Wide-Angle Compton Scattering at JLab

DIS2017 (WG6 Spin and 3D Structure)
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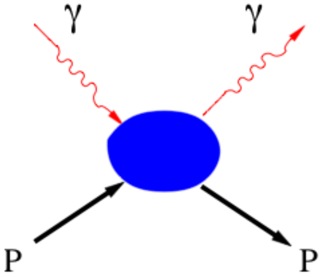
Presentation Outline

- Theoretical Context and Motivation
  - Factorisation of the reaction mechanism
  - Non-perturbative transverse structure of the nucleon
- Experimental and analysis technique
- The Jefferson Lab WACS programme
  - 6 GeV Highlights
  - Plans for the 12 GeV era

WACS: An Introduction

- Hard exclusive nucleon Compton scattering can be investigated in two complementary kinematic regimes:
  - Deeply-virtual: large Q^2; $\left(\frac{-t}{Q^2}\right) \ll 1$
  - Wide-angle: large $-t$, $-u$; $\left(\frac{Q^2}{-t}\right) \ll 1$
- WACS is a powerful yet under-utilised probe of transverse nucleon structure, similar to high-Q^2 elastic electron nucleon scattering.

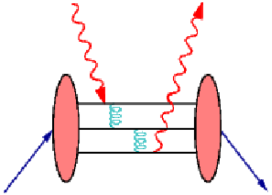


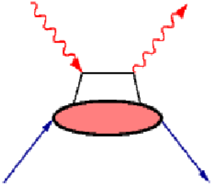
It is, however, one of the least understood of the fundamental reactions in the several GeV regime.

Reaction Mechanism

- A number of theoretical approaches have been proposed over the years:
  - pQCD (two hard gluon exchange)
  - Regge exchange and VMD models
  - GPD-based soft overlap mechanism
  - Relativistic constituent quark model
  - Soft collinear effective theory (SCET)
  - Dyson-Schwinger equations

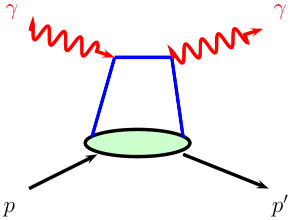
- The two open questions are:
  - How does the reaction mechanism factorise?
  - What new insights on the non-perturbative structure of the proton are accessible?





Non-perturbative Proton Structure

Diehl & Kroll, EPJ C73 (2013)



Provided that $s, -t, -u \gg \Lambda^2$ the handbag mechanism (c.f. Feynman Mechanism, dynamic diquark in DSE) involves factorisation of the amplitudes into:

- Hard photon-parton scattering
- Soft emission and re-absorption of parton by proton

$$\mathcal{M}_{\mu'+,\mu+} = 2\pi\alpha_{\rm em}\Big\{\mathcal{H}_{\mu'+,\mu+}[R_V + R_A] + \mathcal{H}_{\mu'-,\mu-}[R_V - R_A]\Big\}$$

$$\mathcal{M}_{\mu'-,\mu+} = 2\pi\alpha_{\rm em}\frac{\sqrt{-t}}{m}\Big\{\mathcal{H}_{\mu'+,\mu+} + \mathcal{H}_{\mu'-,\mu-}\Big\}R_T$$

Non-perturbative physics encoded in vector, axial-vector and tensor form factors which can be related to $1/x$ moments of high momentum transfer, zero skewedness GPDs $H, \tilde{H}$ and E.

WACS Form Factors

$\gamma p \to \gamma p$

$$R_V(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} H_v^q(x,0,t)$$

$$R_A(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} \tilde{H}_v^q(x,0,t)$$

$$R_T(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} E_v^q(x,0,t)$$

$ep \to ep$

$$F_1(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, H_v^q(x,0,t)$$

$$G_A(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, \tilde{H}_v^q(x,0,t)$$

$$F_2(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, E_v^q(x,0,t)$$

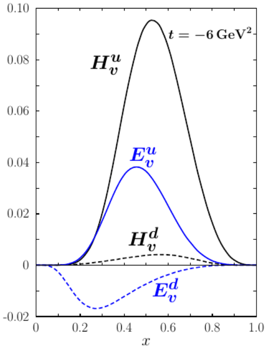
$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{\mathrm{KN}} \left\{ \frac{1}{2}\frac{(s-u)^2}{s^2+u^2}\left[R_V^2(t) + \frac{-t}{4m^2}R_T^2(t)\right] + \frac{1}{2}\frac{t^2}{s^2+u^2}R_A^2(t) \right\}$$

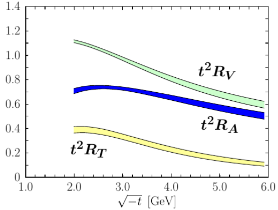
$$A_{LL} = K_{LL} \quad = \quad \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$$

$$A_{LS} = -K_{LS} \quad = \quad A_{LL}\left[\frac{\sqrt{-t}}{2m}\frac{R_T(t)}{R_V(t)} - \beta\right]$$

Form Factor Parameterisation

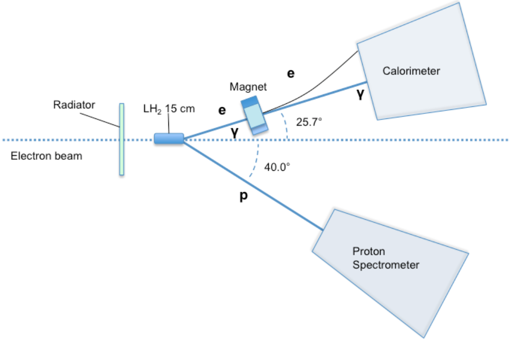
- $R_V(t)$ and $R_T(t)$ form factors parameterised from H and E GPDs extracted from flavour decomposed Dirac and Pauli form factors.
- This approach is not possible for the axial form factor $R_A(t)$; instead a profile function for $\tilde{H}$ was used based on $\Delta q(x)$ data.
- This then allowed for predictions for the experimental observables $\frac{d\sigma}{dt}$, K_{LL}, and K_{LS}.





Experimental Technique

Cross sections are small which requires running at very high luminosity ($d\sigma/dt \leq 1\ \mathrm{pb\,GeV^{-2}}$, $\mathcal{L}_{eff} \geq 1 \times 10^{38}\ \mathrm{cm^{-2}\,s^{-1}}$). This places great demands on experimental equipment in terms of rates and radiation hardness.



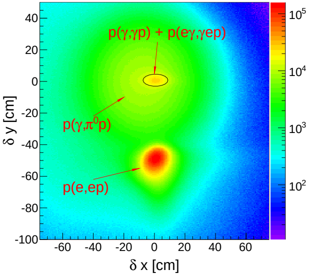
1. A 6 % copper radiator produces a mixed electron-photon beam on a liquid hydrogen target.
2. High-resolution magnetic spectrometer to detect the recoil proton.
3. Highly-segmented electromagnetic calorimeter and deflection magnet to detect the scattered photon.

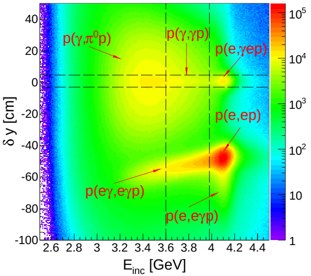
Analysis Technique

- Data analysis relies on utilisation of the kinematic two-body correlation between the scattered photon/electron and the recoil proton.

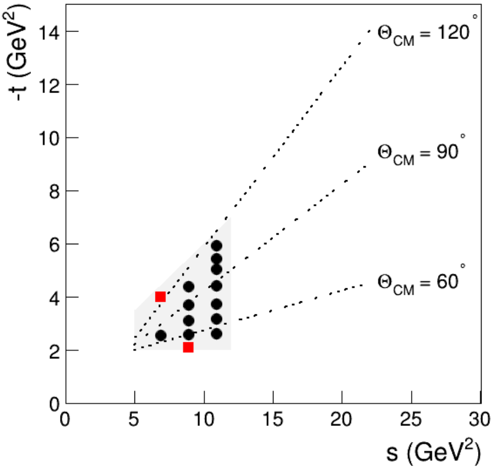
- The three dominant reaction channels within acceptance are:
  - $\gamma p \to \gamma p$
  - $\gamma p \to \pi^0 p$
  - $ep \to ep$ and $(ep\gamma)$

- Extraction of the WACS signal requires excellent angular and momentum resolution in both the photon and proton spectrometers.



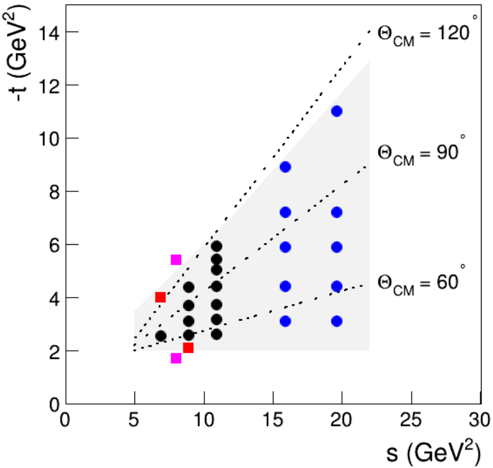


- Two experiments during the 6 GeV era:
    - E99-114
    - E07-002



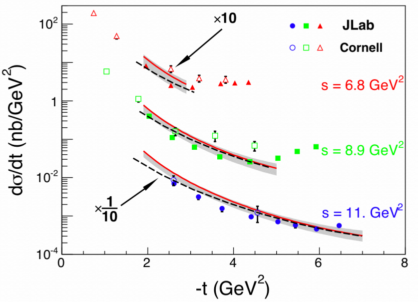
The Jlab WACS Programme

- Two experiments during the 6 GeV era:
  - E99-114
  - E07-002
- Two experiments approved for running at 12 GeV:
  - E12-14-003
  - E12-14-006
- Measurements of $d\sigma/dt$, K_{LL}, K_{LS}, A_{LL} and A_{LS} on the proton.

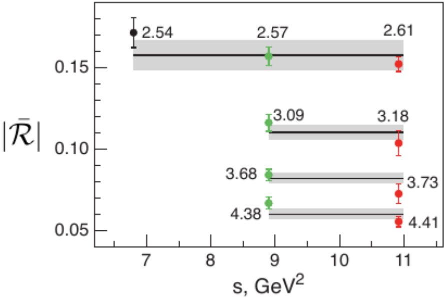


6 GeV Highlights – Differential Cross Section

Danagoulian *et al.* PRL98 (2007)



Kivel & Vanderhaeghen JHEP1304 (2013)

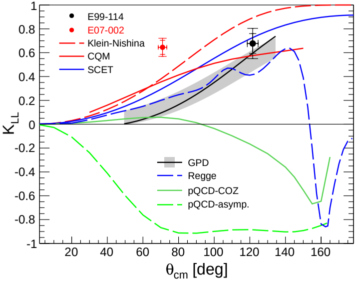


- A factor of 1000 improvement over previous experiments.
- Disagreement with pQCD predictions – cross section scales as $1/s^{7.5}$.

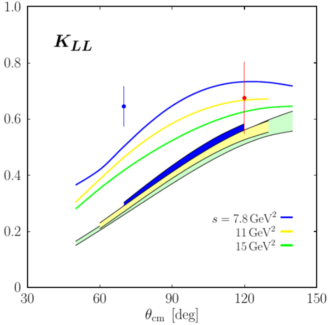
Extracted form factors exhibit strong evidence of s-independence and therefore factorisation provided that $s, -t, -u > 2.5\ \mathrm{GeV}^2$.

6 GeV Highlights – Polarisation Observables

Hamilton *et al.* PRL94 (2005)



Fanelli *et al.* PRL115 (2015)

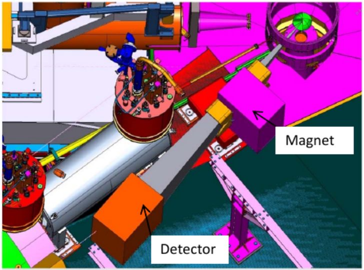


- Results strongly favour leading quark mechanism ($x = 1$).
- $K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$

New result suggests axial nucleon current is larger that vector current at low $-t$, but factorisation and target masss corrections are still an issue.

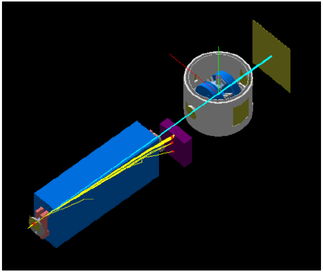
Plans for 12 GeV – Apparatus

NPS



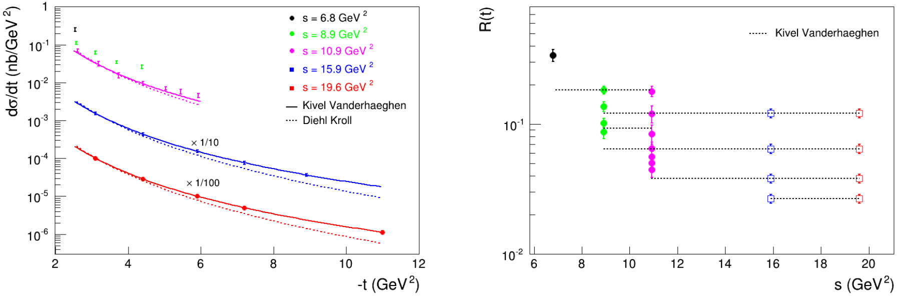
- Development at an advanced stage for a new highly-segmented $PbWO_4$ electromagnetic calorimeter for Hall C.

HIPS



- Work underway on the concept for a high-intensity photon source for use with a solid polarised target for measurements of A_{LL}.

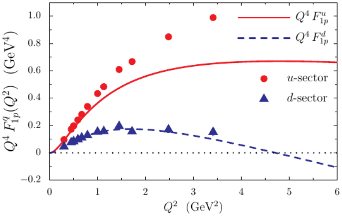
Plans for 12 GeV – Differential Cross Section

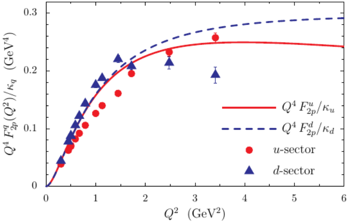


- New measurements (all firmly in the wide-angle regime) will allow for a rigorous test of factorisation and extraction of form factors.
- Extension to highest possible values of $-t$ will offer new insights into non-perturbative proton structure and test universality of leading quark mechanism.

Plans for 12 GeV – nWACS?

- Can we measure the WACS cross section with a deuteron target?
- Would allow flavour separation of the form factors.
- $\sigma_n/\sigma_p \simeq (R_n/R_p)^2 \simeq (e_d/e_u)^2 \simeq 1/16$
- Requires either a tagged photon beam or spectator nucleon tagging – limits luminosity.
- Angular resolution and nuclear corrections might be other concerns.





Summary

- The WACS programme is unique to Jefferson Lab and offers a relatively unexplored window on hadron structure at high $-t$.
- Results from the 6 GeV era demonstrate factorisation appears to be valid for Mandelstam variables above 2.5 GeV^2.
- New experiments are planned for the 12 GeV facility on both unpolarised and polarised observables:
  - These probably represent our last opportunity to study this reaction.
  - Experiments should therefore be carefully designed in light of what we've learned, in order to maximise physics impact.