Measurement of quarkonium polarization in Pb-Pb collisions with ALICE at the LHC

Luca Micheletti (INFN Torino) on behalf of the ALICE collaboration
Vector meson polarization: basic concepts

**Polarization:**
- Defined as the **spin-alignment** with respect to a chosen direction
- Measured as **anisotropies** in the decay products angular distributions

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

\((\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0) \quad \Rightarrow \text{No polarization} \]

\((\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (\pm 1,0,0) \quad \Rightarrow \text{Pure longitudinal}(-)/\text{transverse}(+) \text{ polarization} \]

\[ (\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) \]

\[ (\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) \]

\[ W(\cos\theta, \phi) \]

\[ \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \]

\[ \pm 1,0,0 \]

\[ 0,0,0 \]

\[ \Rightarrow \text{Polarization axis:} \]

- **Helicity (HX):** direction of vector meson in the collision center of mass frame
- **Collins-Soper (CS):** the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame

Figures from P.Faccioli et al. EPJ C69 (2010) 657-673
Quarkonium polarization in pp and AA collisions

Polarization in pp collisions

No sizeable polarization measured at LHC in pp collisions!

But...

Constrains $J/\psi$ production mechanism

⇒ Originally:
  • LO NRQCD ⇒ transverse polarization for high-$p_T$ $J/\psi$
  • NLO color singlet model ⇒ longitudinal polarization

⇒ ongoing theoretical developments...

"Dense parton matter may then screen out of the existence a large part of quarkonia ... but those of them that survive will carry the information about the mechanism of their formation throughout the collision"


The suppression mechanism in heavy ion collisions

⇒ affects differently the various quarkonium states

⇒ Possible modification of $J/\psi$ polarization with respect to pp because the prompt feed-down fractions change

$J/\psi^{\text{Prompt}} : (30\%)[J/\psi-\chi_c] \text{ and } (10 - 15\%)[J/\psi-\psi(2S)]$

⇒ At LHC energies regeneration plays an important role

⇒ possible modification of $J/\psi$ polarization
Quarkonium polarization in pp collisions at LHC

- The ALICE experiment measured inclusive J/ψ polarization in pp collisions at $\sqrt{s} = 7^{(1)}$ and $8\text{ TeV}^{(2)}$
  $\Rightarrow$ all polarization parameters compatible with zero

- LHCb measured prompt J/ψ polarization in pp collisions at $\sqrt{s} = 7\text{ TeV}^{(3)}$
  $\Rightarrow$ the weighted average over all the $(p_T, y)$ bins shows a small longitudinal polarization ($\lambda_\theta = -0.145 \pm 0.027$)

- CMS measured prompt J/ψ and ψ(2S) polarization in pp collisions up to 70 GeV/c at $\sqrt{s} = 7\text{ TeV}^{(4)}$
  $\Rightarrow \lambda_\theta, \lambda_\phi, \lambda_\theta\phi$ compatible with zero even at high $p_T$

(1) PRL 108 (2012) 082001
(2) EPJ C 78 (2018) 562
(3) EPJ C 73 (2013) 2631
(4) PLB 727 (2013) 381-402
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A Large Ion Collider Experiment

The **ALICE experiment** at LHC is designed for the study of heavy-ion collisions.

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**Central barrel:**
- Q̅Q decay mode: $e^+e^-$
- Rapidity coverage: $|y| < 0.9$

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**Muon spectrometer:**
- Q̅Q decay mode: $\mu^+\mu^-$
- Rapidity coverage: $2.5 < y < 4$

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Hard Probes 2020

Introduction

Luca Micheletti
The **ALICE experiment** at LHC is designed for the study of heavy-ion collisions.

**Central barrel:**
- Q̅Q decay mode: $e^+ e^-$
- Rapidity coverage: $|y| < 0.9$

**Muon spectrometer:**
- Q̅Q decay mode: $\mu^+ \mu^-$
- Rapidity coverage: $2.5 < y < 4$

**Focus on the muon spectrometer:**
- In this analysis quarkonium is studied via its decay to a muon pair

**Diagram:**
- I. Front absorber
- II. Tracking system
- III. Dipole magnet
- IV. Trigger system
The **ALICE experiment** at LHC is designed for the study of heavy-ion collisions.

### Central barrel:
- **Qq** decay mode: $e^+e^-$
- Rapidity coverage: $|y| < 0.9$

### Muon spectrometer:
- **Qq** decay mode: $\mu^+\mu^-$
- Rapidity coverage: $2.5 < y < 4$

**Central barrel** detectors crucial for this analysis:

- **V0 detectors**
  - Trigger
  - Centrality estimation
  - Background rejection

- **Silicon Pixel Detector**
  - Vertex determination
Data sample and analysis procedure

Data sample: 2015 and 2018 Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV ($L_{\text{int}} \sim 0.75 \text{ nb}^{-1}$)

Candidate selection

J/$\psi$ and Υ(1S) candidates are built combining muon pairs reconstructed in the muon spectrometer

- Application of all the standard cuts for quarkonium analysis

Analysis procedure

1. Signal extraction: number of J/$\psi$ & Υ(1S) obtained fitting the $\mu^+\mu^-$ invariant mass distribution vs (cos$\theta$, $\phi$)

2. Acceptance $\times$ efficiency correction: number of J/$\psi$ corrected with the $A \times \varepsilon$ obtained with a MC simulation

3. Polarization parameters extraction: fit to the J/$\psi$ $A \times \varepsilon$-corrected distribution with $W$(cos$\theta$, $\phi$)
Data sample and analysis procedure

Data sample: 2015 and 2018 Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($L_{\text{int}} \sim 0.75 \text{ nb}^{-1}$)

In this presentation:

- $\psi$ polarization as a function of $p_T$ from 2 to 10 GeV/c in $2.5 < y < 4$
- $\Upsilon$(1S) polarization for $p_T < 15$ GeV/c in $2.5 < y < 4$

⇒ New paper!
"First measurement of quarkonium polarization in nuclear collisions at the LHC" [arXiv:2005.11128]

- $\psi$ polarization as a function of centrality for $2 < p_T < 6$ GeV/c in $2.5 < y < 4$

⇒ New preliminary result!
**Signal extraction**

**J/ψ polarization vs \( p_T \)**

- The sizeable data sample collected allows to extract the J/ψ yield in \((\cos\theta, \phi)\) cells (**2D approach**)
  - Creation of a 2D grid for signal extraction
  - Angular binning tuned according to the statistical significance of the signal

![Data analysis](image-url)

**Hard Probes 2020**

**Luca Micheletti**
**Y(1S) polarization vs $p_T^\gamma$**

- $Y(1S)$ studied in:
  1. $p_T^{Y(1S)} < 15 \text{ GeV}/c$
  2. $2.5 < y^{Y(1S)} < 4$

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**Graph Details**

- **Plot Title:** ALICE, Inclusive $\gamma(1S) \rightarrow \mu^+\mu^-$
- **Label:** Pb–Pb $\sqrt{s_{NN}} = 5.02 \text{ TeV}, 0 - 90%$
- **Condition:** $p_T < 15 \text{ GeV}/c$, $2.5 < y < 4$, Helicity $|\cos\theta| < 0.1$

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**Legend**

- **Data**
- **Total fit**
- **Background fit**
- **$\gamma(1S)$**
- **$\gamma(2S)$**
Signal extraction

\( Y(1S) \) polarization vs \( p_T \)

- \( Y(1S) \) studied in:
  - \( p_T^{Y(1S)} < 15 \) GeV/c
  - \( 2.5 < y^{Y(1S)} < 4 \)

\( J/\psi \) polarization vs centrality

- \( J/\psi \) studied in:
  - 0–20%, 20–40%, 40–60% and 60–90% centralities
  - \( 2 < p_T^{J/\psi} < 6 \) GeV/c
  - \( 2.5 < y^{J/\psi} < 4 \)

\( J/\psi \) & \( Y(1S) \) yields extracted as a function of \( \cos \theta \) and \( \phi \) separately (1D approach)
**Acceptance × Efficiency**

**J/ψ polarization vs \( p_T \) and centrality**

- Tuning of the \( \cos\theta \) and \( \phi \) input MC shapes
  - **iterative procedure**: tuning of J/ψ generated distribution according to data

1. \( A \times \varepsilon \) from "flat Monte-Carlo"
2. \( N_{J/\psi} \) distribution corrected with \( A \times \varepsilon \)
3. Evaluation of \( \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \)
4. New evaluation of \( A \times \varepsilon \)
5. \( \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \) from previous step used for a new "polarized" Monte-Carlo

**STOP**: no significant variation from one iteration to the other (3 iterations done)
J/ψ polarization vs centrality

J/ψ $p_T$ and $y$ distributions have shown a clear evolution with centrality in Pb-Pb collisions\(^{(1)}\)

- Taken into account in the Monte-Carlo

\(\frac{d^2Y}{dp_T^2} \) (GeV/c)

ALICE Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

$J/\psi \rightarrow \mu^+\mu^-$, 2.5 < $y$ < 4
Extraction of the polarization parameters

\textbf{\(J/\psi\) polarization vs \(p_T\)}

- Fit to the \((\cos \theta, \phi)\) \(J/\psi\) angular distribution corrected for \(A \times \varepsilon\) (2D approach) with 
  \[ W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_\theta \phi \sin 2\theta \cos \phi) \]

\textbf{\(J/\psi\) polarization vs centrality}

- Fit to the \(\cos \theta\) and \(\phi\) \(J/\psi\) distributions corrected for \(A \times \varepsilon\) (1D approach) with the integrated expression of 
  \[ \int W(\cos \theta, \phi) d\phi \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta) \]
  \[ \int W(\cos \theta, \phi) d\cos \theta \propto \frac{2\lambda_\phi}{3 + \lambda_\theta} \cdot \cos 2\phi \]
Quarkonium polarization results

**New paper!**

*arXiv:2005.11128*

**J/ψ polarization vs p_T**

- Polarization parameters as a function of $p_T$ in the **Helicity** and **Collins-Soper** reference frames
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero in HE and CS
  - Maximum deviation of $\sim 2\sigma$ in the low $p_T$ bin
  - Indication of small transverse/longitudinal polarization in $2 < p_T < 4$ GeV/c for HE/CS
- Comparison with **ALICE** results at $\sqrt{s} = 8$ TeV
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible within the uncertainties
- Comparison with **LHCb** results at $\sqrt{s} = 7$ TeV
  - Significant difference in $\lambda_\theta^{HE}$ at low $p_T$
Quarkonium polarization results

**J/ψ polarization vs p_T**
- Polarization parameters as a function of $p_T$ in the Helicity and Collins-Soper reference frames
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero in HE and CS
  - Maximum deviation of $\sim 2\sigma$ in the low $p_T$ bin
  - Indication of small transverse/longitudinal polarization in $2 < p_T < 4$ GeV/c for HE/CS

**ϒ(1S) polarization vs p_T**
- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in HE and CS
  - Significance limited by the available statistics
Quarkonium polarization results

**J/ψ polarization vs p_T**
- Polarization parameters as a function of $p_T$ in the Helicity and Collins-Soper reference frames
  - $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero in HE and CS
  - Maximum deviation of $\sim 2\sigma$ in the low $p_T$ bin
  - Indication of small transverse/longitudinal polarization in $2 < p_T < 4$ GeV/$c$ for HE/CS

**Υ(1S) polarization vs p_T**
- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in HE and CS
  - Significance limited by the available statistics

**J/ψ polarization vs centrality**
- Flat trend for all the polarization parameters as a function of centrality
  - No visible dependence of $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ moving from central to peripheral events
Conclusions & future steps

"First measurement of quarkonium polarization in nuclear collisions at the LHC" arXiv:2005.11128

J/ψ polarization vs $p_T$ New paper!

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ close to zero
- Indication of small transverse/longitudinal polarization in $2 < p_T < 4 \text{ GeV}/c$ for the Helicity/Collins-Soper reference frames ($\sim 2\sigma$ deviation from zero)
- Pb–Pb results compatible with ALICE pp measurement at $\sqrt{s} = 8 \text{ TeV}$
- Comparison with pp results (LHCb) may indicate a significant difference at low $p_T$

$\Upsilon(1S)$ polarization vs $p_T$ New paper!

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ compatible with zero in Helicity and Collins-Soper reference frames

J/ψ polarization vs centrality New preliminary result!

- No centrality dependence observed within uncertainties

FUTURE STEPS

- Event-Plane dependence: effects related to the intense magnetic field produced in heavy ion collisions
Thank you for the attention!
Backup
**Single muon cuts:**
- $-4 < \eta_{\mu} < -2.5$ to reject tracks at the edge of the spectrometer acceptance
- the matching of a track reconstructed in the tracking chambers with a track reconstructed in the trigger system with $p_T > 1$ GeV/$c$
- Radial transverse position at the end of the absorber in the range $17.6 < R_{abs} < 89.5$ cm to remove tracks passing through the inner and denser part of the absorber

**Dimuon cuts:****
- Dimuon rapidity in the range $2.5 < \gamma_{\mu\mu} < 4$
**J/ψ polarization systematic uncertainties**

- **Signal extraction**
  - Choice of various signal and background shapes for the fit to the invariant mass distributions
  - Fix to the MC or keep free the J/ψ width in the signal extraction procedure

- **Trigger efficiency**
  - Use single muon trigger response function extracted from data or MC

- **Input MC distributions**
  - Evaluation of the impact of different $p_T, y$ MC input distributions on the polarization parameters
Prompt / non-Prompt J/ψ polarization

Evaluated in "J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV"\(^{(1)}\)

1.) LHCb measured $J/\psi \leftarrow B$ in $2 < y < 4.5$\(^{(2)}\)
   - $10 < f_B < 15\%$ in $2 < p_T < 10$ GeV/c

2.) **Non-prompt J/ψ** polarization measured by CDF in $p\bar{p}$ collisions\(^{(3)}\)
   - $\lambda_\theta (J/\psi \leftarrow B) \sim -0.1 \Rightarrow$ calculated w.r.t. the J/ψ direction in the LAB

3.) Assuming $|\lambda_\theta (J/\psi \leftarrow B)| \sim 0.2$ and $f_B$ from LHCb
   - $\Delta \lambda_\theta^{\text{Max}} < 0.05$
   - Smaller than the systematic uncertainties!

\(^{(1)}\) PRL 108 (2012) 082001
\(^{(2)}\) EUR. PHYS. J. C71 (2011) 1645
\(^{(3)}\) PRL 99 (2007) 132001