Quarkonium production in small collision systems in ALICE

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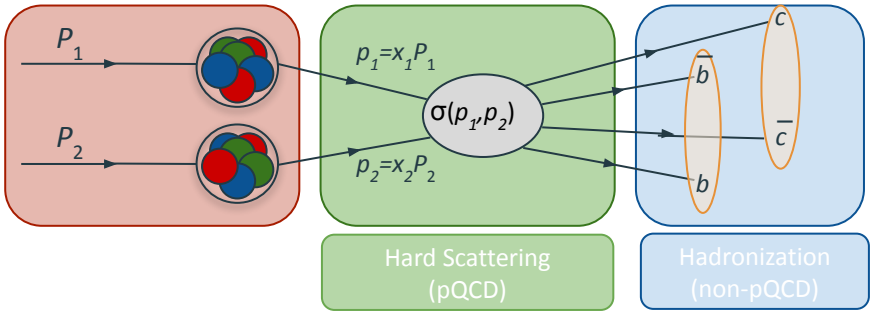
ALICE

Physics Motivations

- Heavy quarks are produced in initial hard scatterings in hadronic collisions
- Quarkonium (i.e. bound states of charm or beauty quark pair) production mechanism description represents challenge for theory
  - ↪ *Test both the perturbative and non-perturbative regimes of QCD*
  - ↪ *Several phenomenological models try to reproduce data with different hadronization approaches*



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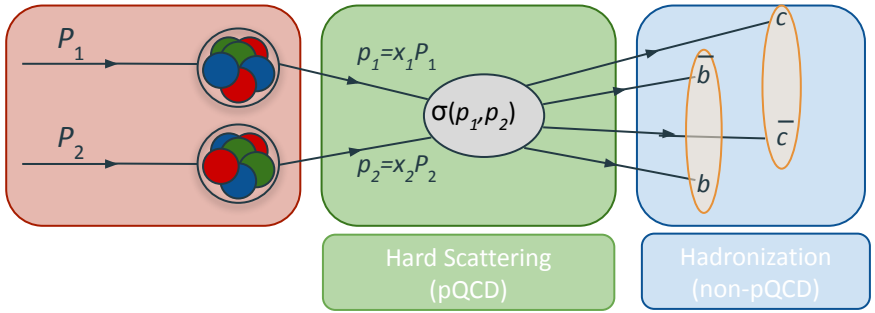

- Study quarkonium production vs multiplicity in pp collision system helps in understanding the interplay between hadronization and multi-parton interaction (MPI)
  - ↪ At LHC energies MPI occur frequently even in pp collisions ⇨ high multiplicity events
    - ↪ If MPI affects heavy quark production, this could introduce a dependence on charged-particle multiplicity (N_{ch})

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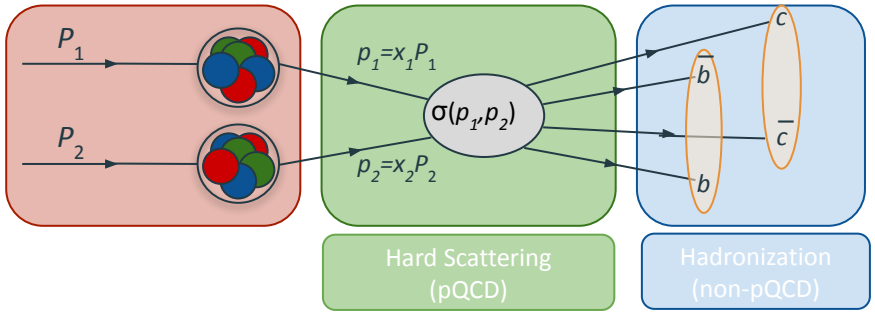

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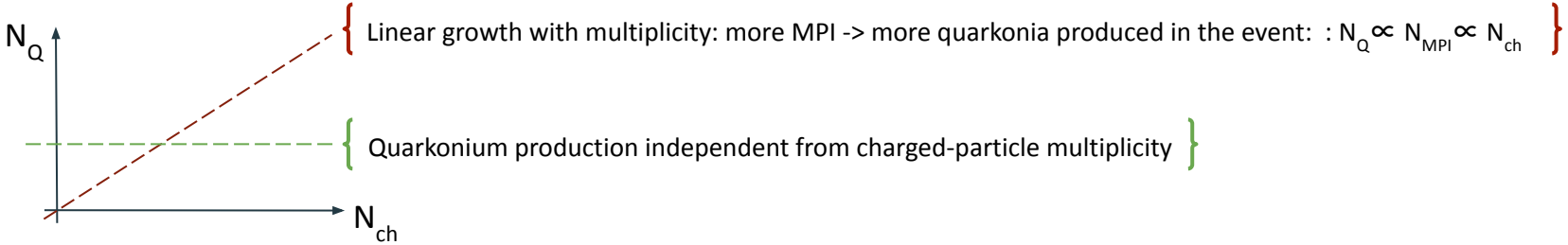


A Large Ion Collider Experiment (Run2)

For reconstructing Quarkonia

Muon spectrometer

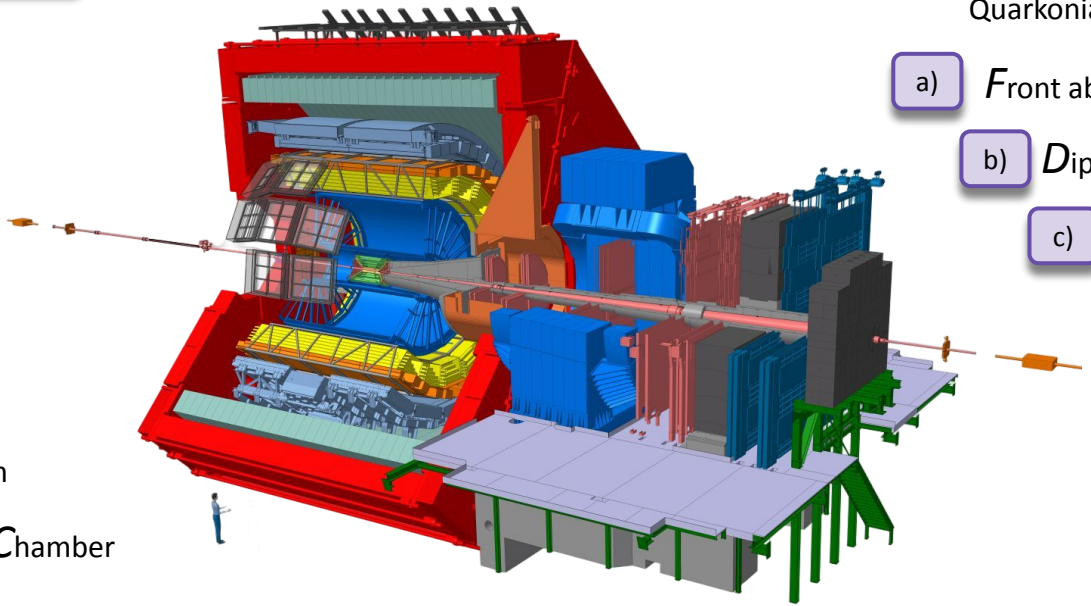
Quarkonia -> $\mu^+\mu^-$ ($2.5 < \eta < 4$)

a) Front absorber

b) Dipole magnet

c) Tracking System

d) Trigger system



Central Barrel

J/Ψ -> e^+e^- ($|\eta| < 0.9$)

a) Inner Tracking System

b) Time Projection Chamber

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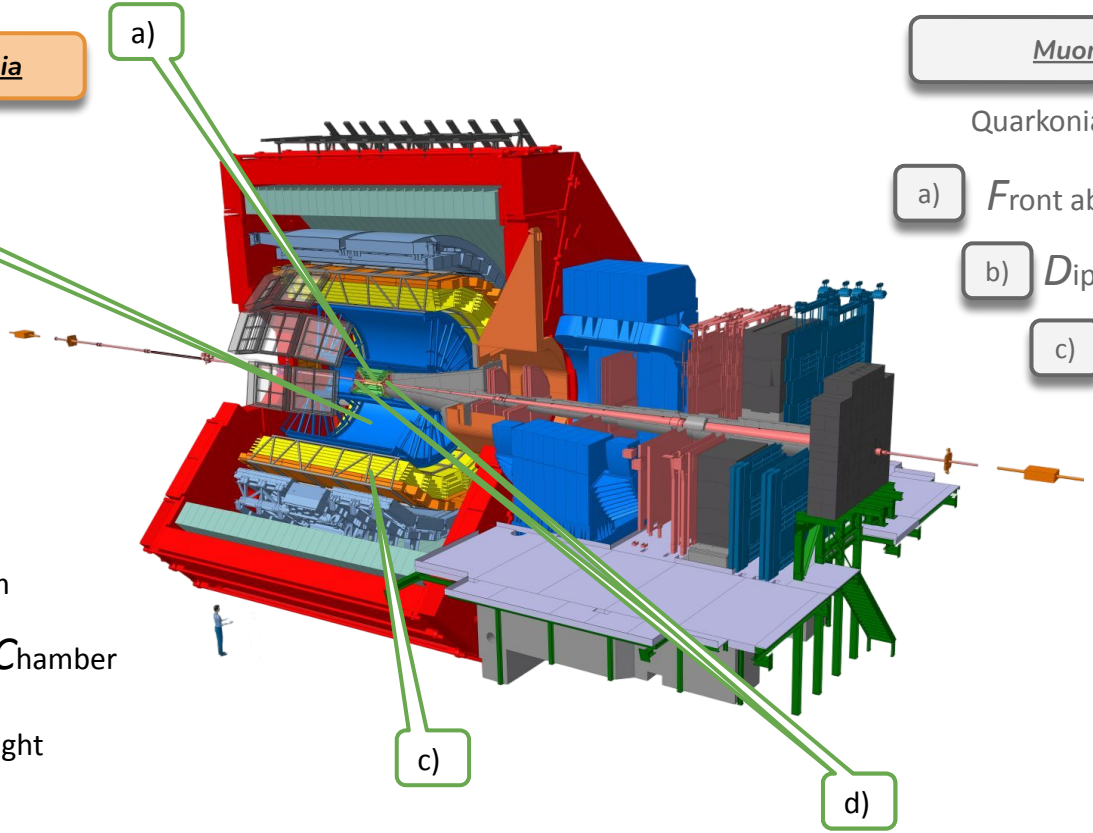

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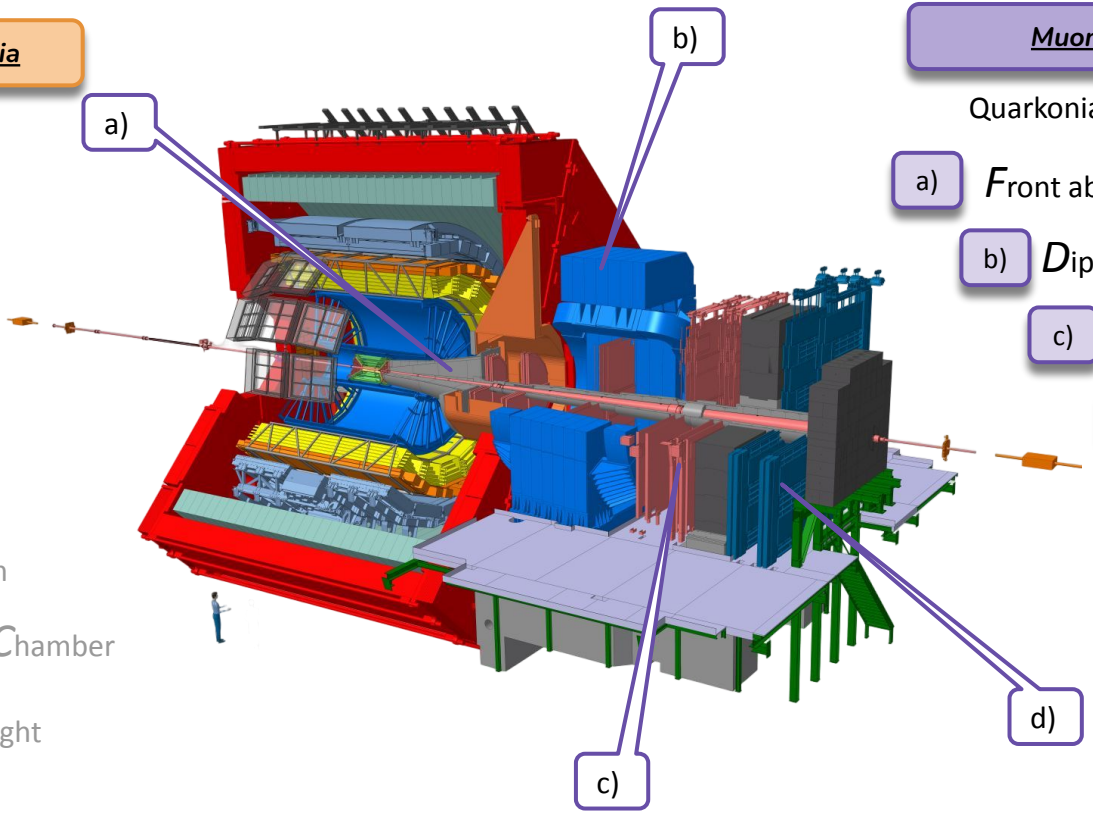

Central Barrel

$J/\Psi \rightarrow e^+e^-(|\eta| < 0.9)$

- a) Inner Tracking System
- b) Time Projection Chamber
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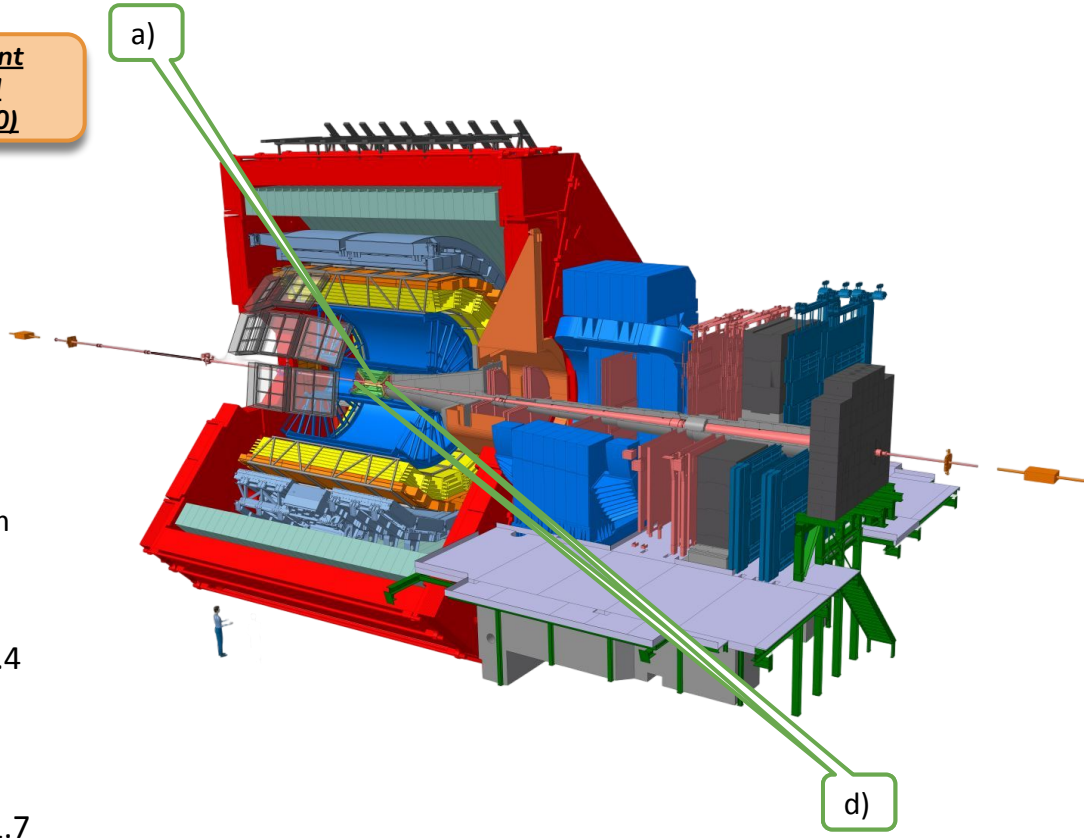
A Large Ion Collider Experiment (Run2)

For multiplicity measurement (+ min.bias triggering and background rejection for V0)



Central Barrel

a) *I*nner *T*racking *S*ystem

↪ *SPD tracklets*

- *1° layer* $|\eta| < 2$
- *2° layer* $|\eta| < 1.4$

d) *V0*

- *V0A:* $2.8 < \eta < 5$
- *V0C:* $-3.7 < \eta < -1.7$

Outline

Quarkonium and heavy-quark production results in pp

- J/Ψ cross section at mid and forward rapidity
- Double J/Ψ cross-section at forward rapidity
- J/Ψ production in jet at mid-rapidity
- Charm and beauty cross section with dilepton measurement

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Quarkonium production vs multiplicity in pp collisions

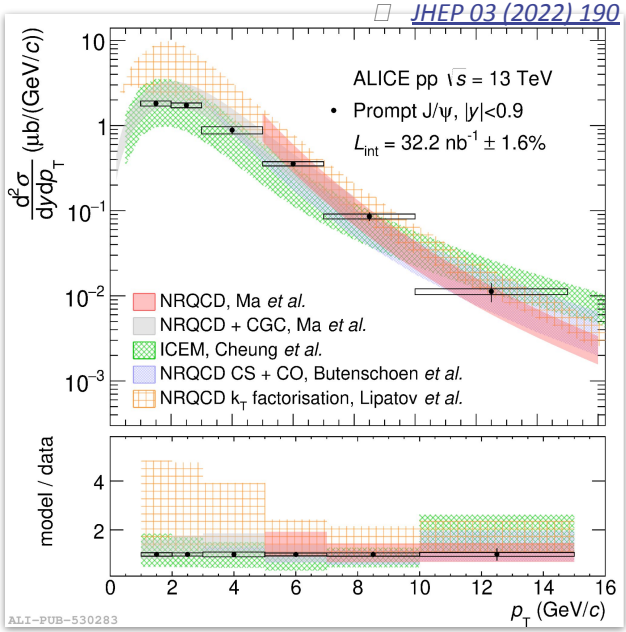
- J/Ψ production vs multiplicity at mid and forward rapidity
- Ψ(2S) production vs multiplicity at forward rapidity
- ϒ(nS) vs multiplicity at forward rapidity

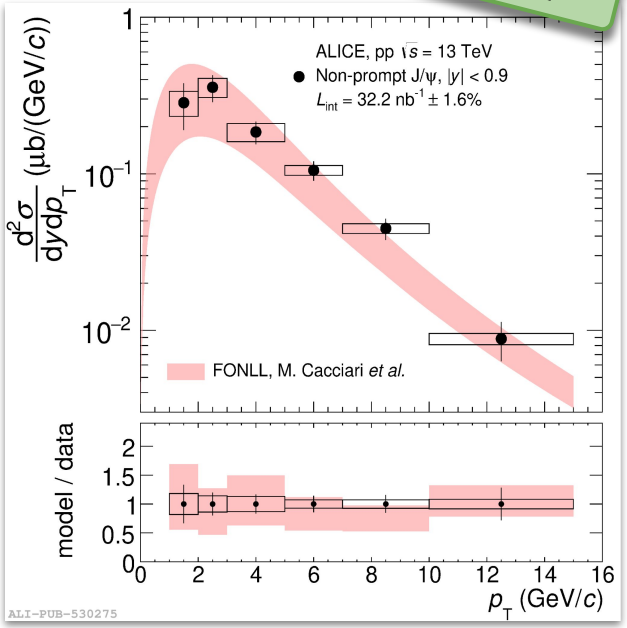
Quarkonium and heavy-quark production results in pp

J/ψ production

mid-rapidity

JHEP 03 (2022) 190





prompt J/ψ at 13 TeV:

- NRQCD + CGC and ICEM (*I*mproved *C*olor *E*vaporation *M*odel) well reproduce the differential cross section, in particular for low-p_T
- Uncertainties on model calculations do not allow to discriminate among models for prompt J/ψ

non-prompt J/ψ at 13 TeV:

- FONLL predictions in fair agreement with data

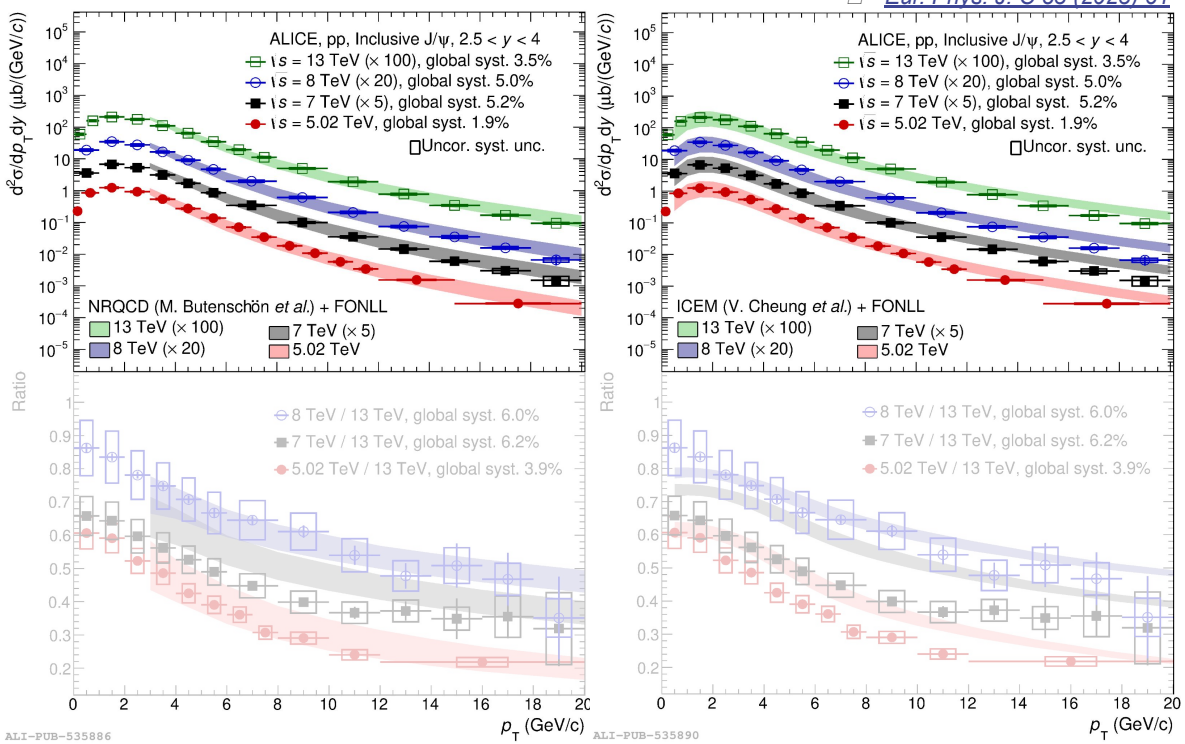
Models:

- Ma et al, Phys. Rev. Lett. 106 (2011) 042002 (NRQCD)
- Butenschoen et al, Phys. Rev. Lett. 106 (2011) 022003 (NRQCD CS + CO)
- Lipatov et al, Phys. Rev. D 100 no. 11, (2019) 114021 (NRQCD kT factorization)
- Ma et al, Phys. Rev. Lett. 113 no. 19, (2014) 192301 (NRQCD + CGC)
- Cheung et al, Phys. Rev. D 98 no. 11, (2018) 114029 (ICEM)
- Cacciari et al, JHEP 10 (2012) 137 (FONLL)

J/ψ production

fwd-rapidity

Eur. Phys. J. C 83 (2023) 61



- ***at 5 TeV***: new measurement (10 times more stat. w.r.t earlier publication)
- both NRQCD and ICEM models well reproduce the cross section vs pt for all energies also at forward rapidity

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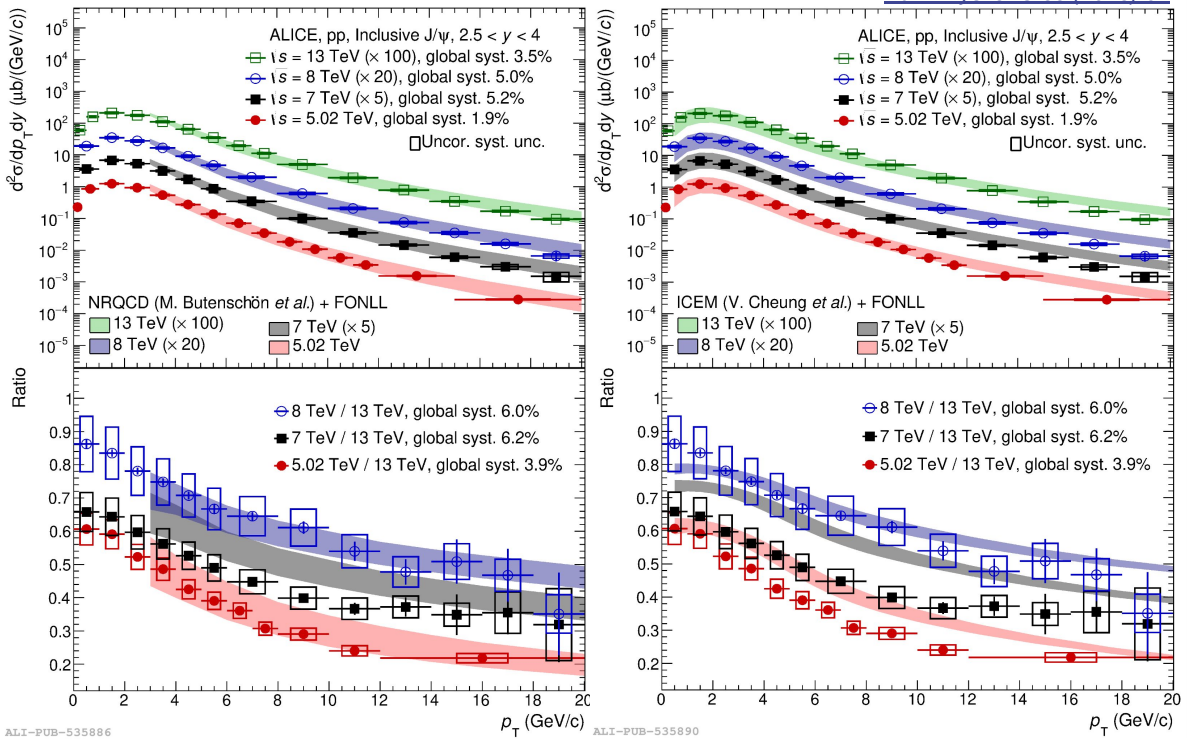

- ***at 5 TeV***: new measurement (10 times more stat. w.r.t earlier publication)
- both NRQCD and ICEM models well reproduce the cross section vs pt for all energies also at forward rapidity
- Models have difficulties to reproduce at the same time all the cross section ratios among energies, but are still compatible within the experimental and theoretical uncertainties

Models:

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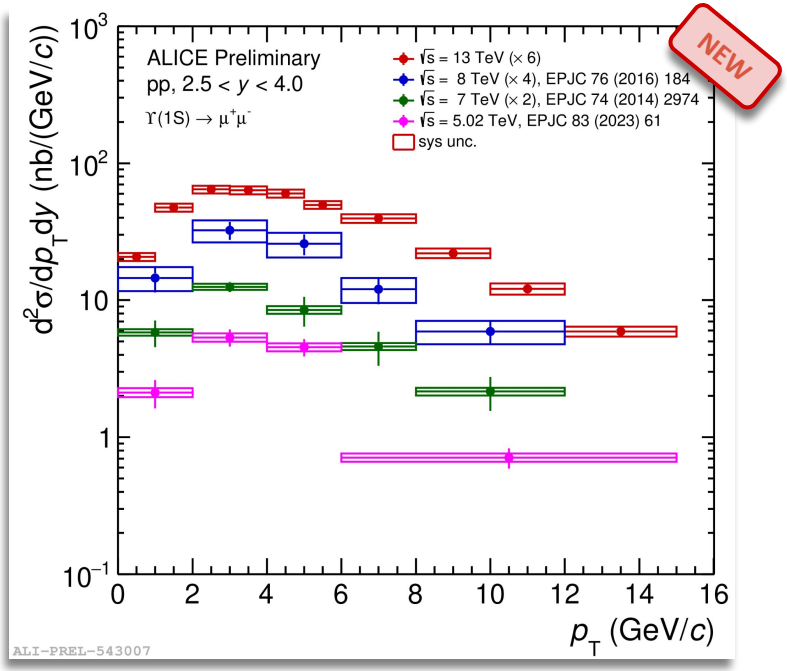
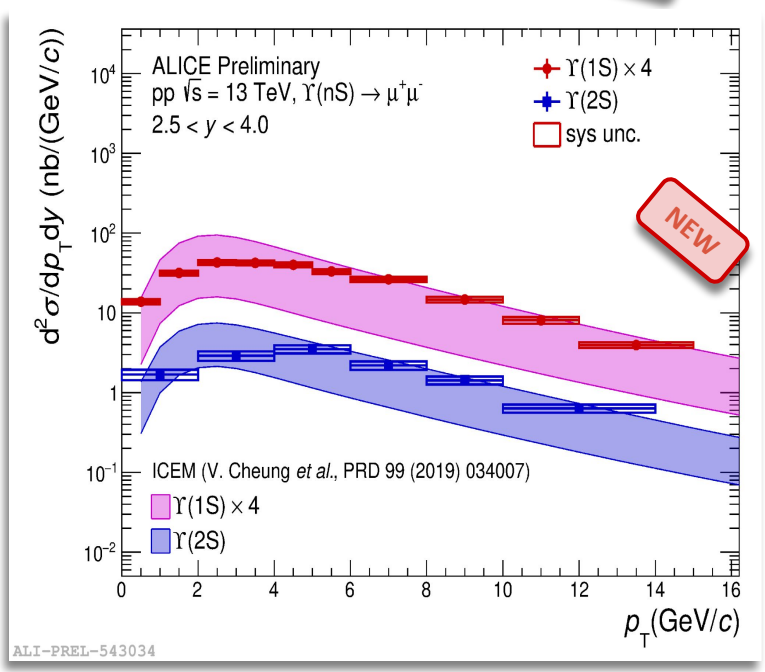
Υ(nS) production

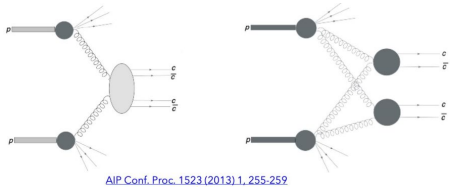
fwd-rapidity





ICEM predictions in qualitatively good agreement with data within the experimental uncertainties

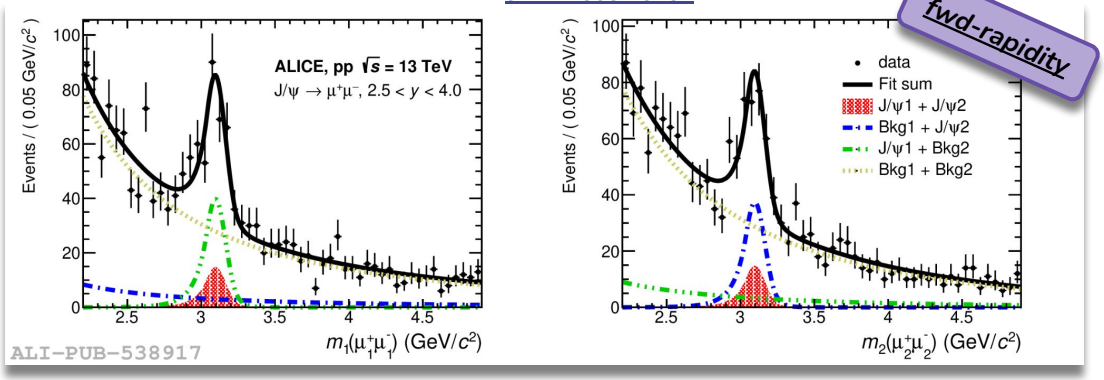
Double J/Ψ production



- Insight on double-parton scattering (DPS) and access small x-Bjorken at LHC energies
- Understand J/ψ production mechanism
  - Different sensitivity to feed-down from excited states than single J/ψ production
  - Constrain theoretical models at forward *y*

arXiv:2303.13431

fwd-rapidity



	Cross sections (nb)
ALICE	*10.3±2.3(stat.)±1.3(syst.)*
LHCb	*15.2±1.0(stat.)±0.9 nb(syst.)*

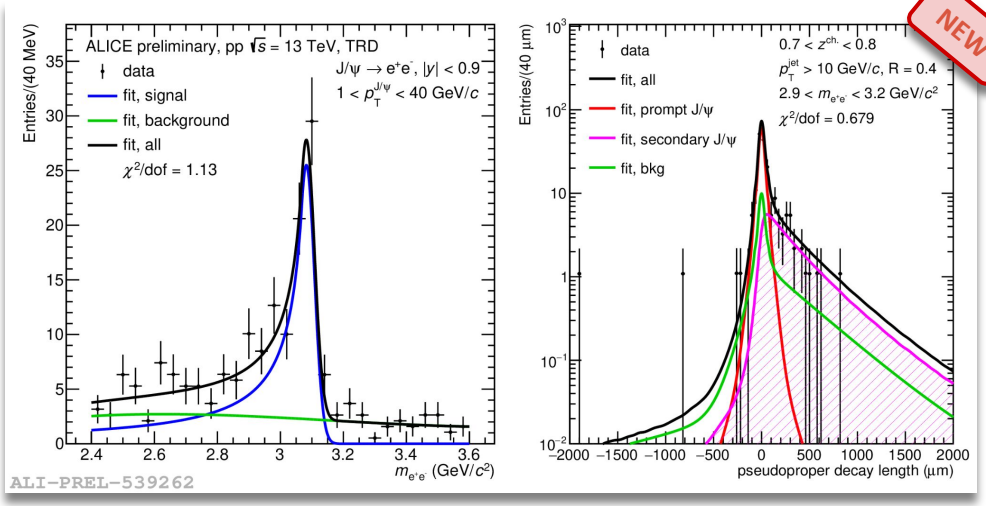
Consistency with LHCb cross section measurement, with two caveats:

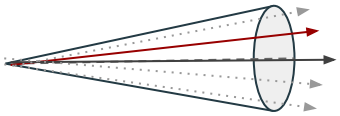
- ➢ Prompt J/ψ measured in LHCb, inclusive J/ψ in ALICE
- ➢ Slightly different rapidity ranges

J/ψ in jets

mid-rapidity

NEW





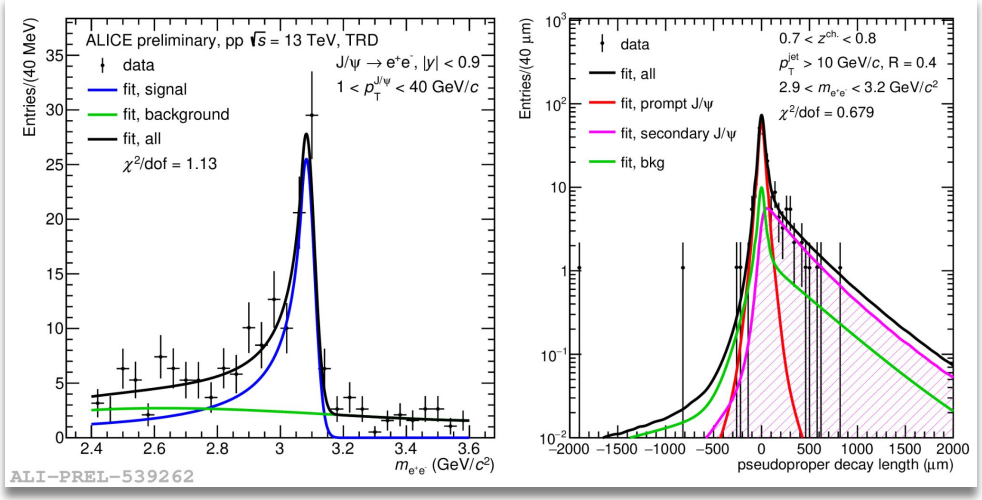
$$z^{ch} = \frac{p_T^{J/\psi}}{p_T^{jet,ch}}$$

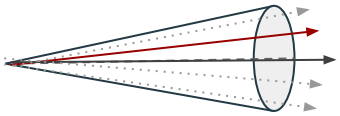
fragmentation function

- Jets tagged with presence of a reconstructed J/Ψ in the e^+e^- channel at mid-*y*
- Fit of the invariant mass and pseudoproper decay length distributions with a template of prompt/non-prompt signal and background

J/ψ in jets

mid-rapidity





$$z^{ch} = \frac{p_T^{J/\psi}}{p_T^{jet,ch}}$$

fragmentation function

- Prompt and non-prompt J/ψ fragmentation functions are found to be similar within uncertainties
- Comparison with models are needed ⇒ Ongoing Pythia8 studies
- Insight on the J/ψ production/fragmentation interplay with the underlying event

- Jets tagged with presence of a reconstructed J/Ψ in the e^+e^- channel at mid-*y*
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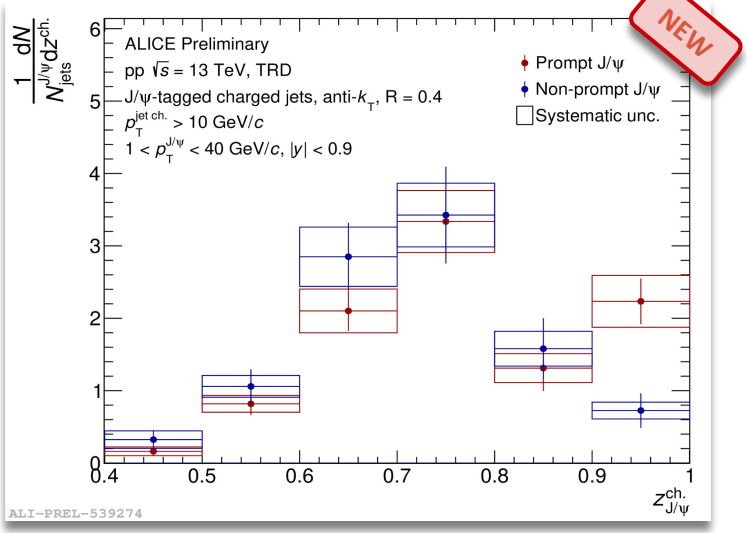
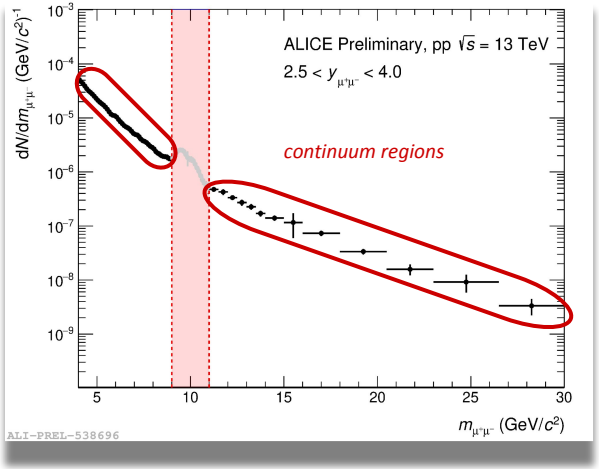
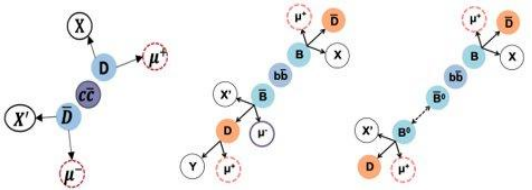


Charm and beauty cross sections with dileptons

- Measure HF cross section in ALICE via dimuon production
- $\mu^+\mu^-$ production in these *continuum regions* mainly due to semileptonic decays of HF hadrons





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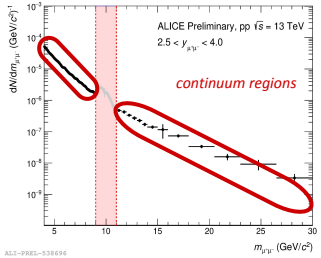

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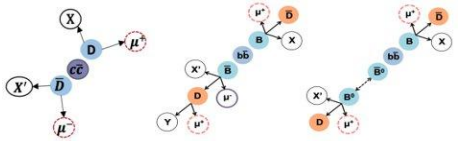
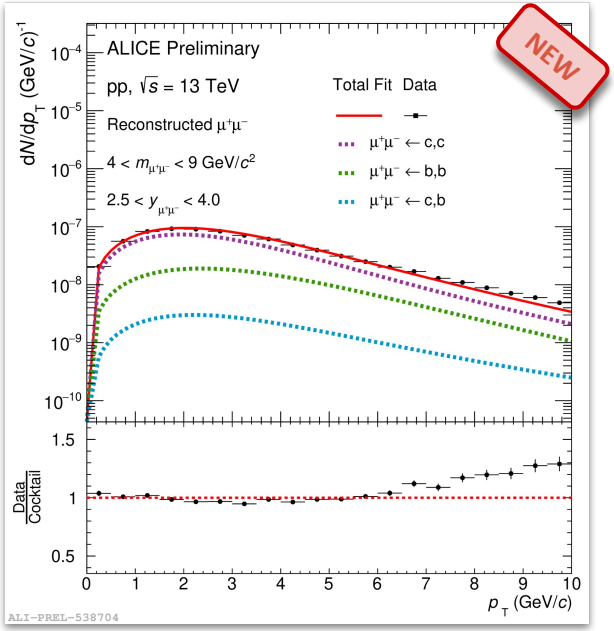
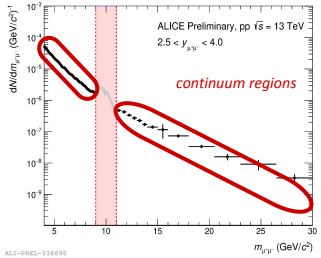


- Estimation of the charm and beauty yields by performing a ***simultaneous unbinned fit*** to the dimuon m and p_T data distributions using templates of HF sources
  - $\mu^+\mu^-$ <- c,c : both μ from prompt charm particles decay
  - $\mu^+\mu^-$<- b,b : both μ from beauty particles decay (include non prompt charm component)
  - $\mu^+\mu^-$ <- c,b : one μ from prompt charm particle, the other μ from beauty particle (include non prompt charm component)
- Kinematic region of the fit: $4 < m_{\mu\mu} < 9$ GeV/c^2 and $p_T < 10$ GeV/c



- Good agreement between the fit and the data in the m and p_T region studied
- Slight underestimation at high-p_T => ***possible contribution from Drell-Yan*** (ongoing studies)

Charm and beauty cross sections with dileptons



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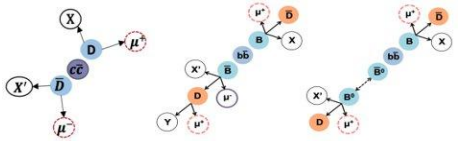

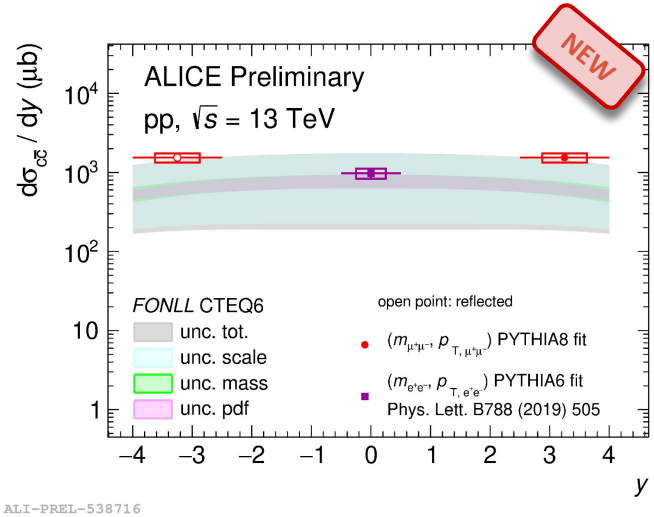

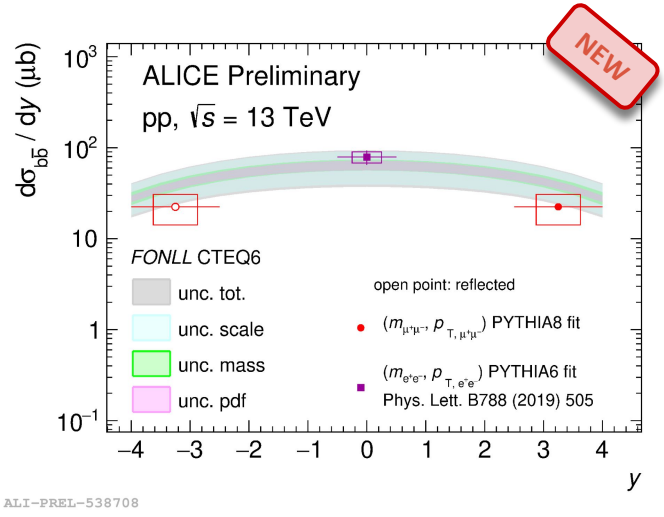

- ✓ *C*harm and beauty pairs cross-section measured at *forward rapidity* (never measured before) compared with the previous measurement at *mid-rapidity*
- ✓ *G*ood agreement with FONLL predictions within uncertainties

- Cacciari et al, JHEP 10 (2012) 137 (FONLL)

Summary on quarkonium production in pp

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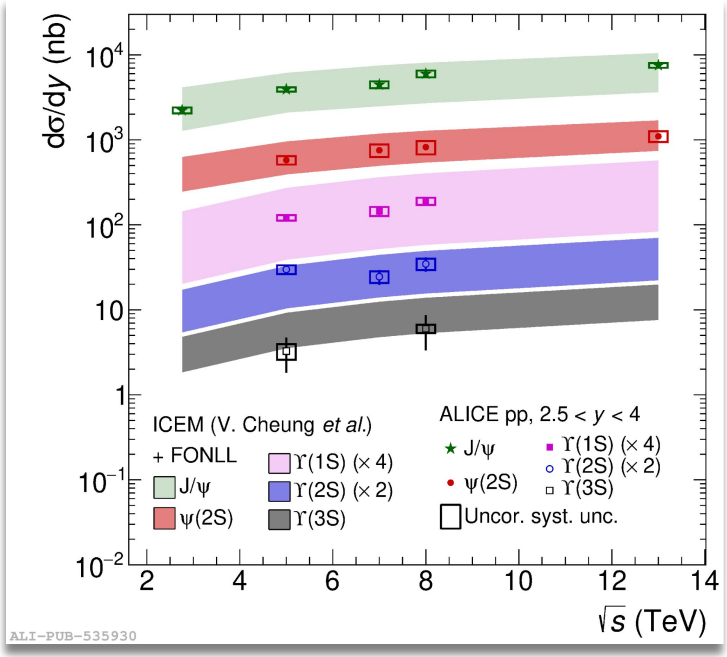
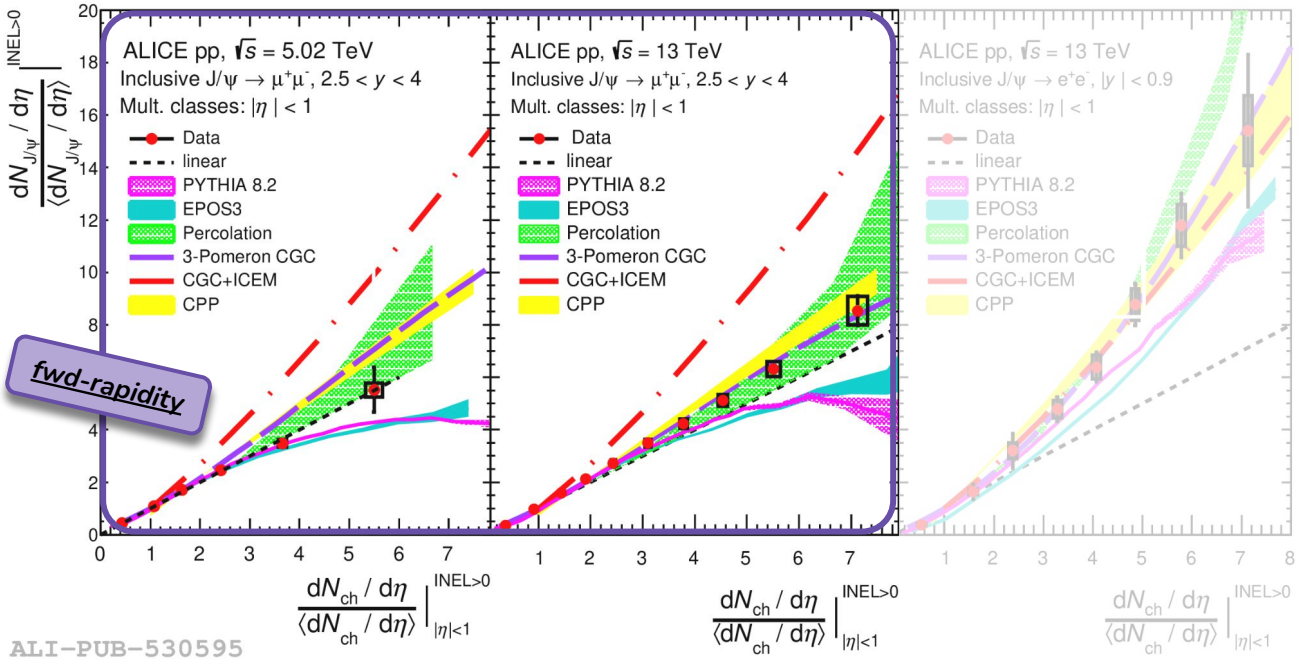


- ✓ ICEM and NRQCD based models (+FONLL for non-prompt charmonia) fairly reproduce quarkonium cross section vs p_T both at mid and forward rapidity
- ✓ Current theoretical uncertainties do not allow to discriminate among models
- ✓ J/ψ pair production provides an important probe for theory to understand multi-parton scatterings:
  - ↪ results in agreement with LHCb
- ✓ Measured charm and beauty cross section with dileptons are in agreement with FONLL predictions

Multiplicity dependence of quarkonium production in pp collisions

J/ψ production vs multiplicity: a closer look

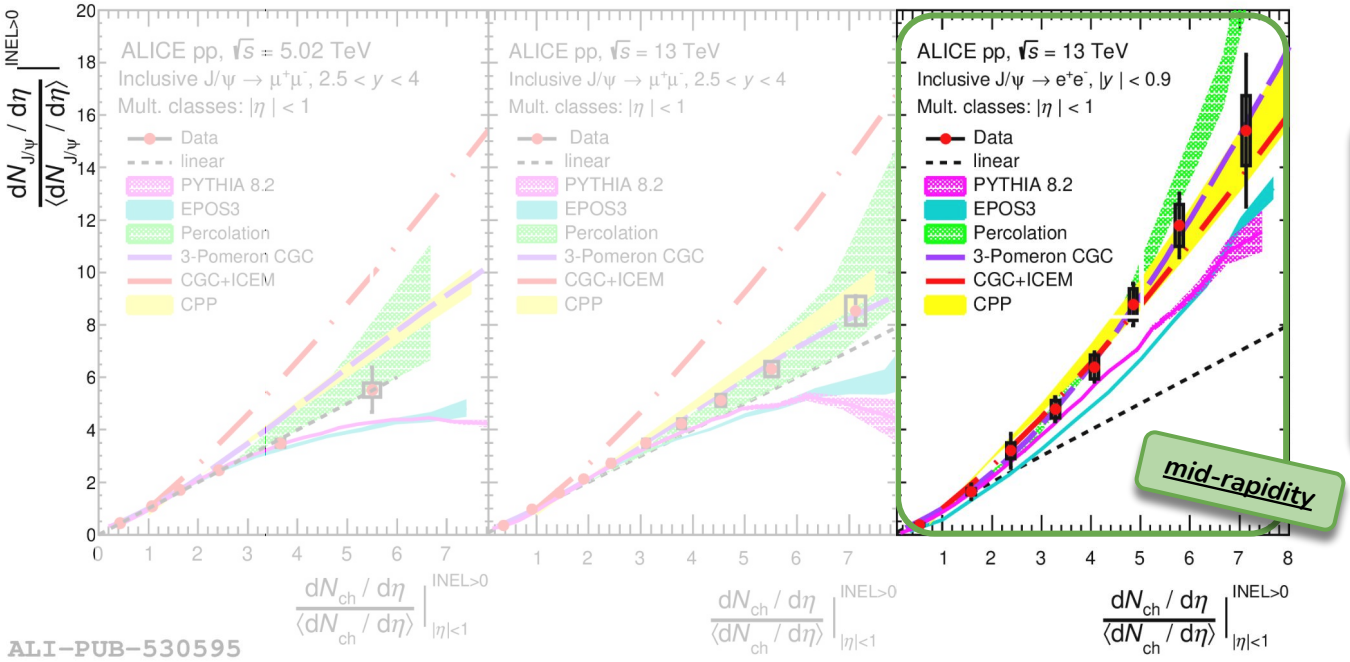


JHEP 06 (2022) 015

The self-normalized J/ψ yield vs multiplicity:

✓ ***at forward rapidity***: approximately grows linearly independently of the collision energy ⇨ $N_Q \propto N_{MPI}$

J/ψ production vs multiplicity: a closer look



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- ✓ ***at midrapidity***: faster than linear growth

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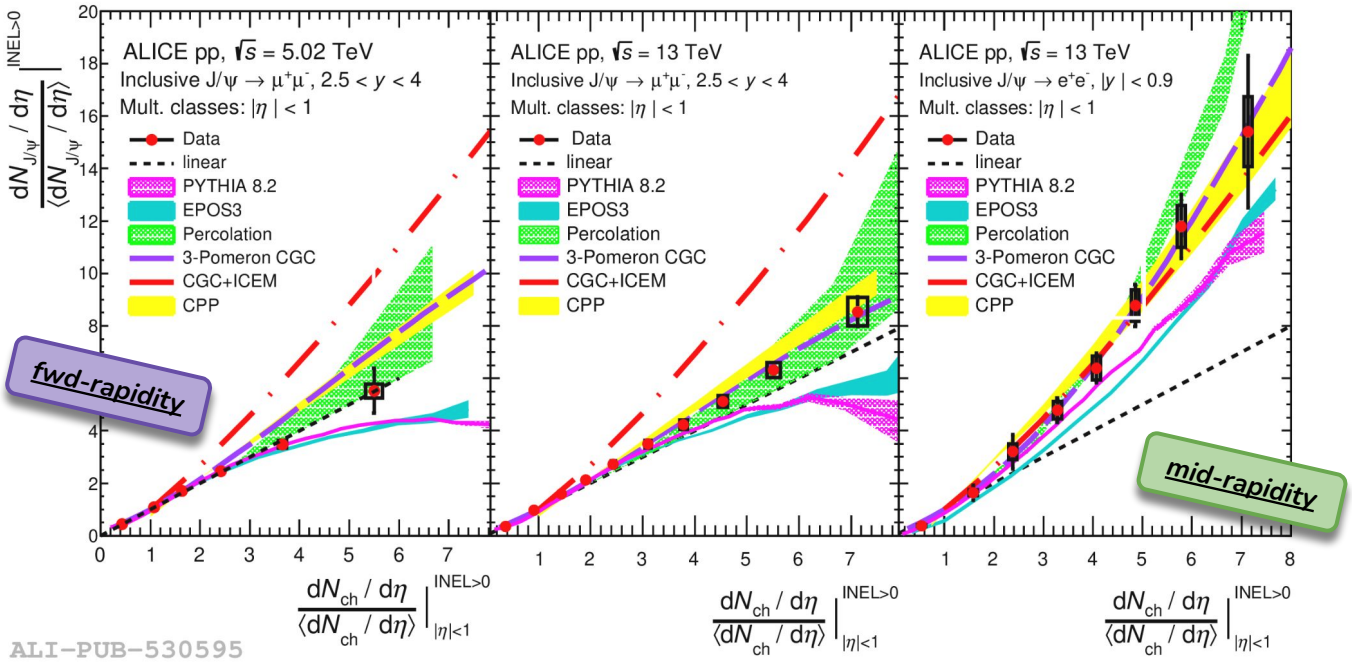

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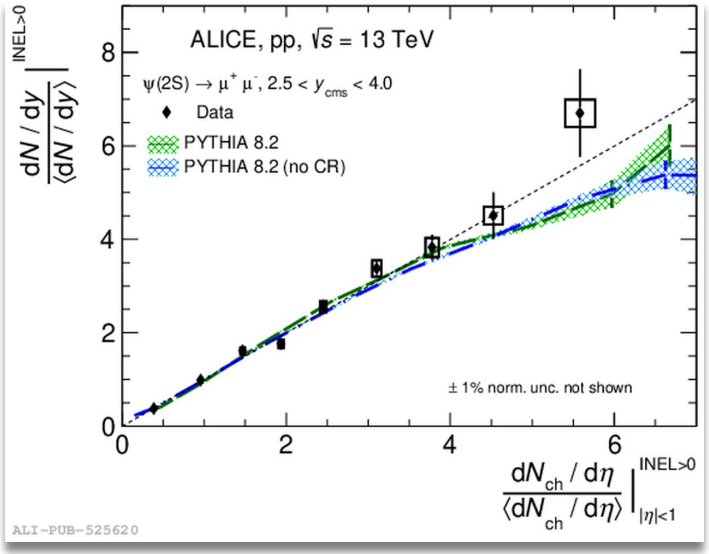
- ✓ ***at midrapidity***: faster than linear growth

- *Good agreement at 13 TeV provided by the Coherent Particle Production (CPP), the 3-Pomeron Color Glass Condensate and Percolation models in both rapidity intervals*
- *Stronger than linear correlation at midrapidity well reproduce by the models although the exact origin of this behaviour is still not well understood*

ψ(2S) production vs multiplicity

fwd-rapidity

- arXiv:2204.10253



- ✓ The self-normalized Ψ(2S) yield exhibits a similar linear trend as observed for J/Ψ, with the slope close to unity
- ✓ PYTHIA8 well reproduced the data up to 5 times the average multiplicity (both with or w/o Color reconnection)
  - Charmonium is not sensitive to details of parton showers mechanism

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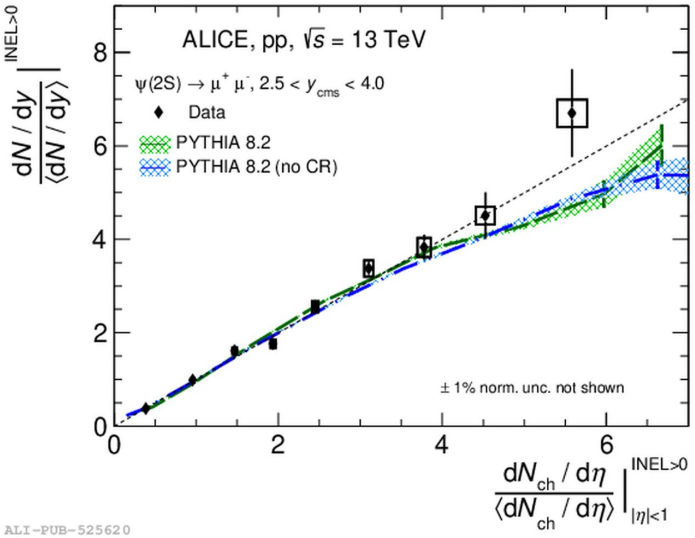

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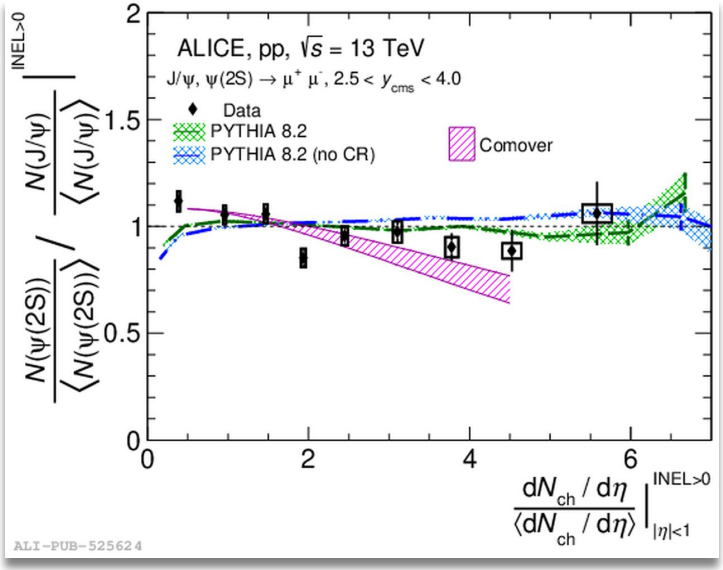
- ✓ PYTHIA8 well reproduced the data up to 5 times the average multiplicity (both with or w/o Color reconnection)
  - Charmonium is not sensitive to details of parton showers mechanism

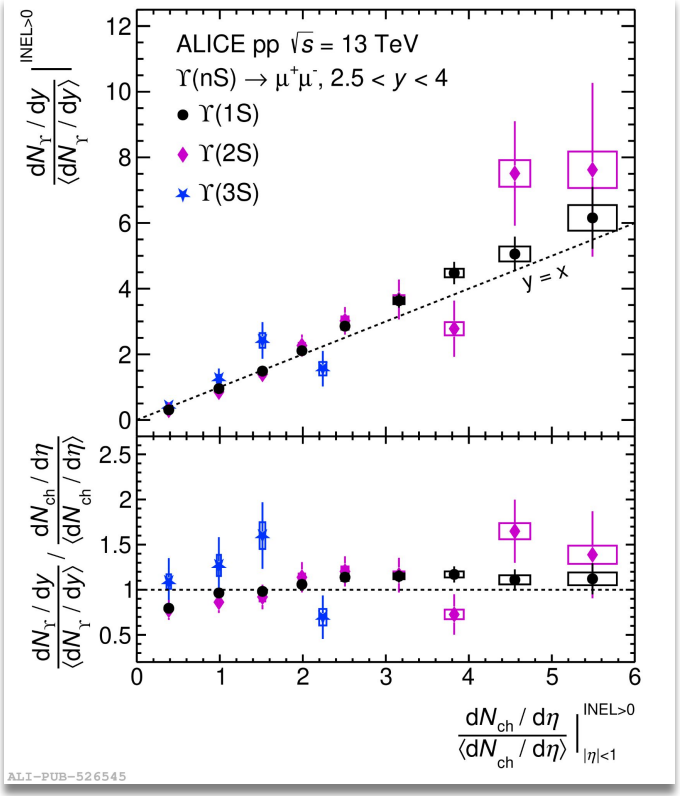


- ✓ The self-normalized Ψ(2S)-to-J/Ψ ratio close to unity as a function of charged particles multiplicity
  - ➢ Similar multiplicity dependence for both states
- ✓ PYTHIA8 predictions and comover model in fair agreement with the data

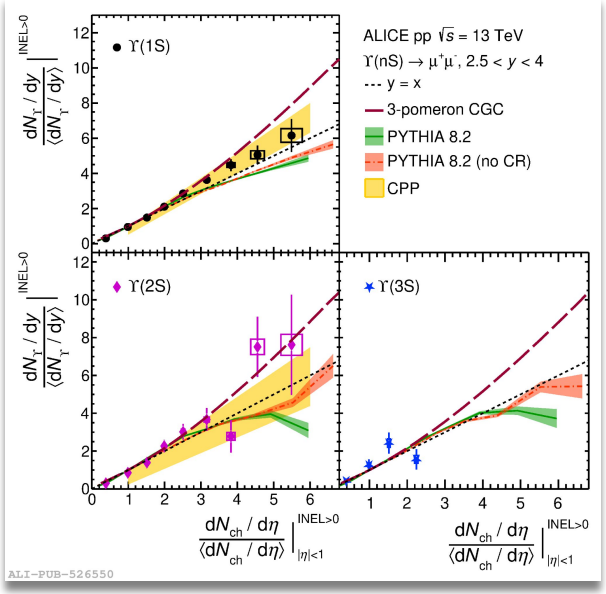
Υ(nS) production vs multiplicity

fwd-rapidity

arXiv:2209.04241



- ✓ The self-normalized Υ(*n*S) yield exhibits a similar linear trend as observed for charmonium, with the slope close to unity
- ✓ CPP well reproduces Υ(1S) and Υ(2S) data
- ✓ 3-pomeron CGC overstestimates Υ(1S) data above 4 times the average multiplicity

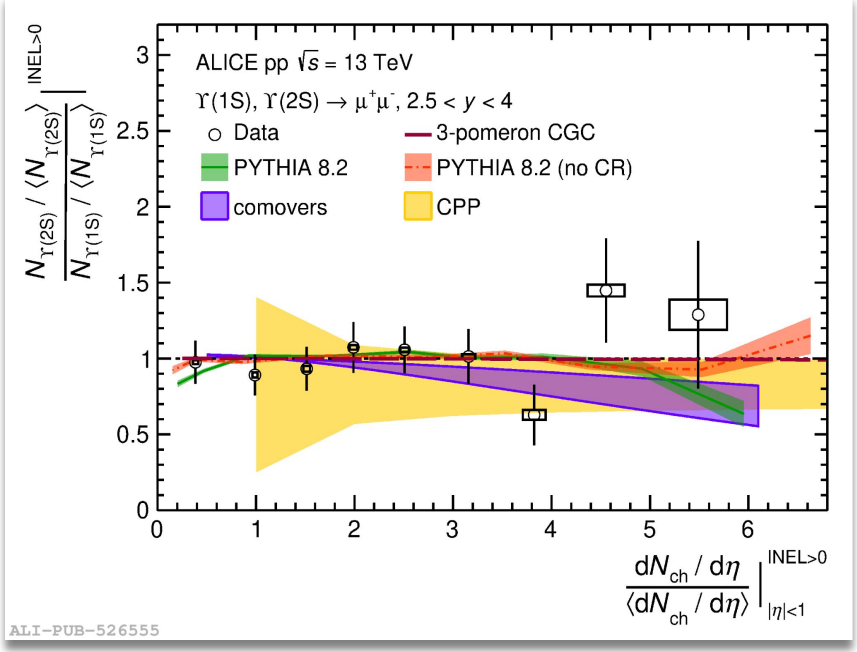


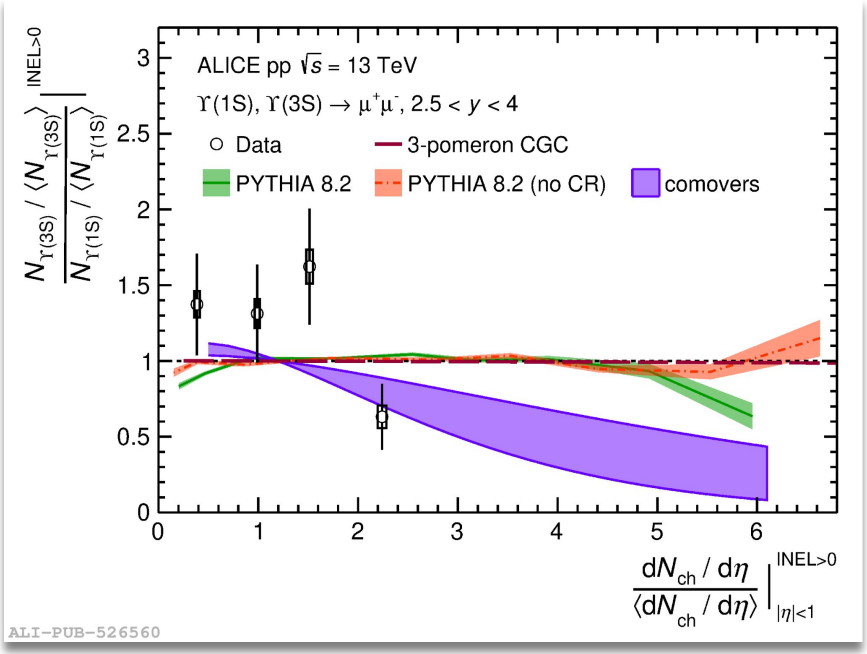
ϒ(nS) production vs multiplicity: a closer look

fwd-rapidity

- ✓ Looking at the excited-to-ground states ratio, a close to unity trend is observed, within uncertainty
- ✓ CPP, 3-pomeron CGC, comover and PYTHIA8 (with and w/o CR) fairly describe the Y(2S)-to-Y(1S) ratio

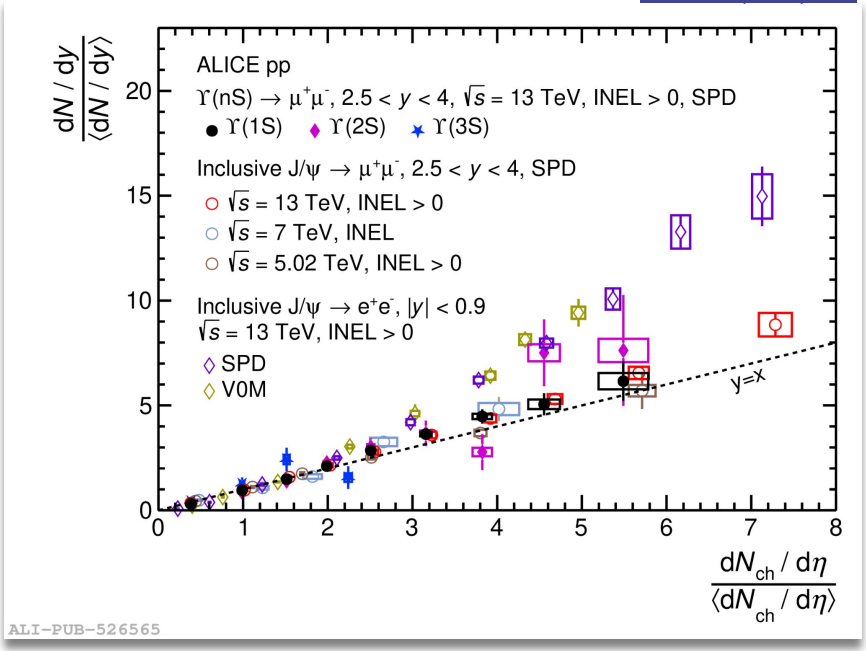
arXiv:2209.04241





Summary on quarkonium vs multiplicity in pp

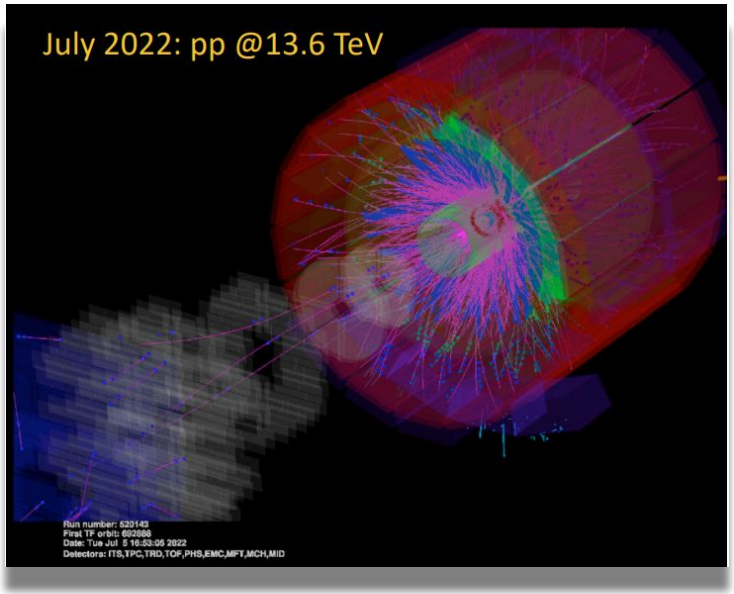
JHEP 06 (2022) 015



- ✓ ALICE provides a very comprehensive set of measurements, both at forward and midrapidity
- ✓ Quarkonium production is correlated to charged particle multiplicity
- ✓ Many phenomenological models are able to reproduce at the same time forward and midrapidity results
- ✓ Further theory developments needed to fully understand the mechanism at the origin of such difference

Conclusions and Summary

- Quarkonium studies represent a perfect playground to study QCD in pp collisions
- Although more than 40 years of studies, a global understanding of quarkonium production and polarization is still missing
- ALICE unique geometry provides results over a wide rapidity range



Run3, the future is now

- ALICE-ITS upgrade will provide more precise measurement a midrapidity
- the new ALICE-MFT will allow to discriminate prompt and non-prompt charmonium at forward *y*
- Larger multiplicity could be achieved with the increased data-taking rate

Additional material

J/Ψ production in pp

mid-rapidity

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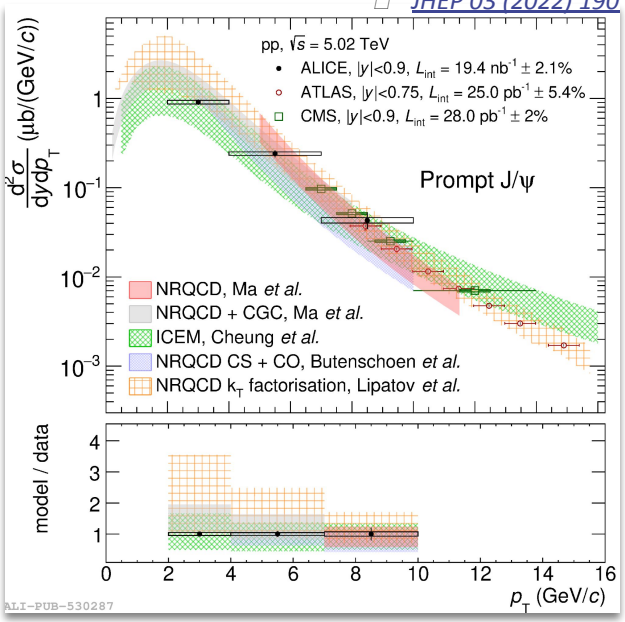
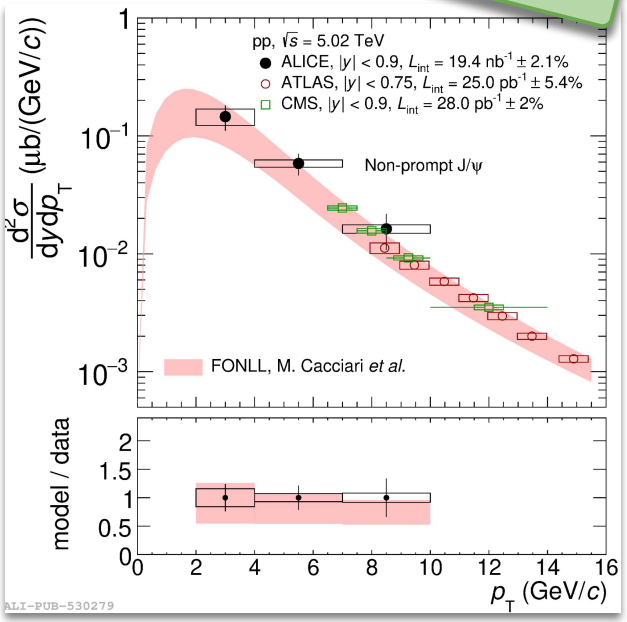




prompt J/ψ at 5.02 TeV:

- NRQCD and ICEM well reproduced the differential cross section
- Uncertainties on model calculations do not allow to discriminate among models for prompt J/ψ
- Good agreement with ATLAS and CMS measurement

Models:

- Butenschoen et al, Phys. Rev. Lett. 106 (2011) 022003 (NRQCD CS + CO)
- Ma et al, Phys. Rev. Lett. 106 (2011) 042002 (NRQCD)

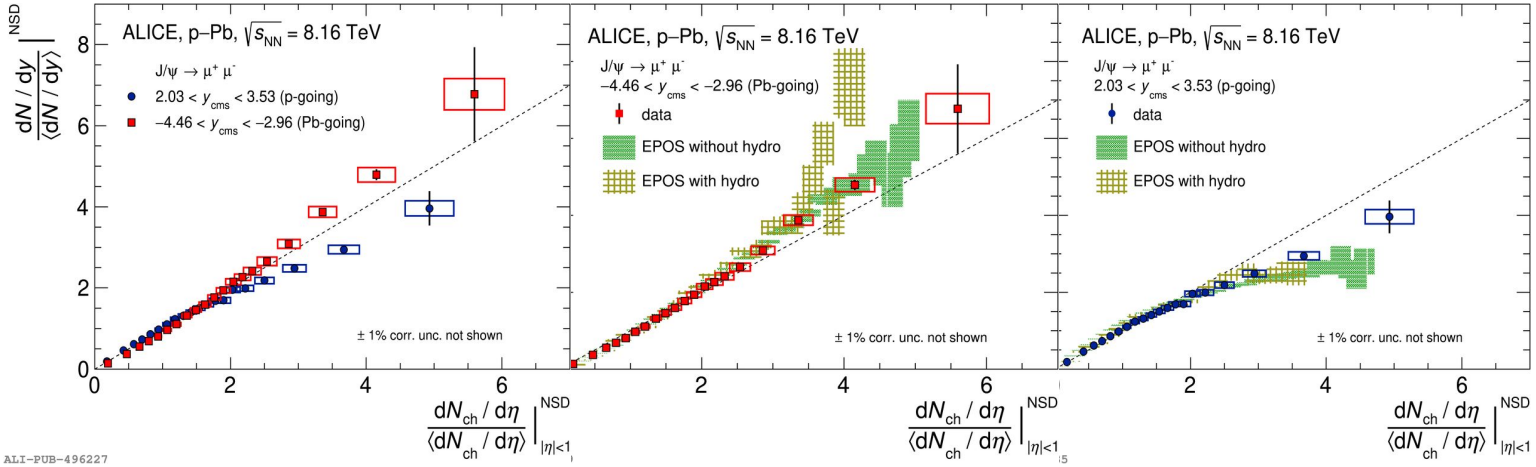
not-prompt J/ψ at 5.02 TeV:

- FONLL slightly underestimate the data
- Consistency observed with ATLAS and CMS measurements

- Lipatov et al, Phys. Rev. D 100 no. 11, (2019) 114021 (NRQCD kT factorization)
- Ma et al, Phys. Rev. Lett. 113 no. 19, (2014) 192301 (NRQCD + CGC)
- Cheung et al, Phys. Rev. D 98 no. 11, (2018) 114029 (ICEM)
- Cacciari et al, JHEP 10 (2012) 137 (FONLL)

J/Ψ production vs multiplicity in p–Pb

JHEP 2009 (2020) 162

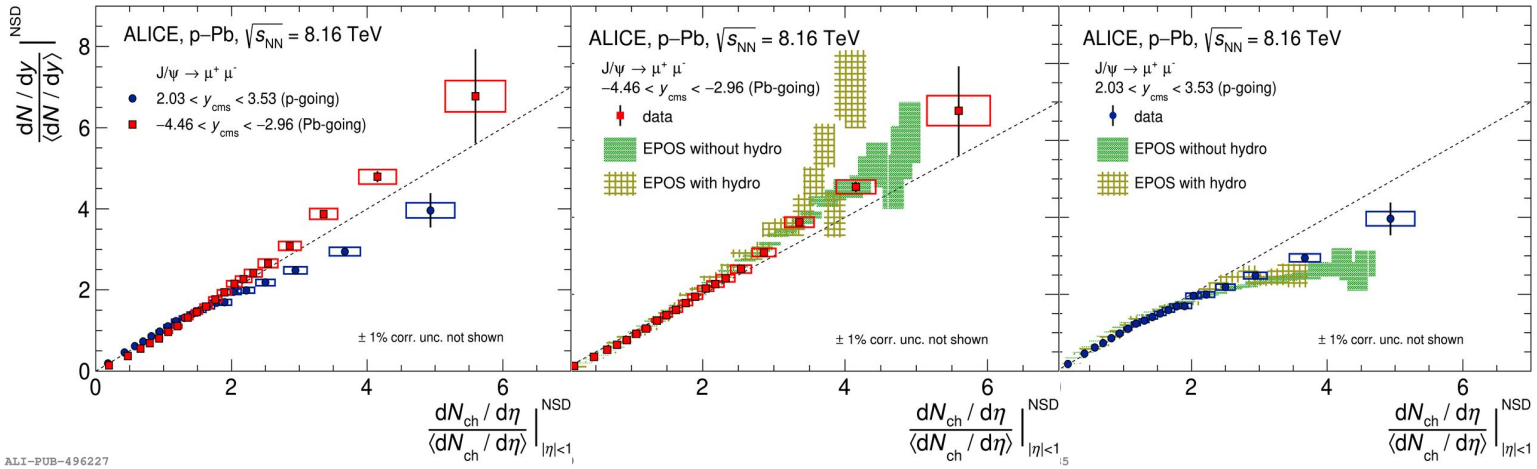


✓ The J/ψ yield approximately grows linearly as a function of the event multiplicity

➢ At ***forward rapidity (p-going)*** the correlation is weaker w.r.t the ***backward rapidity (Pb going)***

J/Ψ production vs multiplicity in p–Pb

JHEP 2009 (2020) 162



✓ The J/ψ yield approximately grows linearly as a function of the event multiplicity

➢ At ***forward rapidity (p-going)*** the correlation is weaker w.r.t the ***backward rapidity (Pb going)***

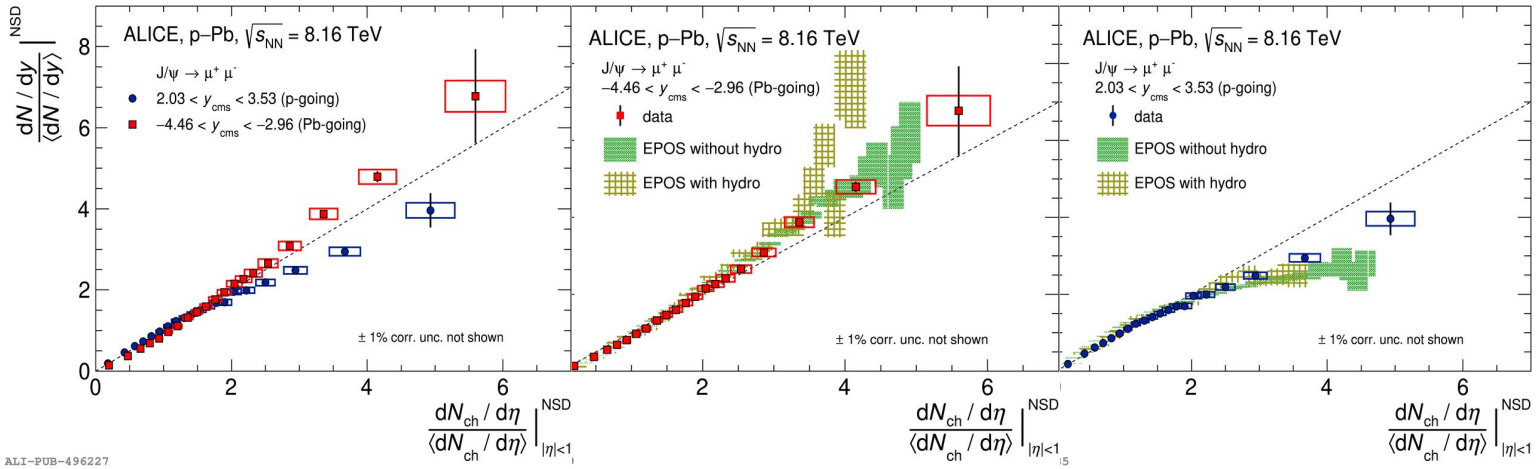
✓ This measurement allows to access different Pb nucleus Bjorken-x regime:

➢ ***forward rapidity (p-going)*** : low Bjorken-x regime ($x_{Pb} \sim 10^{-5}$);

➢ ***backward rapidity (Pb going)*** : intermediate Bjorken-x regime ($x_{Pb} \sim 10^{-2}$);

J/Ψ production vs multiplicity in p–Pb

JHEP 2009 (2020) 162



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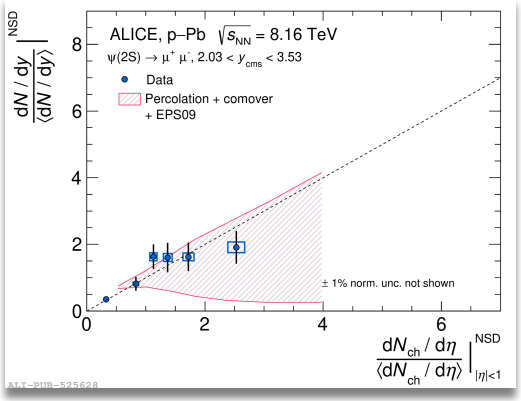
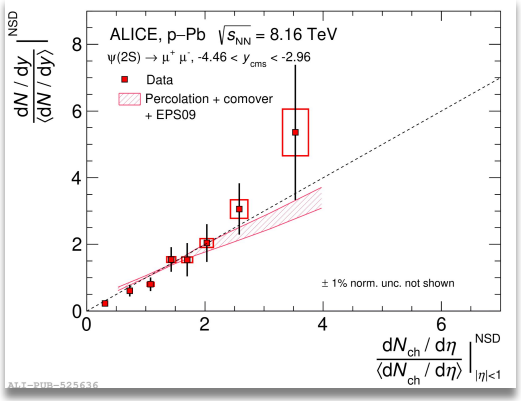
- EPOS3 generator without hydrodynamics correction fairly reproduces the data, suggesting that J/ψ production is governed by a superposition of parton-parton scatterings

Ψ(2S) production vs multiplicity in p–Pb

arXiv:2204.10253

- ✓ The ψ(2S) production exhibits as linear growth as a function of the event multiplicity
- ✓ As the for J/ψ, the correlation is weaker at ***forward*** w.r.t ***backward*** rapidity due to the different Bjorken-x region accessed





Ψ(2S) production vs multiplicity in p–Pb: a closer look

arXiv:2204.10253

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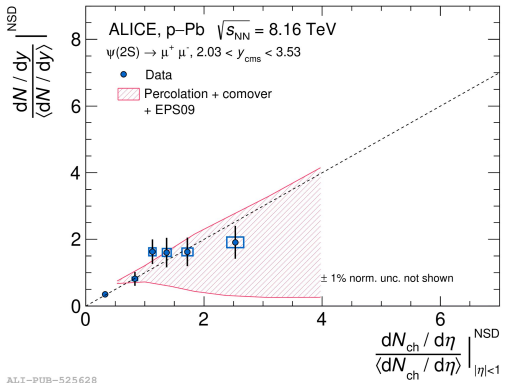

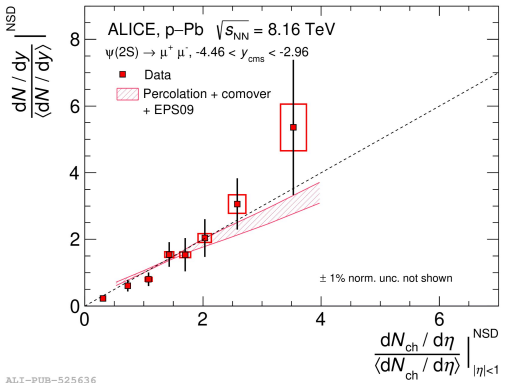

- ✓ Looking to the excited-to-ground states ratio, it is close to unity within the uncertainty
- ✓ Percolation+comover model is in agreement with data but no firm conclusion can be given