Lambda polarization in heavy ion collisions: from RHIC BES to LHC energies

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"First clear positive signal of global polarization in heavy ion collisions!"

Iurii Karpenko, Lambda polarization from RHIC BES to LHC
Theory side: polarization of fermions from the fluid

Also: Ren-hong Fang, Long-gang Pang, Qun Wang, Xin-nian Wang, Phys. Rev. C 94 (2016), 024904

Mechanism: spin-vorticity coupling at local thermodynamic equilibrium.

- Cooper-Frye prescription: \( p^0 \frac{d^3N}{d^3p} = \int d\Sigma \lambda p^\lambda \frac{1}{\exp\left(\frac{p \cdot u - \mu}{T}\right) \pm 1} \)

- For the spin \( \frac{1}{2} \) particles at the particlization surface: \( \langle S(x, p) \rangle = \frac{1}{8m} (1 - f(x, p)) \epsilon_{\mu \nu \rho \sigma} p^\rho \partial_\nu \beta_\sigma \),
where \( \beta_\mu = \frac{u_\mu}{T} \) is the inverse four-temperature field.

\[
S^\mu(p) = \frac{\int d\Sigma \lambda p^\lambda f(x, p) \langle S(x, p) \rangle}{\int d\Sigma \lambda p^\lambda f(x, p)}
\]

Polarization depends on the thermal vorticity \( \varpi_{\mu \nu} = -\frac{1}{2} (\partial_\mu \beta_\nu - \partial_\nu \beta_\mu) \).

- polarization is close or equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients

⇒ Let’s examine the polarization observable in the 3D viscous hydro model for RHIC BES!
A model for RHIC BES: UrQMD + vHLLE (+ UrQMD)

**Pre-thermal evolution: UrQMD cascade** until \( \tau = \tau_0 = \text{const}, \ \tau_0 = \frac{2R}{\gamma v_z} \)

Fluctuating initial state, event-by-event hydrodynamics

**Hydrodynamic phase:**

\[
\partial_\nu T^{\mu\nu} = 0, \quad \partial_\nu N^\nu = 0
\]

\[
\langle u^\gamma \partial_\gamma \pi^{\mu\nu} \rangle = - \frac{\pi^{\mu\nu} - \pi_{NS}^{\mu\nu}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_\gamma u^\gamma
\]

* Bulk viscosity \( \zeta = 0 \), charge diffusion=0

**vHLLE code:** free and open source. Comput. Phys. Commun. 185 (2014), 3016

https://github.com/yukarpenko/vhlle

**Fluid→particle transition and hadronic phase**

Cooper-Frye prescription at \( \varepsilon = \varepsilon_{sw} \):

\[
p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x, p) p^\mu \Delta \sigma_\mu
\]

\[
f(x, p) = f_{eq} \cdot \left( 1 + (1 \mp f_{eq}) \frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2 (\varepsilon + p)} \right)
\]

- \( \Delta \sigma_i \) using Cornelius subroutine*
- Hadron gas phase: back to UrQMD cascade

Validating the model for bulk hadronic observables at RHIC BES energies

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

Iurii Karpenko, Lambda polarization from RHIC BES to LHC
Λ polarization signal from the model

with no additional tuning!

geometry sketch:
First thing first: Collision energy dependence

\( P_J \): mean polarization of \( \Lambda \) along the angular momentum of the system.

\[
P_J^* \quad \text{Au-Au, 20-50\% central}
\]

\[
\sqrt{s_{NN}} \quad [GeV]
\]

\[
P_J^* \quad P_J \quad \omega_{xz} (\Omega_J)
\]

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Why does $P_J$ (global polarization) increase at lower BES energies?

1) Different initial vorticity distribution
2) Longer hydrodynamic evolution at higher $\sqrt{s_{NN}}$ further dilutes the vorticity

These two effects result in lower polarization at higher collision energies.
Interactions in the post-hydro stage


Only about 25% of $\Lambda$ are thermal ones! The rest is coming from resonance decays.

Spin (polarization) transfer in two-body resonance decay: $S_{\Lambda, \Sigma^0}^* = C_{X \rightarrow \Lambda, \Sigma^0} \cdot S_X^*$

Direct $X \rightarrow \Lambda$ and two-step $X \rightarrow \Sigma^0 \rightarrow \Lambda$ decays are taken into account.

$S_{\Lambda}^* = \frac{N_{\Lambda} S_{\Lambda, \text{prim}} + \sum_X N_X S_X^* [C_{X \rightarrow \Lambda} b_{X \rightarrow \Lambda} - \frac{1}{3} C_{X \rightarrow \Sigma^0} b_{X \rightarrow \Sigma^0}]}{N_{\Lambda} + \sum_X b_{X \rightarrow \Lambda} N_X + \sum_X b_{X \rightarrow \Sigma^0} N_X}$

<table>
<thead>
<tr>
<th>$X$</th>
<th>$J^P$</th>
<th>$S_X^*$</th>
<th>$C_{X \rightarrow \Lambda, \Sigma^0}$</th>
<th>$S_{\Lambda(X)}$ / $S_{\Lambda, \text{prim}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma^0$</td>
<td>(1/2)$^+$</td>
<td>1</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\Sigma(1385)$</td>
<td>(3/2)$^+$</td>
<td>5</td>
<td>1/3</td>
<td>5/3</td>
</tr>
<tr>
<td>$\Lambda(1405)$</td>
<td>(1/2)$^-$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>(3/2)$^-$</td>
<td>5</td>
<td>-1/5</td>
<td>-1</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>(1/2)$^+$</td>
<td>1</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\Sigma(1660)$</td>
<td>(1/2)$^+$</td>
<td>1</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\Sigma(1670)$</td>
<td>(3/2)$^-$</td>
<td>5</td>
<td>-1/5</td>
<td>-1</td>
</tr>
</tbody>
</table>

Overall feed-down effect: 15% suppression.

Not taken into account (yet): $\Lambda$ and $\Sigma^0$ actively rescatter in hadronic phase $\rightarrow$ expected to suppress polarization.
\( \Lambda \) and \( \bar{\Lambda} \): \textit{UrQMD+vHLLE vs experiment}

- \( \Lambda \) within experiment error bars.
- Much smaller and opposite sign \( \bar{\Lambda}-\Lambda \) splitting. Only \( \mu_B \) effect in the model, and it is small.
- MHD interpretation: vorticity creates the average \( \Lambda+\bar{\Lambda} \), magnetic field makes the splitting.
- Magnetic field at particlization?
Collision energy dependence is robust with respect to variation of the parameters of the model.

- There is no big difference between event-by-event and single shot hydrodynamic description.
Same $P(\sqrt{s_{NN}})$ trend in other hydro and non-hydro models

- **PICR**: Y.L. Xie, D.J. Wang, L.P. Csernai, Phys. Rev. C 95, 031901 (2017)
- **AMPT**: Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, PRC 96, 054908
- **CKE**: Yifeng Sun, Che Ming Ko, Phys. Rev. C 96, 024906 (2017)
Mean polarization further decreases towards 2.76 TeV LHC energy.
At high energies, the dominant component is $P^z$.

$P^z$ is:
- nonzero in 2D boost-invariant hydrodynamics
- related to transverse expansion

20-50% central Pb-Pb, $\sqrt{s_{NN}} = 2.76$ GeV
\( P^z: \) hydro versus preliminary STAR data

**vHLLE+Glissando IS**

Preliminary STAR data: Takafumi Niida, talk at Chirality workshop 2018

Similar \( \sin(2\phi) \) structure is observed, with opposite sign!
Fourier expansion for $P^z$

$$P^z(p_T, y = 0) = \sum_{k=1}^{\infty} f_{2k}(p_T) \sin 2k(\phi_p - \Psi)$$

- requires identification of event plane $\Psi$
- Blast-Wave model:

$$f_2(p_T) = 2 \frac{dT}{d\tau} \frac{1}{mT} v_2(p_T)$$

$P^z$ emerges because of anisotropic transverse expansion, same way as $v_2$. 
Corresponding $\Lambda$ spin correlations

The quadrupole structure leads to correlations of $P^z$ of $\Lambda$ pairs

$$P^z = P^z_0 \sin 2(\phi - \Psi) \quad \Rightarrow \quad \langle P^z(\phi)P^z(\phi + \Delta \phi) \rangle = \frac{1}{2}(P^z_0)^2 \cos 2\Delta \phi$$

average hydro

event-by-event hydro


$\Lambda$ spin correlations due to vorticity induced by initial state fluctuations

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What causes transverse and longitudinal components of polarization?

\[ S^\mu = \varepsilon^{\mu\rho\sigma\tau} \tilde{\omega}_{\rho\sigma} p_\tau = \varepsilon^{\mu\rho\sigma\tau} (\partial_{\rho} B_{\sigma}) p_\tau = \varepsilon^{\mu\rho\sigma\tau} p_\tau \partial_\rho \left( \frac{1}{T} \right) u_\sigma + \frac{1}{T} [\omega^\mu (u \cdot p) - u^\mu (\omega \cdot p)] + \varepsilon^{\mu\rho\sigma\tau} p_\tau A_\sigma u_\rho \]

**Global transverse** \( P_J \):

- \( P^j \) at low \( p_\perp \) is dominated by vorticity
- \( P^z \) is dominated by acceleration and gradients of temperature
Summary

Λ polarization is calculated in UrQMD + 3D EbE viscous hydro model for $\sqrt{s_{NN}} = 7.7\ldots200$ GeV A+A collisions, extended with Glauber + 3D viscous hydro for $\sqrt{s_{NN}} = 2760$ GeV LHC.

- We observe a strong increase of global mean polarization of Λ along the angular momentum direction towards lowest RHIC BES energies.
- The calculated mean Λ polarization is (almost) within the experimental error bars.
- Feed-down: $\approx 15\%$ suppression.
- At LHC energies, the largest component of polarization is $P^z$ (along the beam axis), reaching 1% for $p_T = 3$ GeV Λ at midrapidity.
- $P^z(p_T)$ is a more generic effect, emerging in boost-invariant hydrodynamics due to anisotropy of transverse expansion ($v_2$). It probes velocity/temperature gradients at particlization surface.
- $P_J \Leftrightarrow$ vorticity($\omega_{xz}$), $P^z \Leftrightarrow$ transverse acceleration / grad $T$. 
The end (so far)
Parameter values used to approach the basic hadronic observables

EoS: Chiral model, $\varepsilon_{sw} = 0.5$ GeV/fm$^3$.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$\tau_0$ [fm/c]</th>
<th>$R_\perp$ [fm]</th>
<th>$R_z$ [fm]</th>
<th>$\eta/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>3.2</td>
<td>1.4</td>
<td>0.5</td>
<td>0.2</td>
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<td>8.8</td>
<td>2.83</td>
<td>1.4</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>11.5</td>
<td>2.1</td>
<td>1.4</td>
<td>0.5</td>
<td>0.2</td>
</tr>
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<td>17.3</td>
<td>1.42</td>
<td>1.4</td>
<td>0.5</td>
<td>0.15</td>
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<tr>
<td>19.6</td>
<td>1.22</td>
<td>1.4</td>
<td>0.5</td>
<td>0.15</td>
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<tr>
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<td>1.2</td>
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<td>0.12</td>
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<tr>
<td>39</td>
<td>0.9*</td>
<td>1.0</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>62.4</td>
<td>0.7*</td>
<td>1.0</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>200</td>
<td>0.4*</td>
<td>1.0</td>
<td>1.0</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*here we increase $\tau_0$ as compared to $\tau_0 = \frac{2R}{\gamma v_z}$.

Green band:

same $v_2$ and $\pm 5\%$ change in $T_{eff}$.

! Actual error bar would require a proper $\chi^2$ fitting of the model parameters (and enormous amount of CPU time).
A closer look at the parameter dependence

- Polarization observable is more sensitive to details of initial state rather than to details of hydro evolution.
- No sensitivity on the value of particlization energy density $\varepsilon_{sw}$.

NEW

$\sqrt{s_{NN}} = 7.7$ GeV

$\eta/s : 0.2 \rightarrow 0$

EoS: crossover $\rightarrow$ 1PT

$R_\perp \times 0.6$

$R_\perp \times 1.4$

$T^{\tau\eta} \times 0.5$

$T^{\tau\eta} \times 2.0$
Why does $P_f$ increase at lower BES energies?

1) Different initial vorticity distribution:

baryon stopping at lower $\sqrt{s_{NN}}$  
⇓  
shear flow in beam direction  

transparency at higher $\sqrt{s_{NN}}$