Polarization Observables in Wide-Angle Compton Scattering

David Hamilton[†]

D. Day, D. Keller, G. Niculescu, B. Wojtsekhowski, J. Zhang
and the Neutral Particle Spectrometer Collaboration

[†] david.j.hamilton@glasgow.ac.uk

SBS Collaboration Meeting

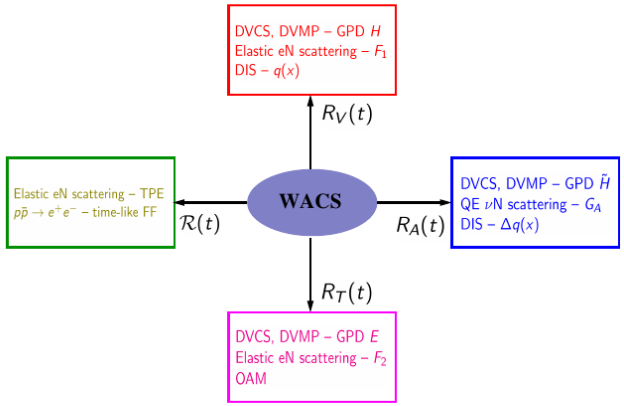
March 3rd 2026

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 at JLab
- Proposed measurements at 12 GeV
- Summary

WACS: an introduction

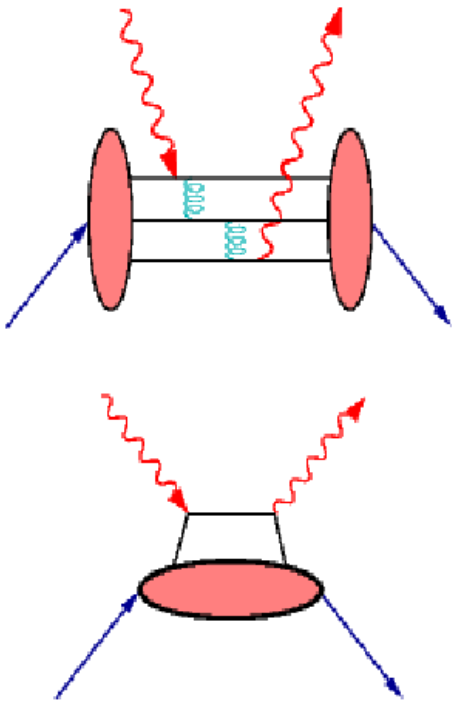
- Hard exclusive nucleon Compton scattering can be investigated in two complementary kinematic regimes:
  - Deeply-virtual: large Q^2; $\left(\frac{-t}{Q^2}\right) \ll 1$
  - Wide-angle: large $-t$, $-u$; $\left(\frac{Q^2}{-t}\right) \ll 1$
- WACS is a powerful yet under-utilised probe of transverse nucleon structure, similar to high-Q^2 elastic electron nucleon scattering.
- Unlike elastic eN experiments, WACS is sensitive to the nucleon's axial structure and therefore related to neutrino scattering.



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

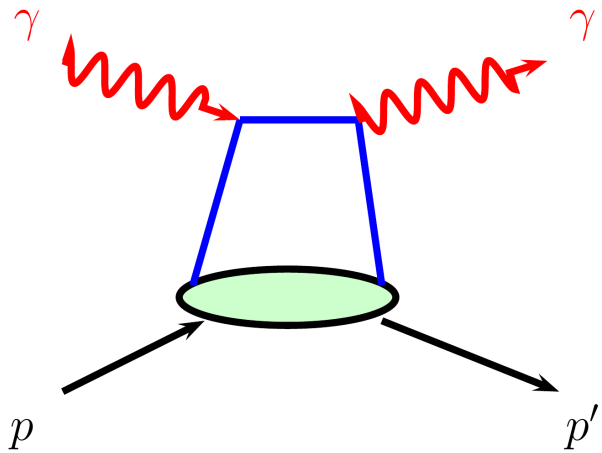
Factorization and the WACS reaction mechanism

- 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 structure: GPD-based approach

Diehl & Kroll, EPJ C73 (2013)



Provided that $s, -t, -u \gg \Lambda^2$ the handbag mechanism involves factorization of the amplitudes into:

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

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

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

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 structure: WACS form factors

$\gamma p \to \gamma' p$

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

poorly constrained even at moderate $-t$

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

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

$ep \to e' p$

$$F_1(t) = \sum_q e_q \int_0^1 dx\, H_v^q(x,0,t)$$

poorly constrained even at moderate $-t$

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

$$F_2(t) = \sum_q e_q \int_0^1 dx\, E_v^q(x,0,t)$$

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

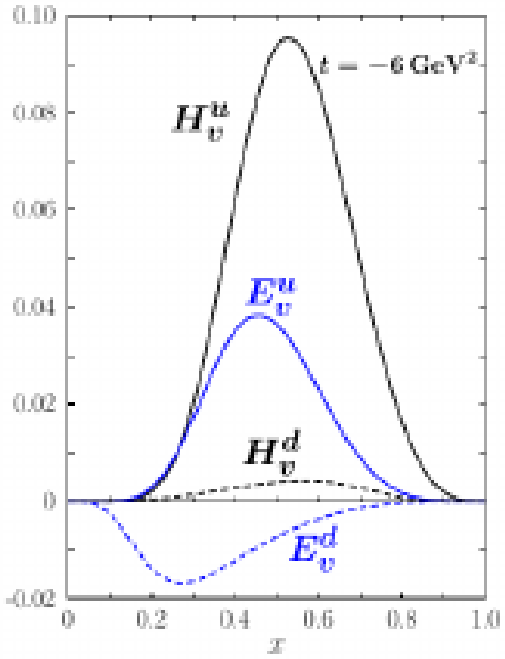
$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\rm KN}$$

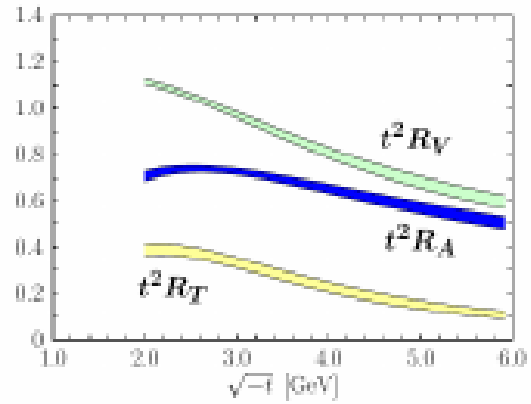
$$A_{LS} = -K_{LS} = A_{LL} \left[\frac{\sqrt{-t}}{2m} \frac{R_T(t)}{R_V(t)} - \beta \right]$$

Diehl & Kroll, EPJ C73 (2013)

Parameterisation of the form factors

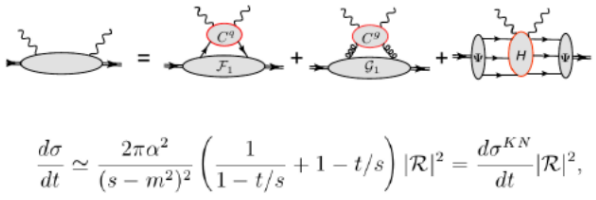
- $R_V(t)$ and $R_T(t)$ form factors parameterised from H and E GPDs extracted from flavour decomposed Dirac and Pauli form factors.
- This approach is not possible for the axial form factor $R_A(t)$; instead a profile function for $\tilde{H}$ was used based on $\Delta q(x)$ data.
- This then allowed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





Non-perturbative structure: SCET and rCQM

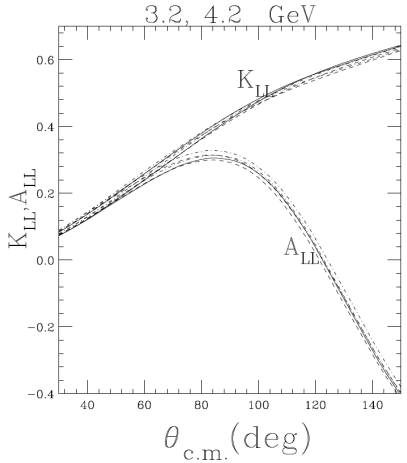
Kivel & Vanderhaeghen JHEP 4 (2013)



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

- 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.

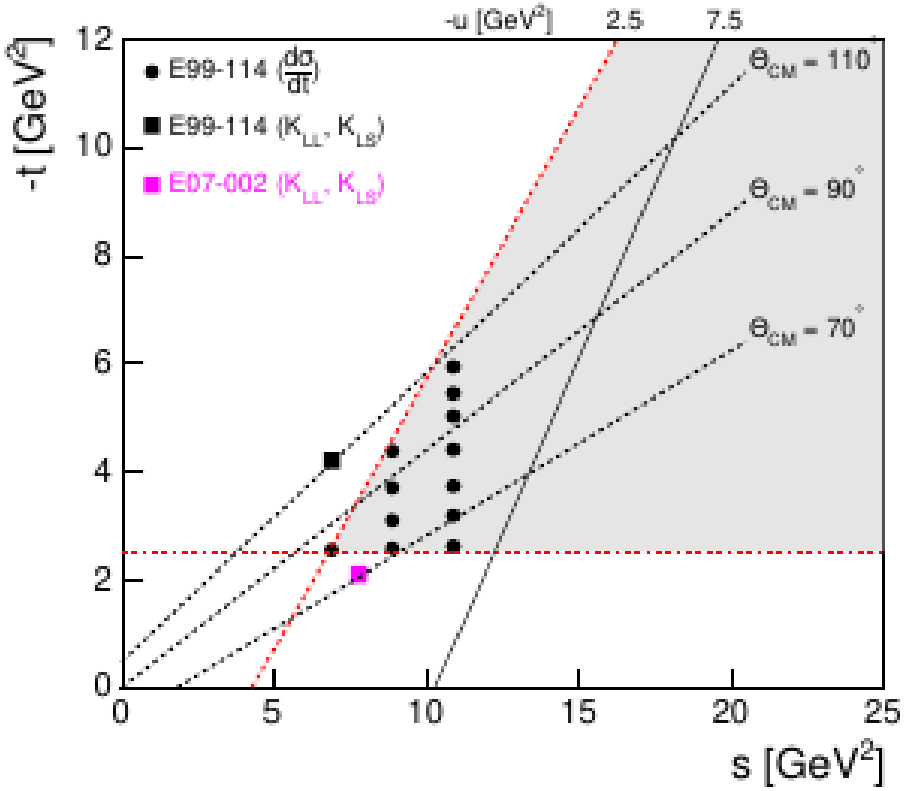
Miller, Phys Rev C 69 (2004)



- The relativistic Constituent Quark Model has been successful in describing 6 GeV JLab results on elastic ep scattering and WACS.
- It is a handbag-based approach in which relativistic and quark mass effects induce significant quark transverse and orbital angular momentum.

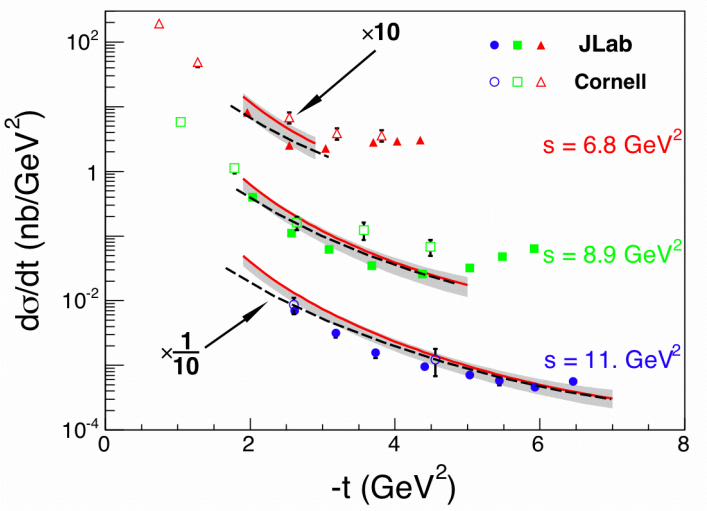
The Jlab WACS program – 6 GeV

- 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 abd BigCal (Pb-glass)

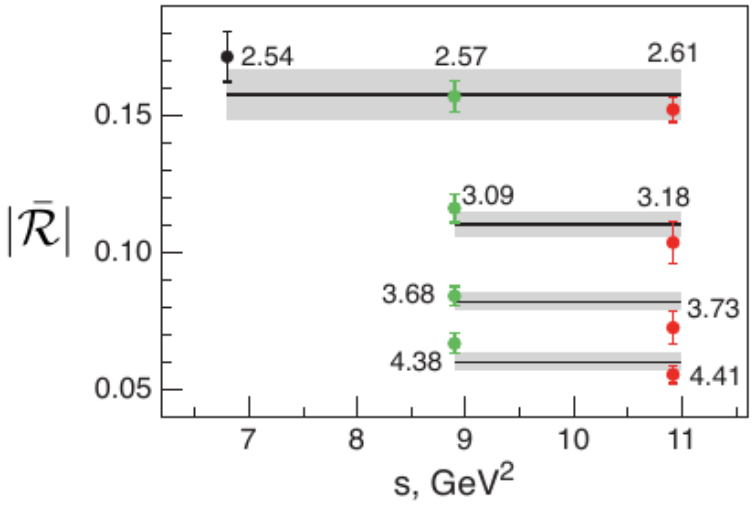


6 GeV results – differential cross section

Danagoulian *et al.* PRL98 (2007)



Kivel & Vanderhaeghen JHEP 4 (2013)

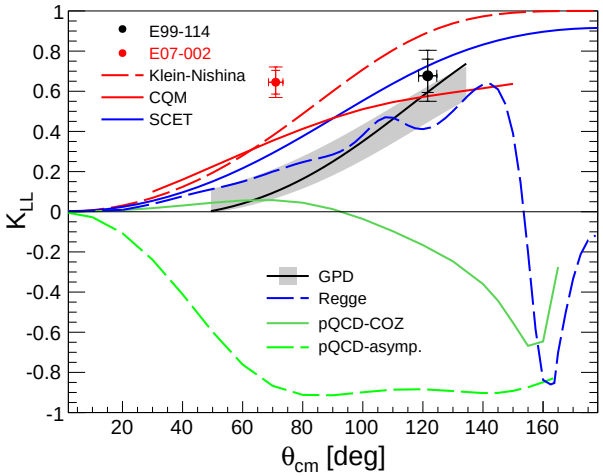


- A factor of 1000 improvement in figure-of-merit over previous experiments.
- Disagreement with pQCD predictions – cross section scales as $1/s^{7.5}$.

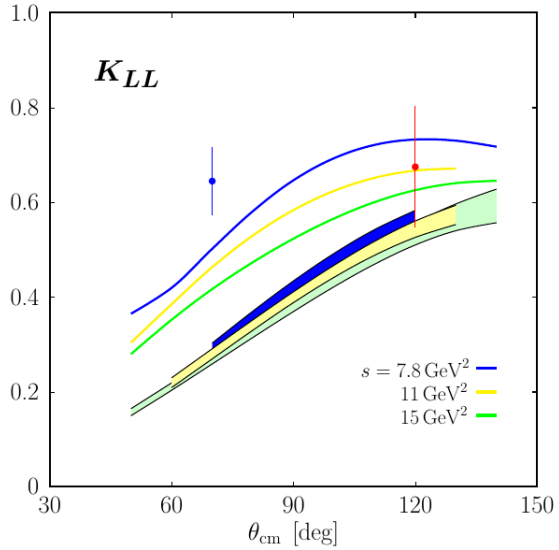
Extracted vector/SCET form factor exhibits strong evidence of s-independence and therefore factorization provided that $s, -t, -u > 2.5\ \mathrm{GeV}^2$.

6 GeV results – polarisation observables

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



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

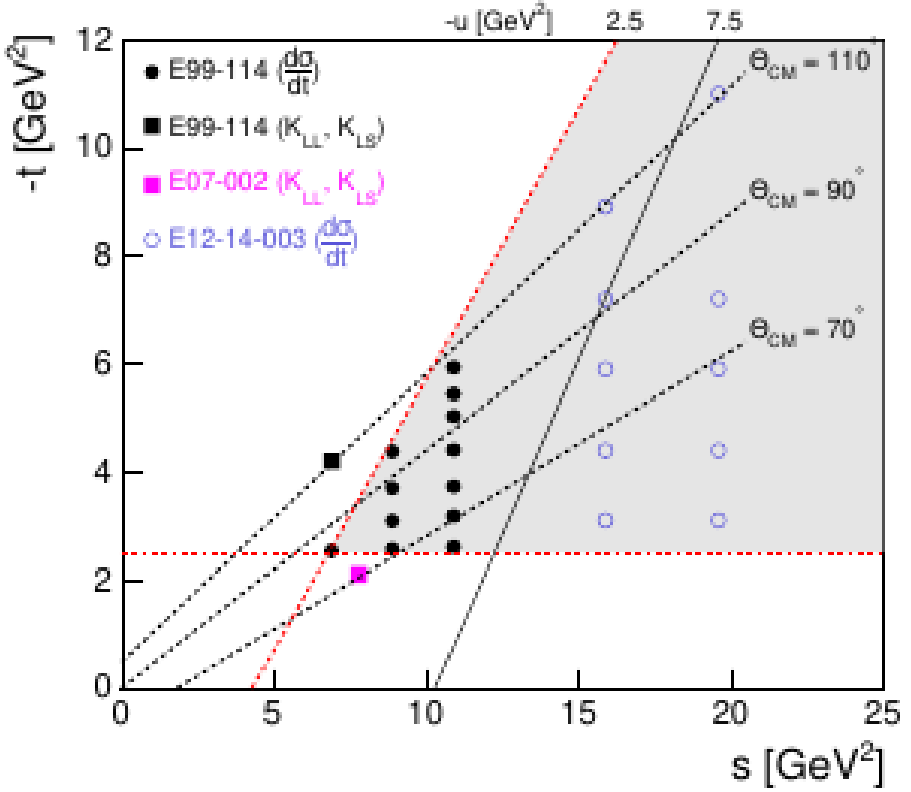


- Results strongly favour leading quark mechanism ($x = 1$).
- E07-002 result is larger than all predictions including Klein-Nishina: $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}}$.

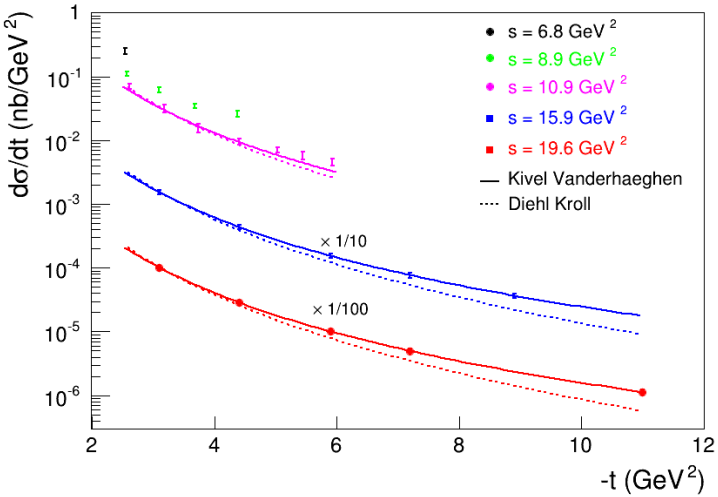
Most recent result suggests axial nucleon current is larger that vector current at moderate $-t$.

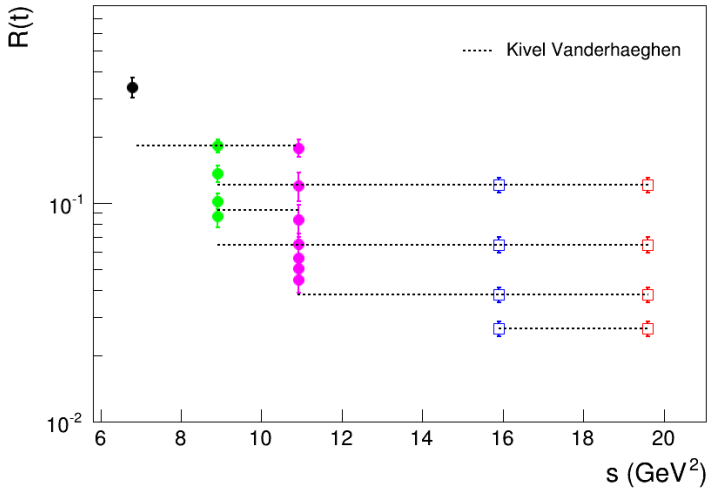
The Jlab WACS program – 12 GeV

- 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 abd BigCal (Pb-glass)
- Cross section experiment approved by PAC42 (A-):
  - E12-14-003 in Hall C with HMS and NPS ($PbWO_4$)



E12-14-003 – differential cross section



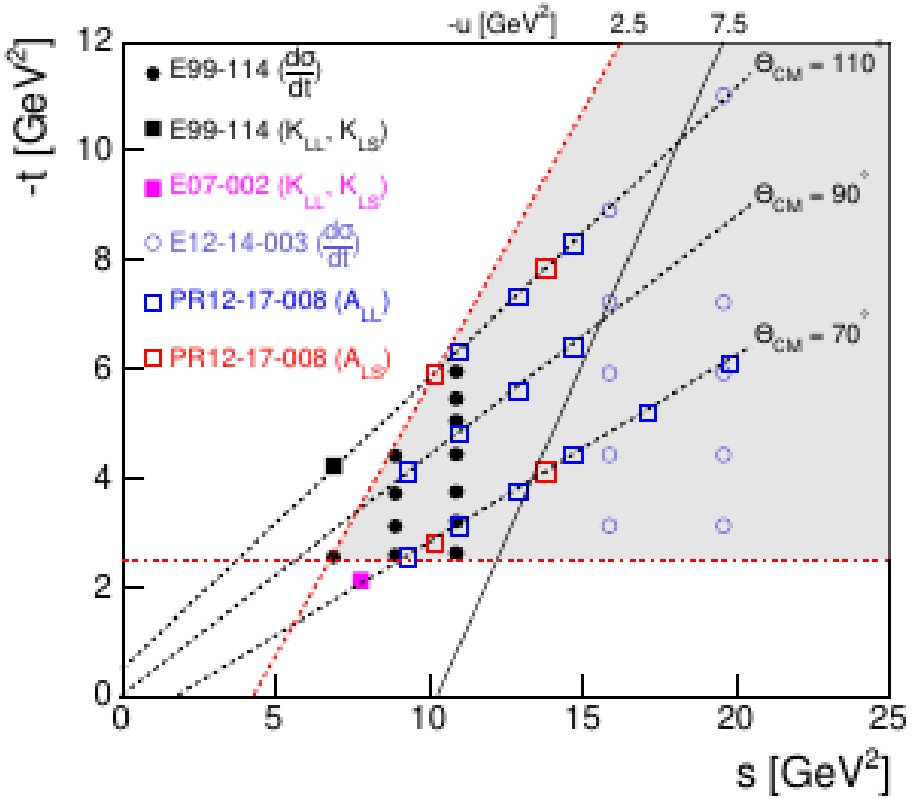


- New measurements (all firmly in the wide-angle regime) will allow for a rigorous test of factorization in hard exclusive reactions and extraction of vector/SCET form factor.

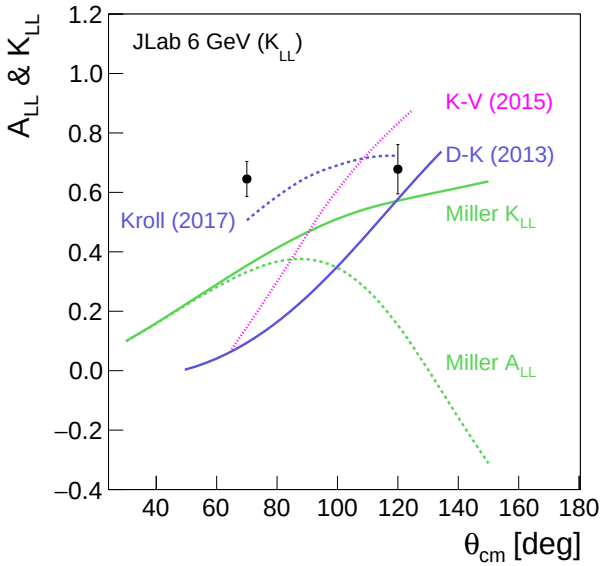
- Extension to highest possible values of $-t$ will:
  - Offer new insights into the interplay between hard and soft physics and non-perturbative proton structure.
  - Allow for a direct comparison between $R_V(t)$ and the Dirac form factor and test the universality of leading quark mechanism.

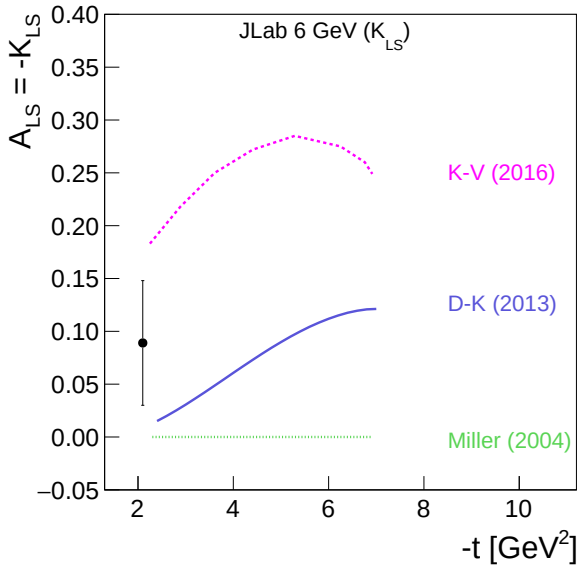
E12-17-008 – polarization observables

- 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 abd BigCal (Pb-glass)
- Cross section experiment approved by PAC42 (A-):
  - E12-14-003 in Hall C with HMS and NPS ($PbWO_4$)
- Polarised target experiment approved by PAC45 (A-):
  - E12-17-008 in Hall C with BigBite, NPS and new CPS.



Key physics questions

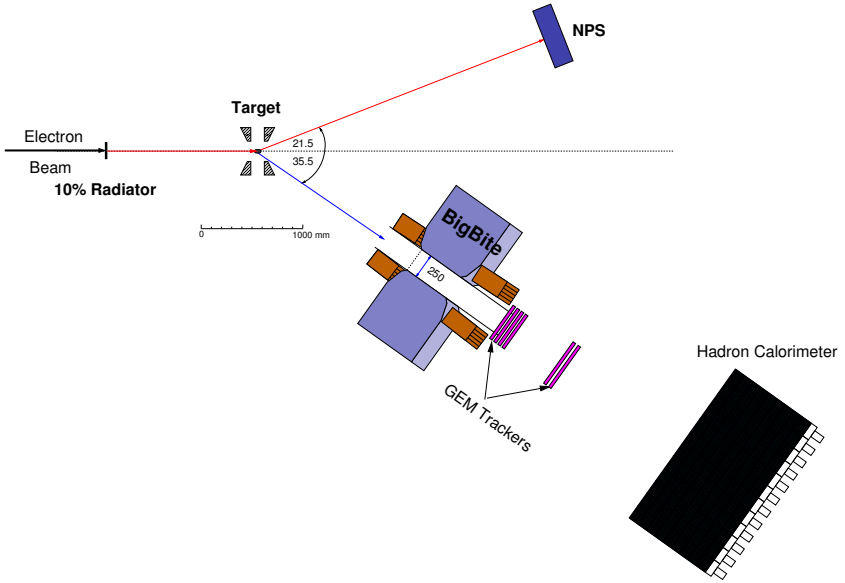




- To what degree is the factorized mechanism dominant and how significant are theoretical corrections?
- What are the constraints on GPD moments and what do they tell us about the proton's axial and tensor structure?
- Is the quark which absorbs and emits photons a constituent or a current quark?
- What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

Experimental technique

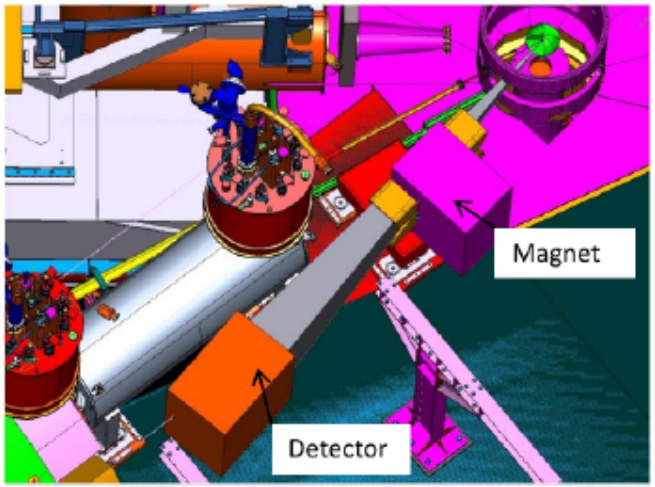
- A 3 μA polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS).
- The proton target is the UVA/JLab solid polarized ammonia target.
- The recoil proton is detected with the BigBite spectrometer equipped with GEM trackers and trigger detectors.
- The highly-segmented $PbWO_4$ 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.

Experimental technique: instrumentation

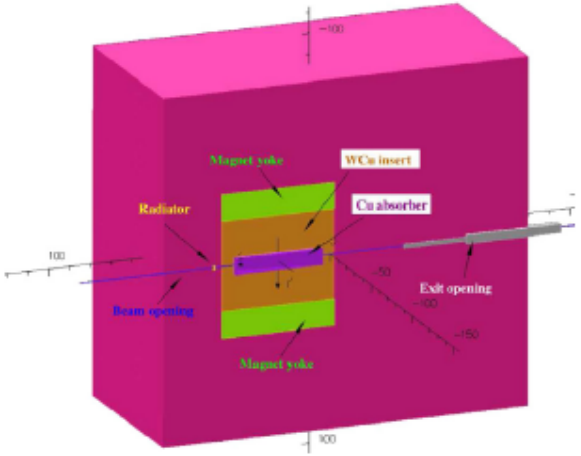
Neutral Particle Spectrometer



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

Horn *et al.* NIM A956 (2020)

Compact Photon Source

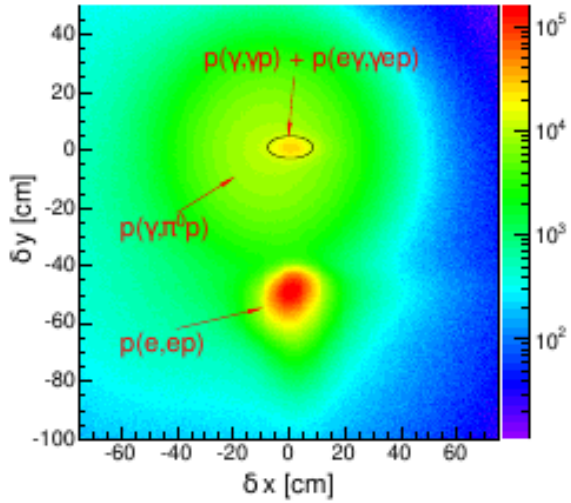


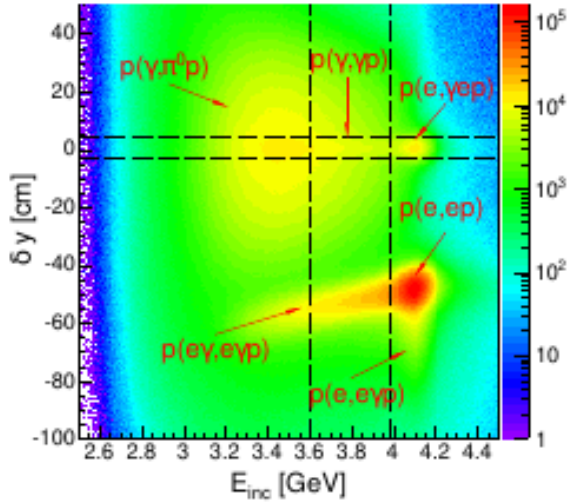
- Work well underway on a new high-intensity compact photon source (CPS) for use with a solid polarised target for measurements of A_{LL}.

Day *et al.* NIM A957 (2020)

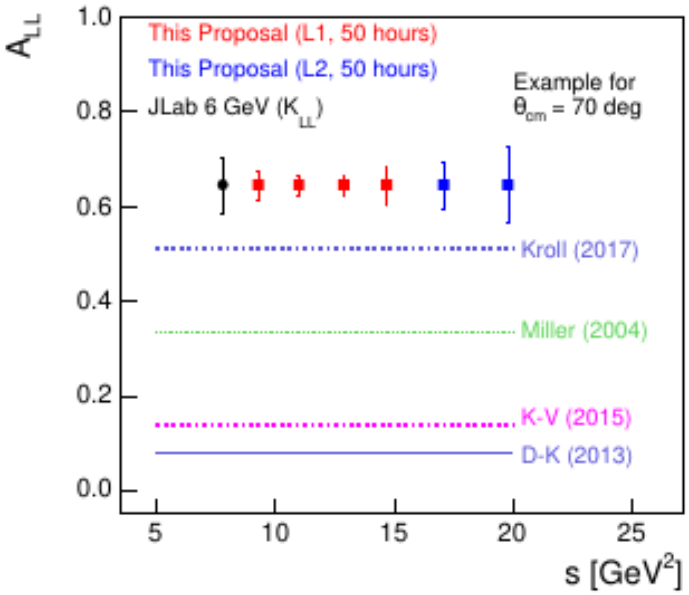
Analysis technique

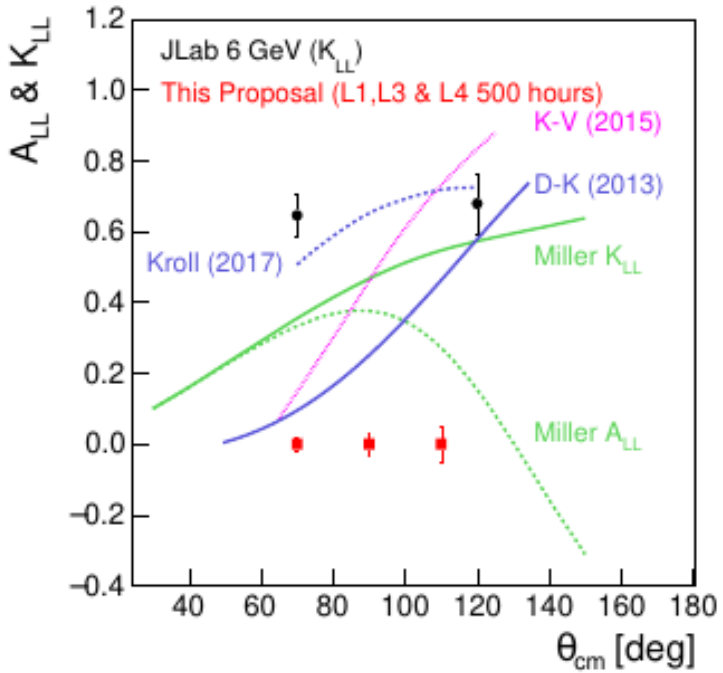
- Data analysis relies on utilization of the kinematic two-body correlation between the scattered photon/electron and the recoil proton.
- The three dominant reaction channels within acceptance are:
  - $\gamma p \rightarrow \gamma p$
  - $\gamma p \rightarrow \pi^0 p$
  - ~~$ep \rightarrow ep$ and $(ep\gamma)$~~
- 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.





Expected results – reaction mechanism

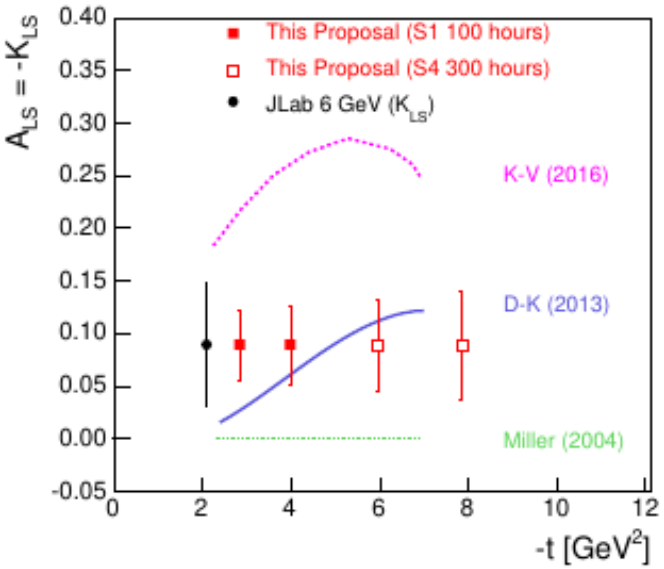


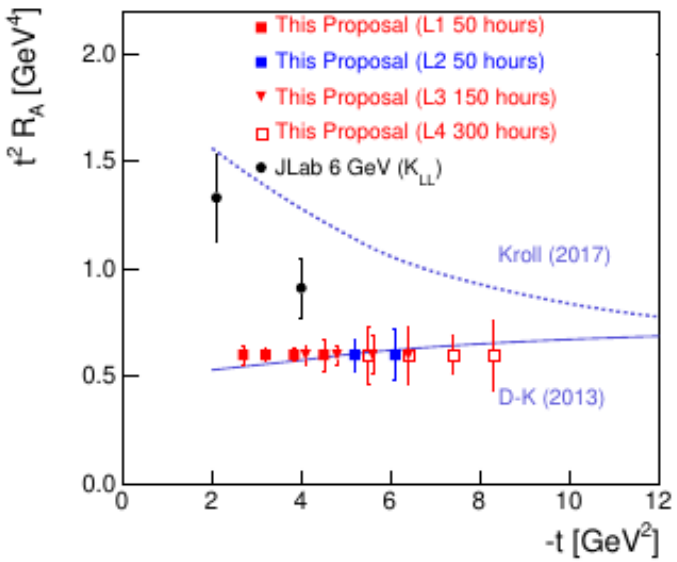


- Make an explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed θ_p^{cm}, and verify that target mass corrections and higher twist effects are small.

- 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.

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 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 (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.

Thank you for your attention.