Initial State Helicity Correlation in Wide Angle Compton Scattering

E05-101

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Hall C Workshop
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Physics goals of this experiment complement those of E99-114 and benefits from its experience with the RCS experimental technique.
Real Compton Scattering: Introduction

- Key element in Program of Hard Exclusive Reactions
  - RCS
  - Elastic Form Factors
  - DVCS
  - DVMP

- Common issues:
  - interplay between hard and soft processes
  - Onset of asymptotic regime
  - Role of hadron helicity flip

- Uniqueness
  - Vary both $s$ and $t$
  - Weighting of quarks, $e_q^2$
  - independent integral of GPD’s, $\chi^{-1}$
Compton Scattering off nucleons provides information on the substructure of nucleon in terms of quark and gluon d.o.f. → extremely complicated

Compton scattering in various kinematical regions

- low energy
  → dominated by nucleon as a whole

- deeply virtual CS; low $|t|$, large $Q^2$
  → handbag diagram involving skewed parton distributions

- 'wide angle' CS; low $Q^2$, large $|t|$ and $s$ ensures dominance of short distance behaviour

What is the reaction mechanism?
What is the reaction mechanism?

- 3 active quarks
- 2 hard gluons
- 3-body "form factor"

- 1 active quark
- 0 hard gluons
- 1-body "form factor"

Which, if either, dominates at few GeV?

We will be able to distinguish among the competing mechanisms.
Asymptotic (pQCD) Mechanism

- momentum shared by hard gluon exchange
- 3 active quarks
- valence configuration dominates
- soft physics in distribution amplitudes, $\Phi(x_1, x_2, x_3), \Phi(y_1, y_2, y_3)$
- constituent scaling: $\frac{d\sigma}{dt} = f(\theta_{CM})/s^6$
- Must dominate at "sufficiently" high energy(?)
- Has predictions for polarization observables, $K_{LL} = A_{LL}$

Brodsky/Lepage
Kronfeld, Nizic
Vanderhaeghen, Guichon
Brooks, Dixon, ...
Constituent Scaling

\[ \gamma p \rightarrow \gamma p \]

Approximate scaling

\[ \frac{d\sigma}{dt} = f(\theta_{CM})/s^6 \]

Cornell data approximately support scaling but ...

Asymptotically we expect pQCD to be dominant, but when?
Handbag Mechanism for \((s, -t, -u) \gg M^2\)

- One active parton
- Momentum shared by soft overlap
- Feynman mechanism
  - struck quark nearly real \((x \sim 1)\) (co-linear with proton)
- Form factor like expression
  \[
  \frac{d\sigma}{dt} = \frac{d\sigma}{dt} \bigg|_{KN} f(t)
  \]
- Straightforward predictions for polarization observables
Factorize into hard scattering on single quark and moments of GPD’s at skewness $\xi = 0$

- Hard scattering: Klein-Nishina from nearly on-shell parton
- Soft physics: Compton form factors $R_V(t)$, $R_A(t)$ and $R_T(t)$ relating emission and reabsorption of struck quark in the proton

Compton form factors:

$$
R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x, 0, t)
$$

$$
R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \text{sign}(x) \hat{H}^a(x, 0, t)
$$

$$
R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x, 0, t)
$$

Elastic form factors:

$$
F_1(t) = \sum_a e_a \int_{-1}^{1} dx H^a(x, 0, t)
$$

$$
G_A(t) = \sum_a \int_{-1}^{1} dx \text{sign}(x) \hat{H}^a(x, 0, t)
$$

$$
F_2(t) = \sum_a e_a \int_{-1}^{1} dx E^a(x, 0, t)
$$
Cross section from E99-114

\[ \frac{d\sigma}{dt} = \frac{d\sigma_{KN}}{dt} \left[ f_V R_V^2(t) + (1 - f_V) R_A^2(t) \right] \]

Polarization Observables

\[ A_{LL} \frac{d\sigma}{dt} = \frac{1}{2} \left[ \frac{d\sigma(++)}{dt} - \frac{d\sigma(+-)}{dt} \right] \]

\[ A_{LL} = K_{LL} \approx K_{KN} \frac{R_A(t)}{R_V(t)} \]

Related to \( \frac{\Delta u}{u} \) at moderate to high \( x \).
Handbag in CQM

Miller in IA approximation of handbag.

- Massive quark
- Model wave function same as for E/M form factors
- Orbital angular momentum and nonconservation of proton helicity
- Good agreement with cross section data
- But $A_{LL} \neq K_{LL}$, backward angles
  $A_{LL} \approx -K_{LL}$

\[0\]
Physics Goals

- Measure $A_{LL}$ (never been measured) at two scattering angles:
  \[ \theta_{CMS}^{\gamma} = 70^\circ \text{ corresponding to } -t = 2.4 \text{ (GeV/c)}^2 \]
  \[ \theta_{CMS}^{\gamma} = 140^\circ \text{ corresponding to } -t = 6.4 \text{ (GeV/c)}^2 \]

- Provide an experimental test of the RCS reaction mechanism: does the photon interact with a constituent or a current quark?

- Provide an additional test for hadron helicity conservation and pQCD
Experimental Layout

Kinematic Range

\[ E_\gamma = 4.3 \text{ GeV}, \quad s = 9 \text{ GeV}^2 \]
\[ \theta_{\text{cms}} = 70^\circ, 140^\circ \]

- mixed \( e - \gamma \) beam
  \[ \rightarrow e - p/\text{RCS} \]
  discrimination needed
  \[ \rightarrow \text{control of backgrounds} \]
- good angular resolution
- Polarized target

Require HMS trigger only

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Initial State Helicity Correlation in Wide Angle Compton Scattering – p.13/31
Calorimeter

- 1750 lead glass blocks, TF-1 type
- Arranged as 56 rows in 32 columns
- Approximately 1.2 meters by 2.1 meters
- Built by GEP-III, to be used by SANE and SemiSANE (BETA) and E03-003
Deflection of electrons by magnetic field.
Polarized Target

- Microwave Input
- NMR Input
- Refrigerator
- Refrigerator
- Liquid Helium
- Liquid Helium
- LN$_2$
- LN$_2$
- To Pumps
- To Pumps
- Magnet
- Target (inside coil) $1^\circ$K
- NMR Coil
- B 5T

- frozen(doped) NH$_3$
- $^4$He evaporation refrigerator
- 5T polarizing field
- remotely movable insert
- dynamic nuclear polarization

Initial State Helicity Correlation in Wide Angle Compton Scattering – p.16/31
## Kinematics

<table>
<thead>
<tr>
<th>P#</th>
<th>$t$ (GeV/c)$^2$</th>
<th>$\theta_{\gamma}^{lab}$ degree</th>
<th>$\theta_{\gamma}^{cm}$ degree</th>
<th>$\theta_{p}^{lab}$ degree</th>
<th>$E_{\gamma}^{lab}$ GeV</th>
<th>$p_p$ GeV/c</th>
<th>$L$ m</th>
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</thead>
<tbody>
<tr>
<td>P1</td>
<td>-2.4</td>
<td>25</td>
<td>70</td>
<td>39</td>
<td>3.00</td>
<td>2.02</td>
<td>7.0</td>
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<tr>
<td>P2</td>
<td>-6.4</td>
<td>82</td>
<td>140</td>
<td>12</td>
<td>0.87</td>
<td>4.25</td>
<td>2.5</td>
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<table>
<thead>
<tr>
<th>P#</th>
<th>$\theta_{\gamma}^{lab}$ degree</th>
<th>$t$ (GeV/c)$^2$</th>
<th>$\theta_{\gamma}^{cm}$ degree</th>
<th>$\frac{d\Omega_{\gamma}}{d\Omega_p}$</th>
<th>$D$</th>
<th>$N_{RCS}$ total</th>
<th>$\Delta A_{LL}$</th>
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<tbody>
<tr>
<td>P1</td>
<td>25</td>
<td>-2.4</td>
<td>70</td>
<td>0.58</td>
<td>1.6</td>
<td>1850</td>
<td>0.05</td>
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<tr>
<td>P2</td>
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<td>-6.4</td>
<td>140</td>
<td>24.5</td>
<td>5.5</td>
<td>3250</td>
<td>0.07</td>
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<table>
<thead>
<tr>
<th>P#</th>
<th>$\theta_{e}^{V}$ degree</th>
<th>$\theta_{p}^{V}$ degree</th>
<th>HMS degree</th>
<th>$p$(proton) GeV/c</th>
<th>$\theta_{rms}$ mrad</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>4.1</td>
<td>39</td>
<td>2.02</td>
<td>1.75</td>
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<tr>
<td>2</td>
<td>15.4</td>
<td>0.6</td>
<td>12</td>
<td>4.25</td>
<td>0.83</td>
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<tr>
<td>Kin.</td>
<td>Procedure</td>
<td>beam, nA</td>
<td>time hours</td>
<td></td>
<td></td>
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<tr>
<td>------</td>
<td>---------------------------</td>
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<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>BigCal calibration</td>
<td>1000</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>RCS data taking</td>
<td>90</td>
<td>176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>RCS data taking</td>
<td>90</td>
<td>240</td>
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<tr>
<td></td>
<td>Packing Fraction Measurements</td>
<td>90</td>
<td>16</td>
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<td>Moller Measurements</td>
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<tr>
<td></td>
<td>Beam Time</td>
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<td>BigCal angle change</td>
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<td>Target Anneals</td>
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<td>52</td>
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<td>Stick Changes</td>
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<td>36</td>
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<td></td>
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<tr>
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<td>Overhead Time</td>
<td></td>
<td>96</td>
<td></td>
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<tr>
<td></td>
<td>Requested Time</td>
<td></td>
<td>506</td>
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<td></td>
</tr>
</tbody>
</table>
Asymmetry measurement relaxes demands on some systematic error sources (solid angles etc) which cancel but requires attention to others. The largest sources are:

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target polarization</td>
<td>2%</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>2%</td>
</tr>
<tr>
<td>$\pi^0$ subtraction (shape)</td>
<td>3%</td>
</tr>
<tr>
<td>$e\rho\gamma$ subtraction</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.2%</strong></td>
</tr>
</tbody>
</table>
Conclusions

- Experiment straightforward - based on experimental data and extensive experience.
- Test onset of handbag approach in terms of GPD’s.
- Positive indications for handbag allows extraction of non-perturbative structure of hadrons in form of GPD’s.
- Explore role of finite quark masses in polarization observables.
- Shed light on nature of quark helicity flip processes.
- As byproduct $\tilde{A}^{\pi}_{LL}$ will also be measured.
- Scheduling with SANE and Semi-SANE captures setup savings.
Merely due to lack of available beam time, the PAC recommends that only the kinematic point in the backward hemisphere be measured.
Approved with A− rating for 14 days.
Simulation

- Presence of radiator creates unique conditions
  - Beam blows up
  - Large number of secondary particles (electrons, photons) - implications for rates in calorimeter; where to place shielding.
  - Include target magnetic field

- Physics backgrounds
  - Elastic electron scattering
  - Quasielastic electron scattering
  - $\pi^0 \rightarrow 2\gamma$ from proton and target materials
  - Include target magnetic field
Status

- GEANT4 - Justin Wright, UVA graduate student
- Electromagnetic part moving along well
- Second part hindered by lack of the physics in GEANT4
- Also by our unfamiliarity with the standard practice for incorporating new physics.
GEANT4 Simulation

- **Geometry**
  - Upstream beam pipe
  - Downstream beam pipe (Helium bag or flaring Aluminum tube)
  - Upstream copper radiator (10%)
  - Target can (simplified), including the target cell and magnet
  - Big Cal
  - Simple plane detectors to represent the solid angle openings of the Calorimeter and the HMS

- **Fields**
  - The target magnet's field (read in from a table)

- **Electromagnetic processes as currently implemented by the Geant4 collaboration**
  - Electron Ionization
  - Electron Bremsstrahlung
  - Photo Electric Effect
  - Compton Scattering (from electron)
  - Pair Production
  - Annihilation

- **Data collection and analysis**
  - Each primary electron represents a single event
  - All daughter particles are tracked fully
  - All physical objects can be treated as perfect detectors, recording all interactions
  - Separate code converts this data into root trees or paw ntuples
1 µA on radiator instead of 100 nA

Radiator

Magnet(s)

Polarized target

Beam dump on floor

Existing beam dump
### Details

<table>
<thead>
<tr>
<th>Details</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HMS resolution</strong></td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td><strong>HMS acceptance</strong></td>
<td>$\pm 27(h) \pm 70(v)$ mr</td>
</tr>
<tr>
<td><strong>HMS $\frac{\Delta p}{p}$</strong></td>
<td>$\pm 9%$</td>
</tr>
<tr>
<td><strong>Angle Resolution</strong></td>
<td>0.9 mr (h) 0.9 mr(v)</td>
</tr>
<tr>
<td><strong>HMS vertex resolution</strong></td>
<td>$\pm 1$ mm</td>
</tr>
<tr>
<td><strong>Photon fluence</strong></td>
<td>$\frac{d\kappa}{k}(0.10 + 0.018 + 0.01)$</td>
</tr>
<tr>
<td><strong>BigCal block sizes</strong></td>
<td>$4 \times 4$ cm</td>
</tr>
<tr>
<td><strong>BigCal $\sigma_E$</strong></td>
<td>$5%/\sqrt{E}$</td>
</tr>
<tr>
<td><strong>BigCal</strong></td>
<td>$1.2 \times 2.1$ m</td>
</tr>
<tr>
<td><strong>Möller</strong></td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td><strong>Target thickness</strong></td>
<td>$1.5$ g/cm$^2$ of NH3, $0.3$ of He</td>
</tr>
<tr>
<td><strong>Multiple scattering</strong></td>
<td>$1.7$ (P1), $0.8$ (P2) mr</td>
</tr>
</tbody>
</table>

| Lucite Cerenkov hodoscope | | | |
|--------------------------|---|---|---|---|
|                          | thick | horiz. | vert. | # |
| x                        | 1.25  | 80     | 12.5  | 16 |
| y                        | 2.5   | 12.5   | 160   | 8  |

10 p.e. 11% r.l., $x_{\text{rms}} = 3.6$ cm

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<th>kin.</th>
<th>$t$ (GeV/c)$^2$</th>
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Magnet coils restrict access to range of angles: here the field direction is along the beam line.
\( \pi^0 \) photons
Dilution from other materials - Hall A Al data

\[
\frac{N_{\text{quasi}}}{N_{\text{free}}} \times \left( \frac{P_N + P_{\text{He}}}{P_{\text{free}}} \right) = 0.02 \times \frac{(7 + 2.4)}{3} \approx 0.06
\]
Dilution from other materials - Simulation results

\[ F = \frac{N_p^\pi}{N_{\pi_{\text{free}}}^\pi} \times T_p \times T_\pi \times CL \times (P_N + P_{\text{He}})/P_{\text{free}} = \frac{1}{3.5} \times 0.55 \times 0.4 \times \frac{1}{2} \times (7 + 2.4)/3 \sim 0.10 \]
Counting rate vs. threshold  11/28/2001

- **Beam energy**: 3.3 GeV
- **Beam current**: 10 µA
- **Target**: 15 cm LH₂
- **Calorimeter angle**: 35°
- **Calorimeter to target**: 10.6 m
- **Solid angle**: 0.36 msr

Graph showing the relationship between counting rate (Hz) and threshold (mV) with data points plotted against energy (GeV).
Miller approach compared to Huang et al.

**Miller**
- constituent quark model
- soft physics embodied in wave function (power law)
- $m_q \simeq 350$ MeV
- non-zero quark-helicity flip
- $\Rightarrow K_{LL} \neq A_{LL}$

**Huang et al.**
- current quarks
- proton helicity flip non-zero
- $\Phi_2 = -\Phi_6$; double-flip amplitudes
- $\Phi_2, \Phi_6$ are non-zero with $\alpha_s$ corrections, without both are zero.
- $\Rightarrow K_{LL} = A_{LL}$

Miller’s quark helicity flip implies $\Phi_2 \neq -\Phi_6$ even with $\alpha_s$ corrections, and large compared to non-helicity flip.