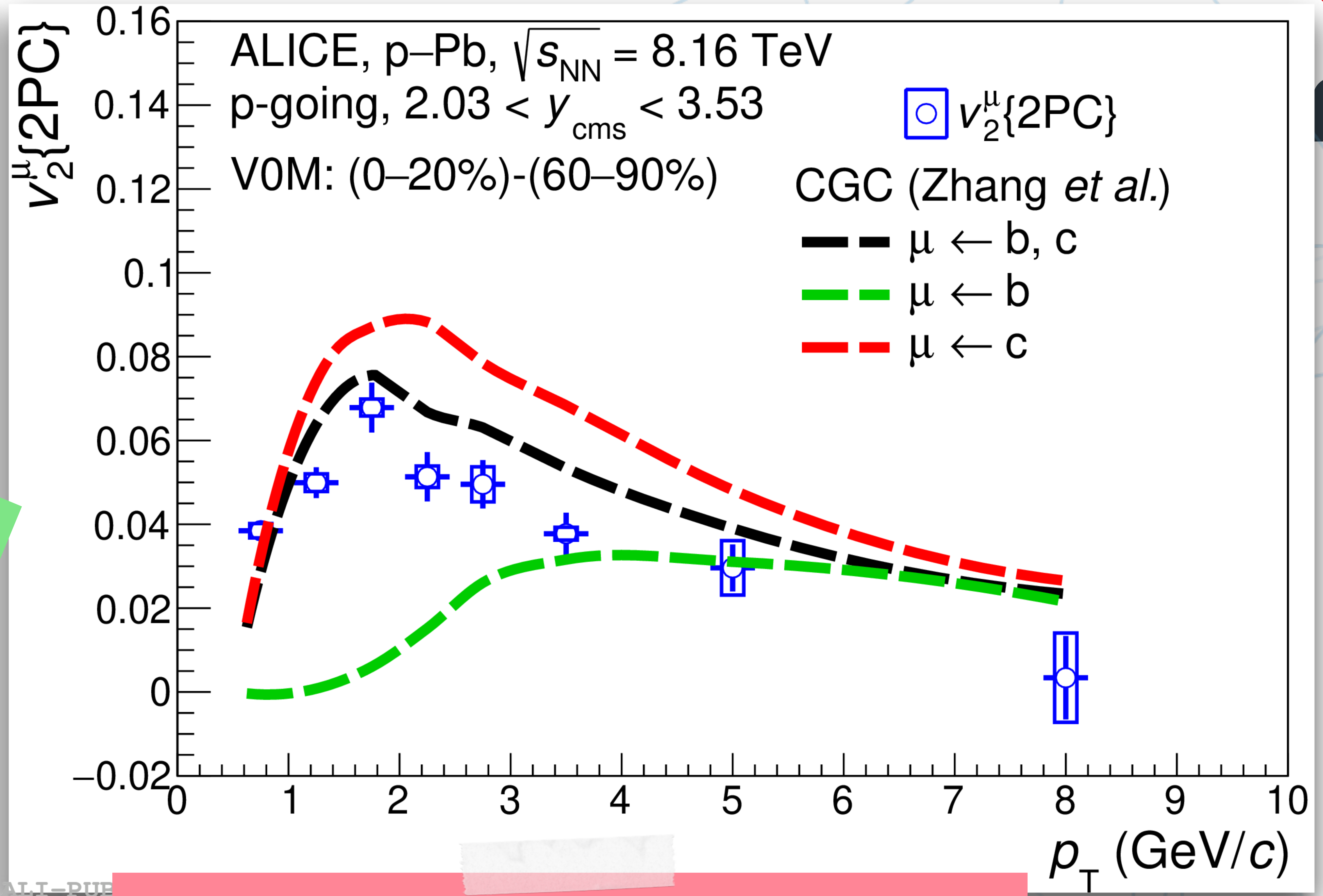



$v_2$ in AMPT⌘ →

Flow explained by the anisotropic parton escape mechanism

Color Glass Condensate (CGC)⌘ →

qualitative agreement with data⌘

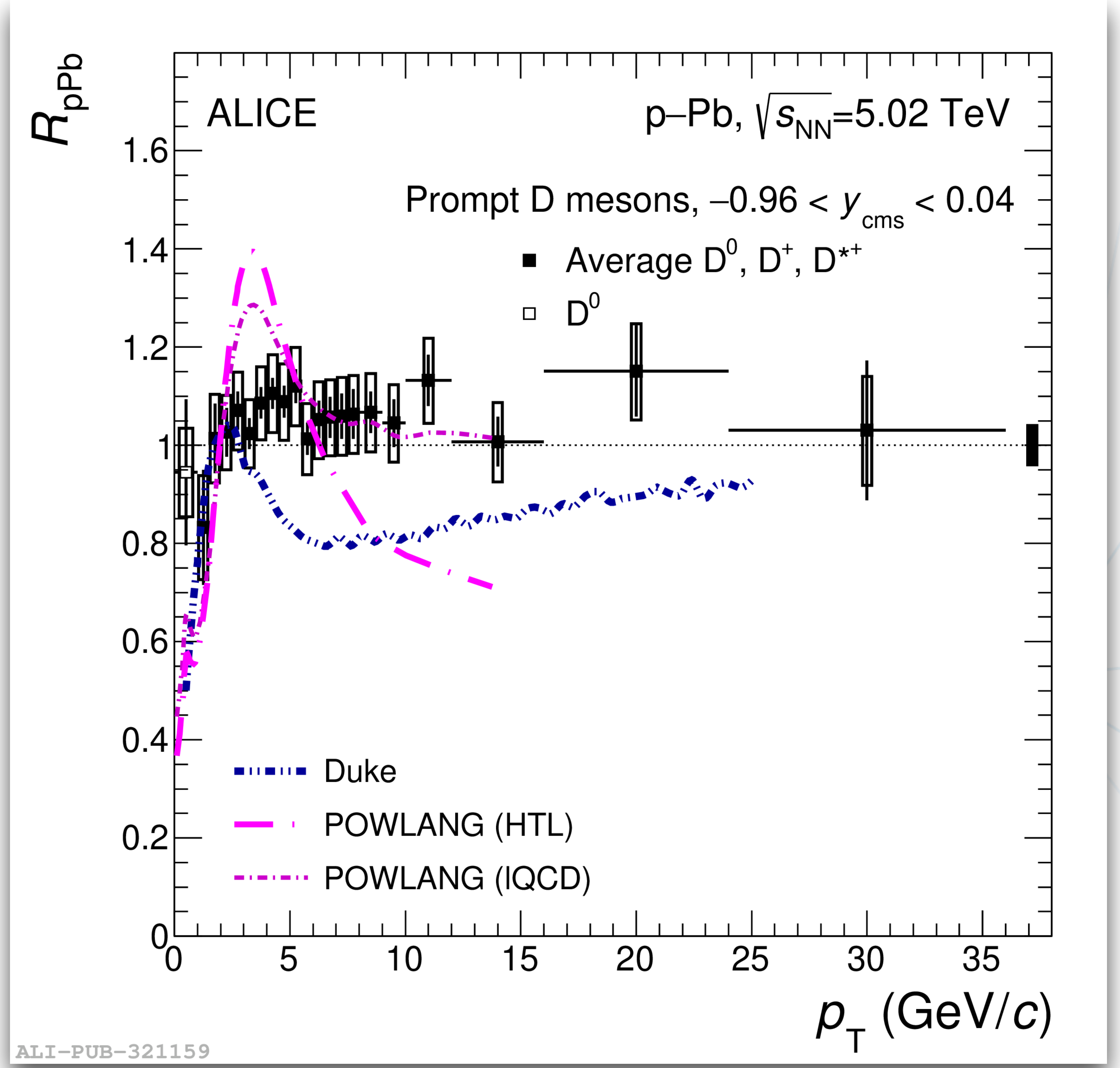
Possible contributions from initial-state effects

⌘ALICE, Phys. Lett. B 846 (2023), 137782

⌘Li et. al, Phys. Rev. C, 99 (2019), 044911

⌘Zhang et. al, Phys. Rev. D, 102 (2020), 034010

# Nuclear Modification Factor ($R_{pPb}$) of Open Charm Hadrons




$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \cdot d\sigma_{pp}/dp_T}$$

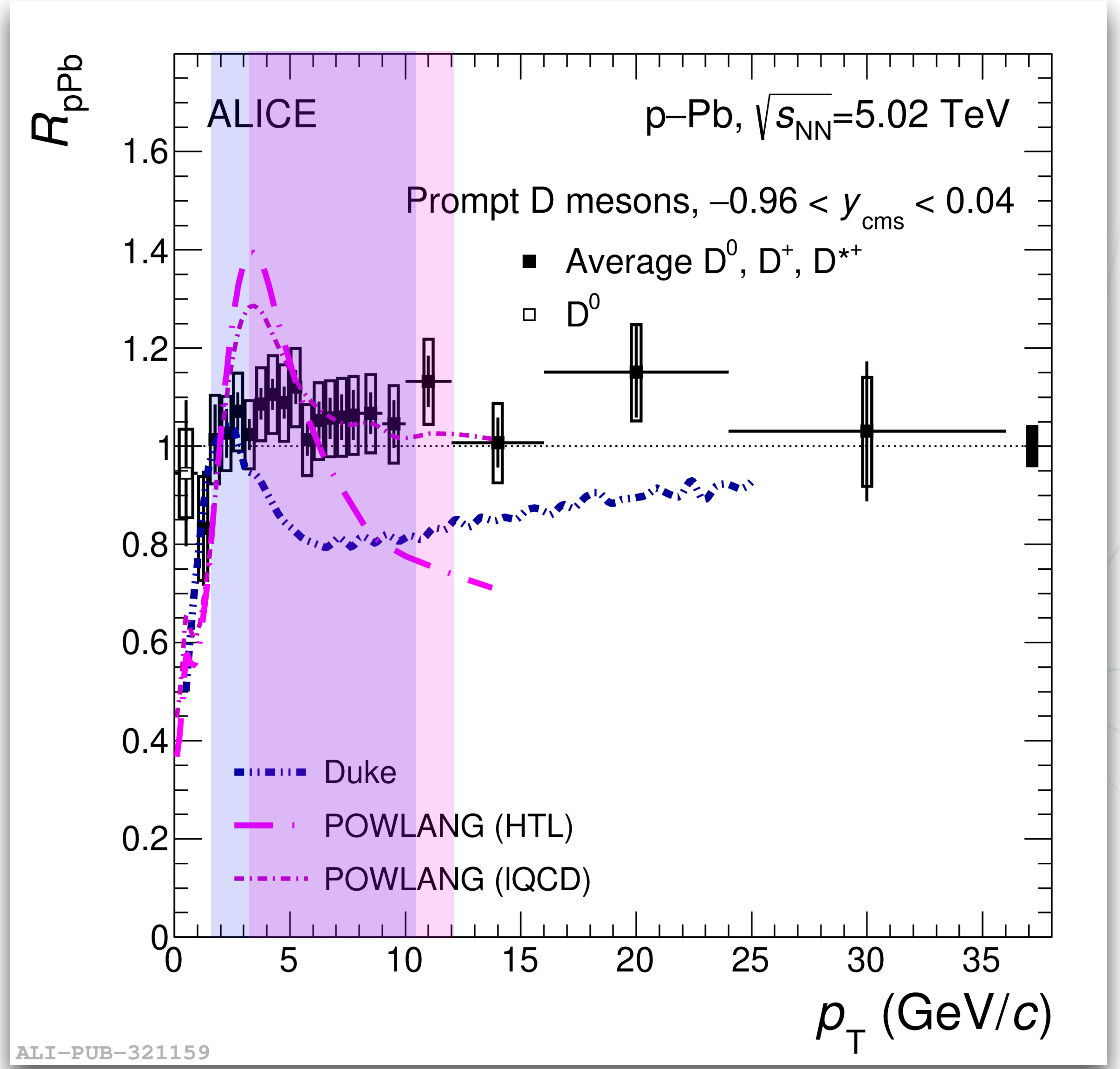
**POWLANG⌘ → Transport of charm quarks in a quark-gluon plasma using transport coefficients from Hard Thermal Loop (HTL) or Lattice QCD (lQCD) calculations**

**Duke Transport Model⌘→ Includes collisional and radiative energy loss**

⌘ALICE, JHEP 12, (2019), 012
⌘Beraudo et al JHEP 03 (2016) 123
⌘Xu et al PRC 97, (2018), 064915

# Nuclear Modification Factor ($R_{\mathrm{pPb}}$) of Open Charm Hadrons

ALICE




$$R_{\mathrm{pPb}} = \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{A \cdot \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

POWLANG⌘ → Transport of ... arm quarks in a quar... transp... using ... from Hard Therm... or Lattice QCD (lQCD) calculations

**Peak at $p_{\mathrm{T}} \approx 0.35$ GeV/c followed by supression (HTL)**

**Not supported by data⌘**

Duke Transport Mod... udes collisional ... energy loss

**Peak at $p_{\mathrm{T}} \approx 0.25$ GeV/c followed by supression**

⌘ALICE, JHEP 12, (2019), 012

⌘Beraudo et al JHEP 03 (2016) 123

⌘Xu et al PRC 97, (2018), 064915

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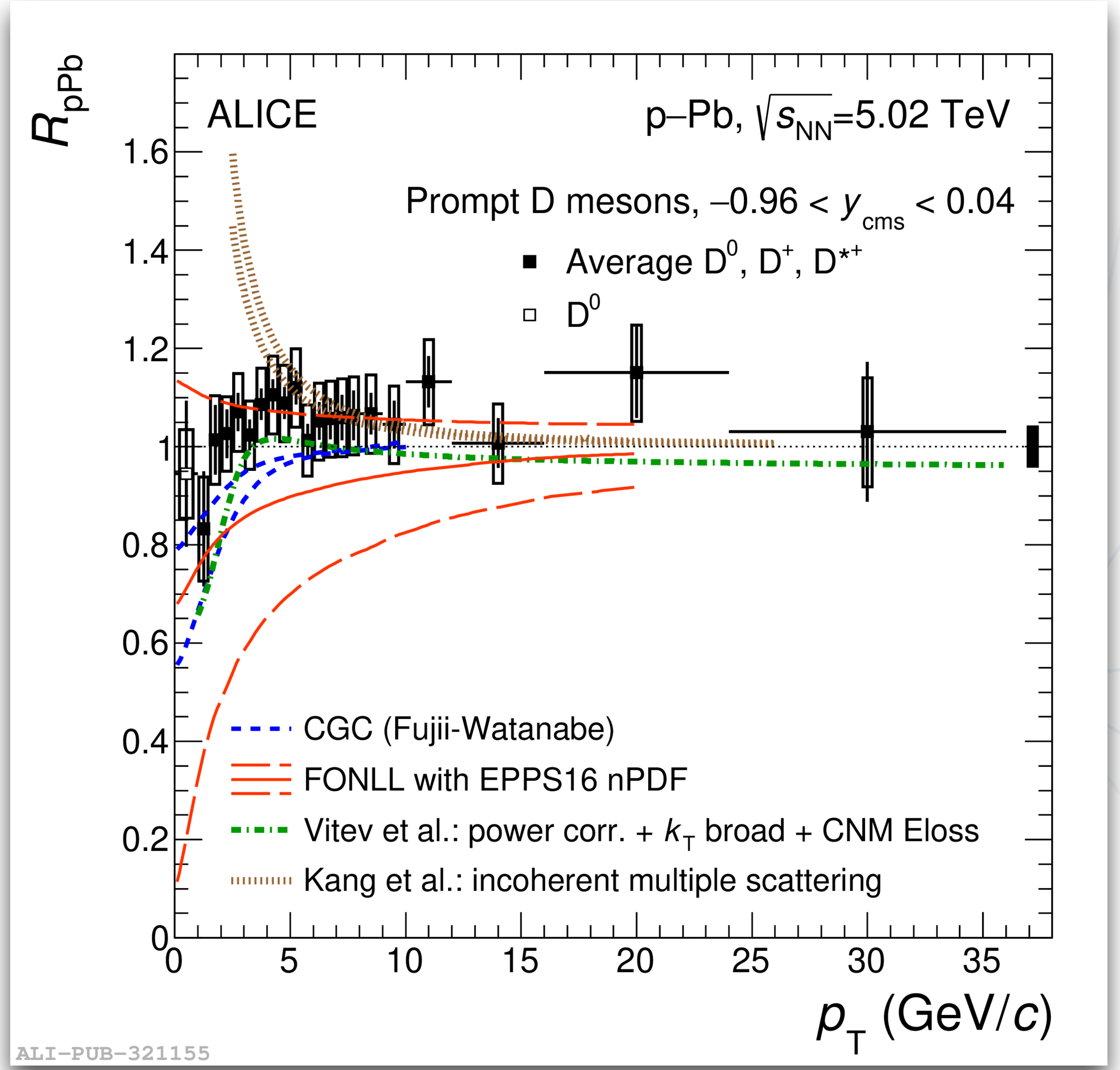



**Color Glass Condensate formalism⌘ with CNM effects**

**FONLL calculation⌘ with EPPS16 NLO⌘ nuclear modification**


⌘ALICE, JHEP 12, (2019), 012

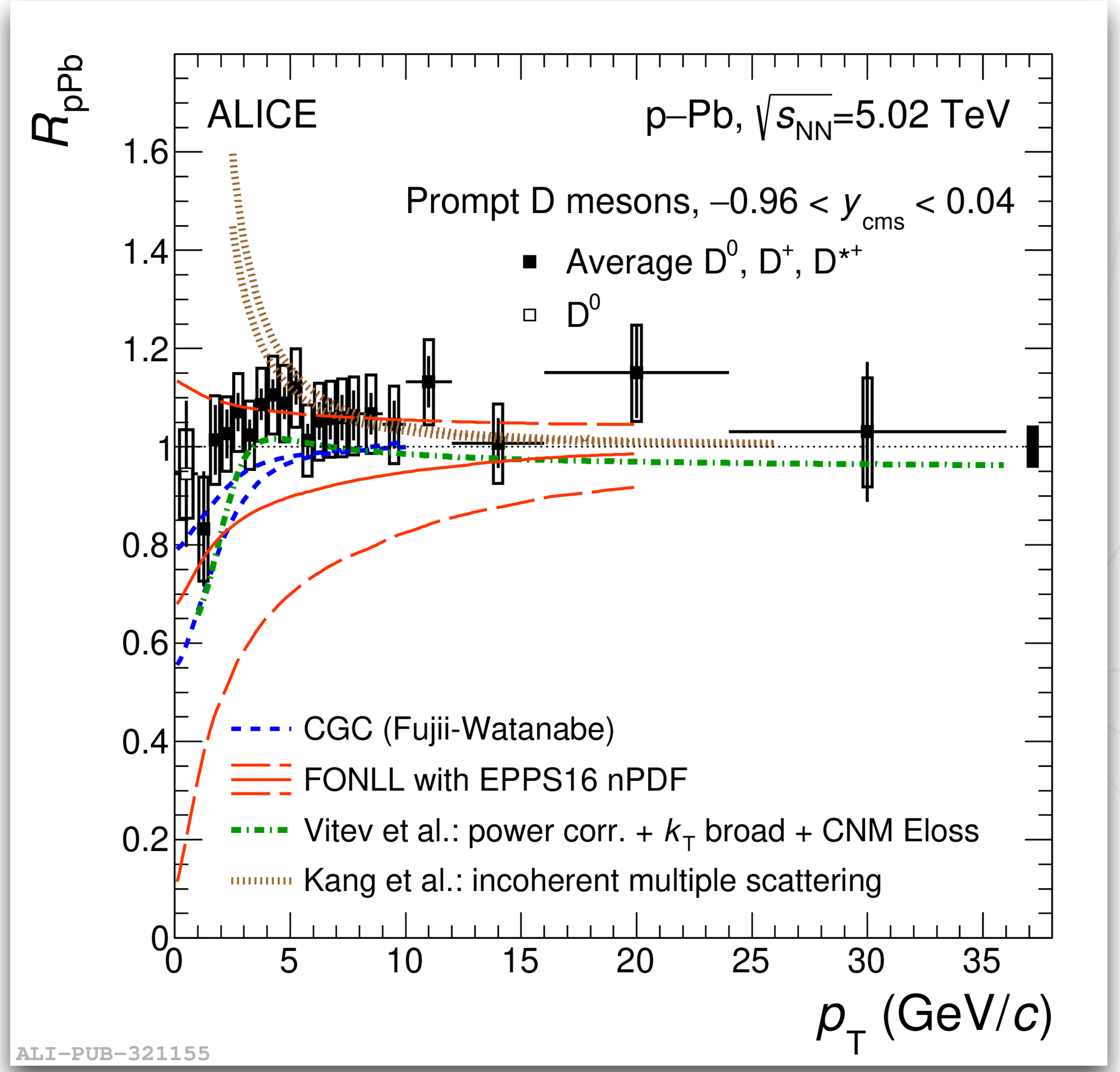
⌘ Fujii et. al arXiv: 1706.06728

⌘Cacciari et al, JHEP 2012, (2012) 137

⌘ Eskola et al, EPJ C 77 (2017), 163

# Nuclear Modification Factor ($R_{pPb}$) of Open Charm Hadrons

ALICE




Color Glass Cond... te formalism

Description of data within 2$\sigma$ uncertainty

$p_T$ < 6 GeV/$c$ → Systematically underestimates data⌘

FONLL calculation⌘ with EPPS1... nuclear ...

Description closer to upper limit of EPPS16 nPDF uncertainty band

⌘ALICE, JHEP 12, (2019), 012

⌘ Fujii et. al arXiv: 1706.06728

⌘Cacciari et al, JHEP 2012, (2012) 137

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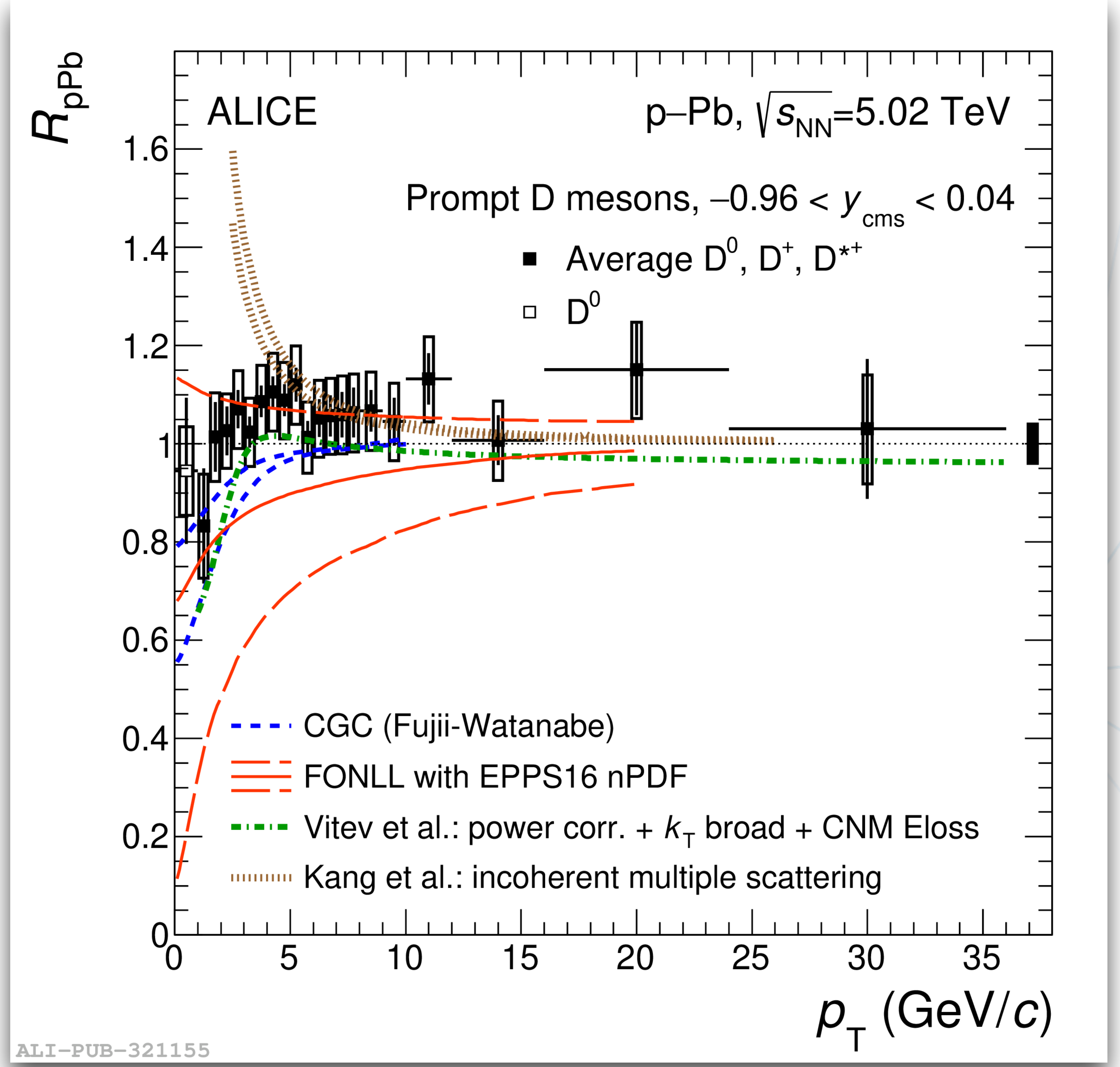


**LO pQCD calculation with CNM (Vitev et al)⌘**

→ Intrinsic $k_T$ broadening

→ Nuclear shadowing

→ Energy loss of the charm quarks

**Kang et. al⌘ → Higher-twist calculation based on incoherent multiple scatterings**


⌘ALICE, JHEP 12, (2019), 012

⌘ Vitev et al, Phys. Rev. C 80, (2009), 054902

⌘ Kang et al, Phys. Lett. B 740, (2015), 2329

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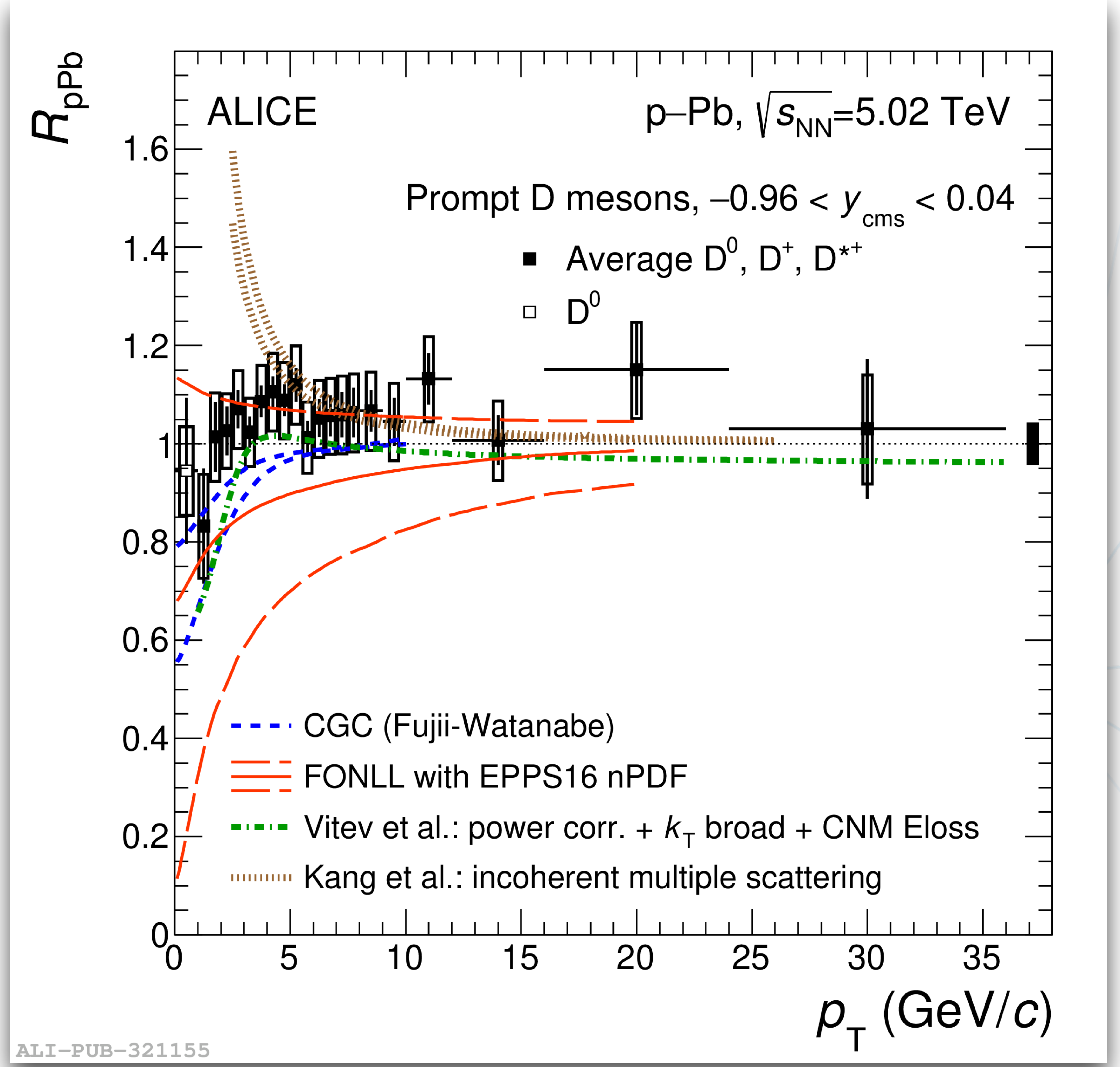


LO pQCD calculation with CNM (Vitev et al)⌘

→ Intrinsic $k_T$ broadening

→ Nuclear shadowing

→ Energy loss of the charm quarks

**Comparable to data**

Kang et. al⌘ → Higher-twist calculation based on incoherent multiple scatterings

**Overestimates data for $p_T$ < 4 GeV/c**

⌘ALICE, JHEP 12, (2019), 012

⌘ Vitev et al, Phys. Rev. C 80, (2009), 054902

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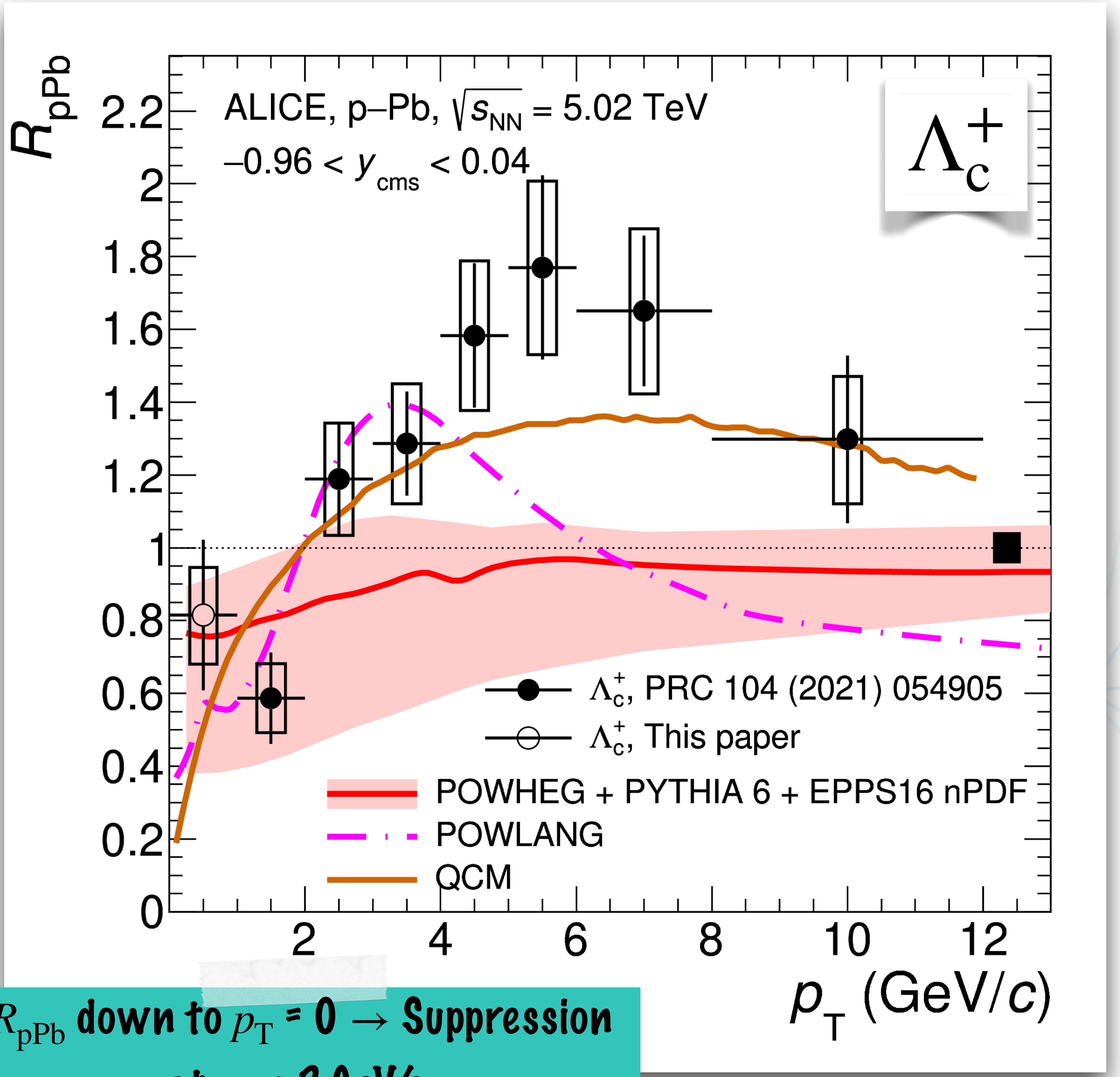


$R_{pPb}$ down to $p_T$ = 0 → Suppression at $p_T$ < 2 GeV/$c$

POWHEG+PYTHIA6⌘ coupled to EPPS16⌘ nPDF parametrization

POWLANG⌘ → Transport of charm quarks in a quark gluon plasma using transport coefficients from HTL

Quark (re)Combination Model (QCM)⌘ → No cold nuclear matter or initial state effects


⌘Frixione et al JHEP 09 (2007) 126
⌘Eskola et al EPJC 77, 163 (2017)
⌘Sjöstrand et al JHEP 05 (2006) 026
⌘ALICE, PRC 107 (2023) 064901
⌘ALICE, PRC 104 (2021) 054905
⌘Beraudo et al JHEP 03 (2016) 123
⌘Li et al PRC 97 (2018) 064915

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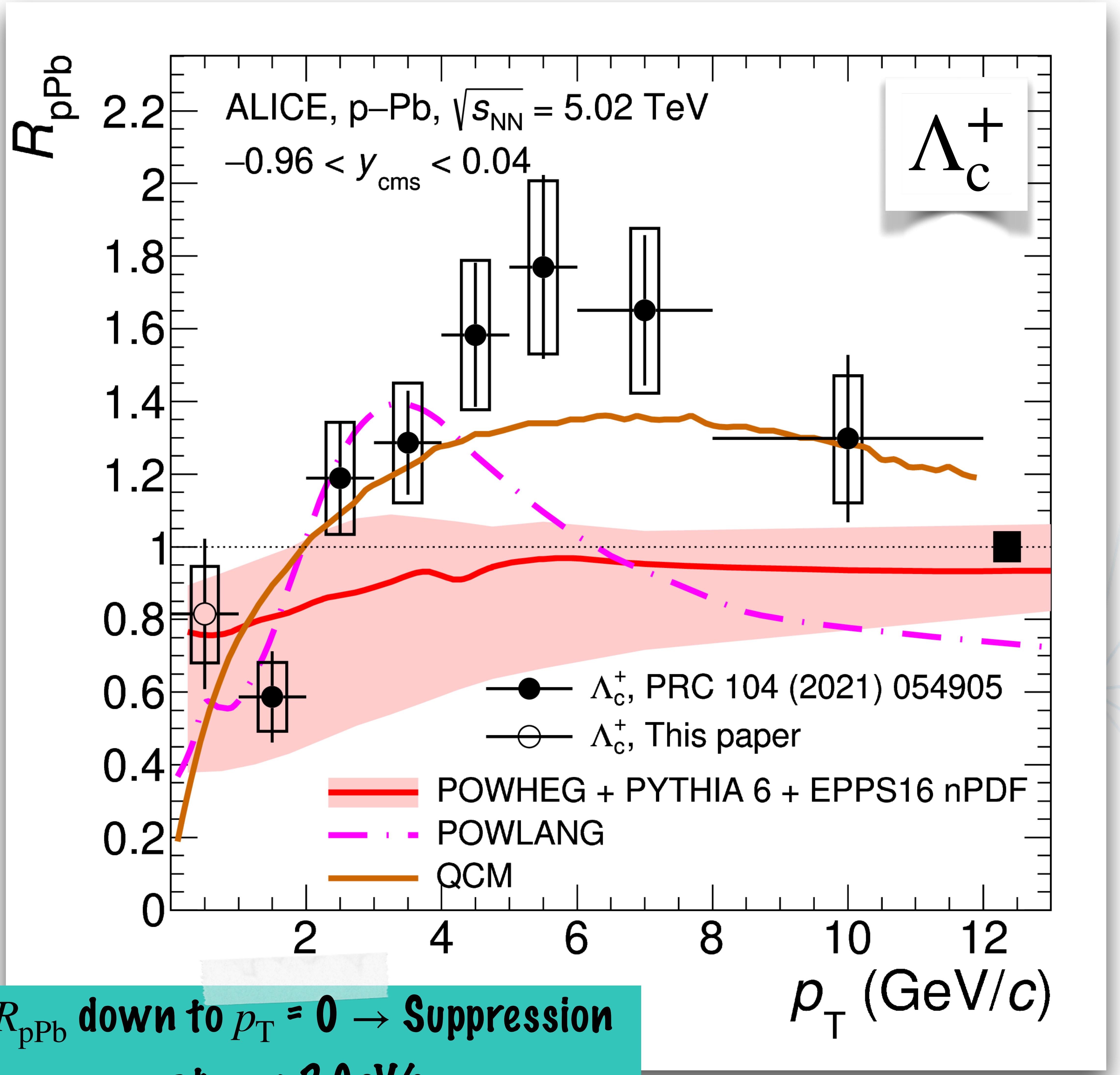



$R_{pPb}$ down to $p_T$ = 0 → Suppression at $p_T$ < 2 GeV/c

POWHEG+PYTHI... to EPPS16⌘

n... ...n

Below unity and constant beyond $p_T$ > 4 GeV/c

POWLANG ... Transport of c...

...k gluc... ...fficien...

2 < $p_T$ < 4 GeV/c → Description of the trend

$p_T$ > 4 GeV/c → Deviates from data⌘

Quark (re)Combination M... (QCM)⌘

→ No cold n... ...atter or initial ...tate effects

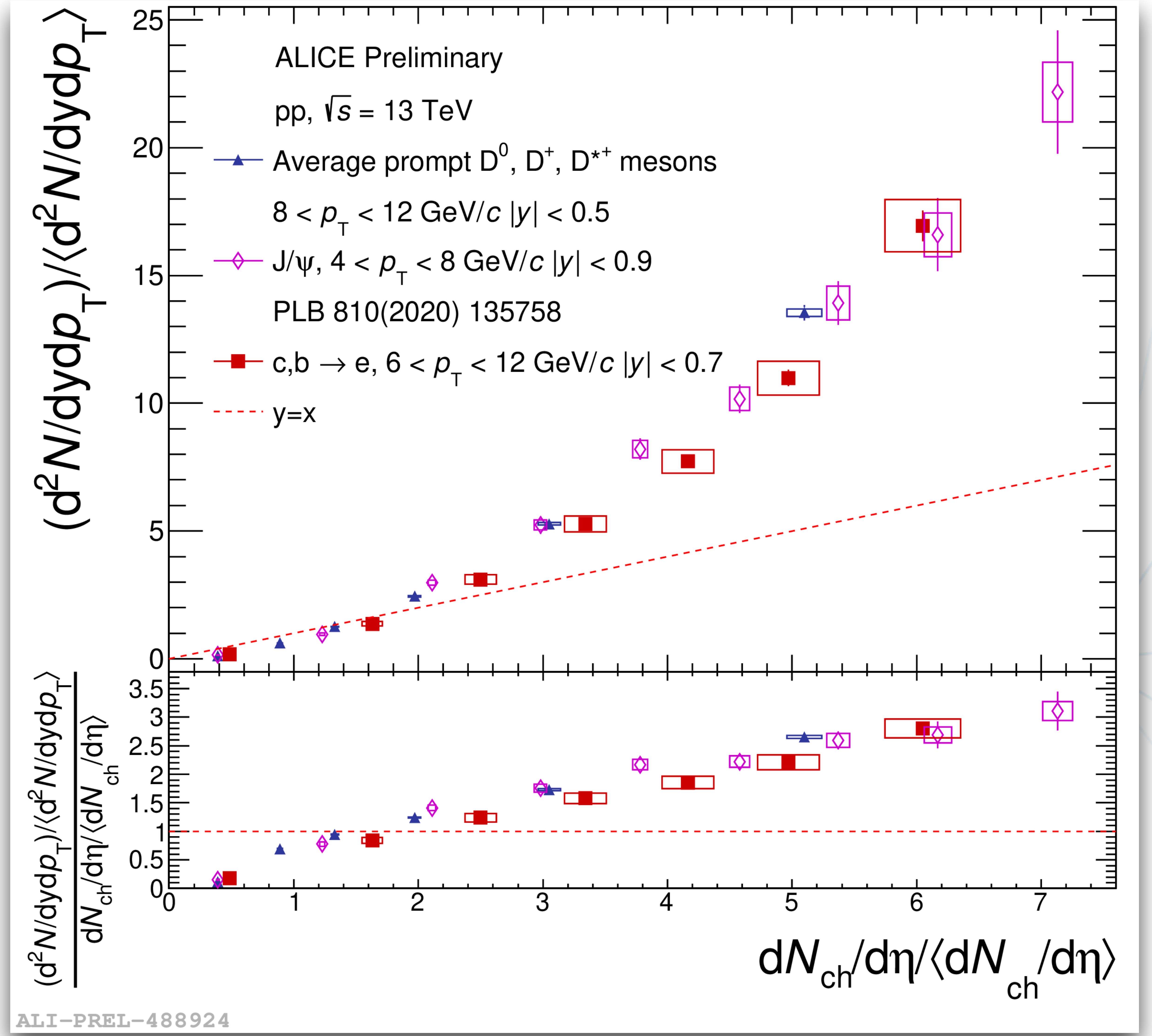
Closest description of data

⌘Frixione et al JHEP 09 (2007), 126
⌘Eskola et al EPJC 77, 163 (2017)
⌘Sjöstrand et al JHEP 05 (2006), 026

⌘ALICE, PRC 107 (2023), 064901
⌘ALICE, PRC 104 (2021), 054905
⌘Beraudo et al JHEP 03 (2016) 123
⌘Li et al PRC 97 (2018), 064915

ALICE

# Heavy-Flavour Self-Normalised Yields




**Similar trend of self-normalized yields for D mesons, electrons from heavy-flavour hadron decays⌘, and J/ψ⌘ at mid rapidity**

**Contribution from auto-correlation⌘ between heavy-flavour yields and charged-particle production**

⌘ALICE, JHEP 2023, 6 (2023)

⌘ALICE, Phys. Lett. B 810 (2020) 135758

⌘Weber et al, EPJ C, 79, 36 (2019)

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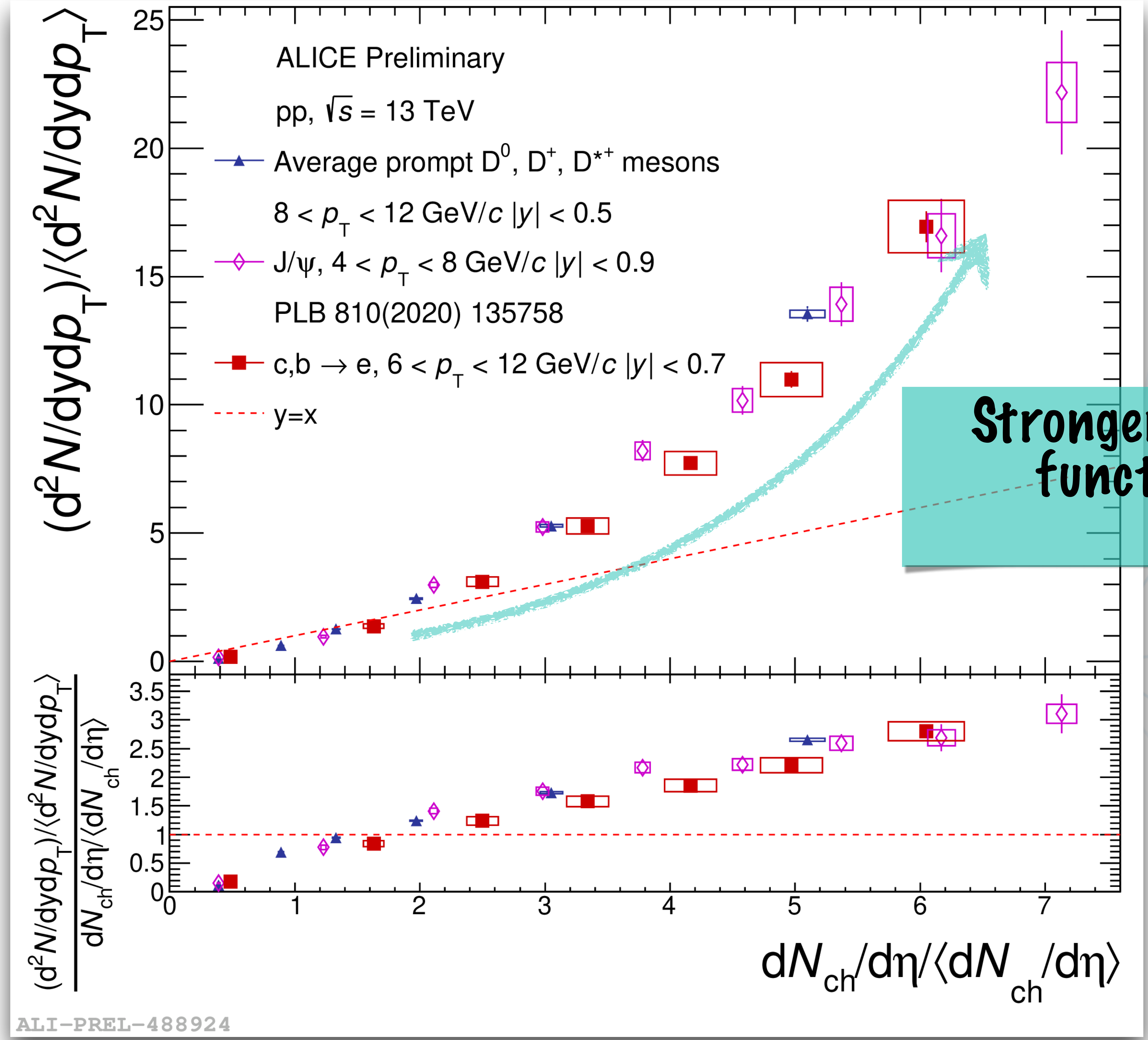


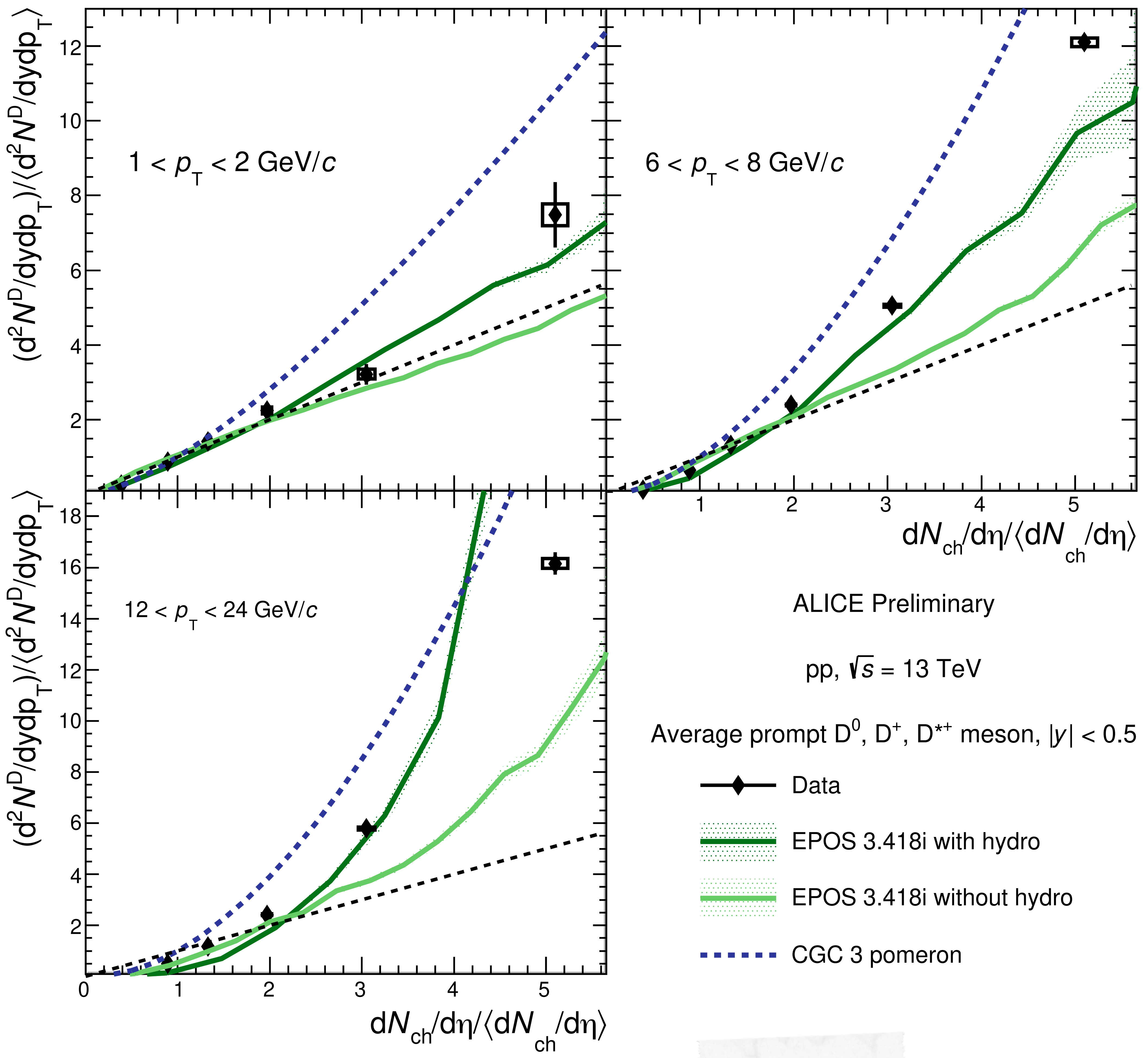

Similar trend of self-normalized yields for D mesons, electrons from heavy-flavour hadron decays⌘, and J/$\psi$⌘at mid rapidity

Stronger than linear increase as a function of charged-particle multiplicity

Contribution from auto-correlation⌘ between heavy-flavour yields and charged-particle production

⌘ALICE, JHEP 2023, 6 (2023)
⌘ALICE, Phys. Lett. B 810 (2020) 135758
⌘Weber et al, EPJ C, 79, 36 (2019)

# Heavy-Flavour Self-Normalised Yields




ALI-PREL-488879

⌘⌘Werner et al, Phys. Rev. C 89.064903 (2014)

⌘Schmidt & Siddikov, Phys. Rev. D 101.094020 (2020)

EPOS3 without hydro⌘⌘ → particle production via flux-tube expansion and fragmentation

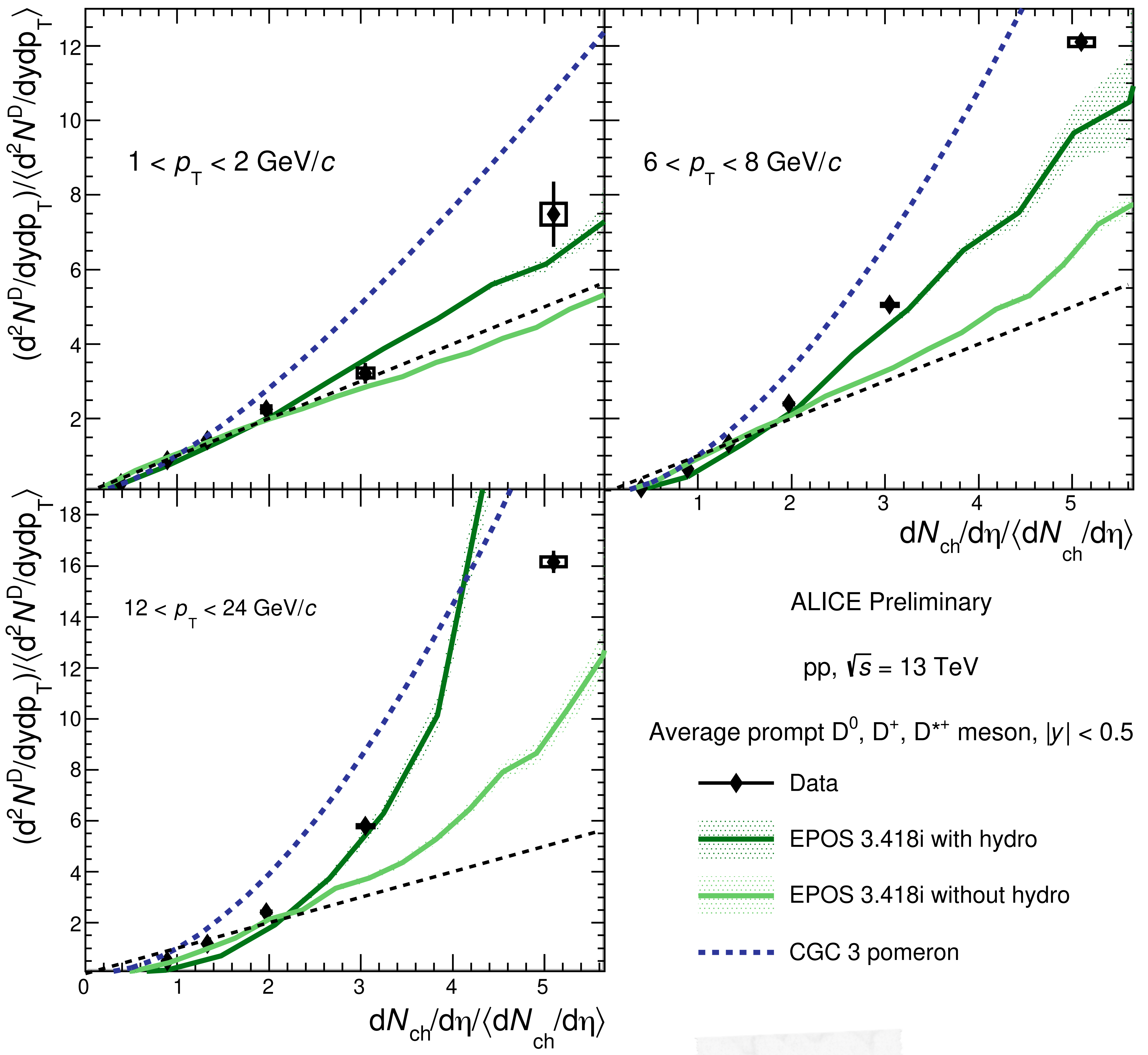
EPOS3 with hydro⌘⌘ → particle production via flux-tube expansion and fragmentation followed by a hydrodynamic evolution

→ Reduces multiplicity

→ Amplifies stronger than linear rise

3-pomeron Color Glass Condensate⌘ → particle production via three pomeron fusion correction

# Heavy-Flavour Self-Normalised Yields




⌘⌘Werner et al, Phys. Rev. C 89.064903 (2014)

⌘Schmidt & Siddikov, Phys. Rev. D 101.094020 (2020)

EPOS3 without hy... particle production ... tube expansion and fragmentation

**Underestimates the results**

EPOS3 with hydro⌘ → particle production ... x-tube ... fragmentation f... hydrodynamic ...tion

**Comparable to data**

**Deviating at high multiplicities**

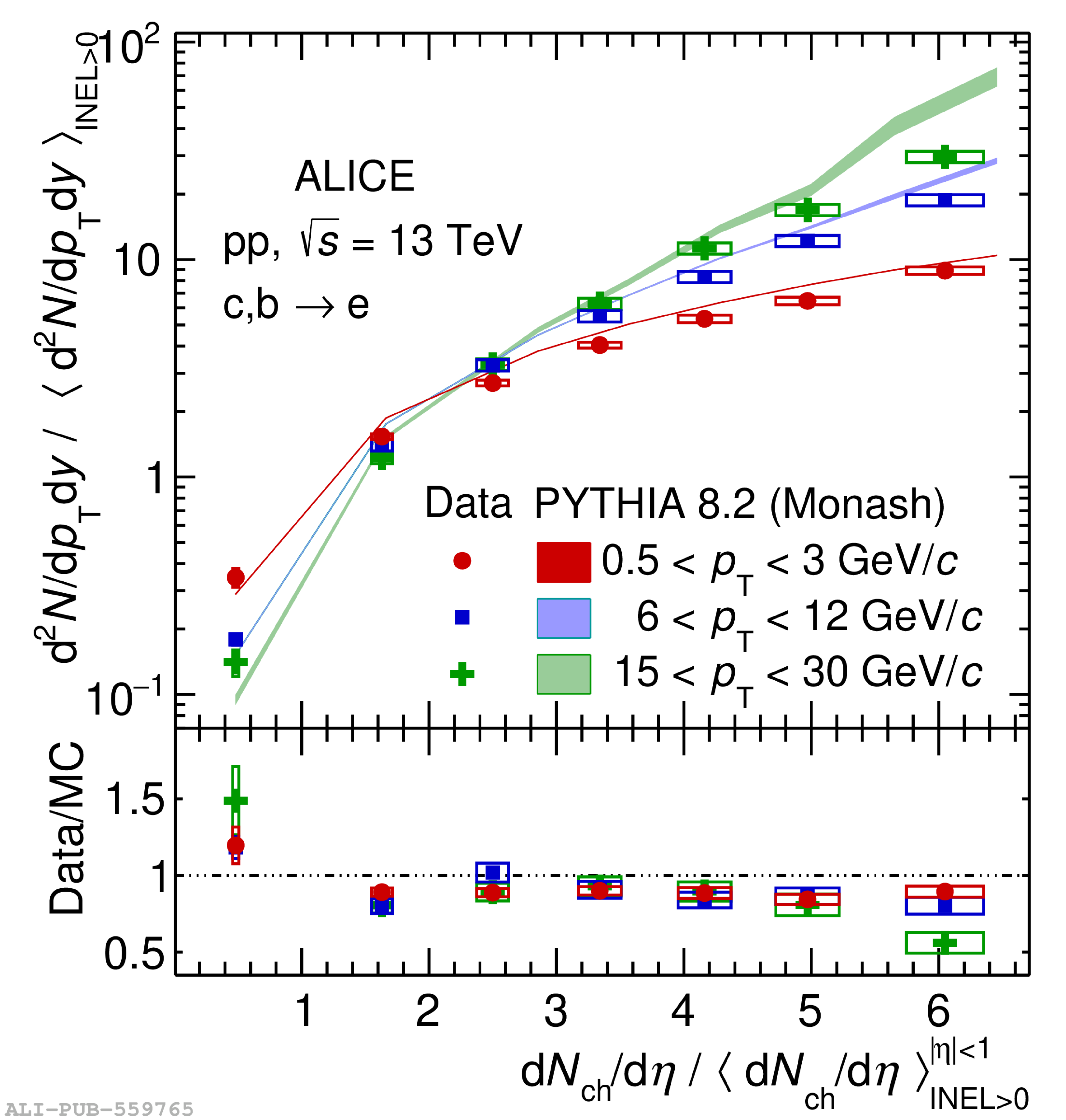
→ Reduces multiplicity

→ Amplifies stronger than linear rise

3-pomeron Color Glass C...sate⌘ → particle pro... via three pomeron ...sion correction

**Overestimates the results**

# Heavy-Flavour Self-Normalised Yields




Stronger than linear trend for electrons⌘ from heavy-flavour hadron decays

PYTHIA8 + Monash⌘

Comparable to data

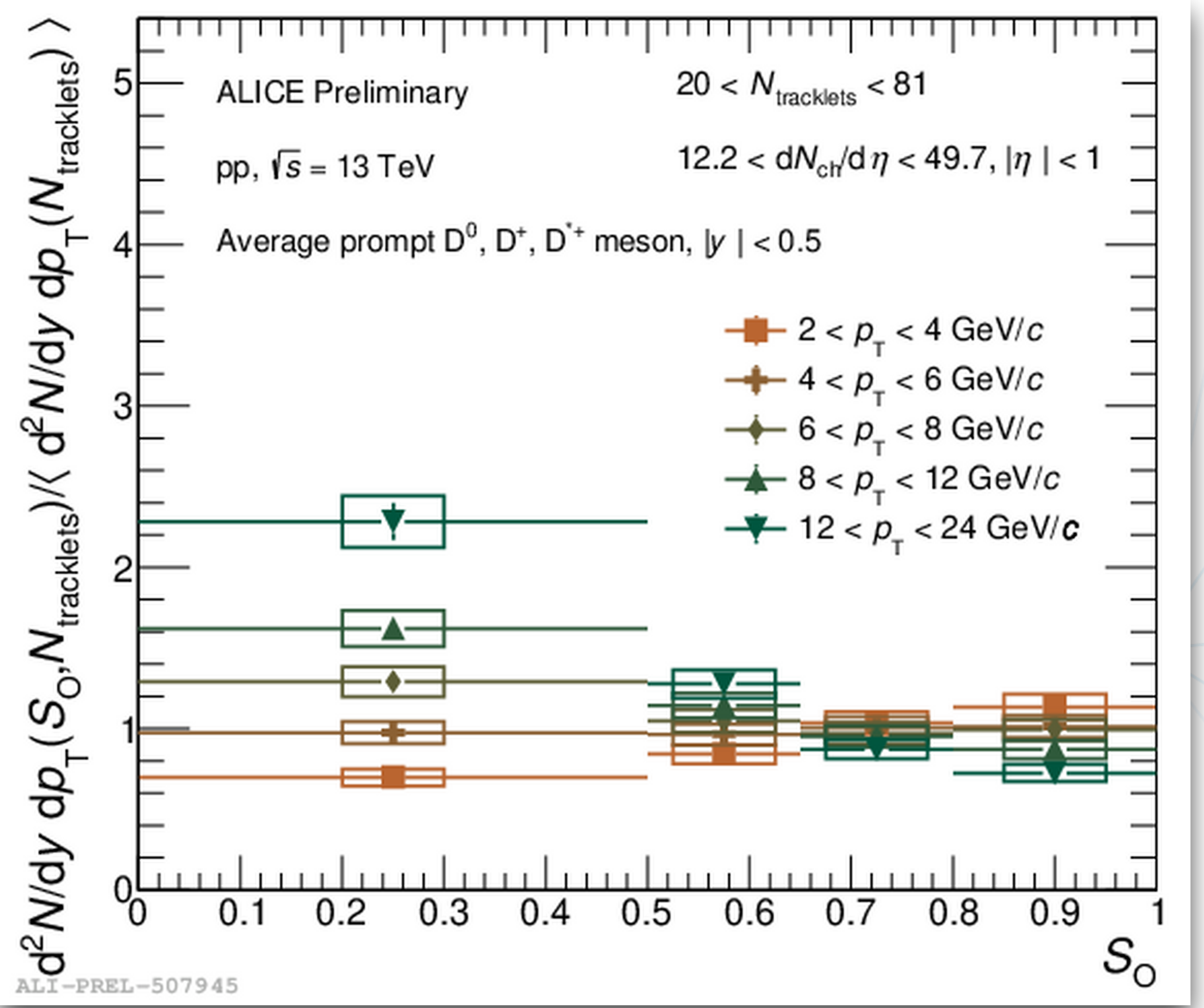
Multiparton Interactions (MPI) and Colour Reconnection (CR) mechanism in hadronisation → Important to describe data

⌘ALICE, JHEP 2023, 6 (2023)

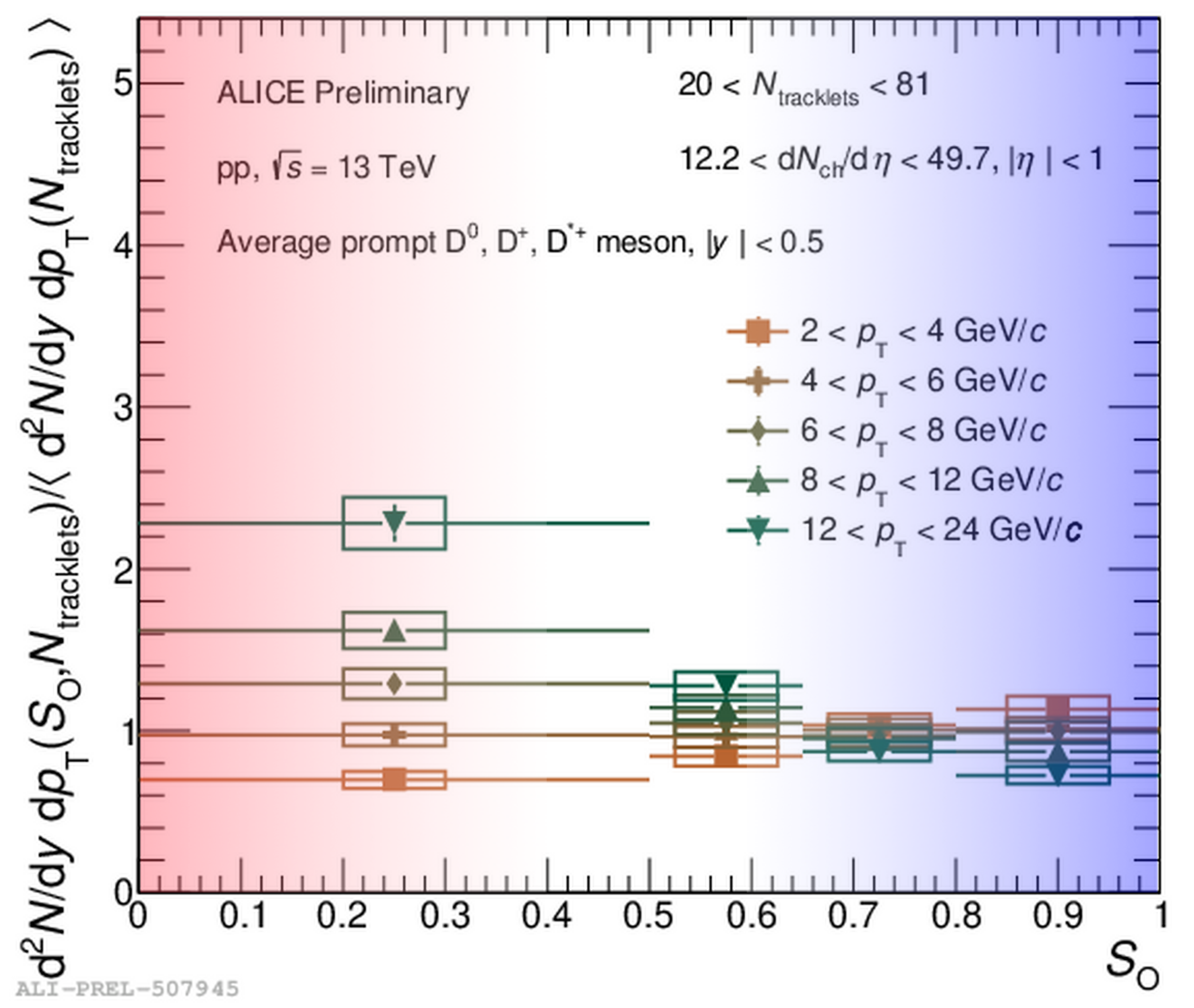
⌘Skands et al, EPJ C74 (2014) 3024

# •• Heavy-Flavour and Transverse Spherocity

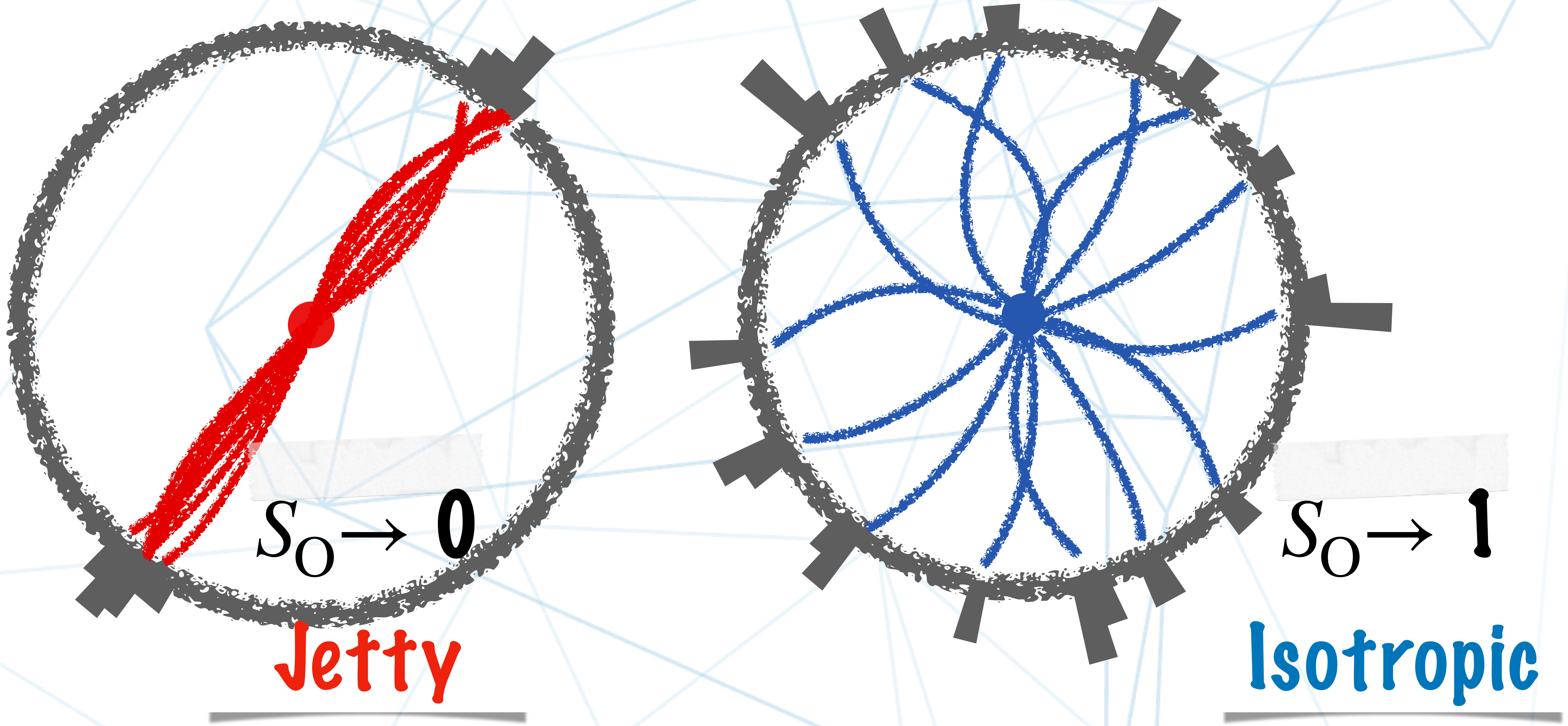
$$S_{O}^{(p_{T}=1.0)} = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left( \frac{\Sigma_i |\hat{p}_{T_i}^{(p_T=1.0)} \times \hat{n}|}{N_{\text{tracks}}} \right)^2$$



# •• Heavy-Flavour and Transverse Spherocity



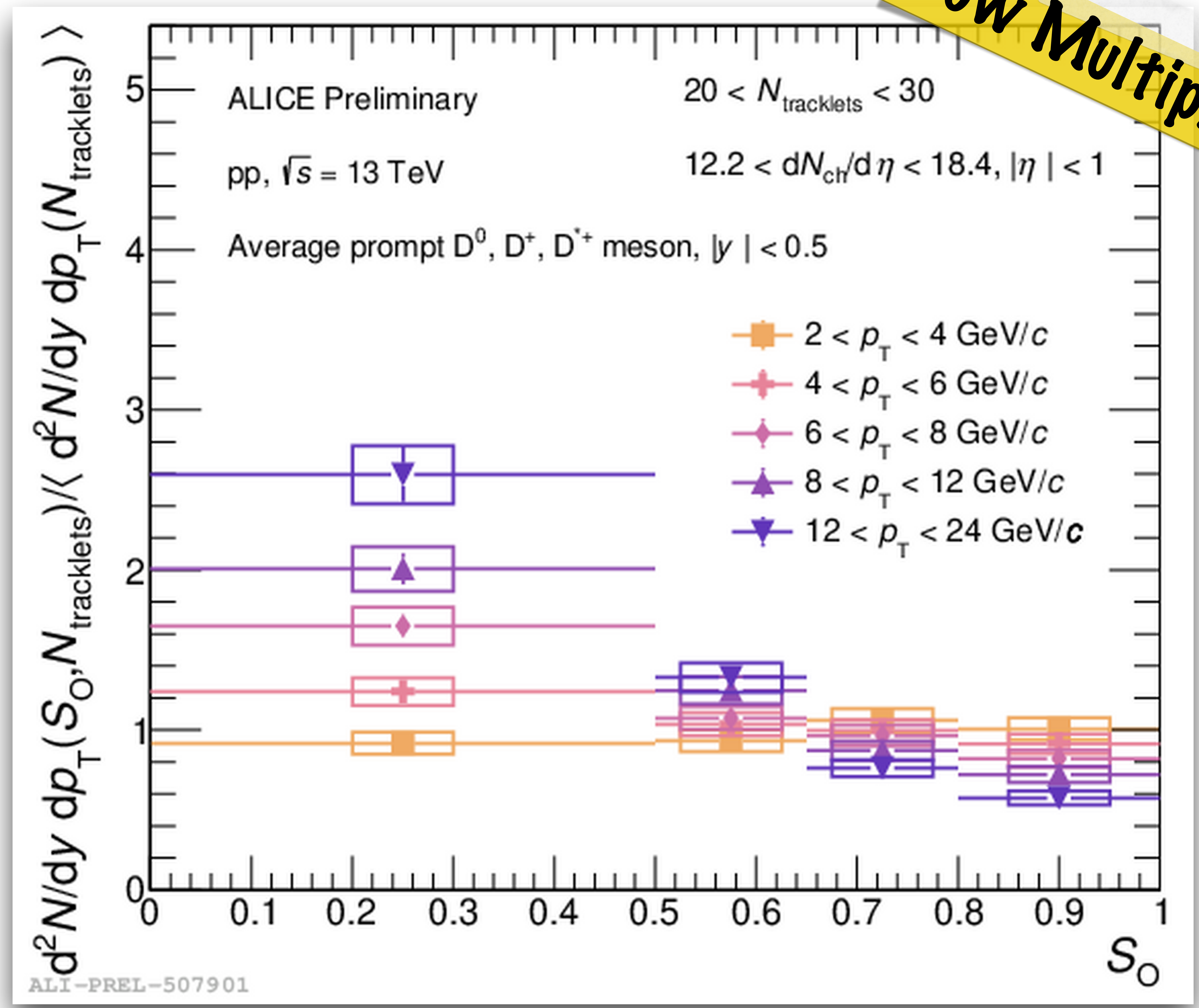

$$S_O^{(p_T=1.0)} = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left( \frac{\Sigma_i |\hat{p}_{T_i}^{(p_T=1.0)} \times \hat{n}|}{N_{\text{tracks}}} \right)^2$$



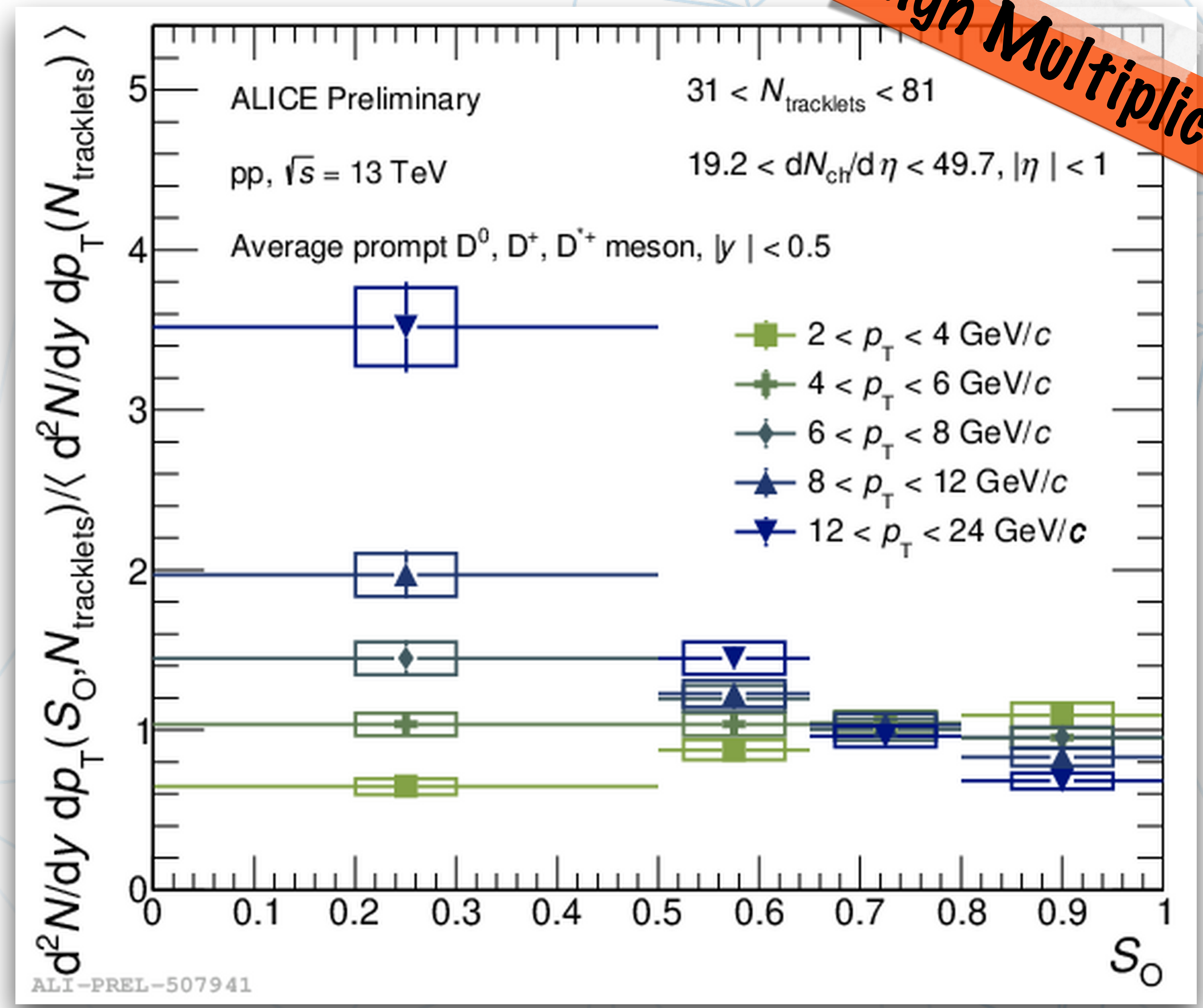

**Sensitive to initial hard scatterings and the "underlying event"**

# Heavy-Flavour and Transverse Spherocity

**Low Multiplicity**



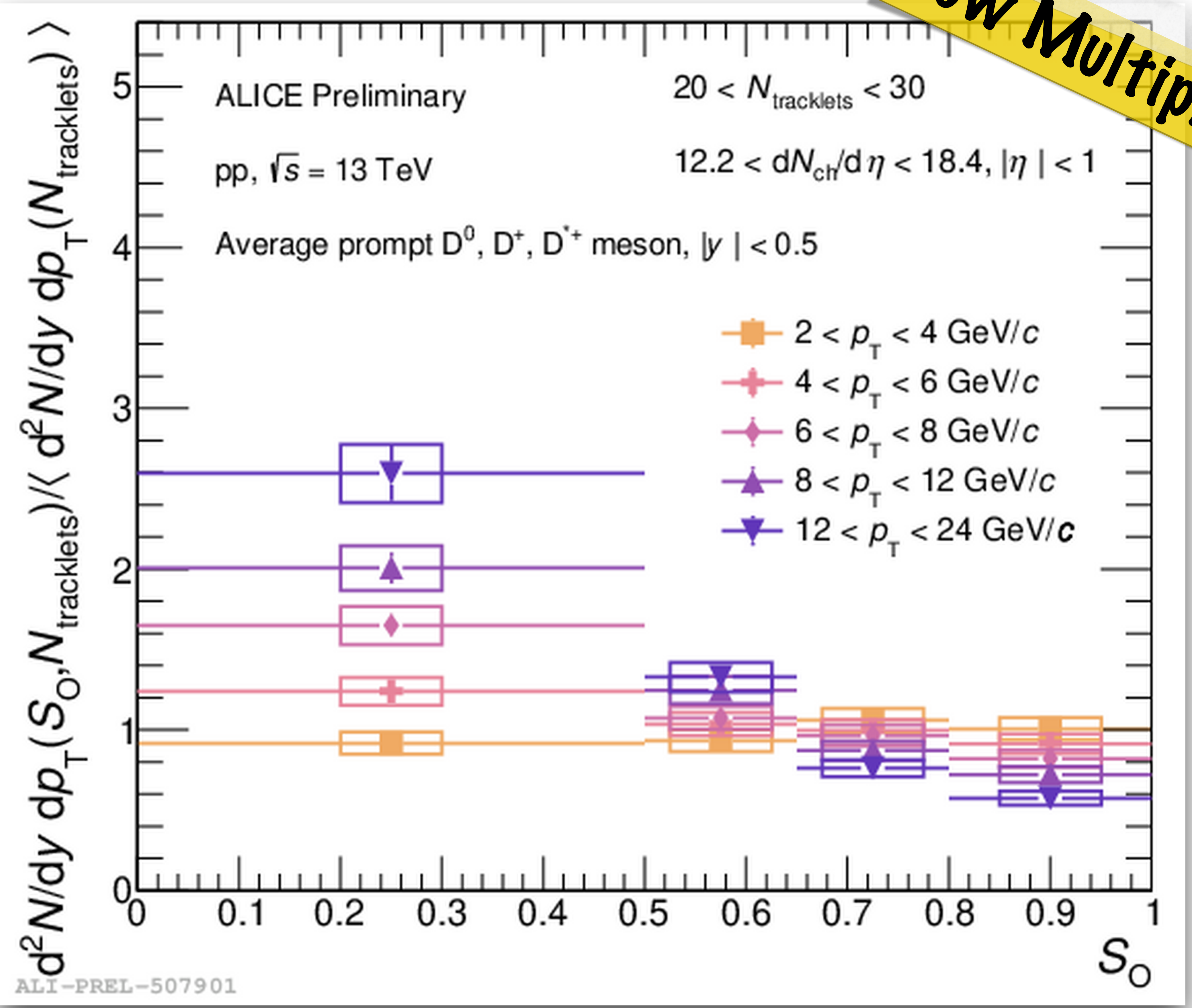

**High Multiplicity**

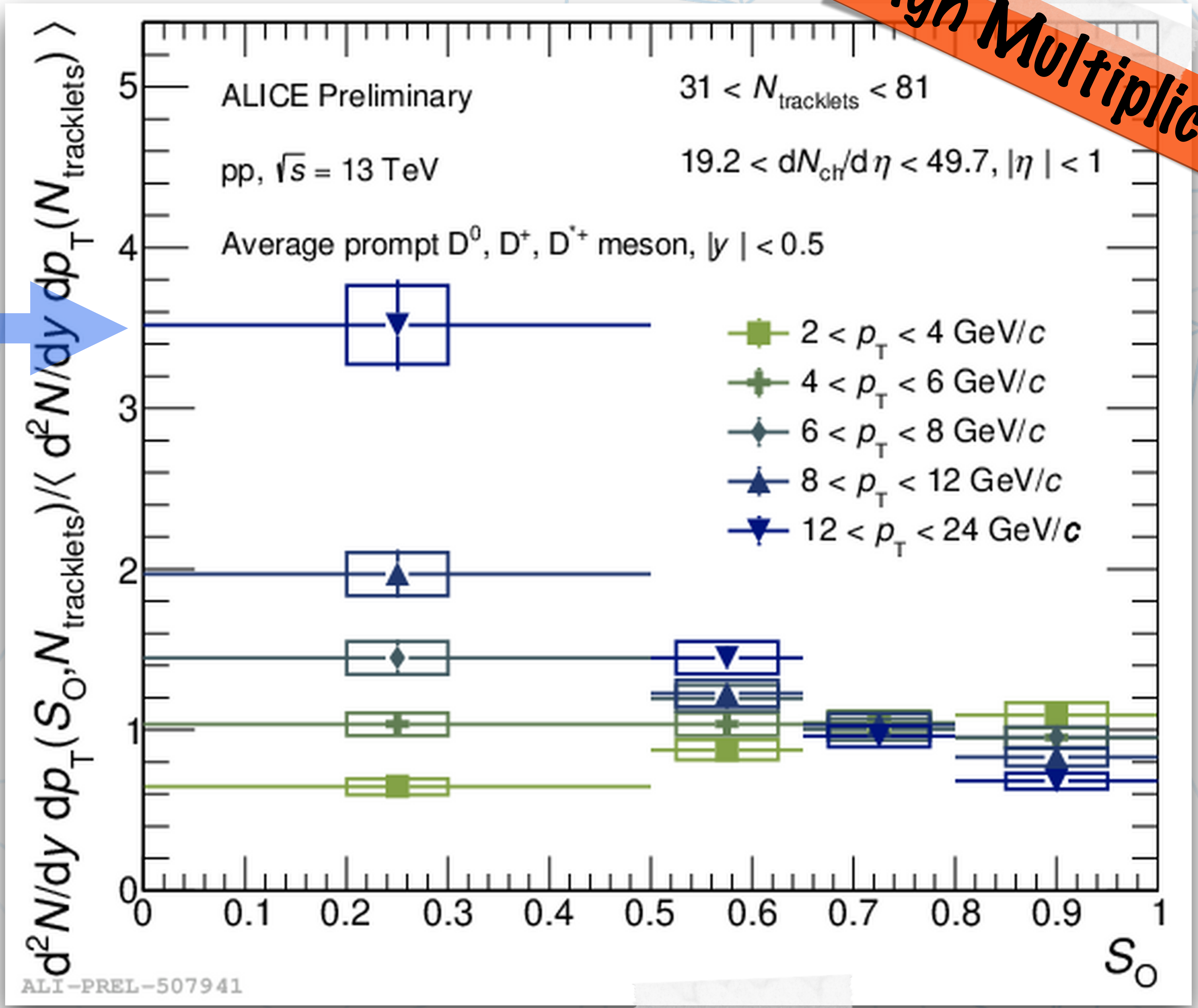


# Heavy-Flavour and Transverse Spherocity

Low Multiplicity

High Multiplicity




Effect of hard scatterings leading to high multiplicity

Hint of enhancement of D-meson production from high-multiplicity jetty events

# Conclusions

* Positive inclusive muon $v_2$ in high multiplicity p—Pb collisions
  - Hint of collectivity in small systems
  - Possible role of initial state effects

* $R_{\mathrm{pPb}}$ of $\Lambda_c^+$ shows suppression below $p_T < 2$ GeV/c
  - QCM offers closest description without CNM or initial state effects

* Auto-correlation between heavy-flavour yields and charged-particle multiplicity → Stronger than linear trend with multiplicity
  - MPI and CR essential to reproduce charged-particle multiplicity

* Open charm production vs transverse spherocity → Isolation of charm production in hard and soft QCD
  - Hint of an enhancement for high-multiplicity jetty events


Thank you for your attention !