Quarkonium polarization in Pb-Pb collisions with the ALICE experiment

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1. Basic concepts

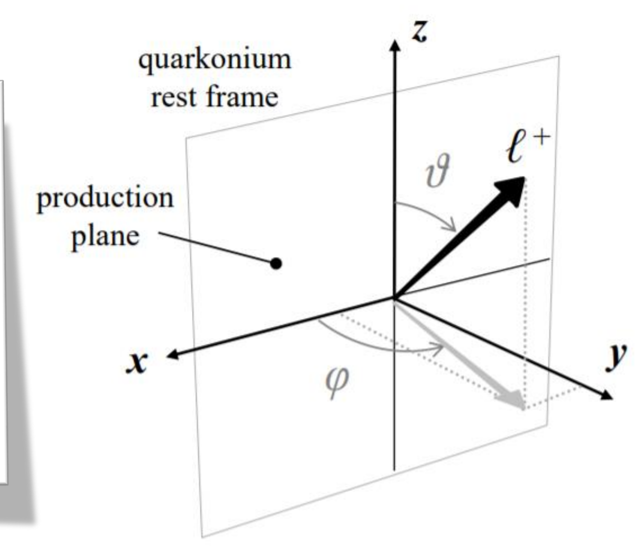
- Polarization: degree to which the spin of a particle is aligned to a chosen axis
- In a two-body decay the geometrical shape of the angular distribution of the decay products reflects the polarization of the quantum state

Theory input

- J/ψ ($J^{PC} = 1^{--}$) total angular momentum (J) can be expressed as the linear combination:

$$|J, J_Z\rangle = \mathbf{b_{-1}}|1,-1\rangle + \mathbf{b_0}|1,0\rangle + \mathbf{b_{+1}}|1,+1\rangle$$

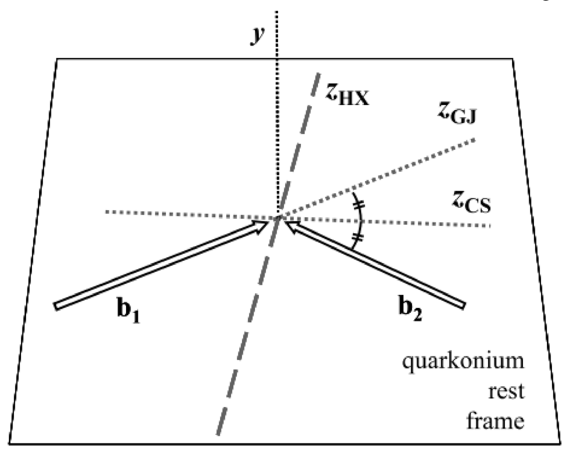
- The coefficients $\mathbf{b_{-1}}, \mathbf{b_0}, \mathbf{b_{+1}}$ are related to the quarkonium polarization state



- Given the decay kinematics it is possible to obtain the expression of the **observable angular distribution**, which allows to measure experimentally quarkonium polarization

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

- $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0,0,0)$ → No polarization
- $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0)$ → Longitudinal polarization
- $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (+1,0,0)$ → Transverse polarization



Reference frames

- **Helicity (HX)**: direction of J/ψ in the center of mass frame
- **Collins-Soper (CS)**: the bisector of the angle between the direction of one beam and the opposite of the direction of the other, in the J/ψ rest frame

pp collisions

- Crucial for the understanding of the quarkonium production mechanism (gluon fusion)
- Different models predicts different quarkonium polarization state
- All LHC measurements are comparible with the hypothesis of no polarization

Pb-Pb collisions (this analysis)

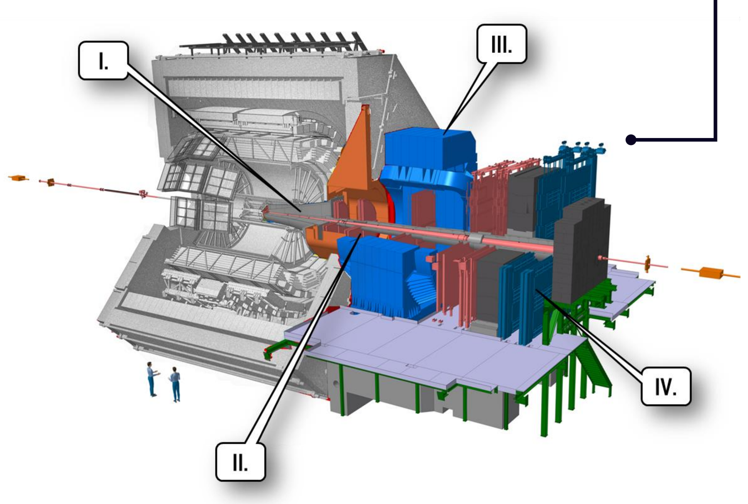
- A strongly interacting medium is produced in heavy-ion collisions at LHC energies
- Quarkonium polarization may be modified via:
  - modification of the feed-down fractions due to the QGP-induced quarkonium suppression
  - production of a fluid with non-zero vorticity
  - strong magnetic field produced by the spectators during the collision

2. The ALICE detector

The ALICE experiment is designed for the study of heavy-ion collisions

- Central barrel : quarkonium studied via their decay into an electron-positron pair → $|y| < 0.9$
- **Muon spectrometer** : quarkonium studied via their decay into a $\mu^+\mu^-$ pair → $2.5 < y < 4.0$

Muon Spectrometer



- I. **Front absorber**: reduces the particle rate coming from the interaction point, filtering out hadrons
- II. **Tracking system**: used to reconstruct muon tracks, consists of 10 cathode pad chambers arranged in 5 stations
- III. **Dipole magnet**: provides a magnetic field of 0.7 T
- IV. **Trigger system**: located after an iron wall, consists of 4 RPC planes arranged in two stations

V0 hodoscopes and Zero Degree Calorimeters (**ZDC**) used for trigger and centrality estimation

3. Data sample & analysis steps

Pb-Pb collision dataset collected at $\sqrt{s_{NN}} = 5.02$ TeV in 2015 ($L_{int} \sim 0.2\ nb^{-1}$)

Muon/Dimuon cuts:

- $-4 < \eta_\mu < -2.5$ to reject tracks at the edge of the spectrometer acceptance
- Matching of a track reconstructed in the tracking chambers with a track reconstructed in the trigger system with $p_T > 1$ GeV/c
- Cut on the distance of closest approach to the primary interaction vertex
- $2.5 < y_{\mu\mu} < 4$ to match the spectrometer acceptance

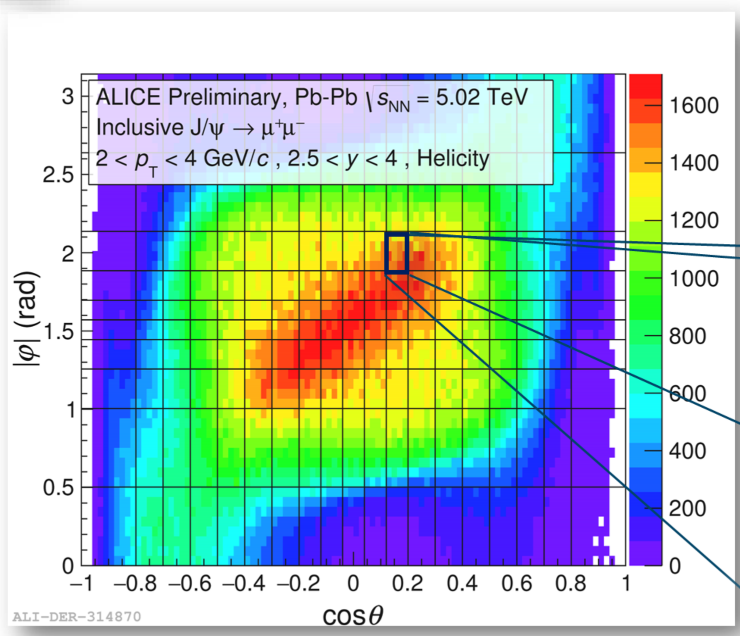
Analysis steps:

1. Signal extraction as a function of $\cos\theta$ and φ of the decay muons
2. Acceptance and efficiency are evaluated via a MC simulation and used to correct the quarkonium raw spectrum as a function of the angular variables
3. Extraction of the polarization parameters by fitting the corrected distribution

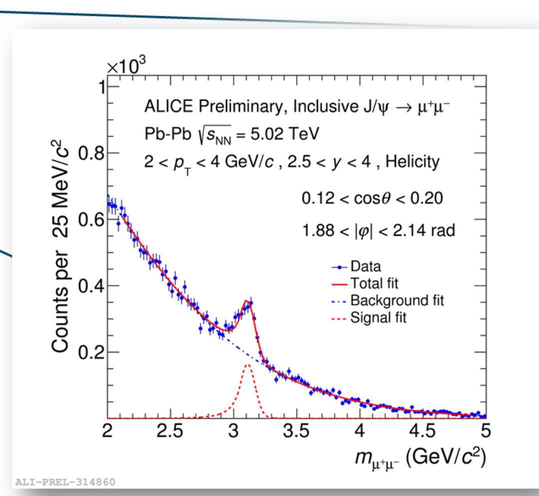
The statistics collected for J/ψ allows to perform a **2D approach**, which is less sensitive than the 1D approach to the Monte Carlo input distributions (p_T,y,polarization) used to calculate the $A \times \varepsilon$

4. Data analysis

1. Signal extraction



- Creation of a 2D grid for signal extraction
  - the binning is tuned according to the statistical significance of the signal
- In each bin, the number of J/ψ is obtained using a fit to the invariant mass distribution with various signal and background shapes



2. Acceptance-efficiency correction

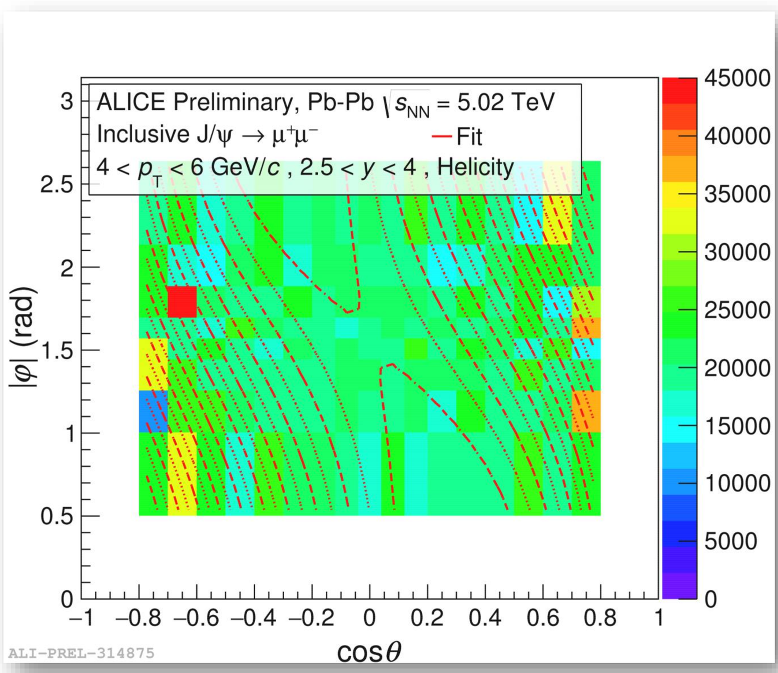
$A \times \varepsilon$ evaluated in a Monte-Carlo simulation in which J/ψ are generated flat as a function of $\cos\theta$ and φ, corresponding to the hypothesis of no polarization $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi} = 0)$

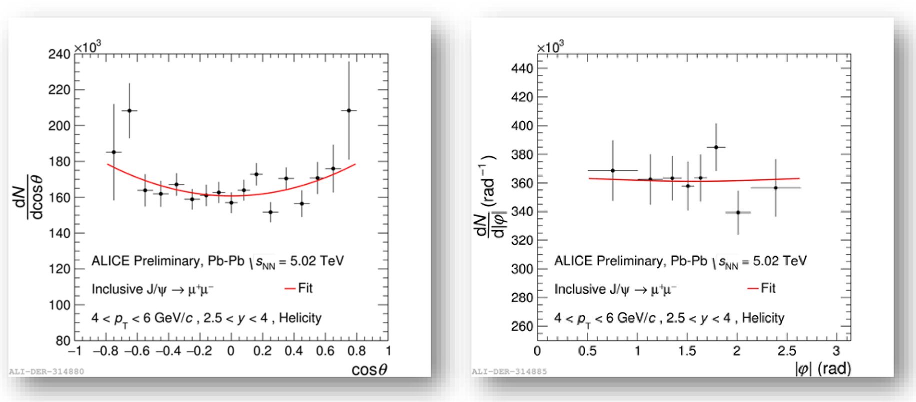
- To take into account the sensitivity of the $A \times \varepsilon$ with respect to the input MC shapes ($p_T, y, cos\theta, \varphi$) an iterative procedure is performed
  - **Iterative procedure**: consists in the tuning of J/ψ generated distribution according to the polarization obtained from data. The procedure is repeated until the value of the polarization parameters does not change significantly from one iteration to the other

3. Extraction of the polarization parameters

Polarization parameters are obtained fitting the J/ψ angular distribution corrected for $A \times \varepsilon$

- the distribution is projected along $\cos\theta$ and φ to check the quality of the fit

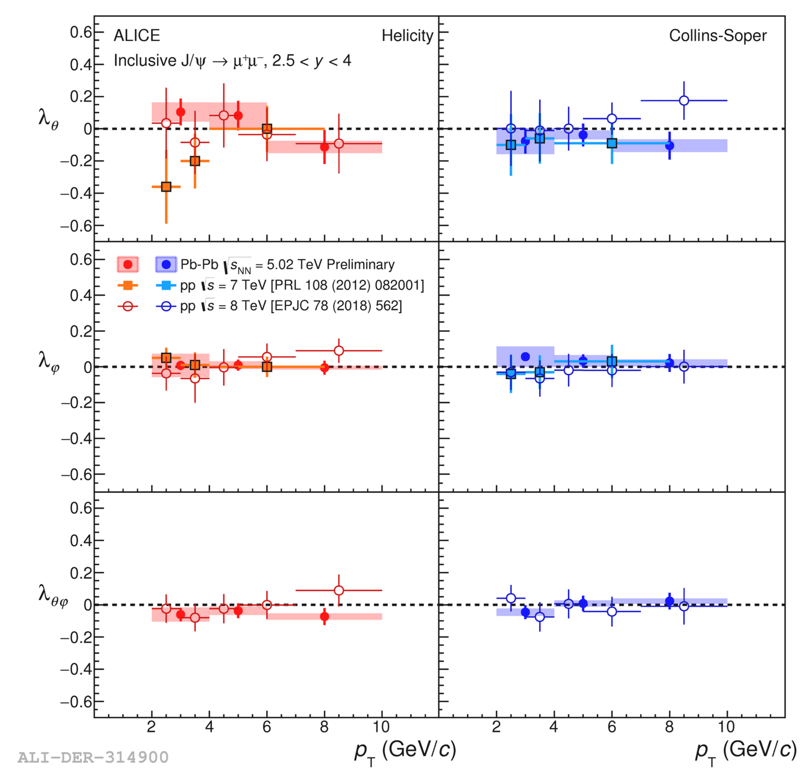




- Different sources of systematic uncertainties can impact on the evaluation of $\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$
  - I. choice of different signal/background shapes in the signal extraction
  - II. variation of the p_T, y MC input distributions within their measured uncertainties
  - III. sensitivity to trigger response functions in data or Monte-Carlo

5. Results

➢ J/ψ polarization in Pb-Pb collisions



! First measurement of quarkonium polarization in heavy-ion collisions

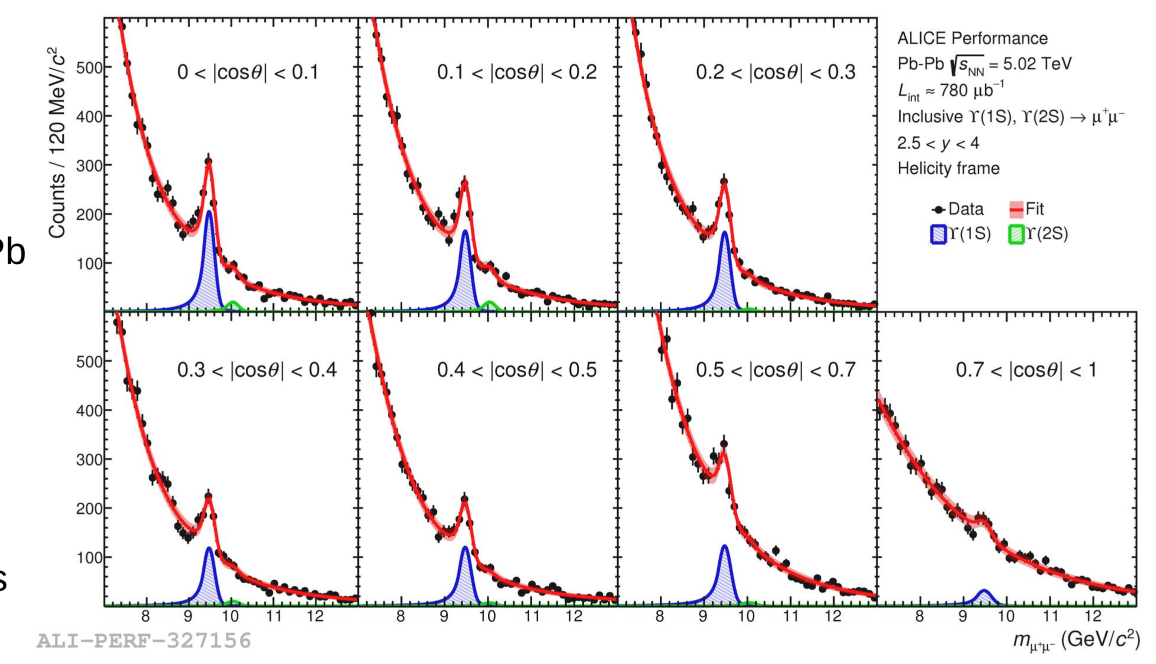
The polarization parameters are measured as a function of p_T in the **Helicity** and **Collins-Soper** reference frames

- $\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$ compatible with zero
  - ➡ This first measurement suggests weak or no J/ψ polarization also in heavy-ion collisions
- Comparison with ALICE results at $\sqrt{s} = 7$ and 8 TeV in pp collisions
  - ➡ No significant difference between $\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$ obtained in large (Pb-Pb) and small (pp) systems

➢ $\Upsilon(1S)$ polarization in Pb-Pb collisions: feasibility study

The sizeable data set collected in 2018 during the Pb-Pb data taking period allows to perform the study of $\Upsilon(1S)$ polarization

- Merging the 2015 and 2018 Pb-Pb data samples ($L_{int} \sim 780\ \mu b^{-1}$) ~3600 $\Upsilon(1S)$ are collected
- **1D approach** performed for the extraction of the polarization parameters
- $\Upsilon(1S)$ raw yield obtained in 7 bins in $\cos\theta$, 5 bins in φ and $\tilde{\varphi}$



➢ Possibility to study more p_T bins under investigation…

6. Summary

- ✓ First measurement of J/ψ polarization in Pb-Pb collisions at the LHC: $\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$ compatible with zero and with ALICE pp results at $\sqrt{s} = 7$ and 8 TeV
- ✓ Feasibility study of $\Upsilon(1S)$ polarization in Pb-Pb collisions: possible exploiting all the data sample collected in the 2015 and 2018 Pb-Pb data taking periods

Future steps…

- ➡ Study of the centrality dependence of the J/ψ polarization using the high statistics 2018 data sample
- ➡ Study of the J/ψ polarization with respect to the event plane of the collision
- ➡ Measurement of $\Upsilon(1S)$ polarization in Pb-Pb collisions

References :
[1] "Towards the experimental clarification of quarkonium polarization", P.Faccioli et al. EPJ C69 (2010) 657-673
[2] "Quarkonium polarization in heavy ion collisions as a possible signature of the quark-gluon plasma", Ioffe & Kharzeev, Phys. Rev. C68 (2003) 061902
[3] "J/ψ polarization in pp collisions at √s = 7 TeV", B. Abelev et al. Phys. Rev. Lett. 108, 082001
[4] "Measurement of inclusive J/ψ polarization at forward rapidity in pp collisions at √s = 8 TeV ", S. Acharya et al. EPJC 78 (2018) 562