Quarkonium polarization measurement in hadronic and nuclear collisions at forward rapidity

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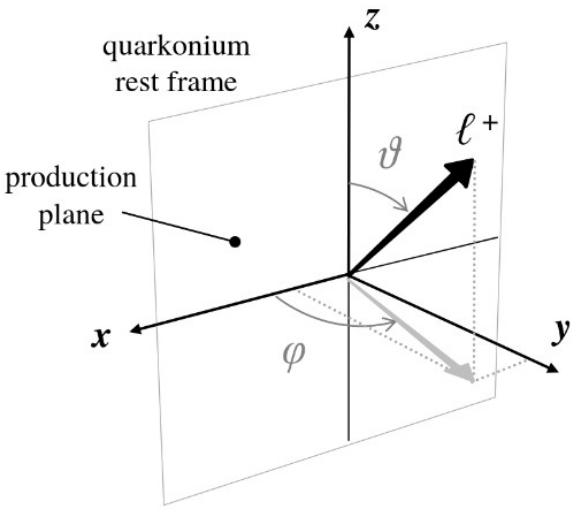
ALICE

Quarkonium Polarization: an Introduction

- 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/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S), 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 ⇔ Decay daughters angular distribution

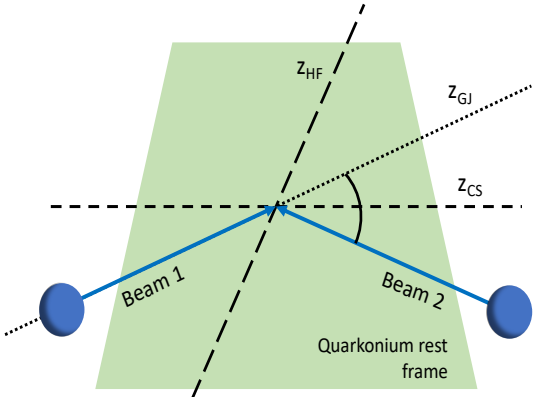
$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

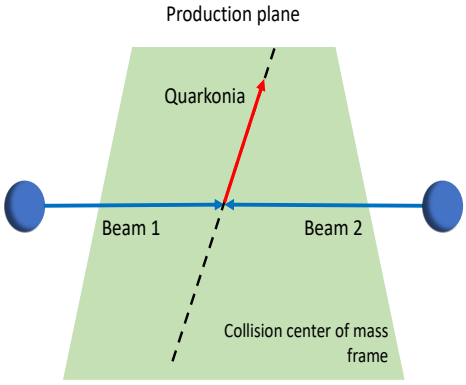
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1,0,0) \rightarrow$ Pure transverse polarization
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0) \rightarrow$ Pure longitudinal polarization
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0) \rightarrow$ No polarization

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

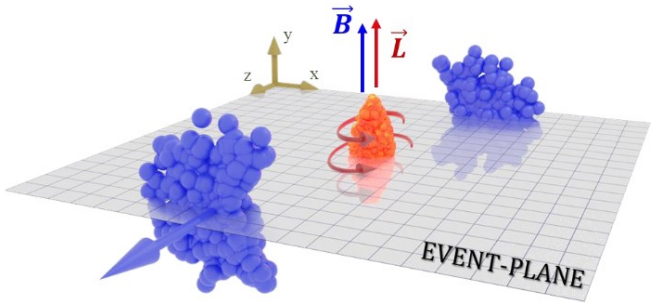
Quarkonium Polarization: Frame of Reference

- 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

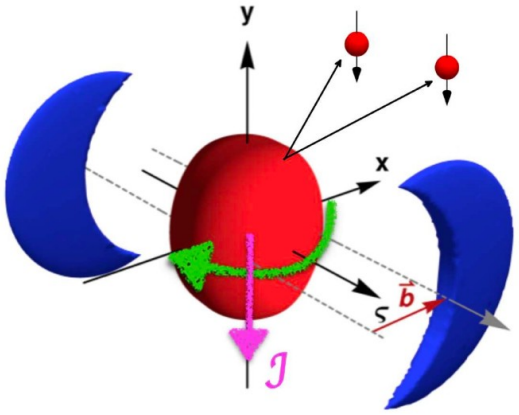
- Constrains J/ψ production mechanism
  - No sizeable polarization has been measured at LHC

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

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

Polarization in AA collisions

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

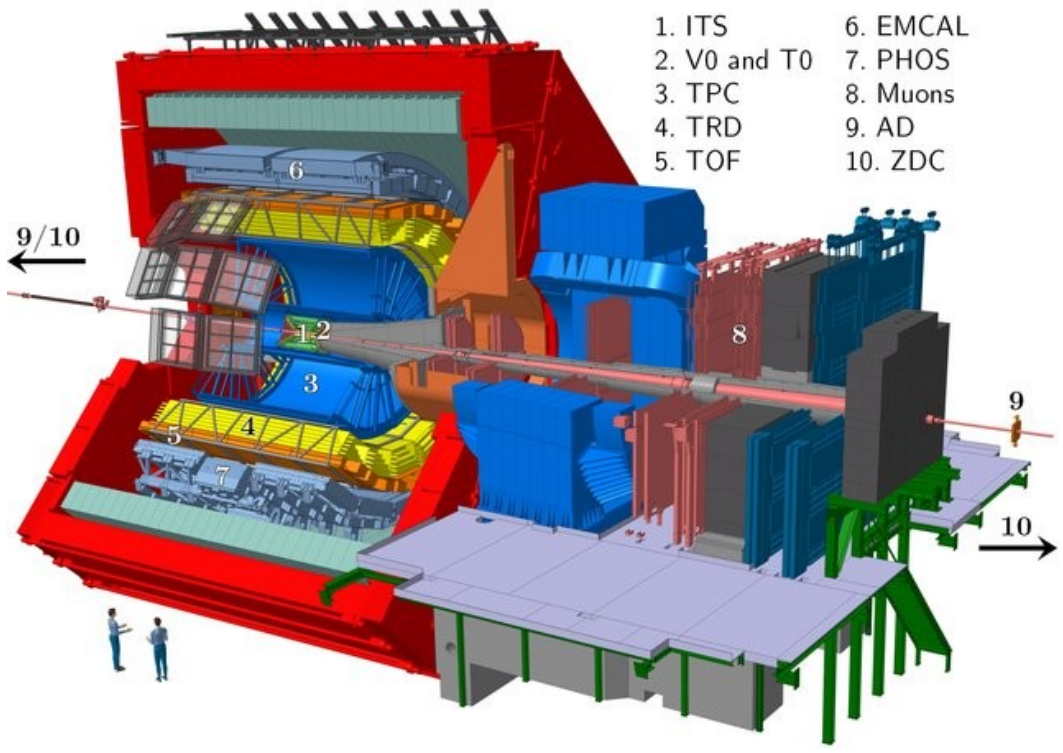


Prog. Nucl. Phys, 108, 103709 (2019)

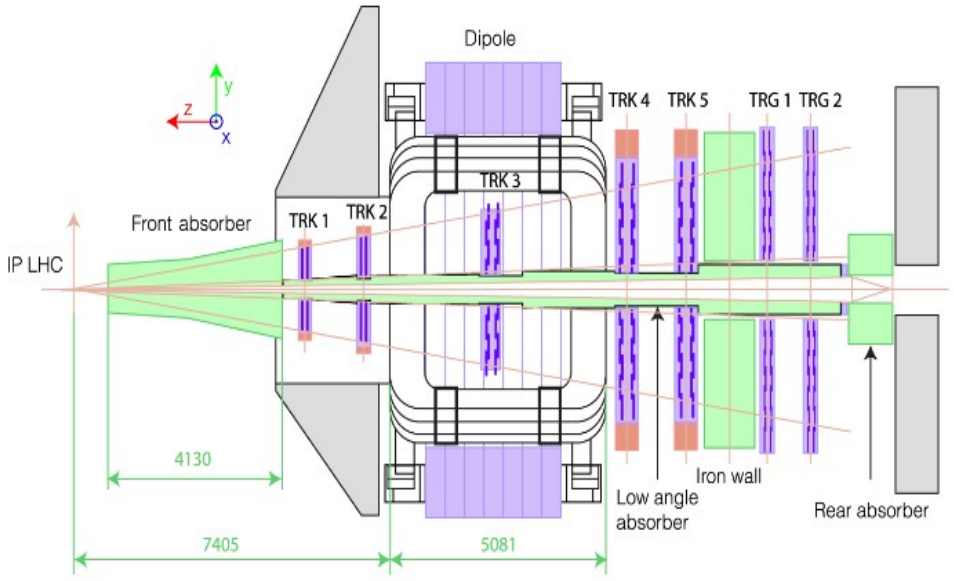
Phys. Lett. B 815, 136146 (2021)

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

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

Analysis Procedure

Candidate selection

Quarkonium candidates are built combining muon pairs reconstructed in the muon spectrometer

- 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 cosθ and φ

2. Acceptance × efficiency correction

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

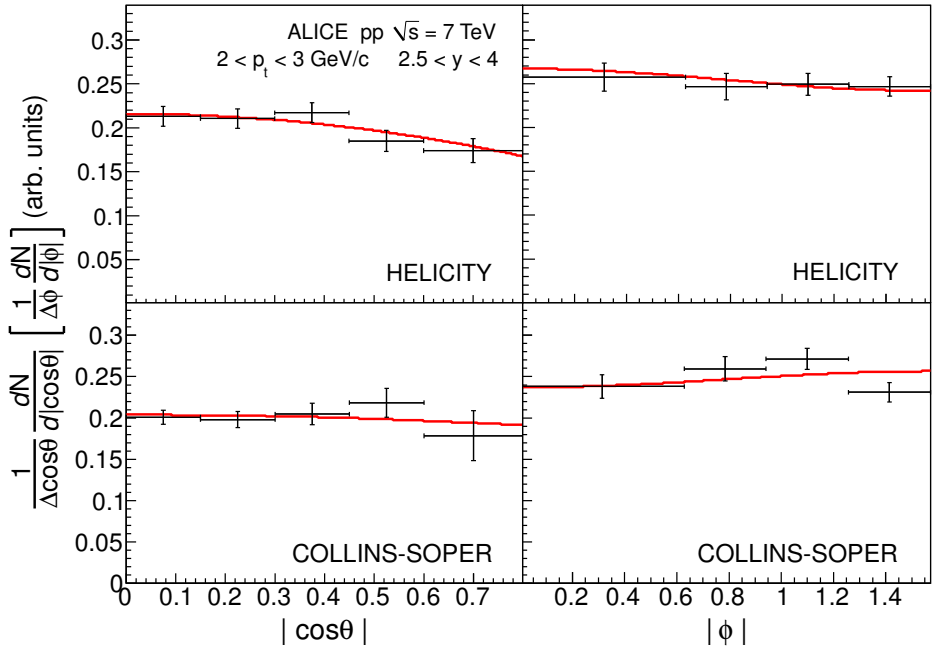
3. Polarization parameters extraction

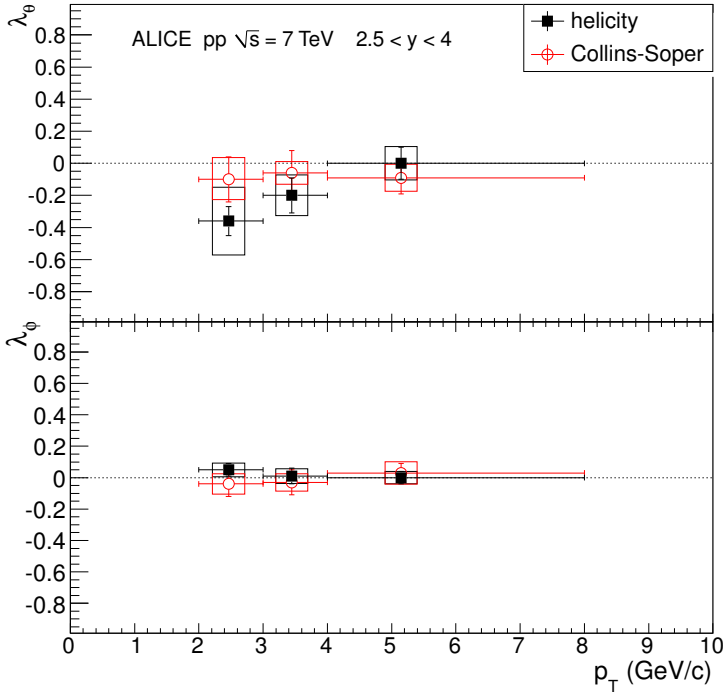
   - Fit to the acc × eff. corrected distribution with $W(\cos\theta, \varphi)$ to obtain the polarization parameters

GOAL

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

Quarkonium polarization: pp @ √s = 7 TeV



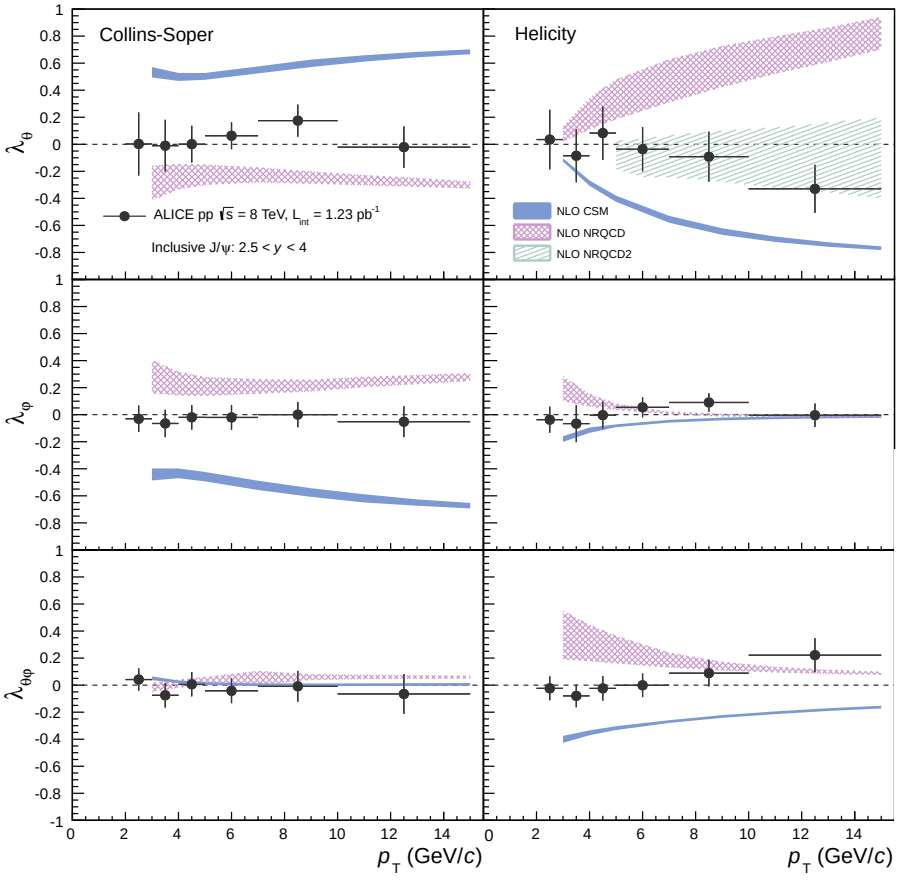


- The angular distribution of J/ψ is measured in pp collisions at √s = 7 TeV in the CS and HE frames

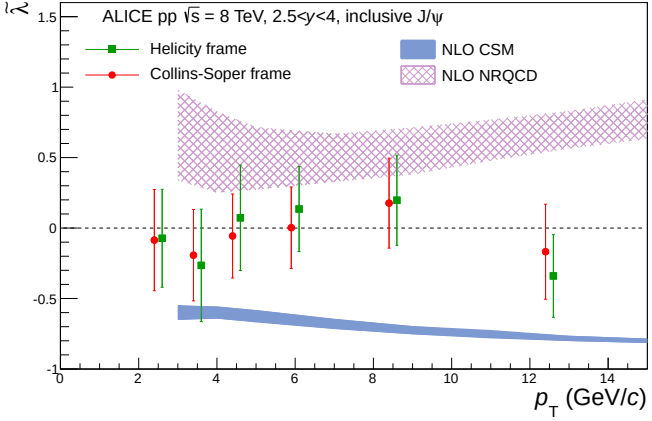
Phys. Rev. Lett. 108, 082001 (2012)

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

Quarkonium polarization: pp @ √s = 8 TeV



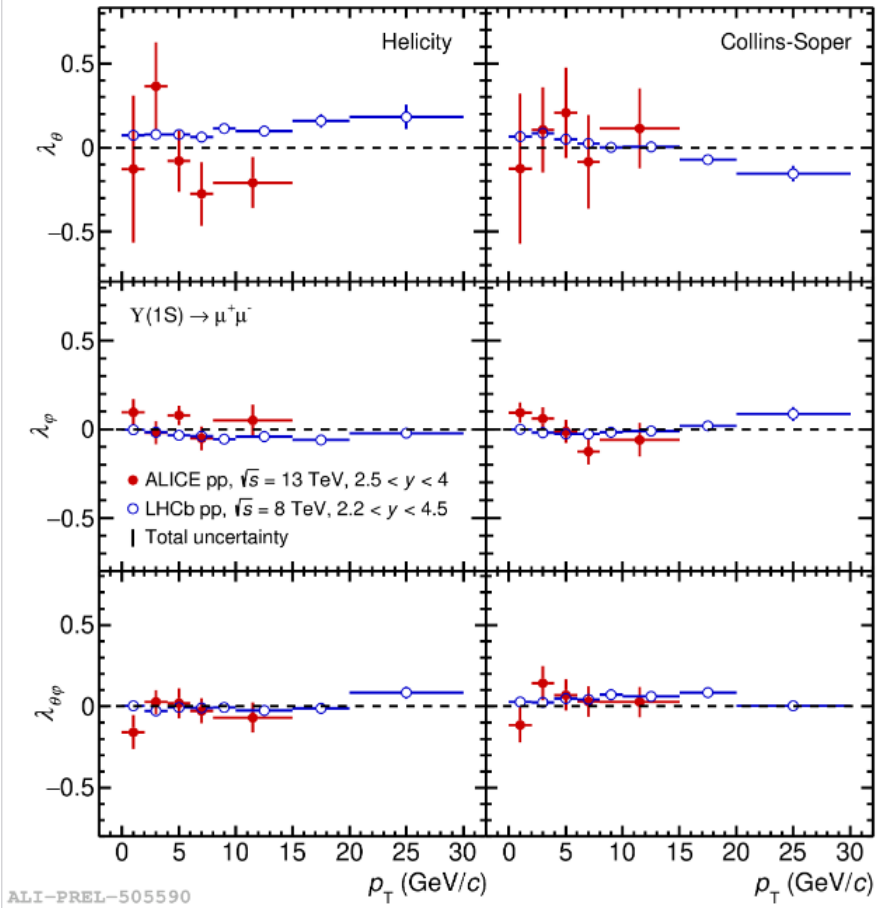
- J/ψ polarization parameters are measured in pp collisions at √s = 8 TeV in both CS and HE frames
- No significant polarization observed by ALICE at forward rapidity. However, the theoretical models based on CSM and NRQCD predicts a strong polarization
- New analyses of J/ψ and ψ(2S) in pp collisions at √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

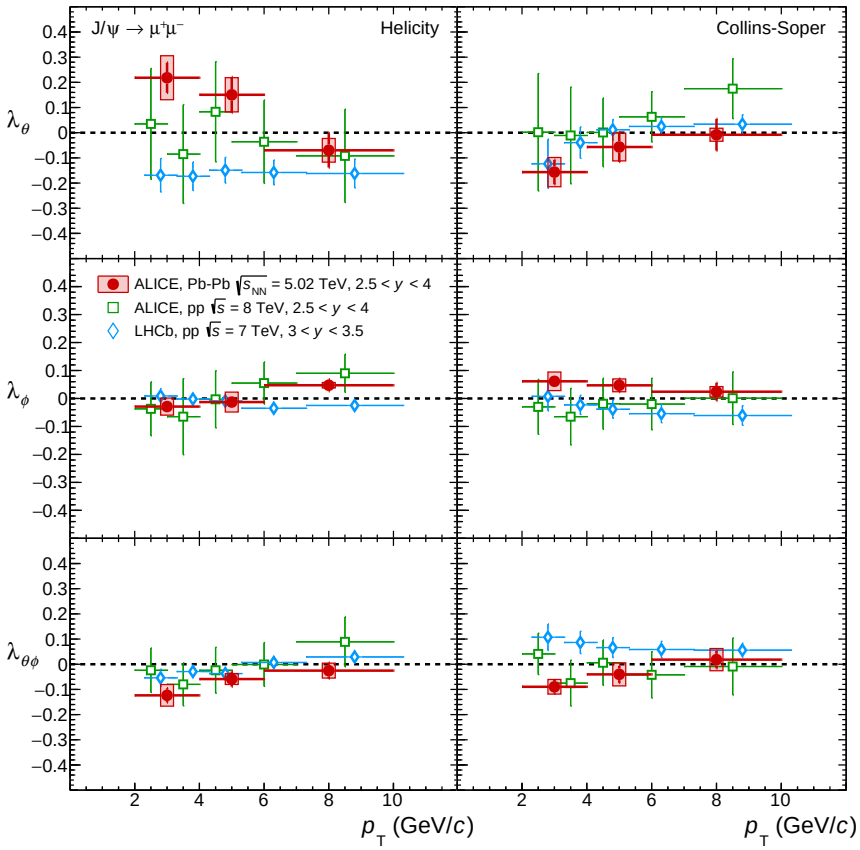
Eur. Phys. J. C 78, 562 (2018)

Quarkonium polarization: pp @ √s = 13 TeV



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

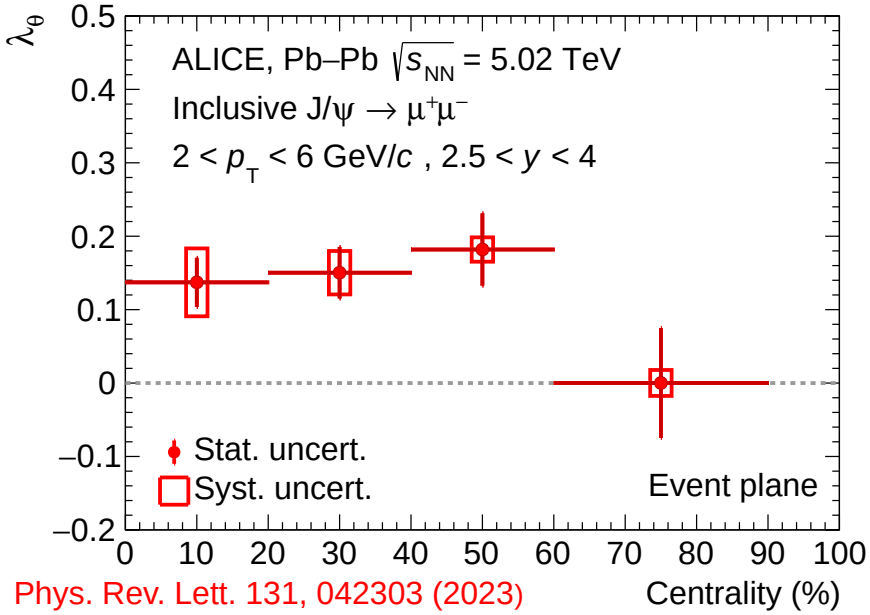
Quarkonium polarization: Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV



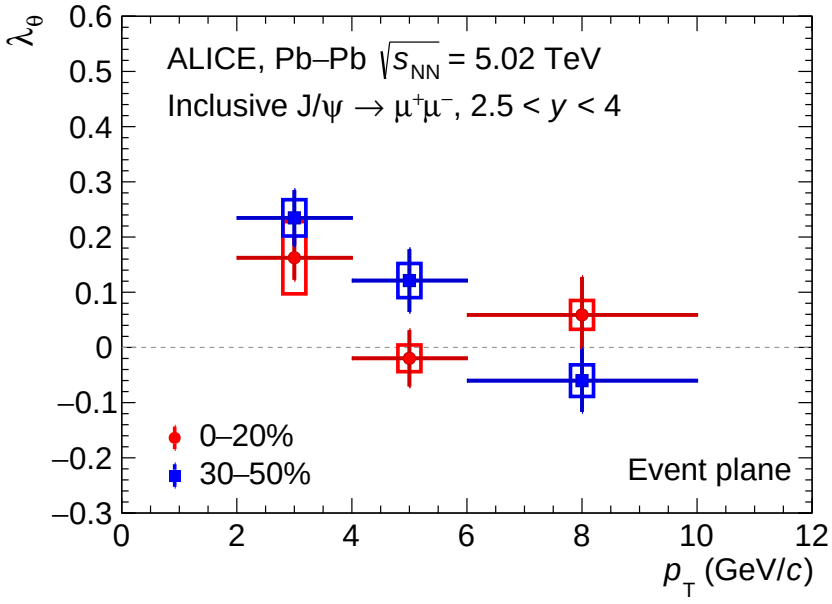
- The inclusive J/ψ polarization is measured by ALICE in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in HE and CS frames
- λ_θ indicates a slight transverse polarization at low p_T (∼2.1σ) in HE frame, while a weak longitudinal polarization (∼2.1σ) in CS frame
- All values of λ_φ and $\lambda_{\theta\varphi}$ are smaller than 0.1, except for $\lambda_{\theta\varphi}$, which is −0.124 at low p_T and deviates from zero by ∼ 2.4σ
- A significant difference (3.3σ) is found with respect to LHCb results at √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

Phys. Lett. B 815, 136146 (2021)

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



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



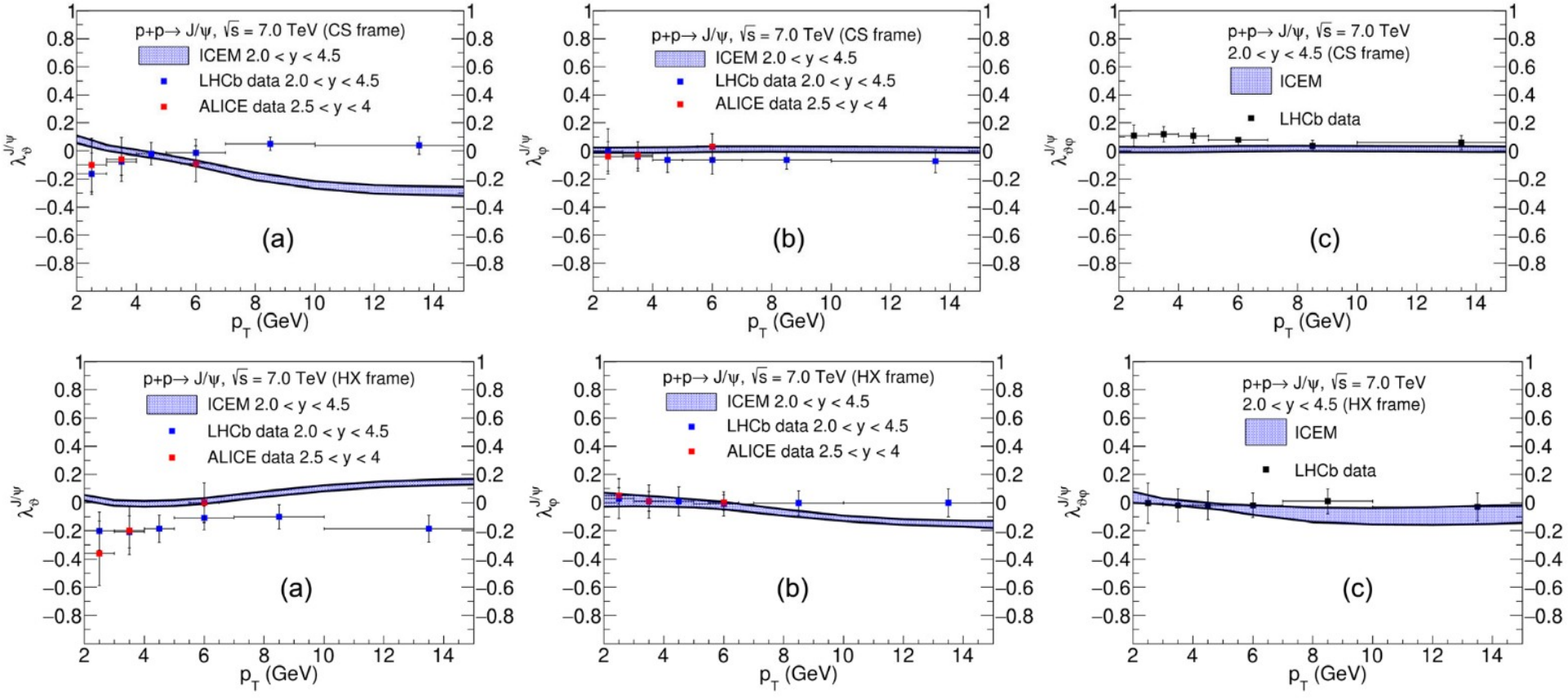
- First measurement of J/ψ polarization in Pb−Pb collisions with respect to the Event Plane (EP) at $\sqrt{s_{NN}}$ = 5.02 TeV
- Finite polarization (~ 3.5σ) of J/ψ is observed in Pb-Pb collisions for (40-60)% centrality class at $\sqrt{s_{NN}}$ = 5.02 TeV
- Significant deviation (~ 3.9σ) is observed 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 ψ(2S) polarization analyses is ongoing in pp collision at √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

Back Up

ICEM model predictions



PHYS. REV. D 104, 094026 (2021)