Multiplicity-dependent Quarkonium Production in pp collisions with ALICE

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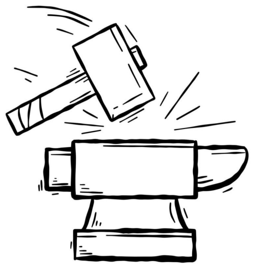
Introduction



Heavy quarks produced in **hard scatterings**: Quarkonium production → hard scale (+ hadronization)

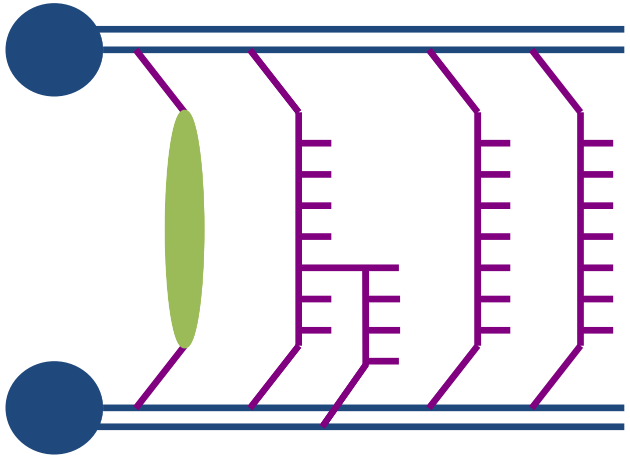
Charged particles mainly produced in **soft scatterings**: Charged-particle multiplicity → soft scale

Multiplicity-dependent quarkonium production → interplay of hard and soft scales in the same event:

- Characterize the role of multi-parton interactions
- Investigate the specificities of high-multiplicity environments
- Disentangle initial- and final-state effects

Charged-particle multiplicity: key parameter to build a coherent framework linking the observations from small to large collision systems. Today's presentation will focus on pp collisions only

Focus on MPIs



Multi-parton interactions: the simultaneous occurrence of several incoherent binary partonic interactions in a single nucleon-nucleon collision

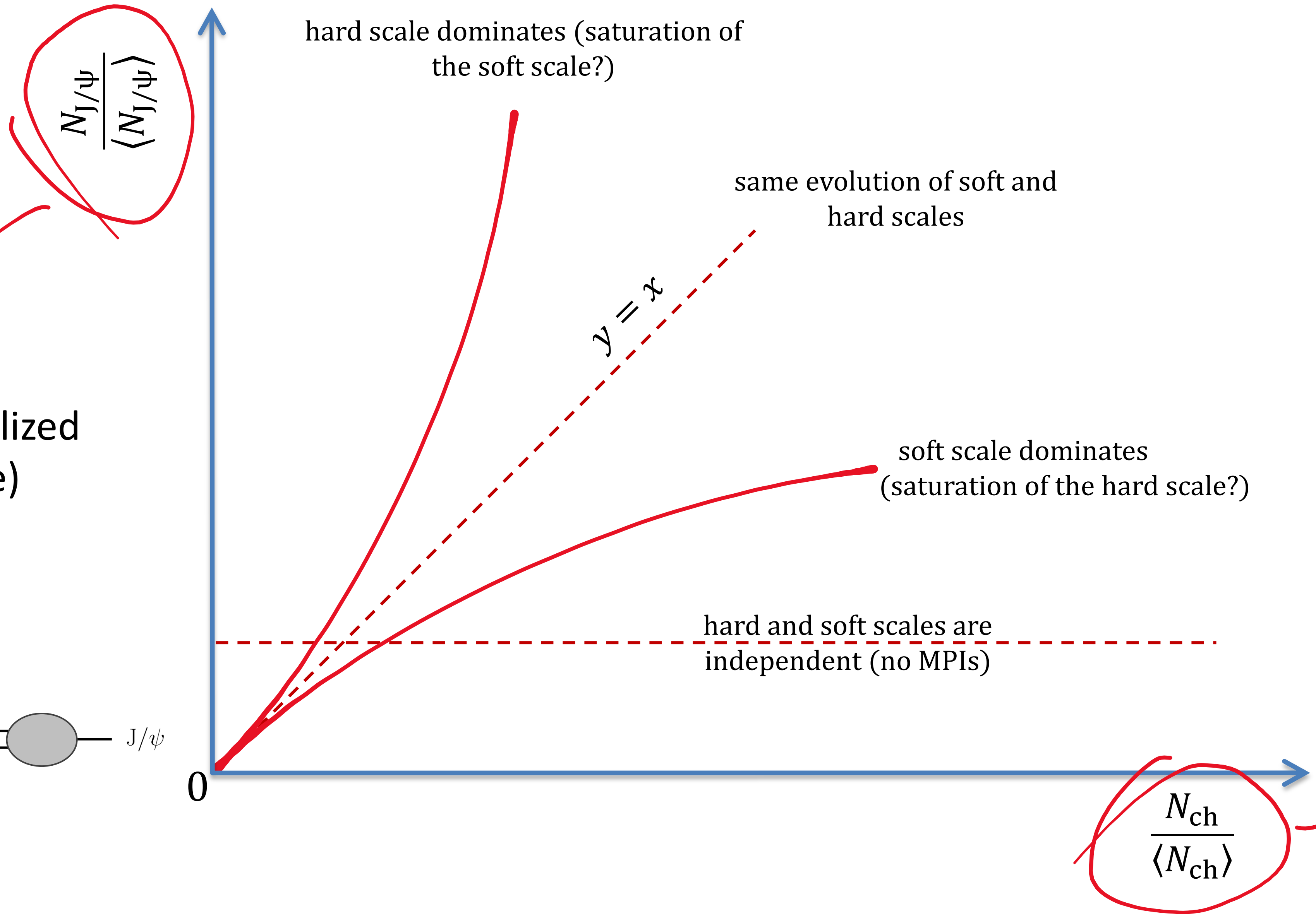
➔ One of the possible mechanisms responsible for the existence of high charged-particle multiplicity density events

Complex picture:

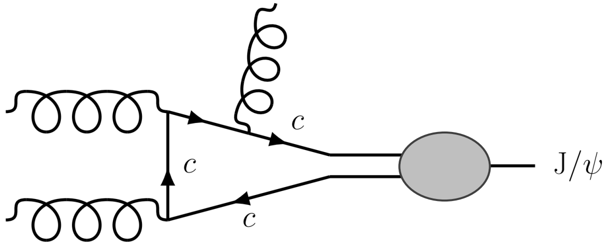
- Mix of soft and hard partonic interactions
- Re-interaction of partons with others: ladder splitting
- Re-interaction within ladders either in initial state (screening, saturation) or in final state (color reconnection)
- Initial-state radiation (ISR) and final-state radiation (FSR), hadronic activity accompanying hard processes

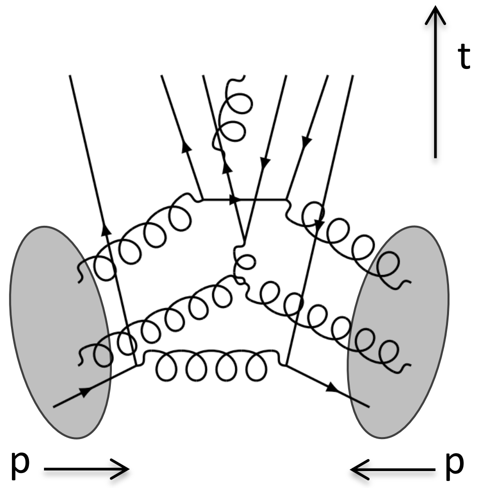
MPIs play a significant role in describing the soft component of the hadronic interactions: implemented in generators to describe the charged-particle multiplicity distributions in hadronic interactions

What to expect?



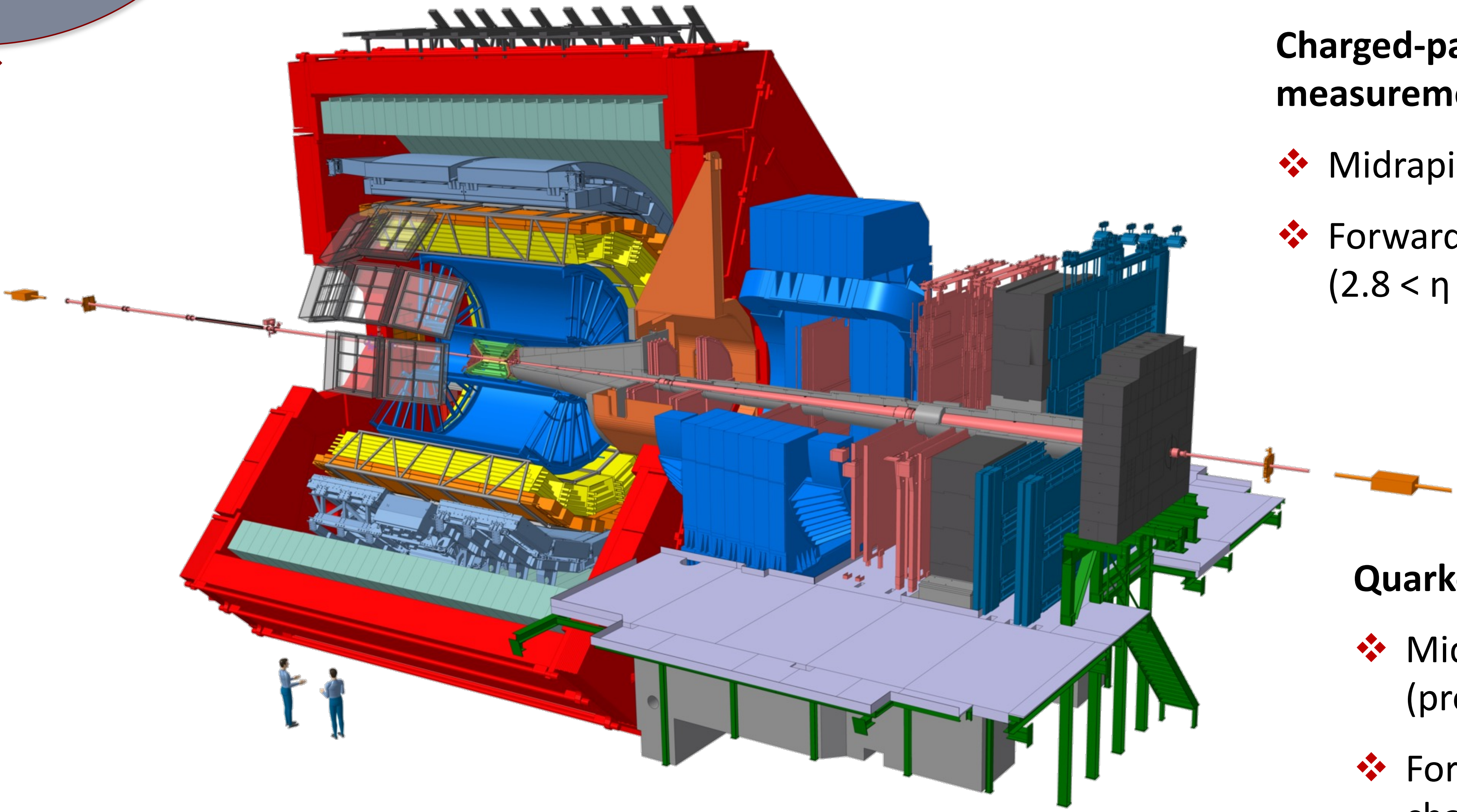
J/ψ yield (normalized to its mean value) increases with $N_{MPI,hard}$





Charged-particle multiplicity (normalized to its mean value) increases with N_{MPI}

Quarkonium and Multiplicity in ALICE (Runs 1+2)



Charged-particle multiplicity measurement:

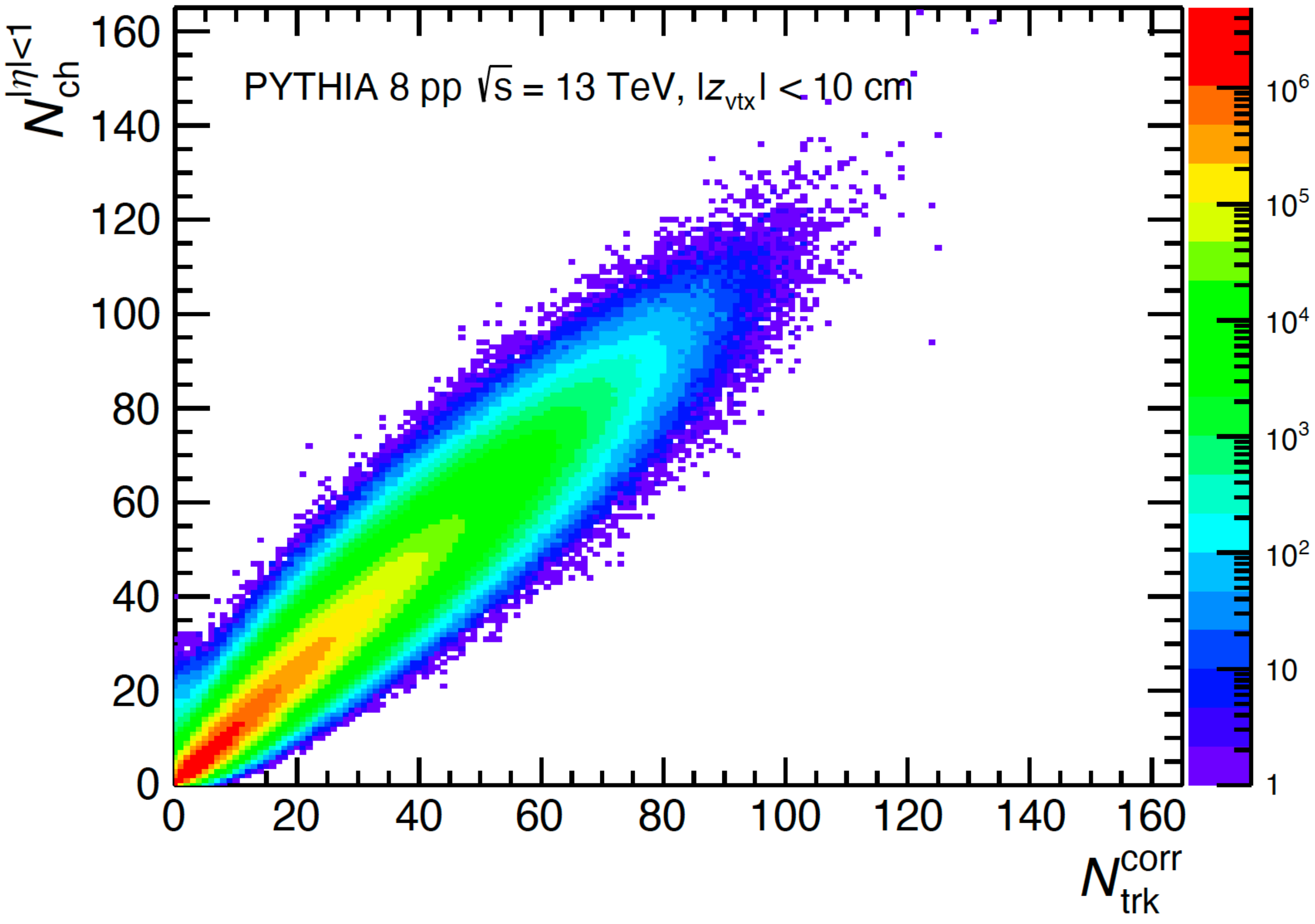
- Midrapidity: ITS (SPD, $|\eta| < 1$)
- Forward rapidity: V0 ($2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$)

Quarkonium measurement:

- Midrapidity: dielectron channel (prompt, non-prompt)
- Forward rapidity: dimuon channel (inclusive only)

Multiplicity Estimation

Monte Carlo simulations: correlation between the experimental proxy (number of tracklets in the SPD, amplitude of the V0 signal) and the number of charged particles in a given pseudorapidity region



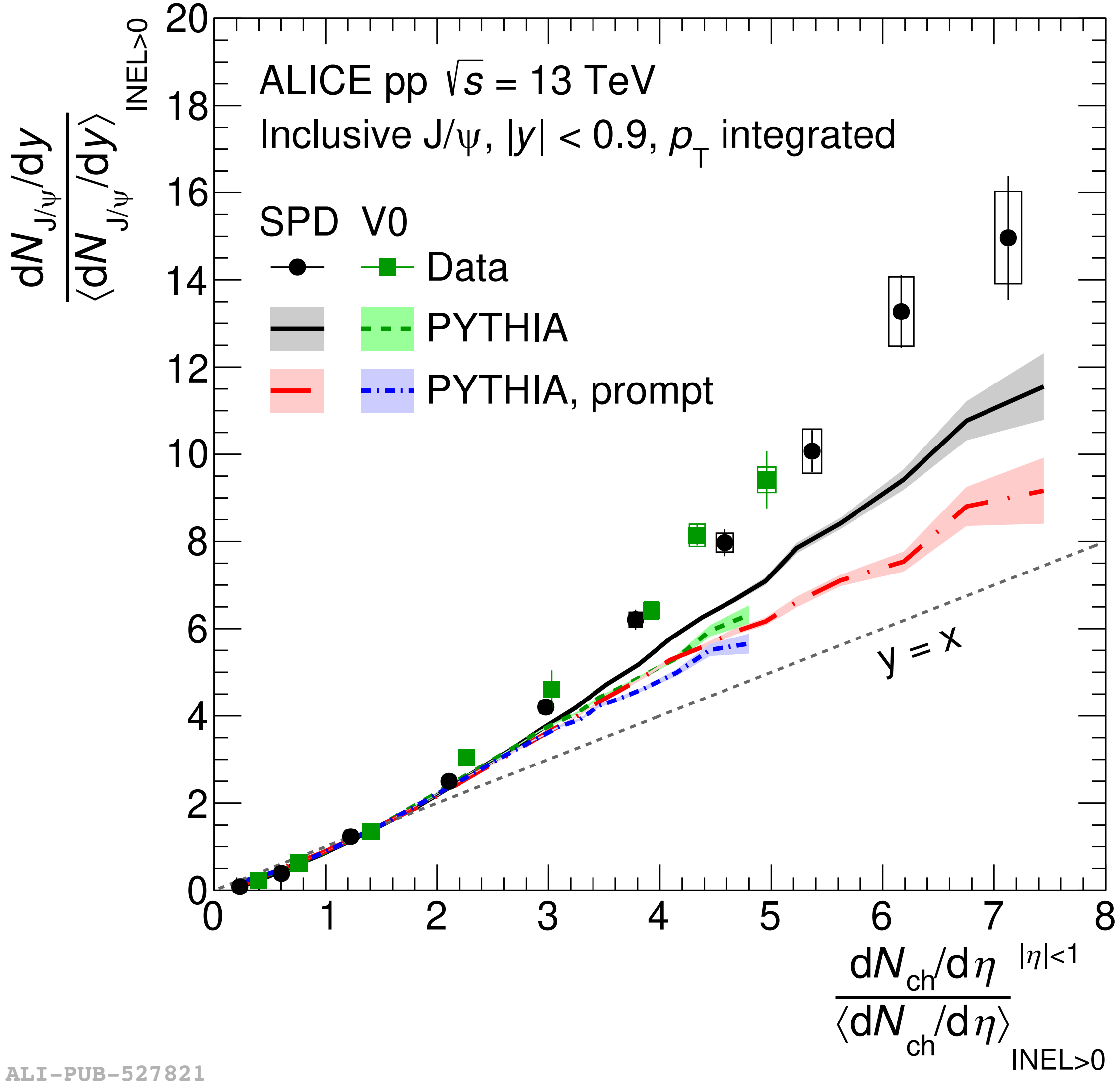
Profile of the correction fitted with an ad-hoc function. Two or more alternative MC models considered to estimate the systematic uncertainty

To be accounted for:

- Geometrical acceptance (dead zones, z_{vtx} dependence)
- Aging effects (for the V0)
- Removal of the signal corresponding to the decay products of the quarkonium state

J/ψ production at midrapidity

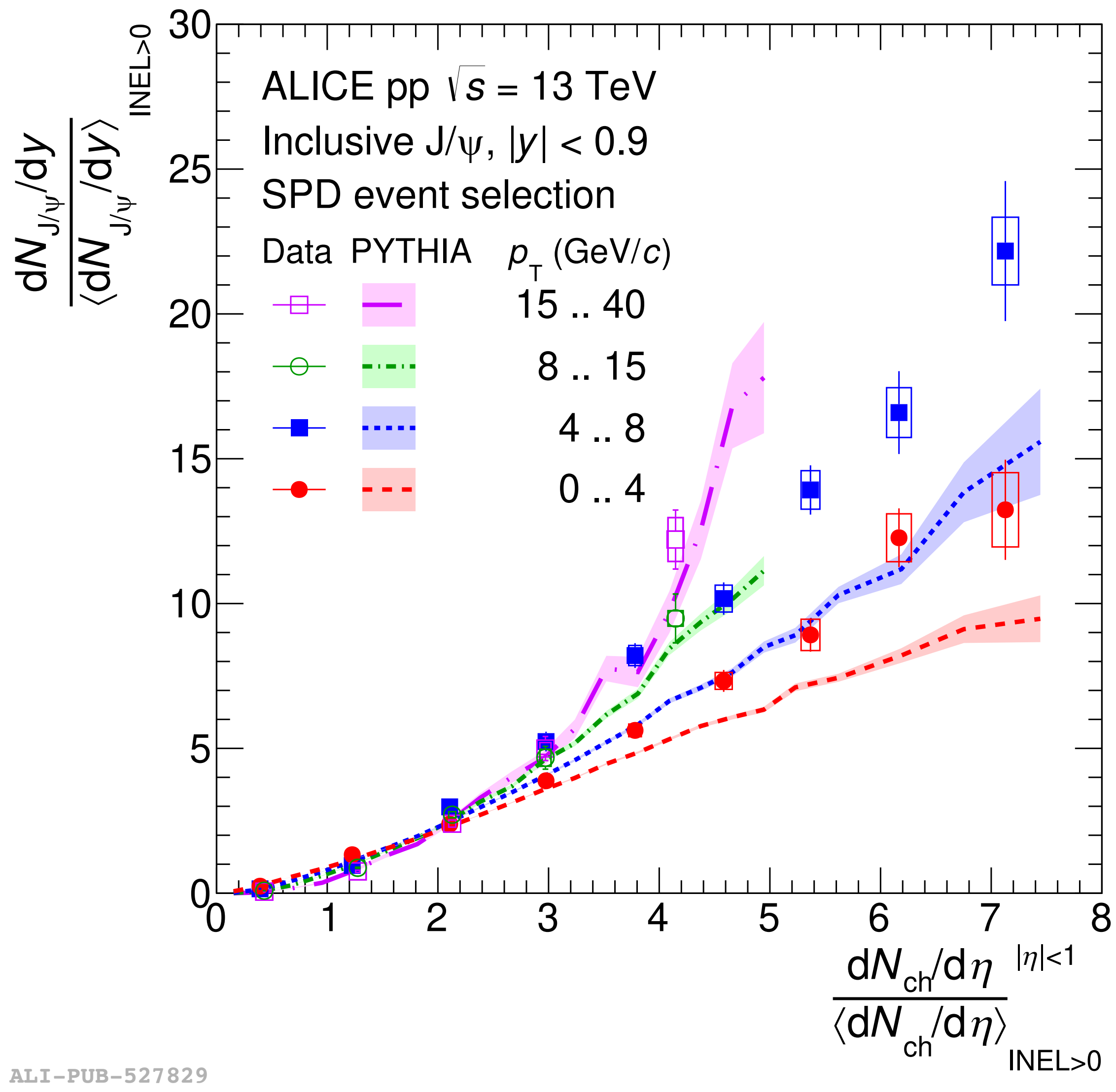
Phys. Lett. B 810 (2020) 135758



- **Faster than linear increase of inclusive J/ψ self-normalized yield with multiplicity**
- The trend doesn't seem to depend on the pseudorapidity region where the multiplicity is estimated

J/ψ production at midrapidity

Phys. Lett. B 810 (2020) 135758

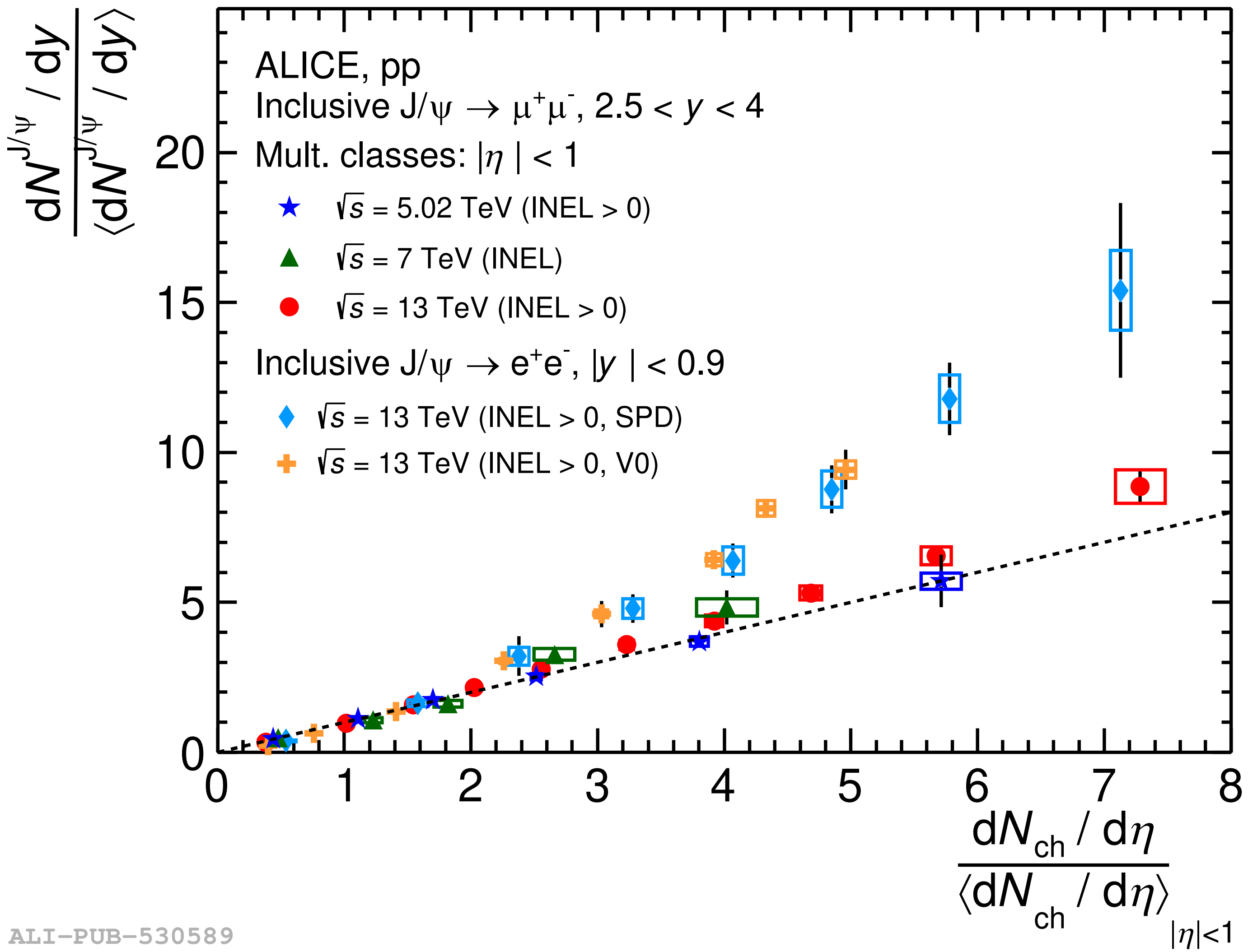


- **Faster than linear increase of inclusive J/ψ self-normalized yield with multiplicity**
- The trend doesn't seem to depend on the pseudorapidity region where the multiplicity is estimated
- **The multiplicity dependence varies as a function of p_T: stronger enhancement at higher p_T**
- PYTHIA 8.2 qualitatively describes the p_T dependence of the multiplicity dependence

J/ψ production at forward rapidity

Comparison between J/ψ measurements at mid and forward rapidity

JHEP 06 (2022) 015



Observations at forward rapidity:

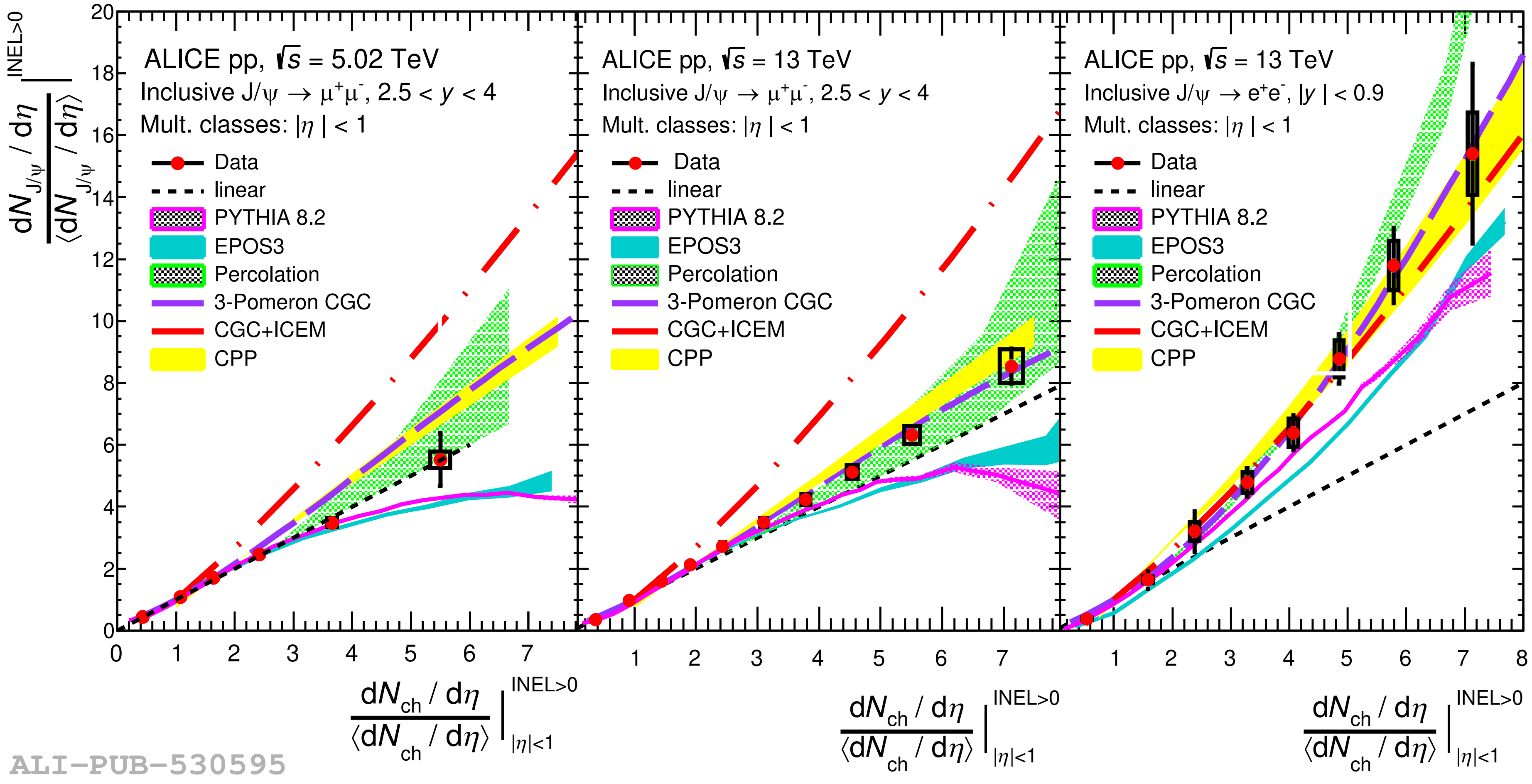
- Almost linear trend, small departure from linearity
- Weak dependence on energy (5 → 13 TeV)

Stronger increase for mid compared to forward rapidity:

- Different role of initial state effects (i.e. saturation) in the two rapidity regions?
- Autocorrelations at midrapidity? But the results don't change when defining the multiplicity classes at forward rapidity…

J/ψ production at forward rapidity

Most of the models describe data qualitatively, catching the difference between mid and forward rapidity. PYTHIA8 and EPOS3 always underestimate the data, while CGC+ICEM overestimates forward rapidity data



- **3-pomeron CGC, CGC+ICEM:** initial-state effects only (MPIs, gluon saturation)
- **PYTHIA8, EPOS3, Percolation, CPP (coherent particle production):** both initial-state and final-state effects

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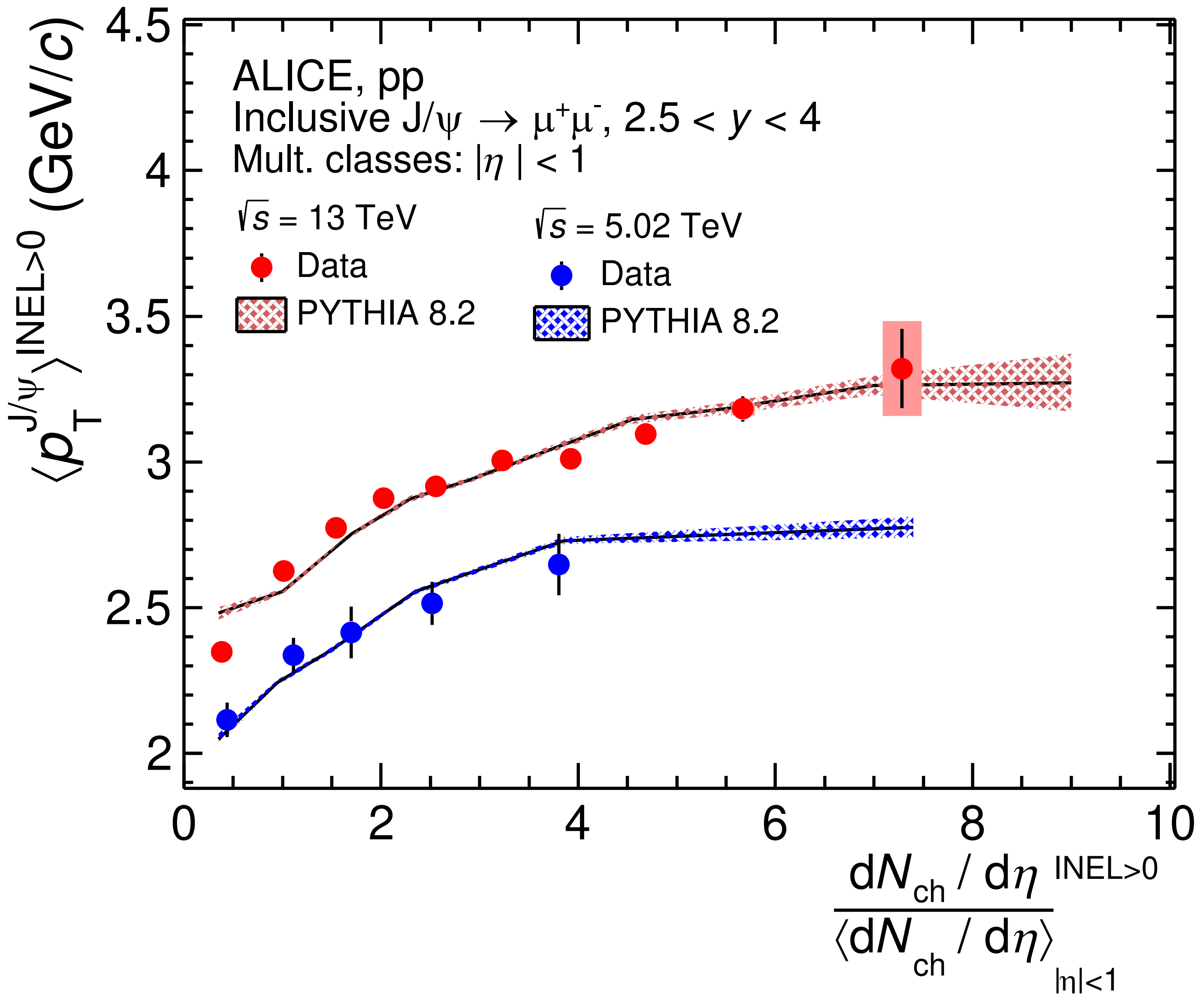
J/ψ production at forward rapidity: mean p_T



- **Increase of $\langle p_T \rangle$ as a function of the multiplicity** at both 5 and 13 TeV, coherent with the trend observed at mid-rapidity
- Saturation at high-multiplicity → good agreement with PYTHIA8. Weaker role of Color Reconnection, leading to an incoherent superposition of MPI?

JHEP 06 (2022) 015

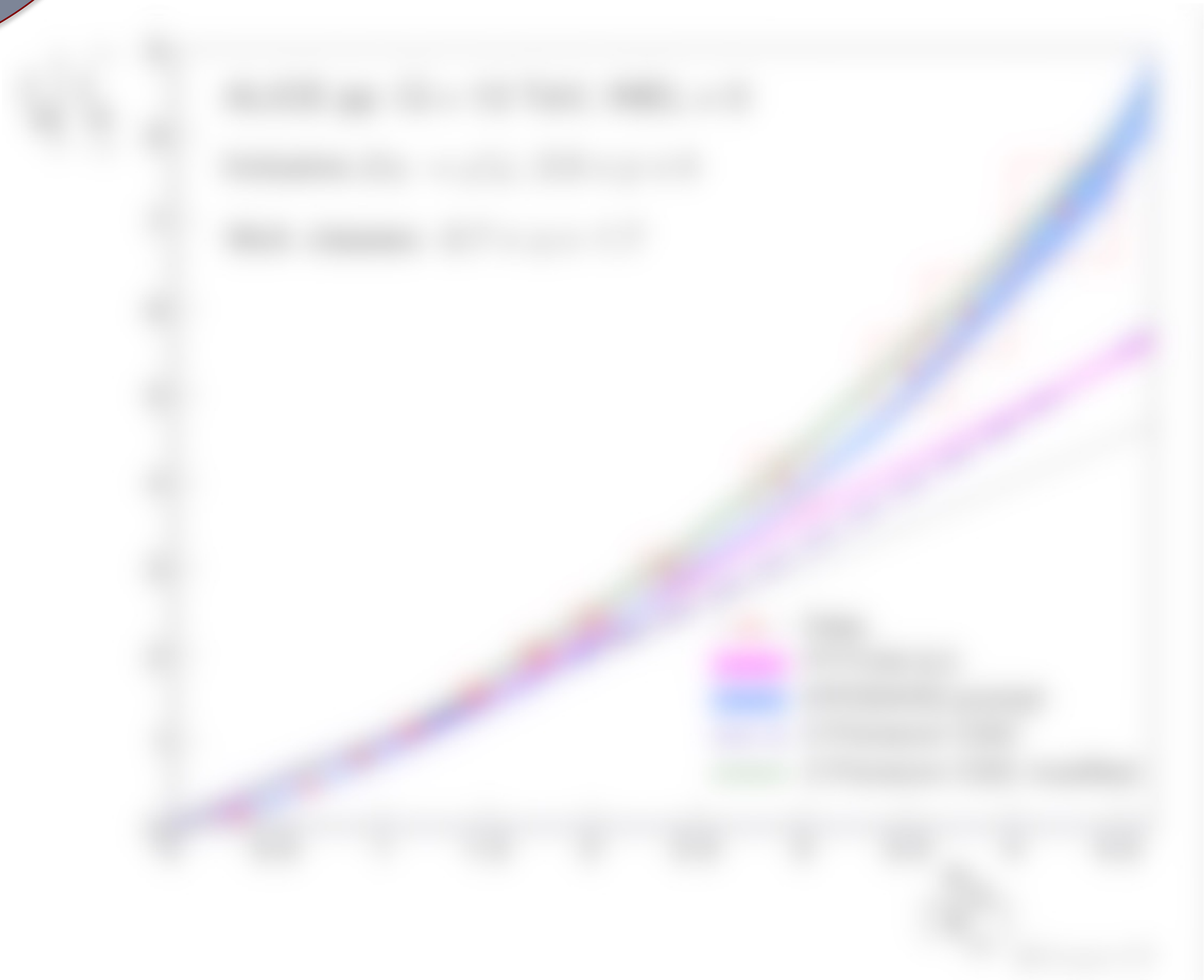
J/ψ production at forward rapidity

Sarah Herrmann's PhD thesis, work in progress (with C. Cheshkov, A. Uras)

Both J/ψ and multiplicity measured at forward rapidity:

- Stronger-than-linear trend
- Compatible with the results where both J/ψ and multiplicity are measured at mid-rapidity
- Auto-correlations strike back… but what about the results with J/ψ at mid-rapidity and the multiplicity at forward rapidity??

J/ψ production at forward rapidity



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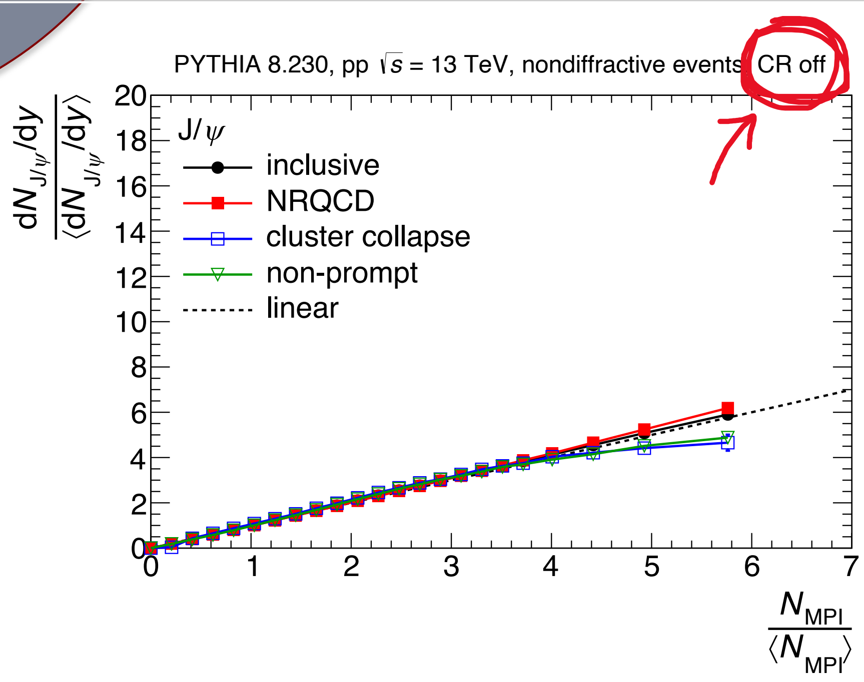
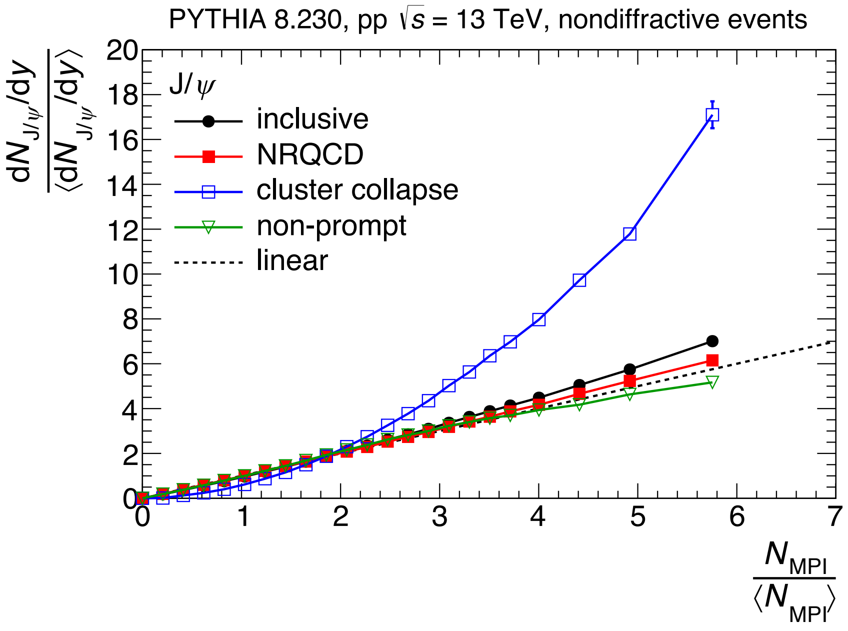
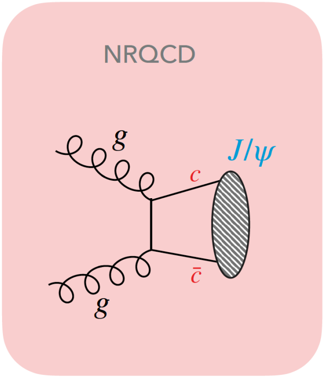
Auto-Correlations: what PYTHIA says

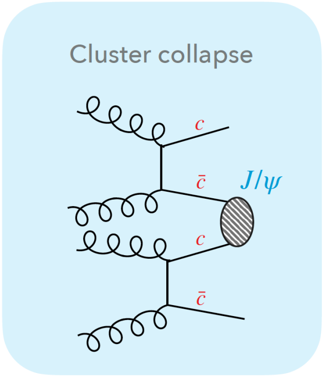


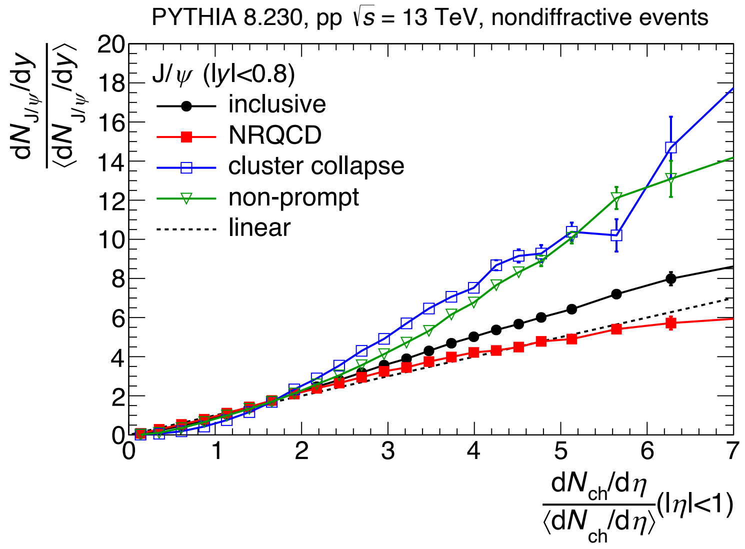


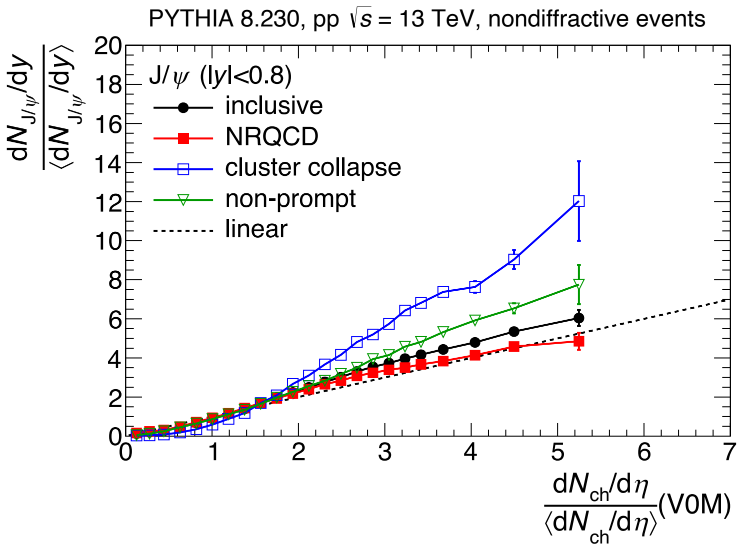
Color Reconnection activates mechanisms responsible for faster-than-linear trends

Eur. Phys. J. C (2019) 79:36



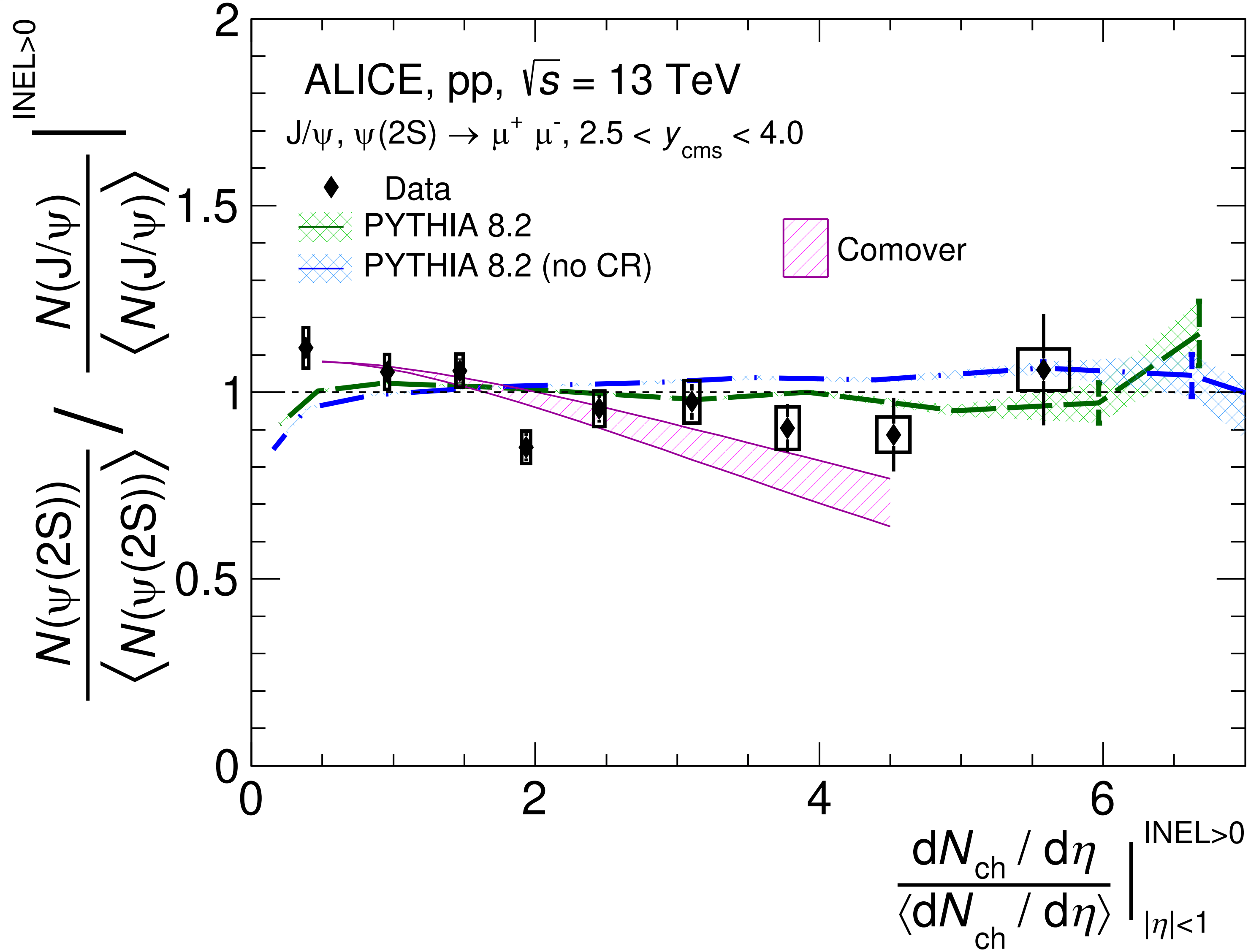






Cluster collapse: main responsible for autocorrelations inducing faster-than-linear trends vs multiplicity, even when signal and multiplicity are measured in different rapidity regions

ψ(2S) production at forward rapidity

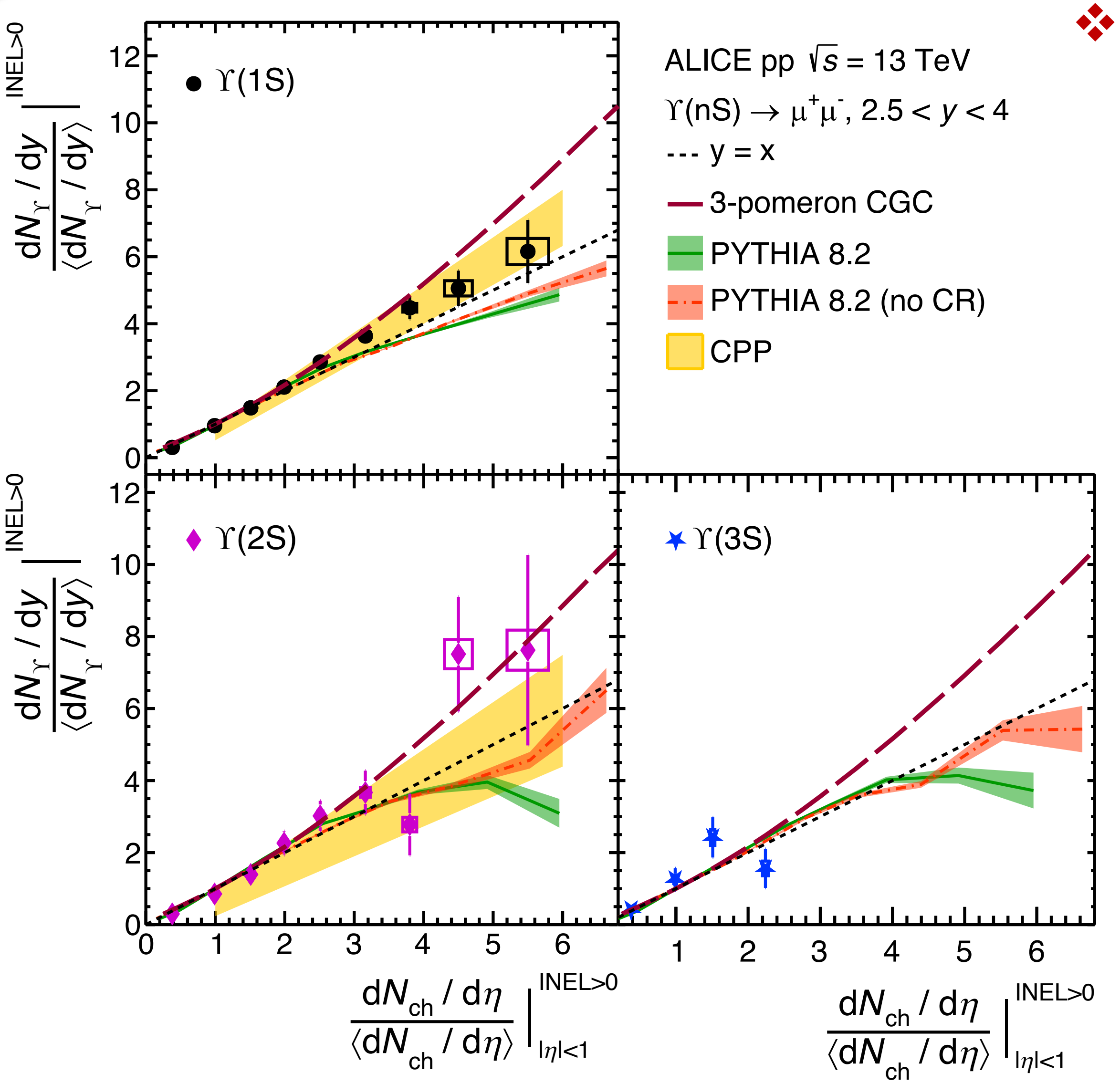


Same trend as J/ψ as a function of multiplicity, but smaller multiplicity reach due to limited statistics

- No evidence for ψ(2S) suppression relative to J/ψ within current uncertainties
- Comover: quarkonium breaking by co-moving particles in the medium → higher dissociation probability for ψ(2S) w.r.t. J/ψ
- Comover model not excluded as well, within the current uncertainties

JHEP 06 (2023) 147

Υ(nS) production at forward rapidity

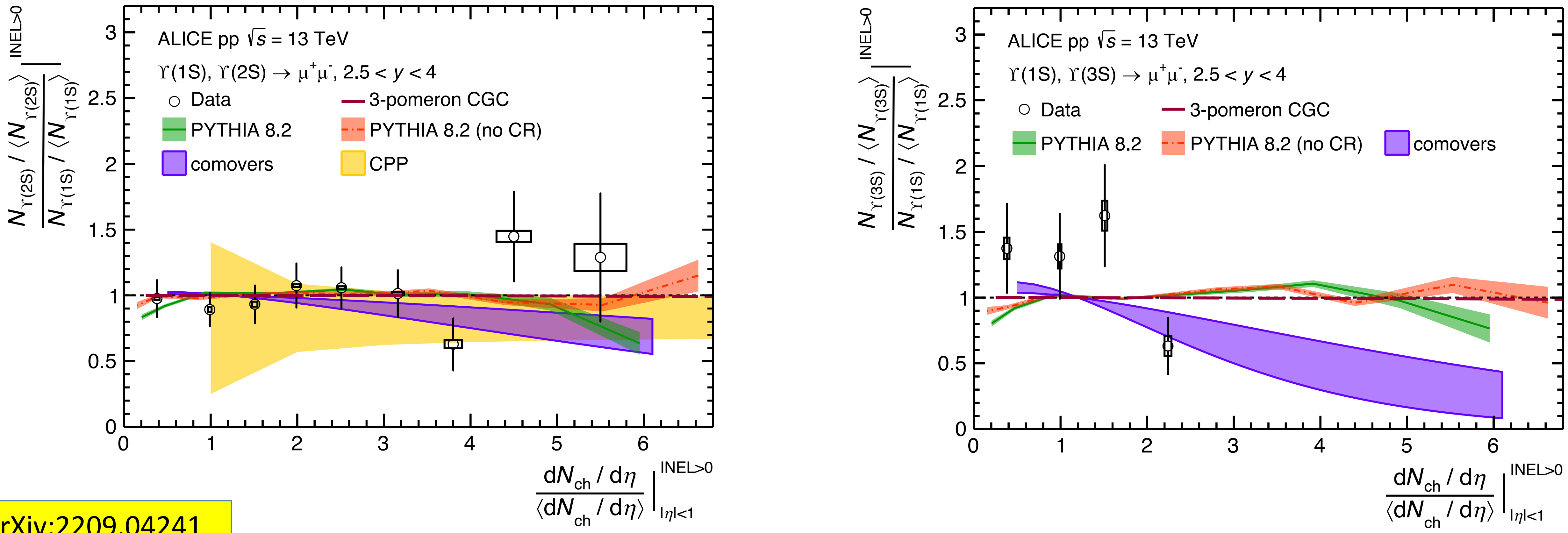


- Bottomonium production measured at forward rapidity as a function of the multiplicity estimated at mid-rapidity: no evidence of departure from linearity
  - Good agreement between models and data, at least until ≈ 4 times the average multiplicity
- Statistically limited measurement, especially for Υ(3S)
- Consistent with the measurements at mid-rapidity by CMS (not shown here)

Yanchun Ding PhD (CCNU + IP2I-Lyon)

arXiv:2209.04241

Υ(nS) production at forward rapidity: excited/ground

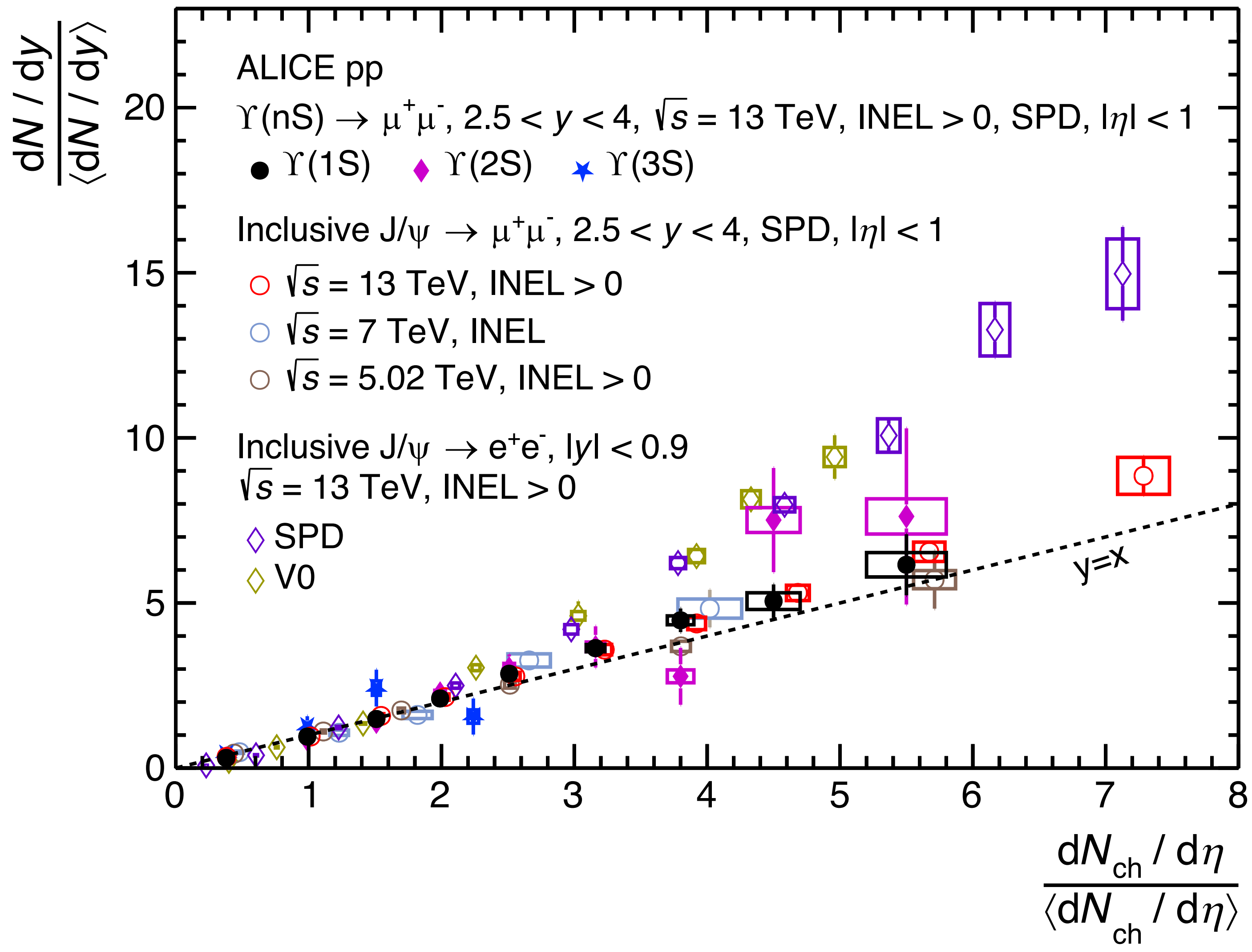


arXiv:2209.04241

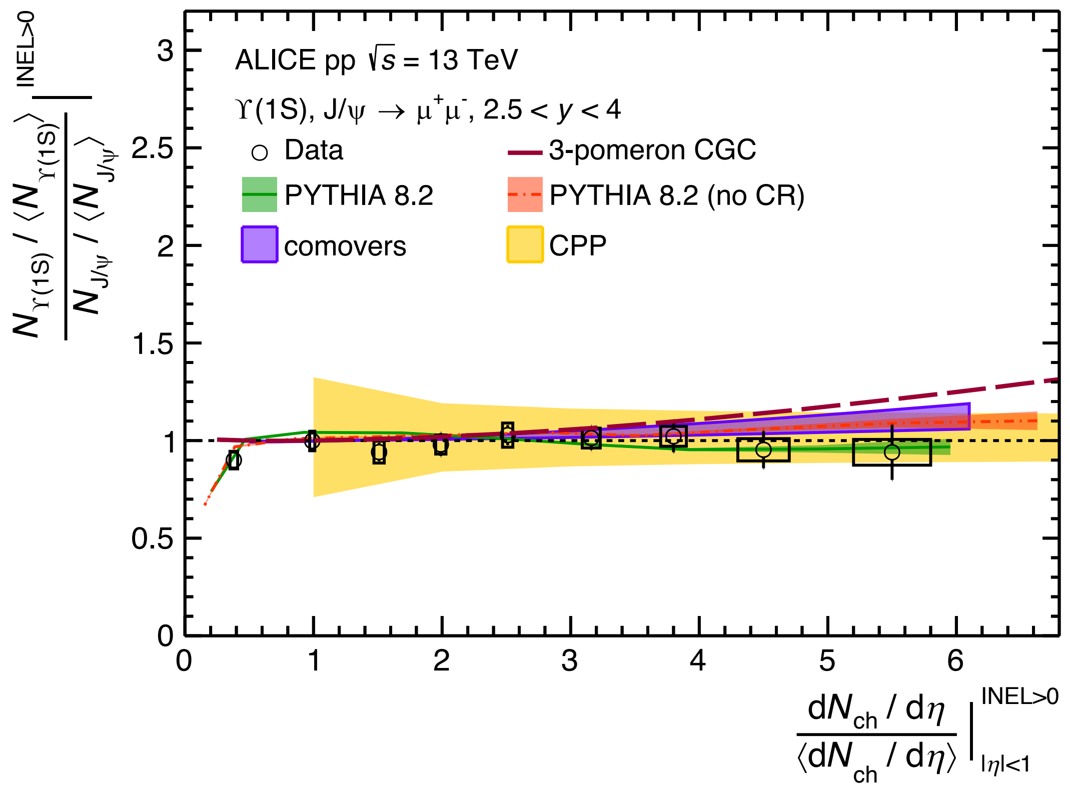
- Limited statistics for the excited states → data compatible with all models within uncertainties
- **No evidence of increased dissociation as a function of multiplicity for the less bound states**

An overall picture?

arXiv:2209.04241



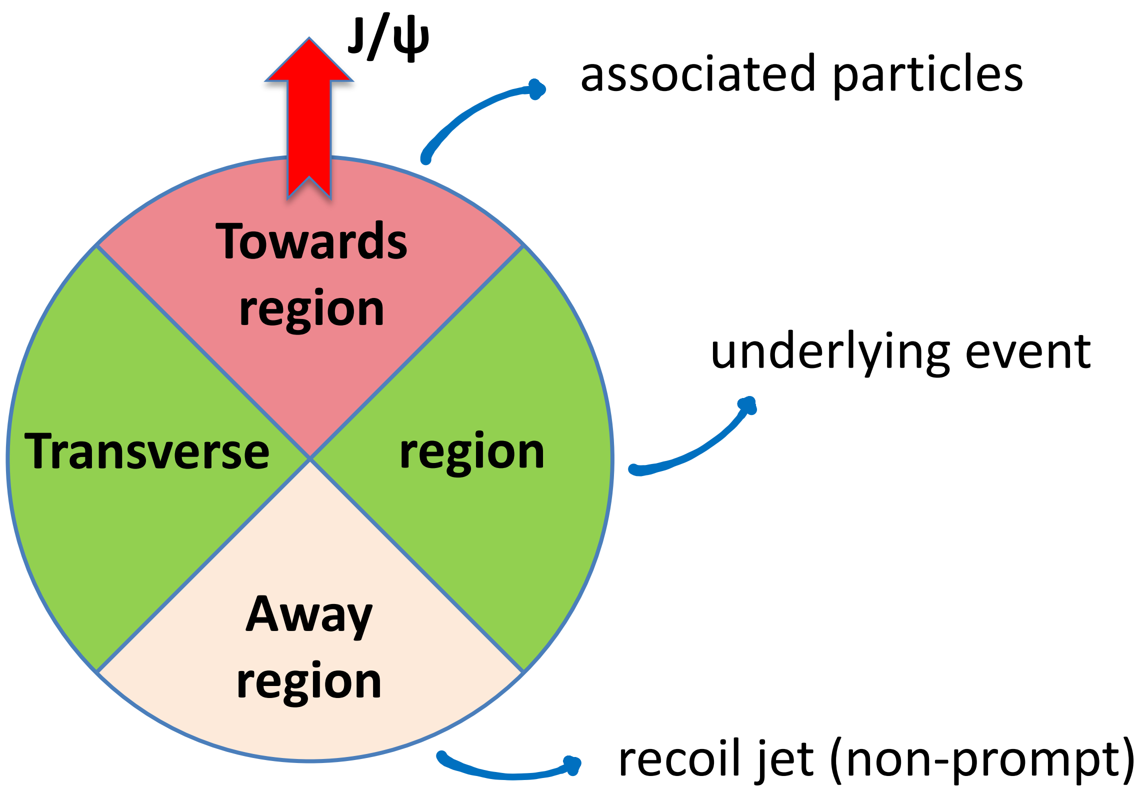
Similar scaling with the self-normalized charged-particle multiplicity density for charmonium and bottomonium states at forward rapidity



More to come…

Identify non-prompt production to disentangle the corresponding, specific effects (e.g. recoil jets)

Multiplicity separated in azimuthal regions → characterize (and disentangle) auto-correlation effects
(see talk by A. Morsch and Eur. Phys. J. C 79, 36 (2019))



Other avenues:

- J/ψ as function of transverse-spherocity → event-shape observable to distinguish hard-QCD (jetty) and soft-QCD (isotropic) events
- Further reduce the bias arising from local multiplicity fluctuations and auto-correlation effects studying the event flattenicity (see talk by A. Ortiz)

Conclusions and Outlook

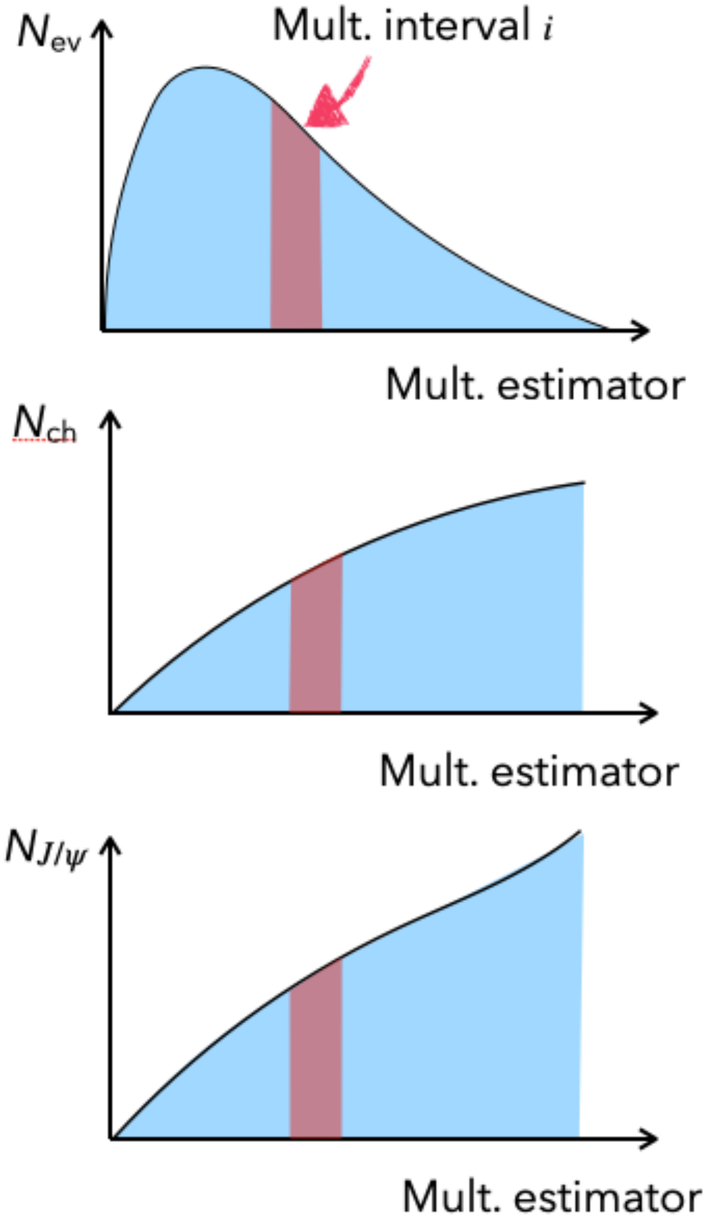
Quarkonium vs multiplicity → production mechanism + interplay between soft and hard scales. Some questions still hanging, despite the increasing number of measurements…

- J/ψ: stronger-than-linear and linear increase both observed in data. Driven by the rapidity region of the signal or by the rapidity gap between signal and multiplicity?
- $\psi(2S)$: No evidence for $\psi(2S)$ suppression relative to J/ψ within current uncertainties
- Bottomonium measured at forward rapidity as a function of the multiplicity estimated at mid-rapidity: no evidence of departure from linearity
- Models reproduce some features of the data both for charmonium and bottomonium → not yet able to disentangle the role of initial-state and/or final-state effects with the current uncertainties
- Expectation for Run 3 and 4: better secondary vertex resolution at midrapidity for prompt/non-prompt separation, secondary vertexing at forward rapidity (MFT), better multiplicity estimation at forward rapidity (MFT), higher minimum bias statistics, new ideas to better control auto-correlations

Backup Slides

What are the observables ?

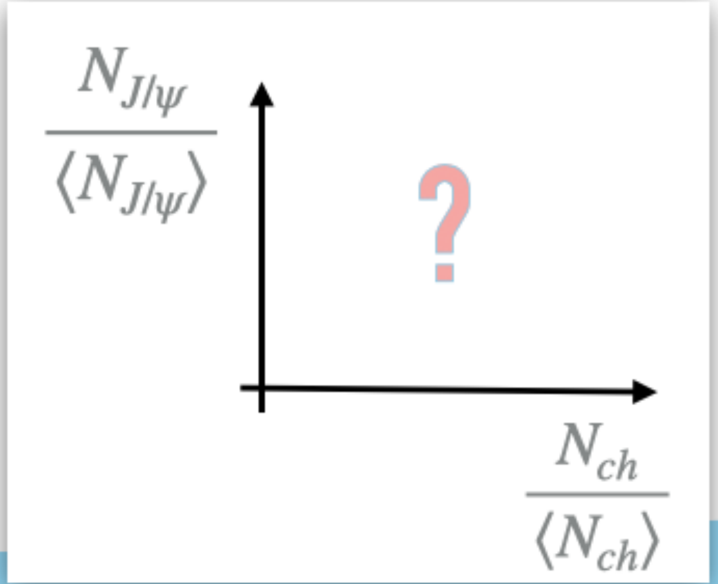
(courtesy Sarah Herrmann)



Determine multiplicity intervals using a multiplicity estimator in Minimum Bias events

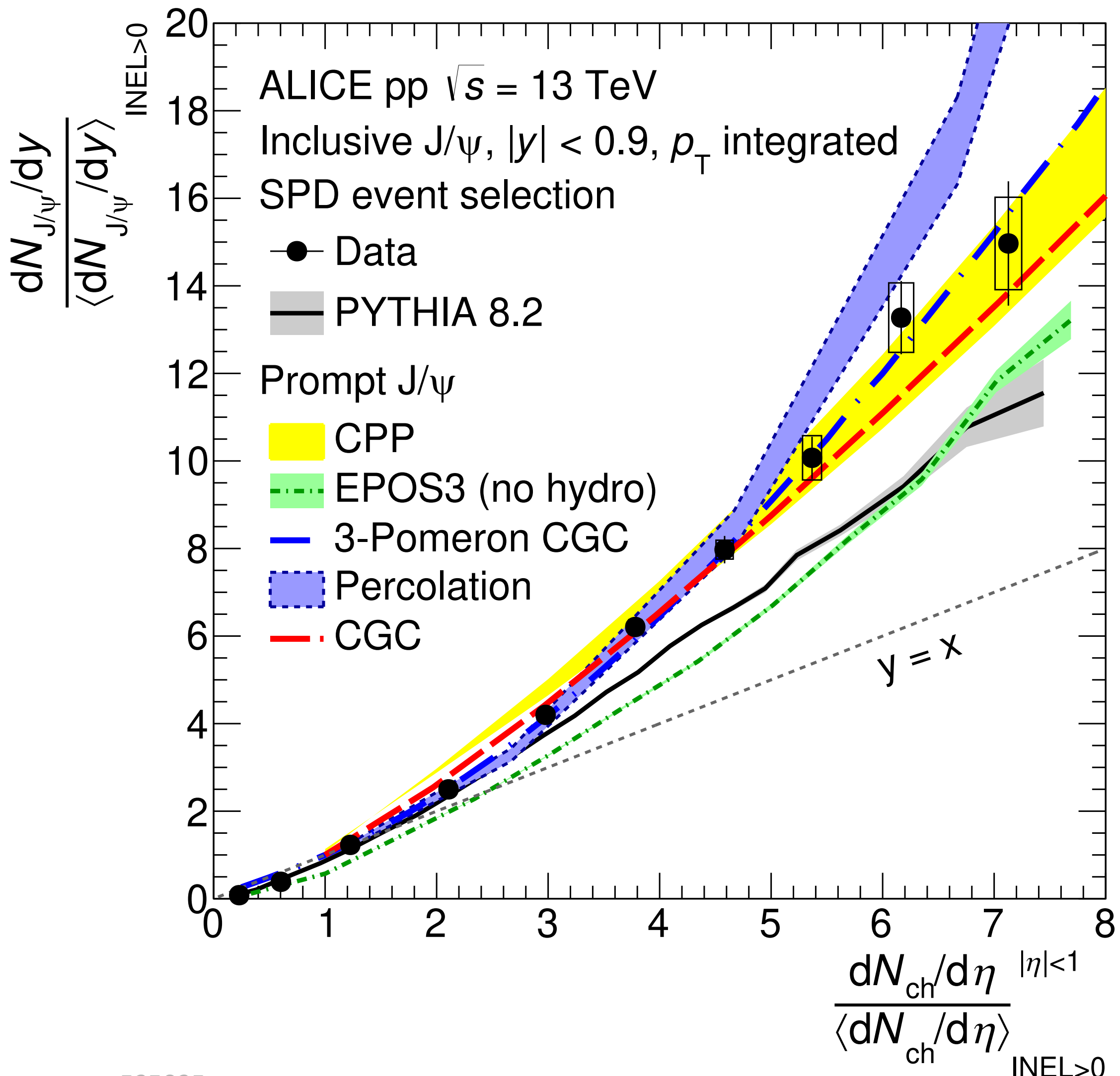
$$\frac{N_{ch}(i)}{\langle N_{ch} \rangle} = \text{Relative multiplicity value in interval } i$$

$$\frac{N_{J/\psi}(i)}{\langle N_{J/\psi} \rangle} = \frac{J/\psi \text{ yield in mult. interval } i}{J/\psi \text{ yield in all MB events}}$$



J/ψ yield = number of J/ψ per event

J/ψ production at midrapidity



ALI-PUB-527825

- Faster than linear increase of inclusive J/ψ self-normalized yield with multiplicity
- The trend doesn't seem to depend on the pseudorapidity region where the multiplicity is estimated
- Most of the models describe data qualitatively, but PYTHIA and EPOS3 underestimate the increase of the J/ψ yield with multiplicity

PYTHIA 8.2: Eur. Phys. J. C79 no. 1, (2019) 36
EPOS3: Phys. Rev. C89 no. 6, (2014) 064903
Percolation: Rev. C86 (2012) 034903
CPP: Phys. Rev. D88 no. 11, (2013) 116002
3-Pomeron CGC: Eur. Phys. J. C 80 no. 6, (2020) 560
CGC: Phys. Rev. D98 no. 7, (2018) 074025