Studies of Proton Structure from Photo- and Electro-Production of Light Vector Mesons

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Abstract

The analysis of light vector meson production by a high-energy electron or photon beam in a particle accelerator provides insight into the composition of the proton, further expanding the fundamental understanding of physics. The electro-production of light vector mesons off of protons happens when a high virtuality photon interacts with a quark, which can be studied to extract the Generalized Parton Distributions (GPDs). These functions provide access to the correlation between the longitudinal momenta of partons and their transverse position. They can be further interpreted to obtain multidimensional images of the proton. Vector mesons are particularly sensitive to the GPDs H and E and allow for flavor decomposition of the proton's GPDs. We implemented the rho vector meson ρ^0 in a generator used in simulations for Jefferson Laboratory (DEEPGen) and for EIC (DEEPSim). Our goal is to contribute to the development of future Hard Exclusive (light) Vector Meson experiments for Jefferson Laboratory and EIC. We will discuss the physical interest of measuring light vector mesons for accessing GPDs, then present our work with the event generator and our projections for future experiments.

1 Introduction

In the pursuit of new knowledge of the physical world, we study increasingly minute structures to understand the nature of fundamental particles. Experiments currently being conducted in several particle accelerator laboratories probe the nucleon (protons and neutrons) at high energies to extract information about the partons (quarks, antiquarks, and gluons) contained inside. The information is then studied to build upon and refine the current knowledge of the Standard Model of Elementary Particles, depicted in Figure 1, particularly concerning the interactions of partons and their distribution in the nucleon [1].

Nucleons are probed using electron or photon beams, which interact with the nucleon via highly-virtual photons. At beam energies up to around 1 GeV, we may be able to resolve the three quarks that make up the nucleon as point-like particles. At the "deep", or "hard scale" energies greater than 1 GeV, we are able to resolve more details inside the nucleon, such as self-interacting gluons and quark-antiquark pairs that come into and out of existence. This turbulent distribution of energy throughout the nucleon is metaphorically referred to as a "sea" of quarks [2]. When an electron of high enough energy nears a proton, it is able to interact with a sea quark via a virtual photon, causing one of several types of reactions. The reaction we are interested in, in order to study the production of the rho vector meson ρ^0, is Hard Exclusive Meson Production (HEMP), illustrated in Figure 2. Because this reaction involves virtual photon energy greater than 1 GeV, it is also called Deeply Virtual Meson Production (DVMP) [3]. HEMP may be a more descriptive name, since the reaction produces mesons exclusively. In HEMP, the virtual photon has enough energy to "kick" a sea quark out of the nucleon, bringing a new quark into existence with the energy transferred. The exiting quarks form a meson [4], and in our case, they form the ρ^0 meson.

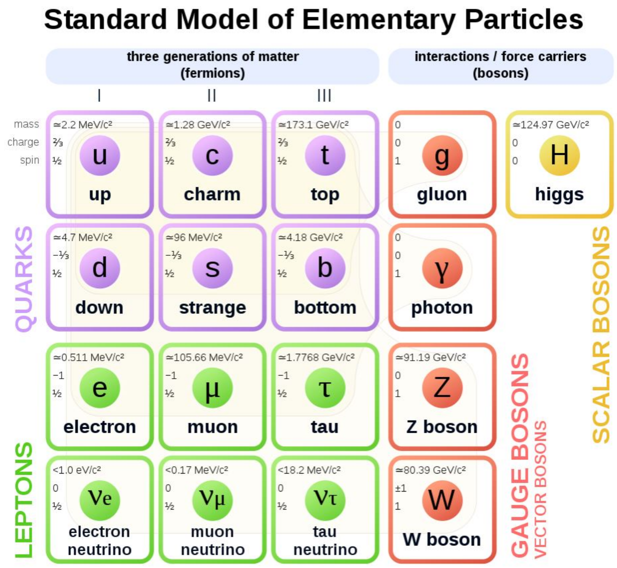

Figure 1: The Standard Model of Elementary Particles categorizes the smallest particles currently known. Source: Wikimedia [5]

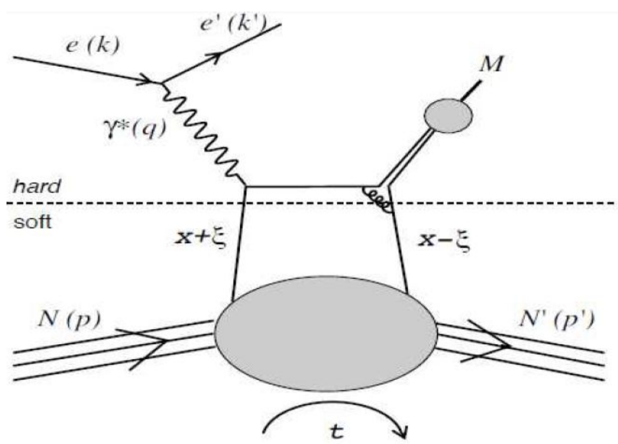

Figure 2: This Feynman diagram shows the momentum transfer to the nucleon (t) in the "soft" process known as the Generalized Parton Distribution (GPD). The "hard" process shows the measurable energy brought in (by the high-virtuality photon) and carried out (by the meson). Source: "Hard Exclusive Reactions and Generalized Parton Distributions" [3]

To analyze the build of a nucleon through scattering processes, we separate the calculable "hard" process from the non-calculable "soft" process. The "soft" process refers to interactions at the energy levels at which gluon exchange and sea quark creation/annihilation occur. The "hard" process and "hard scale" energy refer to the scale of energy that allows factorization of a Feynman diagram [2], such as the diagram of Figure 2. We use a Feynman diagram because it is designed to intuitively provide a way to decompose the cross-section for specific reactions [6] and express it as a function of the calculable hard process multiplied by the soft process [4].

For production of the ρ^0 vector meson, the scattering process we focus on is HEMP, in which a high-energy electron beam interacts with a proton via a highly-virtual photon. We use a mathematical function, called the Generalized Parton Distribution (GPD), to describe the "soft" process by combining descriptions of the distribution of partons in the nucleon in such terms as longitudinal momentum versus transverse position. By measuring the "hard" process of energy going into and out of the system, we can gain insight into the GPD of the proton. From the GPD, a multidimensional image of the proton may be constructed [4].

When measuring the outgoing invariant mass (denoted as Q'^2), we see a distribution in which more counts are recorded for specific energy levels. These peaks correlate with the type of meson produced, such as the π^0, ρ^0, and ϕ mesons in Figure 3. The distribution is the sum of outgoing energy recorded, so it acts as a (unnormalized) probability of reaction types. For the purpose of this experiment, we consider all reaction types besides HEMP as background counts for the energy range analyzed. By running simulations in an event generator (such as DEEPGen and DEEPSim) for each peak, then adding them together with background, we can form a theoretical model of the outgoing energy distribution, which can be tested at Jefferson Laboratory and EIC. The testing provides insight into which parameters most directly affect each isolated reaction. By controlling the energy of the beam into the system, and with an accurate prediction of energy leaving the system, we produce a clearer picture of the parameters in which the GPDs can be understood.

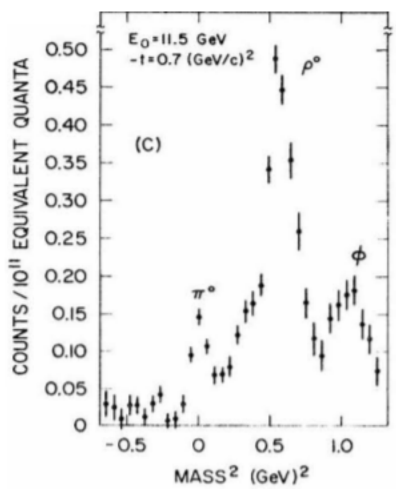

Figure 3: Distribution of recorded outgoing invariant mass versus counts. The peaks correlate with the outgoing neutral mesons produced in scattering reactions. Source: "High Energy Photoproduction of Neutral Mesons" [7]

Vector mesons were chosen for the subject of this experiment because they are sensitive to the unpolarized types of GPDs (H and E) that allow for flavor decomposition [4]. The ρ^0 meson was specifically chosen because it has a large cross-section and serves as a manageable first step in implementing the production of vector mesons in an event generator. Analyzing vector meson production gives us the advantage of implementing flavor decomposition, which allows the GPD to be factorized into smaller, more manageable pieces for each quark flavor. The disadvantage in studying vector meson production is that the GPD functions grow larger, since the meson itself must also be described by a GPD due to its own intrinsic gluon interactions [8]. The model of Hard Exclusive ρ^0 meson production that we have implemented into DEEPGen (and are currently implementing into DEEPSim) provides a way for us to see how different parameters affect the expected measurements of the HEMP process and which energy range we should focus on to observe the creation of ρ^0 mesons in physical experiments at Jefferson Laboratory and EIC.

2 Methods

The event generators DEEPGen and DEEPSim are written by Dr. Marie Boër in C++ using CERN's ROOT library. To implement the HEMP reaction for ρ^0, the DEEPGen was modified to run iterations of the isolated reaction with the proper distribution shape of the produced invariant mass Q'^{2}, weighted with the cross-section for either electroproduction or photoproduction of the meson (depending on the beam type selected by the user).

An input file specific to ρ^0 was created to allow the user to specify several parameters: beam type (electron or photon beams), beam energy, number of events generated, outgoing particles, target type, beam and target polarization, incoming photon virtuality (denoted with Q^2), and range of the angle of scattering. Since the ρ^0 meson has a very short lifetime, physical detectors will not be able to observe them directly, so they are reconstructed by the detection of their decay products. It effectively only has one decay mode, so the outgoing particles in its HEMP reaction are the π^+ and π^- particles [1]. The beam energy range is chosen to limit the range of Q'^{2} so that it covers the majority of the reconstructed ρ^0 peak, while cutting out other meson peaks. When the value of these cuts are determined and applied to experimental data, the background counts from other reactions are reduced, and we can observe isolated ρ^0 meson production with high confidence. The data can then be easily compared to the theoretical model. We have made a practice of generating 1,000,000 events to produce a large enough data set to understand the trends in the distribution. The target type we are concerned with is an unpolarized, stationary proton. The beam is also unpolarized.

The shape of the distribution of Q'^{2} follows a relativistic Breit-Wigner distribution [7] as follows:

$$f(Q'^2) = \frac{k}{(Q'^2 - M^2)^2 + M^2\Gamma^2} \tag{1}$$

where k is a constant:

$$k = \frac{2\sqrt{2}M\Gamma\gamma}{\pi\sqrt{M^2+\gamma}} \quad \text{and} \quad \gamma = \sqrt{M^2(M^2+\Gamma^2)}$$

with M, the mass of the particle, being 775.26 MeV, and Γ, the decay width, being 149.1 MeV [1]. The resulting shape (unnormalized and unweighted) is displayed in Figure 4.

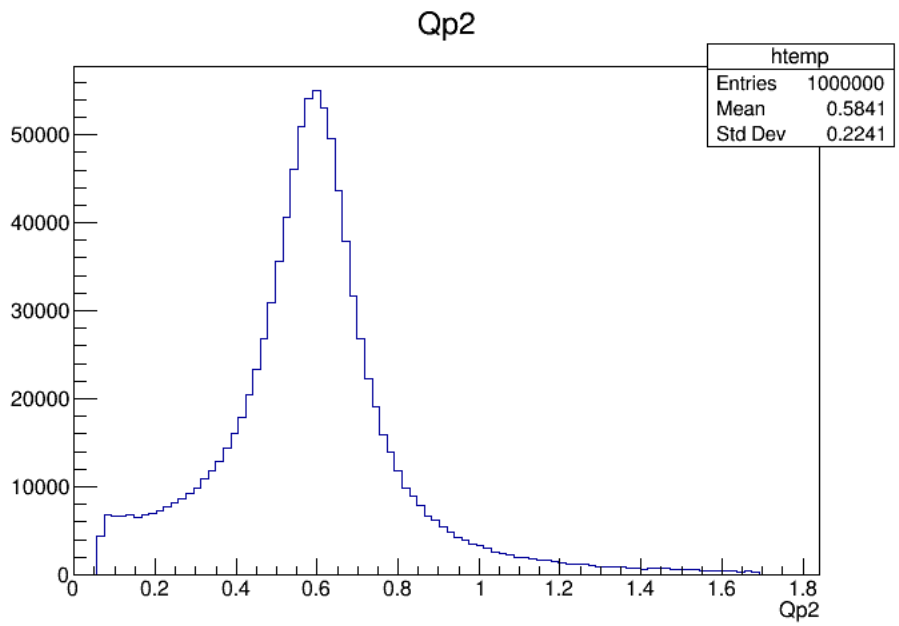

Figure 4: Unnormalized Breit-Wigner distribution of invariant mass (Q'^{2}) versus counts for ρ^0.

To weigh the output distribution with the likelihood of obtaining specific Q'^{2} values for ρ^0, we use its cross-section. The cross-section for its electroproduction may be calculated as the product of the effective photon flux and the cross-section its photoproduction as such:

$$\frac{d^2\sigma_{ep\to ep\rho^0}}{dydQ^2} = \Phi(y, Q^2) \cdot \sigma_{\gamma p\to\rho^0 p} \tag{2}$$

where the effective photon flux Φ is given by:

$$\Phi(y, Q^2) = \frac{\alpha}{2\pi Q^2 \left(1 + \frac{Q^2}{M_\rho^2}\right)^2} \left[\frac{1 + (1-y)^2}{y} - \frac{2(1-y)}{y} \left(\frac{Q^2_{min}}{Q^2} - \frac{Q^2}{M_\rho^2}\right)\right] \tag{3}$$

where y is the ratio of the gamma energy to electron energy, M_ρ is the mass of the ρ^0 meson (775.26 MeV), Q^2 is the invariant mass of the virtual photon, and Q^2_{min} is the minimum value of Q^2, based on conservation of energy from the electron's energy [9]. The cross-section of the photoproduction may be approximated as such:

$$\sigma_{ep \to ep\rho^0} = \frac{100}{8} \left(e^{8t} - e^{8t_{min}}\right) + \frac{3}{5} \left(e^{2.5t} - e^{2.5t_{min}}\right) \tag{4}$$

where t is the momentum out and t_{min} is the minimum momentum transferred based on energy conservation in relativistic kinematics [7]. Then $t - t_{min}$ is the momentum transferred in the reaction, whose distribution may be insightful to visualize.

It may also be insightful to calculate X_{bj} for each reaction, which is a dimensionless factor to aid in understanding the scale on which we make observations. It is not put to immediate use for the purpose of this project, but it is implemented in the code as such:

$$X_{bj} = \frac{Q^2}{2M_p E_\gamma} \tag{5}$$

where M_p is the mas of the proton, and E_γ is the gamma energy.

3 Analysis

3.1 Results

After implementing the HEMP reaction for ρ^0 into the event generator DEEPGen, we ran the code for 1,000,000 iterations, resulting in the distribution shown in Figure 5.

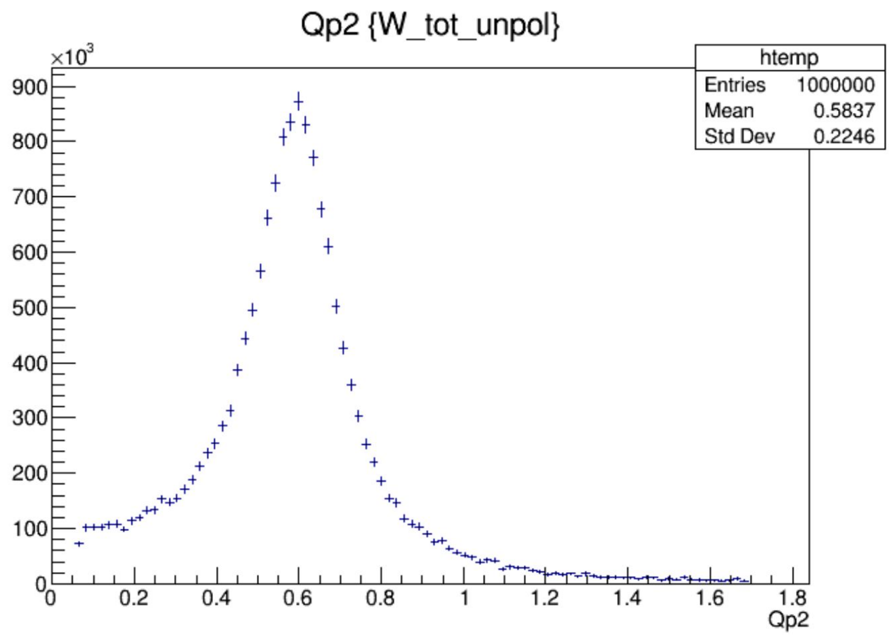

Figure 5: The invariant mass (Q'^{2}) versus counts distribution for ρ^0.

To visualize the distribution of momentum transferred in the reaction, we first look at the the total momentum out in Figure 6. The variable used in DEEPGen for the momentum is tt, and it is calculated as GeV with a negative number since it is momentum taken from the original particles. The variable for the minimum momentum calculated is ttmin, and it is also a negative value of GeV. Then the histogram of 7 is the distribution momentum transferred for the reaction.

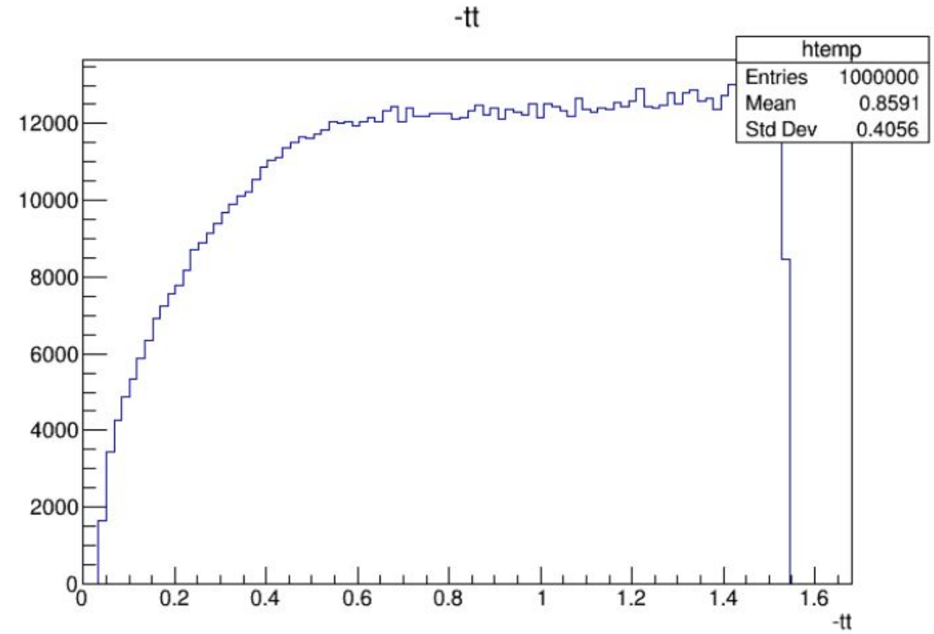

Figure 6: Distribution of meson momentum out. DEEPGen's variable for the momentum is tt, and it is calculated as GeV with a negative number. The axis of the histogram is inverted for a more intuitive understanding of momentum distribution.

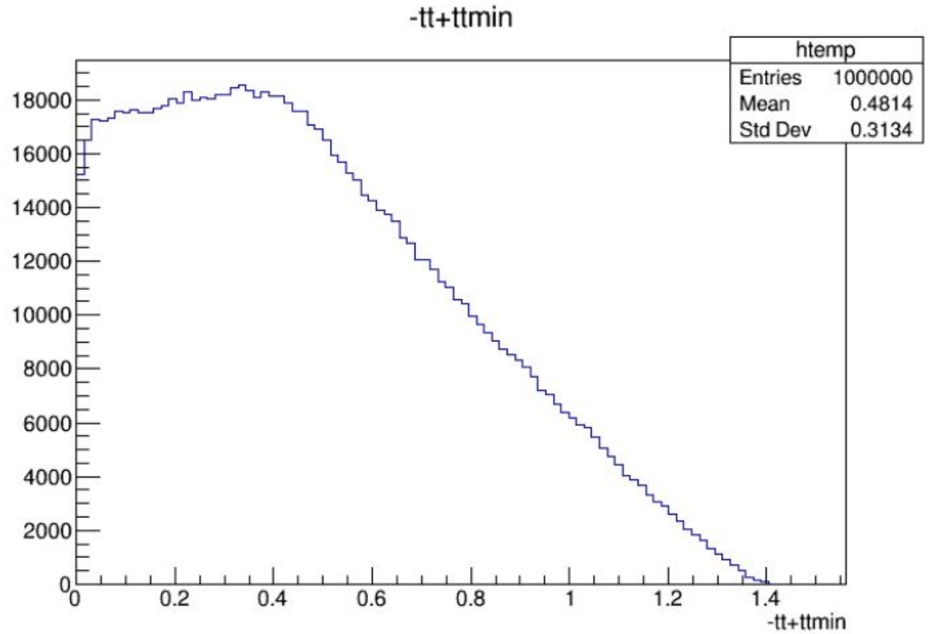

Figure 7: Distribution of momentum transferred. DEEPGen's variable for the momentum transferred is ttmin, and it is calculated as GeV with a negative number. The axis of the histogram is inverted for a more intuitive understanding of momentum distribution.

The plot of Q^2 versus X_{bj} is shown in 8, where the variables in DEEPGen are Q2 and Xbj, respectively. The plot shows a proportionality between the two, as expected.

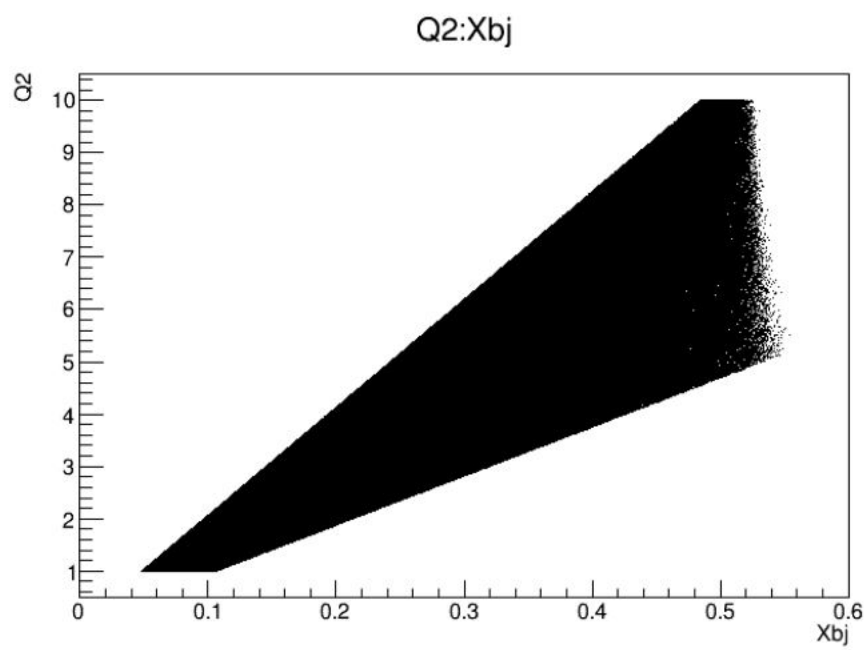

Figure 8: The plot of Q^2 versus X_{bj} shows a proportionality between the two, as expected.

3.2 Discussion

From Figure 6, we can see that the meson's momentum tends to be above 0.4 GeV, with a cutoff at about 1.55 GeV. From Figure From Figure 6 and 7, we can see that the momentum transfer tends to stay low, linearly decreasing in likelihood with higher higher values. Figure 8 shows the expected correlation between Q^2 and X_{bj}, which helps verify that it was implemented in the code correctly and may be used for future development of DEEPGen and DEEPSim.

The distribution generated for ρ^0 meson production in Figure 4 will guide us in determining the cutoffs in Q'^2 measurements in which we can observe the reaction, isolated for ρ^0, in experiments at Jefferson Laboratory and EIC. The study of this vector meson gives us access to the unpolarized H and E GPDs. Limiting the scope of Q'^2 allows us to make more accurate measurements for the production of the ρ^0 meson, providing better insight to GPDs. With better insight to GPDs, we can progress in utilizing them to understand the structure of the proton.

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