φ Meson and K*0 Global Spin Alignment at STAR

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Introduction

- Initial angular momentum $\mathbf{L} \sim 10^3 \hbar$ in non-central heavy-ion collisions at RHIC.
- Baryon stopping transfers this angular momentum, in part, to the fireball.
- Due to vorticity and spin-orbit coupling, particle’s spin may align with $\mathbf{L}$.
- Spin alignment/polarization is a sensitive probe to vortical structure of QGP, fluid property and particle production mechanisms.

Sergei A. Voloshin, nucl-th/0410089, and many others
Significant $\Lambda$ and $\bar{\Lambda}$ global polarization observed.

Most vortical fluid produced at RHIC.
Why $\phi$ and $K^*$

- Originate predominantly from primordial production, thus less affected by feed-down compared to $\Lambda$ and anti-$\Lambda$.

- Spin-1 particles, daughters’ polar angle distribution is even function. No local cancellation associated with odd function (the case for spin-1/2 particles e.g. $\Lambda$) when integrate over time and phase space.

- Additional access to strange and light quark polarization (in particular for $\phi$ meson, clean access to strange quark polarization).
Global Spin Alignment

• For $S=1$ particles, spin alignment can be determined from the angular distribution of the decay products:

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

$N_0$: normalization.
$\theta^*$: the angle between the polarization direction $\mathbf{L}$ and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

$\rho_{00}$: deviation from $1/3$ signals net-spin alignment.

$\rho_{00} > 1/3$: 
$\rho_{00} = 1/3$: 
$\rho_{00} < 1/3$: 

Hadronization Scenarios and Spin Alignment

• Recombination of polarized (anti)quarks: $\rho_{00} < 1/3$

$$
\rho_{00}^{\phi(\text{rec})} = \frac{1 - P_s^2}{3 + P_s^2}, \quad \rho_{00}^{K^0(\text{rec})} = \frac{1 - P_q P_s}{3 + P_q P_s}
$$

• Fragmentation of polarized quarks: $\rho_{00} > 1/3$

$$
\rho_{00}^{\phi(\text{frag})} = \frac{1 + \beta P_s^2}{3 - \beta P_s^2}, \quad \rho_{00}^{K^0(\text{frag})} = \frac{f_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2}
$$

$p_q = -\frac{\pi}{4} \frac{\mu p}{E(E + m_q)}$ is the global quark polarization

$p_q^{\text{frag}} = -\beta p_q$ is the polarization of the (anti-)quark created in the fragmentation process

$n_s$ and $f_s$ are the strange quark abundances relative to up or down quarks in QGP and quark fragmentation, respectively.


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STAR’s Previous Results

- STAR has published results with data taken in year 2004.
- Updated \( \phi \) meson results shown at QM’17, with data taken in year 2010 & 2011.
- Both of the above use the 2nd-order event plane (EP) obtained from TPC. The published result is consistent with 1/3 for both \( \phi \) and \( K^*_0 \); QM’17 results with reduced uncertainties for \( \phi \) suggest a \( p_T \) dependence.
- In this analysis: \( \sim 20 \) times more data than that was used in 2004; the 1st-order EP for \( \phi \).

\[ \begin{matrix}
\begin{array}{c}
\text{fragmentation:} \\
P_pP = 0.3 \\
\text{coalescence:} \\
p_pP < 0.15
\end{array}
\end{matrix} \]
The STAR Detector

The Solenoidal Tracker at RHIC

- Large acceptance ($2\pi$ azimuthal angle coverage).
- Excellent particle identification capabilities.
- EP reconstruction by ZDC-SMD, BBC (the 1st-order EP) or by TPC (the 2nd-order EP).
Procedure of $\rho_{00}$ Measurement

1. Invariant mass of daughter pairs
2. Background subtraction
3. Yield extraction
4. Raw $\rho_{00}$ extraction ($\rho_{00}^{\text{obs}}$)
5. $\rho_{00}$ after correction for EP resolution ($\rho_{00}^{\text{rec}}$)

(Finite $\eta$ acceptance effect has been determined to be negligible compared to other systematics. The de-correlation between the 1st- and 2nd-order EP has not been accounted for.)
φ Meson: Reconstruction and Yields

- φ meson:
  - K+K- invariant mass
  - Normalized mixed events background

- Signal fitting:
  - Breit-Wigner function
  - Linear residual background

\[
BW(m_{inv}) = \frac{1}{2\pi} \frac{A\Gamma}{(m - m_\phi)^2 + (\Gamma / 2)^2}
\]

- Yield extraction:
  - Integrate Breit-Wigner function over
    \([m_\phi - 2\Gamma, m_\phi + 2\Gamma]\)

Invariant mass distribution before/after background subtraction
Au+Au 200 GeV
Centrality: 40%-50%

Fitting of a single \(p_T\) & \(\cos\theta^*\) bin.
Au+Au 200 GeV
Centrality: 40%-50%  \(p_T\): 1.2~1.8 GeV/c  \(\cos\theta^*\): 1/7~2/7

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**K*⁰ : Reconstruction and Yields**

- **K*⁰:**
  - $\pi K$ invariant mass
  - Rotated pairs background.

- **Signal fitting:**
  - Breit-Wigner function
  - Linear residual background

\[
BW(m_{inv}) = \frac{1}{2\pi} \frac{A\Gamma}{(m - m_{K^*0})^2 + (\Gamma / 2)^2}
\]

- **Yield extraction:**
  - Histogram bin counting.

Invariant mass distribution before/after background subtraction

Au+Au 39 GeV
Centrality: 20%-60%  \( p_T: 1.2-5.0 \text{ GeV/c} \)  \( \cos\theta^*:0-0.2 \)
Observed $\rho_{00}$ Extraction for $\phi$ and $K^{*0}$

- Observed $\rho_{00}$ is extracted by fitting the yield with

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

Here $\theta^*$ is what we observed from the raw data and can be different from the real value.

**STAR preliminary**

$$dN \propto dL \cdot \vec{p}_{k^*} \cdot \cos \theta^*$$

Fitting of $\phi$ yield vs. $\cos\theta^*$

- Au+Au 200 GeV
- Centrality: 40-50%
- $p_T$: 1.2-1.8 GeV/c

$$\rho_{00}^{\text{obs}} = 0.3785 \pm 0.0048$$
The Smearing of EP

- The observed EP $\psi'$ may be different from the real EP $\psi$. The smearing can be quantified by $R$:

$$ R = \langle \cos 2\Delta \rangle $$

where $\Delta$ is the difference between observed and real EP angle:

$$ \Delta = \psi - \psi' $$

- The smearing of EP tends to decrease possible deviations of $\rho_{\text{obs}}^{00}$ from the value of $1/3$, which should be corrected for.

The 1st-order EP is obtained from ZDC-SMD, while the 2nd-order EP is obtained from TPC.
EP Resolution Correction

- The correction is applied with the formula* for S=1 particles:
  \[ \rho_{00}^{rec} - \frac{1}{3} = \frac{4}{1 + 3R} (\rho_{00}^{obs} - \frac{1}{3}) \]

*Verifying the correction formula: events are generated by Pythia* with \( \Delta \) following the probability density function**:

\[ P(\Delta) = \frac{1}{2\pi} \left[ e^{-\frac{\Delta^2}{2}} + \sqrt{\frac{\pi}{2}} \cos(\Delta) e^{-\frac{\Delta^2}{2}} \times (1 + \text{erf}(\Delta \cos \frac{\Delta}{\sqrt{2}})) \right] \]

\( \rho_{00} \) are at expected values after correction.


Following slides will include these results:

- Previous $\phi$ measurement:
  - $\rho_{00}$ reconstructed with the 2nd-order EP
  - $p_T$ and energy dependences
  (systematic uncertainty overestimated due to incomplete understanding of the effect of EP resolution by QM'17.)

- Updated $\phi$ measurement:
  - $\rho_{00}$ reconstructed with the 1st-order EP
  - $p_T$, centrality and energy dependence

- Updated $K^{*0}$ measurement:
  - $\rho_{00}$ reconstructed with the 2nd-order EP
  - more data taken in year 2010 & 2011
  - $p_T$ and energy dependences
• The results are integrated over centrality 20-60%.

• $p_T$ dependence is seen. $\rho_{00} > 1/3$ at $p_T \sim 1.5 \text{ GeV/c}$.

(Systematic uncertainty for the 2nd-order EP result was overestimated due to incomplete understanding of the effect of EP resolution by QM’17.)
Centrality Dependence of $\phi \rho_{00}$

- The results are integrated over $1.2 < p_T < 5.4$ GeV/c.
- For non-central collisions, $\rho_{00}$ is significantly larger than 1/3.
Energy Dependence of $\phi \rho_{00}$ in Au+Au collisions

- The results are integrated over $1.2 < p_T < 5.4$ GeV/c and centrality 20-60%.

- No significant energy dependence.

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$\phi$ meson
$1.2 < p_T < 5.4$ GeV/c
Centrality 20-60%
The results are integrated over centrality 20-60%.

For $p_T > 1.2$ GeV/c, $K^{*0} \rho_{00}$ is less than 1/3, with a deviation between 1$\sigma$ and 2$\sigma$. 
Energy Dependence of K^*0 ρ_{00}

• The results are integrated over 1.2 < p_T < 5.0 GeV/c and centrality 20-60%.

• No significant energy dependence.
Reconciling Measurements: Open Questions

<table>
<thead>
<tr>
<th>Particle symbol</th>
<th>Quark content</th>
<th>Rest mass (MeV/c²)</th>
<th>Mean lifetime (fm/c)</th>
<th>Alignment/polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>K*</td>
<td>d̅s</td>
<td>891.66±0.026</td>
<td>~4</td>
<td>ρ₀₀ &lt; 1/3 for p_T &gt; 1.2 GeV/c</td>
</tr>
<tr>
<td>φ(1020)</td>
<td>s̅s</td>
<td>1019.461±0.019</td>
<td>~46</td>
<td>ρ₀₀ &gt; 1/3 at p_T ~ 1.5 GeV/c</td>
</tr>
<tr>
<td>Λ⁰</td>
<td>uds</td>
<td>1115.683±0.006</td>
<td>~7.9×10¹³</td>
<td>P_H &gt; 0</td>
</tr>
</tbody>
</table>

\[
\rho^{φ_{\text{rec}}}₀₀ = \frac{1 - P_s^2}{3 + P_s^2}, \quad \rho^{K^{0}_{\text{rec}}}₀₀ = \frac{1 - P_q P_s}{3 + P_q P_s}
\]

\[
\rho^{φ_{\text{frag}}}₀₀ = \frac{1 + \beta P_s^2}{3 - \beta P_s^2}, \quad \rho^{K^{0}_{\text{frag}}}₀₀ = \frac{f_s \left(1 + \beta P_q^2\right)}{n_s + f_s} + \frac{n_s \left(1 + \beta P_q^2\right)}{n_s + f_s}
\]

- Observations do not fit a naive coalescence/recombination picture*.

- Contribution from gluon and sea-quark polarization? (Recall the gluon contribution to proton spin.)

- Lock parton polarization at different production time?

• Significant Λ global polarization is observed. $P_H$ decreases with the increase of energy.

• The spin alignment of $\phi$ and $K^{*0}$ do not show significant energy dependence.
Odd function of $x$ (the unit vector in reaction plane perpendicular to the beam line) and $\eta$.

$\Lambda$ polarization partially cancels when taking an average over $\eta$ and $x$.

Cancellation is severe at high energy for which the vorticity field is closer to a perfect odd function.

Spin alignment is sensitive to the strength, not the sign, of the vorticity field. Thus there is no cancellation for $\phi$ and $K^{*0}$ spin alignment.


The difference in energy dependence between $\Lambda$ polarization and $\phi/K^{*0}$ spin alignment may be due to the different response to the vorticity field between spin-1/2 and spin-1 particles.
Summary

• For $\phi$ meson, the dependence of $\rho_{00}$ as a function of $p_T$ and centrality has been observed. In Au+Au collisions at 200 GeV, the measured $\rho_{00}$ is $> 1/3$ at $p_T \sim 1.5$ GeV/c in centrality 20-60%.

• For $K^*$, in Au+Au collisions at 39 GeV, $\rho_{00}$ is $< 1/3$ with $1\sigma$-$2\sigma$ deviation, for $p_T > 1.2$ GeV/c in centrality 20-60%.

• For both $\phi$ and $K^*$ $\rho_{00}$, no significant energy dependence is seen.

• Particle production and vorticity induced by initial angular momentum are possible sources that might contribute to the observation. However, at $p_T \sim 1.5$ GeV/c $\rho_{00}$ for $\phi$ ($K^*$) is $> 1/3$ ($< 1/3$), which does not fit a simple picture of coalescence/recombination/fragmentation with polarized quarks.

• Additional theoretical efforts are needed to understand these features.
Backups
The de-correlation can be applied with the formula* for S=1 particles:

\[ \rho_{00}^{1st} - \frac{1}{3} = \frac{1 + 3R_2}{1 + 3D_{12} \cdot R_1} (\rho_{00}^{2nd} - \frac{1}{3}) \]

where

\[ R_{1,2} = \langle \cos 2(\Psi_{1,2} - \Psi) \rangle \]
\[ D_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle \]

* A. Tang, B. Tu, C. S. Zhou, arxiv:1803.05777

The de-correlation between the 1st- and 2nd-order EP explains part of the difference.

For now we keep the 2nd-order EP results the same as the previous.
For the final results, the de-correlation correction will be applied on the 2nd-order EP (and the systematic error will be reduced with the understanding of the detector effect).
• $\phi$ meson efficiency*acceptance is calculated with $K^+$ and $K^-$ embedding data and shows very weak $\cos\theta^*$ dependence, and the effect on $\rho_{00}$ is negligible.

• Here “acceptance” is the acceptance of $\phi$ meson.

• The acceptance of daughter particles will affect the result*. The correction for effect will be considered in next two backup slides.

Acceptance Correction

- The TPC does not have full acceptance. In our analysis, a cut of $|\eta|<1$ is required for daughters.

- This cut may introduce an artificial spin alignment. To quantify it, we regard the observed distribution as a convolution of real signal and acceptance effect:

$$\left[ \frac{dN}{d\cos\theta^*d\beta} \right]_{|\eta|<1} = \frac{dN}{d\cos\theta^*d\beta} \cdot g(\cos\theta^*,\beta)$$

- Note that this effect is symmetrical w.r.t the z-axis, we can describe it as:

$$g(\cos\theta^*,\beta) = 1 + F^* \cos^2 \theta$$

$$= 1 + F^* \sin^2 \theta^* \sin^2 \beta$$

$$= 1 + F^* \sin^2 \theta^* \frac{1 - \cos 2\beta}{2}$$

$$= 1 + \frac{F^*}{2} - \frac{F^*}{2} \cos^2 \theta^* - \frac{F^*}{2} \sin^2 \theta^* \cos 2\beta$$

$$\approx 1 + F \cos^2 \theta^* + F \sin^2 \theta^* \cos 2\beta$$

where $F = \frac{F^*}{2 + F}$

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Acceptance Correction

- With the EP resolution correction and acceptance correction term \( g(\cos\theta^*, \beta) \) both considered, we have:

\[
\left[ \frac{dN}{d\cos\theta^*} \right]_{|\eta|<1} \propto (1+\frac{B' F}{2}) + (A' + F) \cos^2 \theta^* + (A' D - \frac{B' F}{2}) \cos^4 \theta^* 
\]

where:

\[
A' = \frac{A(1+3R)}{4 + A(1-R)}, \quad B' = \frac{A(1-R)}{4 + A(1-R)}
\]

here \( A = (3\rho_{00}^{\text{real}} - 1)/(1 - \rho_{00}^{\text{real}}) \), \( R \) is the resolution. \( F \) describes the effect of acceptance.


A Monte Carlo simulation to verify the acceptance correction procedure. \( \rho_{00} \) are at expected values after correction.