Spin polarization measurements in heavy-ion collisions

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Global vorticity and polarization in heavy-ion collisions

- In relativistic non-central nuclear collisions:

- Large initial orbital angular momentum perpendicular to the reaction plane:

  \[ L \approx 10^5 - 10^7 \text{ } \hbar \]

  S. A. Voloshin, nucl-th/0410089

- Strong initial magnetic field perpendicular to the reaction plane:

  \[ B \approx 10^{13} - 10^{14} \text{ } \text{T} \]


- Both \( \vec{L} \) and \( \vec{B} \) can polarize particles and antiparticles produced in such collisions.
• Vorticity along the system orbital angular momentum due to initial shear in longitudinal flow velocity.

• “Global polarization” → particle/antiparticle polarization along system’s orbital angular momentum.

• Strong magnetic field due to charged spectators → splitting in particle/antiparticle polarization.

• Mostly sensitive to the initial stages of the collisions.

\[
\omega_y = \frac{1}{2} (\nabla \times \mathbf{v})_y \approx -\frac{1}{2} \frac{\partial v_z}{\partial x}
\]
Hyperon polarization estimation

$\Lambda$ ($\bar{\Lambda}$) hyperons → Parity violating weak decay

$\Lambda \rightarrow p + \pi^-$  
(BR: 63.9%, $c\tau \sim 7.9$ cm)

$\alpha_\Lambda = 0.750 \pm 0.009$

$\alpha_{\bar{\Lambda}} = -0.758 \pm 0.01$

- Daughter baryon is preferentially emitted in the direction of hyperon spin (opposite for antiparticle)-

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \vec{P}_H \cdot \hat{p}_p^*),$$

(• denotes hyperon rest frame)

$\vec{P}_H =$ hyperon polarization vector

$\alpha_H =$ hyperon decay parameter

$\hat{p}_p^*$ = unit vector along daughter baryon momentum


Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).
Hyperon polarization estimation

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(\( \cdot \) denotes hyperon rest frame)

\( \mathbf{P}_H = \) hyperon polarization vector

\( \alpha_H = \) hyperon decay parameter

\( \hat{\mathbf{p}}_p^* = \) unit vector along daughter baryon momentum

- Polarization estimation procedure:

  a) Identify the reference axis (e.g along x, y, or z) \( \to \) vorticity sources are different along different directions.
  
  b) Take a projection of the daughter proton’s momentum direction on the reference axis.
  
  c) Average that projection over all hyperons in all events under consideration.

Global hyperon polarization measurement in heavy-ion collisions

- Deflection of the spectators determines the direction of $\mathbf{L} = \mathbf{b} \times \mathbf{P}_{\text{beam}}$.
- On average spectators deflect outwards.


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Global hyperon polarization measurement in heavy-ion collisions

![Diagram showing quark-gluon plasma and deflected spectator fragments.]

- $\vec{P}_{\text{beam}}$ = momentum of the projectile (moving toward positive rapidity: known).
- $\vec{b}$ = Impact parameter
- $\Psi_{SP}$ = spectator plane angle (azimuthal angle of $\vec{b}$).
- $\phi^*_P$ = azimuthal angle of daughter proton in $\Lambda(\bar{\Lambda})$ rest frame
- $R_{SP}^1$ = Resolution of $\Psi_{SP}$


Λ(Λ̅) polarization in heavy-ion collisions

- Polarization at mid-rapidity \((P/P_H)\) decreases with collision energy. \(P_H\) at LHC consistent with zero within experimental uncertainties. \(\text{ALICE, Phys. Rev. C 101, 044611 (2020)[erratum]}\)

- The \(\sqrt{s_{NN}}\) dependence of \(P_H\) in good agreement with hydro and transport model calculations.
\( \Lambda(\bar{\Lambda}) \) polarization in heavy-ion collisions

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- The \( \sqrt{s_{NN}} \) dependence of \( P_H \) in good agreement with hydro and transport model calculations. Three-fluid hydro (3FD) works better at lower \( \sqrt{s_{NN}} \).

- Centrality dependence of \( P_H \) follows the angular momentum dependence of impact parameter
\(\Lambda(\bar{\Lambda})\) polarization in heavy-ion collisions (Centrality and \(p_T\) dependence)

- Polarization at mid-rapidity (P/P\(_H\)) decreases with collision energy. P\(_H\) at LHC consistent with zero within experimental uncertainties. ALICE, Phys. Rev. C 101, 044611 (2020)[erratum]

- The \(\sqrt{s_{NN}}\) dependence of P\(_H\) in good agreement with hydro and transport model calculations. Three-fluid hydro (3FD) works better at lower \(\sqrt{s_{NN}}\).

- No significant \(p_T\) dependence observed in any \(\sqrt{s_{NN}}\).
- Polarization at mid-rapidity decreases with collision energy.
- Bjorken boost invariance at mid-rapidity? Vorticity migrates to forward rapidity?
- For higher $\sqrt{s_{NN}}$ (i.e. higher $y_{beam}$), not possible to measure $P_H$ at forward rapidities at STAR/ALICE (needs detector upgrade).

Ivanov, Toneev, Soldatov

Iu. Karpenko, F. Becattini
For STAR FXT ($\sqrt{s_{NN}} = 3$ GeV), $P_H$ measured over large rapidity coverage → no rapidity dependence observed (boost invariance not a good approximation at 3 Gev?)

• STAR forward upgrade ongoing - meaningful rapidity coverage at 200 GeV possible.
Finite $\Lambda/\bar{\Lambda}$ global polarization in Ru+Ru and Zr+Zr collisions at 200 GeV.

- No observed effect/splitting of $P_{\Lambda}/P_{\bar{\Lambda}}$ due to different magnetic (B) fields in Ru+Ru and Zr+Zr.

- $P_{\Lambda(\bar{\Lambda})}$ in Isobar collisions are consistent with Au+Au collisions, no collision system dependence observed.
\[ \Xi = \Lambda + \pi, \; \Lambda = p + \pi \]
\[ \Omega = \Lambda + K, \; \Lambda = p + \pi \]

- \( \mathbf{P}_{\Xi,\Omega} \) can be estimated from the daughter \( \Lambda \) angular distribution in the parent hyperon rest frame:

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left( 1 + \alpha_{\Xi,\Omega} \mathbf{P}_{\Xi,\Omega} \cdot \hat{\mathbf{p}}^* \right),
\]

\[
\alpha_{\Xi} = -0.401 \quad \alpha_{\Omega} = 0.0157,
\]

Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

Becattini et al., PRC 95, 054902 (2017)
Polarization of multi-strange hyperons

\[ \Sigma = \Lambda + \pi, \ \Lambda = p + \pi \]
\[ \Omega = \Lambda + K, \ \Lambda = p + \pi \]

- \( P_{\Sigma, \Omega} \) can be estimated from the daughter \( \Lambda \) angular distribution in the parent hyperon rest frame:

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\Sigma, \Omega} P_{\Sigma, \Omega} \cdot \hat{p}_\Lambda^*),
\]

\( \alpha_{\Sigma} = -0.401 \quad \alpha_{\Omega} = 0.0157 \),

Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

- \( P_{\Omega} \) measurement directly from the daughter \( \Lambda \) angular distribution is not possible (Reason: very small \( \alpha_{\Omega} \)).

- \( P_{\Sigma, \Omega} \) can be measured from the polarization of daughter \( \Lambda \)

\[ \Lambda( = p + \pi, \alpha_\Lambda = 0.732) \]

\[ P = \frac{\langle s \rangle}{s} \approx \frac{(s + 1) \omega}{3} T, \]

Becattini et al., PRC 95, 054902 (2017)
Polarization of multi-strange hyperons

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\]

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- \( \mathbf{P}_{\Xi,\Omega} \) can be measured from the polarization of daughter \( \Lambda \)

\[ \Lambda( = p + \pi, \alpha_{\Lambda} = 0.732) \]

- Parent polarization partially transferred to the daughter particles:

\[ \mathbf{P}_{\Lambda} = C_{\Xi,\Lambda} \mathbf{P}_{\Xi} = \frac{1}{3} (1 + 2\gamma_{\Xi}) \mathbf{P}_{\Xi} \]


\[ \mathbf{P}_{\Lambda} = C_{\Omega,\Lambda} \mathbf{P}_{\Omega} = \frac{1}{5} (1 + 4\gamma_{\Omega}) \mathbf{P}_{\Omega} \]

\[ \Xi = \Lambda + \pi, \ \Lambda = p + \pi \]
\[ \Omega = \Lambda + K, \ \Lambda = p + \pi \]

- \( \gamma_{\Xi,\Omega} \) can be estimated from \( \alpha^2 + \beta^2 + \gamma^2 = 1 \)


\[ \alpha = \text{parity violation parameter} \]
\[ \beta = \text{time reversal symmetry violation parameter} \]
\[ \gamma = \text{decay parameter} \]

\[ C_{\Xi - \Lambda} = 0.944 \]

HyperCP Collaboration; PRL 93, 011802 (2004).
Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

\[ C_{\Omega - \Lambda} = 1 \text{ or } -0.6 \]
\[ (\gamma_{\Omega} = \pm 1) \]


\[ P = \frac{\langle s \rangle}{s} = \frac{(s + 1) \omega}{3 T}, \]

Becattini et al., PRC 95, 054902 (2017)

\[ \mathbf{P}_{\Omega} \text{ should be positive. Precision measurement of } \mathbf{P}_{\Lambda}(\Omega = \Lambda + K) \text{ can constrain the uncertainty of the parameter } \gamma_{\Omega}. \]
• Measured from the angular distribution of the daughter particle in parent’s rest frame:

$$\frac{dN}{dcos\theta^*} = N_0[1 - \rho_{0,0} + \cos^2 \theta^* (3\rho_{0,0} - 1)]$$

- $\theta^*$: Angle between momentum of daughter and polarization axis in parent’s rest frame.
- $\rho_{0,0}$: Spin density matrix element, Probability that vector meson is in spin state = 0.
Spin alignment of Vector mesons ($\rho_{00}$)

- Measured from the angular distribution of the daughter particle in parent’s rest frame:

\[
\rho_{00}(\omega) < 1/3
\]

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

**Physics process** | **Theory** | **Remarks** | **Reference**
--- | --- | --- | ---
Vorticity ($\omega$) | $\rho_{00}(\omega) < 1/3$ | $\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta \omega)^2$ | F. Becattini et al., Phys. Rev. C 95 (2017) 054902
Magnetic field (B) | $\rho_{00}(B) > 1/3$ | Electrically neutral vector mesons | Y. Yang et al., Phys. Rev. C 97 (2018) 034917
| $\sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1q_2}{m_1m_2} B^2$ | Electrically charged vector mesons |
| $\rho_{00}(B) < 1/3$ | |
| $\sim \frac{1-p_q p_q}{3+p_q p_q}$ | |
| $\rho_{00}(\text{frag}) > 1/3$ | Fragmentation | Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301
| $\sim \frac{1+\beta p_q p_q}{3-\beta p_q p_q}$ | |
Coherent meson field | $\rho_{00} > 1/3$ | $\phi$ mesons | X. L. Sheng et al., arXiv:1910.13684

\[\frac{dN}{d\cos\theta^*} = N_0[1 - \rho_{0,0} + \cos^2 \theta^*(3\rho_{0,0} - 1)]\]

- $\theta^*$: Angle between momentum of daughter and polarization axis in parent’s rest frame.
- $\rho_{0,0}$: Spin density matrix element. Probability that vector meson is in spin state 0.


Spin alignment of Vector mesons ($\rho_{00}$)

- Spin Alignment ($\rho_{00} < 1/3$) observed for spin 1 particle at low $p_T$.
- Maximum spin alignment observed for mid-central collisions.
- No spin alignment ($\rho_{00} \sim 1/3$) observed for spin 0 particle and in pp collisions.


ALICE-DESIREE

Spin alignment of Vector mesons ($\rho_{00}$)

- Vector meson spin alignment measurements are not consistent with $\Lambda$ (̅$\Lambda$) polarization measurements.

\[
P_H \sim P_q \quad \text{and} \quad P_V \sim P_q^2 \quad (P_q = \text{quark polarization})
\]

- At LHC, $P_\Lambda \sim (0.01)\% \quad \rightarrow \rho_{00} \sim 1/3$ (expected).

- The measured spin alignment is surprisingly large! $\rightarrow$ A puzzle.

\[
\rho_{00}(\text{rec}) = \frac{1-P_q^2 P_q}{3+P_q^2 P_q}
\]


Quark recombination model
For 20-60%: \( \rho_{00} (\phi) > 1/3, \rho_{00} (K^0) \sim 1/3! \)

Polarization by a strong force field of vector meson ??

Can it explain centrality and \( p_T \) dependence??

- The puzzle remains (need input from theory…)

\[ K^0 \text{ vs. } K^{*+/−}: \sim 3.9 \sigma \text{ difference.} \]

Ordering opposite to the expectation from B field!
• Similarly to light flavors ($K^0, \phi$) maximum polarization for \textit{semitentral} collisions at low $p_T$

  \begin{center}
  \framebox{PRL 125 (2020) 012301}
  \end{center}

\begin{itemize}
  \item Smaller absolute polarization
    \[
    |\lambda_{J/\psi}^\theta| < |\lambda_{\phi}^\theta| < |\lambda_{K^0}^\theta|
    \]
  \item Different sign of the deviation:
    \[
    \lambda_{J/\psi}^\theta > 0 \neq \lambda_{\phi,K^0}^\theta < 0
    \]
\end{itemize}

• Charmed vector meson ($D^*$) polarization study ongoing.

• Baseline study in pp 13 TeV is complete.

• Machine learning (ML) techniques (Boosted Decision Tree) used to separate prompt from non-prompt candidates.

• The puzzle remains (need input from theory…)

Talk by Luca Micheletti (Tue T02-I)

Talk by Sebastien Perrin (Tue T05-II)
Strong elliptic flow assumes significant asymmetries in the transverse velocity fields. This results into non-zero vorticity component and particle polarization along the beam direction dependent on the location of the fluid element in the transverse plane.

\[ P_z \propto \sin(2\theta) \]

• Sources of vorticity along the beam direction (z axis):

Elliptic flow -

• Particle spin polarization has azimuthal angle dependence - local polarization.

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
Elliptic flow induced polarization along the beam direction ($P_z$)

$P_z(\phi) \approx \sin(2\phi - 2\Psi_2)$

S. Voloshin, EPJ Web Conf.171, 07002 (2018)

$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle}$

(if perfect detector)

$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_H}$

Local polarization (along $z$ axis)-

$P_z \approx \langle (\hat{p}_p^* \cdot \hat{z}) \rangle$


$\langle (\cos\theta_p^*)^2 \rangle = \text{correction for finite acceptance along } z$

$P_{z,s2} = \langle P_z \sin(2\phi - 2\Psi_2) \rangle$

$P_{z,s2}$ estimates magnitude and phase of $P_z$. 

$\theta_p^*$ = polar angle of daughter baryon in hyperon rest frame 

$\vec{p}_p^*$ = hyperon momentum in hyperon rest frame 

$\vec{p}_\pi^*$ = pion momentum 

$\vec{S}_{\Lambda}$ = hyperon spin 

$\vec{\rho}$ = beam direction

(BR: 63.9%, c\tau \approx 7.9 \text{ cm})
Strong elliptic flow assumes significant asymmetries in the transverse velocity fields. This results into non-zero vorticity component and particle polarization along the beam direction dependent on the location of the fluid element in the transverse plane.

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- Local polarization (along z axis)-

\[ P_z \approx \langle (\hat{p}_p^* \cdot \hat{z}) \rangle \]

\[ P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle} = \frac{3\langle \cos\theta_p^* \rangle}{\alpha_H} \] (if perfect detector)


\[ \langle (\cos\theta_p^*)^2 \rangle = \text{correction for finite acceptance along z} \]

\[ P_{z,s2} = \langle P_z \sin(2\phi - 2\Psi_2) \rangle \]

\( P_{z,s2} \) estimates magnitude and phase of \( P_z \).

- No difference between \( \Lambda \) and \( \bar{\Lambda} \) polarization.

\[
\begin{align*}
\langle \cos(\theta_p^*) \rangle_{\text{sub}} & = 0.001 \\
\langle \cos(\theta_p^*)^2 \rangle_{\text{sub}} & = 0.0001 \\
\end{align*}
\]

STAR, PRL, 123, 132301 (2019)
Elliptic flow induced polarization along the beam direction ($P_z$)

$\langle P_z \sin(2\Psi - 2\phi) \rangle$

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$P_z$ at the LHC</th>
<th>$P_z$ at top RHIC energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Similar in magnitude to top RHIC energy (tends to be smaller in semicentral collisions).</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Similar in magnitude to top RHIC energy (tends to be smaller in semicentral collisions).</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Similar in magnitude to top RHIC energy (tends to be smaller in semicentral collisions).</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Similar in magnitude to top RHIC energy (tends to be smaller in semicentral collisions).</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Similar in magnitude to top RHIC energy (tends to be smaller in semicentral collisions).</td>
<td></td>
</tr>
</tbody>
</table>

- At $p_T < 2.0$ GeV/c, $P_{z,s2}$ at the LHC is smaller than the STAR results in semi-central collisions.

- $v_2(p_T)$ at top RHIC and the LHC energies are comparable!
Elliptic flow induced polarization along the beam direction ($P_z$)

\[ \langle P_z \sin(2\varphi) - 2\Psi \rangle \]

Centrality (%)

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
- ALICE ($\Lambda + \bar{\Lambda}$)
- AMPT + MUSIC ($S$ quark)
- AMPT + MUSIC ($\Lambda$)

Au-Au $\sqrt{s_{NN}} = 200$ GeV
- STAR $\times$ 0.856 ($\Lambda + \bar{\Lambda}$)
- AMPT + MUSIC ($\Lambda$)

STAR, PRL, 123, 132301 (2019)

\[ \alpha_H = 0.750 \quad \text{ALICE, arXiv:2107.11183 [nucl-ex] (accepted in PRL)} \]
\[ \alpha_H = 0.642 \quad \text{STAR, PRL, 123, 132301 (2019)} \]

- The data results are compared with the (fluid shear + thermal vorticity) based $P_{z,s2}$ values estimated using AMPT + MUSIC model.

- This model generates positive $P_{z,s2}$ in case $\Lambda(\bar{\Lambda})$ inherits the spin information from the constituent strange quark.
• $P_{z,s2}$ at the LHC does not exhibit a significant dependence on rapidity.

• The AMPT + MUSIC model can describe the data with $s$ quark as the spin carrier.

### Anisotropic flow induced polarization along the beam direction ($P_z$)

**Takafumi Niida, Poster Session 1 T02**

- Local polarization (along z axis)- $P_z \approx \langle (\hat{p}_p \cdot \hat{z}) \rangle$
  
  $P_z = \frac{\langle \cos \theta^* \rangle}{\alpha_H \langle (\cos \theta^*)^2 \rangle}$

- Elliptic flow induced polarization along beam axis: $\sin(2\varphi - 2\Psi_2)$ dependence

- Triangular flow induced polarization along beam axis: $\sin(3\varphi - 3\Psi_3)$ dependence

- No difference between $\Lambda$ and $\bar{\Lambda}$ polarization.

**Equations**

- $P_{z,s2} = \langle P_z \sin(2\varphi - 2\Psi_2) \rangle$

- $P_{z,s3} = \langle P_z \sin(3\varphi - 3\Psi_3) \rangle$

**Graphs**

1. Ru+Ru&Zr $\sqrt{s_{NN}} = 200$ GeV
   - STAR preliminary
   - Centrality: 20%-60%


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**Diagram:**

- Elliptic flow induced polarization along beam axis: $\sin(2\varphi - 2\Psi_2)$
- Triangular flow induced polarization along beam axis: $\sin(3\varphi - 3\Psi_3)$
• $P_{z,s2}$ and $P_{z,s3}$ are comparable in isobar collisions.

• $P_{z,s2}$ from Isobar data compared to Au+Au and Pb+Pb results (hint of system size dependence?)

• Complex local vortical structure. Measurement with event shape engineering will be useful.
Summary and Outlook

• Global hyperon polarization ($P_H$) increases with decreasing $\sqrt{s_{NN}}$ and this trend continues upto STAR FXT and HADES energies.

• Origin: boost invariance at mid-rapidity? Vorticity migrates to forward-backward rapidity? Measurements at higher $\sqrt{s_{NN}}$ need forward detector upgrade (ongoing at STAR).

• Effect of magnetic field on global polarization not observed in isobar collisions at STAR. Also, no system size dependence observed.

• Vector meson spin alignment results are not consistent with polarization results. Need more input from theory.

• Polarization along the beam direction ($\langle P_z \sin(2\varphi - 2\Psi_2) \rangle$) is positive at RHIC and the LHC can be explained by thermal vorticity and thermal shear based model calculations (with additional assumptions).

• Longitudinal polarization in isobar data shows dependence on system size.

• New high statistics datasets at STAR and upcoming Run 3 at the LHC will allow more differential and precision measurements of global and local polarization in heavy-ion collisions.

Stay Tuned… Thank you
Back Up
Global vorticity and directed flow from tilted source

\[ \nu_1 = \cos(\phi - \Psi_{RP}) \]

- Asymmetries in the initial velocity field generate vorticity (tilt) in the system → generates directed flow ($V_1$).
  

- To describe the $v_1$ in heavy-ion collisions → vorticity (tilt) has to be taken into account.


\[ \eta_m = 2.0 \]
\[ \eta/s = 0.1 \]

Model: 3+1D hydro

$\eta_m$ = parameter to introduce vorticity/tilt in the initial condition
Global vorticity and directed flow from tilted source

- Polarization and $\frac{dv_1}{d\eta}$ are strongly correlated $\rightarrow$ decreases with increase in $\sqrt{s_{NN}}$

- $v_1$ at the LHC $\rightarrow$ three times smaller than $v_1$ at top RHIC energy.


- $P_H$ at the LHC energies $\rightarrow$ at least three times smaller than at RHIC (need high statistics for precision measurement).


STAR, PRC76.024915 (2007)

STAR prelim. (20-60%)

ALICE prelim. (15-50%)

Karpenko, Becattini, EPJ C77(2017)213
Local polarization ($P_z$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE

- At $p_T < 2.0$ GeV/c, $P_z,s^2$ at the LHC is smaller than the STAR results in semi-central collisions.
- $v_2\{4\}$ vs $p_T$ at top RHIC and the LHC energies are comparable!
- The AMPT + MUSIC model generates positive $P_z,s^2$ only in case $\Lambda(\bar{\Lambda})$ inherits the spin information from the constituent strange quark.
• The global vorticity is along orbital angular momentum (along -y direction)
• $P_{\mathcal{H}} (P_\phi)$ has higher value in plane (along x) compared to out of plane (along y)!
• (Fluid shear + thermal vorticity) based $P_{\mathcal{H}}$ estimation can explain this (with the assumption of isothermal local equilibrium or using s quark as the spin carrier).
**P_z** in heavy-ion collisions (Data - Model comparison)

- Blast-Wave model (kinematic vorticity) describes the $P_{z,s2}$ data.
- Hydro and transport models describe the elliptic flow in heavy-ion collisions reasonably well.
- However, hydro models and AMPT generate negative $P_{z,s2}$ (opposite to experimental observation: “spin sign puzzle”).

F. Becattini and I. Karpenko, PRL.120.012302 (2018) (Hydro)

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
Global polarization ($P_H$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV in ALICE

\[ \Lambda = p + \pi^- \]
\[ \bar{\Lambda} = \bar{p} + \pi^+ \]

- $P_H$ consistent with zero within experimental uncertainties.
- No visible difference between $\Lambda$ and $\bar{\Lambda}$ polarization.
- $P_H$ decreases with collision energy (due to higher baryon transparency at higher collision energies).


\[ \Lambda = p + \pi^- \]
\[ \bar{\Lambda} = \bar{p} + \pi^+ \]
• Polarization at mid-rapidity decreases with collision energy (Bjorken boost invariance at mid-rapidity, vorticity migrates to forward rapidity!).

• For higher energies (higher y beam), not possible to measure pH at forward rapidities without detector upgrade at RHIC/LHC
Measuring global polarization ($P_H$) in ALICE using invariant mass method

\[ \Lambda = p + \pi^- \quad \bar{\Lambda} = \bar{p} + \pi^+ \]

\[ P_H = -\frac{8}{\pi \alpha_H} \frac{\langle \sin(\varphi^*_p - \Psi_{SP}) \rangle}{R_{SP}^1} \]

- $P_H$ measured from the fit to $Q \left( \langle \sin(\varphi^*_p - \Psi_{SP}) \rangle \right)$ -

\[ Q(M_{inv}) = f^S(M_{inv})Q^S + f^{BG}(M_{inv})Q^{BG}(M_{inv}) \]

$f^S$, $f^{BG}$ signal, background fraction of $\Lambda$ ($\bar{\Lambda}$)

$Q^S \rightarrow$ polarization signal,

$Q^{BG}(M_{inv}) \rightarrow \Lambda$ ($\bar{\Lambda}$) background contribution.


Counts

\[ \langle \sin(\varphi^*_p - \Psi_{SP}) \rangle \]

M(p\pi^-)(GeV/c^2) M(\bar{p}\pi^+)(GeV/c^2)