Δ Polarization in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV

Measured With HADES

Frederic Kornas for the HADES collaboration

Strange Quark Matter 2019
Global Polarization Measurement:

- System created in high-energy HICs successfully described by relativistic hydrodynamics.
- In peripheral collisions: $|L| \sim 10^5 \hbar$
- What is the effect on fluid/transport?

Vorticity: $\vec{\omega} = \frac{1}{2} \vec{\nabla} \times \vec{v}$

- Vorticity could be very high $\omega \approx 10^{21} s^{-1}$

How to measure the vorticity?

- Large orbital momentum $\Rightarrow$ Polarization of the particle spins
  
  $\rightarrow$ Two contributions:
  
  1. Spin-orbit coupling (same for $q$ and $\bar{q}$)
  2. Electromagnetic coupling (opposite for $q$ and $\bar{q}$)
**How to measure the particle spin?**

- Spin measurement for most of the hadrons very difficult
  → Concentrate on **self-analyzing weak decays**
- Good candidate: \( \Lambda \rightarrow p + \pi^- \)
- **Proton is predominantly emitted in spin direction!**
- **Spin measurement → Momentum measurement**

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Polarization can be measured:

\[
P_A = \frac{8}{\pi \alpha_{\Lambda}} \frac{\langle \sin(\Psi_{EP} - \phi_p^*) \rangle}{R_{EP}}
\]

- Decay parameter \( \alpha_{\Lambda} = 0.642 \pm 0.013 \)
- Orientation with respect to the event plane \( \Psi_{EP} \)
- Azimuthal angle of the proton in the \( \Lambda \) frame \( \phi_p^* \)
High Acceptance DiElectron Spectrometer

Fixed-target experiment

Fast detector: $8 kHz$ trigger rate for Au+Au

High acceptance: full azimuthal coverage, 18 – 85° polar angle
**High Acceptance DiElectron Spectrometer**

**Fixed-target experiment**

**Fast detector:** 8kHz trigger rate for Au+Au

**High acceptance:** full azimuthal coverage, 18 – 85° polar angle

Au+Au run at $\sqrt{s}_{NN} = 2.4\, \text{GeV}$

- Overall: $2.4 \cdot 10^9$ events analyzed

![Diagram of the experimental setup](image)
Centrality Estimation

Offline centrality selection based on hit or track multiplicity

- Centrality determination using Glauber
- Distributions agree with transport model calculations (*processed by GEANT*)
- Task: relate observable quantities to the centrality of the collision
- Assumption: \( \langle N_{\text{participant}} \rangle \sim \langle N_{\text{produced}} \rangle \)

Number of inelastic collisions for a single nucleon

Impact parameter \( b = 6 \text{fm} \)

Event Plane Reconstruction

\[ Q_{EP} = \sum_{i=0}^{N} \vec{u}_i \]

Event Plane Resolution:
- Based on hits of charged projectile spectators in the Forward Wall

Event Plane Resolution:
- Determination of Full Resolution from Sub-Event Resolution (distribution randomly divided into 2 sub-samples)
- Based on method by J.-Y. Ollitrault (arXiv:nucl-ex/9711003)

![Graph showing Event Plane Resolution](image)
Analysis procedure

\[ P_\Lambda(centrality) = \frac{8}{\pi \alpha_\Lambda} \frac{\left< \sin(\Psi_{EP} - \phi^*_p) \right>}{R_{EP}} \]

\( \phi^*_p \): Azimuthal angle of the proton in the \( \Lambda \) rest frame

⇒ Particle identification

\[ \beta = \frac{p}{m} \frac{1}{\sqrt{\left( \frac{p}{m} \right)^2 + 1}} \]

Observables:
- Velocity
- Momentum
- Energy Loss
- RICH information
Create all possible combinations of $\pi^-$ and $p$ within one event:

**Decay channel:**
\[ \Lambda \rightarrow p + \pi^- \]

**Decay topology**
- $d_1$: $\Lambda$ has to come from the primary vertex
- $d_2, d_3$: $p$ and $\pi^-$ are most likely not pointing to the global vertex
- $d_t$: common crossing point for $p$ and $\pi^-$ track
- $d_v$: $\Lambda$ distance before it decays ($ct \sim 8cm$)
- $\Delta \alpha$: Opening angle, added to account for efficiency loss of closed pairs
Decay Topology

- **Simulations:** Thermal $\Lambda$s embedded into real data (1 $\Lambda$ per event)

- **Mixed-event method** on real data to describe the background

- **Enough statistics** very crucial for the polarization analysis (Hard-cut analysis removes a lot of the signal)

- **Employ neural network** in order to gain more statistics!
Neural Network Analysis

Toolkit for Multivariate Data Analysis (TMVA) included in ROOT (https://root.cern.ch/tmva)

Input

Signal: Thermal Δs embedded into real data

Background: Mixed-Event – π⁻ from one event and p from another event

Input Parameters

Topological parameters: \( d_v, d_1, d_2, d_3, d_t \)

In addition: \( m_\pi, m_p, p_\Lambda \)  

significant increase of the efficiency

Training

Convergence of the weights for maximal discrimination between signal and background!

Required output

Signal: \( D_{\text{ideal}} = 1 \)  

Background: \( D_{\text{ideal}} = 0 \)

Actual Output: \( 0 < D_{\text{real}} < 1 \)
Neural Network Analysis

Toolkit for Multivariate Data Analysis (TMVA) included in ROOT (https://root.cern.ch/tmva)

MVA Response

- Clear discrimination of signal and background:
  Simulated $\Delta s$ peak at $D=1$ while mixed-event background peaks at $D=0$ as expected
  - In real data (same event) the signal fraction is much lower:
    $\sum S \ll \sum B$
  - Vary $D$ to find the ideal cut value (i.e. with maximum significance) $D_{\text{min}} = 0.9$
Invariant mass distribution

"Hard cut" analysis:

This analysis
0-40% centrality

<table>
<thead>
<tr>
<th>Topology Parameter</th>
<th>Cut Style</th>
<th>Hard Cut</th>
<th>Pre-Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$ [mm]</td>
<td>&lt;</td>
<td>5</td>
<td>12</td>
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<tr>
<td>$d_2$ [mm]</td>
<td>&gt;</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>$d_3$ [mm]</td>
<td>&gt;</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>$d_v$ [mm]</td>
<td>&gt;</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>$d_t$ [mm]</td>
<td>&lt;</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>$\Delta \alpha$ [°]</td>
<td>&gt;</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

$N^\text{old}_\Lambda = 0.7 \cdot 10^5$

$SIG = 188.49$

$N^\text{new}_\Lambda = 3.0 \cdot 10^5$

$SIG = 448.02$

Polarization analysis for 10-40% centrality:

$N^{10-40\%}_\Lambda = 1.9 \cdot 10^5$

- MVA strongly suppresses the background
- Even with lower topological cuts, the significance is much higher
- Increase of the identified $\Lambda$s by $\sim 300\%$ compared to hard-cut analysis
# Λ Polarization: two approaches

<table>
<thead>
<tr>
<th>General procedure</th>
<th>(1) Event plane method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>➢ Get dN/dM_{inv} in a certain Δφ^*_p-bin</td>
</tr>
<tr>
<td></td>
<td>➢ Get net amount of Λs in that bin</td>
</tr>
<tr>
<td></td>
<td>➢ Plot distribution of N_Λ(Δφ^*_p)</td>
</tr>
<tr>
<td></td>
<td>➢ Fit this distribution to get \langle \sin(Δφ^*_p) \rangle</td>
</tr>
<tr>
<td></td>
<td>➢ Calculate P_Λ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Correction for R_{EP}</th>
<th>(2) Invariant mass fit method</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Final result is corrected by 1/R_{EP} while R_{EP}^{10-40%} is used</td>
<td>➢ Plot the distribution of \langle \sin(Δφ^*<em>p) \rangle</em>{tot} as a function of M_{inv}</td>
</tr>
<tr>
<td>➢ Get S/B-ratio in each bin: f(M_{inv})</td>
<td>➢ Make assumption for \langle \sin(Δφ^*<em>p) \rangle</em>{BG}</td>
</tr>
<tr>
<td>➢ Fit the distribution to get \langle \sin(Δφ^*<em>p) \rangle</em>{SG}</td>
<td>➢ Calculate P_Λ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantage/Drawback</th>
<th>(1) Event plane method</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ D: second decomposition in Δφ^*_p-bins</td>
<td></td>
</tr>
<tr>
<td>➢ A: no background assumption</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantage/Drawback</th>
<th>(2) Invariant mass fit method</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ A: direct extraction of \langle \sin(Δφ^*<em>p) \rangle</em>{SG}</td>
<td></td>
</tr>
<tr>
<td>➢ D: background assumption needed</td>
<td></td>
</tr>
</tbody>
</table>

1/R_{EP}^{10\%} in 10\% centrality bins is weighted event-by-event when filling \langle \sin(Δφ^*_p) \rangle_{tot}
(1) Event plane method

Description of the distribution: *Landau + 2 Gaussian*

\[ f_{\text{global}}(M_{\text{inv}}) = \frac{C}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{s \cdot \log(s) + M_{\text{inv}} s} ds + G_1^{\mu,\sigma_1, A_1}(M_{\text{inv}}) + G_2^{\mu,\sigma_2, A_2}(M_{\text{inv}}) \]

- Fix: \( \mu, \sigma_1, \sigma_2, A_1/A_2 \) for the \( \Lambda \) peak and \( L_1, L_2 \) for BG

Global fit
8 par.

Differential fit
2 par.

Also very good description by the mixed-event method
(1) Event plane method

Fit the distribution of the polarization angle $\Delta \phi_p^* = \Psi_{EP} - \phi_p^*$

- Get distribution of $M_{inv}$ in a certain $\Delta \phi_p^*$-bin
- Get net amount of $\Lambda$s in that bin
- Plot distribution of $N_\Lambda(\Delta \phi_p^*)$
- Fit this distribution to get $\langle \sin(\Delta \phi_p^*) \rangle$
- Calculate $P_\Lambda$

$$\frac{dN}{d\Delta \phi_p^*} = N_0 [1 + 2b_1 \sin(\Delta \phi_p^*) + 2c_1 \cos(\Delta \phi_p^*) + 2b_2 \sin(2\Delta \phi_p^*) + 2c_2 \cos(2\Delta \phi_p^*) + \ldots]$$

$$P_\Lambda = \frac{8b_1}{\pi \alpha_\Lambda R_1}$$

$\Rightarrow P_\Lambda [\%] = 3.762 \pm 0.699 \text{ (stat.)}$

- $c_1$: comparable magnitude to $b_1$
(2) Invariant mass fit method

Fit the distribution of $\langle \sin(\Delta \phi_p^*) \rangle$

- Plot the distribution of $\langle \sin(\Delta \phi_p^*) \rangle_{tot}$ as a function of $M_{inv}$
- Get S and B in each bin: $f(M_{inv}) = S/(S+B)$
- Make assumption for $\langle \sin(\Delta \phi_p^*) \rangle_{BG}$
- Fit the distribution to get $\langle \sin(\Delta \phi_p^*) \rangle_{SG}$
- Calculate $P_\Lambda$

$$\langle \sin(\Delta \phi_p^*) \rangle_{tot} = f(M_{inv})\langle \sin(\Delta \phi_p^*) \rangle_{SG} + (1 - f(M_{inv}))\langle \sin(\Delta \phi_p^*) \rangle_{BG}$$

$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \langle \sin(\Delta \phi_p^*) \rangle_{SG}$$

$$\Rightarrow P_\Lambda[\%] = 3.548 \pm 0.754 (stat.)$$

- Background shows non-zero correlations with magnitude similar to the $\Lambda$ signal!
**Λ Polarization: Results**

- Both methods are consistent:
  \[ P_{\Lambda}^{EPM} [%] = 3.762 \pm 0.699 \text{ (stat.)} \]
  \[ P_{\Lambda}^{IMM} [%] = 3.548 \pm 0.754 \text{ (stat.)} \]

- But background correlations of the same order:
  \[ P_{BG}^{EPM} [%] = 3.689 \pm 1.133 \text{ (stat.)} \]

- Effect not seen in the uncorrelated background (mixed-event, φ rotation) ⇒ correlated effect!

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**Comparison to STAR @ \( \sqrt{s}_{NN} = 200 \text{GeV} \):**

- Event Plane Method for background under the Λ peak:
  \[ P_{\Lambda}^{EPM} [%] = 3.762 \pm 0.699 \text{ (stat.)} \]
  \[ P_{\Lambda}^{IMM} [%] = 3.548 \pm 0.754 \text{ (stat.)} \]
Summary and Outlook

Summary:
- Neural network to improve $\Lambda$ identification:
  $\rightarrow$ factor $\sim 4$ more $\Lambda$s in comparison to previous analysis
- Polarization measurement:
  $\rightarrow$ 2 different methods applied: both in consistence
- Dominant source of systematics:
  $\rightarrow$ Non-zero background correlations in the $P_\Lambda$ signal extraction, which has similar magnitude

Outlook:
- Estimate systematic errors: check where the background polarization comes from and apply corrections
- **How does the finite detector acceptance influences the polarization measurement?**
  $\rightarrow$ Use Pluto (Monte-Carlo simulation framework for HIC collisions and hadronic physics) to generate $\Lambda$s:
  1. **Unpolarized:** Guide them through the HADES detector (GEANT) and apply analysis procedure (result $P_\Lambda = 0$, but without flow)
  2. **Different degree of polarization:** Do the same procedure $\rightarrow$ What do we measure as $P_\Lambda$?
Back Up
Neural network analysis

Input
Signal: Thermal Λs embedded into real data
Background: Mixed-Event – π− from one event and p from another event

Input Parameters
Topological parameters: 𝑑𝑝, 𝑑1, 𝑑2, 𝑑3, 𝑑𝑡
In addition: 𝑚π, 𝑚p, 𝑝Λ significant increase of the efficiency

Synapse
Connections between the neurons, adjusted with a weight 𝑤𝑖𝑗

Hidden Layers
1. Synapse Function:
   \[ 𝜅: (x_{ij}^{l-1} | w_{ij}^{l-1}) \mapsto w_{0j}^{l-1} + \sum_{i=1}^{n} w_{ij}^{l-1} x_{i}^{l-1} \]
2. Neuron Activation Function:
   \[ 𝜶: x \mapsto \frac{1}{1+e^{-kx}} \text{(Sigmoid)} \]

Output Layers
Combines the information into one discriminant D
Back Up
Neural network analysis

**Input**

- **Signal:** Thermal $\Lambda$s embedded into real data
- **Background:** Mixed-Event – $\pi^-$ from one event and $p$ from another event

**Training**

Convergence of the weights for maximal discrimination between signal and background!

**Required output**

- **Signal:** $D_{\text{ideal}} = 1$
- **Background:** $D_{\text{ideal}} = 0$

Actual Output: $0 < D_{\text{real}} < 1$

**Adjusting the weights: Back-Propagation**

- **Error function:** $E(x_1, ..., x_N) = \sum_{n=1}^{SG+BG} \frac{1}{2} (D_{\text{ideal}} - D_{\text{real}})^2$
- **Aim:** Minimize the error function!
- **Weights are updated:** $w^{k+1} = w^k - \eta \nabla E$

Weights of the next training cycle
Weights of the current training cycle
Learning rate
Max. gradient in w-space
Back Up
Event Plane Method – Fit Parameter

Signal distribution

Range: $\mu \pm 2\sigma$

Background distribution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/10^{-3}</th>
<th>Error/10^{-3}</th>
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</thead>
<tbody>
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<td>$N_0$</td>
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<tr>
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<td>$c_1$</td>
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<tr>
<td>$c_3$</td>
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<th>Parameter</th>
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<th>Error/10^{-3}</th>
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<tbody>
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<td>$b_1$</td>
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<tr>
<td>$c_3$</td>
<td>0.97</td>
<td>2.68</td>
</tr>
</tbody>
</table>
Phi Rotation with probability distribution according to $\phi_p^*$ (right panel)

- Parameters consistent with 0!
- Background polarization must be a correlated effect

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</thead>
<tbody>
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<tr>
<td>$c_3$</td>
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