Quarkonium production and polarization in pp collisions with ALICE

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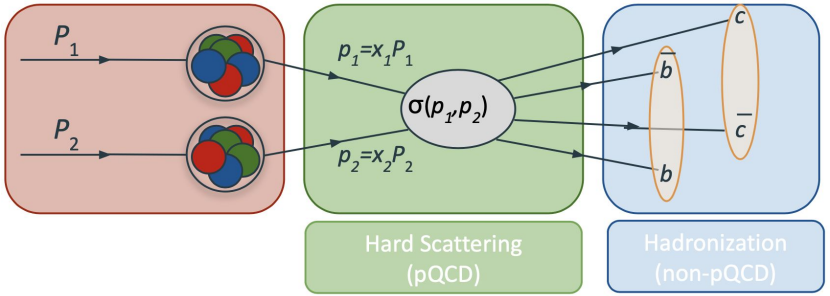
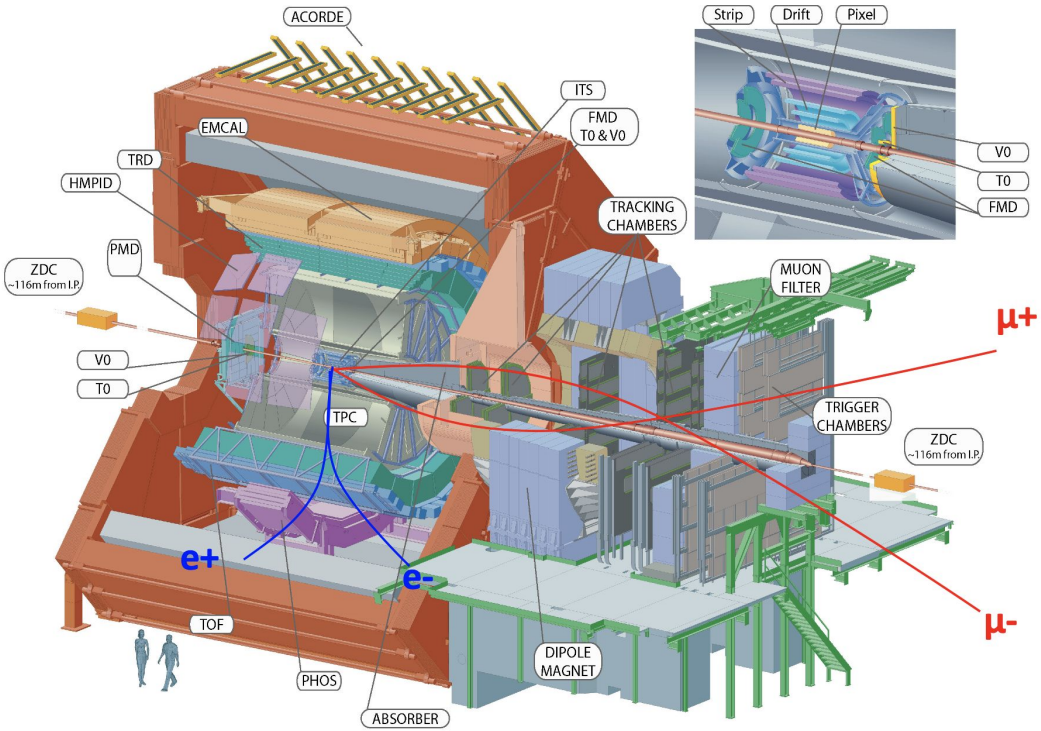
Quarkonium in proton-proton collisions

- Quarkonium production mechanisms: both perturbative (i.e. $q\bar{q}$ formation) and non-perturbative (bound state) QCD processes involved
  - Refine QCD based models
- Simultaneous measurements of polarization and cross sections crucial for constraining production mechanisms
- Particle production ratios (e.g. ψ(2S)/(J/ψ) ratio) helpful for studying production as common uncertainties cancel out in the ratio
- J/ψ in jets to study how J/ψ production is affected by the underlying event
- Quarkonium production in high multiplicity events
  - multiplicity dependence measurements allows the investigation of
    - Multi parton interactions (MPI)
    - Interplay between soft and hard processes
  - Investigation of collective effects



ALICE detector (Run 2)

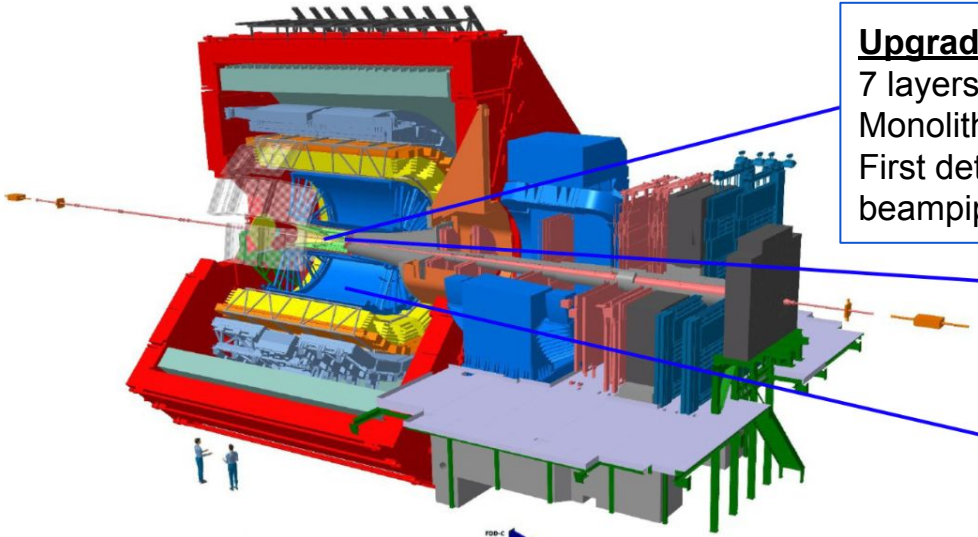


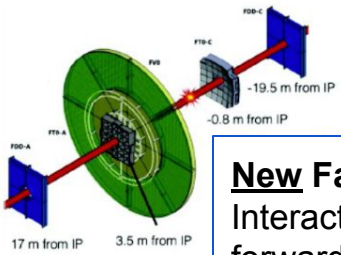
- Central Barrel ($|y| < 0.9$)
  - $J/\psi \rightarrow e^+e^-$
- Muon Arm ($2.5 < y < 4.0$)
  - J/ψ, $\psi(2S)$, $\Upsilon(nS) \rightarrow \mu^+\mu^-$

➔ Inclusive quarkonium down to p_T=0

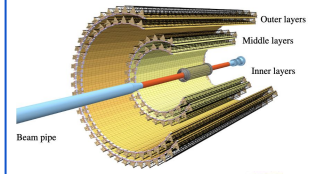
➔ Separation of prompt and non-prompt J/ψ down to low p_T (midrapidity)

ALICE detector (Run 3)

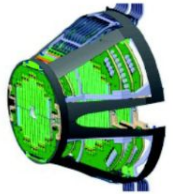




<u>Upgraded</u> Inner Tracking System:
7 layers (10 m^2 silicon tracker) based on Monolithic Active Pixel Sensor (MAPS).
First detection layer at 20 mm (thanks to new beampipe)

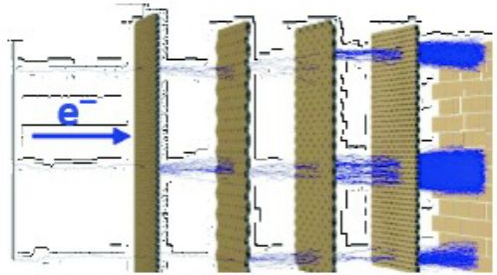


<u>New</u> Muon Forward Tracker:
5 planes of MAPS at forward rapidity, forward vertexing and tracking for muons



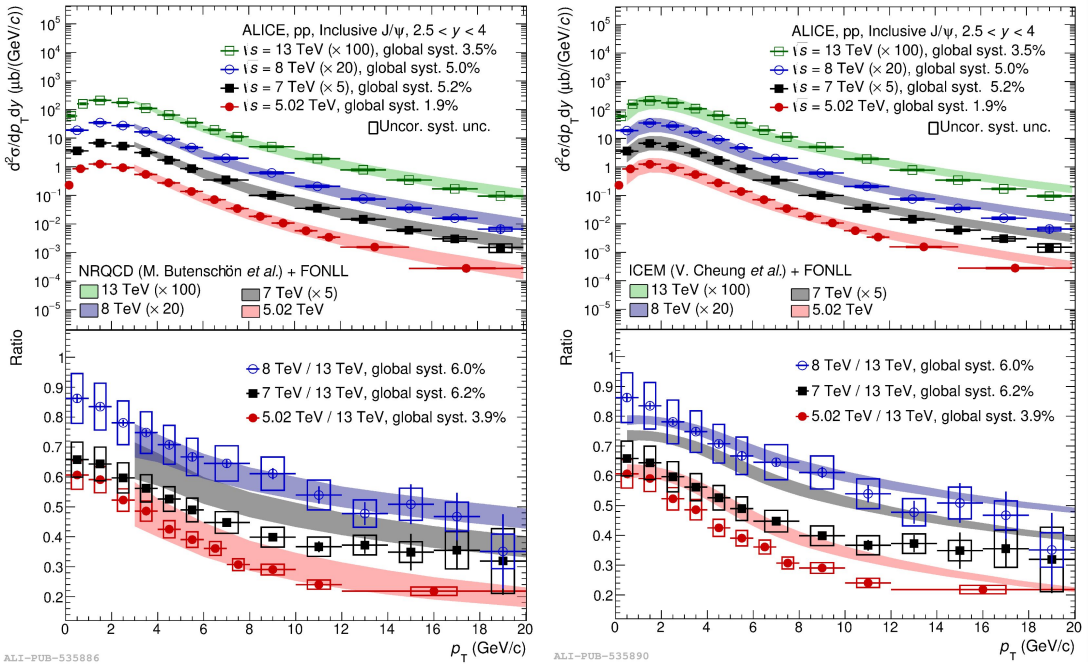
<u>Upgraded</u> Time Projection Chamber:
New readout chambers with Gas Electron Multipliers (GEM)

<u>New</u> Fast Interaction Trigger:
Interaction trigger, online luminometer, forward multiplicity



J/ψ production in pp collisions at $\sqrt{s}$ = 5.02 TeV (forward rapidity)

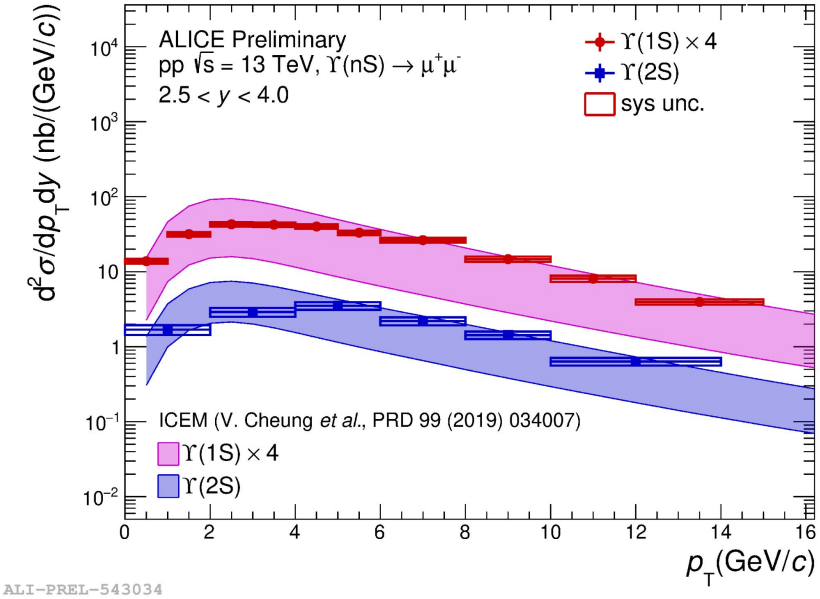
Eur. Phys. J. C 83 (2023) 61



- NRQCD: M. Butenschoen et al, Phys. Rev. Lett. 106 (2011) 022003
- FONLL: M. Cacciari et al, JHEP 10 (2012) 137
- ICEM: V. Cheung et al, Phys. Rev. D 98 (2018) 114029

- Comparison to cross sections at $\sqrt{s}$ = 5.02, 7, 8 and 13 TeV
- New measurement at 5.02 TeV (10 times more stat. w.r.t previous publication)
- Both NRQCD and ICEM models reproduce the cross section vs p_T for all energies
  - Ratios 5.02-to-13 TeV and 8-to-13 TeV well described by NRQCD
  - ICEM calculation can only satisfactorily describe the 8-to-13 TeV ratio
- Stronger hardening of the p_T spectra is observed in the collisions at $\sqrt{s}$ = 13 TeV with respect to the $\sqrt{s}$ = 5.02, 7, and 8 TeV data
  - Increase of the prompt J/ψ $\langle p_T \rangle$ with energy
  - Increasing contribution from non-prompt J/ψ at high p_T

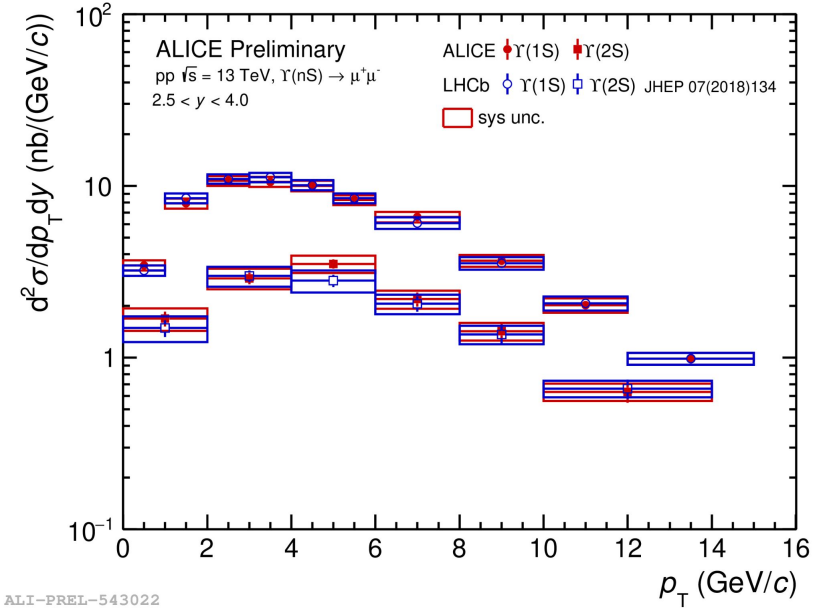
Y(nS) production in pp collisions at $\sqrt{s}$ = 13 TeV



ICEM: V. Cheung et al, PRD 99 (2019) 034007

- Good consistency with previous LHCb measurement in the same rapidity region

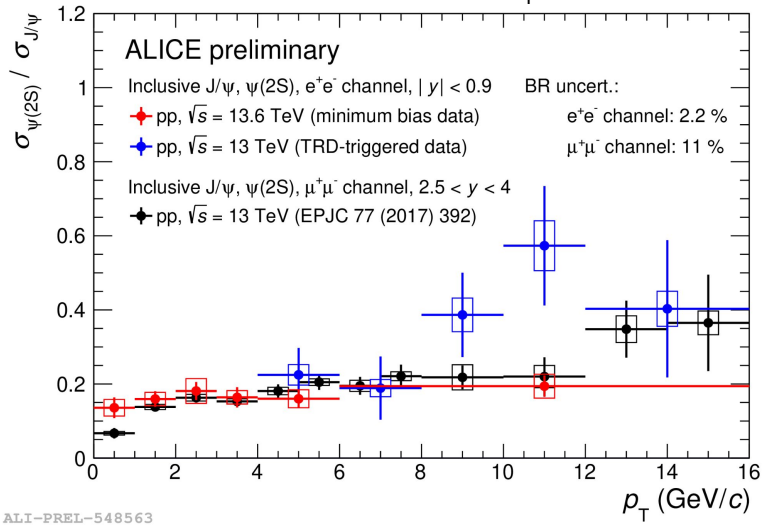
- Y(nS) cross section vs p_T
- ICEM calculations describes the data within uncertainties



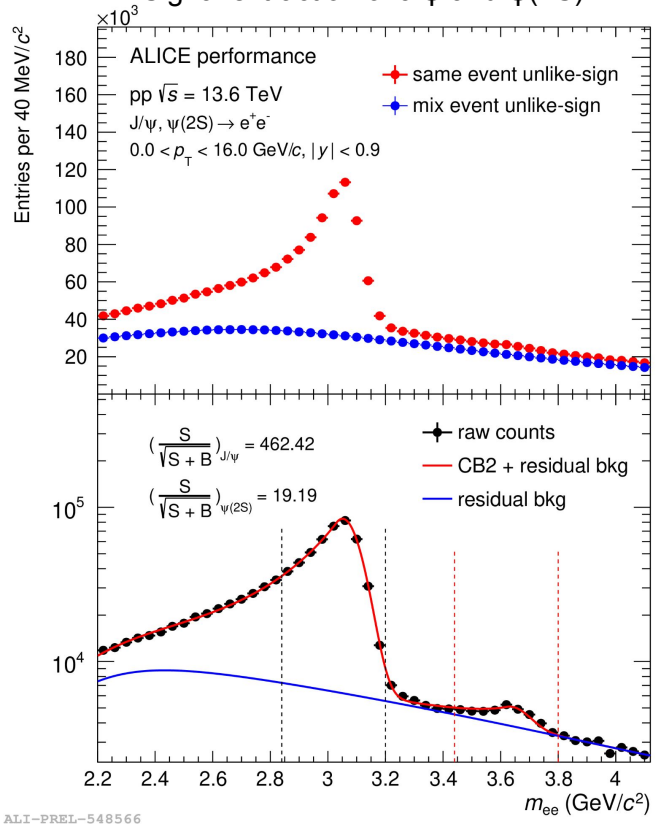
New ψ(2S)/(J/ψ) in pp collisions at $\sqrt{s}$ = 13.6 and 13 TeV

ALICE new results

ψ(2S)/(J/ψ) vs p_T



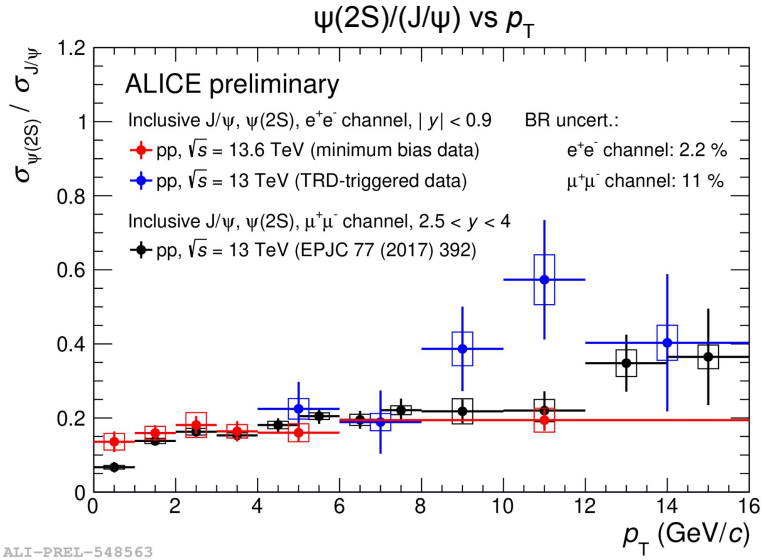
Signal extraction of J/ψ and ψ(2S)

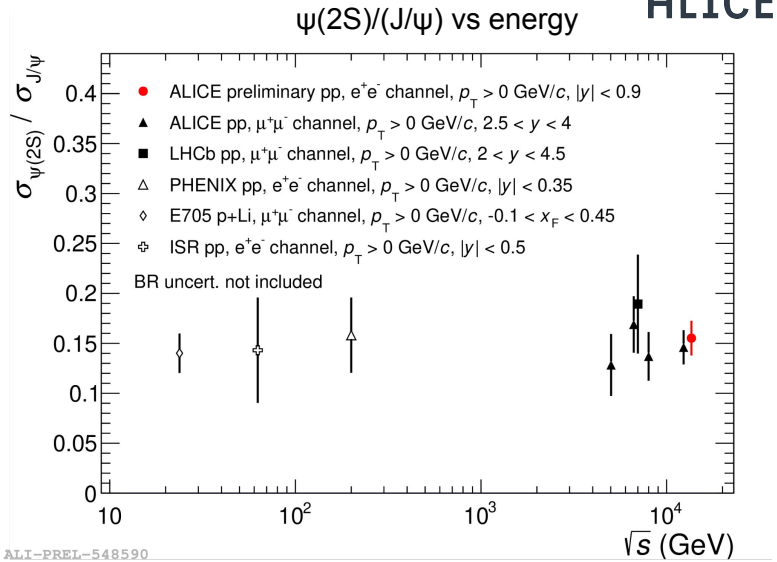


- New Run 3 measurements of ψ(2S)/(J/ψ) ratio at midrapidity performed at $\sqrt{s}$ = 13.6 TeV
- New and first measurement of the ψ(2S)/(J/ψ) ratio at midrapidity using the TRD-triggered data (Run 2 data)
- ψ(2S)/(J/ψ) ratios at midrapidity compatible within uncertainties
- Forward rapidity Run 3 measurements will soon be available

New ψ(2S)/(J/ψ) in pp collisions at $\sqrt{s}$ = 13.6 and 13 TeV

ALICE new results





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- ψ(2S)/(J/ψ) ratios at midrapidity compatible within uncertainties
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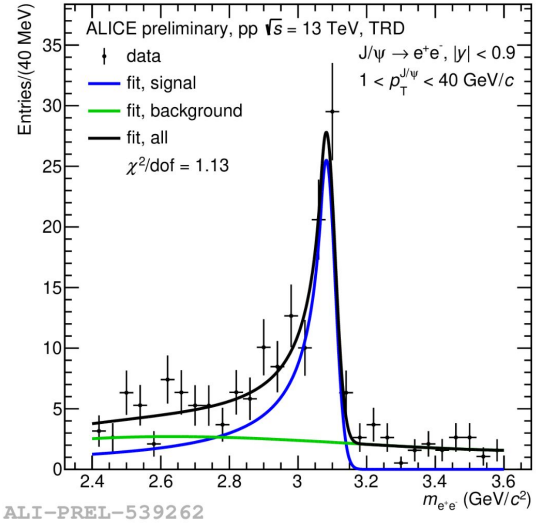
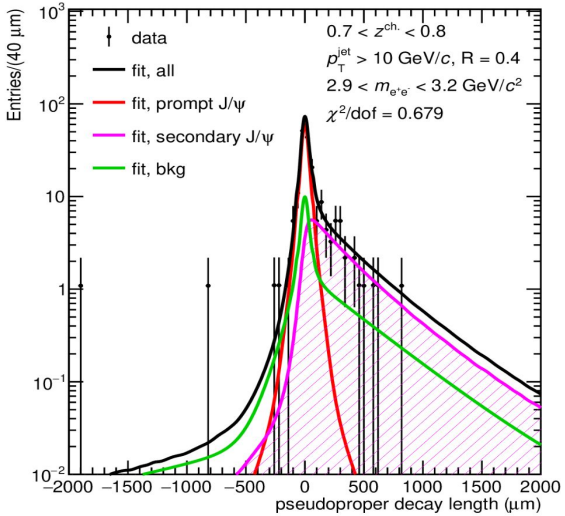
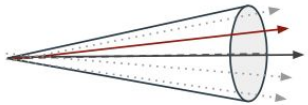
- No significant energy dependence observed for the p_T-integrated (p_T > 0) ψ(2S)/(J/ψ) ratio

J/ψ production in jets







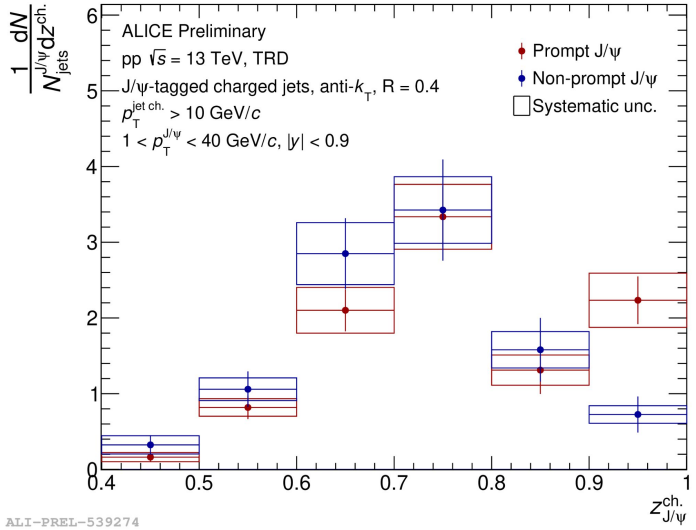
$$z^{ch} = \frac{p_T^{J/\psi}}{p_T^{jet,ch}}$$

Fragmentation function

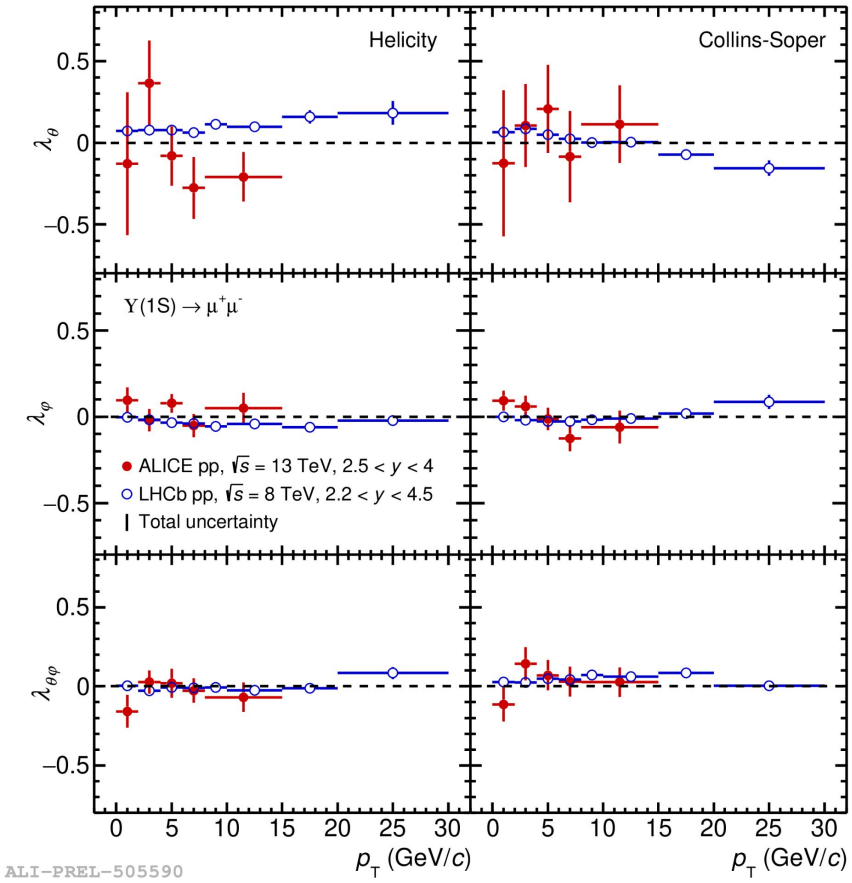
- Prompt and non-prompt J/ψ fragmentation functions are found to be similar within uncertainties
- Insight on J/ψ production/fragmentation interplay with underlying event

Jets tagged with presence of a reconstructed J/ψ in the e^+e^- channel at midrapidity

Separate prompt and non-prompt J/ψ signal with maximum likelihood fit



Y(1S) polarization



- Polarization, i.e. the alignment of the particle spin with respect to a chosen axis, is studied via the angular distribution of the dilepton decay products of the charmonium:

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

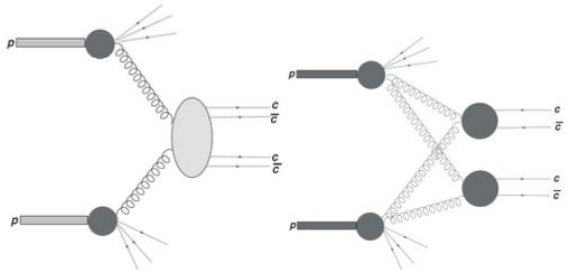
- First measurement of Υ(1S) polarization by ALICE in pp collisions
- No polarization observed within uncertainties
- Result is compatible with LHCb measurement at $\sqrt{s}$ = 8 TeV

LHCb: JHEP 12 (2017) 110

J/ψ pair production

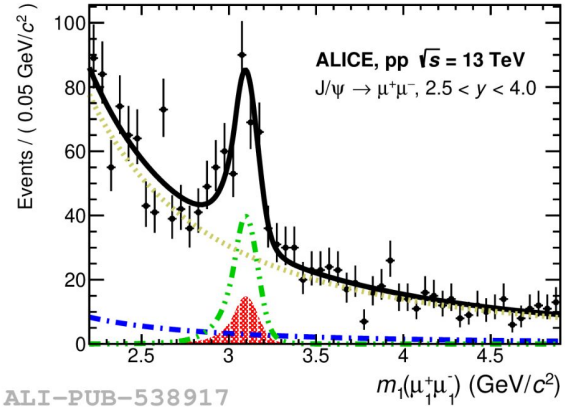
arXiv:2303.13431

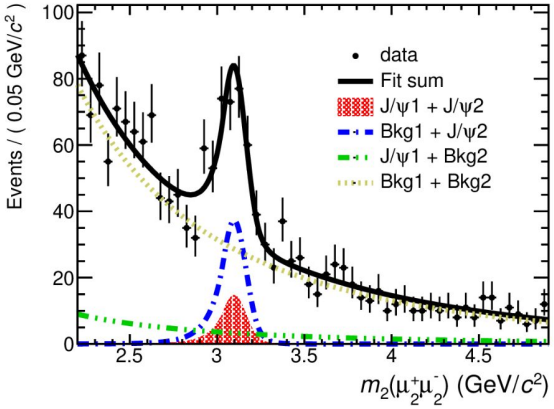
AIP Conf. Proc. 1523 (2013) 1



	Cross sections (nb)
ALICE	$10.3 \pm 2.3(\text{stat.}) \pm 1.3(\text{syst})$
LHCb	$15.2 \pm 1.0(\text{stat.}) \pm 0.9(\text{syst})$

LHCb: JHEP 06 (2017) 047





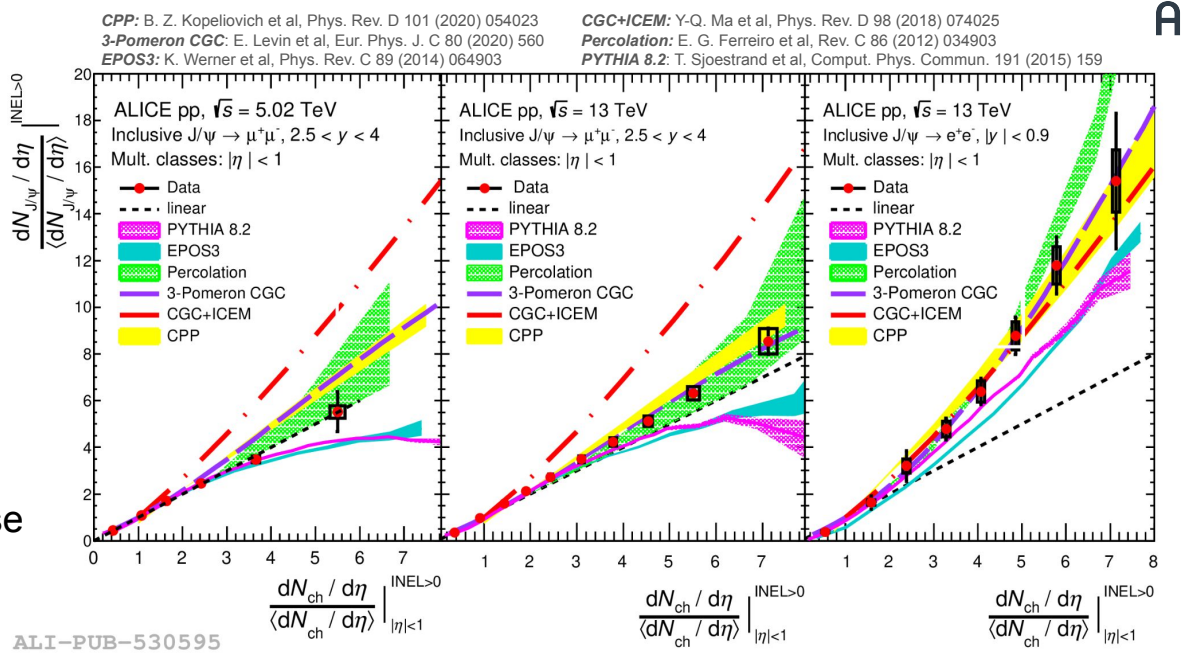
- Insight into double-parton scattering (DPS)
- Results are compatible with previous LHCb measurement
  - Inclusive J/ψ measured in ALICE vs prompt J/ψ measured by LHCb
  - Slightly different rapidity regions ($2.0 < y < 4.5$ for LHCb)

J/ψ production vs multiplicity

JHEP 06 (2022) 015

The self-normalized J/ψ yield vs midrapidity multiplicity

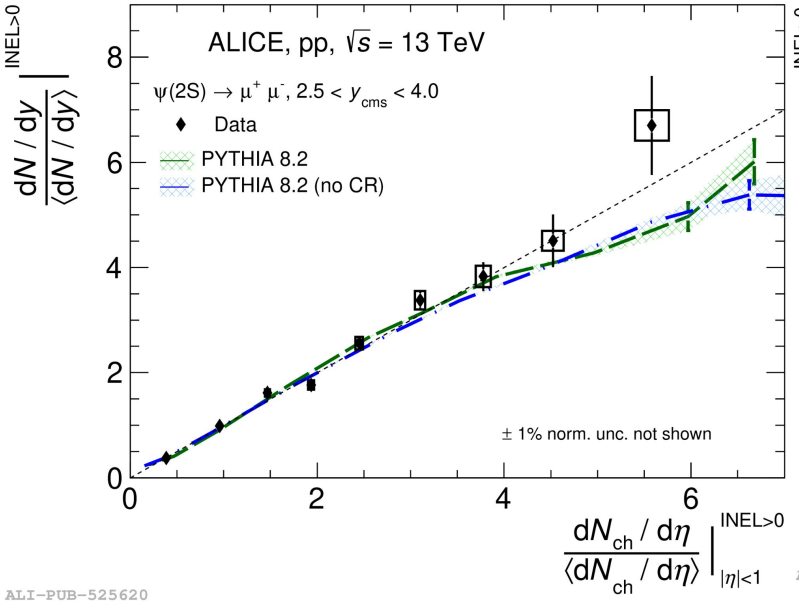
- J/ψ at forward rapidity (left & middle panels)
  - Approximately increases linearly independently of the collision energy
- J/ψ at midrapidity (right panel)
  - Faster than linear increase

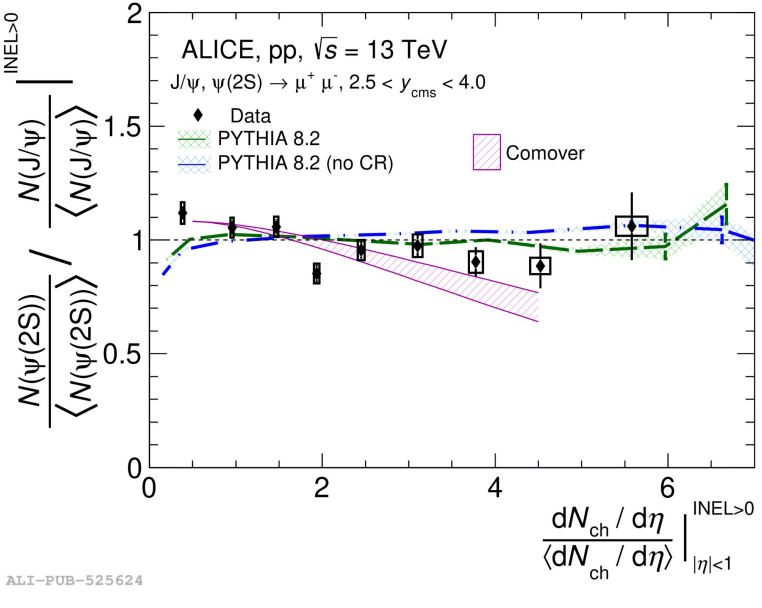


- Good agreement at $\sqrt{s}$ = 13 TeV provided by the Coherent Particle Production (CPP), the 3-Pomeron CGC and Percolation models in both rapidity intervals
- Stronger than linear correlation at midrapidity well reproduced by the models although the exact origin of this behaviour is still not well understood

ψ(2S) production vs multiplicity

JHEP 06 (2023) 147



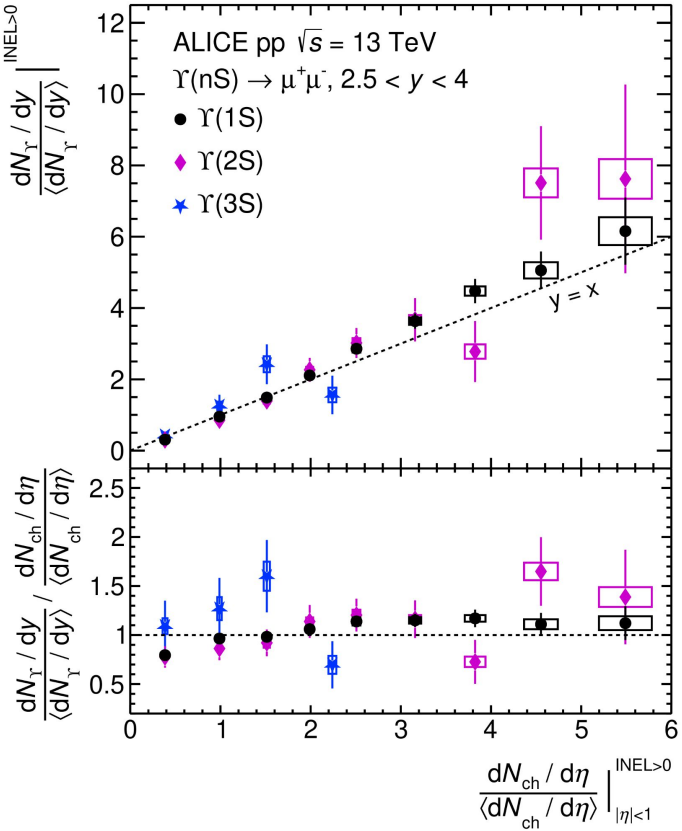


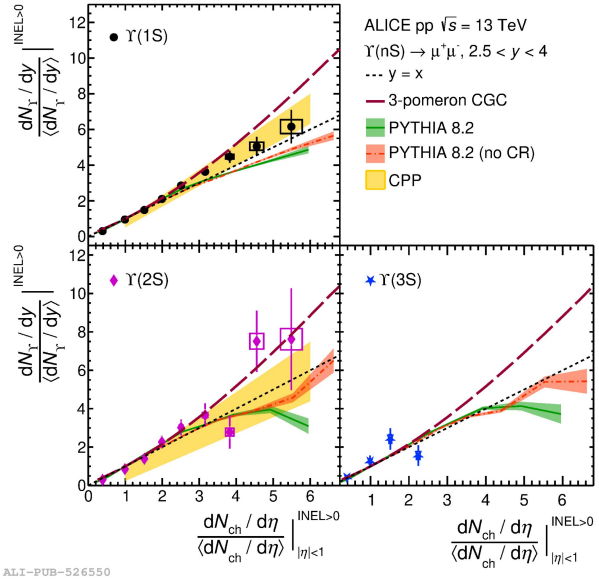
PYTHIA 8.2
JHEP 08 (2015) 003
Comover
PBL 731 (2014) 57
JHEP 10 (2018) 094

- Linear correlation between self-normalized forward ψ(2S) yield and midrapidity charged-particle multiplicity,
- Excited-to-ground state ratio (ψ(2S)/(J/ψ)) is consistent with unity within uncertainty
  - Qualitatively good description provided by
    - PYTHIA 8.2 with(out) color-reconnection (CR)
    - Comover model
  - The statistical precision of data doesn't allow to conclude on the presence/abscence of final state effects

Y(nS) production vs multiplicity

arXiv:2209.04241





3-pomeron:
E. Levin et al, Eur. Phys. J. C 80 (2020) 560
PYTHIA 8.2:
T. Sjoestrand et al, Comput. Phys. Commun. 178 (2008) 852–867
CPP:
Z. Kopeliovich et al, Phys. Rev. D 101 (2020) 054023

- The self-normalized forward Y(nS) yield exhibits a similar linear trend as observed for charmonium, with the slope close to unity
- CPP well reproduces Y(1S) and Y(2S) data
- 3-pomeron CGC slightly overestimates Y(1S) data above 4 times the average multiplicity
- PYTHIA slightly underestimates Y(1S) and Y(2S) data above 3 times the average multiplicity

Summary & outlook

Summary

- Measurements of J/ψ production at $\sqrt{s}$ = 5.02, 7, 8 and 13 TeV data well described by NRQCD and ICEM models
  - Hardening of the p_T spectra for pp collisions at $\sqrt{s}$ = 13 TeV
- Y(nS) production described by ICEM model
- J/ψ pair production measured and compatible with LHCb results
- J/ψ in jets
  - Prompt and non-prompt J/ψ fragmentation functions are compatible within uncertainties
- Self-normalized quarkonium yield vs multiplicity
  - Linear dependence at forward rapidity (J/ψ, ψ(2S), Y(nS))
  - Faster than linear enhancement at midrapidity (J/ψ)
- Y(1S) polarization compatible with zero within uncertainties
- New results of quarkonium production at $\sqrt{s}$ = 13.6 TeV

Outlook

- Higher multiplicity reach in Run 3, higher luminosity to study associated production of quarkonium and open heavy-flavour hadrons
- More precise measurements for polarization of all quarkonium states

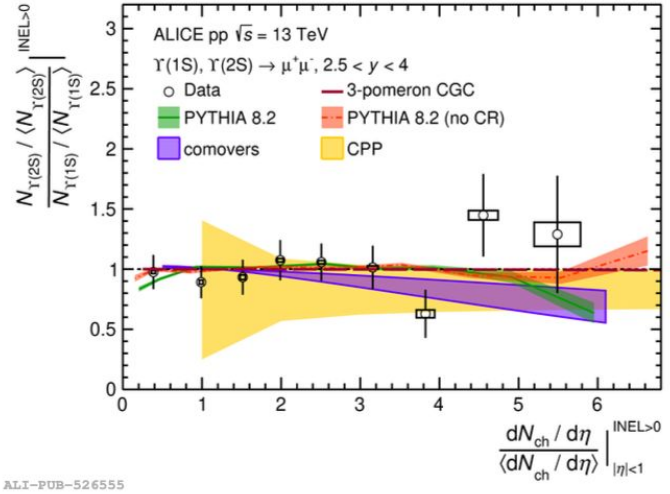
Thanks for your attention!

Back up

Excited-to-ground state ratio

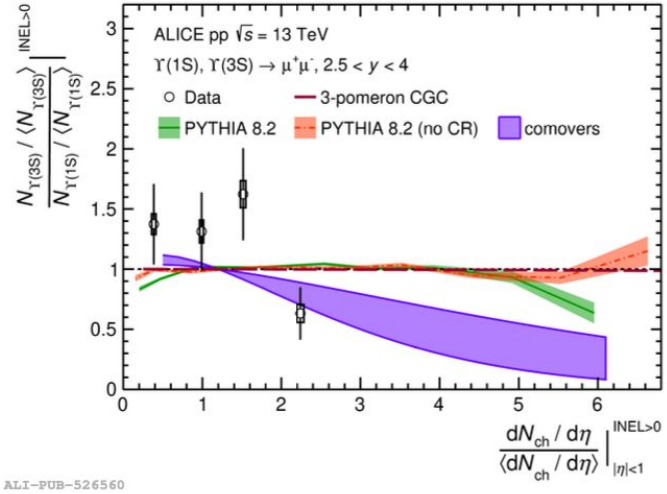
$\Upsilon(2S)/\Upsilon(1S)$

arXiv:2209.04241



$\Upsilon(3S)/\Upsilon(1S)$

arXiv:2209.04241



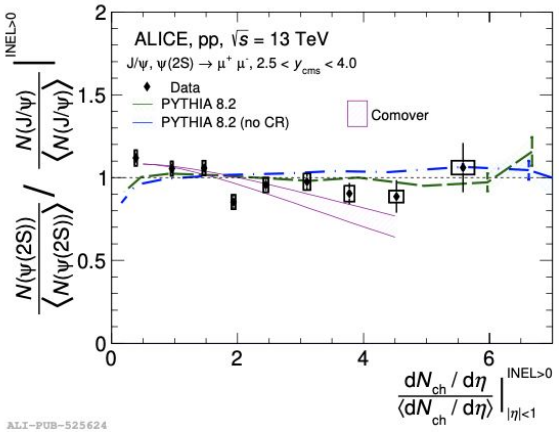
3-pomeron CGC:
EPJC80 (2020) 560

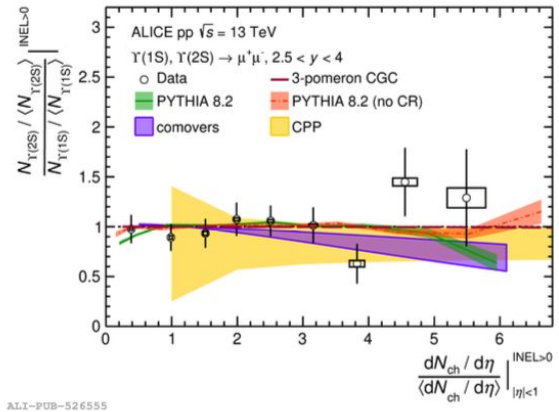
PYTHIA 8.2:
JHEP08 (2015) 003

CPP:
PRD101 (2020) 054023

Comover:
PBL 731 (2014) 57
JHEP 10 (2018) 094

- Excited-to-ground state ratios consistent with unity within uncertainties
  → None or weak dependence of measured correlation with the binding energy of the state
- Models describe the observed trend within uncertainties
  → Not possible to disentangle any final state effects with current uncertainties





PYTHIA 8.2 with Color Reconnection JHEP08 (2015)003

- Combination of *initial* and *final* state effects
- Final state effect at play with MPI where strings are merged based on a QCD full color flow calculation with a loose modeling of dynamical effect via a global saturation

Coherent particle production (CPP) PRD101 (2020) 054023

- Includes nuclear-like effects and gluon saturation in the *initial* stage

3-pomeron CGC EPJC80 (2020) 560

- *Initial* state effects
- Increased quarkonium production probability from multi-pomeron mechanism

Comover model PBL 731 (2014) 57, JHEP 10 (2018) 094

- Quarkonia dissociated in *final* state by interactions with comoving particles