Wide-Angle Compton Scattering in Hall C at Jefferson Lab

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for the JLab WACS, Neutral Particle Spectrometer (NPS) and Compact Photon Source (CPS) Collaborations

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Backward-Angle (u-channel) Physics Workshop
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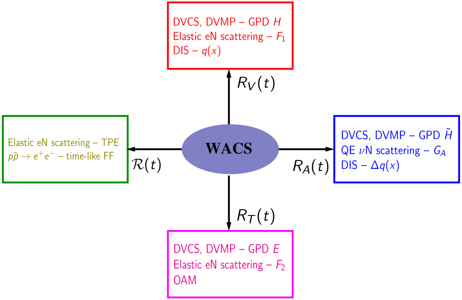
Presentation Outline

- Theoretical context and motivation
  - Factorization of the reaction mechanism
  - Non-perturbative transverse structure of the proton
    - GPD-based approach
    - Soft Collinear Effective Theory
    - Relativistic Constituent Quark Model
- The Jefferson Lab WACS program
  - 6 GeV results and perspectives for the 12 GeV era
- Experimental technique
  - A promising new approach for polarized physics with real photons
- Proposed measurements at 12 GeV
- Summary

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 scattering.
- However, unlike elastic eN experiments WACS is sensitive to the nucleon's axial structure and therefore related to high-Q^2 neutrino scattering experiments.



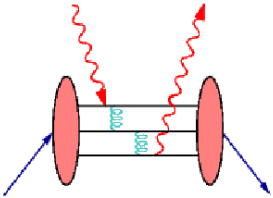
It is one of the least explored of the fundamental reactions in the several GeV regime.

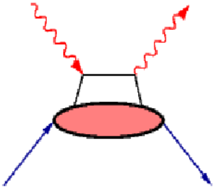
Factorization and the WACS Reaction Mechanism

- 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
    - Soft collinear effective theory (SCET)
    - Relativistic constituent quark model

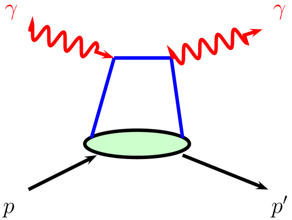
    - Dyson-Schwinger equations
- How does the reaction mechanism factorize?
- Having established the dominant factorization scheme, what new insights on the non-perturbative structure of the proton are accessible?





Non-perturbative Proton Structure: GPD-based Approach

Radyushkin, Phys Rev D58 (1998)
Huang *et al.* EPJ C23 (2002)
Diehl & Kroll, EPJ C73 (2013)



- Provided that $s, -t, -u \gg \Lambda^2$ the handbag mechanism involves factorization of the scattering amplitude into:
  - Hard photon-parton scattering
  - Soft emission and re-absorption of parton by proton

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

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

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.

Non-perturbative Proton Structure: WACS Form Factors

$\gamma p \to \gamma' p$

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

poorly constrained even at moderate $-t$

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

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

$ep \to e' p$

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

poorly constrained even at moderate $-t$

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

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

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

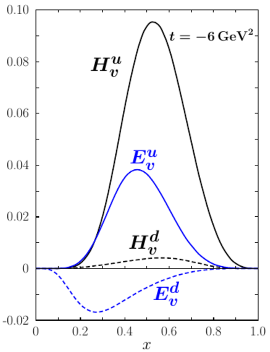
$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$$

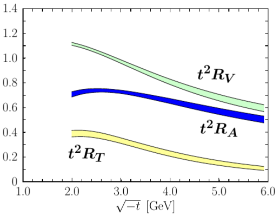
$$A_{LS} = -K_{LS} = A_{LL}\left[\frac{\sqrt{-t}}{2m}\frac{R_T(t)}{R_V(t)} - \beta\right]$$

Diehl & Kroll, EPJ C73 (2013)

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}.





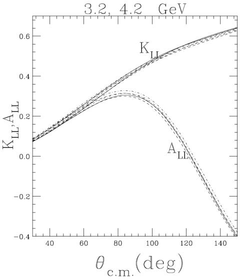
Non-perturbative Proton Structure: SCET and rCQM

Kivel & Vanderhaeghen JHEP 4 (2013)

$$\frac{d\sigma}{dt} \simeq \frac{2\pi\alpha^2}{(s-m^2)^2}\left(\frac{1}{1-t/s}+1-t/s\right)|\mathcal{R}|^2 = \frac{d\sigma^{KN}}{dt}|\mathcal{R}|^2,$$

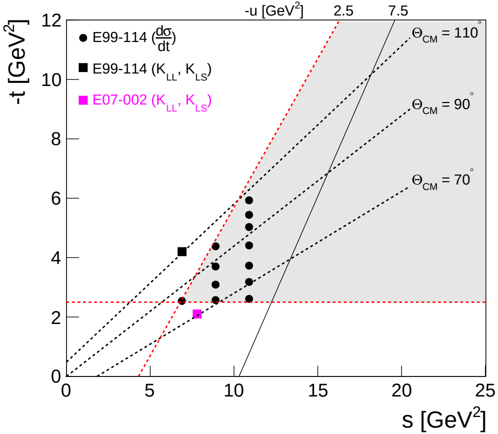
- The Soft Collinear Effective Theory represents an alternative factorized QCD-based approach to WACS.
- It has shown the importance of WACS in understanding two-photon exchange effects in elastic ep scattering.
- In this framework, a new universal form factor is introduced which describes the soft-overlap contribution in a variety of hard exclusive reactions, such as time-like Compton scattering.

Miller, Phys Rev C 69 (2004)

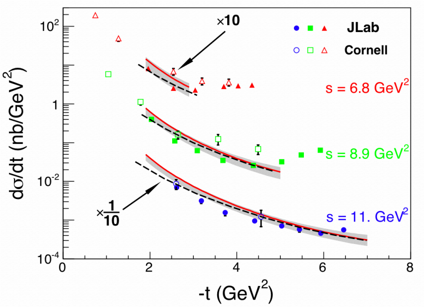


- The relativistic Constituent Quark Model is a handbag-based approach in which relativistic and quark mass effects induce significant quark transverse and orbital angular momentum.
- If the active quark mass is large ($M_p/3$) $A_{LL} \neq K_{LL}$.

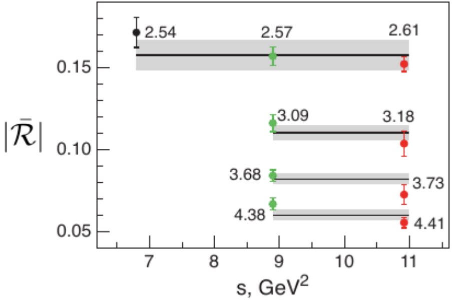
- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass)
  - E07-002 in Hall C with HMS and BigCal (Pb-glass)



Danagoulian *et al.* PRL98 (2007)



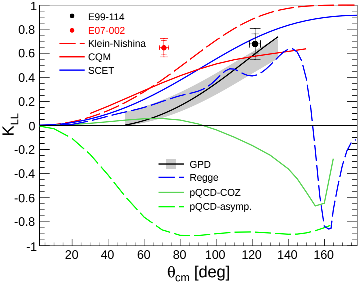
Kivel & Vanderhaeghen JHEP 4 (2013)



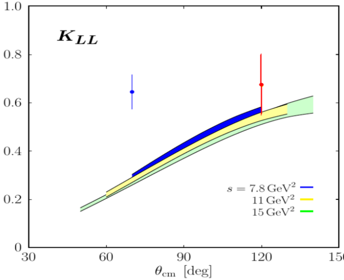
- A factor of 1000 improvement in figure-of-merit over previous experiments.
- Disagreement with pQCD predictions – cross section scales as $1/s^{7.5}$.

Extracted vector/SCET form factor exhibits strong evidence of s-independence and therefore factorization provided that $s, -t, -u > 2.5\ \mathrm{GeV}^2$.

Hamilton *et al.* PRL94 (2005)
Fanelli *et al.* PRL115 (2015)



Diehl & Kroll Eur. Phys. J. C73 (2013)



- Results strongly favour leading quark (Feynman) mechanism ($x \approx 1$).
- E07-002 result is larger than all predictions including Klein-Nishina: $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

Hamilton *et al.* PRL94 (2005)
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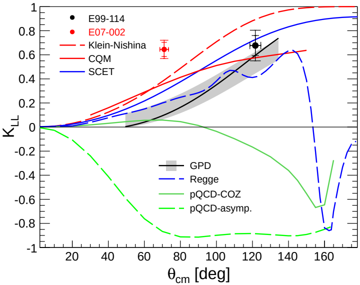
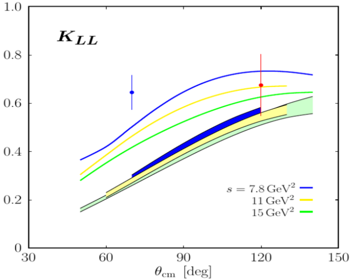


Diehl & Kroll Eur. Phys. J. C73 (2013)
Kroll arXiv:hep-ph/1703.05000 (2017)



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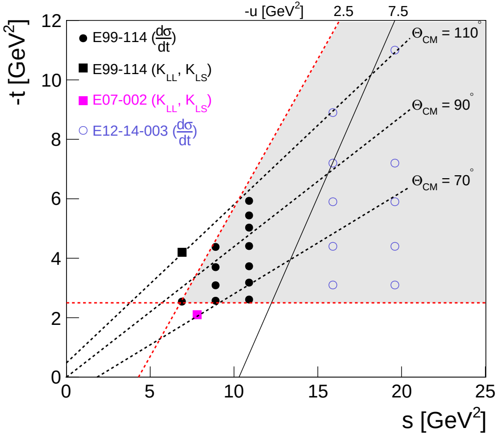
  $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

New result suggests axial nucleon current is larger that vector current at moderate $-t$, but validity of factorization and mass corrections are potentially problematic.

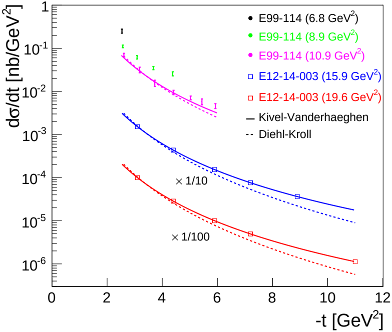
The JLab WACS Program – 12 GeV

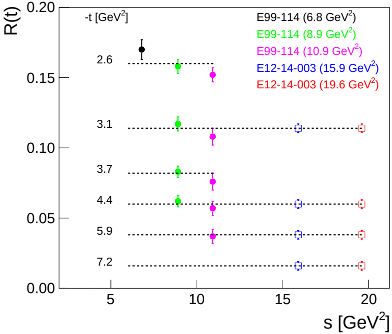
- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass)
  - E07-002 in Hall C with HMS and BigCal (Pb-glass)
- Cross section experiment approved by PAC42 (A-) for running at 12 GeV:
  - E12-14-003 in Hall C with HMS and NPS ($\mathrm{PbWO_4}$)



E12-14-003 – Differential Cross Section

Wojtsekhowski *et al.* JLab Proposal PR12-14-003

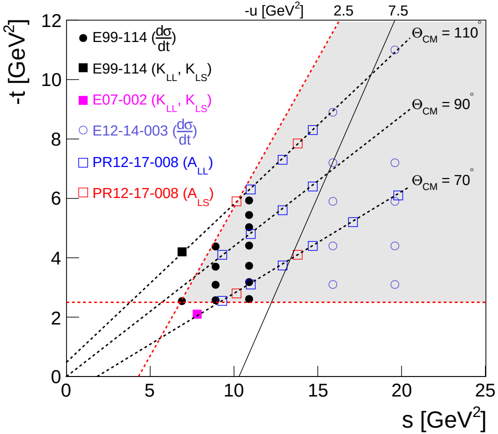




- New measurements (all firmly in the wide-angle regime) will allow for a rigorous test of factorization in hard exclusive reactions and extraction of vector/SCET form factor.
- Extension to highest possible values of $-t$ will:
  - Offer new insights into the interplay between hard and soft physics and non-perturbative proton structure.
  - Allow for a direct comparison between $R_V(t)$ and the Dirac form factor (different quark charge and x weightings) and test the universality of leading quark mechanism.

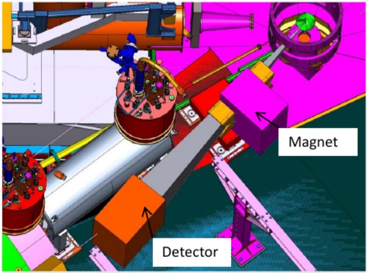
The JLab WACS Program - Polarization Observables

- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass).
  - E07-002 in Hall C with HMS and BigCal (Pb-glass).
- Cross section experiment approved by PAC42 (A-):
  - E12-14-003 in Hall C with HMS and NPS ($\mathrm{PbWO_4}$).
- Polarized target experiment approved by PAC45 (A-):
  - E12-17-008 in Hall C will measure A_{LL} and A_{LS} with BigBite, NPS and new CPS.



Plans for 12 GeV – Apparatus

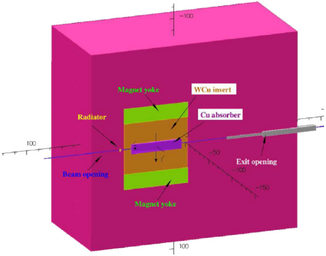
Neutral Particle Spectrometer



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

Horn *et al.* NIM A956 (2020)

Compact Photon Source



- Work well underway on a new high-intensity compact photon source (CPS) for use with a solid polarised target for measurements of A_{LL}.

Day *et al.* NIM A957 (2020)

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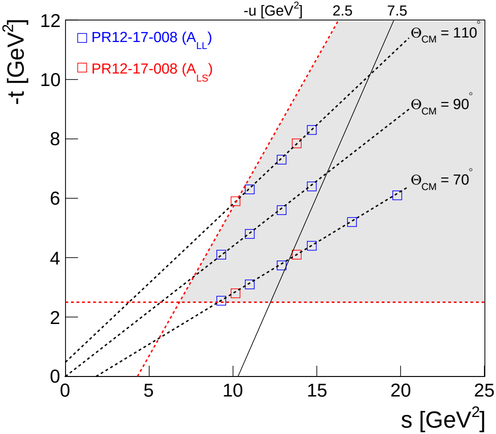
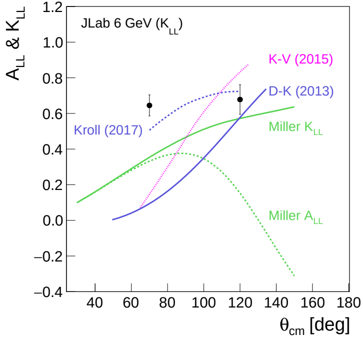
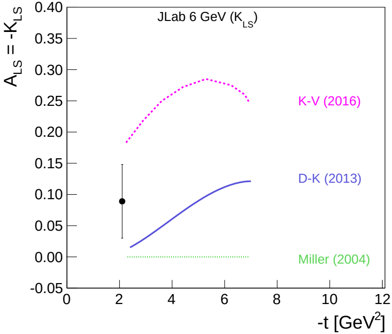


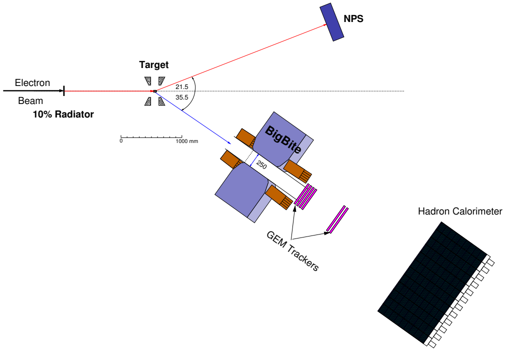
Key Physics Questions





- To what degree is the factorized mechanism dominant and how significant are theoretical corrections?
- What are the constraints on GPD moments and what do they tell us about the proton's axial and tensor structure?
- Is the quark which absorbs and emits photons a constituent or a current quark?
- What does comparison of the SCET and GPD predictions tell us about proton structure and the role of hadron helicity-flip?

1. A 3 $\mu\mathrm{A}$ polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS) produces a high-intensity untagged photon beam.
2. The proton target is the UVA/JLab solid polarized ammonia target.
3. The recoil proton is detected with the BigBite spectrometer equipped with GEM trackers and trigger detectors.
4. The highly-segmented PbWO_4 NPS calorimeter is used to detect the scattered photon.



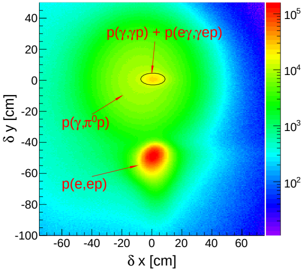
The use of the CPS and BigBite results in a significantly improved figure-of-merit over all previous experiments and opens up a new range of polarized physics opportunities at JLab.

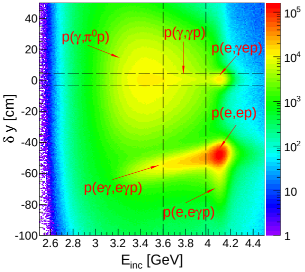
Analysis Technique

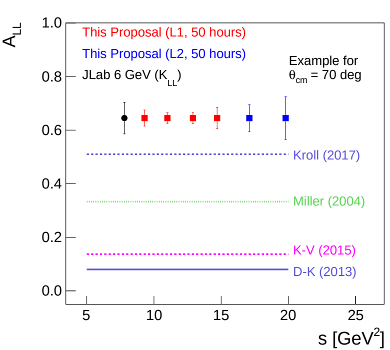
- Data analysis relies on utilization of the kinematic two-body correlation between the scattered photon/electron and the recoil proton.

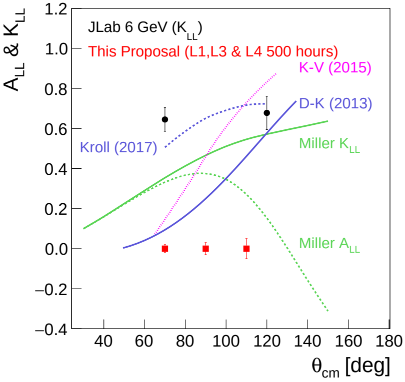
- The three dominant reaction channels within acceptance are:
  - $\gamma p \to \gamma p$
  - $\gamma p \to \pi^0 p$
  - ~~$ep \to ep$ and ($ep\gamma$)~~

- Robust extraction of the WACS signal requires:
  - Excellent angular and momentum resolution in both the photon and proton spectrometers.
  - Precise determination of π^0 background shape, particularly at large scattering angles.



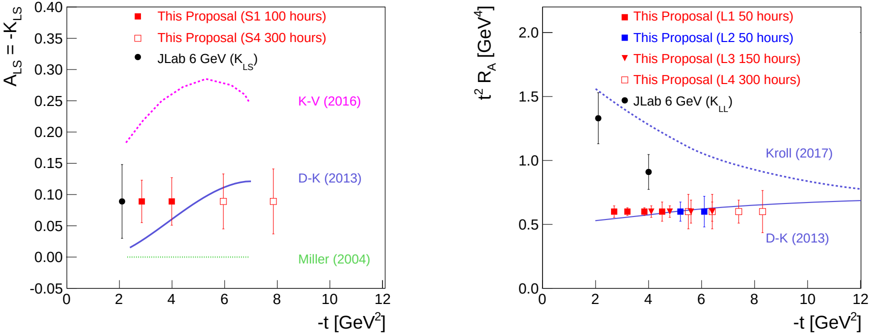






- Make an explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed θ_p^{cm}, and verify that target mass corrections and higher twist effects are small.
- Measurement of A_{LL} at large CM scattering angle will allow for a singular test of whether current or constituent quarks are the relevant degree of freedom in hard exclusive reactions at these sub-asymptotic energies.

E12-17-008 Expected Results – Proton Structure



- Systematically improve our knowledge of the non-perturbative matrix elements of the handbag mechanism in the GPD and SCET approaches.

- Constrain the GPDs $\tilde{H}$ and E at high $-t$ and compare with the Axial and Pauli form factors, which will have a significant and broad impact in the fields of electron and neutrino scattering.

Summary

- The WACS programme is unique to Jefferson Lab and offers a relatively unexplored window on hadron structure at high momentum transfer.

- Results from the JLab 6 GeV era demonstrate factorization appears to be valid for Mandelstam variables above 2.5 GeV^2 – this will be tested unambiguously with the proposed measurements.

- The results will have a significant impact beyond WACS and JLab (e.g. at Belle and MINERvA) by systematically improving our knowledge of handbag-based theoretical approaches and transverse proton structure.

- The proposed experimental technique with a high-intensity photon beam and polarized target opens up physics possibilities that have hitherto been inaccessible at tagged photon facilities.

- New experiments are planned for the 12 GeV facility on both unpolarised and polarised observables with unprecedented precision and kinematic reach.