φ-meson Global Spin Alignment at RHIC

- Results and Practical Considerations

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Outline

I : Global spin alignment of $\phi$-meson at RHIC - Results

II : Practical considerations for measuring global spin alignment of $\phi$-meson

Conclusion
In non-central collisions, large orbital angular momentum $L$ ($\sim 10^3$ at RHIC energies) is deposited in the interaction region.

Viscosity dissipates the vorticity to QGP fluid at a larger scale.
Local orbital angular momentum (vorticity) transferred to spin degree of freedom of final-state hadrons. **Classical Mechanics ➔ Quantum Mechanics.**

Shed light on the fundamental spin-rotation coupling.
Most Vortical Fluid

STAR Collaboration, NATURE 548 62 (2017)

Fluid produced at RHIC: the least viscous and the most vortical!
Why $\phi$ spin alignment?

- $\phi$-mesons are expected to originate predominantly from primordial production ➔ less decay contributions if compared to hyperons, more sensitive to early dynamics.

- Daughter’s polar angle distribution is even function for spin-1 particles ➔ no local cancelation when integrating over phase space as opposed to spin-1/2 particles. The alignment is in general additive over space and time.

- Clean access to strange quark polarization.
Interconnection to Other Physics

• Spin-orbit coupling ➔ magnitude of the vorticity. (connection to CVE)

• Reaction plane dependence of alignment/polarization ➔ transport properties (e.g. viscosity).

• Transverse momentum dependence of alignment/polarization ➔ Hadronization.

• Degree of Thermalization ?

• Vorticity induced magnetic field ?

New channel, insight to rich physics
Connection to Chiral Vortical Effect

Baryonic Charge Separation

$$\vec{J}_B = \frac{N_c \mu_5}{\pi^2} \mu_B \vec{\omega}$$

Constrain the vorticity ($\omega$) : φ spin alignment (and (anti)Λ polarization) w.r.t. the system angular momentum (L).

Electric Charge Separation

$$\vec{J}_E = \frac{N_c \mu_5}{3\pi^2} \vec{B}$$

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Kharzeev & Son PRL 106 062301 (2011)
Vorticity, maximum in the reaction plane, may not be propagated efficiently from in- to out-of-reaction plane due to the low viscosity of the system. This may lead to larger in-plane than out-of-plane polarization/spin alignment.

For $\phi$ spin alignment,

- Recombination of polarized (anti)quarks: $\rho_{00} < 1/3$.
  
  $\rho_{00}^{\phi({\text{rec})}} = \frac{1 - P_s^2}{3 + P_s^2}$

- Fragmentation of polarized quarks: $\rho_{00} > 1/3$.
  
  $\rho_{00}^{\phi({\text{frag})}} = \frac{1 + \beta P_s^2}{3 - \beta P_s^2}$

$P_s$: strange quark polarization
$\beta$: the ratio of polarization of antiquark, in the opposite direction, to that of leading quark.
Relativistic Heavy Ion Collider (RHIC)
STAR : Uniform and Large Acceptance

- EEMC
- Magnet
- MTD
- TPC
- TOF
- BBC

ZDCSMD
STAR : Excellent PID and Tracking

Charged hadrons

Hyperons & Hyper-nuclei

Neutral particles

Jets & Correlations

High pT muons

Heavy-flavor hadrons
The 00-component of $\phi$-meson spin density matrix ($\rho_{00}$) can be measured via angular distribution of decay daughter ($\phi \rightarrow K^+K^-$) using:

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

A deviation of $\rho_{00}$ from 1/3 would indicate a non-zero spin alignment.

$$\rho_{00} = \frac{1}{3}$$

$$\rho_{00} > \frac{1}{3}$$

$$\rho_{00} < \frac{1}{3}$$
Consistent with $\rho_{00} = 1/3$ with large uncertainties.

Both done with $2^{nd}$-order event plane with TPC.
First time seeing $\rho_{00} > 1/3$ in heavy-ion collisions.
Non-trivial $p_T$ dependence.
Fragmentation around 1.5 GeV/c? Model over-simplified?
The relation between the two measurements will be discussed later in this talk.
Smooth centrality dependence, strongest in semi-central collisions.
Significant alignment observed at 200 and 39 GeV. Supporting the picture of strong vorticity.
\( \rho_{00} \) vs Energy

\[ \begin{align*}
\rho_{00} : \text{seemingly weaker dependent on energy} \\
\text{if compared to } P_H
\end{align*} \]
Odd function of $x$ and $\eta$.

$\Lambda$ polarization cancel each other when taking average.

Cancellation is severe at high energy for which the vorticity is more close to perfect odd function.

No cancellation for $\phi$ spin alignment.

Could the difference in energy dependence between $\Lambda$ polarization and $\phi$ spin alignment explained by the different response to the vorticity field?
Practical Considerations for Measuring Global Spin Alignment of Spin-1 Vector Mesons

Derivation of Event Plane Resolution Correction

For spin-1 particles, their daughter’s angular distribution can be written in a general form as a function of $\theta^*$ and $\beta$:

$$\frac{dN}{d \cos \theta^* d \beta} \propto 1 + A \cos^2 \theta^* + B \sin^2 \theta^* \cos 2\beta + C \sin 2\theta^* \cos \beta$$

where

$$A = \frac{3\rho_{00} - 1}{1 - \rho_{00}}$$

We have

$$\cos \theta^* = \sin \theta \sin(\phi - \psi)$$

$$\cos \theta = \sin \theta^* \sin \beta$$

where $\theta$ is the angle between z-axis and the momentum direction of a daughter particle in the rest frame.
The observed event plane $\psi'$ may be different from the real event plane: $\psi' = \psi + \Delta$.

The distribution of $\Delta$ is supposed to follow an even function, so we can assume

\[
\langle \cos 2\Delta \rangle = R, \quad \langle \sin 2\Delta \rangle = 0.
\]

When $\psi' \rightarrow \psi$, $\theta^* \rightarrow \theta^*$, $\beta \rightarrow \beta'$, we have

\[
\begin{pmatrix}
1 \\
A \\
B \\
C
\end{pmatrix} \rightarrow \begin{pmatrix}
1 \\
A' \\
B' \\
C'
\end{pmatrix} = \frac{1}{4 + A(1 + 3R) + B(3 - 3R) + A(1 - R) + B(3 + R) + 4 \cdot C \cdot R + 4 + A(1 - R) + B(-1 + R)}
\]

When $B = 0$, $A' = \frac{A(1 + 3R)}{4 + A(1 - R)}$

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

It can be shown that it is consistent with the correction procedure (Voloshin SQM2017)

\[
\rho_{00}^{\text{real}} - \frac{1}{3} = -\frac{4}{3} \langle \cos 2(\varphi - \psi_{EP}) \rangle
\]
Recall the resolution correction,

\[ R = \langle \cos 2\Delta \rangle \]

For the 1\textsuperscript{st}-order EP, the corresponding correction term becomes

\[ R_1 = \langle \cos 2(\psi_1 - \psi) \rangle \]

and for the 2\textsuperscript{nd}-order EP with the consideration of de-correlation, the correction term can be written as:

\[ R_{12} = \langle \cos 2(\Psi_2 - \Psi_1 + \Psi_1 - \Psi) \rangle = D_{12} \cdot R_1, \]

where

\[ D_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle \]

Then we can take the corrected \( \rho_{00} \) from the 1\textsuperscript{st}-order EP as real \( \rho_{00} \), and use the resolution correction formula to recover the 2\textsuperscript{nd}-order EP result.

\[
\rho_{00}^{2nd} - \frac{1}{3} = \frac{4}{1 + 3R_2} (\rho_{obv}^{2nd} - \frac{1}{3}) = \frac{1 + 3R_{12}}{1 + 3R_2} (\rho_{00}^{1st} - \frac{1}{3})
\]
The de-correlation between the 1\textsuperscript{st} and 2\textsuperscript{nd} event planes explains part of the difference. The remaining difference may due to $B\neq 0$ in the angular distribution:

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A \cos^2 \theta^* + B \sin^2 \theta^* \cos 2\beta + C \sin 2\theta^* \cos \beta$$
Effect of Finite $\eta$ Acceptance

Finite $\eta$ coverage can introduce an artificial $\rho_{00}$

AMPT Au+Au 200GeV

- $\eta$ cuts on $K$ and $\phi$-meson
- $\eta$ cuts on $K$ only
- $\eta$ cuts on $\phi$-meson only
- $\eta$ and $p_T$ cuts on $K$ and $\phi$-meson

Input $\rho_{00} = 1/3$

Input $\rho_{00} = 0.2$
Correction for Finite $\eta$ Acceptance

Recall the correction for EP resolution:

$$\rho_{00}^{\text{real}} - \frac{1}{3} = \frac{4}{1 + 3R} (\rho_{00}^{\text{obs}} - \frac{1}{3})$$

for random $\Psi$ in the transverse plane, $R=0$:

$$\rho_{00}^{\text{real}} - \frac{1}{3} = 4(\rho_{00}^{\text{obs}} - \frac{1}{3})$$

The observed $\cos\theta^*$ distribution can be regarded as a convolution of distribution caused by real spin alignment ($f(\theta^*)$) and that caused by finite $\eta$ coverage ($g(\theta^*)$),

$$\left[ \frac{dN}{d(\cos\theta^*)} \right]_{\text{observed}} \propto f(\theta^*)g(\theta^*) \quad \text{where } (g(\theta^*)) \text{ remains the same with random } \Psi.$$  

To cancel $g(\theta^*)$, we propose to measure the distribution of $\cos\theta^*$ with EP randomized in transverse plane as well, and take the ratio of usual measurement to it

$$\left[ \frac{dN}{d(\cos\theta^*)} \right]_{\text{observed}} \propto \frac{(1 - \rho_{00}^{\text{obs}}) + (3\rho_{00}^{\text{obs}} - 1)\cos^2\theta^*}{(1 - \rho_{00}^{\text{rdm}}) + (3\rho_{00}^{\text{rdm}} - 1)\cos^2\theta^*}$$

$$= \frac{5 + \rho_{00} + R(3\rho_{00} - 1) + (1 + 3R)(3\rho_{00} - 1)\cos 2\theta^*}{5 + \rho_{00} + (3\rho_{00} - 1)\cos 2\theta^*}$$

which can be used to extract $\rho_{00}$. 

Aihong Tang  Chirality Workshop  
Galileo Galilei Institute 19-22 March 2018
Correction for Finite $\eta$ Acceptance

With correction, $\rho_{00}$ from different $\eta$ acceptances converge onto the right value.
A finite spin alignment in helicity frame will cause an artificial azimuthal angle dependence, and such artificial azimuthal dependence will be there w.r.t any plane, not just EP.

We propose to rotate the global angular momentum vector $L$ randomly in 3-dimensional space, with that the real spin alignment signal will be destroyed completely, and the artificial one remains.

The observed signal can be regarded as

$$\left[ \frac{dN}{d(\cos \theta^*)} \right]_{\text{observed}} \propto (1 + A_{\text{random3D}} \cos^2 \theta^*)(1 + A \cos^2 \theta^*)$$

with $A_{\text{random3D}}$ measured independently, the real $A$ can be extracted.
Complications for Measuring Azimuthal Angle Dependence

The correction for EP resolution is a non-trivial task, because smearing of EP will affect both $L$ (thus $\theta^*$) and $(\phi-\psi)$ angle.

![Diagram showing the effect of smearing on bins](image)
Complications for Measuring Azimuthal Angle Dependence

\[
\begin{bmatrix}
\rho_{00,1}^{\text{obs}} - \frac{1}{3} \\
\rho_{00,2}^{\text{obs}} - \frac{1}{3} \\
\vdots \\
\rho_{00,n}^{\text{obs}} - \frac{1}{3}
\end{bmatrix}
= A
\begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\begin{bmatrix}
\rho_{00,1}^{\text{real}} - \frac{1}{3} \\
\rho_{00,2}^{\text{real}} - \frac{1}{3} \\
\vdots \\
\rho_{00,n}^{\text{real}} - \frac{1}{3}
\end{bmatrix}
\]

\[
a_{ij} = \frac{M_{ji}}{\sum_i M_{ji}} \frac{4}{1+3r_{ji}} \frac{\sum_k m_{ij}^k \cos[2*(\Psi_{\text{obs}}^k - \Psi_{\text{RP}})]}{M_{ij}}, \quad w_{ij} = \frac{\sum m_{ij}}{\sum m_{kj}}
\]

The procedure accurately recovers input values. With slight modification, can also be used in the study of azimuthal dependence of (anti)Lambda global polarization.
Summary

◆ **Significant $\phi$ global spin alignment is seen at RHIC.** Particle production and vorticity induced by initial angular momentum are possible sources that might contribute to the new observation.

◆ A few important practical considerations for measuring $\phi$ global spin alignment discussed.
  - Correction for event plane resolution,
  - Comparison between $\rho_{00}$ measured with different planes,
  - Correction for finite pseudorapidity coverage,
  - Complications in measuring azimuthal dependence and how to handle.
Backup Slides
Chiral Vortical Effect vs Chiral Magnetic Effect

<table>
<thead>
<tr>
<th>Chiral Vortical Effect</th>
<th>vs</th>
<th>Chiral Magnetic Effect</th>
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<tbody>
<tr>
<td>Chirality Imbalance ($\mu_A$)</td>
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<tr>
<td>Fluid Vorticity ($\omega\mu_B$)</td>
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<td>Magnetic Field ($\omega\mu_e$)</td>
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<td>Baryon Number ($j_B$)</td>
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<td>Electric Charge ($j_e$)</td>
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Baryonic Charge Separation  Electric Charge Separation
Particle Level Resolution

For particles that stay in the vicinity bins after smearing, their events experience less EP perturbation than those that end further from the original bin. Thus the EP resolution correction should be applied differently for different bins.

Define particle level resolution $r_{ij}$, which takes care of particles that are from bin \(i\) before smearing and end in bin \(j\) after smearing,

$$r_{ij} = \frac{\sum_k m_{ij}^k w_{ij} \cos[2*(\Psi_{obs}^k - \Psi_{RP}^k)]}{M_{ij}}$$

Where $w_{ij} = \frac{\sum_j m_{ij}}{\sum_j m_{ij}^k}$, and $\langle L \rangle$ denotes the average over events.
Simulation on EP smearing

For a given $\Delta\Psi$, we can trace the contribution from original bin $i$ to bin $j$ after smearing, by integrating the relative particle yield:

$$\frac{1}{2\pi} \int_{x_1}^{x_2} 1 + 2v_2 \cos(2\phi) d\phi = \left(\frac{1}{2\pi} (\phi - v_2 \sin(2\phi))\right)_{x_1}^{x_2}$$

This process can be repeated over many $\Delta\Psi$ for which the pdf. is given by:

$$f(\Delta\Psi) = \frac{1}{2\pi} \left[ e^{-\frac{x^2}{2}} + \sqrt{\frac{\pi}{2}} z \cos(\Delta\Psi) e^{-\frac{z^2 \sin^2(\Delta\Psi)}{2}} \left(1 + \text{erf}(z \cos \frac{\Delta\Psi}{\sqrt{2}})\right)\right]$$


Thus $a_{ij} = \frac{M_{ij}}{\Sigma_i M_{ij}} \times \frac{4}{1 + 3r_{ij}}$ can be determined