Wide-Angle Compton Scattering at 8 and 10 GeV Photon Energies

David J. Hamilton
University of Glasgow

for Simon Sirca, Bogdan Wojtsekhowski and the
WACS and NPS Collaborations

Hall A/C Collaboration Meeting
June 5th 2014

An NPS Collaboration Proposal to PAC42

Proposal to Jefferson Lab PAC 42

Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

D. J. Hamilton (co-spokesperson), J. R. M. Annand, D. I. Glazier, D. G. Ireland, K. Livingston, I.J.D. MacGregor, B. McKinnon, B. Seitz, D. Sokhan
University of Glasgow, Glasgow, Scotland

S. Širca (co-spokesperson), J. Beričič, M. Mihovilovič, S. Štajner
J. Stefan Institute and Dept. of Physics, University of Ljubljana, Slovenia

B. Wojtsekhowski (spokesperson-contact), A. Camsonne, S. Covrig, P. Degtiarenko, R. Ent, D. Gaskell, D. Higinbotham, M. K. Jones, C. Keppel, V. Kubarovksy, D. Mack, P. Nadel-Turoński, B. Sawatzky, M. Ungaro, S. A. Wood
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

I. Albayrak, M. Carmignotto, N. Hlavin, T. Horn, F. Klein, B. Nepal, I. Sapkota
The Catholic University of America, Washington, DC 20064

S. Abrahamyan, A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan, A. Shahinyan, H. Voskanyan, S. Zhamkochyan
A.I. Alikhanyan National Science Laboratory, Yerevan 0036, Armenia

V. Bellini, F. Mammoliti, F. Noto, M. C. Sutera
INFN Catania and Dept. of Physics and Astronomy, University of Catania, Catania, Italy

F. De Persio, F. Meddi, F. Salmé, G. M. Urciuoli
INFN Rome and University of Rome "La Sapienza", Rome, Italy

E. Cisbani, F. Garibaldi, S. Frullani
INFN Rome—Sanità Group and Italian National Institute of Health, Rome, Italy

C. Fanelli
INFN Rome—Sanità Group and University of Rome "La Sapienza", Rome, Italy

A. del Dotto
University of Rome "Roma Tre" and INFN, Sezione di "Roma Tre", Rome, Italy

G.B. Franklin, V. Mamyan, B. Quinn
Carnegie Mellon University, Pittsburgh, PA 15213

R. Gilman, K. Myers, R. Ransome
Rutgers, The State University of New Jersey, Piscataway, NJ 08854

D. Nikolenko, I. Rachek, Yu. Shestakov
Budker Institute, Novosibirsk, Russia

W. Boeglin, P. Markowitz
Florida International University, Miami, FL 33199

V. Punjabi
Norfolk State University, Norfolk, VA 23504

B. Vlahovic
North Carolina Central University, Durham, NC 03824

A. Ahmidouch, S. Danagoulian
North Carolina A&T State University, Greensboro, NC 27411

A. K. Opper, I. Strakovsky
The George Washington University, Washington, DC 20052

D. Androic
University of Zagreb, Zagreb, Croatia

M. Kohl
Hampton University, Hampton, VA 23668

T. Averett, C. Perdrisat
College of William and Mary, Williamsburg, VA 23185

J. Dunne, D. Dutta, M. H. Shabestari
Mississippi State University, Mississippi State, MS 39762

S. L. Allison, M. Amaryan, L. El Fassi, C. Hyde, A. Radyushkin, M. N. H. Rashad
Old Dominion University, Norfolk, VA 23529

D. Day, R. Lindgren, D. Keller, N. Liyanage, B. E. Norum, O. Rondon, J. Zhang
University of Virginia, Charlottesville, VA 22901

P. Solvignon
University of New Hampshire, Durham, NH 03824

F. Sabatié
CEA Saclay—Irfu/SPhN

C. Muñoz Camacho
Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France

Z. Ahmed, G. M. Huber, W. Li, D. Paudyal
University of Regina, Regina, SK S4S 0A2

and

The Neutral Particle Spectrometer collaboration:
https://wiki.jlab.org/cuawiki/index.php/Collaboration

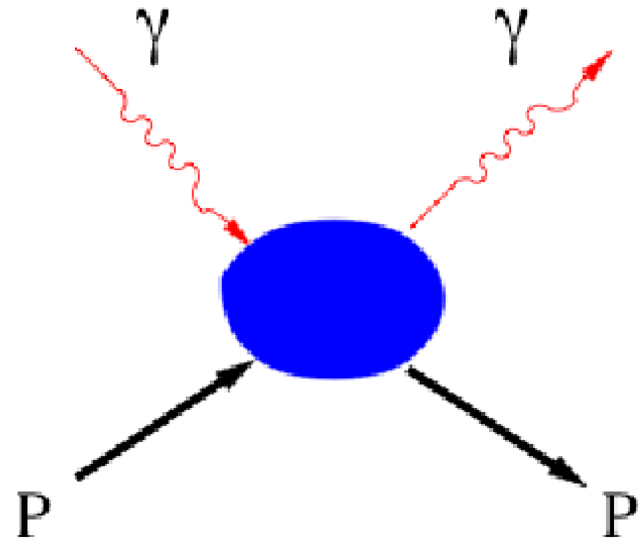
June 2, 2014

Outline

- Physics Motivation
  - Hanbag Mechanism and GPDs
  - Soft Collinear Effective Theory (SCET)
- The Jefferson Lab WACS program
- Experimental technique
- Kinematic settings
- Backgrounds, resolution and uncertainties
- Expected results and beamtime request

Physics Motivation

- Proton Compton scattering in the wide-angle regime (**s, -t, -u >> $m^2_{nucleon}$**) is a powerful and under-utilized probe of nucleon structure.
- It is an elegantly simple reactions, involving only a real photon and ground-state nucleon in both initial and final states.
- The physics in play is similar to that in elastic ep scattering or DVCS: **to characterize the electromagnetic response of the nucleon without complications from additional hadrons**.
- It is, however, one of the **least understood** of the fundamental reactions in the several GeV regime.



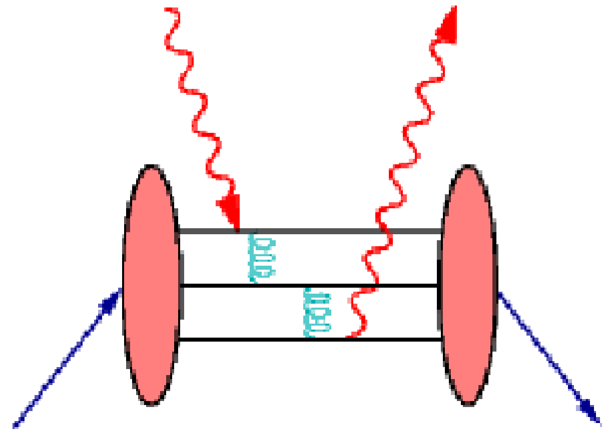
We propose to measure the differential cross section for WACS at photon energies of 8 and 10 GeV over a wide range of -t

Beamtime Request = 18 days

Reaction Mechanism

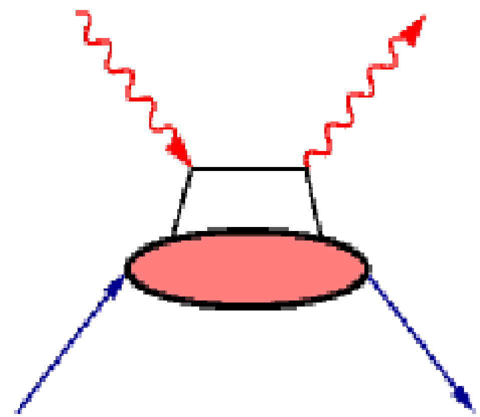
A number of reaction mechanisms for WACS have been proposed over the years:

- **pQCD (two-gluon exchange)**
- **The Handbag Mechanism (GPDs)**
- **Relativistic Constituent Quark Models**
- **Soft Collinear Effective Theory**



The main questions we intend to address are:

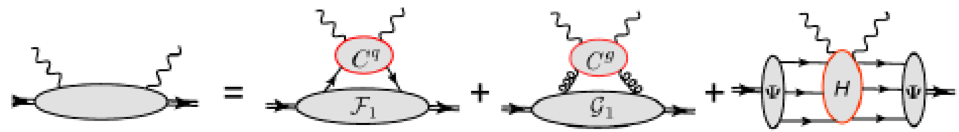
- **Does large -t ensure dominance of short-distance physics?**
- **What factorization scheme is valid?**
- **Is it indeed true that the WACS reaction proceeds through the interaction of the photon with an individual quark?**
- **What information can be extracted concerning the structure of the proton from measurements of the WACS form factors?**
- **Given the fact the pQCD is not expected to be valid at this kinematic scale, why are the scaling predictions so close to the observed value?**



Reaction Mechanism: SCET

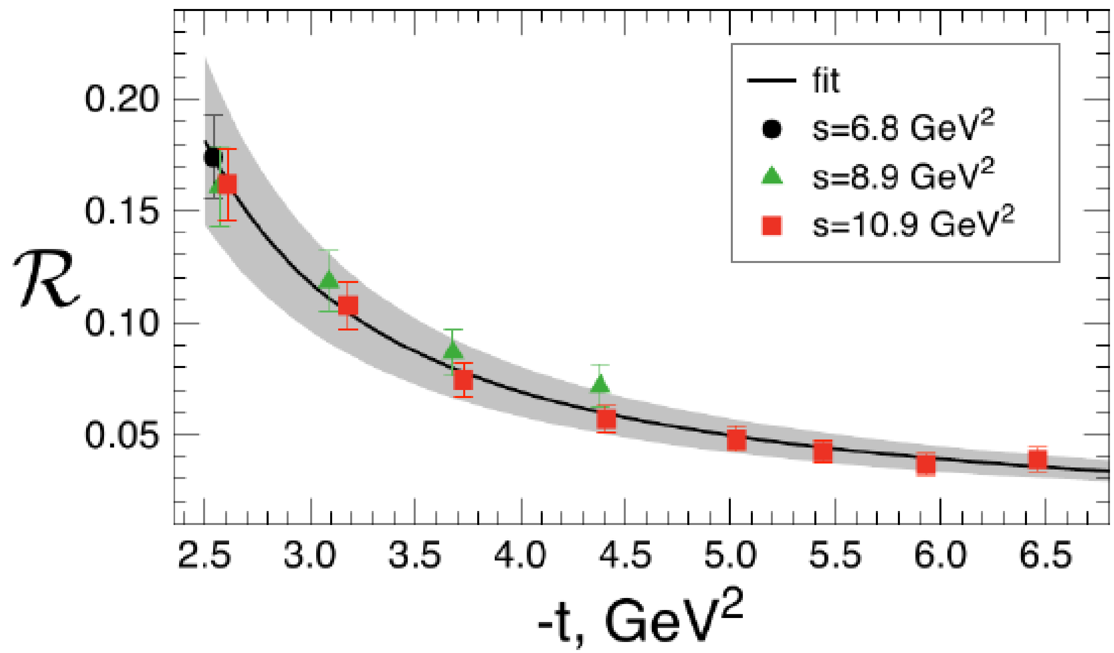
N. Kivel and M. Vanderhaeghen, JHEP 1304 (2013)

The recent development of the SCET approach has shown the importance of WACS in understanding **Two Photon Exchange (TPE)** effects in elastic ep scattering.



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

Due to universality considerations the **form factor** which describes TPE at high Q^2 can be determined from WACS cross section data.



Extending the measurements of this form factor R(t) to higher s and -t will provide valuable insights into the **validity of factorization** in both WACS and TPE in elastic ep scattering and help learn more about the **soft physics describing proton structure** in the 12 GeV regime.

Reaction Mechanism: GPDs

M. Diehl and P. Kroll, arxiv 1302.4604

$$\gamma p \to \gamma p \qquad\qquad ep \to ep$$

$$R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t), \qquad F_1(t) = \sum_a e_a \int_{-1}^{1} dx\, H^a(x,0,t),$$

$$R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \operatorname{sign}(x)\, \hat{H}^a(x,0,t), \qquad G_A(t) = \sum_a \int_{-1}^{1} dx \operatorname{sign}(x)\, \hat{H}^a(x,0,t),$$

$$R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x,0,t), \qquad F_2(t) = \sum_a e_a \int_{-1}^{1} dx\, E^a(x,0,t),$$

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

Studying WACS can lead to constraints on GPDs at large -t and x, which differ from electromagnetic form factors due to 1/x and e_a^2 factors.

WACS at Jlab in the 6 GeV Era

Jlab Experiment E99-114 (Hall A, 2002)

Measurements of spin averaged WACS cross section over a broad kinematic range of **$6.8 < s < 11$ GeV², $2 < -t < 7$ GeV²** and polarization transfer K_{LL} and K_{LT} at a single point of **$s = 6.9$ GeV², $-t = 4$ GeV²**.

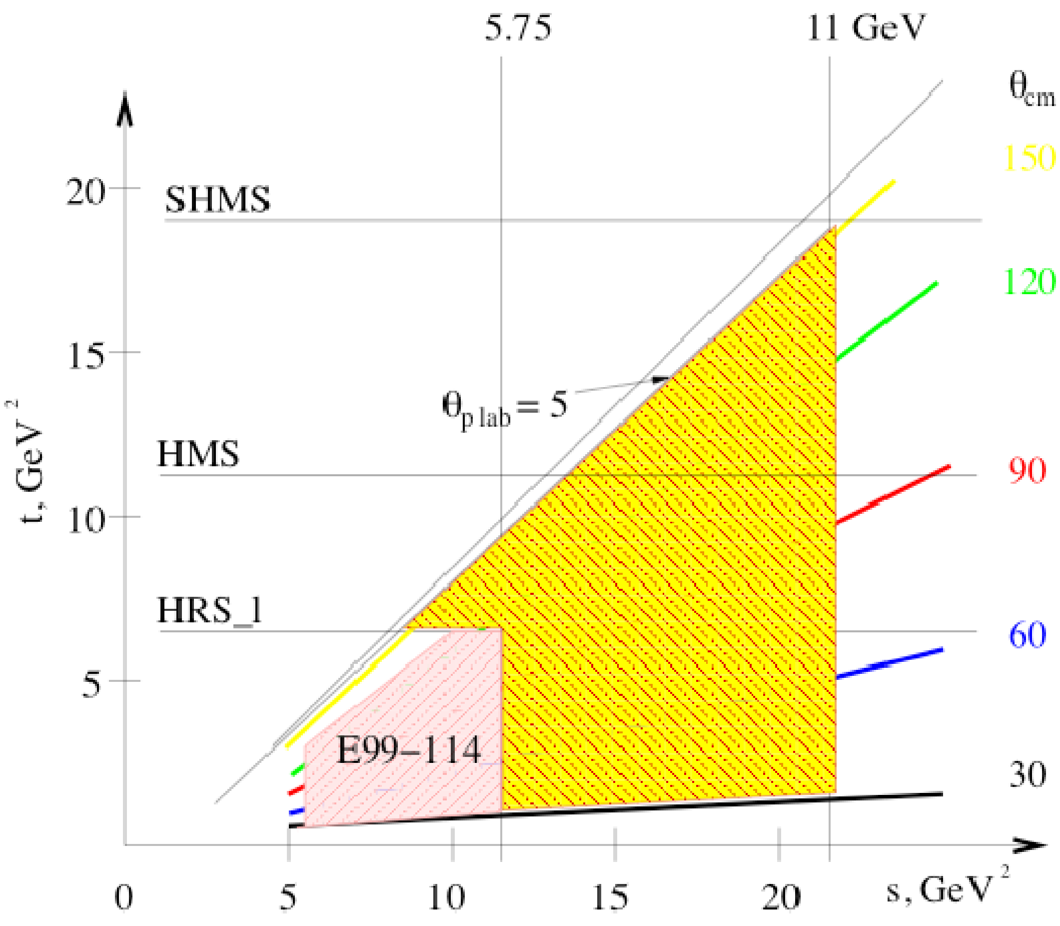
Two publications in PRL and one in NIM.

Ongoing PhD thesis work by Johan Sjoegren (Glasgow) on neutral pion photoprodution cross sections.

Jlab Experiment E07-002 (Hall C, 2008)

Measurement of polarization observables K_{LL}, K_{LT}, and P_N at **$s = 8.0$ GeV², $-t = 2.1$ GeV²**.

PhD analysis nearing completion by Cristiano Fanelli (ISS Rome).

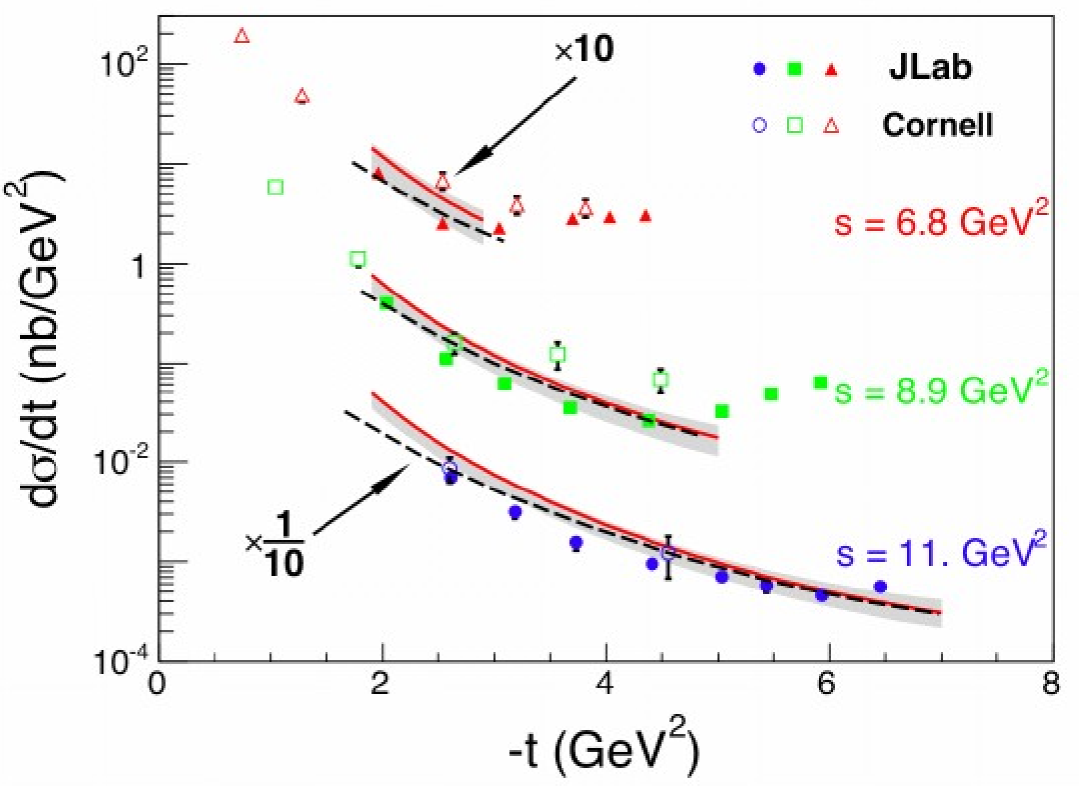


WACS at Jlab in the 6 GeV Era

The experimental technique represented a **factor of 1000** improvement in productivity ($\mathcal{L}_{\gamma p}$) over the last Cornell experiment.

This allowed for a very significant improvement in precision, and the measurement of **polarization observables** in this kinematic regime for the first time.

A. Danagoulian et al, PRL 98 (2007)



WACS at Jlab in the 6 GeV Era

D. J. Hamilton et al, PRL 94 (2005)

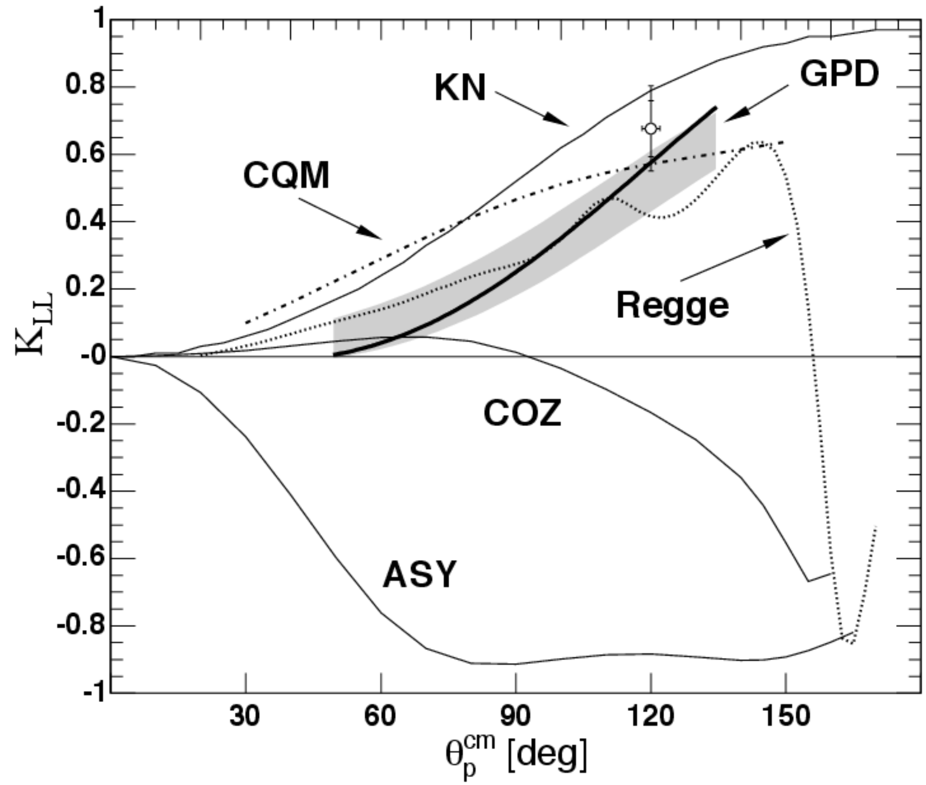
The experimental technique represented a **factor of 1000** improvement in productivity ($\mathcal{L}_{\gamma p}$) over the last Cornell experiment.

This allowed for a very significant improvement in precision, and the measurement of **polarization observables** in this kinematic regime for the first time.

The results show evidence for **factorization of the reaction mechanism**, and dominance of the handbag mechanism.

As with elastic ep scattering results, recoil polarization results have helped gain even greater insight: the results strongly favor a **leading quark mechanism (x ~ 1).**

However, some data-points did not fully meet the wide-angle condition (**s, -t, -u >> $m^2_{nucleon}$**) because of a low value of -u.



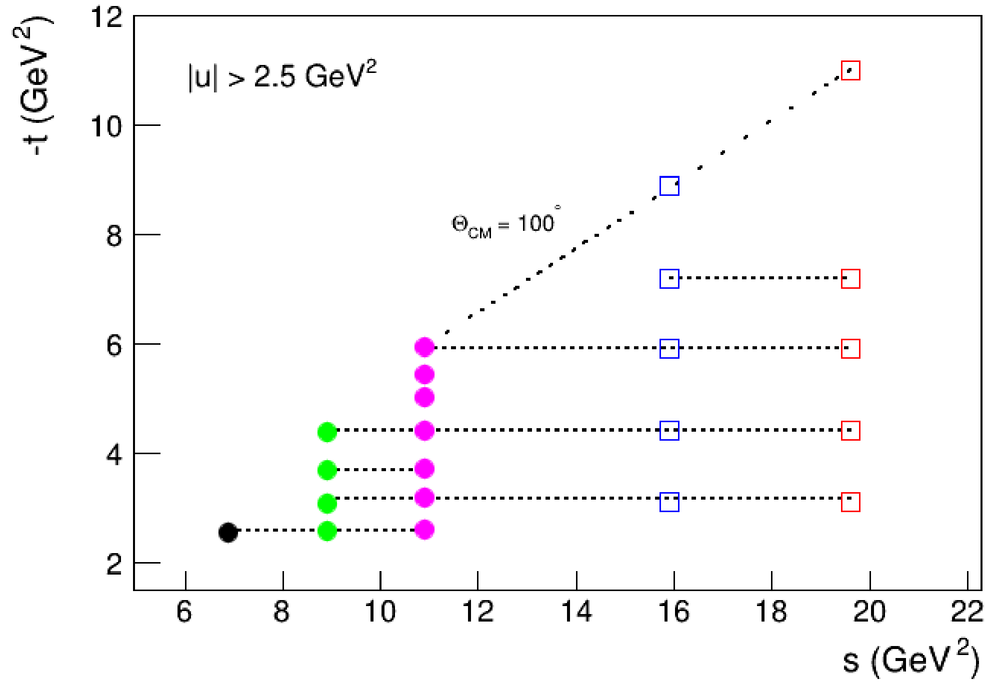
WACS at JLab in the 12 GeV Era

The current proposal includes measurements of the differential cross section at

10 carefully chosen kinematic points

These measurements will allow for a determination of the cross section scaling power n at fixed Θ_{CM} and therefore the **dominant reaction mechanism**.

The broad range in -t will allow for extraction of the WACS form factor R(t), providing **direct experimental evidence for factorization** and leading to constraints of GPDs at high x and -t and TPE effects in elastic ep scattering at high Q^2.

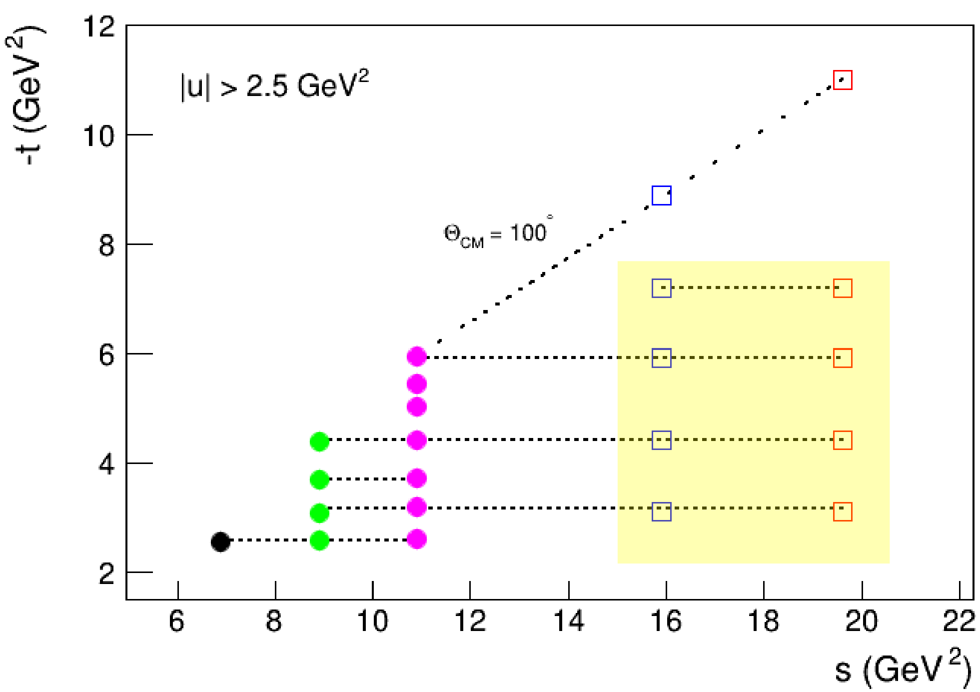


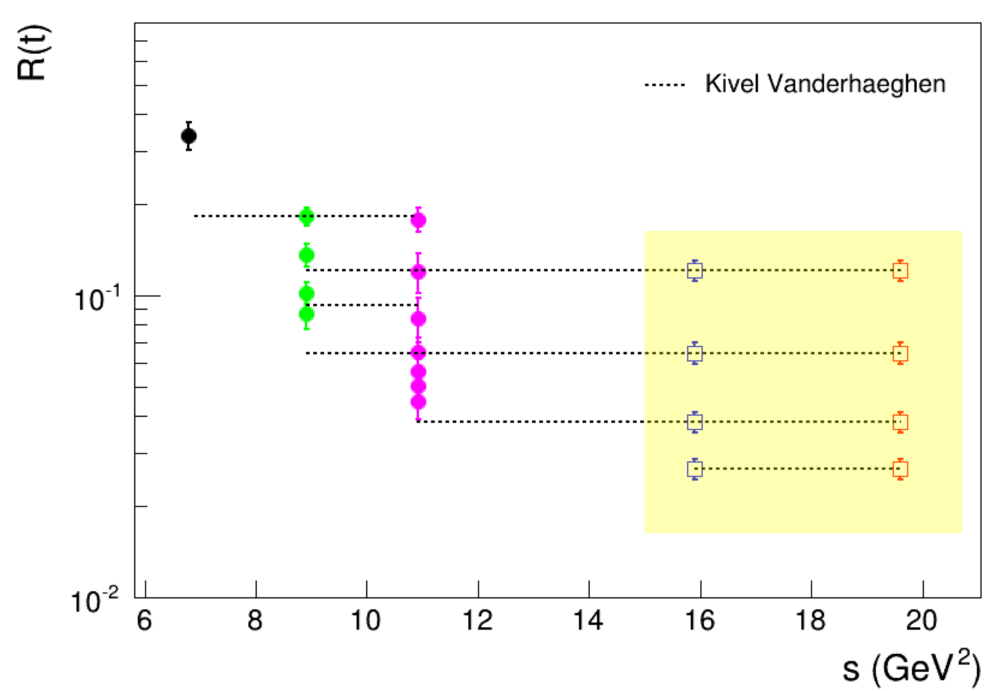
All kinematic settings unambiguously meet the wide-angle condition that **$s, -t, -u \gg m^2_{nucleon}$**

PAC 40 Comments to PR12-13-009

Furthermore, the PAC was also not convinced on the choice of kinematic points to make the strongest physics case. To perform the above mentioned factorization study, the PAC felt that it would be more promising to focus on a fixed intermediate value of –t, combining the s-range from the previous 6 GeV experiment with the proposed extension in s.

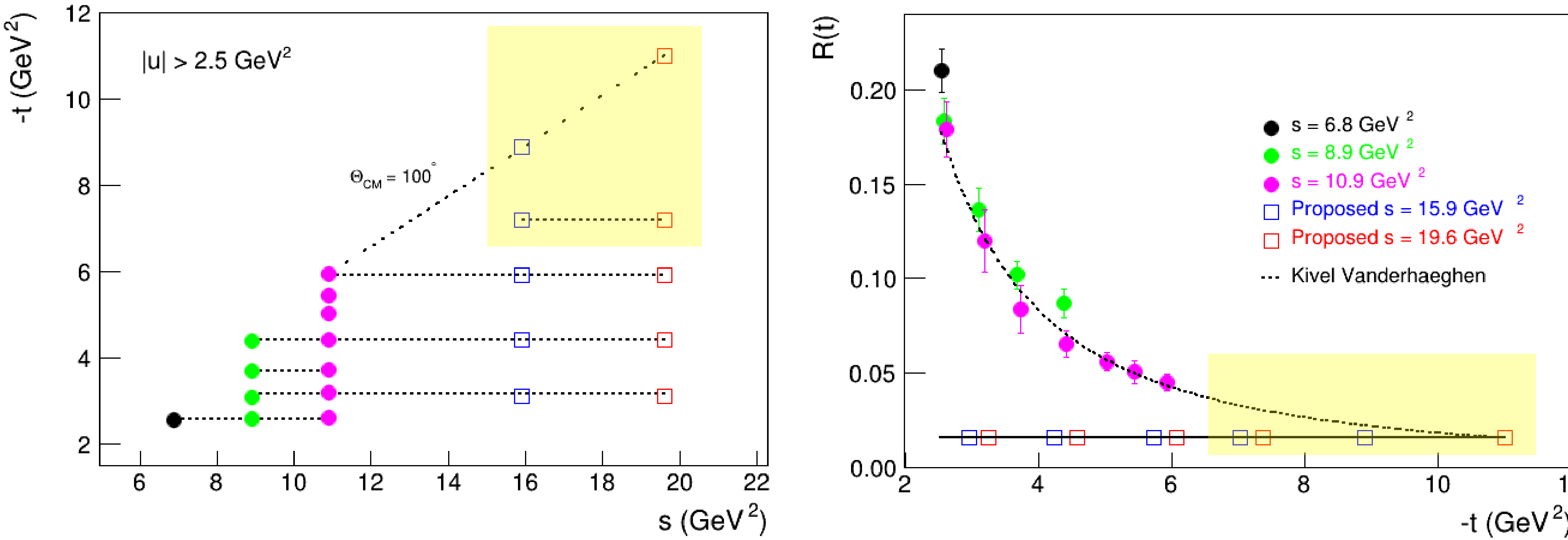
PAC40 Report



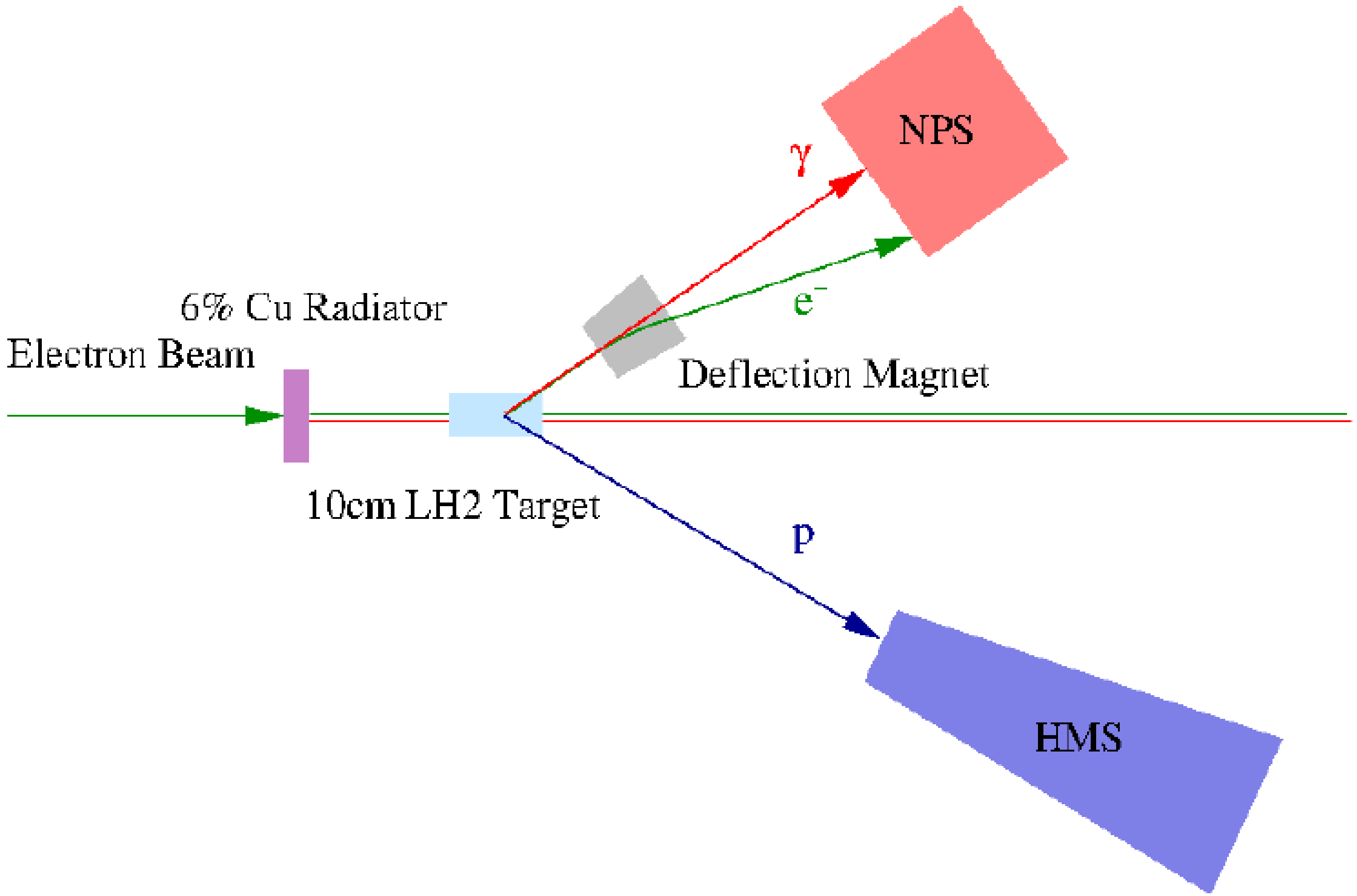


PAC40 Report

Several theoretical model approaches have been presented to interpret the result of such WACS cross sections. To interpret a factorization of the s- and t-dependence, the PAC would also like to see a sharpened physics case, indicating how such data would lead to systematic improvements within the specific models.

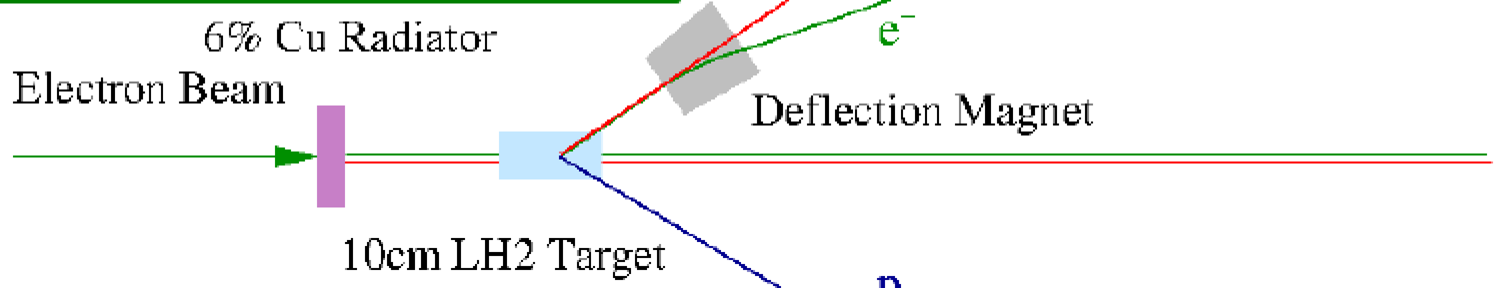


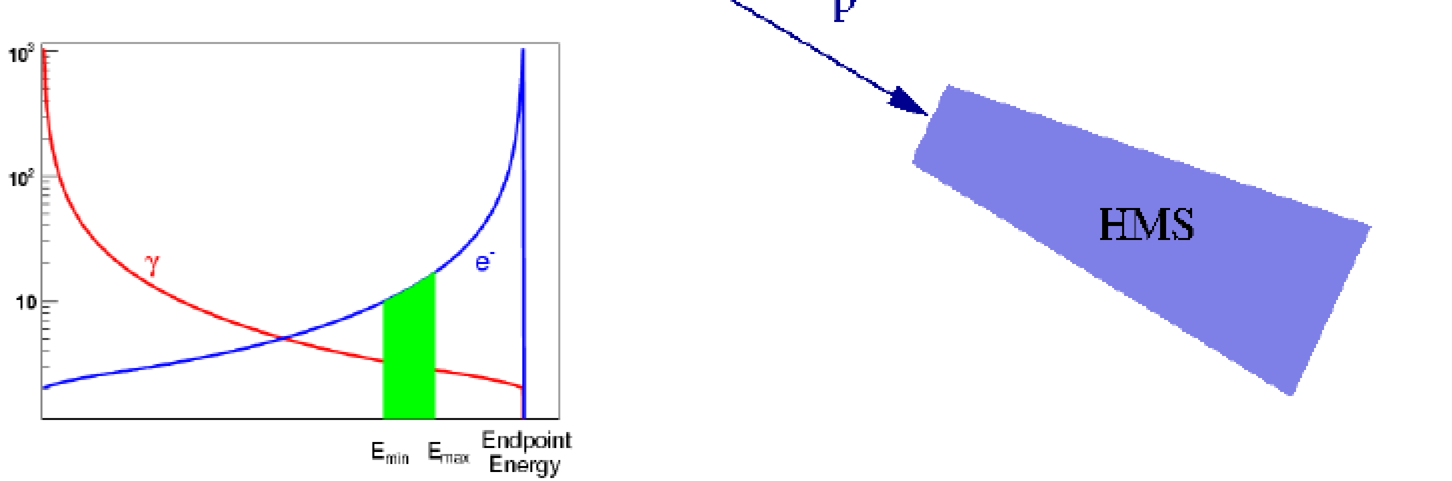
Experimental Technique



Experimental Technique

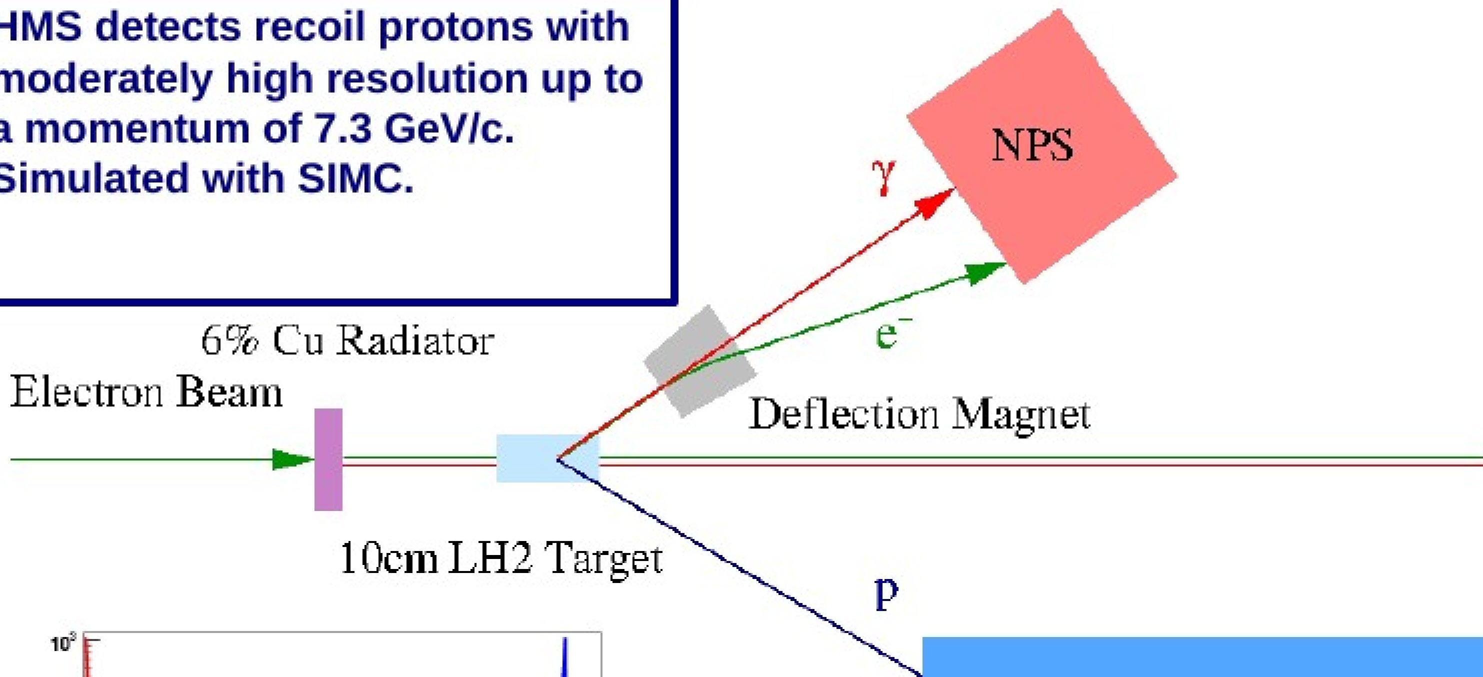
A 6% Copper radiator is used to produce a mixed electron/photon beam incident on a 10 cm LH_2 target.
Simulated with Geant4.

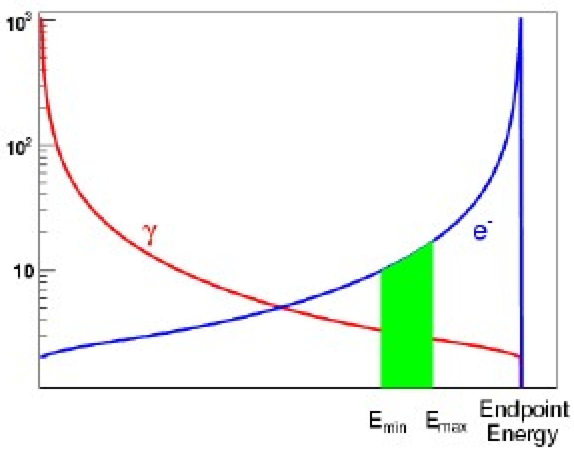


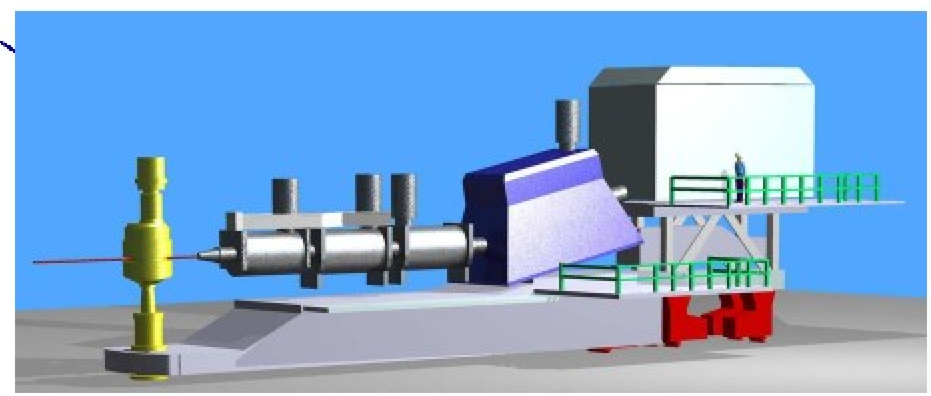


Experimental Technique

HMS detects recoil protons with moderately high resolution up to a momentum of 7.3 GeV/c. Simulated with SIMC.

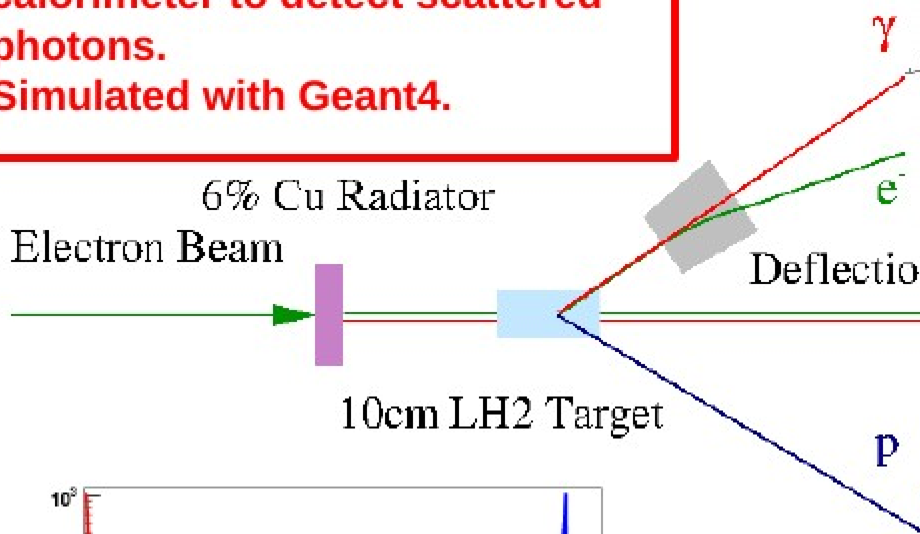


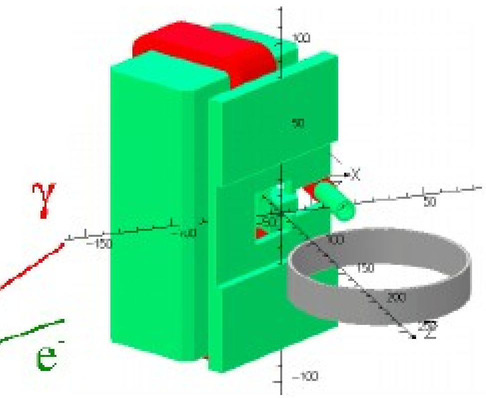


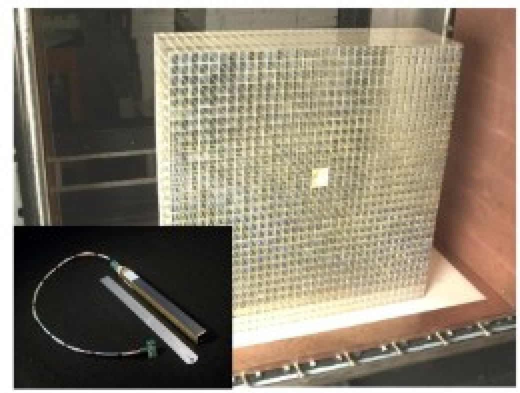


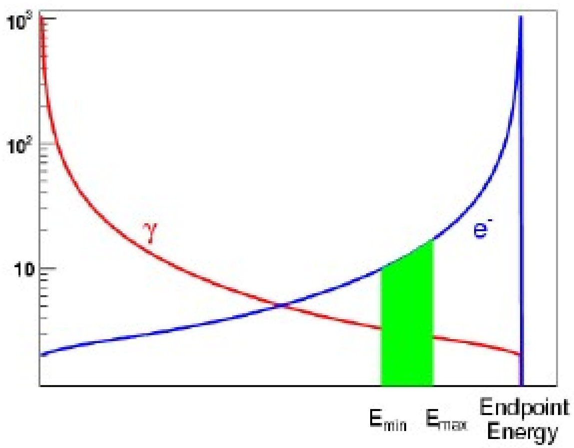
Experimental Technique

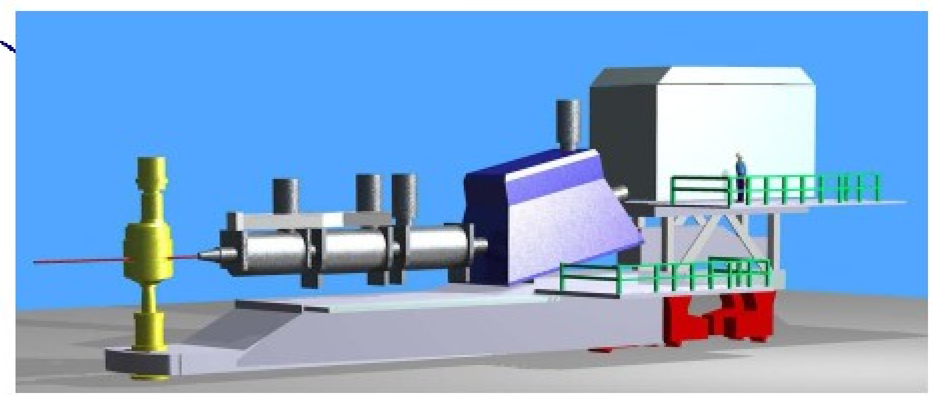
New vertical deflection magnet and 1116 element $PbWO_4$ calorimeter to detect scattered photons.
Simulated with Geant4.





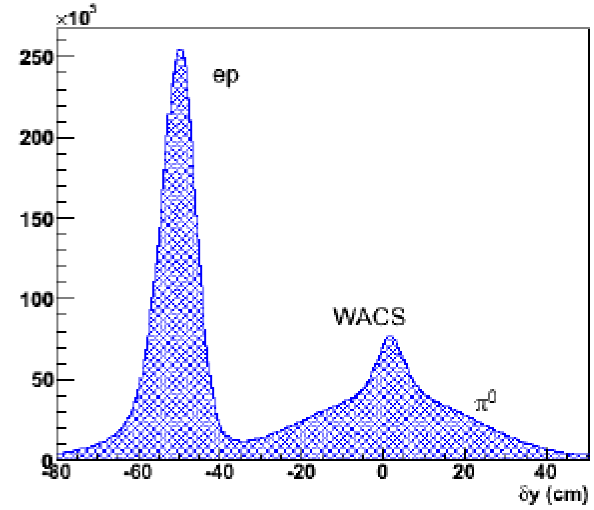






Analysis Technique and Background Processes

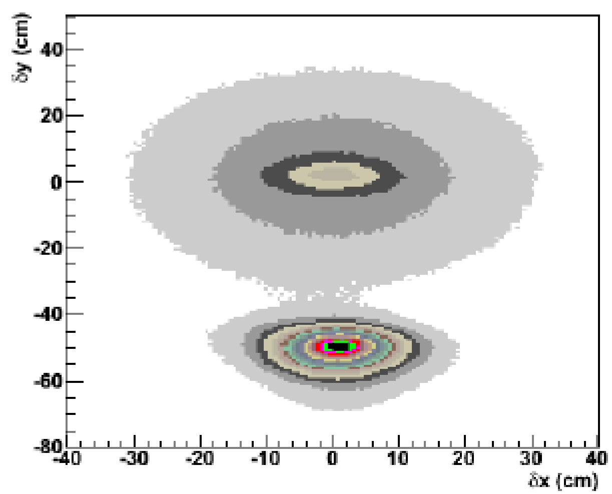
The analysis technique relies on the utilization of the **two-body kinematic correlation** between photon/electron and proton to identify the WACS events and extract their yield.



Three main reaction channels:

- **$\gamma p \rightarrow \gamma p$**
- **$ep \rightarrow ep$ (and $ep \rightarrow ep\gamma$)**
- **$\gamma p \rightarrow \pi^0 p \rightarrow \gamma\gamma p$**

A deflection magnet is used to cleanly separate the elastic ep scattering and the WACS events.



There is however still significant background under the WACS peak from π^0 and $ep\gamma$ events. Simulations have shown that these background dilutions have the following range:

R_{π^0} = 0.12(high -t) – 0.90 (low -t)
$R_{ep\gamma}$ = 0.03 (low -t) – 0.78 (high -t)

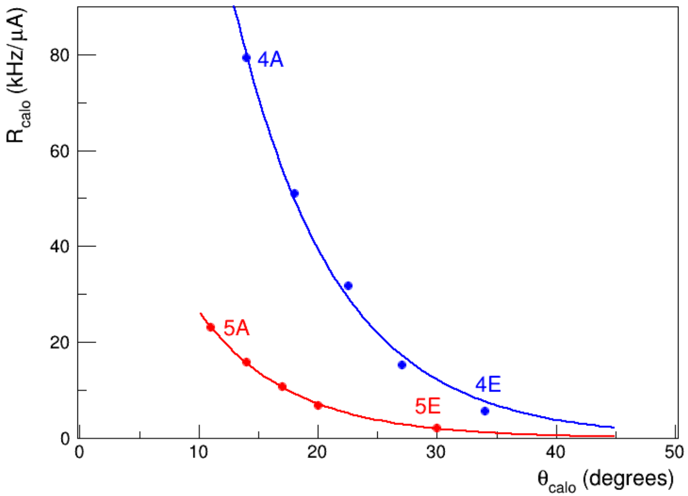
Projected Rates

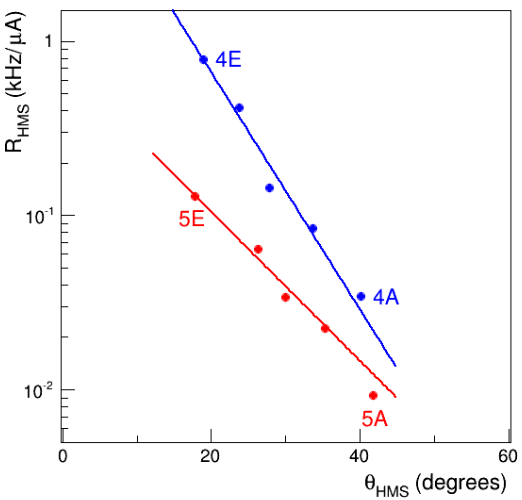
- Rates and radiation levels have been calculated based on experience with E99-114, E07-002 and both physics and DINREG Monte Carlo simulations.
- For each HMS trigger, every NPS cluster (5x5) with a crystal threshold greater than **25 % of the expected Compton scattered energy** will be read out (16 samples from F250 FADC's = 64 ns will be sufficient).
- This leads to a maximum data rate of **10 MB/s** and a total maximum data-set of **7 TB**.
- Accumulated dose on the NPS is expected to be **150 kRad**; radiation level in the hall around **200 mR/hr**.

cross section solid angle photon flux

$$N_{RCS} = \frac{d\sigma}{dt}_{RCS} \left(\frac{(E_\gamma^f)^2}{\pi} \Delta\Omega_p \frac{d\Omega_\gamma}{d\Omega_p} \right) f_{\gamma p} \left(\frac{\Delta E_\gamma^f}{E_\gamma^f} \frac{t_{rad}}{X_o} \right) \mathcal{L}_{e\vec{p}}$$

Projected Rates



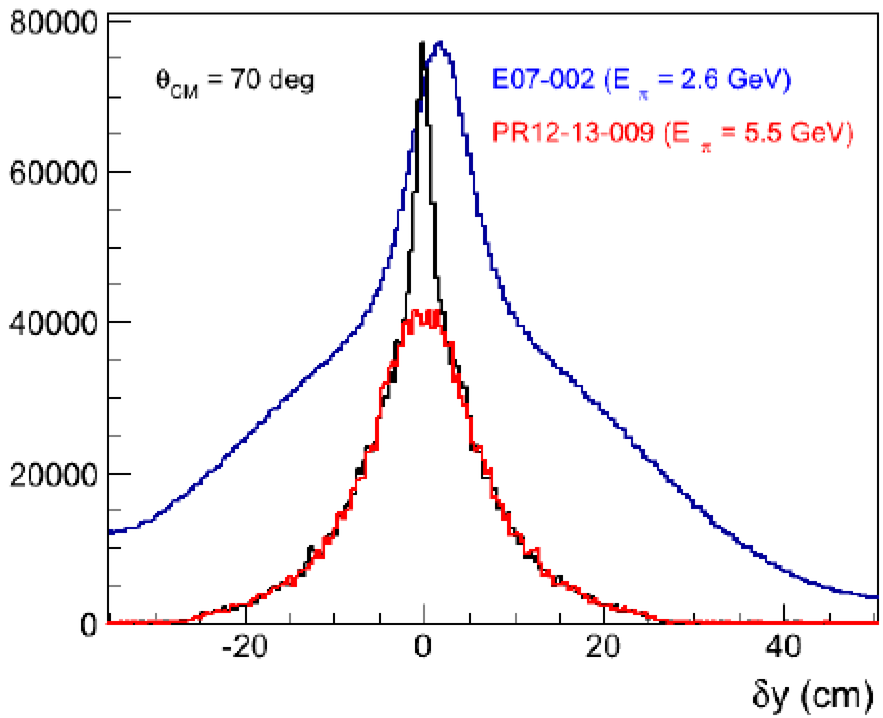


Kin	θ_γ [°]	θ_p [°]	$\dot{N}_{RCS}$ [$\mu A^{-1} h^{-1}$]	N_{RCS}	δ_{stat}	I_{beam} [μA]	t [h]
4A	14.2	40.1	15.0	1500	0.05	5	20+7
4B	17.9	33.7	6.0	1300	0.05	15	20+7
4C	22.5	27.8	3.0	1800	0.05	30	20+7
4D	26.9	23.7	1.5	2500	0.05	60	30+7
4E	34.0	18.9	0.7	2000	0.08	60	50+7
5A	11.0	41.7	9.0	2400	0.05	20	15+7
5B	13.8	35.3	3.0	1900	0.05	30	20+7
5C	16.9	30.0	1.6	1800	0.05	60	20+7
5D	19.7	26.3	1.0	2400	0.05	60	40+7
5E	29.9	17.8	0.3	2200	0.08	60	120+7
Total							425

Systematic Uncertainties

University of Glasgow

Isolating the WACS peak from the π^0 background is much more difficult than 6 GeV experiments because of **narrower π^0 distribution**.



Source	Uncertainty [%]
Incident photon flux: accumulated beam charge	1.0
Incident photon flux: target thickness	1.0
Incident photon flux: bremsstrahlung calculation	3.0
Detector: NPS detection efficiency	1.5
Detector: HMS acceptance	1.5
Detector: HMS tracking efficiency	1.5
Yield Extraction: π^0 background	3.0
Yield Extraction: $ep\gamma$ background	3.0
Total	**6.0**

Total is dominated by systematic uncertainties in **incident photon flux determination** and **yield extraction (primarily due to π^0 background)**

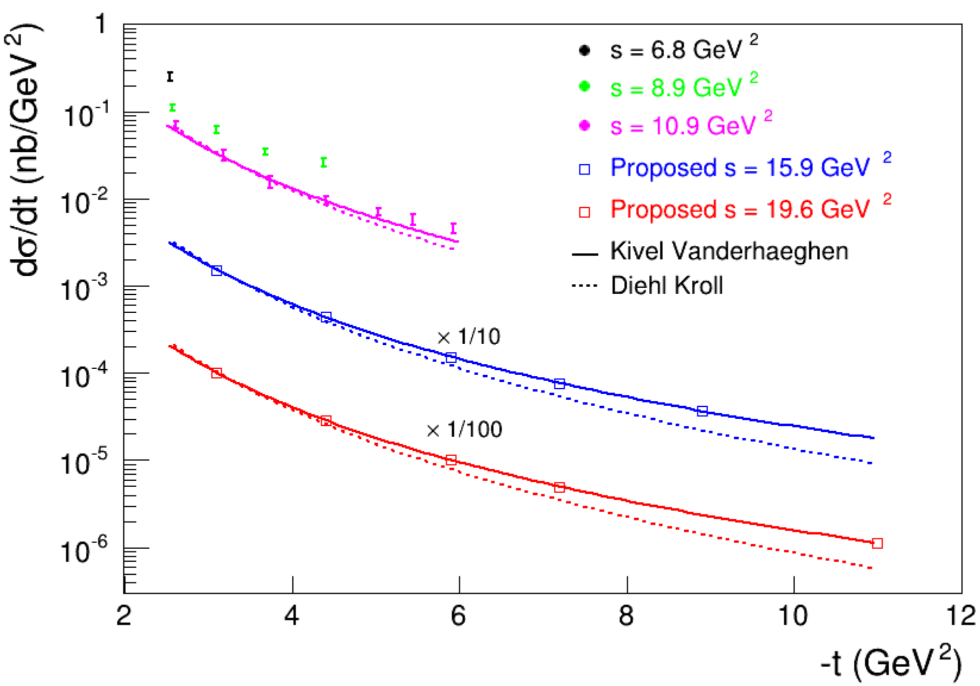
Expected Results and Beamtime Request

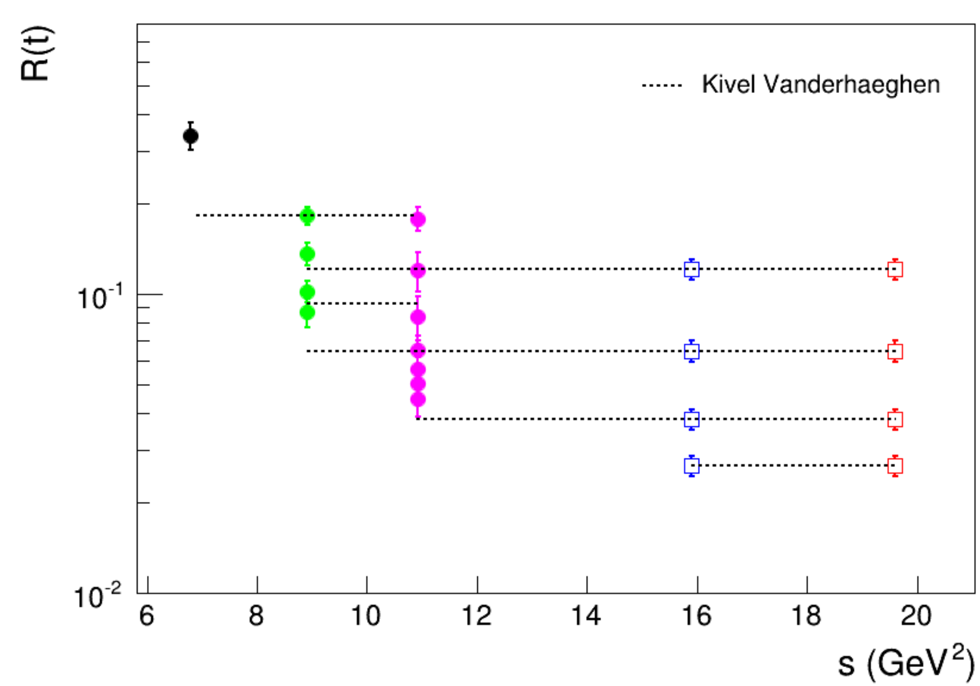
University of Glasgow

> The PAC40 sees a strong potential for the WACS to be a process of choice to explore factorization in a whole class of wide-angle processes.

We propose precision measurements of the WACS differential cross section at 10 kinematic settings, doubling the range in s and -t over previous Jlab data. **The total beamtime request is 18 days.**

With 4 fixed -t scans we will make a rigorous test of factorization of the WACS reaction mechanism.





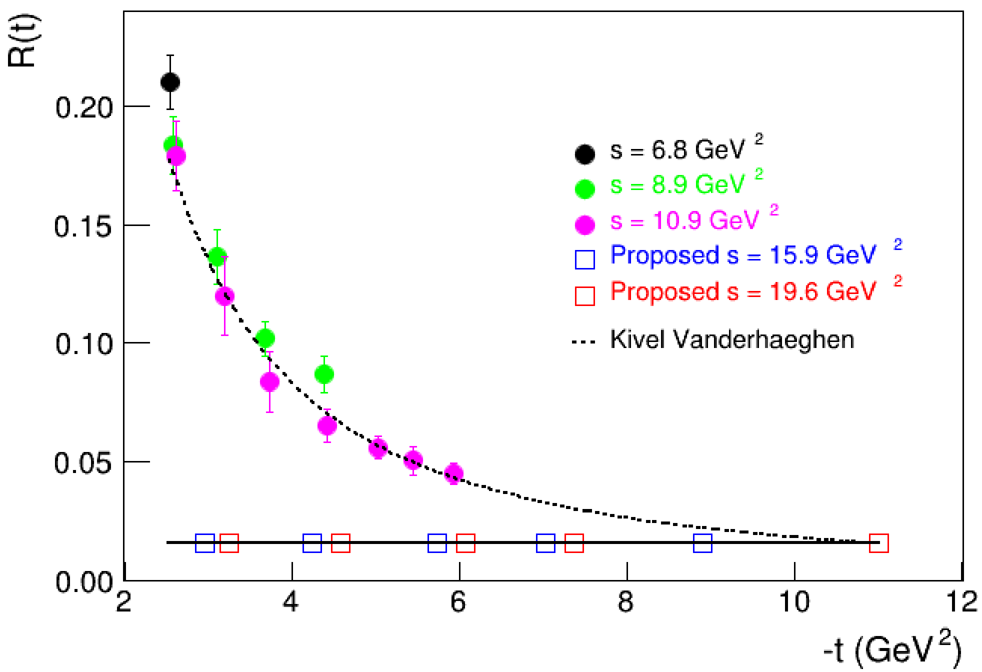
University of Glasgow

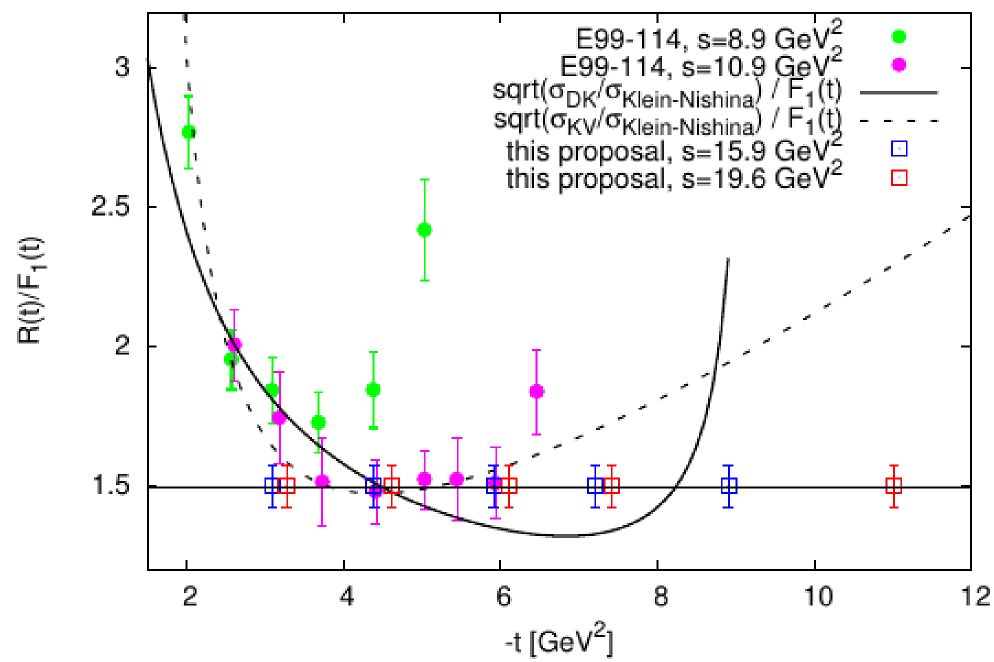
Expected Results and Beamtime Request

The PAC40 sees a strong potential for the WACS to be a process of choice to explore factorization in a whole class of wide-angle processes.

We propose precision measurements of the WACS differential cross section at 10 kinematic settings, doubling the range in s and -t over previous Jlab data. **The total beamtime request is 18 days.**

With 4 high -t points we will explore the link between electromagnetic and time-like form factors, and provide important constraints on TPE contributions at high momentum transfer.





Neutral Pion Photoproduction

The next simplest photo-induced reaction after WACS is neutral pion photoproduction. A separate proposal to analyse the data from the current proposal and request an additional 56 hours of beamtime was submitted to PAC42 (D. Dutta et al).

It is anticipated that both experiments could form a run group to comprehensively explore wide-angle photo-induced reactions at Jlab in the 12 GeV era.