$\gamma p \rightarrow K^+\Lambda$ Differential Cross Section and Recoil Polarization Measurements from $g11a$

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OUTLINE

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Excited Baryons and CQM Predictions

- The Constituent Quark Model is the currently accepted model of the baryon spectrum in the non-pQCD regime.
- Quark Model calculations of excited nucleon states have been made by Capstick and Roberts.
- However, many of the states predicted have never been conclusively observed → The Missing Baryon Problem
- Possible explanations for non-observation:
  - Missing resonances exist, but cross-sections are smaller than current experimental sensitivity
  - Missing resonances exist, but do not couple to $N\pi$ → most of the world’s data
  - Corrections to quark model...
**Motivation**

**Why study $K^+\Lambda$?**

- Self-analyzing $\Lambda$ decay allows for measurement of all particle spins $\Sigma$, $T$, $P_\Lambda$, $O_x$, $O_z$, $C_x$, $C_z$
- A full characterization will allow for a comprehensive study of production mechanisms.
- Some $N^*$ states have been observed to couple to $K^+\Lambda$
  - $S_{11}(1650)^{***}$, $D_{13}(1700)^{**}$, $P_{11}(1710)^{**}$, $P_{13}(1720)^{**}$, ...
- $I = \frac{1}{2}$ of the $K^+\Lambda$ final state couples only to $N^*$, NOT $\Delta^*$
Why study $K^+\Lambda$?

- Self-analyzing $\Lambda$ decay allows for measurement of all particle spins $\Sigma, T, P_\Lambda, O_x, O_z, C_x, C_z$
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- Some $N^*$ states have been observed to couple to $K^+\Lambda$
  - $S_{11}(1650)^{**}, D_{13}(1700)^{**}, P_{11}(1710)^{**}, P_{13}(1720)^{**}, ...$
- $I = \frac{1}{2}$ of the $K^+\Lambda$ final state couples only to $N^*$, NOT $\Delta^*$
- A problem: discrepancies in previous $d\sigma$ results
  - These discrepancies lead to interpretation ambiguities
  - Most notable - CLAS shows large enhancement at $\sqrt{s} \approx 1.9$ GeV
Motivation

Why study $K^+\Lambda$?

-0.15 < cos$\theta$ < -0.05

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Why study $K^+\Lambda$?

![Graph showing the cross-section $\sigma$ in microbarns ($\mu$b) as a function of the square root of the energy $\sqrt{s}$ in GeV.]


**g11a Collection and Statistics**

- *g11a* is a relatively high-statistics photon on liquid hydrogen dataset taken by the CLAS detector from May-July 2004.
- Tagged, unpolarized bremsstrahlung from 4.023 GeV end-point energy electron beam
- Event trigger - coincidence between:
  - CLAS Level 1 - coincidence of 2 charged tracks (TOF and start-counter, sector-wise)
  - Photon tagger - recoil electron in any of the 40 highest-energy T-counters ($E_\gamma \geq 1.58$ GeV)
  - lower photon energies are recorded due to coincidental higher-energy photons
- $\approx 20 \times 10^9$ triggers
- Able to extract $d\sigma$ and $P_\Lambda$ for $1.62 \text{GeV} < W < 2.84 \text{GeV}$. (Previous measurements up to 2.5 GeV and 2.3 GeV, resp.)
Event Selection

- We access the $K^+\Lambda$ final state by considering the charged decay mode of the $\Lambda$ ($\Lambda \rightarrow p\pi^-$).
- In order to test our understanding of CLAS acceptance, we produce two separate analyses of the data...
**Event Selection: \( pK^+\pi^- \) Topology**

- Consider all events with "+ : + : −" final-state charge
- Assign "\( p : K^+ : \pi^- \)" and "\( K^+ : p : \pi^- \)" mass hypotheses
- Kinematic fit to \( \gamma p \rightarrow K^+ p\pi^- \)
  - Remove events with confidence levels < 1%
- Remaining background is removed with two-dimensional cuts on calculated masses
  - \( K^+ \) and \( p \) masses calculated from tracking and timing
  - \( m_K < 0.8 \text{ GeV} \) OR \( m_p > 0.8 \text{ GeV} \)
- Fiducial cuts
- After all cuts, the three-track topology contains \( 6.67 \times 10^5 \) events
- Less than 2% background in all \( \sqrt{s} \) bins (most below 1%)
- Binning: 10-MeV-wide in \( \sqrt{s} \)
**Event Selection:** \( pK^+\pi^- \) **Topology**

![Histogram of missing mass off K+ (GeV/c^2)](image_url)
Event Selection: $pK^+(\pi^-)$ Topology

- Only $\approx 28\%$ of the $g11a$ dataset used
- Consider all events with “$+:+$” final-state charge
- Assign “$p:K^+$” and “$K^+:p$” mass hypotheses
- Kinematic fit to $\gamma p \rightarrow K^+ p (\pi^-)$ (missing $\pi^-$)
  - Remove events with confidence levels $< 5\%$
- Two-dimensional cuts on calculated masses applied
- Background is further reduced with M. Williams’ event-based subtraction
- Fiducial cuts
- After all cuts, the two-track topology contains $1.66 \times 10^6$ events
- Binning: 10-MeV-wide in $\sqrt{s}$
Acceptance

- Generated $300 \times 10^6 \gamma p \rightarrow K^+ \Lambda$ events from phase-space dists.
- Processed events with GSIM (GSIM models $\Lambda \rightarrow p\pi^-$)
- Apply correction for $\Lambda$s that decay outside of start counter
  - $c\tau_\Lambda = 7.89$ cm, ST $\approx 10$ cm
- Applied identical analysis and fiducial cuts
- No physics model...
**Data Expansion/Mother Fit**

- BUT, it is unlikely that nature obeys only phase-space!
- Expand the data in a large set of basis states (replaces a physics model)
- Generate $s$-channel $\gamma p \rightarrow J^P \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$ amplitudes for each data and accepted and raw MC event
  - qft++
  - $\frac{1}{2}^\pm \leq J^P \leq \frac{11}{2}^\pm$ as “complete basis”
  - each amplitude has 2-3 free parameters
- Un-binned maximum log-likelihood fit in each $\sqrt{s}$ bin
- We then weight the acc/raw MC by the fit results
  - Weighted acc matches data in all observables
  - Weighted raw shows data before detector acceptance
- NOT interpreted as physics!
Data Expansion/Mother Fit
Extracting $d\sigma$

- With $\eta$, $d\sigma$ is calculated in the usual way
  - 0.1-wide $\cos \theta_{CM}^{K}$ bins, $-0.95 \leq \cos \theta_{CM}^{K} \leq 0.95$
  - results presented at bin centroids (non-zero acceptance)

- Normalization is handled with $gflux$ package

- Systematic Uncertainty

<table>
<thead>
<tr>
<th>Error</th>
<th>$pK^{+}\pi^{-}$ $\sqrt{s} &lt; 1.66$ GeV</th>
<th>$pK^{+}(\pi^{-})$ $\sqrt{s} \geq 1.66$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle ID</td>
<td>0.11%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Confidence Level Cuts</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>3%-6%</td>
<td>3%-6%</td>
</tr>
<tr>
<td>Normalization</td>
<td>7.9%</td>
<td>7.9%</td>
</tr>
<tr>
<td>Target Characteristics</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\Lambda \rightarrow p\pi^{-}$ Branching Fraction</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
| Total                                | 9%-10.4%                              | 10%-11%                                 | 9%-10.4%
Extracting $P_\Lambda$

- $P_\Lambda$ can be extracted from our data expansion
  - Amplitudes from the expansion contain the $\Lambda$ decay
  - Amplitudes are written in terms of the particle spins projected along the $z$-axis (beam-line)
  - Simple Pauli matrix application allows us to project the out-of-plane polarization given the amplitudes and fit results
  - Same binning as $d\sigma$

- Systematic Uncertainty
  - 0.05 estimated from acceptance study
**g11a Internal Agreement**

We find excellent agreement between the two- and three-track topologies!

\[
0.45 < \cos\theta < 0.55
\]

\[
d\sigma/d\cos\theta_{CM} (\mu b)
\]

- **g11a two-track**
- **g11a three-track**
We find excellent agreement between the two- and three-track topologies!

\[ 0.55 < \cos\theta < 0.65 \]
**g11a Internal Agreement**

We find excellent agreement between the two- and three-track topologies! For comparisons to other measurements, we calculate a weighted mean of the two results...
**Results: \( d\sigma / d \cos \theta_{\text{CM}}^K \)**

\[-0.85 < \cos \theta < -0.75\]

- **g11a average**
- **CLAS g1c Bradford 2005**
- **SAPHIR Glander 2003**
- **LEPS Hicks 2007**
- **LEPS Sumihama 2006**

\[ g11a \ \gamma p \rightarrow K^+ \Lambda \]
Results: \( \frac{d\sigma}{d\cos\theta^K_{CM}} \)

\(-0.25 < \cos\theta < -0.15\)

\(W\) (GeV)

- 1.6
- 1.8
- 2
- 2.2
- 2.4
- 2.6
- 2.8

\(d\sigma/d\cos\theta_{CM}\) (\(\mu\)b)

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1
- 1.2
- 1.4

- g11a average
- CLAS g1c Bradford 2005
- SAPHIR Glander 2003
- LEPS Hicks 2007
- LEPS Sumihama 2006
Results: $d\sigma / d\cos \theta^K_{CM}$

$0.05 < \cos \theta < 0.15$

$W$ (GeV)

1.6 1.8 2 2.2 2.4 2.6 2.8

$\theta$

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

$\mu (CM\theta/d\cos\sigma d)$

$\text{g11a average}$

- CLAS $g1c$ Bradford 2005
- SAPHIR Glander 2003
- LEPS Hicks 2007
- LEPS Sumihama 2006

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Results: \( \frac{d\sigma}{d\cos \theta_{CM}^K} \)

\[ 0.35 < \cos \theta < 0.45 \]

- \( \sigma/\cos \theta \)

- Graph showing data points for different experiments:
  - g11a average
  - CLAS g1c Bradford 2005
  - SAPHIR Glander 2003
  - LEPS Hicks 2007
  - LEPS Sumihama 2006

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**Results: $P_\Lambda$**

- $-0.55 < \cos \theta < -0.45$

![Graph showing the distribution of $P_\Lambda$ vs. $W$ (GeV) with data points and error bars for different experiments.](image)
**Results**: $P_\Lambda$

\begin{align*}
W (\text{GeV}) & \quad 1.6 & 1.8 & 2 & 2.2 & 2.4 & 2.6 \\
\Lambda P \quad -1 & -0.5 & 0 & 0.5 & 1 & < -0.05 & \theta < -0.15 < \cos \theta < -0.05
\end{align*}

-0.15 < cosθ < -0.05

$g11a$
- CLAS McNabb 2004
- SAPHIR Glander 2004
- GRAAL Lleres 2007

$\gamma p \rightarrow K^+ \Lambda$

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RESULTS: $P_\Lambda$

$0.15 < \cos \theta < 0.25$

$P_\Lambda$

- $0.15 < \cos \theta < 0.25$
- $\gamma p \rightarrow K^+ \Lambda$
- g11a
- CLAS McNabb 2004
- SAPHIR Glander 2004
- GRAAL Lleres 2007
**Results: $P_\Lambda$**

$0.45 < \cos \theta < 0.55$

- $W$ (GeV): 1.6, 1.8, 2, 2.2, 2.4, 2.6, 2.8
- $\Lambda P$: -1, -0.5, 0, 0.5, 1

- $\theta$: $0.45 < \cos \theta < 0.55$

- g11a
- CLAS McNabb 2004
- SAPHIR Glander 2004
- GRAAL Lleres 2007

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Results: $P_\Lambda$

$0.75 < \cos\theta < 0.85$

- $g_{11a}$
- CLAS McNabb 2004
- SAPHIR Glander 2004
- GRAAL Lleres 2007
**Results: Total Cross Section**

- **g11a**
- **CLAS - Bradford (05)**
- **SAPHIR - Glander (04)**
- **ABBHHM**

The graph shows the total cross section in micrometers (µb) as a function of the square root of energy (GeV) for different models. The data points are plotted with error bars, illustrating the variation in cross section at each energy level.
**Conclusions**

- g11a results provide $\approx 30\%$ extension of kinematic range and increase in precision for $\gamma p \rightarrow K^+\Lambda$ reaction.
- Independent two- and three-track analyses show good agreement.
- g11a $d\sigma$ measurements agree with previous CLAS results, as well as LEPS data.
- $d\sigma$ results confirm interesting structure, especially at $W \approx 1.9$ GeV.
- $P_\Lambda$ measurement shows agreement with previous measurements with a significant increase in range and precision.
- $P_\Lambda$ shows many interesting structures!
- To be submitted to Phys. Rev. C. (*ad hoc* review in prog.)
- Thanks to the CLAS Collaboration!