University of Glasgow

ECT* Workshop on Probing Transverse Nucleon Structure at High Momentum Transfer

19th April 2016

Wide-angle Compton Scattering at 8 and 10 GeV in JLab Hall C

David Hamilton

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- The Jefferson Lab WACS program at 6 GeV
- Theoretical Context and Motivation for 12 GeV
  - Soft collinear effective theory
  - The handbag mechanism and GPDs
  - Dyson-Schwinger equations
- Experimental Technique
- The Hall C Neutral Particle Spectrometer
- Analysis Technique
- Background, resolution and uncertainties

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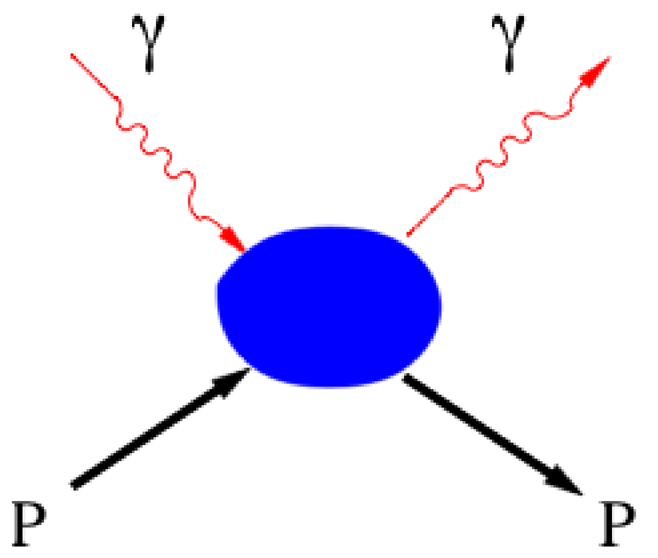
Why?

How?

WACS: An Introduction

- Proton Compton scattering in the wide-angle regime (s, -t, -u >> M^2) is a powerful and under-utilized probe of nucleon structure.
- It allows us to characterize the electromagnetic response of the nucleon without complications from additional hadrons.
- As such, it is complementary nucleon structure approach to elastic ep scattering and DVCS.
- It is, however, one of the least understood of the fundamental reactions in the several GeV regime.



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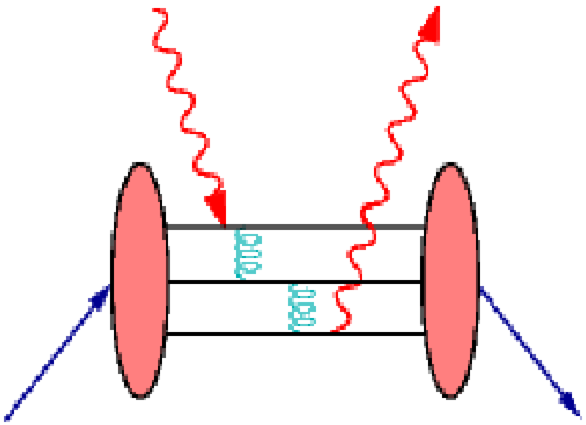
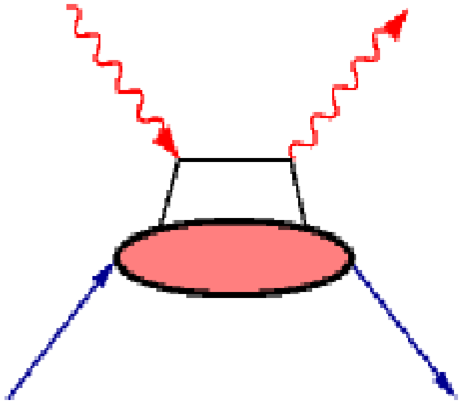
Theoretical Approaches

- A number of reaction mechanisms have been proposed over the years:
    - pQCD (two-gluon exchange)
    - Relativistic constituent quark
    - Dyson-Schwinger equation
    - Handbag Mechanism (GPD's)
    - Soft collinear effective theory
- The two main open questions are:
    - How does the reaction mechanism factorize?
    - What new insights on the non-perturbative structure of the proton are accessible?





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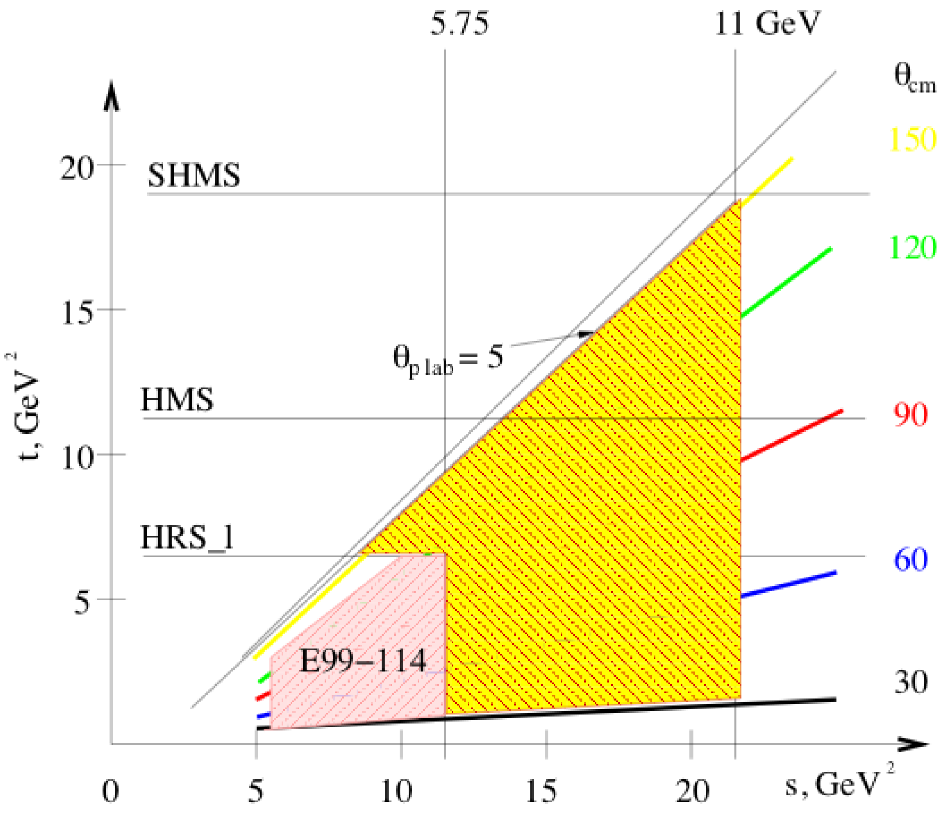
The 6 GeV Program

- Jlab Experiment E99-114 (Hall A, 2002)
  - Measurement of differential cross section over a broad kinematic range and of polarization transfer observables for one kinematic setting.
- Jlab Experiment E07-002 (Hall C, 2008)
  - Extension of the measurements of polarization transfer observables for an additional kinematic point.



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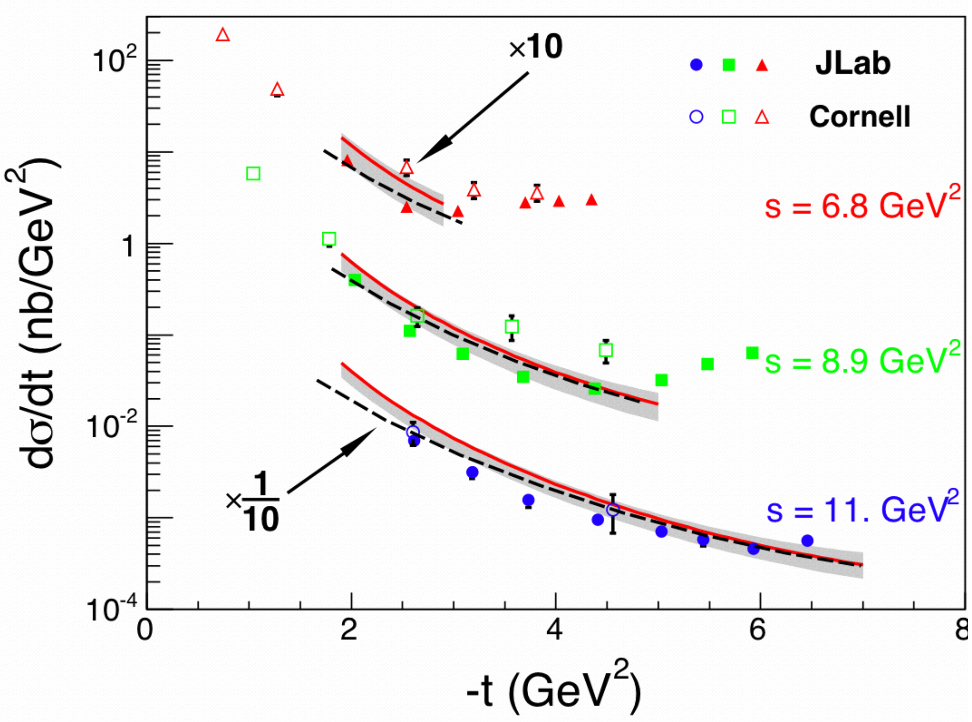
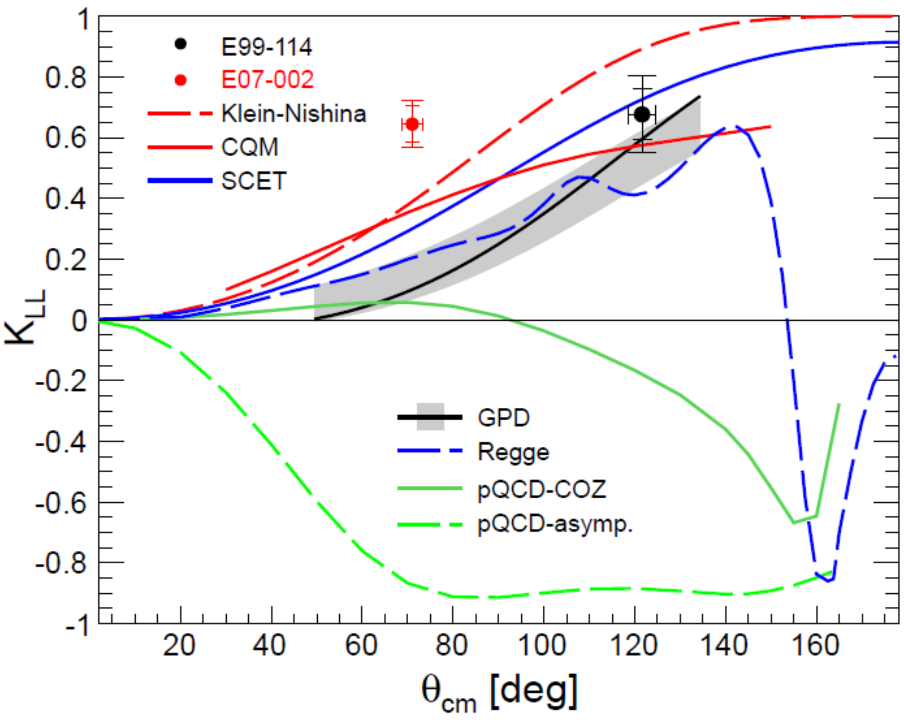
6 GeV Highlights



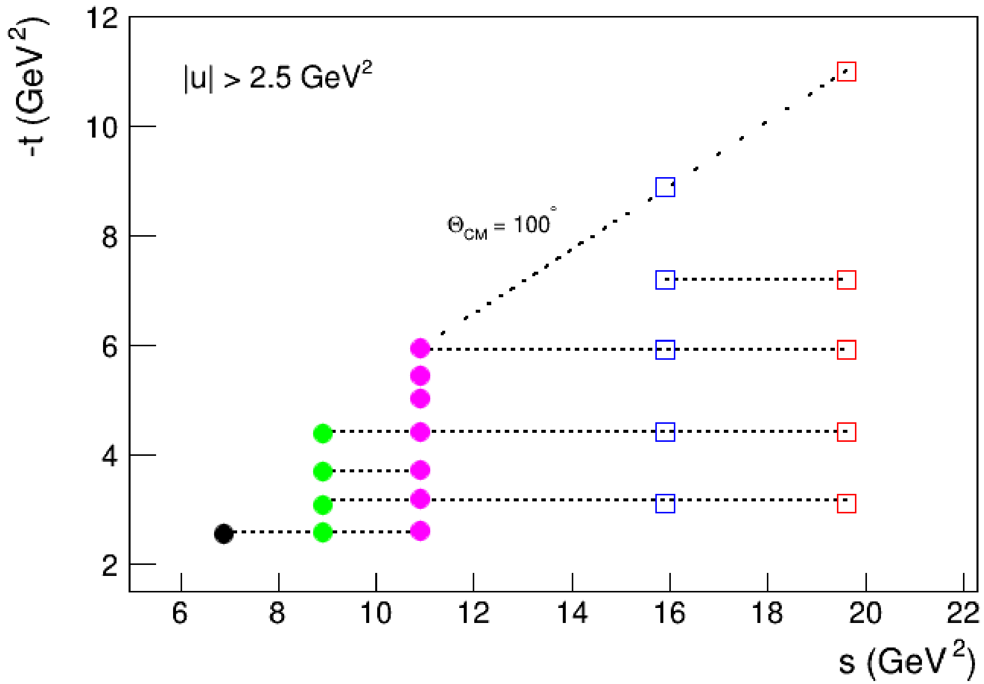
PRL 98, 152001 (2007)



PRL 94, 242001 (2005)
PRL115, 152001 (2015)

12 GeV Kinematics

- We propose to measure the differential cross section for WACS at photon energies of 8 and 10 GeV at ten carefully chosen kinematic points.



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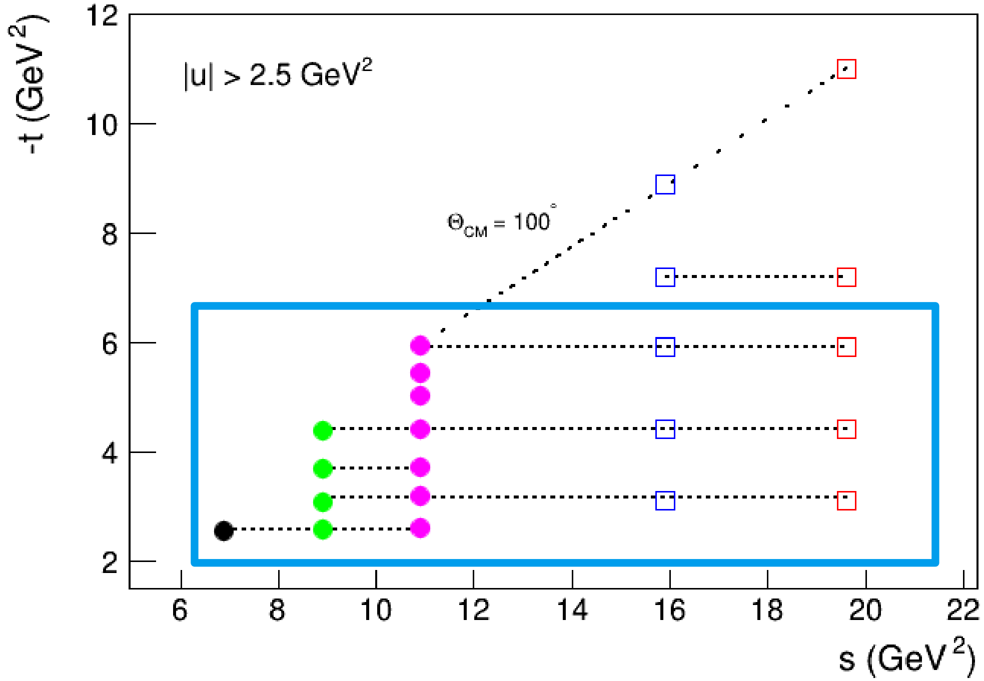
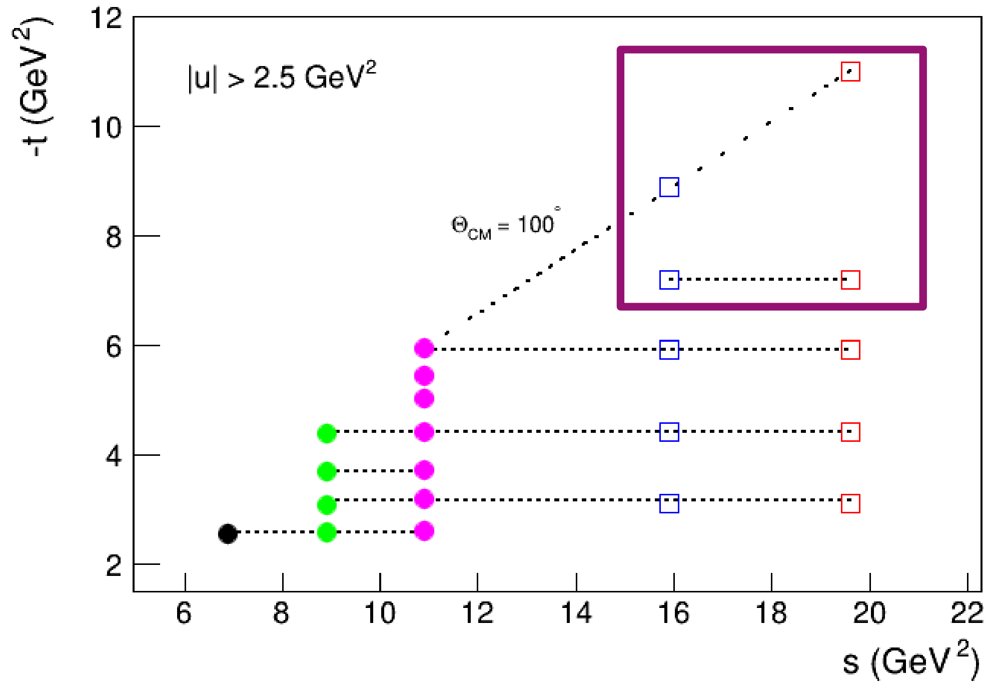
- Factorization study combining 6 GeV data.



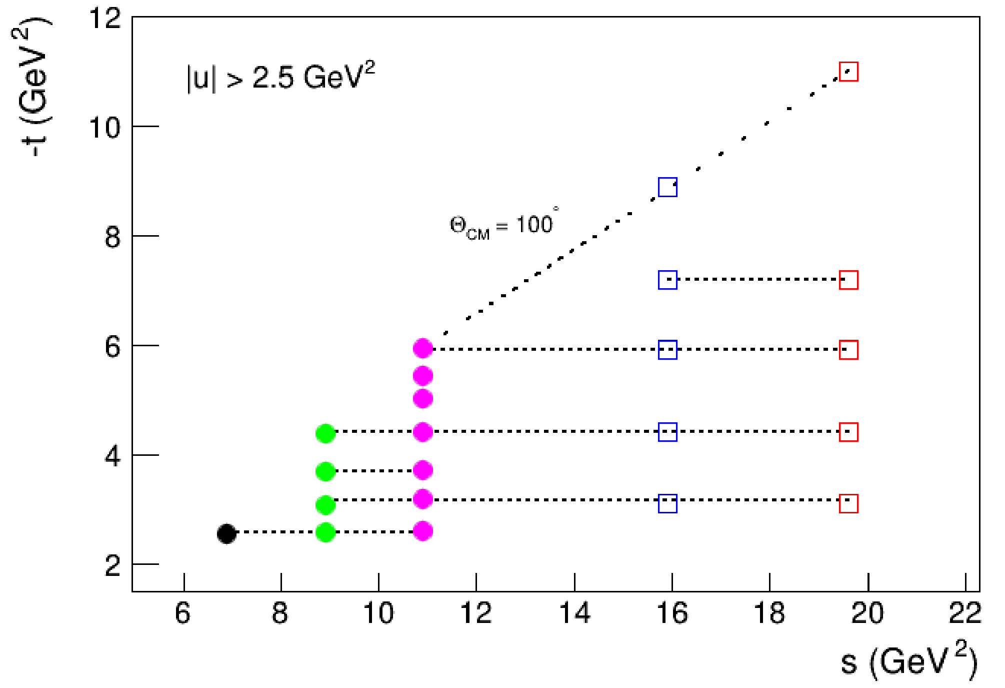
12 GeV Kinematics

- We propose to measure the differential cross section for WACS at photon energies of 8 and 10 GeV at ten carefully chosen kinematic points.
- Factorization study combining 6 GeV data.
- Extend range in momentum transfer to 11 GeV^2.



12 GeV Kinematics

	Θ_{CM} (deg)	s (GeV^2)	-t (GeV^2)	-u (GeV^2)
4A	55.8	15.89	3.10	11.03
4B	67.6	15.89	4.39	9.75
4C	80.4	15.89	5.91	8.22
4D	90.9	15.89	7.20	6.93
4E	104.8	15.89	8.90	5.23
5A	48.9	19.65	3.07	14.81
5B	59.5	19.65	4.41	13.47
5C	70.1	19.65	5.91	11.97
5D	78.7	19.64	7.21	10.68
5E	103.2	19.65	11.01	6.88



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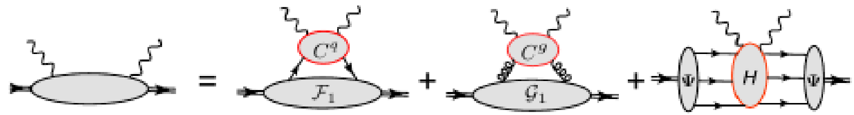
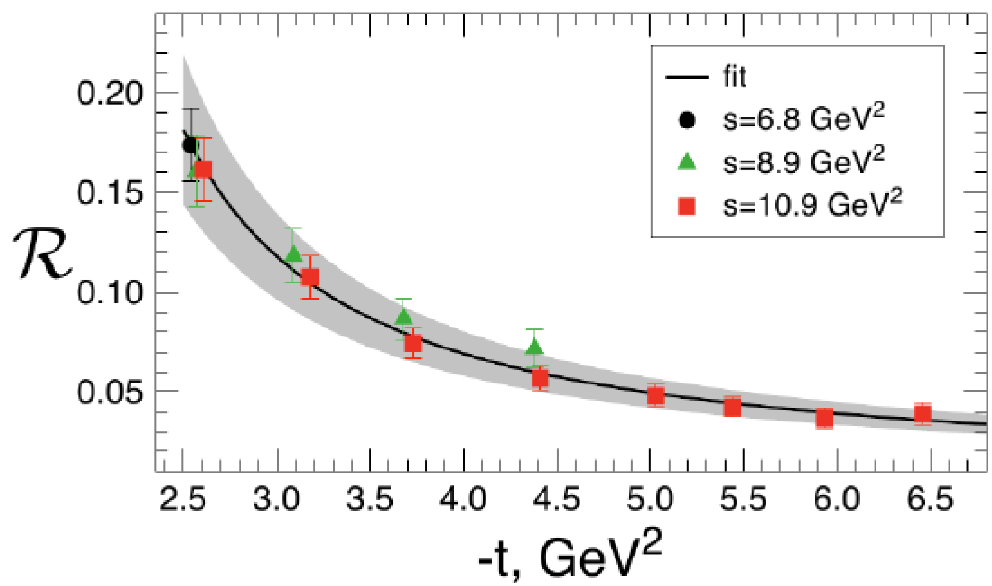
Soft Collinear Effective Theory

- The SCET approach 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, the t-dependence of which is extracted from WACS cross section data.
- This form factor describes the soft-overlap contribution in a variety of hard exclusive reactions, such as time-like Compton scattering.

JHEP 04, 029 (2013) & arxiv:13125456



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



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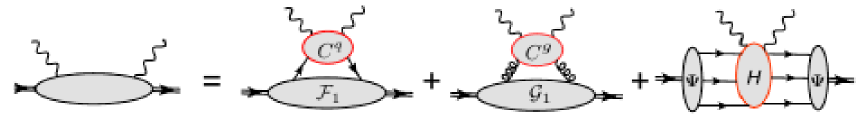
Soft Collinear Effective Theory

- To test the s-dependence of the SCET form factor over a broad kinematic range and firmly establish factorization.
- To extract the t-dependence of the form factor, which cannot be predicted from theory, up to -t = 11 GeV^2. This directly impacts interpretation of 12 GeV elastic form factor data.
- To explore the relationship between the space-like and time-like form factors to high -t, where data from BELLE is expected. This helps to assess the relative dominance of soft overlap contributions.

JHEP 04, 029 (2013) & arxiv:13125456



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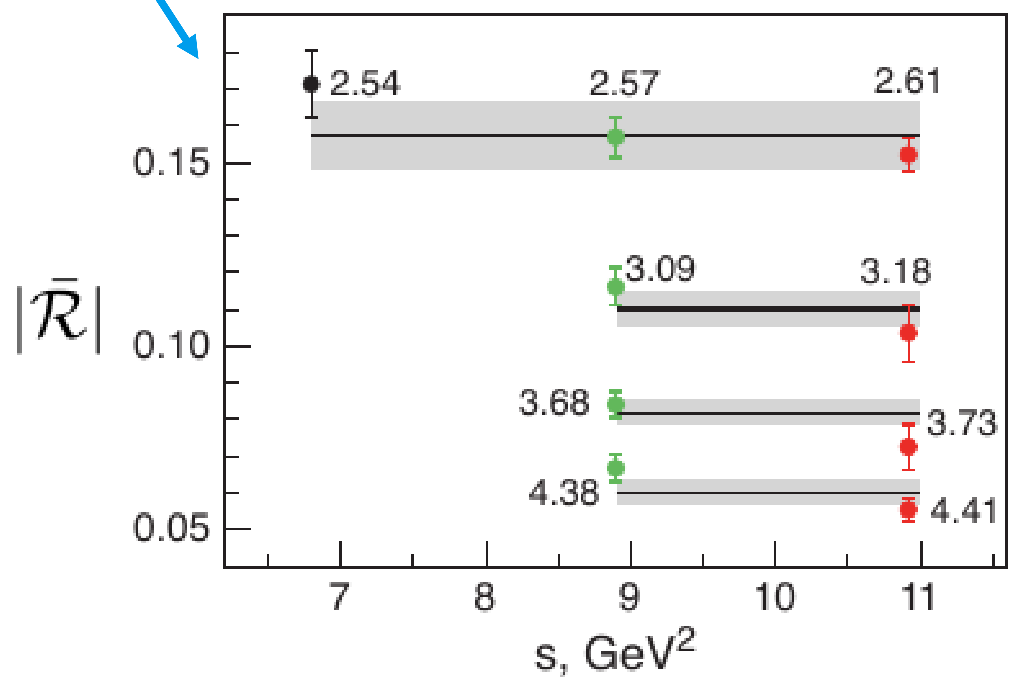

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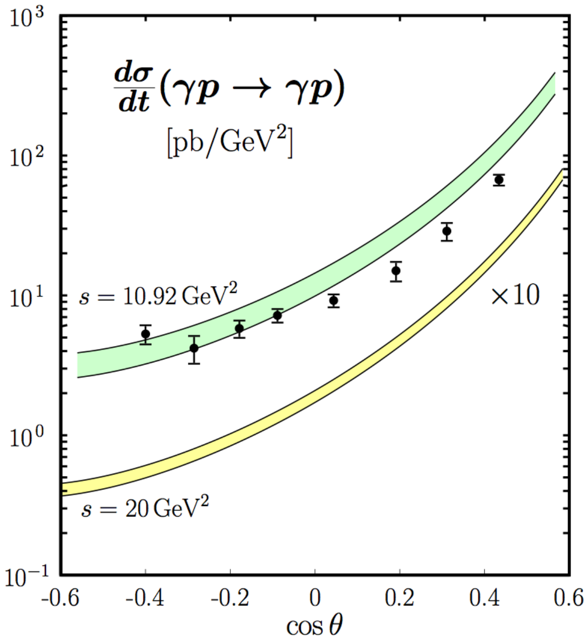
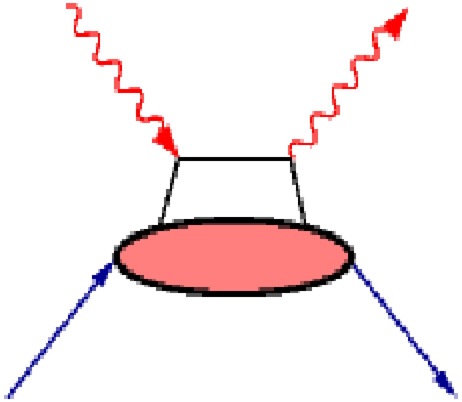
GPD Approach

Eur Phys C 73, 2397 (2013)





- The handbag mechanism within a GPD-based framework is firmly established in analysis of DVCS data.
- Its application to WACS by Kroll, Diehl and others has a long and successful history. A new analysis for 12 GeV WACS has recently been undertaken.
- In this approach, WACS gives access to form factors that are moments of the underlying GPDs.
- These form factors differ from their elastic counterparts as their dependence on quark flavour and momentum fraction (x) is different.
- A comparison between the two with the proposed data will therefore allow access to the momentum fractions that dominate the respective form factors.

GPD Approach

M. Diehl and P. Kroll, arxiv 1302.4604

$$\gamma p \rightarrow \gamma p$$

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

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

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

$$ep \rightarrow ep$$

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

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

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

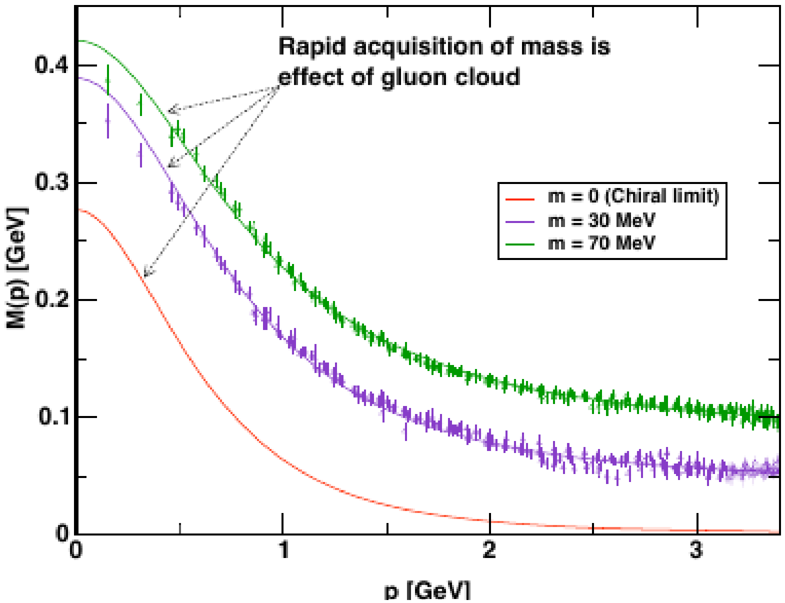
$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}_{KN} \left\{ \frac{1}{2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 + R_A^2 \right] - \frac{us}{s^2+u^2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 - R_A^2 \right] \right\}$$

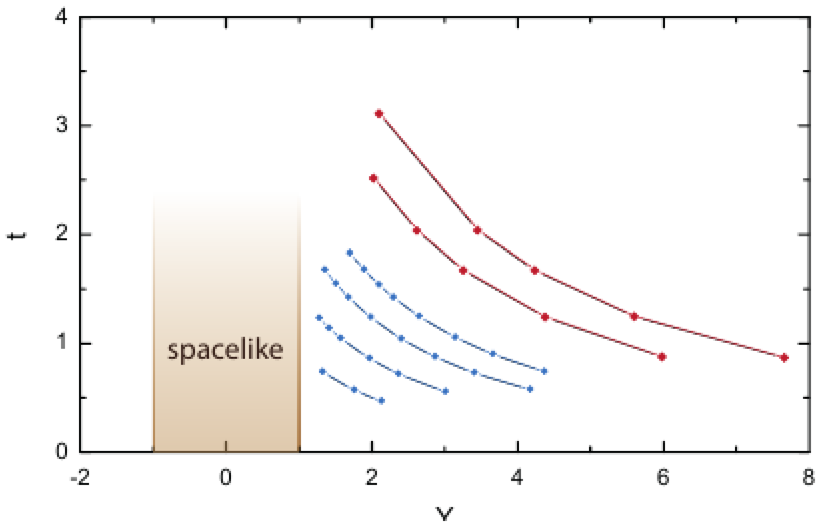
Studying WACS can lead to constraints on GPDs at large -t and x, which differ from electromagnetic form factors due to 1/x and e_a^2 factors.

DSE Approach

PRD 87, 036006 (2013)

- A very recent development has seen the groundwork laid for WACS phenomenology in the DSE approach.
- This framework has already seen success in interpretation of elastic form factor data by assuming the dominance of a di-quark coupling in the nucleon wavefunction.
- The proposed data points, particularly those at moderate -t, will allow theorists to test the evolution of the amplitude as one moves from the dominant t-channel poles.





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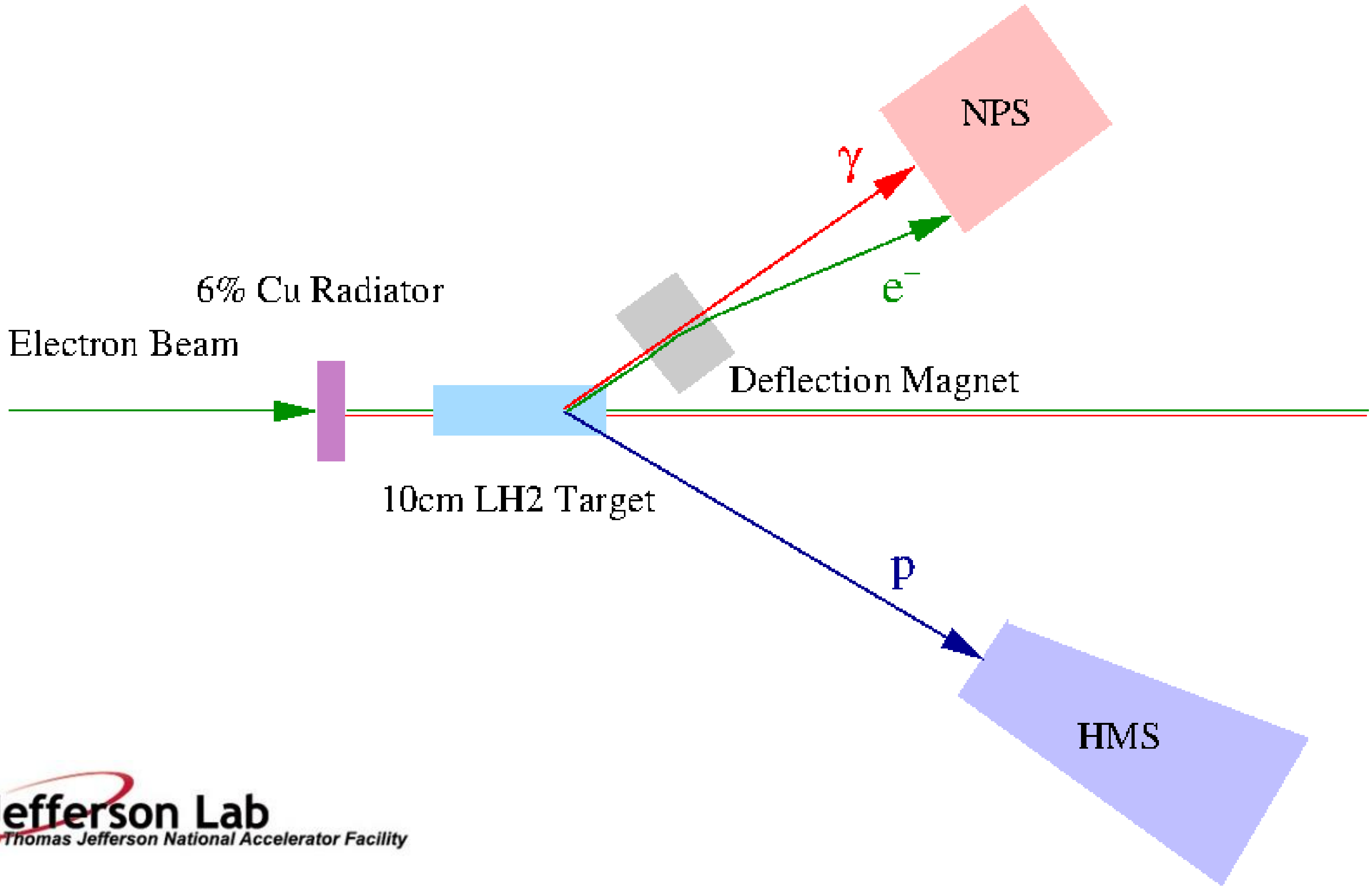
Experimental Technique



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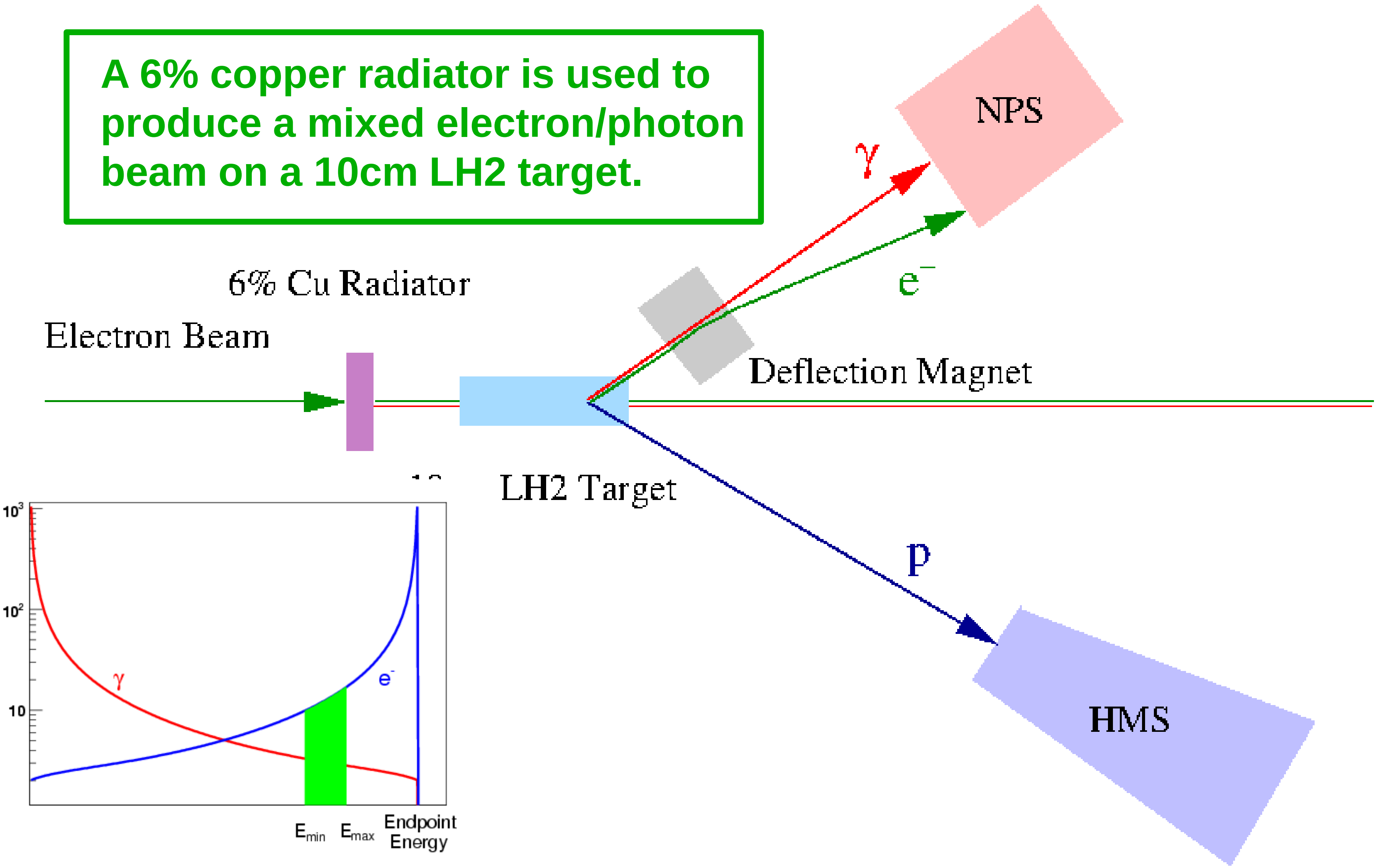
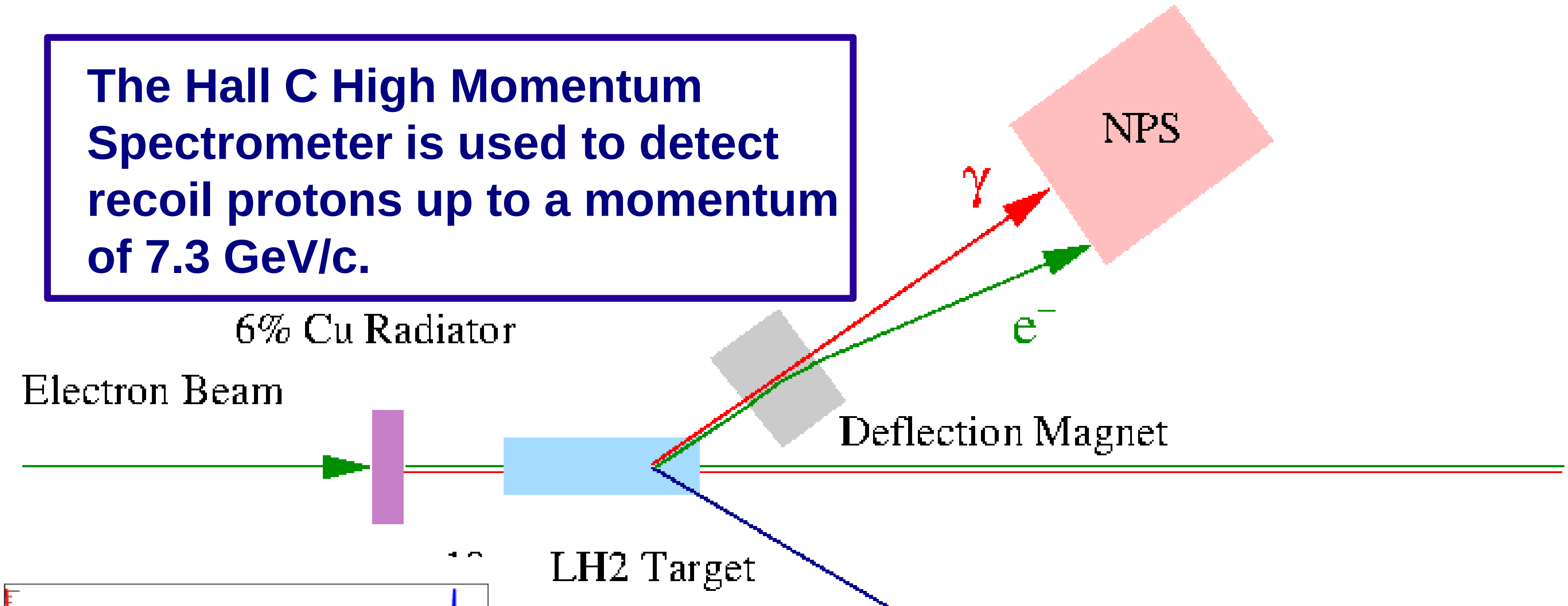
Experimental Technique

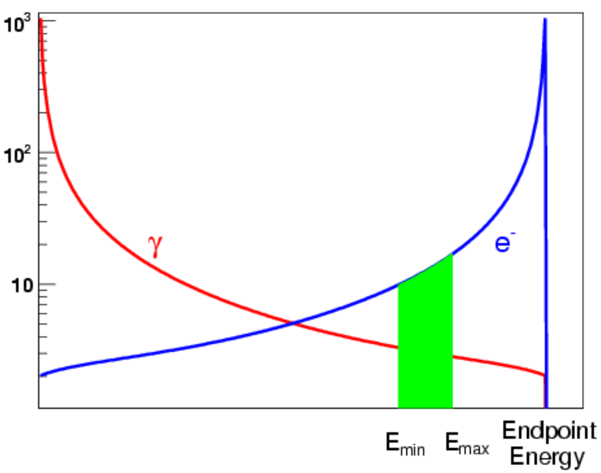
A 6% copper radiator is used to produce a mixed electron/photon beam on a 10cm LH2 target.

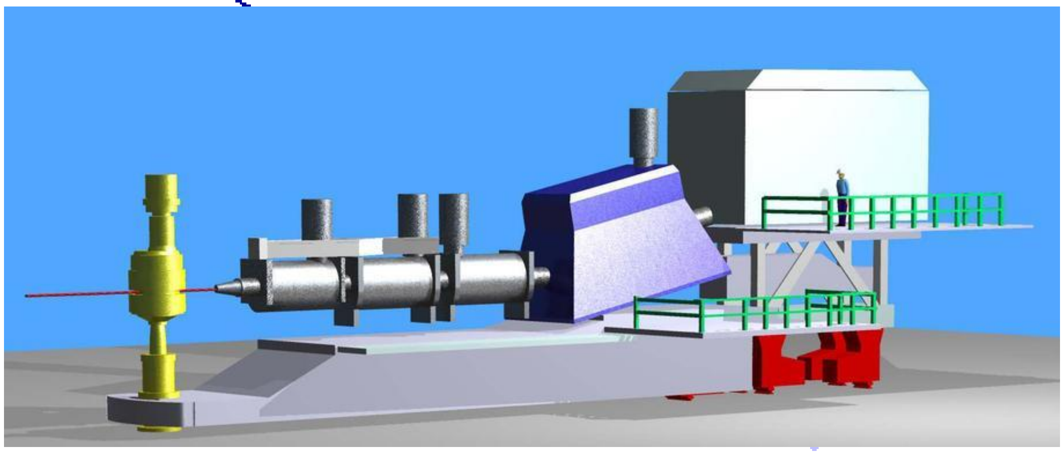


Experimental Technique

The Hall C High Momentum Spectrometer is used to detect recoil protons up to a momentum of 7.3 GeV/c.

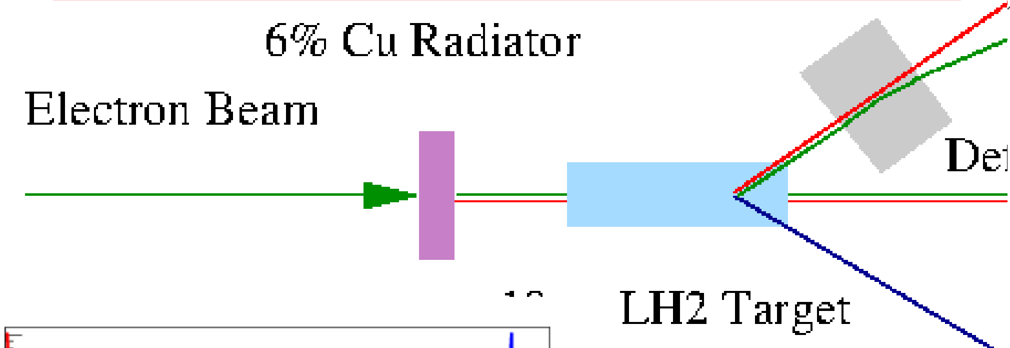


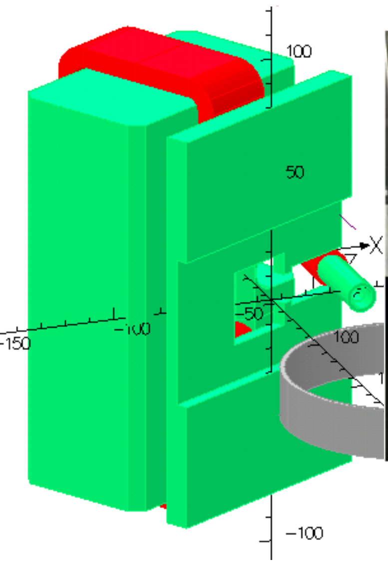


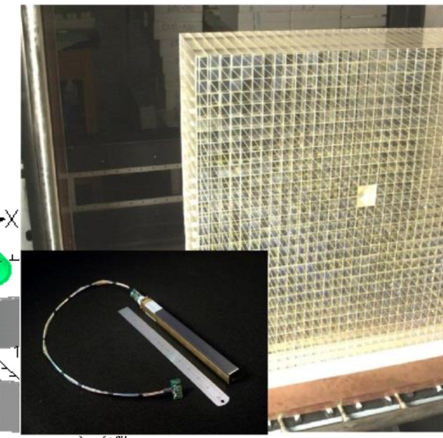


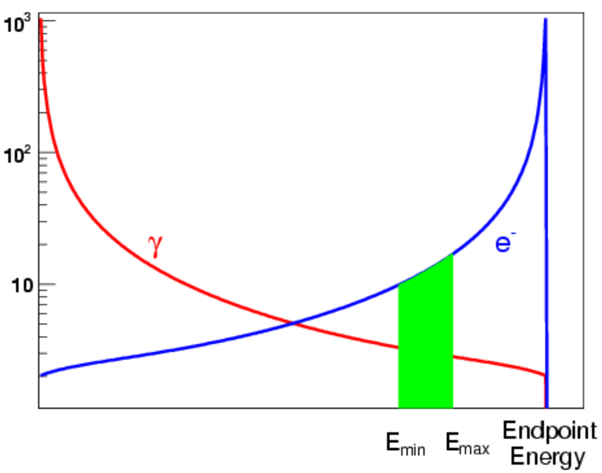
Experimental Technique

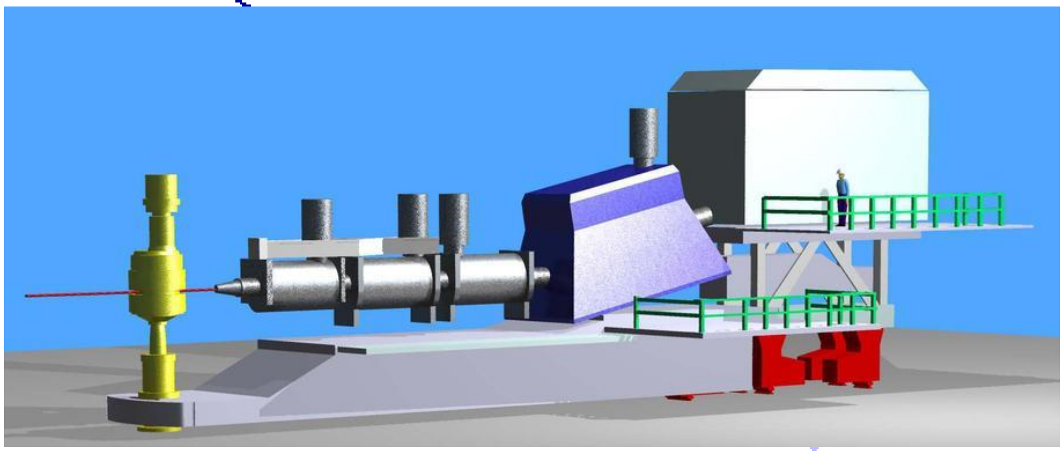
A new vertical deflection magnet and 1116 element PbWO4 calorimeter to detect scattered photons and electrons.







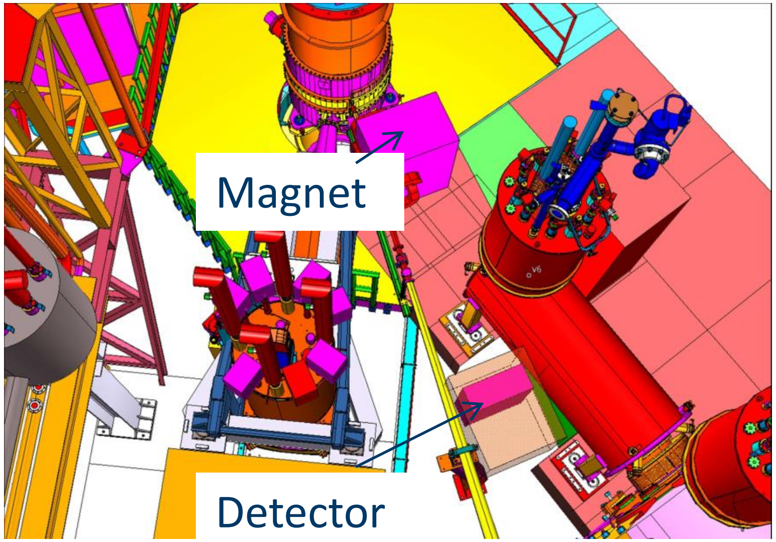




NPS

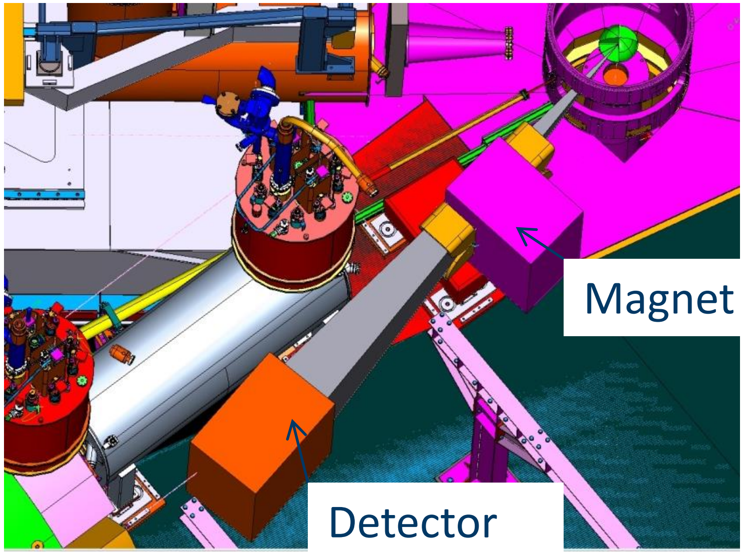
- The NPS is a standalone 25 msr spectrometer allowing for precision (coincidence) cross section measurements of neutral particles.
- Consists of a PbWO4-based calorimeter preceded by a sweeping magnet

NPS cantelevered off SHMS platform



NPS angle range: 5.5 – 30 degrees

NPS on SHMS platform



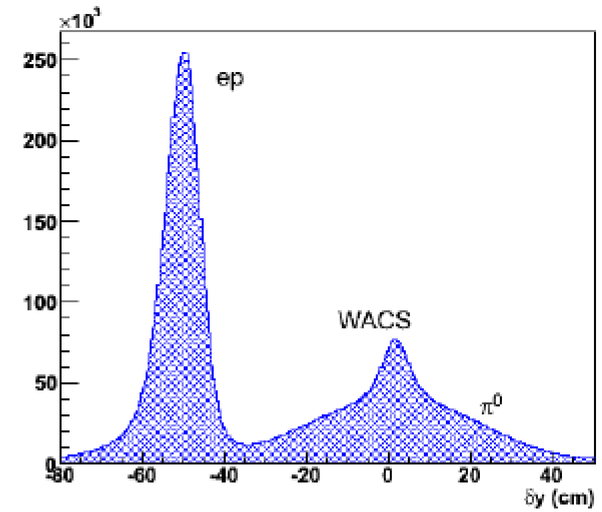
NPS angle range: 25 – 60 degrees

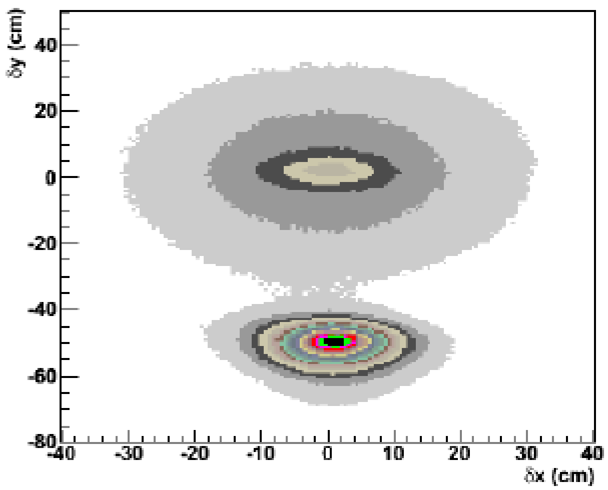
NPS Program

- To extract the rich information on nucleon structure encoded in GPD and TMDs one needs to show that the scattering process is understood.
- 5 experiments have been approved by the JLab PAC to date:
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
  - E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering
- The two-arm combination of a neutral-particle detection and high-resolution magnetic spectrometers, e.g., the HMS (or SHMS) in Hall C, offer the scientific capabilities for these measurements requiring both precision and high luminosity

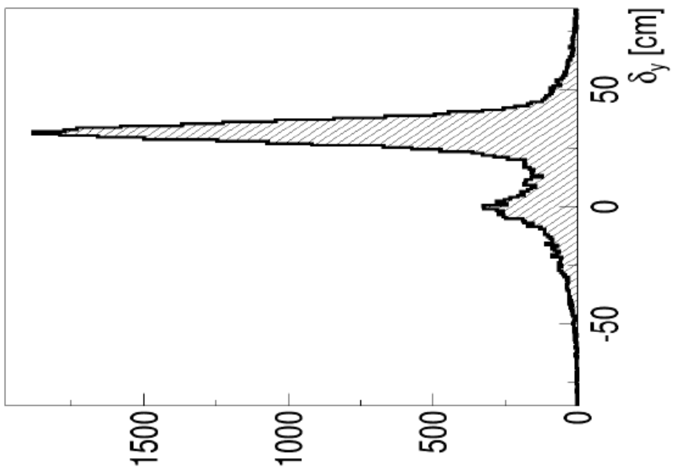
Analysis Technique

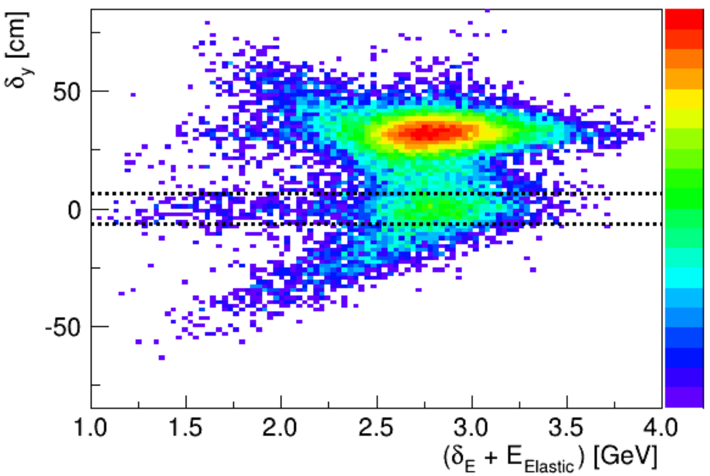
- The analysis technique relies on utilization of the two-body kinematic correlation between the scattered photon/electron and the recoil proton.
- The three dominant reaction channels are:
  - $\gamma + p \rightarrow \gamma + p$
  - $\gamma + p \rightarrow \pi^0 + p \rightarrow \gamma + \gamma + p$
  - $e + p \rightarrow e + p$ (and $ep\gamma$)
- The Compton peak sits on top of a background from both neutral pion and $ep\gamma$ reactions.





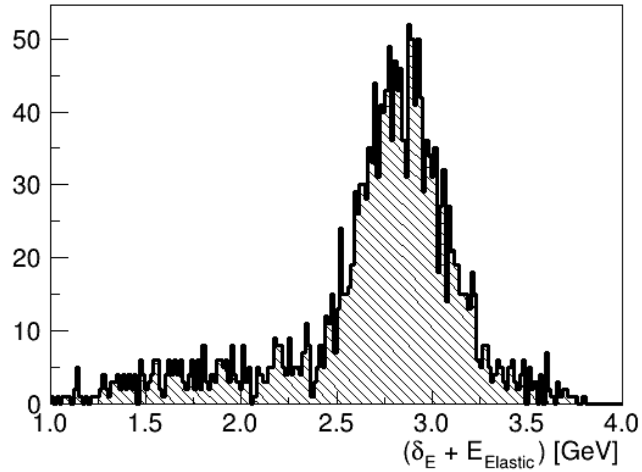
Analysis 6 GeV Data



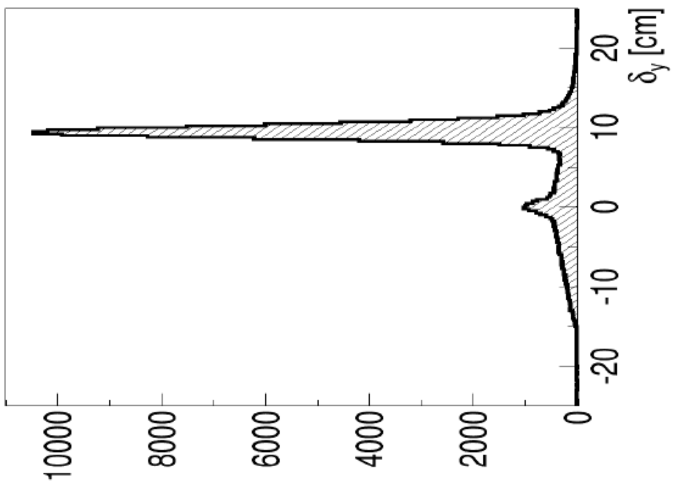


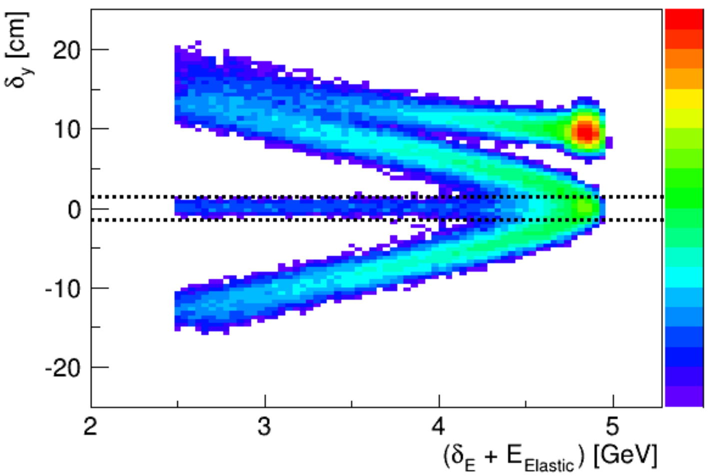
E99-114 Kin 4C

All Events



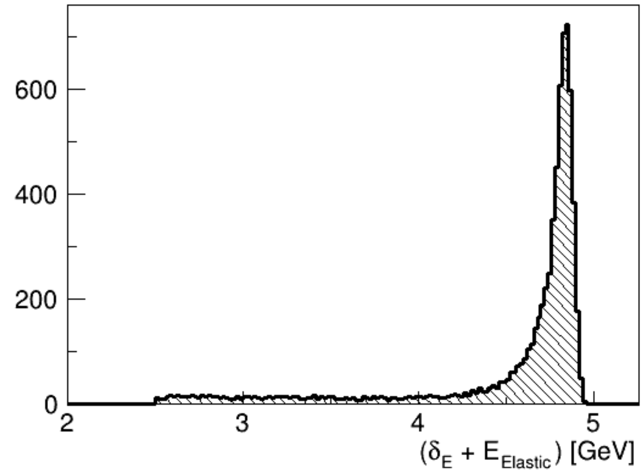
Analysis 12 GeV Data





Kin 4C

All Events



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Rates and Uncertainties

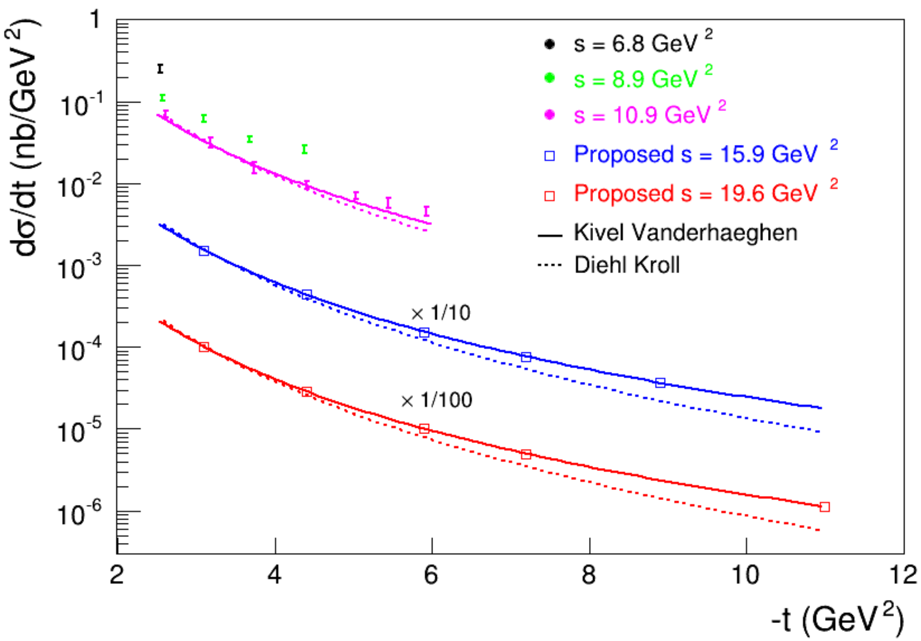
cross section   solid angle   photon flux

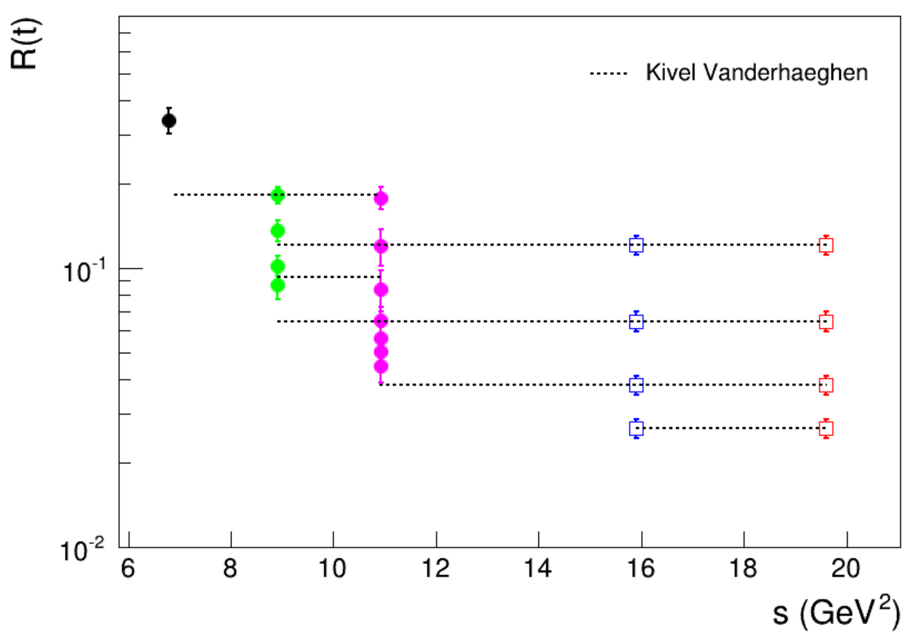
$$N_{RCS} = \frac{d\sigma}{dt}_{RCS} \left(\frac{(E^f_\gamma)^2}{\pi} \Delta\Omega_p \frac{d\Omega_\gamma}{d\Omega_p}\right) f_{\gamma p} \left(\frac{\Delta E^f_\gamma}{E^f_\gamma} \frac{t_{rad}}{X_o}\right) \mathcal{L}_{e\vec{p}}$$

	N_{RCS} (/h)	I (μA)	δ_{NRCS}/N_{RCS}	Time (h)
4A	15.0	5	0.05	20+7
4B	6.0	15	0.05	20+7
4C	3.0	30	0.05	20+7
4D	1.5	60	0.05	30+7
4E	0.7	60	0.08	50+7
5A	9.0	20	0.05	15+7
5B	3.0	30	0.05	20+7
5C	1.6	60	0.05	20+7
5D	1.0	60	0.05	40+7
5E	0.3	60	0.08	120+7
Total				**425**

Source	Uncertainty (%)
Beam 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
Pion Background Subtraction	3.0
epγ Background Subtraction	3.0
Total	**6.0**

Expected Results





All kinematic settings unambiguously satisfy the wide-angle condition that $s, -t, -u \gg M^2$

Four fixed -t scans, three of which overlap with 6 GeV data, will allow for a rigorous test of factorization.

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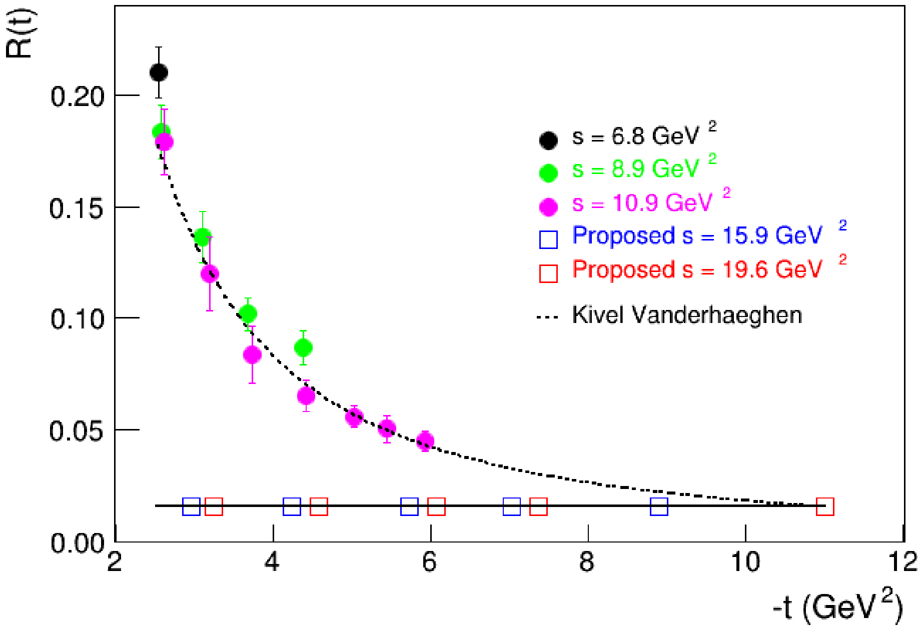
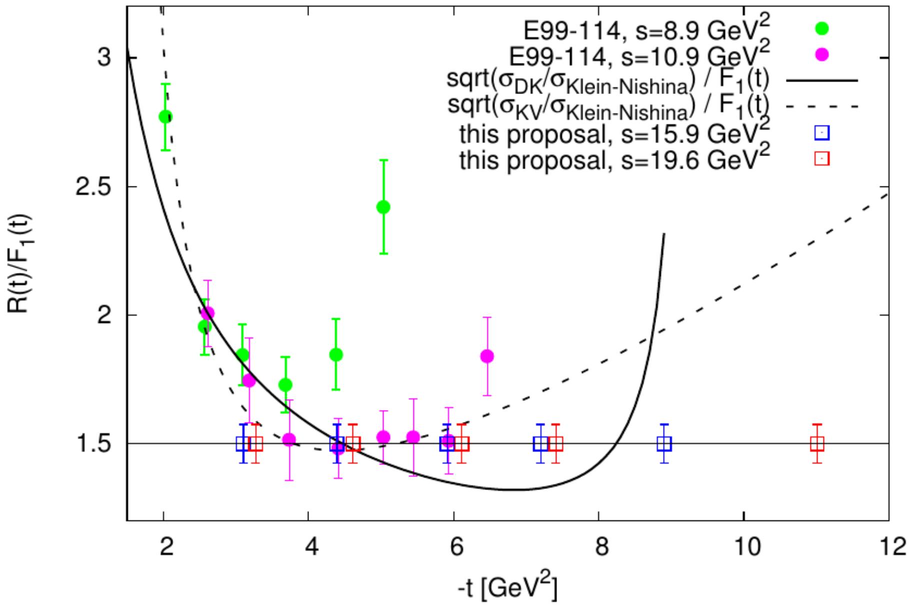
Expected Results





The t-dependence of the Compton form factor will be measured up to -t =11 GeV^2 in order to gain valuable insights into proton structure at high momentum transfer and compare against data from other reactions.

Summary

- WACS is a powerful and under-utilized probe of proton structure.
- We will measure the cross section at Jlab with the NPS at 8 and 10 GeV.
- The new data will allow for a rigorous test of factorization in exclusive processes.