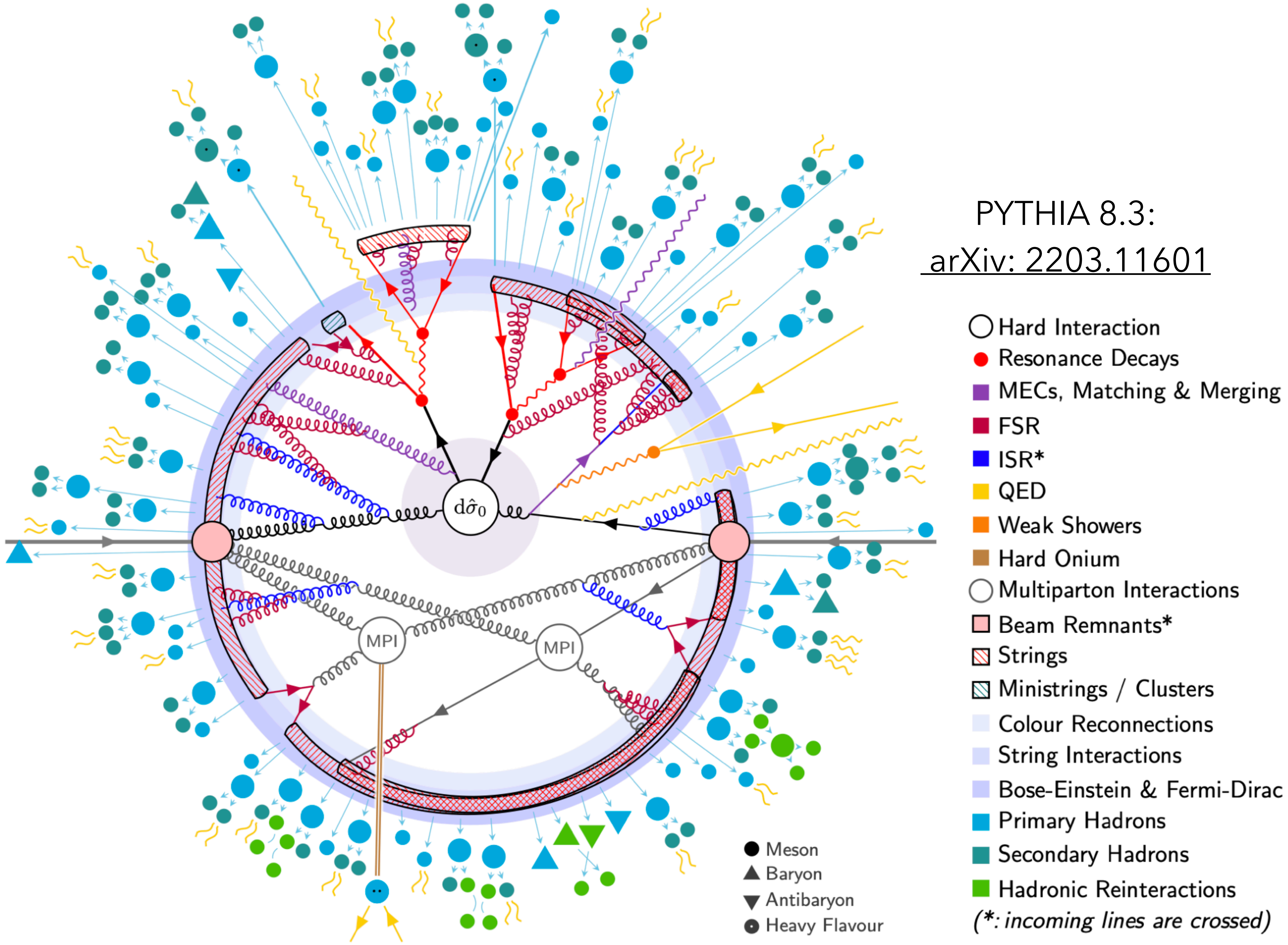
Heavy quarks and quarkonia in small systems

Zaida Conesa del Valle on behalf of the ALICE, ATLAS, CMS and LHCb Collaborations
Laboratoire de Physique des 2 infinis Irène Joliot-Curie – IJCLab
(CNRS/IN2P3, Université Paris-Saclay)

QCD@LHC2022, 28 Nov. – 2 Dec. 2022, Orsay (France)

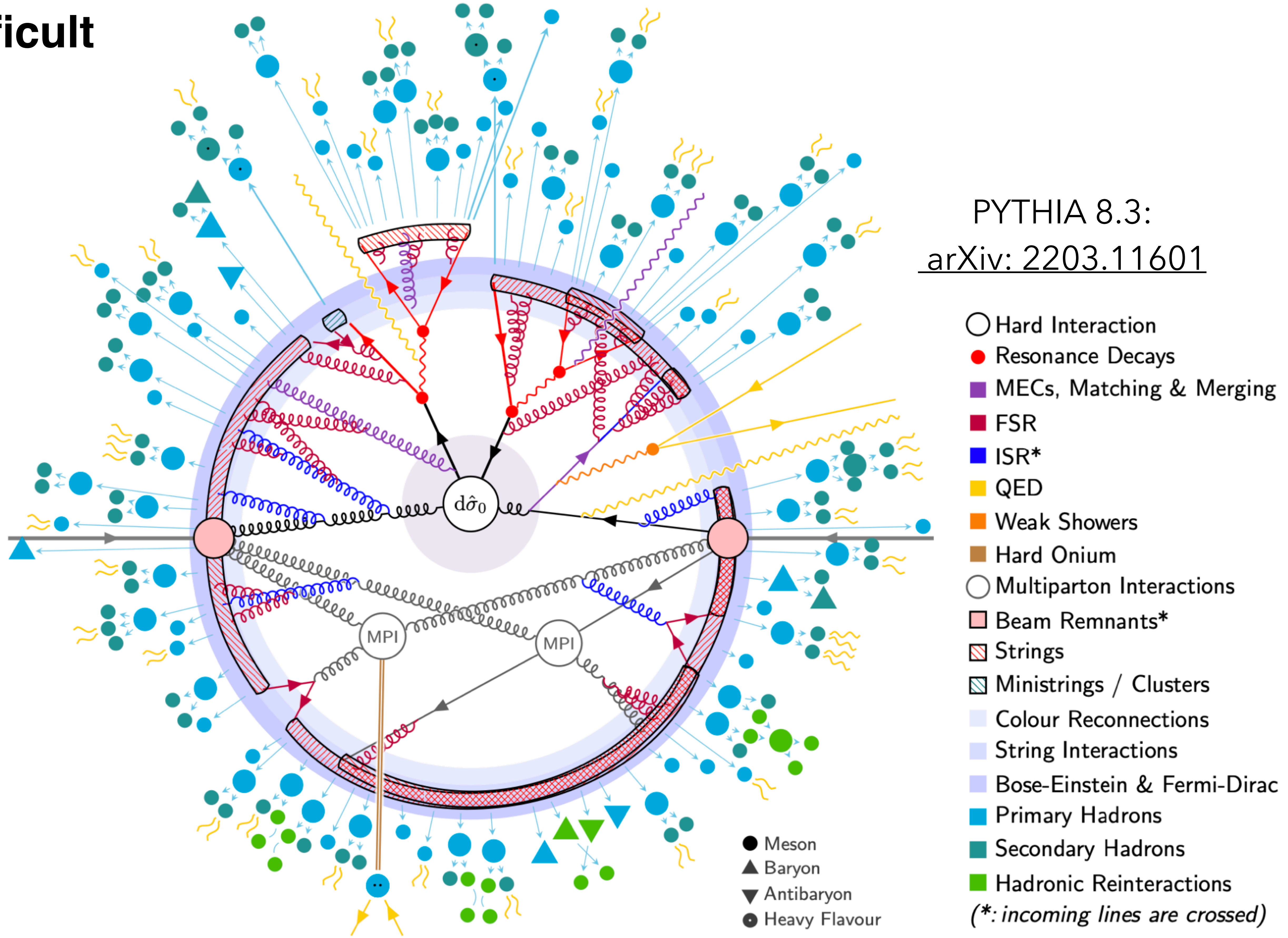
Why heavy flavours ?



PYTHIA 8.3:
arXiv: 2203.11601

Why heavy flavours ?

- Heavy quarks are produced in initial hard scatterings with **large Q^2 → calculable with pQCD.**
- Large masses $m_b > m_c \gg \Lambda_{QCD}$ → short formation time → **experience whole medium evolution**
- Interactions with the medium don't change the flavour, but can modify the phase-space distribution. Thermal production rate in the QGP is expected to be 'small'.
  → **destruction or creation in the medium is difficult**



PYTHIA 8.3:
arXiv: 2203.11601

Why heavy flavours ?

- Heavy quarks are produced in initial hard scatterings with **large Q^2 → calculable with pQCD.**
- Large masses $m_b > m_c \gg \Lambda_{QCD}$ → short formation time → **experience whole medium evolution**
- Interactions with the medium don't change the flavour, but can modify the phase-space distribution. Thermal production rate in the QGP is expected to be 'small'.
  → **destruction or creation in the medium is difficult**

- Factorization approach:

$$\frac{d^2\sigma}{dp_T dy}(AB \to CX) \propto \sum_{abcd} \int_0^1 dx_a \int_0^1 dx_b\, f_A^a(x_a, Q^2) f_B^b(x_b, Q^2) \frac{d\sigma}{dt}(ab \to cd)\, D_c^C(z_c, Q^2)$$

Parton distribution functions — Partonic cross section — Fragmentation function

- **Fragmentation functions assumed to be universal** across collision systems.
- For the quarkonium case, the binding of the quark pair involves soft scales, non-perturbative nature.

Why heavy flavours in small systems ?

- Sensitive to **fragmentation / hadronization**
  - Fragmentation fraction universality being questioned by recent LHC data.
  - Scrutinize hadron formation / nature

  → **Ratios of particle species, exotica**

- **Underlying event / multiple parton interactions**
  - Interplay between soft/hard processes
  - Multiple parton interaction (MPI) contribution

  → Associated particle production, **yield evolution with multiplicity**

- **Initial state effects**
  - saturation / modification of PDFs in nuclei
  - …

  → **Particle yields, azimuthal distributions**

system size

- **Final state effects**
  - energy loss
  - nuclear absorption
  - comover interaction
  - …

  → **Particle yields, azimuthal distribution**

Why heavy flavours in small systems ?

Laboratoire de Physique des 2 infinis
Irène Joliot-Curie

- Sensitive to **fragmentation / hadronization**
  - Fragmentation fraction universality being questioned by recent LHC data.
  - Scrutinize hadron formation / nature

  → **Ratios of particle species, exotica**

- **Underlying event / multiple parton interactions**
  - Interplay between soft/hard processes
  - Multiple parton interaction (MPI) contribution

  → Associated particle production, **yield evolution with multiplicity**

- **Initial state effects**
  - saturation / modification of PDFs in nuclei
  - …

  → **Particle yields, azimuthal distributions**

- **Final state effects**
  - energy loss
  - nuclear absorption
  - comover interaction
  - …

  → **Particle yields, azimuthal distribution**

- **Understand particle production across collision system size.**
- **Investigate the source of collective effects.**

Hadronization and multiplicity dependence

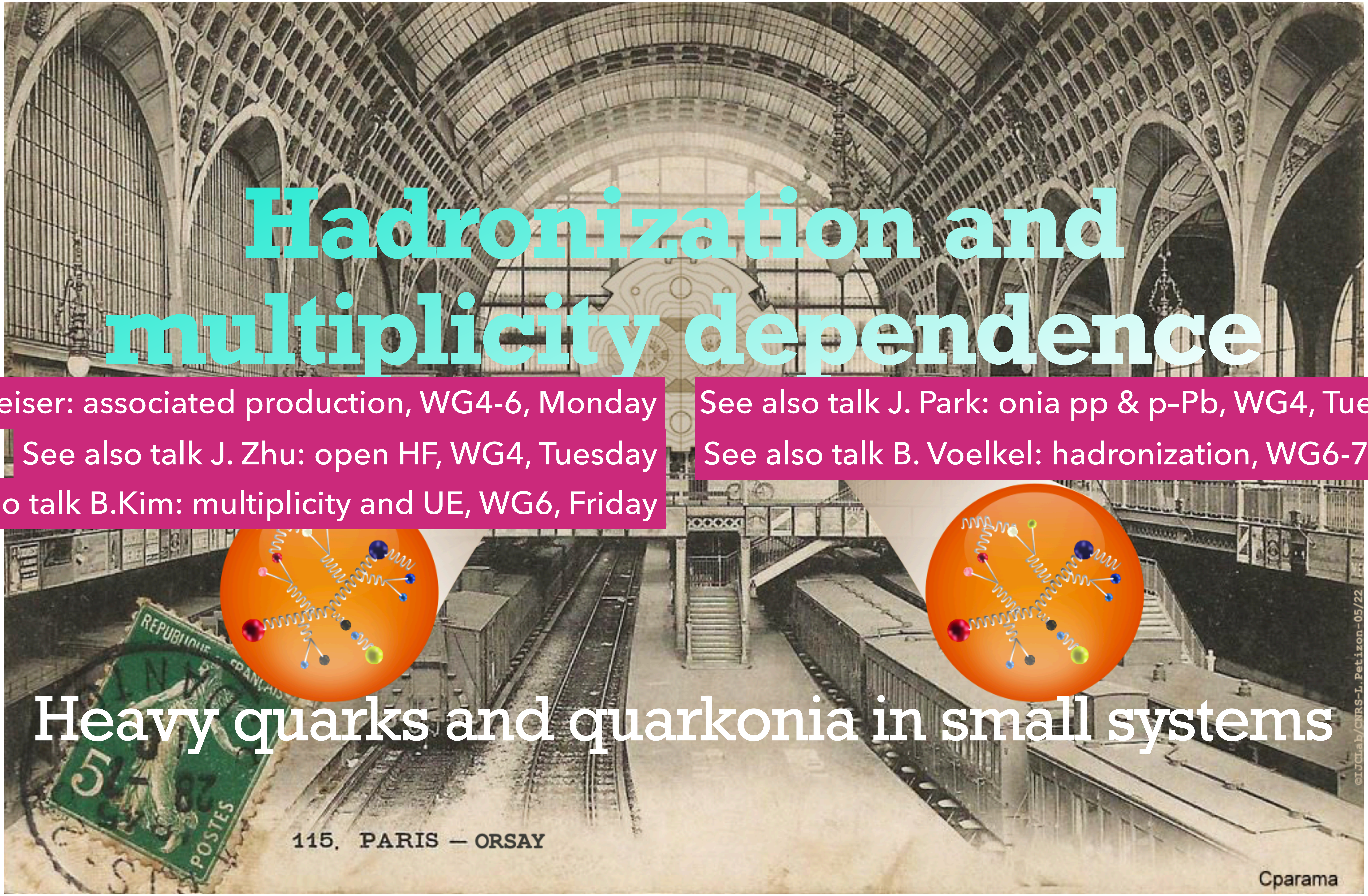
See also talk A.Geiser: associated production, WG4-6, Monday

See also talk J. Zhu: open HF, WG4, Tuesday

See also talk B.Kim: multiplicity and UE, WG6, Friday

See also talk J. Park: onia pp & p–Pb, WG4, Tuesday

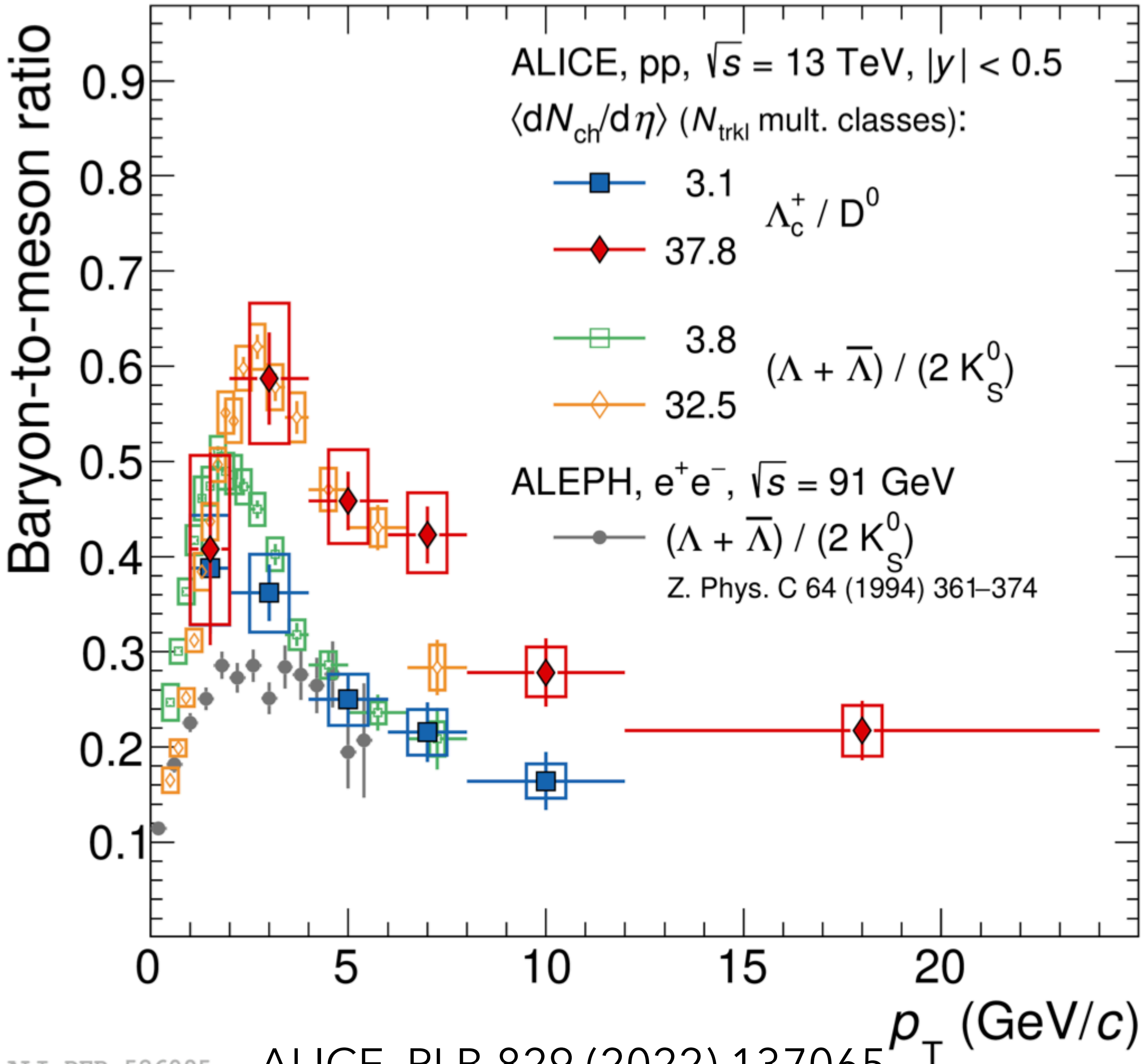
See also talk B. Voelkel: hadronization, WG6-7, Tuesday



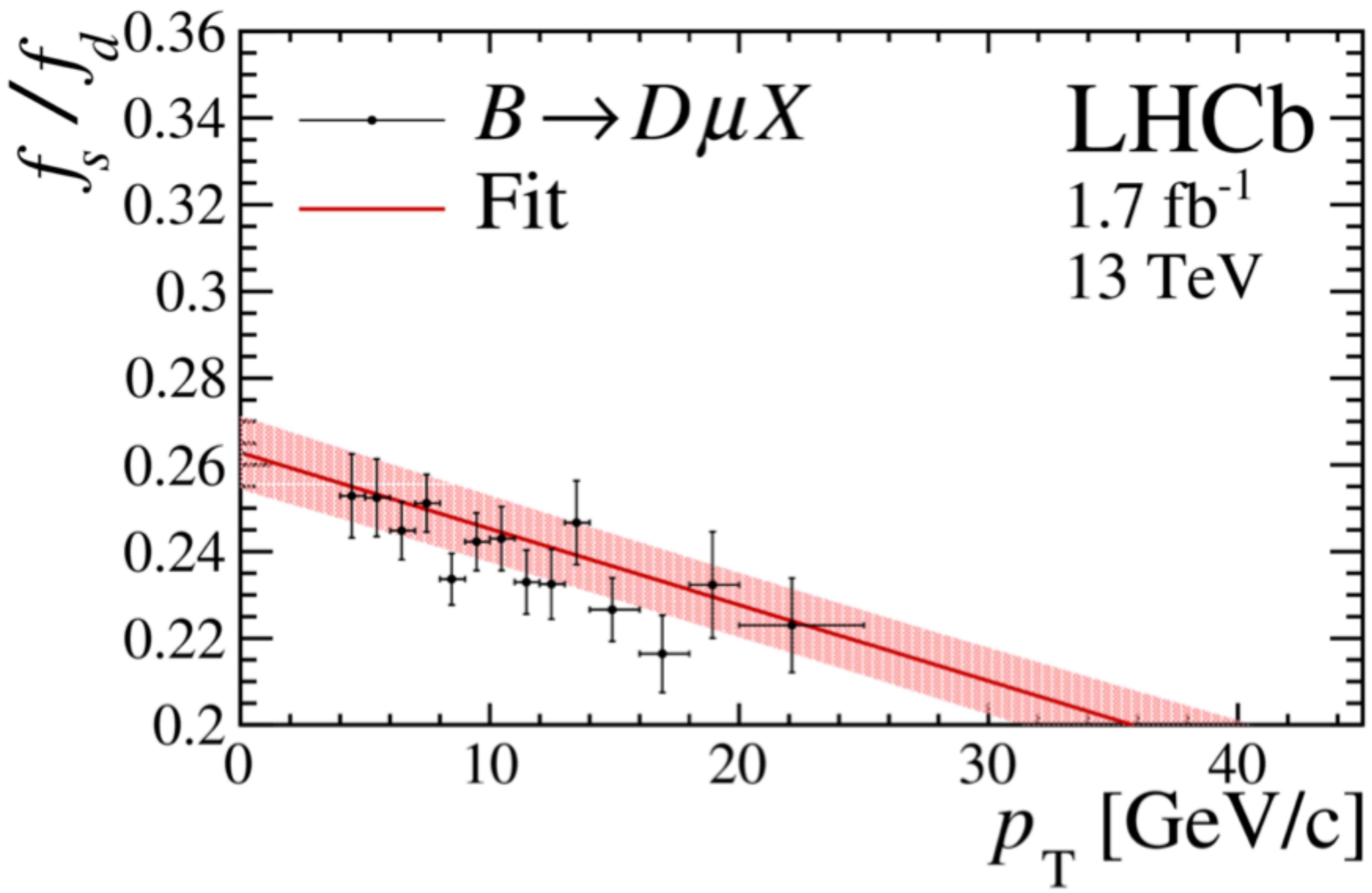
Heavy quarks and quarkonia in small systems

Λ_c^+/D^0 and B^0_s/B^0 in pp

- ALICE observed a **strong p_T dependence of the baryon-to-meson ratios in the charm sector**, similar to that observed in the light-flavour sector.
- **Likely due to a redistribution of momentum**, rather than to an overall enhancement of baryon yield.
- LHCb recently measured the multiplicity dependence of B^0_s /B^0 ratio, comparing the fraction of b quarks that hadronize with an s quark to that hadronizing with a d quark, f_s/f_d.
- **Significant f_s/f_d p_T dependence observed in the beauty sector**.



ALICE, PLB 829 (2022) 137065

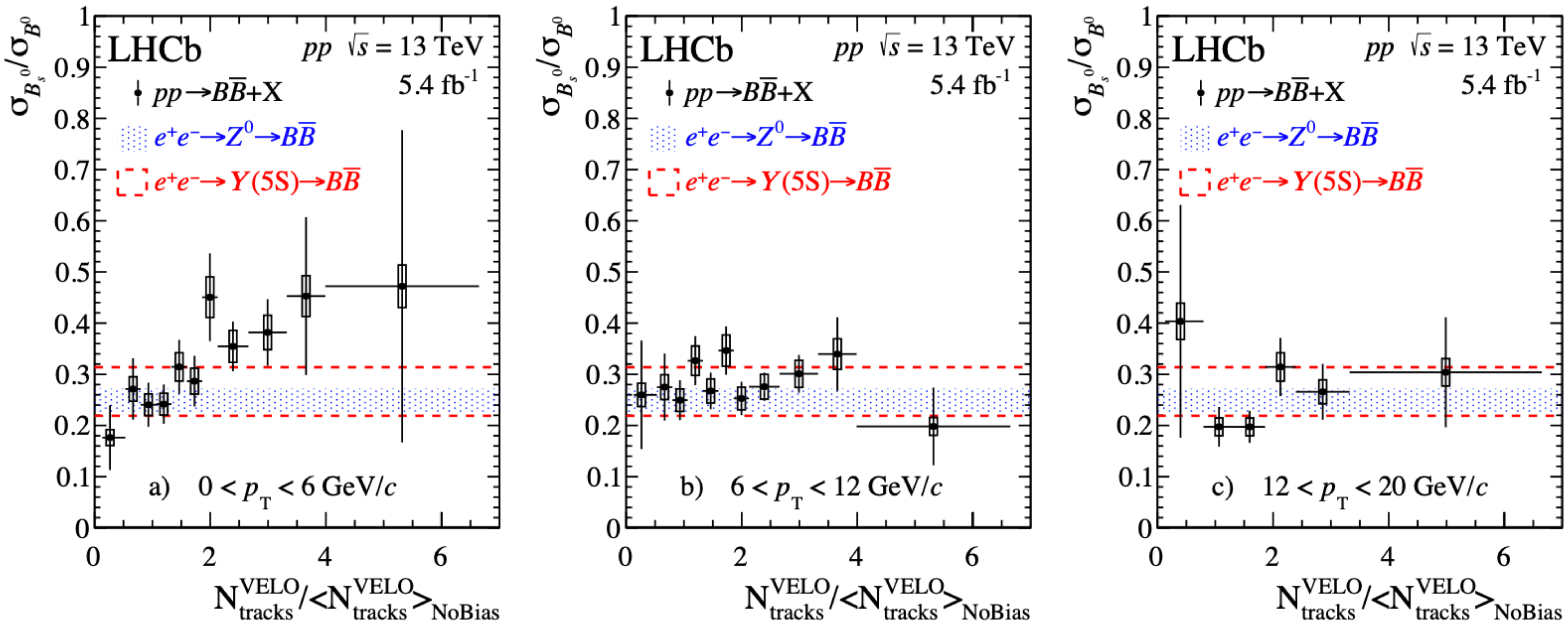


LHCb, Phys. Rev. D 104, 032005

B^0_s/B^0 vs. multiplicity in pp

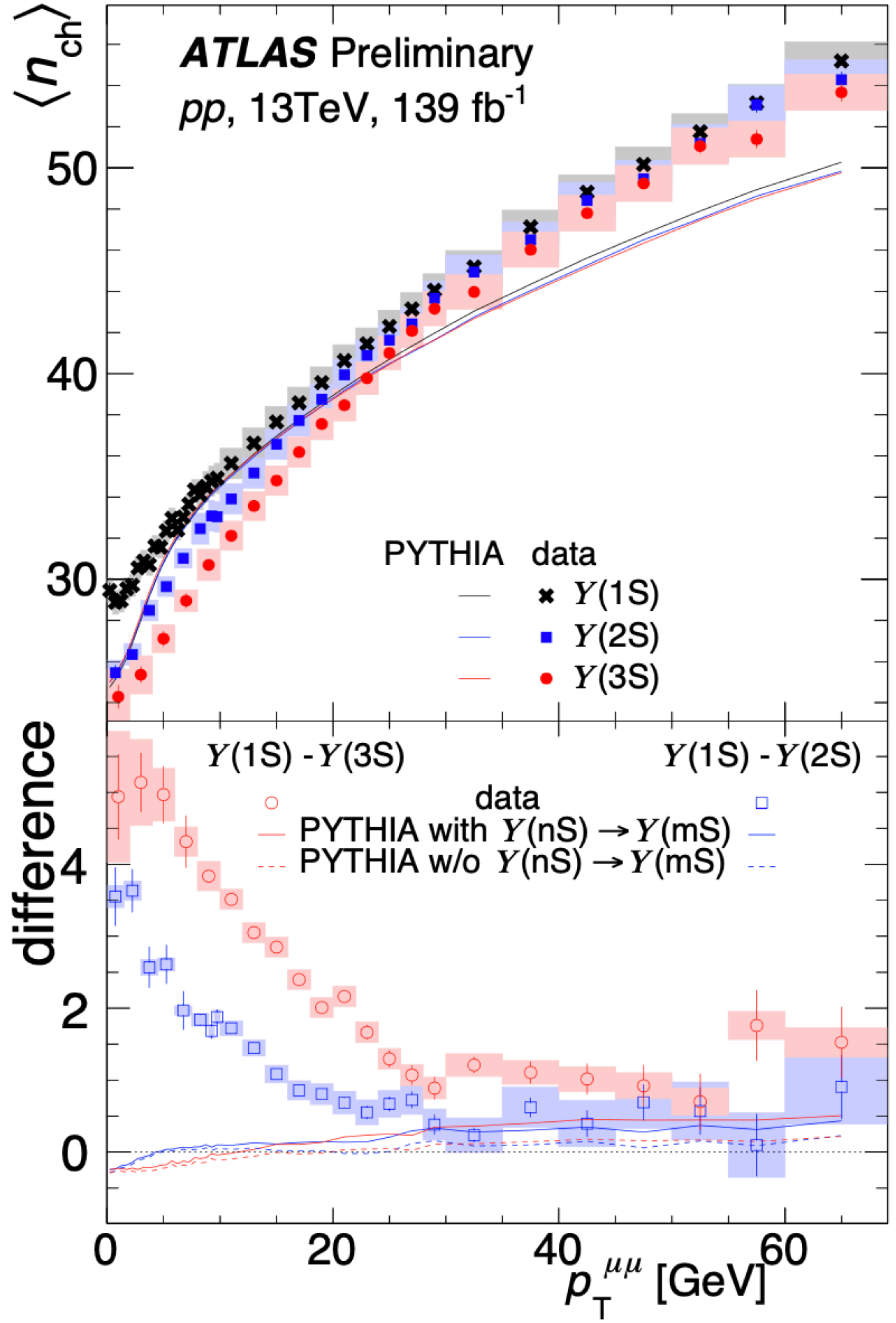
- Both measured in the same decay channel → $J/\psi\ \pi^+\pi^-$
- **Evolution with charged-particle multiplicity at low p_T, no dependence at intermediate-to-large p_T.**
- **Different** ratios in pp with respect **to e^+e^-** collisions for p_T<6 GeV/c.
- Expected in a scenario where low-p_T production is affected by **coalescence**, whereas high p_T is dominated by vacuum **fragmentation**.

LHCB-PAPER-2022-001, arXiv: 2204.13042



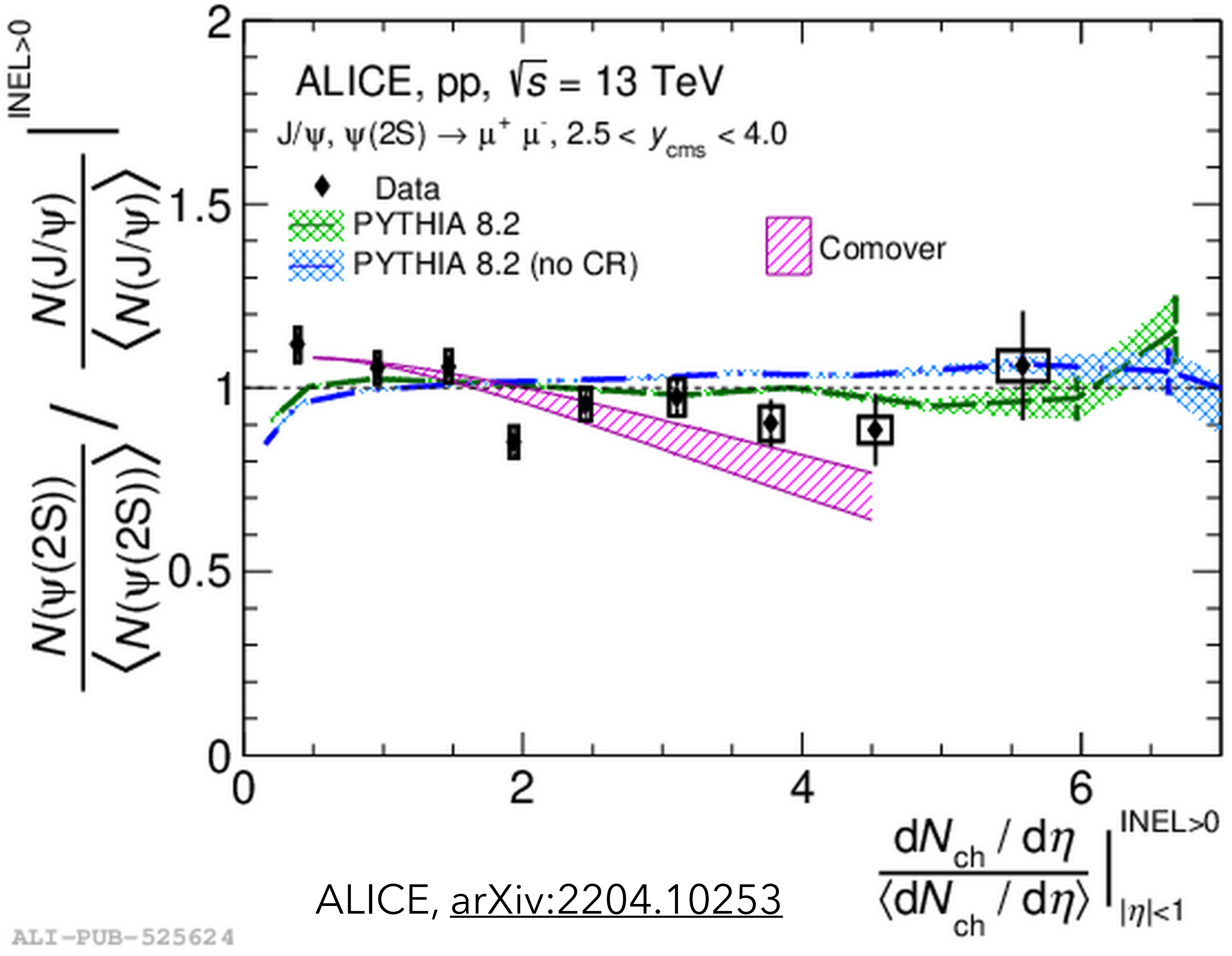
ϒ(nS) and the underlying event in pp

- Study of charged particle multiplicity (and particle kinematics) in the event for each ϒ(nS) state to study the underlying event.
- **Different multiplicity distribution** observed for each one of the states.
- Differences are **strongly momentum dependent**: decrease at high p_T.
- **Excited states are less likely to be found at larger multiplicities, compared to the ground state.**
- **Not explained by PYTHIA** simulations, which show similar distributions for the three states, independently of the color reconnection scheme used.
- May it be due to suppression of excited states? Or to enhancement of the ground state?
- Provides further inputs for modeling the underlying event.

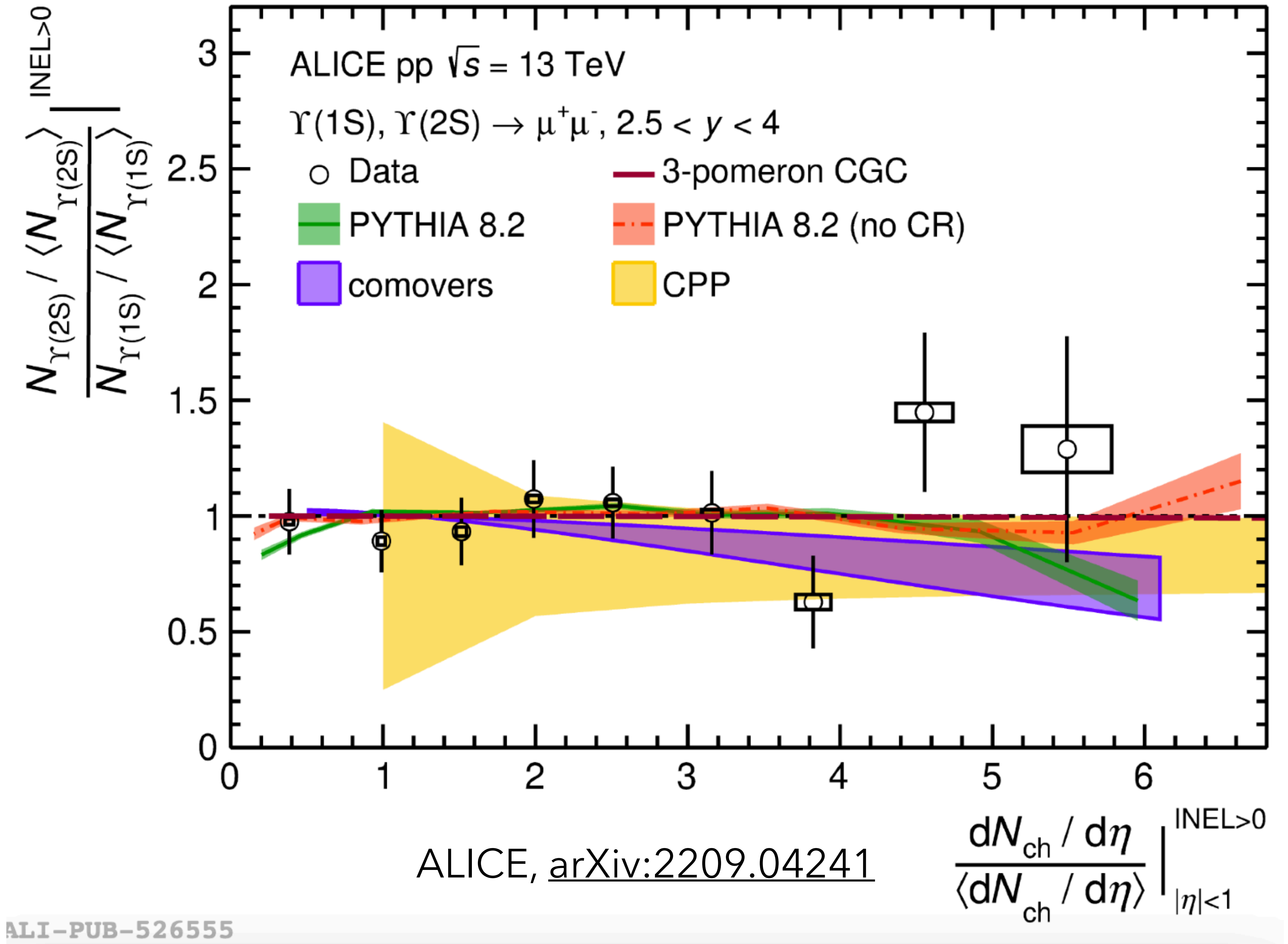


ATLAS-CONF-2022-023

Excited-to-ground state quarkonium ratios in pp



ALICE, arXiv:2204.10253



ALICE, arXiv:2209.04241

- Excited-to-ground state ratios provide information on final state effects, as most of the initial state effects cancel in the ratio, and the higher mass states are characterized by a lower binding energy.
- **ψ(2S)/J/ψ and Υ(2S)/Υ(1S) ratios as a function of multiplicity are consistent with unity and model calculations including initial and/or final state effects** within uncertainties.

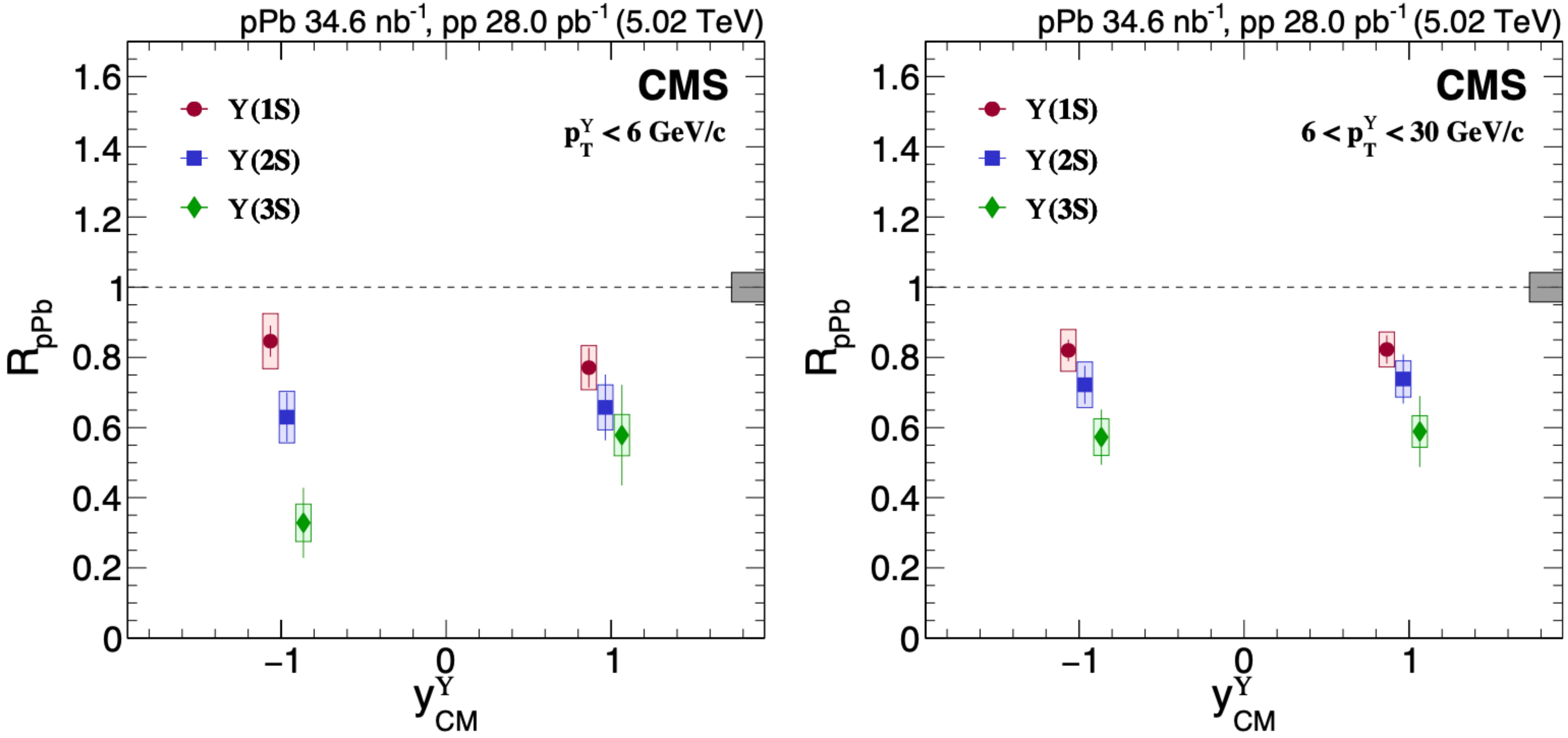
Nuclear modification of Υ(nS) in p–Pb

[CMS-PAS-HIN-18-005; Phys. Lett. B 835 (2022) 137397]

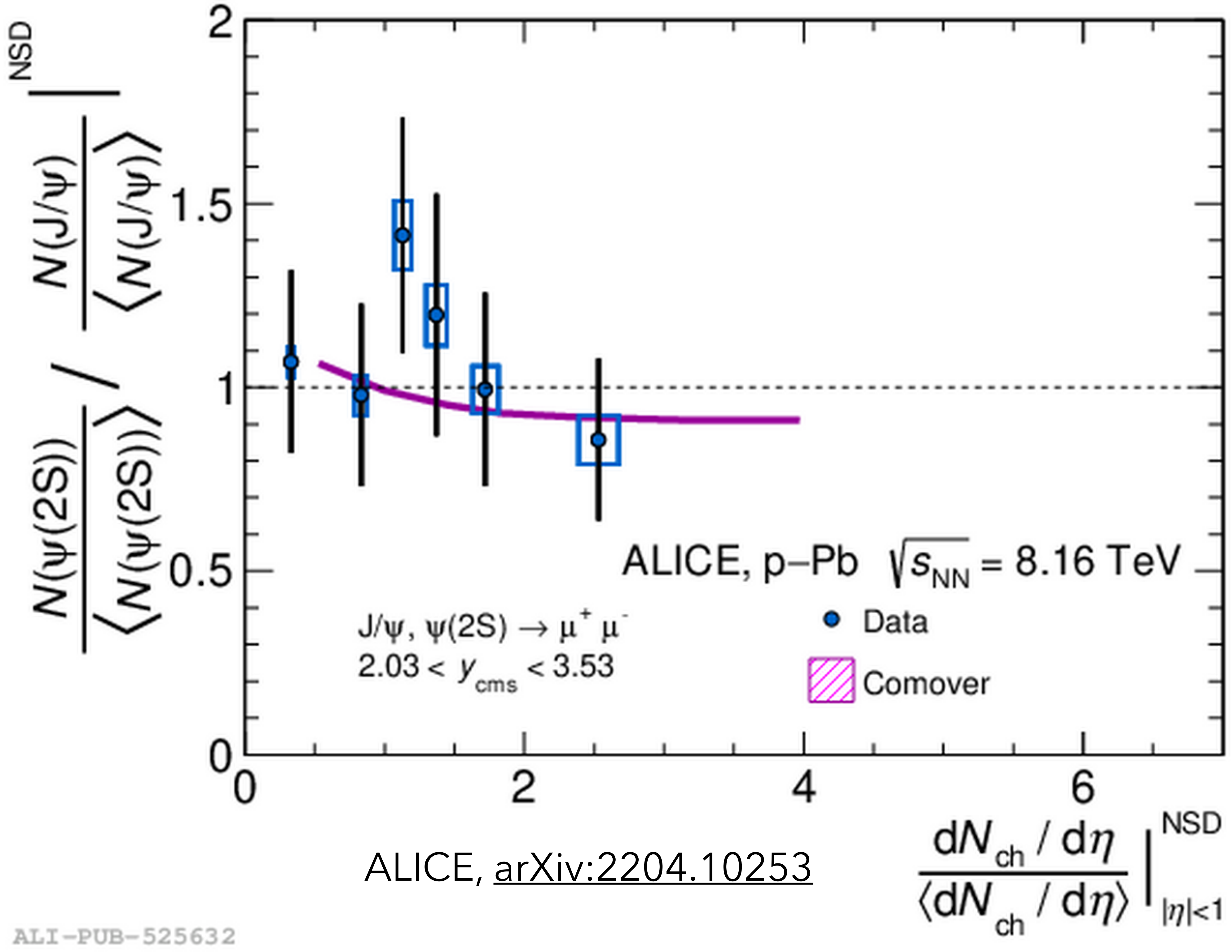
[ATLAS, EPJC 78 (2018) 171]

- **Suppression of Υ(ns) yields** measured by CMS in p–Pb collisions, consistent with a constant in the kinematic interval (p_T<30 GeV/*c*, |*y*|<2), and with the increase observed by ATLAS vs. p_T.
- **Separation of the Υ(ns) states, larger in the Pb-going direction at low p_T.**
- Consistent with calculations including both initial and/or final state effects.

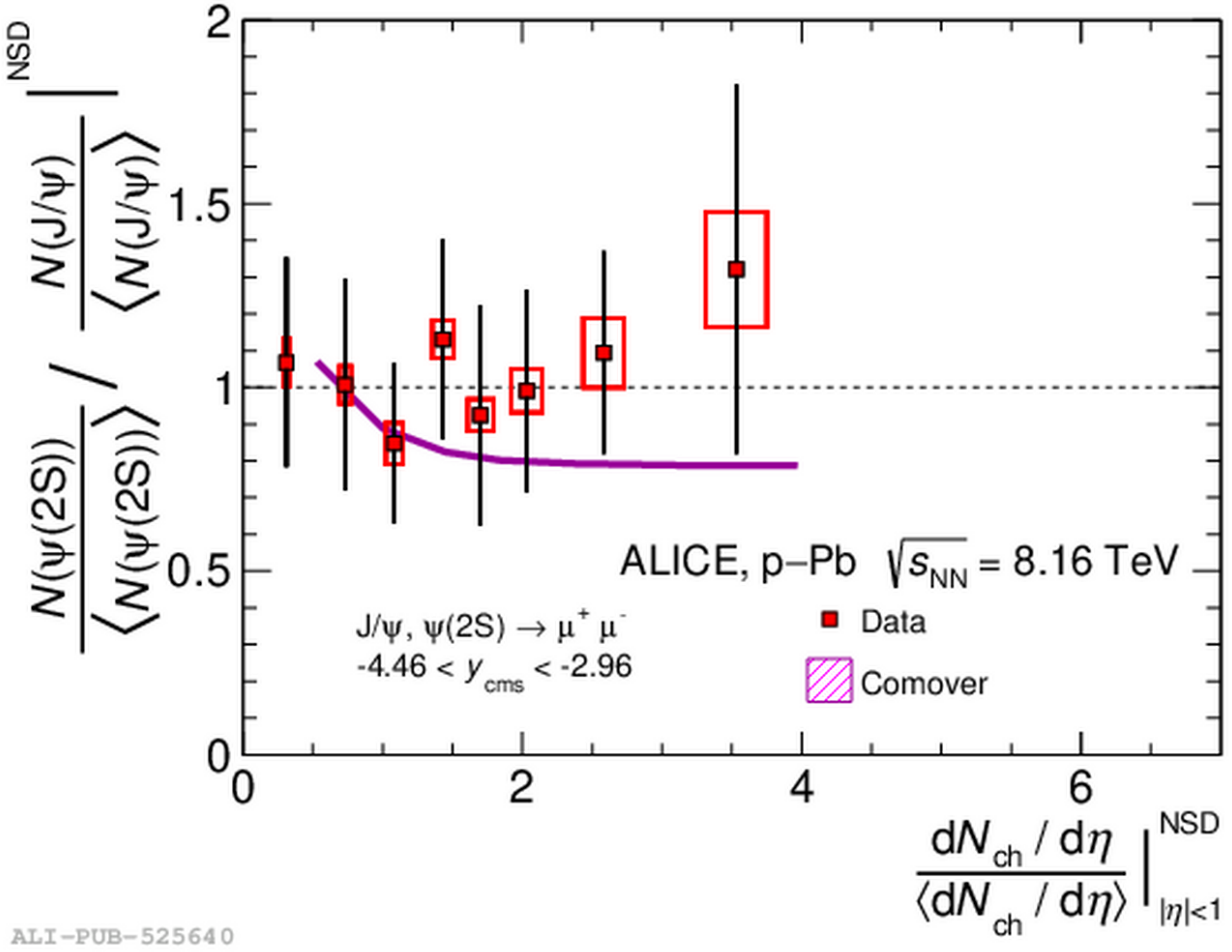
$$R_{\mathrm{pPb}}(p_T^{\Upsilon}, y_{\mathrm{CM}}^{\Upsilon}) = \frac{(\mathrm{d}^2\sigma/\mathrm{d}p_T^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pPb}}}{A(\mathrm{d}^2\sigma/\mathrm{d}p_T^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pp}}},$$



Excited-to-ground state quarkonium ratios in p–Pb



ALICE, arXiv:2204.10253



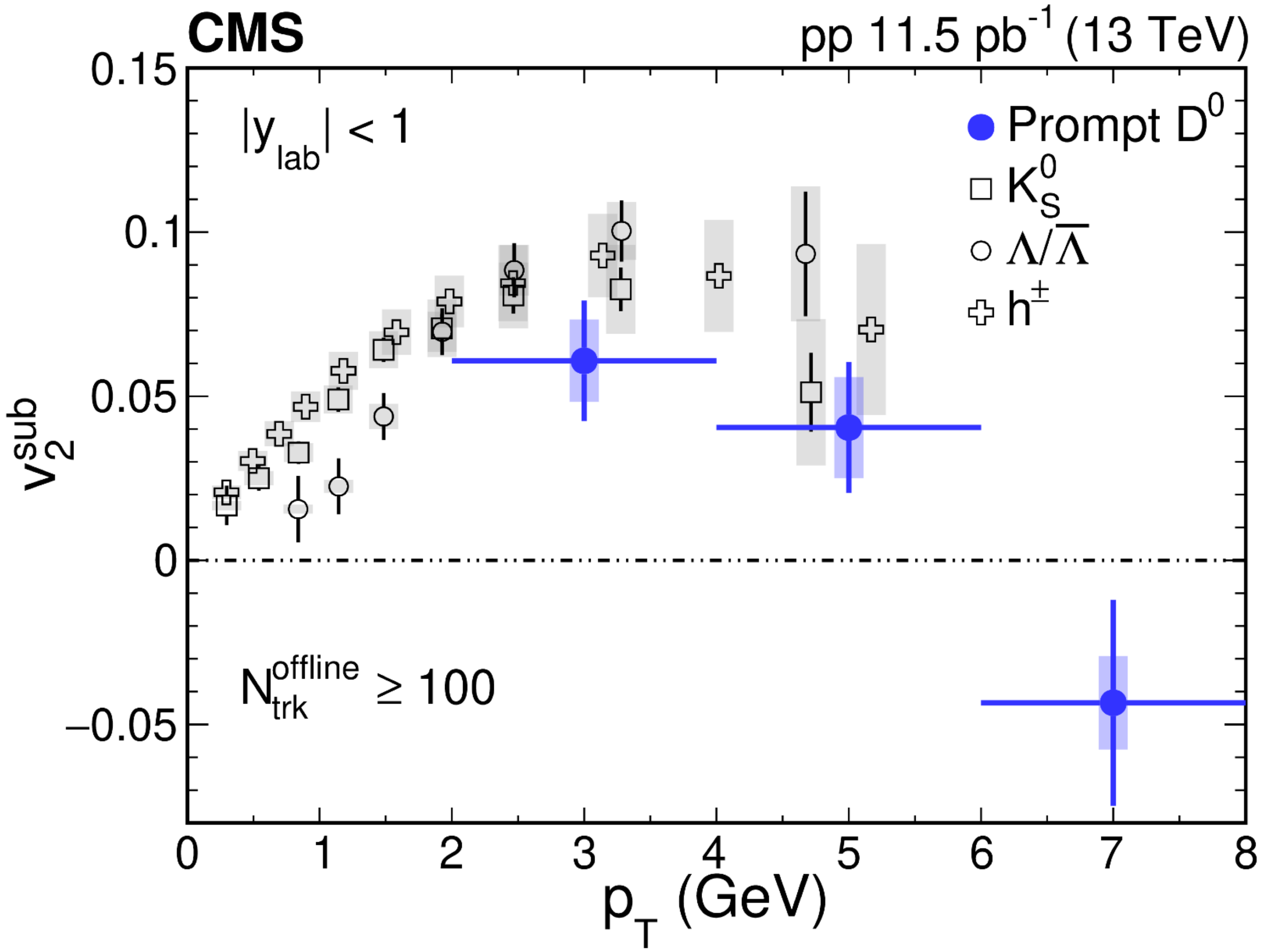
- **ψ(2S)/J/ψ ratio as a function of multiplicity in p–Pb collisions is consistent with unity and model calculations** at both forward and backward rapidities.

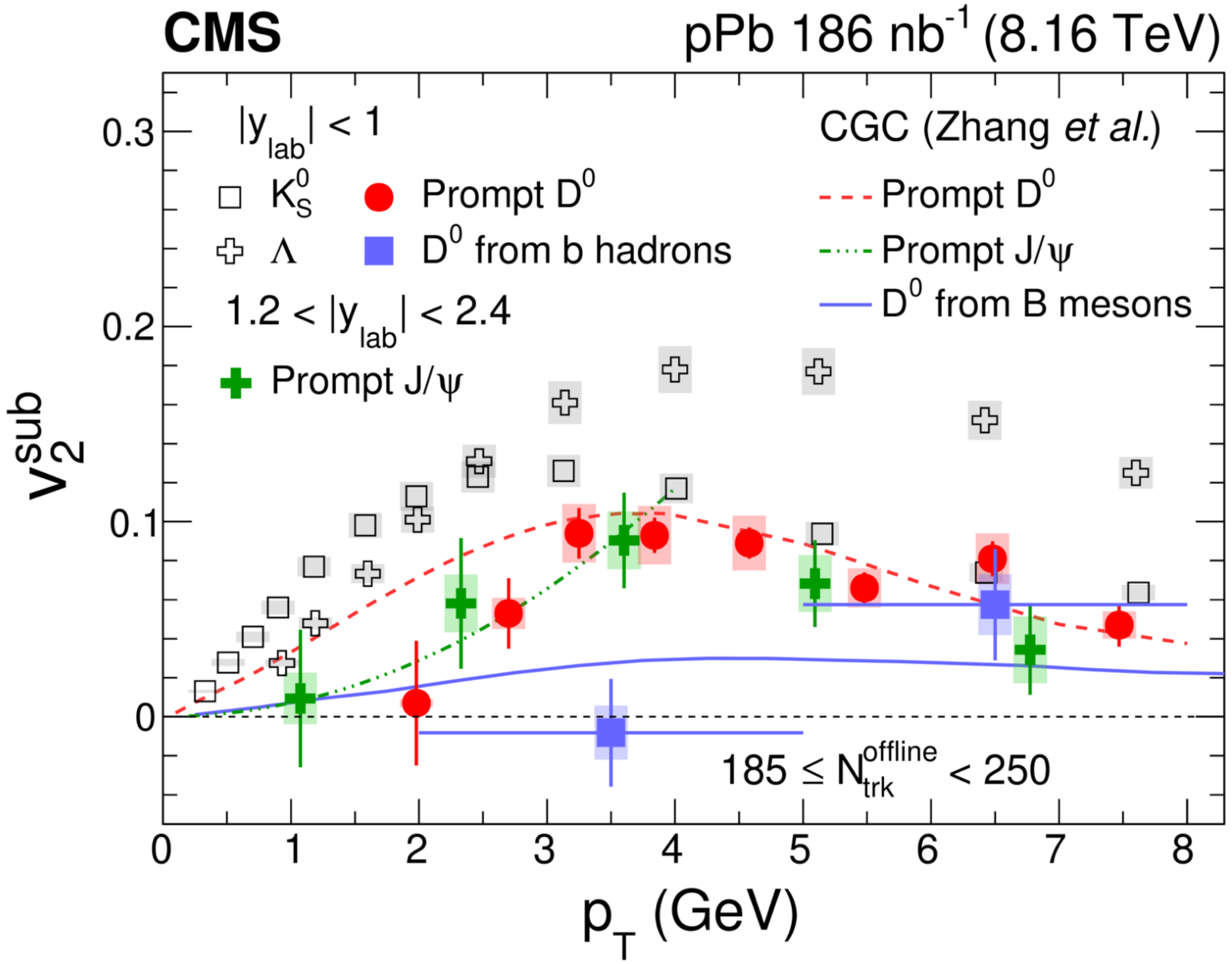
Azimuthal anisotropy

See also talk G.Krintiras: HF in Pb–Pb, WG6, Friday

Heavy quarks and quarkonia in small systems

Azimuthal anisotropy of D^0





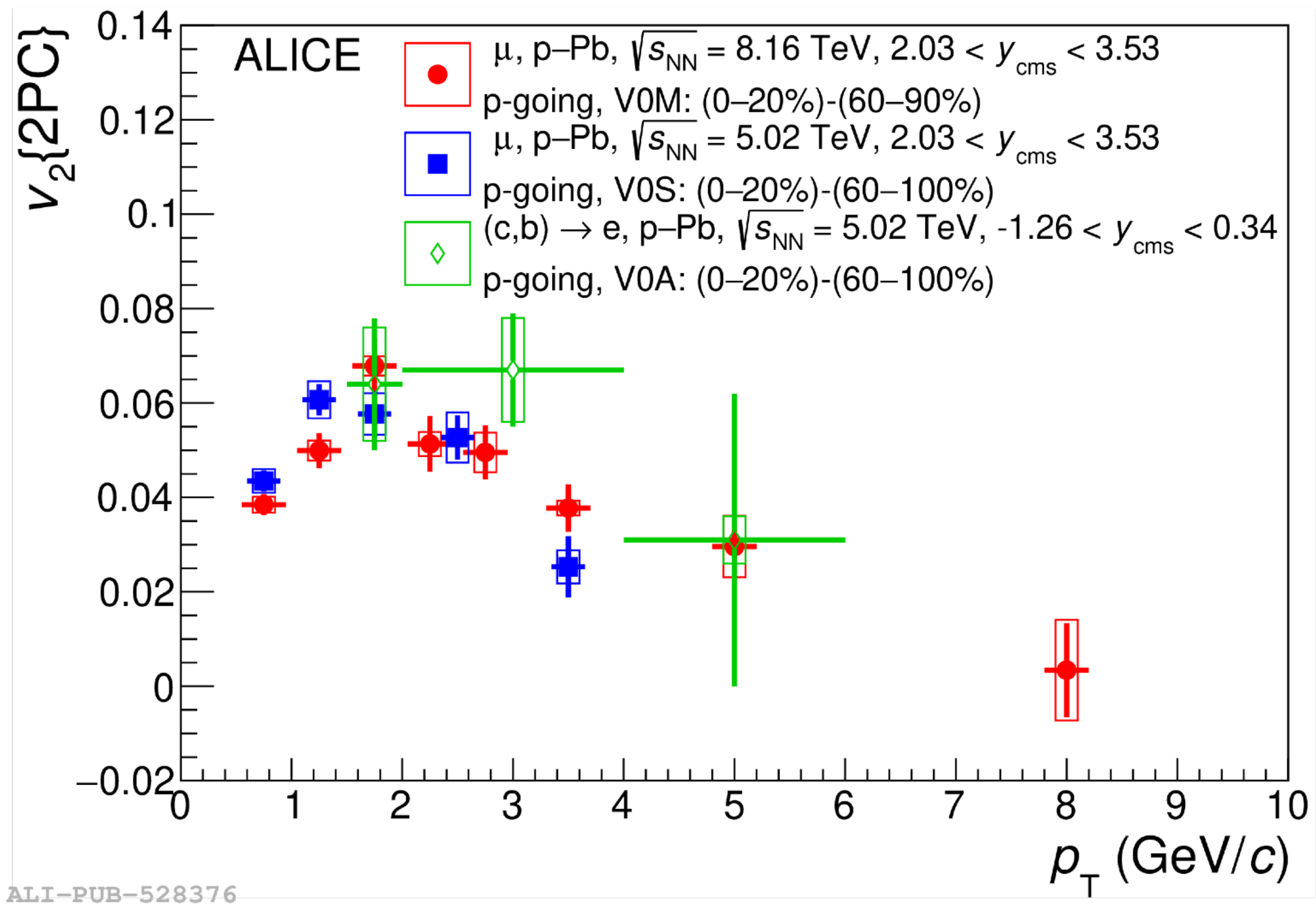
- **In pp**, positive prompt D^0 v_2^{sub} at high multiplicity → **collectivity being developed for charm** similar to that of light hadrons.
- **Comparable prompt D^0 v_2^{sub} values in pp and p–Pb at similar multiplicities.**
- Results consistent with **v_2 flavour hierarchy** for $2 < p_T < 5$ GeV/c in p–Pb **v_2 (non-prompt D^0) < v_2 (prompt D^0)**. Compatible with scenarios where v_2 is generated either via final state scatterings or via a large impact of initial state effects.

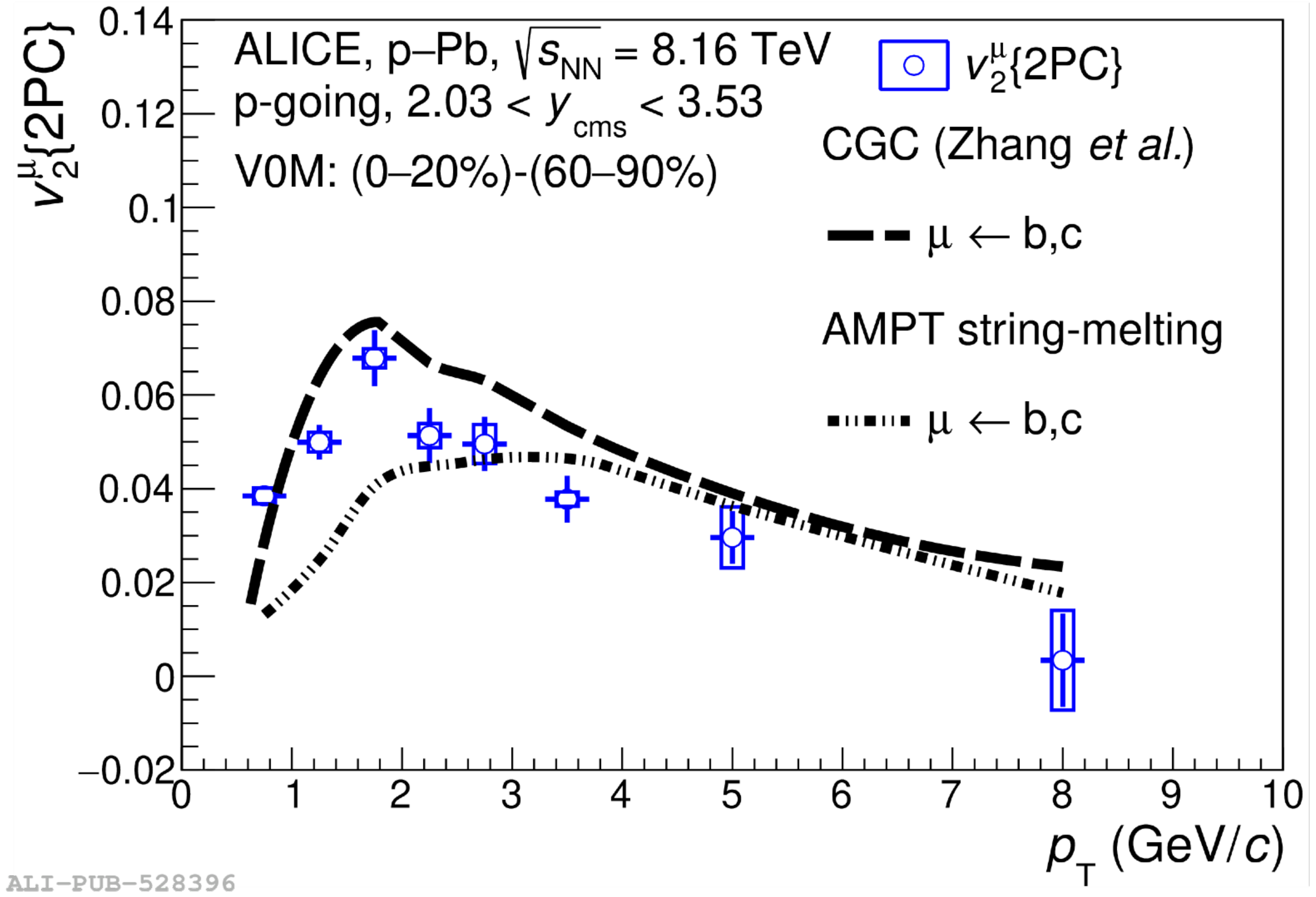
CMS-PAS-HIN-19-009; Phys. Lett. B 813 (2021) 136036

Dong et al, Ann. Rev. Nucl. Part. Sci. 69 (2019) 417-445

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

Azimuthal anisotropy of HF-decay muons in p–Pb



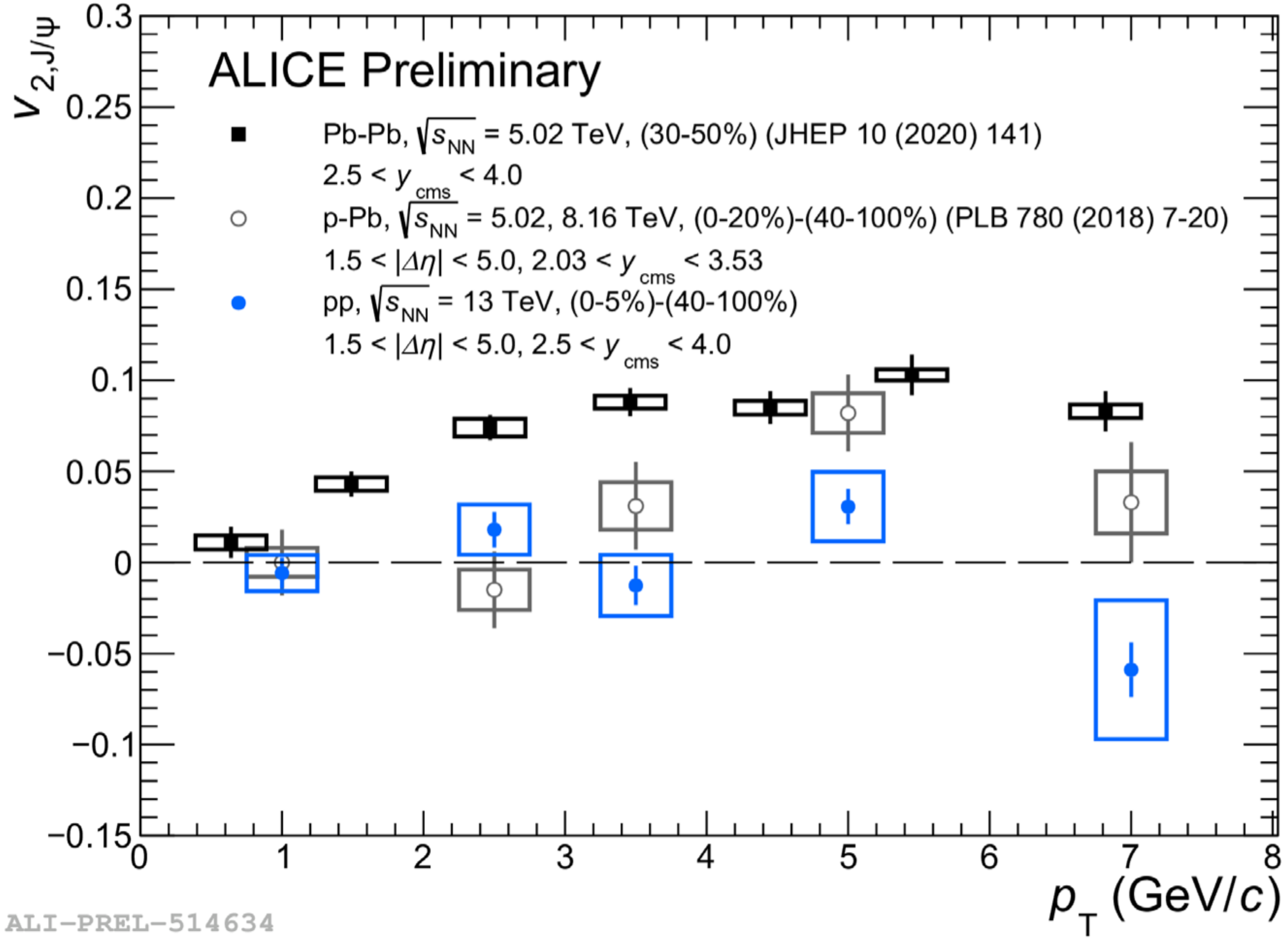


ALICE, arXiv:2210.08980

- **Positive v_2 of HF-decay muons in high multiplicity p–Pb collisions.**
- Well described by CGC model, and by AMPT for $p_T > 2$ GeV/c.
- Collective motion in high-multiplicity p–Pb collisions due to final state effects (QGP droplet)? Or behaviour related to initial state effects (e.g. gluon saturation)?

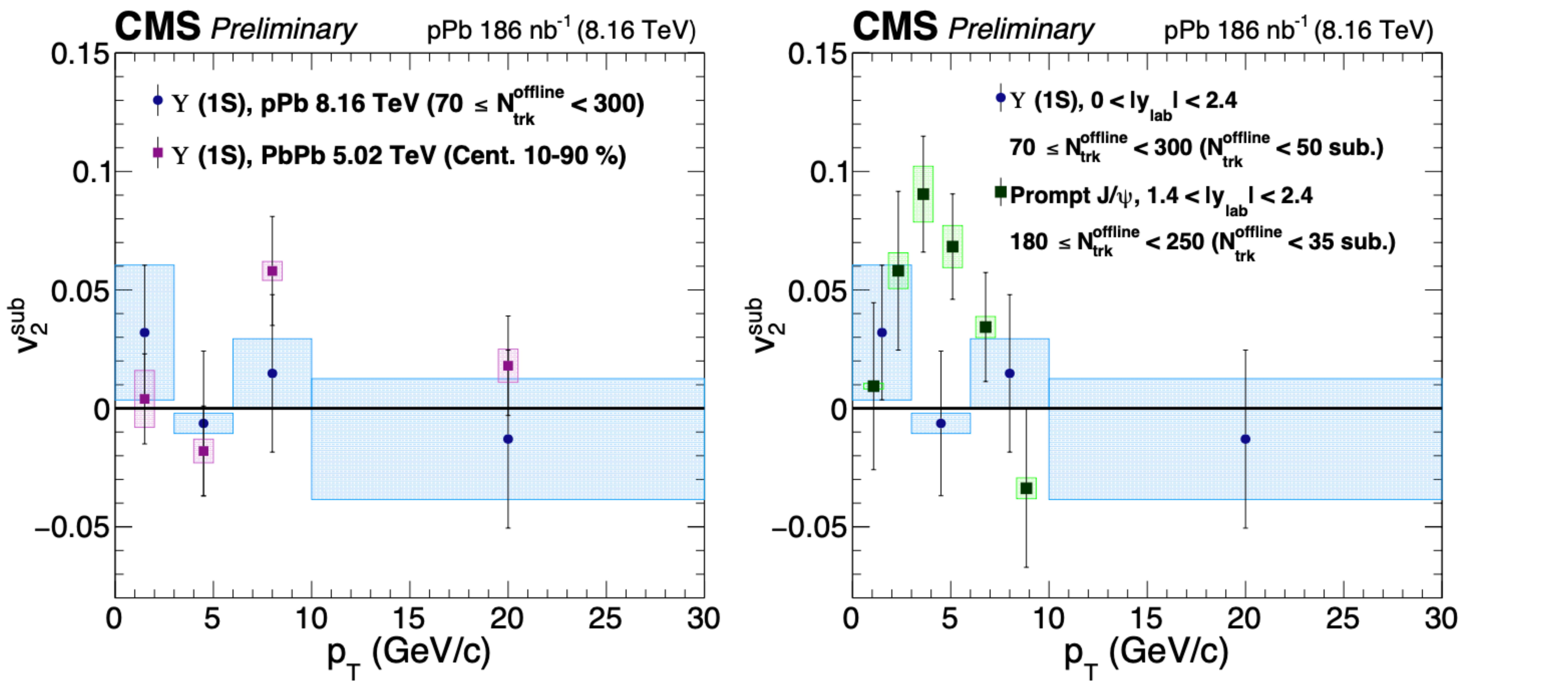
Azimuthal anisotropy of J/ψ across systems

- **Positive v_2** of J/ψ in **semicentral Pb–Pb** collisions, sign of strong collective effects.
- Significant v_2 at intermediate p_T **in p–Pb** collisions at high multiplicity, not explained by transport models.
- **No hint of collective behaviour observed for J/ψ in pp data** at high multiplicity.
- Possibly a common mechanism at the origin of collective behaviour in both p–Pb and Pb–Pb.



ALICE, JHEP 10 (2020) 141 (Pb-Pb)
ALICE, PLB 780 (2018) 7-20 (p-Pb)

Azimuthal anisotropy of Υ(1S) across systems



CMS-PAS-HIN-21-001

- **v_2^{sub} values in p–Pb** collisions at high multiplicity are **within one standard deviation from zero**, and **consistent with Pb–Pb results.**
- **No significant dependence of bottom-quark modification on in-medium path length.**

Exotica

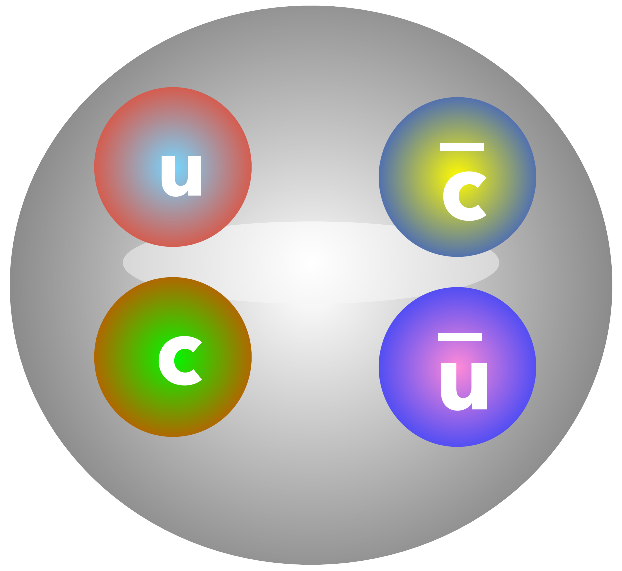
See also talk M.Sarpis: exotics, WG4, Tuesday

Heavy quarks and quarkonia in small systems

Heavy flavours as a tool to study exotica: the $\chi_{c1}(3872)$ case

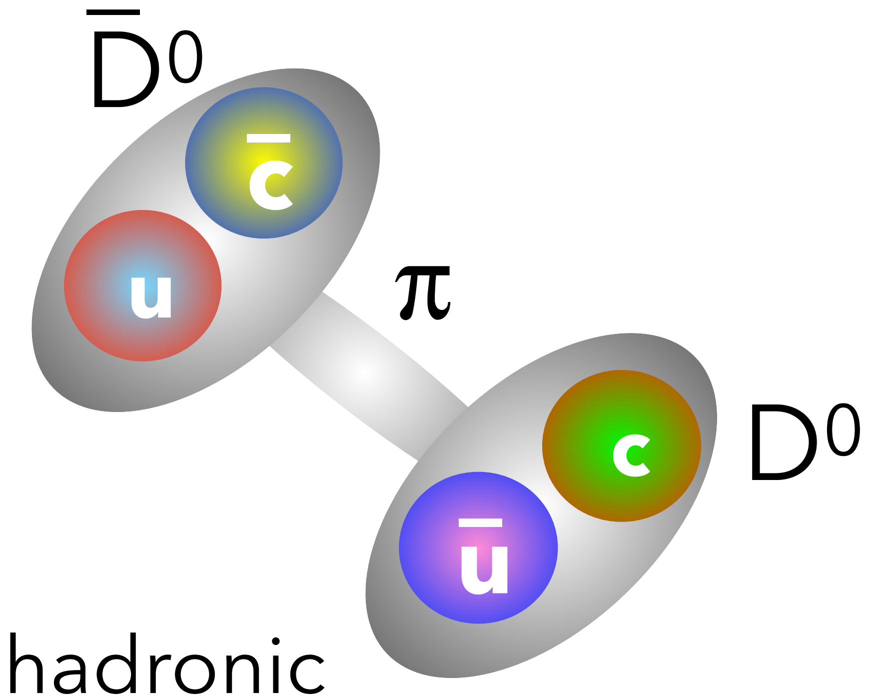
- The exotic $\chi_{c1}(3872)$ was first observed in 2003 by Belle in b-decays $B^+ \rightarrow K^+ \pi^+\pi^- J/\psi$
- Its nature is still under scrutiny: can the multiplicity dependence help?
  - compact tetraquark: tightly bound with small radius ~ 1 fm
  - hadronic molecule: very weakly bound with a large radius ~ 10 fm
  - hadrocharmonium / adjoint charmonium

Belle, Phys.Rev.Lett. 91 (2003) 262001



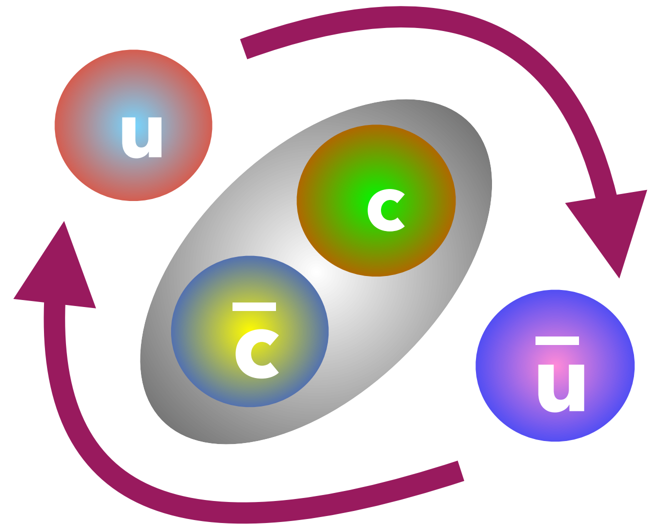
compact tetraquark
diquark – diquark

Maiani et al, PRD 71, 014028 (2005)
Hooft et al, PLB 662 424 (2008)



hadronic
molecule

Tornqvist et al, PLB 590 209 (2004)
Braaten et al, PRD 77 014029 (2008)
Chen et al, PRD 100 011502 (R) (2019)



hadrocharmonium /
adjoint charmonium

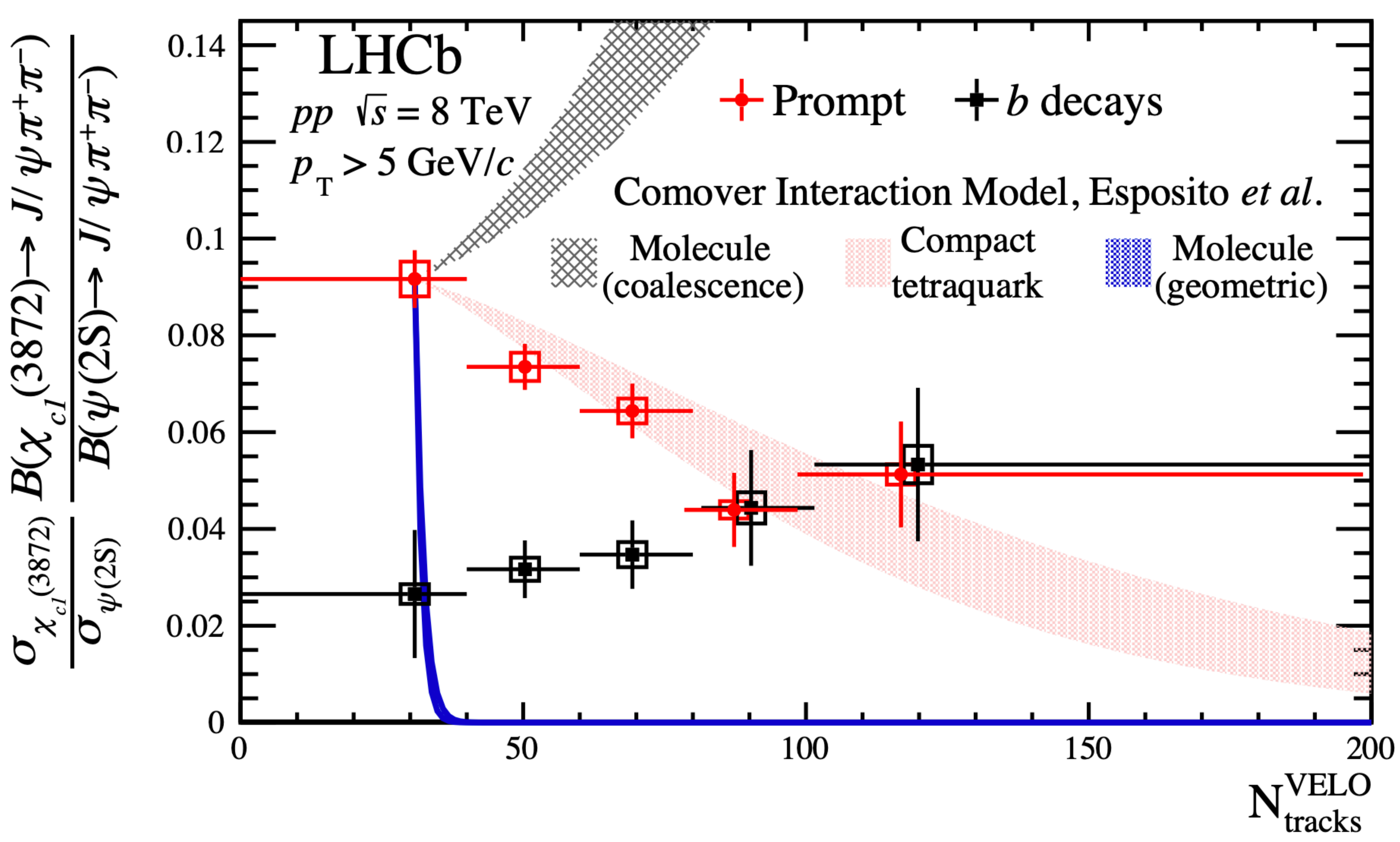
Dubynskiy et al, PLB 666 344 (2008)
Dubynskiy et al, PLB 671 82 (2009)
Hanhart et al, EPJ A47: 101-110 (2011)

Multiplicity-dependent $\chi_{c1}(3872)$ / $\psi(2S)$ in pp

LHCB-PAPER-2020-023, Phys.Rev.Lett. 126 (2021) 092001

- **The prompt ratio decreases with multiplicity ➡ stronger $\chi_{c1}(3872)$ suppression than $\psi(2S)$**
- Non-prompt ratio shows no significant variation with multiplicity.

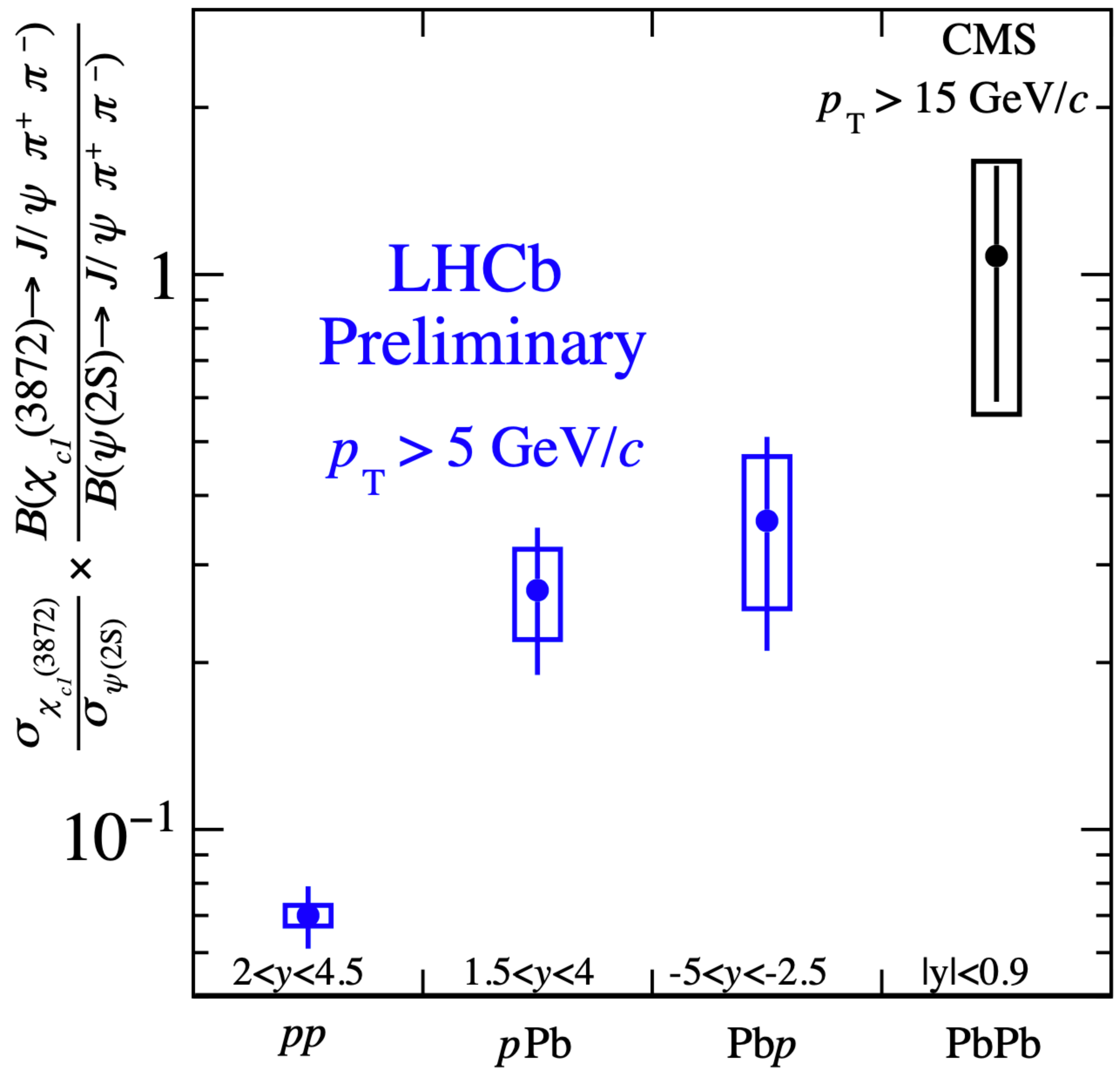
  Behaviour consistent with a scenario of a weakly-bound $\chi_{c1}(3872)$, being more dissociated than a more tightly-bound $\psi(2S)$.



- Comover interaction model by Esposito et al., EPJC 81 (2021) 669, favors the compact tetraquark scenario.
- Different assumptions in the model by Braaten et al., PRD 103 (2021) 071901, suggests the $\chi_{c1}(3872)$ is a D-meson molecule.

χ_{c1}(3872) / ψ(2S) across systems

- Ratio sensitive to final-state effects, as most of initial state effects cancel in the ratio.
- **Increase of the ratio with the system size.** Opposite trend to the decreasing one observed in pp vs. multiplicity.
- Scenarios:
  - ψ(2S) suppression in p-Pb/Pb-Pb might bring this ratio up if there are no final state effects at play for χ_{c1}(3872).
  - Particle density in large systems might allow coalescence to play a dominant role.
- **Different dynamics at play ➡ constraints on the hadron nature, as well as on in-medium hadronization and transport models**



LHCB-PAPER-2020-023, Phys.Rev.Lett. 126 (2021) 092001

LHCB-CONF-2022-001

CMS, Phys. Rev. Lett 128 (2022) 032001

Summary and outlook

- Plenty of heavy flavour measurements released by the LHC Collaborations exploiting Run 1 and Run 2 pp and p–Pb data.

  - Charm baryon-to-meson ratios, as well as charm and beauty baryon ratios in pp data present **significant differences to e^+e^-, ep collisions**.
  - **Non universal fragmentation** across colliding systems ?
    Interplay of coalescence and fragmentation ?
  - ϒ(nS) excited states are less likely to be found at larger multiplicities, compared to the ground state.

  - Observed **positive elliptic flow of open heavy flavour** production in **pp** collisions at high multiplicity, as well as in **p–Pb** collisions.
  - For **J/ψ, a positive elliptic flow** is observed in high multiplicity **p–Pb** collisions (as for open HF), while there is **no evidence** of collective motion in high-multiplicity **pp** collisions.
  - The origin of the collective motion (initial and/or final state effects) in small systems is still under debate.

  - Studies of **exotic** heavy flavour hadrons in high multiplicity pp or heavy-ion collisions provide further input to elucidate hadron formation nature.

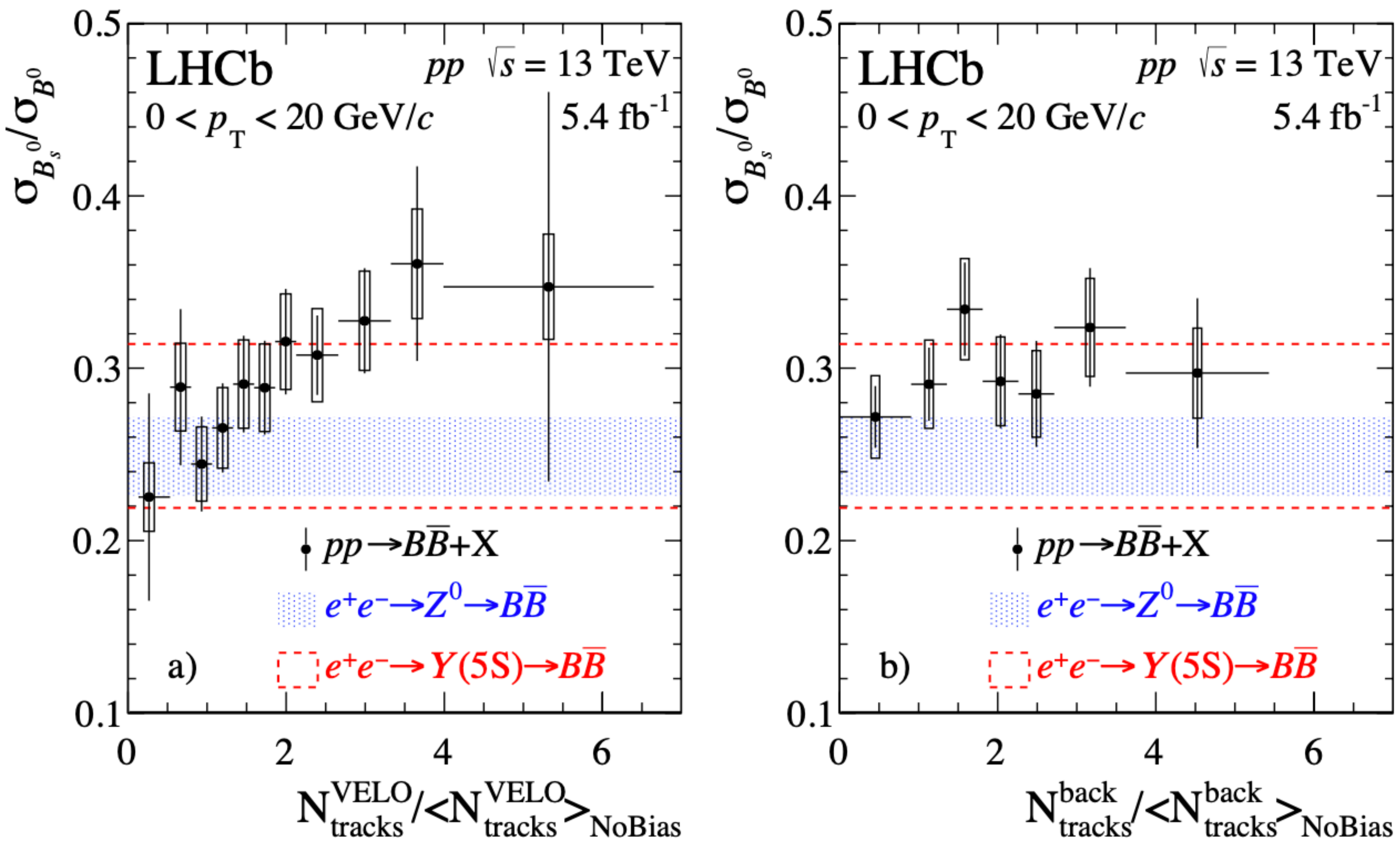
- Eagerly waiting first results from Run 3 data taking!

Additional material

Zaida Conesa del Valle for the ALICE, ATLAS, CMS and LHCb Collaborations

B^0_s/B^0 vs. multiplicity in pp

- Lack of dependence with multiplicity at backward rapidity.
- Mechanism possibly related to local particle density in a similar rapidity interval to that of the production of the B



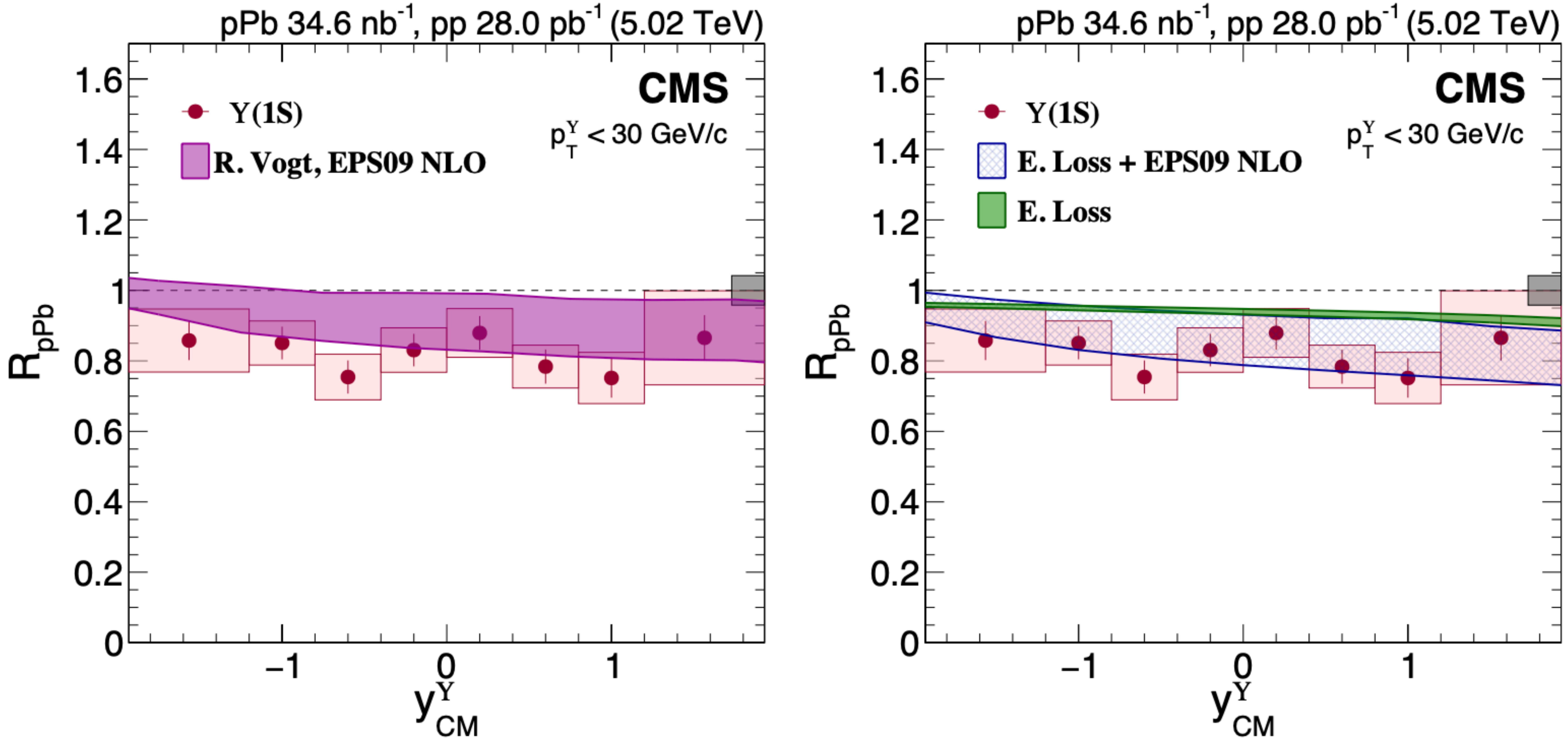
LHCB-PAPER-2022-001, arXiv: 2204.13042

Nuclear modification of Y(nS) in pPb

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}^{\Upsilon}, y_{\mathrm{CM}}^{\Upsilon}) = \frac{(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pPb}}}{A(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pp}}},$$

CMS-PAS-HIN-18-005; Phys. Lett. B 835 (2022) 137397

- Comparison to nPDF and ELoss models

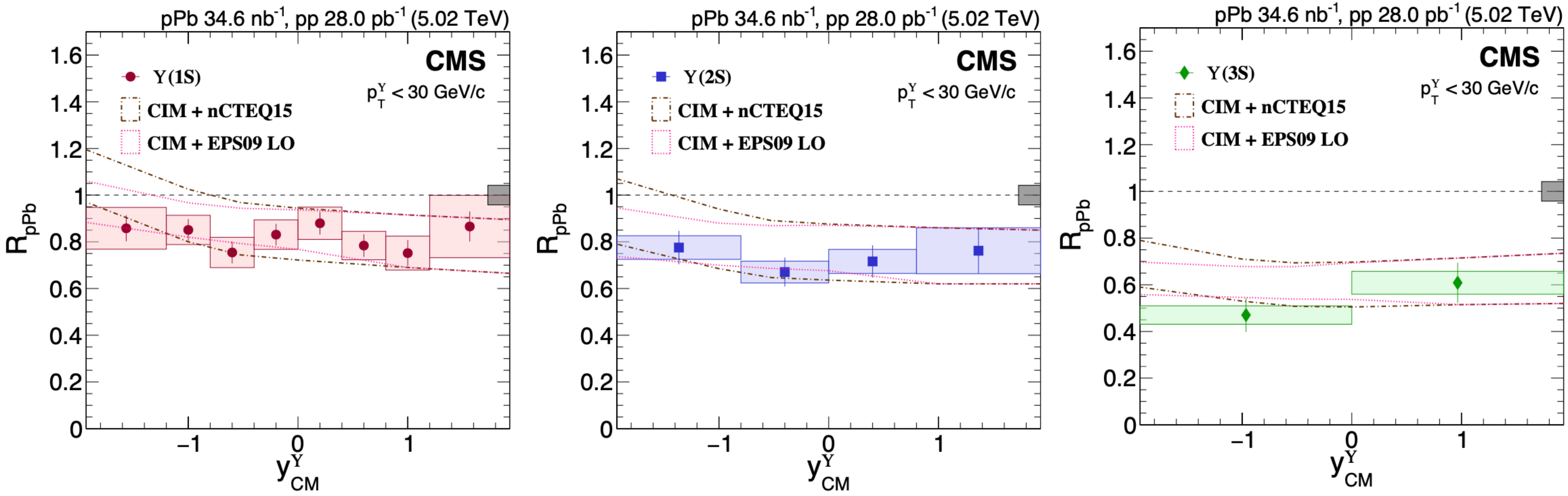


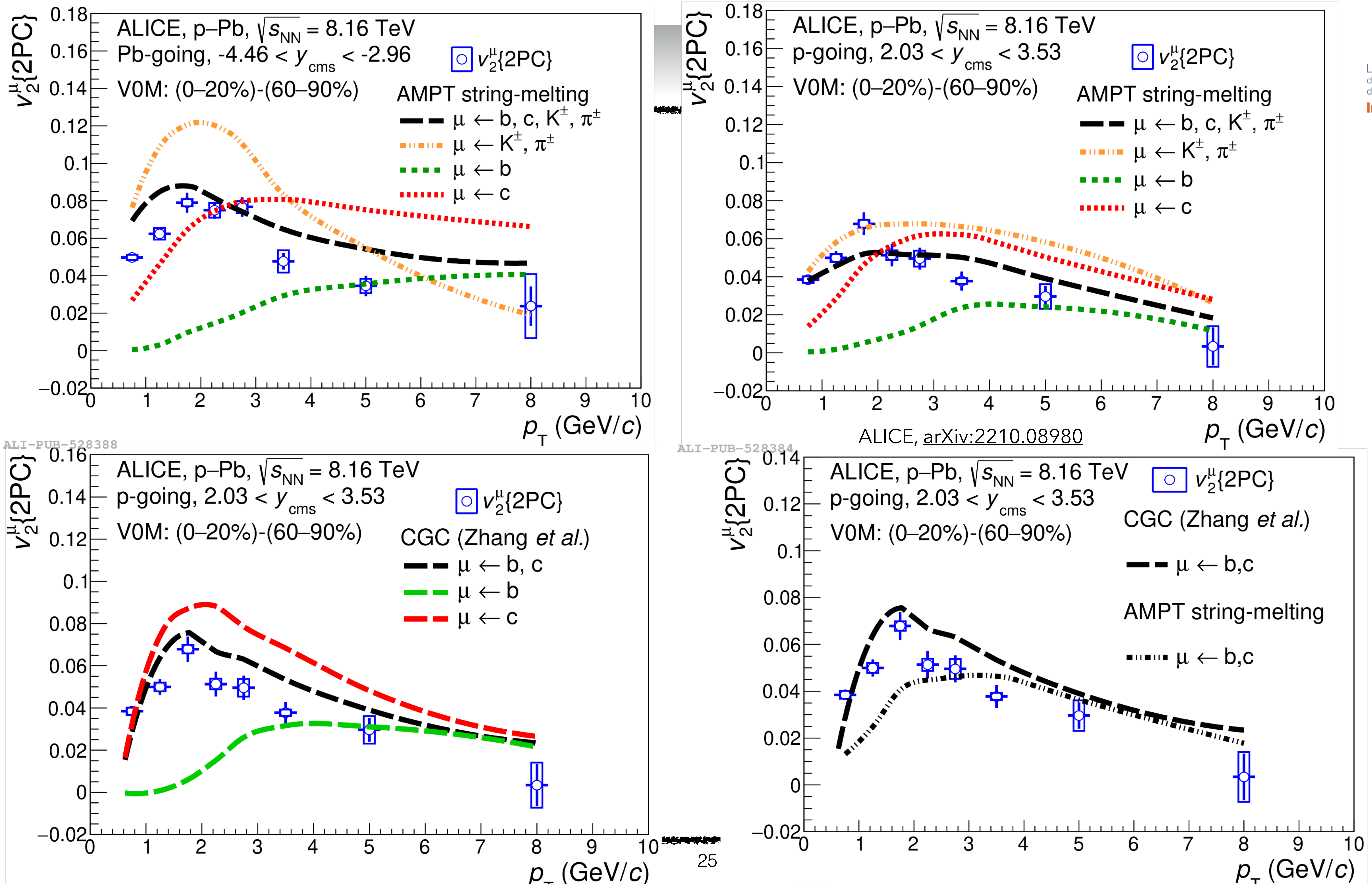
Nuclear modification of Υ(nS) in pPb

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}^{\Upsilon}, y_{\mathrm{CM}}^{\Upsilon}) = \frac{(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pPb}}}{A(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}^{\Upsilon}\mathrm{d}y_{\mathrm{CM}}^{\Upsilon})_{\mathrm{pp}}},$$

CMS-PAS-HIN-18-005; Phys. Lett. B 835 (2022) 137397

- Comparison to comover interaction model





ALICE, arXiv:2210.08980