J/ψ polarization in pp collisions with ALICE

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Abstract. The ALICE experiment at the LHC has studied J/ψ polarization in pp collisions at \( \sqrt{s} = 7 \) TeV, measuring the anisotropies in the angular distribution of the muons coming from J/ψ decay. The study was performed in the forward rapidity region \( 2.5 < y < 4 \), differentially in transverse momentum. In this work, the analysis is reviewed and the results are presented and compared to new theoretical predictions. Perspectives for the polarization measurement in Pb-Pb collisions are also discussed.

1. J/ψ hadroproduction and the importance of polarization

After almost forty years from the first observation of charmonium, the J/ψ hadroproduction mechanism is still a puzzling issue. Given the high mass of the c quark, charmonium production involves different energy scales: the formation of the quark-antiquark pair is a hard process and can be reliably described through perturbative QCD calculations, but the dynamics of the bound state formation and evolution is intrinsically non-relativistic and involves soft energy scales. For this reason, no full-QCD description of quarkonium production can be carried out and theoretical models have been developed. Among them, the effective field theory NonRelativistic QCD (NRQCD), at LO [1], was found to reproduce the cross-sections measured at the Tevatron, which were significantly underestimated by Color Singlet Model (CSM) calculations at LO [2]. Nevertheless, the prediction of the J/ψ degree of polarization was contradicted by a measurement by CDF [3] and new calculations at NLO of both NRQCD and CSM [4, 5] tend to slightly mitigate but not to solve the discrepancy, that still remains an issue on which the Large Hadron Collider (LHC) is expected to provide a valuable contribution.

2. The ALICE experiment and the forward muon spectrometer

The ALICE experiment [6] is based on a central barrel, covering the pseudorapidity region \(|\eta| < 2\), and a muon spectrometer, with rapidity coverage \( 2.5 < y_\mu < 4 \). The polarization results presented here refer to inclusive J/ψ production, measured via the J/ψ → μ⁺μ⁻ decay channel in the muon spectrometer. The spectrometer consists of a 10 interaction length (\( \lambda_I \)) thick front absorber, to remove hadrons, followed by a 3 T·m dipole magnet. Charged particles which exit the front absorber are tracked in a detector system made up of five stations, each one with two planes of cathode pad chambers. The tracking system is followed by a 7.2 \( \lambda_I \) iron wall, which absorbs secondary hadrons escaping the front absorber and low-momentum muons. Finally, a trigger system, based on resistive plate chambers, is used to select candidate muons with a transverse momentum larger than a given programmable threshold. Vertex reconstruction is provided by the Inner Tracking System (ITS), an array of six layers of silicon detectors covering mid-rapidity.

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3. **J/ψ polarization in pp collisions: analysis technique and results**

**J/ψ** polarization was studied by the ALICE Collaboration [7], at forward rapidity, through the analysis of the angular distribution of the decay products, which follows the general formula:

\[
W(\cos \theta, \phi) = \frac{d^2N}{d\cos \theta d\phi} \propto \frac{1}{3 + \lambda_\theta} \cdot \left(1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi\right),
\]

(1)

where \( \theta \) and \( \phi \) are the polar and azimuthal angles of one of the two muons with respect to a given reference frame [8]. The parameters \( \lambda_\theta, \lambda_\phi \) and \( \lambda_{\theta\phi} \) quantify the degree of polarization; in particular \( \lambda_\theta > 0 \) indicates transverse polarization and \( \lambda_\theta < 0 \) means longitudinal polarization.

Two different definitions of the polarization axis were considered:

- helicity (HE), defined as the direction of the **J/ψ** in the pp collision rest frame;
- Collins-Soper (CS), the bisector of the angle between the directions of one incoming proton and the opposite of the other incoming proton.

Data collected during 2010, approximately corresponding to 100 nb\(^{-1}\) of integrated luminosity, were used after the application of some standard selection criteria: events with at least one vertex reconstructed in the ITS where retained if they contained at least two tracks in the muon spectrometer, out of which at least one had to satisfy the trigger condition (1 GeV/c \( p_T \) threshold). Moreover, tracks must satisfy the condition 2.5 < \( y \) < 4 and must also have 17.6 < \( R_{abs} \) < 88.9 cm, where \( R_{abs} \) is the radial distance of the track from the beam axis at the downstream end of the front absorber. The latter requirement eliminates tracks passing through high-Z material regions of the absorber which are strongly affected by multiple scattering.

The two-dimensional acceptance and efficiency maps presented in Figure 1, obtained with a Monte Carlo simulation based on a parametric generator [9], show the decrease of the detector acceptance for low \( p_T \) and large \( \cos \theta \) in the helicity reference frame. A similar behaviour is found for the Collins-Soper reference frame. In order to avoid very low acceptance regions, an additional cut on the \( p_T \) of the dimuons, \( p_T > 2 \) GeV/c, was applied and the analysis was performed in the \( |\cos \theta| < 0.8 \) region. For statistics reasons the study was also restricted to \( p_T < 8 \) GeV/c. After implementing all these cuts (6800 ± 140) **J/ψ** candidates survive for the analysis.

![Figure 1](image.png)

**Figure 1.** Acceptance times efficiency \((A \times \epsilon)\) maps from Monte Carlo simulation [9] in the helicity reference frame for pp collisions at \( \sqrt{s} = 7 \) TeV: \( \cos \theta - p_T \) (left), \( \phi - p_T \) (right).

In principle, the values of the parameters could be extracted by means of a fit to the acceptance-corrected (\( \cos \theta - \phi \)) 2D distributions. However, the limited **J/ψ** statistics made a 2D binning impossible and the study of the angular distributions was separately performed on the polar and azimuthal variables. In particular, \( \lambda_\theta \) and \( \lambda_\phi \) were extracted from the study of
the distributions
\[ W(\cos\theta) \propto \frac{1}{3 + \lambda_\theta} \times \left(1 + \lambda_\theta \cos^2 \theta\right); \quad W(\phi) \propto 1 + \frac{2\lambda_\phi}{3 + \lambda_\theta} \cos 2\phi, \hspace{1cm} (2) \]
orbit obtained by integrating Eq. 1 in the \( \phi \) and \( \cos \theta \) variables, respectively. In this approach the \( \lambda_\phi \) parameter was assumed to be zero and this assumption was found to be realistic with an a-posteriori check [9].

The polarization parameters were obtained by correcting the number of signal events for each bin in the angular variables for the product \( A \times \epsilon \) of acceptance times detection efficiency, calculated via MC simulation [9], and then fitting the angular distributions with the functions shown in Eq. 2. The distributions of the angular variables to be used to perform the MC simulation are not known a priori, but rather represent the outcome of the data analysis: for this reason an iterative procedure was followed, reaching convergence in at most 3 steps [9].

A simultaneous study of the \( J/\psi \) polarization variables in several reference frames is particularly interesting since consistency checks on the results can be performed, using combinations of the polarization parameters which are frame-invariant [8]. In particular we made use of the invariant \( F = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi) \), performing a simultaneous fit of the \( |\cos \theta| \) and \( |\phi| \) distributions in the two reference systems and further constraining the fit by imposing \( F \) to be the same in the CS and HE frames. In Fig. 2 we present, as an example, the result of such a fit for \( 2 < p_T < 3 \text{ GeV/c} \).

The final results are shown in Figure 3: in both frames, all the parameters are compatible with zero, with a possible hint for a longitudinal polarization at low \( p_T \) (at a 1.6\( \sigma \) level) in the HE frame. The comparison with recent theoretical calculations at NLO in the NRQCD and CSM frameworks, reported in [10, 11], show a better (although not perfect) agreement with NRQCD, in particular in the Collins-Soper reference frame. A conclusive comparison of data with theory requires the experiments to probe higher \( J/\psi \) transverse momenta and, in ALICE, this will be possible exploiting the higher statistics data sample collected during 2011 and 2012 (more than ten times in terms of \( J/\psi \) with respect to 2010).
4. Perspectives for the study of polarization in Pb-Pb collisions

The study of the degree of polarization of $J/\psi$ produced in Pb-Pb collisions is particularly interesting for two reasons. On the one hand, all the results published by ALICE (and the other LHC experiments) on $J/\psi$ production in heavy-ion collisions were obtained assuming no polarization. This assumption has to be carefully checked since, if not confirmed, the acceptance estimate must include polarization effects. On the other hand, a value of the parameters sensibly different from zero would reveal interesting mechanisms at play in nuclear collisions and not in pp, where there is basically no polarization.

Data collected during 2011 by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Figure 4: statistics are sufficient to divide the sample in bins of angular variables and, therefore, to extract the polarization parameters. The analysis of these data is currently in progress.

5. Conclusions

ALICE has measured the polarization parameters $\lambda_\theta$ and $\lambda_\phi$ for inclusive $J/\psi$ production in $\sqrt{s} = 7$ TeV pp collisions at the LHC. The measurement was carried out in the kinematical region $2.5 < y^{J/\psi} < 4$, $2 < p_T^{J/\psi} < 8$ GeV/c. The polarization parameters are consistent with zero, in both the helicity and Collins-Soper reference frames. The comparison with NLO calculations of CSM and NRQCD shows a better qualitative agreement with the latter, but a firm conclusion will be only possible when higher $p_T$ is reached by the experiments.

With the statistics collected during the Pb-Pb run of 2011, ALICE will likely be able to perform the same analysis for heavy-ion collisions.

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