Timelike Compton Scattering off transversely polarized proton

C12-18-005

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Proposal for Hall C, with NPS and CPS collaborations
This proposal

Following E12-18-005 conditionally approved (C2) in 2018

Main TAC concerns in 2018
- high rates in hodoscopes
- proton tracking accuracy

Main updates:
- hodoscopes replaced by GEM+scintillators hodoscopes for proton detection and tracking
- trigger with GEM+scintillators+calorimeter
- improved background and tracking studies

This presentation:
1) New additions to the setup
2) Other parts of the experimental setup
3) Physics goals of our experiment
4) Analysis and what is expected
Experimental setup

$\gamma P \rightarrow e^+ e^- P'$

All 3 final particles in coincidence detected

11 GeV
85% pol.
2.5 μA
electron (CEBAF)

Compact Photon Source (CPS)

Transverse polarized NH$_3$ target (DNP)
3 cm long (JLab/UVa)

5.5-11 GeV photons, 50-85%
circularly polarized
1.5 x 10$^{12}$ γ/sec

electron dump in magnet

~ 2m

$\gamma P \rightarrow e^+ e^- P'$

spectrometer part

PbWO$_4$
calorimeters
(Neutral Particle Spectrometer, NPS)

5.5-11 GeV photons, 50-85%
circularly polarized
1.5 x 10$^{12}$ γ/sec

scintillator hodoscopes

±6° horizontal / 17° vertical

21.7°

P'

~1.5m

Top view cartoon

Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

Integrated luminosity: 5.85 x 10$^5$ pb$^{-1}$ for 30 PAC days of "physics"
Experimental setup

- Radiator: Compact Photon Source
- Target: $\perp$ polarization, NH$_3$
- GEMs (new), scintillator hodoscopes
- Calorimeters: PbWO$_4$
- Trigger: 3 particles, GEM+hodoscope+calorimeter
Trackers: GEM

Main addition to our setup since 2018

SBS BT GEM prototype

from: Gnanvo et al. NIM. A 782 (2015)

4 groups, 3 layers

SBS BT GEM module

- Tolerance rate $10^6$ Hz/mm$^2$
- Tracking accuracy: $\sim$ 100 μm
- Tolerance to magnetic field: 1.4 T [as tested with BONUS]
- 3 parallel layers, split in 4 symmetric quadrants 50x50 cm

As per several Hall A experiments using SBS, PRad, SoLID
Trackers: scintillator hodoscopes

Modification to our setup since 2018

- 2x2x5 cm³ active elements scintillators with light detectors on the rear
- Along particle trajectory
- dE/dX for low momentum protons, complete tracking

\[ \text{dE/dx for protons, } \pi \text{ and } K \text{ vs momentum} \]

Note: particles bended by target magnetic field
Trigger and DAQ

Main modification to our setup since 2018

\[ \gamma P \rightarrow e^+ e^- P' \] 3 final particle in trigger

**Trigger level 1**

1. Request 2 strongest clusters in the calorimeters, in the opposite quadrants, with energy > 1 GeV each, with combined energy > 5 GeV
2. Request energy depositions in 2 hodoscope blocks, correlated in time and location with the calorimeter clusters.

**Trigger level 2**

3. Request 2 coincident clusters in the calorimeters (e+, e-)
4. Request hit in scintillator (recoil proton) correlated in time with the calorimeter clusters, and corresponding 2 hits out of 3 in GEM-s.

4 x 23x23 crystals and scintillators = 2116 x 2 = 4,232 fADC
4 x (5 layers of GEM chambers 50 cm x 50 cm) = 16 x 2 x 500/0.4 = 50,000 channels of VMM3

VTP : VXS Trigger Processor
10% Cu radiator

used for beam dump with 3.2 T warm magnet

W/Cu shielding: minimal radiation, negligible interference with target field

$1.5 \times 10^{12} \gamma/s$ at 2.5 μA, 5.5 to 11 GeV
(5.8x10^5 pb^{-1} integrated luminosity)

$\sim 1$ mm spot size at 2m

used for WACS approved experiment, in development
Transverse JLab/UVa polarized target

- Target: $^{15}\text{NH}_3$ in $^4\text{He}$ at 1K, 0.6 packing fraction
- DNP at 140 GHz; 20 W RF field
- 5T magnetic field by superconducting Helmhotz coils used for bending particles in spectrometer
- "live" polarization monitoring by NMR
- Acceptance: $\pm 17^\circ$ horizontal, $\pm (6^\circ - 21.7^\circ)$ vertical
- Up/down (~10 mm) and 1 Hz rotation of target cup to avoid radiation damage and depolarization effects
- Dilution factor (from MC) for our reaction ~20%
- Rotation 90° of magnet and scattering chamber for $\perp$
Calorimeters

- 2x2x20 PbWO$_4$ calorimeters: 2116 blocks total divided in 4 groups of 23x23 matrix (active area 0.74m$^2$)
- Hamamatsu R4125 PMTs (3/4" diameter bialkali photocathode)
- 22.5 radiation lengths deep
- Vertical aperture $\theta = \pm 1.6^\circ$: region affected by high rates from transverse magnetic field [BH region]
- Resolutions 2.5/$\sqrt{E} + 1\%$, $\sigma_x \approx 3$mm at 1 GeV
- In-situ calibration using $\pi^0$ electroproduction
Timelike Compton Scattering

\[ \gamma P \rightarrow e^+ e^- P' = \text{TCS} + \text{Bethe-Heitler} \]

Why measuring TCS off a transversely polarized proton?
• Unique access to GPD E of the proton
• GPD universality studies (TCS vs DVCS)
• Independent observables for GPD data sets and global fits in valence region
• Most knowledge on GPDs from DVCS: complex conjugate, TCS access same information
Transverse target spin asymmetries

Dependence in GPD parametrization and $J_u, J_d$ (VGG model) vs $\phi$ and $\phi_S$

- TCS contribution through interference → purely imaginary, BH cancels
- Sensitive to GPD parametrization
- Angular momenta $J_u, J_d$ and GPD $E$

Need of experimental data!

calculations based on Boër, Guidal, Vanderhaeghen
GPDs from Vanderhaeghen, Guidal, Guichon (VGG)
Compton Form Factors from DVCS and TCS

DVCS: \( \sigma, \Delta \sigma_{LU} \)

accessible with Halls A, B, C

TCS: \( \sigma, \Delta \sigma_{\omega U} \)

Hall A, B (if higher statistics)

Caveat: for comparison purpose and sensitivity studies; assuming same uncertainties for all cases (based on Boër, Guidal...)

• CFFs from TCS can be extracted at same level than DVCS
• \( \text{Im}(\mathcal{E}) \) extracted thanks to transverse target
• Precision on H greatly improved with new constraints

Main goal: GPD E (proton) → unique, not measured in other exp.
Secondary goal: complement universality studies
→ universality or breaking? Higher twist/NLO effects?
- Studied with \( Q^2 \) evolution in other experiments
- Comparison of fit results DVCS only, TCS, TCS+DVCS
→ interpretation depends on size of observed effects

[fit of simulations with same errors]
Main cuts:
- triple coincidence: 2 leptons, 1 proton
- Physics: cut out regions near BH peaks by \((E, \theta, Q'^2)\) \(\phi\) and \(\theta\) dependent cut
- Trigger thresholds: triple coincidence, minimum 1 GeV/lepton and 5 GeV/2 leptons in calorimeter
- Exclusivity: momentum/energy/missing mass balance

Analysis: exclusivity cuts and/or machine learning for better background rejection \((\pi^+\pi^- \ldots)\)
Anticipated results on CFFs

Mostly dominated by complementary unpolarized experiments, due to correlation with GPD $H$.

(combined errors on 2 orthogonal $\perp$ asymmetries for first sinus moment, for all bins (to be compared with size of asymmetries vs $\varphi_s$)

- Im($H$), Re($H$), Im($\bar{H}$), Im($E$) extracted even with very large experimental uncertainties (E, F, G)
- Results mostly depend on unpolarized cross section errors (other experiments off LH2)
- Our experiment will put constraints on GPD E, $J_u$ & $J_d$, and reduce errors on Im+Re($H$)
Beam time request

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>setup and installation</td>
<td>2.5 (PAC days)</td>
</tr>
<tr>
<td>signal and electronic checkout</td>
<td>2.5</td>
</tr>
<tr>
<td>gain matching of the detector's channels</td>
<td>0.5</td>
</tr>
<tr>
<td>Decommissioning</td>
<td>1.5</td>
</tr>
<tr>
<td>Overhead</td>
<td>7.5</td>
</tr>
<tr>
<td>commissioning with beam</td>
<td>5</td>
</tr>
<tr>
<td><strong>physics</strong></td>
<td><strong>30</strong></td>
</tr>
</tbody>
</table>

Total: 49.5 PAC days, 35 days with beam

<table>
<thead>
<tr>
<th>Overhead</th>
<th>Number</th>
<th>Time Per (hr)</th>
<th>total (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization/depolarization</td>
<td>60</td>
<td>2.0</td>
<td>120</td>
</tr>
<tr>
<td>Target Anneals</td>
<td>15</td>
<td>4.0</td>
<td>60</td>
</tr>
<tr>
<td>Target T.E. Calibrations</td>
<td>10</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>Packing fraction/Dilution runs</td>
<td>6</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Target Material Change</td>
<td>8</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>NPS Crystal Recovery</td>
<td>1</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>BCM/BPM Calibration</td>
<td>8</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Moller Measurements</td>
<td>1</td>
<td>1</td>
<td>42</td>
</tr>
<tr>
<td><strong>Total Overhead</strong></td>
<td></td>
<td></td>
<td><strong>346 (14.4 days)</strong></td>
</tr>
</tbody>
</table>

Projections:
30 physics PAC day, L=5.85x10^5 pb^{-1} with 11 GeV e⁻ beam and CPS (1.5x10^{12} γ/s or 10^{35} γ/cm²/s)
Summary

Physics

- Unique access to GPD E of the proton
- **Extraction of CFFs** from transverse polarized asymmetries + complementary TCS measurements
  Reduce correlation uncertainties by ~x10 compared to only unpolarized+beam polarized experiments
- Contribution to GPD data sets, **universality studies** with complementary TCS / DVCS experiments

Experimental setup

- New: Tracking with **GEM detectors**, to handle high background rates + scintillator hodoscopes
- New: **Trigger with calorimeters + GEMs, triple coincidence**, high thresholds (> 1 GeV /lepton)
- High intensity **real photon beam** from radiator (CPS collaboration)
- 2 splits PbWO₄ electromagnetic **calorimeters** (NPS collaboration)
- Transversely polarized **DNP target**, ammonia (JLab/UVA target)

Main advantages of this experiment and dedicated setup: GPD E, high intensity real photons
backup
Trigger details

- Each of four quadrants will provide in pipeline (2-3 micro seconds delay) parameters per cluster
  - Location, time, and energy of two strongest clusters in the calorimeter,
  - Energy deposition in the scintillator block correlated in time and location
- VTP (VXS trigger processor) will use the combined energy (> 5 GeV) for the trigger level 1
  - Search for proton signals in the scintillator hodoscope correlated in time to e+/e-
  - Initiate readout of GEM DAQ
- Preliminary proton tracking using GEM information in VMM3 (modern GEM chamber chip, an implementation under development for the SOLID preRD)

Calorimeter cluster trigger

- Compute all 4x4 sums, one sum above threshold
- Request “seed” energy > 1 GeV, 2 quadrant combined energy > 5 GeV

  ✓ Exclude hot blocks (1/8 fraction) close to beam pipe (~23% reduction of useful events)
  ✓ ~3 MHZ integral hit rate in each quadrant (energy above1 GeV), reasonable for trigger formation
  ✓ 38 kHZ background trigger rate, reasonable for trigger formation
  ✓ At least 90% efficiency for TCS events (estimate with no background)
VMM3 chip

- ASIC for ATLAS New Small Wheel
- Radiation hard similar to APV25 : > 100 Mrad
- 64 channels
- Low noise over wide range of input capacitance (<1 pF to ~1 nF)
- Shaping times: 25 ns, 50 ns, 100 ns, 200 ns
- Pulse amplitude proportional to charge at input
- Gains: 0.5, 1, 3, 4.5, 6, 9, 12, 16 mV/fC
- **6 bit ADC (25 ns conversion) and 10 bit ADC (250 ns conversion)**, 8 bits TDC (1 ns resolution), 12 bits Beam Crossing time stamp
- 4 MHz of rate per channel thanks to multilevel FIFO
- Continuous or triggered readout on normal data path
- Latency up to 16 ms in triggered mode
- **Fast direct outputs (64 channels) for ATLAS trigger (6b ADC, ToT)**
- Normal data link up to 320 Mb/s
Scheme of DAQ

Hodoscopes

PbWO4

PbWO4

SAMPA
Or VMM3

18 ? VXS crates

4 x 23x23 crystals and scintillators
= 2116 x 2 = 4,232 fADC

4 x (5 layers of GEM chambers 50 cm x 50 cm)
= 16 x 2 x 500/0.4 = 50,000 MVV3

VTP : VXS Trigger Processor

Inclusion of GEM in trigger will be developed
Extracting spin asymmetry

Here (also in proposal): fit of first moment - for illustration

Method that will be used: direct fits of CFFs on full asymmetries combined with unpolarized and beam polarized cross sections → takes all moments into account and reduce CFFs correlations

Error on CFFs will be dominated by complementary unpolarized experiments

\[ \sin(\phi - \phi_S) \] fitting of kinematic bin 4\(^{th}\), vs \( \phi \), 8 bins in \( \phi_S \)

<table>
<thead>
<tr>
<th>Bin</th>
<th>( 0 &lt; \phi_S &lt; \pi/8 )</th>
<th>( \pi/8 &lt; \phi_S &lt; \pi/4 )</th>
<th>( \pi/4 &lt; \phi_S &lt; 3\pi/8 )</th>
<th>( 3\pi/8 &lt; \phi_S &lt; \pi/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 / ndf )</td>
<td>11.34 / 15</td>
<td>13.58 / 15</td>
<td>22.33 / 15</td>
<td>16.58 / 15</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>-0.006185 ± 0.001480</td>
<td>0.00659 ± 0.00127</td>
<td>-0.03027 ± 0.001100</td>
<td>-0.02633 ± 0.001086</td>
</tr>
</tbody>
</table>

- 0.15 \( < \xi < 0.22 \)
- 4 \( < Q^2 < 7 \text{ GeV}^2 \)
- 0.2 \( < t < 0.4 \text{ GeV}^2 \)

first moment: not our fit method

+ smeared simulations (with dilution factors+errors)
- ideal fit (on unsmeared data)
- 1 attempt fit (on smeared data)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>VALUE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>target polarization</td>
<td>0.05</td>
<td>NMR measurement</td>
</tr>
<tr>
<td>packing fraction</td>
<td>0.03</td>
<td>target spec</td>
</tr>
<tr>
<td>target dilution factor</td>
<td>≈ 0.02</td>
<td>depend on analysis cuts / possibility of run off frozen N similar target</td>
</tr>
<tr>
<td>interaction with target material</td>
<td>negligible</td>
<td>with vertex reconstruction, exclusivity</td>
</tr>
<tr>
<td>background subtraction ($\pi^\pm$, accidental)</td>
<td>0.03</td>
<td>measurements other Halls and MC</td>
</tr>
<tr>
<td>proton resonances</td>
<td>&lt; 0.01</td>
<td>thanks to proton detection</td>
</tr>
<tr>
<td>trigger and tracking efficiency</td>
<td>0.01</td>
<td>from MC</td>
</tr>
<tr>
<td>beam polarization (for $A_{\odot}$)</td>
<td>0.01</td>
<td>measured (not main measurements)</td>
</tr>
<tr>
<td>luminosity (for $\sigma$ and $\sigma_{\odot}$)</td>
<td>-</td>
<td>(not main measurement, in development)</td>
</tr>
</tbody>
</table>

Total ~ 0.07

**Measurements dominated by statistic uncertainties and corrections to dilution factors**
Impact of dynamic twist corrections on DVCS+TCS fits

- Corrections applied: target mass and restauration of gauge invariance
- Impact on CFFs: $\sim 10\%$ on Re, $\sim 1\%$ on Im, opposite sign in DVCS and TCS
- Impact on DVCS+TCS fits: between "twist 2" and "DVCS" results; $1\%$ (Im) to $10\%$ (Re)
  → below uncertainties on CFFs

**Corrections**

mass and $\Delta=(p-p')$ in skewness variable:

\[
\xi' = -\frac{\bar{q}^2}{2P \cdot \bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s-m^2) + \Delta^2 - Q'^2}
\]

\[
\xi = -\frac{\Delta \cdot \bar{q}}{2P \cdot \bar{q}} = \frac{Q'^2}{2(s-m^2) + \Delta^2 - Q'^2}
\]

(corrected - asymptotic) asymmetries

**Fit results**

- fit result (+1%) DVCS+TCS
- generated TCS
- twist 2 CFF
- generated DVCS

fit from all (un)polarized DVCS+TCS combinations
Dynamic twist corrections for TCS

- leading-twist TCS hadronic part of amplitude with "Ji's" GPDs decomposition

\[
H_{\mu \nu}^{TCS} = \frac{1}{2} (-g_{\mu \nu} - \sum_{-1}^{1} dx \left( \frac{1}{x - \xi - i\epsilon} + \frac{1}{x + \xi + i\epsilon} \right) \left( H(x, \xi, t) \bar{u}(p') \gamma_5 u(p) + E(x, \xi, t) \bar{u}(p') \sigma^{\alpha \beta} n_\alpha \frac{\Delta \beta}{2m} u(p) \right) - \frac{i}{2} (\epsilon_{\nu \mu}) \sum_{-1}^{1} dx \left( \frac{1}{x - \xi - i\epsilon} - \frac{1}{x + \xi + i\epsilon} \right) \left( \bar{H}(x, \xi, t) \bar{u}(p') \gamma_5 u(p) + \bar{E}(x, \xi, t) \bar{u}(p') \gamma_5 \frac{\Delta \cdot n}{2m} u(p) \right) \Delta = (p' - p)
\]

- ad-hoc twist 3 corrections for gauge-invariance

\[
H_{\mu \nu}^{G} = H_{LO}^{\mu \nu} - \frac{P_{\mu}}{2P \cdot \bar{q}} \cdot (\Delta_\perp)_\kappa \cdot H_{LO}^{\nu \kappa} + \frac{P_{\nu}}{2P \cdot \bar{q}} \cdot (\Delta_\perp)_\lambda \cdot H_{LO}^{\mu \lambda} - \frac{P_{\mu} P_{\nu}}{4(P \cdot \bar{q})^2} \cdot (\Delta_\perp)_\kappa \cdot (\Delta_\perp)_\lambda \cdot H_{LO}^{\nu \kappa}
\]

- mass and \(\Delta\) terms in skewness variables, related to light cone momentum fractions

\[
\xi' = -\frac{\bar{q}^2}{2P \cdot \bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s - m^2) + \Delta^2 - Q'^2}
\]

\[
\xi = -\frac{\Delta \cdot \bar{q}}{2P \cdot \bar{q}} = \frac{Q'^2}{2(s - m^2) + \Delta^2 - Q'^2}
\]

\(R = \) corrected / asymptotic unpolarized cross sections, vs \(t\) (left) and vs \(Q'^2\) (right)

Experimental setup (simplified pic)