Partial Wave Analysis of the ϕ Meson

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Abstract

Quantum Chromodynamics (QCD) is the leading theory describing the nuclear, or strong interaction. The nuclear force binds the smallest known constituents of matter, quarks, together in states known as hadrons. Due to the Uncertainty Principle, these resonances have a broad mass, and often overlap with one another. One method used to study such resonances is Partial Wave Analysis (PWA), which separates these interfering states by decoupling contributing resonances to determine the individual wave contributions. This project performs a PWA on the two-kaon system in the reaction $\gamma\ p \rightarrow p\ K+\ K-$ on events produced during the g12 data run in the CLAS detector at Jefferson Lab. The PWA was used to determine the differential cross section of the ϕ meson to higher four-momentum transfer than previously studied.

1 Introduction

This experiment aims to measure how the cross section of the ϕ meson varies with four-momentum transfer (-t) in photoproduction, which describes the reaction's production mechanism. The pomeron is a hypothetical particle in Quantum Chromodynamics made of quarks and gluons with the quantum numbers of empty space. In pomeron exchange, either one or both of the interacting particles can be excited into high-mass resonances by the energy absorbed from the pomeron. Existing experimental data from the 1970's demonstrates that the production of the ϕ meson (Figure 1) is well described by pomeron exchange up to a four-momentum transfer of about $-t = 1\ GeV^2$ [1-5]. A more recent experiment by Anciant, et al., from the CLAS detector indicated that, at large four-momentum transfer up to $-t = 4\ GeV^2$ [6], the reaction is better described by two-gluon exchange (Figure 2). Anciant suggests that this occurs because, at larger -t, a quark in the ϕ meson and a quark in the proton get close enough to exchange two gluons, which do not have time to interact to form a pomeron (Figures 3 and 4). In this experiment, photoproduction of the ϕ meson was measured up to a four-momentum transfer of $-t = 7\ GeV^2$ (Figure 5).

Previous analysis of the ϕ meson has been conducted with sideband subtraction. Because resonances can overlap, sideband subtraction fits polynomials to background resonances and subtracts them from the distributions. PWA extracts more information about the wave contributions to the final data set because it looks at the angular momentum decomposition of the waves, as well as their interferences. By using PWA to study the reaction, we hope to get more accurate information about the t-evolution of the ϕ.

2 Methods

2.1 CLAS Detector

The Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) is the permanent detector in Hall B at Jefferson Lab. It is exposed to an electron beam, and in this experiment a converter was used to produce a photon beam incident on a stationary proton target. Toroidal magnets bend positive particles outward away from the beam line and negative particles toward the beam line. Drift chambers that surround the target are used to determine the momentum of outgoing particles, while time-of-flight scintillators determine the velocity. From these two pieces of information the identity of the particle can be determined.

2.2 Data

The data was obtained by detecting both the proton and the K+ in the CLAS detector, and then identifying the K- from the missing mass off of the K+ p. The reaction γ p → p K+ K- was produced from incident photons ranging in energy from 3.5 GeV to 5.5 GeV. Only the $\phi(1020)$ mass was considered for this analysis by making a cut on the mass of the KK mass system from 1.01 GeV to 1.03 GeV.

2.3 Monte Carlo

γ p → p K+ K- Monte Carlo events were generated with an incident beam energy from 3.5 GeV to 5.5 GeV in proportion to the flux of the experiment. These events had a -t slope of 2.4 GeV^2 to correspond with the data. These events were generated isotropically in the Gottfried-Jackson frame, or the rest frame of the ϕ meson with the beam along the z-axis and the y-axis normal to the production plane. Approximately ten million events were simulated through CLAS.

2.4 PWA

This analysis used the PWA program developed by Dr. Dennis Weygand. The PWA fitting program calculates decay amplitudes using quantum mechanics, and then fits the production amplitudes to the data (Figure 1) [7].

$$I(\tau) = \sum_{\varepsilon,k} \left\{ \left| \sum_{\beta} {}^{\varepsilon}V_{k\beta} \, {}^{\varepsilon}A_{\beta}(\tau) \right|^2 \right\} \tag{1}$$

V represents the production amplitudes, *A* represents the decay amplitudes, and τ represents the polar and phi angles of the K+ in the Gottfried-Jackson frame of reference. The intensity distribution is fit with the extended maximum likelihood function (Equation 2), which uses a Poisson distribution to determine an event's probability of being detected.

$$\mathcal{L} = \left[\frac{\bar{n}}{n!} e^{-\bar{n}} \right] \prod_{i}^{n} \left[\frac{I(\tau_i)}{\int I(\tau_i)\eta(\tau)d\tau} \right] \tag{2}$$

The η(τ) term is the detector acceptance function.

3 Results

A pure D wave with approximately 130,000 events was simulated to validate the fitting program (Figure 6). These events had no effects from the detector, and also had 100% acceptance. The PWA program was then asked to compare the input events to nine different waves. The fitting program returned near perfect results by indicating that the majority of the events were a D wave, with few events misidentified.

4 Discussion, Conclusions, and Future Research

Although the PWA program is still in development, these results are promising. The next step is to acceptance-correct the wave through the CLAS detector to see whether the PWA program returns the correct results. In addition, mixes of partial waves will be included. Once the fitting program is validated on simulated data, it will be applied to the $\gamma p \rightarrow p K+ [K-]$ data. We hope to do two analyses with this data. Of particular interest is the a_0(980) meson concentration underneath the ϕ, which has a high branching ration to KK. Though the a_0(980) is below threshold, the upper tail of its distribution can interfere with the ϕ. In addition, we hope to perform a PWA in bins of four-momentum transfer. This should allow us to determine characteristics of the ϕ production mechanism at higher -t than previously measured.

Because the ϕ is a clean signal, it should be simpler to perform the PWA (Figure 8). However, once the fitting program is validated and returns expected results on the low-mass ϕ, the same procedure can then be applied to higher KK resonances with less clean signals.

5 Figures

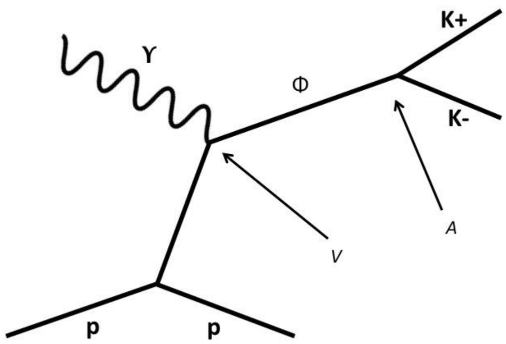


Figure 1: Feynman diagram of the reaction: γ p → p K+ K-. At low -t, the four-momentum transfer indicates that the exchange particle is a pomeron. At high -t, two-gluon exchange dominates ϕ production.

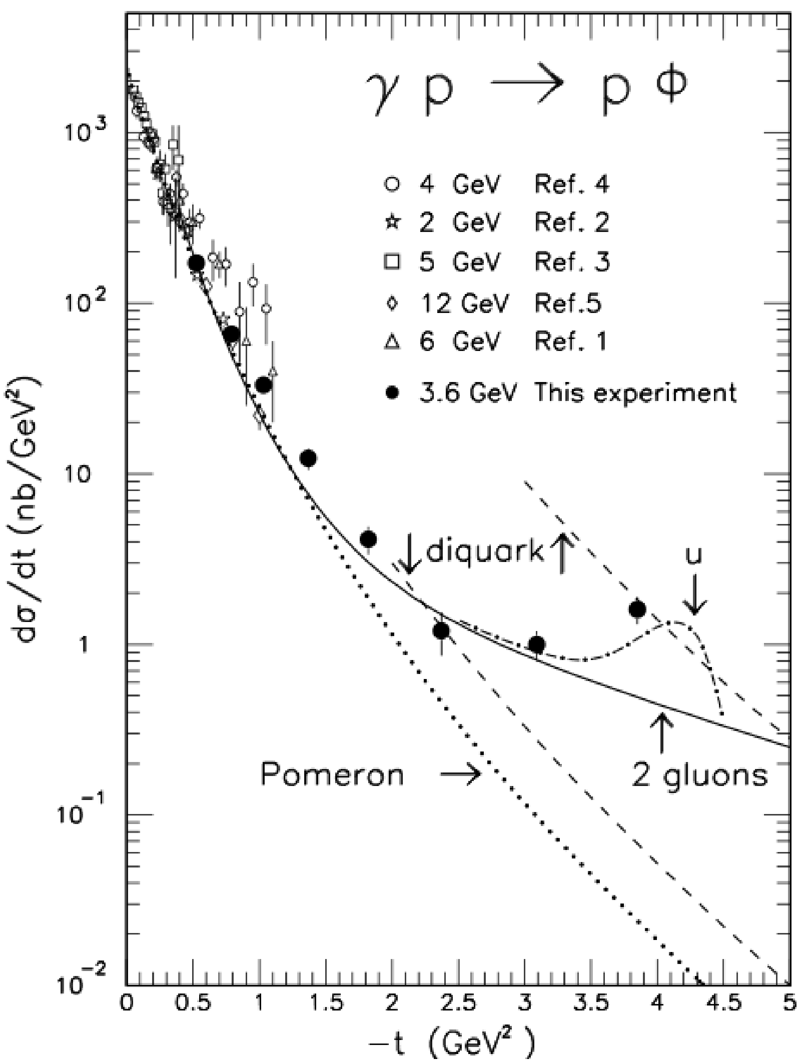
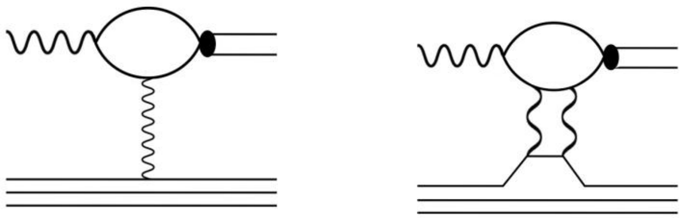


Figure 2: Anciant, et al's [6] results. At low four-momentum transfer, the differential cross section indicates that the ϕ is produced via pomeron exchange. At higher four-momentum transfer, the differential cross section rises, indicating that the ϕ is predominantly produced via two-gluon exchange. The results also indicate the possibility of u-channel production.



Figures 3 and 4: The connected quark diagrams of the interaction.

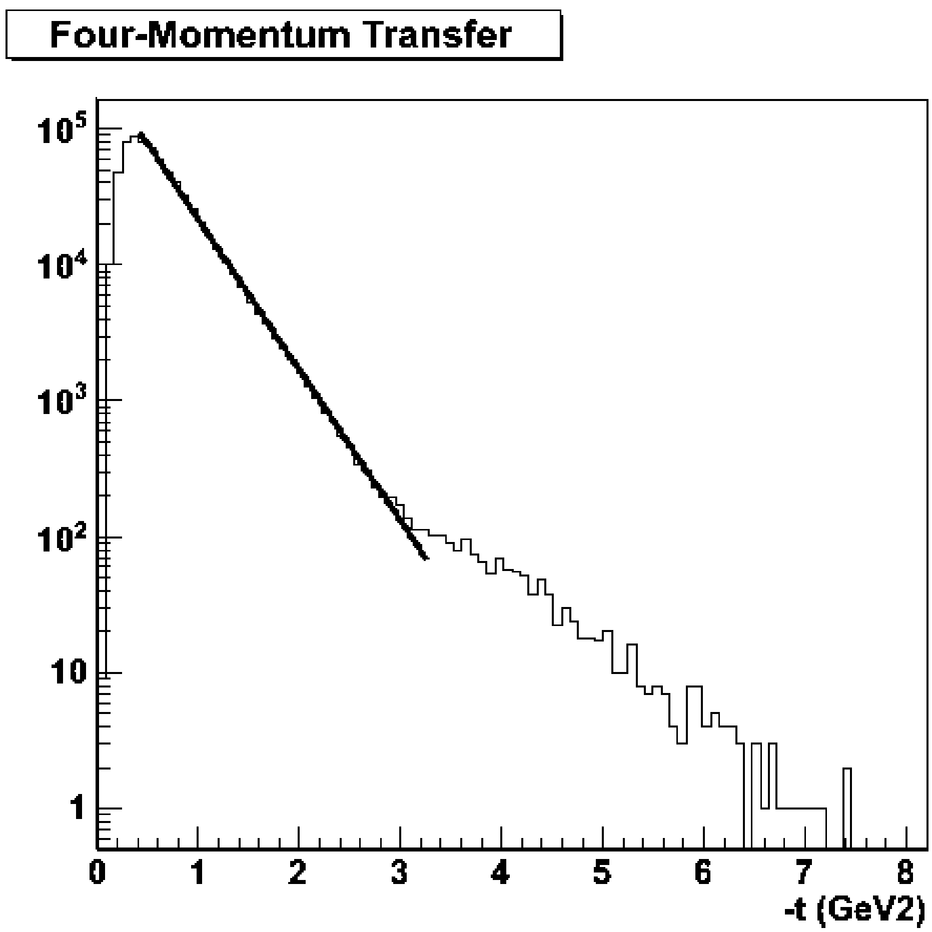


Figure 5: Four-momentum transfer of the ϕ events in this experiment. These events have not been acceptance-corrected, and include all events from 1.01 GeV to 1.03 GeV, but do demonstrate that we reach higher four-momentum transfer than previous experiments.

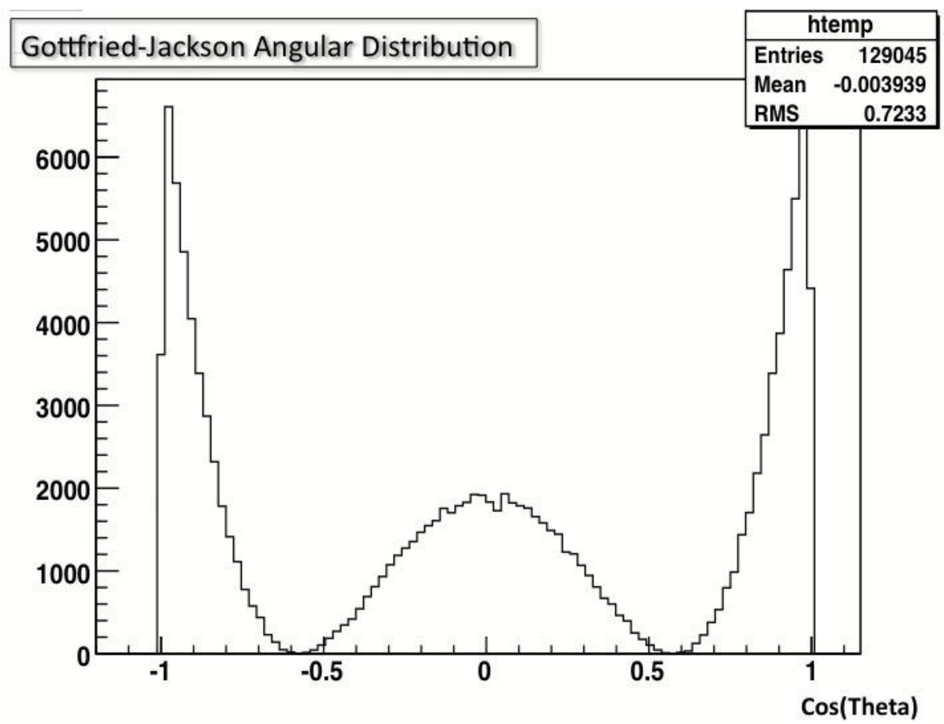


Figure 6: Pure simulated D wave. These events were given to the PWA program to validate the results.

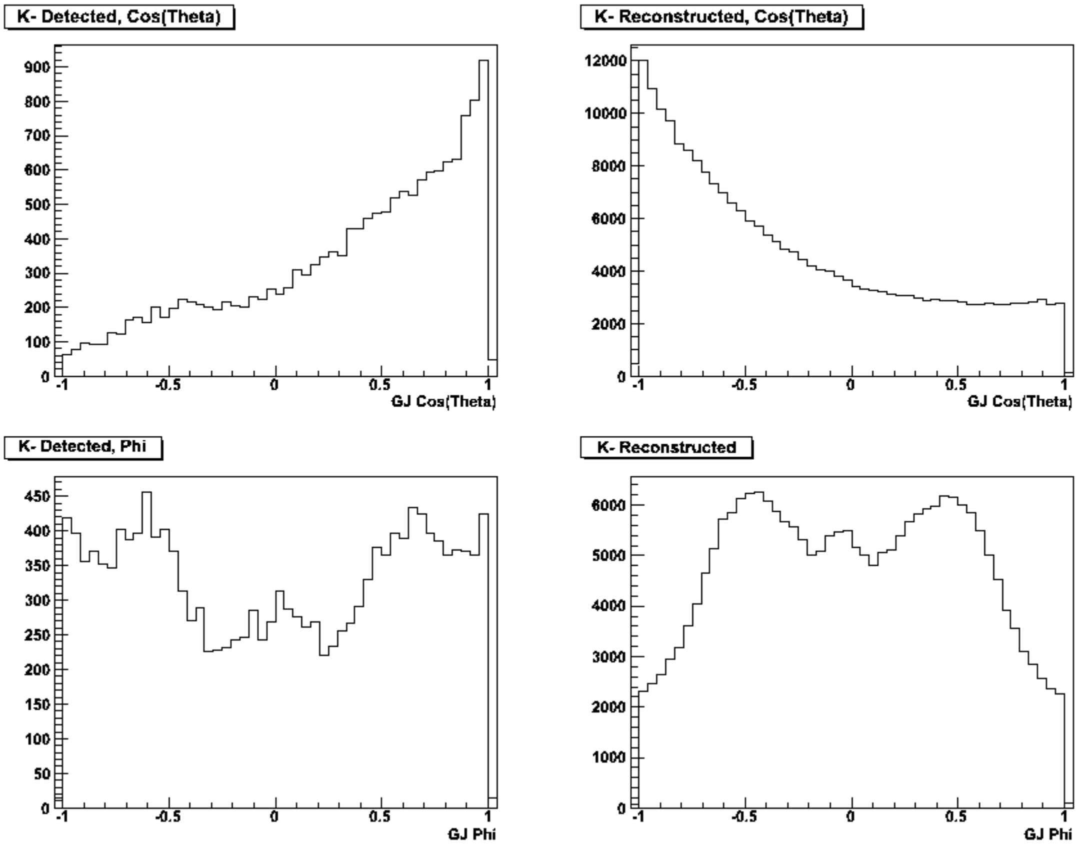


Figure 7: Angular distributions of the data in the Gottfried-Jackson frame. Two different data sets were used: one where the K- was detected (left), and one where the K- was reconstructed from missing mass (right). The top distributions are the cos(θ) distributions. The difference in structure is due to whether the K- was detected; if the K- is detected, it must be going forward in the detector because of the toroidal magnets. If the K- is reconstructed, the K+ is going backward into the detector.

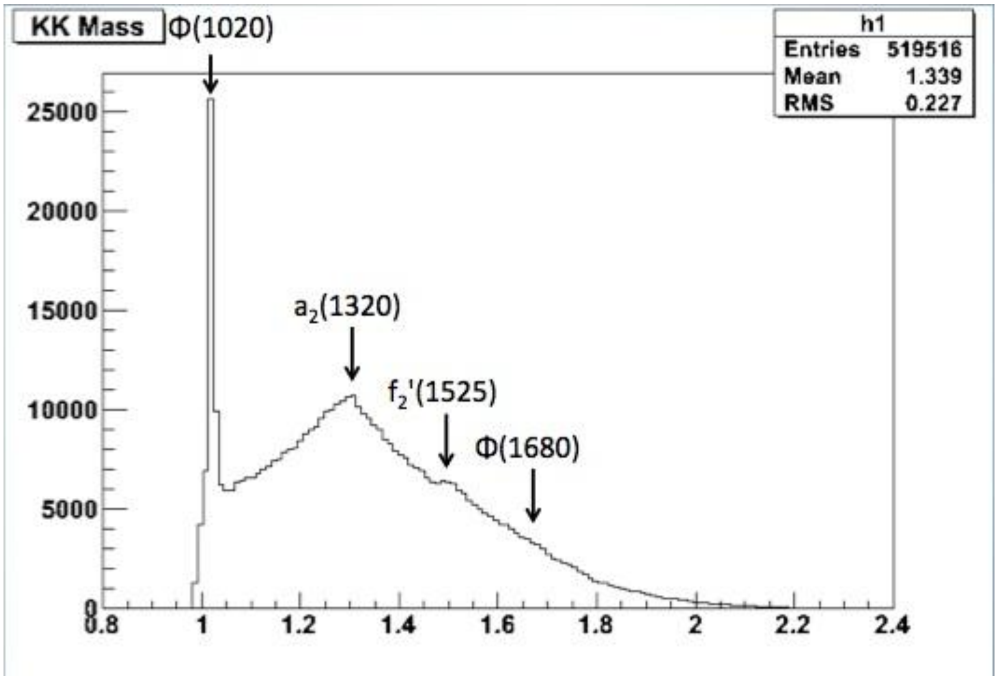


Figure 8: This analysis focuses on the $\phi(1020)$ resonance, which is a clean signal. Once the PWA program is validated, it can then be used to analyze higher-mass resonances.

5. Bibliography

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