Energy Calibration of the NPS Calorimeter

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1 Introduction

Simulations of various elastic kinematics were completed in preparation for the DVCS experiment using the NPS calorimeter. Elastic calibration, where scattered electrons and recoiling protons are measured in coincidence, is required for every block of the calorimeter at various particle energies incoming on the blocks. The calibration makes it possible to establish the relationship between the FADC signal and the incoming particle energy. Our choice is to measure an elastically recoiling proton in the HMS in coincidence with the scattered electron in the NPS calorimeter (see Figure 1). In this configuration the precisely measured proton momentum and the knowledge of the beam energy can be used to predict the energy of the scattered electron. Due to the combined acceptance of both the HMS and the calorimeter, it is not guaranteed that coincidental elastic events can be recorded for every block of the calorimeter. Varying calorimeter angle and distance from the target allows for a greater acceptance for coincidence events. This study found that a calorimeter distance of 6 meters from the pivot point provides an apt balance between increasing the vertical coincidence acceptance and keeping a reasonable rate of events. At that distance, the calorimeter angle will need to be adjusted several times to calibrate all blocks; the number of adjustments, along with the rates, depends on the kinematics.

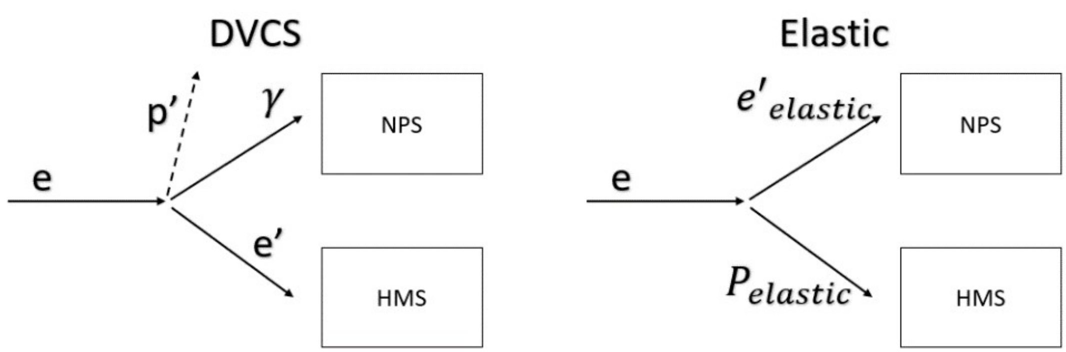

Fig. 1: Diagram of DVCS Experiment vs Elastic Calibration.

2 Experiment Set-Up

The target is liquid hydrogen, with density 0.07229 g/cm^3, and length of 10 cm. It is centered on a pivot point, where the detector distances are measured from; the target lies along the z-axis. The rest mass of the protons in the target is 0.938272 GeV/c^2. The electron beam travels along the z-axis and has energy values in the GeV range. The calorimeter is in the negative y-direction, or to the left of the beam-path viewed from above; this can be seen in Figure 2. It is on a track and can be placed between 3m and 11m from the pivot point. The angle of the calorimeter with respect to the beam-line can be adjusted from 6 degrees to 23 degrees. The face of the calorimeter is 65 cm wide by 74 cm tall, consisting of 1116 blocks.

The High Momentum Spectrometer, or HMS, in Hall C is in the positive y-direction, or to the right of the beam-path viewed from above. Again this can be seen in Figure 2. The collimator face is fixed at 1.6637 m from the pivot point. The angle of the HMS can be adjusted from 12.5 degrees to roughly 90 degrees. The collimator of the HMS is octagonal in shape, with a maximum width of 9.15 cm and a maximum height of 23.292 cm. It accepts momentum values ranging from 0.5 to 7.5 GeV. Above 5 GeV, however, the magnets of the HMS begin to saturate, though there has been data taken with the HMS up to 6.3 GeV. This will require extra calibration for both the DVCS experiment and the elastic calibrations. The momentum acceptance used for this simulation is $\pm$ 8%.

3 The Simulation

The simulation requires some input values to run – the beam energy and the detector positions. After these values are taken, three more are generated for each simulated event. First a vertex,

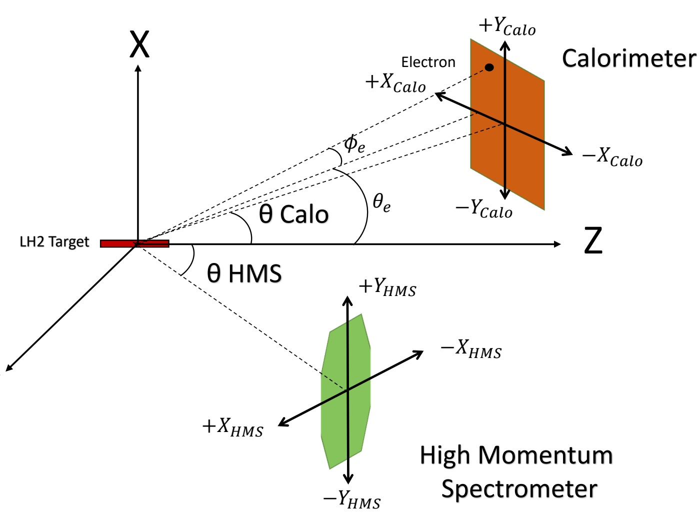

Fig. 2: Diagram of simulated experiment set-up, with axes. The origin is the pivot point centered on the LH2 target. The beam travels along in the positive Z-direction.

or scattering origin point, is randomly generated. The electrons in the beam may hit a proton anywhere along the target; given the target dimensions a vertex is chosen from -0.05m to 0.05m. Next, given the position of the calorimeter, a scattering angle for the electron is randomly generated. For a given position of the calorimeter (angle with respect to the beam line and distance to the target center) and a given length of the target, the minimum and maximum electron scattering angle resulting in a detection are computed. The electron scattering angle, see Figure 2, with respect to the beam-line, in the y-z plane (θ_e^C)[1] is generated to be within this region adding (subtracting) 1 degree on far (near) side of the detector face/entrance, where far (near) is referring to proximity to the beam line. Finally, the electron's out of plane scattering angle (ϕ^C) is generated within $\pm$ 7 degrees. This was chosen as it generates a solid angle covering the calorimeter face for any allowed distance from the center of the target to the calorimeter. Together, the horizontal and vertical angle ranges generate a solid angle over-encompassing the face of the calorimeter. These bounds are seen in Figure 3 in the top plots, as the black data points.

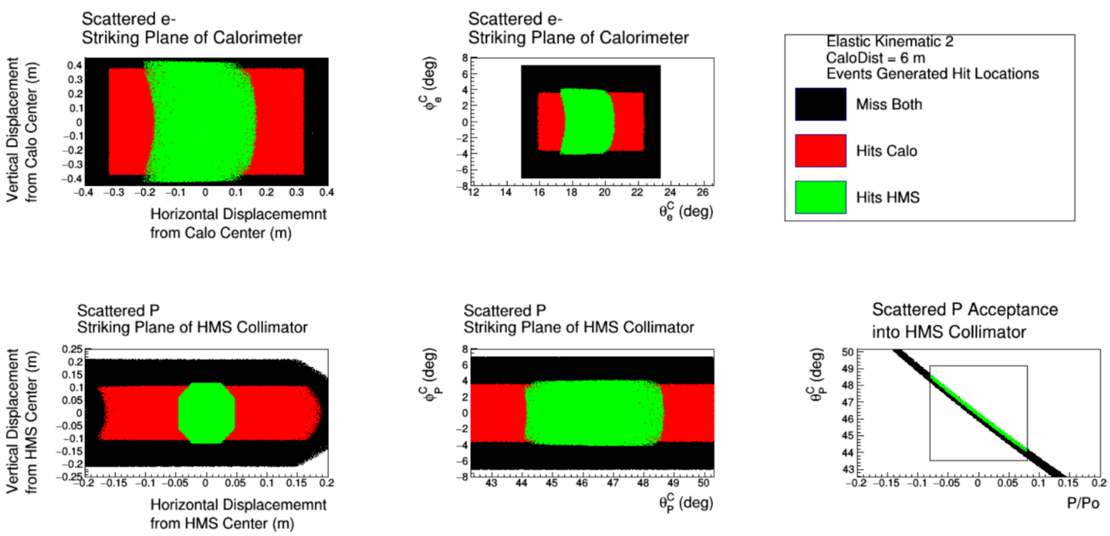

Fig. 3: Results of the simulation of elastic kinematic 2, at a calorimeter distance of 6 meters from the pivot point. The first subfigure shows electrons striking the plane of the face of the calorimeter. Similarly, the fourth shows where protons strike the plane of the collimator of the HMS. The second and fifth subfigures show the same results but with electron and proton angles (Cartesian). The sixth subfigure shows the limitations of the HMS acceptance, with the X-axis being normalized momentum and the y-axis being incoming θ^C angle.

As this is an elastic kinematic, the scattered momenta and angles of both particles are calculated from what has been determined so far. ϕ_P, the out-of-plane angle of the scattered proton is simply the opposite of ϕ_e, the out-of-plane angle of the scattered electron. θ_e, the spherical angle of the scattered proton, is then calculated using the beam energy and electron scattering angle.

$$\theta_P = atan(\frac{1}{(1+k/m_p)tan(\theta_e/2)}) \tag{1}$$

[1] θ and ϕ are spherical angles while θ^C and ϕ^C are Cartesian angles.

Similarly, the momentum of the scattered proton and electron are determined.

$$k' = \frac{k}{1 + \frac{2k}{m_p} sin^2\theta_e/2} \tag{2}$$

$$P = \sqrt{(k + m_P - k')^2 - m_P^2} \tag{3}$$

From the trajectory of the scattered particles and their intercept with the planes at the face/entrance of the detectors, the simulation next checks to see if the particles hit the entrance face of their respective detectors. The first check in that regard is where the particles strike the plane of the detectors. This is done using the position of the detector, factoring in the offset from the vertex value, and using the difference in θ and ϕ angles between the detector and particle. For simplicity, the center of the detector face was set to be the origin of its own coordinate system. The vertical displacement is defined as positive upwards and negative downwards; the horizontal displacement is defined as positive away from the beam-line and negative towards the beam-line. Note that this results in mirrored coordinate systems between the calorimeter and HMS, where the former has a positive vertical displacement to the left while the latter has one to the right. If the particle position lands within the bounds of the detector's face, then it will hit the calorimeter. This is seen in Figure 3 as the red data points in the top figures. For the HMS, the simulation also checks for the scattered proton's momentum, as the HMS only has a ± 8% acceptance for its nominal momentum value. If the momentum falls within that range and lands within the entrance of the HMS, it is considered a 'hit'. The 'hit' region is seen in Figure 3 as the green data points in the bottom plots. Note that due to the additional constraint of the momentum acceptance, the region in green is less-defined than the red in sub-figures 1, 2, and 5. The last plot explicitly shows the ± 8% acceptance. The simulation generates 1 million events for a given kinematic, uniformly generating electron scattering angle and vertex for each event, then saves the results. The simulation was initially run for dozens of kinematic settings in addition to several calorimeter distances.

4 Rate Calculation

From these results, a separate script calculates the rate at which coincidence events occur. First the luminosity of the experiment is calculated for the liquid hydrogen target, assuming a beam current of 1 μA.

$$L = \frac{Q \times N_A \times \rho \times l}{e \times A_H} = 2.7 \times 10^{36} cm^{-2}/s \tag{4}$$

Where L is the luminosity of the experiments, Q is the charge (1 μA per second), N_A is Avagadro's number, ρ is the density of the hydrogen target (0.07229 g/cm^3), l is the length of the target (again, see Experiment Set-Up), e is the charge of the electron, and A_H is the molar mass of hydrogen in g/mol. Next, from the results of the simulation, an average $\frac{d\sigma}{d\Omega}$ is calculated from coincidence events. $d\Omega$ is found using

$$d\Omega = \Delta\theta\Delta\phi \times N_{Co}/N_G \tag{5}$$

where $\Delta\theta$ and $\Delta\phi$ are the range in Cartesian angles of the scattered electron allowed by the simulation. N_{Co}/N_G is the ratio of the number of coincidence events to the total number of events generated. These three terms, luminosity, cross section, and solid angle, then result in a product which is the rate of coincidence events per second, R.

$$R = \frac{d\sigma}{d\Omega} \times d\Omega \times L \tag{6}$$

Following this, the rate of coincidence events per second per block, R_B, is then

$$R_B = \frac{R}{N_{Co}/N_{Calo} \times B} \tag{7}$$

where N_{Co}/N_{Calo} is the ratio of number of coincidence events to the number of events that have a calorimeter 'hit', and B is the number of calorimeter blocks, 1116.

5 Results

Variable	Units	Kin2	Kin6	Kin11
k	GeV	4.4	6.6	8.8
k'	GeV	3.5	5.5	7.5
θ_e	deg	19.1	13.7	11
P	GeV	1.58	1.81	2.03
(θ_P)	deg	46.3	46	44.9
Rate	Events/sec	87	64	45
Rate per Block	$\times 10^{-2}$ Events/sec	24	25	22
Time to 1000 Events per Block	hrs	1.2	1.1	1.3
% Calorimeter in Coincidence	%	30	21	17

Tab. 1: Proposed Elastic Kinematics, maximizing cross section while restricted by experimental bounds (see Experiment Set-Up). Angles are taken as absolute value in this study. Rate is calculated for 1 μA. The full height of the calorimeter is in coincidence with the HMS, seen by the green over-encompassing the red vertically. This ensures that, given multiple runs at varying angles, every block will eventually be in coincidence with the HMS. Note that the k' values do not match DVCS q' values exactly.

To reiterate, the goal of this simulation is to calibrate the calorimeter for NPS-DVCS. This will be done with elastically scattered electrons of energies comparable to those of the real photons of the NPS-DVCS kinematics, as seen in Tables 2 and 3. Therefore, when simulating kinematics for calibration, the scattered electron energy is constrained by what is needed for the NPS-DVCS kinematics. There are two other major constraints on the simulation: ensuring every calorimeter block is calibrated and minimizing data-taking time.

To calibrate every block, the distance from the calorimeter to the target must be large enough such that the vertical extension of the calorimeter face is covered by coincidence events. As seen in Figure 5, it was found that this occurs at approximately a 6 meter distance from the target to the calorimeter. This result is independent of the kinematics. While the entirety of the calorimeter is not struck by coincidence events in this kinematic, full horizontal coverage is achievable by repeated runs at varying calorimeter angles. Note that further increasing the calorimeter's distance to the target will increase the horizontal coverage, but at the cost of increasing events missed in the vertical. This leads to an overall decrease in event-rate which increases data-taking time (see section 4).

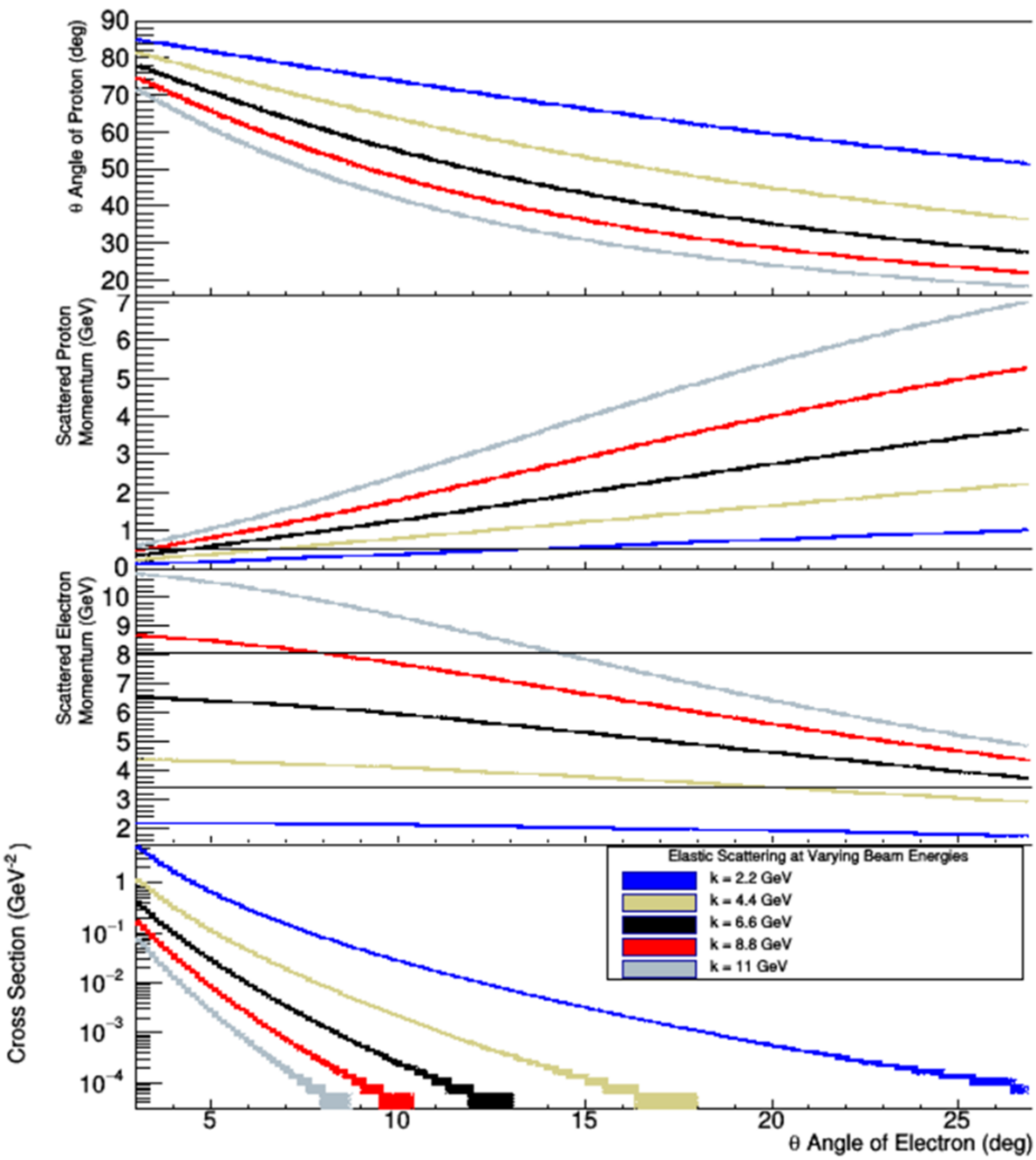

Fig. 4: Plots of scattered electron θ angle varying beam energy. The subplots show from top to bottom, proton scattering angle θ, scattered proton momentum, scattered electron momentum, and cross section. In the second subplot, the black horizontal line shows the lower limit of the HMS nominal momentum, 0.5 GeV. In the third subplot, the black horizontal lines show the range of scattered photon energies expected for NPS-DVCS: 3.4 to 8.1 GeV (see Tables 2 and 3)

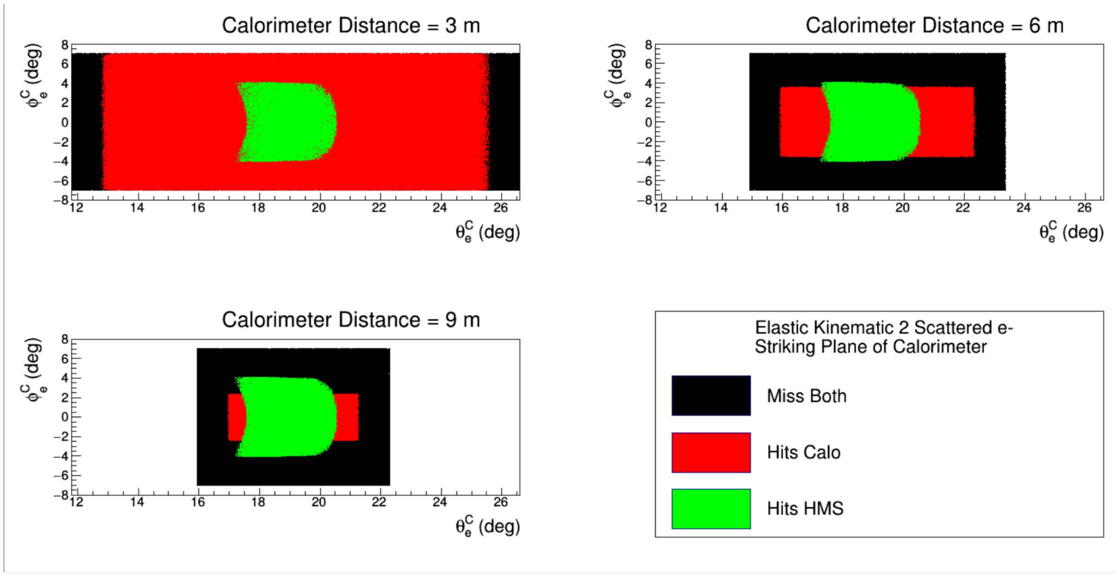

Fig. 5: Results of the simulation of elastic kinematic 2, varying distance from the calorimeter to the target center. The figures show electrons striking the plane of the face of the calorimeter, with the axes plotting θ_e^C vs ϕ_e^C.

To minimize data-taking time, the cross section must be maximized. The relationship between cross section and other factors in the simulation can be seen in Figure 4. Decreasing beam energy and θ_e will drastically increase the cross section. However, the goal is still to collect scattered electrons of specific energy levels. As such, for a given scattered electron energy, the beam energy must always be greater.

Considering these constraints and limitations, fourteen kinematics were simulated and their rates calculated, with the distance from the calorimeter to the target fixed at 6 meters [2]. These kinematics are seen in Tables 4 and 5. The scattered electron momenta span a range similar to the NPS-DVCS photons, but using the lowest possible beam energy[3]. A kinematic was studied for every 0.5 GeV from 3 to 8.5 GeV, cycling through the entire range of scattered photon momenta expected in the NPS-DVCS experiment. There were three immediate issues with these elastic kinematics: the momenta of the elastic proton collected by the HMS, the required angle of the calorimeter for collecting the scattered electron, and the coincidence event rate. Because beam energy was minimized, the energy of the scattered electrons approaches the beam energy in some of the kinematics. As this happens, the scattered momentum of the proton can fall below what the HMS can collect and the angle of the scattered electron can become too small for the calorimeter to reach. On the other hand, the larger the difference between the beam energy and scattered electron momentum, the cross section (and proportionally the event rate) drops off. Also with this, the calorimeter angle increases, sometimes beyond what the calorimeter can reach (see 2). These relationships can be seen in Figure 4. Considering these limitations, many kinematics were not simulated. The ones removed from consideration had either θ_e outside the bounds of the

[2]These kinematics differ from those presented at the February 2020 NPS meeting. The previous kinematics used the NPS-DVCS k and q' values as their k and k' values (see Table 2) Kinematics discussed here share only the same range of energy values for k' with the NPS-DVCS q' values (see Tables 4 and 5).

[3]Kinematics here use the nominal beam energy. These values will be adjusted closer to the experiment.

calorimeter, scattered momenta of the proton below what the HMS can receive, or smaller cross sections (any cross section resulting in a coincidence event rate per block less than 0.1 Events/sec). This left 3 kinematics (Kine 2, 6, 11), as seen in Table 1. These kinematics were simulated using the aforementioned script.

The rates were calculated assuming a beam current of 1 μA, and examining the time to achieve 1000 events per block. Table 1 shows that this is achievable for all 3 kinematics in just over an hour. A restriction of this, however, is that the entirety of the calorimeter cannot be covered at once, see Figure 5. Using the percentage of the calorimeter covered by coincidence events, we can assume 4 to 6 runs, with calorimeter angle adjustments between, will be required to fully calibrate. The number of adjustments can by reduced by moving the calorimeter further from the pivot point, but at the cost of increased data-taking time. If the distance is increased from 6 to 11 meters, for example, the percentage of the calorimeter covered roughly doubles while the time to 1000 coincidence events approximately quadruples.

6 Conclusion

From this simulation, it was found that full coverage of the calorimeter by elastic coincidence events is achievable by adjusting the calorimeter distance to be 6 meters from the pivot point, then adjusting calorimeter angle for multiple runs to cover the horizontal spread of its face. This will allow every calorimeter block to be calibrated by elastic events. Fixing the calorimeter distance, 14 kinematics were examined. From these, three were found to be possible given the experiment's limitations, which were then simulated. These kinematics, labeled 2, 6, and 11, range in scattered electron momentum by 3.5, 5.5, and 7.5 GeV. At 1 μA beam current, each of these kinematics simulated were found to achieve 1000 coincidence events per block in just over an hour. A higher beam current or lower coincidence event threshold will decrease this time further. Given the percentage of the calorimeter face covered by coincidence events, each calibration will need to be run 4 to 6 times, adjusting calorimeter angle to sweep its face horizontally.

7 Appendix

Variable	Energy Dependence at fixed (Q^2,x_B)												Low-x_B				High-Q^2
x_B	0.36					0.5			0.60				0.2				0.36
Q^2 (GeV^2)	3.0			4.0		3.4		4.8	5.1			3.0	2.0			3.0	5.5
k (GeV)	6.6	8.8	11	8.8	11	8.8	11	11	6.6	8.8	11	11	6.6	8.8	11	11	11
k' (GeV)	2.2	4.4	6.6	2.9	5.1	5.2	7.4	5.9	2.1	4.3	6.5	5.7	1.3	3.5	5.7	3.0	2.9
q' (GeV)	4.4	4.4	4.4	5.8	5.8	3.4	3.4	4.9	4.2	4.2	4.2	5.0	5.3	5.3	5.3	8.0	8.1

Tab. 2: Approved PAC 40 DVCS and $\pi 0$ kinematics for Hall C.

Variable	Jeopardy Kinematics			
x_B	0.480	0.600		
Q^2 (GeV^2)	5.334	6.822		8.40
k (GeV)	10.617	8.517	10.617	8.517
k' (GeV)	4.696	2.458	4.558	1.057
q' (GeV)	5.736	5.697	5.697	7.089

Tab. 3: PAC 47 DVCS jeopardy kinematics for Hall C.

Variable	Kine1	Kine2	Kine3	Kine4	Kine5	Kine6	Kine7
k (GeV)	4.4	4.4	4.4	6.6	6.6	6.6	6.6
k' (GeV)	3	3.5	4	4.5	5	5.5	6
θ_e (deg)	25.8	19.1	11.85	20.99	17.3	13.7	9.7
θ_P (deg)	37.5	46.3	59.43	33.9	39.2	46	55.8
P (GeV)	2.14	1.58	0.9543	2.89	2.35	1.81	1.22
$\theta_e + \theta_p$ (deg)	63.3	65.4	71.28	54.89	56.5	59.7	65.5
Rate (Events/sec)	2.7	87	2082	2.9	11	64	791
Rate per Block ($\times 10^{-2}$ Events/sec)	2.1	24	870	0.67	3.3	25	420
Time to 1000 Events per Block (hrs)	13	1.2	0.032	41.7	8.2	1.1	0.066
% Calorimeter in Coincidence	42.50	30.00	20.00	36.00	28.00	21.00	15.00

Tab. 4: Potential Elastic Kinematics, arranged in increasing k'

Variable	Kine8	Kine9	Kine10	Kine11	Kine12	Kine13	Kine14
k (GeV)	6.6	8.8	8.8	8.8	8.8	8.8	11
k' (GeV)	6.5	6.5	7	7.5	8	8.5	8.5
θ_e (deg)	3.8	15.79	12.4	11	8.37	5	12.86
θ_P (deg)	75.1	34.79	39.3	44.9	52.8	65.7	34.89
P (GeV)	0.44	3.1	2.57	2.03	1.46	0.81	3.308
$\theta_e + \theta_p$ (deg)	78.9	50.58	51.7	55.9	61.17	70.7	47.75
Rate (Events/sec)	74500	2.9	10	45	374	13000	2.7
Rate per Block ($\times 10^{-2}$ Events/sec)	102000	0.92	3.9	22	233	11100	1.1
Time to 1000 Events per Block (hrs)	0	30.2	7.2	1.3	0.12	0.0025	26.1
% Calorimeter in Coincidence	4.00	26.00	21.00	17.00	13.00	9.00	21.00

Tab. 5: Potential Elastic Kinematics, arranged in increasing k'