PR-12-13-009

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

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An NPS Collaboration Proposal

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https://wiki.jlab.org/cuawiki/index.php/Collaboration

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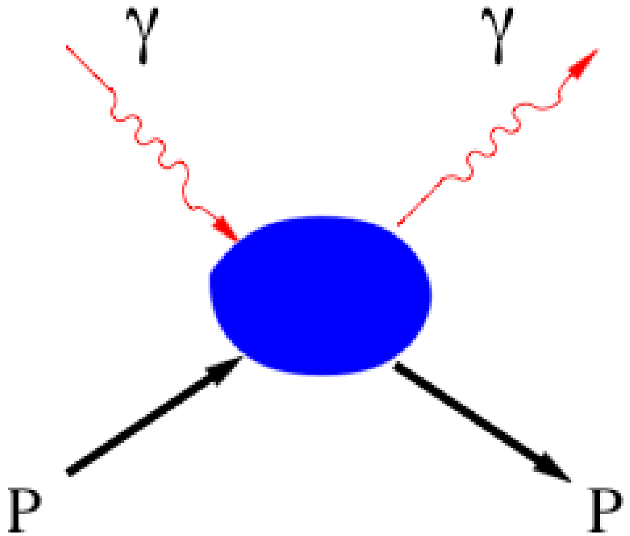
Outline

- 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 -t.

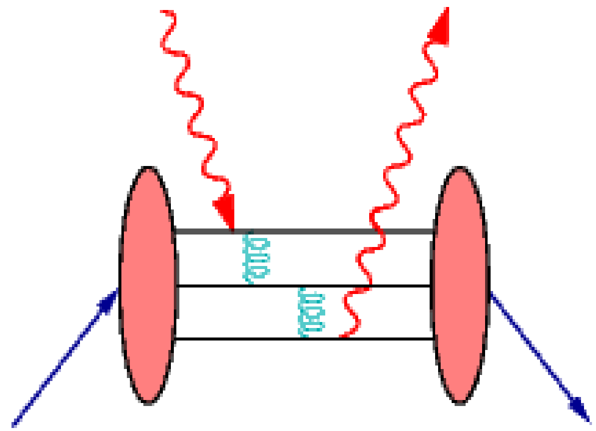
Beamtime Request = 42 days*

* includes time for configuration changes, calibration runs and DAQ/analysis overheads

WACS: Reaction Mechanism

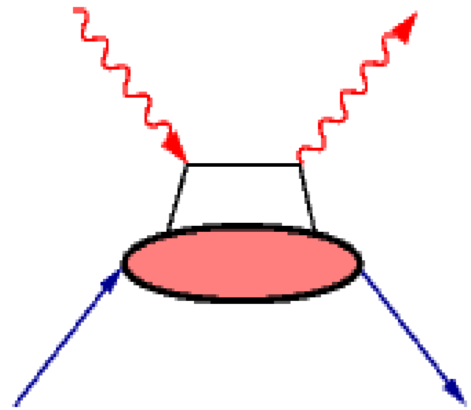
A number of reaction mechanisms for WACS have been proposed over the years:

- **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?**



Handbag Mechanism and GPDs

M. Diehl and P. Kroll, arxiv 1302.4604

$$\gamma p \longrightarrow \gamma p \qquad\qquad ep \longrightarrow ep$$

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

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

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

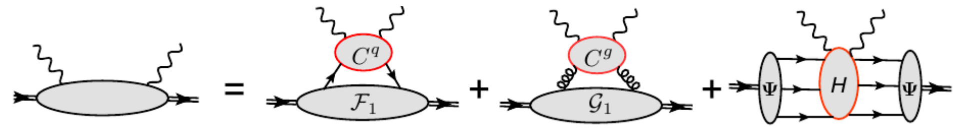
$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}_{KN} \left\{ \frac{1}{2}\left[R_V^2 + \frac{-t}{4m^2} R_T^2 + R_A^2 \right] - \frac{us}{s^2+u^2}\left[R_V^2 + \frac{-t}{4m^2} R_T^2 - R_A^2 \right] \right\}$$

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.

Soft Collinear Effective Theory

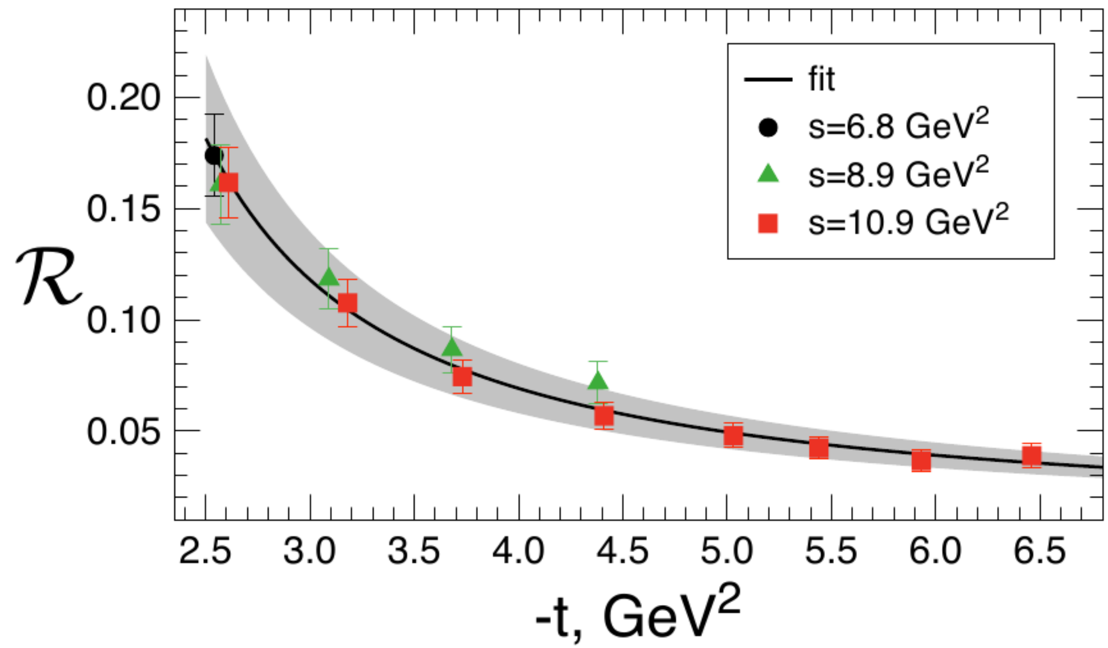
N. Kivel and M. Vanderhaeghen, JHEP 1304 (2013)

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.

The Jlab WACS Program: 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**.

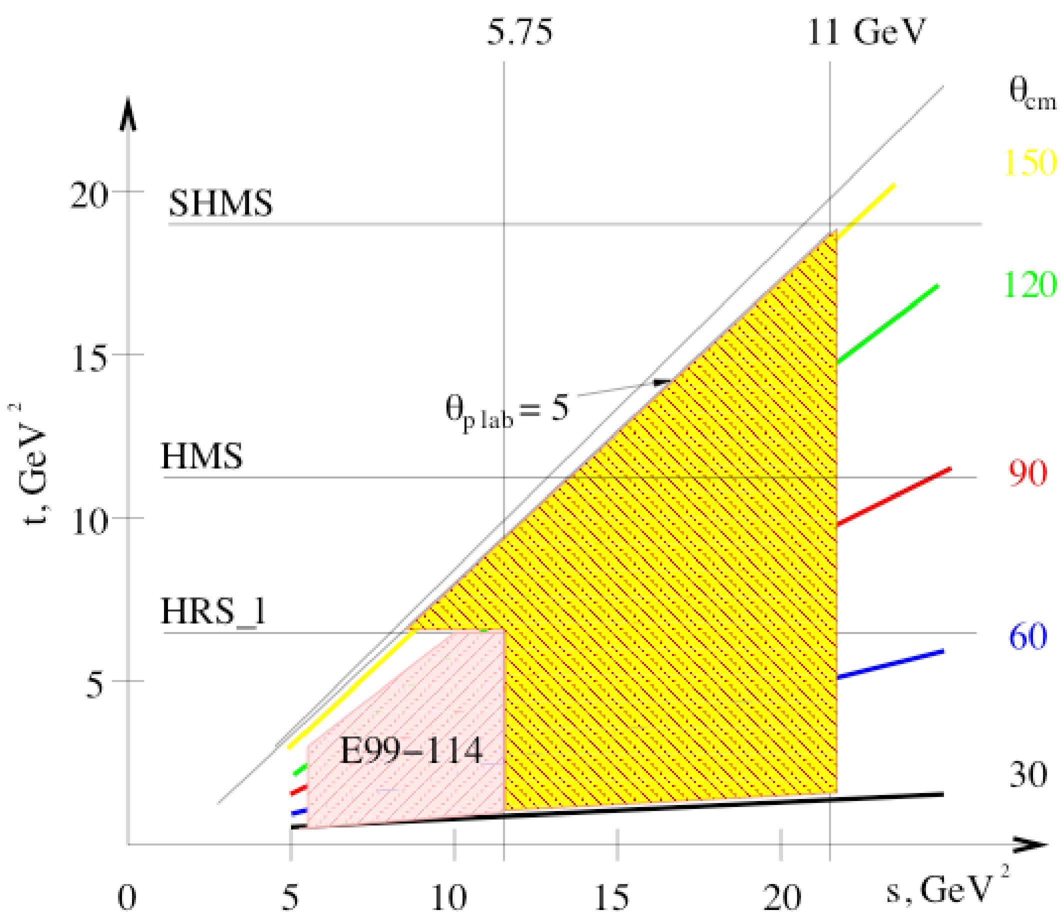
Two publications in PRL and one in NIM.

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).

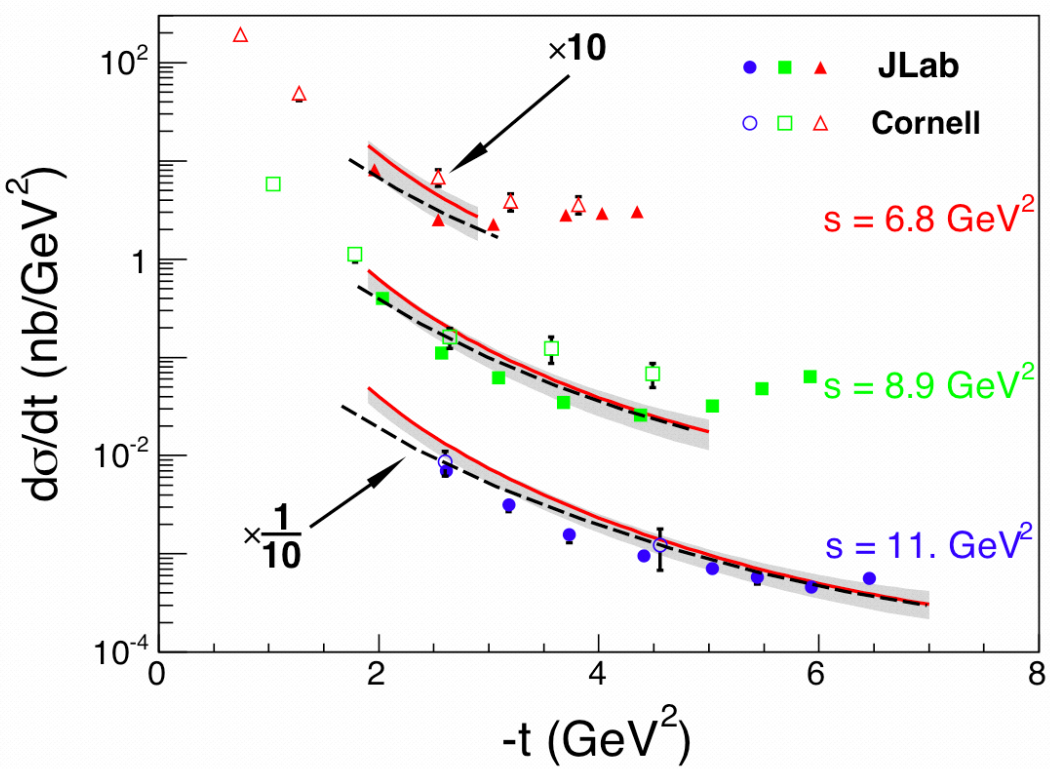


6 GeV Highlights

A. Danagoulian et al, PRL 98 (2007)

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.



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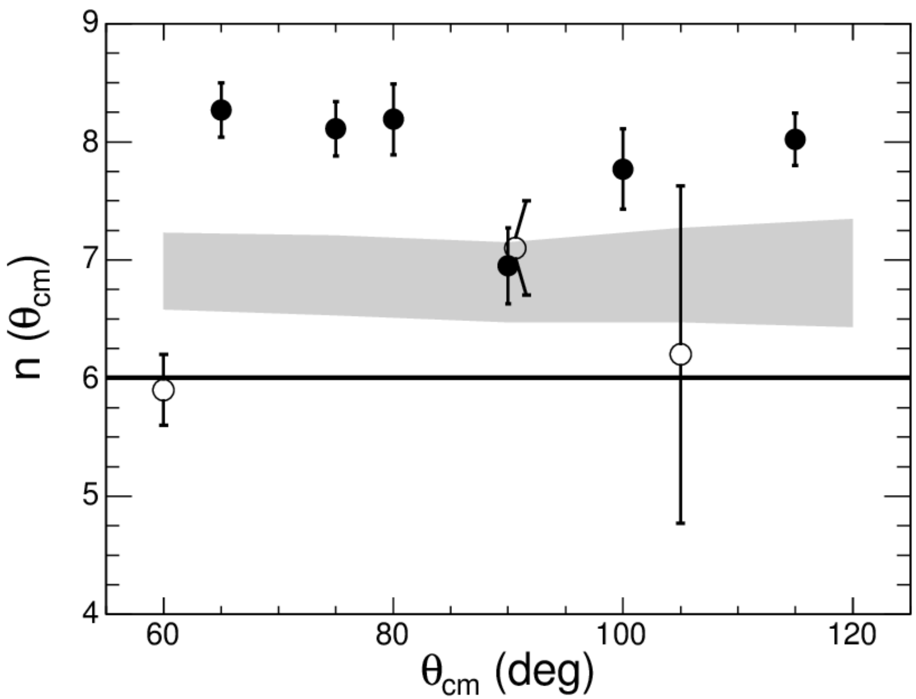
The results show evidence for **factorization of the reaction mechanism**, and dominance of the handbag mechanism.



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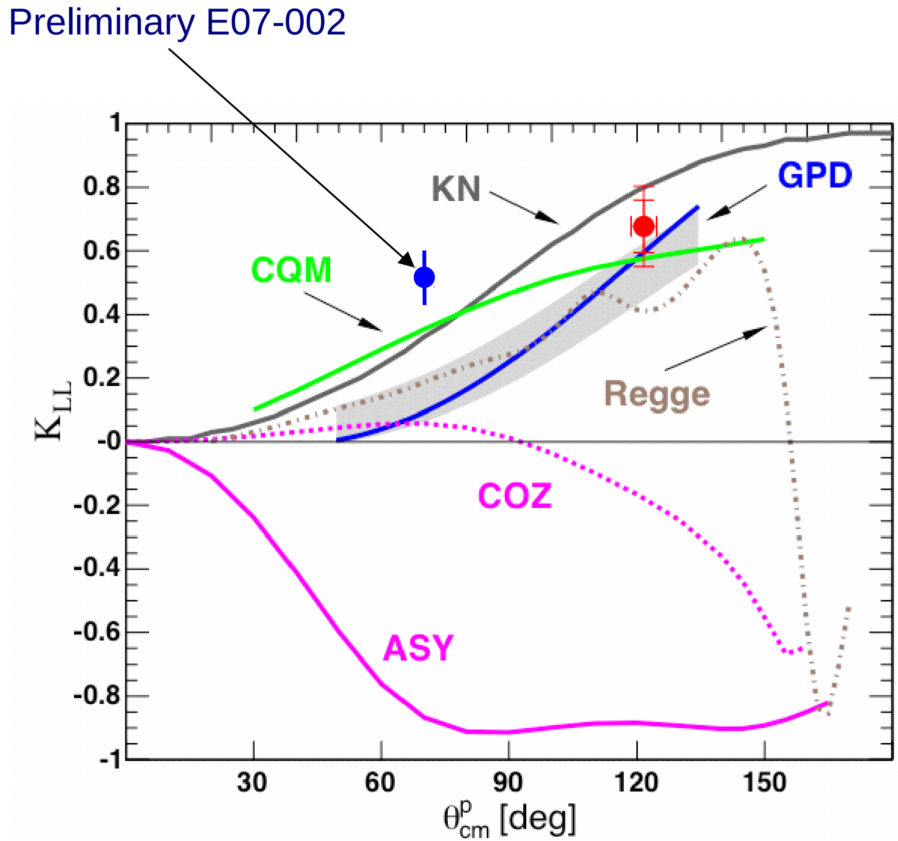
The results show evidence for **factorization of the reaction mechanism**, and dominance of the handbag mechanism.

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.

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



The Jlab WACS Program: 12 GeV Era

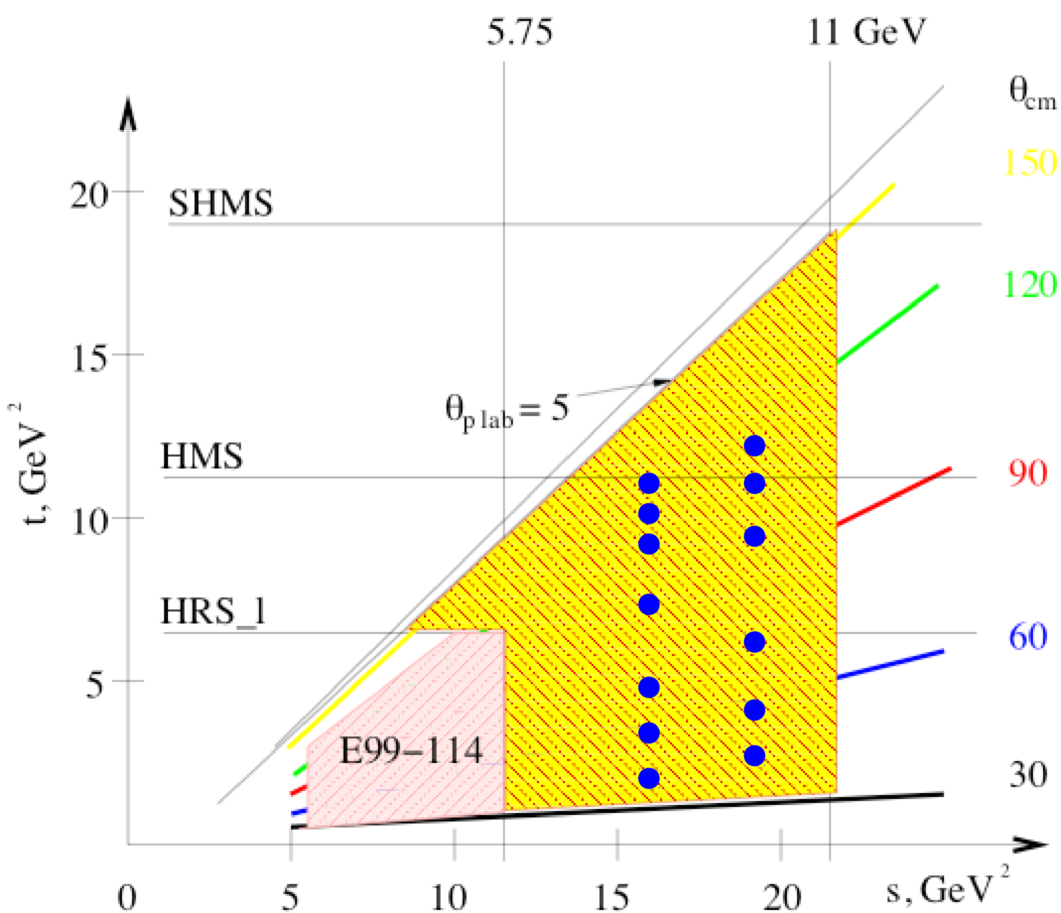
Jlab Proposal PR12-13-009

The current proposal includes measurements of the differential cross section at **13 kinematic points.**

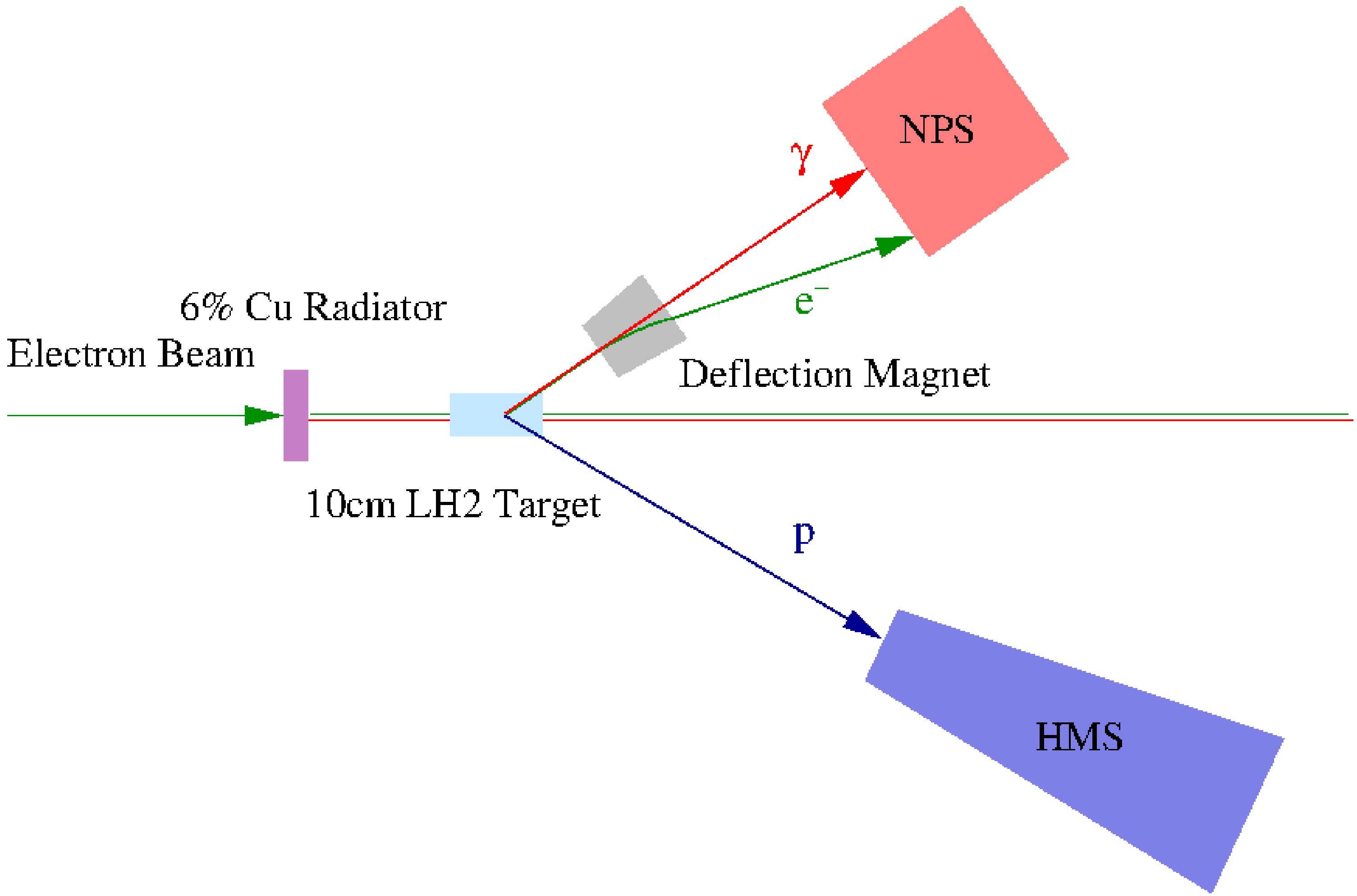
These measurements will allow for a determination of the cross section scaling power n at fixed Θ_{CM} and therefore the **dominant reaction mechanism**.

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
$s, -t, -u >> m^2_{nucleon}$

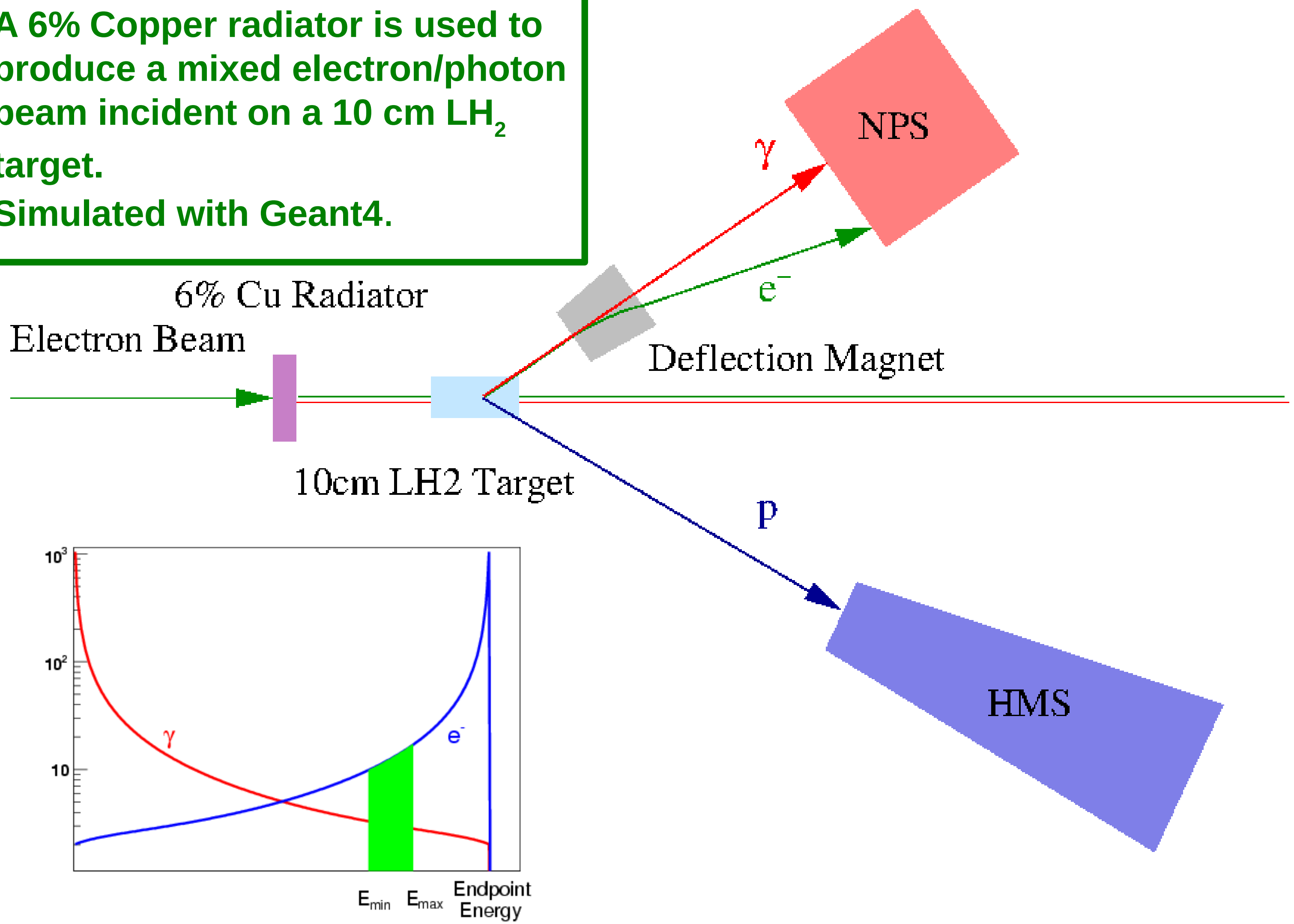


Experimental Technique



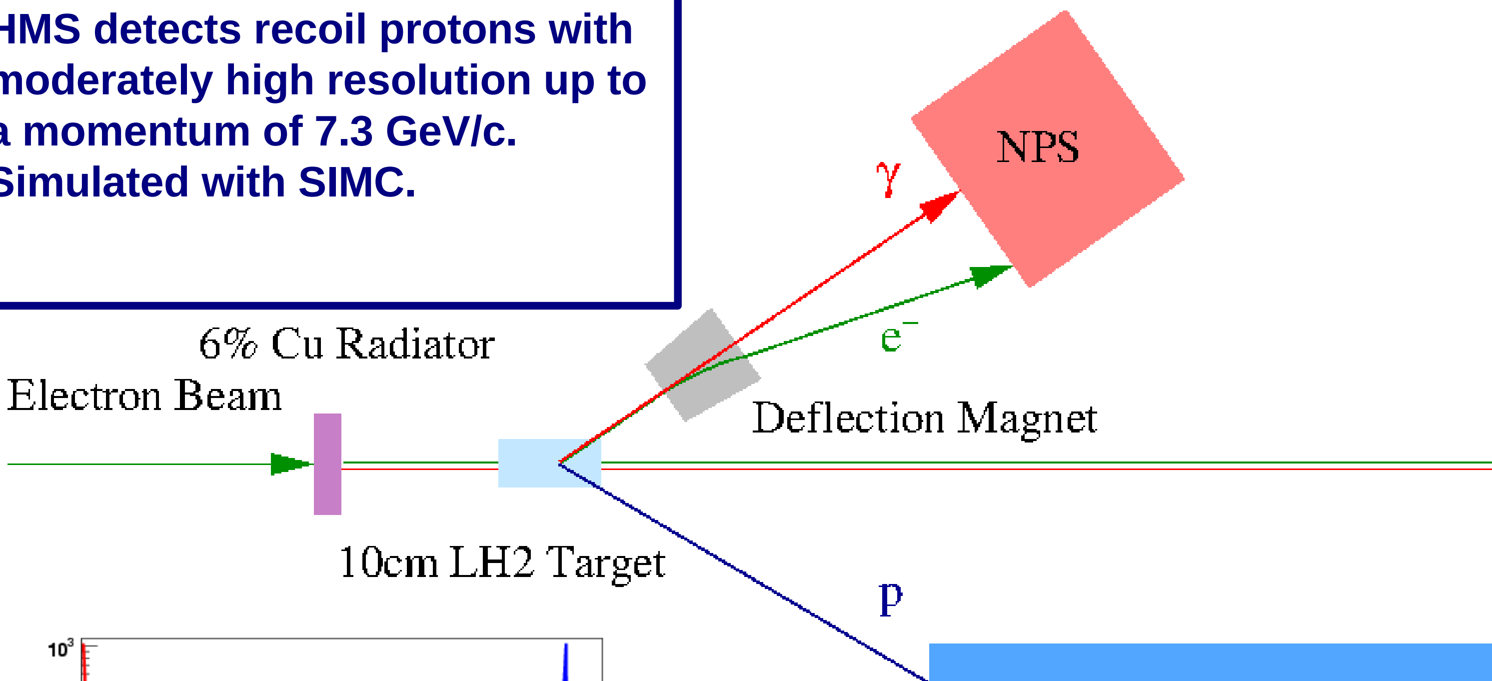
Experimental Technique

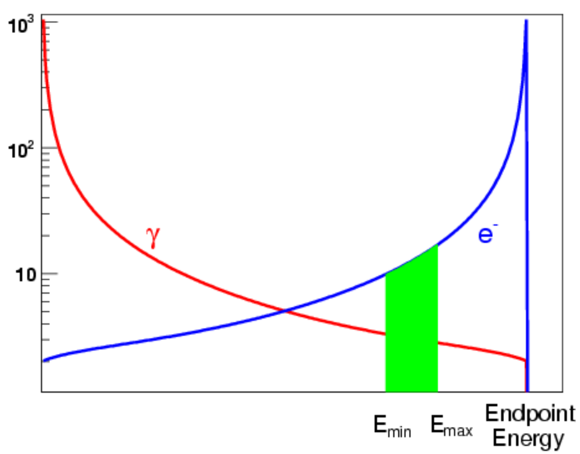
A 6% Copper radiator is used to produce a mixed electron/photon beam incident on a 10 cm LH_2 target.
Simulated with Geant4.

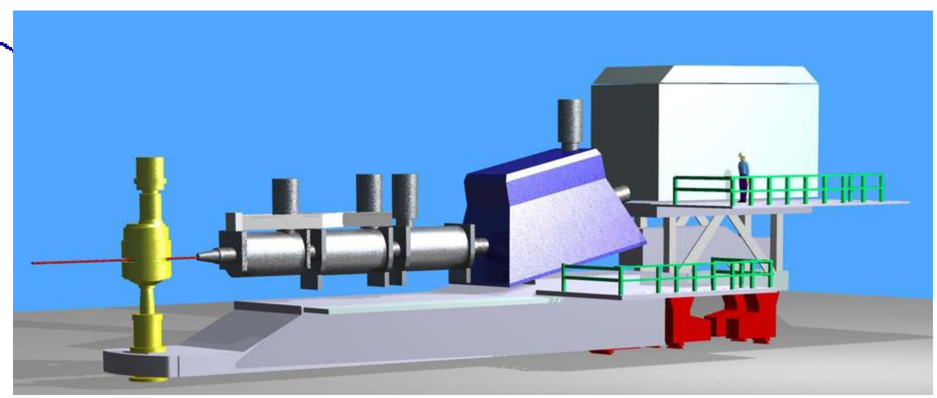


Experimental Technique

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

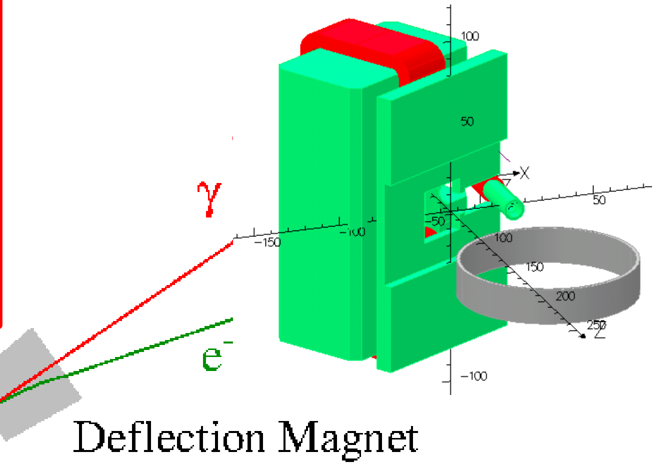


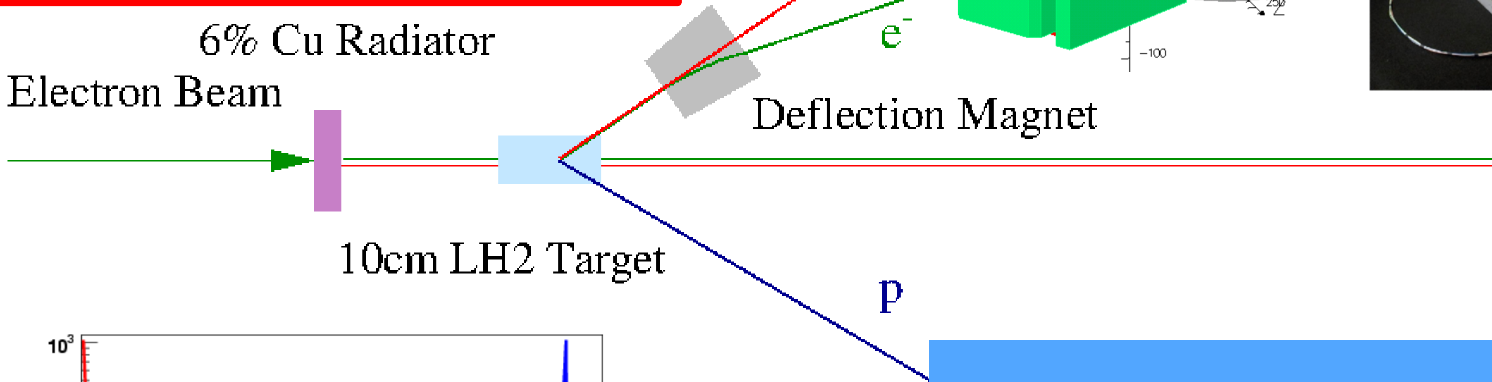


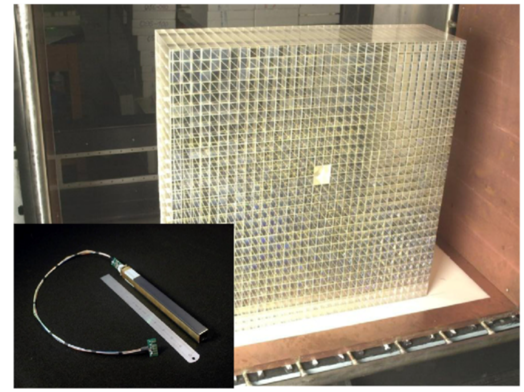


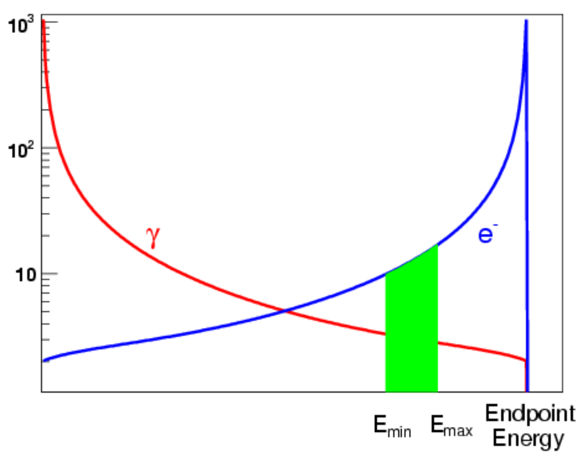
Experimental Technique

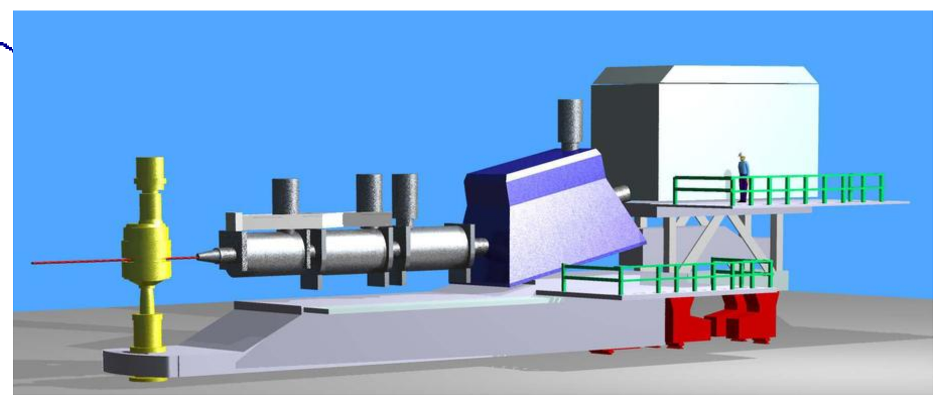
New vertical deflection magnet and 1116 element $PbWO_4$ calorimeter to detect scattered photons.
Simulated with Geant4.











Kinematic Settings

- We propose to make measurements at 13 kinematic settings:
  7 points with 4-pass beam (8.8 GeV).
  6 points with 5-pass beam (11 GeV).

- The corresponding range of incident photon energies used in the beamtime estimate was:
  7.5 – 8.5 GeV for 4-pass settings.
  9.3 – 10.7 GeV for 5-pass settings.

	E_{in} (GeV)	Θ_γ (deg)	E_γ (GeV)	Θ_p (deg)	P_p (GeV/c)
4A	8	11	6.92	47.5	1.79
4B	8	15	6.20	38.6	2.57
4C	8	19	5.46	32.1	3.35
4D	8	28	4.00	22.8	4.84
4E	8	33	3.37	19.5	5.49
4F	8	40	2.67	16.1	6.20
4G	8	48	2.09	13.3	6.78
5A	10	10	8.61	44.4	2.14
5B	10	14	7.60	34.9	3.21
5C	10	18	6.57	28.4	4.26
5D	10	24	5.21	22.0	5.66
5E	10	30	4.12	17.8	6.75
5F	10	36	3.30	14.8	7.59

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- **Kinematic Setting 5F re-calculated for a proton momentum of 7.3 GeV/c in response to TAC comments.**

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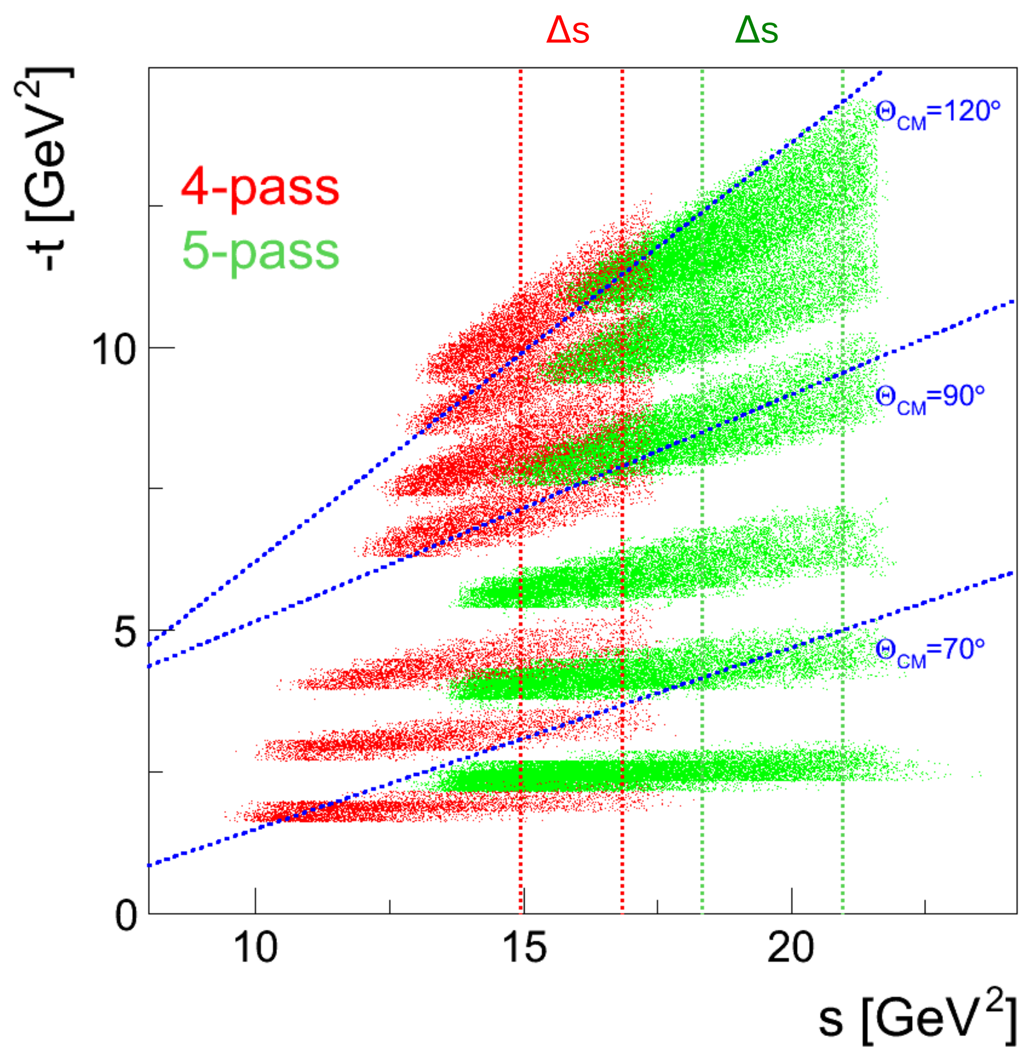
- Range of kinematic coverage:
  15 .0 < s < 21.0 GeV^2
  2.03 < -t < 12.05 GeV^2
  3.05 < -u < 15.30 GeV^2



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:

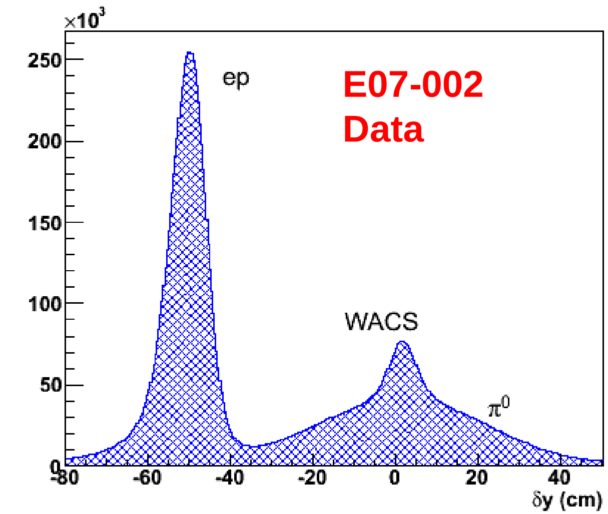
- $\gamma p \rightarrow \gamma p$
- $ep \rightarrow ep$ (and $ep \rightarrow ep\gamma$)
- $\gamma p \rightarrow \pi^0 p \rightarrow \gamma\gamma p$

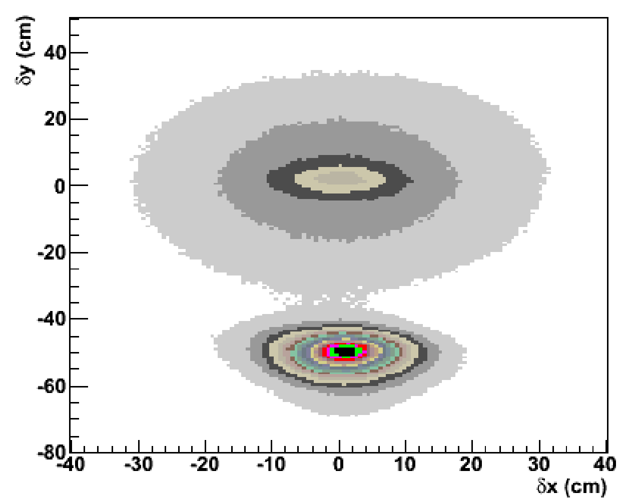
A deflection magnet is used to cleanly separate the elastic ep scattering and the WACS events.

There is however still significant background under the WACS peak from π0 and epγ events. Simulations have shown that these background dilutions have the following range:

$$N_{WACS}/N_{\pi 0} = 0.34 - 27.3$$
$$N_{WACS}/N_{ep\gamma} = 0.11 - 2.50$$

These background ratios have been obtained with a relatively simple analysis technique. It is anticipated that these ratios can be made more favourable.

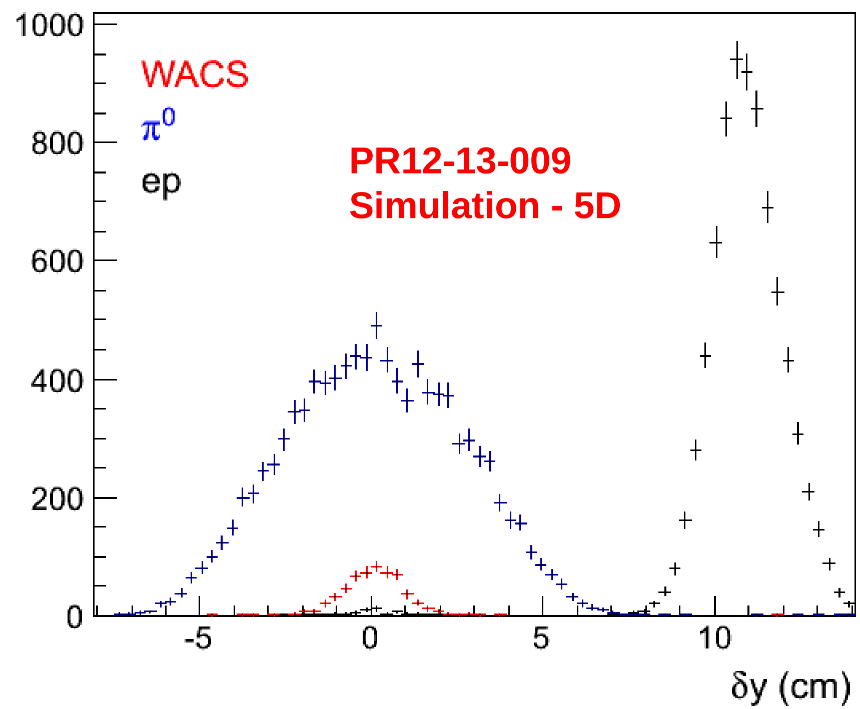




Projected Resolution and Deflection Magnet

	Resolution
NPS position (cm)	0.3
HMS (+LH_2) in-plane angle (mrad)	1.5 – 2.5
HMS (+LH_2) out-of-plane angle (mrad)	1.7 – 3.8
HMS (+LH_2) momentum (dp/p x 10^{-4})	5 – 7.5
Combined δx hit position (cm)	1.15 – 5.85
Combined δy hit position (cm)	0.81 – 1.11

WACS yield extraction from background events depends critically on the resolution of the **combined hit difference distributions**, which is dominated by HMS resolution.



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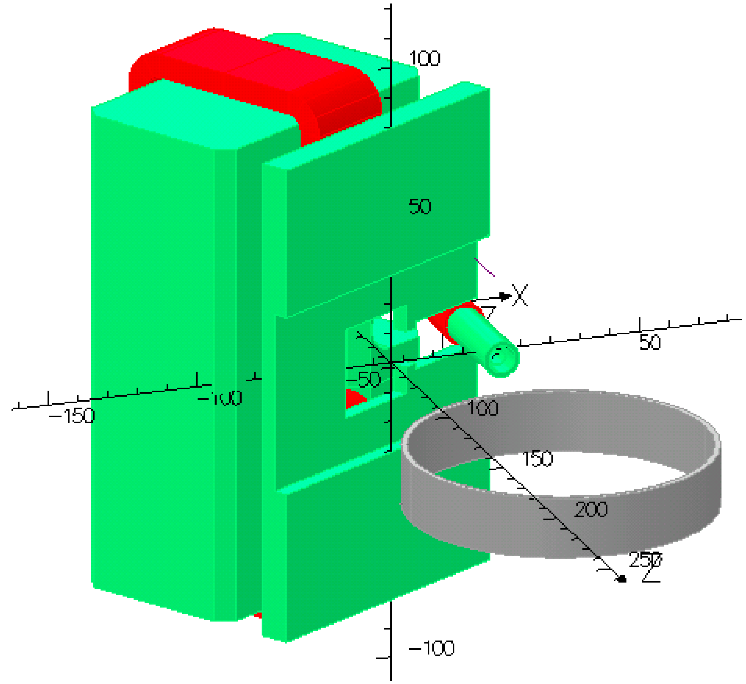
WACS yield extraction from background events depends critically on the resolution of the **combined hit difference distributions**, which is dominated by HMS resolution.

Due to poor in-plane resolution, clean separation between the WACS and elastic ep events can only be achieved with a **deflection magnet with a vertical bend**.

A suitable magnet has been designed which will be **located between 1.1 and 2.6 m** from the target and have a **field integral of up 0.6 Tm**.



Vertical deflection of electrons vary over the kinematic settings between **7.2 – 9.5 cm**.

Stray fields on the downstream beamline require **shielding and post-target correctors** to reduce the field integral to a negligible level

Projected Uncertainties

Three main sources of systematic uncertainty:

- incident flux → Charge, Target thickness, Photon flux

- detector acceptances / efficiencies → NPS detection efficiency, HMS Acceptance, HMS tracking efficiency

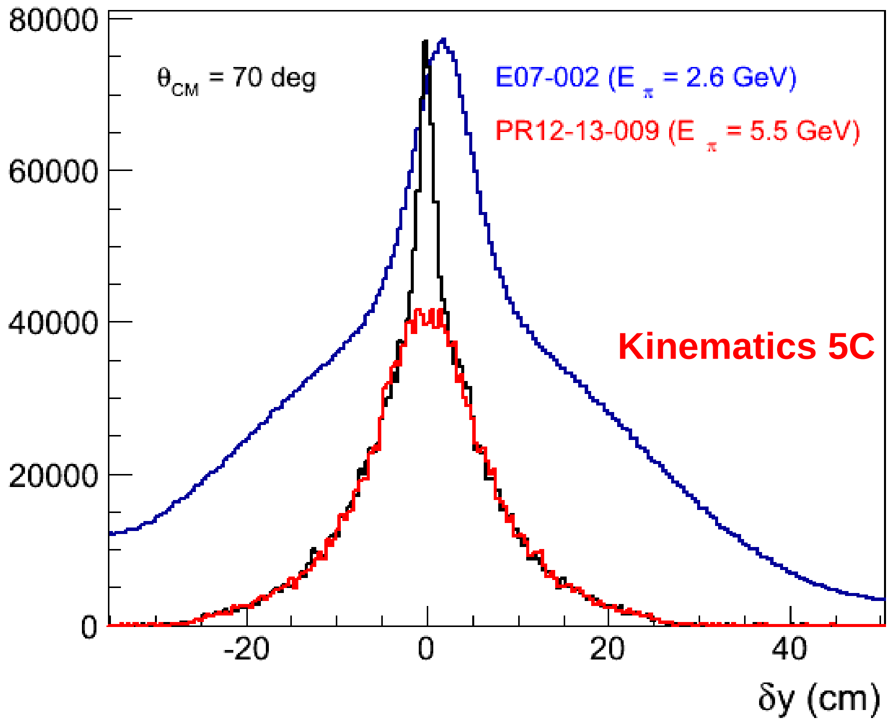
- yield extraction → epγ background, π^0 background

	Uncertainty (%)
Charge	1.0
Target thickness	1.0
Photon flux	3.0
NPS detection efficiency	< 1.5
HMS Acceptance	< 1.5
HMS tracking efficiency	< 1.5
epγ background	2.5
π^0 background	5.0
Total	**7.0**

Projected Uncertainties

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

This is the reason for the proposed 2% statistical uncertainty on the WACS yield – **otherwise yield extraction systematic uncertainty becomes prohibitively large**.



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HMS Acceptance	< 1.5
HMS tracking efficiency	< 1.5
epy background	2.5
π^0 background	**5.0**
Total	**7.0**

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

Expected Rates

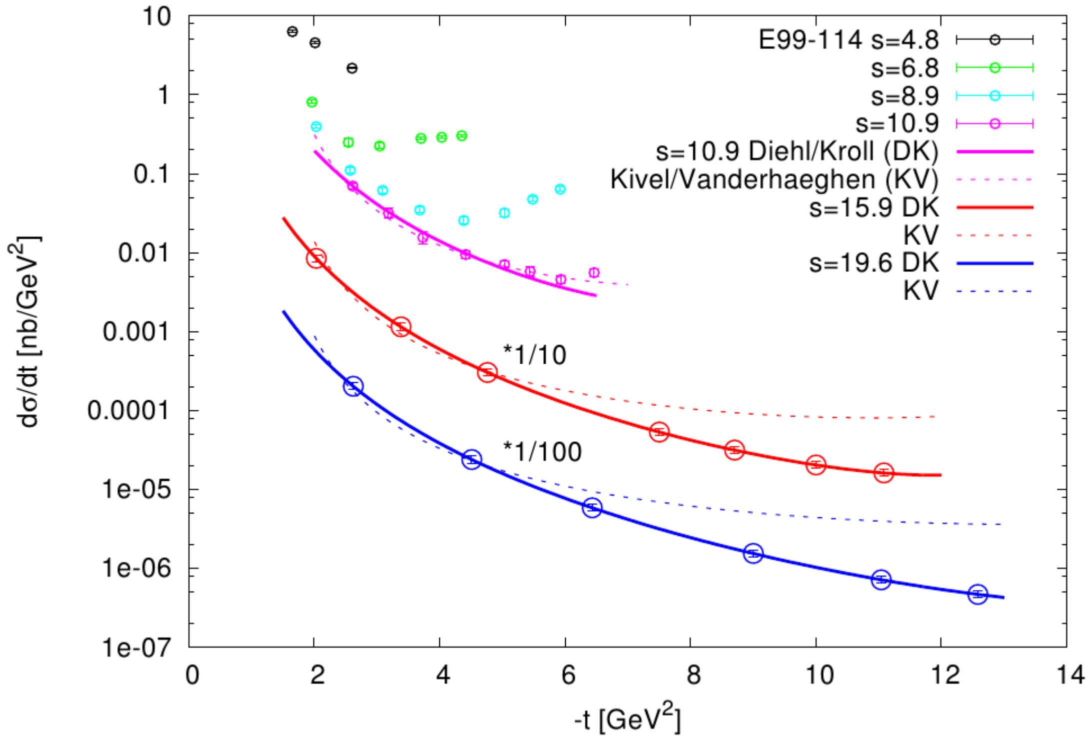
- Rates and radiation levels have been calculated based on experience with E99-114, E07-002 and both physics and DINREG Monte Carlo simulations.
- For each HMS trigger, every NPS cluster (5x5) with a crystal threshold greater than **25 % of the expected Compton scattered energy** will be read out (16 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

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

	4A	4B	4C	4D	4E	4F	4G	5A	5B	5C	5D	5E	5F
NPS Singles (MHz)	0.9	1.2	2.2	4.3	4.8	5.2	3.9	1.2	1.8	2.4	4.3	6.2	12.5
HMS Singles (kHz)	1.00	0.30	0.18	0.15	0.15	0.15	0.08	1.75	0.13	0.08	0.06	0.06	0.03
WACS Rate (h^{-1})	340	150	160	100	70	45	25	225	110	60	40	25	17

Expected Results: Differential Cross Section



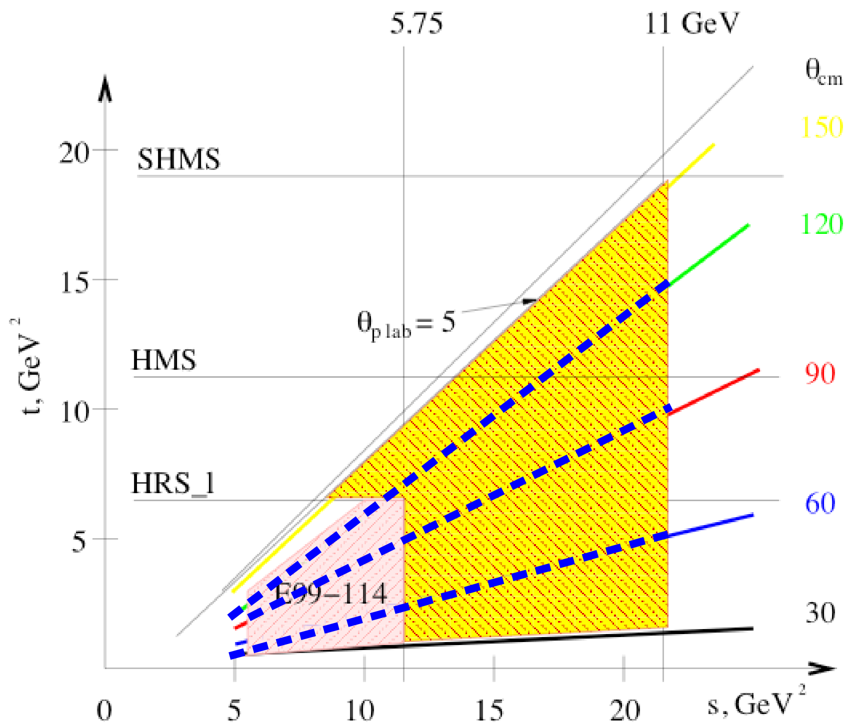
All kinematic settings unambiguously meet the wide-angle condition that **s, -t, -u >> $m^2_{nucleon}$**

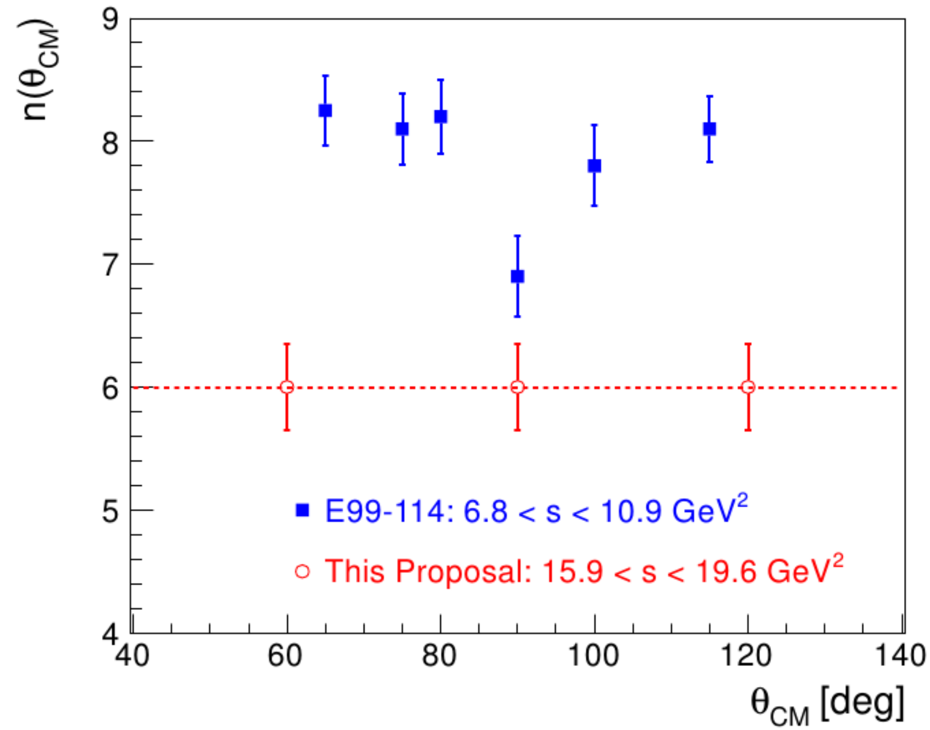
We propose to measure the differential cross section for WACS at photon energies of 8 and 10 GeV over a wide range -t.

Beamtime Request = 42 days*

* includes time for configuration changes, calibration runs and DAQ/analysis overheads

Expected Results: Scaling Power n at Fixed θ_{CM}





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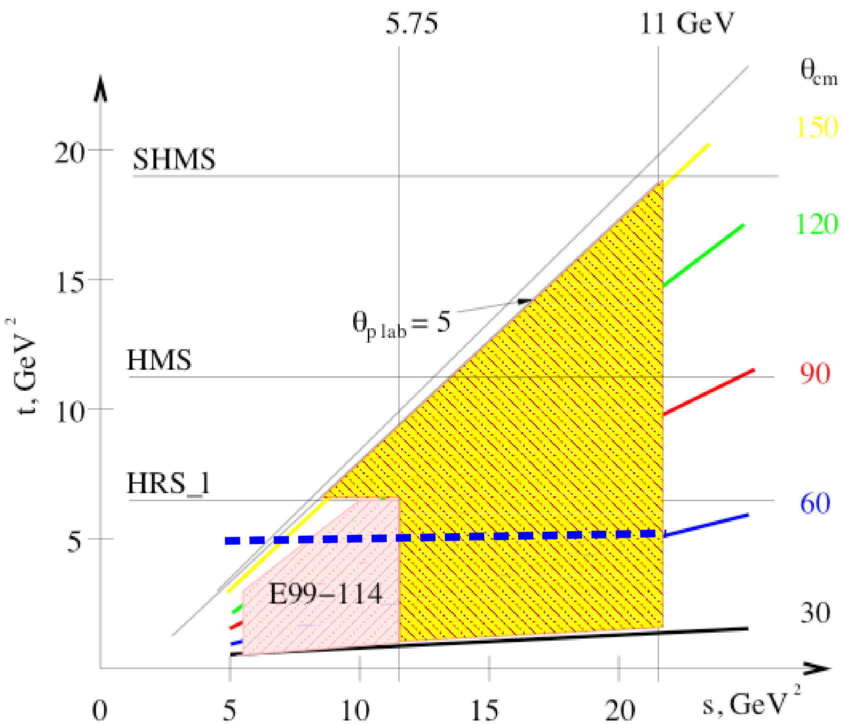
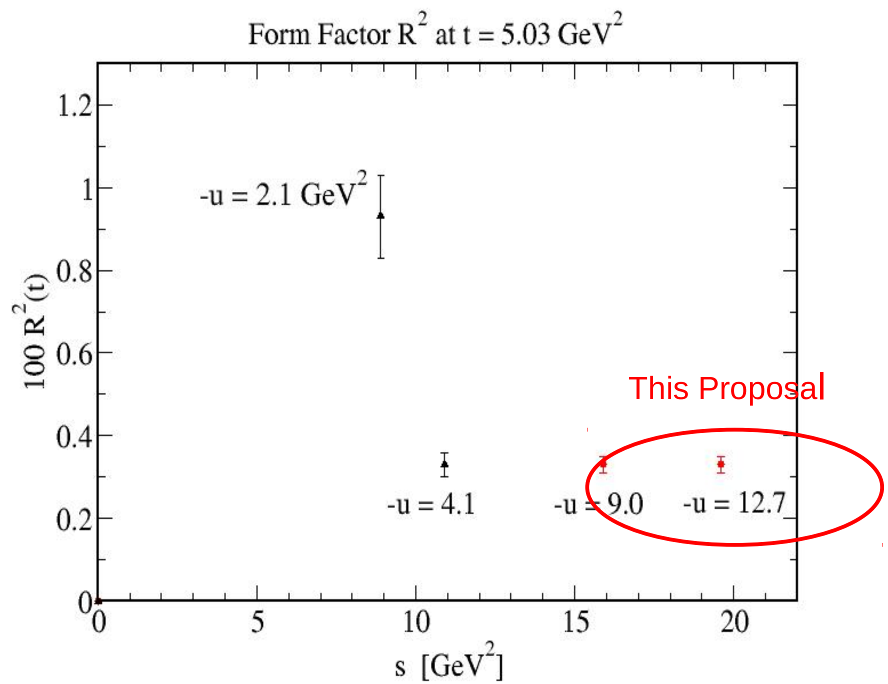
Expected Results: s-independence of SCET Form Factor





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Summary and Beamtime Request

The Jlab 12 GeV upgrade has renewed experimental and theoretical interest (SCET, GPDs, DSE) in Wide-angle Compton Scattering.

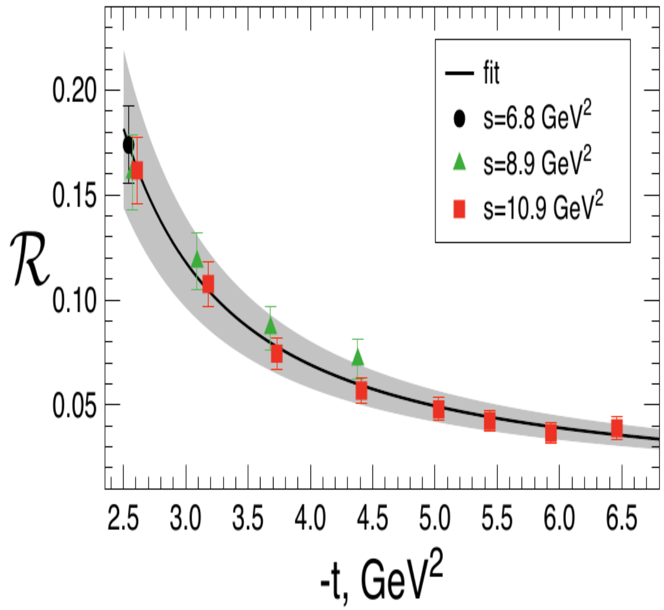
PR12-13-009 proposes measurements of the differential cross section for WACS over a large range of s and -t using the HMS and NPS in Hall C.

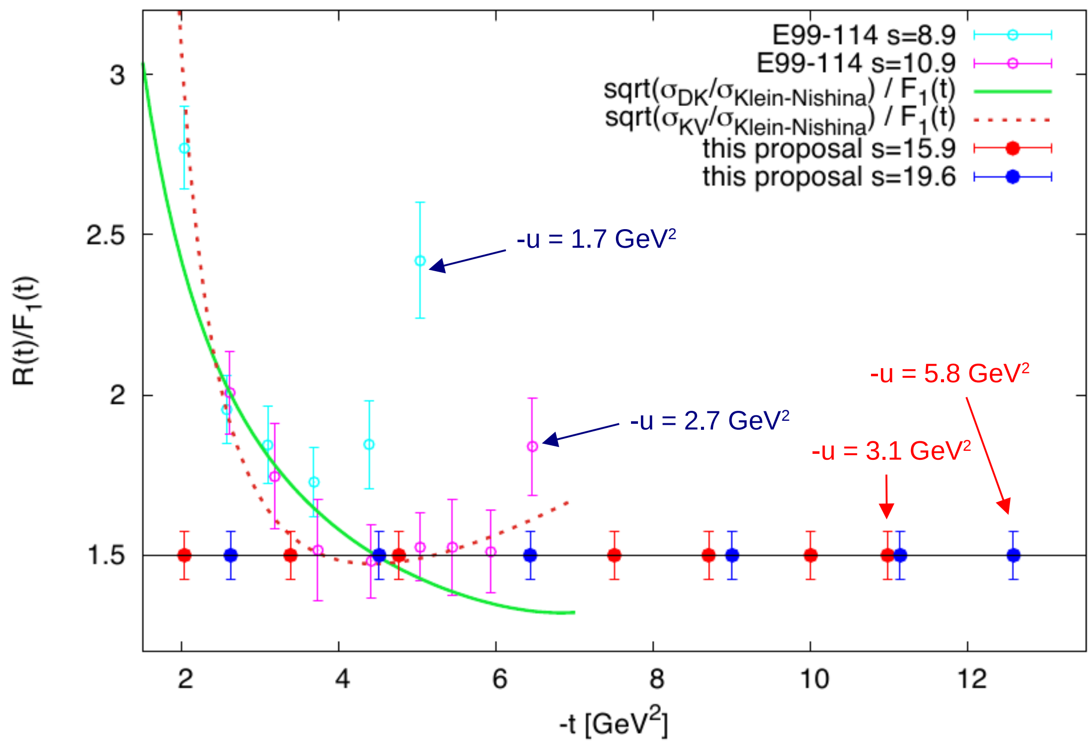
The experimental and analysis techniques are tried and tested, the detector systems will be operating well within their capabilities and radiation levels on the NPS and in the hall are manageable.

These measurements will allow for a rigorous test of factorization, establish the scaling behavior of the cross section at fixed CM angle and provide crucial insights in to proton structure at high -t through mapping the WACS form factors.

	4A	4B	4C	4D	4E	4F	4G	5A	5B	5C	5D	5E	5F
Set-up (beam & detectors)	14	-	-	-	-	-	-	10	-	-	-	-	-
Spectrometer move	-	2	2	2	2	2	2	-	2	2	2	2	2
HMS sieve slit	-	-	-	-	-	-	-	-	-	-	-	-	12
Optics target	1	1	1	1	1	1	1	1	1	1	1	1	1
No radiator	4	4	4	4	8	12	12	4	4	6	8	12	12
Production	8	18	18	27	40	60	110	12	18	42	64	110	150
Total beam-on-target	13	23	23	32	49	73	123	17	23	49	73	123	163
Adjusted beam-on-target	16	28	28	38	58	88	148	20	28	58	88	148	196
Total (hours)	**30**	**30**	**30**	**40**	**60**	**90**	**150**	**30**	**30**	**60**	**90**	**150**	**210**

Back-up: Expected Results





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