Measurement of global spin alignment of vector mesons at RHIC

Subhash Singha
Institute of Modern Physics Chinese Academy of Sciences, Lanzhou
(For the STAR Collaboration)
Outline

• Motivation

• Global spin alignment ($\rho_{00}$) analysis method

• Results:

  - Au+Au at $\sqrt{s_{\text{NN}}} = 11.5 - 200$ GeV (BES): $\phi$ and $K^*$
  - Ru+Ru & Zr+Zr at $\sqrt{s_{\text{NN}}} = 200$ GeV (Isobar): $K^0$ and $K^{*+/-}$

• Summary
Motivation

In non-central heavy-ion collisions

- A large orbital angular momentum (OAM) imparted into the system
  \[ L = r \times p \sim bA \sqrt{s_{NN}} \sim 10^4 \, \hbar \]
- Such a huge OAM can polarize quarks and antiquarks due to “spin-orbit” interaction.
Motivation

In non-central heavy-ion collisions

- **Initial strong magnetic field** \((B)\) is expected
  \[ eB \sim m^2_\pi \sim 10^{18} \text{ Gauss} \]
- Such strong \(B\) field can also polarize quarks. Can induce different spin polarization for quarks and anti-quarks with different magnetic moments

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Vector meson spin alignment ($\rho_{00}$)

**Spin alignment ($\rho_{00}$):**
Measured from the angular distribution ($\theta^*$) of the daughter particle in parent’s rest frame.

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[ (1 - \rho_{00}) + (3\rho_{00} - 1) \cos^2\theta^* \right]$$

$\rho_{00}$: 00$^{th}$ component of spin density matrix

$\theta^*$: Angle between momentum of daughter and polarization axis in parent’s rest frame

▶ Deviation of $\rho_{00}$ from (1/3) indicates spin alignment

**References:**
The STAR detector and event plane

- Second order event plane ($\Psi_2$) is measured using the TPC with $0.15 < p_T < 2.0$ GeV/c

- Uniform acceptance, full azimuthal coverage
- TPC: tracking, centrality and event plane
- TPC+TOF: particle identification

Polarization axis $\rightarrow$ Perpendicular to $\Psi_2$

STAR Preliminary

$\sqrt{s_{NN}} = 200$ GeV

- $\text{Ru + Ru}$
- $\text{Zr + Zr}$
Signal reconstruction

**φ → K⁺K⁻**

**K*⁰ → K⁺π⁻**

**K*⁺ → K⁰⁺π⁺**

Mixed event (φ) and rotational background (K*⁰ and K*⁺⁻) subtraction

Yield is calculated from histogram integration

\[
\text{Breit Wigner} = \frac{1}{2\pi} \frac{\Gamma}{(m - m_0)^2 + \Gamma^2/4}
\]
Analysis method

• Raw yield of $K^*0$ is extracted from five $|\cos \theta^*|$ bins
• Yield of $K^*0$ is corrected for efficiency and acceptance using STAR detector simulations

\[
\frac{dN}{d(\cos \theta^*)} = N_0 \times \left[ (1 - \rho_{00}^{\text{obs}}) + (3\rho_{00}^{\text{obs}} - 1) \cos^2 \theta^* \right]
\]

• Observed $\rho_{00}^{\text{obs}}$ is calculated from fitting the yield with function:

\[
\rho_{00}^{\text{obs}} = \frac{1}{\frac{4}{1 + 3R} \left( \rho_{00}^{\text{obs}} - \frac{1}{3} \right)}
\]

Analysis method

- Raw yield of $K^{*+}$ is extracted from five $|\cos \theta^*|$ bins
- Yield of $K^{*+}$ is corrected for efficiency and acceptance using STAR detector simulations

\[
\frac{dN}{d(\cos \theta^*)} = N_0 \times \left[(1 - \rho_{00}^{obs}) + (3\rho_{00}^{obs} - 1) \cos^2 \theta^*\right]
\]

- Observed $\rho_{00}^{obs}$ is calculated from fitting the yield with function:
  - $\rho_{00}^{obs} = \frac{1}{3} \left(1 + \frac{4}{1 + 3R} (\rho_{00}^{obs} - \frac{1}{3})\right)$

\(\text{Tang et. al., Phys. Rev. C 98, 044907 (2018)}\)

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Results: Au+Au Beam Energy Scan

\[
\sqrt{s_{NN}} = 11.5 - 200 \text{ GeV} : \phi \text{ and } K^{*0}
\]

<table>
<thead>
<tr>
<th>Particle Species</th>
<th>Quark content</th>
<th>Mass (GeV/c^2)</th>
<th>Spin</th>
<th>Lifetime (fm/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>( s\bar{s} )</td>
<td>1.092</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>( K^{*0} )</td>
<td>( d\bar{s} )</td>
<td>0.896</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
\( \rho_{00} (\sqrt{s_{NN}}): \phi \text{ and } K^*0 \text{ from BES-I} \)

For 20-60%:

- For \( \sqrt{s_{NN}} \leq 62.4 \text{ GeV} \):
  - \( \phi \rho_{00} = 0.3451 \pm 0.0017 \text{ (stat.)} \pm 0.0018 \text{ (sys.)} \)
  - \( \rho_{00} > 1/3 \) with 8.4\( \sigma \)

- For \( \sqrt{s_{NN}} \leq 54.4 \text{ GeV} \):
  - \( K^*0 \rho_{00} = 0.3356 \pm 0.0034 \text{ (stat.)} \pm 0.0043 \text{ (sys.)} \)
  - \( \rho_{00} \sim 1/3 \)

STAR Collaboration, arXiv: 2204.02302


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### Expectation of $\rho_{00}$ from theory

<table>
<thead>
<tr>
<th>Physics Mechanisms</th>
<th>$(\rho_{00})$</th>
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<tbody>
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<td>$c_\Lambda$: Quark coalescence</td>
<td>$&lt; 1/3$</td>
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<td>vorticity &amp; magnetic field$^1$</td>
<td>(Negative $\sim 10^{-5}$)</td>
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<tr>
<td>$c_\varepsilon$: Vorticity tensor$^1$</td>
<td>$&lt; 1/3$</td>
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<td>(Negative $\sim 10^{-4}$)</td>
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<tr>
<td>$c_E$: Electric field$^2$</td>
<td>$&gt; 1/3$</td>
</tr>
<tr>
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<td>(Positive $\sim 10^{-5}$)</td>
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<tr>
<td>Fragmentation$^3$</td>
<td>$&gt; \text{or, } &lt; 1/3$</td>
</tr>
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<td>($\sim 10^{-5}$)</td>
</tr>
<tr>
<td>Local spin alignment and helicity$^4$</td>
<td>$&lt; 1/3$</td>
</tr>
<tr>
<td>Turbulent color field$^5$</td>
<td>$&lt; 1/3$</td>
</tr>
<tr>
<td>$c_\phi$: Vector meson strong</td>
<td>$&gt; 1/3$</td>
</tr>
<tr>
<td>force field$^6$</td>
<td>(Can accommodate large positive signal)</td>
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Expectation of $\rho_{00}$ from theory

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- Like electric charges in motion can generate an EM field, $s$ and $\bar{s}$ quarks in motion can generate an effective $\phi$-meson field
- The electric part of the $\phi$-meson field can polarize $s$ and $\bar{s}$ quarks with a large magnitude due to strong interaction (large coupling constant $g_\phi$)

$$
\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi; \\

\begin{align*}
    c_\phi & \equiv \frac{g_\phi^4}{27m_s^4m_\phi^4T_{\text{eff}}^2} \langle p^2 \rangle_\phi \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle; \\
    C_s(y) & \equiv g_\phi^4 \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle
\end{align*}
$$
• Surprisingly large $\phi$ $\rho_{00}$ cannot be accommodated by conventional mechanisms

• Polarization by a strong force field of vector meson → Can accommodate large deviation for $\phi$ $\rho_{00}$ at mid-central collisions

$$\rho_{00}(\sqrt{s_{NN}}): \phi \text{ and } K^*0 \text{ from BES-I}$$

\[\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_e + c_E + c_\phi;\]

\[c_\phi \equiv \frac{g_\phi^4}{27m_s^4m_\phi^4T_{eff}^2} \langle p^2 \rangle_\phi \langle \Bar{E}^2_{\phi,z} + \Bar{E}^2_{\phi,x} \rangle;\]

\[C_s(y) \equiv g_\phi^4 \langle \Bar{E}^2_{\phi,z} + \Bar{E}^2_{\phi,x} \rangle\]
**ρ₀₀ (centrality): φ and K*₀ from BES-I**

- **For central at 200 GeV:**
  - \( φ, K^*₀ \rho₀₀ < 1/3 \)
  - Local spin alignment\(^1\)
  - or, helicity contribution\(^2\)

- **For mid-central and peripheral:**
  - \( φ, K^*₀ \rho₀₀ \sim 1/3 \)

- Need inputs from theory to understand centrality differential \( \rho₀₀ \)

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\(^1\) Xia et al, Phys. Lett. B 817, 136325 (2021)
\(^2\) Gao, Phys. Rev. D 104, 076016 (2021)
\( \rho_{00} (p_T): \phi \) and \( K^*0 \) from BES-I

STAR Collaboration, arXiv: 2204.02302

- For 20-60%: non-trivial \( p_T \) dependence

- Need inputs from theory to understand \( p_T \) differential \( \rho_{00} \)

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**Results: Zr+Zr and Ru+Ru (Isobar collisions)**

\[ \sqrt{s_{NN}} = 200 \text{ GeV: } K^0 \text{ and } K^{*+/-} \]

<table>
<thead>
<tr>
<th>Particle Species</th>
<th>Quark content</th>
<th>Mass (GeV/c^2)</th>
<th>Spin</th>
<th>Lifetime (fm/c)</th>
<th>Magnetic moment</th>
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<tr>
<td>( K^0 ) ( (\text{anti-}K^0) )</td>
<td>( d\bar{s} ) (( \bar{d}s ))</td>
<td>0.896</td>
<td>1</td>
<td>4</td>
<td>( \mu_d \approx -0.97\mu_N )</td>
</tr>
<tr>
<td>( K^{*+/-} )</td>
<td>( u\bar{s} ) (( \bar{u}s ))</td>
<td>0.892</td>
<td>1</td>
<td>4</td>
<td>( \mu_u \approx 1.85\mu_N )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mu_s \approx 0.61\mu_N )</td>
</tr>
</tbody>
</table>

\[ \rho_{00}(B) \approx \frac{1}{3} - \frac{4}{9} \beta^2 \mu_{q_1}\mu_{q_2}B^2 \]

(Expect negligible contribution)

\[ \rho_{00}(B) > 1/3 \text{ for } K^0 \]

\[ \rho_{00}(B) < 1/3 \text{ for } K^{*+/-} \]

K* ρ₀₀ from Isobar collisions

- K*⁺⁻ : First measurement of global ρ₀₀
- K*₀ vs. K*⁺⁻ : ~ 3.9σ difference
  - Ordering opposite to the expectation from B field
  - Contribution from vector meson strong force field?

- Need inputs from theory to understand this behavior

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$\rho_{00}$ (Centrality): $K^*0$ and anti-$K^*0$

- **Species dependence:**
  - $K^*0 \rho_{00} \sim \text{anti-}K^*0 \rho_{00}$
$\rho_{00}$ (Centrality): $K^{*0}$ and anti-$K^{*0}$

- **Species dependence:**
  - $K^{*0} \rho_{00} \sim$ anti-$K^{*0} \rho_{00}$

- **System size dependence:**
  - $\rho_{00}$ Au+Au $\sim$ Zr+Zr $\sim$ Ru+Ru

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\( \rho_{00} (p_T): K^*0 \) and anti-\( K^*0 \)

- **Species dependence:**
  - \( K^*0 \) \( \rho_{00} \) \( \sim \) anti-\( K^*0 \) \( \rho_{00} \) \( \sim 1/3 \)

- Plot shows data points for Ru+Ru and Zr+Zr collisions at 200 GeV, with species dependence indicated through graphical representation.
\( \rho_{00} (p_T): K^*0 \) and anti-\( K^*0 \)

- **Species dependence:**
  - \( K^*0 \) \( \rho_{00} \) ~ anti-\( K^*0 \) \( \rho_{00} \) ~ 1/3

- **System size dependence:**
  - \( \rho_{00} \) Au+Au ~ Zr+Zr ~ Ru+Ru
$\rho_{00}(p_T): K^*+/-$

```
\begin{itemize}
  \item System size dependence:
  \begin{itemize}
    \item $\rho_{00} \text{ Zr+Zr} \sim \text{ Ru+Ru}$
  \end{itemize}
\end{itemize}
```
$\rho_{00}(p_T)$: $K^*/-\text{ and } K^*0$

- **System size dependence:**
  - $\rho_{00}$ Zr+Zr $\sim$ Ru+Ru

- **Particle species dependence:**
  - $K^*/-$ $\rho_{00}$ $> K^0$ $\rho_{00}$
Summary

- We presented $\rho_{00}$ of $\phi$ and $K^*$ from Au+Au BES-I at 11.5-200 GeV

- For 20-60%: $\rho_{00}(\phi) > 1/3$, $\rho_{00}(K^*) \sim 1/3$

- Beam energy dependence of $\phi$ $\rho_{00}$ at mid-central collisions is consistent with a model fitting with vector meson force fields

- We presented $\rho_{00}$ of $K^*$ and $K^{*/-}$ from RHIC Isobar (Ru+Ru & Zr+Zr) at 200 GeV
  - For 20-60%: $\rho_{00}(K^{*/-}) > \rho_{00}(K^*)$
  - $\rho_{00}(K^*)$: Zr+Zr ~ Ru+Ru ~ Au+Au

- More inputs from theory are needed to interpret the $\rho_{00}$ measurements
Thank you for your attention
Backup slides
\( \rho_{00} (\text{Centrality}): K^*0 \text{ and anti-}K^*0 \text{ from isobar} \)

- **Species dependence:**
  - \( K^*0 \rho_{00} \sim \text{anti-}K^*0 \rho_{00} \)

- **System size dependence:**
  - \( \rho_{00} \text{ Au+Au } \sim \text{Zr+Zr } \sim \text{Ru+Ru} \)
Simulation framework for efficiency and acceptance

Input: embedded MC K* + real data tracks

Calculate Ψ from real data tracks

Reject MC K* in φ-Ψ to mimic measured K* v2(pT)

Calculate \( \cos \theta^* \) wrt Ψ for MC K* tracks

Reconstructed (RC) K*

RC K* and its daughters
Apply experimental acceptance and track cuts on daughters
&
Consider K* v2(pT) effects accordingly

Calculate \( \cos \theta^* \) wrt Ψ for RC tracks

Results corrected for K* v2 bias

Efficiency \times\text{ Acceptance} = \frac{\text{RC}}{\text{MC}}

Correction factor includes acceptance and efficiency (pT, φ-Ψ, \( \cos \theta^* \)) with v2 effect included
Efficiency and acceptance for $K^*$

Isobar 200 GeV, 20-60%, $2.0 < p_T < 2.5$ GeV/c

MC Embedding ($K^0$)

Efficiency $\times$ Acceptance for $K^0$

Isobar 200 GeV, 20-60%, $2.0 < p_T < 2.5$ GeV/c

MC Embedding ($K^+$)

Efficiency $\times$ Acceptance for $K^+$
$\rho_{00} (\sqrt{s_{NN}})$: $\phi$ and $K^{*0}$ for central collisions from BES-I

STAR Collaboration, arXiv: 2204.02302

Au+Au (0-20% & $|y| < 1.0$)