Graduiertenkolleg 2149
Research Training Group

Universität Münster

Multiplicity-dependent quarkonia measurements from pp to p-Pb collisions

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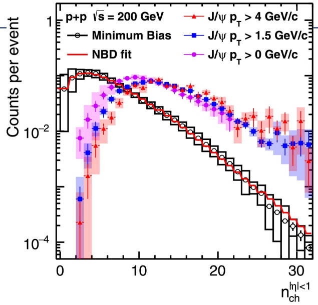
Quarkonia As Tools 2025

Motivations

At RHIC:



Phys.Lett.B 786 (2018) 87-93, arXiv:1805.03745

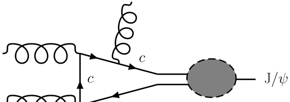
- Heavy quarks produced in hard scattering
  → **Quarkonium = hard scale** (+ hadronization)
- Most charged particle produced in soft scattering
  → **Charged-particle multiplicity = soft scale**

Different scales: affected differently by several effects (including Multiple Partonic Interactions)

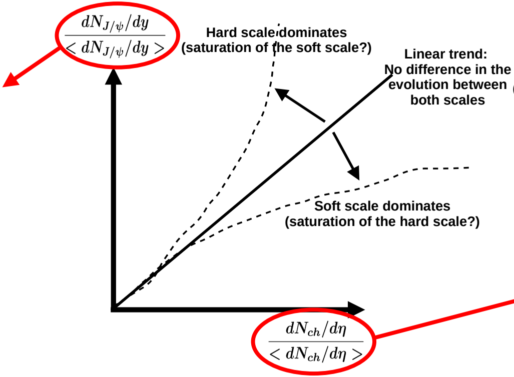
- **What if we correlate both together?** → interplay and differences between hard and soft scale

What is happening in **high charged-particle multiplicity density** environment? → Study (smooth??) evolution from pp to p-Pb and Pb-Pb

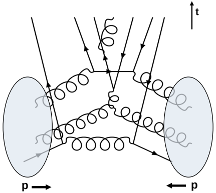
What could we expect?



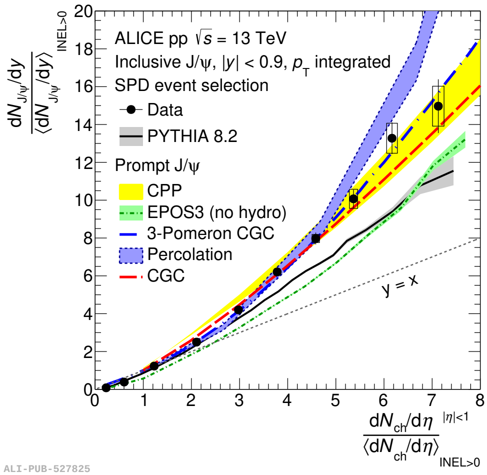
J/ψ yield (normalised to its mean value) **increases** with $N_{MPI_{hard}}$



Charged-particle multiplicity (normalized to its mean value) increases with N_{MPI} (= Multiple Parton-parton Interactions in the same collision)



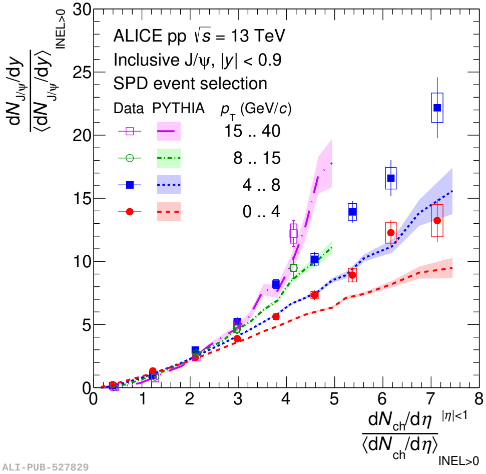
Self-normalized J/ψ



- **Stronger-than-linear increase** when both J/ψ and multiplicity at midrapidity
- Reproduced qualitatively by models implementing:
  - **initial-state** effects (MPI, gluon saturation in Color Glass Condensate...)
  - **final-state** effects (high string density...)
- Also quarkonium production mechanism and decays could come into play

PLB 810 (2020) 135758, arXiv:2005.11123

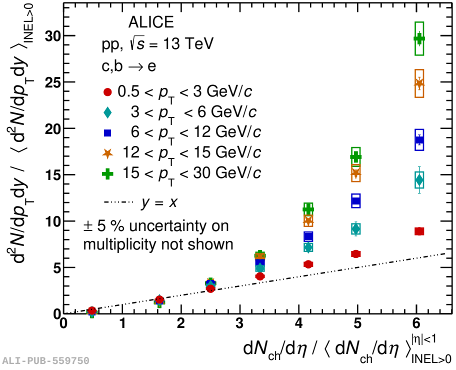
Self-normalized J/ψ



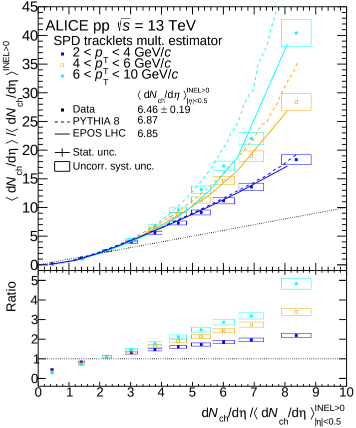
PLB 810 (2020) 135758, arXiv:2005.11123

- **Stronger increase** with **higher p_T**
- Inclusive J/ψ measurement: any difference between prompt and non-prompt J/ψ?
- Pythia also reproduces increase with p_T, but always underestimates data
- → Any link with Pythia underestimating event activity associated with prompt J/ψ?

Multiplicity dependence of hard probes



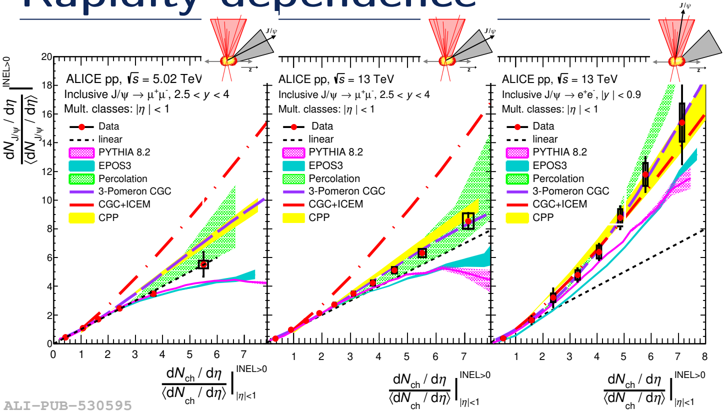
JHEP 08 (2023) 006, arXiv:2303.13349



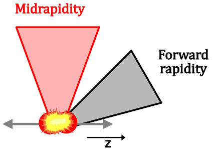
Eur. Phys. J. C 79 (2019) 857, arXiv:1905.07208

- Stronger-than-linear increase not specific to J/ψ, but also appears for other hard probes

Rapidity dependence



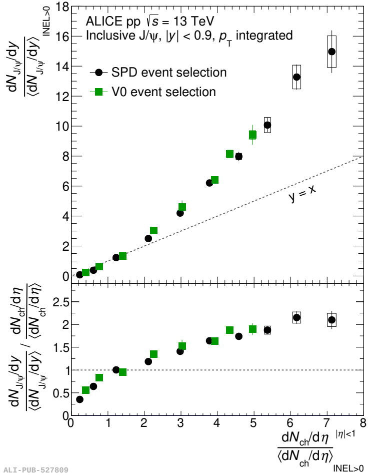
JHEP 06 (2022) 015, arXiv:2112.09433v2



- J/ψ at forward or midrapidity, multiplicity at forward rapidity
- Increase faster at midrapidity than at forward rapidity

- **Rapidity gap** in forward measurement: remove effects of **associated particles** (hadronization, decays)
- However, in pp collisions, high charged-particle density at midrapidity does not necessarily mean high density also at forward rapidity

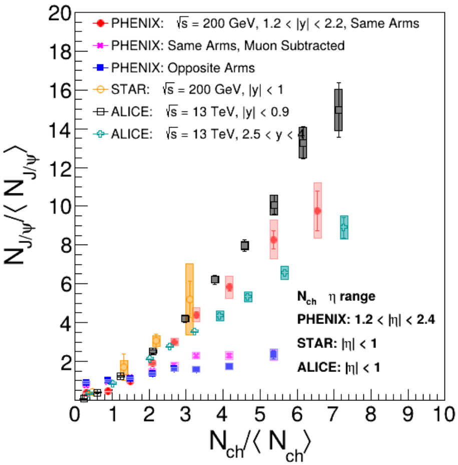
Impact of the autocorrelations



PLB 810 (2020) 135758, arXiv:2005.11123

- SPD selection: multiplicity measured directly at midrapidity
- V0 selection: multiplicity measured at forward rapidity, then converted to midrapidity multiplicity using correlation from unbiased events
- V0 selection supposed to **remove effects of associated particles** (autocorrelations) → similar increase could indicate no autocorrelation effects
- However, presence of J/ψ could influence the whole event (including through recoil), including forward rapidity → interpretation not straightforward

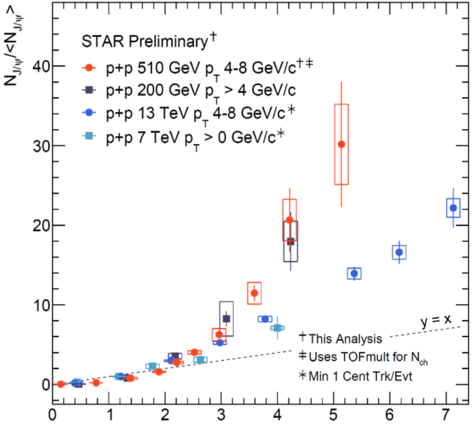
At RHIC



arXiv:2409.03728

- Self-normalized increase with multiplicity also measured at RHIC (PHENIX and STAR)
- **Lower increase** for PHENIX compared to ALICE (but different rapidity regions)
- RHIC energy: Lower charged-particle multiplicity → **less effects** due to **density and saturation**
- However, higher relative impact of associated particles (complicating the interpretation) → seen for example when removing the decay daughters N_{ch}

At RHIC

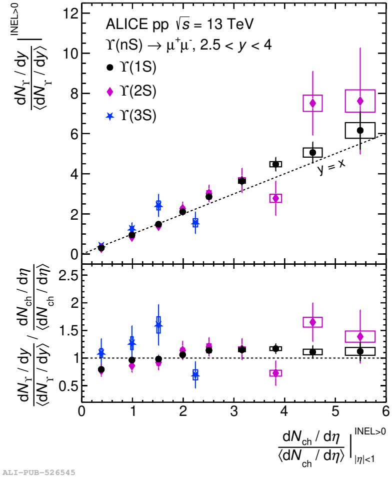


STAR, Physics Letters B 786 (2018) 87–93
ALICE, Phys. Lett. B 810 (2020) 135758
ALICE, Physics Letters B, 712 (2012) 165–175

STAR

- Self-normalized increase with multiplicity also measured at RHIC (PHENIX and STAR)
- STAR: stronger increase than ALICE for $4 < p_T < 8$ GeV/c

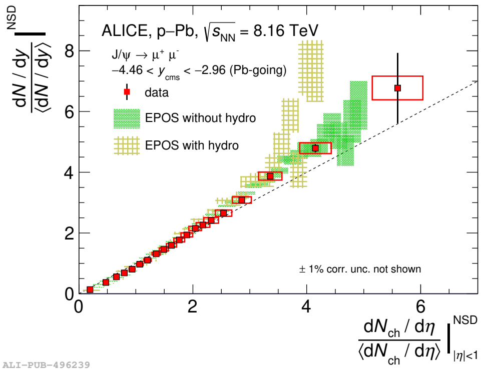
Multiplicity-dependent $\Upsilon(nS)$

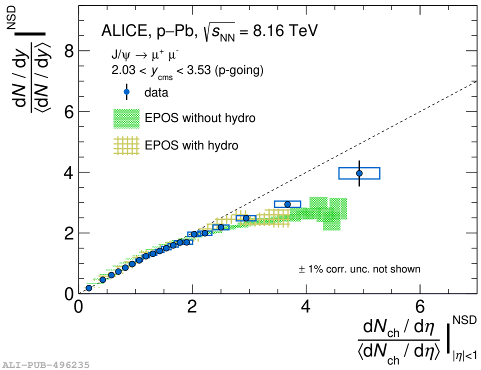


arXiv:2209.04241

- $\Upsilon(nS)$ measurement by ALICE at forward rapidity
- Bottomonium production: very similar to J/ψ measurement, no evidence of departure from linearity
- Statistically limited measurement, especially for $\Upsilon(3S)$

In p-Pb collisions

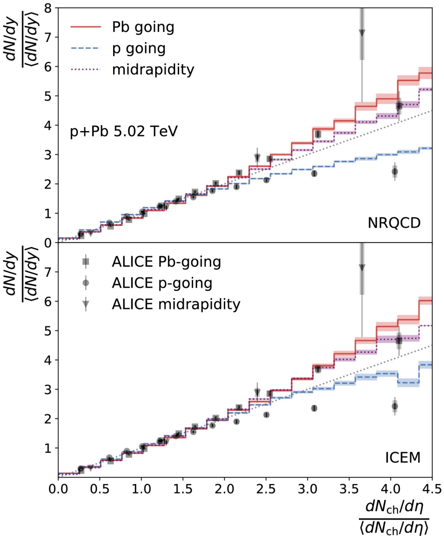




JHEP 2009 (2020) 162, arXiv:2004.12673

- **Stronger** increase in **Pb-going** direction than in **p-going** (multiplicity at midrapidity in both cases)

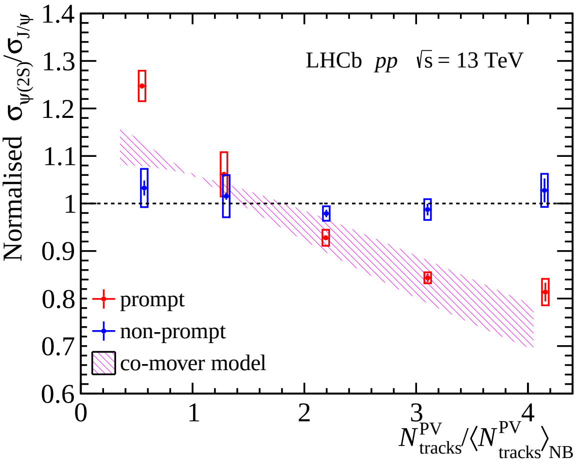
In p-Pb collisions, with CGC



Phys.Lett.B 827 (2022), arXiv:2112.04611

- Different **x values** probed inside the Pb (p-going: $x_{Pb} \sim 10^{-5}$, Pb-going: $x_{Pb} \sim 10^{-2}$)→ difference due to initial-state effects?
- Some calculations in the CGC framework with saturation also can reproduce the trend at forward and backward, however not at midrapidity
- However also **higher charged particle density** in Pb-going direction

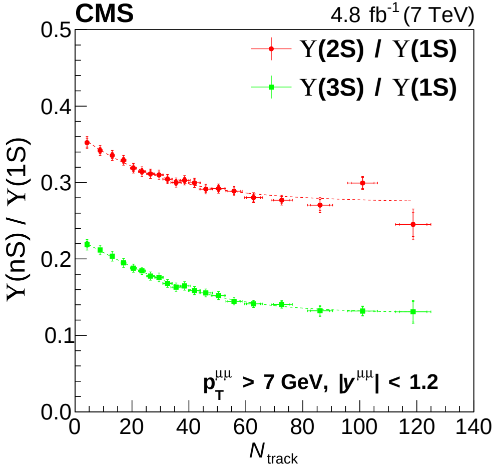
Excited-to-ground state ratios



JHEP 05 (2024) 243, arXiv:2312.15201

- **Decrease** of prompt $\psi(2S)$-to-J/ψ ratio with multiplicity seen by LHCb
- $\psi(2S)$ **less bound** than J/ψ → more sensitive to **final-state effects** at high-multiplicity
- **Medium** effects (as in PbPb) or **comover** effect (breaking by particles flying in the same direction)?

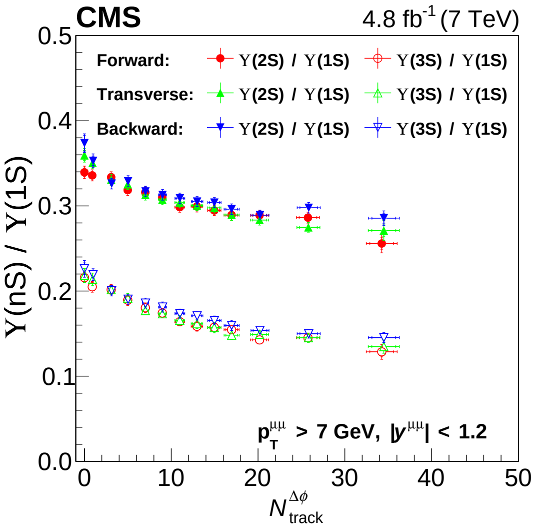
Excited-to-ground state ratios

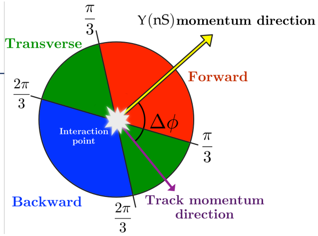


JHEP 11 (2020) 001, arXiv:2007.04277

- $\Upsilon(nS)$ measurement by CMS as a function of N_{track}
- **Higher suppression of excited states** with respect to ground state also in bottomonium sector

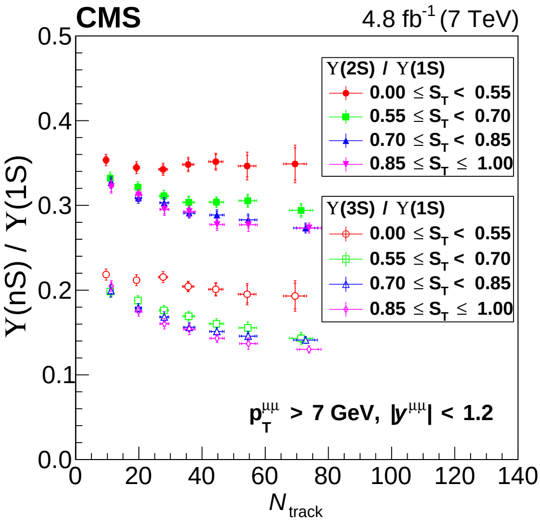
Excited-to-ground state ratios





- Multiplicity separated in 3 different **azimuthal regions** with respect to $\Upsilon(nS)$ momentum direction → investigate whether decrease depend on **local multiplicity**
- Decrease seen in all 3 regions → connected to **Underlying Event (UE)**?
- Separation in azimuthal regions → could also help understanding the impact of autocorrelations and UE in the increase of J/ψ production with multiplicity

Excited-to-ground state ratios



- Transverse sphericity: separate **isotropic** ($S_T \sim 1$) and **jetty** ($S_T \sim 0$) events
- Decrease is seen mainly in isotropic events, not when multiplicity is localized inside a jet

Conclusion

- Quarkonium vs multiplicity allows study of interplay between **hard and soft scales**, and evolution with system size

- Many results from different experiments show:
  - **Stronger than linear** increase with multiplicity
  - Slight **suppression of excited states** relative to ground states

- Interpretation involve **initial-state** or **high-density** effects, but also some impact of **quarkonium production mechanism** and **autocorrelations** → could measurement in different azimuthal or rapidity regions help understand it?

Thank you for your attention!

Model references

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CGC+ICEM: Y.-Q. Ma, P. Tribedy, R. Venugopalan, and K. Watanabe, "Event engineering studies for heavy flavor production and hadronization in high multiplicity hadron-hadron and hadron-nucleus collisions," Phys. Rev. D98 no. 7, (2018) 074025, arXiv:1803.11093

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CPP: B. Z. Kopeliovich, H. J. Pirner, I. K. Potashnikova, K. Reygers, and I. Schmidt, "J/ψ in high-multiplicity pp collisions: Lessons from pA collisions," Phys. Rev. D88 no. 11, (2013) 116002, arXiv:1308.3638

Comovers: E. G. Ferreiro, "Excited charmonium suppression in proton–nucleus collisions as a consequence of comovers", Phys. Lett. B 749 (2015) 98–103, arXiv:1411.0549

CGC (p-Pb comparison): F. Salazar, B. Schenke, A. Soto-Ontoso, "Accessing subnuclear fluctuations and saturation with multiplicity dependent J/ψ production in p+p and p+Pb collisions", Phys.Lett.B 827 (2022) 136952, arXiv:2112.04611