# Quarkonium production and elliptic flow in small systems with ALICE

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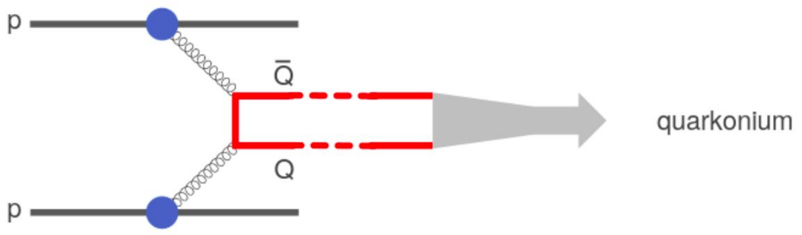
# Physics motivation for quarkonium studies in pp collisions

- Quarkonium production measurements in pp provide constraints to theoretical models (e.g. Color evaporation, NRQCD, ...). Different QCD scales involved:
  - **Hard-scales**: heavy-quark pair production in the initial hard scattering described by pQCD
  - **Soft-scales**: binding of quark pairs into a colorless final state probe non-perturbative physics




- **High-multiplicity events to probe collectivity**:
  - Elliptic flow of charged particles and strange hadrons production showed similarities in small systems (high-multiplicity pp, p–Pb) and Pb–Pb collisions [ALICE, PLB 719 29 (2013)] [ALICE, Nature Phys 13, 535–539 (2017)]
  - Multiple parton-parton interactions (MPI) taking place in a single hadron-hadron collision are one of the main explanations for these observations ➞ double quarkonium production and quarkonium vs multiplicity in small systems offer a way to probe MPI
- **Investigate beauty production** via non-prompt charmonium measurements
- **Reference systems to study heavy-ion collisions** and the quark-gluon plasma effects

# ALICE detector

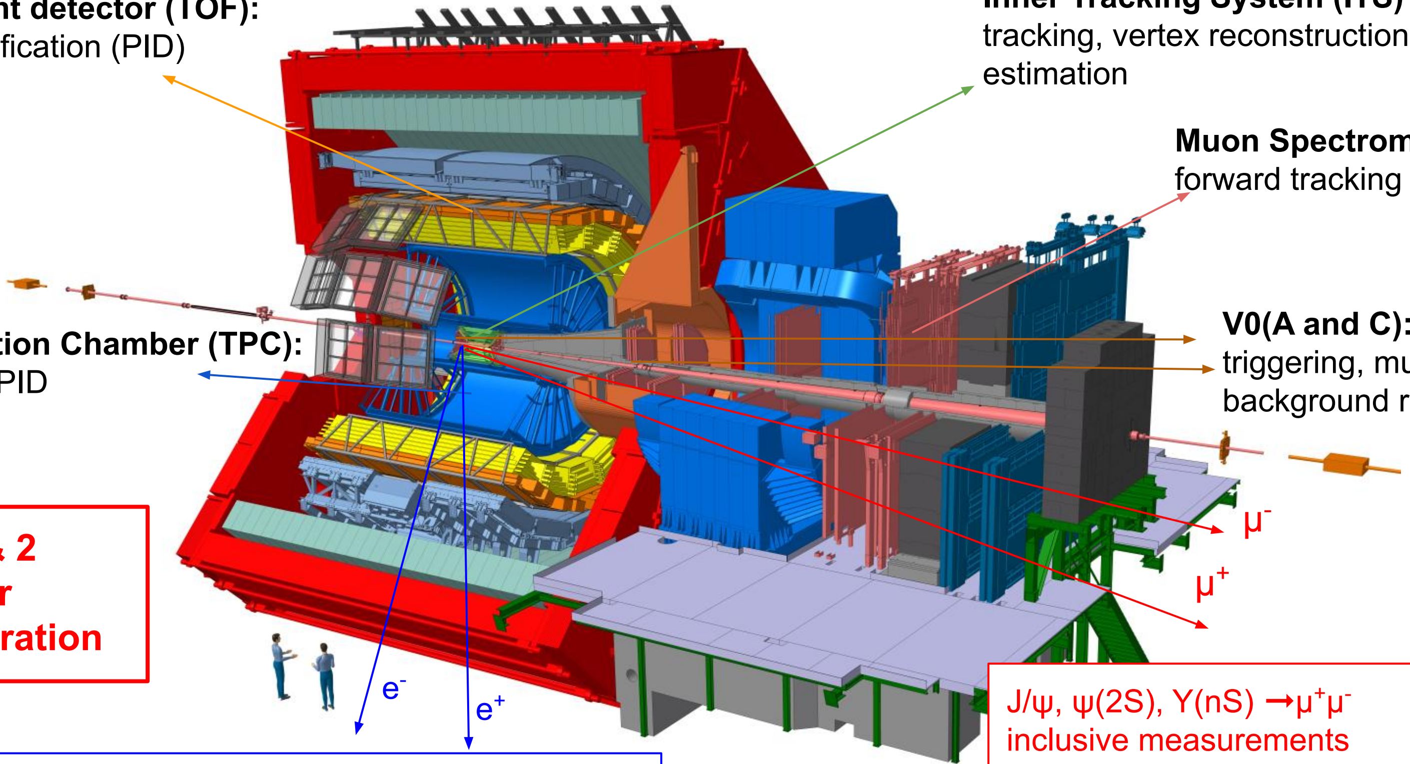
**Time of Flight detector (TOF):**
particle identification (PID)

**Inner Tracking System (ITS)**
tracking, vertex reconstruction, multiplicity estimation

**Muon Spectrometer:**
forward tracking and muon triggering

**Time Projection Chamber (TPC):**
tracking and PID

**V0(A and C):**
triggering, multiplicity estimation, background rejection

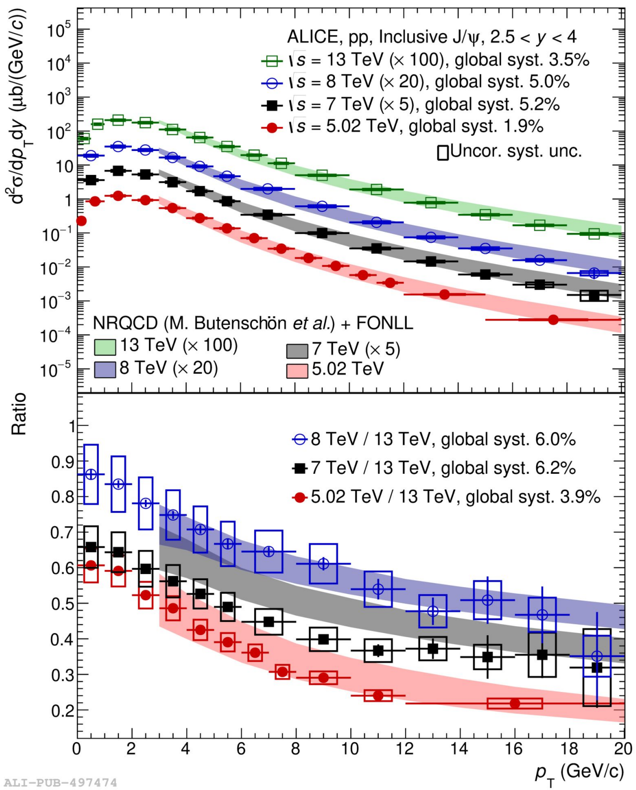



**Run 1 & 2 detector configuration**

$J/\psi$ → $e^+e^-$, $|y_{cms}| < 0.9$
Distinction between prompt $J/\psi$ (produced at the primary vertex) and non-prompt $J/\psi$ (from beauty hadron decays)

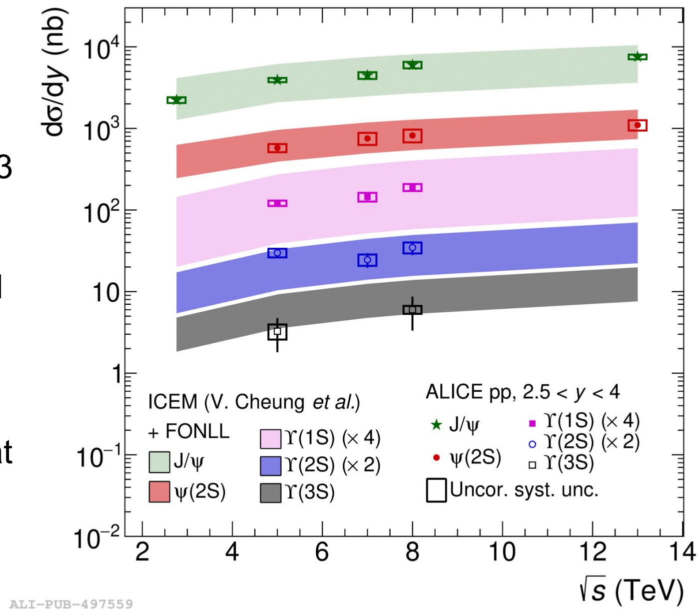
$J/\psi$, $\psi(2S)$, $\Upsilon(nS)$ → $\mu^+\mu^-$
inclusive measurements
$2.5 < y_{cms} < 4.0$ in pp

# Quarkonium production at forward rapidity




- New measurements in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV:
  - $\sqrt{s}$ = 5.02 TeV ➞ 10 times more statistics w.r.t. the previous measurement
- Hardening of the $p_T$-spectra at 13 TeV compared to lower $\sqrt{s}$
- **Cross sections are reproduced within uncertainties by both NRQCD** [arXiv:1009.5662] [arXiv:1205.6344] **and ICEM** [arXiv:1808.02909] calculations at all energies
- **Difficulties to reproduce all the cross section ratios among energies**, but are still compatible within the experimental precision

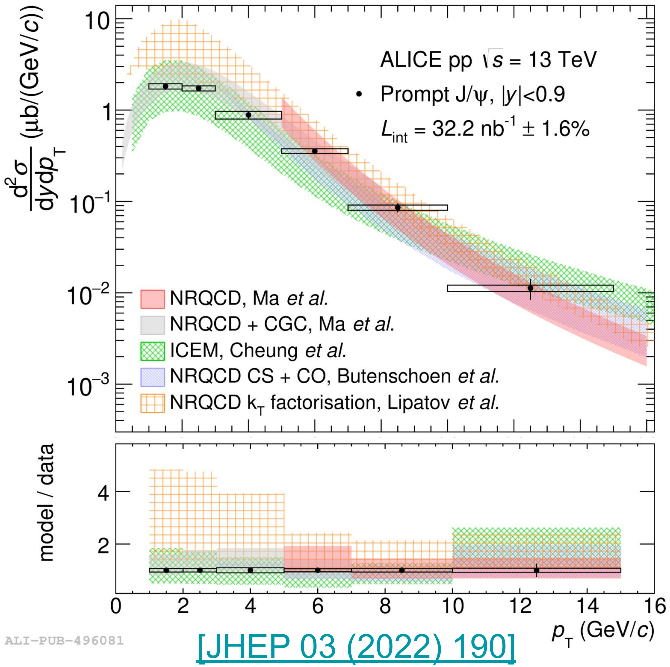
[arXiv:2109.15240]




- $p_T$-integrated quarkonium cross sections at different energy well **reproduced by ICEM calculations for different species**

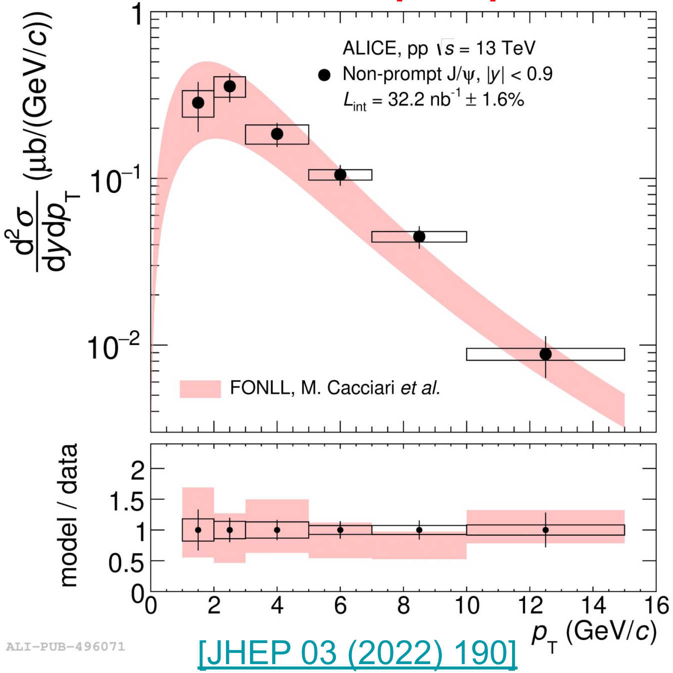
# Quarkonium production at midrapidity

prompt




[JHEP 03 (2022) 190]

non-prompt



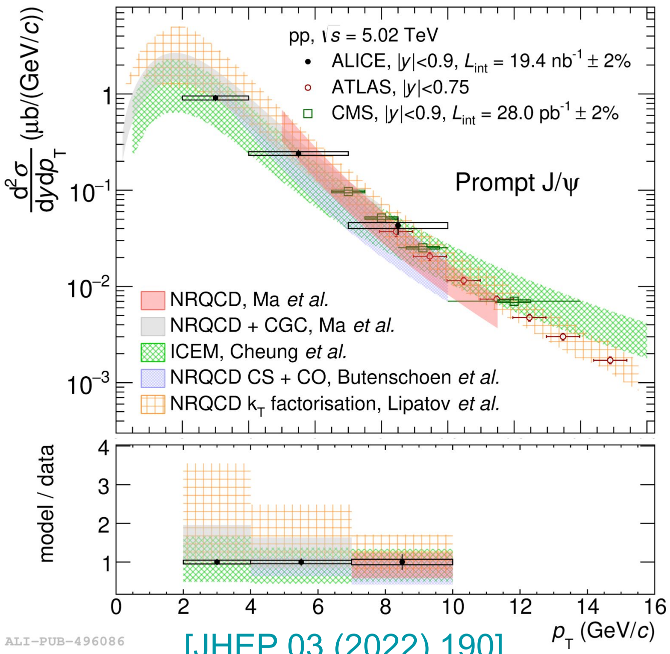

[JHEP 03 (2022) 190]

- **Models describe well both prompt (NRQCD [arXiv:1009.3655][arXiv:1906.07182][arXiv:1408.4075], ICEM) and non-prompt (FONLL [hep-ph/9803400]) J/ψ $p_T$-differential cross sections** at midrapidity, at $\sqrt{s}$=13 TeV

- Fraction of non-prompt J/ψ:
  - **$f_B^{visible}$ ($\sqrt{s}$=13 TeV, $|y|$ < 0.9, $p_T$ > 1 GeV/$c$) = 0.185 ± 0.015 (stat.) ± 0.014 (syst.)**

# Quarkonium production at midrapidity

**prompt**

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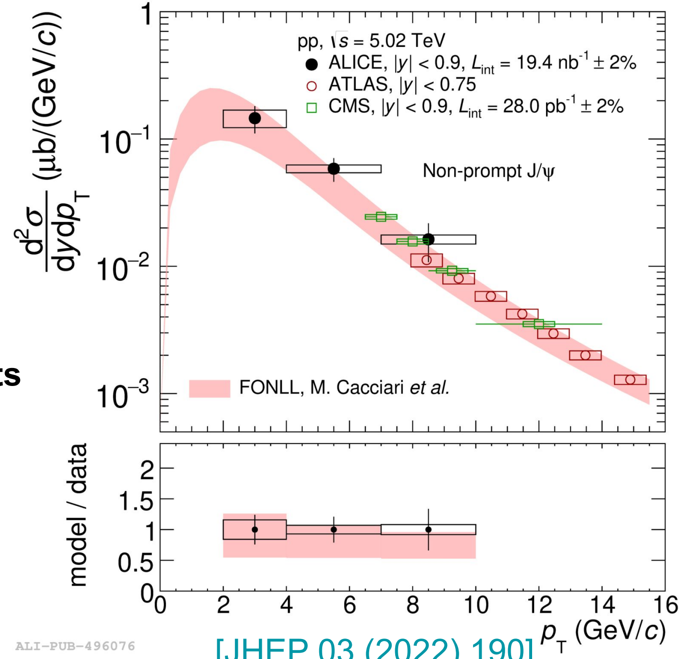
**non-prompt**



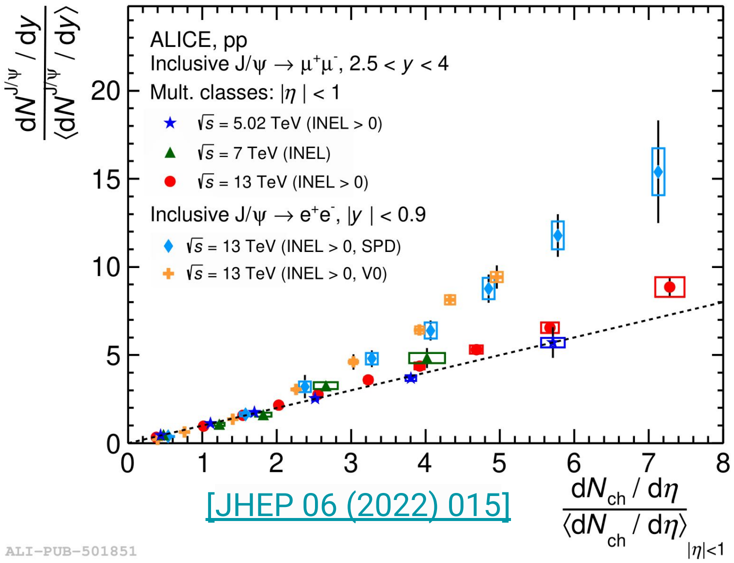

[JHEP 03 (2022) 190]

- **Similar conclusion for data-model comparison** at $\sqrt{s}$=5.02 TeV
- Good **agreement with the corresponding measurements from ATLAS and CMS** in the overlapping $p_{\mathrm{T}}$ range

- Fraction of non-prompt J/ψ:
  - **$f_B^{visible}$ ($\sqrt{s}$=5.02 TeV,|$y$| < 0.9, $p_{\mathrm{T}}$ > 2 GeV/$c$) = 0.157 ± 0.023 (stat.) ± 0.016 (syst.)**
- Indication of a decrease of the $f_B^{visible}$ at lower collision energies

# Multiplicity dependent quarkonium production: J/ψ

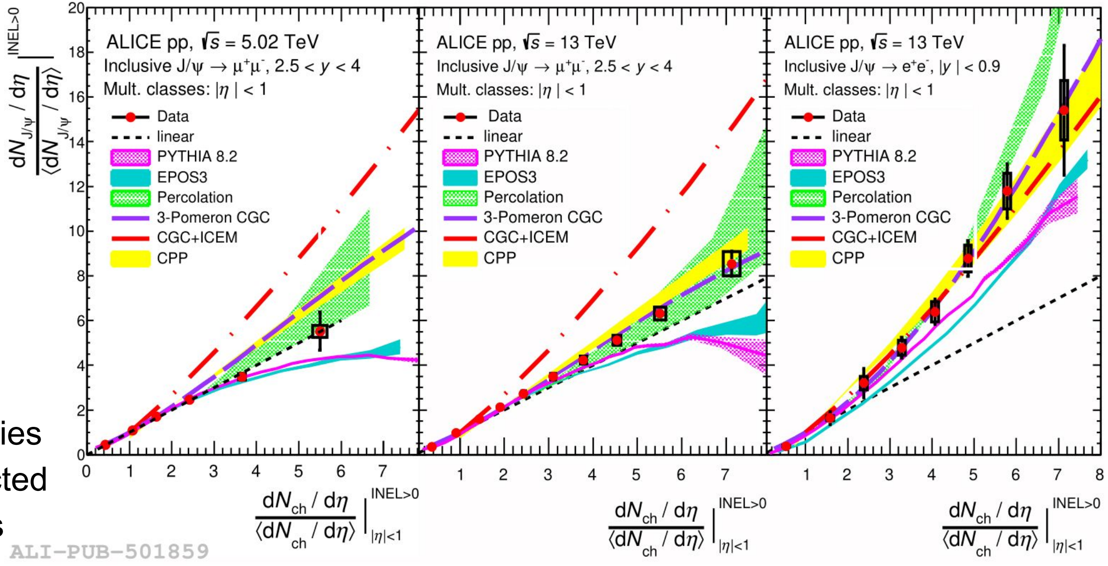
ALICE




[JHEP 06 (2022) 015]

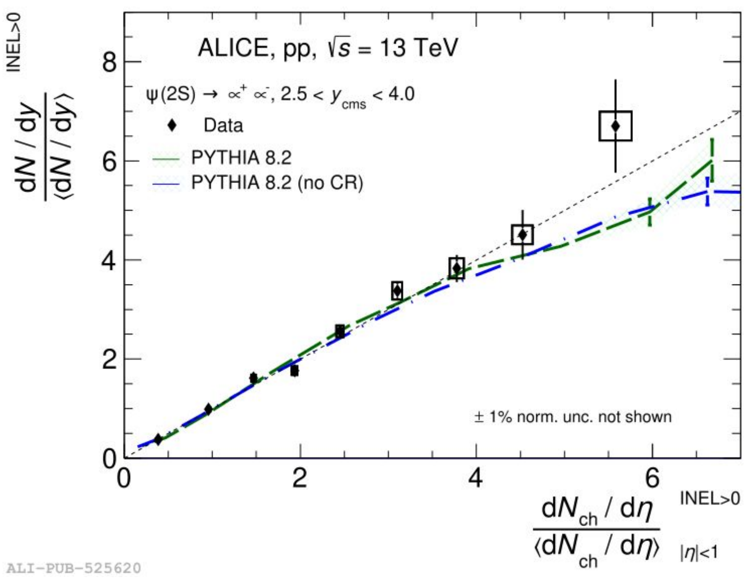
- Production measurement vs charged particle multiplicity:
  - **Midrapidity region: stronger than linear increase**
  - **Forward rapidity region: trend compatible with a linear dependence** on multiplicity, regardless of the collision energy

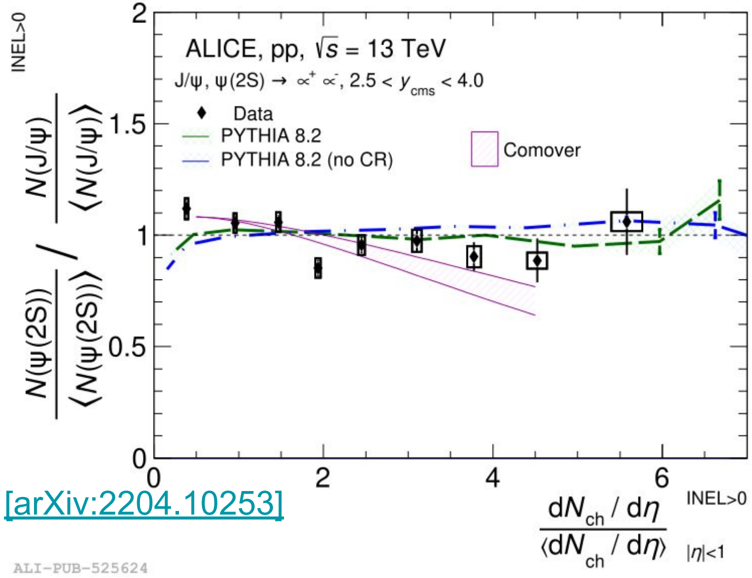
[JHEP 06 (2022) 015]




- Comparison with models:
  - CPP [arXiv:1910.09682] and 3-Pomeron CGC [arXiv:1910.13579] models in agreement with the data within uncertainties
- Faster-than-linear increase at midrapidity predicted by different models due to different mechanisms

# Multiplicity dependent quarkonium production: ψ(2S)



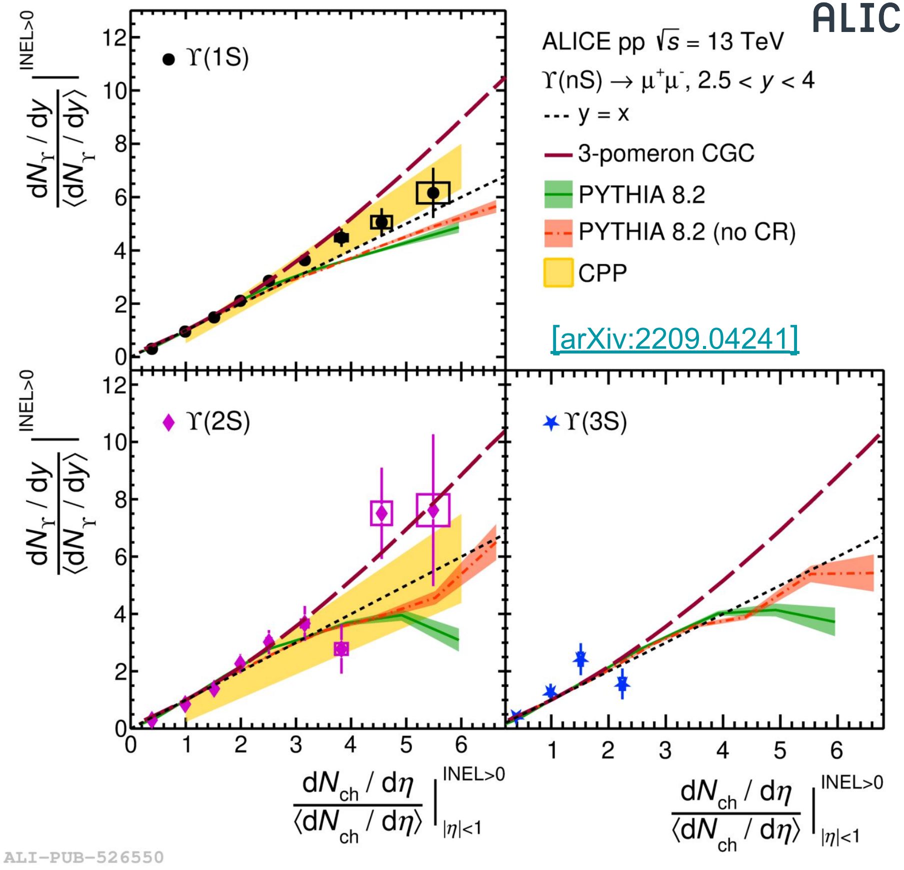




[arXiv:2204.10253]

- ψ(2S) production at forward rapidity as a function of midrapidity multiplicity exhibits a linear dependence
- **Self-normalized ψ(2S)-to-J/ψ ratio vs multiplicity compatible with unity**:
  - Forward production is independent of the charmonium state
- PYTHIA(with/without color reconnections) [arXiv:1410.3012] in good agreement with data:
  - ψ(2S) yield: tension at high multiplicity
  - ψ(2S)-to-J/ψ ratio: tension at low multiplicity
- Comovers [arXiv:1411.0549]: predict suppression of the ψ(2S) w.r.t. J/ψ at high multiplicity

# Multiplicity dependent quarkonium production: Υ(nS)

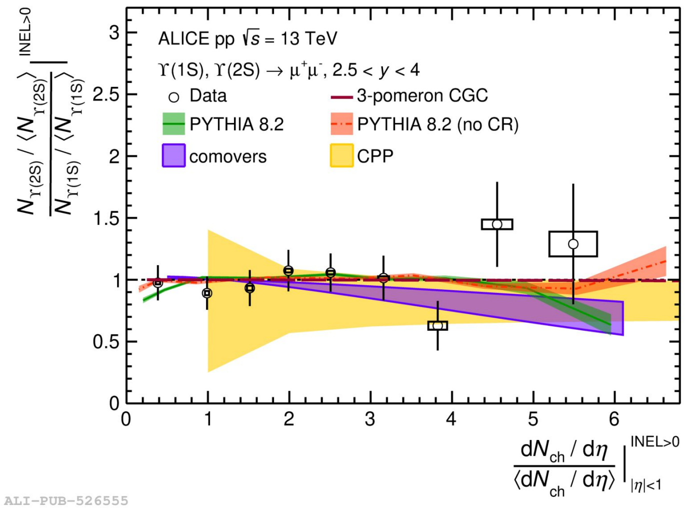
- The Υ(nS) production yields as a function of charged particle multiplicity, both self-normalized, show a **linear trend** with a slope compatible with unity
- This behavior is qualitatively reproduced up to 4 times the mean multiplicity by PYTHIA 8.2 with and without the color reconnection scenario, by CPP, and by the 3-pomeron CGC approach
- **At high multiplicities, the theoretical computations but CPP diverge:**
    - The 3-pomeron CGC tends to overestimate the observed trend
    - PYTHIA 8.2 underestimates the production

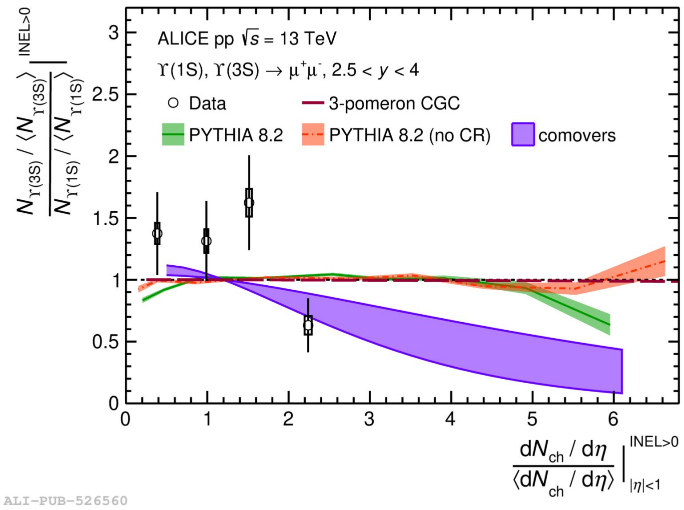



[arXiv:2209.04241]

# Multiplicity dependent quarkonium production: Y(nS)

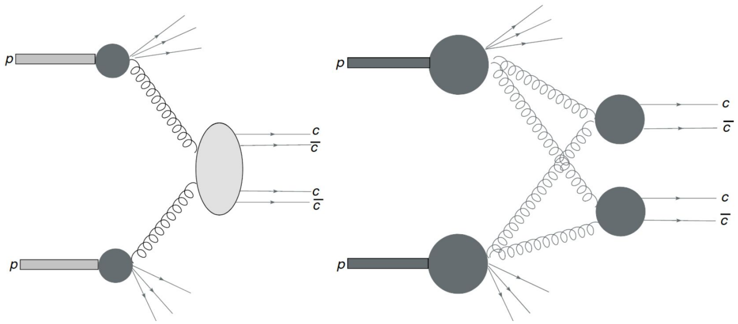
[arXiv:2209.04241]



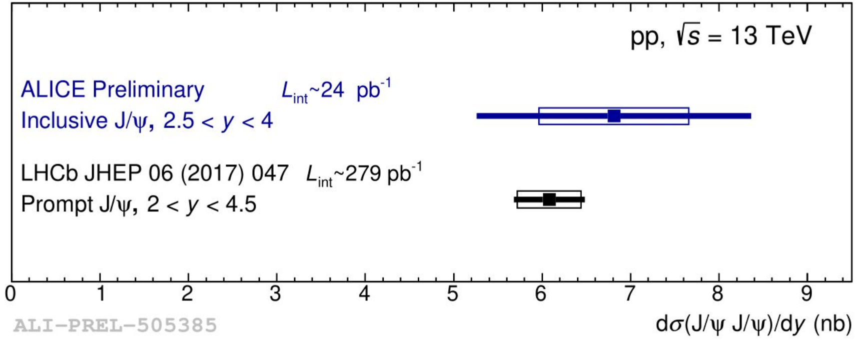




- Excited Y(nS) to ground state ratios as well are **compatible with unity**
- Agreement with the predictions of PYTHIA 8.2, CPP and 3-pomeron CGC
- The comovers model predict a suppression of the Y(2S) and Y(3S) w.r.t. the Y(1S) states at high-multiplicity:
  - The large uncertainties don't allow to confirm nor exclude any final state effects

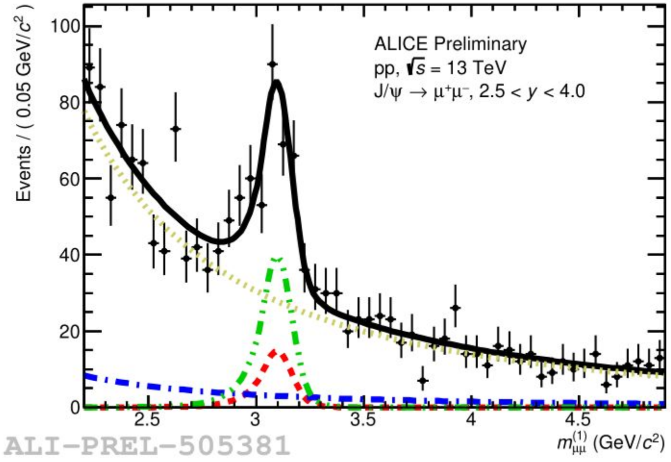
# J/ψ pair production




[arXiv:1505.04067]

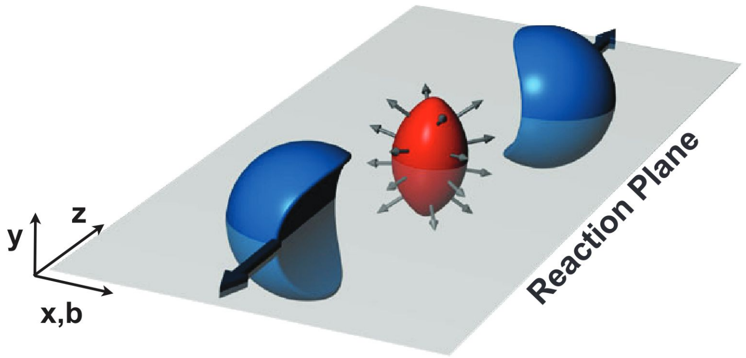



- Constrain long-distance matrix elements of NRQCD models
- Different sensitivity to feed-down from excited states than single J/ψ production
- Insights on double parton scattering and associated production




- **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 $v_2$ in high multiplicity pp collisions

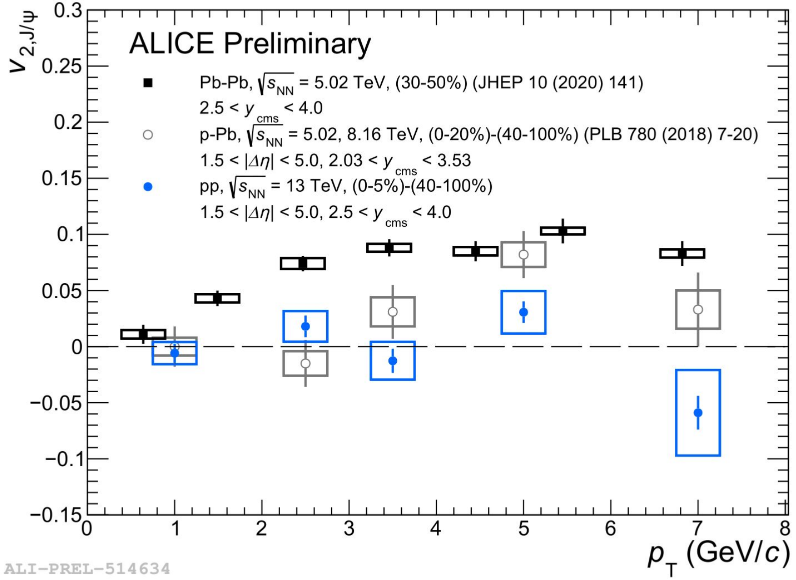



- Collective effects for heavy flavors in small systems can be accessed by studying flow observables through 2-particle correlations ➞ elliptic flow coefficient $v_2$

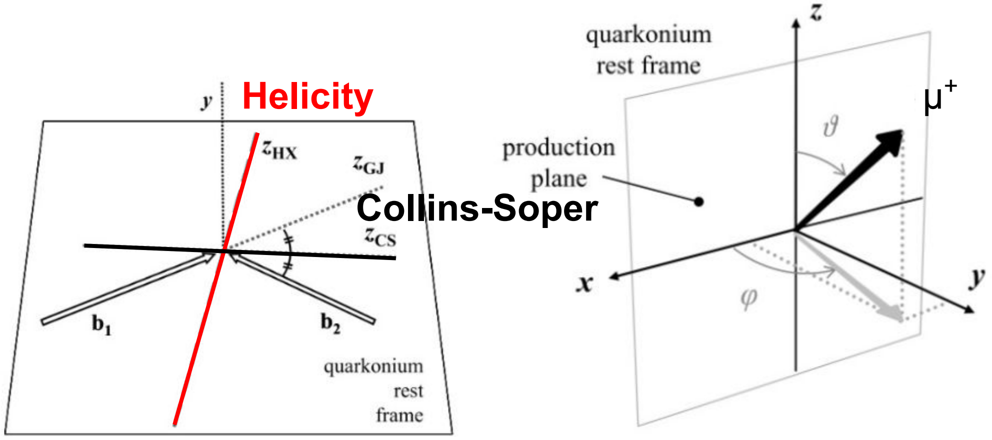
$$\frac{dN^{\text{pairs}}}{d\Delta\phi} \propto (1 + \sum_{n=1}^{\infty} 2v_n^2 cos(n\Delta\phi))$$

- J/ψ elliptic flow measurement vs $p_T$:
  - **First results in pp down to zero $p_T$**
  - No significant deviation of $v_2$ from zero
  - **No collective behavior observed** at high multiplicity for the J/ψ

- The J/ψ elliptic flow increases with the system size: $v_2^{J/\psi}$(pp) < $v_2^{J/\psi}$(pPb) < $v_2^{J/\psi}$(PbPb)



# Y(1S) polarization in pp collisions

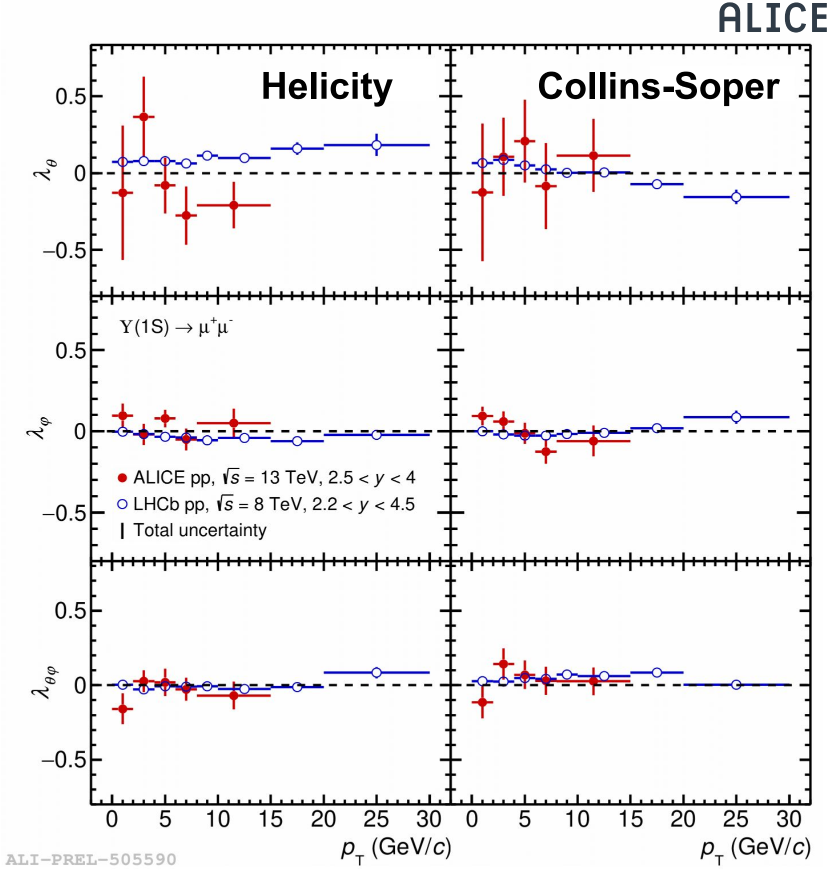



- Y(1S) has $J^{PC} = 1^{--}$ ➞ it can be produced in three angular momentum states related to their polarization state

- The polarization can be extracted from the angular distribution of the Y(1S):

$$W(cos\theta, \varphi|\vec{\lambda}) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta cos^2\theta+\lambda_\varphi \sin^2\theta cos2\varphi+\lambda_{\theta\varphi} sin2\theta cos\varphi)$$

- **All polarization parameters are compatible with zero** within uncertainties for both reference frames ➞ no significant polarization observed



# Conclusion and Outlook

- **Quarkonium production in pp collisions**:
  - Prompt J/ψ is well reproduced by NRQCD and ICEM, and non-prompt by FONLL
- **Measurements of multiplicity dependent charmonium production** in pp collisions:
  - Different behavior versus charged particle multiplicity for the J/ψ produced at mid and forward rapidity
  - Same linear trend versus multiplicity for the J/ψ, ψ(2S), and Υ(nS) at forward rapidity
- First **elliptic flow measurements for J/ψ** in pp collisions at 13 TeV ➞ no significant elliptic flow
- Measurement of the **double J/ψ cross section**: results in agreement with LHCb
- First measurement of the **Υ(1S) polarization** in pp collision at 13 TeV ➞ no significant polarization

- **Perspective for LHC Run 3:**
  - **Larger multiplicity** can be achieved with increased statistics
  - Separation of the **prompt and non-prompt charmonia at forward rapidity** thanks to the new Muon Forward Tracker
  - Improved spatial resolution at midrapidity thanks to the upgraded ITS