Status of $\gamma p \rightarrow K^+ \Sigma^0$ analysis of G11A –
Differential Cross Sections, Recoil Polarizations
and some Physics

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Outline

1. Introduction and Event Selection
2. Differential Cross Sections
3. Recoil Polarization
4. Physics
5. Summary
INTRODUCTION AND EVENT SELECTION

DIFFERENTIAL CROSS SECTIONS

RECOIL POLARIZATION

PHYSICS

SUMMARY
Introduction and Event Selection

Introduction

- **G11A dataset** – unpolarized photoproduction
- 20 billion event triggers recorded by **CLAS** (May-July 2004)
- Liquid Hydrogen cryotarget – 40 cm long, 2 cm radius
- 6 azimuthal “sectors” in CLAS – *at least two “sector-based” charged tracks* in Start Counter for triggering
- CM energy 1.55 GeV to 2.84 GeV – baryon spectroscopy for “missing” baryon resonances (amongst other physics goals)
- **CMU PWA group** is analysing $\gamma p \rightarrow K^+\Sigma^0, K^+\Lambda, p\omega, p\eta, p\eta', \ldots$
**INTRODUCTION**

- **G11A dataset** – unpolarized photoproduction
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- CMU PWA group is analysing $\gamma p \rightarrow K^+\Sigma^0, K^+\Lambda, p\omega, p\eta, p\eta'$, ...
Event Selection – 2- and 3-track “topologies”

Utilize the decay $\Sigma^0 \rightarrow \gamma \Lambda \rightarrow \gamma p\pi^-$

3-track: $\gamma p \rightarrow K^+ p\pi^- (\gamma_f)$

- Demand “+:+:-” final state and $\textit{Kinematically Fit}$ to “$K^+ : p : \pi^-$” / “$p : K^+ : \pi^-$” with zero total missing mass (outgoing photon)
- KFit confidence level $\geq 1\%$ and timing cuts for event selection
- Reconstruct $\gamma_f$ from missing momentum
- All four final state 4-momenta, and thus both $\Sigma^0$ and $\Lambda$ 4-momenta are known
- $\Lambda$ decay vertex from tracking information – set this $p/\pi^-$ for energy loss corrections

2-track: $\gamma p \rightarrow K^+ p (\pi^- \gamma_f)$

- “+:+” final state. “$K^+ : p$” / “$p : K^+$” particle hypotheses with $0.15 \text{ GeV} \leq MM(K^+, p) \leq 0.28 \text{ GeV}$. $\textit{NO Kinematic fitting}$
- Only timing cuts
- $\pi^-$ and $\gamma_f$ 4-momenta NOT known
- Only $\Sigma^0$ can be reconstructed
- Set $p/\pi^-$ vertices to event vertex
Utilize the decay $\Sigma^0 \rightarrow \gamma \Lambda \rightarrow \gamma p \pi^-$

**3-track:** $\gamma p \rightarrow K^+ p \pi^-$ ($\gamma_f$)

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- $1.8$ GeV $\leq \sqrt{s} \leq 2.84$ GeV

**2-track:** $\gamma p \rightarrow K^+ p (\pi^- \gamma_f)$

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- Only timing cuts
- $\pi^-$ and $\gamma_f$ 4-momenta NOT known
- Only $\Sigma^0$ can be reconstructed
- Set $p/\pi^-$ vertices to event vertex
- $1.69$ GeV $\leq \sqrt{s} \leq 2.84$ GeV and greater coverage in backward angles (yay!)
**G11A Start Counter correction**

- Start Counter sits \( \approx 10 \text{ cm} \) around target
- Requires 2 tracks to trigger
- \( c \tau \approx 7.89 \text{ cm} \) for \( \Lambda \)
- A good \% of \( \Lambda \)'s decay outside the Start Counter. These events won’t trigger in Data.
- Accepted Monte Carlo does not include this effect – needs correction

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**Only on the Monte Carlo:**

- Earlier (3-track) : \( \Lambda \) decay vertices not stored by GSIM but probability based cut from \( \vec{p}_\Lambda \)
- 2-track – \( \vec{p}_\Lambda \) not known. Needed to tweak GSIM code to produce \( \Lambda \) vertices directly (hard cut on the vertices at Start Counter boundary after this)
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**Acceptance Calculation**

- **Fit Data using a large number of partial waves** $J^P = \frac{1}{2}^\pm, \ldots, \frac{11}{2}^\pm$.

- Accepted Monte Carlo weighted by the fit results should match the Data.

- Use weighted Acc MC for (physics-weighted) acceptance calculation.

- Above PWA requires knowledge of all final state 4-momenta – not available in 2-track dataset. Use unweighted Monte Carlo for acceptance calculation.

- However, breakup momenta in both $\Sigma^0$ and $\Lambda$ decays are small.

- **Unweighted acceptance calculation (2-track)** is a very good approximation to the physics-weighted acceptance calculation (3-track).
**Differential Cross Sections**

\[ \frac{d\sigma}{d\cos \theta_{CM}^{K^+}}: 2- \text{ AND } 3-\text{TRACK RESULTS} \]

![Graph showing differential cross sections](image)

**Even though they are from the same dataset, the two topologies employ widely different analysis techniques**

**Agreement** between the two results lends confirmation towards our overall understanding of the g11a systematics

**Final g11a** \( \frac{d\sigma}{d\cos \theta_{CM}^{K^+}}: \)

- Weighted average of the two results
- 10 MeV wide \( \sqrt{s} \) binning. Energy coverage: \( 1.69 \text{ GeV} \leq \sqrt{s} \leq 2.84 \text{ GeV} \)
- 0.1 wide binning in \( \cos \theta_{CM}^{K^+} \). Angular coverage: \( -0.95 \leq \cos \theta_{CM}^{K^+} \leq 0.95 \)
- Wide coverage in both energy and production angles – 2113 independent kinematic points
**Systematic Uncertainties**

- Kinematic Fitter Confidence Level (3-track) – 3%
- 3-track PID – 0.62%
- 2-track PID – 1.8%
- Acceptance calculation – 4 – 6% ($\sqrt{s}$ dependent)
- $\Lambda \rightarrow p\pi^-$ branching fraction (PDG) – 0.5%
- Target characteristics: density – 0.11%, length – 0.125%
- Photon flux normalization – 7.3%
- Live time – 3%

9 – 12% estimated overall systematic uncertainty
Differential Cross Sections

Comparison with World Data

Backward angles

\[-0.75 < \cos \theta_{CM}^{K^+} < -0.65\]

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</tbody>
</table>
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PWA Group (CMU)
Comparison with World Data

Mid angles

\[-0.05 < \cos\theta_{CM}^{K^+} < 0.05\]

- \(\pm \frac{d\sigma}{d\cos\theta_{CM}^{K^+}}\) vs. \(\sqrt{s}\) (GeV)

- CLAS g11a
- CLAS g1c (2005)
- SAPHIR (2004)
COMPARISON WITH WORLD DATA

Forward angles

$0.65 < \cos \theta_{CM}^{K^+} < 0.75$

- CLAS g11a
- CLAS g1c (2005)
- SAPHIR (2004)
- LEPS (2006)
Differential Cross Sections

\[ g_{11a} \frac{d\sigma}{d\cos\theta_{CM}^{K^+}} \] RESULTS – PROMINENT FEATURES

- **Backward** angles:- excellent agreement with previous CLAS \( g_{1c} \). Confirms **structure** around \( \sqrt{s} \approx 2.2 \text{ GeV} \). Absent in SAPHIR.

- **Mid** angles:- excellent agreement with \( g_{1c} \). Prominent **peak** at \( 1.9 \text{ GeV} \).

- **Mid-forward** angles:- **possible** “shoulder” at \( \sim 2.1 \text{ GeV} \). \( 1.9 \text{ GeV} \) peak still persistent. Fair to good agreement with previous world data.

PWA Group (CMU)
**Differential Cross Sections**

\[ g_{11a} \, d\sigma / d \cos \theta_{CM}^{K^+} \]  

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Note: backward angle measurements were possible only with the (new!) 2-track analysis.
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- General pseudo-scalar meson photoproduction – 4 complex CGLN amplitudes. Seems like, we need 7 independent quantities (4 magnitudes, 3 relative phases)
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  Unpolarized: $\sigma$ (diff. $c$-$s$), $P$ (recoil pol.)
  Single polarization: $\Sigma$ (beam pol.), $T$ (target pol.)
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GRAAL, LEPS
Recoil Polarization

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CLAS $g1c$
Polarization Observables for $K^+\Sigma^0$

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CLAS g1, SAPHIR, GRAAL
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CLAS $g_1$, SAPHIR, GRAAL
(new!) CLAS $g_{11a}$ – much higher statistics, wide kinematic coverage
Recoil Polarization

**Polarization Observables for $K^+\Sigma^0$**

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(upcoming!) CLAS g9 (FROST)
Recoil Polarization $P_{\Sigma}$

“Traditional” approach

\[ I \propto 1 + \alpha \langle \vec{P}_\Lambda \rangle \cos \theta^\Lambda_{\Lambda HF} = 1 + \alpha \left( -\langle \vec{P}_\Sigma^0 \rangle \cos \theta^\Lambda_{\Sigma HF} \right) \cos \theta^\Lambda_{\Lambda HF} \]

If $\gamma$ is not measured (2-track analysis):

\[ I \propto 1 - \frac{\alpha}{3.9} \langle \vec{P}_\Sigma \rangle \cos \theta^\Lambda_{\Sigma HF} \]

“PWA” approach

PWA fit amplitudes carry $m_{\Sigma} = \pm \frac{1}{2}$ spin-projections.

Project out expectation value of $\sigma_y$: $P_{\Sigma} = \frac{\text{Tr} \left[ \rho \sigma_y \right]}{\text{Tr} [\rho]}$

CM frame

Rotate $z$ axis into $\Sigma^0$ flight dir. Boost to its RF. This is the $\Sigma^0$ Helicity Frame.

Similarly, next, go to the $\Lambda$ Helicity Frame

$\Lambda$ decay is self-analysing
Recoil Polarization $P_\Sigma$

"Traditional" approach

$$I \propto 1 + \alpha \langle \vec{P}_\Lambda \rangle \cos \theta_{\Lambda_{HF}}^p = 1 + \alpha \left( -\langle \vec{P}_\Sigma^0 \rangle \cos \theta_{\Sigma_{HF}}^\Lambda \right) \cos \theta_{\Lambda_{HF}}^p$$

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Compare: **PWA** / **Traditional** method of Polarization extraction

![Graph showing comparison between PWA and Traditional methods for various ranges of \( \cos K_{CM} \) values, indicating differences in polarization extraction.](image)
Recoil Polarization

Compare: $P_\Sigma$ world data

$\sqrt{s}$ (GeV)

$P_\Sigma$

CLAS g11a
CLAS g1 (2004)
SAPHIR (2004)
GRAAL (2007)
Recoil Polarization

$P_\Sigma$: FEATURES

- $P_\Sigma$ “tends towards” zero/negative values in the backward angles.
- Predominently positive with high degree of polarization in the forward direction.
- Data shows lots of structures.
- Systematic errors are estimated $\sim 3\%$
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**BACKGROUND CONTRIBUTIONS: t-CHANNEL AND u-CHANNEL INTERPLAY**

\[ t\text{-channel: } |t| \to 0 \text{ (forward angles)} \]

\[ u\text{-channel: } |u| \to 0 \text{ (backward angles)} \]
**Background contributions: t-channel and u-channel interplay**

- **t-channel:** $|t| \rightarrow 0$ (forward angles)
- **u-channel:** $|u| \rightarrow 0$ (backward angles)

Strong presence of both t- and u-channel non-resonant background contributions.
**Scaling behaviour at high energies – t-channel**

- At high $s$, Bradford et al (PRC 73, 035202) saw scaling of $d\sigma/dt$ with $s^2$ in CLAS $g1c$ data.
- $g1c$ went till $\sqrt{s} \approx 2.53$ GeV. With $g11a$ data, similar behavior seen at even higher $s$.
Regge scaling – \( t \)-channel (contd.)

Scaling is reminiscent of Regge behavior – 
\[
\frac{d\sigma}{dt} \sim D(t) \left( \frac{s}{s_0} \right)^{2\alpha(t) - 2}
\]

Scaling power reveals what Regge exchanges occurring. \( s^2 \) means \( \alpha(t) \sim 0 \) near \( t \sim 0 \)

Guidal, Laget and Vanderhaegan (Nucl. Phys. A627, 645): \( t \)-channel Regge exchanges in kaon photoproduction similar to pion production. Correspondence:

\[
\begin{align*}
\pi & \leftrightarrow K^+ \\
\rho & \leftrightarrow K^*(892)
\end{align*}
\]

Reasonable fits to both \( K^+\Lambda \) and \( K^+\Sigma^0 \) at forward angle high \( \sqrt{s} \) using just \( K^+ \) and \( K^*(892) \) exchanges

Bradford et al noted: \( \alpha(t)_{K^+} + \alpha(t)_{K^*(892)} \sim 0 \) near \( t \sim 0 \).

Could explain why \( \alpha \) is effectively zero around \( t \sim 0 \)
Guidal et al noted that similar Regge behavior can be expected in the $u$-channel (high energy, backward angles). Instead of $(2\alpha(t) - 2)$, we now have $(2\alpha(u) - 2)$.
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Do we see scaling at high $\sqrt{s}$ and $|u| \to 0$?
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Do we see scaling at high $\sqrt{s}$ and $|u| \to 0$? Yes!
Regge scaling – u-channel (contd.)

- u-channel – hyperon exchanges. What are the Regge trajectories?
  \[ \alpha(t)_\Lambda \sim -0.6 + 0.9t \]
  \[ \alpha(t)_\Sigma \sim -0.8 + 0.9t \]

- u-channel: \( t \rightarrow u \), physical region: \( u < 0 \)
- At \( |u| \rightarrow 0 \):
  \[ (2\alpha - 2)_\Lambda \approx -3.2 \]
  \[ (2\alpha - 2)_\Sigma \approx -3.6 \]
- It is thus conceivable that the scaling power \(-(2\alpha - 2)\) be \( > 2 \).
Regge scaling – $u$-channel (contd.)

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- It is thus conceivable that the scaling power $-(2\alpha - 2)$ be $> 2$.

Questions:

- Do we need a Regge description (as opposed to usual Feynman propagators) for the $u$-channel?
- Theoretical difficulties from lowest pole $u = m^2_\Lambda$ being far removed from the physical region ($u < 0$).
- Can we extract a best fit “effective” $\alpha(u)$ from the scaling behavior?
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- Fair to excellent agreement with previous world data – besides higher statistics, $\sim 300$ MeV increase in energy coverage.

- Prominent structure at $\sim 1.9$ GeV. We also confirm structure at $\sim 2.2$ GeV seen in CLAS $g_{1c}$ data in the backward angles.

- Our recoil polarizations ($P_{\Sigma}$) measurements represent a vast improvement over previous world data – in statistics, kinematic coverage and precision (intermediate $\Lambda$ directions no longer summed over).

- $P_{\Sigma}$ is large and positive at forward angles. “Tends towards” zero/negative values in backward directions. Lots of structures seen.

- Confirm scaling at forward angles, high $\sqrt{s}$ seen in previous CLAS $g_{1c}$ data indicating $t$-channel Regge exchange.

- Results very strongly suggests presence of $u$-channel for $K^+\Sigma^0$. For the first time, scaling seen at backward angles at high $\sqrt{s}$ indicating $u$-channel Regge behavior. Needs further investigation.

- Our differential cross-section and polarization results are almost ready to be submitted to the CLAS review committee. Begun running initial PWA to look for missing resonances.
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**Event-background separation**

“Quality factor” $Q$ extracted for each event from *event-based* fits

Weigh: signal ($Q$) background $(1-Q)$

2-track:

- $1.9 \text{ GeV} \leq \sqrt{s} \leq 2.1 \text{ GeV}$
- $2.3 \text{ GeV} \leq \sqrt{s} \leq 2.5 \text{ GeV}$
- $2.7 \text{ GeV} \leq \sqrt{s} \leq 2.84 \text{ GeV}$

3-track:

- $1.9 \text{ GeV} \leq \sqrt{s} \leq 2.1 \text{ GeV}$
- $2.3 \text{ GeV} \leq \sqrt{s} \leq 2.5 \text{ GeV}$
- $2.7 \text{ GeV} \leq \sqrt{s} \leq 2.84 \text{ GeV}$
Timing Cuts

Three-track

Two-track
Dilution effect of averaging over intermediate Λ's in measuring $P_Σ$