Multiplicity-dependent quarkonium measurements

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Quarkonia As Tools 2024

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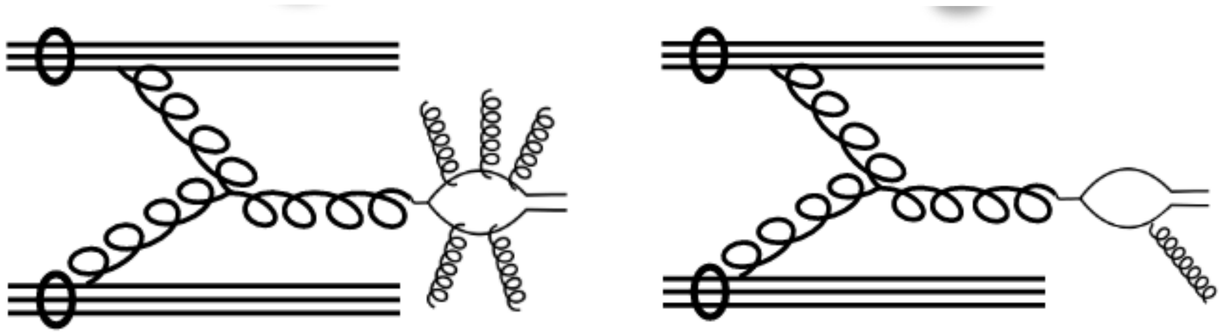
Why measuring quarkonia with multiplicity?

- Quarkonium production mechanism in hadronic collisions is **not yet fully understood**
  - Several approaches (NRQCD with different LDMEs parametrizations; ICEM) coexist
  - New observables are needed!

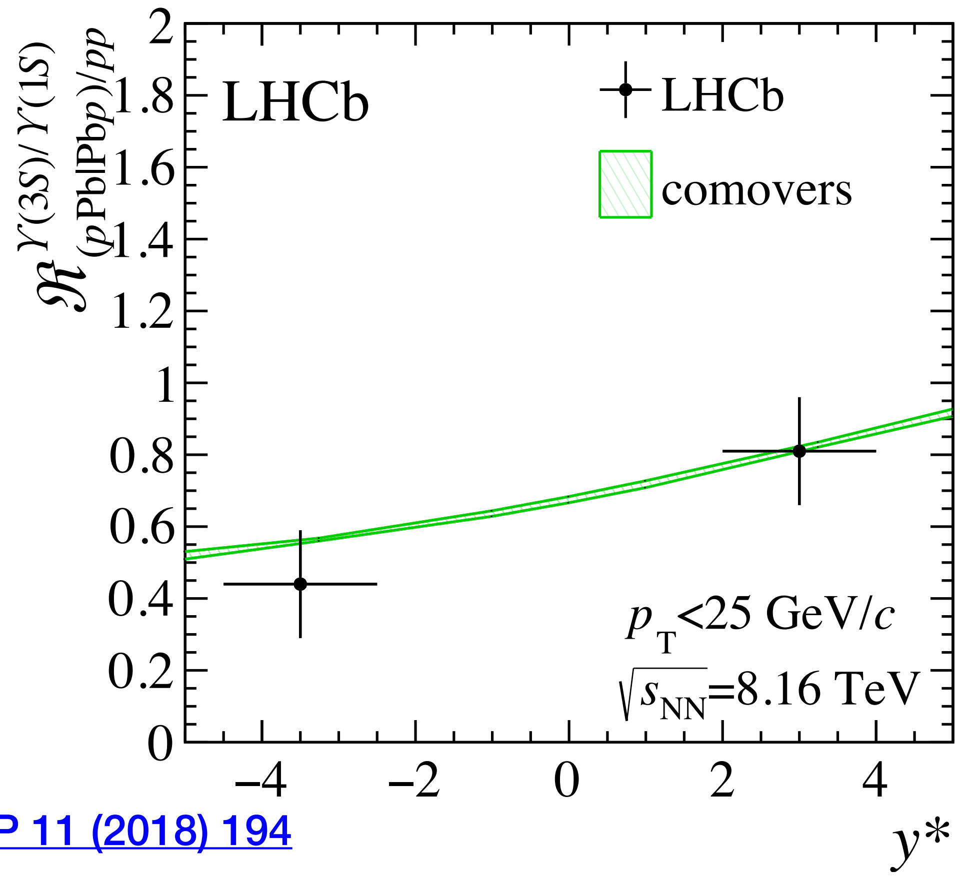


- Measurements of hadron multiplicity produced along with the quarkonia may reveal new information:
  - extra gluons from octet produce additional particles in the final state, but underlying event (UE) activity is very similar to that from the octet → see Lidia's talk of yesterday
  - general purpose generators are, in general, not able to describe underlying event activity of quarkonia events
    - ✳ **We need to have a good description of the UE**
    - ✳ Charged particle multiplicity is a first proxy of the UE

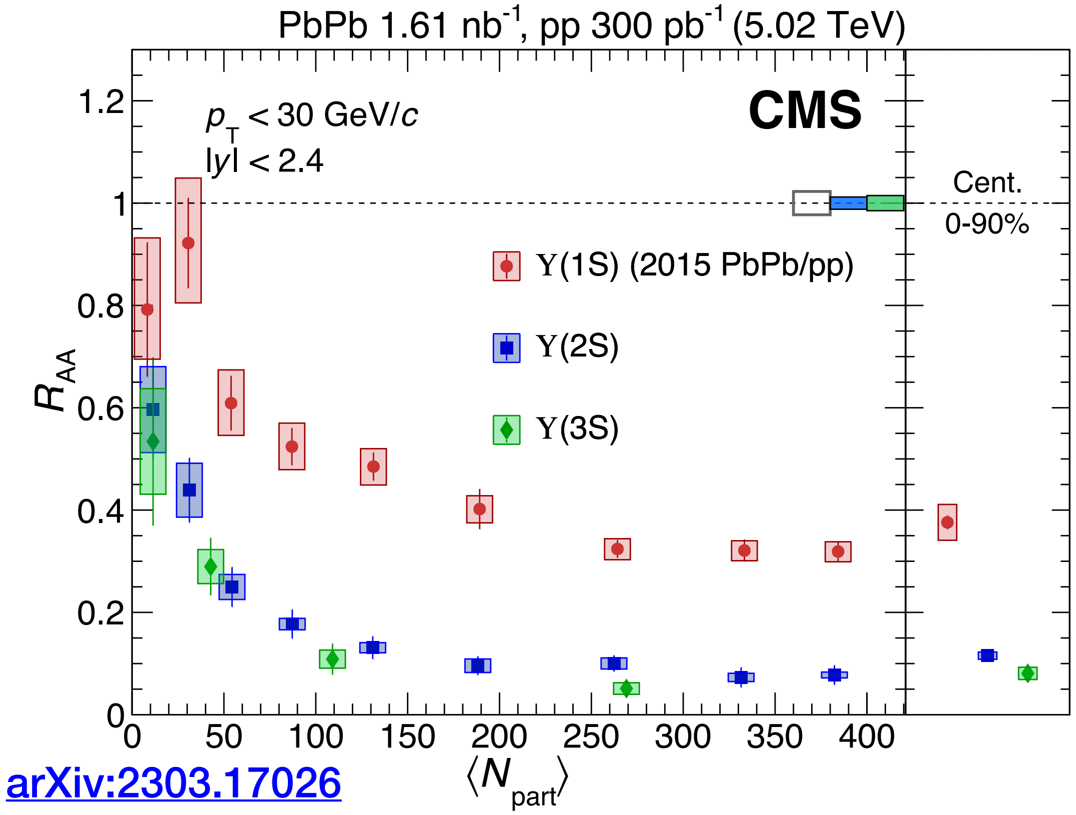
- In this talk, I will review of some of the quarkonia studies at LHC that are looking into this concept

From small to large systems: quarkonia

- Multiplicity dependent studies in small systems can **help benchmark quarkonium studies** in AA
  - Help understanding complex dynamics of large systems, many effects at play
- Study case: quarkonia final-state effects
  - usually claimed to explain excited-to-ground state suppression
  - in comover scenario, stronger effect in backward region of pPb due to higher multiplicity (JHEP 10 (2018) 094)
  - can we see this also in pp at high-multiplicity?
    - ✳ pp data would offers larger statistics to better characterise the mechanism
- Accurate quantification of this effect needed for interpretation of quarkonium data in AA



JHEP 11 (2018) 194

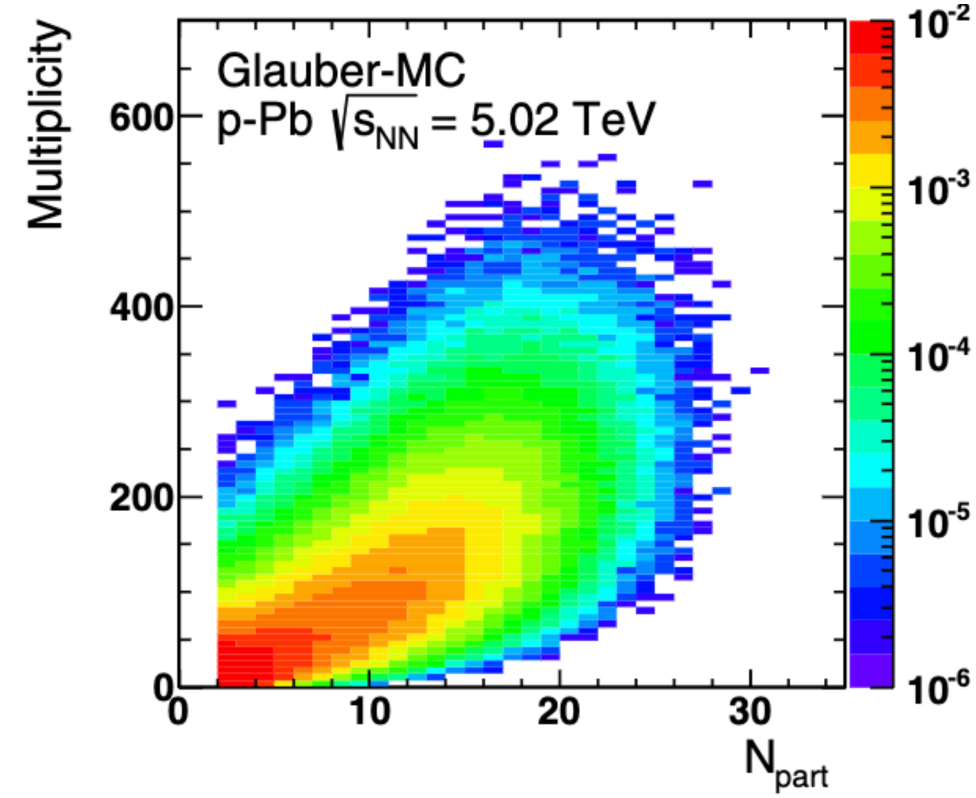


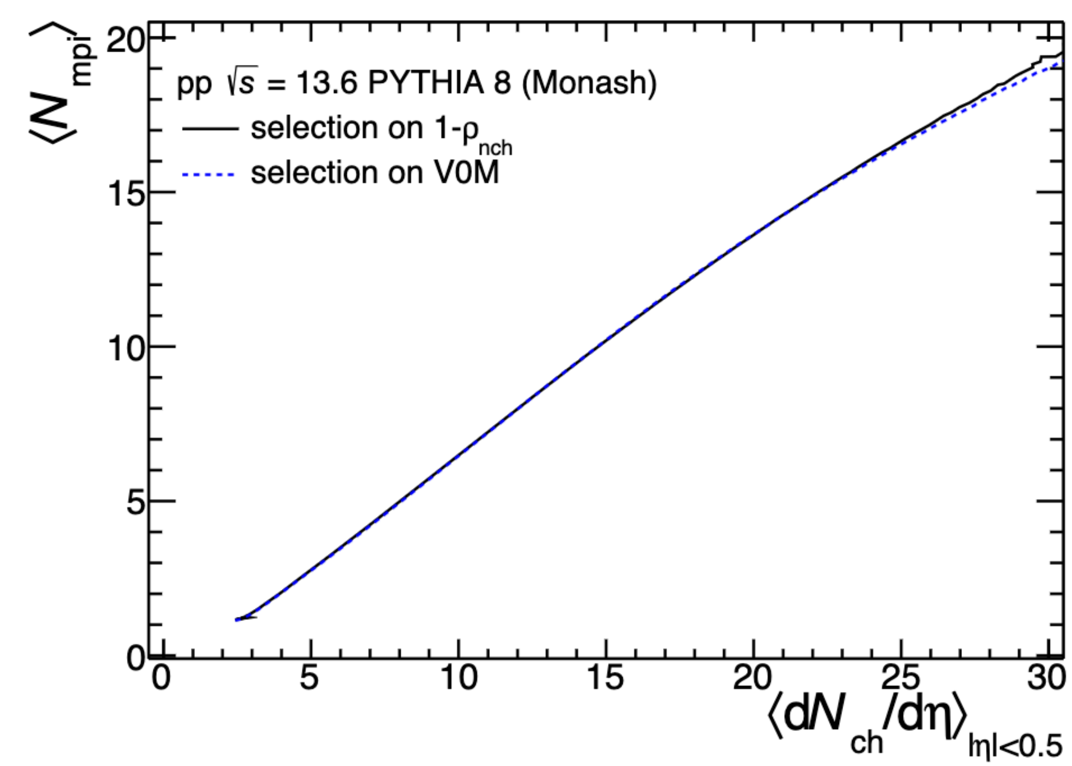
arXiv:2303.17026

From small to large systems with multiplicity

- Charged hadron multiplicity is becoming more and more used as a proxy for medium energy density
- An alternative to collision centrality, which has large biases in small systems
  - ✓ - Pro: use same variable across different systems
  - ✗ - Con: less direct connection to phenomenology
- In pp collisions, multiplicity can be related with multiple parton interactions (MPI)
- Important notes: particle multiplicity is not a "universal" variable as it depends on:
  - detector acceptance, also in relation with quarkonia kinematics
  - charged particles p_{T} (soft-hard scale)
  - if detector efficiencies and backgrounds are corrected
  - charged particle definition (see ALICE-PUBLIC-2017-005)
- **Special care when comparing measurements from different experiments**

ALICE: PRC 91, 064905 (2015)





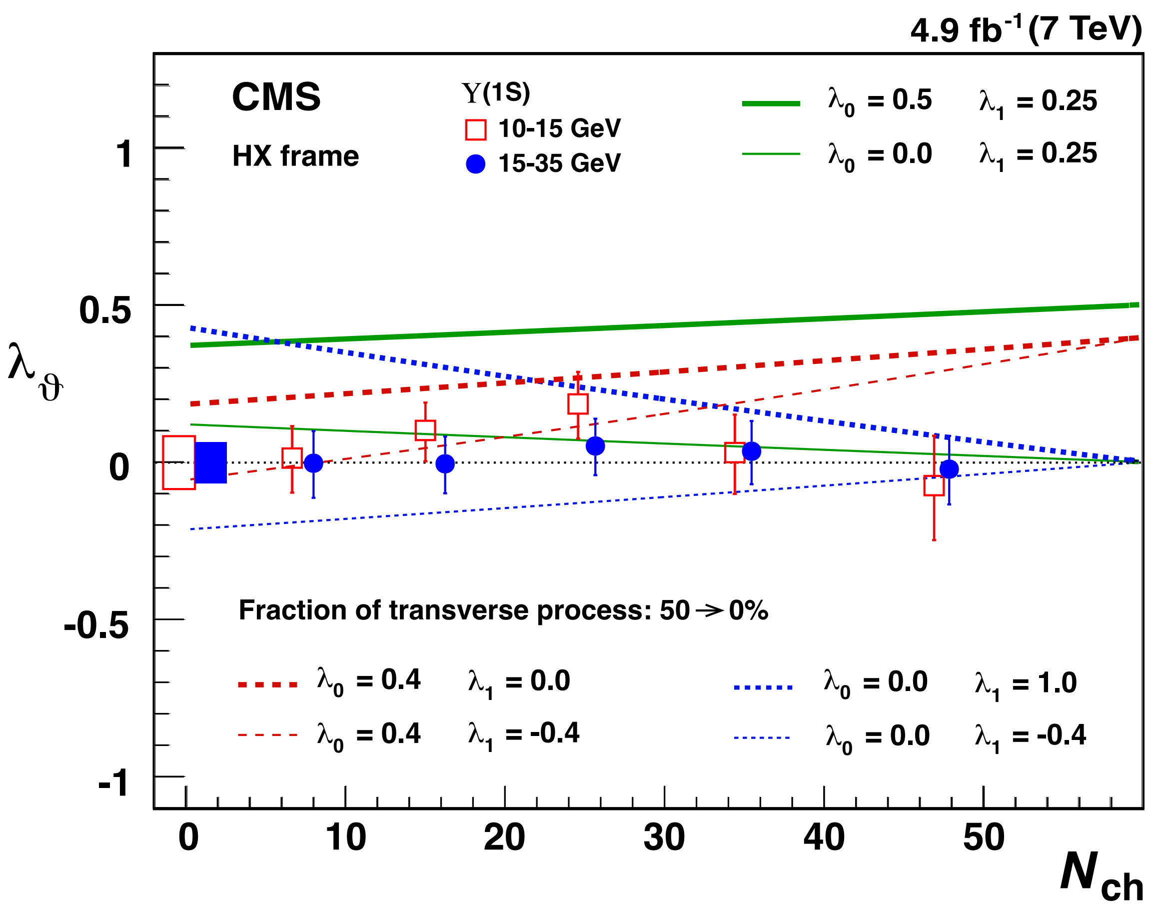
Phys.Rev.D 107 (2023) 7, 076012

Observables studied so far

- **Self-normalised production with multiplicity**
  - Study multiparton interactions effect on quarkonia production
- **Ratio excited-to-ground state with multiplicity**
  - Study presence of final-state effects sensible to quarkonium binding energy/size

Focus of this talk

- **Azimuthal correlations with multiplicity** → See talk by Chenxi tomorrow!
- **Quarkonia in jets** → discussed yesterday by Lidia
- **Quarkonia polarisation with multiplicity**:
  - How do charmonium production description depends on multiplicity → Test LDMEs universality
  - Measurement of Υ polarisation by CMS (Phys.Lett.B 761 (2016) 31-52)
    - ✳ No significant dependence with multiplicity seen
    - ✳ Higher-mass feed-downs (P states) complicate interpretation



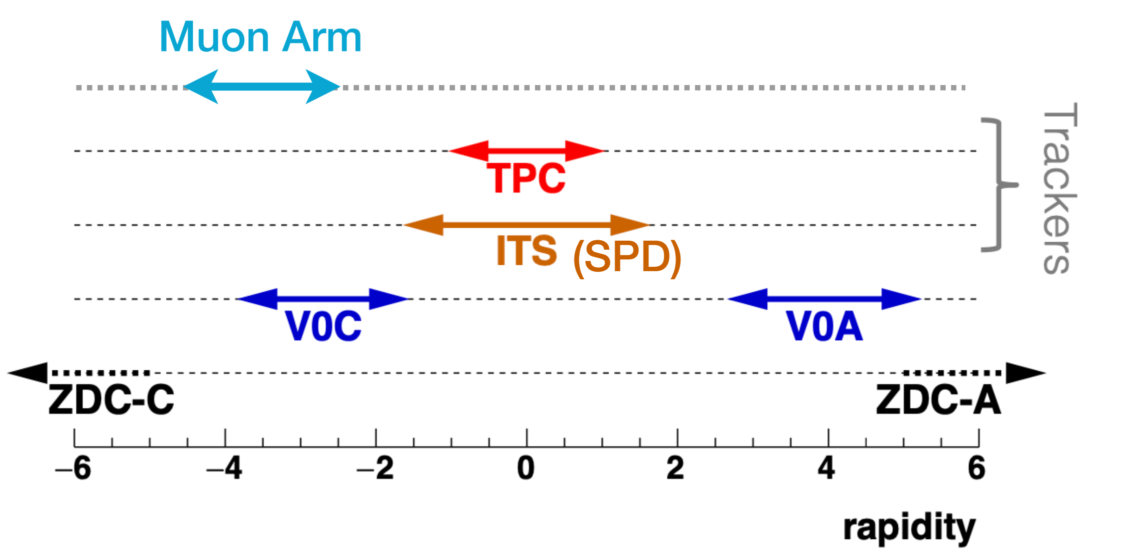
Quarkonia with multiplicity from ALICE

Quarkonia production with multiplicity in ALICE

Central barrel
$|y| < 0.9$
- only $J/\psi \to e^+e^-$ (hard $\psi(2S)$ or Υ, low statistics)
- prompt & non-prompt separation

Muon arm
$-4 < y < -2.5$
- decay $\to \mu^+\mu^-$; $J/\psi, \psi(2S), \Upsilon$
- inclusive measurement

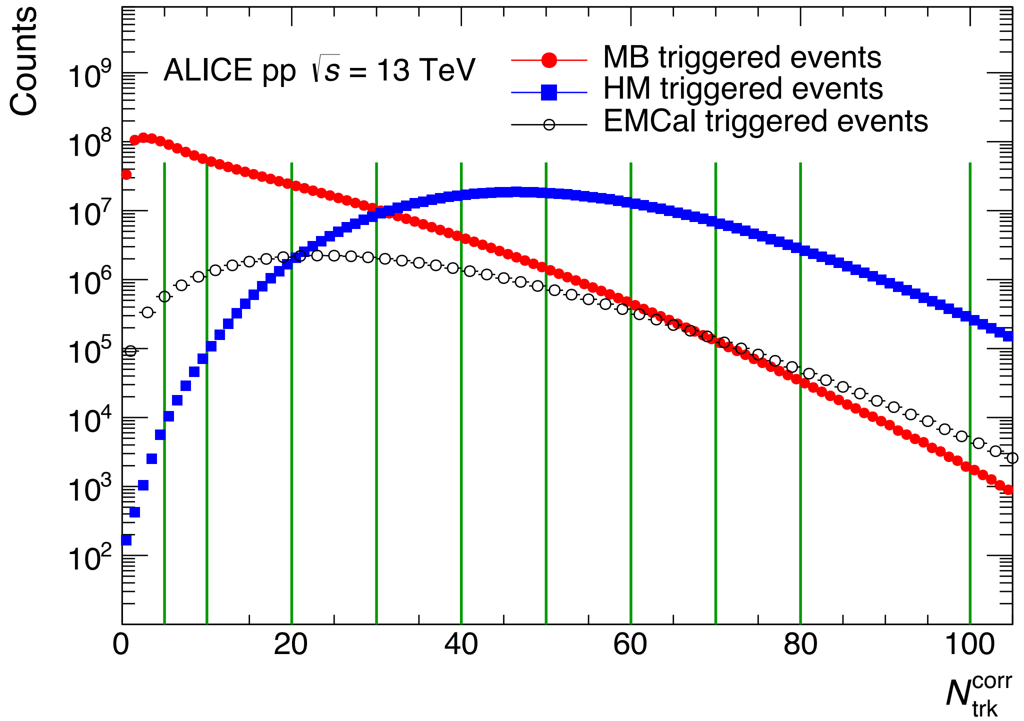
(figure from David Dobrigkeit Chinellato)



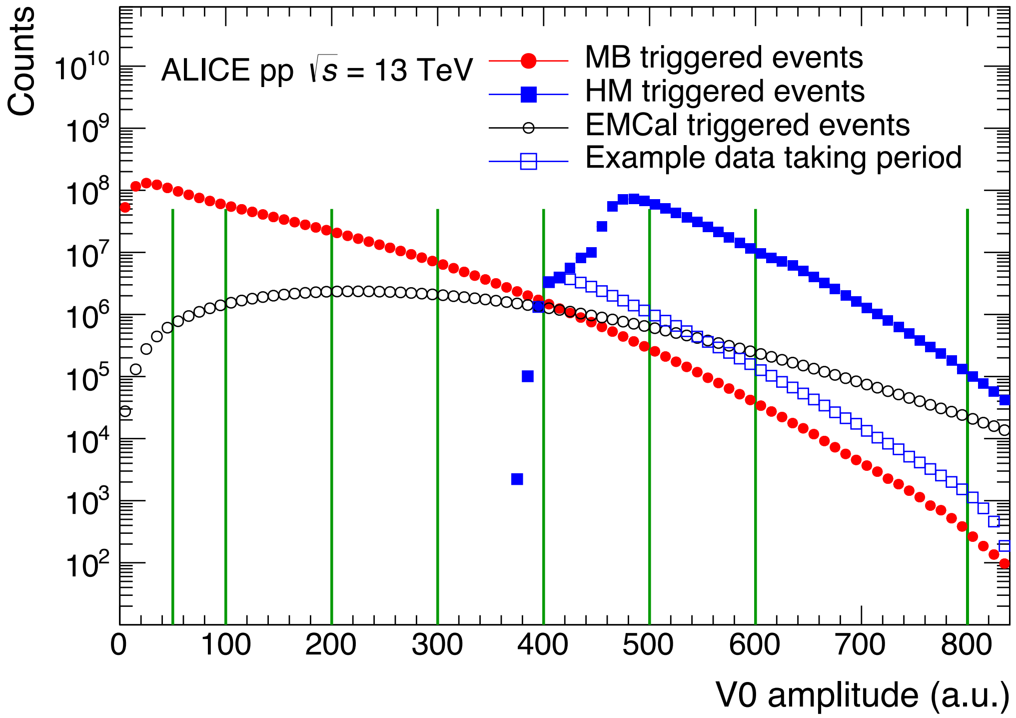
Multiplicity determination

- Define activity classes with SPD (midrapidity) or V0 (forward+backward)
- Average charged particle multiplicity in each mult. class measured at midrapidity (with SPD)

SPD activity classes



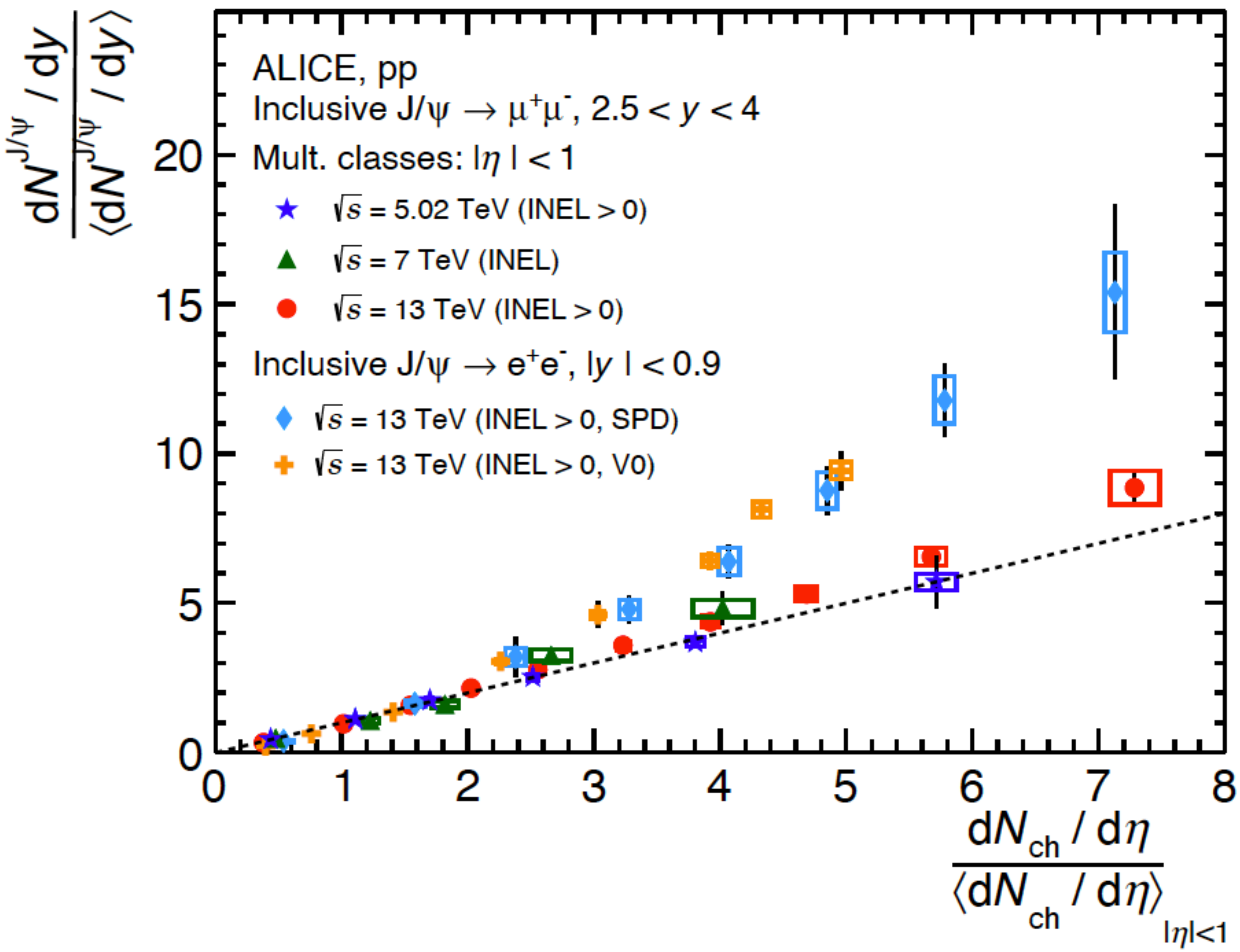
V0 activity classes



Green: multiplicity intervals used

midrapidity J/ψ (Run 2)
PLB 810 (2020) 135758

J/ψ production with multiplicity



- Midrapidity: faster than linear growth
  - No difference observed when using SPD or V0 event activity classes
- Forward: mostly linear trend, but there is a 4.9σ deviation from linear at $\sqrt{s} = 13\,\mathrm{TeV}$
- Inclusive measurement → harder to interpret, as non-prompt production comes from B decays
  - Good prospects for Run 3, prompt & non-prompt separation with MFT
  - MFT might be able to directly measure multiplicity in the forward region

forward 5, 13TeV: JHEP 06 (2022) 015

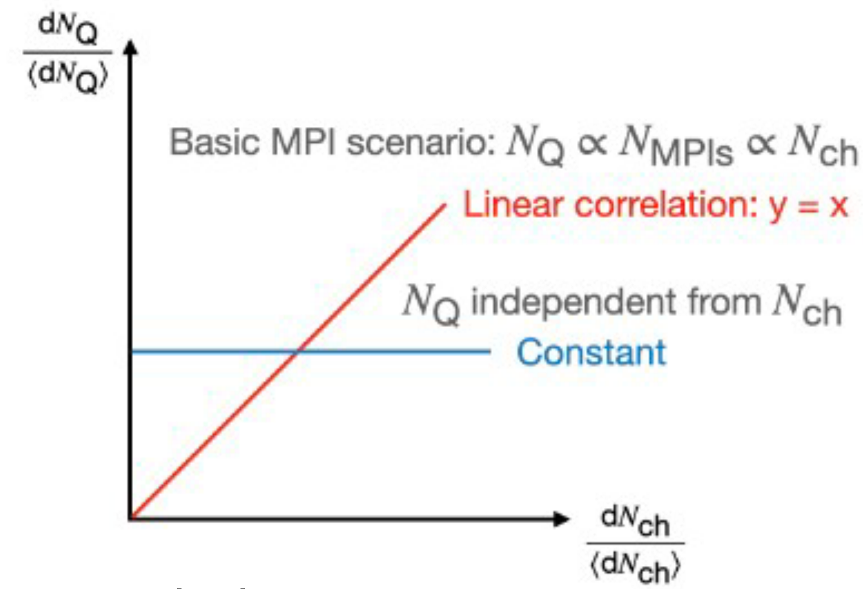
midrapidity J/ψ (Run 1) PLB 712 (2012) 165-175

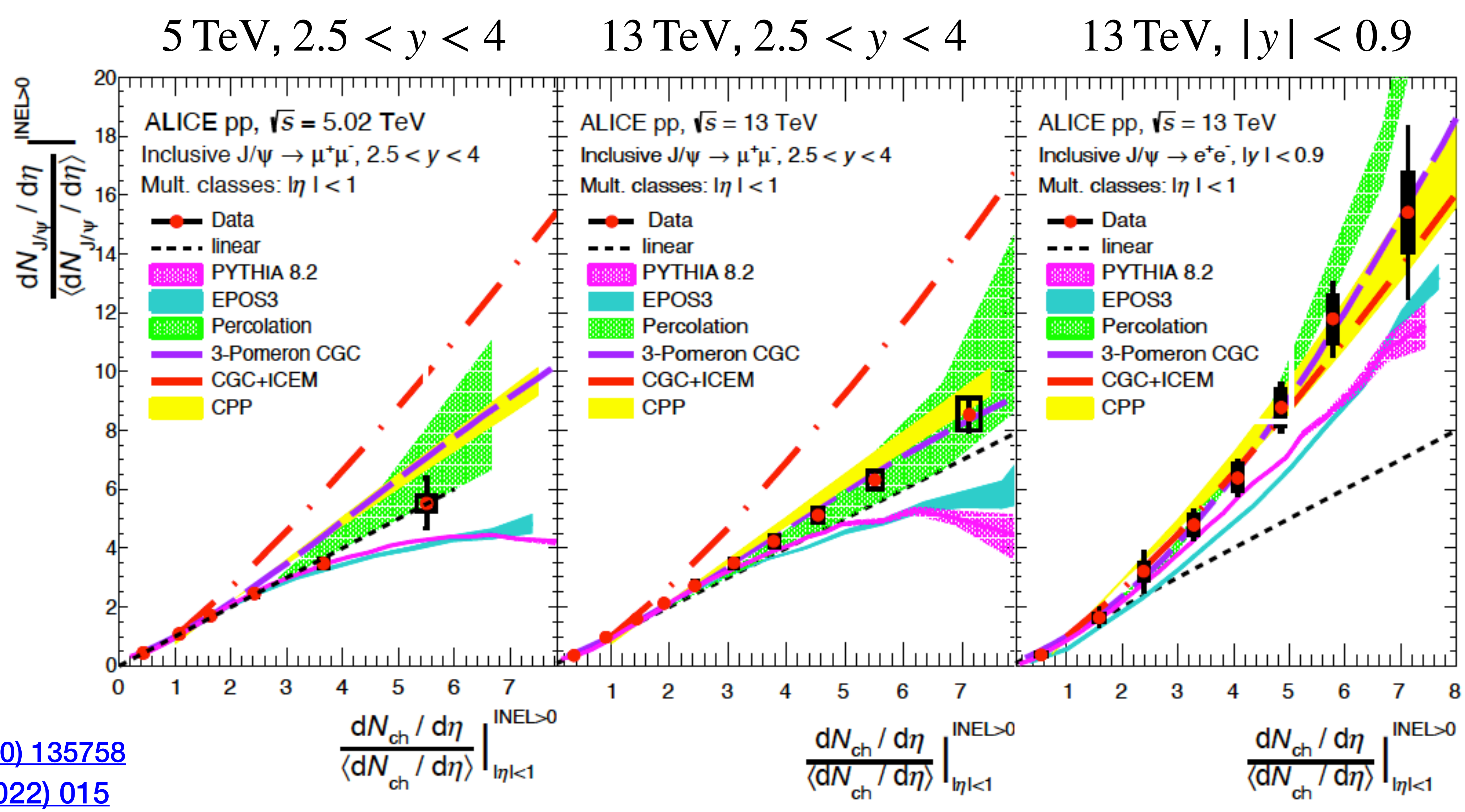
midrapidity J/ψ (Run 2) PLB 810 (2020) 135758

central Υ: arXiv:2209.04241

J/ψ production with multiplicity: model comparison

- Faster than linear increase reproduced by different approaches:
  - Color string reconnection, gluon saturation, coherent particle production, 3-gluon fusion in gluon ladders/pomerons…
  - Additional complexity to the simple MPI scenario
- Excited state $\psi(2S)$ in forward shows comparable behaviour to J/ψ (JHEP 06 (2023) 147)





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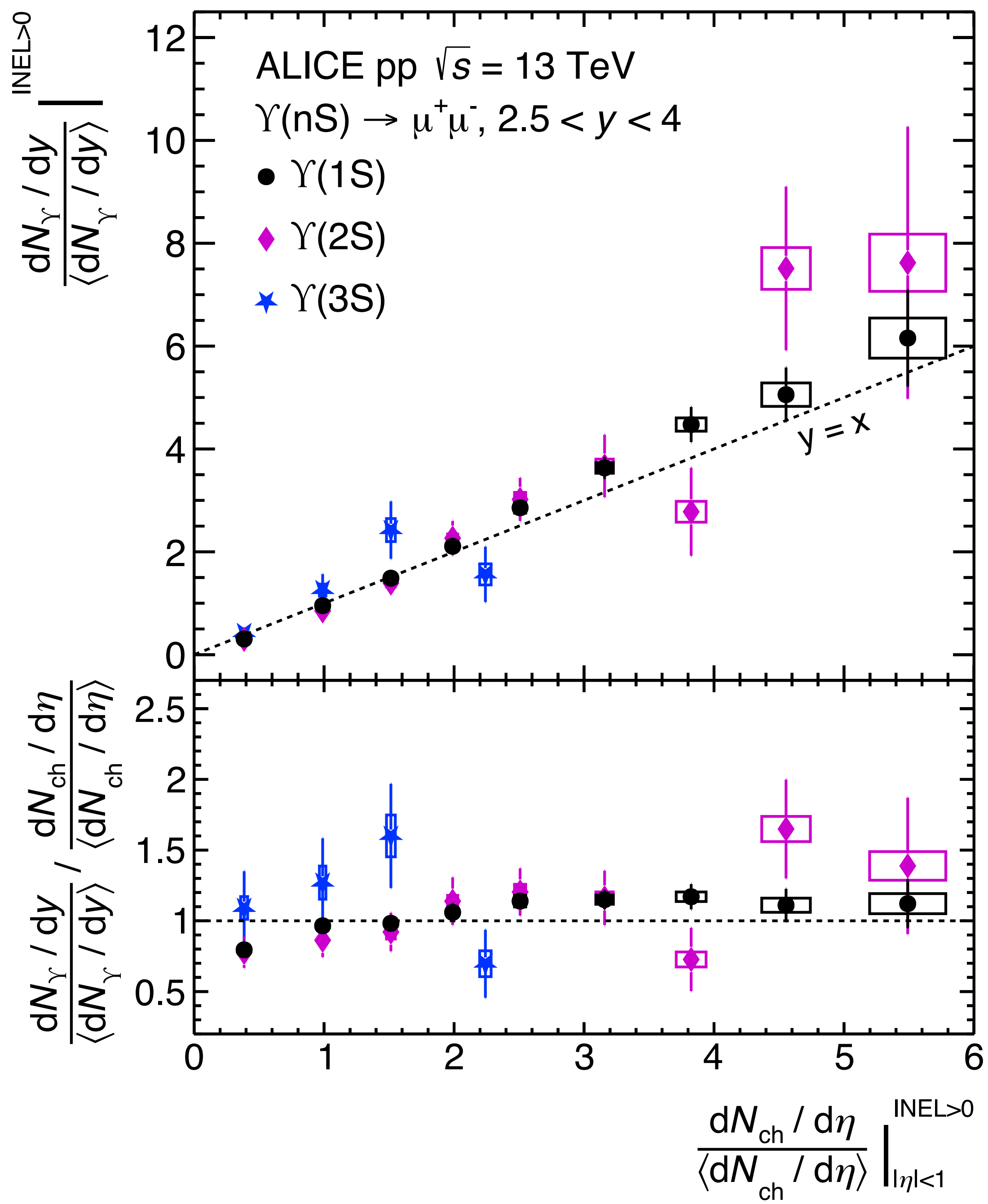
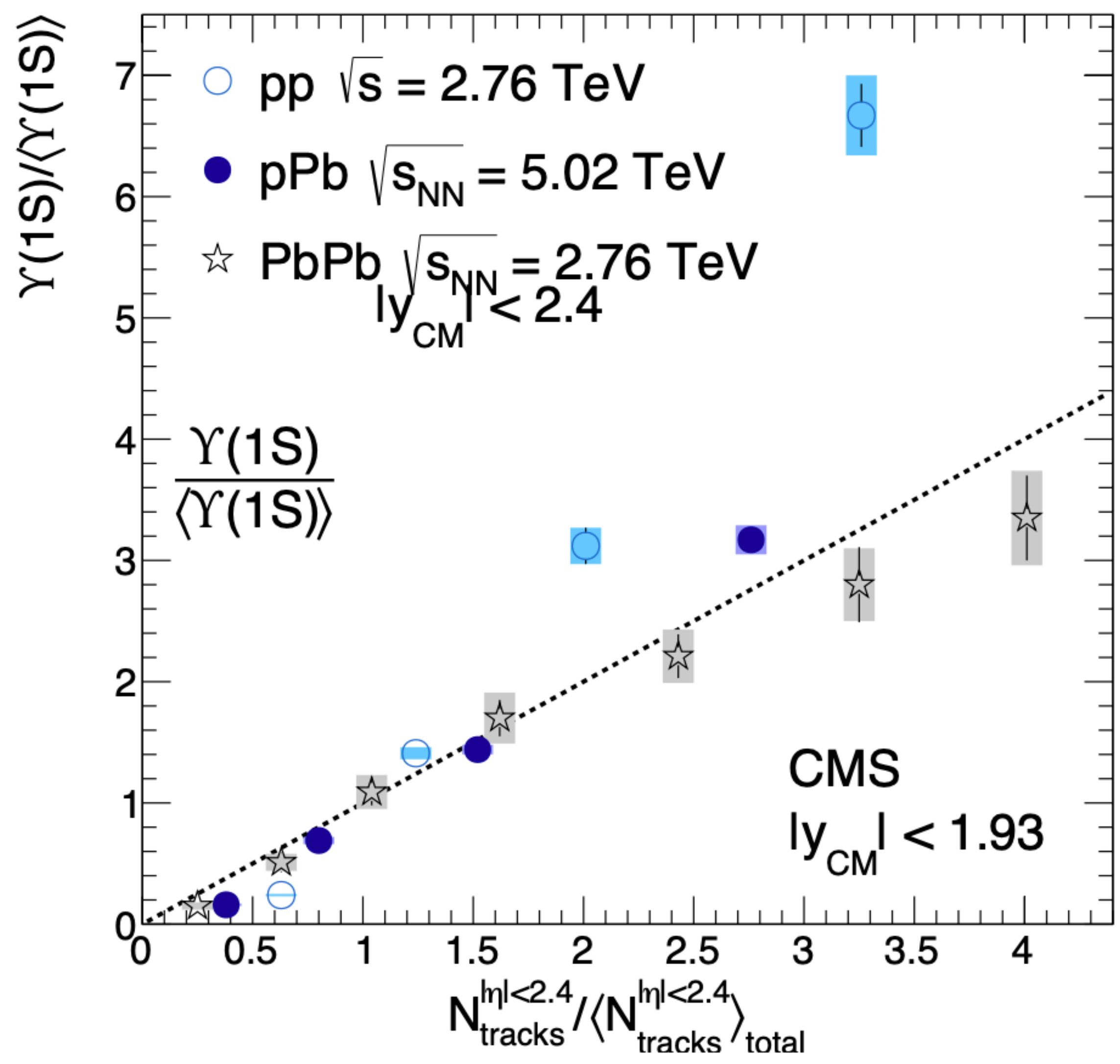
JHEP 06 (2022) 015

$\Upsilon(1S)$ production with multiplicity

- ALICE $\Upsilon(nS)$ with forward muon arm:
  - Linear trend, similar pattern as J/ψ



- CMS result at midrapidity:
  - growth faster than linear, similar to J/ψ



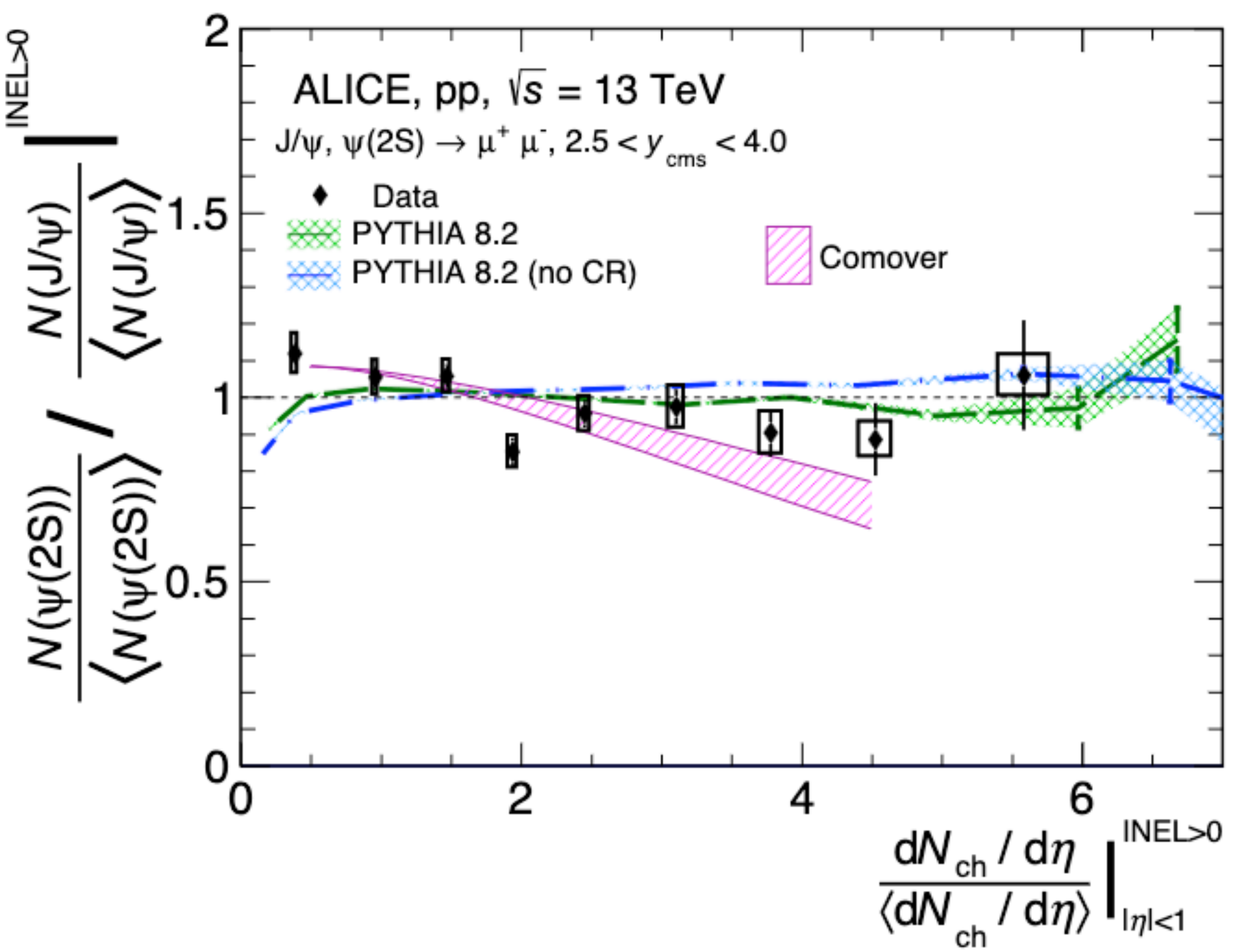
ALICE forward 5, 13TeV: JHEP 06 (2022) 015
CMS midrapidity Υ: JHEP 04 (2014) 103

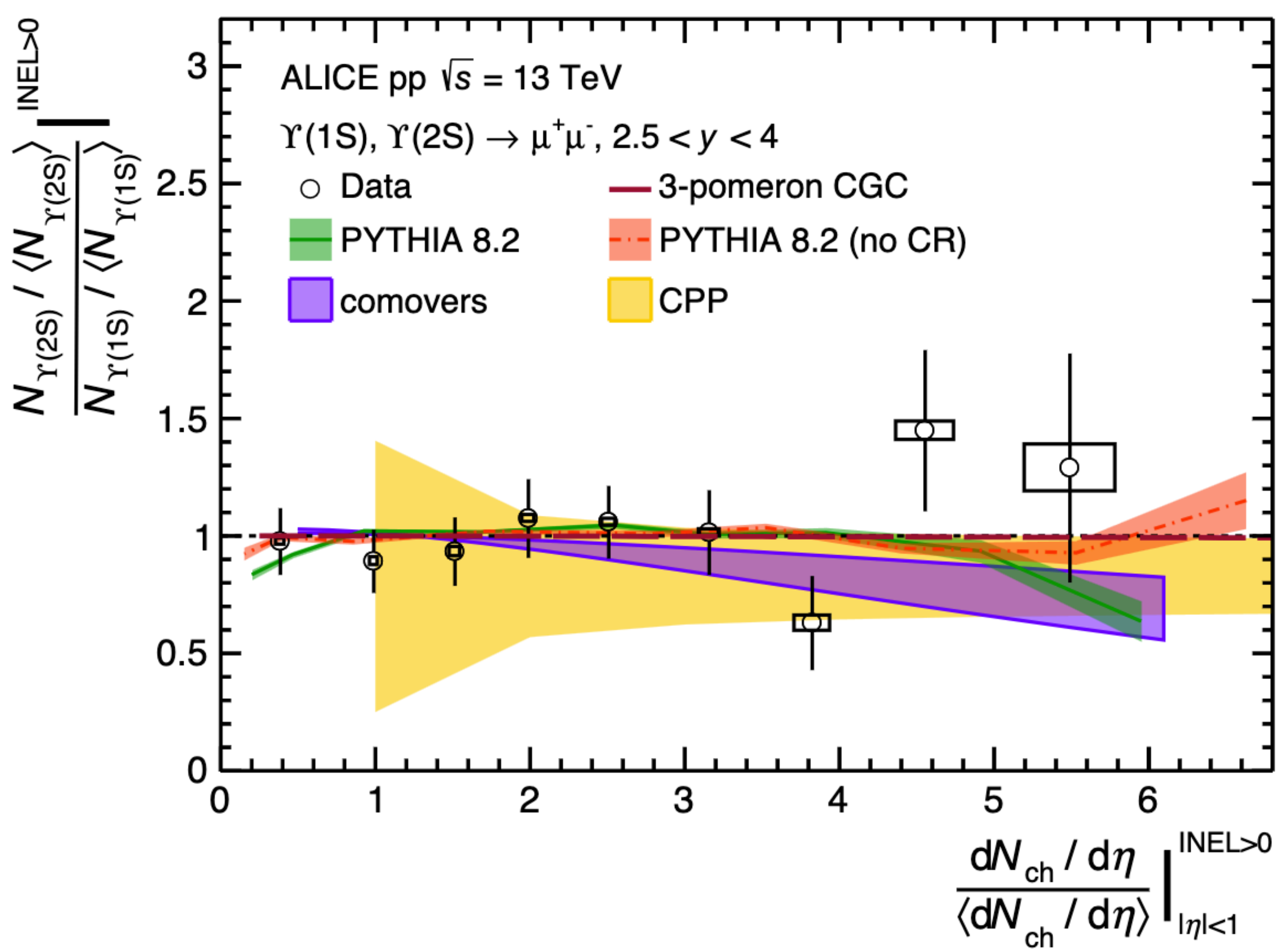
Excited-to-ground state ratio with multiplicity

$\psi(2S), J/\psi$: JHEP 06 (2023) 147

Υ: arXiv:2209.04241

- ALICE measured ratios of $\psi(2S)/J/\psi$ and $\Upsilon(nS)/\Upsilon(1S)$
  - only in forward region with muon arm, inclusive $\psi(2S), J/\psi$





No significant deviation from unity is seen

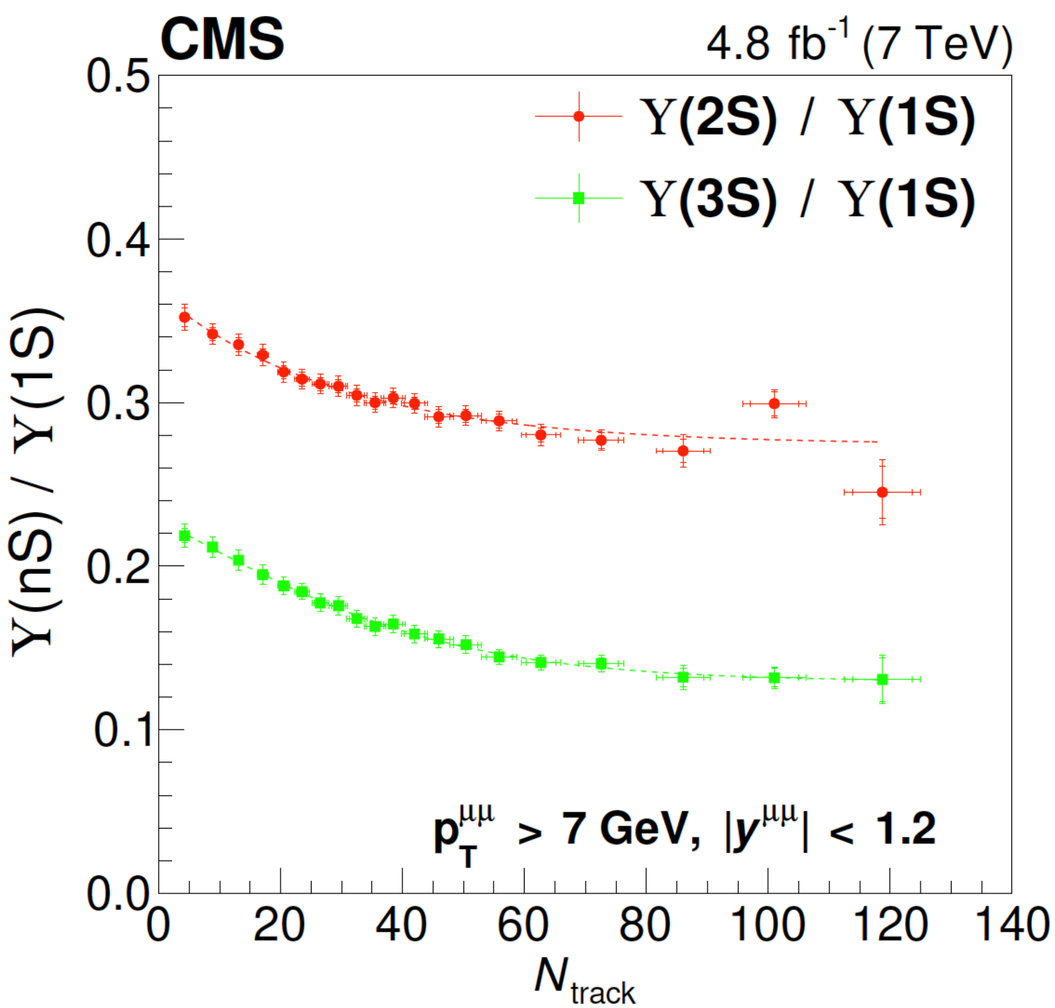
- Color reconnection (CR) in PYTHIA almost no effect
- Need more precision to distinguish decreasing trend of comover model

Ratios $\Upsilon(nS)/\Upsilon(1S)$ with event activity from CMS

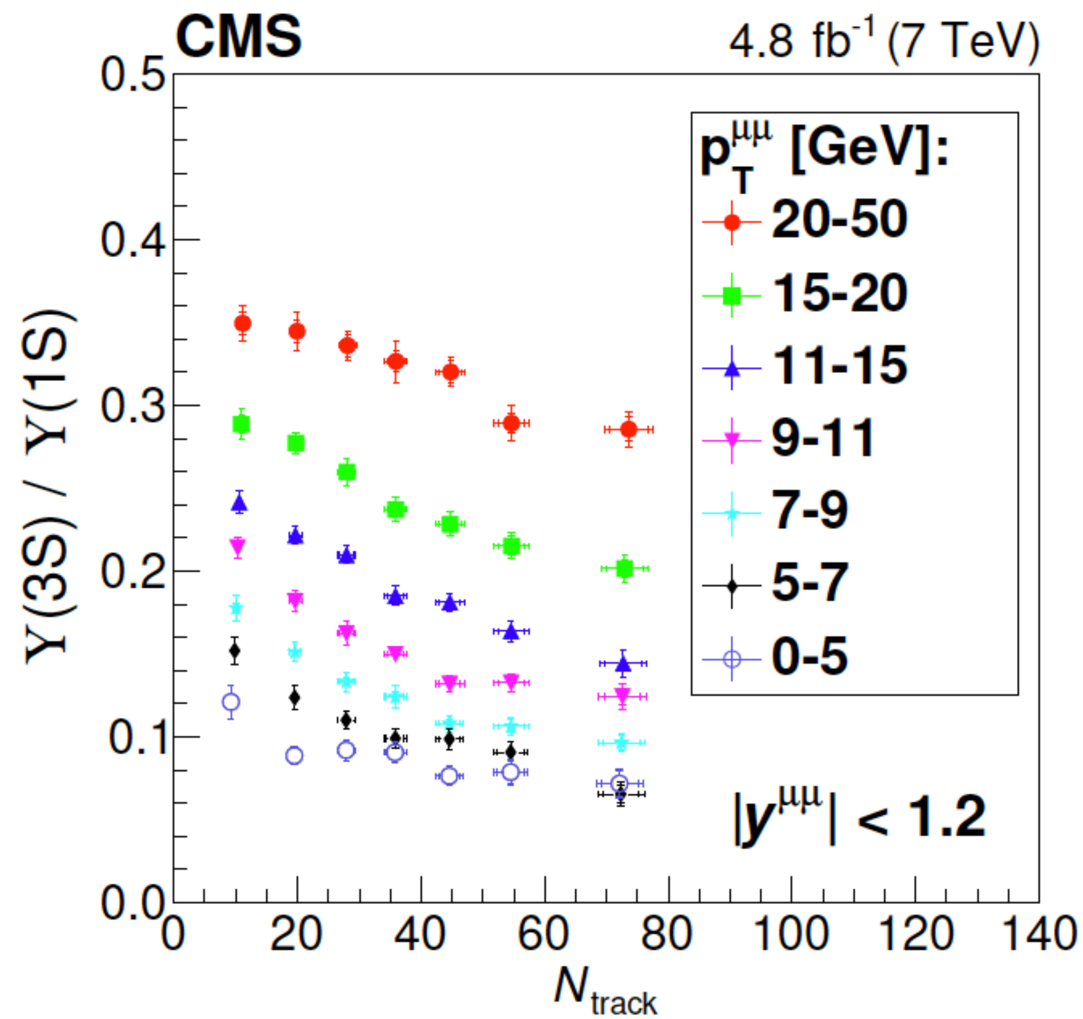
$\Upsilon(nS)$ cross-section ratios in pp collisions

JHEP 11 (2020) 001
JHEP 04 (2014) 103

- Study cross-section ratios of $\Upsilon(nS)$ as a function of multiplicity
- Use $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ (trigger requirement in high-statistics sample)
- Multiplicity N_{tracks}: tracks with $p_{\mathrm{T}}^{\mathrm{track}} > 0.4\,\mathrm{GeV}/c$, $|\eta^{\mathrm{track}}| < 2.4$, efficiency corrected



Clear decreasing trend with multiplicity, decrease $\Upsilon(3S)/\Upsilon(1S)$ > $\Upsilon(2S)/\Upsilon(1S)$

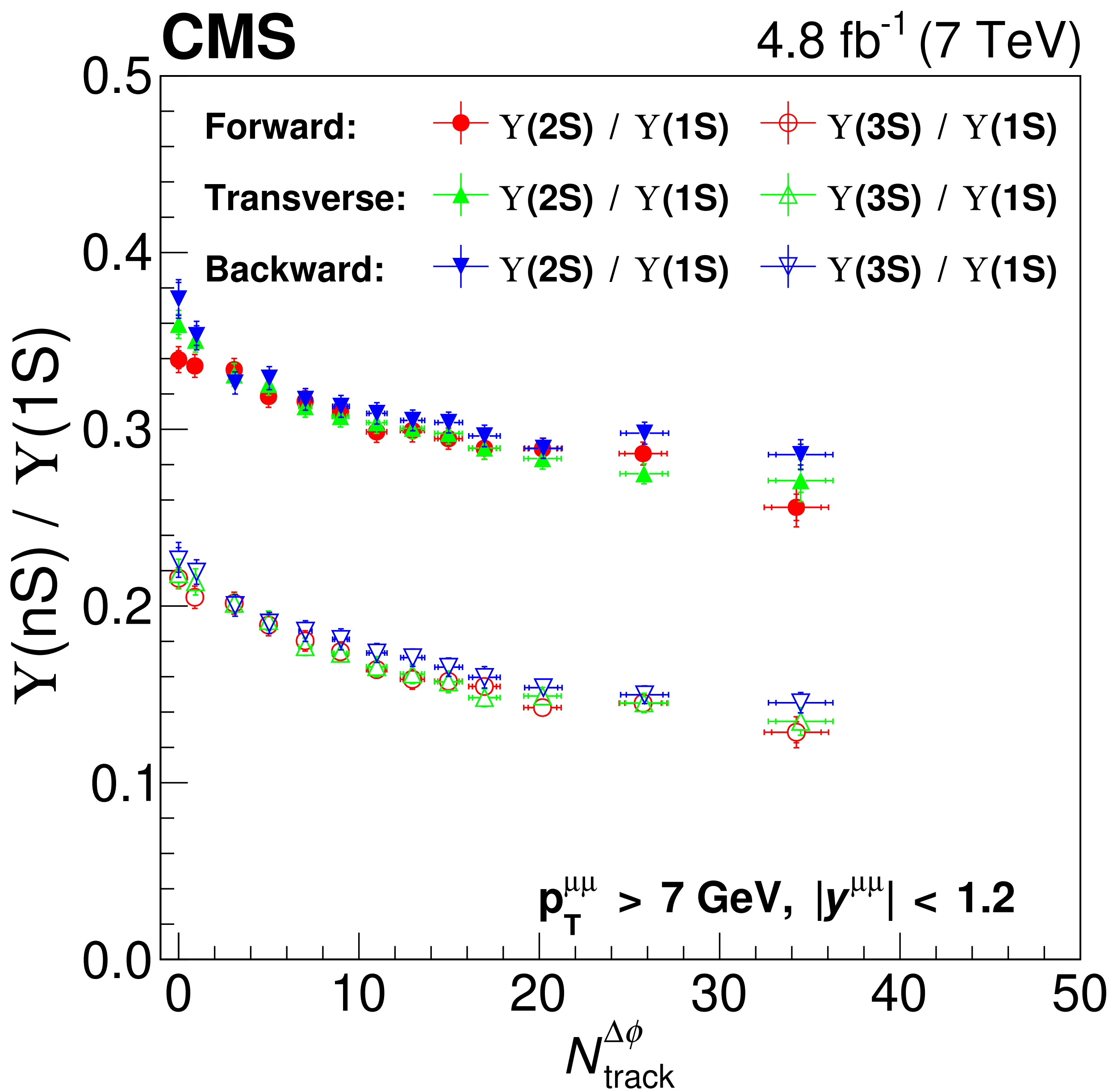


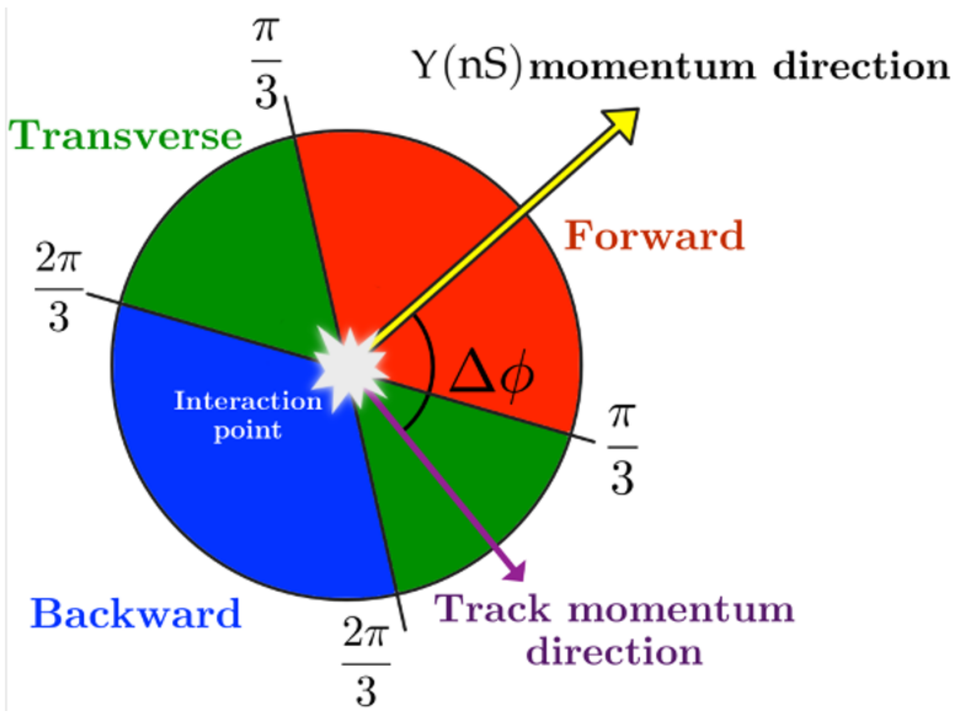
More pronounced drop at lower p_{T}

$\Upsilon(nS)$ ratios: local multiplicity dependence

[JHEP 11 (2020) 001]

- Use $\phi^{\mu\mu}$ to study dependence with local multiplicity and underlying event
  - distinguish effects from feed-down and production (linked to toward & backward) from UE (transverse)



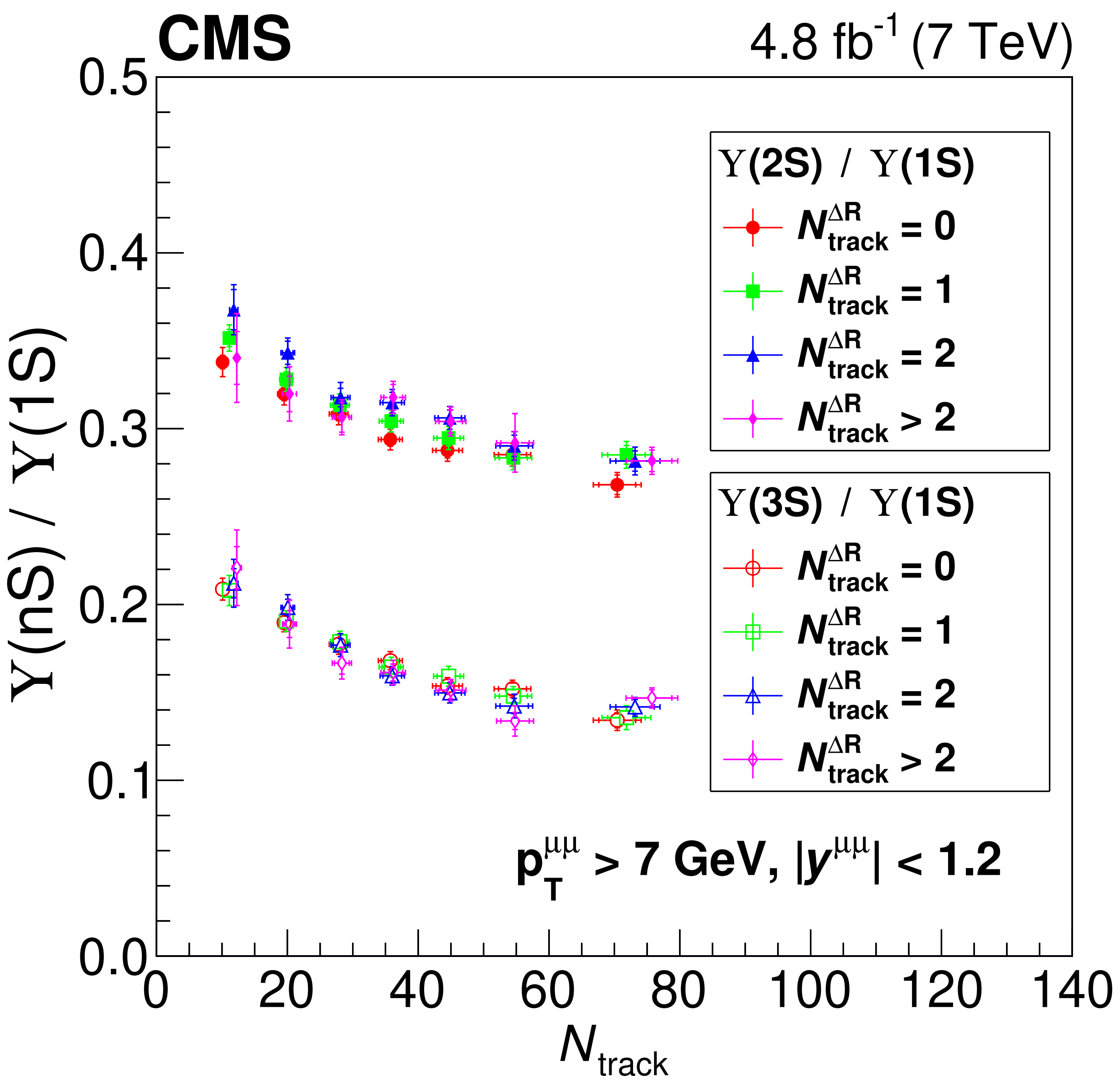


- Similar trend for the three regions, main differences at low $N^{\Delta\phi}_{\mathrm{track}}$
- Decrease also observed in transverse region
  - ✳ could indicate of correlation with UE
- keep in mind correlation between different $N^{\Delta\phi}_{\mathrm{track}}$ estimators

$\Upsilon(nS)$ ratios: dependence on isolation

JHEP 11 (2020) 001

- Define a cone around Υ: $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} < 0.5$
- Need to correct for some feed-downs:
  - significant bias at low multiplicity from $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$



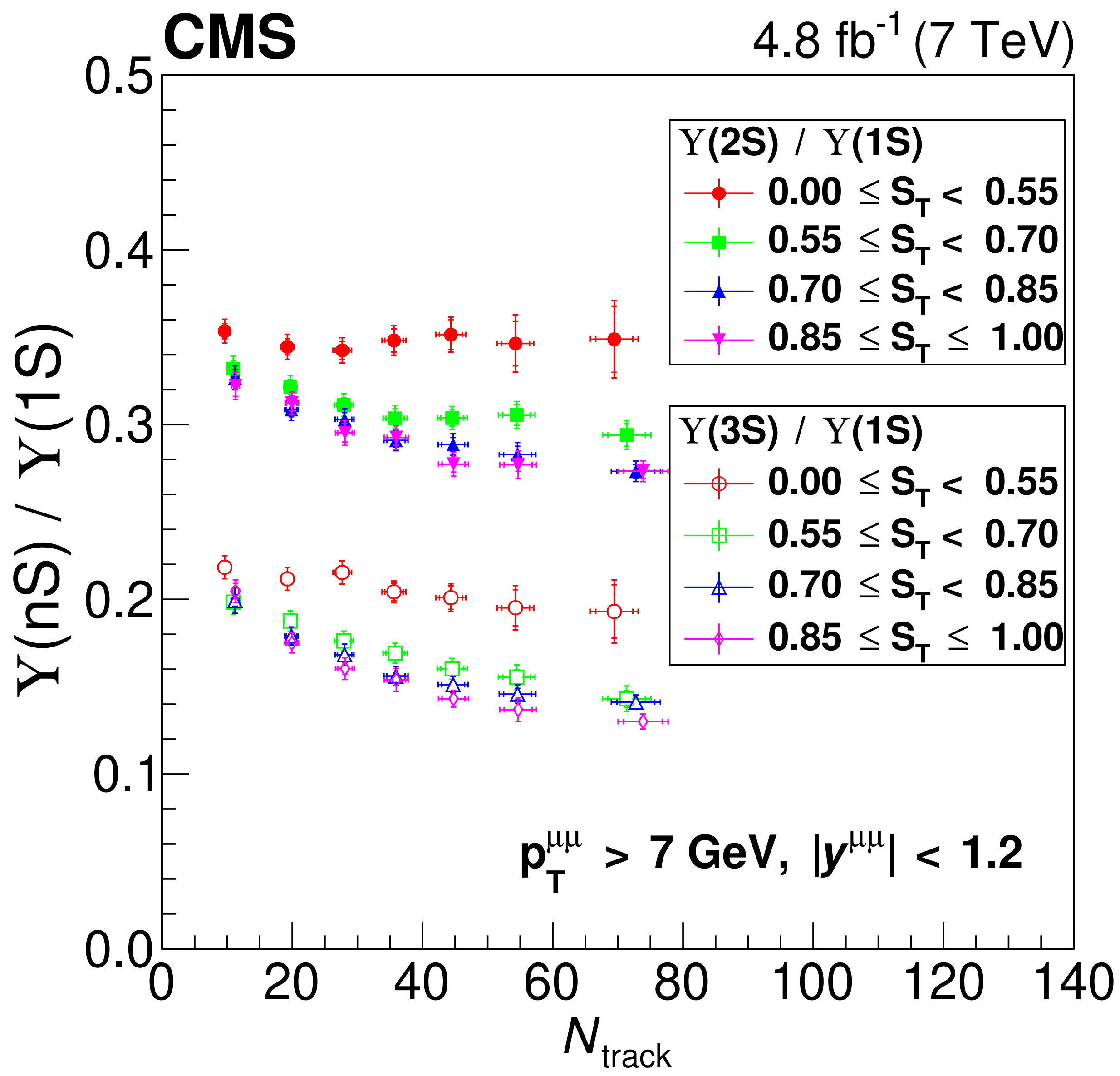
- Aiming to see if comovers are affecting the ratio
- No significant differences between different track multiplicity in the cone are seen
- My thoughts:
  - Rather high $p_T^{\mu\mu}$ may result on reduced comover effect (?)
  - Could it be interesting to study UE activity for the different categories (for instance using $N^{\Delta\phi}_{track}$)

$\Upsilon(nS)$ ratios: dependence on event isotropy

JHEP 11 (2020) 001

- Sphericity: $S_{\mathrm{T}} = \frac{2\lambda_2}{\lambda_1 + \lambda_2}, \quad S^T_{xy} = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$

  p_i: momentum of every event charged particle
- Interpretation:
  - $S_{\mathrm{T}} = 1 \implies$ isotropic event
  - $S_{\mathrm{T}} = 0 \implies$ jet-like event
- No suppression at high multiplicities with low S_{T} (jet-like events)
  - could indicate that suppression mechanism is connected to UE
- Events with low S_{T} have a higher p_{T} on average
  - could p_{T} biasing be also behind this difference?
- Sphericity not infrared safe, other alternatives (JHEP06(2010)038, JHEP08(2020)084)

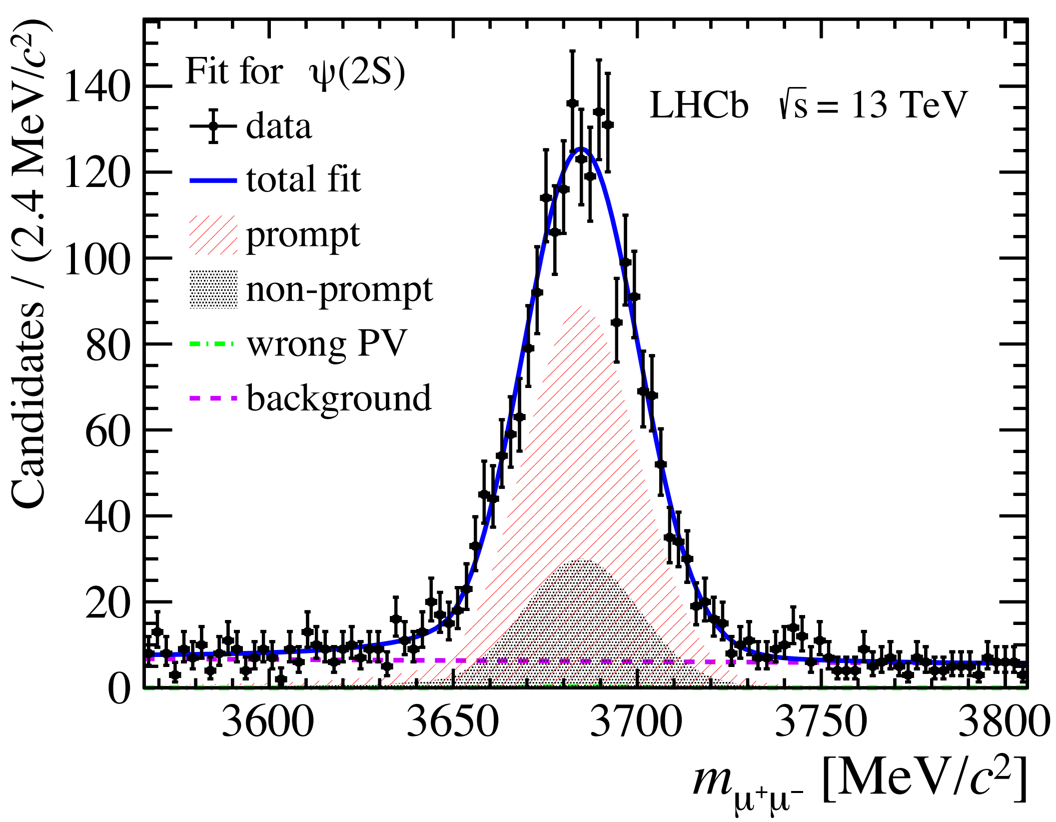


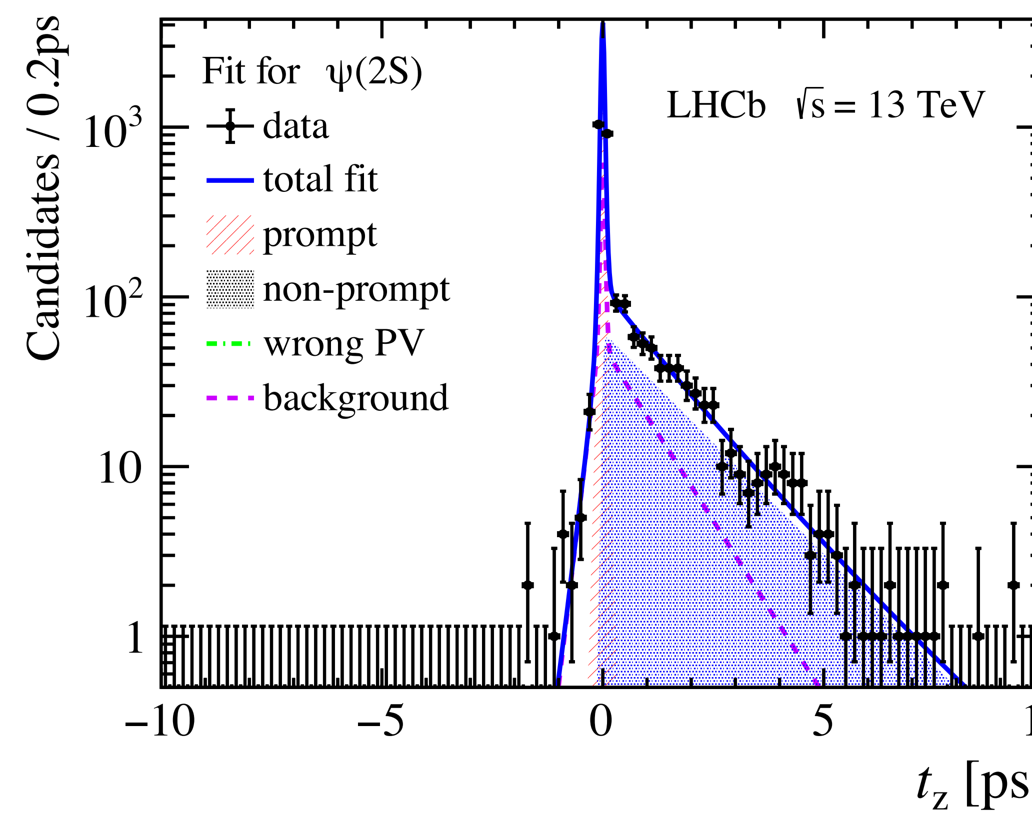
$\psi(2S)/J/\psi$ with multiplicity from LHCb

$\psi(2S)/J/\psi$ with multiplicity from LHCb

New! arXiv:2312.15201

- New LHCb measurement: arXiv:2312.15201
- Measure multiplicity dependency of $\psi(2S)/J/\psi$ ratio in pp collisions at $\sqrt{s} = 13\,\text{TeV}$
- Key points:
  - Exploits huge LHCb dataset in pp from Run 2 → double-differential study in y and p_T
  - Charmonia measured precisely down to very low p_T
  - Separation between prompt and non-prompt (from B hadrons) charmonia
  - Event multiplicity variable: normalised number of PV tracks





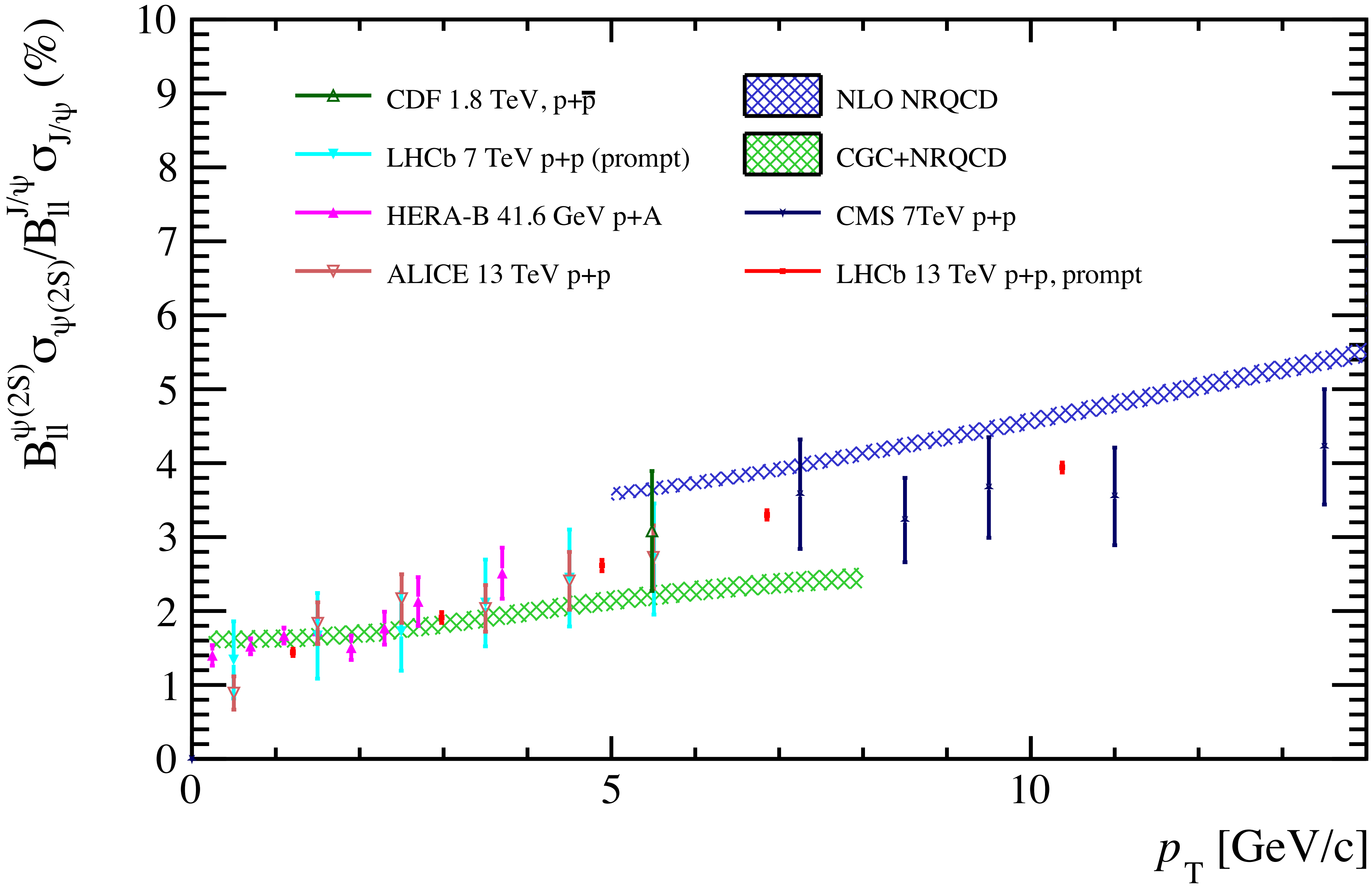
Prompt & non-prompt signal extraction for $4 < N_{\text{tracks}}^{\text{PV}} < 20$, $2.8 < y < 3.5$ **and** $6 < p_T < 8\,\text{GeV}/c$

$\psi(2S)/J/\psi$ cross-section ratio

New! arXiv:2312.15201

- High precision using full 2016 dataset of $2\,\mathrm{fb}^{-1}$!

CGC+NRQCD, NLO NRQCD: PRL 113, 192301
Measurements: PR C95 (2017) 034904 (refs. therein)

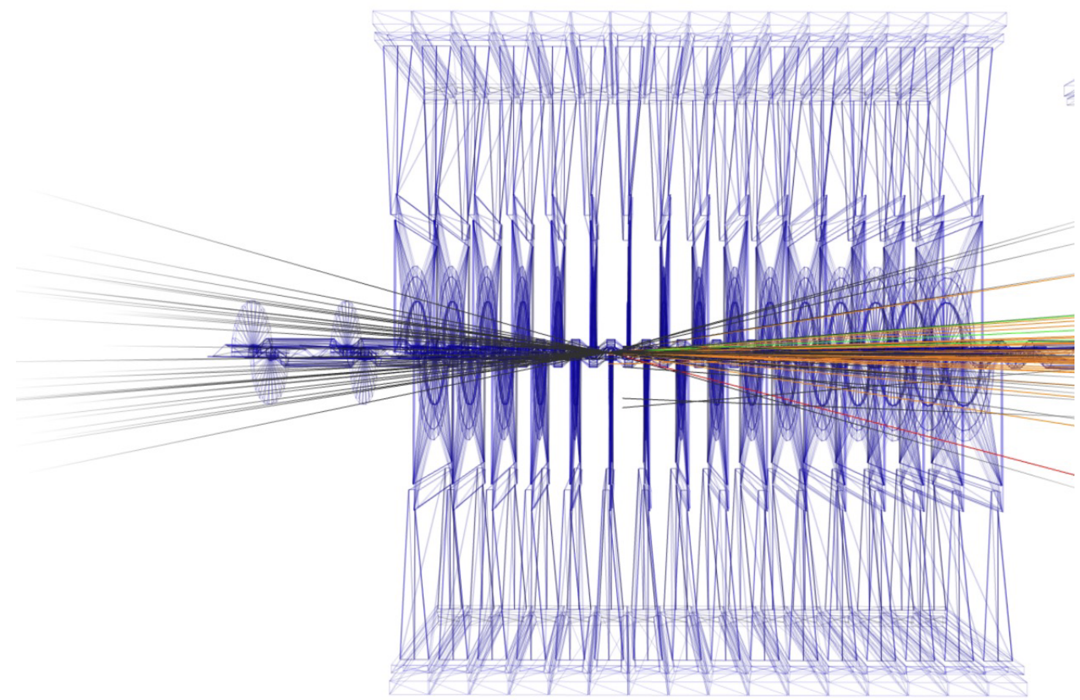


Event multiplicity determination at LHCb

- Three multiplicity variables:
  - N^{PV}_{forward}: tracks in forward direction used in primary vertex (PV) reconstruction
  - N^{PV}_{backward}: tracks in backward direction used in PV reconstruction
  - $N^{PV}_{\text{tracks}} = N^{PV}_{\text{backward}} + N^{PV}_{\text{forward}}$
- VELO not forward-backward symmetric:
  - more tracking stations in the forward region
  - Use region of $-60 < z_{PV} < 180\,\text{mm}$ to ensure constant acceptance and self-normalised ratios
  - Tracks not efficiency corrected (VELO efficiency $> 95\,\%$ in forward)

Backward Tracks $\approx -3 < \eta < -2$ $\longleftarrow$

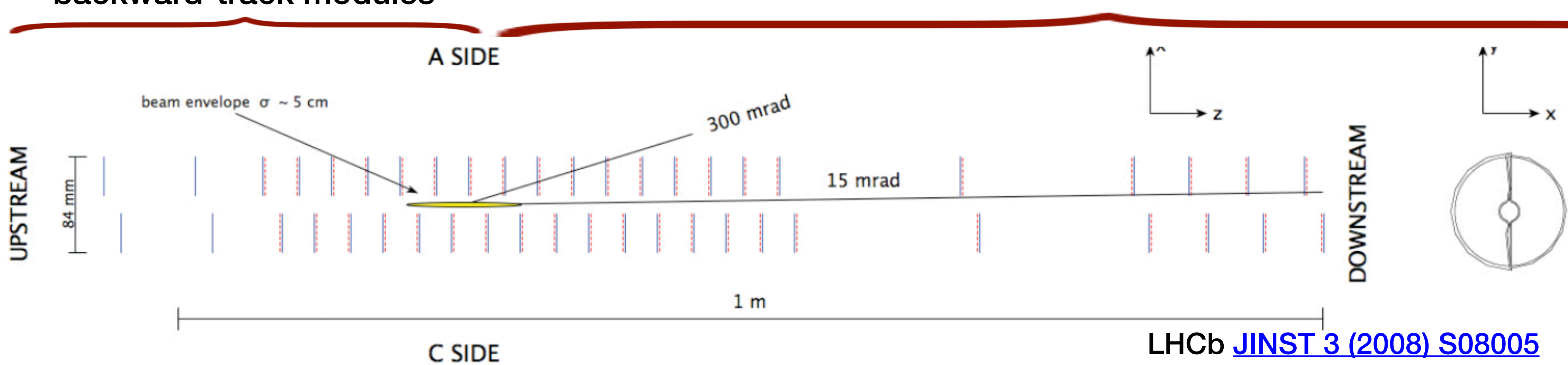
Forward Tracks $2 < \eta < 5$ $\longrightarrow$



VELO XZ profile

backward-track modules

forward-track modules



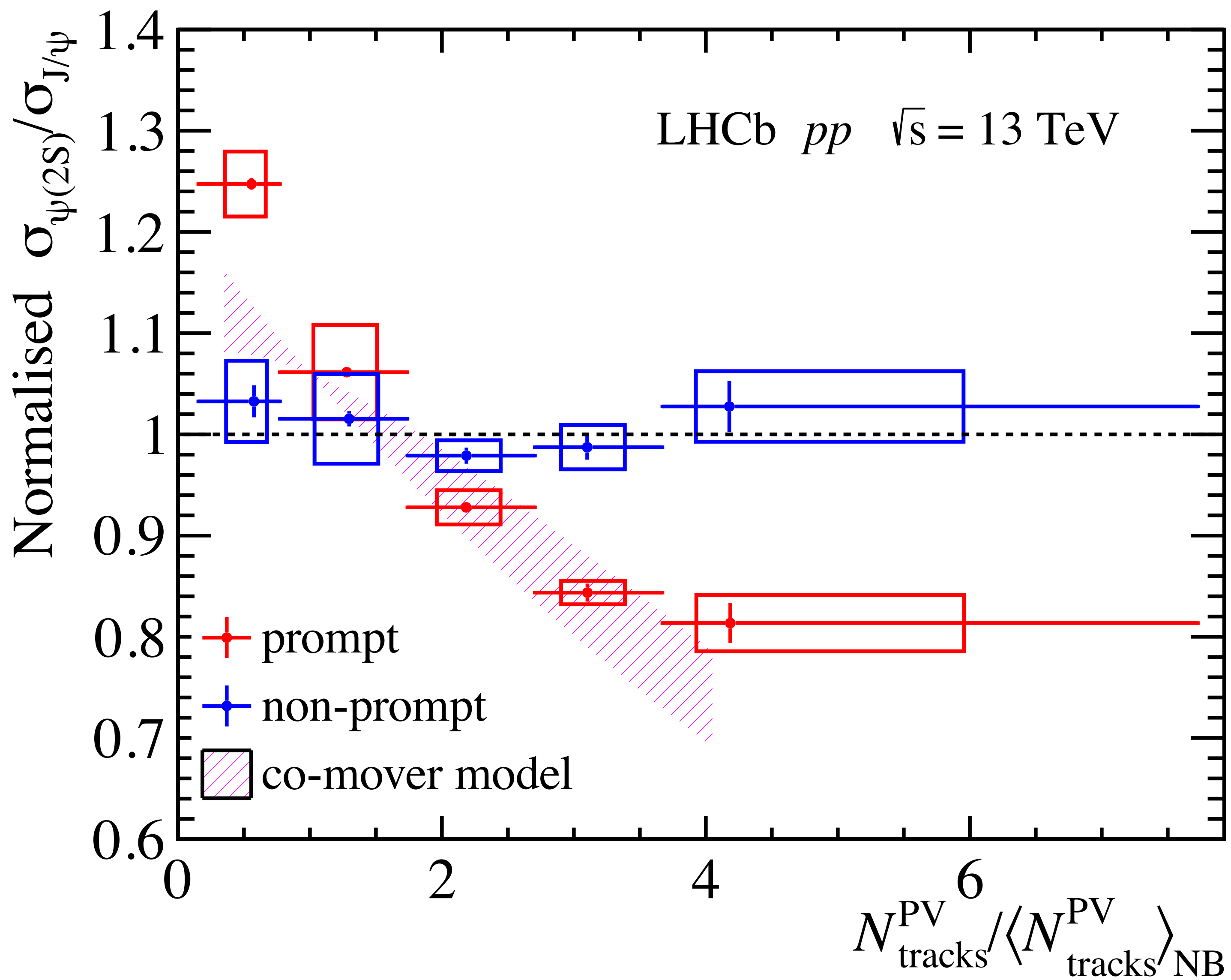
LHCb JINST 3 (2008) S08005

VELO performance JINST 9 (2014) P09007

$\psi(2S)/J/\psi$ with multiplicity from LHCb

New! arXiv:2312.15201

- p_T and y integrated result in $0.3 < p_T < 20\,\text{GeV}/c$ and $2.0 < y < 4.5$



- No significant dependency for non-prompt ratio
  - expected in principle as both J/ψ and $\psi(2S)$ decay from B hadrons
- Decreasing trend seen in prompt ratio
- Comover interaction model describes decreasing trend
  - Estimates break-up of $\psi(2S)$ and J/ψ from partons or hadrons
  - Sets $< N_{\text{ch}} >_{NB} = 1$ as reference (no suppression)
  - $\psi(2S)$ preferentially broken as a result of $E_b^{J/\psi} > E_b^{\psi(2S)}$

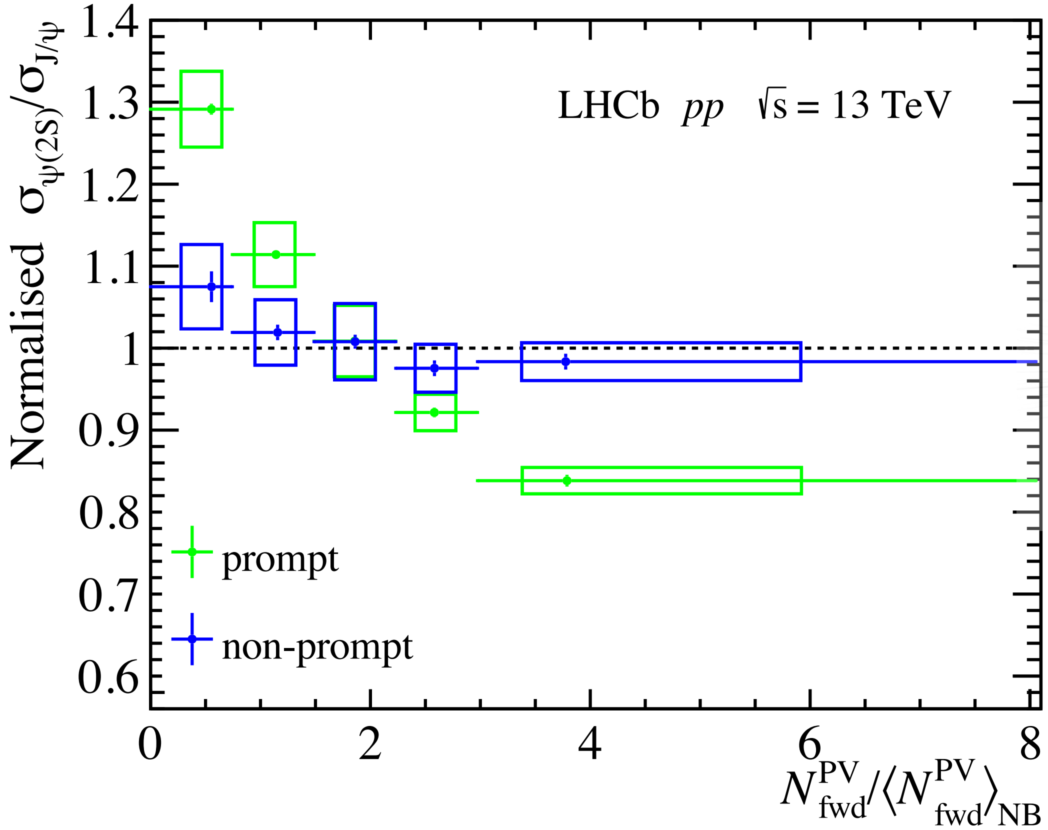
Normalised = divided by multiplicity-integrated $\sigma_{\psi(2S)}/\sigma_{J/\psi}$

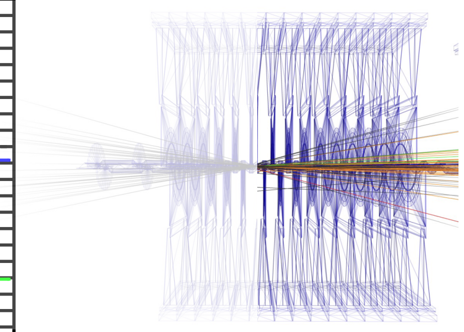
Phys. Lett. B731 (2014) 57

$\psi(2S)/J/\psi$: dependence with multiplicity classifier

$0.3 < p_T < 20\,\mathrm{GeV}/c,\ 2.0 < y < 4.5$

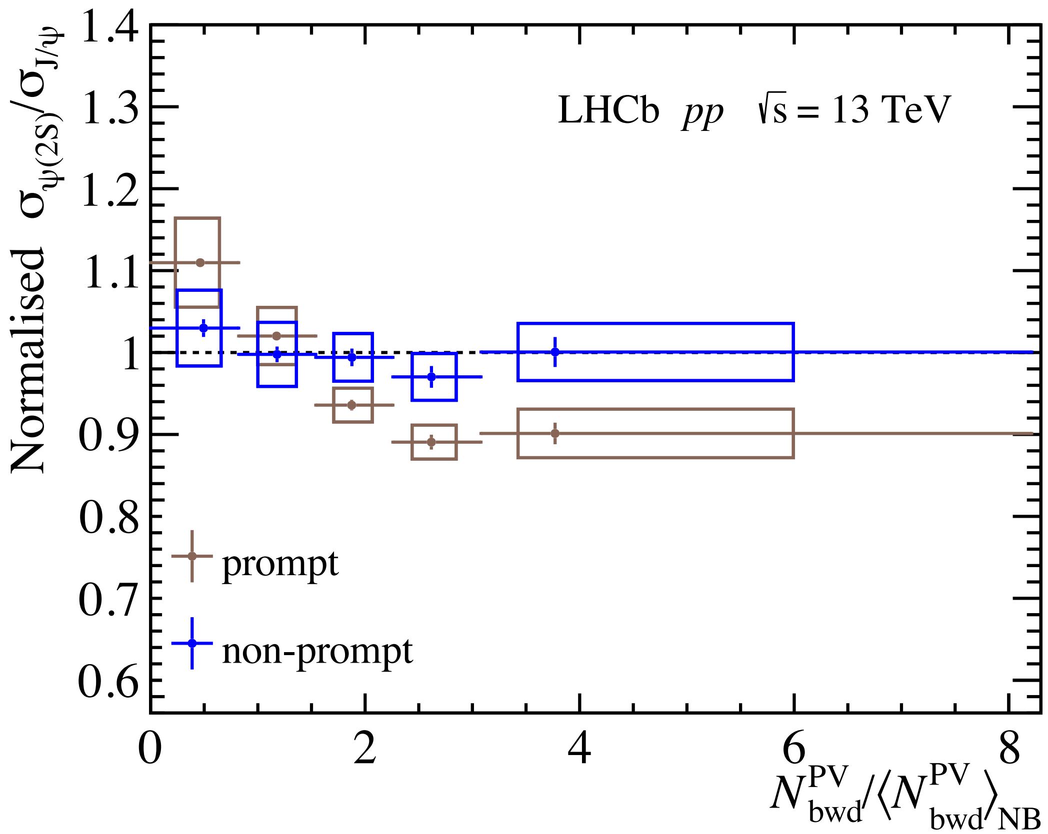
New! arXiv:2312.15201

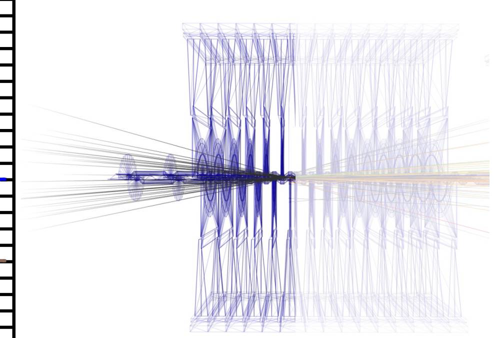




Multiplicity from forward tracks

- Non-prompt data compatible with **one**
- Prompt data shows a **pronounced decreasing trend**





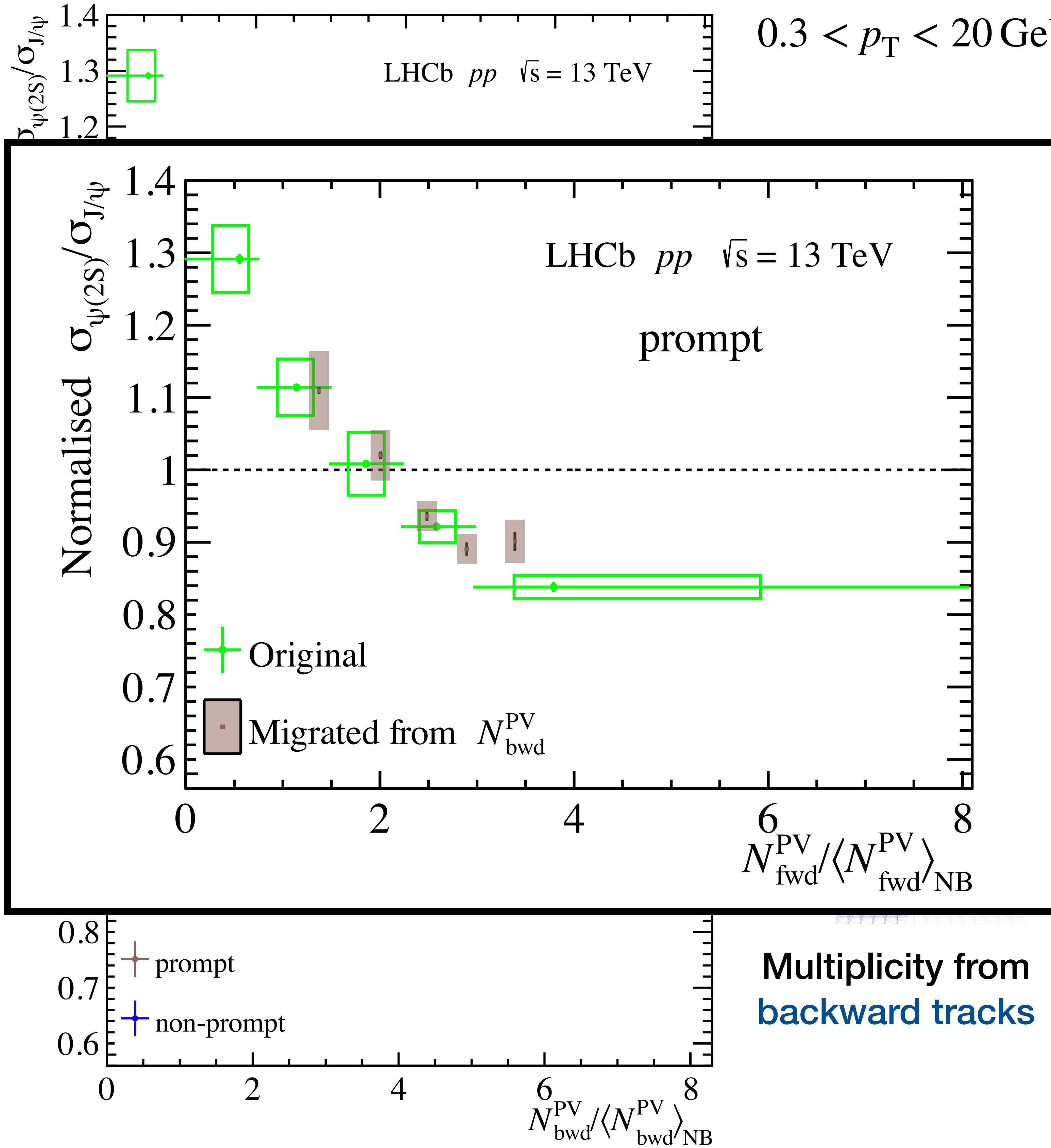
Multiplicity from backward tracks

- Non-prompt data compatible with **one**
- Prompt data shows a **decreasing trend less pronounced** than for N^{PV}_{fwd}

$\psi(2S)/J/\psi$: dependence with multiplicity classifier

$0.3 < p_T < 20\,\mathrm{GeV}/c,\ 2.0 < y < 4.5$

New! arXiv:2312.15201

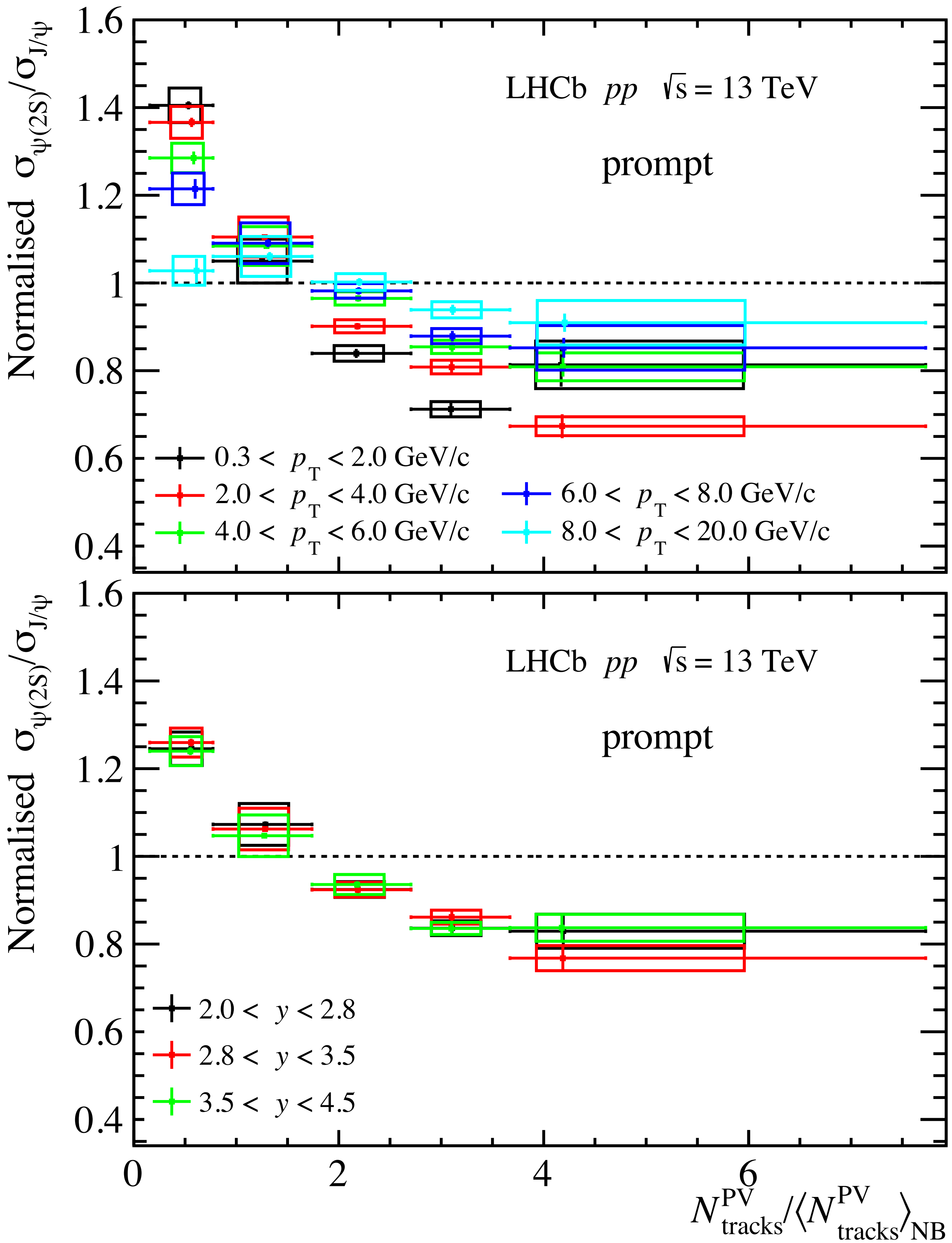


- N^{PV}_{fwd} and N^{PV}_{bkw} are correlated
- Migrate $N^{PV}_{bwd}/\langle N^{PV}_{bwd}\rangle_{NB}$ to $N^{PV}_{fwd}/\langle N^{PV}_{fwd}\rangle_{NB}$ according to correlation
- **Correlation could explain observed trend with backward multiplicity**

Multiplicity from backward tracks

$\psi(2S)/J/\psi$ vs mult.: kinematic dependence

New! arXiv:2312.15201



- Significant p_{T} dependence for prompt ratio
  - Gradual variation, little decreasing trend at high p_{T} → consistent with CMS observation with Υ
  - Possible explanation: As event multiplicity bulk is rather low-p_{T}, could indicate that effect emerges from interaction between comovers and the charmonium

- No significant p_{T} or y dependence for non-prompt ratio
- No significant y dependence for prompt ratio

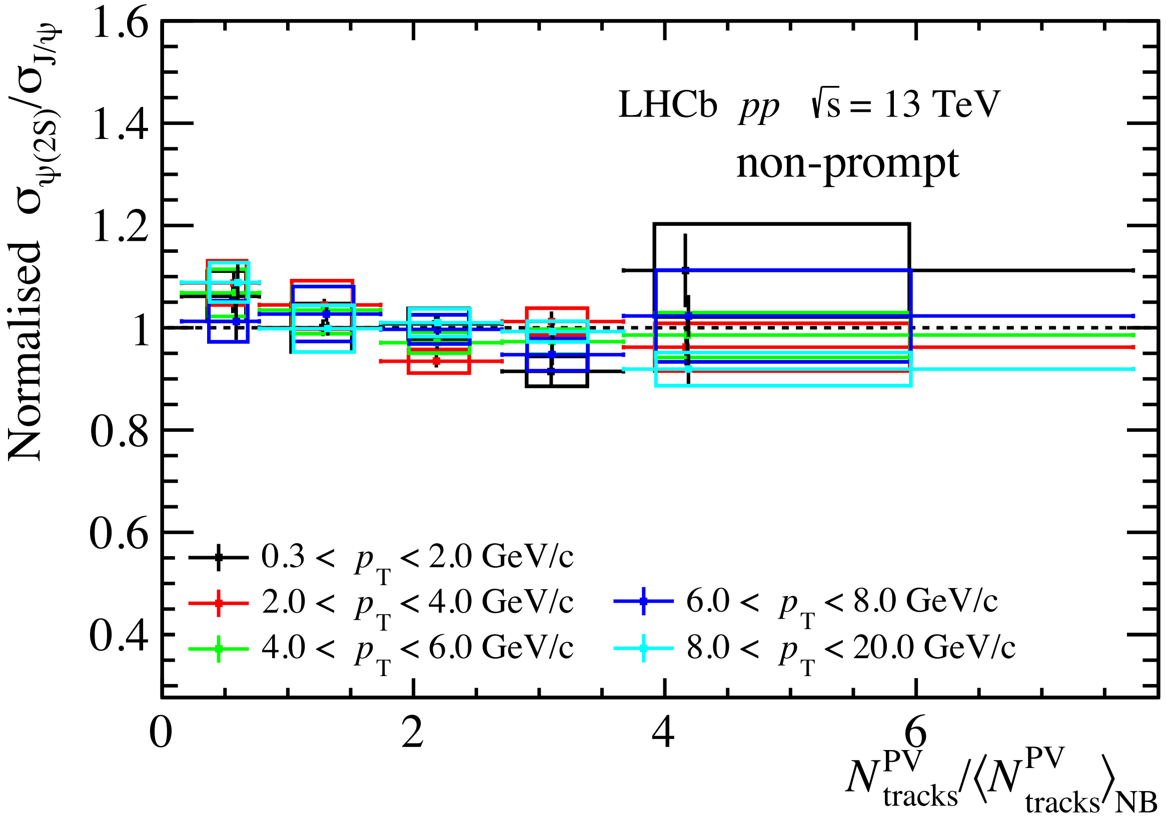
Conclusions

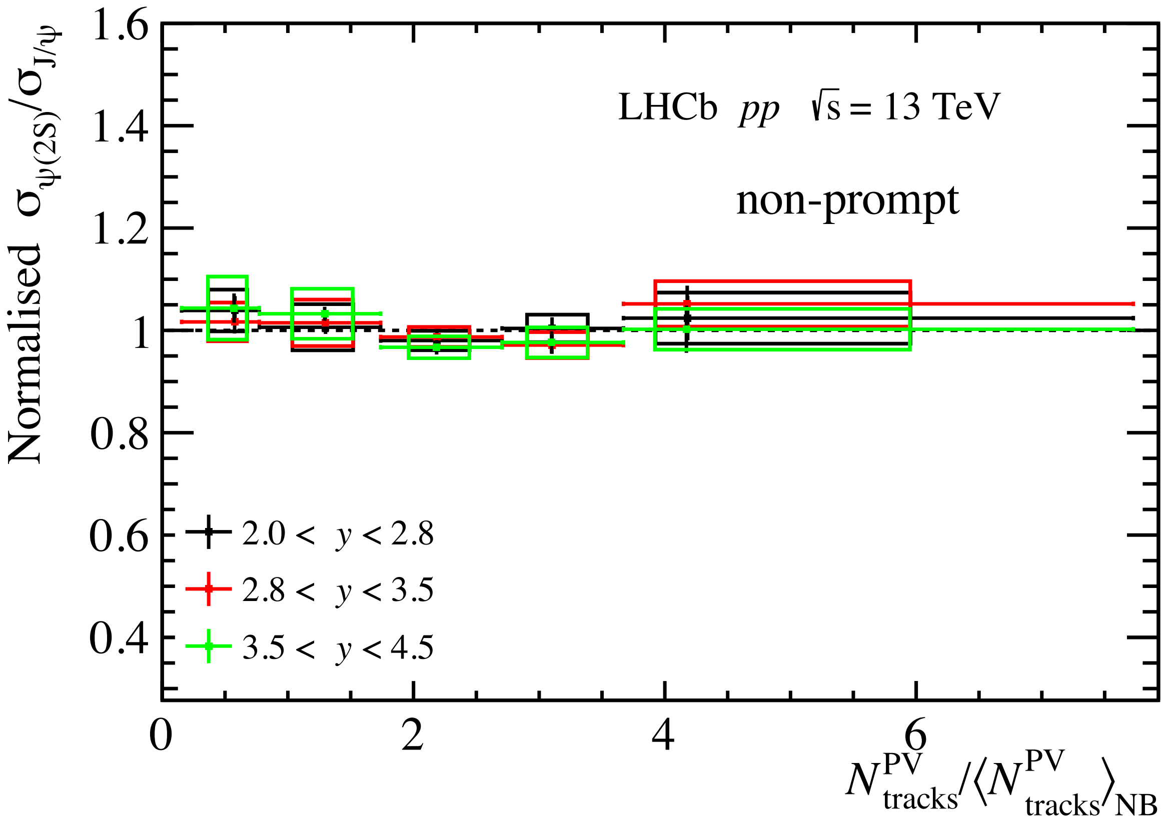
- We discuss several measurements to help describing interplay between quarkonium hadroproduction and the underlying event:
  - quarkonia self normalised ratios: faster than linear trend seen by ALICE (J/ψ) and CMS ($\Upsilon(nS)$) at midrapidity:
    - a variety of mechanisms are able to explain the data
  - CMS observed a decreasing trend of $\Upsilon(3S)/\Upsilon(1S)$ and $\Upsilon(2S)/\Upsilon(1S)$ with multiplicity, which could be linked to the underlying event, but confirmation is needed
  - new LHCb measurement shows a decrease of $\psi(2s)/J/\psi$ ratio with multiplicity, which can be explained by comover break up
- We need to better understand UE in events with quarkonia production:
  - for example, measuring isolated quarkonia relies on a good UE description by generators
  - need to propagate knowledge from measurements to generators (RIVET and tuning)
- Important to gradually build a global picture between systems of different size → evolve from self-normalised ratios to direct multiplicity measurement
  - self-normalised ratios do not allow to compare multiplicities across different systems due to different $\langle N_{\mathrm{ch}} \rangle_{\mathrm{NB}}$
- **Many improvements achievable with Run 3 data** (new ALICE MFT, much larger statistics thanks to new trigger scheme; LHCb, larger statistics, easier access to unconventional quarkonia with new trigger, upgrade of fixed-target program) → see Rita's talk for more details!

Backup

$\psi(2S)/J/\psi$ vs mult.: non-prompt kinematic dependence

New! arXiv:2312.15201

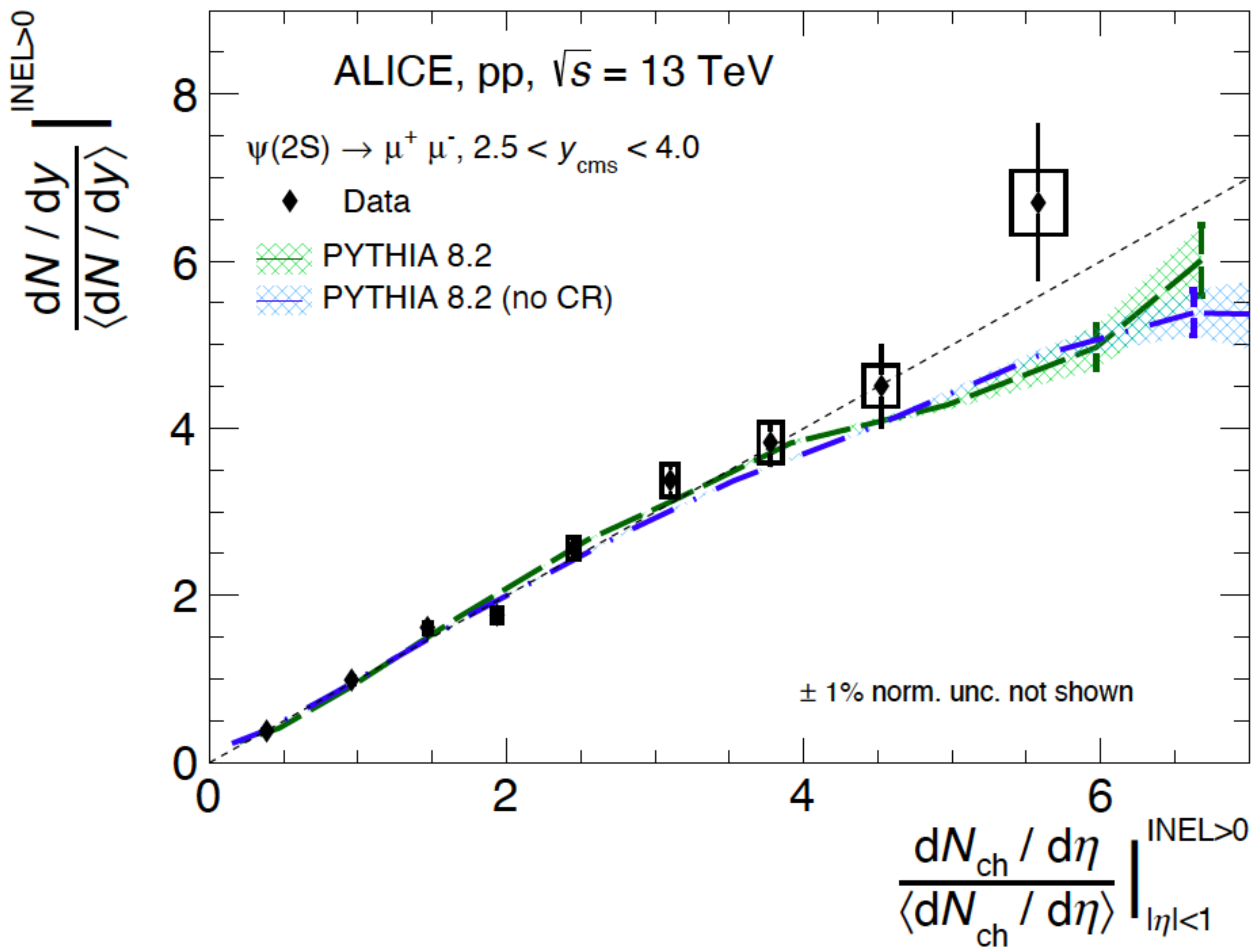




- No significant p_T dependence for non-prompt ratio
- No significant y-dependence for non-prompt ratios

$\psi(2S)$ production with multiplicity

Forward: [JHEP 06 (2023) 147]



J/ψ production with multiplicity: p_{T} dependence

midrapidity J/ψ (Run 2)
[PLB 810 (2020) 135758]