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Meson Spectroscopy in Few-body Decays

Gary Adams,[6] G. Audit,[2] D. Armstrong,[8] John Cummings,[6] A. Empl,[6] J. Hu,[6] M. Khandaker,[3,5] J. Manak,[3] C. Marchand,[2] C. Meyer,[1] G. Mutchler,[7] Jim Napolitano,[6] Philip Page,[4] V. Punjabi,[5] C. Salgado,[3,5] S. Stepanyan,[3,9] P. Stoler,[6] D. Weygand[3], and the CLAS Collaboration

[1] *Carnegie Mellon Univ., Pittsburgh, PA 15213*
[2] *CEA Saclay, 91191 Gif/Yvette CEDEX, France*
[3] *Jefferson Lab, Newport News, VA 23606*
[4] *LANL, Los Alamos, NM 87545*
[5] *Norfolk State Univ., Norfolk, VA 23504*
[6] *Rensselaer Polytechnic Institute, Troy, NY 12180*
[7] *Rice Univ., Houston, TX 77251*
[8] *College of William and Mary, Williamsburg, VA 23187*
[9] *Yerevan Physics Institute, Yerevan, Armenia*

Spokespersons: G. Adams (RPI), C. Salgado[a] (NSU), and D. Weygand (JLAB)

Abstract

Photoproduction of mesons decaying to three-meson final states will be measured in CLAS. These measurements will sample the $\rho\pi$, $\eta\phi$, and K^*K meson decay channels. The data will be used to identify new mesons with masses up to 2 GeV. Spectroscopic information on exotic mesons and strangonium states will be extracted from a partial-wave analysis of the data.

a. Contact person.

1. Introduction

A great deal is known about the spectrum of low lying mesons, as one can easily see from an inspection of the PDG compilation. [Ba-96a] Numerous mass multiplets have been mapped out and coupling strengths to many final states are known. However surprisingly little order emerges from ones examination of mesons above about 1.5 Gev in mass. It is likely that our poor understanding of the known spectra is due at least in part to a lack of knowledge about gluonic configurations.

Photoproduction reactions have provided little spectroscopic information in the past, primarily due to the low intensity of the available beams. For example the Omega collaboration collected a total tagged photon sample of less than 10^{11} photons in the energy range 20-70 GeV. [At-84a] The CLAS spectrometer will allow us to make a detailed study of three-meson final states, which is expected to identify mesons with exotic structure (e.g. $q\bar{q}g$ hybrids) and those with dominantly $s\bar{s}$ configurations. It is particularly important to determine the strangonium spectrum in the vicinity of 2 GeV because they are expected to mix with the low lying glueball states. [Se-95]]

Several recent hadronic experiments have discovered new states with exotic quantum numbers $J^{PC}= 1^{-+}$. [Ad-98, Th-97] These states are incompatible with a simple $q\bar{q}$ assignment and therefore could represent an important component of the expected gluonic meson spectrum. If some of these states are excited with sufficient strength, photoproduction will allow us to confirm the quantum number assignments of the hadronic experiments. In addition, since the excitation mechanism will in general be different in photoproduction we can expect to identify new states that have not yet been observed in hadroproduction.

The beam-energy threshold for producing a 2 GeV meson is 4 GeV. Therefore it is necessary to use photons with energy well above this value in order to have sufficient phase-space for exciting the state in a peripheral process. This point is emphasized in the theoretical predictions of Afanasev and Page [Af-98], shown in Fig. 1.

2. Exotic Mesons in three-pion decays

Our present knowledge of low energy QCD suggests that a rich spectrum of hybrid mesons containing constituent gluon fields should exit in nature, [La-97, Be-97, Is-85] and yet only two solid candidates have been reported in the literature. [Ad-98, Th-97] The possibility of identifying a spectrum of mesons with exotic quantum numbers, for example $J^{PC}= 1^{-+}$, has prompted a great deal of interest. Since these states will not mix with the conventional mesons, they should provide interesting new constraints for QCD. Lattice gauge calculations place the lowest hybrids at less than 2 GeV, [Be-97, La-97] which is consistent with the earlier predictions of the flux-tube model. [Is-85]

The flux-tube model offers a simple explanation why exotic hybrids have been so hard to find. [Is-85, Cl-95] In this model the lowest lying states have ground-state quarks coupled to an excited gluon flux-tube, or string. The spectrum is then one of a quantum rotor with the excited states starting at around 1.9 GeV. Hadronic form factors suppress those decays which couple the flux tube orbital motion to relative motion of the final mesons. Thus two-body decays involving one L=0 and one L=1 meson are favored. It is important to note that our limited experimental knowledge of exotic mesons has come primarily from the unfavored channels $\eta\pi$ and $\rho\pi$. The presence of a strong isovector $J^{PC}= 1^{-+}$ signal at 1.6 GeV in $\rho^0\pi^-$ is particularly relevant to the present proposal since that decay populates the three-pion final state (see Fig. 2). [Ad-98] One should also note that in $\eta\pi$ hadroproduction there is a large signal in natural parity exchange, which again suggests a large $\rho\pi$ coupling for the exotic wave. From isospin symmetry one expects this state to decay to $\rho^+\pi^-$ as well.

One of the tenets of hadron spectroscopy is that new discoveries should be verified in as many separate experiments as possible. New states seldom show up as peaks in the experimental mass spectra and different partial-wave fits often yield different resonance interpretations of the same reaction. The high intensity tagged photon beam in CLAS is ideal for studying the few-body decays of excited mesons. If one assumes that a peripheral photon interaction can be described in terms of vector-meson-dominance (VMD) then a typical reaction of interest may be depicted as in Fig. 3. Theoretical estimates of hybrid meson photoproduction suggest that these states should be readily observed in 5-6 GeV real photon beams. One such prediction is depicted in Fig. 1. [Af-98]

Little work of relevance to three-pion photoproduction has been published. In the 20-70 GeV beam energy range the $\pi^+\pi^-\pi^0$ mass spectrum is predominantly isoscalar, with most events populating the $\rho\pi$ final states. [At-84a] The only high-mass feature that is visible in the unfitted data is a small isoscalar peak at 1.67 GeV, probably the $\omega_3(1670)$. Even this feature could not be rigorously studied due to the low statistics in the data. Older measurements in the 4.0-6.3 GeV beam energy range also show comparable strengths in all three $\rho\pi$ charge combinations. [St-76]

An experiment at SLAC revealed a peak at 1.775 GeV which is consistent with an exotic $J^{PC}= 1^{-+}$ assignment. [Co-91] However no partial-wave fits were done so a definitive assignment was not possible. The background-subtracted mass spectrum is shown in Fig. 4. Measurements at 5 GeV yield a cross section of about 300 nb for a low-statistics peak at this same mass (Fig. 5). [Ei-69] Both of those experiments measured the $\pi^+\pi^+\pi^-$ final state and the peak is visible in the $\rho^0\pi^+$ component as well. From isospin symmetry one expects this isovector state to have an equal decay width to $\rho^+\pi^-$ and $\rho^-\pi^+$. The $\rho^0\pi^0$ channel will be populated only by isoscalar decays. Clearly a high-statistics three-pion data sample coupled with a partial-wave analysis will be needed in order to make unambiguous assignments in this mass region. No matter what the outcome of such an analysis, the results will have a big impact on our understanding of exotic mesons. The present experiment will study this mass region in both the charged and neutral decay channels.

3. Strangonium decays to K^*K and $\eta\phi$

In principle the above discussion of hybrid meson decays to vector+pseudoscalar final states applies equally well to the strange-quark sector. The predicted $s\bar{s}g$ hybrids start at about 1.9 GeV as before, [La-97, Is-85] but in this case we have no experimental candidates to guide us in our choice of final states to study. The flux-tube model results would have us believe that K_1K is the preferred decay channel, [Is-85] but we already have experimental evidence of an exotic meson in $\rho\pi$ decay (not preferred by the flux-tube model) so one should not take this prediction too seriously. Thus $\eta\phi$, for example, emerges as a logical extension of the exotic meson search to isoscalar states. This decay will be detected in the $K^+K^-\eta$ final state.

Guided again by VMD we can speculate on the utility of photoproduction as a tool for conventional meson spectroscopy. Photons readily hadronize in low-t collisions, with a significant portion of the incident beam appearing as virtual ϕ mesons. Thus one can expect to excite $s\bar{s}$ mesons rather easily, as depicted in Fig. 6. As demonstrated in Fig. 7, the strangonium spectrum is poorly determined above 1.5 GeV. [Go-94] This is a particularly important issue due to the fact that pure-glue states, glueballs, are predicted to lie in this mass range. [Se-95] Overpopulation of the isoscalar tensor and scalar spectra has been a long-standing problem. [Ba-96b] Since glueball and conventional states are likely to be strongly mixed by the hadronic interaction it will only be possible to untangle their relative strengths by measuring a variety of production and decay amplitudes. Photoproduction offers a convenient tool to change the production vertex, and three-meson decays provide selectivity as well.

The predicted partial widths for typical non-strange quarkonia to decay to K^*K are in the range 5-40 MeV according to the $^3P_0$ model. [Ba-97a] In contrast, the same model predicts several $s\bar{s}$ states should have dominant K^*K widths. [Bl-97] For example, if the $\phi(1680)$ is assigned to the 2^3S_1 configuration a K^*K width of about 245 MeV is predicted. Conversely, this assignment yields an $\eta\phi$ width of only 44 MeV. The present experiment will provide valuable new data on these branching rates, and on the quantum numbers of any newly observed resonances. In our experiment K^*K and $\eta\phi$ decays will be detected in the hadronic states $K^+K^-\pi^0$, and $K^+K^-\eta$ respectively.

The $\phi(1680)$ state is a particularly interesting one to focus on because its structure is not well determined. It appears as a well defined peak in K^+K^- [Bu-89] and in e^+e^- production of K^*K. [Bi-91] The PDG lists its width as 150 MeV but with a large uncertainty. Surprisingly, the OMEGA experiment studied this mass region in K^*K decay but did not observe a peak. [At-84b] Unfortunately they did not obtain enough data to do a partial-wave analysis. Thus a partial-wave analysis of photoproduced K^*K events in CLAS will provide valuable insight into the nature of this state.

4. Experiment

The CLAS spectrometer is well suited to studies of peripheral production reactions which populate few-body final states. Using a 5.5 GeV electron beam one can tag photons which span the interesting mass region from 1.5 to 2.0 GeV. The photon energy threshold for producing a meson of mass M and a recoil proton is given approximately by,

$$E = M + \frac{M^2}{2}$$

therefore photon energies as low as 2.6 GeV are kinematically allowed. However the limited phase space available near threshold puts the useful threshold energy closer to 3.5

GeV. Therefore the entire upper 1/3 of the tagger range (3.5 to 5.2 GeV) will contribute useful data.

Typically the kinematics of peripheral production events is dominated by the characteristic t dependence of the low lying Regge trajectories,

$$\frac{d\sigma}{dt} = Ae^{-bt}$$

where t is the four-momentum transfer. Thus it is important to detect final-state particles at small angles.

The topologies of interest are $n\pi^+\pi^+\pi^-$, $pK^+K^-\gamma\gamma$ and $p\pi^+\pi^-\gamma\gamma$, where the two photons come from the decay of a π^0 or an η. We will typically detect the positive charged particles and the photons in those cases, and the negative mesons will be reconstructed by missing mass. For the $n\pi^+\pi^+\pi^-$ final state all three charged tracks will be detected, and the recoil neutron will be reconstructed by missing mass.

The running conditions for this experiment were chosen to match the next G6 running period. They are summarized in Table 1.

Table 1: Running conditions

E_e	$\geq$ 5.5 GeV
target	17 cm LH2
B field	maximum
trigger	2 charged particles; high E_γ tagger section; L2
acquisition rate	$\geq$ 2.0 kHz

The trigger electronics will require at least two charged tracks in CLAS, with positive charges bent outward. The required photons will be detected in the CLAS EC and reconstructed off-line.

The expected trigger rates have been estimated from the published level-1 rates, [Ba-97b] and from recent tests of the Level-2 rate. We estimate a total trigger rate of about 1.5 kHz, with most of the triggers coming from accidental coincidences between high energy tagged photons and low energy events or cosmic rays. Preliminary results from the previous G6 run show that these events are easily rejected by kinematic constraints.

5. Monte Carlo Simulations

The CLAS detector was simulated in its standard configuration for the topologies listed above, using the SDA program. Full field was used in the CLAS simulation. The events were generated with E_γ = 5 GeV and b = 5 GeV^{-2}.

The simulation of X(1775) decay to $\rho^+\pi^-$ was carried out in some detail, as was ϕ(1680) decay to $K^{*+}K^-$. These channels involve photon detection so they have worse resolution than the charged topology. Events were generated uniformly in the Gottfried-Jackson frame. The EC was simulated with a 300 MeV photon-energy threshold and 8% resolution. These parameters are in good agreement with measured data. For this study the detected particles were π^0, π^+, and p, in any sectors of the CLAS.

The missing-mass resolution is shown in Fig. 8. This is a conservative estimate because no kinematic fitting has been done on the photons, therefore the π^0 mass constraint has not yet been applied. Constrained fits are now underway, but these results already show sufficient resolution to reject most events with two missing pions. This is an important result since many of the triggered events will contain baryon resonances in the final state. One can gain some insight into the relative importance of this cut by comparing the cross section for four pion production to that for three pion production. Total cross sections have been published for $\rho^0\pi^+\pi^-$ and $\rho^0\pi^+$ channels and there the four pion yield is only about 30% of the three pion yield. [St.-76] These background events are also depicted in Fig. 8, assuming they follow a phase space distribution.

The decay angular distributions of the ρ in the resonance center-of-mass frame are shown in Fig. 9. We observe that the center-of-mass acceptance of the CLAS spectrometer is rather smooth, despite the fact that the detector has dead regions which are localized in the laboratory frame. Also note that $\rho^+\pi^-$ decays are accessible in two very different combinations of detected particles, $p\pi^+\gamma\gamma$ (missing π^-) and $p\pi^+\pi^-$ (missing π^0). This will allow independent analyses to be made on the same channel, thus providing a valuable check on the accuracy of the results.

The overall detector acceptance for some of the important decay channels is summarized in Table 2. We find acceptances in the range 7-25%, which is comparable to

Table 2: CLAS acceptance for a two charged particle trigger. The standard CLAS configuration was assumed.

meson decay channel	topology	CLAS acceptance
$\rho^+\ \pi^-$	$p\pi^+\pi^-\gamma\gamma$	0.25
$\rho^0\ \pi^+$	$n\pi^+\pi^+\pi^-$	0.11
$K^{*+}\ K^-$	$pK^+K^-\gamma\gamma$	0.07
$\phi\eta$	$pK^+K^-\gamma\gamma$	0.10

values observed in BNL experiment E852. We expect similar values for the other experimentally accessible channels $\rho^-\pi^+$ and $\rho^0\pi^0$.

6. Data Rates

In order to estimate the running time required for this experiment, we assume running conditions similar to those in the previous G6 run. The average tagging rate in the upper section of the tagger will be about 10 MHz. A 17 cm LH2 target is assumed. The data rates in the vicinity of the X(1775) are estimated for the $p\pi^+\pi^-\gamma\gamma$ and $n\pi^+\pi^+\pi^-$ topologies, and the rates for $\phi(1680)$ are estimated for the $pK^+K^-\gamma\gamma$ topology. The detector acceptance was taken from Table 2 in each case. Finally, we assume an overall 50% reconstruction and data reduction efficiency, including rejection of tagger accidentals and baryon resonance events.

The total cross section for $\rho^+\pi^-$ photoproduction is known for 5.0-6.3 GeV photons. [St-76] It is about 1.3 μb, or 65 nb per 50 MeV mass bin. Mass spectra from that experiment are shown in Fig. 10. The data will be sorted into approximately 20 mass bins. The $\rho^+\pi^-$ yield represents about 11% of the total $\pi^+\pi^-\pi^0$ yield (excluding ω and η decay) so we can expect a production cross section of 590 nb per mass bin in the interesting region. This will produce data at the rate of 4.1 events/s per mass bin. Applying the CLAS acceptance (0.25) and analysis (0.5) factors we will measure a rate of 0.52/s per 50 MeV bin.

In principle the actual strength going to any particular state, such as the X(1775), will depend on the allowed exchange spectrum, which may be different for the charged and neutral production. The total production cross section for $n\pi^+\pi^+\pi^-$ is about 250 nb per mass bin, yielding a data rate of 0.10/s per bin.

The cross section for $K^{*+}K^-$ photoproduction was measured at 20-70 GeV by the OMEGA collaboration. [At-84b] They obtained a cross section of about 0.64 nb per 50 MeV mass bin. This represents about 16% of the total $K^+K^-\pi^0$ yield. Our lower beam energy should increase the yield somewhat for resonance production so we estimate a cross section of 1.3 nb per 50 MeV bin for $K^{*+}K^-$ production, and about 8 nb per bin for the total $K^+K^-\pi^0$ production cross section. The data will be sorted into approximately 20 mass bins. This will produce an event rate of 0.057 events/s per mass bin. Applying the CLAS acceptance (0.07) and analysis (0.5) factors we will detect a total rate of 0.0020 events/s per 50 MeV bin. Kaon decay will reduce this rate by a small amount. As for the three-pion case, the actual strength going to any particular resonance, such as $\phi(1680)$, has not yet been determined. These rates are summarized in Table 3.

Table 3: Detected rates per day in one mass bin.

$p\pi^+\pi^-\pi^0$	45,000
$n\pi^+\pi^+\pi^-$	8,600
$pK^+K^-\pi^0$	173

From these estimates we see that all three topologies will each provide large data samples which will enable us to perform an accurate partial-wave analysis. Using a target value of 1700 events per mass bin for the smallest of the three rates listed above, we arrive at a total beam-time request of 10 days. Much larger rates will be measured for the pion channels than the kaon channels. Therefore it will be possible to sort the pion data into several beam-energy bins.

7. Partial-wave Analysis

A partial-wave analysis of the data is essential if one is to obtain reliable resonance information. We will use the BNL E852 partial-wave code, modified to accommodate incident photons, to fit the present data. This code uses the isobar model to make a maximum likelihood fit to each bin in total mass. Our experience with previous three-pion fits suggests that stable fits can be obtained with as little as 1000 events in each mass bin. It is impossible to make an accurate estimate of the resulting resonance information without knowing the spectrum ahead of time, but it is clear that the expected data samples will easily allow the dominant waves to be extracted. Since very little is known about meson photoproduction in this mass region, it is very likely that interesting new spectroscopic information will be obtained.

One final point that needs to be addressed is the systematic uncertainty associated with a partial-wave analysis. Finite acceptance and resolution can conspire to shift strength from a large wave into a small wave at the same mass. Since we are in fact quite interested in the dominant waves that will emerge from our fits this is not a major issue. However since this effect ultimately determines the reliability of the small amplitudes we have studied it for CLAS.

In a test of the three pion PWA, events corresponding to two coherent waves were generated at a mass of 1.775 GeV. We label the waves according to J^{PC} M^{ε} L m, where these are the angular momentum, parity, C-parity, spin projection, exchange naturality, orbital angular momentum of the isobar and pion, and isobar, respectively. Events were generated in the 2^{++} 1^{+} D ρ^0 (53%) and 1^{-+} 1^{+} P ρ^0 (42%) waves with a 45 degree relative phase. The fit erroneously assigned about 1% of the events to the exotic 1^{-+} 1^{+} P ρ^{+} wave. Thus we conclude that in spite of the unusual angular acceptance of the CLAS detector we will be able to make an accurate PWA analysis of the complex three-meson systems. The fits will provide spectroscopic information for all but the very small waves. Studies are now underway to asses the effect of geometrical errors on the fit.

8. Other JLAB Experiments

Few meson spectroscopy experiments have been approved for beam time in Hall B, and none in the other halls. The one which has the biggest influence on the present proposal is 93-031, “Photoproduction of Vector Mesons at High t”, by Marchand, et al. The physics goals of that experiment are restricted to the ρ, ω, and ϕ so there is no overlap with the present proposal. As discussed above, we will take our data during the time they already have scheduled in the next G6 running period. Only one meson -photoproduction experiment, 94-121, “Exotic Meson Spectroscopy with CLAS”, G.S. Adams et al., intends to study the meson spectrum above 1.5 GeV. In that experiment we require high multiplicity triggers and a displaced target in CLAS, so even though there is overlap in the physics goals the data that will be measured are quite different. In fact, the present proposal is intended to be a prototype for 94-121. The results will help justify a dedicated run with a displaced target later on.

Two electroproduction experiments have similar physics goals to the present experiment. Since we are proposing a photoproduction experiment they are complementary to our proposal. Experiment 94-118, “Search for $J^{PC}= 1^{-+}$ Exotic Mesons...”, I. Aznauryan, et al., will study only the $\eta\pi$ final state so there is no overlap with the present proposal. Also, experiment 93-012, “Electroproduction of Light Quark Mesons”, may be sensitive to some of the spectroscopy that is proposed here even though the primary focus of their proposal is to measure form factors.

9. References

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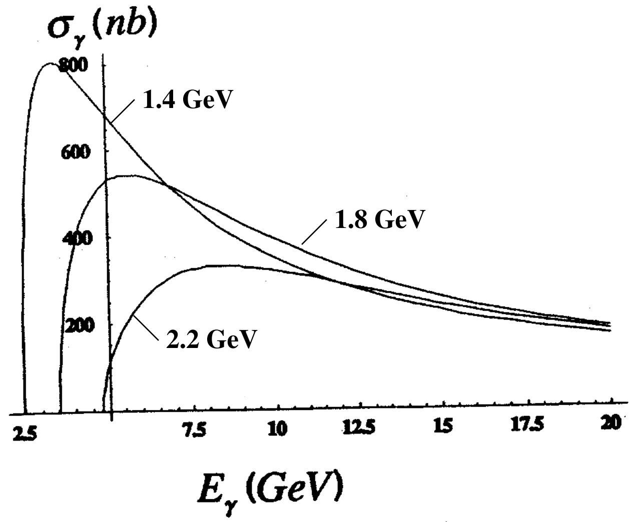

Fig. 1 - Theoretical cross sections for photoproduction of a hybrid meson by charged pion exchange. The curves are for an assumed mass of 1.4, 1.8, and 2.2 GeV.

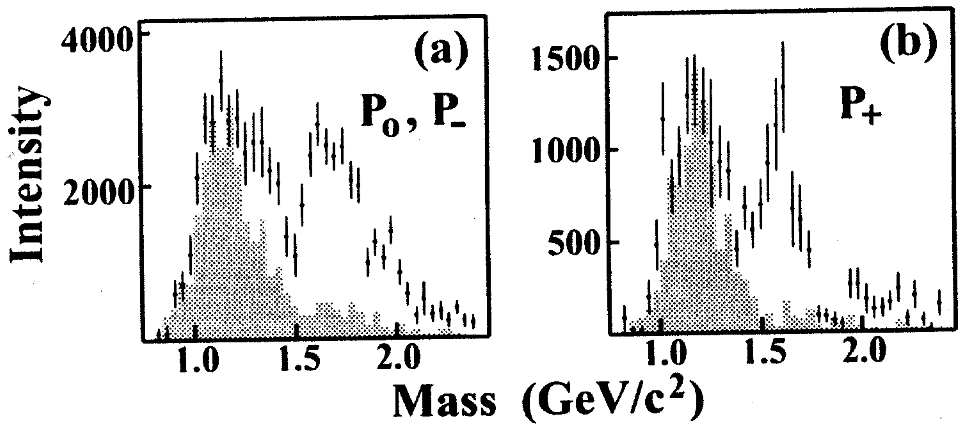

Fig. 2 - P-wave intensities for hadroproduction of 1^{-+} exotic waves with spin projection and naturality M^{ε}equal to a) 0^{-} and 1^{-}, b) 1^{+}. Note the resonance peaks at 1.6 GeV.

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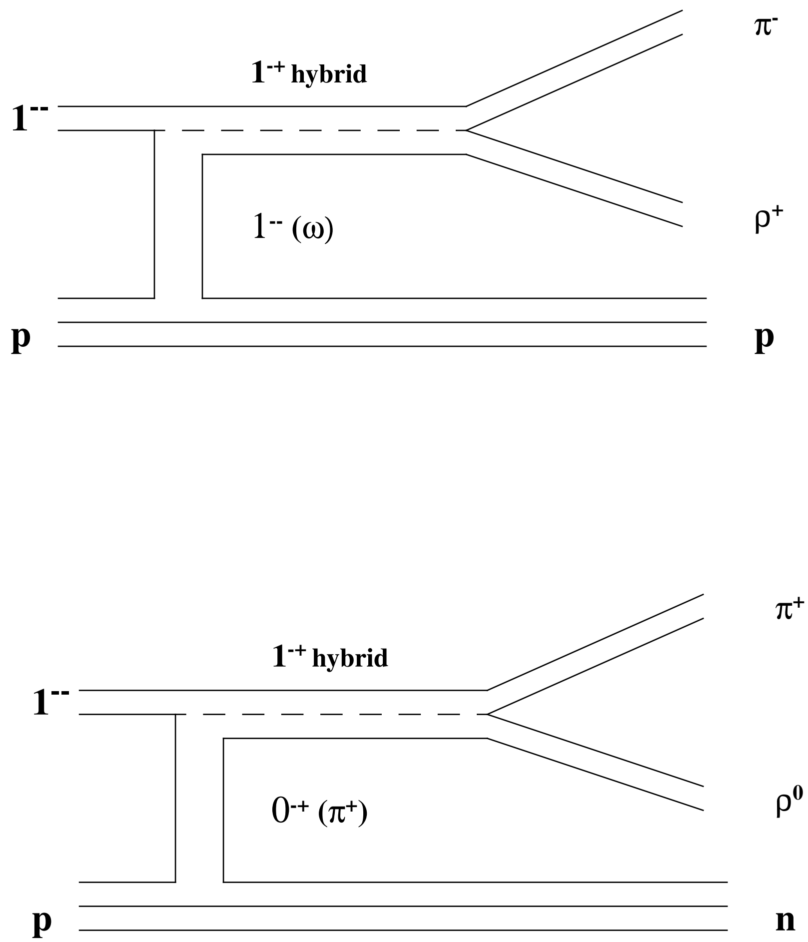

Fig. 3 - Possible excitation mechanisms for hybrid mesons, assuming VMD.

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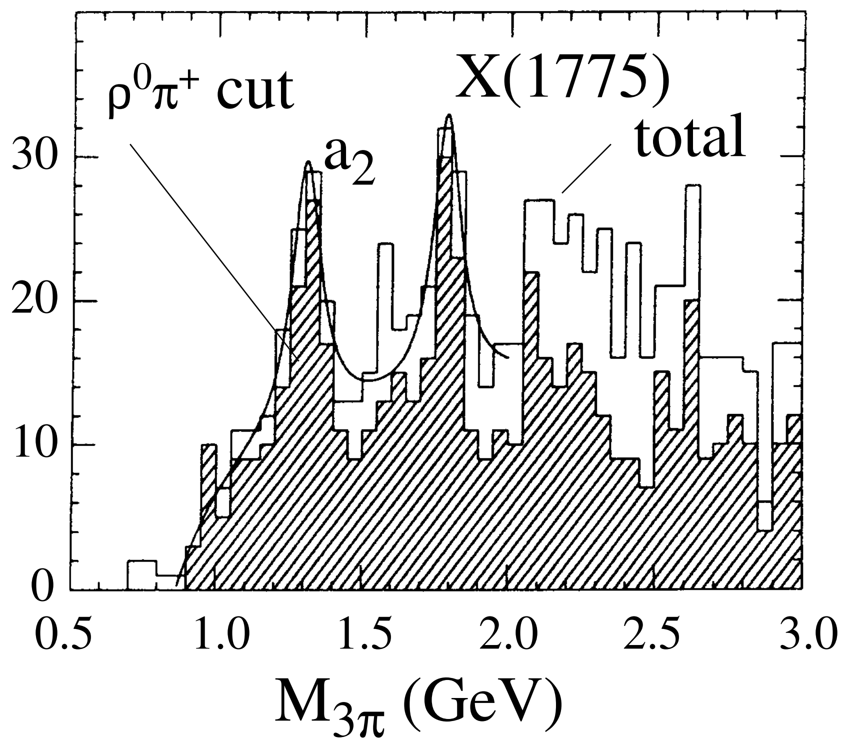

Fig. 4 - SLAC data for three-pion production.

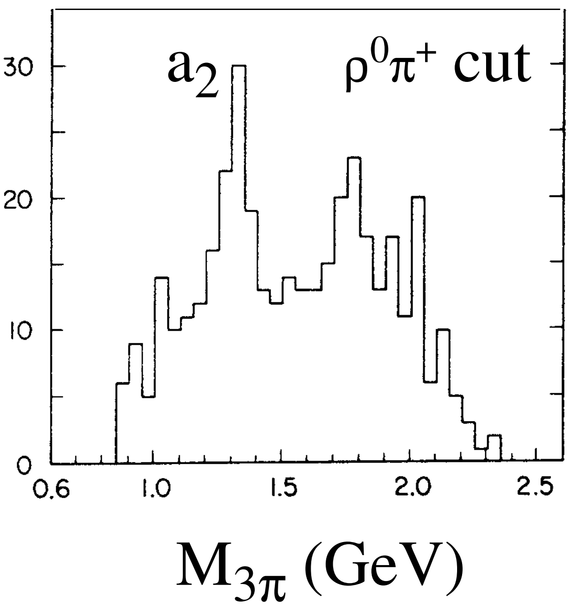

Fig. 5 - Bubble chamber data for three-pion production, after selecting $\rho\pi$.

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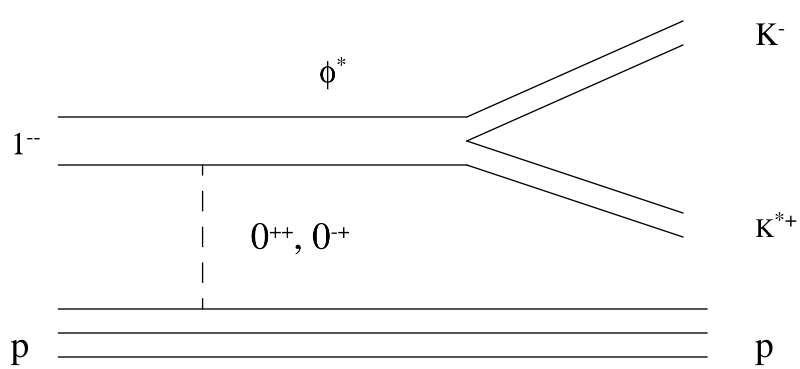


Fig. 6 - Possible excitation mechanisms for strangonium states, assuming VMD.

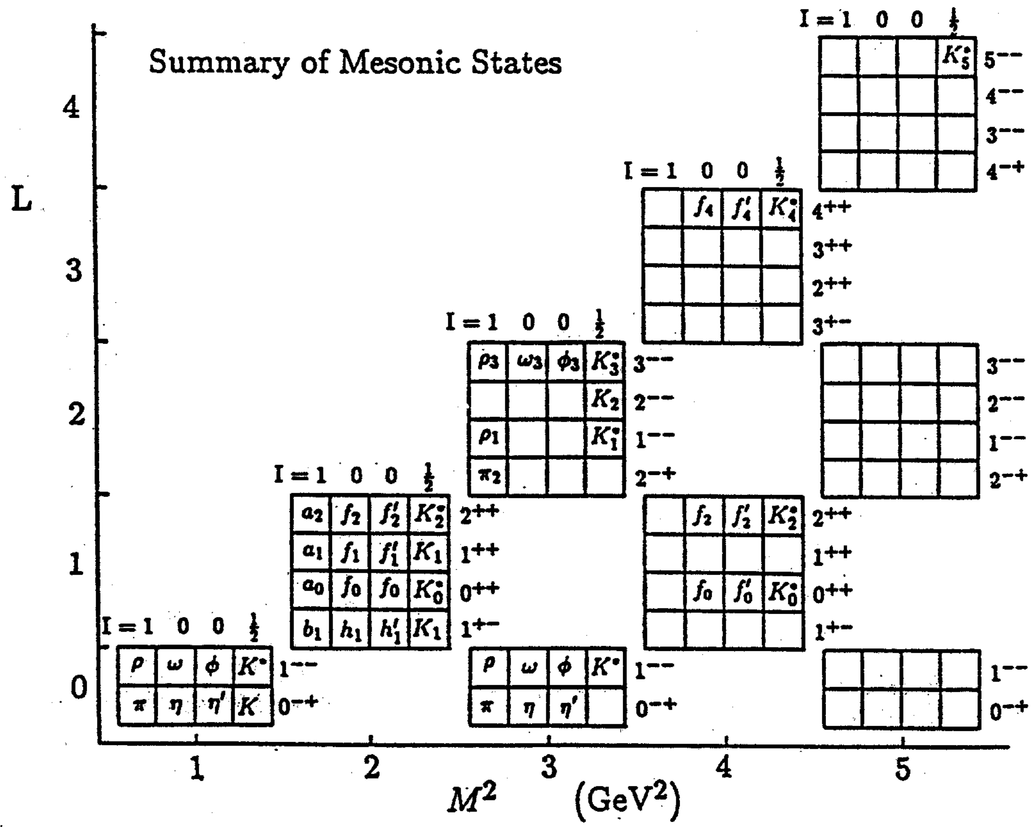


Fig. 7 - Summary of meson spectrum. Filled boxes correspond to well established states.

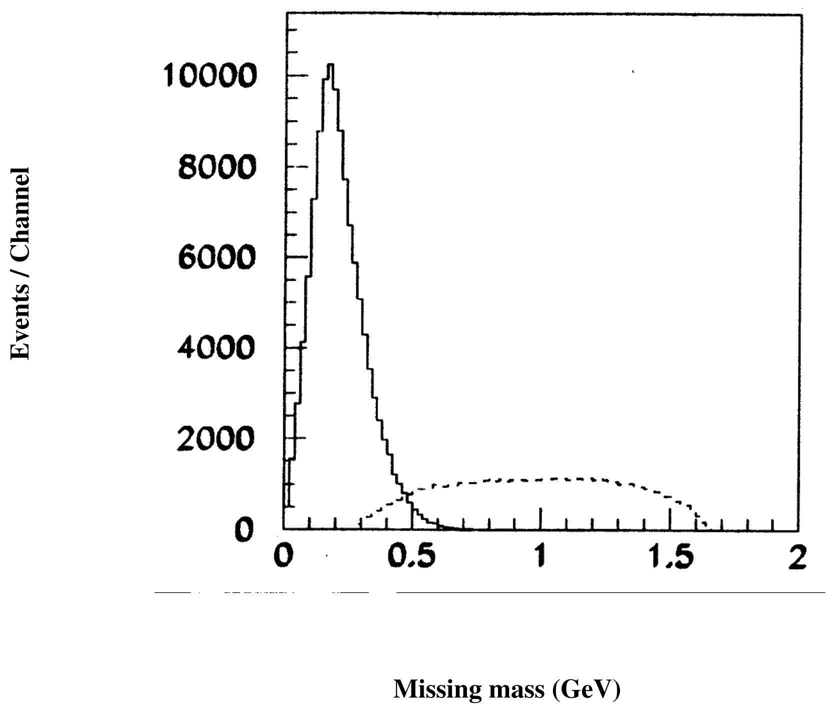


Fig. 8 - Expected missing mass for events with a missing π^-. The dashed line is the expected yield from events with missing $\pi^-\pi^0$ pairs.

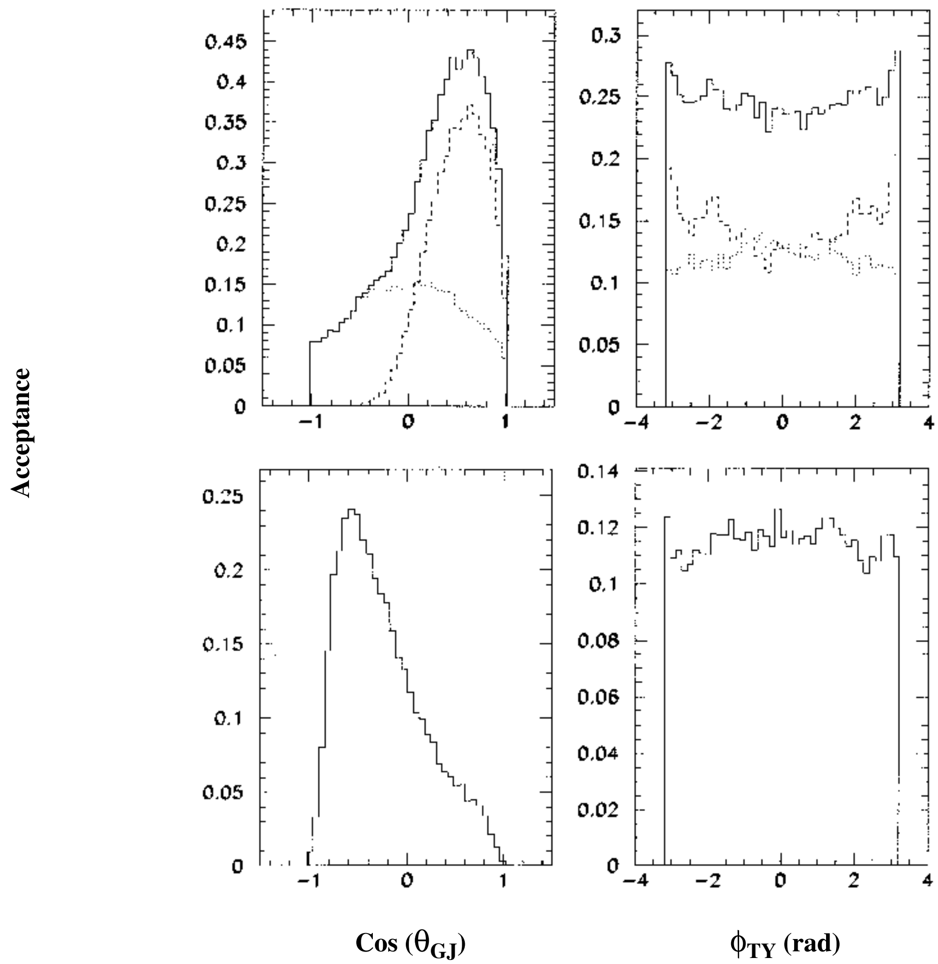
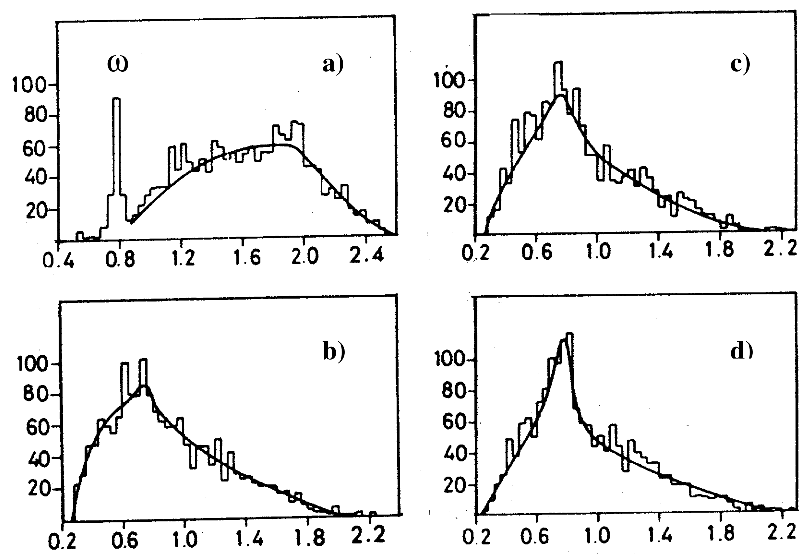


Fig. 9 - Acceptance as a function of ρ decay angles. The solid curve is the total acceptance for $\rho^+\pi^-$ (top), and $\rho^0\pi^+$ (bottom). The acceptance for detecting the three-charged, and two-charged plus neutral components are shown as the dashed and dotted curves, respectively.



Mass (GeV)

Fig. 10 - Measured mass distributions for photon energies between 4.0 and 6.3 GeV for a) $\pi^+ \pi^- \pi^0$, b)$\pi^+ \pi^-$, c) $\pi^+ \pi^0$, and d) $\pi^- \pi^0$. All of the two-pion spectra show large ρ contributions.