Vector meson polarization in pp and Pb–Pb collisions with ALICE at the LHC

Luca Micheletti (CERN) on behalf of the ALICE Collaboration
Physics motivations

- Magnetic field
  - The most intense magnetic field in nature!
  - No strong $b$ dependence
  - Lifetime increases from mid to forward rapidity

<table>
<thead>
<tr>
<th>B (T)</th>
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<tbody>
<tr>
<td>HICs</td>
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<tr>
<td>Pulsar</td>
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<tr>
<td>Earth</td>
</tr>
</tbody>
</table>
Physics motivations

Angular momentum
- The most vortical fluid in nature!  
  📖 Nature 548, 62 (2017), STAR Collaboration
- Strong $b$ dependence  
  📖 PRC 77 (2008) 024906, Becattini et al.
- Affects system evolution / hadronization

| $\omega$ (s$^{-1}$) |  
|-------------------|---|
| QGP               | $10^{22}$ |
| Pulsar            | $10^{2}$  |
| Tornado           | $10^{-1}$  |
Polarization: an introduction

- Spin alignment w.r.t. a chosen direction $\Leftrightarrow$ angular distribution of the decay products

$$W(\cos\theta) \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta$$

$\rho_{00}$ = spin density matrix element

$\rho_{00} = 1/3$ no spin alignment

In quarkonia analyses:

- $W(\cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \cdots)$

$\lambda_\theta$ = polarization parameter

$\lambda_\theta = 0$ no spin alignment

$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$

EPJC 69 (657-673), 2010, Faccioli et al.
Polarization: an introduction

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- **Reaction plane based frame**: axis orthogonal to the reaction plane in the collision center of mass frame
- **Helicity frame**: direction of vector meson in the collision center-of-mass frame
Vector meson production / polarization via 2 different mechanisms in HICs:

**Recombination** of polarized quark (antiquark) in the QGP

\[ \rho_{00} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} = \begin{cases} 1/3^* \Rightarrow \overline{B} \\ < 1/3 \Rightarrow \overline{L} \end{cases} \]

* > 1/3 q=0, < 1/3 q≠0

**Polarized quark (antiquark) fragmentation**

\[ \rho_{00} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3 \]

? **Recombination scenario** at low \( \rho_T \) supported by light flavors (\( K^*0, \phi \)), valid also for heavy flavors?

? Heavy quarks are produced in the first stages of the collision (\( \tau_{cc} \sim 0.1 \text{ fm/c} \))

Possibly affected by the **magnetic field**!
The ALICE detector (Run 2)

Central Barrel
- Rapidity: $|y| < 0.9$

1. Inner Tracking System
2. Time Projection Chamber
3. Time-Of-Flight detector
4. V0 detectors

Muon Spectrometer
- Rapidity: $2.5 < y < 4$

1. Front absorber
2. Tracking system
3. Dipole magnet
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Polarization in pp collisions: baseline
J/ψ polarization in pp collisions

- Important to constrain charmonium production mechanisms in hadronic collisions
  

- Recent improvements in the theoretical description of J/ψ production with ICEM and CGC + NRQCD
  
  \[ \text{JHEP 12 (2018) 057, Yan-Qing Ma et al., PRD 104 (2021) 9, Cheung, Vogt} \]

- General agreement among all results at LHC energies ($\lambda_\theta \sim 0$)

- Models reproduce a smooth trend vs $p_T$ close to zero polarization

\[ \text{LHCb data 7 TeV, ALICE data 7 TeV (inclusive J/ψ), ALICE data 8 TeV (inclusive J/ψ), CGC+NRQCD} \]
First measurement of the **prompt** and **non-prompt** $D^{*+}$ spin alignment at the LHC

- Measurement performed with respect to the helicity axis:
  - **Prompt** $D^{*+}$: no evidence of polarization
  - **Non-prompt** $D^{*+}$: $\rho_{00} > 1/3$ due to the helicity conservation ($B(S = 0) \rightarrow D^{*+}(S = 1) + X$)

- Measurement in agreement with the prediction of PYTHIA 8 + EVTGEN
- Baseline for studies in Pb–Pb collisions
Polarization in Pb–Pb collisions
J/ψ polarization in Pb–Pb collisions

First measurement of quarkonium polarization with respect to the Reaction plane

- **Centrality** dependence:
  Small but significant (3.5σ) polarization observed in 40-60% centrality class and $2 < p_T < 6$ GeV/c

In the dilepton channel:

$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$$

$$\begin{cases} 
\lambda_\theta > 0 & \Rightarrow \rho_{00} < 1/3 \\
\lambda_\theta < 0 & \Rightarrow \rho_{00} > 1/3 
\end{cases}$$
J/ψ polarization in Pb–Pb collisions

First measurement of quarkonium polarization with respect to the Reaction plane

- Centrality dependence:
  Small but significant (3.5σ) polarization observed in 40-60% centrality class and $2 < p_T < 6 \text{ GeV}/c$

- $p_T$ dependence:
  30-50%: significant deviation (3.9σ) at low transverse momentum ($2 < p_T < 4 \text{ GeV}/c$)

- In the dilepton channel:
  \[
  \lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}} \quad \begin{cases} 
  \lambda_\theta > 0 & \rho_{00} < 1/3 \\
  \lambda_\theta < 0 & \rho_{00} > 1/3 
  \end{cases}
  \]

- Qualitatively in agreement with the scenario of quark recombination

- A comprehensive theory of quarkonium polarization in HICs is missing

PRL 131 (2023) 042303, ALICE Collaboration
**D* polarization in Pb–Pb collisions**

- **New ALICE preliminary measurement!**
  First measurement of D**+** polarization with respect to the Reaction plane

  - Multiclass classification algorithm based on BDT used to:
    - reduce combinatorial background
    - distinguish among prompt and non-prompt components

  - \( \rho_{00} \) extracted taking into account:
    - Event plane finite resolution
    - Feed-down contribution

![Graphs showing polarization measurements](image-url)
New ALICE preliminary measurement!

First measurement of $D^{*+}$ polarization with respect to the Reaction plane

• $p_T$ & centrality dependence:
  - $0 – 10\%$ : $\rho_{00}$ compatible with $1/3$
  - $30 – 50\%$ : $\rho_{00} > 1/3$ at high $p_T$
D* polarization in Pb–Pb collisions

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- $y$ dependence:
  - significant deviation at forward ($0.3 < |y| < 0.8$) than at mid ($|y| < 0.3$) rapidity
**D* polarization in Pb–Pb collisions**

- **New ALICE preliminary measurement!**
  First measurement of D**+** polarization with respect to the Reaction plane

- Qualitatively in agreement with:
  - $\rho_{00} < \frac{1}{3}$ quark recombination at low $p_T$
  - $\rho_{00} > \frac{1}{3}$ quark fragmentation at high $p_T$

- At high $p_T$ the fragmentation of heavy quarks polarized by the magnetic field translates to $\rho_{00} > 1/3$?
  - ➢ Theory guidance needed!

![Graph showing ALICE Preliminary data for D**+** polarization](image-url)
### Summary: before QM2023

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- **pp collisions**: light flavors, D*⁺ and J/ψ are compatible with **zero polarization**
### Summary: new at QM2023

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- **pp collisions**: light flavors, D**+ and J/\psi are compatible with zero polarization
- **Pb–Pb collisions**:
  - $\rho_{00} < 1/3$ for light flavors, J/\psi at low $p_T$ \(\Rightarrow\) recombination scenario
  - $\rho_{00} > 1/3$ for D**+ at high $p_T$ & fwd rapidity \(\Rightarrow\) quark fragmentation scenario
Backup
Magnetic field

LHC: Pb+Pb@2.76 ATeV
b=9.5 fm, x_T=0

$eB_y$ [GeV/fm]

$\eta=1.5$
$\eta=1.0$
$\eta=0.5$
$\eta=0$

$t$ [fm/c]

[Reference: PLB 768 (2017) 260, Das et al.]
Charmonia at LHC and RHIC

- Inclusive $J/\psi \rightarrow \mu^+\mu^-$, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au $\sqrt{s_{NN}} = 0.2$ TeV

- ALICE, 2.5<y<4, 0-20% global syst. = ±8%
- PHENIX, 1.2<y<2.2, 0-20% global syst. = ±10%

- PLB 734 (2014), ALICE collaboration
D* polarization: random plane

ALICE Preliminary

30–50% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

Prompt $D^*$, $0.3 < |y| < 0.8$

- Reaction plane
- Random axis

Stat. unc. only