Quarkonium working group
Online - March 15-19, 2021

Quarkonium production in proton-proton collisions with ALICE

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on behalf of the ALICE Collaboration

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Outline

- Physics motivations
- Quarkonium measurements in ALICE
- Results:
  - Rapidity / p_T-differential cross sections for quarkonia
  - J/ψ polarization at forward rapidity
  - Quarkonium production vs multiplicity
  - J/ψ-hadron correlations at midrapidity
- Summary

Physics motivations

See talks by
L. Massacrier and B. Paul
on Friday morning

- ✔ Important **baseline** for **Pb-Pb and p-Pb** systems to quantify nuclear matter effects
- ✔ **Benchmark test for QCD** based processes: "factorization theorem" can be employed to describe prompt quarkonium production:

  1) $q\bar{q}$ pairs produced by initial hard partonic scattering → pQCD applicable

  - ✔ gluon fusion processes dominant at the LHC → sensitivity to gluon PDFs

  2) Hadronization into a "colourless" bound state → non-perturbative process. Three main production models (**+ new recent updates**):

  - ✔ Color Evaporation Model (CEM) [Phys. Rev. D 12 (1975) 2007]
    - ✔ **Improved CEM (ICEM)** **[Phys. Rev. D 98 (Dec, 2018)]**
  - ✔ Color Singlet Model (CSM) [Phys. Lett. B 67 (1977) 217]]
  - ✔ Non-Relativistic QCD (NRQCD) [Phys. Rev. D 51 (1995) 1125]
    - ✔ **NRQCD + Color Glass Condensate (CGC)** **[Phys. Rev. Lett. 113 no. 19, (2014)]**

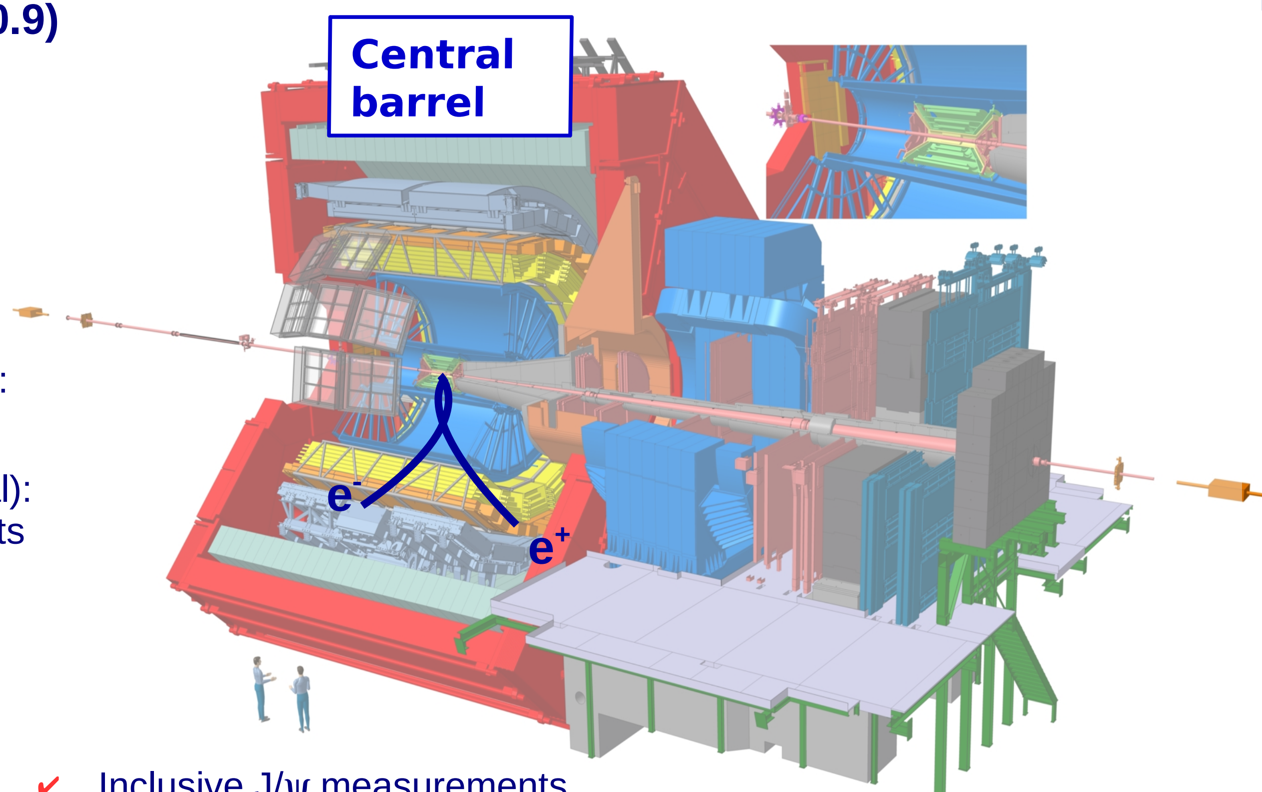
→ more differential measurements based on several "observables" (e.g. cross sections, polarization, quarkonium-hadron correlations, etc.) represent a powerful tool to constrain quarkonium production models

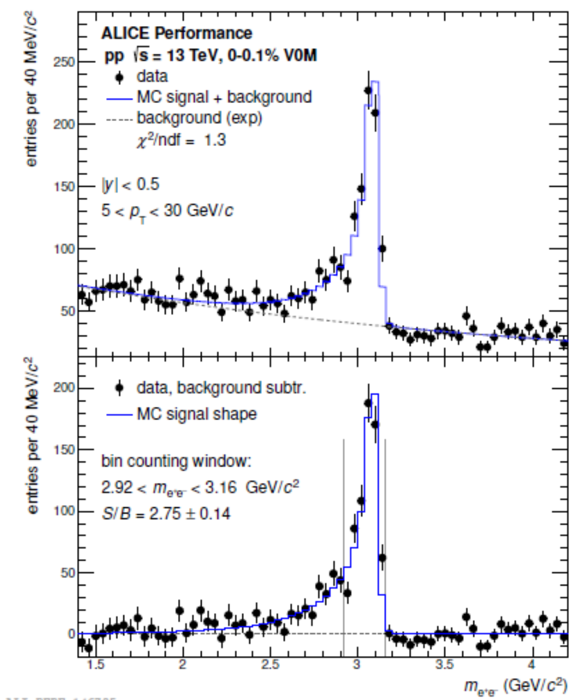
- ✔ Quarkonium studies as a function of multiplicity shed light on **Multiple Parton Interactions** (MPI) [relevant for heavy-flavour production at LHC energies!]

Quarkonium measurements in ALICE

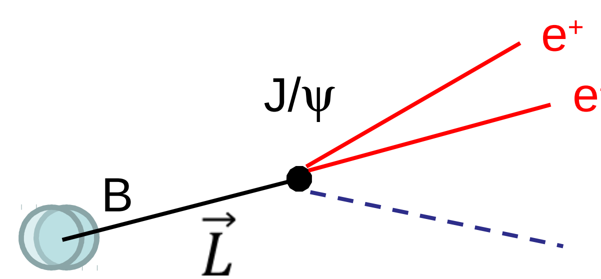
Mid-rapidity measurements ($|y| < 0.9$)

- ✔ **Dielectron** decay channel
- ✔ Time Projection Chamber (TPC): tracking, PID via dE/dx
- ✔ Inner Tracking System (ITS): vertexing, tracking, triggering
- ✔ Transition Radiation Detector (TRD): electron ID, triggering
- ✔ ElectroMagnetic Calorimeter (EMCal): triggering, PID via E/p measurements





- ✔ Inclusive J/ψ measurements down to $p_T = 0$ → unique kinematic coverage at the LHC !
- ✔ Possibility to separate prompt and non-prompt J/ψ down to a few GeV/c thanks to **Silicon Pixel Detectors (SPD)** → access beauty hadron production down to very low p_T

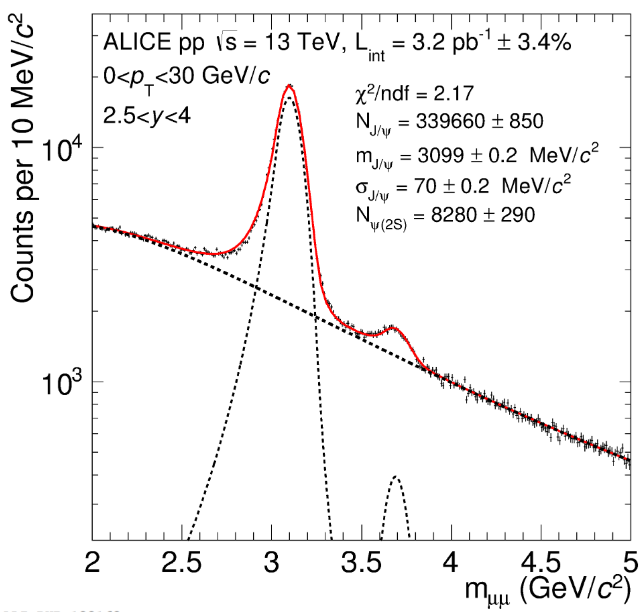


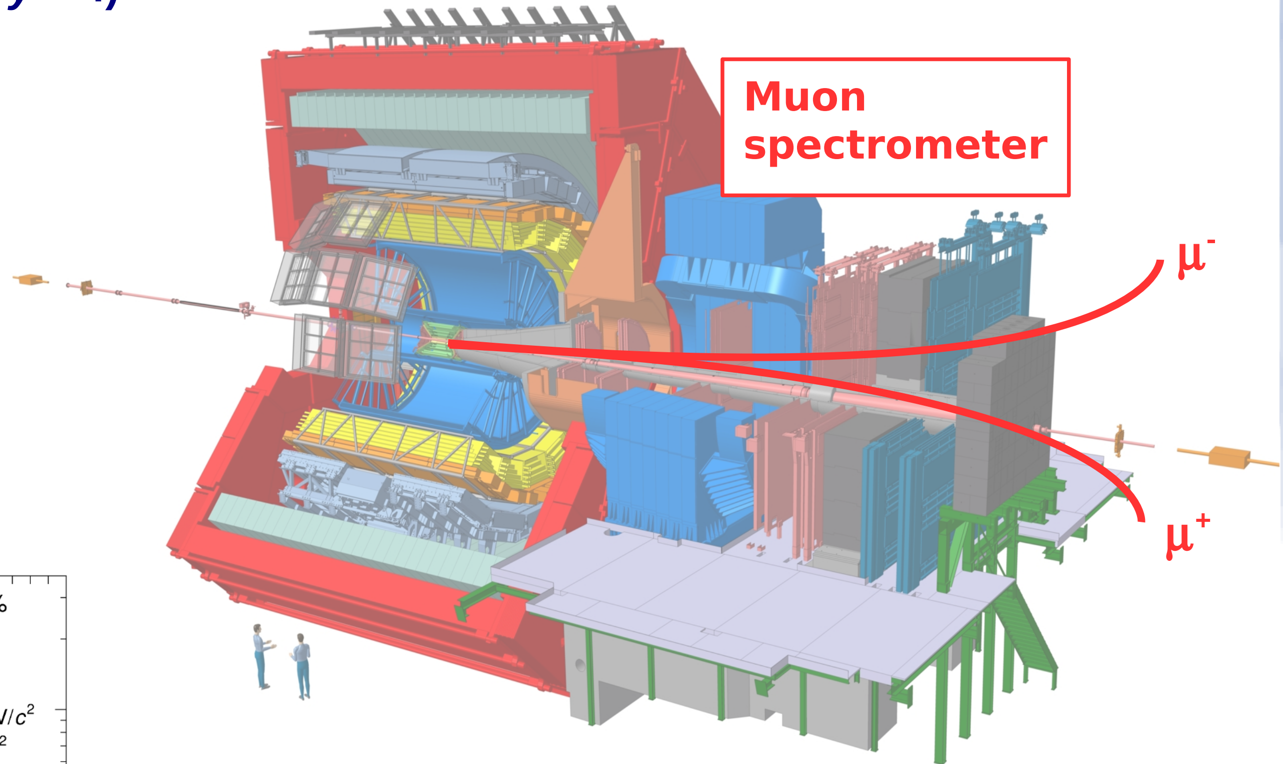
(*) Only detectors relevant for quarkonium analyses discussed here

Quarkonium measurements in ALICE

Fwd-rapidity measurements (2.5 < y < 4)

- ✔ **Dimuon** decay channel
- ✔ Muon spectrometer:
  - – Dipole magnet
  - – Front absorber 10 λ_I
  - – 10 tracking planes (Cathode Pad Chambers)
  - – 4 trigger planes (Resistive Plate Chambers)
  - – Muon filter (7 λ_I)





- ✔ Several charmonia and bottomonia states measured:
  - ✔ J/ψ, ψ(2S), ϒ states
- ✔ Acceptance: down to p_T = 0 for all quarkonium species !

(*) Only detectors relevant for quarkonium analyses discussed here

Quarkonium measurements in ALICE

Minimum Bias trigger based on:

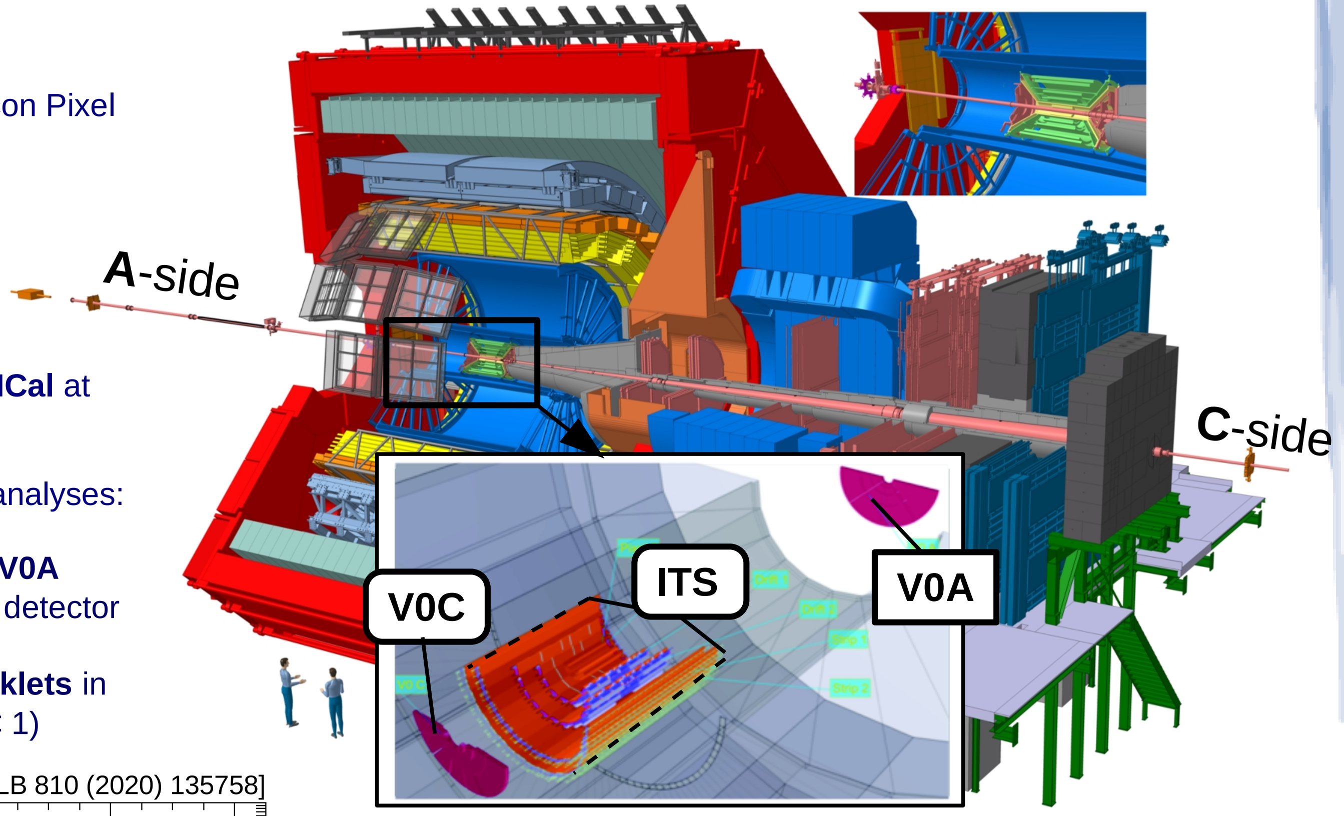
- ✔ Forward scintillator arrays (V0) (+Silicon Pixel Detector (SPD) in Run I)

In addition:

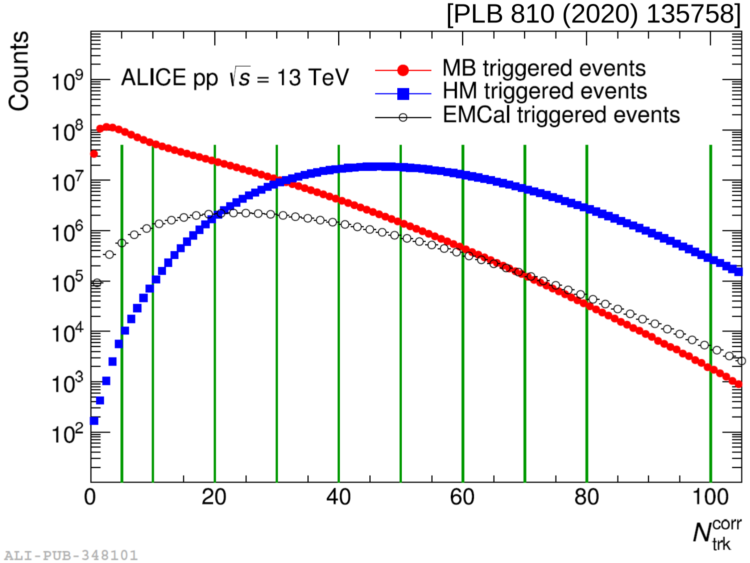
- ✔ trigger on **muon p_T** in the forward spectrometer
- ✔ trigger on energy deposition in the **EMCal** at mid-rapidity

Detectors used for **multiplicity** dependent analyses:

- ✔ VZERO: **amplitude** measured in the **V0A** (2.8 < η < 5.1) **+ V0C** (-3.7 < η < -1.7) detector
- ✔ SPD: **number of reconstructed tracklets** in the two innermost layers of ITS (| η | < 1)



[PLB 810 (2020) 135758]



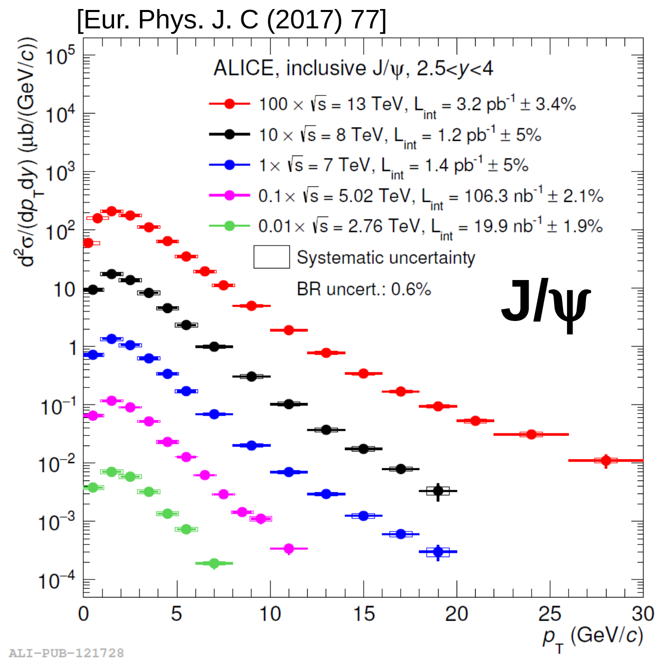
System	Year	√s (TeV)
	Run 1	
pp	2009–13	0.9, 2.76, 7, 8
	Run 2	
pp	2015,17 2015–18	5.02 13

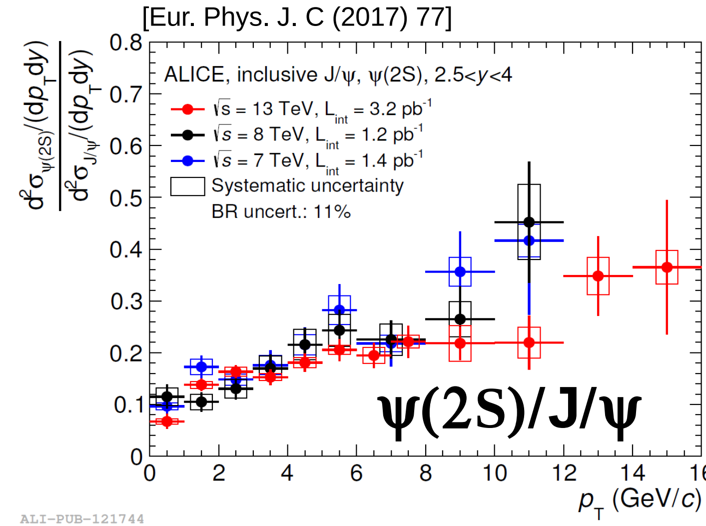
SQM 2017

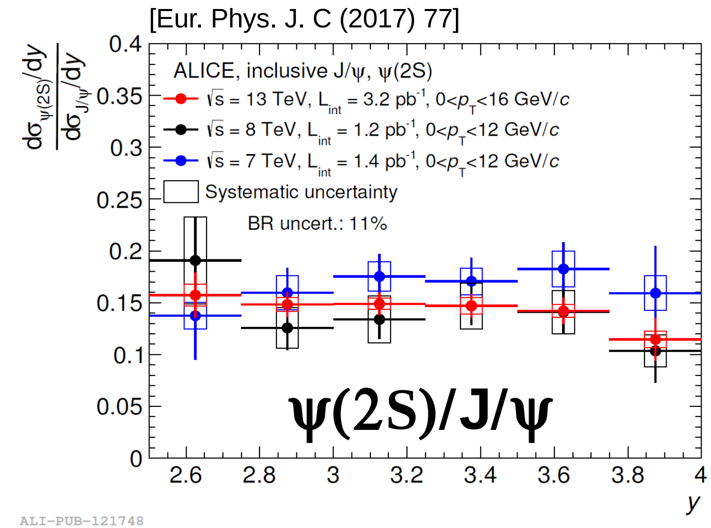
Quarkonium cross sections

fwd-y

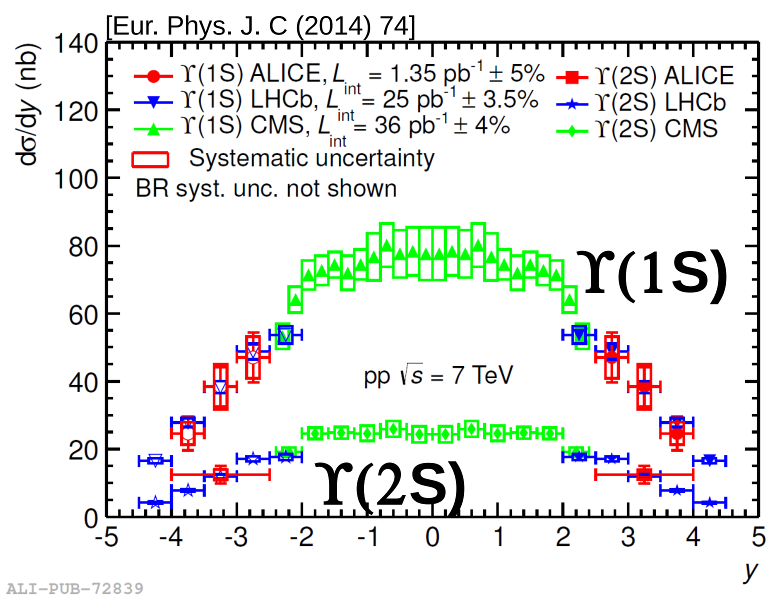
- Extensive and precise charmonium production measurements at several $\sqrt{s}$
  - Hardening of the p_T differential cross sections with increasing energy







- ALICE results are in good agreement with those from other LHC experiments

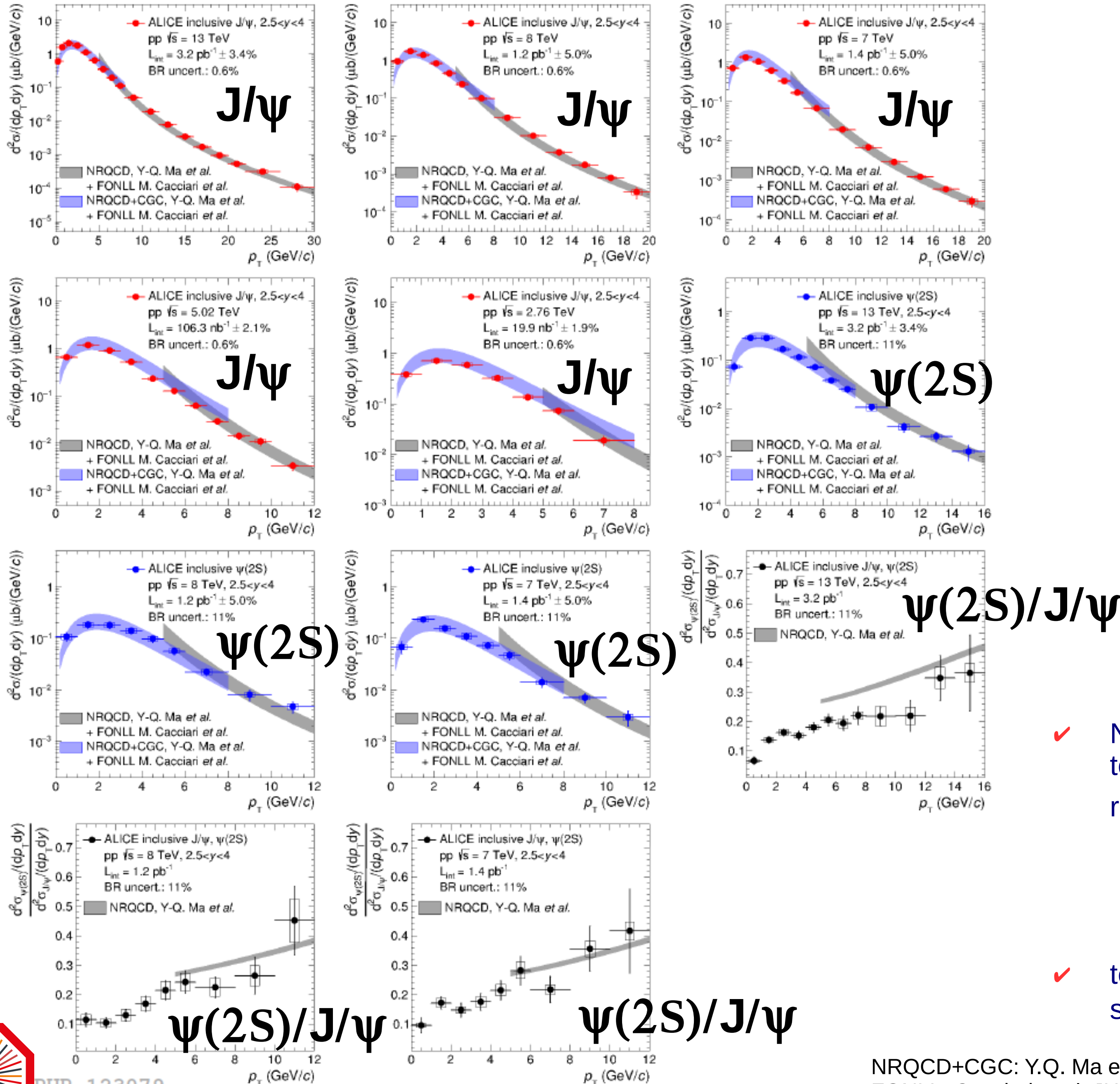


- ψ(2S) / J/ψ cross-section ratio shows:
  – an increasing trend with p_T
  – no significant dependence with rapidity and $\sqrt{s}$

Quarkonium cross sections

fwd-y

[Eur. Phys. J. C (2017) 77]



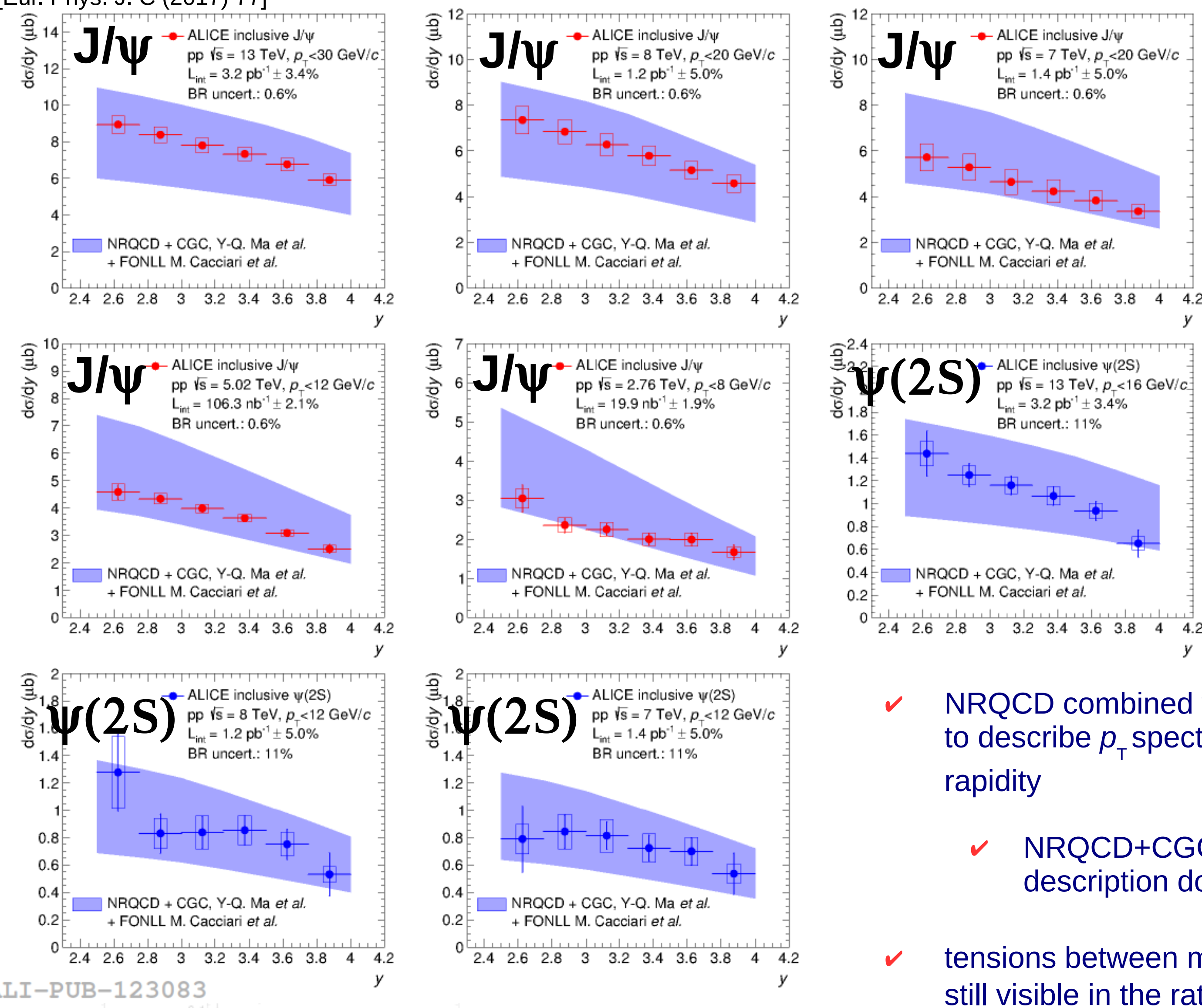
- ✔ NRQCD combined with FONLL is able to describe p_T spectra at forward rapidity
  - ✔ NRQCD+CGC provides a good description down to $p_T = 0$
- ✔ tensions between models and data still visible in the ratio ψ(2S) / J/ψ

NRQCD+CGC: Y.Q. Ma et al, Phys. Rev. Lett. 113 no. 19, (2014)
FONLL: Cacciari et al, JHEP 10 (2012) 137

Quarkonium cross sections

fwd-y

[Eur. Phys. J. C (2017) 77]



- ✔ Good agreement with NRQCD+CGC (+FONLL) observed also as a function of rapidity

- ✔ NRQCD combined with FONLL is able to describe p_T spectra at forward rapidity
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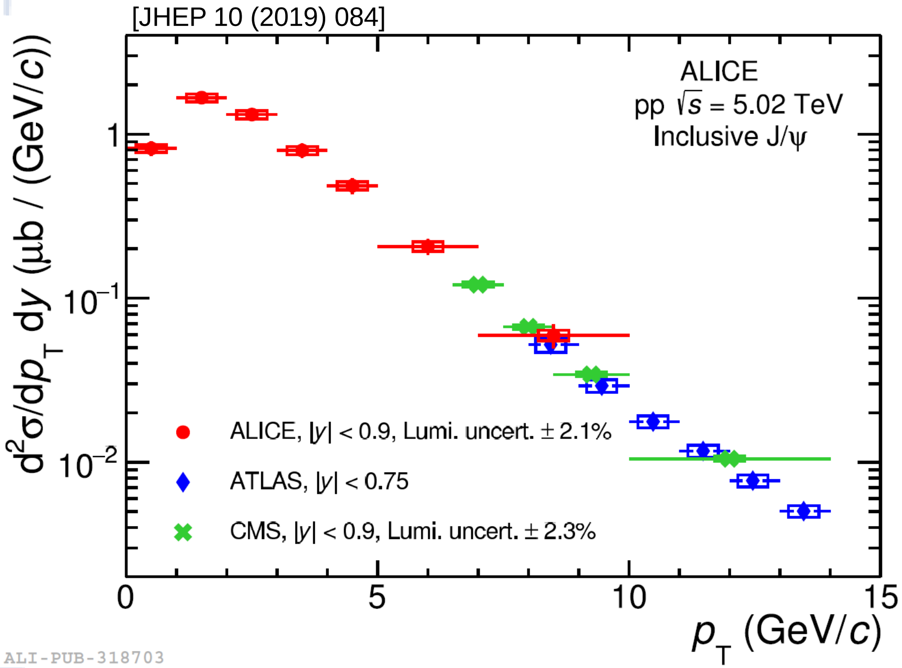
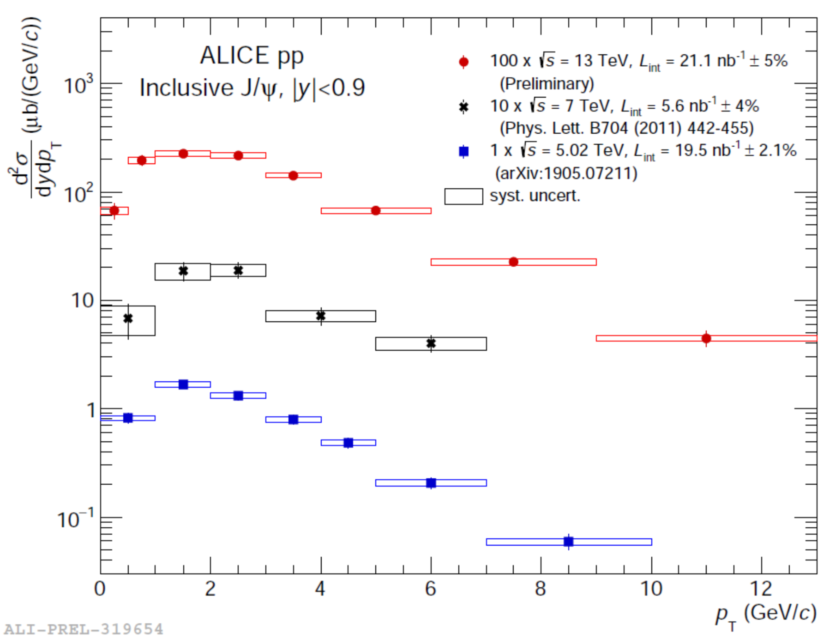
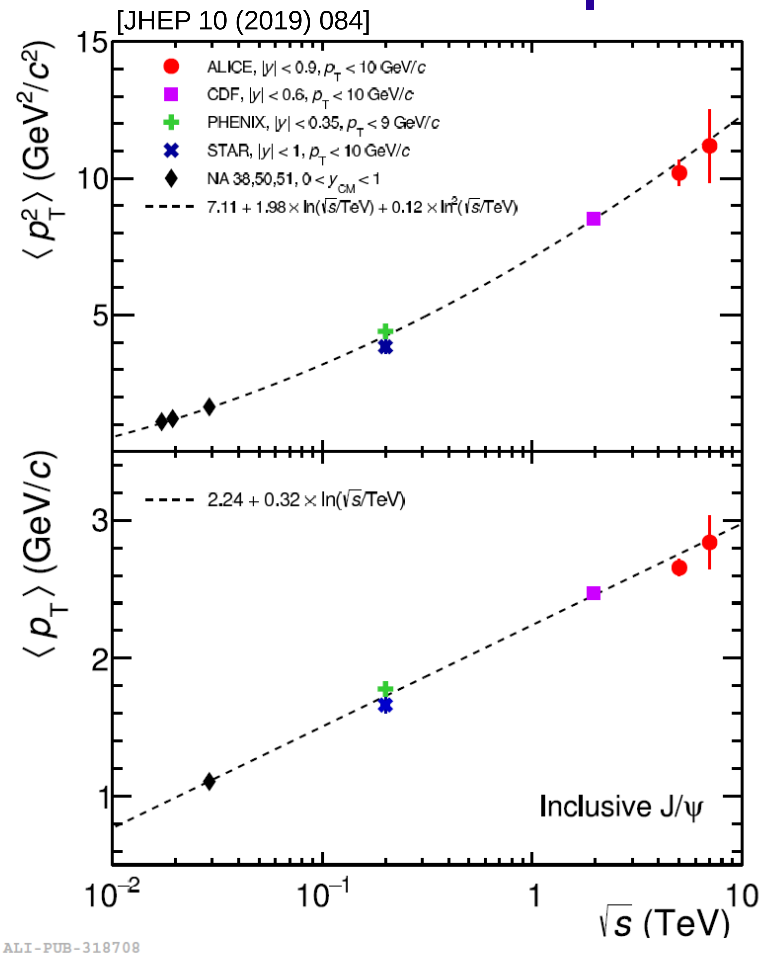
Quarkonium cross sections and $\langle p_T^{(2)} \rangle$

mid-y



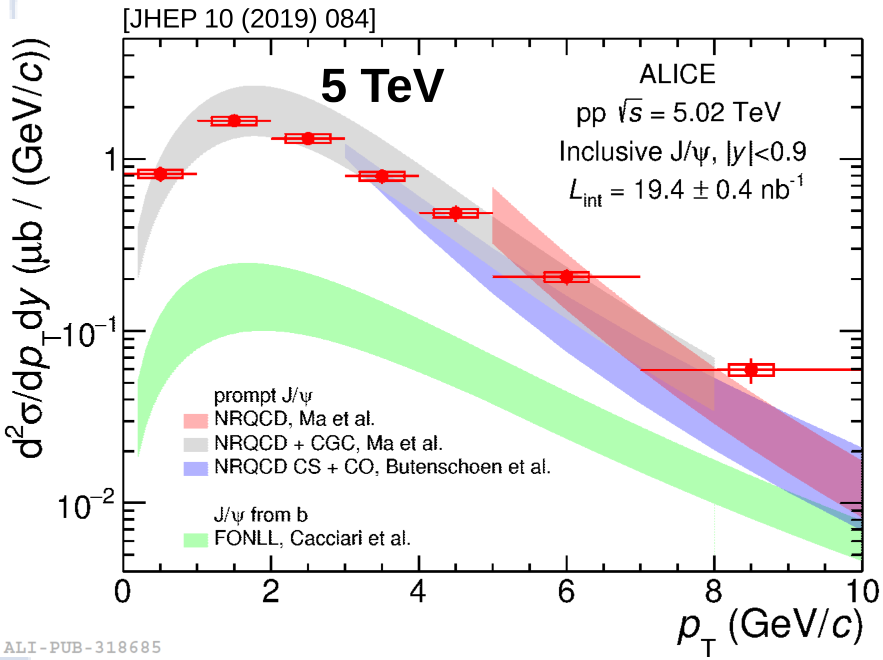


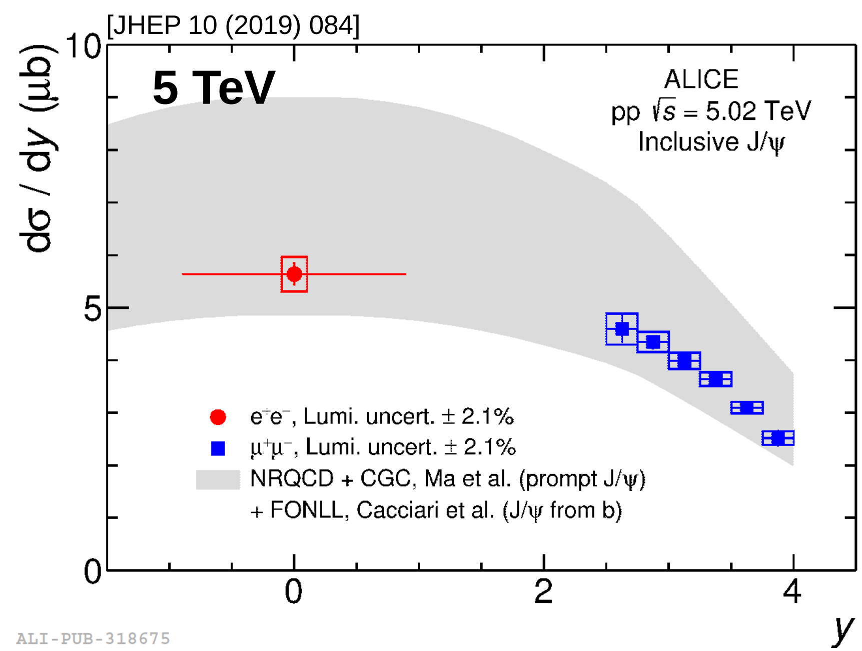


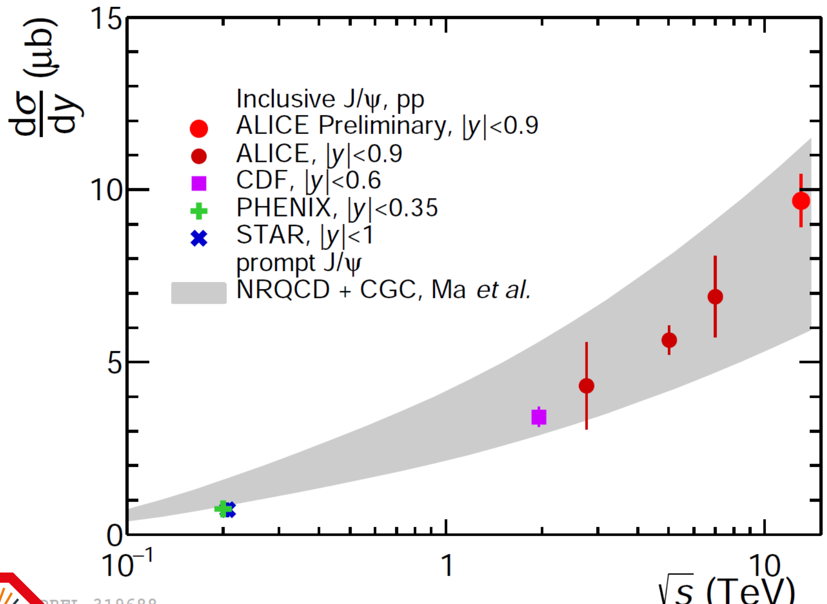
- ✔ Good agreement of ALICE results with ATLAS and CMS in the overlapping region at $\sqrt{s}$ = 5 TeV
- ✔ Hardening of p_T spectra vs $\sqrt{s}$
  - ✔ Steady increase of $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ with the collision energy

Quarkonium cross sections

mid-y





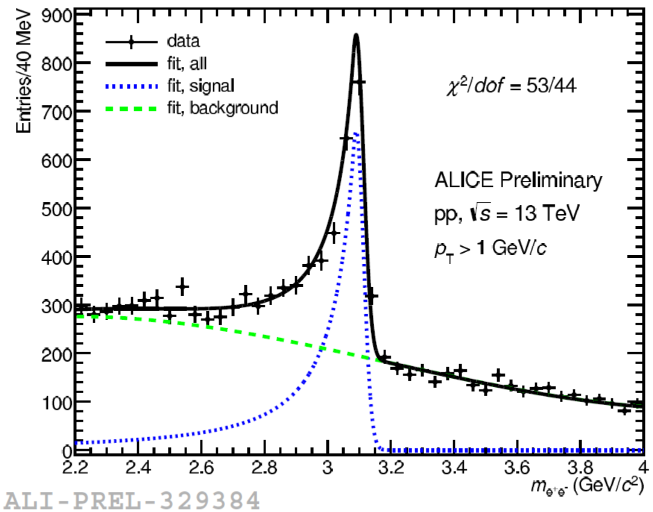


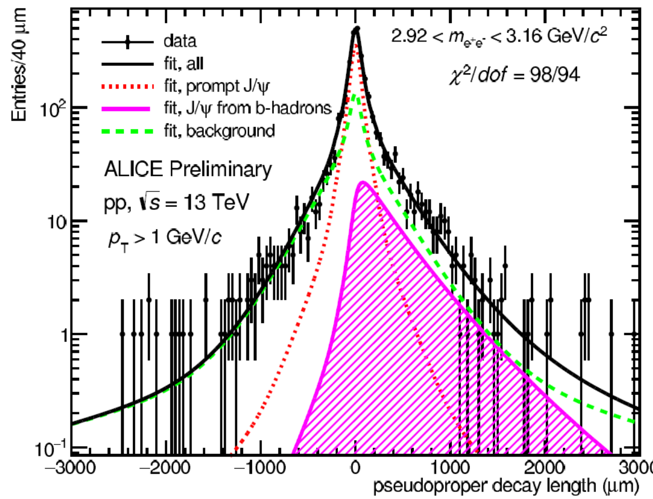
- ✔ NRQCD+CGC (+FONLL) model provides a good description of the p_T-differential cross section in the whole measured p_T range at $\sqrt{s}$ = 5 (similar agreement observed at $\sqrt{s}$ = 13 TeV)
- ✔ Rapidity dependence well reproduced by NRQCD+CGC(+FONLL)
- ✔ Increase of inclusive cross section vs $\sqrt{s}$ → could be affected by non-prompt J/ψ contribution (not included) at higher $\sqrt{s}$

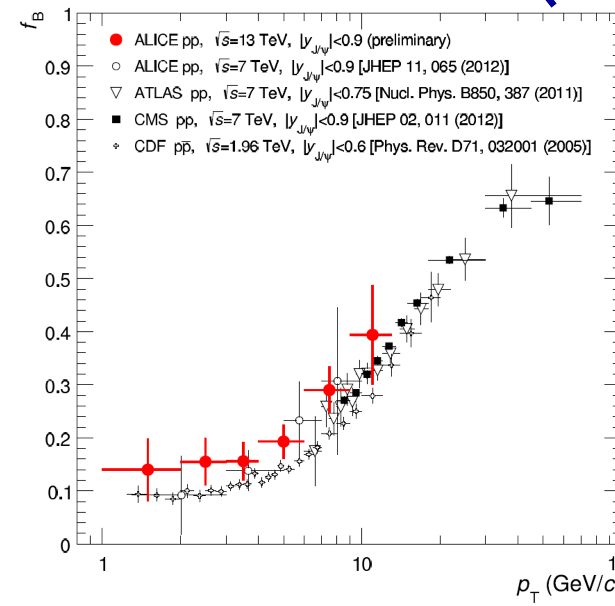
NRQCD+CGC: Y.-Q. Ma and R. Venugopalan, Phys. Rev. Lett. 113 no. 19, (2014)
NRQCD: Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. Lett. 106 (2011) 042002
M. Butenschoen and B. A. Kniehl, Phys. Rev. Lett. 106 (2011) 022003
FONLL: M. Cacciari et al, JHEP 10 (2012) 137

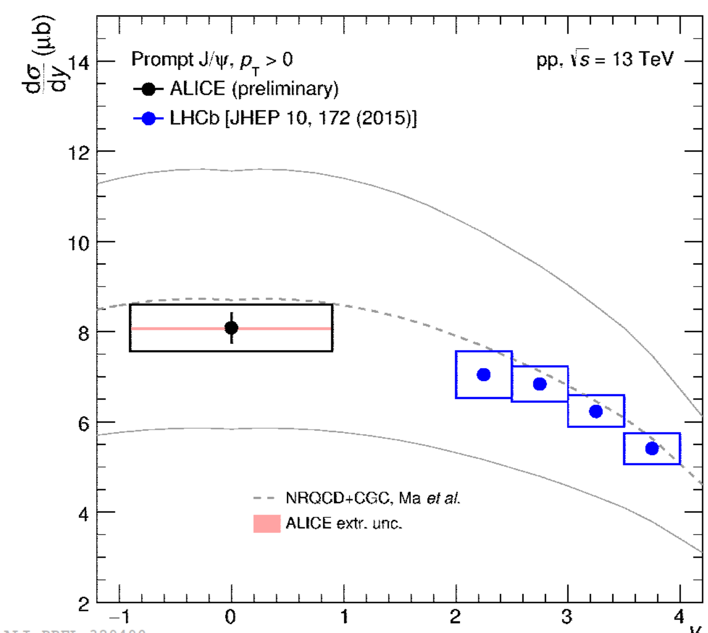
Prompt J/ψ and beauty cross sections

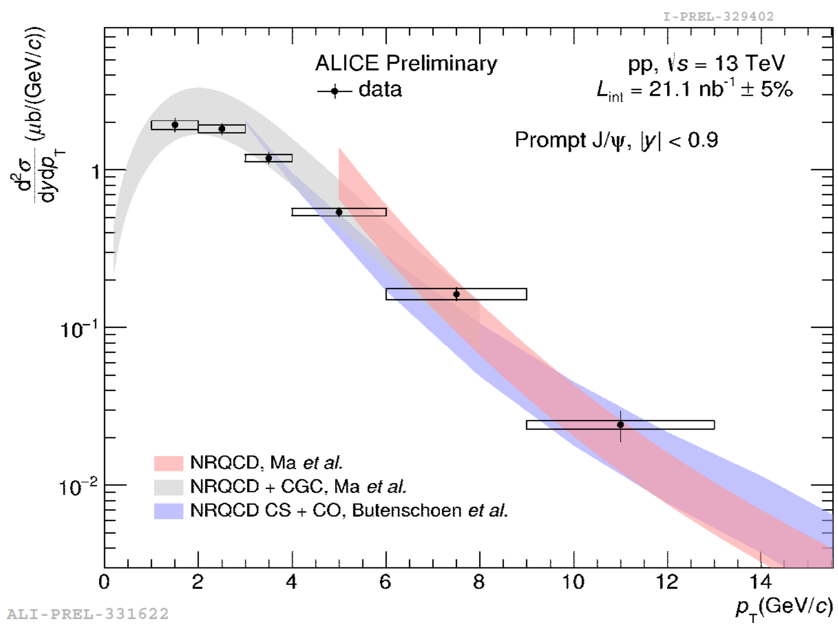
mid-y











- ✔ Possibility to disentangle prompt / non-prompt J/ψ at midrapidity
- ✔ NRQCD+CGC describes well prompt J/ψ cross sections vs p_T and rapidity

NRQCD+CGC: Y.-Q. Ma and R. Venugopalan, Phys. Rev. Lett. 113 no. 19, (2014)
NRQCD: Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. Lett. 106 (2011) 042002
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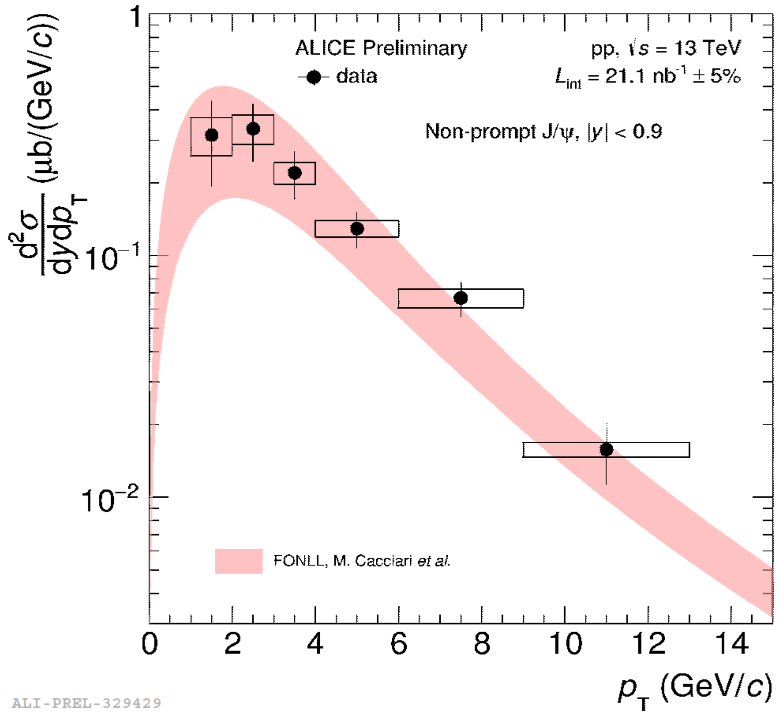
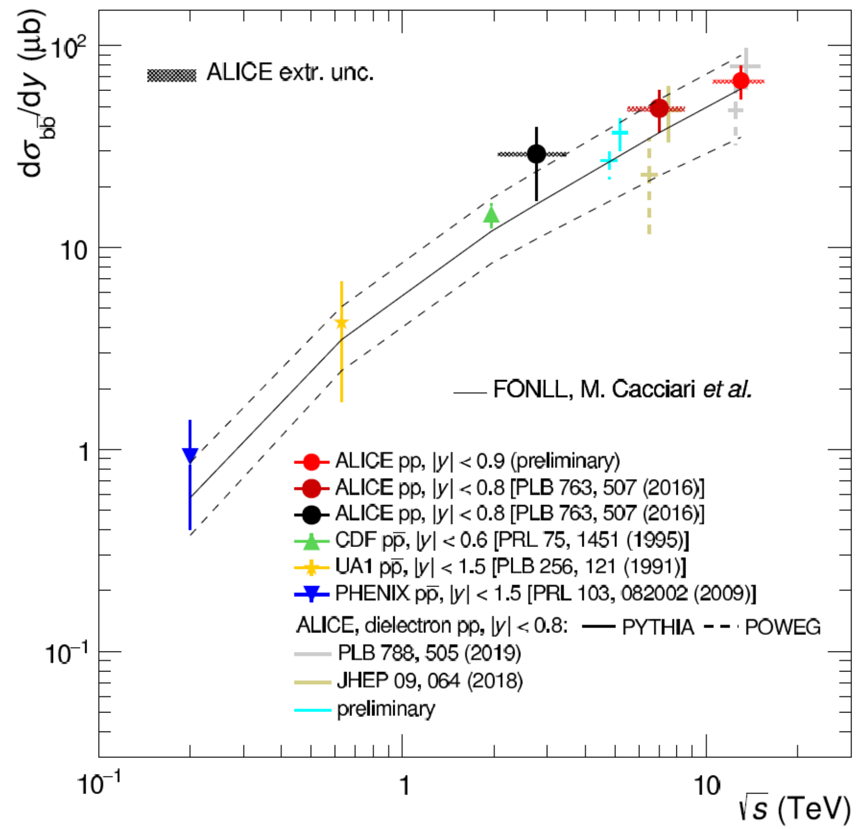
Prompt J/ψ and beauty cross sections

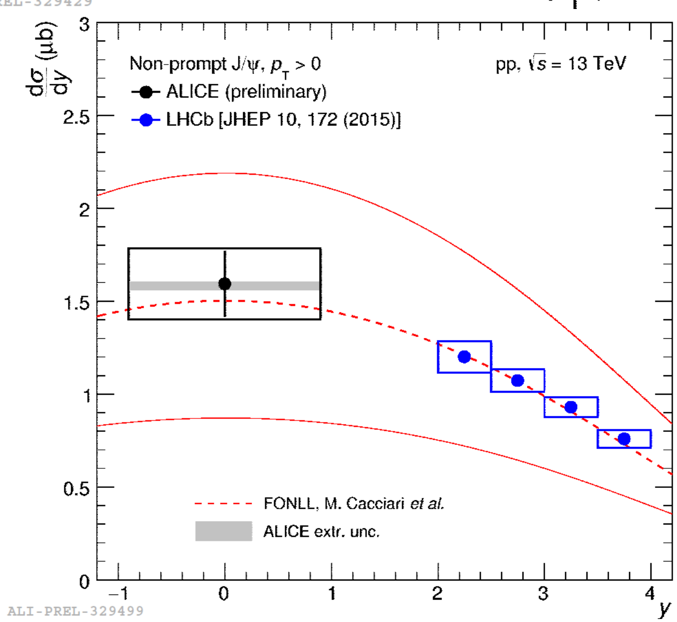
mid-y



ALI-PREL-329429



ALI-PREL-329511



ALI-PREL-329499

- Rapidity and p_T dependent non-prompt J/ψ cross sections well described by FONLL model
- Possibility to extrapolate beauty quark production cross section at midrapidity
  - good agreement with both FONLL ($61.21^{+46\%}_{-42\%}$ μb) and NNLO ($72.77^{+33\%}_{-26\%}$ μb) at √s = 13 TeV

FONLL: M. Cacciari et al, JHEP 10 (2012) 137
NNLO: S. Catani et al, arXiv:2010.11906

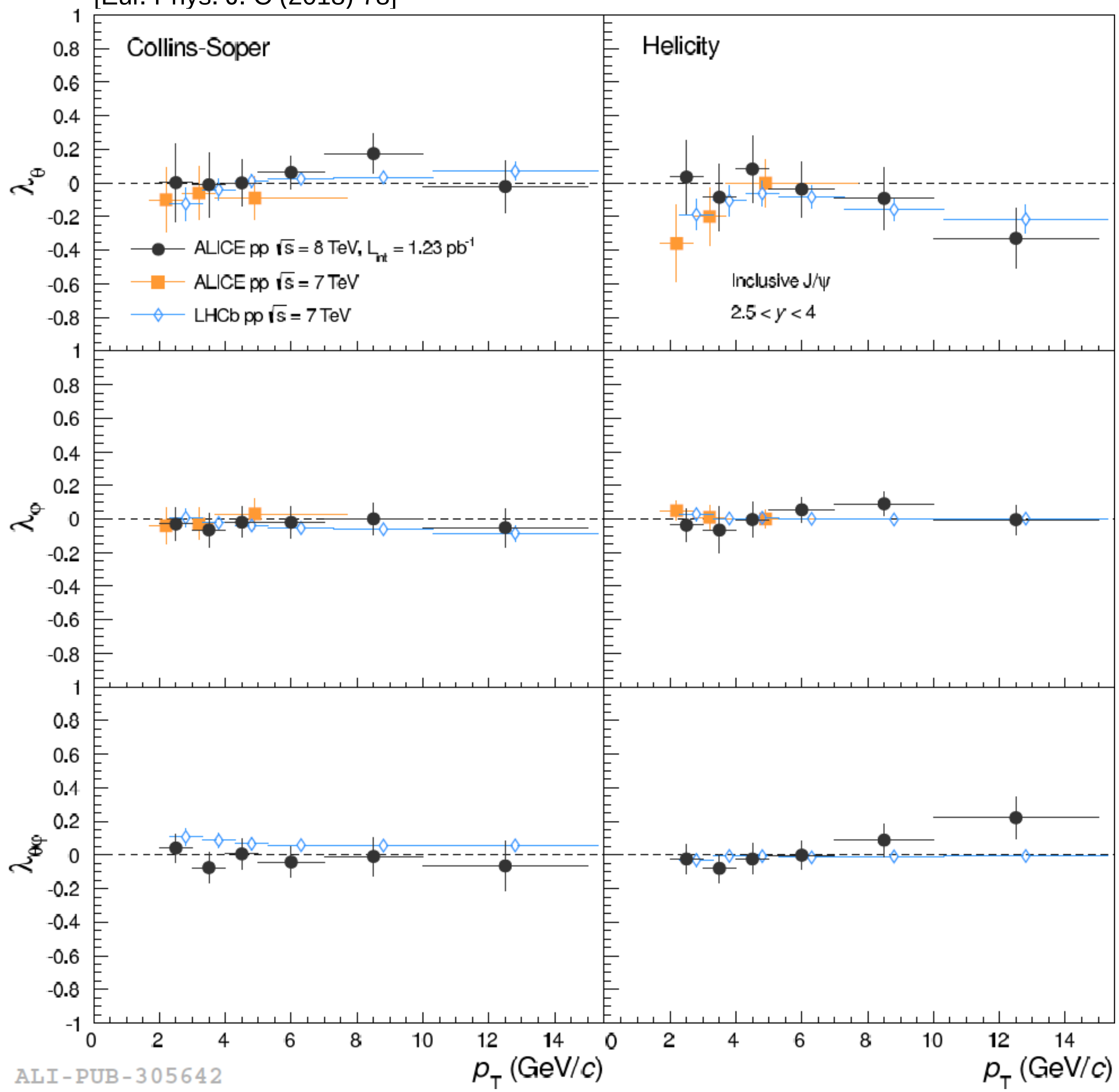
J/ψ polarization

fwd-y

- ✔ Polarization parameters studied through the angular distributions of leptons in the quarkonium rest frame
- ✔ Measurements performed in different polarization frames (Helicity and Collins-Soper)
  - ✔ No significant J/ψ polarization observed
  - ✔ Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\left[1+\lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos(2\varphi) + \lambda_{\theta\varphi} \sin(2\theta)\cos\varphi\right]$$

[Eur. Phys. J. C (2018) 78]



J/ψ polarization

fwd-y

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- Measurements performed in different polarization frames (Helicity and Collins-Soper)
  - No significant J/ψ polarization observed
  - Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV
  - NRQCD calculations not able to describe simultaneosly all measurements (NLO NRQCD2 available only for p_T > 5 GeV/c and for one polarization parameter → difficult to conclude)

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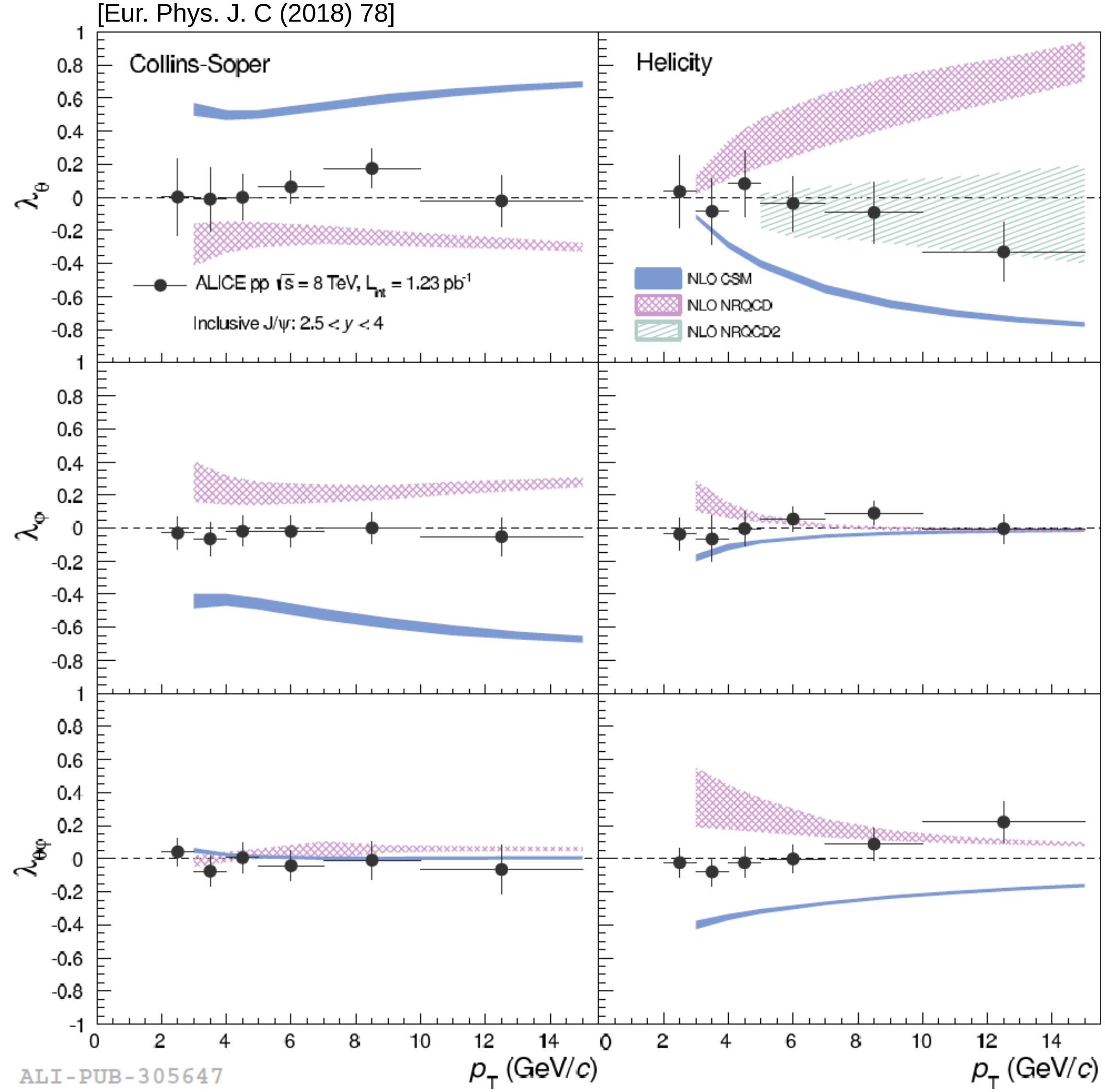
[Eur. Phys. J. C (2018) 78]



CSM, NLO NRQCD: M. Butenschoen and B. A. Knieh, Phys.Rev.Lett. 108 (2012) 172002
NLO NRQCD2: K.-T. Chao, Y.-Q. Ma, H.-S. Shao, K. Wang, and Y.-J. Zhang, Phys.Rev.Lett. 108 (2012) 24200

J/ψ polarization

fwd-y

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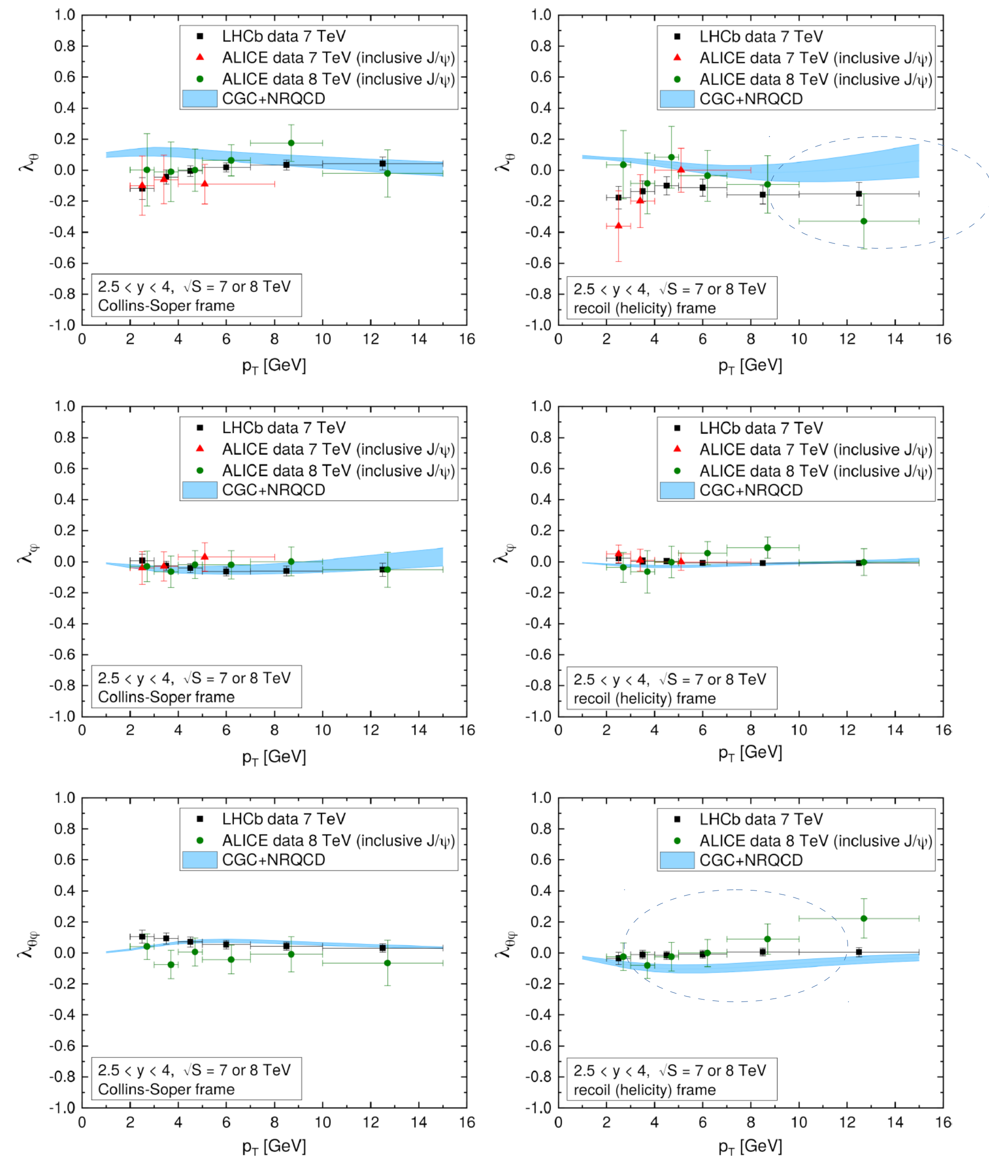
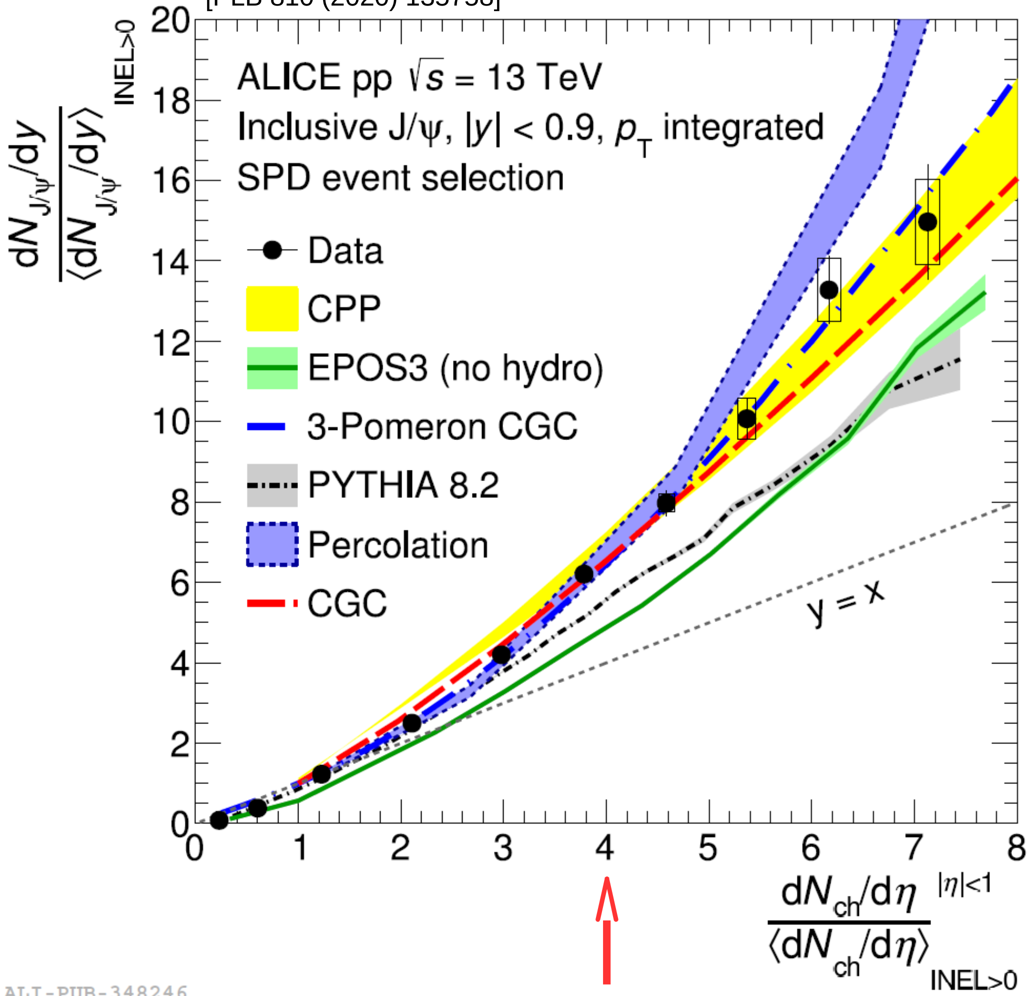


- No significant J/ψ polarization observed
- Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV
- NRQCD calculations not able to describe simultaneosly all measurements (NLO NRQCD2 available only for p_T > 5 GeV/c and for one polarization parameter → difficult to conclude)
- Better agreement within uncertainties observed for NRQCD+CGC → small tensions still visible

NRQCD+CGC: Y.-Q. Ma, T. Stebel and R. Venugopala, JHEP 1812 (2018) 057

Inclusive quarkonium production vs multiplicity mid-y

[PLB 810 (2020) 135758]



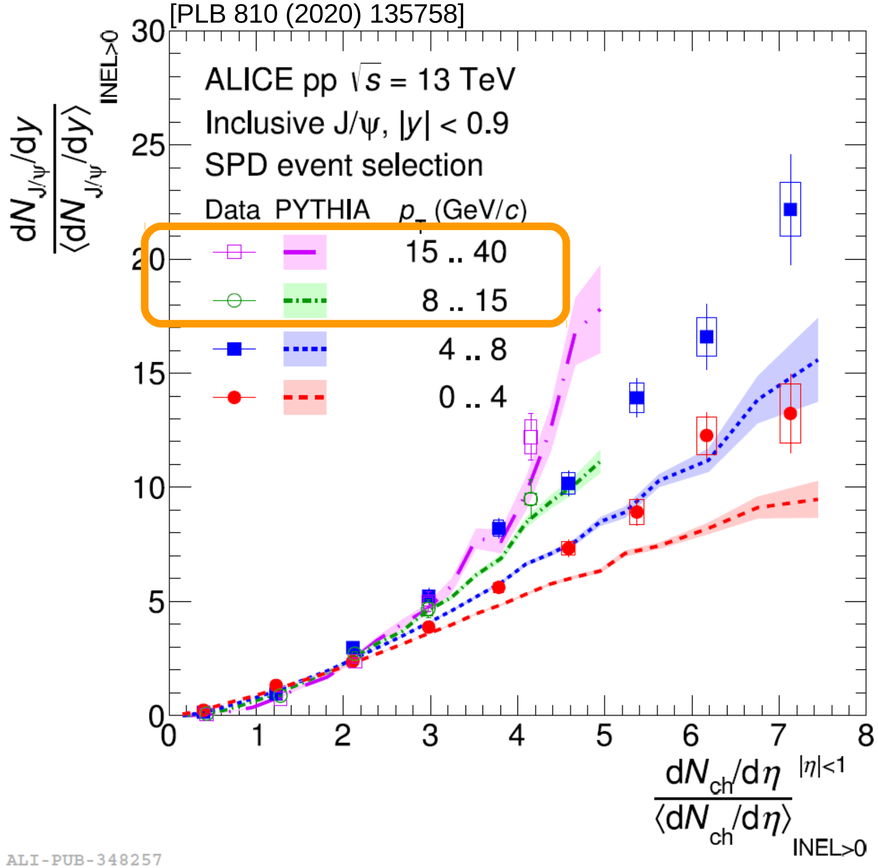
RUN I mult. reach for J/ψ

- ✔ Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!

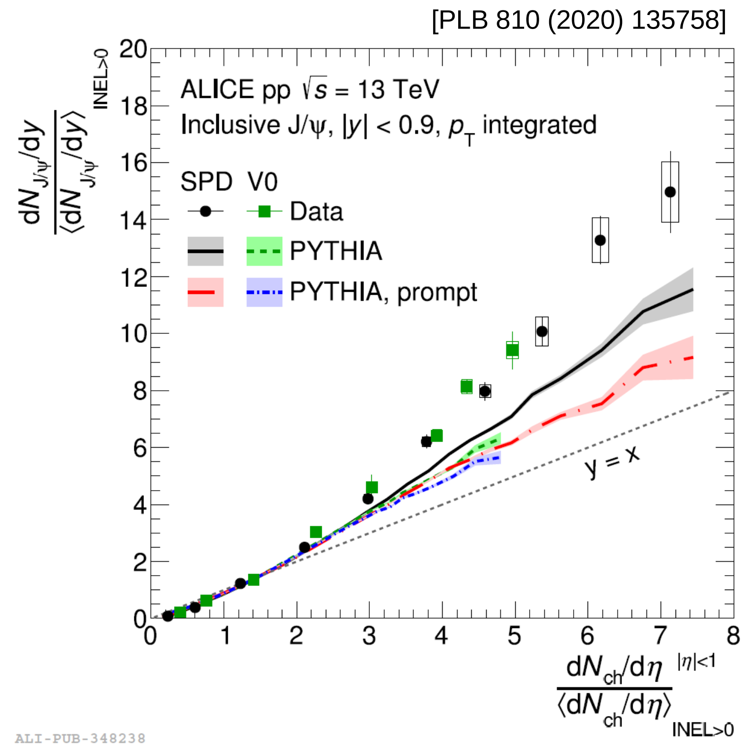
- ✔ All models predict a faster than linear increase
  - ✔ effect of a reduction of charged particle multiplicity (x-axis) realized through different mechanisms, depending on the model
- ✔ Pythia8 and EPOS underpredict data, while percolation model overestimates them at high-multiplicity
- ✔ Good agreement observed for CPP, CGC and 3-Pomeron CGC

CPP: Kopeliovich et al., PRD88 (2013) 116002
EPOS3: Werner et al., Phys.Rept.350 (2001) 93
3-Pomeron CGC: arXiv:1910.13579
PYTHIA8. Sjostrand et al., Comput.Phys.Comm.178(2008)
Percolation: Ferreiro, Pajares, PRC86 (2012) 034903
CGC: Phys. Rev. D98 no. 7, (2018) 074025

Inclusive quarkonium production vs multiplicity mid-y



- Calorimeter (**EMCAL**) trigger significantly extends the p_T range (up to 40 GeV/c)

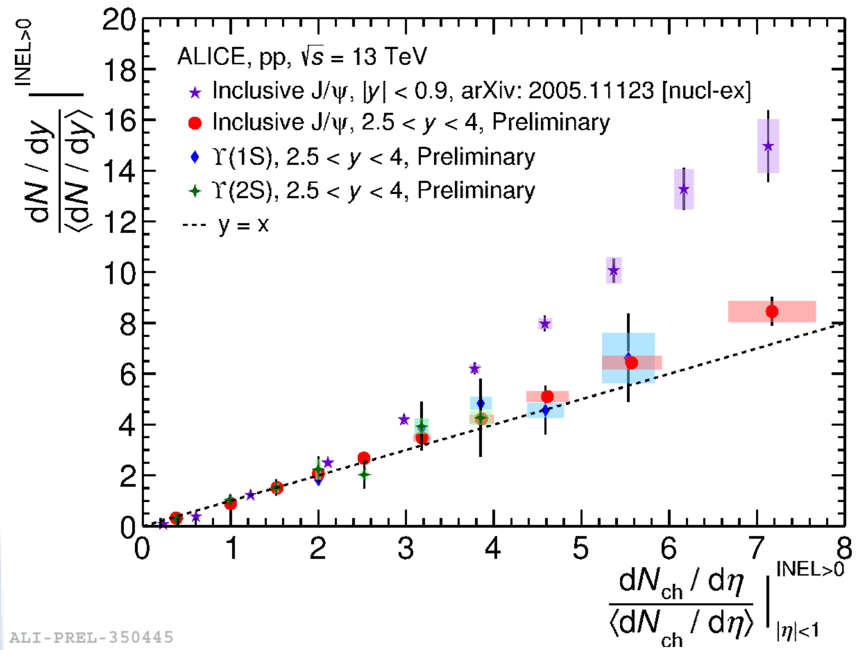


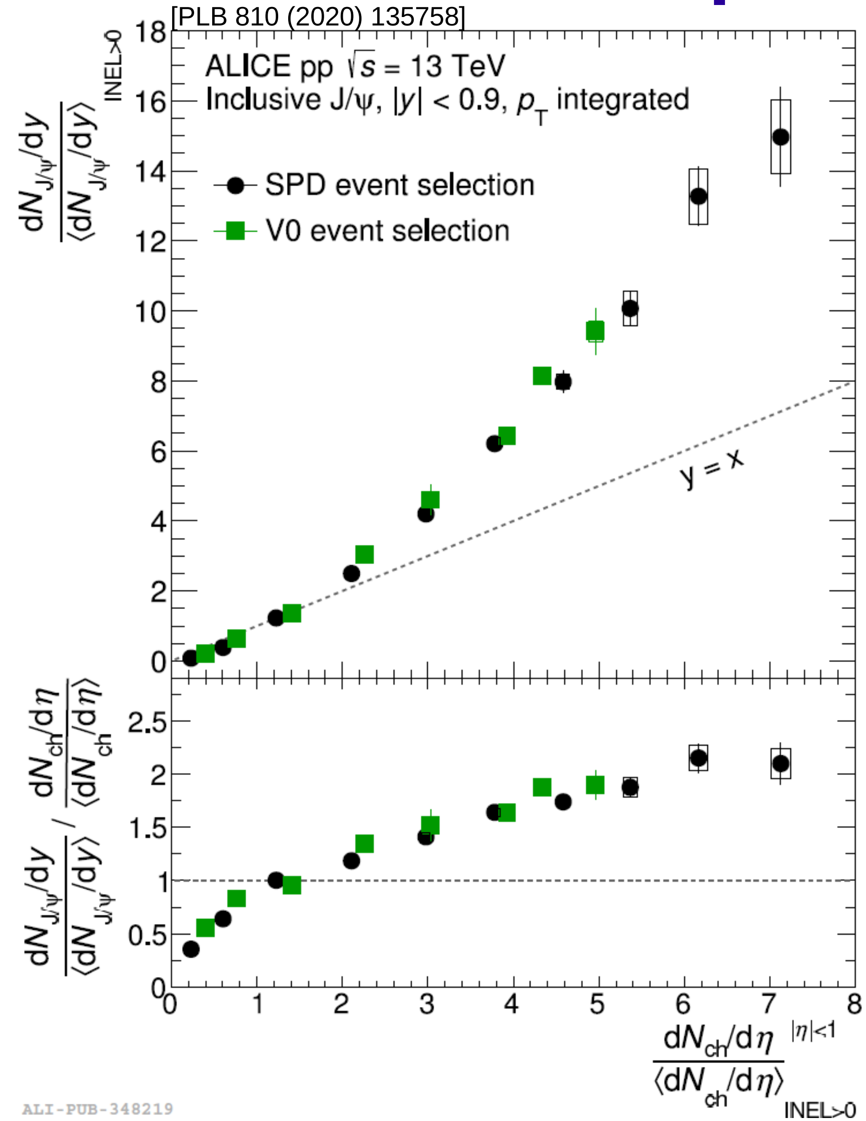
- Faster than linear increase observed also in p_T bins for J/ψ
- Slope increases with the transverse momentum of J/ψ
- Pythia8 model (which includes the contribution from non-prompt J/ψ) qualitatively reproduces the trends observed in the data

PYTHIA8. Sjostrand et al., Comput.Phys.Comm.178(2008)

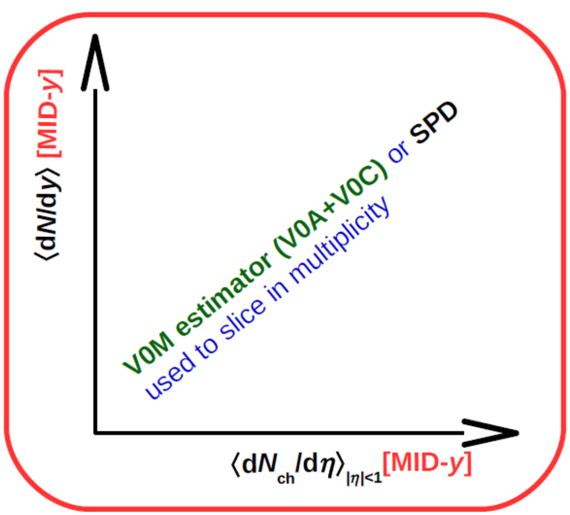
Inclusive quarkonium production vs multiplicity

fwd-y × mid-y





- Linear increase observed for J/ψ, ϒ(1S) and ϒ(2S) at forward rapidity → no significant dependence on mass and heavy quark content

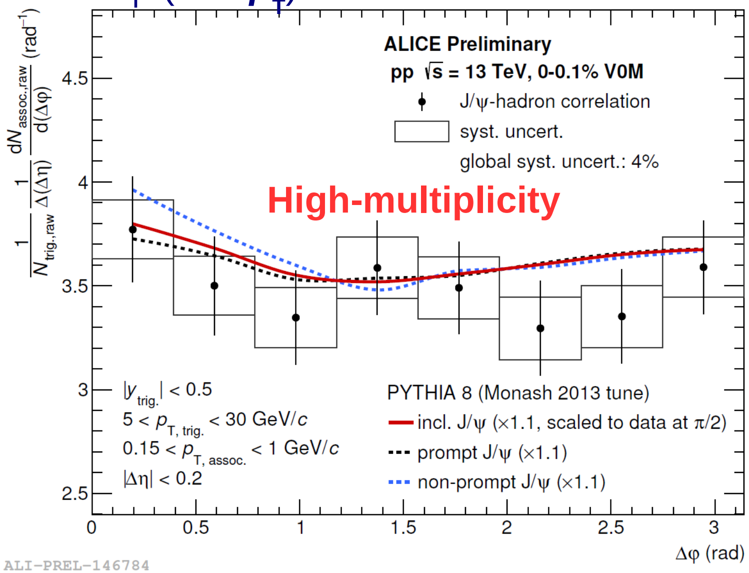


- Faster than linear increase observed for J/ψ at midrapidity
  - Similar trend obtained using multiplicity estimators defined at **midrapidity (SPD)** and **forward rapidity (V0A+V0C)** → no significant auto-correlation bias effects visible

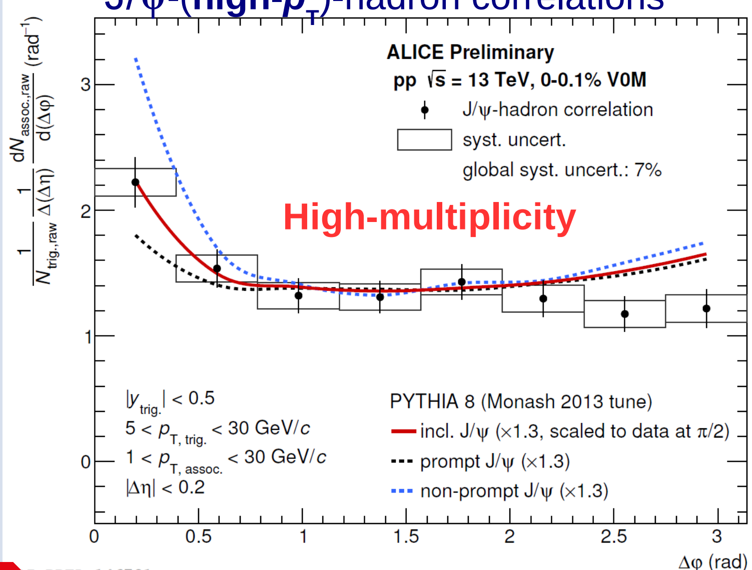
J/ψ-hadron correlations

mid-y

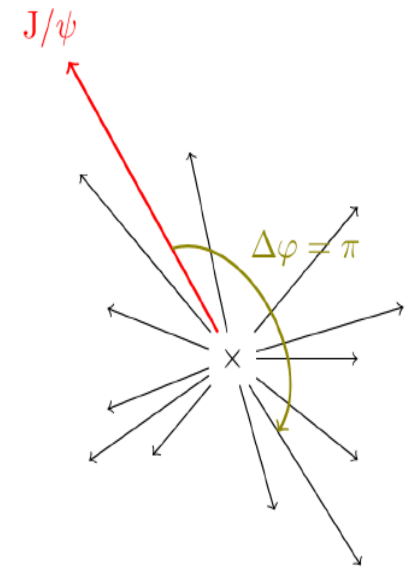
J/ψ-(low-p_T)-hadron correlations



J/ψ-(high-p_T)-hadron correlations



- Correlate J/ψ with hadrons produced in the same event for quantifying hadronic activity in azimuthal regions w.r.t. the J/ψ direction
- Larger hadronic activity could be expected in the J/ψ direction in case of production through COM (compared to CSM)
- Larger hadronic activity expected for non-prompt J/ψ (both in the near / away side) because of the b-quark pairs fragmentation



- Clear near side peak observed by correlating high-p_T J/ψ (p_T > 5 GeV/c) and hadrons with p_T > 1 GeV/c
- Qualitative good agreement observed with PYTHIA8 simulations
- Usage of full Run II statistics (gain of a factor ~100 expected for p_T(J/ψ) > 5 GeV/c) will improve significantly uncertainties allowing finer kinematic scan

PYTHIA8. Sjostrand et al., Comput.Phys.Comm.178(2008)

Summary

- Quarkonium production cross sections:
  - well reproduced by NRQCD+CGC (+FONLL) in a wide range of p_T and rapidity, for both J/ψ and ψ(2S); however tensions between data and models still visible
  - Prompt (non-prompt) J/ψ cross sections at midrapidity ($\sqrt{s}$ = 13 TeV) well reproduced by NRQCD+CGC (FONLL) down to very low p_T
- J/ψ polarization:
  - ALICE results ($\sqrt{s}$ = 7 and 8 TeV) are compatible with LHCb ones ($\sqrt{s}$ = 7 TeV) and show weak or zero polarization
  - CSM and NRQCD NLO calculations predict larger polarization; better agreement observed for NRQCD+CGC
- Multiplicity dependence of quarkonia:
  - Faster than linear increase observed for J/ψ at midrapidity; linear incresing trend observed at forward rapidity
    - Similar trend observed at forward rapidity for ψ(2S) and bottomonium states (ϒ(1S) and ϒ(2S))
    - No auto-correlation bias observed for J/ψ measurements at midrapidity
- J/ψ-hadron correlations:
  - Near-side peak observed; qualitative agreement with PYTHIA8 simulations
  - Significant improvement expected after including full Run-II statistics

Summary

- Quarkonium production cross sections:
  - well reproduced by NRQCD+CGC (+FONLL) in a wide range of p_T and rapidity, for both J/ψ and ψ(2S); however tensions between data and models still visible
  - Prompt (non-prompt) J/ψ cross sections at midrapidity ($\sqrt{s}$ = 13 TeV) well reproduced by NRQCD+CGC (FONLL) down to very low p_T
- J/ψ polarization:
  - ALICE results ($\sqrt{s}$ = 7 and 8 TeV) are compatible with LHCb ones ($\sqrt{s}$ = 7 TeV) and show weak or zero polarization
  - CSM and NRQCD NLO calculations predict larger polarization; better agreement observed for NRQCD+CGC
- Multiplicity dependence of quarkonia:
  - Faster than linear increase observed for J/ψ at midrapidity; linear incresing trend observed at forward rapidity
    - Similar trend observed at forward rapidity for ψ(2S) and bottomonium states (ϒ(1S) and ϒ(2S))
    - No auto-correlation bias observed for J/ψ measurements at midrapidity
- J/ψ-hadron correlations:
  - Near-side peak observed; qualitative agreement with PYTHIA8 simulations
  - Significant improvement expected after including full Run-II statistics

Thank you for your attention !

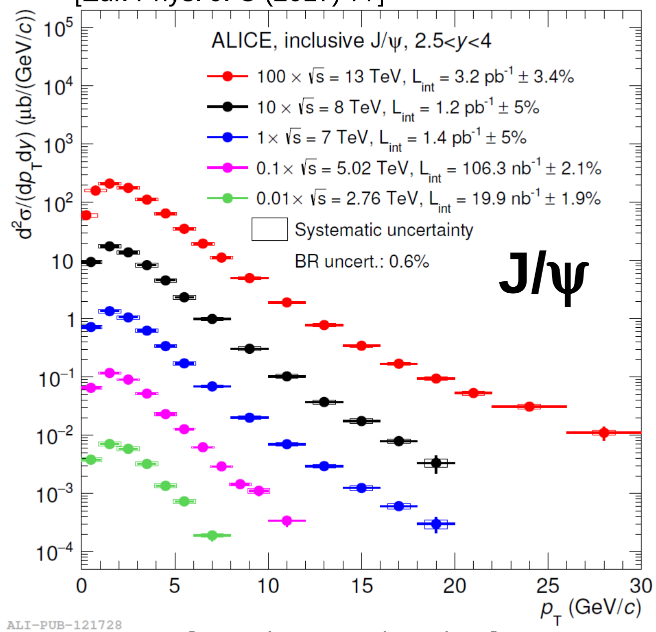
BACK-UP

Quarkonium cross sections

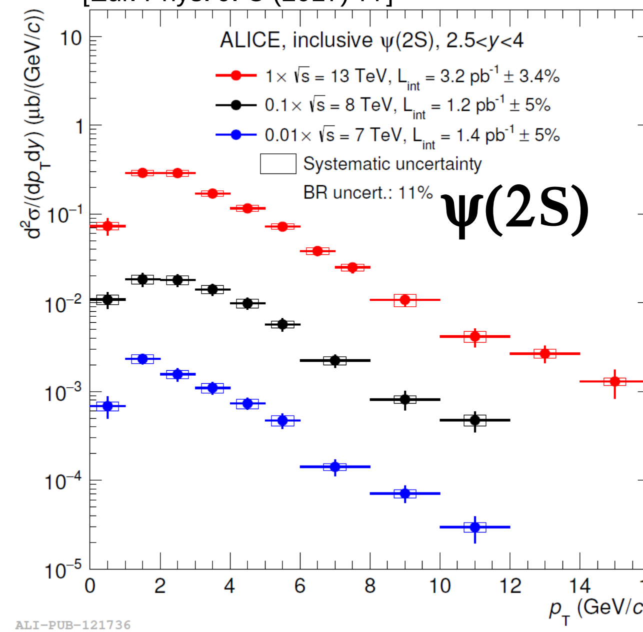
fwd-y

- ✔ Extensive and precise charmonium production measurements at several $\sqrt{s}$
  - ✔ Hardening of the p_T differential cross-sections with increasing energy

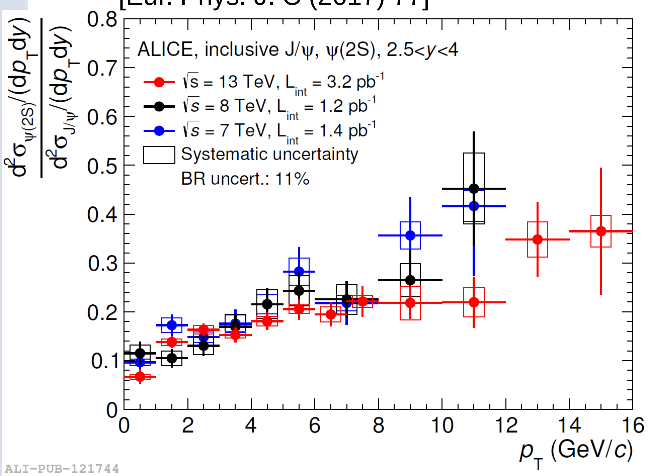
[Eur. Phys. J. C (2017) 77]



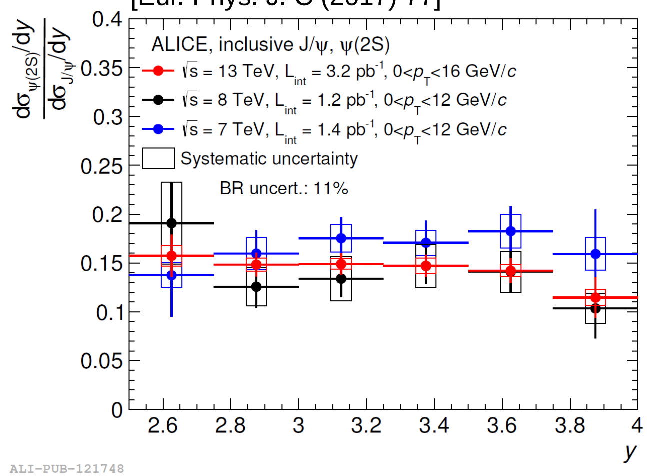
[Eur. Phys. J. C (2017) 77]



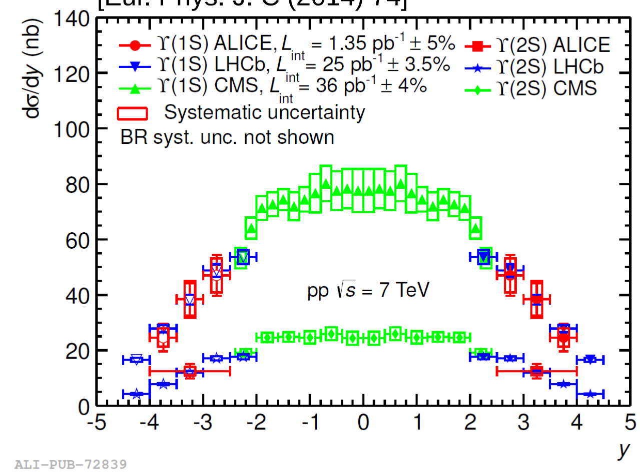
[Eur. Phys. J. C (2017) 77]



[Eur. Phys. J. C (2017) 77]



[Eur. Phys. J. C (2014) 74]

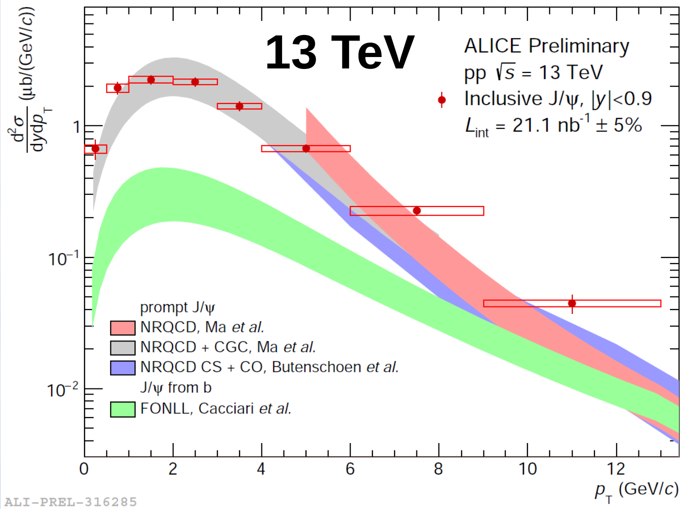


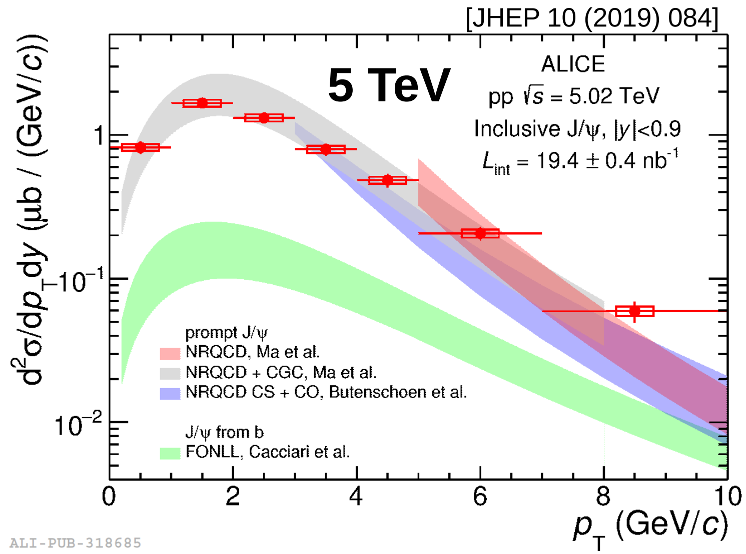
- ✔ ψ(2S) / J/ψ cross-section ratio shows:
  - – an increasing trend with p_T
  - – no significant dependence with rapidity and $\sqrt{s}$

- ✔ ALICE results are in good agreement with results from other LHC experiments

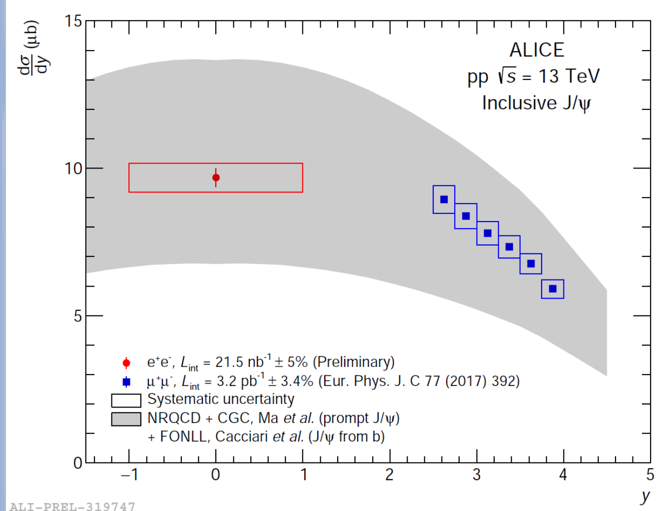
Quarkonium cross sections

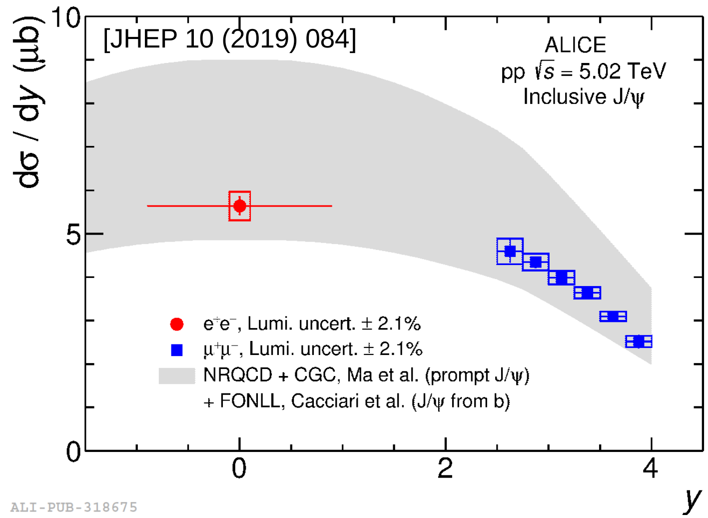
mid-y

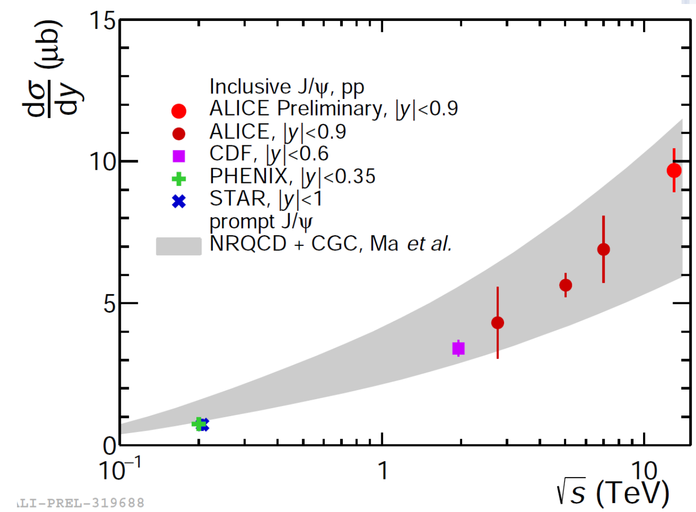




NRQCD+CGC: Phys. Rev. Lett. 113 no. 19, (2014)
NRQCD: Phys. Rev. Lett. 106 (2011) 042002
Phys. Rev. Lett. 106 (2011) 022003
FONLL: JHEP 10 (2012) 137







- ✔ NRQCD+CGC (+FONLL) model provides a good description of the p_T-differential cross section in the whole measured p_T range at both √s = 5 and √s = 13 TeV
- ✔ Rapidity dependence well reproduced by NRQCD+CGC(+FONLL) at both energies
- ✔ Increase of inclusive cross section vs √s → could be affected by non-prompt J/ψ contribution (not included) at higher √s