

Quarkonium polarization measurement in hadronic and nuclear collisions at forward rapidity



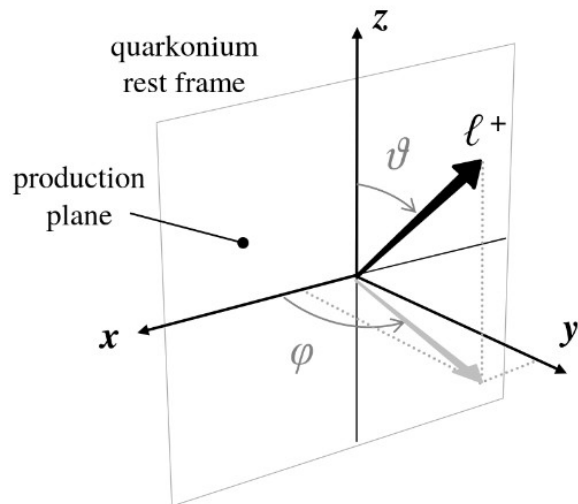
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On behalf of the ALICE Collaboration

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- ☆ Polarization: degree of alignment of particle spin with respect to a chosen direction
- ☆ Measured as the anisotropy in the angular distribution of decay products
- ☆ For a vector meson (V) the total angular momentum (J, J_z) state can be expressed as

$J/\psi, \psi(2S), Y(1S), Y(2S),$
 $Y(3S), \text{ etc. } [J^{PC} = 1^{--}]$



$$|V : J, J_z\rangle = \mathbf{b}_{-1}|1, -1\rangle + \mathbf{b}_0|1, 0\rangle + \mathbf{b}_{+1}|1, +1\rangle$$

Spin alignment \Leftrightarrow Decay daughters angular distribution

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

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1, 0, 0) \rightarrow$ Pure transverse polarization

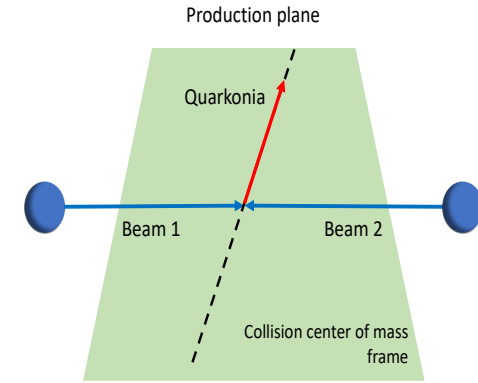
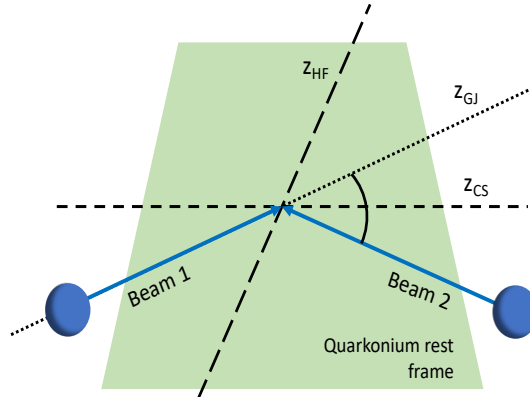
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0) \rightarrow$ Pure longitudinal polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0) \rightarrow$ No polarization

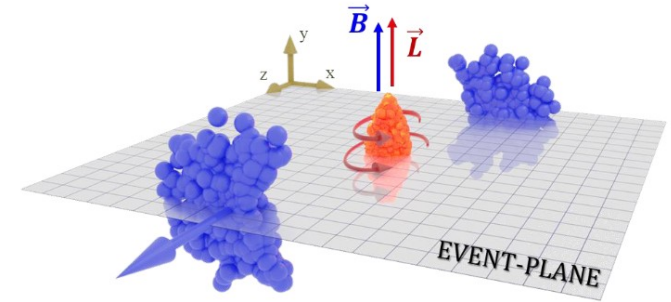
Faccioli et. al, EPJC 69, 657 (2010)

Quarkonium Polarization: Frame of Reference

- ☆ The polarization parameters are frame dependent
- ☆ **Helicity Frame (HF)**
In the direction of quarkonia momentum in the center of the mass frame of the colliding beams
- ☆ **Collins-Soper Frame (CS)**
The bisector of the angle between the momentum of one beam and the opposite of the other beam
- ☆ **Event Plane Frame (EP)**
Axis orthogonal to the collision event plane



Phys.Rev.C 109, 034910 (2024)



Frame invariant parameter

$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

Polarization in pp collisions

Phys. Rev. Lett. 108, 082001 (2012)

Eur. Phys. J. C 78, 562 (2018)

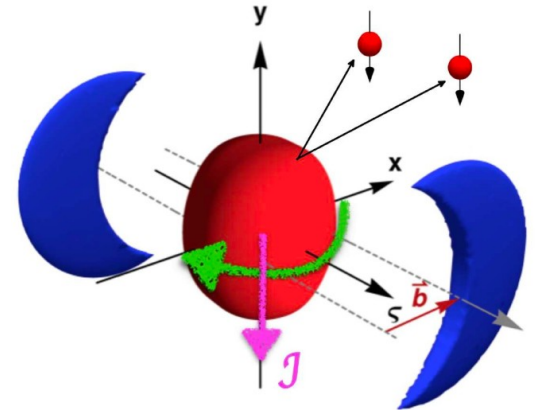
- Constrains J/ψ production mechanism
 - No sizeable polarization has been measured at LHC

Polarization in AA collisions

Phys. Lett. B 815, 136146 (2021)

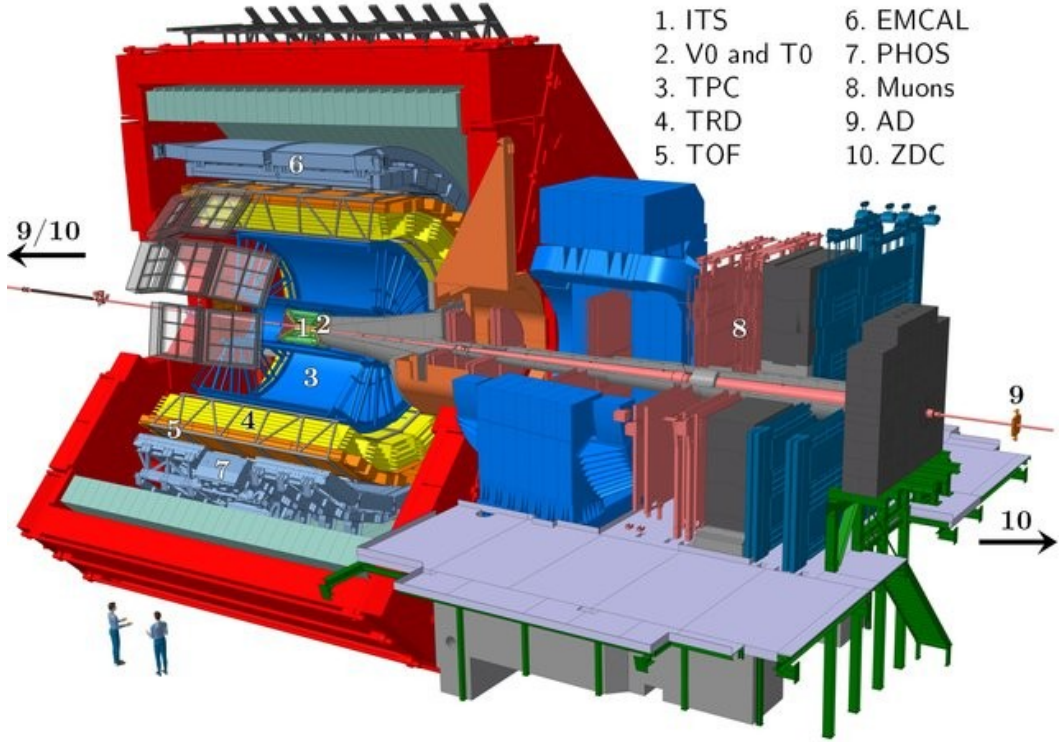
Phys. Rev. Lett. 131, 042303 (2023)

- Various potential sources
 - Vorticity field
 - Electromagnetic field
 - Vector meson force field

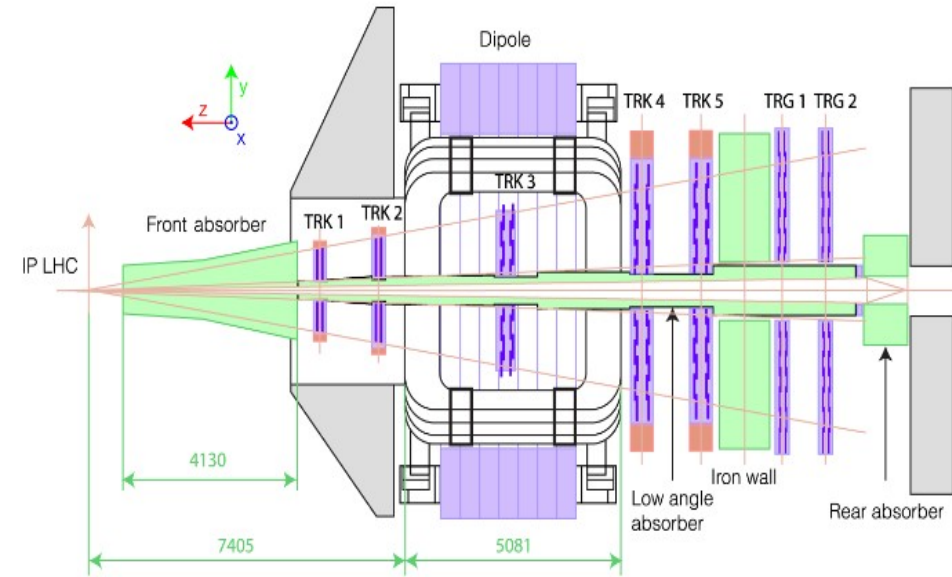


Prog. Nucl. Phys, 108, 103709 (2019)

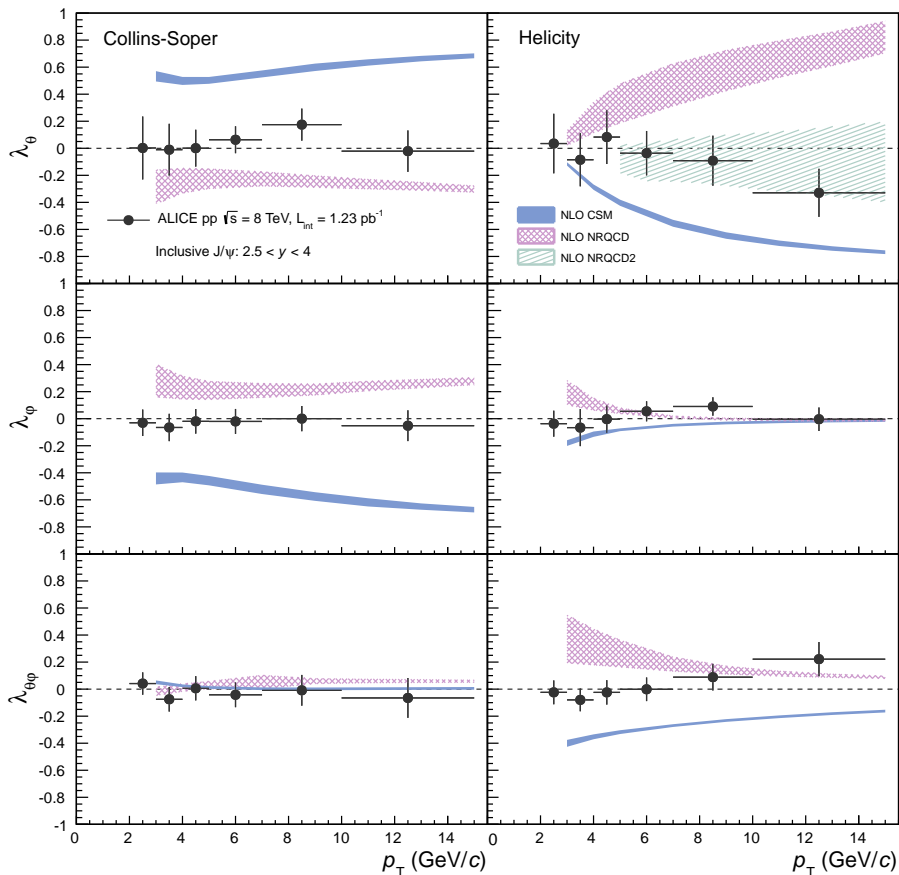
A Large Ion Collider Experiment (Run 2 Configuration)



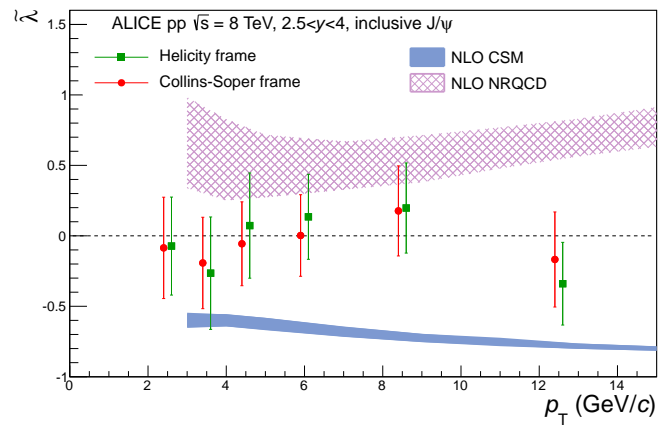
ALICE Muon Spectrometer



- The inclusive quarkonia measurement is performed in ALICE at forward rapidity regions ($-4.0 < \eta < -2.5$) in the **dimuon** decay channel



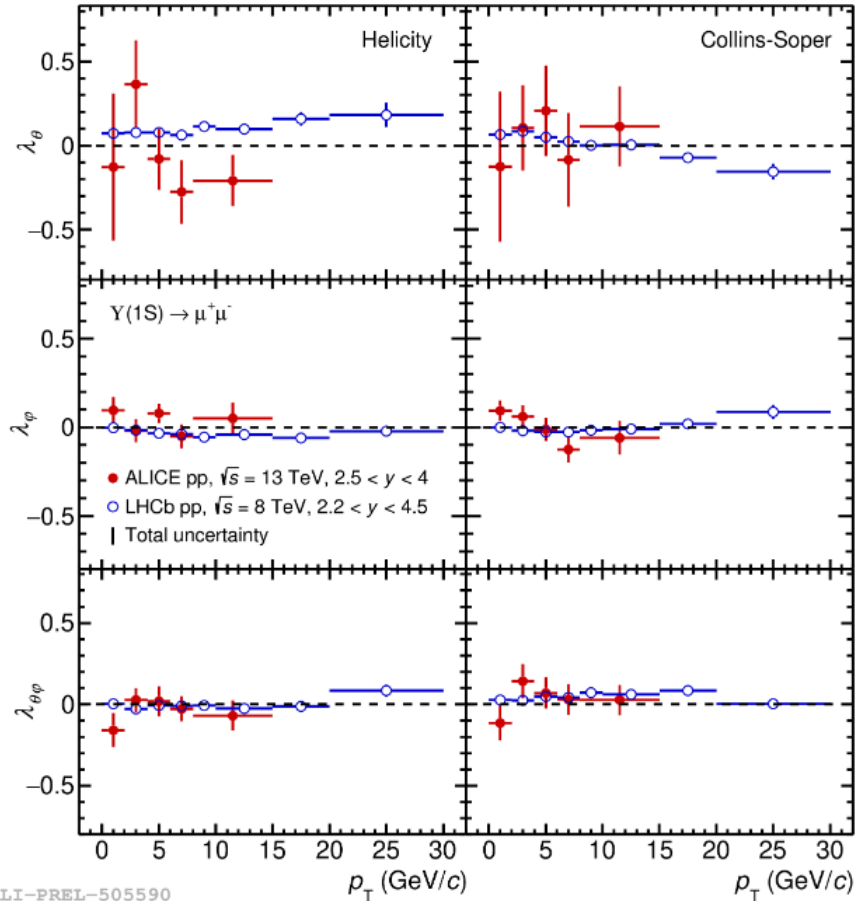
- J/ψ polarization parameters are measured in pp collisions at $\sqrt{s} = 8$ TeV in both CS and HE frames
- **No significant** polarization observed by ALICE at forward rapidity. However, the theoretical models based on **CSM and NRQCD** predicts a strong polarization
- New analyses of J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 13$ TeV with the largest data sample collected in Run 2 is going on



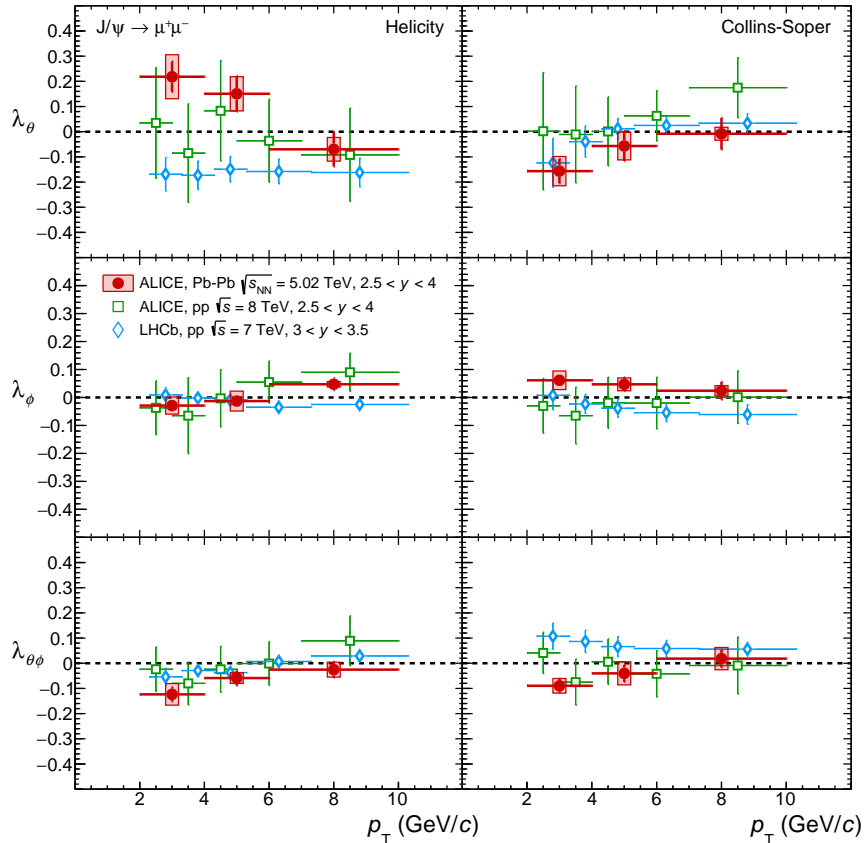
- The lambda invariant parameter is consistent in both the frames

Eur. Phys. J. C 78, 562 (2018)

Quarkonium polarization: pp @ $\sqrt{s} = 13$ TeV

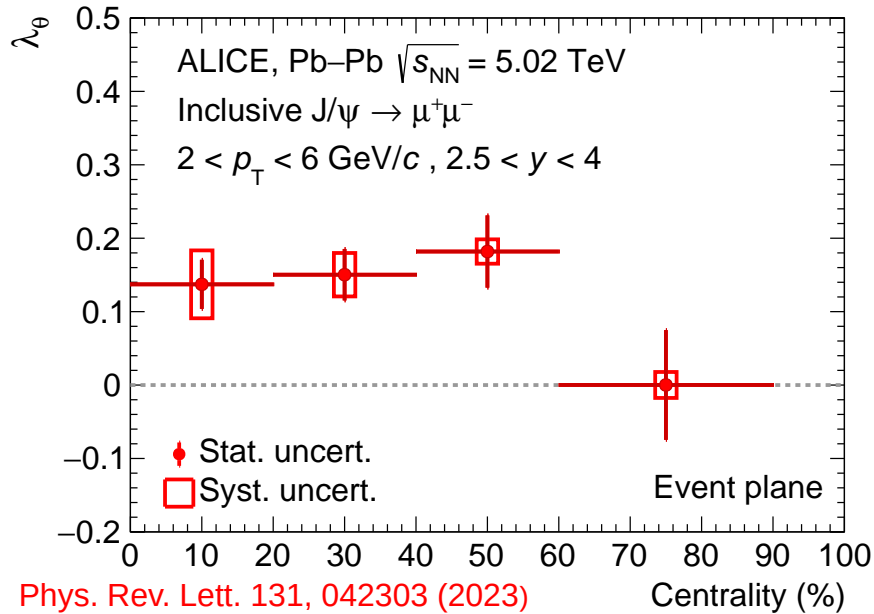


- Recent preliminary measurement of **Y(1S)** polarization in pp collisions at $\sqrt{s} = 13$ TeV from ALICE
- Results compatible with previous LHCb measurements at $\sqrt{s} = 8$ TeV
- Polarization is evaluated down to $p_T \sim 0$ GeV/c
- All values compatible with **zero** within uncertainties
- Large uncertainties due to limited statistical precision

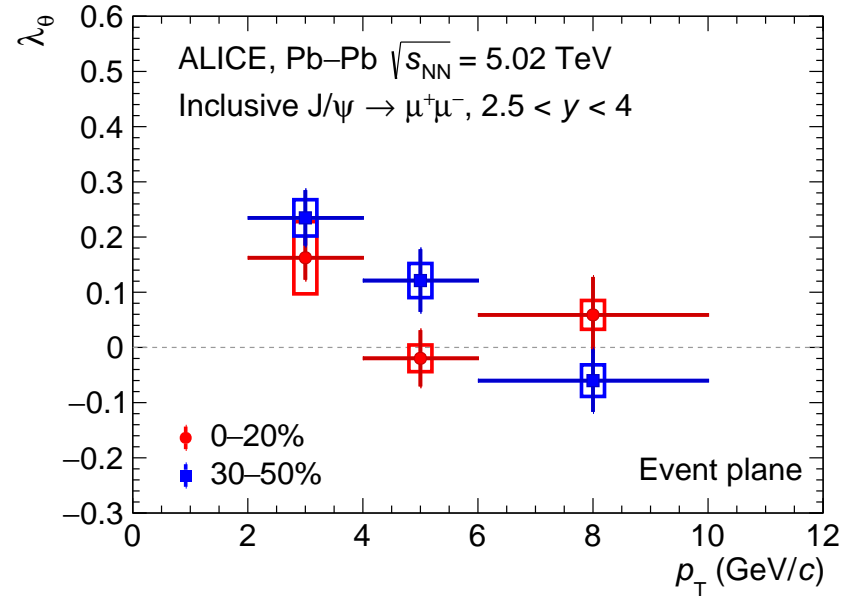


- The inclusive J/ψ polarization is measured by ALICE in **Pb-Pb** collisions at $\sqrt{s_{NN}} = 5.02$ TeV in HE and CS frames
- λ_θ indicates a slight **transverse polarization** at low p_T ($\sim 2.1\sigma$) in HE frame, while a weak **longitudinal polarization** ($\sim 2.1\sigma$) in CS frame
- All values of λ_ϕ and $\lambda_{\theta\phi}$ are smaller than 0.1, except for $\lambda_{\theta\phi}$, which is -0.124 at low p_T and deviates from zero by $\sim 2.4\sigma$
- A **significant** difference (3.3σ) is found with respect to **LHCb** results at $\sqrt{s} = 7$ TeV in the interval $2 < p_T < 4$ GeV/c in **HE** frame
- The observed hint for a **different polarization** in pp and Pb-Pb might be a reflection of the different production, **suppression and regeneration** mechanisms in the two systems

Quarkonium polarization: Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV



Phys. Rev. Lett. 131, 042303 (2023)



- First measurement of J/ψ polarization in Pb-Pb collisions with respect to the Event Plane (EP) at $\sqrt{s_{NN}} = 5.02$ TeV
- Finite polarization ($\sim 3.5\sigma$) of J/ψ is observed in Pb-Pb collisions for (40-60)% centrality class at $\sqrt{s_{NN}} = 5.02$ TeV
- Significant deviation ($\sim 3.9\sigma$) is observed for (30-50)% at low transverse momentum ($2 < p_T < 4$ GeV/c) for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Summary and Outlook



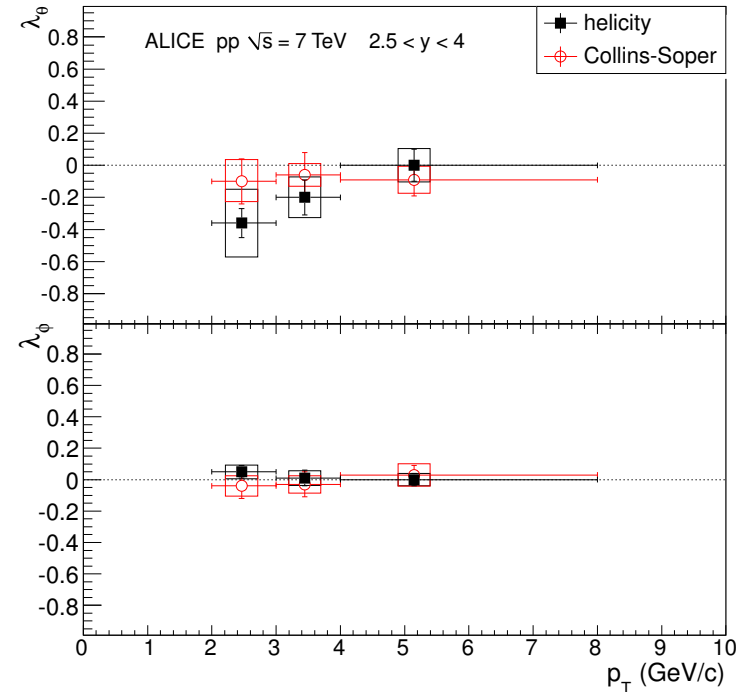
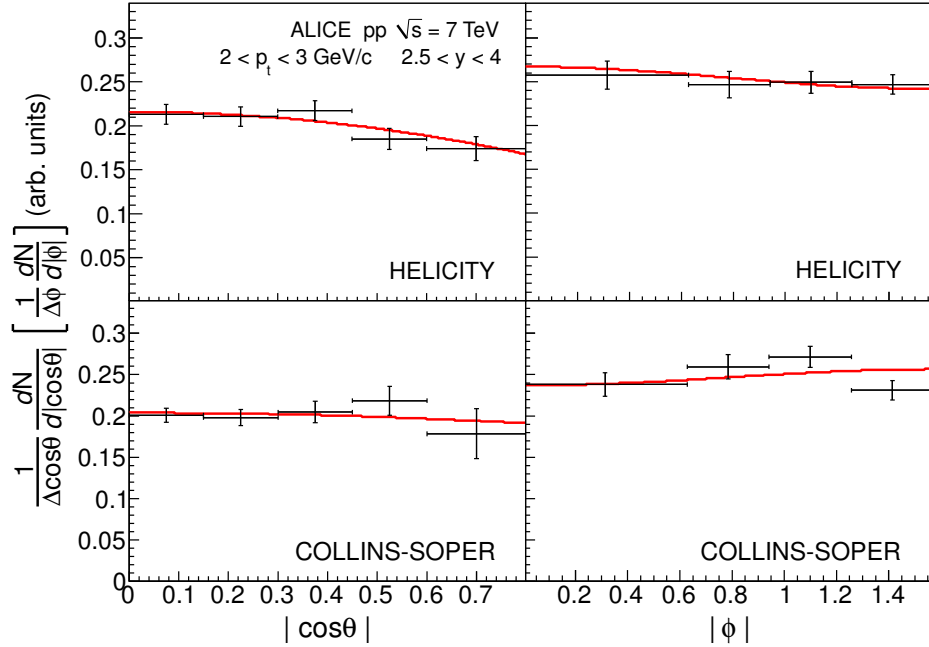
- ALICE has measured the polarization of several **quarkonium states** both in pp and Pb–Pb collisions
- So far, **no sizable** quarkonium polarization is observed in pp collisions. Results are compatible with other LHC measurements
- NRQCD and CSM model could not able to explain the J/ψ polarization in pp collisions. However, recent theoretical model such as **ICEM** and **CGC +NRQCD** model explain the data qualitatively
- Hint of **non-zero polarization** for J/ψ is observed at low p_T in the HE, CS and EP frames in Pb–Pb collisions
- The finite polarization in Pb–Pb collisions indicates the possible correlation between the **vorticity field** and **electromagnetic field** with the QGP medium formed in heavy-ion collision. Apart of these two, there could be various other potential sources for the finite polarization of J/ψ
- New **J/ψ and $\psi(2S)$** polarization analyses is ongoing in pp collision at $\sqrt{s} = 13$ TeV and **13.6** TeV
- ALICE **Run 3** with high luminosity and newly built **MFT detector**, will allow to perform high precision measurements



ALICE

Back Up

Quarkonium polarization: pp @ $\sqrt{s} = 7$ TeV



- The angular distribution of J/ψ is measured in pp collisions at $\sqrt{s} = 7$ TeV in the CS and HE frames

Phys. Rev. Lett. 108, 082001 (2012)

- J/ψ polarization parameters are measured in pp collisions at $\sqrt{s} = 7$ TeV in the CS and HE frames
- No significant polarization observed by ALICE at forward rapidity in both CS and HE frames

Candidate selection

- Quarkonium candidates are built combining muon pairs reconstructed in the muon spectrometer
- o All the standard cuts for quarkonium analysis is applied

Analysis steps

1. Signal extraction

- Number of quarkonia obtained fitting the dimuon invariant mass distribution as a function of $\cos\theta$ and φ

2. Acceptance \times efficiency correction

- Number of quarkonia corrected with the acc \times eff. obtained with a MC simulation

3. Polarization parameters extraction

- Fit to the acc \times eff. corrected distribution with $(\cos\theta, \varphi)$ to obtain the polarization parameters

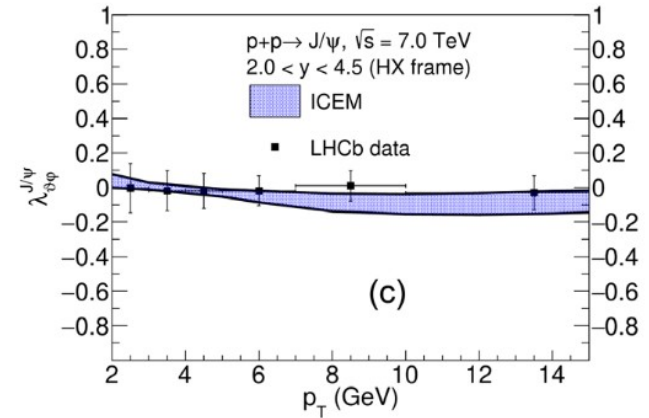
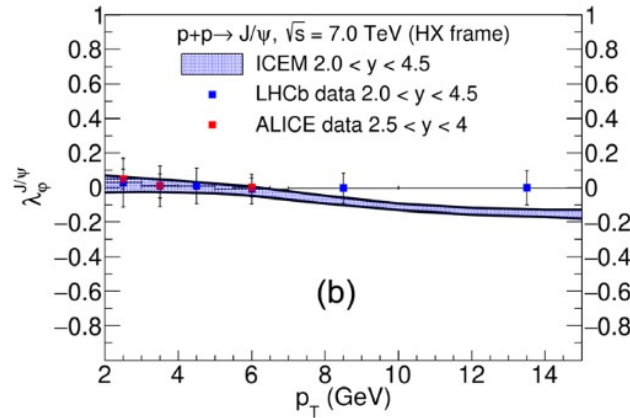
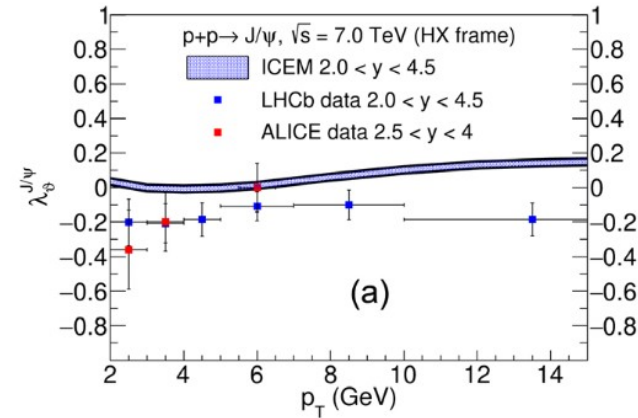
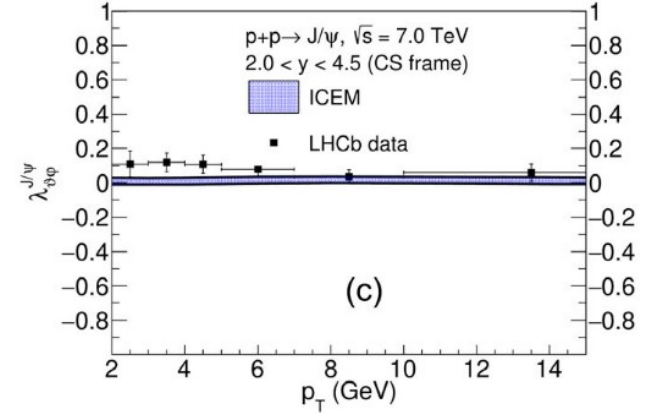
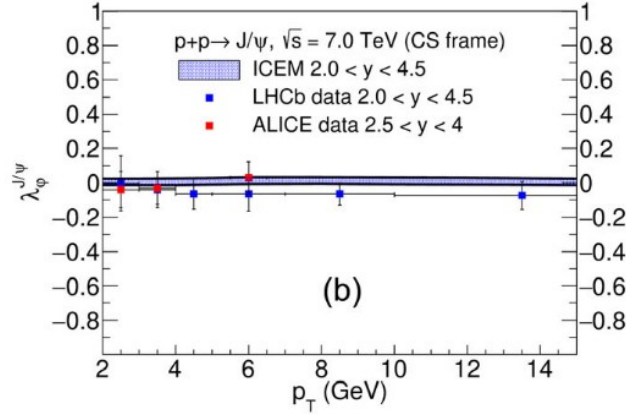
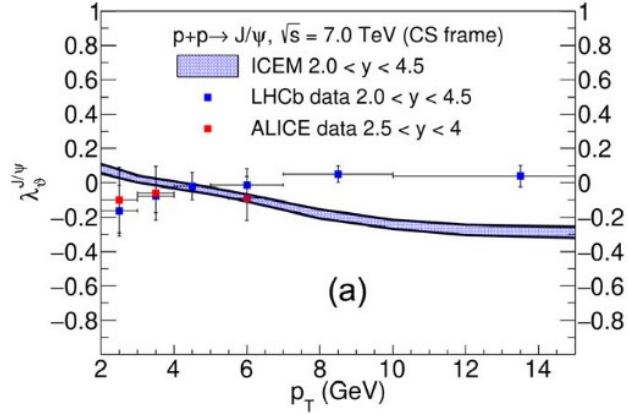
GOAL

$\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$
evaluation

ICEM model predictions



LICE



PHYS. REV. D 104, 094026 (2021)