Multiplicity dependence of prompt and non-prompt J/ψ production in pp collisions with ALICE

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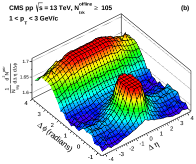
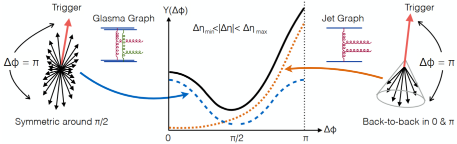
EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC

Motivations

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





Phys. Rev. Lett. 116 172302 (2016), Adv.High Energy Phys. 2016 (2016) 8460349

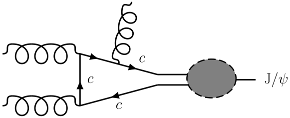
Hints of collective effects in high-multiplicity pp collisions, can be explained both by initial-state and final-state effects → further studies needed to understand what is happening there

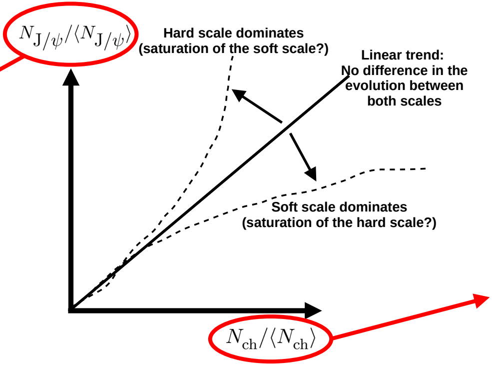
Different scales for particle production: affected differently by several effects (Multiple Partonic Interactions, gluon saturation, high string density or medium effects)

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

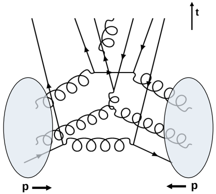
Why J/ψ vs multiplicity?

J/ψ yield (normalised to its mean value) increases with $\mathrm{N}_{MPI_{\mathrm{hard}}}$

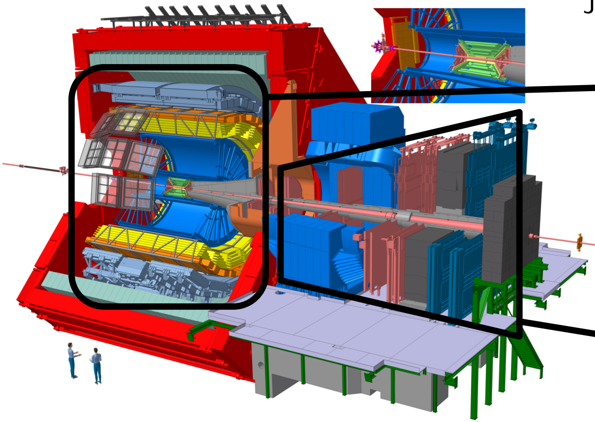




Charged-particle multiplicity (normalized to its mean value) increases with N_{MPI}



ALICE in Run 2 (Int. J. Mod. Phys. A 29 (2014) 1430044)

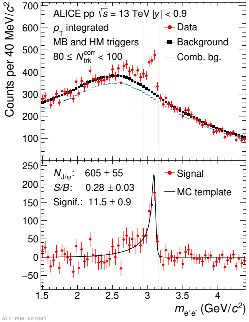


$J/\psi \rightarrow e^+ + e^-$

$|y| < 0.9$

Central Barrel

Dielectron

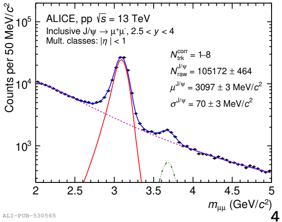


Muon Spectrometer

Dimuon

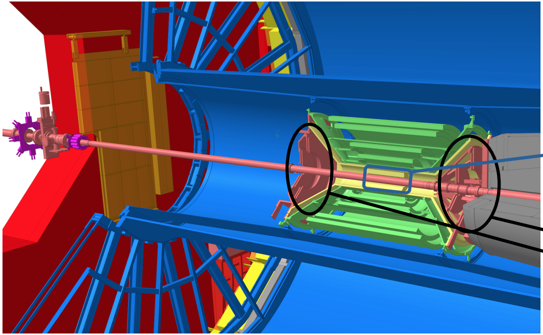
$2.5 < y < 4$

$J/\psi,\ \psi(2S),\ \Upsilon(nS) \rightarrow \mu^+ + \mu^-$



ALICE in Run 2 (Int. J. Mod. Phys. A 29 (2014) 1430044)

SPD: $|\eta| < 1$



Silicon Pixel Detector (SPD) of the Inner Tracking System

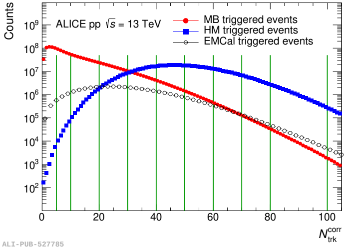
Vertexing and multiplicity

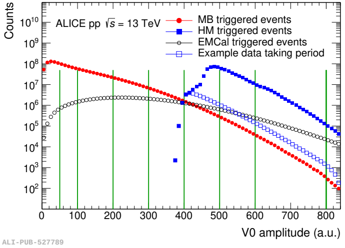
V0

Trigger, multiplicity, background rejection

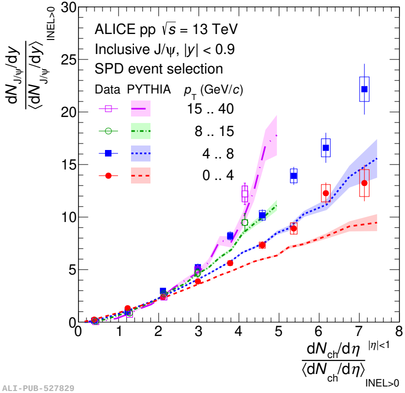
V0A: $2.8 < \eta < 5.1$

V0C: $-3.7 < \eta < -1.7$





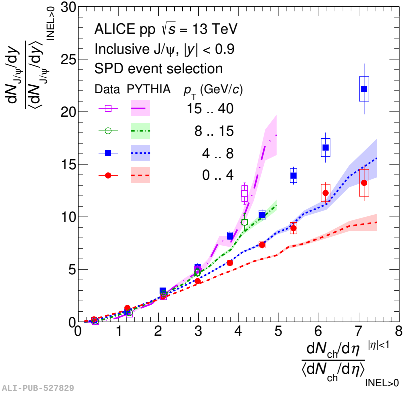
J/ψ production vs multiplicity



PLB 810 (2020) 135758, arXiv:2005.11123

- **Stronger than linear** increase of J/ψ vs. multiplicity, even stronger at higher p_T
- Underestimation by PYTHIA (but reproduce p_T dependence)

J/ψ production vs multiplicity



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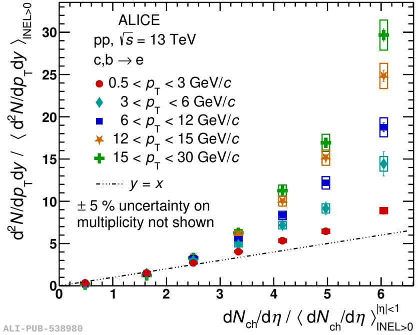
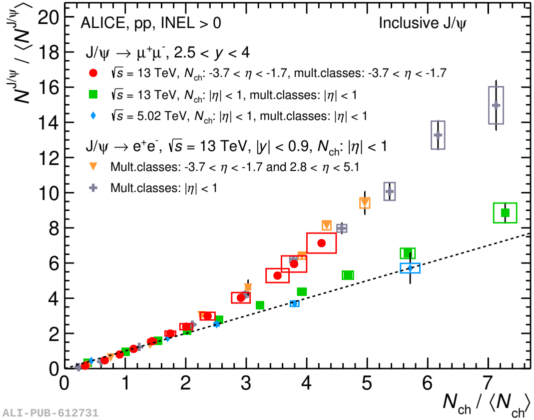


arXiv:2303.13349

- **Stronger than linear** increase of J/ψ vs. multiplicity, even stronger at higher p_T
- Underestimation by PYTHIA (but reproduce p_T dependence)
- Same trend seen in electrons from heavy flavors (right) and many other hard vs soft correlations

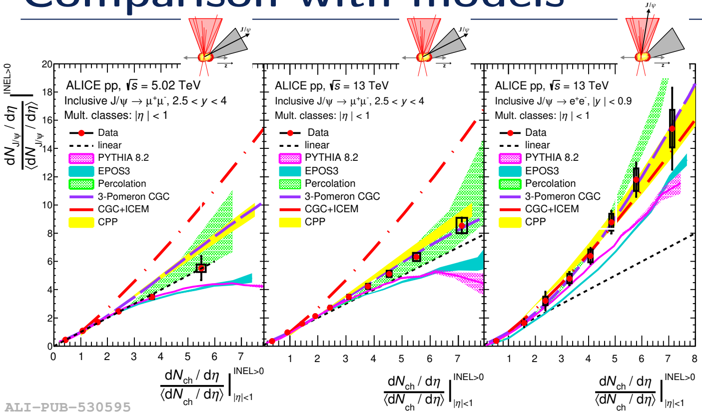
Results in different rapidity regions



JHEP 07 (2025) 238, arXiv:2504.00686

- J/ψ at forward or midrapidity, multiplicity at forward or midrapidity
- Increase stronger when J/ψ and multiplicity are measured in the same rapidity region
- Partly explained by multiplicity correlations between rapidity regions? (not clear whether there is effect due to specific rapidity region)

Comparison with models



JHEP 06 (2022) 015, arXiv:2112.09433v2

PYTHIA 8.2: Sjöstrand et al., Comput. Phys. Commun. 191 (2015) 159–177

EPOS3: Werner et al., Phys. Rev. C 89 (2014) 064903

Percolation: Ferreiro et al., Phys. Rev. C 86 (2012) 034903

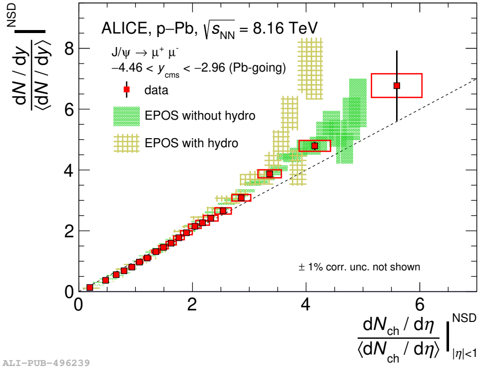
3-Pomeron CGC: Levin et al., Eur. Phys. J. C 80 (2020) 560

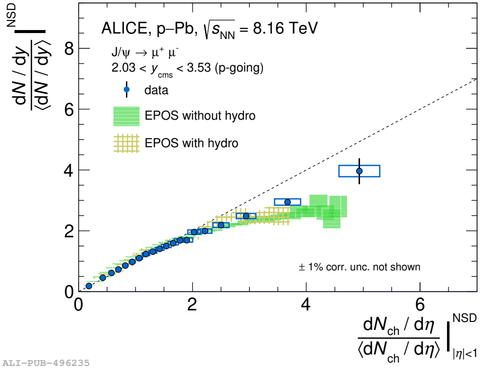
CGC+ICEM: Ma et al., Phys. Rev. D 98 (2018) 074025

CPP: Kopeliovich et al., Phys. Rev. D 101 (2020) 054023

- Models with **initial-state** (MPI, Color Glass Condensate calculations) or **final-state** (high string density during hadronization) saturation effects → not clear yet what is causing the trend
- Models reproduce well qualitatively, (even rapidity dependence), while some do not reproduce the data quantitatively (PYTHIA, EPOS, CGC+ICEM)

In p-Pb collisions

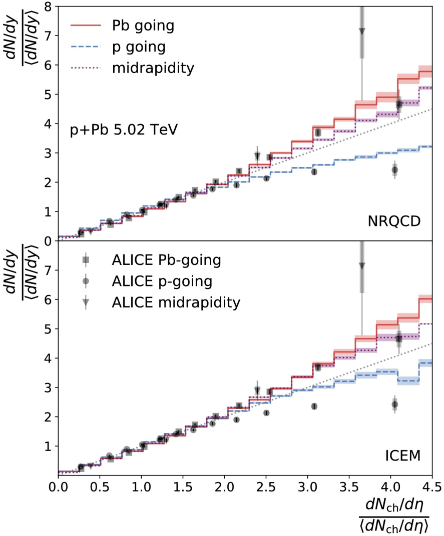




JHEP 2009 (2020) 162, arXiv:2004.12673

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

In p-Pb collisions, with CGC



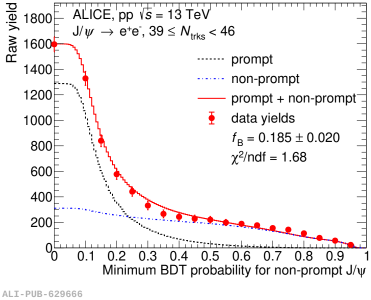
Phys.Lett.B 827 (2022), arXiv:2112.04611

- 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

Prompt vs non-prompt J/ψ

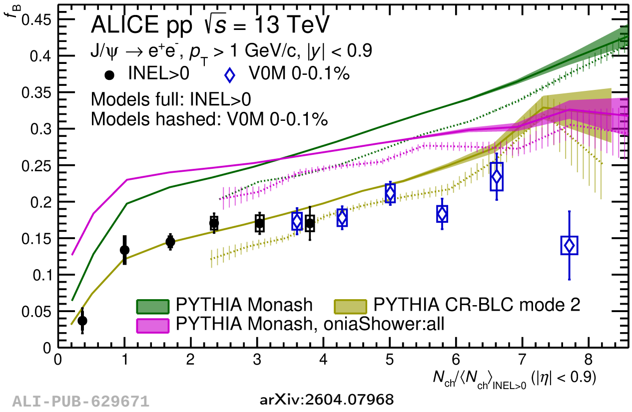
A part of J/ψ comes from **weak decays of open beauty hadrons**:

- J/ψ coming from beauty can be analyzed through decay length-related variables (combined within a BDT)
- Prompt and non-prompt have **different production mechanisms** (Quarkonium hadronization vs open-beauty hadronization)
- Could the harder scale from beauty influence the results?



arXiv:2604.07968

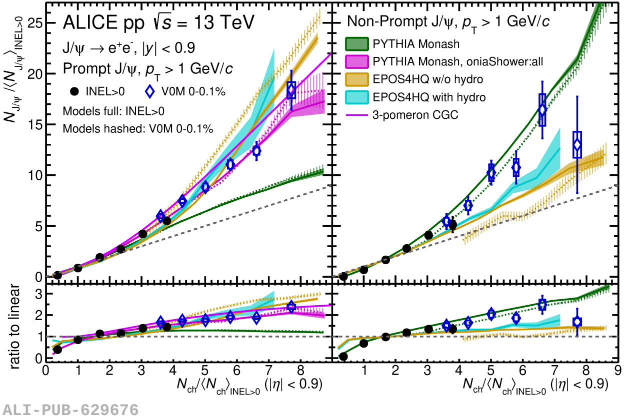
J/ψ non-prompt fraction



arXiv:2604.07968

- No strong difference between quarkonium and open beauty, but still slight increase of the non-prompt fraction (2.6σ significance)
- Slight bias of high. mult. (HM: V0M 0-0.1%) trigger seen in PYTHIA (hashed curves)

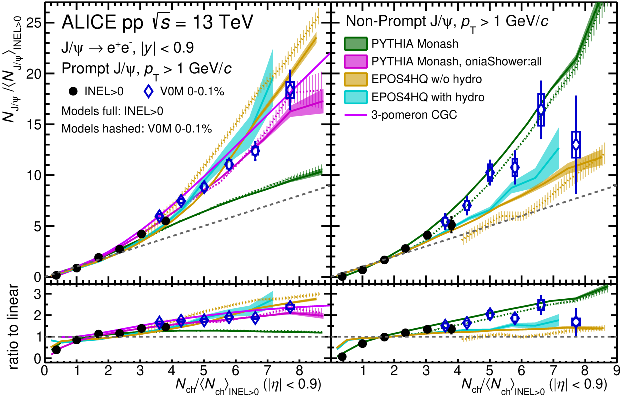
Prompt and non-prompt J/ψ



arXiv:2604.07968

- Both prompt (left) and non-prompt (right) J/ψ increase stronger-than-linear
- PYTHIA Monash largely underestimate prompt J/ψ but reproduce non-prompt J/ψ
- Correct estimation of the prompt yields by oniaShower process (producing quarkonium within parton shower) → strong influence of the production process

Prompt and non-prompt J/ψ

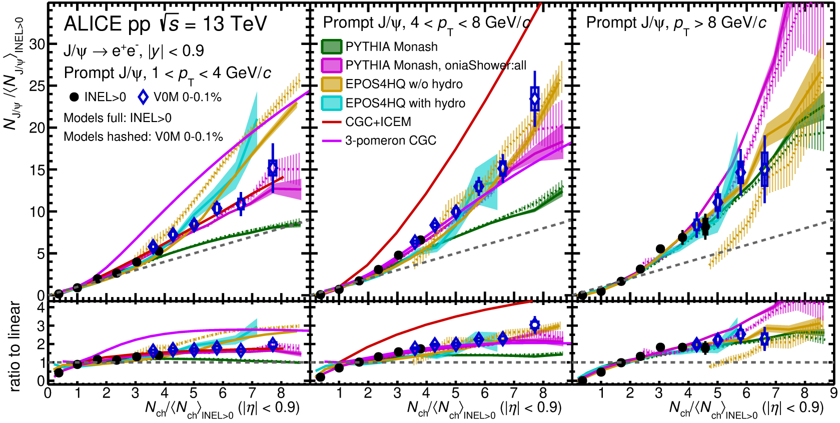


ALI-PUB-629676

arXiv:2604.07968

- In EPOS4HQ, interplay of initial-state saturation effects and final-state hydrodynamics
- Prompt J/ψ formation via coalescence, c and $\bar{c}$ coming from different pairs can recombine → stronger increase
- With and w/o hydro results are very close, open beauty underestimated in both cases at high multiplicity

Multiplicity-dependent J/ψ in p_T intervals



ALI-PUB-629681

arXiv:2604.07968

- Increase stronger at higher p_T, consistent with previous measurements
- The two CGC models compared here cannot reproduce p_T dependence

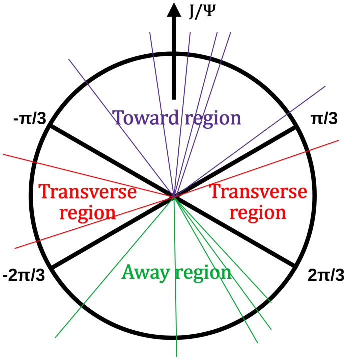
Azimuthal angle regions

Is there an impact of **autocorrelations**? Particles produced in same production process as the J/ψ count in the multiplicity

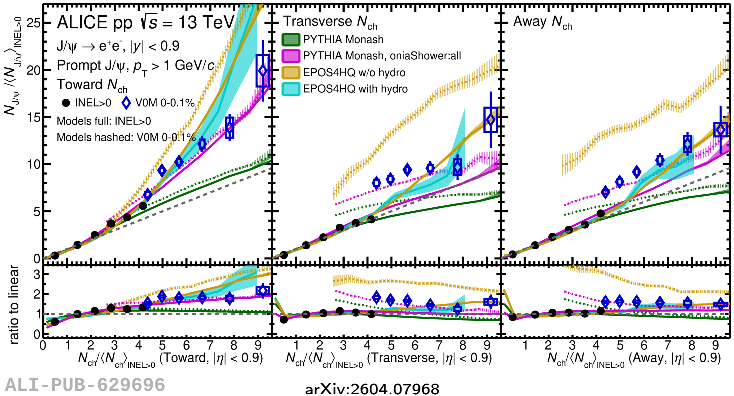
Different effects could be isolated through measurement of the multiplicity in different regions:

- **Toward**: particles associated to J/ψ production
- **Transverse**: underlying event
- **Away**: recoil jet

Could it help to distinguish initial from final-state effects? (Later effects being closer in phase-space to the J/ψ?)



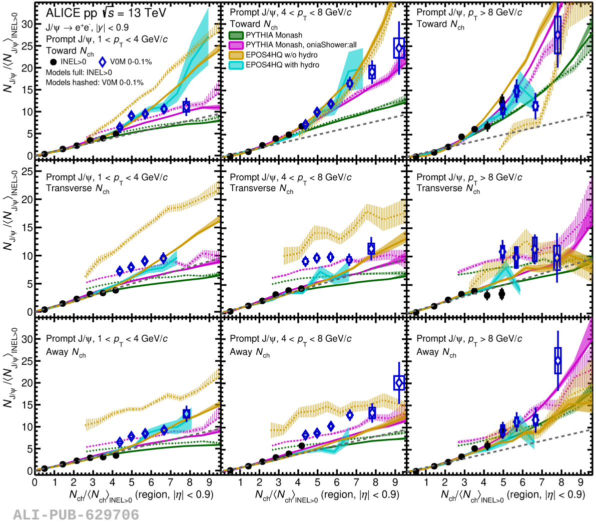
Prompt J/ψ in azimuthal regions



arXiv:2604.07968

- Stronger increase in toward region (left) compared to transverse (middle) and away (right) regions → large impact of associated particles in the multiplicity dependence
- Bias from the HMV0 trigger for transverse and away region, however reproduced by PYTHIA oniaShower
- Slightly stronger than linear in transverse and away region → not only a local autocorrelation effect

Prompt J/ψ in azimuthal regions



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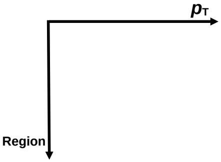
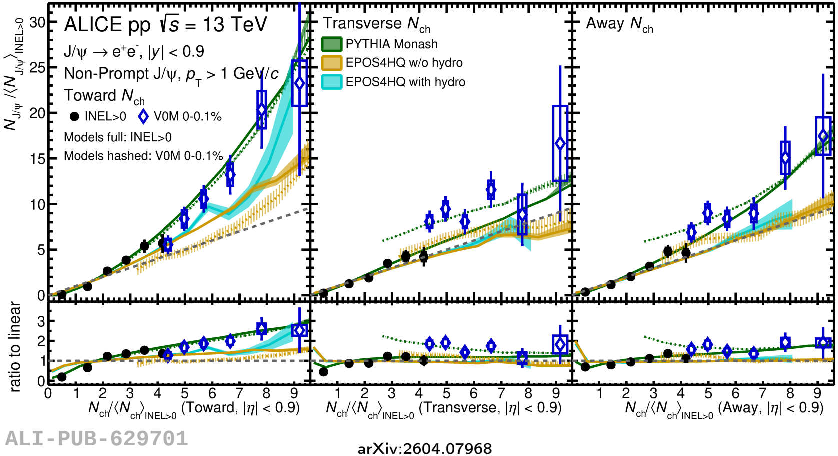


- Stronger trend at higher p_T mostly seen in toward region, not in transverse region
- This hints that dependence with p_T mostly local effect due to associated particles

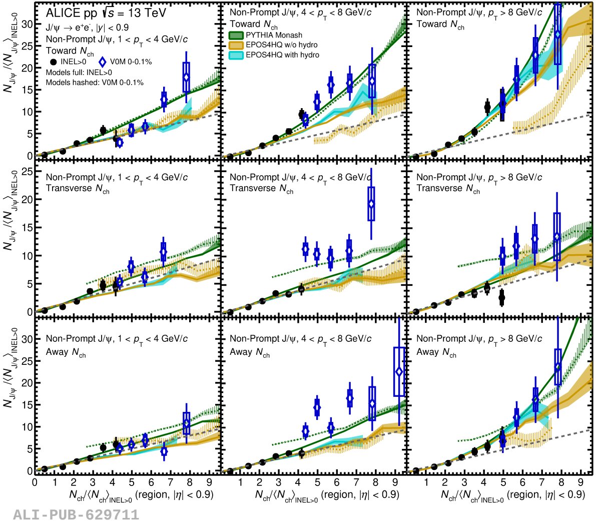
Non-prompt J/ψ in azimuthal regions



arXiv:2604.07968

- Similar conclusions for non-prompt J/ψ as for prompt J/ψ (with larger uncertainties)

Non-Prompt J/ψ in azimuthal regions



arXiv:2604.07968

- Similar conclusions for non-prompt J/ψ as for prompt J/ψ (with larger uncertainties), but with a larger p_{T}-dependence in away region (recoil beauty)

Conclusion

- J/ψ vs multiplicity increase stronger-than-linear → interplay between hard and soft particle production for initial-state and final-state effects
- J/ψ from decay of B hadrons **increases slightly faster** than prompt J/ψ
- Multiplicity separated in azimuthal regions → stronger increase as a function of toward multiplicity than transverse and away → **significant impact of autocorrelations** in the multiplicity dependence, but probably not the only effect
- EPOS4HQ (which has saturation) reproduces trend qualitatively, but PYTHIA with oniaShower tune reproduces very well (w/o saturation) → no clear hint of gluon saturation
- Still many points to be understood, to be compared with predictions with initial-or final-state effects, ...

Thank you for your attention!

Back-up