Rencontres du Vietnam

Windows on the Universe

Quarkonium polarization in pp and Pb-Pb collisions with ALICE

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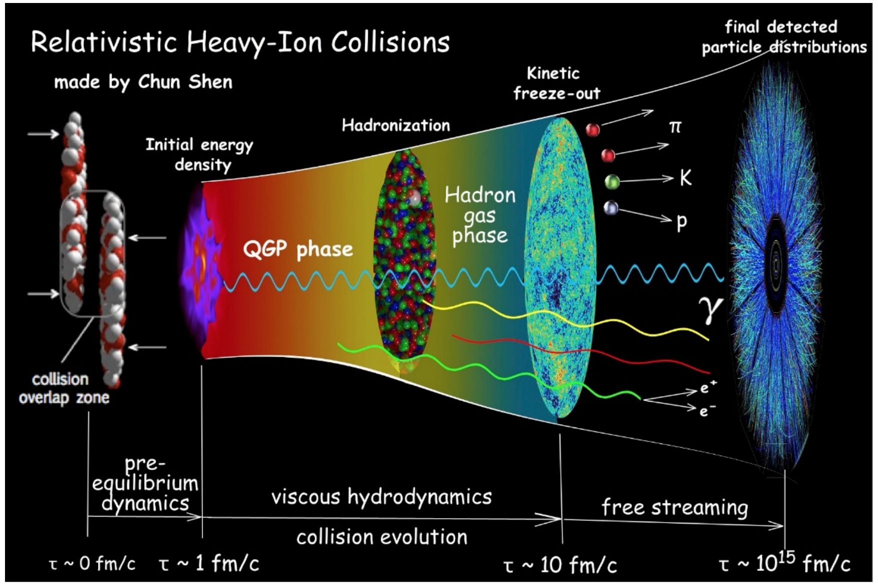
Introduction:

- What is quark–gluon plasma (QGP)?
    - Deconfined thermalized state of quarks and gluons
    - Shows collectivity
    - Formed at extremely high temperature and energy density
- ALICE detector at CERN is devoted to the characterization of the QGP
- Several signatures of QGP have been observed in heavy-ion collisions
    - Strangeness enhancement
    - Quarkonium suppression
    - Formation of ridge-like structures as an indication of collectivity
    - Jet quenching



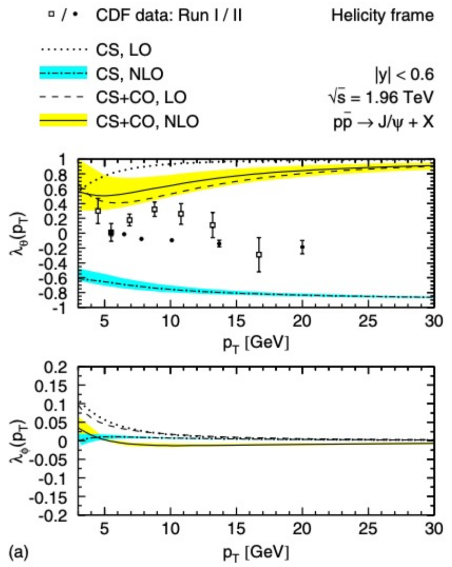
Introduction:

- Why charmonia?
  - Charm and anti-charm quarks produced early in the system's evolution : during the pre-equilibrium phase
  - Affected by suppression and regeneration at LHC energies
  - J/ψ remains largely undiffused in the hadronic phase of a collision which makes it a better probe to study the deconfined phase
  - Charmonium studies in hadronic collisions provide powerful tests of quantum chromodynamics (QCD)
  - Charmonium production yield in Pb—Pb and p—Pb collisions can also be affected by the cold nuclear matter (CNM) effect (e.g. Shadowing effect)
- Polarization in pp collisions:
  - Polarization is the measure of how much the spin of a particle is aligned in a given direction
  - Gluon's polarization is preserved as the $c\bar{c}$ pair evolves into a bound state of charmonium
  - In two-body decays, the spin-alignment will be reflected in the angular distribution of the decay particles

Introduction:

J/ψ polarization puzzle ?

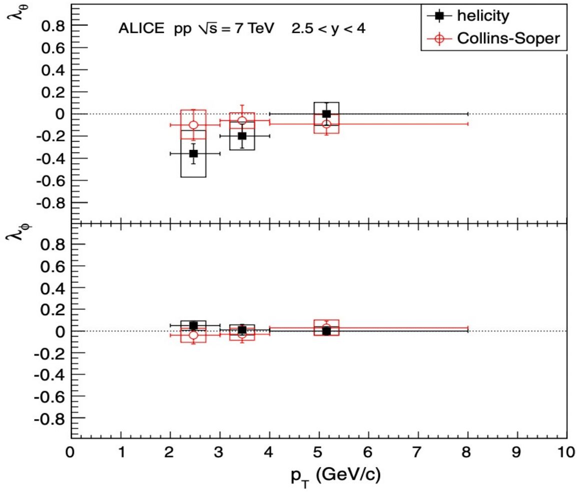
- Measurements of polarization parameters from Tevatron, RHIC and LHC show almost no J/ψ polarization in hadronic collisions
- However, theoretical predictions based on the collinear factorized color singlet production channel at leading order (LO) and next-to-leading order (NLO) suggested substantially non-zero polarization at high p_{T}
- Conflicting theoretical results from non-relativistic quantum chromodynamics (NRQCD) and Color Singlet Model



[Phys. Rev. Lett. 108, 172002 (2012)]

Importance of ψ(2S) polarization study :

- A small prompt J/ψ polarization can be interpreted as reflecting a mixture of directly produced mesons with those produced in the decays of heavier (P-wave) charmonium states
- ψ(2S) is unaffected by feed-down decays from heavier charmonia

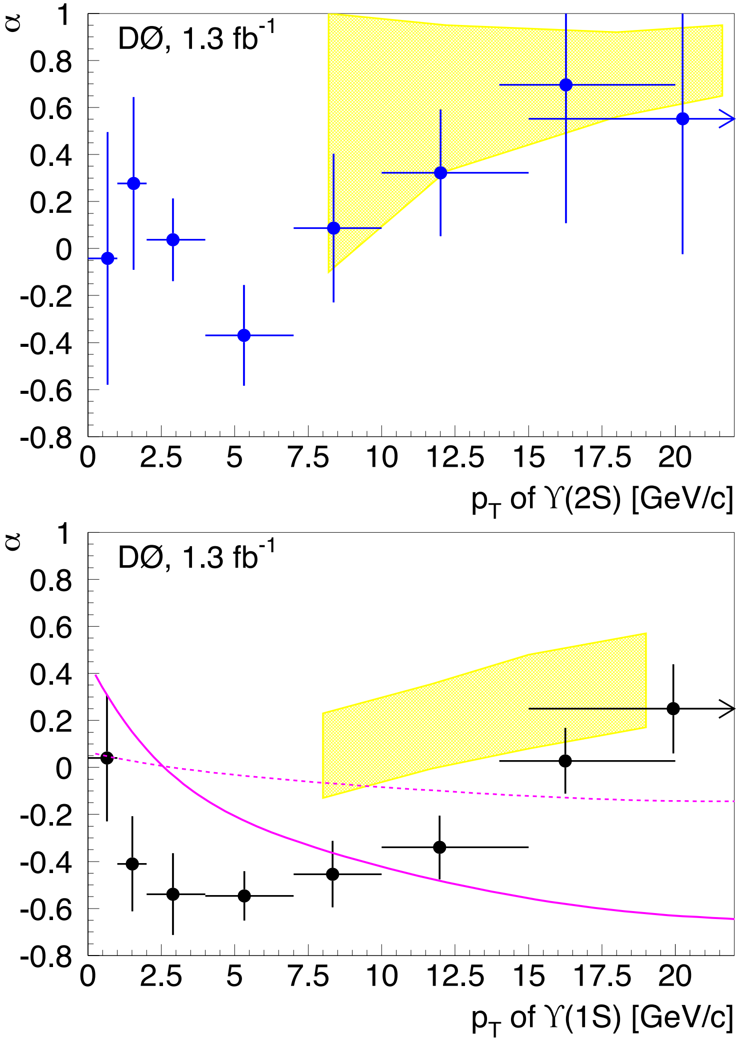


[ALICE Collaboration, Phys. Rev. Lett. 108, 082001 (2012)]

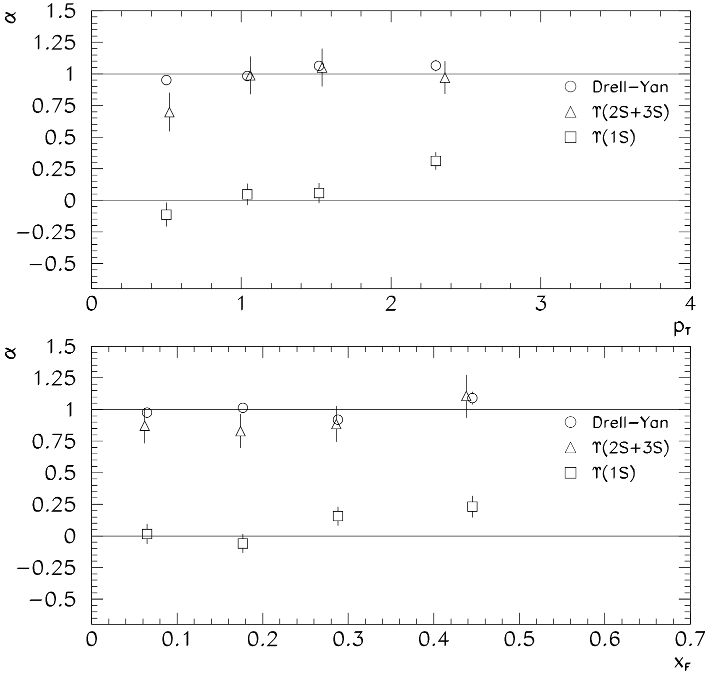
Introduction:

Importance of $\Upsilon(nS)$ polarization study :

- $b\bar{b}$ system satisfies the non relativistic calculations at high p_T much better than the $c\bar{c}$
- Better probe for QCD
- Results from Tevatron show almost no (CDF) or longitudinal polarization for $\Upsilon(1S)$ (D0)
- At lower energy and p_T , the E866 experiment has shown yet a different polarization pattern: the $\Upsilon(2S)$ and $\Upsilon(3S)$ states have maximal transverse polarization
- Unexpectedly, the $\Upsilon(1S)$ found to be only weakly polarized



[DΦ Collaboration, Phys. Rev. Lett. 101, 182004 (2008)



[NuSea Collaboration, Phys. Rev. Lett. 86, 2529 (2001)]

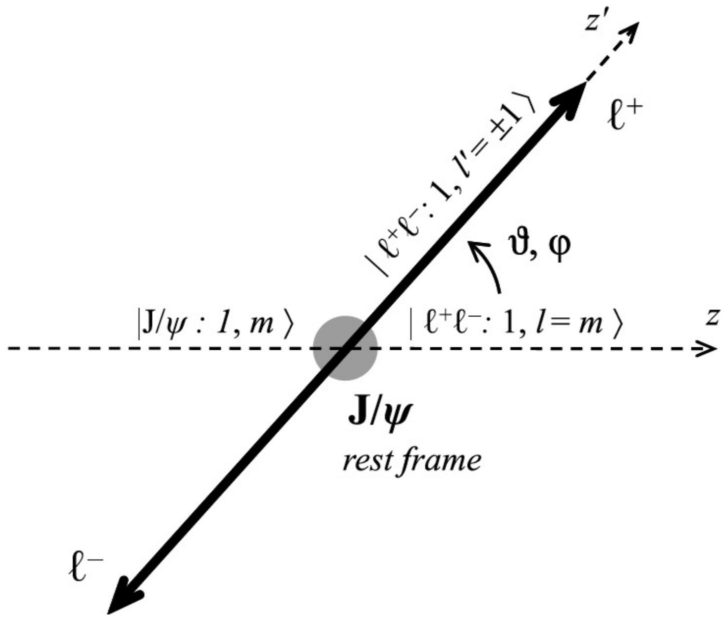
[CDF Collaboration, Phys. Rev. Lett. 88, 161802 (2002)]

Introduction:

- The angular distribution in dilepton decay:

$$\frac{d^2N}{dcos\theta \ d\phi} = \frac{3}{4\pi(3+\lambda_\theta)}(1 + \lambda_\theta \ cos^2\theta + \lambda_\phi \ sin^2\theta \ cos2\phi + \lambda_{\theta\phi} \ sin2\theta \ cos\phi)$$

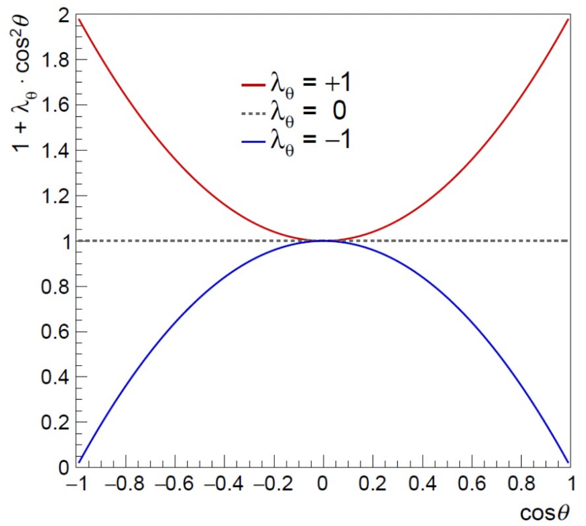
[P.Faccioli, et. al., Eur. Phys. J. C 69, 657 (2010)]



$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1, 0, 0)$ ⟶ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0)$ ⟶ Longitudinal polarization

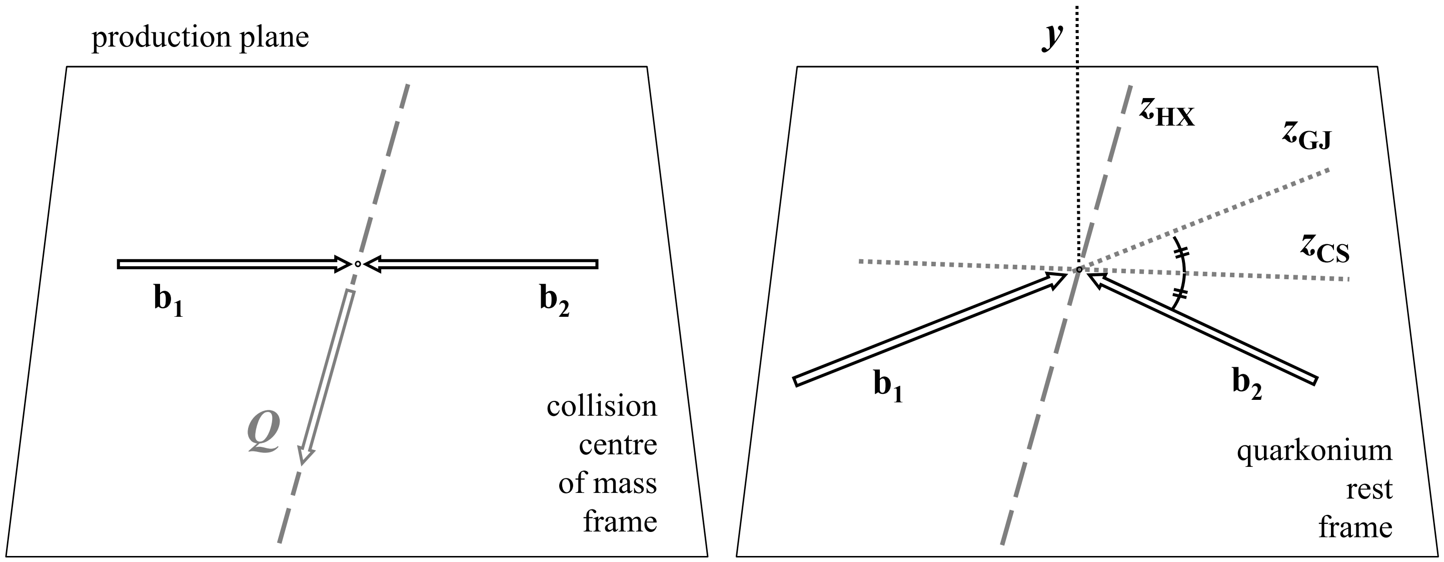
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0)$ ⟶ Unpolarized state



Introduction:

Frames of reference

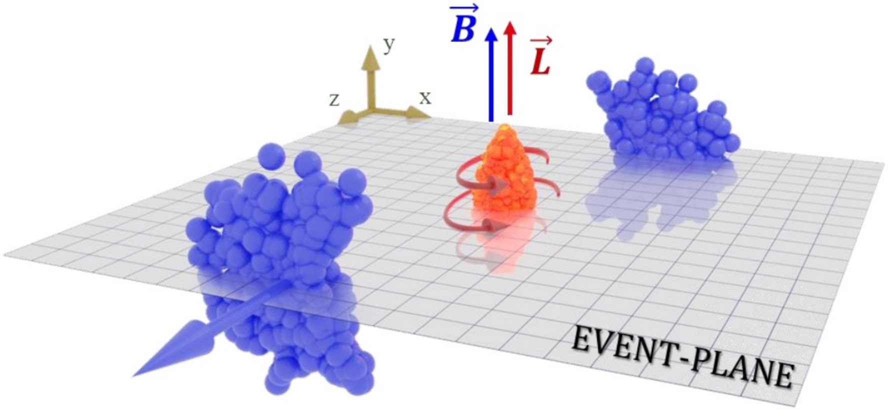
- The helicity frame uses the ψ(2S) momentum as the quantization axis
- In the Collins–Soper frame, the quantization axis is chosen to be the bisector of the angle between the two incoming beams in the rest frame of the ψ(2S) meson
- We can define the frame-invariant variable λ_{inv}



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

Quarkonium polarization in Pb—Pb collisions:

- Large non-zero magnetic field in non-central heavy-ion collisions
- Production of vorticity due to large initial angular momentum
- Both the external magnetic field and the initial angular momentum produced in the non-central heavy-ion collisions may influence the quarkonium polarization
- Event Plane (EP) frame: direction of the polarization axis orthogonal to the event plane in the centre-of-mass of the colliding beams
- The studies in Collins—Soper and Helicity frames are also interesting in AA to study quarkonium suppression/regeneration in the QGP



Magnetic field ($\vec{B}$):

- Huge intensity (10^{14} T)
- Short lived ($\tau = 1\ fm/c$)

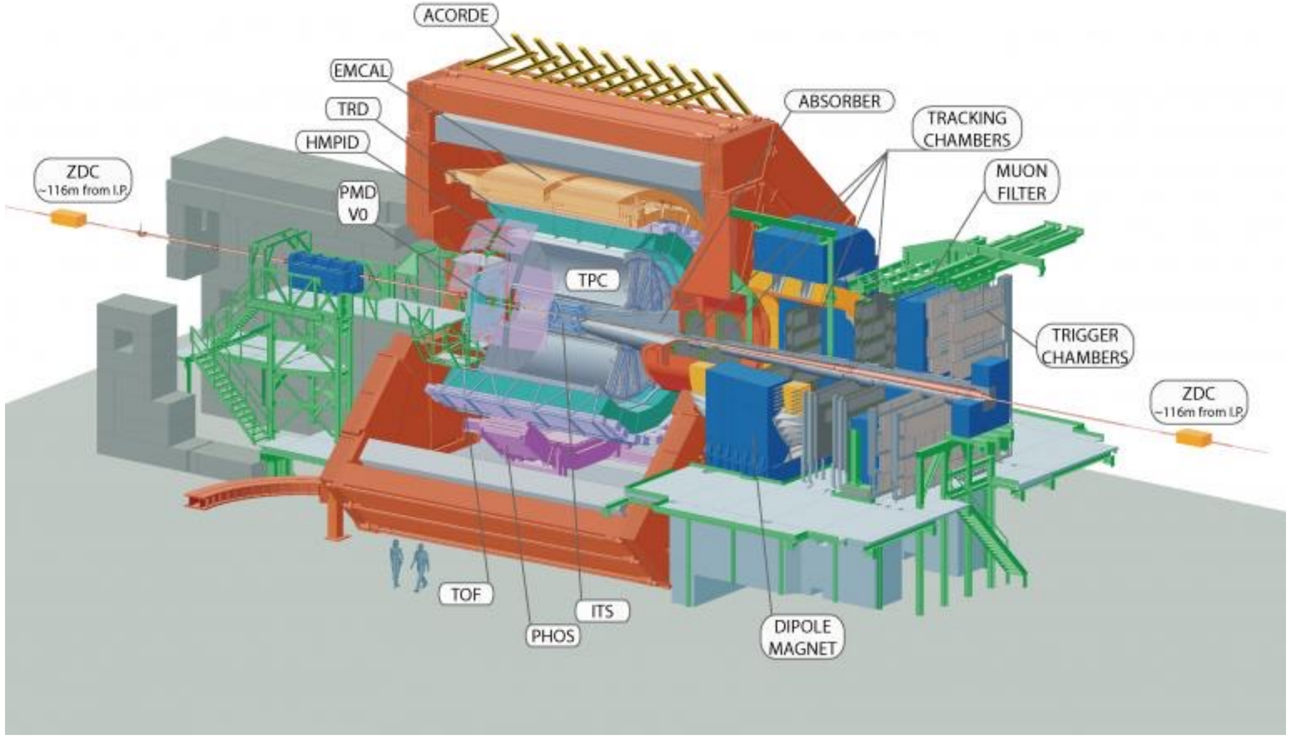
[Kharzeev et al., NPA 803 (2008)]

Angular momentum ($\vec{L}$):

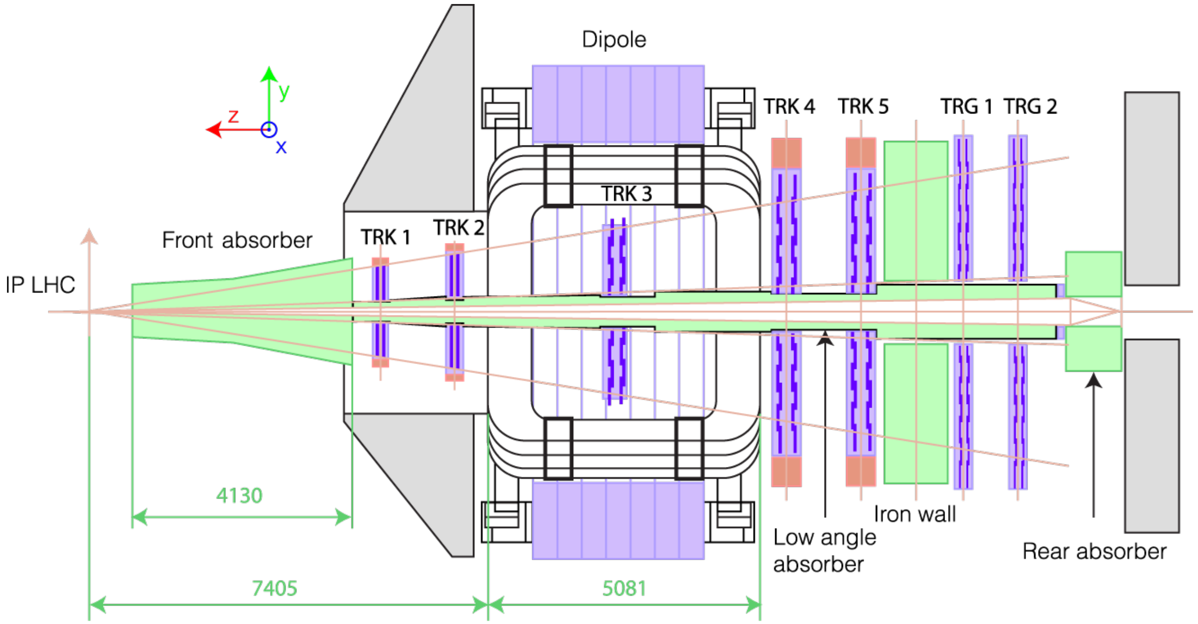
- Largest in semicentral collisions
- Can affect the system evolution till freeze-out

[Becattini et al., PRC 77 (2008) 024906]

ALICE detector (Run 2):



[ALICE Muon spectrometer]



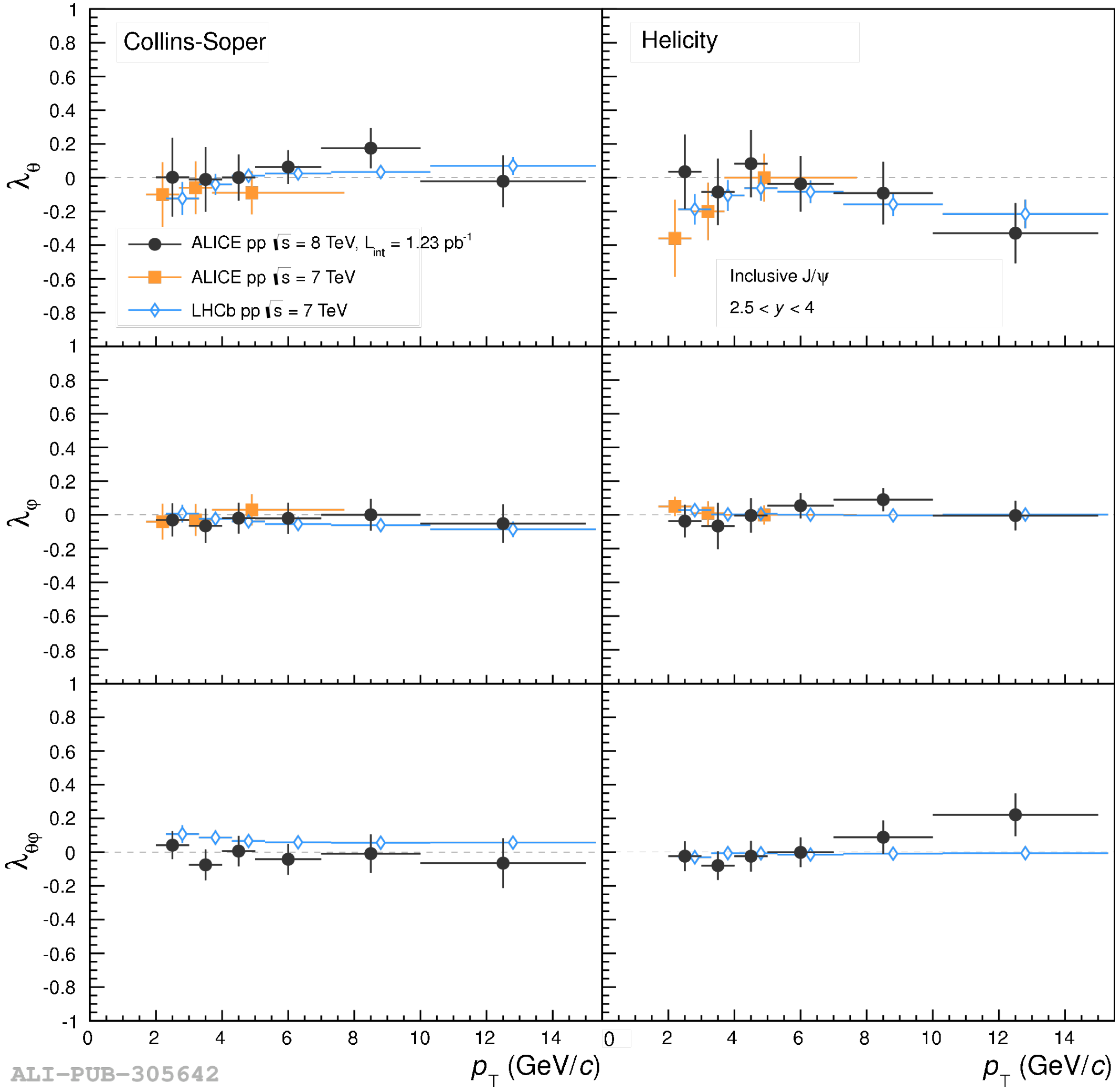
- Inclusive quarkonium measurements performed at forward rapidity in the dimuon decay channel

Muon spectrometer acceptance: -4.0 < η < -2.5

New measurements from Run 2 datasets

- pp : $\sqrt{s}$ = 13 TeV
- Pb-Pb : $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

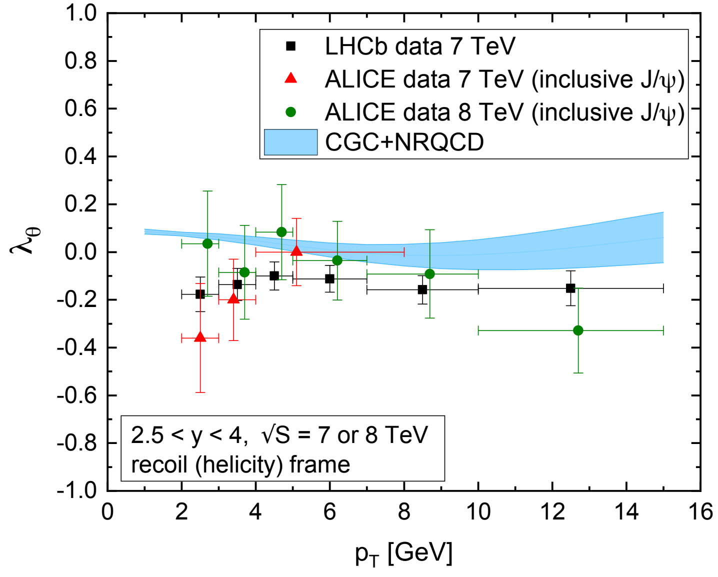
Quarkonium polarization in pp collisions:

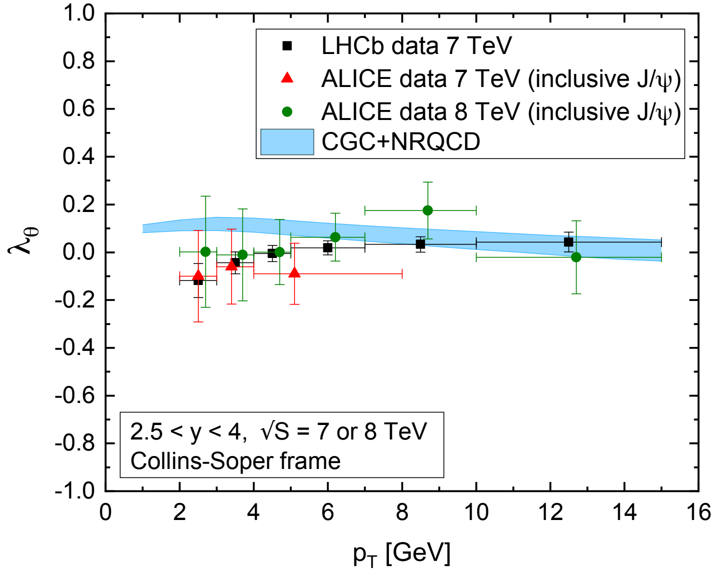


- J/ψ polarization measured in pp collisions in the CS and HE frames
- Dataset : ALICE $\sqrt{s}$ = 7 TeV (2010)
  ALICE $\sqrt{s}$ = 8 TeV (2012)
  LHCb $\sqrt{s}$ = 7 TeV (2011)
- No significant polarisation observed by ALICE and LHCb at forward rapidity
- Need for studies with higher center of mass energies
  - ✓ New ongoing analyses of J/ψ and ψ(2S) in pp collisions at $\sqrt{s}$ = 13 TeV

ALICE Collaboration, Phys. Rev. Lett. 108, 082001 (2012)
ALICE Collaboration, Eur. Phys. J. C 78, 562 (2018)
LHCb Collaboration, Eur. Phys. J. C 73, 2631 (2013)

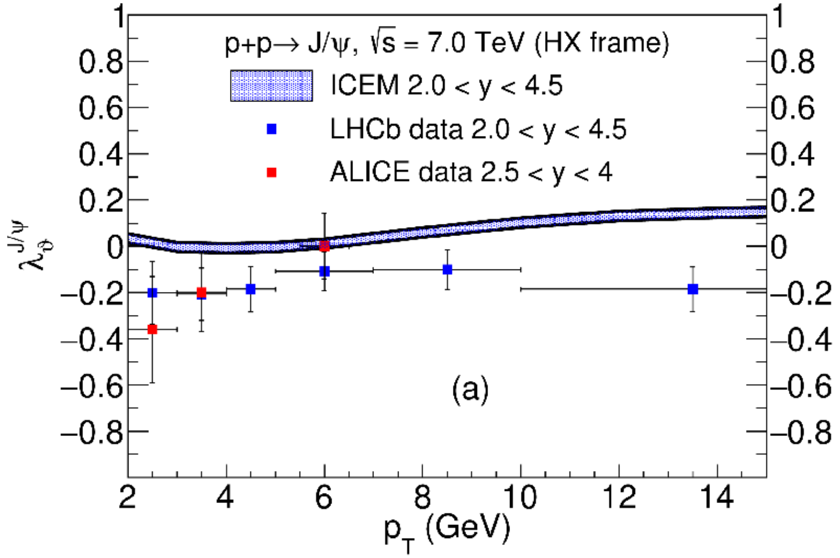
Quarkonium polarization in pp collisions:

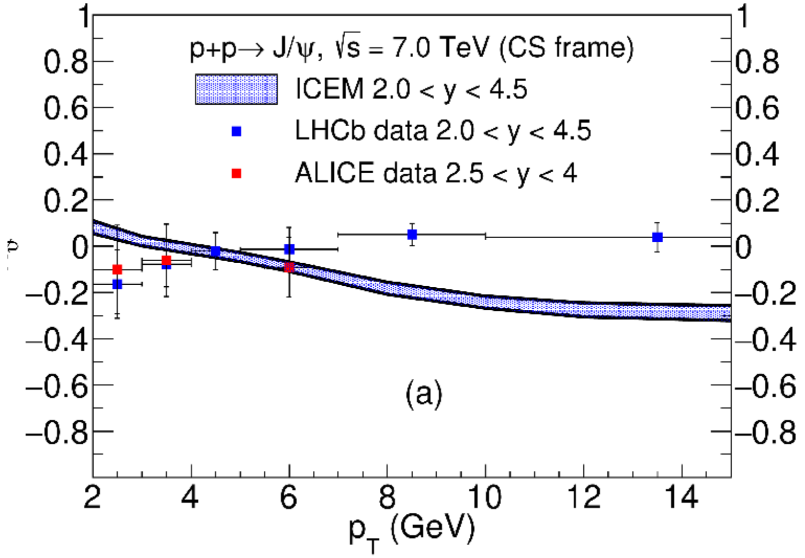




Theoretical comparison:

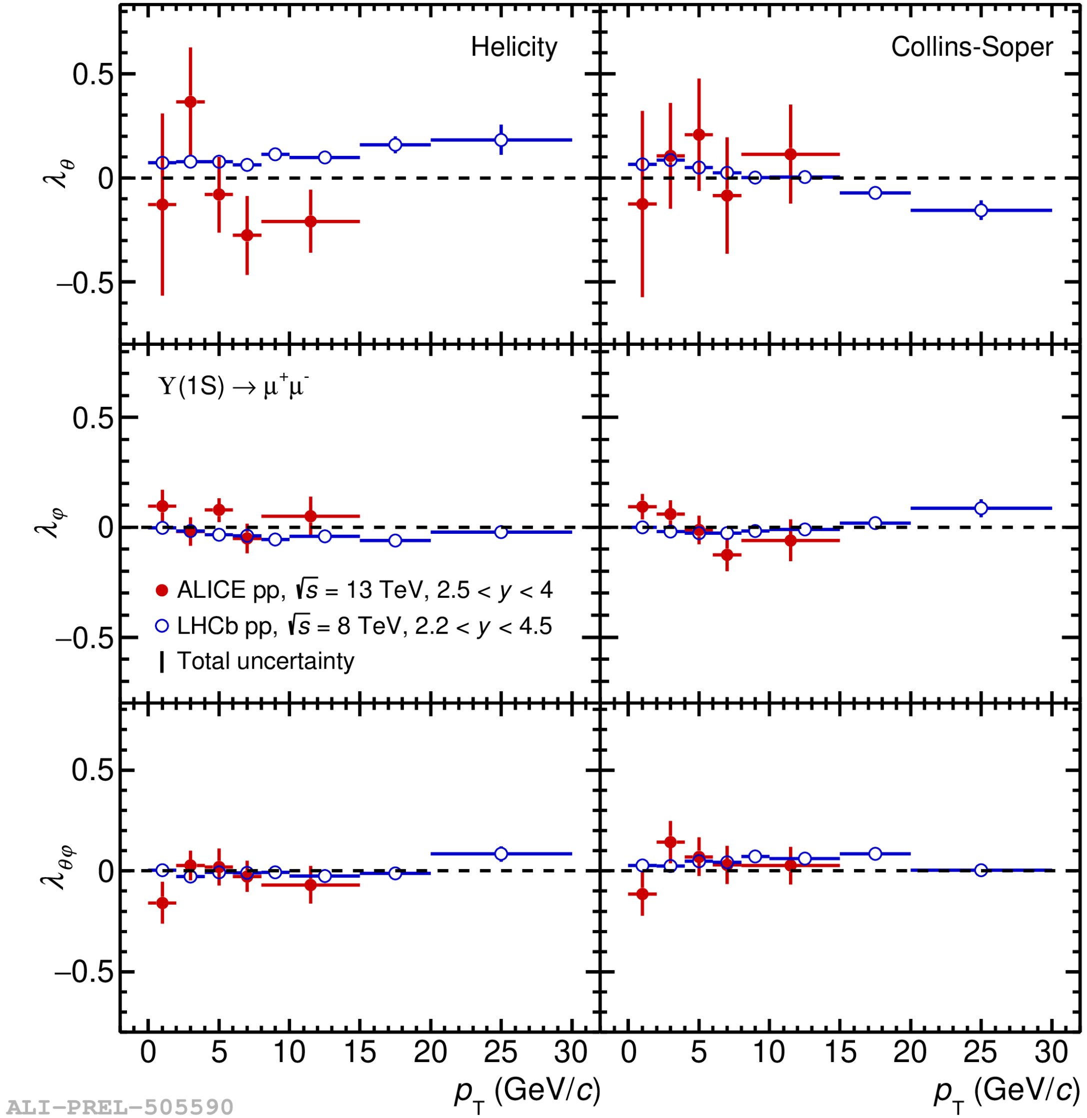
- Color Glass Condensate + NRQCD
- Improved Color Evaporation Model (ICEM)
- General agreement between predictions
- Zero or small polarization predicted in the whole transverse momentum range





JHEP 12, 057 (2018)
Phys. Rev. D 104, 094026 (2021)

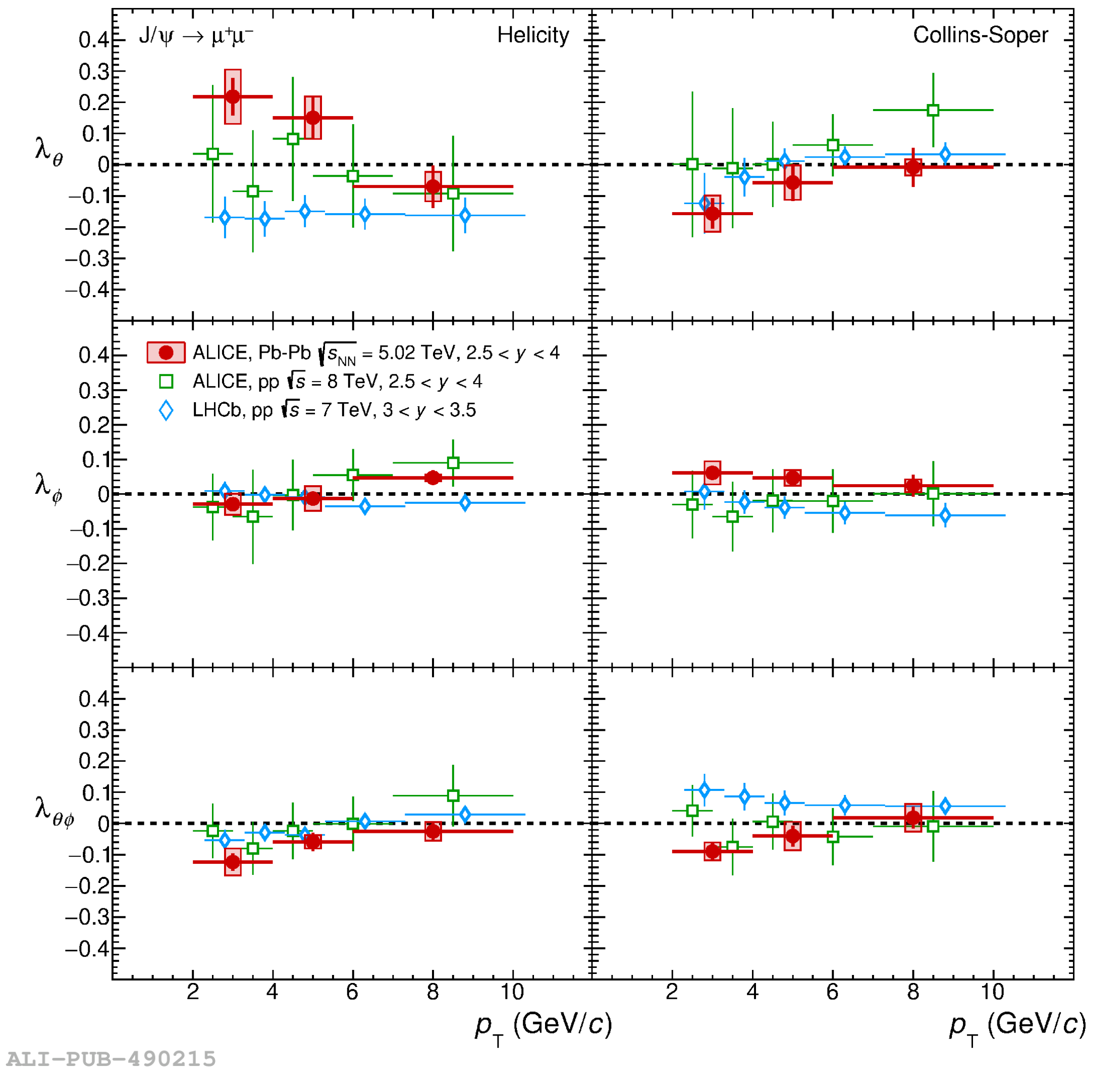
Quarkonium polarization in pp collisions:



- Recent preliminary measurement of $\Upsilon(1S)$ polarization 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 ~ 0
- All values compatible with zero within uncertainties
- Large uncertainties due to limited statistical precision

LHCb Collaboration, JHEP 12, 110 (2017)

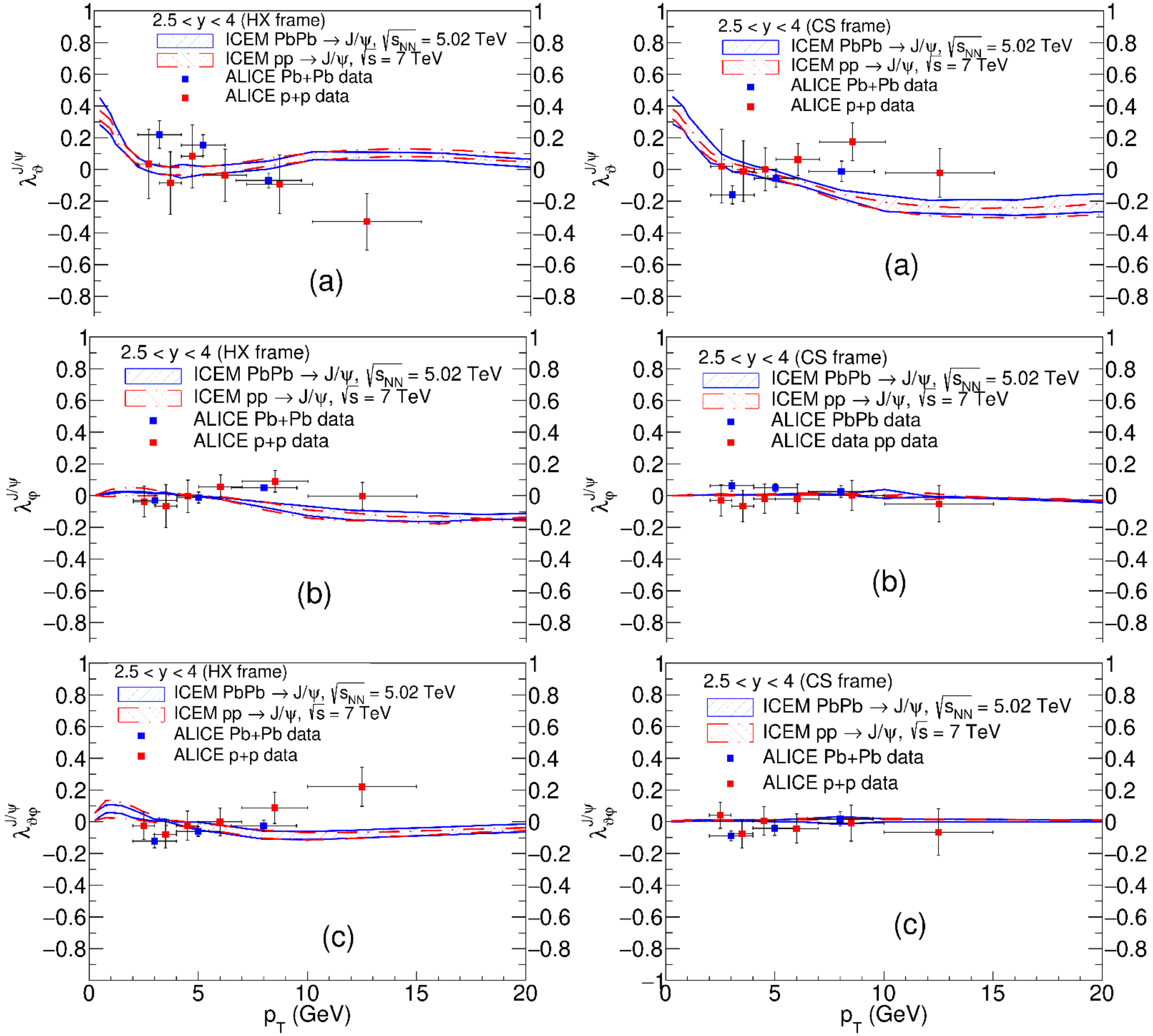
Quarkonium polarization in Pb-Pb collisions:



- ALICE measurement of J/ψ polarization in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in Helicity (HE) and Collins-Soper (CS) reference frames
- λ_θ shows a 2σ deviation from zero at low p_{T}
- 3σ deviation from LHCb measurement in pp collisions in the Helicity frame
- Values compatible with ALICE results in pp collisions within uncertainties

ALICE Collaboration, Phys. Lett. B 815, 136146 (2021)
ALICE Collaboration, Eur. Phys. J. C 78, 562 (2018)
LHCb Collaboration, Eur. Phys. J. C 73, 2631 (2013)

Quarkonium polarization in Pb-Pb collisions:

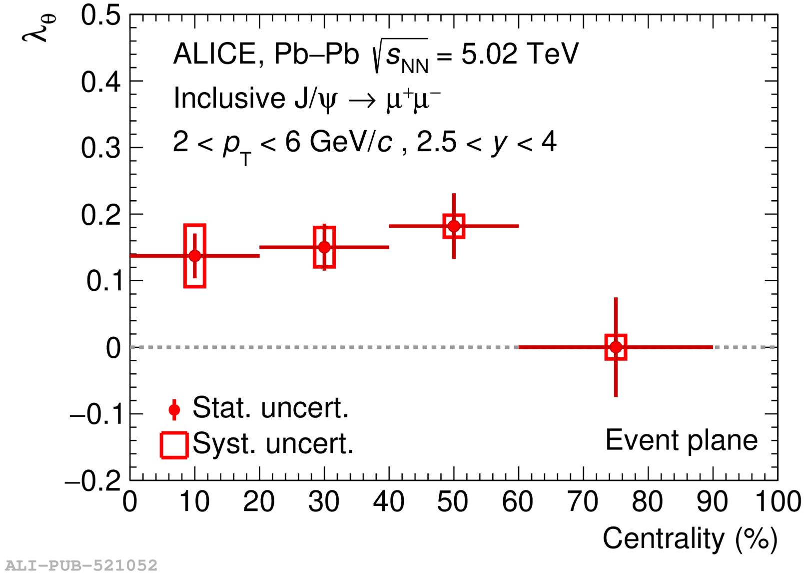


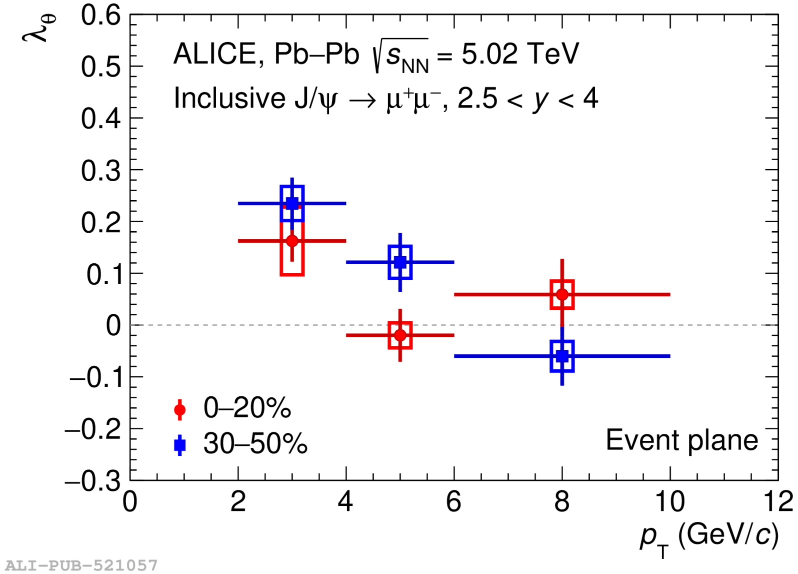
Theoretical comparison:

- Improved Color Evaporation Model (ICEM)
  - No hot nuclear matter effects
  - Direct J/ψ only (no feed-down)
  - CNM effects only in Pb—Pb
  - Small difference between pp and Pb—Pb collisions
- CNM effects not contributing significantly to the polarization

Phys. Rev. C. 105, 055202 (2022)

Quarkonium polarization in Pb-Pb collisions:





- ALICE measurement of J/ψ polarization in Pb—Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV
- First measurement with respect to the Event Plane (EP)
- Small but significant polarisation (3.5σ), particularly in the 40-60% centrality range
- Effect more pronounced at low transverse momentum (2 < $p_{\rm T}$ < 4 GeV/c) in centrality 30-50%
- Qualitatively in agreement with spin alignment observed for light vector mesons [Phys. Rev. Lett. 125, 012301 (2022)]

[ALICE Collaboration, Phys. Rev. Lett. 131, 042303 (2023)]

Conclusion and Outlook:

- ALICE has measured the polarization of several quarkonium states both in pp and Pb—Pb collisions
- No significant quarkonium polarization till now in pp collisions
- New J/ψ and ψ(2S) polarization analyses ongoing in pp collision at $\sqrt{s}$ = 13 TeV
- Results are compatible with other LHC measurements and recent model predictions
- Hint for non-zero polarization at low p_{T} in the HE and CS frames in Pb—Pb collisions
    - Not explained by CNM effects
- From the results of EP frame analysis, possible correlation with $\vec{B}$ and $\vec{L}$ in the QGP formed in heavy-ion collision
- ALICE Run 3 with high luminosity will provide significant statistics for precision measurements

THANK YOU!