Measurement of $\Lambda$ hyperon spin-spin correlations in p+p collisions by the STAR experiment

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In the 70's, it was discovered that \( \Lambda^0 \) hyperons are polarized in collisions of unpolarized p+Be collisions [G.Bunce, et al.: Phys. Rev. Lett. 36, 1113-1116 (1976)]

- Over nearly 50 years, \( \Lambda^0 \) polarization has been seen in p+p, p+A, e+p, e^+e^- collisions up to collision energies about 40 GeV

- These indicate the importance of final-state effects, e.g., fragmentation and hadronization

\[ \text{Phys. Rev. Lett. 36, 1113-1116 (1976)} \]
Λ POLARIZATION PUZZLE

- In the 70’s, it was discovered that Λ⁰ hyperons are polarized in collisions of unpolarized p+Be collisions [G.Bunce, et al.: Phys. Rev. Lett. 36, 1113-1116 (1976)]

- Over nearly 50 years, Λ⁰ polarization has been seen in p+p, p+A, e+p, e⁺e⁻ collisions up to collision energies about 40 GeV

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What is the origin of the Λ⁰ polarization?

- Does polarization of Λ⁰ depend on spin of the target/projectile?
- Is there a contribution of an initial-state effect?
**Λ POLARIZATION MEASUREMENT**

- Single Λ\(^0\) polarization is measured via Λ\(^0\) → \(p\pi^+\) decay channel with \(BR = (64.1 \pm 0.5)\%\). In the Λ\(^0\) rest frame, protons are emitted preferentially in the direction of Λ\(^0\) spin.

- The distribution of protons in Λ\(^0\) rest frame is then given by:

\[
\frac{dN}{d \cos(\theta^*)} = 1 + \alpha_P \Lambda \cos(\theta^*)
\]

- \(P_\Lambda\) is the Λ\(^0\) polarization
- \(\Lambda^0: \alpha_+ = 0.732 \pm 0.014, \overline{\Lambda^0}: \alpha_- = -0.758 \pm 0.012\)
- \(\hat{n}\) is normal vector to the production plane
- Angle \((\theta^*, \text{ or } \theta_p)\) is measured between \(\hat{n}\) and momentum of proton \((p)\) in Λ’s rest frame.

\[\hat{n} = \vec{p}_{\text{beam}} \times \vec{p}_\Lambda\]


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MOTIVATION FOR \( \Lambda \) SPIN-SPIN CORRELATIONS

`Anisotropies` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation as it violates causality.
MOTIVATION FOR \( \Lambda \) SPIN-SPIN CORRELATIONS

CMB radiation

Temperature correlations

Heavy-ion collisions

Momentum correlations

Proton-Proton collisions

Spin correlation

A (more) direct probe to the initial-state parton spin effects

`Anisotropies` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation as it violates causality.

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EXPERIMENTAL METHOD

- Find a $\Lambda^0$ hyperon pair (any combination) in one event
  - Decay channel $\Lambda^0 \rightarrow p\pi^+$ and charge conjugate

Primary vertex

$\Lambda^0$ decay vertex

$p_{\pi^+, \text{lab}}$

$p_{\pi^-, \text{lab}}$

$p_{\bar{p}, \text{lab}}$
EXPERIMENTAL METHOD

- Find a $\Lambda^0$ hyperon pair (any combination) in one event
  - Decay channel $\Lambda^0 \rightarrow p\pi^+$ and charge conjugate
  - $p_{\Lambda^0,lab} = p_{p,lab} + p_{\pi^-,lab}$
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- Boost (anti-)proton from decay of the corresponding $\Lambda^0$ ($\bar{\Lambda}^0$) to rest frame of its mother
  - Proton momenta in mother rest frame: $p_{p,CMS_{\Lambda}}, p_{\bar{p},CMS_{\Lambda}}$
EXPERIMENTAL METHOD

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- Boost (anti-)proton from decay of the corresponding $\Lambda^0$ ($\bar{\Lambda}$) to rest frame of its mother
  - Proton momenta in mother rest frame: $p_{p,CMS\Lambda}, p_{\bar{p},CMS\Lambda}$

- Measure angle $\theta^*$ between the two boosted protons
  - The distribution of pair angle is given by:
    $$\frac{dN}{d \cos(\theta^*)} \sim 1 + \alpha_1 \alpha_2 P_{\Lambda_1\Lambda_2} \cos(\theta^*)$$
  - $\alpha_1$ and $\alpha_2$ are $\alpha_+$ or $\alpha_-$, depending on $\Lambda^0$ hyperon pair

- A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two $\Lambda^0$ ($\bar{\Lambda}^0$) hyperons
**EXPERIMENTAL METHOD**

- Find a $\Lambda^0$ hyperon pair (any combination) in one event
  - Decay channel $\Lambda^0 \rightarrow p\pi^+$ and charge conjugate
  - $p_{\Lambda^0,lab} = p_{p,lab} + p_{\pi^-,lab}$

- Boost to hyperon's CMS and find decay vertex $\Lambda^0$
- Measuring $p_{\Lambda^0,lab}$, $p_{p,lab}$, $p_{\pi^-,lab}$
- A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two $\Lambda^0$ hyperons

- This experimental method is sensitive to selection criteria and detector acceptance
  - Major source is lower cut on $p_T$ of $\pi$
  - Preferential selection of $\Lambda$ decays, where $\pi$ is emitted along $\Lambda$ momentum
  - This is called the *acceptance effect* and is corrected for in this analysis

Proton kinematics in mother’s CMS

- $p_{p,lab}$, $p_{\pi^-,lab}$, $p_{\Lambda^0,lab}$, $p_{\bar{p},CMS_\Lambda}$
- Primary vertex
- $\Lambda^0$ decay vertex
- $\bar{\Lambda}$ decay vertex

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Key subsystems for this analysis:

- Solenoidal magnet
  - 0.5 T magnetic field with low $p_T$ coverage
- Time Projection Chamber (TPC)
  - Measurement of charged particle transverse momentum ($p_T$)
  - Particle identification (PID) based on energy loss in TPC gas
  - Full azimuthal coverage for $|\eta| < 1$
EVENT AND TRACK SELECTION, PID

- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks originating from close to primary vertex

Ionization energy loss in TPC
**Λ SIGNAL EXTRACTION**

- Signal extraction determined from 2D $M_{inv}$ distributions of unlike-sign (US) $\pi\pi$ pairs

- Three components:
  a) **Peak**: $\pi\pi$ from $\Lambda^0$ ($\bar{\Lambda}^0$) decay paired with another $\pi\pi$ from $\Lambda^0$ ($\bar{\Lambda}^0$) decay
  b) **Ridges**: $\pi\pi$ from $\Lambda^0$ ($\bar{\Lambda}^0$) decay paired with combinatorial background
  c) **Continuum**: combinatorial background paired with combinatorial background

- Contributions (b) and (c) are subtracted from (a) and fitted with 2D Gaussian function
  - Signal region is defined as mean $\pm 3\sigma$
**CORRECTIONS, BACKGROUND SUBTRACTION**

- Measured $[dN/d \cos(\theta^*)]_{\text{meas}}$ distribution for $\Lambda^0\Lambda^0$ pairs before acceptance correction
  - (US-US) distribution (red) has a shape which originates from acceptance and resolution of the STAR detector

- Acceptance correction done using mixed (ME) event hyperon pairs
  - Separate for (US-US) and background

- Background distribution is subsequently subtracted from the (US-US) distribution

- Same method repeated for same-sign hyperon pairs
\( \Lambda \) SPIN-SPIN CORRELATION EXTRACTION

- \( dN/d\cos(\theta^*) \) distributions from data after acceptance correction and background subtraction

- Corrected distribution is fitted with
  \[ dN/d\cos(\theta^*) = A[1 + B \cos(\theta^*)] \]
  - \( A \) and \( B \) are parameters of the fit
  - \( A \) is normalization, \( B = \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2} \)

\[ \begin{align*}
\text{(US-US)-Bkg.} & \quad 2012 \text{ p+p } \bar{s} = 200 \text{ GeV} \\
\text{Minimum bias} & \\
\Lambda^0, \bar{\Lambda}^0 & \quad |y| < 1 \\
0.5 < p_{T,1} < 5.0 \text{ GeV/c} & \\
0.5 < p_{T,2} < 5.0 \text{ GeV/c} &
\end{align*} \]
\( \Lambda \) SPIN-SPIN CORRELATIONS

- \( P_{\Lambda_1 \Lambda_2} \) are consistent with zero within uncertainties

- Hint of polarization signal for \( \Lambda^0 \bar{\Lambda}^0 \) pairs at 2\( \sigma \) statistical significance

- Data suggest no significant spin-spin correlation of initial state \( s \) (anti-)quark pair
  - This measurement provides upper limit on \( \Lambda^0 \) hyperon spin-spin correlations in p+p collisions at \( \sqrt{s} = 200 \) GeV

- First experimental search for \( \Lambda^0 \) hyperon spin-spin correlations - \textbf{We encourage theory colleagues to calculate this from different physics frameworks}
We conduct the first experimental search for $\Lambda^0$ hyperon spin-spin correlations
- It is found consistent with zero within uncertainty, although uncertainty is large
- This new approach provides additional insights to the initial-state parton spin effects

**Outlook:**
- Investigate the correlation for $\Lambda^0$ pairs with different rapidity and azimuthal angle gaps
- Study $p_T$ dependence of the spin-spin correlations
- Study the correlations with large rapidity gap utilizing the STAR forward upgrade using $p+p$ collisions at $\sqrt{s} = 200$ GeV to be collected in 2024
- Publication of the 2012 data coming soon!
  - First steps of publication process starting now
THANK YOU FOR ATTENTION
## Event and Track Selection, PID

- **Data-set:**
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
  - Events with primary vertex close to center of STAR detector selected
  - Track selection to ensure good track quality within geometrical acceptance
  - Particle identification to obtain pure proton and pion sample
  - Decay topology to suppress combinatorial background from tracks originating from close to primary vertex

| Event selection          | $|V_z| < 30$ cm |
|-------------------------|---------------|
|                         | $p_T > 150$ MeV/c |
|                         | $|\eta| < 1$ |
|                         | nHitsFit > 20 |
|                         | nHitsFit/nHitsMax > 0.52 |

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<td>$\text{DCA}_{\pi-PV} &gt; 0.3$ cm</td>
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<td>$\text{DCA}_{p-PV} &gt; 0.1$ cm</td>
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<td>$\text{DCA}_{\text{pair}} &lt; 1$ cm</td>
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<td>$2$ cm $&lt; L_{\text{dec}} &lt; 25$ cm</td>
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<td>$\cos(\theta) &gt; 0.996$</td>
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 SYSTEMATIC ERRORS OVERVIEW

- Summary table of systematic uncertainties
  - $\sigma_{ME}$ - Residual effect from ME correction
  - $\sigma_{bckg}$ - Background subtraction systematic uncertainty
  - $\sigma_{\alpha}$ - Uncertainty of polarization from weak decay parameter $\alpha_+$ and $\alpha_-$
  - $\sigma_{cuts}$ - Variation of selection criteria

- $\sigma_{sys} = \sqrt{\sigma_{ME}^2 + \sigma_{bckg}^2 + \sigma_{\alpha}^2 + \sigma_{cuts}^2}$

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<th>$\sigma_{ME}$ [%]</th>
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