An Optimization of Double Deeply Virtual Compton Scattering Experiments at Jefferson Lab Hall C

Josie Robbins[1], Melinda Yuan[2], Marie Boër[3](mentor)

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Abstract

The goal of Double Deeply Virtual Compton Scattering (DDVCS) experiments is to better understand the internal structure of the nucleon. Previous attempts to resolve the internal structure of nucleons have resulted in electromagnetic form factors and parton distribution functions for elastic scattering and deep inelastic scattering processes, respectively. Generalized Parton Distributions (GPDs) are the latest attempt to unify these models of nucleon structure. The GPDs of DDVCS give us ability to investigate off of the diagonal where $x \neq \pm\xi$. The main goal of our analysis is to determine the best experimental setup in order to deduce the kinematic variables on which GPDs depend from the lab observables. The effectiveness of our data collection in the laboratory is by determined the physical kinematics, Q^2, Q'^2,t, x_i,ϕ_{LM}, ϕ_{CMV}, and θ_{CMV}. We can then run the DDVCS experiments and collect data, which is implicitly used to calculate the GPD of the nucleon.

Background

The fundamental aim of particle physics is to discover and understand matter down to its smallest possible constituents. The discovery of the quark in 1964 revolutionized this process, breaking apart nucleons, which were previously believed to be elementary particles[6]. These subatomic particles were detected using scattering, a process in which a high energy particle beam is directed at a stationary object, resulting in collisions between the particles in the beam and object. Data is collected from these collisions, such as cross sections or scattering byproducts, which is then used to infer information about the internal structure of the object. The model that we are attempting to explore is Generalized Parton Distributions, currently the most detailed model of nucleon structure to exist. GPDs are a hybrid of its predecessors, form factors (produced through elastic scattering) and parton distributions (produced through deep inelastic scattering)[8]. The particular scattering process that we are investigating is Double Deeply Virtual Compton Scattering (DDVCS), in which an electron beam is scattered off a proton, exchanging a virtual photon in the process. The outgoing virtual photon will then decay into a detectable muon-antimuon pair as seen in Figure 1[7].

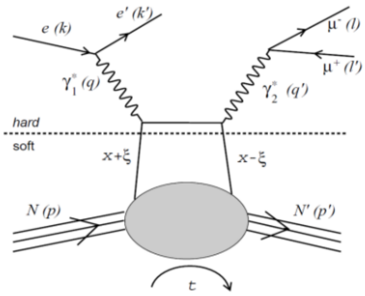

Figure 1: DDVCS $e^- + e^- \rightarrow \mu^+ + \mu^-$[2]

The current reactions studied are Timelike Compton Scattering (TCS) and Deeply Virtual Compton Scattering (DVCS). Both of these collisions include one virtual photon, with TCS containing an outgoing virtual photon and DVCS an incoming virtual photon. In DDVCS experiments, both the initial and final photons are virtual. The virtuality of the photons impacts the matrix elements that describe the reaction. The matrix element refers to the probability amplitude of finding a quark at a space-time point in a nucleon, then finding the same quark at another space-time point in the nucleon which has now changed its momentum[5]. The involvement of 2 space-time points means that the matrix element is non-local, and the differing momenta of the initial and final nucleon makes the matrix element non-forward.

[1]University of Colorado, Boulder
[2]Columbia University
[3]Virginia Polytechnic Institute and State University

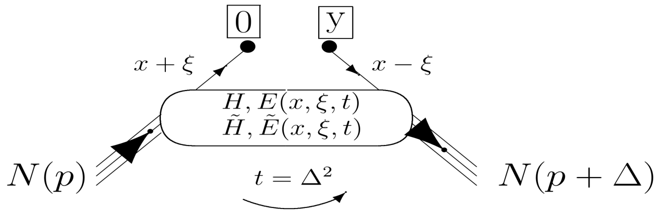

Figure 2: Illustration of non-local non-forward matrix element[5]

GDPs depend on the following kinematic variables: Q^2, the virtuality of the exchanged photon, t, the momentum transfer to the nucleon, Bjorken x (x_{Bj}), the fraction of the total nucleon momentum, and three reaction angles. These kinematics be used to calculate ξ and ξ', components of light cone frame momentum, using the following equations [3].

$$\xi = \frac{Q^2 + Q'^2}{2s + Q^2 + Q'^2 - 2M_p^2 + t} \tag{1}$$

$$\xi' = \frac{Q^2 - Q'^2 + t}{2s + Q^2 + Q'^2 - 2M_p^2 + t} \tag{2}$$

Using ξ and ξ', the longitudinal momentum transfer fraction of incoming spacelike photon, -2($\xi - \xi$'), and the longitudinal momentum transfer fraction of outgoing timelike photon, (2ξ'$-\xi$), can be calculated. These momentum transfers make DDVCS unique, because in a DDVCS reaction, $\xi \neq \xi$' unlike TCS and DVCS reactions where $\xi = \pm\xi$' [3]. When $\xi \neq \xi$', x_{Bj} and ξ dependence can be decoupled, allowing access to 'off diagonal elements' of GPD regions. Currently, with TCS and DVCS, only elements on the diagonal $x_{Bj} = \pm\xi$ are accessible due to the dependence of x and ξ on each other. However, x and ξ decoupling enables newly accessible regions of GPDs, which will allow for a more detailed picture of the distribution of nuclear forces inside a nucleon as well as the determination of parton transverse densities. Such investigation will add to the current model of GPDs and facilitate more detailed tomographies of the nucleon.

Another focus of the DDVCS experiments is the question about the universality of GPDs. Under current theories, GPDs are presumed to be universal, which means that the calculations of GPDs will be the same regardless the experiment used to measure them. However, there is no concrete experimental proof to support this conclusion. DDVCS reactions have the unique ability to simultaneously study spacelike (defined as $Q^2 > Q'^2$) and timelike regions (defined as $Q'^2 < Q^2$) in order to determine the two regions result in the same leading order and twist. The agreement of results between the spacelike and timelike regions would then in turn provide support of the universality of GPDs.

Methods

In order to simulate DDVCS collisions, we used the event generator DEEPGen, developed by Dr. Marie Boër. These event generators, written in C++ and run through ROOT, generate simulated particle collisions events given a certain set of parameters, such as luminosity, beam energy, and phase space. It can be altered depending on the type of collision it is replicating. The version that we used, DEEPGen 5.0, simulates deep exclusive photo- and electro- production of lepton pairs and photons, including DDVCS as well as DVCS and TCS. The parameters of the event generator were set to match experiments at Hall C of Jefferson Lab with an 11 GeV electron beam. The generator creates equal weighted events and uses a Monte-Carlo simulation technique to weight the events with an n-differential cross section[4]. The weights are multiplied by a normalization factor, $N = \sum \frac{W*\Delta\Omega*\mathcal{L}}{N_{TOT}}$ where $\mathcal{L}$ is luminosity and $\Delta\Omega$ is the dimension of the phase space.

There are five weighting options; total unpolarized, DDVCS, Bethe-Heitler (BH), DDVCS/BH, and beam spin asymmetry. The beam spin asymmetry weighting provides insight into how difficult it will be to measure the asymmetric polarization of the electron beam. Simulated events with the total unpolarized weight are proportional to the number of measured events in the physical experiment. The total unpolarized weight is calculated with the DDVCS weight and BH weight, $W_{tot} = |W_{DDVCS} + W_{BH}|^2$. Analyzing the data with DDVCS and BH weighting allows their contributions to be distinguished. The BH contribution is precisely known due to it's dependence on QED calculations and proton form factors[1]. It describes the hard (known) region of DDVCS reactions. The DDVCS contribution, on the other hand, describes the soft region of the reactions and can not be calculated.

The ratio of DDVCS and BH weighting allows for insights into where the so-called 'new physics' can be found. Areas where DDVCS/BH is large are promising in terms of information about the GPDs in the previously inaccessible regions.

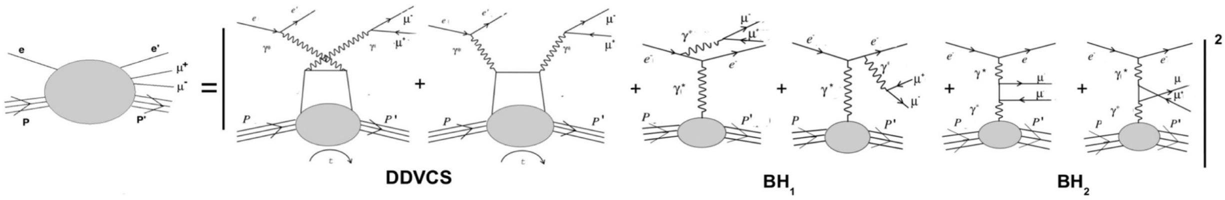

Figure 3: The DDVCS and BH contributions to the total unpolarized weight[2]

After generating the simulated and weighted DDVCS events, we analyzed the data to better understand how the experimental kinematics variables relate to each other. In addition to the variables of t, ξ, ξ' displayed in Figure 1 above, the relationship between the various angles in the particle scattering, shown below, were explored. The experiment takes place on three planes, with the far left plane being created by the initial and final electrons from the electron beam, the middle plane by the photons and the nucleon, and the plane on the far right by the muons. The notation CM indicates the measurements are taken from the center of mass frame. The angles of interest are θ_{CM}, the angle between the incoming and outgoing electrons, ϕ_L, the angle between the plane of the electrons and the plane of the photons, and ϕ_{CM}, is the angle between the plane of the muons and the plane of the photons. The last angle, θ_{CM}, is the angle the scattered muon makes from parallel.

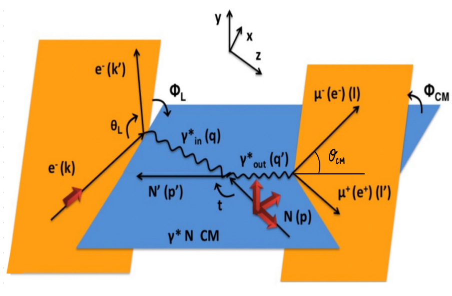

Figure 4: Collision vectors and angles

Discussion

The generated data was analyzed to explore the relationships between kinematics and other variables. While our beginning graphs were practice with the code and the goal was to understand how kinematics, our later graphs explored how events can be interpreted. The first set of graphs (figure 5) traces out the amount of events exists within a certain angle range. The angles here correspond to the angles in figure 4. The ϕ angles have a range of π and the θ graph measures entries between 0 and π. Both of the center of mass angles (ϕ_{CM} and θ_{CM} appear most symmetric without many irregularities. However, the ϕ_L graph displays unexpected asymmetries, which may arise due to relations between all three angles and warrants more exploration.

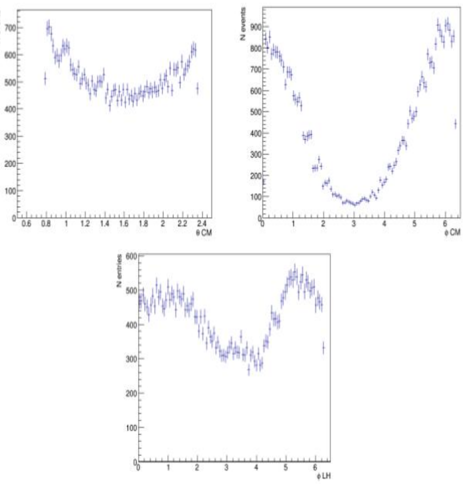

Figure 5: θ_{CM} (upper left), ϕ_{CM} (upper right), and ϕ_L (lower)

A majority of the data analysis was completed to not only relate kinematics but also optimize the experimental set up and data analysis. The next figure which compares $\frac{Q'^2}{Q^2}$ to ξ' provides important information about events that need to be excluded from the data set and events that might be useful for physical interpretation. The events along the timelike and spacelike cut line are events that must be excluded. The line corresponds with $\frac{Q'^2}{Q^2} = 1$ which makes the data difficult to interpret.

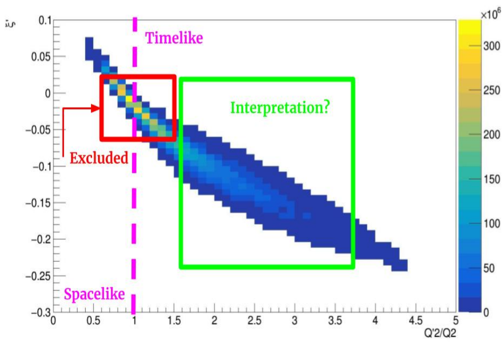

Figure 6: $\frac{Q^2}{Q'^2}$ vs ξ'

Figure 7 is a comparison of ξ and ξ' with boundaries that define later data cuts in Q^2 vs Q'^2. By comparing the ξ and ξ', we are granted the ability to determine how far 'off the diagonal' we can measure our events. The diagonal, in this case, is defined as $x = \pm\xi$ and has previously restricted the investigation of GPDs in the ERBL and DGLAP regions. The cuts that are made focus on areas where measured events can be physically interpreted

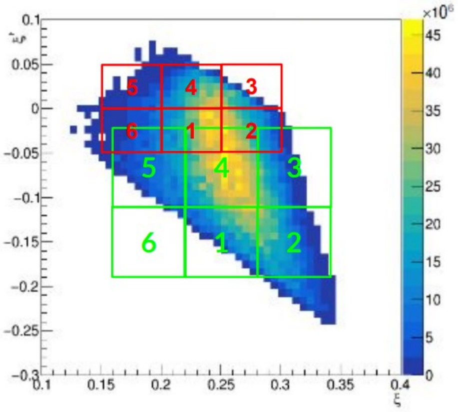

Figure 7: ξ vs ξ'

The cuts on the ξ vs ξ' graph correspond to selected Q^2 and Q'^2 bands (Figure 8). The graphs are also restricted in terms t, between -0.15 GeV and -0.55 GeV. t must be constrained because while there are more events measured between -0.55 GeV and -1.05 GeV, when the momentum transfer becomes too large, approximations are rendered invalid and a physical interpretation loses meaning. Thus, the graphs must be constrained in t.

The value of these graphs are derived from the fact that Q^2 and Q'^2 cannot be measured outright. The transfer of the virtual photon's momentum occurs in the soft region, which is not physically accessible with our current technology, but can still be calculated from the measured kinematics. Using the Q^2 vs Q'^2 selected bands and the Bjorken x hypothesis, the structure of the proton can be determined. The Bjorken x hypothesis states that, for point-like particles, as the limit $Q^2 \to \infty$, GPDs lose dependence on Q^2. Hence, if the GPD demonstrates dependence on Q^2, it's structure cannot be classified as point-like.[9].

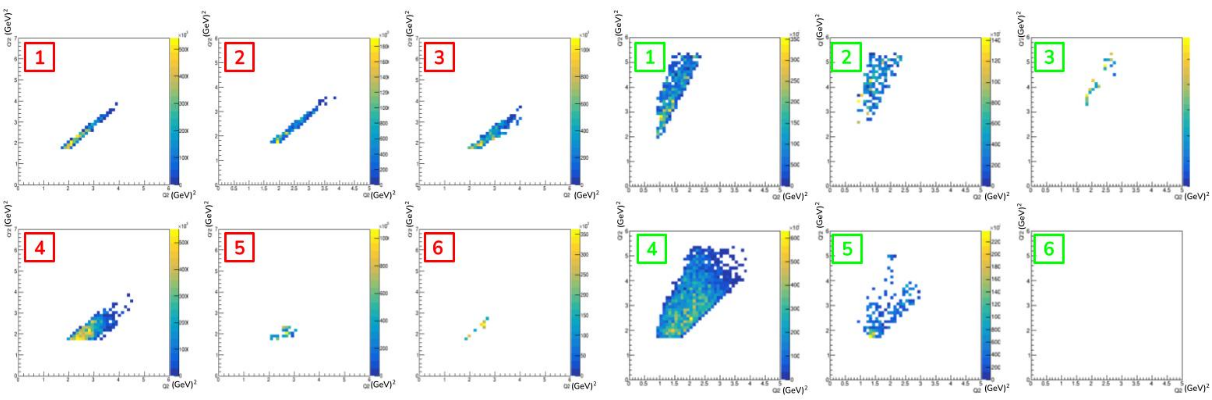

Figure 8: Q^2 vs Q'^2 Selected Bands, Spacelike (left) and Timelike (right)

Summary and Outlook

Double Deeply Virtual Compton Scattering is the next step when it comes to accessing and analyzing GPDs. The incoming and outgoing virtual photons make DDVCS unique from previous experiments, allowing access to regions of Generalized Parton Distributions that were previously unreachable. This is done through taking advantage of the fact that in DDVCS, $\xi \neq \pm\xi$' which allows access beyond the $x = \pm\xi$ diagonal GPDs are currently restricted to. DDVCS also provides opportunity to compare measurements of GPDs in spacelike and timelike regions simultaneously, which can be used to evaluate the validity of GPD universality.

The DEEPGen Event Generator provided events which could be applied to different weighting systems and analyzed. Boundaries were created for Q^2 vs Q'^2 using ξ vs ξ', allowing for greater insight into proton GPDs as well as an understanding of the extent to which measurements can be taken 'off of the diagonal.'

The future of this project requires more data analysis and planning for the Jefferson Lab proposal. The kinematics regarding the Bjorken x Hypothesis contains a vast domain of interpretation that has potential to be explored further. Additionally, more detailed data analysis can be done by with regards to the relationship between the experimental angles and the other kinematics variables, as the this study lacks the proper angular corrections and acceptance cuts from Q^2 and other values. Looking forward, there exists a great deal more investigation into DDVCS to be done, as it appears be an untapped realm when it comes to uncovering more physics regarding proton GPDs.

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