Lambda polarization from RHIC BES to LHC energies in viscous hydrodynamic approach

Iurii KARPENKO

with Francesco Becattini

Istituto Nazionale di Fisica Nucleare - sezione Firenze, Università di Firenze, at present: CNRS/SUBATECH Nantes

Highlight: recent \( \Lambda \) polarization measurement


\[ \sqrt{s_{NN}} (\text{GeV}) \]

\[ \text{Au+Au 20-50\%} \]

\[ \Lambda \text{ PRC76 024915 (2007)} \]

\[ \bar{\Lambda} \text{ PRC76 024915 (2007)} \]
Highlight: recent $\Lambda$ polarization measurement extending to full BES: STAR Collaboration, arXiv:1701.06657

“First clear positive signal of global polarization in heavy ion collisions!”
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: $p^0 \frac{d^3 N}{d^3 p} = \int d\Sigma \lambda p^\lambda \frac{1}{\exp \left( \frac{p \cdot u - \mu}{T} \right) \pm 1}$

- For the spin $\frac{1}{2}$ particles produced at the particlization surface:

$$\langle S(x, p) \rangle = \frac{1}{8m} (1 - f(x, p)) \varepsilon^{\mu \nu \rho \sigma} p_\sigma \partial_\nu \beta_\rho,$$

where $\beta_\mu = \frac{u_\mu}{T}$ is the inverse four-temperature field.

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

- polarization is close or equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients
Polarization calculations in hydro models (before 2016)

- F. Becattini, L.P. Csernai, D.J. Wang, Y.L. Xie,
  IC from Yang-Mills dynamics + 3D ideal hydro
  $\sqrt{s_{NN}} = 200$ GeV Au-Au, $P_J \approx 3\%$

  Glauber IC + parametrized rapidity dependence
  $\sqrt{s_{NN}} = 200$ GeV, $b = 11.6$ fm, $P_J \approx 0.2\%$

- Long-Gang Pang, Hannah Petersen, Qun Wang, Xin-Nian Wang,
  arXiv:1605.04024
  AMPT IC + 3D viscous hydro
  $\sqrt{s_{NN}} = 62.4, 200, 2760$ GeV; $P_J$ around few per mille (no exact value).

- +few other papers, where vorticity is visualized, but polarization is not.

All done for $\sqrt{s_{NN}} = 62.4$ GeV and above!

What hydro picture gives us at lower collision energies, where preliminary measurements report essentially non-zero polarization?
The model: 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:**

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

\[
< u^\gamma \partial_\gamma \pi^{\mu \nu} > = -\frac{\pi^{\mu \nu} - \pi^{\mu \nu}_{NS}}{\tau_\pi} - \frac{4}{3} \pi^{\mu \nu} \partial_\gamma u^\gamma
\]

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

https://github.com/yukarpenko/vhlle

**Fluid→particle transition and hadronic phase**

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

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

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

Validating the model for bulk hadronic observables

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901
Λ polarization signal from the model

geometry sketch:
Collision energy dependence

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

$P_J \Longleftrightarrow \bar{\omega}_{xz} \ (\Omega_J)$

Iurii Karpenko, Lambda polarization from RHIC BES to LHC
Why does $P_J$ increase at lower BES energies?

1) Different initial vorticity distribution:

baryon stopping at lower $\sqrt{s_{NN}}$

\[
\downarrow
\]
shear flow in beam direction

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

\[\sqrt{s_{NN}} = 7.7 \text{ GeV, 20-50\% central Au-Au, averaged IC}\]

\[\sqrt{s_{NN}} = 62.4 \text{ GeV, 20-50\% central Au-Au, averaged IC}\]
Why does $P_J$ increase at lower BES energies?

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

Figs: Distribution of $xz$ component of thermal vorticity (responsible for $P_J$ at $p_x = p_y = 0$) over particlization hypersurface.

- 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: $S^*_\Lambda,S^0 = C_{X \rightarrow \Lambda,S^0} \cdot S^*_X$

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

$$S^*_\Lambda = \frac{N_\Lambda S^*_{\Lambda,\text{prim}} + \sum N_X S^*_X \left[ C_{X \rightarrow \Lambda} b_{X \rightarrow \Lambda} - \frac{1}{3} C_{X \rightarrow \Sigma^0} b_{X \rightarrow \Sigma^0} \right]}{N_\Lambda + \sum b_{X \rightarrow \Lambda} N_X + \sum b_{X \rightarrow \Sigma^0} N_X}$$

<table>
<thead>
<tr>
<th>$X$</th>
<th>$J^P$</th>
<th>$\frac{S_X}{S_{\Lambda,\text{prim}}}$</th>
<th>$C_{X \rightarrow \Lambda,S^0}$</th>
<th>$\frac{S_{\Lambda,X}}{S_{\Lambda,\text{prim}}}$</th>
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<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.

What is not taken into account (yet):

- $\Lambda$ and $\Sigma^0$ actively rescatter in hadronic phase → expected to suppress polarization
Λ and ¯Λ: UrQMD+vHLLE vs experiment

- Λ within experimentan error bars.
- Much smaller and opposite sign ¯Λ-Λ 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?

Au-Au, 20-50% central Feed-down contributions incl.

Iurii Karpenko, Lambda polarization from RHIC BES to LHC 12/21
Sensitivity to parameters of the model

$P_j^* \text{ vs } \sqrt{s_{NN}}$

20-50% central

Initial state:
- $R_\perp$: transverse granularity
- $R_\eta$: longitudinal granularity

Fluid phase:
- $\eta/s$: shear viscosity of fluid

Particlization criterion:
- $\epsilon_{sw} = 0.5$ GeV/fm$^3$

Collision energy dependence is robust with respect to variation of the parameters of the model.
Event-by-event versus single-shot hydrodynamic description

no big difference between event-by-event and single shot hydrodynamic description

NEW
Same $P(\sqrt{s_{NN}})$ trend in other hydro and non-hydro models


- Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, PRC 96, 054908


Mean polarization further decreases towards 2.76 TeV LHC energy.
At high energies, the dominant component is $P^z$

20-50% central Pb-Pb, $s_{NN} = 2.76$ GeV

$P^z$ is:

- nonzero in 2D boost-invariant hydrodynamics
- related to transverse expansion
A 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 $v_2$. 
This can be also accessed via correlation of $P^z$ of $\Lambda$ pairs

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

**Single-shot hydro**

**Event-by-event hydro**


$\Lambda$ spin correlations due to vorticity induced by initial state fluctuations
What causes transverse and longitudinal components of polarization?

\[ S^\mu \propto \varepsilon^{\mu \rho \sigma \tau} \omega_{\rho \sigma} p_\tau = \varepsilon^{\mu \rho \sigma \tau} (\partial_\rho \beta_\sigma) p_\tau = \varepsilon^{\mu \rho \sigma \tau} p_\tau \partial_\rho \left( \frac{1}{T} \right) u_\sigma + \frac{1}{T} 2 \left[ \omega^\mu (u \cdot p) - u^\mu (\omega \cdot p) \right] + \varepsilon^{\mu \rho \sigma \tau} p_\tau A_\sigma u_\rho \]

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

**Longitudinal quadrupole** \( f_2 \):

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

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20/21
Summary

Λ polarization is calculated in UrQMD + 3D EbE viscous hydro model for \( \sqrt{s_{NN}} = 7.7 \ldots 200 \) 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.
- \( P_J \Leftrightarrow \text{vorticity}(\sigma_{xz}), \quad P^z \Leftrightarrow \text{transverse acceleration} / \text{grad} \ T \).
The end (so far)
Parameter values used to approach the basic hadronic observables

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

<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>
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<td>39</td>
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<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 \( \tau_0 = \frac{2R}{\gamma_z} \).

Green band: same \( \nu_2 \) and \pm 5\% change in \( T_{\text{eff}} \).

Actual error bar would require a proper \( \chi^2 \) fitting of the model parameters (and enormous amount of CPU time).

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901
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 $\varepsilon_{sw}$. 