CEBAF PROPOSAL COVER SHEET

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A. TITLE:

Photoproduction of η and η' Mesons

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CEBAF Research Proposal

Photoproduction of η and η' Mesons

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CEBAF Large Acceptance Spectrometer Collaboration

ABSTRACT

Differential cross sections for the photoproduction on the proton of $\eta(549)$ and $\eta'(958)$ mesons will be measured using the CEBAF Hall B bremsstrahlung photon tagger and the CEBAF Large Acceptance Spectrometer in Hall B. Tagged photons of energies from 0.65 to 2.25 GeV will be incident on a liquid hydrogen target. Identification of the η and η' will be made by detection of the recoil proton in the CLAS. The measurements will provide important information on properties of the mesons themselves and on the $S_{11}(1535)$ and $P_{11}(1710)$ nucleon resonances and form a firm basis for future experiments studying η and η' interactions with nuclei.

October 1, 1991

I. Scientific Motivation

A. Introduction

This research proposal seeks early beam time in Hall B using the CLAS and the CEBAF photon tagger to perform high precision measurements of the differential cross sections for $\eta(549)$ and $\eta'(958)$ photoproduction on the proton for photon energies from 0.65 to 2.25 GeV. These measurements are of great interest for many reasons, among which are:

1. Existing data are too sparse in kinematical coverage or are too limited in precision to provide accurate determination of the amplitudes involved in the elementary process $\gamma p \rightarrow \eta p$.

2. Data on the photoproduction of η' mesons from the nucleon are non-existent.

3. η photoproduction cross sections on the nucleon provide an isospin selectivity which will be extremely valuable in unraveling the spectrum of baryon resonances.

4. Significant questions about the structure of the mesons themselves, particularly the η' , exist.

5. It may be possible that the strange content of the mesons can be exploited to help probe the strange quark content, if any, of the nucleon.

6. Investigations of η and η' interactions with the neutron and with nuclei require a detailed understanding of η and η' interactions with the proton.

The present lack of high quality data for photoproduction of these mesons is primarily due to the unavailability of appropriate experimental facilities to make such measurements. The combination of resources to be available at CEBAF in Hall B, however, will be remarkably well-suited to making such measurements. The bremsstrahlung tagged photon spectrometer at CEBAF will provide an ideal tool. As indicated in the Conceptual Design Report(CDR), the tagger will provide good photon energy resolution ($dE/E_0 = 0.3\%$) over a wide energy range (0.20-0.95E_0) at high photon flux ($> 10^7$/s), essential to obtaining cross sections for both particles with high precision in reasonable beam times. The CDR also notes a substantial effort will be devoted to photon beam monitoring to permit precision measurements of absolute cross sections. Within the capabilities specified in the CDR and presently being implemented by the Tagger Working Group, our investigations of the design of this experiment indicate the tagger capabilities will be very suitable for these measurements.

Our experiment design studies described below also indicate that the CEBAF Large Acceptance Spectrometer (CLAS) is more than adequate to perform measurements of kinematical variables with the firm particle identification required to isolate the meson production process from other background processes. The CLAS angular and momentum acceptance allows coverage of most of the center-of-mass angle range with a detection efficiency sufficient to permit the high precision measurements desired within a reasonable period of beam time. Finally, the CEBAF electron accelerator will provide high quality continuous electron beams with energies considerably greater than the 1.446 GeV η' photon energy threshold, making possible measurements at and beyond threshold for the photoproduction of that particle.

Using this combination of unique resources, the cross sections provided by this experiment for η photoproduction will be of much greater precision than existing measurements and will extend over regions presently unmeasured. Simultaneously, the first extensive systematic cross sections for η' photoproduction will be measured. Data taken during this experiment may also result in more precise measurements of the branching ratios for η decays dominated by charged particles. The proposed experiment meshes closely in terms of experimental requirements with several of the approved experiments using the tagger, supplements the present generation of photoproduction experiments elsewhere, and also complements the CEBAF electroproduction measurements presently under consideration by the Nucleon Resonance collaboration. It will also provides a foundation for subsequent studies by the collaboration of the photoproduction of these mesons by heavier targets and with polarized photons and/or polarized targets.

In the following sections we provide a brief overview of the scientific motivations suggested by the considerations noted above, though that list is by no means an exhaustive one. We divide the discussion into issues principally centered on either η or η' photoproduction, and close with the implications of the proposed measurements on future experiments.

B. Photoproduction of η mesons

Because the etas are members of the fundamental meson nonet, the study of η photoproduction shares many of the motivations of the extensive study of pion photoproduction over the past fifteen years or so. Those studies have provided considerable data for investigations of the properties of the $\Delta(1232)$ and its dynamics within the nuclear medium. With the advent of facilities such as CEBAF, the possibility of systematic precision studies of η photoproduction over a broad range of center of mass energies, momentum transfers, and nuclei offers another tool for studying intensively the response of other nucleon resonances in the nuclear medium and the quark model properties of the nucleon itself.

The existing photoproduction differential cross section data set[1–16], as seen in Fig. 1, contains only about 170 points, most of which are concentrated below $W = 1.50$ GeV, with sparse energy coverage at one or two angles above that. Several approaches to understanding this sparse data have been attemped. In one method, studies[16–18] describe the electric and multipole component amplitudes using a sum of resonances and a smooth background. It is clear, however, from Fig. 1 that substantial ambiguity arises when this thinly spread coverage is used to determine Breit-Wigner parameters and coupling constants for many resonances. Such an approach results in many parameters which must be constrained by the slim database, and, consequently, the parameters determined have large uncertainties.

A more recent approach by Mukhopadhyay and collaborators[19–22] is oriented towards formulating a phenomenological Lagrangian for the photoproduction process and nucleon resonances of interest, with the degree of pseudoscalar and pseudovector content adjustable. This effective Lagrangian approach (ELA) has fewer parameters overall, and in practice it appears that only a small number are of significance in describing the data. This approach also provides a method of unraveling the non-resonant background already noted above in the resonance-sum approach. An indication of the relative success of the model can be seen in Fig. 2, from Ref. 19, where comparisons of the theory to the differential cross section data and recoil nucleon polarization are made. While the agreement is satisfactory based on the present database, that figure also demonstrates the clear need for improvement in the database of both observables.

The most recent work using this approach[19] produced several remarkable results. For instance, the pseudoscalar/pseudovector content of the ELA appears to have little effect on the ηNN coupling constant, the result $g_\eta^2/4\pi = 1.4$ being very near the SU(3) value.[23] This is in marked contrast to π^0 photoproduction where there is clear preference for pseudovector coupling based on chiral symmetry and the low energy theorem. The ELA results also made relatively precise estimates of products of the widths and helicity amplitudes which lie within the ranges of quark model estimates for those parameters.[24–27] However, the theory predicts relatively flat angular distributions for the $S_{11}(1535)$ in disagreement with the preliminary results of the Bates photoproduction experiment taken at $E_\gamma = 725$ MeV.

There is a third approach to extracting the important physics of the process, the use of fixed and hyperbolic dispersion relation analyses to determine multipole amplitudes, scattering lengths and coupling constants. Such an approach has been applied to pion photoproduction(e.g., Refs. 28 and 29); the results have provided independent confirmation of the associated strength parameters obtained by other means. However, such an approach is impossible without a comprehensive and accurate set of cross sections; at present, the limited data base simply does not provide enough constraints for this approach.

This brief list of possible approaches, though incomplete, shows the importance of more high precision photoproduction data for the η meson. Further progress along the lines of theoretical investigation sketched here is impossible without much more extensive and precise data.

This situation has provided part of the motivation for the development by a large CEBAF collaboration of a thorough program of studies which will probe in great detail nucleon resonances excited by electron scattering. Because the isospin of the eta mesons is zero, the detection of eta decays from nucleon resonances selectively probes only those resonances with $I = \frac{1}{2}$. This selectivity provides a unique tool for clarifying the overall isospin content of the collection of overlapping nucleon resonances.

The isospin selectivity has motivated an η electroproduction proposal by the Nucleon Resonance collaboration.[30] That study is principally directed towards the two nucleon resonances which have significant η decay branches in the energy range covered in this proposal, the $S_{11}(1535)$ and $P_{11}(1710)$ resonances. While all of the other nucleon resonances have branches of only a few percent or so, the $S_{11}(1535)$ and $P_{11}(1710)$ decays produce etas in roughly one-half and one-quarter of the decays, respectively.[31] Thus, detection of the η provides a "surgical" tool for identifying these two resonances in the large overlapping group of nucleon resonances and determining their properties.

These two resonances are of considerable interest, as noted in Ref. 30 (which also reviews briefly the electroproduction data). The $S_{11}(1535)$ form factor is starkly different from the dipole form factor seen for neighboring resonances and is poorly described by existing calculations. η photoproduction shows a significant preference for excitation via the $S_{11}(1535)$ resonance, for reasons which as yet remain a mystery in terms of quark models.[32] As for the $P_{11}(1710)$ resonance, the photoproduction data have provided the only additional confirmation for the presence of this resonance seen in pion-nucleon scattering. The structure of the resonance is poorly understood, and some theoretical descriptions have indicated that the structure may possess some hybrid non- quark content.[33,34]

The differential cross sections obtained here will be far more accurate (uncertainties of less than 3%) than those taken previously and cover the region up to $W = 2.27$ GeV. Further, the data taken here will provide measurements of the form factor for the various resonances observed at $Q^2 = 0$; extrapolation to $Q^2 = 0$ from form factor measurements of the resonances at non-zero Q^2 is non-trivial and unreliable. And, while the interest in the $S_{11}(1535)$ and $P_{11}(1710)$ resonances provide much impetus for investigations of $\eta - N$reactions, with the experimental facilities available for this experiment, previously unobserved or poorly known resonances with η decay branches will be more amenable to study and provide further input for theories of baryon resonances. Coupled with the results of the CEBAF electroproduction experiments and results from similar and complementary measurements elsewhere, the data from this experiment should complete a crucial collection of information for theoretical models attempting a fundamental description of the nucleon resonance spectrum.

C. Production of η' mesons

As with the pions and kaons, η and η' photoproduction provide important "theoretical laboratories" for tests of quark model predictions of their nucleon photoproduction multipole amplitudes. As members of the basic pseudoscalar nonet, the properties of the eta mesons in principle should be well understood within quark models as simple $q\bar{q}$ systems. (The basic list of particle properties and of the eta mesons is given in Table I.) The simplest considerations used to extend the understanding of these properties are usually couched in terms of SU(3) symmetry breaking. The symmetry breaking then mixes the singlet η_1 with the octet member η_8 to produce the physical particles observed.

This simple quark model description explains much of the interest in the particles themselves, and, though these considerations are very basic, provides insight into the fundamental interest in photoproduction of the η and η' mesons. Some of this importance can be seen in the several puzzles which exist concerning the eta mesons. One of these puzzles concerns the singlet-octet mixing angle predicted by the Gell-Mann-Okubo formula.[31] The mixing angle can be determined from this quadratic mass formula, yielding a value of about -10 degrees, indicating that the η is dominated by the η_8 contribution. However, this mixing angle can also be found by the analysis of $\eta \rightarrow \gamma\gamma$ widths and those data[35-38] indicate[38-41] that the mixing angle is about -20 degrees, nearly twice the value given by the mass formula.

A second and somewhat related puzzle is the failure of the octet mass sum formula for the η and η' masses.[42] While the application of this formula to the masses of the ω and ϕ, the vector nonet counterparts to the pseudoscalar etas, is satisfied to a remarkable accuracy of a few percent, the prediction for the η and η' is off by nearly 40%. Lenz[43] has pointed out that, whereas the mixing angle puzzle affects the predictions of the η /η' mass ratio, the failure of the octet mass sum formula should be recognized as a separate failure to predict the masses via their sum. Attempts have been made to resolve this failure, including inclusion of $c\bar{c}$ admixtures into the eta mesons, but the issue is still debated.[42]

An additional puzzle arises in the studies of J/ψ decays to mesons. These studies have generated a controversy since one of them indicates that a substantial component (perhaps nearly a third!) of the η' appears to be something other than the simple $q\bar{q}$ structure,[44] while another similar study claims no evidence for such an exotic component if disconnected quark diagrams are properly added.[45] (The mixing angle discrepancy is not resolved by similar considerations.) Regardless of the outcome of the J/ψ decay debate, other theoretical investigations of gluonium admixtures into the η -η' system seem to support the existence of some hybrid component.[46-49]

Measured differential cross sections for η' photoproduction should provide insight into the details of the η' -nucleon system, and to the η' meson itself. But to better understand the η' meson itself, data which provide more direct insight into the underlying structure of the meson without uncertainties introduced by the structure of other hadrons (in this case, the nucleon) are very useful. Previous measurements of decay branching ratios have been used to test the simple SU(3) structure of these particles[42], but, as shown in Table I, the knowledge of the branching ratios for the η' is rather poor. Thus, another tool for improving quark models of the η' meson may be available in improved measurements of the branching ratios for decay of the η' to channels dominated by charged particles. As we show below, with appropriate experimental techniques, the CLAS and photon tagger may provide a capability for improving the precision with which some of these branches are known.

From the above, it is clear that, because of the fundamental quark model significance of these questions and ideas, the η and η' are of great interest to investigations of quark model dynamics. The resolutions of these puzzles will depend on the results of a wide variety of experiments. Extensive differential cross sections for photoproduction and refinement of our knowledge of the decay branching ratios, particularly for the η' , should be valuable in providing basic information on the properties of these mesons. As summarized by Lenz,[43]

> ...theoretical calculations strongly suggest the problem of the structure of the η' to be connected to fundamental properties of the strong interactions. Experimental investigation of the structure of the η' should therefore have high priority. Comparison of the interactions of the η' -N system with those corresponding to the more standard members of the nonet (in particular with the η) allows [us] to search for signals of the unusual dynamics apparently active in the η' .

D. Future directions

This experiment should provide an important first step for the next generation of η and η' experiments. As seen in Fig. 2, measured polarization observables at the present time possess such large uncertainties that they provide few constraints on any theory. Thus, the extension of these measurements to polarized targets is a logical and important follow-on step once the measurements here have provided a firm foundation for the cross sections, and the experience gained in this experiment should be invaluable in the design of that experiment.

The measurement of photoproduction of η and η' mesons on the neutron obtained with a deuterium target would also represent a reasonable second step following the cross section measurements. The present data on η photoproduction on deuterium are very puzzling since what appears to be a reasonable theoretical description of the process fares very poorly when compared to the *three* data points available as shown in Fig. 3, missing the data by a factor of about 2.5. Certainly, at this stage, it is doubtful whether we have a sound understanding of the neutron amplitudes, which in turn limits our understanding of the propagation of nucleon resonances within nuclei. With better photoproduction data on the proton and the experience gained from performing such experiments, experiments on deuterium could be extremely valuable.

With improved η photoproduction data, some possible future directions have been suggested by Bennhold and Tanabe for experiments studying η photoproduction on nuclei.[50] These may hold the promise of scrutinizing the dynamics of the $D_{13}(1520)$ isobar and the spin-flip and non-spin-flip components of the production operator. Such ideas are motivated by the observation that the $S_{11}(1535)$ is excited through the E_{0+} multipole, which contains only a spin-flip operator $\sigma \cdot \epsilon$. The experimental status of such studies is primitive and awaits experiments like that proposed here. However, that field of study could hold much promise, as underscored by Bennhold and Tanabe,[50] Just as the dominance of the Δ isobar in π-nuclear reactions allowed the extraction of quantititative information on the Δ-nuclear potential, we would hope to learn about similar medium modifications of the S_{11} and other N^* resonances inside the nuclei via processes involving the η mesons. In addition, due to the lack of η beams, the (γ,η) reaction may help to resolve the question of whether the η -nucleus interaction at threshold is attractive or not.

Any such progress hinges directly on the vast improvement in the database for the fundamental process that this experiment should provide.

Another interesting line of investigation into the structure of the *proton* may be possible. With the availability of precision cross section data on η' photoproduction on the nucleon, improved measurements of several of the η' branching ratios, and more extensive η photoproduction data, we can hope to form a more complete and successful picture of the η and η' wavefunctions by resolving the puzzles noted above. With that description, the possibility may exist of using that information and complementary information from other probes to study the quark content of the nucleon.

Such an idea is predicated on the differing magnitude and sign of the strange quark content of the two mesons, as noted in Table I, and an application of the Okubo-Zweig-Iizuka rule.[42] Using a combination of cross sections from this experiment and other probes, isolation of the strange quark content of the nucleon may be possible. A recent work along such lines by Dover and Fishbane[51] considered the possibility of using η and η' scattering from the proton along with several other reactions to observe the strength of such components. Photoproduction cross sections could be used to test such theories and provide further constraints or, alternatively, be used in a similar combination of cross sections to put limits on any such content. Such an idea is very speculative and, consequently, controversial as well. However, it is certain that high precision measurements such as those proposed here will be invaluable in testing such theories.

While this brief list does not exhaust all possibilities for future η and η' experiments, the discussion underscores the importance of the measurements to be made in this experiment and their relation to further progress in the field. At the same time, this experiment provides an initial basis of experience for the collaboration to perform such future studies.

II. Experimental Method

A. General information

These measurements will use the CLAS and photon tagger in standard configuration as described in the CEBAF Conceptual Design Report. Using an incident electron beam energy of 2.4 GeV, the photon tagger focal plane energy acceptance will be binned in energy bins of 50 MeV or less using the full acceptance of the focal plane. This will provide photon energies from 0.65 GeV (below threshold for η and η' photoproduction) to 2.25 GeV. A tagged photon flux of 1 $\times 10^7$ will be incident on a liquid hydrogen target presently being contemplated for experiments 89-004 and 89 -024.[52,53] (If possible, a higher tagging rate will be used.) All sectors of the CLAS will be necessary for kinematical reconstruction of events, and the shower calorimeters will be required at angles out to 45 degrees. (Though greater coverage is desired and may eventually be present, in the discussions below we assume 45 degrees shower counter coverage).

The kinematics to be explored by photon energies from 0.65 to 2.25 GeV will span a center-of-mass energy range of from 1.48 GeV (corresponding to η threshold) to 2.27 GeV. As noted in Table I, the threshold for η photoproduction is 0.709 GeV, while that for η' is 1.446 GeV; these correspond to center-of-mass energies of 1.49 and 1.90 GeV, respectively. This region is illustrated in Fig. 4, which shows the total γp cross section.

The target to be used for this and other approved first round experiments is presently of unknown dimensions. We have assumed a frequently discussed geometry which, as seen below, represents a "worst-case scenario" for this experiment. This hypothetical target is a liquid-hydrogen-filled cylinder 6 cm in diameter and 14 cm long with very thin entrance/exit walls and would have a density of approximately 1 g/cm^2. For this experiment, a target of considerably smaller diameter (e.g., 1 cm and 1 g/cm^2) would enhance the detector acceptance, as described in subsequent sections, but our simulations indicate that the impact of using the 6-cm-diameter liquid hydrogen target does not greatly compromise the measurements to be made.

B. Event signatures

1. Cross section measurements

To measure the photoproduction cross sections for η photoproduction, previous efforts have focussed on detecting the recoil proton. That method will be used here throughout the energy region proposed for study for both η and η' photoproduction cross section measurements. Since we have chosen to investigate our experimental design using the 6-cm-diameter liquid hydrogen target described above, an important experimental aspect to be explored to ascertain the feasibility of the proposed measurements for the η and η' are the recoil proton acceptance and momentum threshold for detection.

The scattering angles for recoil protons following η production are shown in Fig. 5 for photon energies of 0.8 to 1.8 GeV. From that figure, it is seen that nearly all of the recoil protons have laboratory scattering angles of about 60 degrees or less. Since the CLAS detection solid angle begins at about 8 degrees, which corresponds to about 30 degrees in the center of mass system for the lowest photon energies, the acceptance for smaller recoil angles is affected most by the CLAS design. Hence, the polarity of the CLAS will be chosen to bend the protons outward so as to increase the acceptance for the protons with the lowest scattering angles. ϕ acceptance lowers the overall event rate but does not otherwise affect the differential cross section measurement. Despite the acceptance limitations, the overall detection efficiency is nearly 0.5 for protons resulting from η photoproduction over nearly the entire energy range to be studied, as seen in Fig. 6.

Using this technique for η' photoproduction, the minimum lab scattering angle is similarly restricted. Because of the differing kinematics, however, the angular range subtended by the uninstrumented forward gap in the CLAS results in a more significant loss of solid angle coverage for η' photoproduction, as seen in the scattering angle kinematics shown in Fig. 7. Clearly, it is desirable to get to the lowest possible forward angles. For η' photoproduction at 1.5 GeV, for example, a laboratory angle of 10 degrees corresponds to a center-of-mass angle of 66 degrees, while the corresponding angle for a lab angle of 8 degrees is 50 degrees. If the smallest forward angle is 12 degrees, the center-of-mass coverage begins at 88 degrees. (As suggested in Ref. 53, moving the target upstream could improve the small angle coverage; since such a decision has yet to be made, we have based our simulations on the target described above being located at the standard CLAS target position.) Once above threshold, as for η photoproduction, the overall detection efficiency is approximately 0.5 as well.

Additional limitations on the scattering angles for the recoil proton detection for energies near threshold are imposed by energy loss of the proton within the liquid hydrogen target. Principally, event reconstruction and missing mass determination will be compromised by the effects of multiple Coulomb scattering and straggling for the lower energy recoil protons. To estimate the impact of this consideration, we have estimated the CLAS acceptance assuming that the event reconstruction and missing mass determination is reliable where the recoil proton momentum loss in the target does not exceed 2%; the target design modeled is as noted above. Our preliminary results are shown in Figs. 8 and 9.

As expected, this consideration limits the usable CLAS acceptance beyond the limitations imposed by the CLAS design, with the principal effect near threshold. For 0.8 GeV photons, the momentum loss is always greater than 2.5%. By 0.9 GeV incident photon energy, the 2% cut narrows the angular range to center of mass angles between about 70 degrees and 160 degrees, and the problem rapidly proves to be much less of an impediment with increasing photon energy.

The physics impact of this limitation on the proton recoil detection for η photoproduction cross sections is not very significant since threshold data for η production have already been made in numerous experiments and additional measurements are likely to be made before this experiment runs. Nonetheless, the measurements made here could be substantially more comprehensive than previous or planned measurements if the liquid target diameter is smaller than the 6 cm. The severe restriction on angles for cross section data for threshold η' photoproduction, for which no data exist, is of more concern. Thus, if this experiment is approved, we will pursue some compromise on target diameter and, perhaps, position, with the presently approved first round experiments with the tagger using a hydrogen target.[52,53]

To show the advantages to be gained in this experiment by using even a modestly smaller diameter target, we show predictions for proton recoil momentum loss following η photoproduction using target diameters of 6.0 and 3.5 cm at 0.8 GeV incident photon energy in Fig. 10. In the case of the thinner target, the same recoil momentum loss criterion used above would permit measurements at recoil angles from 12 to 125 degrees near threshold, almost to the uninstrumented forward cone of the CLAS. (These angles correspond to 55 to 168 degrees for the η angle center-of-mass angles; similar results follow from consideration of η' photoproduction angles.) An even smaller diameter target would be preferable, but, again, such decisions require mutual agreement among all experimenters scheduled to use the target.

2. η' branching ratio measurements

As detailed above, this experiment has as its goal the measurement of differential cross sections for η and η' photoproduction. We think that it is interesting to note, however, that if reasonable detection efficiencies can be achieved for the charged particle branches of η' decays, measurements of those decays coupled with the cross sections to be measured as described in the previous section could provide a good opportunity to refine measurements of the η' branching ratios to much greater precision, particularly since the number of η' produced will be on the order of 10^5-10^6. Since the data needed for such a determination would already exist within the data taken for the differential cross section measurements, such a branching ratio measurement would be "free", that is, without the cost of additional beam time.

For example, as noted in Table I, the η' meson has a $\rho\gamma$ decay mode with a quoted branching ratio of 30.1 $\pm$ 1.4 %. The precision of this quoted number is somewhat misleading, however; the actual measurements[54–56] possess uncertainties of 10, 27, and 50 %, based on the bubble chamber observations of 298, 20, and 35 η' decays. Other charged branches possess either fewer observed events or none at all.

In order to determine the feasibility of improving η' branching ratio measurements, we have investigated measurement of the largest charged particle decay mode, the $\rho\gamma$ decay channel, to determine what precision might be reached for that branching ratio. The ρ which arises in this decay will, in turn, decay into two charged pions. We have studied detection of the recoil proton and some combination of the pions and γ following η' decay. η' identification via this branch would then be made via event reconstruction and missing mass determination. These measurements would result in a set of differential cross sections which could be compared to those resulting from the proton recoil measurements described above.

For this method, there are also detection thresholds placed on proton and pion energy which result in an energy dependence for the CLAS acceptance of events through this branch. In order to maximize the acceptance for the recoil protons, as noted above, the polarity of the CLAS should be such that the protons are deflected outward. This would result in the π^- resulting from the decay of the ρ bending inward, with a smaller acceptance for those particles, as seen in Fig. 11. Additionally, the limited coverage of the CLAS for photon detection will place further constraints on the overall acceptance for those events which are reconstructed using photon information. (We note that the azimuthal acceptance will cut the overall counting rate, but not exclude any kinematical region.)

Nonetheless, using this technique with various combinations of cuts still results in a usuable detection efficiency for most combinations, with missing mass resolution acceptable for identification of η' photoproduction, as shown in Figs. 12. In that figure, we have simulated the CLAS details and technique described above and applied it to 2 GeV incident photon η' photoproduction for 100000 events. It is seen that, even when cuts requiring detection of the recoil proton, photon, and pions are made, the acceptance is relatively flat over much of the center of mass angle and the detection efficiency is about 4%. Though it is possible that less restrictive cuts would provide sufficient discrimination from background processes with higher efficiency, even this most restrictive set of cuts would permit an accurate measure of the branching ratio in a reasonable period of beam time.

Since the branching ratio should not be energy dependent, all energy and angle bins can be used to determine the branching ratio, and systematic uncertainties may be greatly reduced. No additional beam time would be necessary to attempt extracting this information from the data taken for the differential cross sections. For instance, the knowledge obtained for the shape of the measured differential cross sections can be used to provide constaints for those differential cross sections determined from $\rho\gamma$ decay. Nonetheless, the acceptance of the spectrometer for the set of cuts used must be determined quite well, which requires further modelling than we have performed at this time. We will continue to investigate these possibilities.

3. Count rates

In order to make an initial prediction of the uncertainties in the differential cross sections to be measured, with corresponding estimates on the accuracy to be achieved in measuring, for instance, the branching ratio for the $\eta' \to \rho\gamma$ decay, we have used the results of the above simulations along with estimates of count rates, assuming 0.5 and 0.04 detection efficiencies for the proton recoil and $\rho\gamma$ decay events, respectively.

In estimating count rates, we have assumed a tagged photon flux of 10^7 photons/sec. The energy distribution of the tagged photons is assumed to drop as $1/E_\gamma$. Using energy bins of approximately 50 MeV results in 32 energy bins going from 0.65 to 2.25 GeV for the 2.4 GeV incident electron energy. This bin size is appropriate to the 100-150 FWHM values of the nucleon resonances in the energy excitation region of interest, but it can be subdivided if desired for those regions of the focal plane corresponding to high photon flux or larger cross section. Using the 50 MeV bin size, we arrive at about 5.6 x 10^5 (1.7 x 10^5) photons/sec in the 50 MeV wide bin at 0.70 GeV (2.25 GeV).

An initial estimate of overall counting rate, including background processes, can be obtained by using Fig. 4 for the total γp cross section and Fig. 1 to estimate the η photoproduction rates. The η' photoproduction cross sections are unknown, but we can make a conservative estimate that the cross sections are approximately half of those for η photoproduction at the same energy for energies above threshold; we are seeking a better theoretical estimate for the cross section magnitude, but the quantity is basically unknown. The total cross sections go from 275 μb to about 150 μb between photon energys of 0.70 GeV and 2.25 GeV, with the η cross section falling from 1/20 to 1/40 of that total cross section.

With these assumptions, for the liquid hydrogen target described above, we can estimate that in the 50 MeV bin at 0.70 GeV, we should have about 90 events/s total, with about 2 η photoproduction events/s. Similar estimates for the 50 MeV wide bin at 2.25 GeV would give 20/s and 0.5/s for the total and η photoproduction event rates, respectively. Assuming the η' photoproduction rate is half that for η photoproduction at 1.5 GeV, we would get an η' rate of 0.25/s. Since the recoil proton detection efficiency is effectively 0.5, requiring a 20 point angular distribution and 1% statistics would require 400000 recoil protons per energy bin, assuming an isotropic angular distribution with well-determined background. At the lower rate, about 450 h would be needed, depending on background, to make the η photoproduction measurements. Because of the larger cross sections and photon fluxes involved, the η photoproduction threshold region could be subdivided into energy bins smaller than 50 MeV with 1% statistical accuracy.

4. Background processes

We have performed intial investigations of the background processes which might hinder the measurements proposed. Since we are interested in detecting the recoil nucleon following eta meson photoproduction, a large source of background comes from nucleon recoil following pion photoproduction on the proton. Thus, this background clearly is energy dependent and must be modelled using the CLAS design.

We have performed simulations at incident photon energies of 0.8, 1.5, 1.7, and 2.0 GeV; these are shown in Figs. 13-16. These estimates are consistent with previous measurements at and below 1 GeV, as shown in Fig. 17. In Figs. 13-16, it is seen that the eta recoil peak is rather prominent on this background and the uncertainty in the cross sections introduced is manageable. Since the signal to noise ratio is better than 0.3 for both η' and η for all energies, an increase in beam time from the above would not significantly improve the accuracy of the background measurement.

Any further kinematical cuts on the data not present in these simulations could make the background even more manageable. We plan to investigate such cuts in the coming months, but note again that the background without such cuts has been found to be manageable in previous experiments and poses no significant problems here.

Backgrounds in any branching ratio measurement are expected to be very small due to the event signatures specified, which may contain three (possibly four) particles.

Backgrounds arising from accidental coincidences between tagged photons and detected protons are estimated to be insignificant since the overall event rate, as described above, is expected to be substantially less than 100/bin/s and the tagger timing resolution should be better than 2 ns. Coincidences arising from events produced by untagged photons coincident with tagged photons at the target should be minimized by appropriate collimation and, of course, form an experimental consideration which will be a factor for all experiments using the tagger.

5. Absolute normalization

Absolute normalization of the cross sections will be based on the relative photon flux monitors in place for the tagger and the estimated density of the liquid hydrogen target under operating conditions. It is estimated that the uncertainties in these separate contributions should result in an overall normalization uncertainty of about 2-3%, though a final estimate cannot be made until the design of the beam monitoring equipment is more complete. (We note that much of this uncertainty will cancel in most branching ratio measurements.)

An additional check on this normalization might be available from tandem measurements of the total γp cross section. It is estimated that this could yield an overall normalization uncertainty of 5% or so.

6. Estimated uncertainty

Based on the above estimates, the overall accuracy of the cross sections will be approximately 1-2% relative uncertainty per η photoproduction cross section point, and approximately 1-3% relative uncertainty per η' photoproduction cross section point. Absolute uncertainties per cross section point should be less than 3-4% for points in the η photoproduction differential cross sections and less than 4-5% for η' cross sections. The uncertainty in the $\eta' \rightarrow \rho\gamma$ branching ratio should be less than 5%.

C. Beam time requirements

1. Development time

As one of the first experiments to use the photon tagger, it is anticipated that some development time will be required to perform initial tests for commissioning the device. This includes time to calibrate the photon flux monitors and the tagger itself, all of which will be required for any experiment using the tagger. That time is not included in the time request for this experiment. Since the collaboration proposing this experiment is made up in large part by those building the device, the expertise of the Tagger Working Group can be of use during that development time and we will participate in all such development activities.

Initial set-up and trigger studies for this experiment can be made in conjunction with those planned for Refs. 52 and 53, totaling about 72 h for set-up and 96 h for exploratory measurements.

2. Data acquisition time

Based on the count rates discussed above, we anticipate that 450 h will be needed to perform the measurements proposed.

3. Total time requested

Total time required for these measurements, including set -up, trigger tests and data acquisition time is 618 h, or approximately 26 d. *No contingency time is included in this estimate.*

C. Accelerator requirements

1. Beam quality requirements

Anticipated accelerator performance for the first cycle of experiments as indicated in the CEBAF equipment plan is acceptable. With the use of the tagger, beam current demand is well within the stated expectations, and the 2.4 GeV beam energy required is also within the anticipated capabilities of the machine during the first Hall B experiments.

2. Special requirements

This experiment does not require a polarized electron beam, use of a polarized target, or polarized photons for the measurements described above.

D. Data acquisition requirements

We anticipate that the standard CEBAF data acquisition system for the CLAS and the photon tagger will be sufficient for this experiment, with a CLAS event handling rate of about 1 kHz. We note that several of the principal participants on this experiment, Profs. Dennis, Preedom, and Whisnant, are also active in the Hall B software development effort, and their expertise will be extremely valuable should this experiment be approved as one of the first Hall B experiments.

III. Relation to other experiments

A. Experiments at CEBAF

This proposal can be placed in context with other experiments planned at CEBAF and elsewhere in terms of experimental design and physics interests. While the physics emphases are very different, we have indicated frequently in the experimental method discussion that our measurements and set-up are compatible with experiments R-89-004 and PR-89-024.[52,53] At this writing, the only significant component of the experiment design which might be affected by this experiment is target design, as described above.

We have also pointed out in the discussion of the scientific motivation for this experiment its complementary nature to those measurements proposed in PR-89-039 by Steve Dytman and the CEBAF nucleon resonance collaboration.[30]

Finally, we note that an approved experiment using the tagger, CLAS, and a *deuterium* target might provide the data mentioned above on η and η' photoproduction on the deuteron if the event trigger is not too restrictive. Presently, such an experimental set-up is envisioned for approved experiment 89-045, with Bernhard Mecking as spokesman.[57] Experiment proposal 89-020, with Dave Jenkins as spokesman, has also requested such a set-up.[58] It would be very desirable to obtain differential cross sections on deuterium for η and η' photoproduction in parallel with those measurements if it is feasible. We have not investigated this possibility in detail, but will begin to shortly.

B. Experiments elsewhere

In addition to the experiments noted in Refs. 1-16, photoproduction of η mesons has been discussed with respect to the PHOENICS project at ELSA.[59,60] However, that experiment will be limited to photon energies of about 1 GeV, well below threshold for η' photoproduction. These measurements will complement those Bonn measurements and extend them to much higher eneriges.

A search of the SPIRES database reveals a number of experiments which have observed η production[61–67] or η' production[61,63–72] among other hadrons which have either run or been proposed, but those are not oriented towards or related to the physics to be addressed in this proposal.

IV. Theoretical support

We have begun initial assessment of theoretical interest in the development of the research goals for this experiment. Profs. R. J. Jacob and W. B. Kaufmann at Arizona State, with backgrounds in pion production via hadrons and photons, have already assisted in the development of this proposal and will continue to work closely with the group. It is anticipated that the data obtained here can be analyzed with dispersion relations in work similar to that performed for pion photoproduction by Jacob and collaborators.

Both Prof. Alfred Svarc at the Ruder Boskovic Institute and Prof. Nimai Mukhopadhyay of Rensselaer Polytechnic Institute, whose theory interests greatly overlap the topics described above, have also expressed interest in working with this group during the planning stages of our measurements. In particular, Prof. Mukhopadhyay and his collaborators have developed and applied the effective Lagrangian approach to the existing photoproduction data, and the extension of that approach to the data to be obtained here are of great interest to them.

V. Equipment contribution

The CLAS and photon tagger devices operating in standard configuration, along with the cryogenic liquid hydrogen target, provide all equipment necessary for this experiment. Though no specific additional equipment will be provided, we note again that a significant portion of the collaboration is involved in the design and construction of the tagger.

VI. Required CEBAF support

Standard operational support for the CLAS will be required, along with cryogenic support for operation of the liquid hydrogen target.

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Table I: Properties of η and η' mesons.[31]

$\eta(549)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass: 548.8 ± 0.6 MeV

$E_{threshold} = 0.709$ GeV

η DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
neutral modes		(70.8 ± 0.8) %	S=1.2	-
2γ		(38.9 ± 0.5) %	S=1.2	274
$3\pi^0$		(31.9 ± 0.4) %	S=1.2	180
$\pi^0 2\gamma$		$(7.1 \pm 1.4) \times 10^{-4}$		258
charged modes		(29.2 ± 0.8) %	S=1.2	-
$\pi^+\pi^-\pi^0$		(23.6 ± 0.6) %	S=1.2	175
$\pi^+\pi^-\gamma$		(4.88 ± 0.15) %	S=1.2	236
$e^+e^-\gamma$		$(5.0 \pm 1.2) \times 10^{-3}$		274
$\mu^+\mu^-\gamma$		$(3.1 \pm 0.4) \times 10^{-4}$		253
e^+e^-		$< 3 \times 10^{-4}$	CL=90%	274
$\mu^+\mu^-$		$(6.5 \pm 2.1) \times 10^{-6}$		253
$\pi^+\pi^-e^+e^-$		$(1.3 ^{+1.3}_{-0.8}) \times 10^{-3}$		236
$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%	175
$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%	211
Charge conjugation (C), Parity (P), or Charge conjugation × Parity (CP) violating modes				
3γ	C	$< 5 \times 10^{-4}$		274
$\pi^+\pi^-$	P, CP	$< 1.5 \times 10^{-3}$		236
$\pi^0 e^+e^-$	C	$< 4 \times 10^{-5}$	CL=90%	258
$\pi^0\mu^+\mu^-$	C	$< 5 \times 10^{-6}$	CL=90%	211

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass: 957.50 ± 0.24 MeV

$E_{threshold} = 1.446$ GeV

$\eta'(958)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(44.2 ± 1.7) %	S=1.2	231
$\rho^0\gamma$	(30.0 ± 1.5) %	S=1.1	171
$\pi^0\pi^0\eta$	(20.5 ± 1.3) %	S=1.3	237
$\omega\gamma$	(3.00 ± 0.31) %		159
$\gamma\gamma$	(2.16 ± 0.17) %	S=1.5	479
$3\pi^0$	$(1.53 \pm 0.26) \times 10^{-3}$	S=1.1	430
$\mu^+\mu^-\gamma$	$(1.06 \pm 0.27) \times 10^{-4}$		467
$\pi^+\pi^-\pi^0$	< 5 %	CL=90%	427
$\pi^0\rho^0$	< 4 %	CL=90%	119
$\pi^+\pi^-$	< 2 %	CL=90%	458
$\pi^0 e^+e^-$	< 1.3 %	CL=90%	469
ηe^+e^-	< 1.1 %	CL=90%	321
$\pi^+\pi^+\pi^-\pi^-$	< 1 %	CL=90%	372
$\pi^+\pi^+\pi^-\pi^-$ neutrals	< 1 %	CL=95%	-
$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1 %	CL=90%	298
6π	< 1 %	CL=90%	189
$\pi^+\pi^-e^+e^-$	$< 6 \times 10^{-3}$	CL=90%	458
$\pi^0\pi^0$	$< 9 \times 10^{-4}$	CL=90%	459
$\pi^0\gamma\gamma$	$< 8 \times 10^{-4}$	CL=90%	469
$4\pi^0$	$< 5 \times 10^{-4}$	CL=90%	379
3γ	$< 9 \times 10^{-5}$	CL=90%	479
$\mu^+\mu^-\pi^0$	$< 6.0 \times 10^{-5}$	CL=90%	445
$\mu^+\mu^-\eta$	$< 1.5 \times 10^{-5}$	CL=90%	272
e^+e^-	$< 2.1 \times 10^{-7}$	CL=90%	479

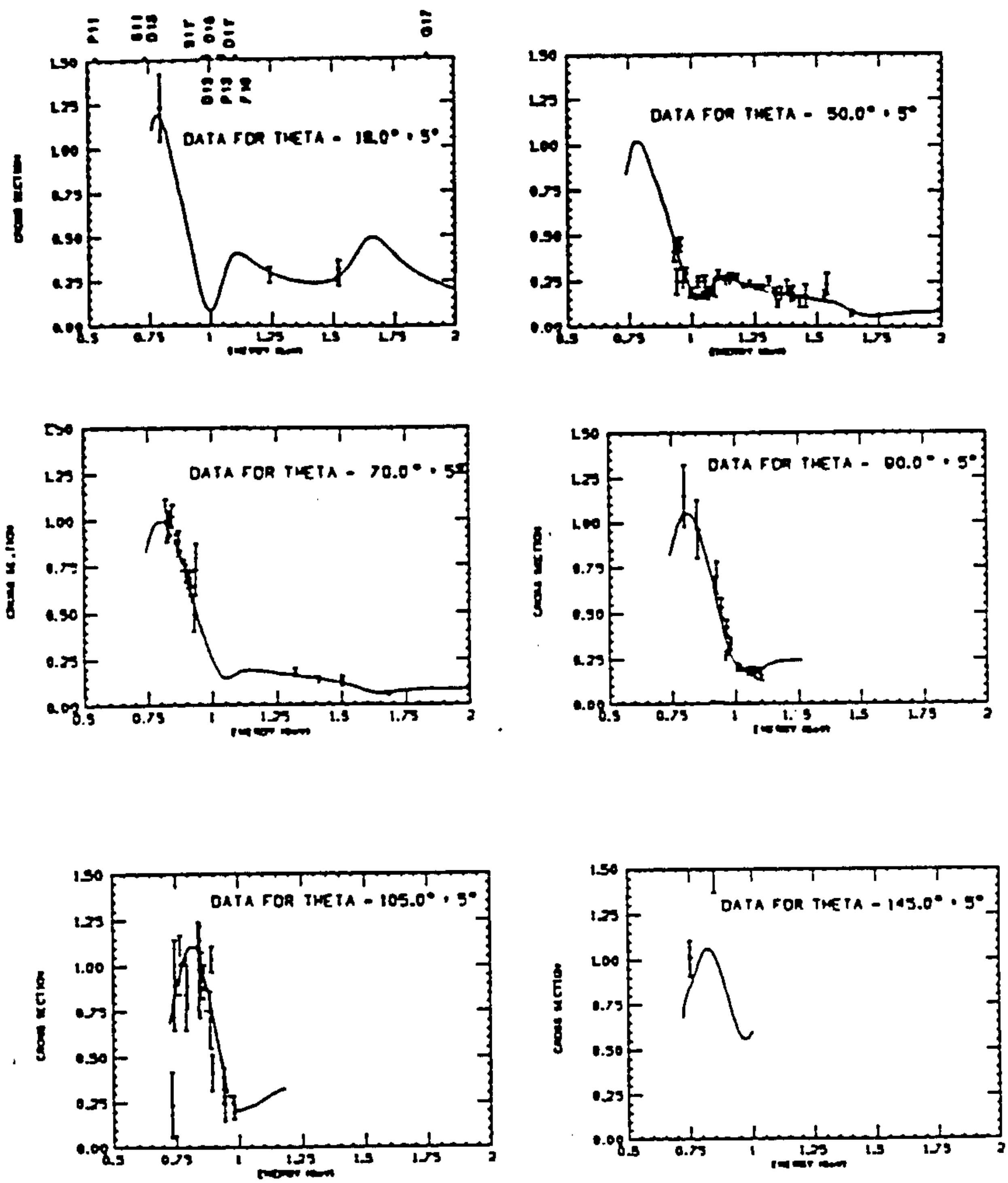

Figure 1: Existing differential cross section data for η photoproduction. (From Ref. 17)

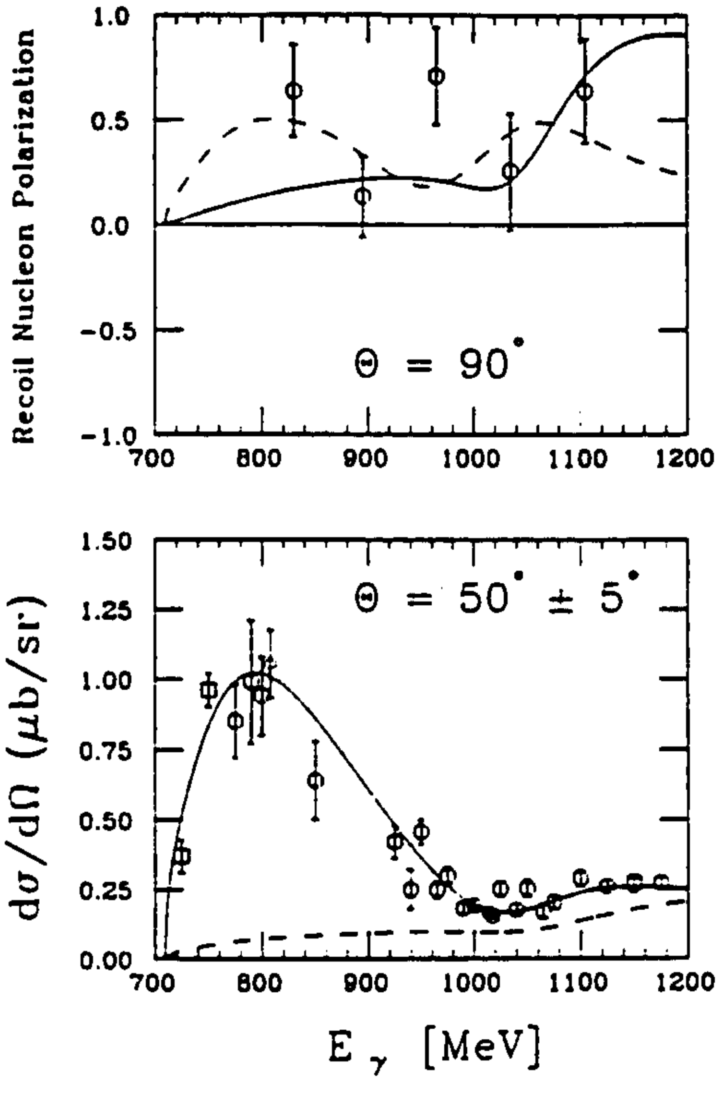

Figure 2: Comparison of predictions of effective Lagrangian approach to differential cross sections and recoil proton polarization for η photoproduction. The solid line represents a full calculation, while the dashed line excludes the $S_{11}(1535)$ resonance. (From Ref. 19)

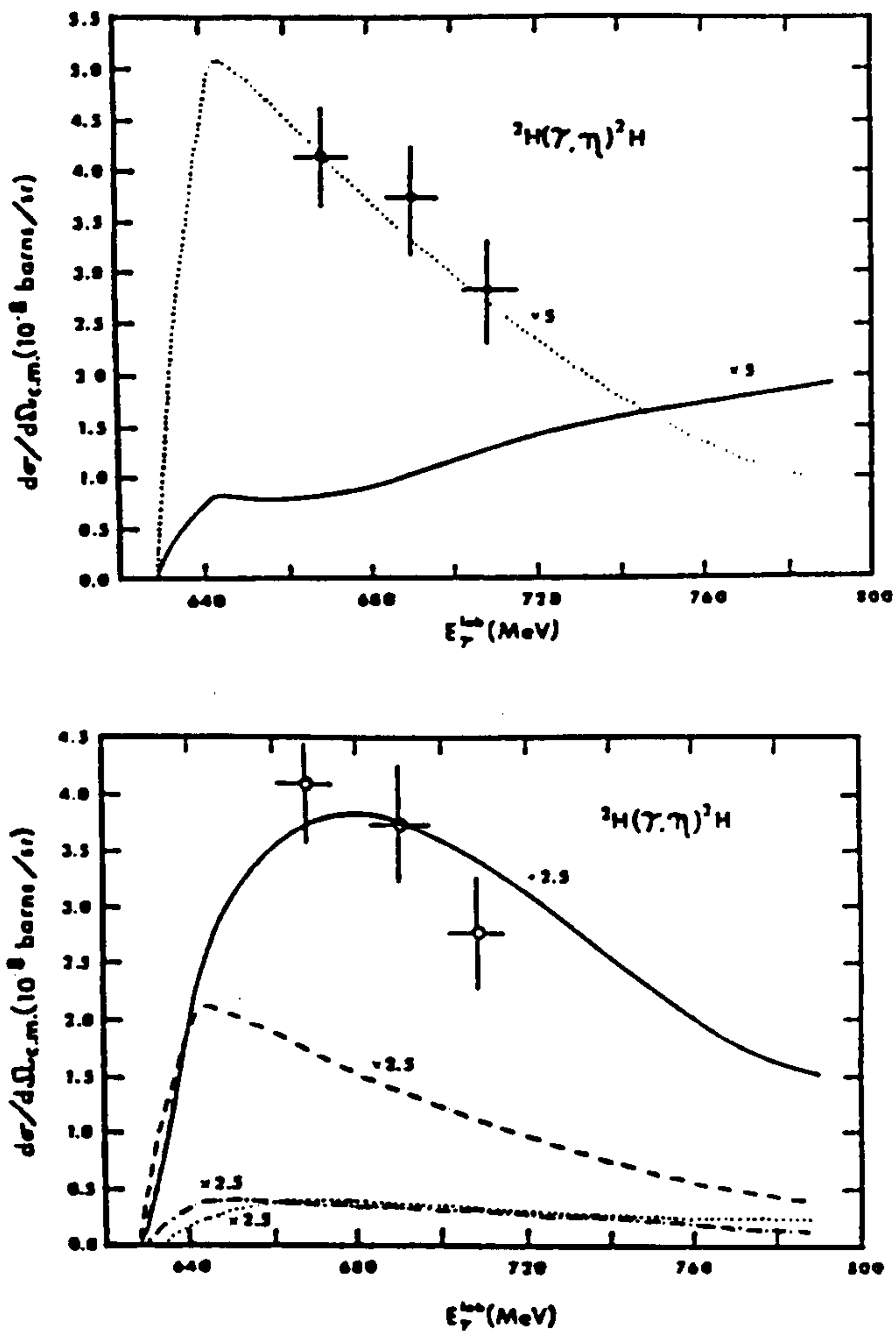

Figure 3: η photoproduction cross sections on deuterium, compared with impulse approximation calculation with rescattering included. (From Ref. 17)

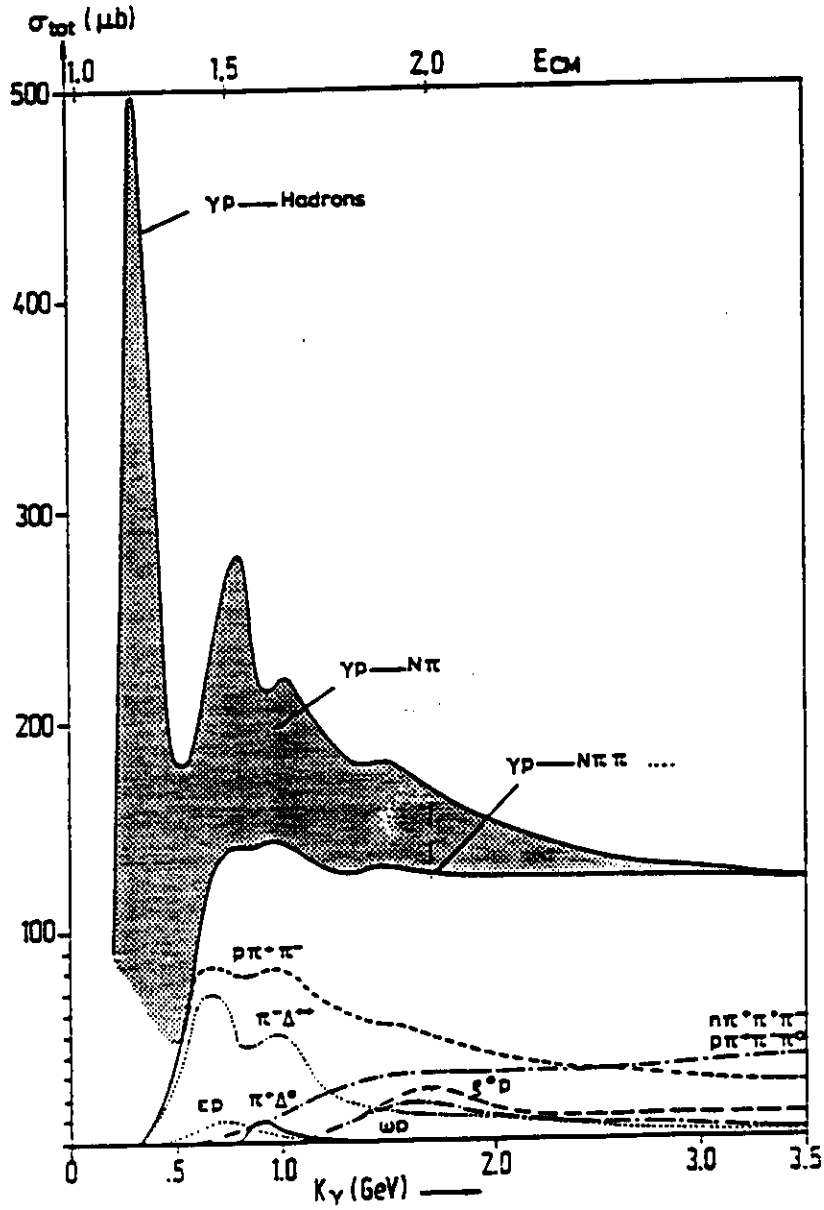

Figure 4: γp total cross section as a function of incident photon energy. Also indicated are threshold energies of interest.

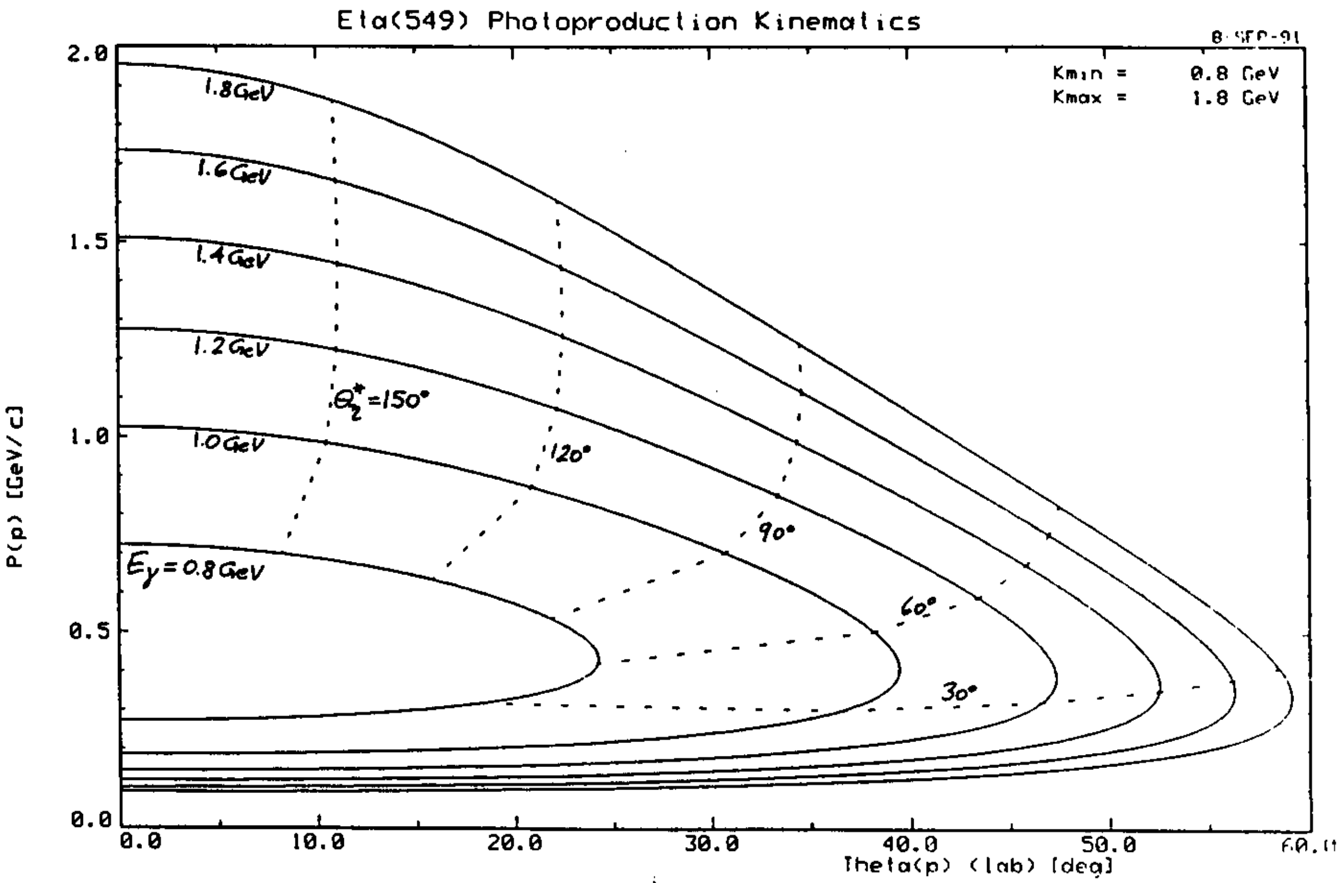

Figure 5: Kinematics for η photoproduction on the proton for various photon energies.

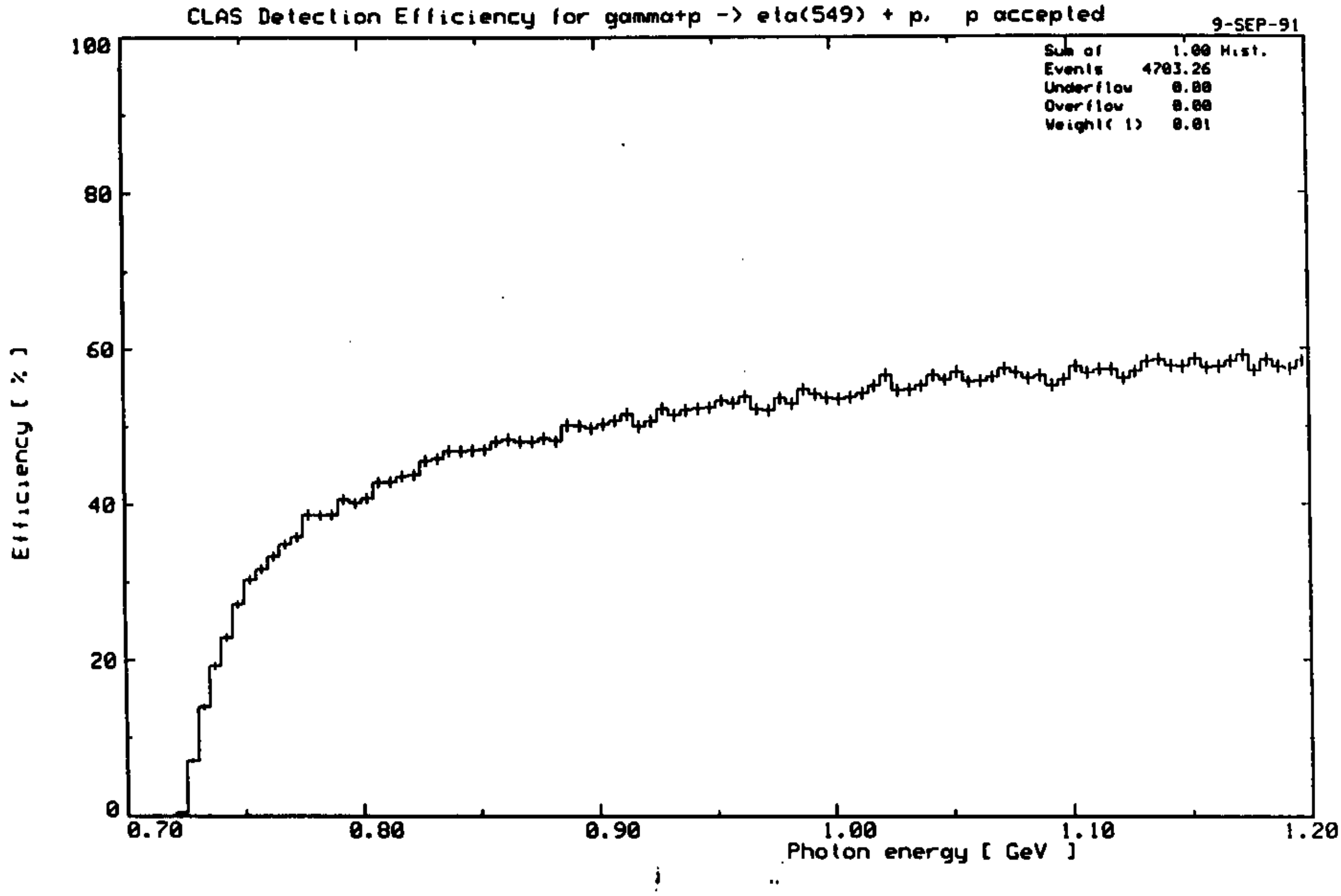

Figure 6: η detection efficiency as a function of incident photon energy assuming CLAS detection of the recoil proton only.

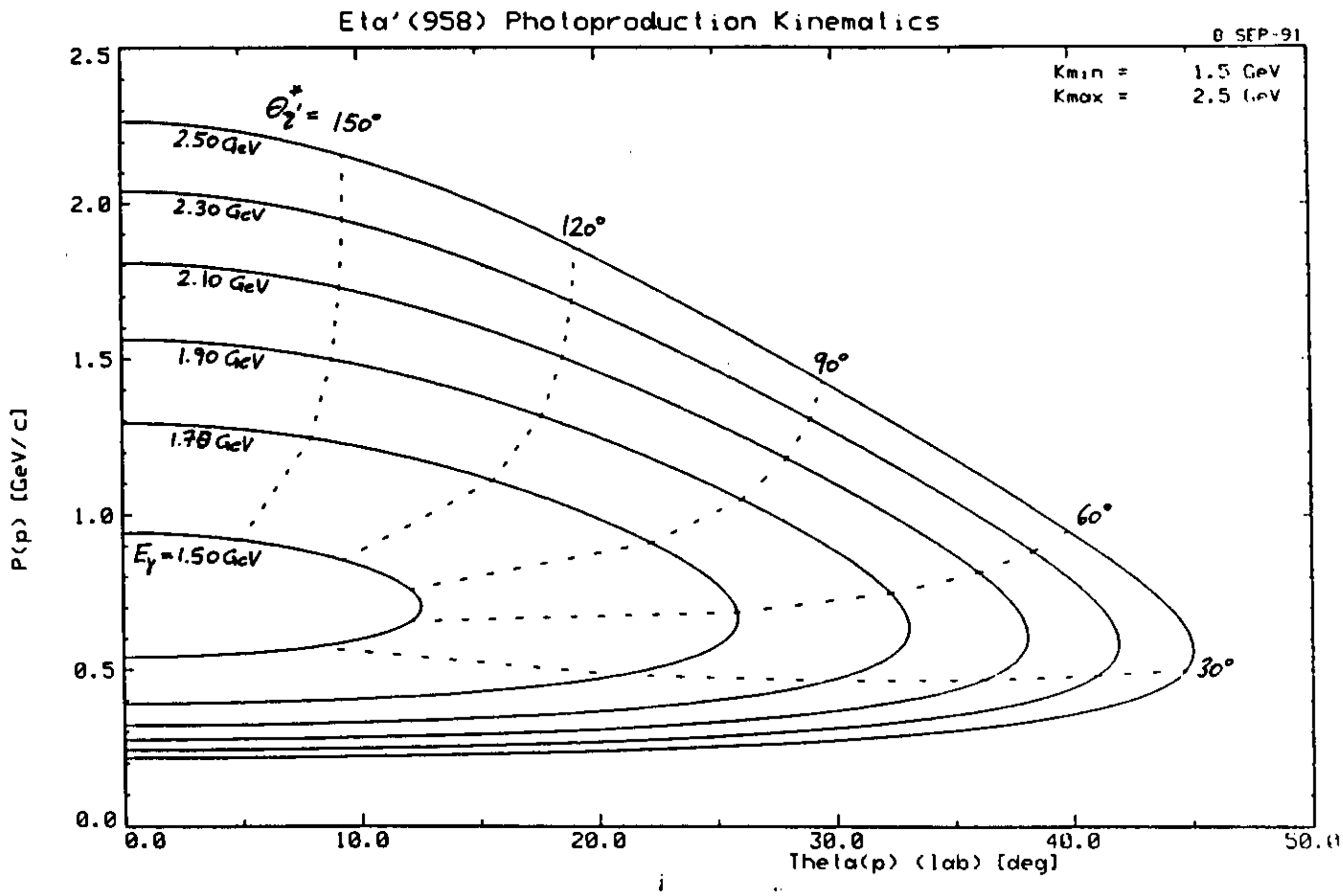

Figure 7: Kinematics for η' photoproduction on the proton.

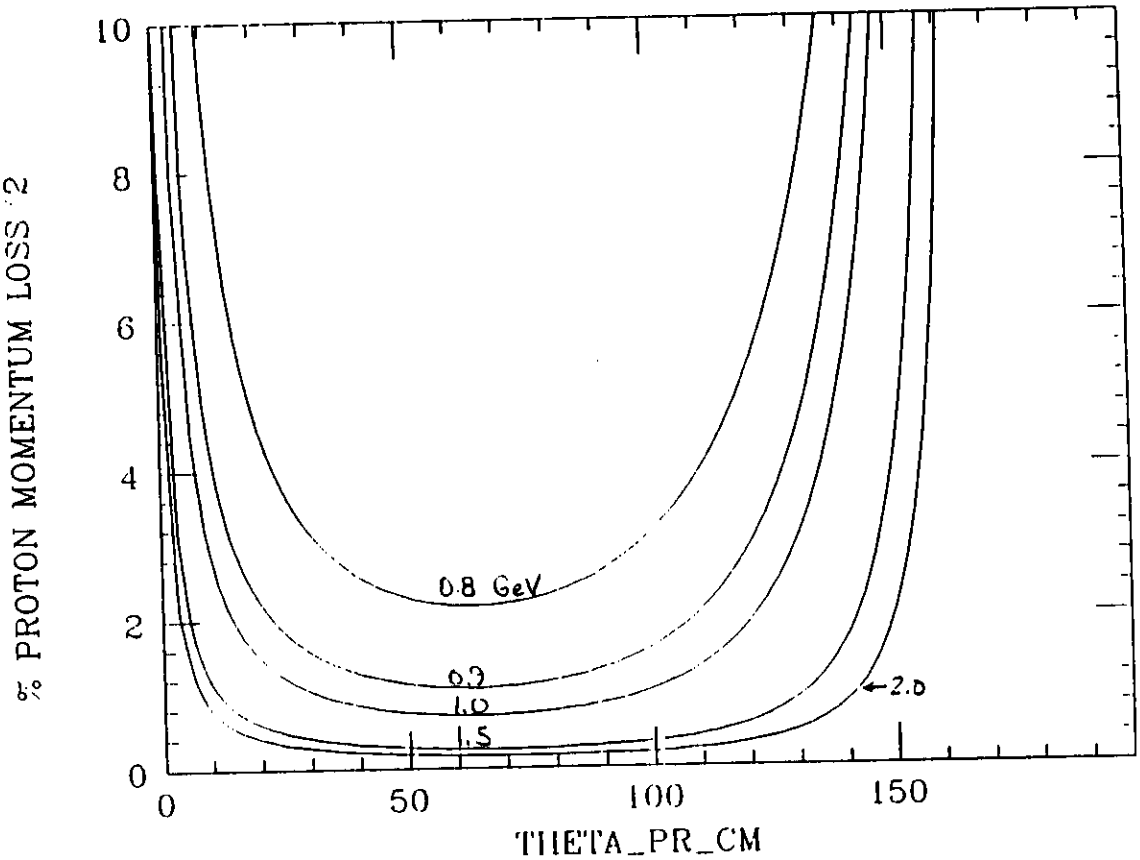

Figure 8: Momentum loss by recoil protons in η photoproduction in a 6 cm diameter liquid hydrogen target.

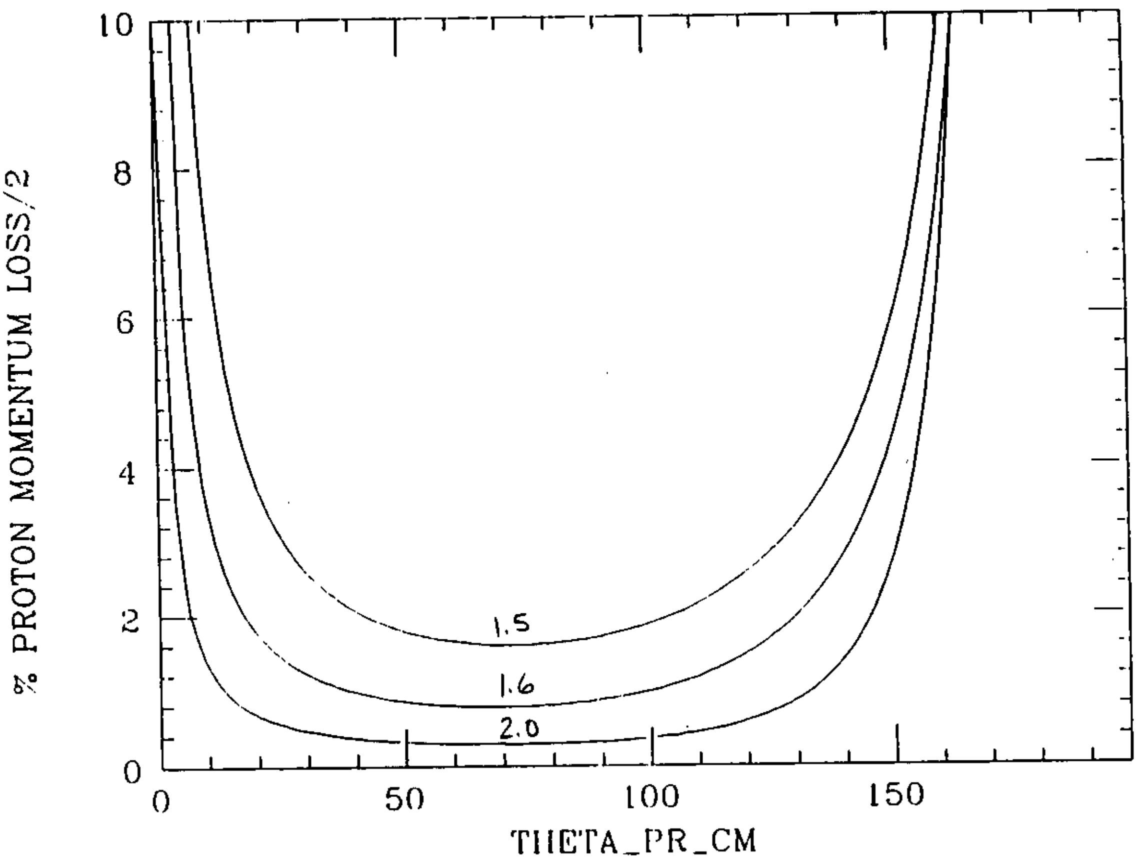

Figure 9: Momentum loss by recoil protons in η' photoproduction in the liquid hydrogen target described in the text.

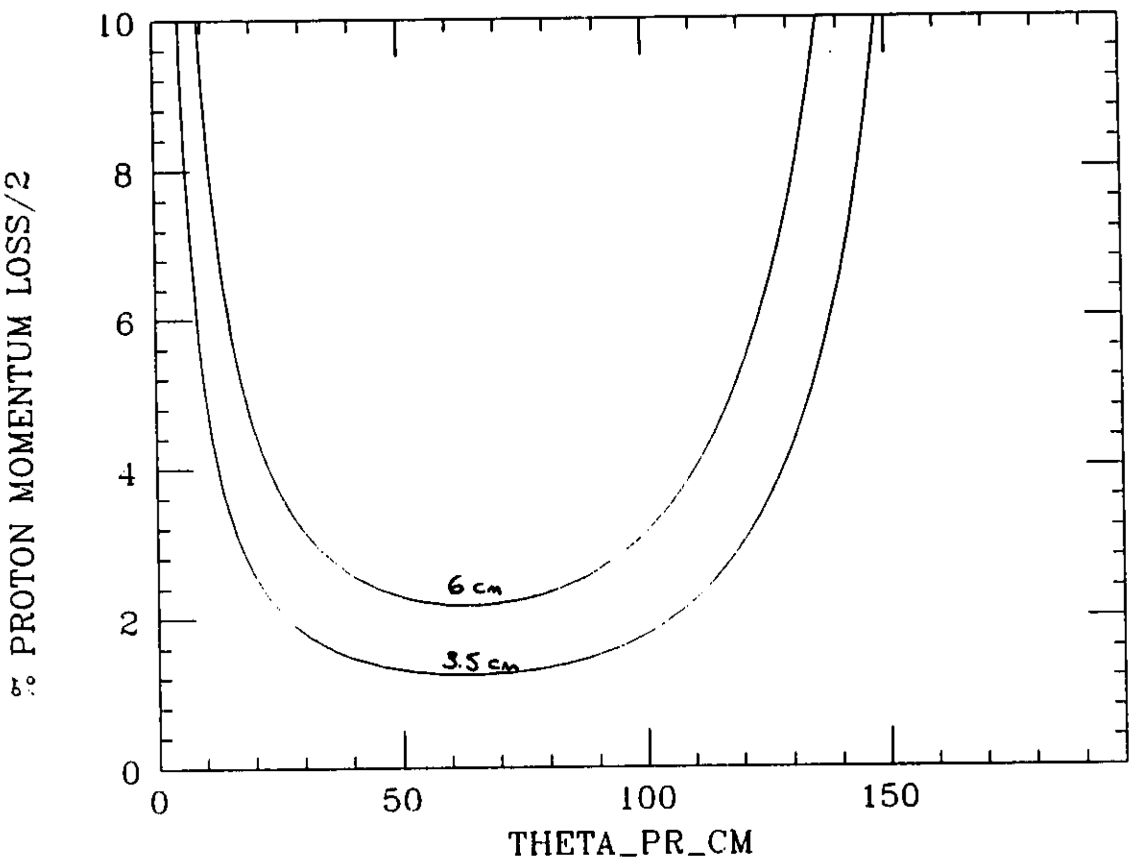

Figure 10: Comparison of recoil proton momentum energy loss for η photoproduction at 0.8 GeV incident photon energy in a 6 cm and 3.5 cm liquid hydrogen target.

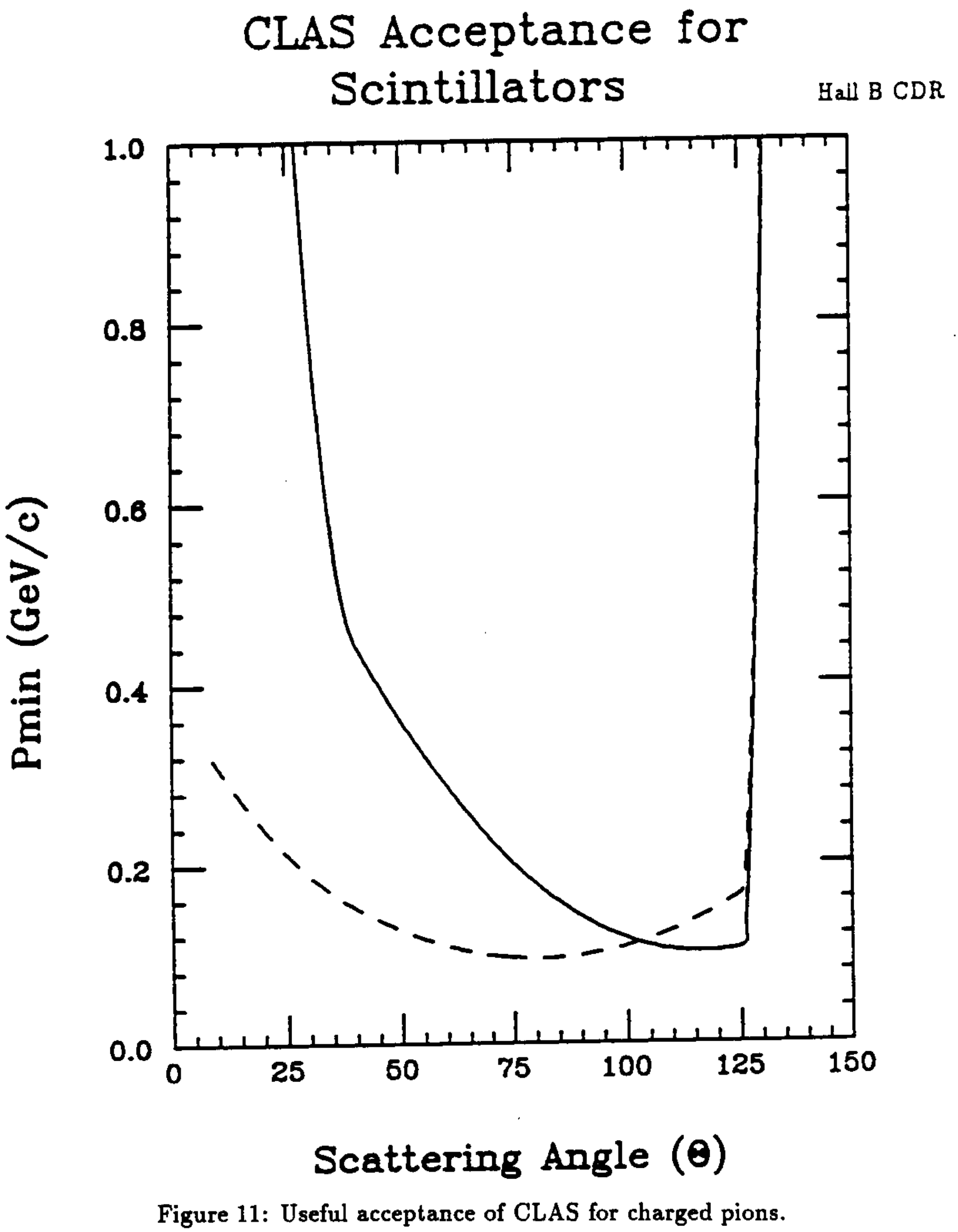

Figure 11: Useful acceptance of CLAS for charged pions.

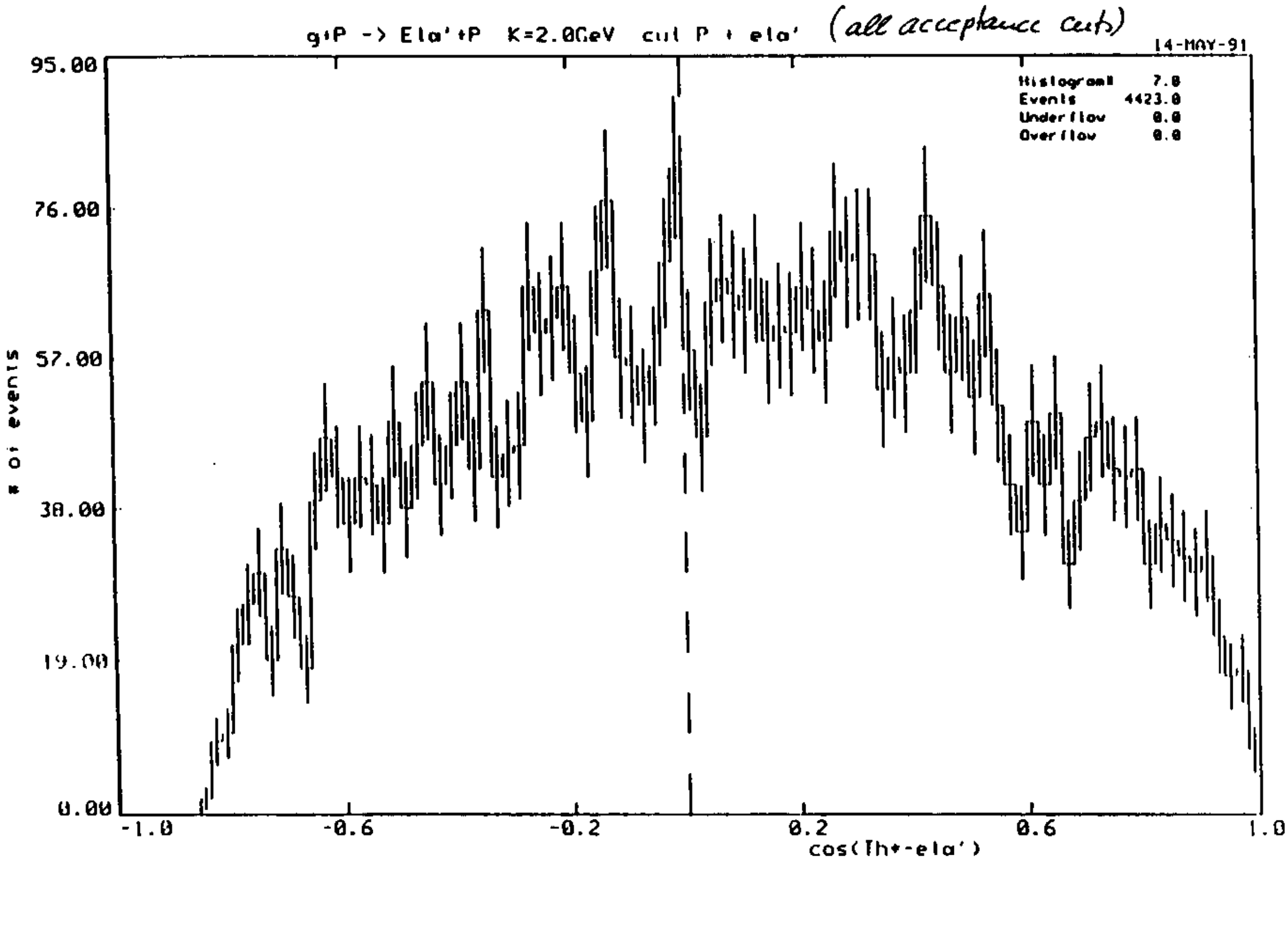

Figure 12: Simulated acceptance spectrum for η' photoproduction leading to $\rho\gamma$ decay. The simulation of 100000 events assumes 2 GeV incident photons with cuts requiring detected photon, pions, and recoil protons.

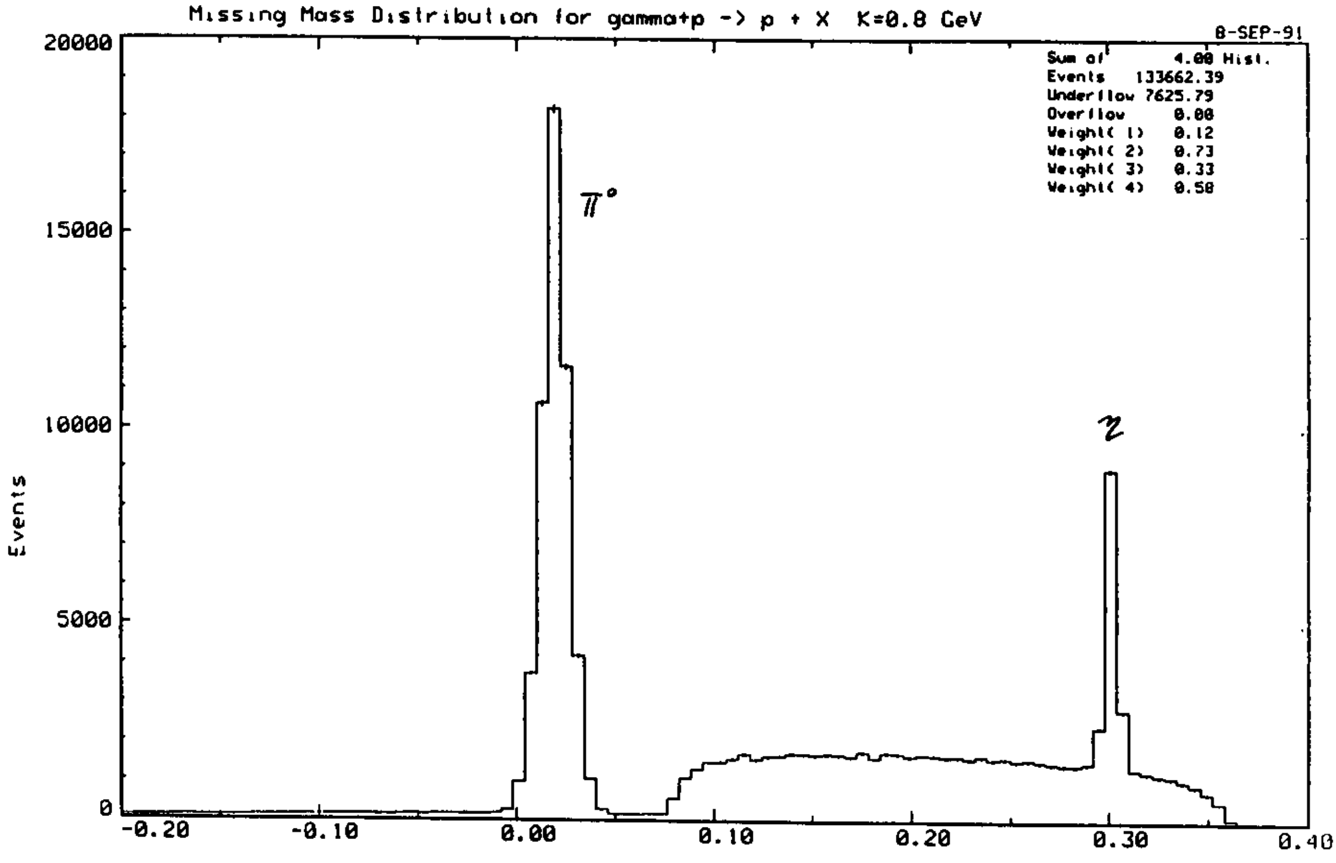

Figure 13: Simulated missing mass spectrum for photoproduction using the CLAS with an incident photon energy of 0.8 GeV.

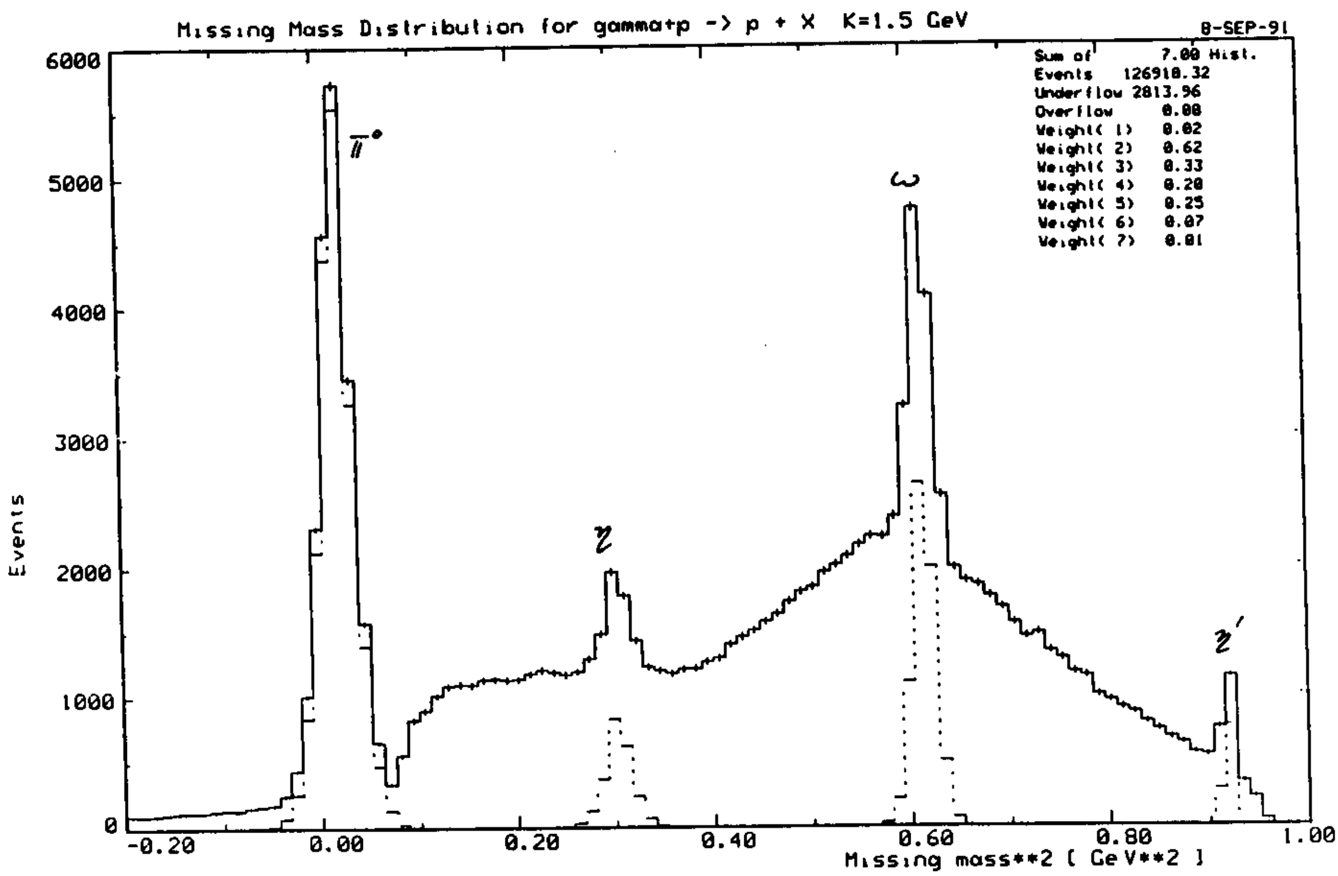

Figure 14: Simulated spectrum missing mass for photoproduction using the CLAS with an incident photon energy of 1.5 GeV.

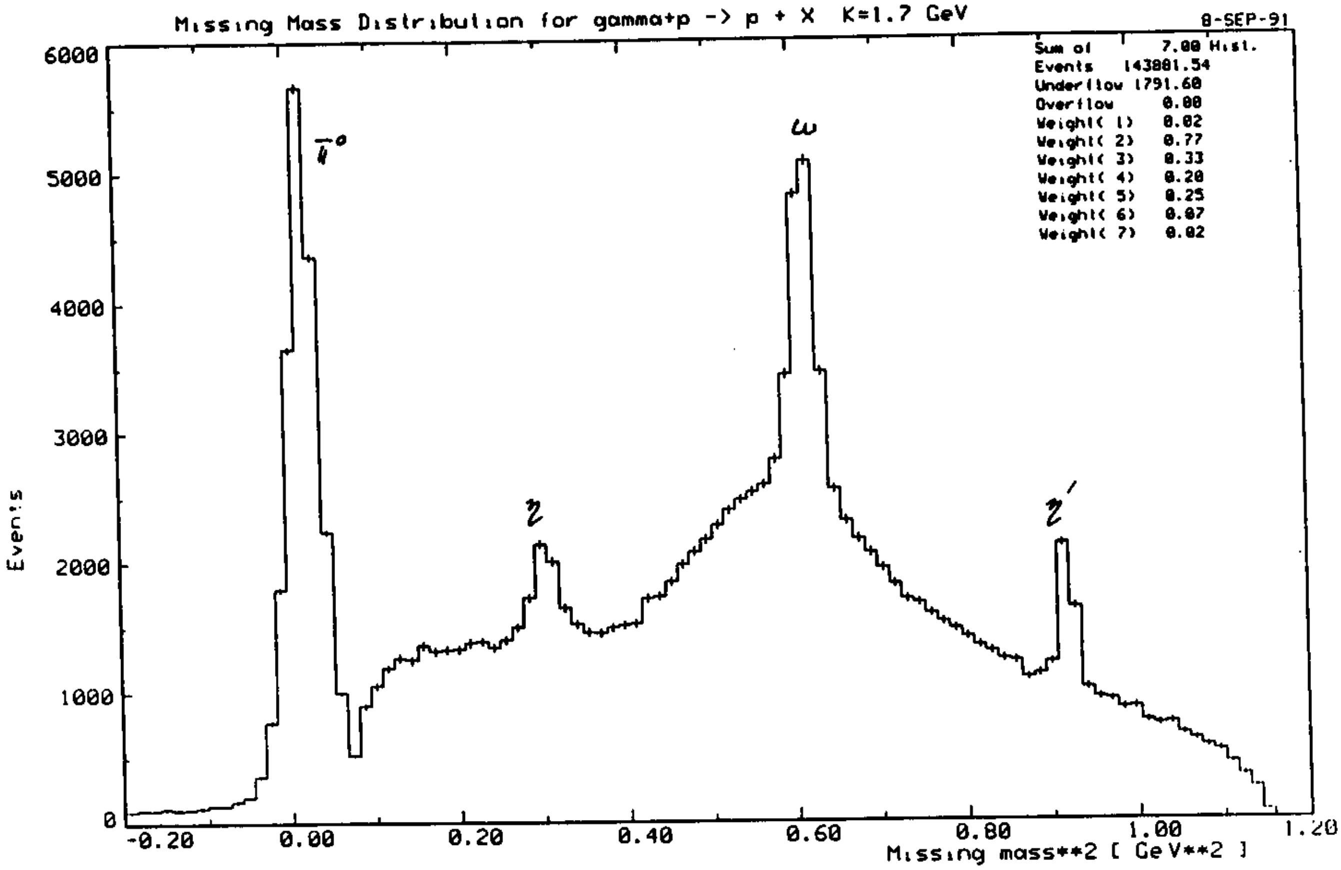

Figure 15: Simulated spectrum missing mass for photoproduction using the CLAS with an incident photon energy of 1.7 GeV.

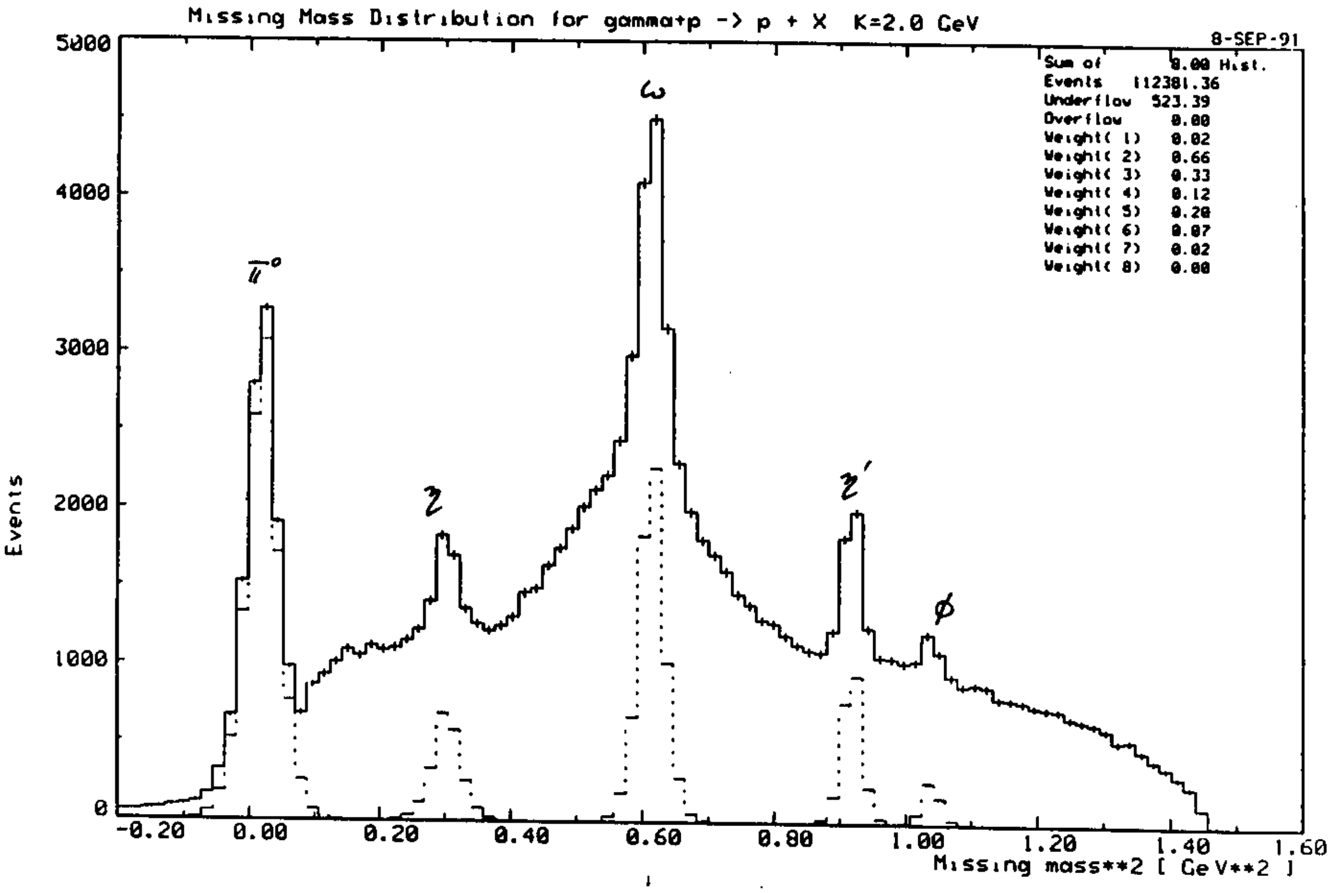

Figure 16: Simulated spectrum for missing mass photoproduction using the CLAS with an incident photon energy of 2.0 GeV.

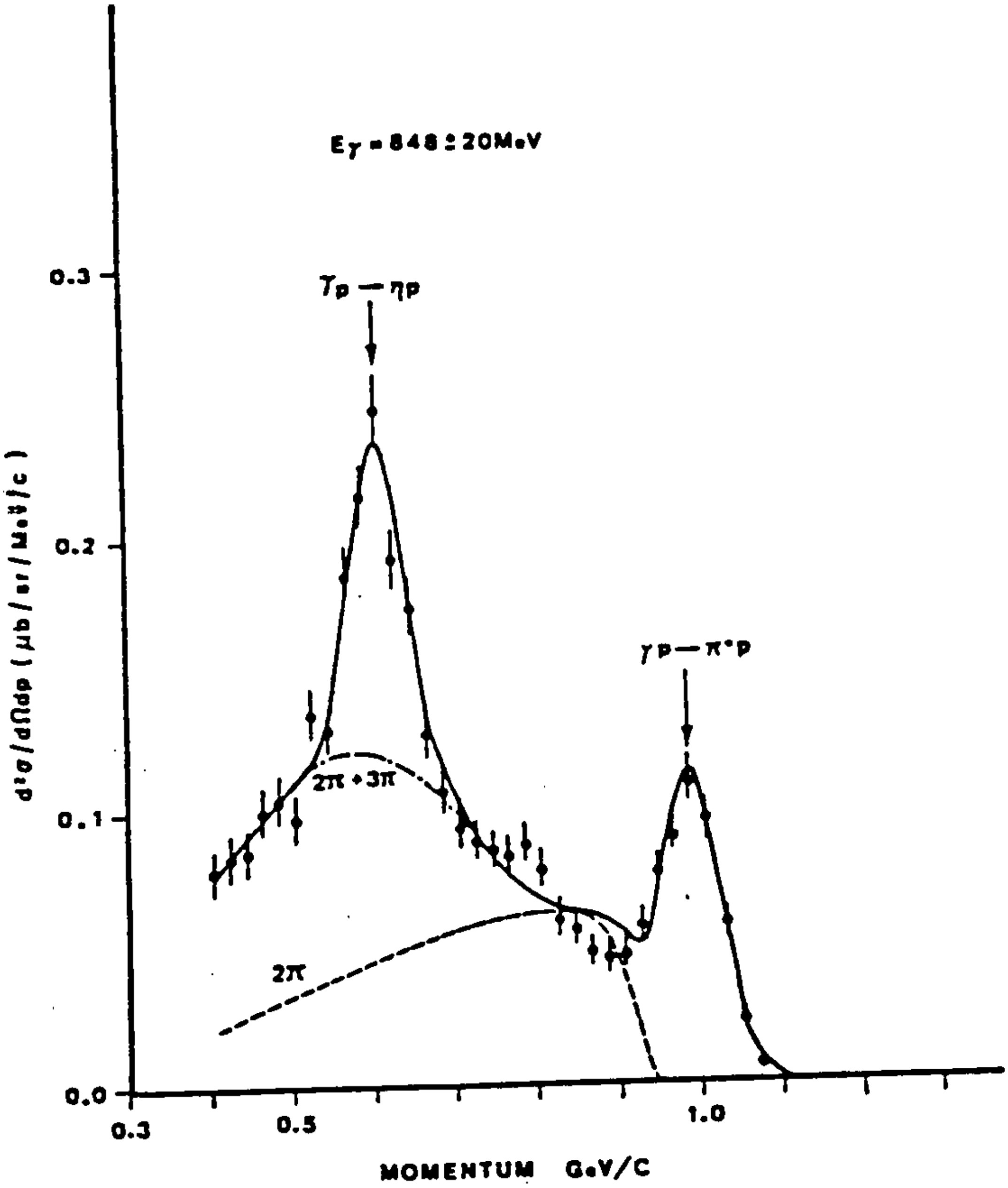

Figure 17: Recoil proton spectrum for η photoproduction from Ref. 16.

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July 5, 1991

Prof. J. Dirk Walecka, Scientific Director
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606

Dear Prof. Walecka,

Enclosed please find 40 copies of an experiment proposal entitled "Photoproduction of η and η' Mesons" for consideration at the upcoming CEBAF Program Advisory Committee.

Sincerely yours,

Barry G. Ritchie
Associate Professor of Physics