# PAC51 Jeopardy Update: E12-17-008 Polarization Observables in Wide-Angle Compton Scattering at large $s$, $-t$ and $-u$

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and the Neutral Particle Spectrometer Collaboration
https://wiki.jlab.org/cuawiki/index.php/Collaboration

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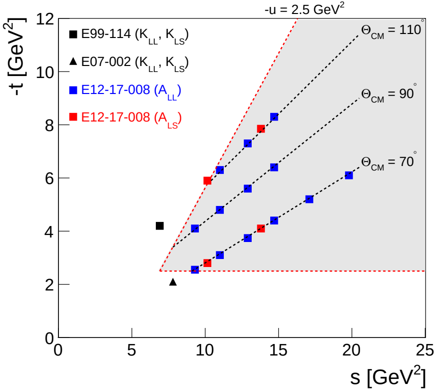
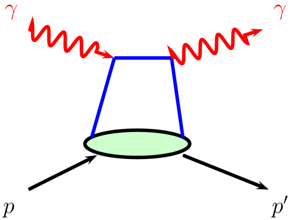
# WACS at JLab: An Introduction

- PR12-17-008 proposed measurements of WACS initial-state polarization observables and was conditionally (C1) approved by PAC45. It was fully approved in 2020.
- The beam time request is for 46 days (38 days production) at six kinematic settings.
- Response to the PAC jeopardy questions:
  1. There has been no new information that affects the scientific importance or impact of the experiment since that time.
  2. The experiment has not yet received any beam time.
  3. There have been no major changes to the collaboration.
  4. We are not seeking a change to the beam time request.



# 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

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

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

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 $E$.

1. A 2.5 $\mu A$ polarized electron beam incident on a 10 % radiator inside a new 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.

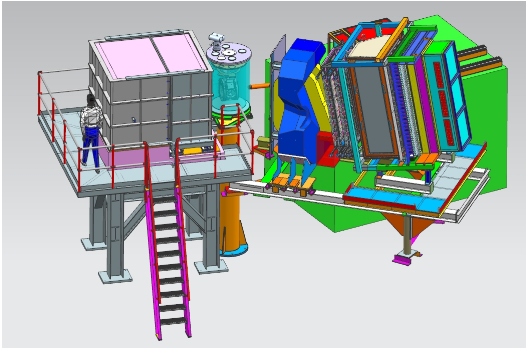


Figure from Steve Lassiter

The use of the CPS and BigBite results in a factor of 30 improvement in figure-of-merit over previous experiments and opens up a new range of polarized physics opportunities at JLab.

HALL C
CPS

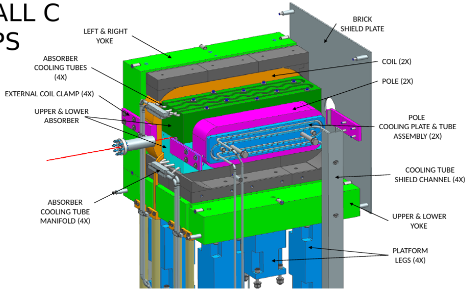



Figure from Steve Lassiter

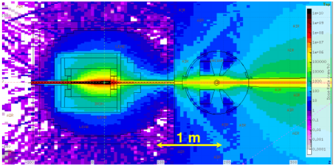



Figure from Pavel Degtiarenko

- E12-17-008 was the primary driver behind the CPS concept of a hermetic magnet-dump with an exit channel for the photon beam.
- FEA studies of the magnetic field and heat flow and FLUKA simulations of prompt and activation radiation load are complete.
- The conceptual design was published [Day *et al.* NIM A957 (2020)].
- Design of the magnet, central absorber, shield layers and support structure is complete and all components have been ordered.

- The polarized target is the UVA/Jlab solid ammonia DNP system.
- It will employ the new JLab magnet which provides a much higher acceptance for running with transverse polarization.
- UVA are working on a target cell motion system for beam-target rastering in order to manage heat load and radiation damage on the target material.

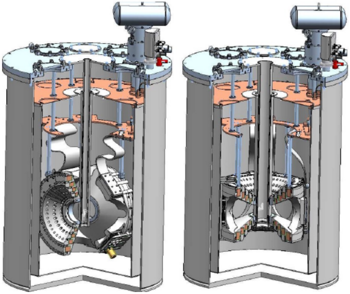


Figure from Chris Keith

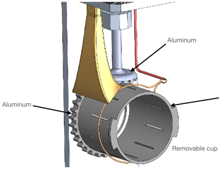
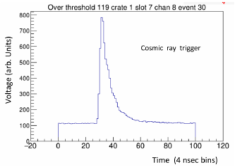
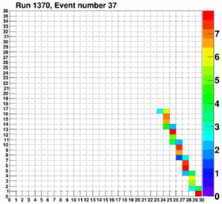



Figure from Dustin Keller

- Construction of the NPS is complete and it is currently being installed in Hall C, with first beam expected in a few months.
- DAQ, slow controls and software commissioning is near completion.

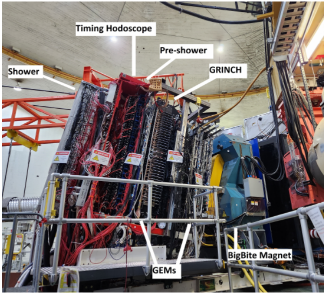



Figures from Carlos Munoz Camacho, Bob Michaels and Simona Malace

# BigBite Spectrometer Status

- The BigBite spectrometer with the new 12 GeV detector stack was commissioned and installed in Hall A in 2021.
- Performance and data-quality during the first SBS form factor experiments (GMn and GEn) have been excellent.
- The collaboration has gained experience operating and analyzing data with large-area GEM trackers at luminosities of $10^{37} - 10^{38}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (c.f. $\sim 10^{36}$ for the proposed measurements).



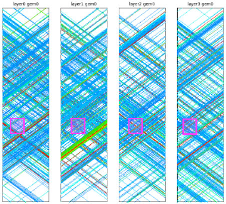




Figure from Andrew Puckett

# Status of the Collaboration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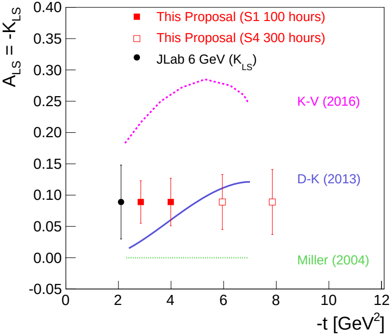
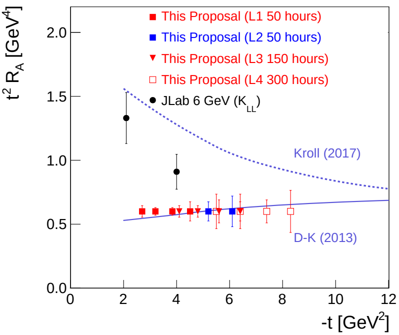
There are a number of groups within the collaboration actively involved with these various development efforts, including:

- CPS: JLab, CUA, JMU, ...
- Polarized target: JLab, UVa, ...
- NPS: JLab, CUA, JMU, Orsay, Ohio, ODU, AANL, Glasgow, ...
- BigBite: JLab, UVa, UConn, Glasgow, ...




- The proposed measurements will:
  - 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.

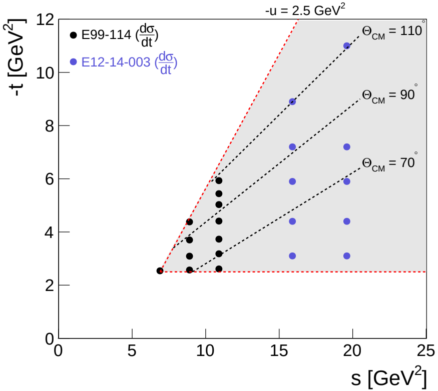
# Summary

- 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 $\mathrm{GeV}^2$ – this will be tested unambiguously with the proposed measurements (and E12-14-003).
- The results will have a significant impact beyond WACS and JLab 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.
- We request re-approval of 46 days of beam time in Hall C for measurements at six kinematic settings.

Back-up Slides

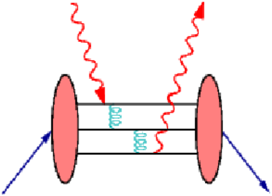
# WACS at JLab: Cross Section Measurements

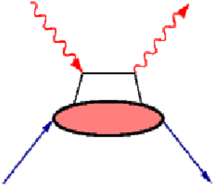
- Hard exclusive nucleon Compton scattering can be investigated in two complementary kinematic regimes:
  - Deeply-virtual: large $Q^2$; $\left(\frac{-t}{Q^2}\right) \ll 1$
  - Wide-angle: large $-t$, $-u$; $\left(\frac{Q^2}{-t}\right) \ll 1$
- Building on a successful 6 GeV program, E12-14-003 was approved by PAC42 to measure cross sections in Hall C with the NPS and HMS.



# Factorization and the WACS Reaction Mechanism

- A number of theoretical approaches have been proposed over the past 30 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
- 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: 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 $-t$

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

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

---

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

---

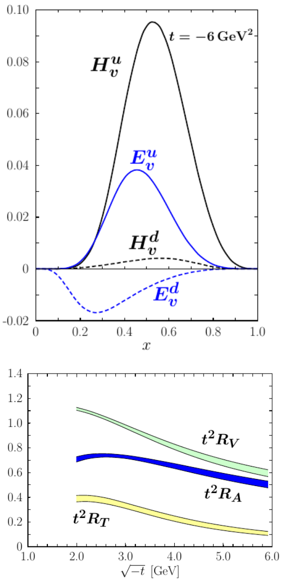
$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$$

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

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 $K_{LS}$.



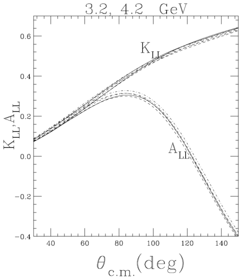
# Non-perturbative Proton Structure: SCET and rCQM

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.

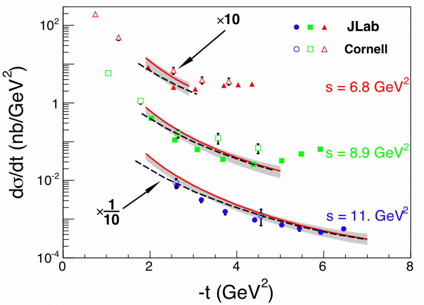
Miller, Phys Rev C 69 (2004)



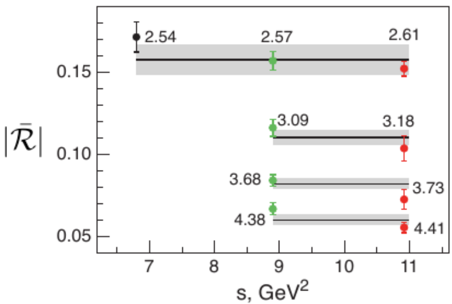

- The relativistic Constituent Quark Model is a handbag-based approach in which relativistic and quark mass effects induce significant quark transverse and orbital angular momentum.
- If the active quark mass is large ($M_p/3$) $A_{LL} \neq K_{LL}$.

# 6 GeV Results – Differential Cross Section

Danagoulian *et al.* PRL98 (2007)



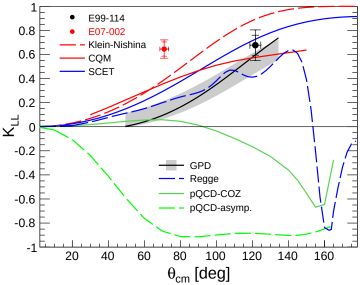

Kivel & Vanderhaeghen JHEP 4 (2013)



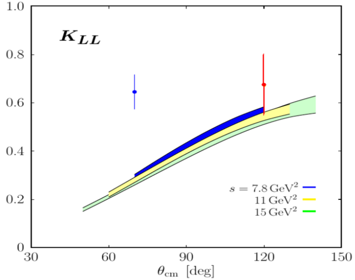

- A factor of 1000 improvement in figure-of-merit over previous experiments.
- Disagreement with pQCD predictions – cross section scales as $1/s^{7.5}$.

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

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



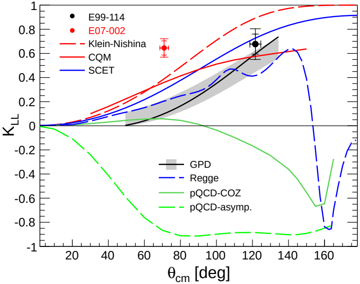

Diehl & Kroll Eur. Phys. J. C73 (2013)



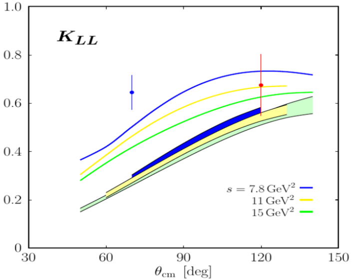

- Results strongly favour leading quark mechanism ($x \approx 1$).
- E07-002 result is larger than all predictions including Klein-Nishina: $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

# 6 GeV Results – Polarization Observables

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




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

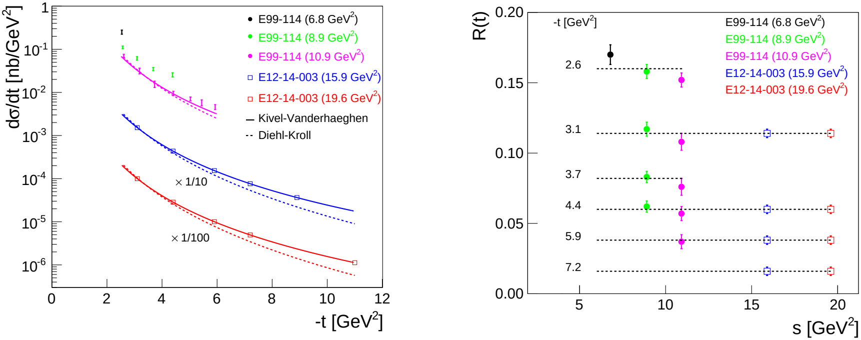



- Results strongly favour leading quark mechanism ($x \approx 1$).
- E07-002 result is larger than all predictions including Klein-Nishina:
  $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

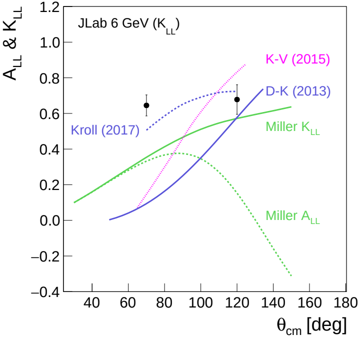
New result suggests axial nucleon current is larger than expected at moderate $-t$, but validity of factorization and mass corrections are potentially problematic.

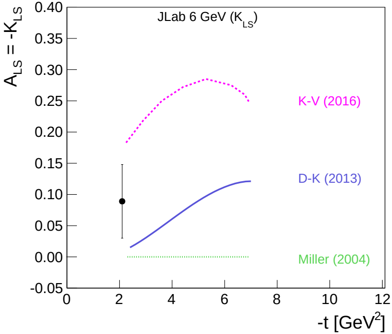
# E12-14-003 – Differential Cross Section

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



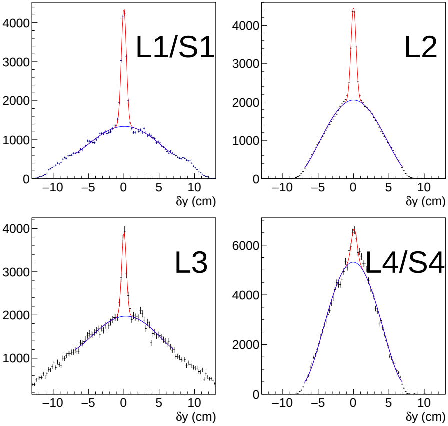

- New measurements (all firmly in the wide-angle regime) will allow for a rigorous test of factorization in hard exclusive reactions and extraction of vector/SCET form factor.
- Extension to highest possible values of $-t$ will:
  - Offer new insights into the interplay between hard and soft physics 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.




- 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?
- What role, if any, does the mass of the quark which absorbs and emits photons play?
- What does comparison of the SCET and GPD predictions tell us about proton structure and the role of hadron helicity-flip?

- 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 $\pi^0$ background shape, particularly at large scattering angles.




The use of a pure photon beam and large acceptance spectrometers makes the data analysis significantly simpler and reduces overall systematic uncertainty.

# Proposed Measurements – Choice of Kinematic Settings

| $\theta_p^{cm}$ | $E_{\mathrm{Beam}}$ | $A_{LL}$ | $A_{LS}$ |
|---|---|---|---|
| 70° | 8.8 GeV | ✓(50 hours) | ✓(100 hours) |
| 70° | 11.0 GeV | ✓(50 hours) | × |
| 90° | 8.8 GeV | ✓(150 hours) | × |
| 90° | 11.0 GeV | × | × |
| 110° | 8.8 GeV | ✓(300 hours) | ✓(300 hours) |
| 110° | 11.0 GeV | × | × |

× – low rate or low $-u$

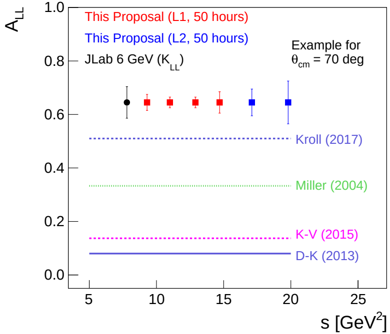
- The development of a new experimental technique based on the CPS and large solid-angle spectrometers makes it possible at last to exploit fully the kinematic range accessible as a result of the 12 GeV upgrade.
- The choice of kinematic settings was driven by:
  - The data **in all bins for all settings** meet the wide-angle condition ($s$,$-t$,$-u > 2.5\ \mathrm{GeV}^2$).
  - Push to as high as possible in $s$, $-t$ and $-u$ without exceeding 300 hours per setting.
- The large acceptance of BigBite makes it possible for the data in each setting to be divided into several $s$-$t$ bins.

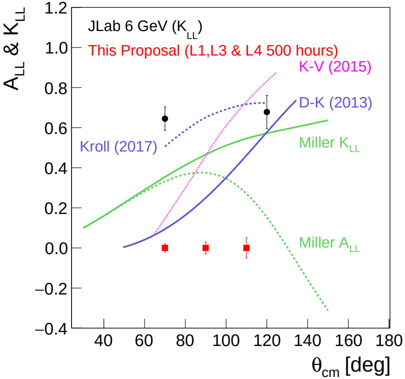
# Proposed Measurements

| Kin | $E_{\rm Beam}$ [GeV] | $E_{\rm in}$ Range [GeV] | s [GeV$^2$] | -t [GeV$^2$] | -u [GeV$^2$] | $\theta^{\rm cm}$ [°] | $\theta_\gamma$ [°] | $\theta_{\rm p}$ [°] | $\theta_H^{\rm targ}$ [°] |
|---|---|---|---|---|---|---|---|---|---|
| L1 | 8.8 | 4 - 8 | 12.1 | 3.5 | 6.9 | 70 | 21.5 | 35.5 | 0 |
| S1 | 8.8 | 4 - 8 | 12.1 | 3.5 | 6.9 | 70 | 21.5 | 35.5 | -20 |
| L2 | 11.0 | 8 - 11 | 18.7 | 5.6 | 11.3 | 70 | 17.4 | 30.5 | 0 |
| L3 | 8.8 | 4 - 8 | 12.1 | 5.3 | 5.2 | 90 | 30.2 | 26.5 | 0 |
| L4 | 8.8 | 4 - 8 | 12.1 | 7.0 | 3.3 | 110 | 42.3 | 19.4 | 0 |
| S4 | 8.8 | 4 - 8 | 12.1 | 7.0 | 3.3 | 110 | 42.3 | 19.4 | +80 |

- Beam-time estimates are based on the requirement of $\pm$0.1 or better statistical uncertainty in at least one *s*-*t* bin.
- The overall systematic uncertainty is estimated to be around 6 - 7 % and is dominated by contributions from the pion background subtraction (shape), the target dilution factor and the proton polarization.
- 200 hours is expected for experimental overheads, such as calibration data-taking, beam polarimetry, target annealing and kinematic changes.

# Expected Results – Reaction Mechanism




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