Studies of Hard Exclusive Light Vector Meson Electroproduction at Medium Energy

Seth Stuller
Mentor: Marie Boer
Physics Department, Virginia Tech,
Blacksburg, Virginia 24061, USA

Abstract: This semester, I conducted research within the field of Hadronic Physics under the supervision of Dr. Marie Boër. I worked with the DEEPGen event generator and an analysis code to implement and produce data for Hard Exclusive Vector Meson Production (VM-HEMP), and the generated events were analyzed. Our goal is to access Generalized Parton Distributions from the vector mesons, and in particular use their difference in masses to get a lever arm for tomographic interpretations, i.e. produce 3D images of the nucleon. I worked on implementing the event generator and analyzing the data. My work involved learning about quantum mechanics, special relativity, particle physics and computing (C++ and ROOT).

Introduction

Within the field of Hadronic Physics, much work is done to study the composition and behavior of subatomic fundamental particles. The standard model acknowledges two major subgroups of particles, bosons and fermions. Hadrons are subatomic particles that are composed of at least two quarks and are held together by a strong interacting force. Figure 1 depicts the various categories within the standard model.

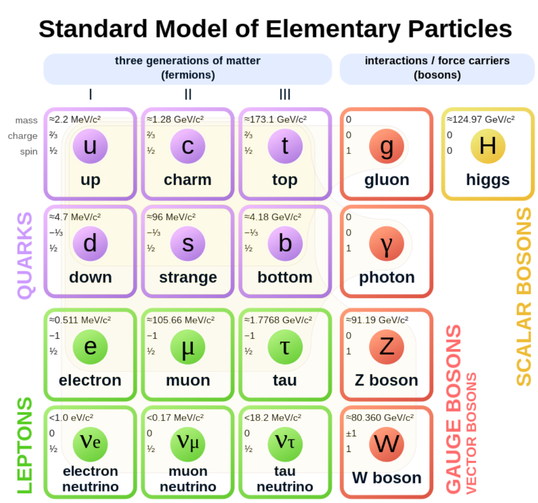


Fig. 1

Deeply Virtual Compton Scattering (DVCS) and Timelike Compton Scattering (TCS) are examples of reactions based on the scattering of photons off a quark within a nucleon, enabling us to extract information about the construction of the nucleon. Within Figure 2 we depict the generic Compton Scattering diagram.

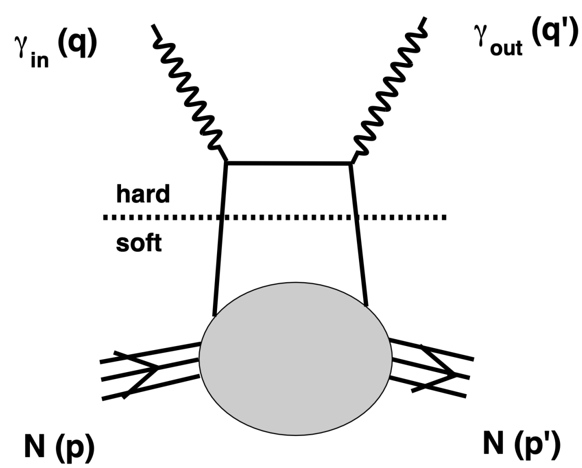


Fig. 2

Generalized Parton Distributions (GPDs) allow us to study the intrinsic variables of nucleons, revealing aspects of hadronic structure. The previously mentioned reactions reveal position and momentum distributions to eventually paint a 3D image of the internal structure of the nucleon.

In the case of DVCS, a highly virtual photon (with large virtuality Q^2) scatters from the nucleon and a real photon or a meson is produced. Due to the large scale Q^2 involved, these hard exclusive processes are factorizable into two parts. One of which can be calculated from perturbative QCD, and the other contains the information on nucleon structure and is parametrized in terms of GPDs. A schematic of the DVCS process can be seen below in Figure 3.

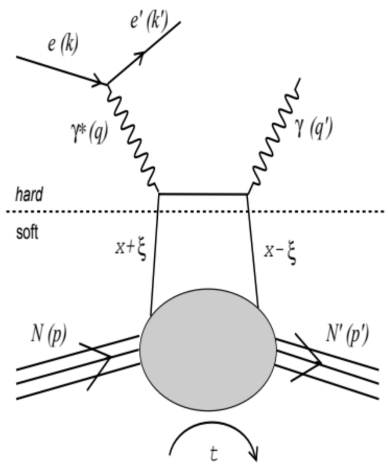


Fig. 3

Double Deeply Virtual Compton Scattering (DDVCS) can be described as the scattering of a spacelike virtual photon from the nucleon with the production of a virtual photon in the final state. Compared to the DVCS process with a real photon in the final state, the virtuality of the final photon in DDVCS yields additional characteristics that can be manipulated. For DDVCS, the Bethe-Heitler process also contributes to the amplitudes of the GPD.

The Bethe-Heitler (BH) process, in which the final state photon is radiated by the incoming or scattered electron and not by the nucleon itself. The BH cross section has the very distinct feature to sharply rise around φ=0◦ and 180◦. These are the regions where the radiated photon is emitted in the direction of the incoming electron or the scattered one. A diagram for the process in which both the BH process is interfering with DVCS can be seen in Figure 4.

The resulting behaviors from these processes is what holds the unique characteristics of the nucleon's structure. Hard Exclusive Meson Production depicts the process in which the outgoing photon is replaced by a meson.

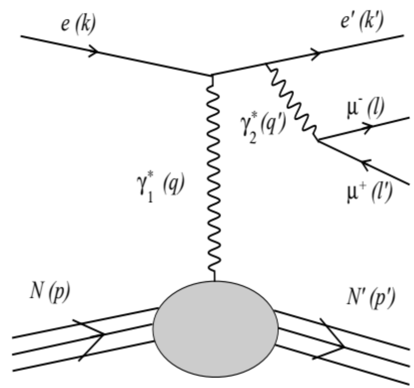


Fig. 4

Experiment

I started to work with code that generated DDVCS reactions and used it to implement meson production. Figure 5 depicts a schematic of the DDCVS reaction, and I will proceed to define the following independent variables:

- φ_L: The azimuthal angle between the plane formed by the incoming and scattered beam and the reaction plane
- φ: The azimuthal angle between the decay lepton pair and the reaction plane,
- θ: The polar angle of the electron compared to the virtual photon direction within the CM frame,

The DDVCS+BH unpolarized cross section depends on 7 independent variables, which we choose to be these 3 angles, and the 4 following invariants:

- t: Mandelstam variable, momentum transfer squared,
- Q^2: Virtuality of the initial photon,
- Q'^2: Virtuality of the outcoming photon,
- $x_{bj} = Q^2/2Mpv$: The Bjorken variable,

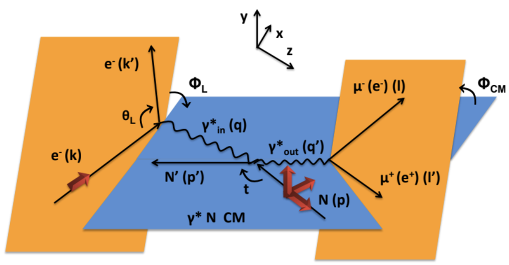


Fig. 5

If we take all the information from the previously described variables and fix Q'^2 to be the meson's mass squared, we can generate like mesons with the same code. The following sections of this paper will discuss the resulting reactions of three vector mesons: ϱ(770), ϕ(1020), and ω(782). All of which maintain a unique mass M and decay width Γ. The mass and Γ values can be seen in units of MeV listed below.

Meson	M	Γ
ϱ(770)	775.65 ± 0.12	149.1±0.8
ϕ(1020)	1019.461 ± 0.016	4.249±0.013
ω(782)	782.65±0.12	8.49±0.08

We use these parameters to constrain the Breit-Wigner distribution, characterizing the mass distributions of mesons decaying via strong interactions.

The Breit-Wigner equation is a continuous probability density function of mass, dependent on the decaying pair mass value, decay width, and center of mass energy. In this case we are mapping the mass distribution to the square root of Q'^2, or in other words $m^2 = Q'^2$. The distribution follows the following form $m^2 = M^2 + M\Gamma(\tan(x))$, where x represents the following.

$$\left[\tan^{-1}\left[\frac{m_{\min}^2 - M^2}{M\Gamma}\right] + \mathcal{R}\left(\tan^{-1}\left[\frac{m_{\max}^2 - M^2}{M\Gamma}\right] - \tan^{-1}\left[\frac{m_{\min}^2 - M^2}{M\Gamma}\right]\right)\right]$$

The total angular momentum follows a linear distribution between the given minimum and maximum value.

Techniques and Work Performed

As previously mentioned, my work revolved around implementing and optimizing one of the potential hard exclusive reactions. In order to do this, I felt it important to take my work in three major steps. The first of which was focused around learning what I can about this field of research. While I had previously taken a Nuclear Physics course here at Virginia Tech, nothing that was covered went as in depth with the kinematics and intricate calculations involved when it comes to extracting Compton Form Factors. Fortunately, I had been provided with a plethora of research papers and publications specializing in the desired reactions using the event generator.

Bringing me to my next major step; learning how the event generator functions. On a surface level, the source code that I had been provided was straight forward. The generator was developed to perform impact studies. The inclusion of options to simultaneously generate several observables in addition to the unpolarized cross sections. The source code is built using two independent functions. The first generates tables of cross sections as a function of kinematic invariants and angular variables. The second provides the calculation of the kinematics and four-vectors of particles involved in the process, and reads the tables for event weighting. Understanding the inner workings of the source code took up a large majority of my time for this project.

This step involved taking the provided source code, rewriting some of the internal functions and actions in Python and C++. I then generated data that depicted the variations of the five kinematic variables for the ϱ(770) meson. This served not only as a check that I understood how the event generator operated, but to gain some intuition of the expected values and behaviors of the kinematic variables. Graphs for the Mandlestrom Variable, it's minimum behavior, the Bjorken Variable, and both incoming and outgoing Virtuality of the ϱ(770) meson can be found in Appendix A. All generated data was crosschecked with known and accepted depictions of previously generated reactions.Primarily via the confirmation of my advisor Dr. Marie Boër.

The third step of my work was to implement the Breit-Wigner distribution within the event generator, forcing the Q'^2 of DDVCS to take the shape of the meson's mass distribution. Via the implementation of an internal function that allowed us to hardcode the mass and Γ values of each of the desired mesons, perform the calculation, and then replace what the generator had previously calculated with the mass distribution.

Results and Discussion

As previously stated, the desired event generation centered around three vector mesons, ϱ(770), ϕ(1020), and ω(782). Figures 6, 7, and 8 depict the mass distributions of those mesons in that order where the y-axis represents the number of events generated.

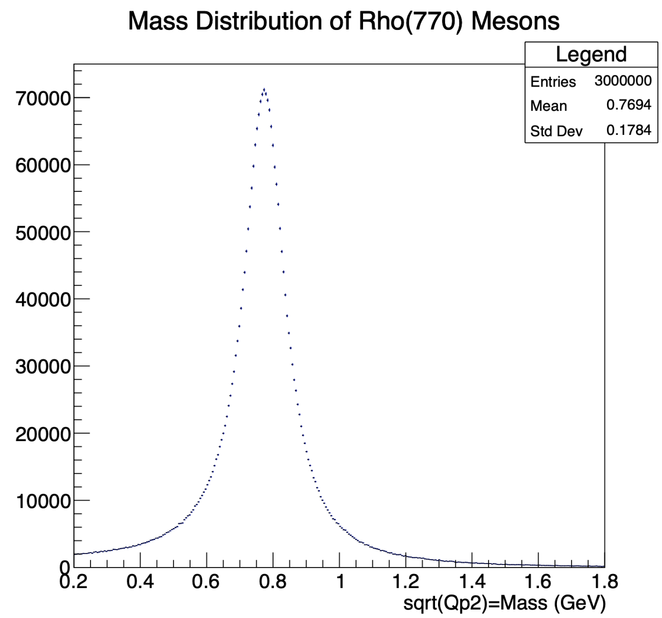


Fig. 6

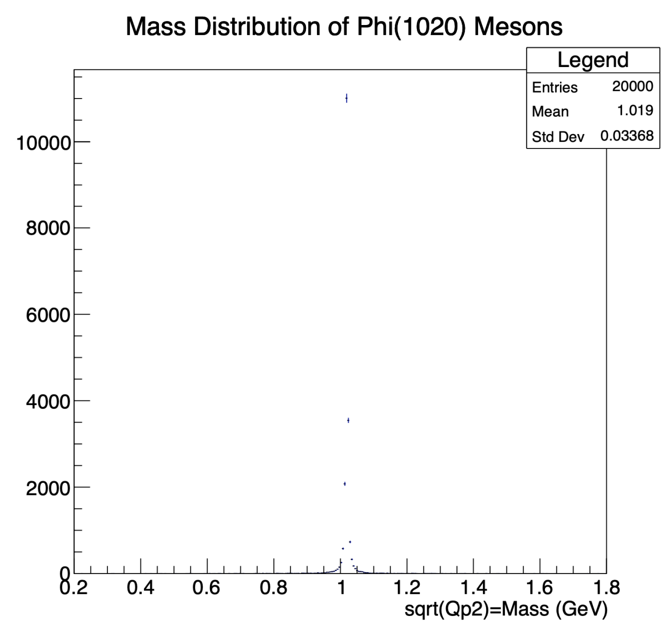


Fig. 7

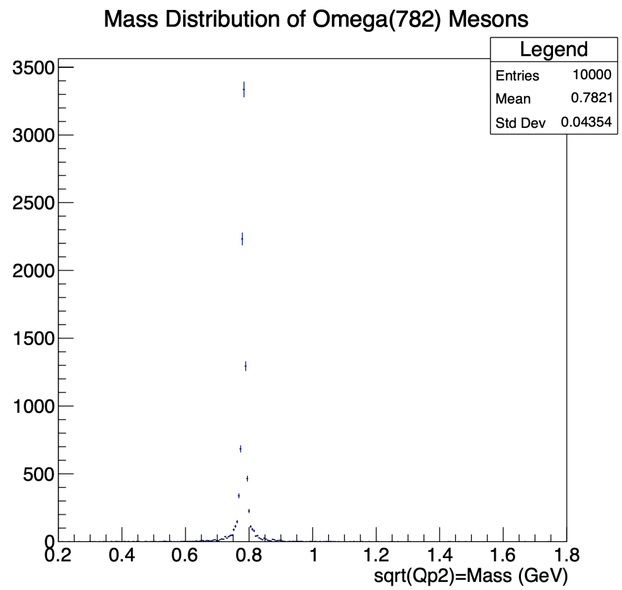


Fig. 8

All three mean values for the mesons fall into their accepted ranges. By implementing the Breit-Wigner distribution we are now able to differentiate the data produced by target mesons from that of interfering decay pairs.

The total number of events generated was selected to artificially influence and exaggerate their presence on graphs that overlap the three contributions, as shown in Figure 9.

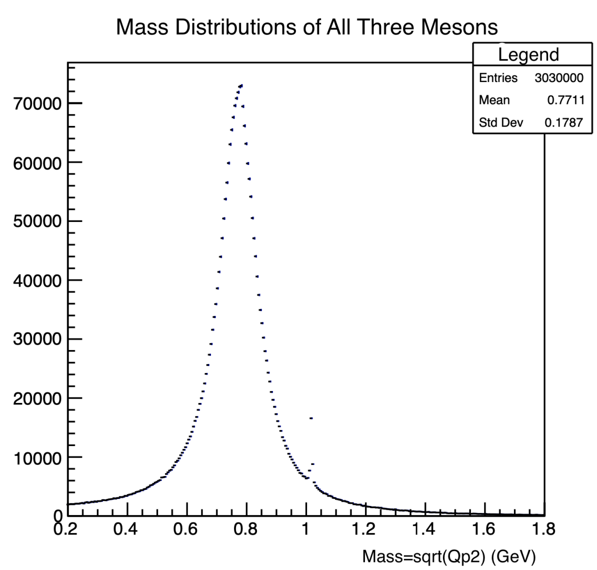


Fig. 9

All three contributions can now be seen as they contribute to the larger spectra of masses. With ϱ(770) being the most dominant peak, ϕ(1020) being represented by the smaller peak to the right; around 1GeV, and ω(782) being responsible for the right leaning skew of the ϱ(770) peak.

Additionally, we also took note of the mean Mandlestrom Variable and its minimum allowed values. In doing so we hope to gain some insight into the cross sections of the generated reaction. All three reactions generated information consistent with the predicted values. However, due to the similarity of the masses of three mesons, each individual graph did not yield information significantly different from the others. Figure 10 displays the data from the ϱ(770) reaction.

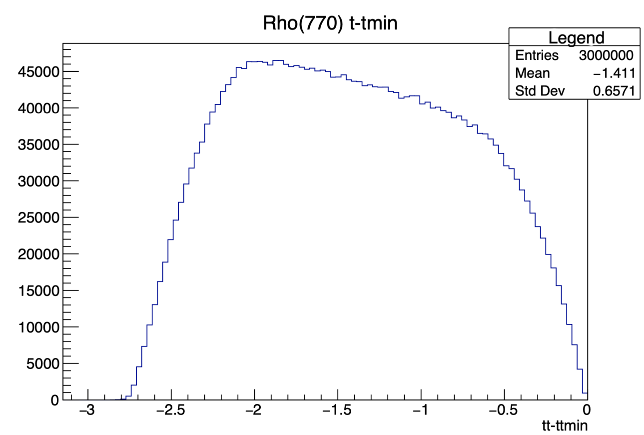


Fig. 10

Given more time, further work would be done to analyze the data of the provided graphs further in order to implement boundaries within the code to optimize accurate reaction data.

Conclusions

By analyzing the creation of specific mesons, we can complement research into various compton scattering reactions by allowing further investigation into certain regions of GPDs.

Moving forward we can use the generation of unique meson reactions to determine cutoffs for the properties of mesons when the time comes to generate these reactions in a non-virtual environment. Those cutoffs will then be implemented to reduce background noise from other decay ranges that will interfere with the data collection of the desired mesons. Within the generation of my own data, we had discovered that the version of the source code I was working with was missing a cutoff parameter that kept certain values from becoming less than zero, and skewing the generated mean values. In the near future this error will be corrected and pushed to a newer model, preventing the generation of unwanted and impossible data values.

Acknowledgements

I'd like to take a moment to thank all members of the Partonic Structure of the Hadrons research group and any other non listed source that aided my work throughout this project.

Bibliography

[1] Michel Guidal, Herv´e Moutard, Marc Vanderhaeghen, "Generalized Parton Distributions in the valence region from Deeply Virtual Compton Scattering", (2013).

[2] Michel Guidal, Marc Vanderhaeghen, "Double deeply virtual Compton scattering off the nucleon", Institut de Physique Nucl´eair, Institut für¨r Kernphysik, Johannes Gutenberg Universita¨t, (2002)

[3] Marie Boër, "Extraction of Compton Form Factors with combined fits of Spacelike and Timelike Deeply Virtual Compton Scattering", Temple University (2018).

[4] Marie Boër, "DEEPGen: an event generator framework to study polarized Deep Exclusive Electro- and Photo-production processes", Temple University (2018).

[5] Suh-Urk Chung, Boris Grube, "Muon-proton Production of the ρ", Technische Universit¨at M¨unchen (2009).

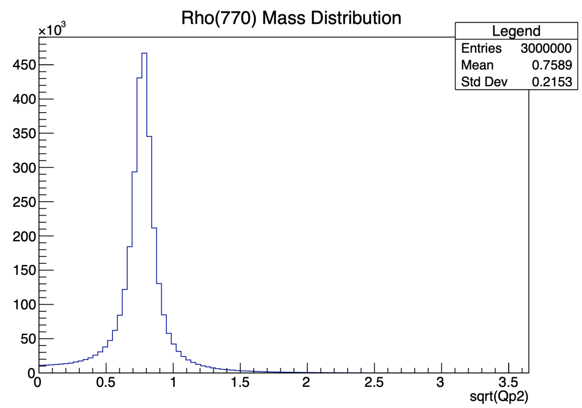
[6] The COMPASS Collaboration, "Transverse target spin asymmetries in exclusive ρ^0 muoproduction", European Organization for Nuclear Research (2013).

[7] The ZEUS Collaboration, "Measurement of the spin-density matrix elements in exclusive electroproduction of ρ^0 mesons at HERA", Eur. Phys. J. C 12, 393–410 (2000)

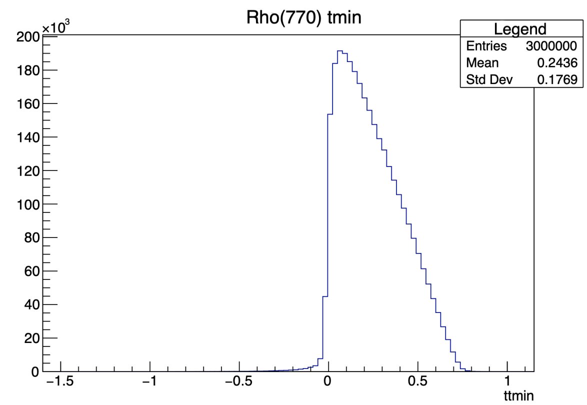
[8] Richardson, Peter. "Introductiontomontecarloeventgeneration lecture1 ..."https://indico.desy.de/event/7132/contributions/81219/attachments/54266/66073/richardson1.pdf.

Appendix

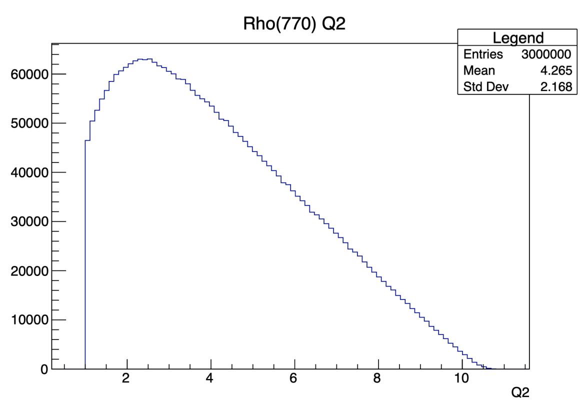
Note: All y-axis are in units of number of entries



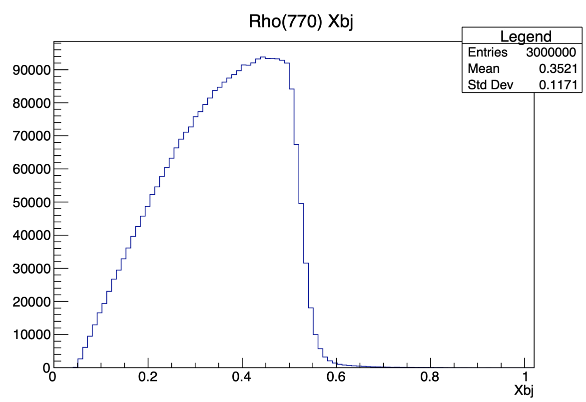
Appendix A: Rho(770) Mass Distribution



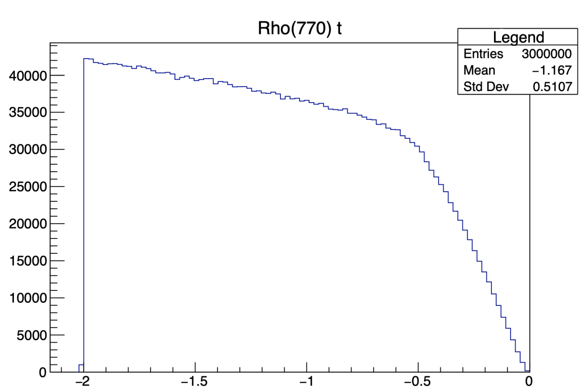
Appendix D: Rho(770) tmin Distribution



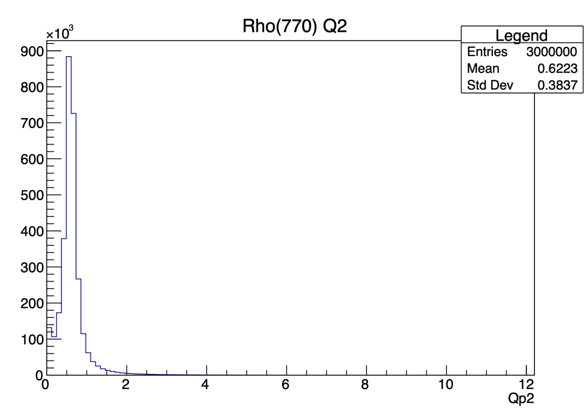
Appendix B: Rho(770) Q^2 Distribution



Appendix E: Rho(770) Xbj Distribution



Appendix C: Rho(770) t distribution



Appendix F: Rho(770) Q'^2 Distribution