Spin alignment of vector mesons measured in Pb-Pb collisions with ALICE

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(On behalf of the ALICE Collaboration)
CERN and NISER

Outline:
- High energy heavy-ion collisions
  - Introduction
  - Initial conditions: Angular momentum & magnetic field
- Spin alignment of vector mesons
  - Observable and theory expectation
  - ALICE physics analysis
  - Results
- Discussions: Comparison to theory expectation and RHIC results
- Summary
- Surprises and Outlook

Based on: arXiv:1910.14408 (ALICE)
Heavy-ion collisions

Relativistic Heavy-Ion Collisions

made by Chun Shen

Initial energy density

QGP phase

Hadron gas phase

Hadronization

Kinetic freeze-out

final detected particle distributions

π
K
p
γ
e⁺
e⁻

collision overlap zone

pre-equilibrium dynamics

viscous hydrodynamics

collision evolution

τ ~ 0 fm/c  τ ~ 1 fm/c

τ ~ 10 fm/c

τ ~ 10¹⁵ fm/c

free streaming
Heavy-ion collisions

Reaction plane: Impact parameter and beam axis
L and B perpendicular to reaction plane
Angular momentum & magnetic field

Impact parameter dependence

Time dependence

Large angular momentum (Conserved Quantity)

Large magnetic field

\[ b = 1 \text{ fm} \]
\[ b = 2 \text{ fm} \]
\[ b = 3 \text{ fm} \]

\[ \tau (\text{fm}) \]

\[ eB (\text{MeV}^2) \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Au Au, \[ s_{NN} = 200 \text{ GeV} \]

Hard Sphere

Woods-Saxon


\[ b = 4 \text{ fm} \]
\[ b = 8 \text{ fm} \]
\[ b = 12 \text{ fm} \]

\[ M^2_{\pi} \sim 2 \times 10^4 \text{ MeV}^2 \sim 3 \times 10^{14} \text{ Tesla} \sim 3 \times 10^{18} \text{ Gauss} \]
Angular momentum & magnetic field

<table>
<thead>
<tr>
<th>System</th>
<th>Angular momentum $(\hbar/2\pi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron in hydrogen atom</td>
<td>$\sqrt{l(l+1)}$</td>
</tr>
<tr>
<td>$^{132}$Ce (highest for nuclei)</td>
<td>70</td>
</tr>
<tr>
<td><strong>Heavy-ion collisions</strong></td>
<td>$10^4 - 10^5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>Vorticity $(s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar sub-surface</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Terrestrial atmosphere</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Great red spot of Jupiter</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Tornado core</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Heated soap bubbles</td>
<td>100</td>
</tr>
<tr>
<td>Turbulent flow in superfluid He</td>
<td>150</td>
</tr>
<tr>
<td><strong>Heavy-ion collisions</strong></td>
<td>$10^7 - 10^{21}$</td>
</tr>
</tbody>
</table>

Focus of the study is to see the effect of large angular momentum and magnetic field in heavy-ion collisions.

<table>
<thead>
<tr>
<th>System</th>
<th>Magnetic Field in Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human brain</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Earth’s magnetic field</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Refrigerator magnet</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Loudspeaker magnet</td>
<td>1</td>
</tr>
<tr>
<td>Strongest field in lab</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Neutron star</td>
<td>$10^6$</td>
</tr>
<tr>
<td><strong>Heavy-ion collisions</strong></td>
<td>$10^{15} - 10^{16}$</td>
</tr>
</tbody>
</table>
Spin and angular momentum

Quarks (spin $\frac{1}{2}$) $\rightarrow$ Vector mesons (spin 1)

What happens in presence of angular momentum?

Can we see experimentally the signature of spin-orbit angular momentum interactions for QCD matter produced in heavy-ion collisions?
Angular distribution of vector mesons

$K^*0$ Vector meson
- Mass – 896 MeV/c$^2$
- Lifetime – 4 fm/c
- Spin 1
- Decays to $K^+$ and $\pi^-$ (B.R – 66%)
- Quark content (d, $\bar{s}$)

$$\frac{dN}{d\cos\theta d\phi} = \langle \theta, \phi, \lambda_1, \lambda_2 | M \rho M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

$$= \sum_{\lambda_V} \sum_{\lambda_{V'}} \langle \theta, \phi, \lambda_1, \lambda_2 | M | \lambda_V \rangle \langle \lambda_V | \rho | \lambda_{V'} \rangle \langle \lambda_{V'} | M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

$\lambda$ = Helicities
$\rho$ = spin density matrix
$M$ = Decay amplitude

Quantization axis
- Normal to production plane
  (Momentum of vector meson and beam axis)
- Normal to reaction plane
  (Impact parameter and beam axis)

Angular distribution of vector mesons

\[ \frac{dN}{d\cos\theta d\phi} = \sum_{\lambda_V} \sum_{\lambda_{V'}} \langle \theta, \phi, \lambda_1, \lambda_2 | M | \lambda_V \rangle \langle \lambda_V | \rho | \lambda_{V'} \rangle \langle \lambda_{V'} | M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle \]

\( \lambda \) = Helicities
\( \rho \) = spin density matrix
\( M \) = Decay amplitude

Quantization axis
- Normal to production plane
  (Momentum of vector meson and beam axis)
- Normal to reaction plane
  (Impact parameter and beam axis)

Angular distribution of vector mesons

In terms of spherical harmonics

\[
\frac{dN}{d\cos\theta d\phi} = |C|^2 \times \sum_{m_1, m_2} Y_{1,m_1}^*(\theta, \phi)Y_{1,m_2}(\theta, \phi)\rho_{m_1,m_2}
\]

Integrating over azimuthal angle

\[
\frac{dN}{d\cos\theta} = |C|^2 \times \frac{3}{8\pi} \left[ \sin^2\theta \rho_{-1,-1} + 2\cos^2\theta \rho_{0,0} + \sin^2\theta \rho_{1,1} \right] \times 2\pi
\]

Normalized spin density matrix – Trace = 1

\[
\rho_{00} = \frac{1}{3} \Rightarrow \text{No spin alignment}
\]

\[\rho_{00}: \text{Probability vector meson is in spin state} = 0\]
Measurements in e^+e^- collisions

In e^+e^- experiments results exists. Goal was to study role of spin on production dynamics.

Spin alignment of leading K*(892) mesons in hadronic Z0 decays

Study of phi (1020), D^*+ and B* spin alignment in hadronic Z0 decays,

Measurement of the spin density matrix for the rho0, K^0 (892) and phi produced in Z0 decays **DELPHI** Collaboration (P. Abreu et al.). Phys.Lett. B406 (1997) 271-286

Our measurements are in heavy-ion collisions to probe spin-orbital angular momentum interactions in QCD matter.
Qualitative theory expectation


- Low $p_T$ phenomena – Hadronization via recombination
- Small spin alignment for central and peripheral collisions
- Maximum effect for mid-central (intermediate impact parameter) collisions
- Effect larger for $K^*$ than $\phi$ mesons (factor 10 lifetime difference, re-scattering effect, heavier mass of strange quark, coherent field)
## Physics process and theory expectation

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Theory</th>
<th>Remarks</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vorticity ((\omega))</td>
<td>(\rho_{00}(\omega) &lt; 1/3)</td>
<td>(\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta \omega)^2)</td>
<td>F. Becattini et al., Phys. Rev. C 95 (2017) 054902</td>
</tr>
<tr>
<td>Magnetic field (B)</td>
<td>(\rho_{00}(B) &gt; 1/3)</td>
<td>Electrically neutral vector mesons</td>
<td>Y. Yang et al., Phys. Rev. C 97 (2018) 034917</td>
</tr>
<tr>
<td></td>
<td>(\sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1 q_2}{m_1 m_2} B^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\rho_{00}(B) &lt; 1/3)</td>
<td>Electrically charged vector mesons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\sim \frac{1-P_q P_q}{3+P_q P_q})</td>
<td></td>
<td>Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301</td>
</tr>
<tr>
<td></td>
<td>(\rho_{00}(\text{frag}) &gt; 1/3)</td>
<td>Fragmentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coherent meson field</td>
<td>(\rho_{00} &gt; 1/3)</td>
<td>(\phi) mesons</td>
<td>X. L. Sheng et al., arXiv:1910.13684</td>
</tr>
</tbody>
</table>
Particle identification: TPC + TOF
Momentum measurement TPC+ITS
Event plane angle measurement: V0

PDG, 2018
### ALICE data set

<table>
<thead>
<tr>
<th>Collision system</th>
<th>pp at 13 TeV, Pb-Pb at 2.76 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidity</td>
<td>$</td>
</tr>
<tr>
<td>No. of events</td>
<td>~ 43 M (pp), 14 M (Pb-Pb)</td>
</tr>
<tr>
<td>Hadrons</td>
<td>pp: $K^0$ and $\phi$</td>
</tr>
<tr>
<td></td>
<td>Pb-Pb: $K^0$, $\phi$ and $K_S^0$</td>
</tr>
<tr>
<td>Background</td>
<td>Mixed events</td>
</tr>
<tr>
<td>Efficiency x acceptance</td>
<td>Corrected</td>
</tr>
<tr>
<td>Quantization axis</td>
<td>pp: Normal to production plane (PP)</td>
</tr>
<tr>
<td></td>
<td>Pb-Pb: Normal to production plane (PP), event plane (EP) and random event plane (RndEP: randomizing the event plane angle in azimuthal plane)</td>
</tr>
<tr>
<td>Event plane resolution (R)</td>
<td>Corrected</td>
</tr>
<tr>
<td></td>
<td>$\rho_0 - \frac{1}{3} = \frac{4}{1 + 3R} (\rho_{0}^{\text{obs}} - \frac{1}{3})$</td>
</tr>
</tbody>
</table>

**K^0** and **φ** vector meson

**K^0** vector meson
- Mass – 896 MeV/c^2
- Lifetime – 4 fm/c
- Spin 1
- Decays to K^+ and π^- (B.R. – 66%)
- Quark content (d, s)

**φ** vector meson
- Mass – 1019 MeV/c^2
- Lifetime – 42 fm/c
- Spin 1
- Decays to K^+ and K^- (B.R. – 49%)
- Quark content (s, s̅)

K^0: Breit-Wigner
φ: Voigtian

Residual background: Polynomial function
Angular distribution of vector mesons

\[ \frac{1}{N_{\text{evt}}} \frac{dN}{d\cos \theta^*} \]

\[ K^0, \text{Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV (10-50\%)} \]

- EP, \( 0.8 \leq p_T < 1.2 \text{ GeV/c} \)

\[ N_0[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*] \]

\( \theta^* \) is the effective polar angle relative to the beam axis.

\( \rho_{00} \) is the isotropic correlation coefficient.

\( \rho_{00} \) is the correlation coefficient for a given pair of particles.

\( \pi, K^0, K^+ \) are pions, kaons.

**Beam axis**

**Quantization axis**

**Imp. param.**
Angular distribution of vector mesons

ALICE

$|y| < 0.5$

$K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)

- EP, $0.8 \leq p_T < 1.2$ GeV/$c$
- PP ($\times 0.3$), $0.4 \leq p_T < 1.2$ GeV/$c$

$- N_0[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*]$
Angular distribution of vector mesons

ALICE

$|y| < 0.5$

$\frac{(1/N_{\text{evt}})}{(dN/d\cos \theta^*)}$

- $K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)
  - EP, $0.8 \leq p_T < 1.2$ GeV/c
  - PP ($\times 0.3$), $0.4 \leq p_T < 1.2$ GeV/c

- $K^0$, pp $\sqrt{s} = 13$ TeV
  - PP ($\times 15$), $0.0 \leq p_T < 0.6$ GeV/c

$- N_0[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*)$
Angular distribution of vector mesons

\[ \frac{1}{N_{\text{evt}}} \frac{dN}{d\cos \theta^*} \]

**ALICE**

\[ |y| < 0.5 \]

- **K^0**, Pb–Pb \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) (10–50%)
  - EP, \( 0.8 \leq p_T < 1.2 \text{ GeV/c} \)
  - PP (× 0.3), \( 0.4 \leq p_T < 1.2 \text{ GeV/c} \)
- **K^0**, pp \( \sqrt{s} = 13 \text{ TeV} \)
  - PP (× 15), \( 0.0 \leq p_T < 0.6 \text{ GeV/c} \)
- **K_S^0**, Pb–Pb \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) (20–40%)
  - EP, \( 0.6 \leq p_T < 0.8 \text{ GeV/c} \)
  - PP (× 0.8), \( 0.6 \leq p_T < 0.8 \text{ GeV/c} \)

\[ - N_0[1 - \rho_{00}^2 + (3\rho_{00} - 1)\cos^2 \theta^*] \]

**ALI-DER-342820**

*arXiv:1910.14408 (ALICE)*
Systematics uncertainties and checks

On $\rho_{00}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Low $p_T$</th>
<th>K$^{*0}$ High $p_T$</th>
<th>Low $p_T$</th>
<th>$\phi$ High $p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extraction procedure</td>
<td>13%</td>
<td>5%</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>Track selection criteria</td>
<td>14%</td>
<td>13%</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>Particle identification procedure</td>
<td>7%</td>
<td>8%</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>

- Closure test (data and MC)
- Data samples with two different magnetic field polarities
- Positive ($0 < y < 0.5$) and negative ($-0.5 < y < 0$) rapidity
- K$^{*0}$ and anti-K$^{*0}$
- Two different event generators are used to determine the reconstruction efficiency
Angular distribution of vector mesons

1. Angular distribution NOT FLAT for vector mesons with respect to quantization axis in heavy-ion collisions

2. Angular distribution FLAT for vector mesons with respect to random quantization axis

3. Angular distribution FLAT for spin-0 mesons $K^0_s$ in heavy-ion collisions

4. Angular distribution FLAT for vector mesons in proton-proton collisions

arXiv:1910.14408 (ALICE)
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arXiv:1910.14408 (ALICE)
Spin alignment of vector mesons: $p_T$ dependence

$K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)

No spin alignment

ALICE

$|y| < 0.5$

Beam axis

Quantization axis

$\theta^*$

Impact parameter

$K^+$

$K^0$
Spin alignment of vector mesons: $p_T$ dependence

$K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)

- Event Plane
- Production Plane

ALICE

$|y| < 0.5$
Spin alignment of vector mesons: $p_T$ dependence

$K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)
- Event Plane
- Production Plane

$K^0$, pp $\sqrt{s} = 13$ TeV

No spin alignment
Spin alignment of vector mesons: $p_T$ dependence

$K^0$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (10–50%)
- Event Plane
- Production Plane

$K^{0}_S$, Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (20–40%)
- Event Plane
- Production Plane

No spin alignment

arXiv:1910.14408 (ALICE)
Spin alignment of vector mesons

1. Spin Alignment ($\rho_{00} < 1/3$) observed for spin 1 particle at low momentum

2. No spin alignment ($\rho_{00} \sim 1/3$) observed for spin 0 particle

3. No spin alignment ($\rho_{00} \sim 1/3$) observed in proton-proton collisions

4. No spin alignment ($\rho_{00} \sim 1/3$) observed for random planes

$\textit{arXiv:1910.14408 (ALICE)}$
Spin alignment: centrality dependence

1. Maximum spin alignment observed for mid-central collisions in low $p_T$ (3σ for $K^0$ and 2σ for $\phi$)

2. $\rho_{00} \sim 1/3$ for high $p_T$ vector mesons

3. $\rho_{00} \sim 1/3$ for peripheral collisions and deviation from 1/3 small for central collisions

arXiv:1910.14408 (ALICE)
Relation between EP and PP

The physical picture is that spin alignment with respect to the event plane is coupled to that in the production plane through the elliptic flow of the system.

The $\rho_{00}$ (RndEP) is lower than $1/3$ as the quantization axis is always perpendicular to the beam axis, resulting in a residual effect.

\[
\rho_{00}^{\text{(PP)}} - \frac{1}{3} = [\rho_{00}^{\text{(EP)}} - \frac{1}{3}] \left[ \frac{1+3v_2}{4} \right]
\]
Theoretical expectation & comparison to RHIC

**Centrality dependence**

![Graph showing centrality dependence of angular momentum](image)

**Centrality dependence of $\rho_{oo}$ like centrality dependence of angular momentum**

arXiv:1910.14408 (ALICE)

**Transverse momentum dependence**

Transverse dependence of $\rho_{oo}$ consistent with polarization of quarks in the presence of large initial angular momentum in heavy-ion collisions and a subsequent hadronization by the process of recombination

STAR: S. Singha, QM2019
Collision energy dependence

- Looks like no energy dependence of $\rho_{oo}$.
- High statistics data at LHC and RHIC will clarify the picture.
- ALICE Pb-Pb analysis at 5.02 TeV under progress.

STAR Preliminary, 10-60%, $1.2 < p_T < 5.0$ GeV/c

ALICE, 10-50%, $0.8 < p_T < 1.2$ GeV/c

arXiv:1910.14408 (ALICE)

STAR: S. Singha, QM2019
 ✓ First evidence of spin alignment in vector mesons in high energy heavy-ion collisions. Both RHIC and LHC observe the phenomenon.
 ✓ Measurement coupled to Event Plane – vanishes for random Event Plane – related to initial angular momentum
 ✓ Spin alignment not observed in proton-proton collisions
 ✓ Spin alignment not observed for spin 0 particles in heavy-ion collisions
Surprises

\[ P_H \sim P_q \quad \text{and} \quad \rho_{00} \sim P_q^2 \]

\[ \rho_{00} \sim 1/3 \]

\[ \rho_{00} \text{ no energy dependence?} \]

STAR: S. Singha, QM2019

*arXiv:1910.14408 (ALICE)*

\[ K^0 \text{ versus } \phi \text{ meson at RHIC and LHC} \]
## Polarization

<table>
<thead>
<tr>
<th>Model</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular momentum polarizes the quark, they coalesce to form vector mesons $\rho_{00}(\text{rec}) \sim \frac{1-P_q P_q}{3+P_q P_q}$ Z. Liang et. al., Phys. Lett. B 629 (2005) 20</td>
<td>Quark polarization $P_s = 0.25 \pm 0.07$ $P_d = 0.80 \pm 0.57$</td>
</tr>
<tr>
<td>Thermal approach and non-relativistic limit $\rho_{00}(\omega) \sim \frac{1}{3} - [(\omega/T)^2]^{\frac{1}{9}}$ $P_V \sim \frac{2}{3} \left(\frac{\omega}{T}\right)$ F. Becattini et al., Phys. Rev. C 95, 054902 (2017)</td>
<td>Vector meson polarization $P_{K^*} = 0.61 \pm 0.17$ $P_{\phi} = 0.28 \pm 0.11$</td>
</tr>
</tbody>
</table>

Estimates based on simple models with assumptions
Outlook

A. Theoretical Side:
- The experimental measurements → challenges to theory
  1. Explain Lambda and vector mesons results simultaneously
  2. Explain the difference in $\rho_{00}$ values of $K^*$ ($< 1/3$) and $\phi$ ($> 1/3$ at RHIC and $< 1/3$ at LHC) meson
  3. Development of proper relativistic spin hydrodynamics
  4. Models with conservation of angular momentum, fraction of initial angular momentum transferred to QCD matter, how to convert $L$ or $\omega$ of fluid → spin of particles

B. Experimental Side:
- Precision measurements may allow sensitivity to initial magnetic field
  1. Lambda and anti-Lambda polarization
  2. Charged $K^*$ and neutral $K^*$ $\rho_{00}$
  3. Working on 2015+2018 Pb-Pb 5.02 TeV data set in ALICE

Establishing & proper treatment of initial conditions in heavy-ion collisions could have impact on the physics and discoveries in the area
BACK UP
\[ \frac{dN}{d \cos \theta^*} = \frac{1}{2} \left( 1 + \alpha_H |\vec{P}_H| \cos \theta^* \right) \]

decay parameter \( \alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013 \)

\[ \omega = k_B T \left( \overline{P}_\Lambda + \overline{P}_{\bar{\Lambda}} \right) / \hbar \]

\( \omega \approx (9 \pm 1) \times 10^{21} \text{ s}^{-1} \)

STAR RESULTS