The Production of $\rho(770)$ Mesons In A Physical Environment

Brendan Lorn (blorn)
Mentor: Marie Boer
Physics Department, Virginia Tech,
Blacksburg, Virginia 24061, USA

Abstract: The production mechanisms of mesons can reveal various things about the nucleon content. Mesons can be produced by a variety of exclusive reactions. These reactions can result in light and heavy mesons as well as other particles. The purpose of the research to be conducted is to understand the nucleon's inner structure in term of quarks and gluons thanks to the exclusive production of mesons. In particular, this research will be focused on the production of light mesons. Utilizing data from an event generator, a large amount of reactions and resulting particles will be recorded. This data will be analyzed to attempt to isolate the creation of $\rho(770)$ mesons from other background reactions. Utilizing cutoffs in mass, theta, and phi we see that we can recreate and isolate $\rho(770)$ mesons in a physical experiment using incoming virtual photons of 1 GeV^2 or higher.

I. INTRODUCTION

A large part of modern high energy physics is the analysis on the structure of the nucleon. The nucleon comes in two forms: the proton, a positively charged subatomic particle, and the neutron, a neutral charged subatomic particle.[1] These nucleons are comprised of elementary particles called quarks, antiquarks, and gluons. Quarks are the elementary blocks of matter and come in six different types as shown in Fig 1.

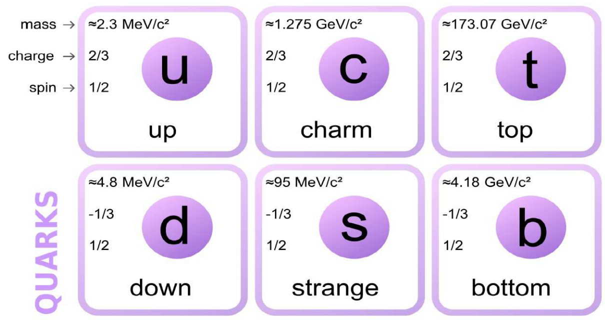

FIG. 1: A chart of the six different types of quarks: up, down, charm, strange, top, and bottom. Taken from "Hard Exclusive Reactions and Generalized Parton Distributions (2/2)".[2]

These elementary particles come in a variety of masses and electric charges while maintaining the same spin. Quarks also carry a color charge that can be one of three colors: red, blue, or green. For each quark there is a corresponding antiquark which are antiparticles with the opposite electric charge and color charge. Quarks can be combined to create hadrons, subatomic composite particles. For example protons consist of two up quarks and one down quark while neutrons consist of one up quark and two down quarks. Hadrons can be characterized into two families: the baryon, and the meson.[3] Baryons are particles that are made up of an odd number of quarks, like the proton and neutron, while mesons are made up of a quark and an antiquark. These particles are held together by the strong force carried by gluons. Gluons have very small mass and no electric charge. Unlike electrons and the electromagnetic force, gluons can interact with not only quarks and antiquarks, but other gluons.

Generalized Parton Distributions (GPDs) are functions combining multiple phenomenological functions such as form factors and parton densities to create a description of nucleons in terms of their subatomic particles.[4] One way to extract GPDs from a hadron is a process called Deeply Virtual Compton Scattering (DVCS). In DVCS, an electron is scattered off a nucleon which results in a photon being emited by the nucleon. This process can be seen in Fig 2.

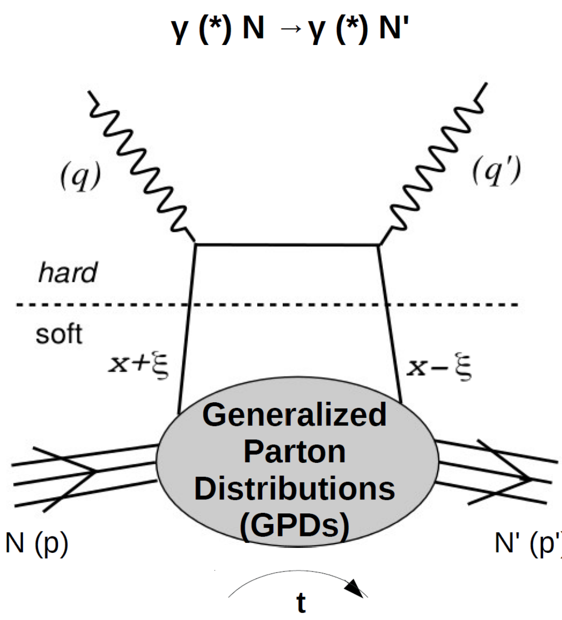

FIG. 2: Handbag diagram of the DVCS process. Taken from "Deeply Virtual Compton Scattering and Generalized Parton Distributions".[5]

Another process to extract GPDs is called Timelike Compton Scattering (TCS). In this process a photon is scattered off a nucleon resulting in a virtual photon being emitted. This virtual photon will later decay into two leptons. This process can be seen in Fig 3.

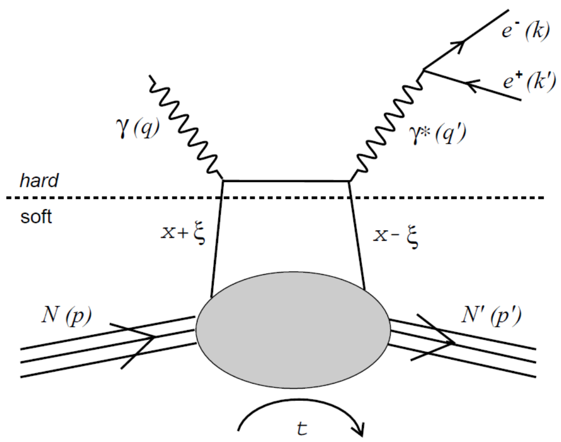

FIG. 3: Handbag diagram of the TCS process. Taken from "Trento contributions".[6]

These processes give a variety of information about the nucleon's structure. However, they are not the only processes of interest. Scattering a photon off of a nucleon can also result in the creation of a meson; a process called Deeply Virtual Meson Production (DVMP) as shown in Fig 4.

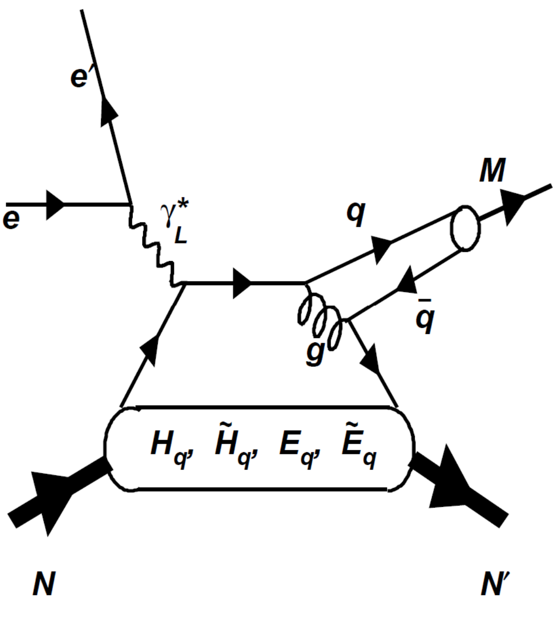

FIG. 4: Handbag diagram of the DVMP process. Taken from "Timelike Compton Scattering".[7]

This process has distinct features when certain mesons are produced and when scattering off certain types of nucleons. By isolating certain meson channels, more information can be gained from the analysis of DVCS and TCS reactions. The meson of interest in this experiment is the $\rho(770)$ meson. The $\rho(770)$ meson can be classified as $I^G J^{PC} = 1^+(1^{--})$ with I being the isospin, J being the total angular momentum and G, P, and C being different parities. The $\rho(770)$ meson will commonly decay into two pions (π meson). More charactisterics of the $\rho(770)$ meson are listed below in Table 1.

$\rho(770)$[8]	
Mass m	775.26 ± 0.25 MeV
Full width Γ	149.1 ± 0.8 MeV
Γ_{ee}	7.04 ± 0.06 keV

The mass of the $\rho(770)$ meson is characterized by a Breit Wigner distribution. By simulating the creation of $\rho(770)$ mesons we can determine the properties that make it different from other particles that are created in TCS and DVCS reactions. This will allow us to separate $\rho(770)$ mesons reactions from background reactions.

The experiment detailed in section II will isolate the $\rho(770)$ channel to see how to produce $\rho(770)$ mesons and by analyzing the production of an event generator, see if this experiment is viable in a physical setting at Jefferson Lab.

II. EXPERIMENT AND RESULTS

For this experiment, an event generator for various TCS and DVCS was adapted and modified to simulate the creation of $\rho(770)$ mesons. The C++ code for the event generator was based upon the DEEPGen Event Generator[9] created by Marie Boer. The first step to allow for the software to create $\rho(770)$ mesons was to allow a new type of reaction type. This was done by adding a new option that can be called which will accept a new input file. This new input file holds all the parameters that are needed for the reaction to create $\rho(770)$ mesons. This input files includes:

- Allowed energy range for the incoming electron or photon beam
- Type of outgoing meson
- Angle Ranges for ϕ and θ
- Number of events to be generated

Because we are looking for the $\rho(770)$ meson, the allowed energy range was set to be between 5.5 MeV and 11 MeV, the type of meson to be $\rho(770)$, and the number of events to be generated to be 1,000,000. This addition and new input file will give the code all the information it needs for the kinematics of the production of $\rho(770)$.

The software generation of mesons was added to the event generator to simulate the creation of $\rho(770)$ using the parameters from the input file. These mesons are created with the corresponding mass mirroring the values that would occur in a physical experiment. The mass of these particles are not exact, but follow a Breit-Wigner distribution as seen in Eq 1.

$$m\Gamma tan(y(x)) + m^2,\ where \tag{1}$$

$$y(x) = -arctan(\frac{m}{\Gamma}) + (\frac{\pi}{2} + arctan(\frac{m}{\Gamma}))x$$

To simulate the accurate creation of $\rho(770)$, a random generator using a Breit-Wigner probability distribution was added to represent the invariant mass of the outgoing mesons. The virtuality, Q'^2, is the square of the invariant mass so this value is squared and set to Q'^2. The total angular momentum follows a linear distribution between the given minimum and maximum value. Running the random event generator with the new input field yields the creation of particles following the distribution in Fig 5 and Fig 6.

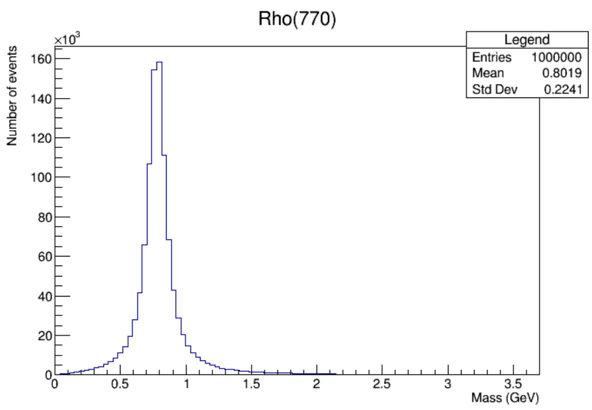

FIG. 5: Rho(770) meson mass distribution

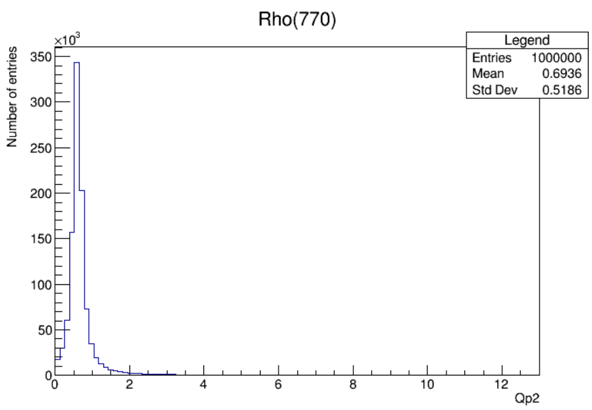

FIG. 6: Rho(770) meson Q'^2 distribution

As seen in Fig 5. using the event generator has generated events in the shape of a Breit-Wigner distribution with a mean mass of 0.8 GeV, which is within range of expectations of the mass of the $\rho(770)$ meson. The Q'^2 graph also lines up with the expected values.

III. DISCUSSION

Looking at physical TCS reactions we see that the virtuality of the resulting particles follows a decreasing trend as shown in Fig 7.

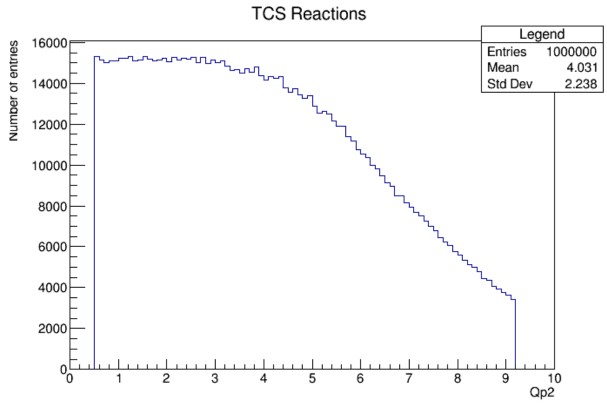

FIG. 7: TCS reaction distribution

From this data we see that a somewhat constant number of events within the range of 0.5 to 4 GeV while decreasing much more after. This means that there are a much higher number of reactions at the lower levels in comparison to the higher. A higher number of events means that a physical experiment would potentially have an easier time to observe mesons at the lower levels in comparison to the higher ones. For example, the $\rho(770)$ meson and J/ψ meson are mesons with differing masses. The $\rho(770)$ meson has a lower mass in comparison to the J/ψ meson, which can be seen in Fig 8. The J/ψ meson follows a gaussion distribution at a higher mass which means there are more spread out events in comparison to the $\rho(770)$ meson.

By selecting events within a certain regime of the TCS reaction we can isolate events that only produce mesons. For the $\rho(770)$ meson, the majority of events occur between 0.5 and 1.0 GeV so that would be the cutoff virtuality in a physical experiment. In comparison, the J/ψ meson would have a cutoff of 6 and 12 GeV. By using the cutoffs described, the amount of background noise can be reduced to more easily isolate the meson production reaction that is desired. However, if the cutoffs are too rigid then there can be some loss in accuracy due to some of the reactions being outside the cutoff range.

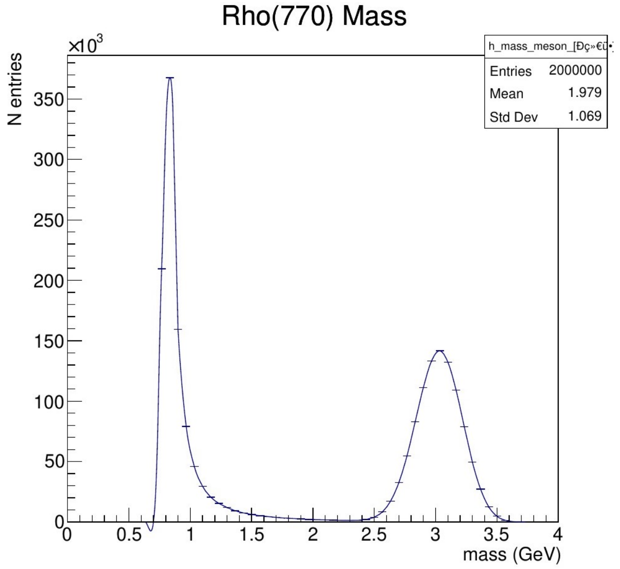

FIG. 8: Mass Distribution of Rho(770) and J/Psi mesons. Taken from combined data of Brendan Lorn and Erik Wrightson.

However, there is no guarantee that there are only mesons within a certain range of virtuality during a physical experiment since some of the produced particles could be outgoing photons, so more cutoffs need to be created to ensure that background reactions are filtered out. Some of these cutoffs include ϕ and θ which can be seen in Fig 9 and Fig 10. From the event generator data ϕ is evenly distributed from the values of 0 to 2π so there is no need for a cutoff, but for θ there is a cutoff from 0.5 to 2.6 rad.

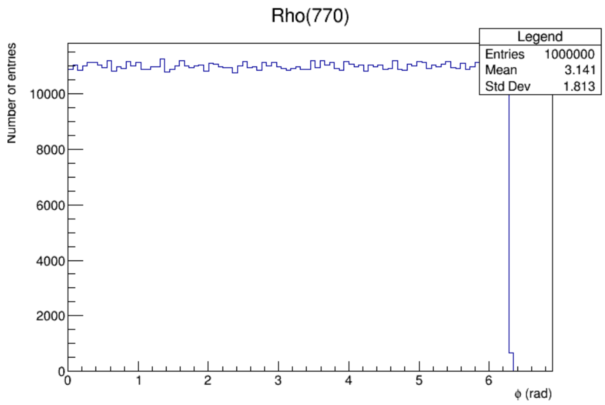

FIG. 9: Phi distribution.

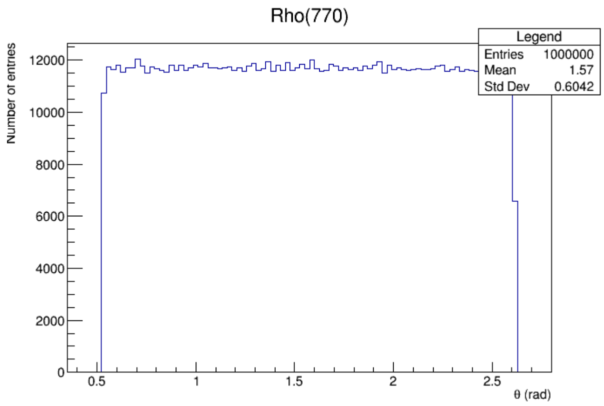

FIG. 10: Theta distribution.

There are also limits to virtuality to get light mesons to be produced. If the incoming photon is virtual, then Q^2 must be larger than 1 GeV^2. For a real photon, the outgoing photon must have a Q^2 value larger than 1 GeV^2 or the outgoing meson must have a mass of 1 GeV or higher. This means that its more appropriate to use virtual incoming photons with Q^2 larger than 1 GeV^2 since the mass of $\rho(770)$ is on the edge of this limit. While it is still possible to extract information about the nucleon's GPDs around this limit, there are higher order corrections that need to be added to the model to account for this limit. The data obtained from this experiment supports that light meson production can be replicated in a physical setting if these constraints are considered when conducting the experiment, revealing important information about GPDs and the nucleon's structure.

IV. CONCLUSION

By analyzing the creation of mesons, particularly light mesons such as $\rho(770)$, we can complement research into TCS and DVCS reactions by allowing further investigation into certain regions of GPDs. By looking at $\rho(770)$ mesons created in a virtual event generator we can determine cutoffs for the properties those mesons have to isolate them in a physical experiment. These cutoffs can be used to reduce the background reactions that would dilute meson production data. In a physical experiment, due to the limits that come from low Q'^2 extra constraints needed to be added to detect light mesons consistently, its still feasible. While this experiment looked at light mesons specifically, the type of meson can be varied to observe different regions of GPDs and gain further knowledge of the structure of the nucleon.

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