Polarization Measurements of Hyperons and Vector Mesons in Heavy Ion Collisions at STAR

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• Motivations
• Detector Setup and Analysis Technique
• Results
  – \( \Lambda \) Global Polarization Measurement
  – Spin alignment measurement of vector mesons \( (K^*, \phi) \)
  • w.r.t. Reaction Plane – Global Polarization
  • w.r.t. Production Plane – Production dynamics
• Conclusions

System orbital angular momentum

- Large orbital angular momentum possessed in non-central Au+Au collisions:

\[ \Delta p_z = \Delta x \frac{dp_z}{dx} \]
\[ L_y = -\Delta x \Delta p_z \]
\[ = -\Delta x^2 \frac{dp_z}{dx} \]

Global Polarization

• Transformation of the large angular momentum $\vec{L}$ into the particle spin

  $\rightarrow$ Global Polarization

• Features of global polarization:
  – For non-central collisions, it should have a finite value, at small $p_T$
    in central rapidity;
  – It should increase with the impact parameter $b$;
  – It should vanish in central collisions

$\vec{L}$ is perpendicular to the reaction plane
Correlations with respect to (w.r.t.) the reaction plane
(Anisotropic flow technique)

Global vector meson spin alignment and global hyperon polarization
### Spin Alignment (w.r.t. the reaction plane) – probe global polarization in HIC

It is sensitive to different hadronization scenarios in different kinematic region

- **Coalescence** ($\rho_{00} < 1/3$)
  
  \[ \rho_{00}^{(\text{rec})} = \frac{1 - P_q^2}{3 + P_q^2}, \]

  \[ \rho_{00}^{K^*(\text{rec})} = \frac{1 - P_q P_s}{3 + P_q P_s}. \]

- **Fragmentation** ($\rho_{00} > 1/3$)
  
  \[ \rho_{00}^{\rho^{\text{frag}}} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}, \]

  \[ \rho_{00}^{K^*(\text{frag})} = \frac{f_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s} \frac{1 + \beta P_s^2}{3 - \beta P_s^2}. \]

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### Spin alignment w.r.t the production plane – production mechanisms

- particle formation dynamics or to intrinsic quark transverse spin distribution

  - B. Andersson et. al. PLB 85, 417 (1979); J. Szwed PLB 105, 403 (1981); R. Barni et. al. PLB 296, 251 (1992); J. Soffer et. al. PRL 68, 907 (1992)

- May be correlated with the global polarization convoluted with an azimuthal angular anisotropy ($v_2$)

  S. Voloshin, nucl-th/0410089

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\[ \rho_{00} \text{ -- spin density matrix element (1/3 for unpolarized case)} \quad \rho_{00} = 1 - \rho_{11} - \rho_{-1-1} \]
Heavy Ion Collisions: \( \text{Au} + \text{Au}, \text{Cu} + \text{Cu}, \text{d} + \text{Au} \) \( \sqrt{s_{NN}} = 200 \) GeV

Polarized p + p Collisions: \( \vec{p} + \vec{p}, p \uparrow + p \uparrow \) \( \sqrt{s} = 200 (500) \) GeV
Detector, Data Sample & Reconstruction

Solenoidal Tracker At RHIC (STAR)

*Time Projection Chamber* ($|\eta|<1$, full azimuth)

Data Samples:
- Au+Au 200 GeV minimum bias
  - ~23 M events
- Au+Au 62.4 GeV minimum bias
  - ~8 M events
- p+p 200 GeV Non-Singly Diffractive
  - ~6 M events

*Topological reconstruction*

*Mixed-event method to describe the combinatorial background*

- $\Lambda \rightarrow p\pi^-$
- $K^* \rightarrow K^+\pi^-$
- $K^0 \rightarrow K^+\pi^-$
- $\phi \rightarrow K^+K^-$

Oct. 6-11th, 2008, SPIN 2008, Charlottesville, VA   X. Dong / LBNL
Analysis Technique

Measuring the decay daughter momentum distribution in the rest frame of its parent particle w.r.t. the polarization direction.

**Lambda global polarization**

\[
\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H P_H \cos \theta^*
\]

decay parameter = 0.642 for $\Lambda$

\[
P_H = \frac{3}{\alpha_H} \langle \cos \theta^* \rangle
\]

**Vector meson spin alignment**

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

\(\rho_{00} \) -- spin density matrix element

1/3 for unpolarized case
Event Plane Reconstruction

Standard event plane reconstruction method in flow analysis in STAR.


\[
Q_n \cos(n \Psi_n) = X_n = \sum_i w_i \cos(n \phi_i)
\]

\[
Q_n \sin(n \Psi_n) = Y_n = \sum_i w_i \sin(n \phi_i).
\]

\[
\Psi_n = \left( \tan^{-1} \frac{\sum_i w_i \sin(n \phi_i)}{\sum_i w_i \cos(n \phi_i)} \right) / n
\]

Global polarization – similar to $v_1$ analysis

Use tracks at the Forward TPC detectors ($2.8 < |\eta| < 3.8$) for the 1st order event plane reconstruction.

The direction is fixed by convention that spectator neutrons are deflected along the direction of the impact parameter.

Spin alignment of vector mesons - similar to $v_2$ analysis

advantage: no need to know the polarization direction

use tracks in the TPC (mid-rapidity) for the 2nd order event plane reconstruction.

Finite event plane resolutions were corrected in the final physics results.
Lambda Global Polarization

Filled:
200 GeV, 20-70%

Open:
62.4 GeV, 0-80%

\( P_{\Lambda, \bar{\Lambda}} \) is consistent with zero with statistical error ~ 0.01

no obvious dependence on \( p_T, \eta, \) centrality
Lambda Global Polarization

- $P_{\Lambda,\bar{\Lambda}}$ is consistent with zero with statistical error $\sim 0.01$
  $P_{\Lambda,\bar{\Lambda}} = (2.6 \pm 9.5) \times 10^{-3}$

- No obvious dependence on $p_T$, $\eta$, centrality.

- Major Systematic Errors
  - Acceptance effect $\sim 20\%$
  - Feed-down from $\Sigma^0$ $\sim 30\%$
  - Multistrange feed-down $\sim 15\%$
  - Reaction Plane $\sim 30\%$

Upper limit for the global Lambda polarization in Au+Au collisions at RHIC

$$|P_{\Lambda,\bar{\Lambda}}| \leq 0.02$$
Spin alignment w.r.t. the reaction plane

- Data favor no large global polarization for vector mesons in heavy ion collisions.
- Consistent with Lambda global polarization measurements.
- Current uncertainty cannot distinguish different hadronization mechanisms.

\[ K^0 \ (0.8<p_T<5.0 \text{ GeV/c}): \]
\[ \rho_{00} = 0.32 \pm 0.03 \pm 0.09 \]

\[ \varphi \ (0.4<p_T<5.0 \text{ GeV/c}): \]
\[ \rho_{00} = 0.34 \pm 0.02 \pm 0.03 \]
Within current sensitivity, our measurement exhibits no strong spin alignment for vector meson at all collision centralities, presumably because the spin-orbit coupling for quark polarization is not large enough to be manifested in our measurement.
Spin alignment w.r.t. the production plane

**Production plane:**
produced particle momentum and beam line

Similar analysis as that was done w.r.t. reaction plane

\[ p_T < 2.0 \text{ GeV}/c \]
\[ \rho_{00}(K^*) = 0.43 \pm 0.04 \pm 0.09 \; ; \; \rho_{00}(\varphi) = 0.42 \pm 0.02 \pm 0.04 \]

\[ p_T > 2.0 \text{ GeV}/c \]
\[ \rho_{00}(K^*) = 0.38 \pm 0.04 \pm 0.09 \; ; \; \rho_{00}(\varphi) = 0.38 \pm 0.03 \pm 0.05 \]

In p+p, \[ \rho_{00}(\varphi) = 0.39 \pm 0.03 \pm 0.06 \]
Comparison between different systems

**DELPHI Col. PLB 406 (1997) 271**

The spin density matrix elements for the $\rho^0$, $K^*(892)$ and $\phi$ produced in hadronic $Z^0$ decays are measured in the DELPHI detector. There is no evidence for spin alignment of the $K^*(892)$ and $\phi$ in the region $x_p \leq 0.3$ ($x_p = p/p_{beam}$), where $\rho_{00} = 0.33 \pm 0.05$ and $\rho_{00} = 0.30 \pm 0.04$, respectively. In the fragmentation region, $x_p \geq 0.4$, there is some indication

$$e^+e^- \rightarrow Z \rightarrow q\bar{q} \rightarrow K^*^0 + X$$

- At small $x_p$ region, $\rho_{00}$ are consistent with 1/3 from ee, pp, to AuAu collisions
Conclusions

• **Lambda global polarization w.r.t. The reaction plane** is consistent with zero with statistical uncertainty ~ 0.01. **Upper limit** $|P_{\Lambda,\bar{\Lambda}}| \leq 0.02$

• **w.r.t the reaction plane**, $\rho_{00}(p_T)$ of $(K^*, \phi)$ are consistent within 1/3 within statistical and systematic uncertainty in the measured $p_T$ up to 5 GeV/c and no strong dependence on collision centrality or transverse momentum was observed.

→ **Vector mesons and hyperons in the measured kinematic region** appear not to be produced with a strong global polarization despite the presence of a large orbital angular momentum for the system created in non-central Au+Au collisions.

• **w.r.t. the production plane**, $\rho_{00}(p_T)$ is less than 2 standard deviation above 1/3 and is similar to the results from p+p collisions.

→ **Vector mesons in the measured $p_T$ region at mid-rapidity** don’t seem to carry a significant polarization through production dynamics.