Feasibility study of the measurement of J/ψ polarization in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE experiment at the LHC

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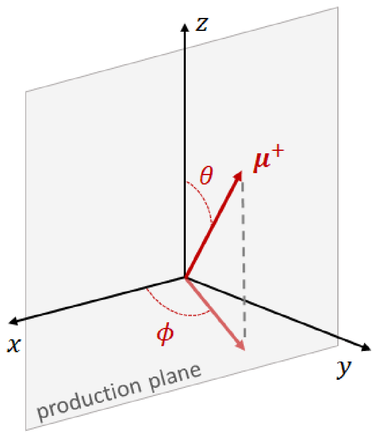
Abstract Polarization is a key observable to determine the quarkonium production mechanism in elementary hadronic collisions. For the J/ψ, the very small value of the polarization parameters measured at the LHC in pp collisions represents a challenge for the commonly-used theoretical models and remains a major standing issue in the field. On the other hand, phenomenological studies have shown that primordial quarkonium in AA interaction can be polarized by the strong magnetic field generated by the two colliding nuclei, while re-combined quarkonium is expected to be completely unpolarized. We present a feasibility study for the $p_{\rm T}$ - differential measurement of J/ψ polarization in $\sqrt{s_{\rm NN}} = 5.02$ TeV Pb-Pb collisions at the LHC. The analysis strategy and technique are discussed and various performance plots are presented.

Basic concepts

- Polarization measures the degree to which the spin of a given particle is aligned to a certain axis (z-axis)
- For J/ψ → μ⁺μ⁻ ,the polarization can be reconstructed from the angular distribution of the decay dimuons
- Reference frame
  - z-axis :
    - **Helicity** → direction of J/ψ in the CMS-frame
    - **Collins-Soper** → the bisector of the angle between the direction of the beam and the opposite of the direction of the other, in the J/ψ rest frame
  - y-axis : perpendicular to the production plane (the plane containing the J/ψ momentum and the beam axis)
  - x-axis : chosen so that (x,y,z) is right-handed



- The angular distribution of decay muons follows the equation :

$$f(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos2\varphi+\lambda_{\theta\varphi}\sin2\theta\cos\varphi)$$

Integrated expressions

$$f(\cos\theta) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta)$$

$$f(\varphi) \propto 1+\frac{2\lambda_\varphi}{3+\lambda_\theta}\cdot\cos2\varphi$$

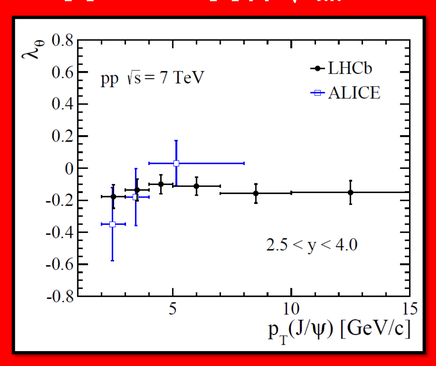
- $(\lambda_\theta,\lambda_\varphi,\lambda_{\theta\varphi}) = (0,0,0)$ → No polarization
- $(\lambda_\theta,\lambda_\varphi,\lambda_{\theta\varphi}) = (-1,0,0)$ → Longitudinal polarization
- $(\lambda_\theta,\lambda_\varphi,\lambda_{\theta\varphi}) = (+1,0,0)$ → Transverse polarization

Physics motivations

pp collisions

Polarization measurements are a test for different quarkonium production mechanisms

LHCb [2] + ALICE [3] pp $\sqrt{s_{\rm NN}} = 7$ TeV

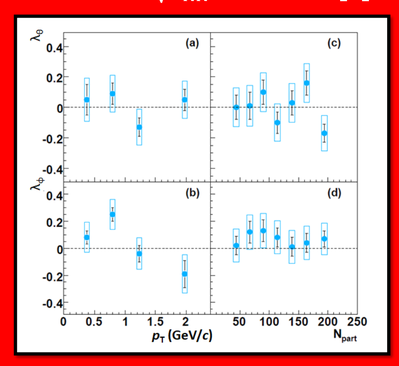


- ALICE and LHCb experiments measured small or no polarization for J/ψ in pp collisions

AA collisions

Possible effects of QGP formation on J/ψ polarization [1]

NA60 In-In $\sqrt{s_{\rm NN}} = 17$ GeV [4]



- NA60 is the only experiment which extracted the polarization parameters in nuclear collisions (results compatible with zero)

Data sample & analysis procedure

J/ψ is studied in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (2015 data taking)

→ Sample of ~3×10⁵ reconstructed J/ψ → μ⁺μ⁻ , in $2.5 < y < 4$ (rapidity coverage of ALICE muon spectrometer)

Analysis steps

1. Signal extraction as a function of cosθ and φ of the decay muons
2. Correction for Acceptance × efficiency (A×ε) evaluated with a MC simulation
3. Extraction of polarization parameters via :

Fit of $\mathrm{d}N_{J/\psi}/d\cos\theta$ and $\mathrm{d}N_{J/\psi}/\mathrm{d}\varphi$ with $f(\cos\theta)$ and $f(\varphi)$ (**1D-approach**)

⟷

Fit of $\mathrm{d}^2N_{J/\psi}/\mathrm{d}\cos\theta\,\mathrm{d}\varphi$ with $f(\cos\theta,\varphi)$ (**2D-approach**)

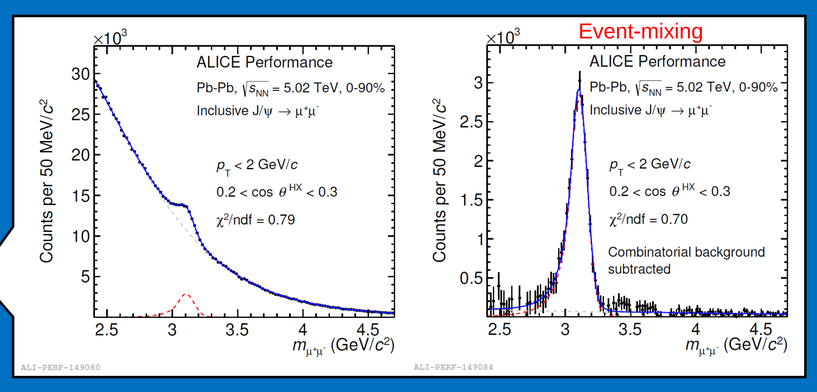
Analysis : 1D approach

1. Signal extraction

- The number of J/ψ is obtained from fits to the μ⁺μ⁻ invariant mass distribution for a certain range of cosθ (integrating over φ) or φ (integrating over cosθ)

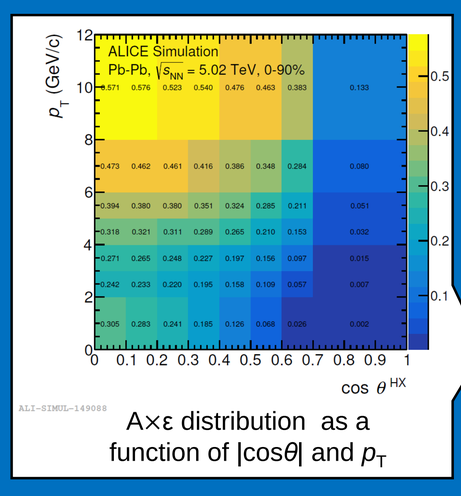
Range of measured quantities :
- $0 < |\cos\theta| < 1$, 8 bins
- $0 < \varphi < \pi$, 8 bins
- $0 < p_{\rm T} < 12$ GeV/c, 7 bins

Examples of fits of the μ⁺μ⁻ invariant mass distribution for $0 < p_{\rm T} < 2$ GeV/c, $0.2 < |\cos\theta| < 0.3$ and integrated over φ, with and without event mixing

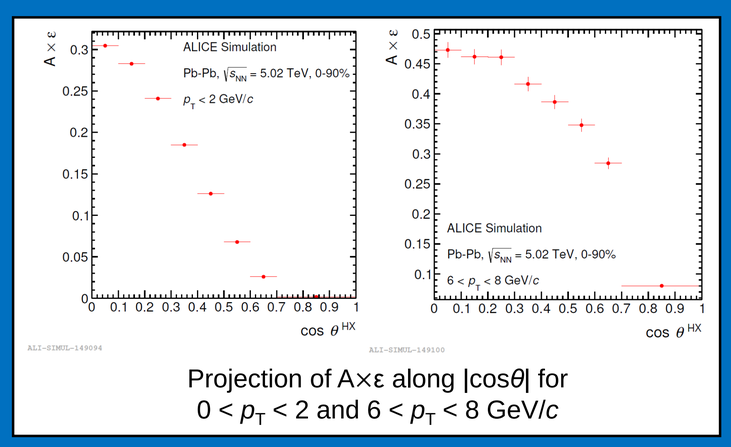


2. Acceptance × efficiency (A×ε)

- obtained via Monte Carlo, the simulated J/ψ signal is embedded in real events in order to better account for detector related effects



A×ε distribution as a function of |cosθ| and $p_{\rm T}$



Projection of A×ε along |cosθ| for $0 < p_{\rm T} < 2$ and $6 < p_{\rm T} < 8$ GeV/c

- A×ε has a maximum at $\cos\theta = 0$ for all $p_{\rm T}$ intervals
- A×ε steeply decreases at large cosθ (corresponds to decays where there is a maximum asymmetry between the momenta of muons, and the softer one is stopped in the hadron absorber of the muon spectrometer)

❑ Extraction of polarization parameters from cosθ and φ distributions is in progress

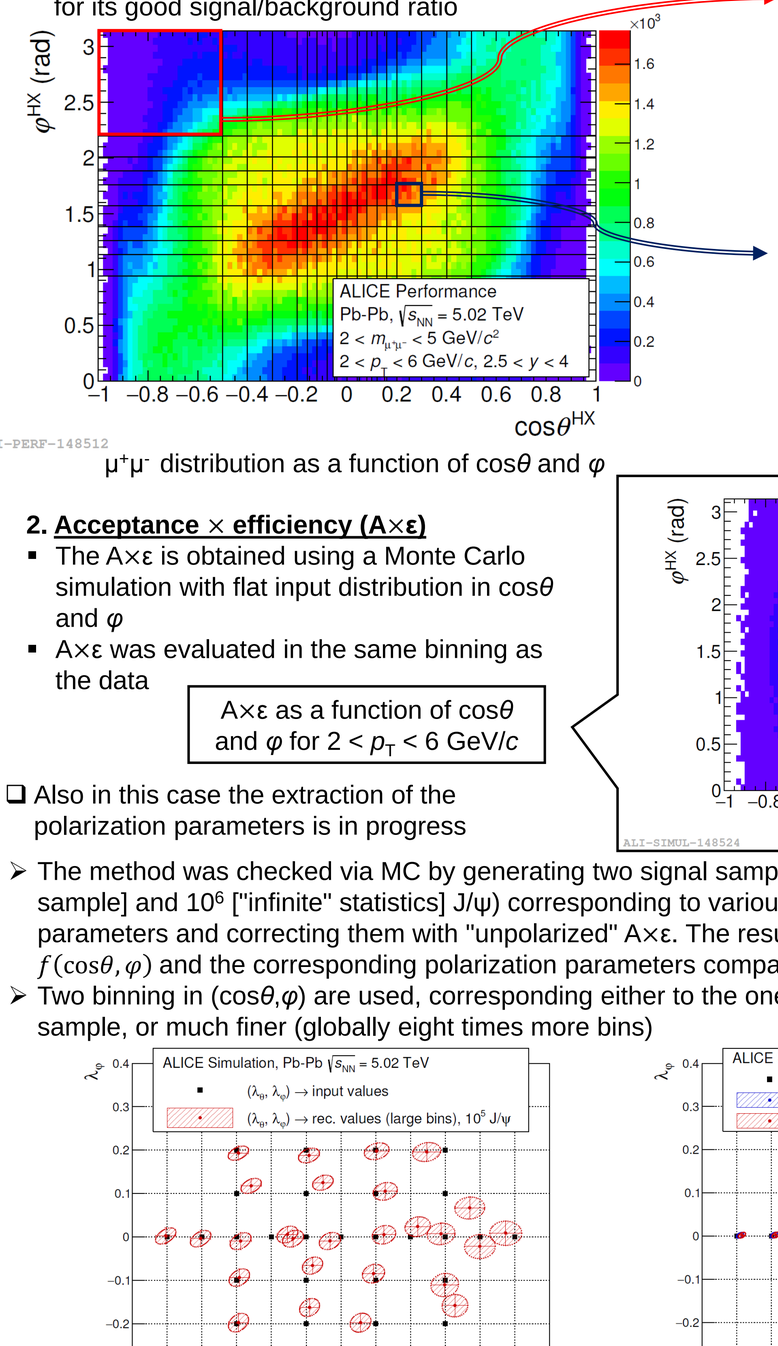
Analysis : 2D approach

❑ J/ψ can be studied as a function of cosθ and φ simultaneously

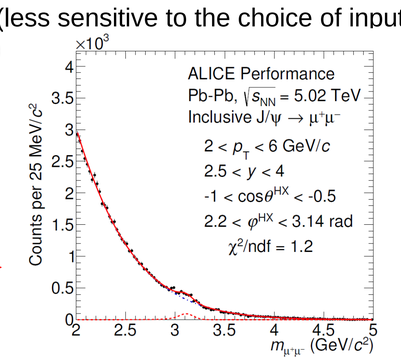
❑ 2D approach preserves correlations between angular variables (less sensitive to the choice of input differential distributions for cosθ and φ used for A×ε evaluation)

1. Signal extraction

- The fit of the μ⁺μ⁻ invariant mass distribution is performed in (cosθ,φ) bins
- The binning is defined to have enough statistics to fit the μ⁺μ⁻ invariant mass distribution
- For the moment the range $2 < p_{\rm T} < 6$ GeV/c is investigated for its good signal/background ratio



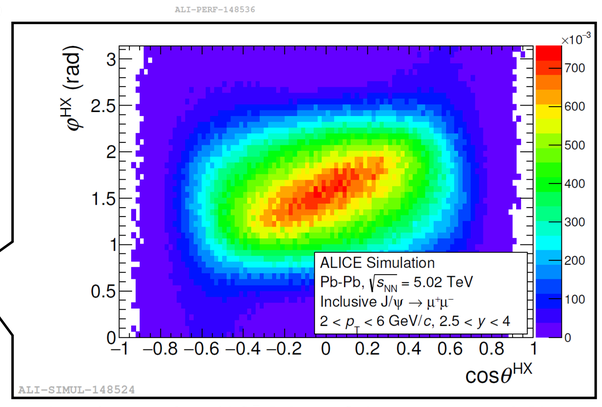
μ⁺μ⁻ distribution as a function of cosθ and φ



2. Acceptance × efficiency (A×ε)

- The A×ε is obtained using a Monte Carlo simulation with flat input distribution in cosθ and φ
- A×ε was evaluated in the same binning as the data

A×ε as a function of cosθ and φ for $2 < p_{\rm T} < 6$ GeV/c

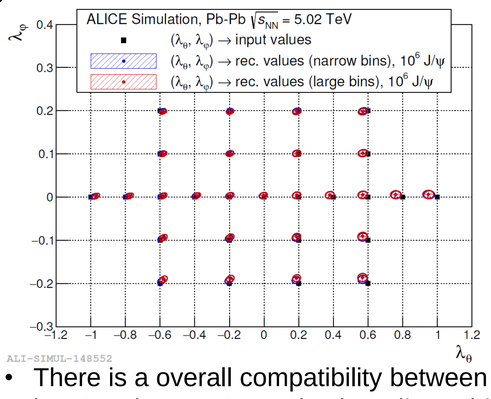


❑ Also in this case the extraction of the polarization parameters is in progress

➢ The method was checked via MC by generating two signal samples (10^5 [size of the measured J/ψ sample] and 10^6 ["infinite" statistics] J/ψ) corresponding to various combinations of polarization parameters and correcting them with "unpolarized" A×ε. The resulting distributions were fitted with $f(\cos\theta,\varphi)$ and the corresponding polarization parameters compared to the generated ones

➢ Two binning in (cosθ,φ) are used, corresponding either to the one used for the measured data sample, or much finer (globally eight times more bins)

- For a statistics corresponding to the measured sample (~10^5 J/ψ) the reconstructed parameters fluctuate around input values within few sigmas



- There is a overall compatibility between input and reconstructed values (λ_θ and λ_φ are reconstructed with ~1% accuracy)

Summary & conclusions

➢ A feasability study of J/ψ polarization in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV has been performed, investigating 1D and 2D approaches

➢ Both the 1D and 2D analysis approaches look feasible, in particular, the performance of the 2D approach was tested by running a MC closure test. Injecting certain values of the polarization parameters in the J/ψ input distributions, the reconstructed values are statistically compatible with the generated ones

❑ Next steps :
- extract J/ψ polarization parameters in various reference frames, comparing 1D and 2D approaches
- investigate the dependence of J/ψ polarization parameters on $p_{\rm T}$ and centrality

[1] "Quarkonium polarization in heavy ion collisions as a possible signature of the quark gluon plasma", B.L. Ioffe & D.E. Kharzeev, 2003, PhysRevC.68.061902
[2] "Measurement of J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV", R. Aaij *et al.* (LHCb collaboration), 2013, Eur. Phys. J. C73.11(2013)
[3] "J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV ", B. Abelev *et al.* (ALICE collaboration), 2012, PhysRevLett.108.082001
[4] "J/ψ production in p-A and A-A collisions at fixed target experiments", R. Arnaldi for the NA60 collsboration, 2009, Nucl. Phys. A830(2009)