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SELECTED TOPICS ON BOSON RESONANCES

Gerson Goldhaber

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SELECTED TOPICS ON BOSON RESONANCES

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I. The ω-ρ Interference Effect--Revisited.

II. The A_2 Puzzle Becomes a Mystery.

I. THE ω-ρ INTERFERENCE EFFECT--REVISITED

A little over a year ago at the 1970 Washington meeting I reviewed the status of the ω-ρ interference effect; this is available in print.[1]

Here I want to give you a very brief introduction and then proceed to the new developments, as well as possible future developments, in this field.

1. Review

In 1961 Glashow proposed that electromagnetic mass mixing could occur between the ω and ρ which had just been discovered. According to this the physical states $|\rho\rangle$ and $|\omega\rangle$ are linear superpositions of the states $|\rho^0\rangle$ and $|\omega^0\rangle$ which are eigenstates of I and G. Namely,

$$|\rho\rangle = |\rho^0\rangle - \epsilon|\omega^0\rangle$$
$$|\omega\rangle = \epsilon|\rho^0\rangle + |\omega^0\rangle$$

where ϵ is a small complex number given by $\epsilon = \dfrac{\delta}{m_\rho - m_\omega - i(\Gamma_\rho - \Gamma_\omega)/2}$. Here $\delta = -\langle\rho|M|\omega\rangle$ is the off-diagonal element of the mass mixing matrix.

1.1. The ω-ρ Interference Pattern

The shape of the ω-ρ interference pattern depends on:

(a) the overall phase difference φ between the ω and ρ amplitudes for decay into the same final state;

(b) the degree of coherence between the initial ω and ρ states;

(c) the $\omega \to 2\pi$ branching ratio R (only for the $\pi^+\pi^-$ final state).

For an understanding of the gross features of the ω-ρ interference effect it is advantageous to separate the overall phase difference φ into two components; the relative ω-ρ production phase β and the decay phase β',

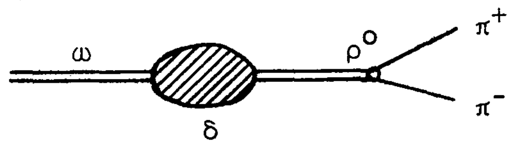
$$\varphi = \beta + \beta' \quad .$$

This is a simplified (linear) treatment and I have discussed second-order corrections earlier.[1] Here β is related to the strong or electromagnetic production process and thus varies from one reaction to another as well as with s and t. It is the experimental determination of β which can yield new and important insight on strong and electromagnetic interactions in that it allows a direct measurement of the relative ω and ρ production phase.

On the other hand β' is characteristic of the transition of the ω into the final state. This is independent of the production process. Here we must distinguish between two cases:

Case I. The final state $\pi^+\pi^-$.

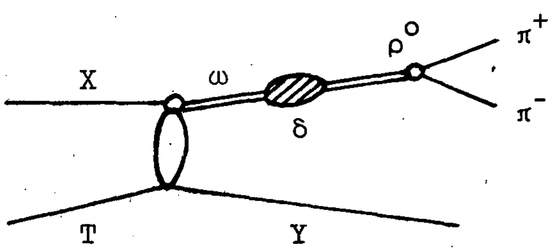
If we represent the process of $\omega \to 2\pi$ by:

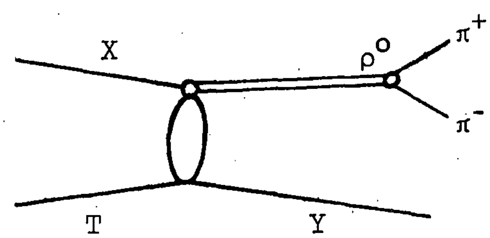


and in the approximation that δ is real (see for example A. Goldhaber, Fox, and Quigg (GFQ)[2]), the phase β' is given approximately by the phase of the ρ at the mass of the ω

$$\beta'_{\pi\pi} \cong \tan^{-1}\left(\frac{\Gamma_\rho/2}{m_\rho - m_\omega}\right) \cong 106^\circ \quad .$$

In this case the ω-ρ interference occurs between amplitudes which can be represented by the two diagrams for ω and ρ production.





and $\varphi_{\pi\pi} = \beta + \beta'_{\pi\pi}$
$\cong \beta + 106^\circ.$

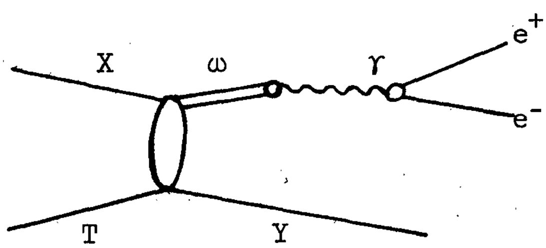
Here X is any incident particle (e.g., π or γ ray), T the target particle which can be a proton or a nucleus, and Y the recoil system. In the case of photoproduction the photon X changes to the vector meson γ—o═V with coupling constant $em_V^2/2\gamma_V$ and the latter then diffraction scatters at the indicated vertex. Alternately ω and ρ formation has also been studied in e^+e^- colliding beams.

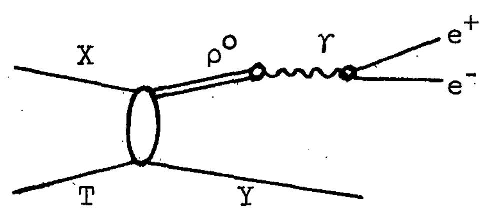
Case II. The final state e^+e^-.

The ω-ρ interference effect has also been observed in this final state. There is an essential difference here in that we are now observing interference between ω and ρ which each have a small branching ratio into the same leptonic decay mode. For completely coherent production the interference is thus between the total ω and ρ decay amplitudes into the leptonic mode. The most recent branching ratios from the Particle Data Tables are

$$B(\omega \to e^+e^-) = (6.6\pm1.7)10^{-5}$$
$$B(\rho \to e^+e^-) = (6.0\pm0.8)10^{-5} \quad .$$

In this case the ω-ρ interference occurs between the amplitudes given by the diagrams below:





and $$\varphi_{ee} = \beta + \beta'$$
$$\cong \beta + 0^{\circ}$$

since from electromagnetic theory combined with vector dominance we expect the relative ω and ρ decay phase β' to be zero. The same results should hold if the $\mu^+\mu^-$ pairs are studied. So far this experiment is not yet available in sufficient detail.

2. New Experimental Results

I will now discuss the new experimental results that have become available during the last year.

The largest progress has been made in photoproduction experiments; these are all in reasonable agreement as far as $\pi^+\pi^-$ production is concerned. Some mysterious differences still persist in the e^+e^- production experiments.

There is at present no generally accepted unique formulation of the ρ amplitude and the treatment of the background problem. I will in each case give the formulation used by the various authors. Fortunately the quantities relevant to ω-ρ interference, the phase φ and the $\omega \to 2\pi$ branching ratio R, are not too sensitive to the detailed assumptions on the ρ shape.

2.1. Photoproduction Data From the DESY-MIT Group -- $\gamma + A \to \pi^+\pi^- A$

New data on the $\pi^+\pi^-$ mass spectrum as obtained from photoproduction has been reported by Ting of the DESY-MIT Group at the 1970 Kiev Conference and more recently by Becker at the 1971 Washington Meeting.[3]

The DESY-MIT Group have studied photoproduction on hydrogen, carbon and lead for a Bremsstrahlung spectrum with $E_{\gamma max} = 7.4$ GeV with a double arm spectrometer of 8 MeV FWHM resolution shown in Fig. 1. Their results are in good agreement with the earlier work on the $\gamma + C$ reaction at Daresbury reported by Gabathuler at the 1970 Philadelphia Conference on Meson Spectroscopy. Figure 2 shows the $\pi^+\pi^-$ spectrum for the three reactions studied. In each case the deviation from a pure ρ spectrum is very clear. The fitted values are given in Table I. The data for the three elements were fitted to two different mass distributions $R_1(m)$ and $R_2(m)$ where $R_1(m)$ corresponds to the Ross-Stodolsky factor $(m\rho/m)^4$ while $R_2(m)$ uses a nonresonant $\pi\pi$ background according to Kramer and Quinn or Pumplin.

The expressions used are:

$$\frac{d\sigma}{dtdm}(m,p,t_\perp) = 2mR_i(m)f_A(t_\parallel,t_\perp) + BG(m,p) \quad , \quad A = H,\ C,\ Pb \quad .$$

$$R_1(m) = m_\rho\Gamma_\rho(m)\,\frac{1}{\pi}\left|\left(\frac{m_\rho}{m}\right)^2 \frac{1}{D_\rho(m)} + \xi\,\frac{e^{i\alpha}}{D_\omega(m)}\right|^2 \quad ,$$

$$R_2(m) = m_\rho \Gamma_\rho(m) \frac{1}{\pi} \left| \frac{1}{D_\rho(m)} + \frac{2F_A(m_\rho^2 - m^2)}{m^2 D_\rho(m)} + \frac{\xi e^{i\alpha}}{D_\omega(m)} \right|^2 ,$$

$$BG(m,p) = \frac{1}{p^2} (am^2 + bm + c)$$

$$f_H(t_\parallel, t_\perp) = \frac{d\sigma}{dt} (\gamma p \to p\rho) \Big|_{t=0} e^{8t} , \quad \text{where} \quad t = t_\parallel + t_\perp ,$$

$t_\parallel$ is the four-momentum transfer for photoproduction of a particle of mass m and momentum p in the forward direction.

For f_C and f_{Pb} optical model calculations were used. $D_V(m) = m_V^2 - m^2 - im_V\Gamma_V(m)$, $\Gamma_V(m) = \Gamma_V(m_V/m)[(m^2 - 4m_\pi^2)/(m_V^2 - 4m_\pi^2)]^{3/2}$.

The free parameters for the fits to the individual elements (Method a) were

$$\frac{d\sigma}{dt}\Big|_{t=0}^{\text{nucleon}} , \; m_\rho, \; \Gamma_\rho, \; m_\omega, \; \xi, \; \alpha, \; a, \; b, \; c, \; F_A \; .$$

Differences in ξ and α for the two different forms $R_1(m)$ and $R_2(m)$ were considered as systematic errors. Furthermore fits were made (Method b) for which $\frac{d\sigma}{dt}\Big|_{t=0}^{\text{nucleon}}$, m_ρ, Γ_ρ, m_ω, ξ and α were considered the same for all three elements. However, a, b, c, and F_A were allowed to vary for each element. The average best values from Method b are

$$\xi = 0.0106 \pm 0.0012$$

$$\alpha = 96 \pm 15^\circ \; .$$

From these the authors deduce

$$R\left(\frac{\omega \to 2\pi}{\omega \to 3\pi}\right) = 1.22 \pm 0.30\%$$

$$\delta = 2.09 \pm 0.25 \text{ MeV}$$

$$\Gamma_{\omega \to 2\pi} \to 0.145 \pm 0.035 \text{ MeV} \; .$$

In Table II is furthermore shown the sensitivity of the fits to the various parameters.

2.2. Photoproduction Data From the Rochester-Cornell-NAL Group -- $\gamma A \rightarrow \pi^+\pi^- A$

A Rochester-Cornell-NAL Group (Behrend et al.[4]) has carried out a photoproduction experiment on carbon, aluminum, and lead at the Cornell Synchrotron. The photon beam was a Bremsstrahlung beam with $E_{\gamma_{max}} = 9.4$ GeV and pion pairs with energy 7 to 9.15 GeV were accepted.

The apparatus is shown in Fig. 3 where S_1-S_6 are wire spark chambers whose output was recorded online in a magnetostrictive readout and F, M and B are trigger counters. The rms mass resolution was $\sim \pm 5$ MeV varying slightly for the three elements studied, and known to an accuracy of 6%. The "e-pair target" shown was used for resolution studies and was removed during the data taking.

Figure 4a shows the experimental result for the experiment on carbon. In Fig. 4b the first derivative of the mass spectrum is plotted which shows up the ω-ρ interference effect in a very dramatic fashion. The data was fitted with an expression very similar to $R_1(m)$ defined in the previous section which includes the Ross-Stodolsky factor. The results are shown in Table III. A sensitivity test of the relevant factors was carried out and it showed that a change in the absolute mass scale by $\pm 0.25\%$ corresponds to changes in ξ by $\pm 3\%$ and φ by $\pm 13^{\circ}$, independent of A. Furthermore a change in mass resolution (or Γ_ω) by 10% changes ξ by 5% but does not affect φ appreciably. The ω mass M_ω was held fixed and the above sensitivity is included in the overall errors. Allowing Γ_ρ to be a free parameter gave $\Gamma_\rho = 160 \pm 15$ MeV, for all three elements studied. In the fits in Table III Γ_ρ was set at $\Gamma_\rho = 145$ MeV as obtained in independent experiments. Finally, Behrends et al. also investigated the model dependence viz. Ross-Stodolsky, Soding, etc. These changes affected ξ by $\pm 2.5\%$ and φ by $\pm 5^{\circ}$ at most.

2.3. New Results from Orsay on $e^+e^- \to \pi^+\pi^-$

The problem of the very large value of φ ($\varphi = 164^\circ \pm 28^\circ$) observed in the initial Orsay e^+e^- storage ring experiments[5] has now been resolved with a repetition of the experiment. The new results were presented by Lefrancois at the 1971 Ithaca Symposium on electron and photon interactions at high energies.[6] In this experiment the Orsay group used a rather ingenious large solid angle (0.6 of 4π steradian) detector. This consisted of two sets of 16 optical spark chambers interspersed with eleven 0.5-radiation length Pb sheets and 5 scintillation counters, forming a cylinder around the interaction region. See Fig. 5. The light from the sparks, which emerged along the circumference after several reflections, was photographed by a single camera.

The data shown in Fig. 6 was fitted with a Gounaris-Sakurai[7] formula, G.S., for the ρ meson, interfering with a fixed Γ_ω Breit-Wigner expression for the ω. Here G.S. is given by:

$$\text{G.S.} = M_\rho^2(1 + \delta\Gamma_\rho/M_\rho)/(M_\rho^2 - 4E^2 - iM_\rho\Gamma_\rho(P/P_o)^3 M_\rho/2E) \quad .$$

Aside from the usual P-wave barrier factors this expression contains an extra parameter δ which takes account of a finite width correction. The authors made fits with δ as a free parameter and also fixed at 0.48 as dictated by theoretical considerations. The essential results were not sensitive to the value of δ and were:

$$M_\rho = 779.6 \pm 5.7 \text{ MeV} \qquad \Gamma_\rho = 147.6 \pm 6.5 \text{ MeV}$$

$$B^{1/2}_{\omega\to 2\pi} = 0.20 \pm 0.05 \qquad \varphi = 86^\circ \pm 15^\circ \quad .$$

It is not completely clear what caused the large φ value in the first data set but the authors suspect possible difficulties in the original electron, pion separation.

At any rate, this new result is very consistent with all the other available data on interference in the $\pi^+\pi^-$ final state.

2.4. A Mystery Still With Us: The Daresbury $\gamma + C \to e^+e^-C$ Data Compared to the DESY-MIT $\gamma + Be \to e^+e^-Be$ Data on ω-ρ Interference

In the study of e^+e^- pairs photoproduced on a nucleus there are five diagrams that contribute. Of these diagrams, shown in Fig. 7, the first two correspond to the Bethe-Heitler process, the second two to diffraction production of the two vector mesons ρ and ω each decaying via the rare leptonic e^+e^- mode while the last corresponds to incoherent vector meson production via the OPE process followed by leptonic decay. The amplitude $A = A_{BH} + A_\rho + A_\omega + A_X$. The two Bethe-Heitler diagrams can be calculated from Q.E.D. and involve two photon exchanges. The e^+e^- pairs produced are thus even under charge conjugation C. On the other hand, the vector production diagrams involve one photon and the corresponding e^+e^- pairs are thus odd under C. This feature can be exploited experimentally in that by observing the e^+e^- pairs symmetrically the interference terms between the B-H amplitude and the remaining diagrams vanish. Alternately these interference terms can be studied by measuring asymmetric e^+e^- pairs.

The Daresbury results which correspond to the measurement of symmetric e^+e^- pairs and I discussed previously, give a vector meson to γ coupling constant ratio[1] of $\gamma_\omega^2/\gamma_\rho^2 = 7.0^{+2.0}_{-0.9}$ and a surprisingly large phase angle $\varphi_{ee} = 100^{\circ}{}^{+38^\circ}_{-30^\circ}$ for the reaction $\gamma + C \to e^+e^-C$. Furthermore the Daresbury group has just carried out an additional series of experiments whose main purpose was the determination of the ρ nucleon forward scattering amplitude which however also yields another measurement of the ρ-ω production phase φ_{ee}. The original measurements of Biggs et al.[8] were carried out with a symmetric configuration of their spectrometers. This eliminates interference terms between the electron pairs from the Bethe-Heitler process and the Compton process including the ρ and ω production. The new measurements[9] were carried out with asymmetric pairs; i.e., e^+e^- pairs with unequal four momenta as a means of utilizing these interference terms to obtain the ρ nucleon forward scattering amplitude or the phase

$\varphi_{\rho A}$. The two spectrometer arms were adjusted at unequal angles but set for equal momenta. N^+ refers to the e^+e^- pairs yield when the e^+ was detected in the smaller angle spectrometer. The magnet currents were then reversed and N^- refers to the corresponding situation when the e^- was detected in the smaller angle spectrometer. These respective yields are given in Fig. 8. It can then be shown that for the difference and sum of these sets of measurements at each mass bin; $(N^+ - N^-)/2$ corresponds to the Bethe-Heitler-Compton (i.e., vector meson production) interference while $(N^+ + N^-)/2$ corresponds to the sum of the B-H and Compton yields which includes the ρ-ω interference effect.

Figure 9 gives these sum and difference graphs which show the ω-ρ interference effect clearly. I will not go into the details of the analysis here, but the results of a fit to the data gave the phase $\varphi_{\rho A} = 16.5^\circ \pm 6.2^\circ$ and what is relevant for our discussion here, the ω-ρ interference phase $\varphi_{ee} = 118^{\circ}{}^{+13^\circ}_{-22^\circ}$. Thus this second experiment again yielded a rather high value of φ_{ee}.

On the other hand the DESY-MIT group[10] has carried out a measurement on the reaction $\gamma + Be \rightarrow e^+e^- Be$. They measured the e^+e^- pairs in both the symmetric and asymmetric configuration. For the symmetric configuration a total of 4000 events were measured with a mass resolution of $\pm$ 4 MeV at 5.1 GeV. They used this data to study the ω-ρ interference effect. The resulting spectra are shown in Fig. 10. The best fit to the data gave:

$$\frac{\gamma_\omega^2 \; \sigma_{\rho N}}{\gamma_\rho^2 \; \sigma_{\omega N}} = 9.4^{+2.6}_{-1.6}$$

and $$\varphi_{ee} = 41^\circ \pm 20^\circ \quad .$$

If one assumes equal diffraction scattering cross sections for ρ and ω; i.e., $\sigma_{\rho N} = \sigma_{\omega N}$, the value for the vector meson coupling constant ratio $\gamma_\omega^2/\gamma_\rho^2$ is in good agreement with the vector dominance model.

The origin of the difference between the values of φ_{ee} from the two laboratories is not understood at present. The lower value of $\varphi_{ee} = 41^{\circ}\pm 20^{\circ}$ from the DESY-MIT experiment fits readily into the model of ω-ρ interference discussed here.

2.5 Combined Analysis of the Vector Meson Photoproduction and $e^+e^- \to \pi^+\pi^-$ Experiments

Just as I was completing this manuscript I received a preprint from Lemke and Sachs[11] who have analyzed and averaged the same experiments I have discussed here. They choose to represent the data in terms of three model-independent complex parameters and have evaluated the best values for these parameters from the existing experiments. These parameters are: ϵ, the intrinsic ρ-ω mixing parameter; r_ω, the ratio of ω-photon to ρ-photon coupling at an energy corresponding to the mass of the ω; and P_ω/P_ρ, the ratio of nuclear photoproduction amplitudes for ω and ρ. The ϵ is the same as I defined in Sec. 1. Thus $|\epsilon|$ determines $|\delta|$ and $\arg\epsilon = \beta'$ in terms of my variables. $|r_\omega| = 1/\left|\sqrt{\gamma_\omega^2/\gamma_\rho^2}\right|$ which I quoted in Sec. 2.4.

Lemke and Sachs point out that in view of the present, on the average, 10% level of experimental accuracy one can only determine relative phases. They thus choose r_ω to be real.

With this assumption they find for the most consistent representation of the data:

$$|\epsilon| = 0.034\pm 0.004$$

$$|r_\omega| \equiv \gamma_\rho/\gamma_\omega = 0.34\pm 0.07$$

$$|P_\rho/P_\omega| = 3.44\pm 0.19$$

$$\left.\begin{array}{l}\arg\epsilon = 95^{\circ}\pm 15^{\circ}\\ \arg(P_\omega/P_\rho) = 0^{\circ}\pm 21^{\circ}\end{array}\right\}\quad \text{if } r_\omega \text{ is real}$$

Thus at the 10% experimental accuracy level $\arg\epsilon \equiv \beta'$ is consistent with expectations of simple electromagnetic ω-ρ mixing, ω-ρ mixing is negligible in e^+e^- pair production experiments, $\arg(P_\omega/P_\rho)$ and $|r_\omega|$ are consistent with vector meson photoproduction and diffraction scattering according to the vector dominance model. Finally, Lemke and Sachs point out that when 1% level experiments become available second-order corrections to these simple models will be necessary to determine the best set of parameters.

3. Interfering Boson Resonances as a Tool in Strong Interactions

In the remainder of my talk I will concentrate on a few specific ideas for future experiments. Much of the material in this part of my talk has been developed in conjunction with various of my colleagues; in particular, Dr. Gerald Abrams.[12,13]

In what follows I will use the simple first-order theory of GFQ.[2] Namely, the $\pi^+\pi^-$ mass spectrum in the ρ region is given by

$$\frac{dN}{dm} = |B_\rho(m)A_\rho|^2 F(m)$$

where

$$F(m) = \left|1 + \frac{A_\omega}{A_\rho} \frac{\delta}{m_\omega - m - i\Gamma_\omega/2}\right|^2 .$$

Here F(m) is a modulating factor multiplying the Breit-Wigner distribution

$$B_\rho(m) = \frac{\sqrt{\Gamma_2/2\pi}}{m_\rho - m - i\Gamma_\rho/2}$$

which describes ρ production. A_ρ and A_ω are the amplitudes for ρ and ω production, δ is the ω-ρ mass mixing parameter, $\frac{1}{m_\omega - m - i\Gamma_\omega/2}$ is the propagator of the ω. The production, amplitudes A_ρ, A_ω are related to N_ρ and N_ω, the experimental number of ρ,ω events observed in the t' interval studied, by the following expression:

$$\frac{A_\omega}{A_\rho} = \sqrt{\frac{N_\omega}{N_\rho}}\, e^{i\beta}$$

where β is the relative production phase. As I discussed in detail earlier[1] β depends on the production process. In particular, one can choose the charge symmetric reactions:

$$\pi^+ n \to \rho^o p \qquad \text{(dip at } \omega \text{ mass)}$$
$$\pi^- p \to \rho^o n \qquad \text{(peak at } \omega \text{ mass)} \quad .$$

For these GFQ pointed out that there would be a change in sign at the ρ vertex and hence a change in the value of β from $\sim 90^o$ (corresponding to a dip) to $\sim 270^o$ (corresponding to a peak).

3.1. Charge Symmetric Reactions for ρ^o and ω Production - Breakdown of Charge Symmetry

My main point here is to point out that by choosing different production mechanisms, you can obtain different values for β and observe different interference patterns. That much is well known; as for the future, I would like to suggest that a very accurate experiment could be done on the reactions

$$\text{(a)} \qquad \pi^+ n \to \pi^+ \pi^- p$$
$$\text{(b)} \qquad \pi^- p \to \pi^+ \pi^- n$$

to study the breakdown of charge symmetry induced by ω-ρ mass mixing. Furthermore, one should investigate ω production in the reaction

$$\text{(c)} \qquad \pi^+ n \to \pi^+ \pi^- \pi^o p$$
$$\text{(d)} \qquad \pi^- p \to \pi^+ \pi^- \pi^o n \quad .$$

In reactions (c) and (d) one can examine the effect of $\rho \to 3\pi$ on ω production.

In the case of ω production, the modulating function which multiplies the ω Breit-Wigner distribution can be given as:

$$F(m)_{3\pi} = \left| 1 + \frac{A_\rho}{A_\omega} \frac{\delta}{m_\rho - m - i\Gamma_\rho/2} \right|^2 \quad .$$

Here A_ω, A_ρ, δ are as defined previously, $\frac{1}{m_\rho - m - i\Gamma_\rho/2}$ is the ρ propagator. For our purposes the ω Breit-Wigner can be considered as a delta function and then $F(m_\omega) \cong$ constant.

The influence of the 3π decay of the ρ on the ω thus has the effect of changing the amplitude for ω production. In that case one expects a larger value for the ω production cross section in π^+n than in π^-p reactions. In particular:

$$\rho_{oo}\left(\frac{d\sigma}{dt}\right)_{\pi^+n\to\omega p} > \rho_{oo}\left(\frac{d\sigma}{dt}\right)_{\pi^-p\to\omega n} \quad .$$

Thus one should do both the π^+ and the π^- experiments in order to measure this difference. This should show a clear case of the breakdown of charge symmetry; i.e., a very marked difference in cross section for ω production in π^+n and π^-p reactions. This would also be the first complete test of the mass mixing theory which we now accept, to the best of my knowledge, without complete experimental verifications.

In order to eliminate experimental biases, the experiment has to be done on deuterium. Thus we have to detect the two reactions

$$\pi^+d \to \omega pp$$

$$\text{and} \qquad \pi^-d \to \omega nn \quad .$$

There are experimental difficulties in detecting the two nucleons in the final state. One will probably have to do the experiment by detecting the three outgoing mesons; i.e., detecting the π^+ and π^- directly and the π^o via its 2γ decay mode.

In Fig. 11 I show the natural parity contribution to ω production in the reaction $\pi^+p \to \omega^o\Delta^{++}$ at 3.7 GeV/c $\left(\rho_{oo}\left(\frac{d\sigma}{dt}\right)_{\pi^+p\to\omega^o\Delta^{++}}\right)$. The distribution is flat in the forward direction. There is a dip at $t' \cong 0.14$ (GeV/c)^2. So far we have succeeded in establishing coherence between ρ and ω for $t' <$ 0.14 (GeV/c)^2. There were not enough events to establish whether or not coherence is present beyond this point. The data in Fig. 11 show what the π^+p differential cross sections look like; we expect a lower cross section for the π^-p case. The question is, increase or decrease relative to what? The curve in Fig. 11 represents an absolute prediction of a model proposed by G. Abrams and U. Maor,[14] which does not take into account ρ-ω interference. The model suggests that there are an excess of events in the forward direction, but one has to measure the π^- reactions to see if this is indeed the case.

The dip at $t' \cong 0.14\ (\mathrm{GeV}/c)^2$ is not understood as yet. It might be related to ρ-ω interference, and this is another reason one should see what the π^-p reaction looks like. Will it show a peak or a dip at $t' \cong 0.14\ (\mathrm{GeV}/c)^2$? An answer to these questions demands a study of the two reactions I mentioned.

3.2. Search for C Violation in Electromagnetic or Semi-Strong Interactions Via ρ-ω Interference

I would like to discuss another topic based upon the same general ideas; namely, a search for C violation in ρ decay using the ρ-ω interference effect. In looking for the effects of the $\rho \to 3\pi$ decay on ω decay we observed a charge asymmetry on the ω Dalitz plot. It occurred to us[12] that there is an opportunity here, in principle, to look for C violation in electromagnetic or sub-strong interactions.

The question is how does the ρ meson decay into 3π's? There are four possible ways.

(a) Electromagnetic decay with $\Delta I = 1$ to $I = 0$. Here the ρ turns into an ω via an electromagnetic interaction with $\Delta I = 1$. In this case the final state which decays into 3π's has the same quantum numbers as the ω: $I = 0$, $J^{PC} = 1^{--}$. Thus there is no interference which alters the shape of the matrix element on the Dalitz plot.

(b) C violating decay with $\Delta I = 0$ to $I = 1$. Here the ρ decays into 3π's with $\Delta I = 0$. From the relation $G = C(-1)^I$, since G changes from $+1$ to -1

and $\Delta I = 0$, C must change sign. The final state $I = 1$, $J^{PC} = 1^{-+}$ has a matrix element that vanishes along the y axis ($T_+ - T_- = 0$) of the Dalitz plot and hence will give rise to a left-right asymmetry on interference with the ω.

(c) Electromagnetic decay with $\Delta I = 1$ to $I = 2$. Here the final state after decay has $I = 2$, $J^{PC} = 1^{--}$. The matrix element for such a state vanishes along the $x = 1/3$ line ($T_0/Q = 1/3$). This gives rise to an asymmetry along the y axis of the Dalitz plot on interference with the ω.

(d) C-violating decay with $\Delta I = 2$ to $I = 3$. Here the final state is $I = 3$, $J^{PC} = 1^{-+}$. The matrix element for such a decay vanishes along the lines of sextant symmetry. This will give rise to an asymmetry between adjacent sextants. This is illustrated in Table IV.

Let me concentrate on the search for a C violating effect with $\Delta I = 0$. First, why is it important to look for other C-violation effects besides η decay for which careful measurements are already being done? There is an important difference between the two cases. The interference between the (normal) $\Delta I = 1$ electromagnetic decay of the η and the conjectured $\Delta I = 0$ C-violating decay gives rise to a sextant asymmetry on the Dalitz plot. As T. D. Lee pointed out[15] there are strong angular momentum barriers suppressing the $I = 0$ final state in η decay. Thus what is being searched for in the current measurements is only the $\Delta I = 2$ C-violating effect. The latest results from Wonyong Lee et al.[16] at Columbia are at present that there is no significant asymmetry corresponding to the $\Delta I = 2$ transition. However, suppose C violation does occur for $\Delta I = 0$ rather than $\Delta I = 2$. In such a case the study of $\eta \to \pi^+\pi^-\pi^0$ decay might <u>not</u> lead to a definitive result, because of the angular momentum barriers. As I have outlined in the ω-ρ interference case one can look for a possible $\Delta I = 0$ C-violating transition.

Our interest in this problem was aroused by the fact that we have actually observed a 3.5 standard deviation asymmetry effect in the ω decay as I will discuss below.

First let me say a few words about what could be the significance of the asymmetry we observed. There are at least four mechanisms which can give rise to an asymmetry:

(1) C violation in ω decay. This will proceed via $\Delta I = 1$. There is good evidence against this hypothesis as I will show below.

(2) C violation in $\rho \to 3\pi$ via $\Delta I = 0$.

(3) Background amplitude with spin parity $J^{PC} = 1^{-+}$ which is coherent with the ω (Yuta-Okubo effect).[18]

(4) Existence of an exotic state $\tilde{\rho}$ near the ω mass with $J^{PC} = 1^{-+}$. The question is, can one distinguish among these four possibilities? In a systematic search for C violation using the ρ-ω interference effect, one could proceed as follows: One must first measure the production phase β from ω-ρ interference in the $\pi^+\pi^-$ mass spectrum and determine the interval of coherence in t. After that a fit to the asymmetry on the ω decay Dalitz plot would measure β_1, the characteristic phase of C violation in the decay of the $\rho \to 3\pi$ with $\Delta I = 0$. The asymmetry is related to

$$\sim \mathrm{Re}\left\{\frac{\epsilon_\omega - i}{\epsilon_\omega^2 + 1}\, e^{i(\beta'-\beta+\beta_1)}\right\}$$

where:

$\beta' \equiv$ phase angle of the ρ amplitude at the ω mass $\beta' \cong 106^\circ$;

$\beta \equiv$ relative ω,ρ production angle;

$\beta_1 \equiv$ characteristic C violation phase for $\Delta I = 0$ decay of $\rho \to 3\pi$; and

$\epsilon_\omega = (m_\omega - m)/(\Gamma_\omega/2)$.

Once β_1 has been measured in one reaction you can predict the expected asymmetry in other reactions. We thus expect different types of asymmetries on the ω decay Dalitz plot depending on the value of β_1.

Let me now show you some data from our π^+p experiment at 3.7 GeV/c. The reaction studied is

$$\pi^+ p \rightarrow \pi^+\pi^+\pi^-\pi^0 p \qquad 16{,}000 \text{ events}.$$

In Fig. 12a,b we show the $\pi^+\pi^-\pi^0$ mass spectrum in the interval near the η and ω masses. Figure 12a corresponds to the left side of the Dalitz plot ($x < 0$); Fig. 12b corresponds to the right side of the Dalitz plot ($x > 0$). If there were any left-right asymmetry, you would expect a different number of ω events in the two plots. The background level is somewhat different, but there is no statistically significant difference in the ω signal above background. From this one concludes that there is no $\Delta I = 1$ C violation in the ω decay itself. Similar results were observed earlier by Flatté et al.[17]

In Fig. 13a we show the ω Dalitz plot decay for about 4000 ω events. In Fig. 13b,c we show the projection on the X,Y axis and note that there is no overall asymmetry. The curves represent the expected number of events assuming no asymmetry.

Next, we restrict ourselves to the reaction

$$\pi^+ p \rightarrow \pi^+\pi^-\pi^0\Delta^{++} \quad ,$$

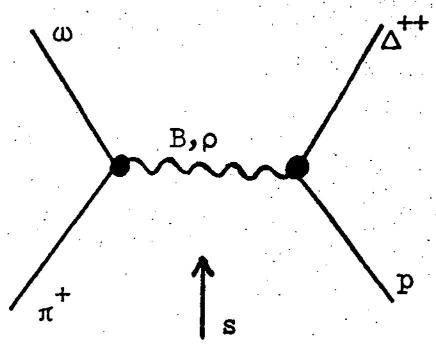
and study the question of asymmetry as a function of t'. In Fig. 14 we show $\left(\frac{d\sigma}{dt'}\right)_{\pi^+p\rightarrow\omega\Delta^{++}}$ where + (cross) corresponds to events with $X > 0$ and ■ (square) corresponds to events with $X \leqq 0$. Notice that in the very low t' region, $t' < 0.14$, where ρ-ω coherence has been established, we find only a very slight difference (if any) in the two differential cross sections. However, in the t' interval $0.08 \leqq t' < 0.2$ (GeV/c)^2 for $\pi^+p \rightarrow \pi^+\pi^-\pi^0\Delta^{++}$ we have observed a difference. In Fig. 15a,b we show the three meson invariant mass for $X > 0$ and $X < 0$. Note that the background level is very low but nonzero, and that the difference in the number of events is not in the background but in the ω signal. The asymmetry is $\alpha = 0.18\pm0.05$ and its statistical significance is clear to everyone; it could conceivably be a statistical fluctuation, but that is very unlikely. In Fig. 16a we show the Dalitz plot distribution for these events. In Fig. 16b,c we show the X,Y projection and note that there are more events with $X > 0$ than $X < 0$. The two curves on the X projection represent no asymmetry (dotted line) and a fit to an asymmetry of the form $\vec{q}(a + bX)$ where $\vec{q} = \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}$ is the matrix element for ω decay and $b \equiv$ asymmetry parameter. For no asymmetry $b = 0$. The result of the best fit are reproduced by the solid curve, and correspond to $b = 0.67 \pm 0.22$. Note that the fits are not influenced by the spike near $X = 0$ and that the effect is there even if this spike is removed. The chisquare for the two fits are (binning the data in 8 bins)

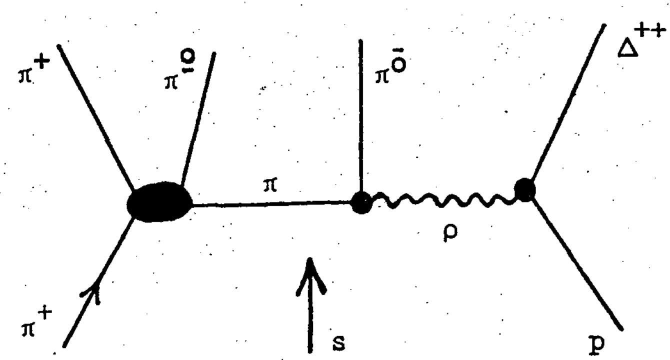
$$b = 0 \qquad \chi^2 = 18.7$$

$$b = 0.67 \pm 0.22 \qquad \chi^2 = 9.7 \ .$$

If the asymmetry should be due to the Yuta-Okubo effect, this implies, however, in view of the low background intensity, that about 50% of the background is entirely in one state, namely, $J^{PC} = 1^{-+}$. The other two more-far-reaching possibilities are the existence of an exotic particle $\tilde{\rho}$ with $J^{PC} = 1^{-+}$ and production cross section at about the 1% level compared to ω production, or C violation in $\rho \to 3\pi$ decay with $\Delta I = 0$. We certainly do not claim to have observed either of these two more exciting possibilities but we feel this is a very promising field for further investigation.

When I presented this data at the Pasadena Workshop on Particle Physics at Intermediate Energies, Ed Berger of ANL[19] stated that he was able to account for the asymmetry quantitatively on the basis of the interference of the ω as produced by ρ exchange with a background diagram by projecting out the $J^{PC} = 1^{-+}$ state. The diagrams are:





where the shaded oval represents the full $\pi\pi$ scattering amplitude. To ascertain whether this is indeed the correct interpretation, it will be interesting to compare these predictions with the similar data at 2-3 GeV from Gidal et al. (LBL) and 7 GeV from Flatté et al. (LBL). Furthermore one should also be able to project out the $J^{PC} = 1^{--}$ state which would interfere with the ω to modulate the ω cross section. Perhaps the sharp dip in $\rho_{00} \frac{d\sigma}{dt}(\omega)$ is related to this.

In conclusion, I have suggested a number of experiments today. Being an experimentalist you may ask why do I not just carry out these experiments myself? Well, what I proposed is really an entire series of experiments which have to be done. We are actually repeating our π^+p experiment to increase the statistics 10-fold, but at the same time to really identify the asymmetry the experiment needs to be done under several different conditions as I have outlined; this is much more work than any one group can do.

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TABLE I. Results of fits by Eq. (1). Upper part, for individual elements, $\Gamma_\omega = 11.9$ MeV; lower part, for H, C, and Pb simultaneously. DESY-MIT experiment.

Element	Fit	$d\sigma/dt \|^{nucl.}_{t=0}$	m_ρ	Γ_ρ	m_ω	ξ	α	χ^2/DF
		$\mu b/(GeV)^2$	MeV	MeV	MeV	-	degrees	-
H_2	$R_1(m)$	113 ± 5	760 ± 2	130 ± 5	783.8 ± 1.9	$.0140 \pm .0014$	78 ± 14	0.89
C	$R_1(m)$	109 ± 2	768 ± 1	140 ± 2	735.3 ± 1.1	$.0106 \pm .0007$	90 ± 10	1.05
Pb	$R_1(m)$	126 ± 2	781 ± 2	150 ± 3	788.8 ± 1.7	$.0121 \pm .0014$	106 ± 15	1.09
H_2	$R_2(m)$	119 ± 6	764 ± 3	136 ± 5	784.8 ± 1.9	$.0131 \pm .0013$	85 ± 16	0.90
C	$R_2(m)$	110 ± 2	769 ± 2	141 ± 3	785.7 ± 1.2	$.0105 \pm .0007$	92 ± 10	1.05
Pb	$R_2(m)$	128 ± 3	778 ± 2	154 ± 4	787.7 ± 1.8	$.0120 \pm .0013$	96 ± 14	1.09
	$R_1(m)$	115 ± 1	771 ± 1	136 ± 1	787.4 ± 1.1	$.0095 \pm .0005$	109 ± 10	1589/1379
	$R_2(m)$	125 ± 1	775 ± 1	147 ± 2	787.1 ± 0.9	$.0100 \pm .0005$	100 ± 8	1417/1376

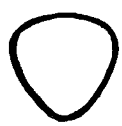
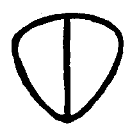
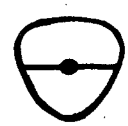
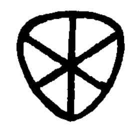
TABLE II. Sensitivity of ξ and α to deviations from best-fit values. DESY-MIT experiment.

changed parameter		$\Delta\xi$	$\Delta\alpha$ (deg)	$\Delta\chi^2$
$\left.\frac{d\sigma}{dt}\right\vert_{t=0}$ nucl.	+ 10 μb/GeV^2	-	+ 7	+ 39
	- 10 μb/GeV^2	+ .0005	- 15	+ 7
m_ρ	+ 10 MeV	+ .0008	+ 17	+ 37
	- 10 MeV	+ .0005	- 44	+ 60
Γ_ρ	+ 10 MeV	+ .0005	- 3	+ 14
	- 10 MeV	- .0008	+ 27	+ 31
m_ω	+ 2 MeV	-	+ 16	+ 5
	- 2 MeV	-	- 15	+ 5
Γ_ω	+ 1.8 MeV	+ .0011	-	+ 4
	- 1.8 MeV	- .0011	-	- 3
Δm	+ 50%	+ .0010	-	+ 4
	- 50%	- .0010	-	- 2.3
BG(m,p)	+ 50%	-	- 12	+ 115
	- 50%	-	+ 4	+ 113

Table III. Results of two sets of fits, either fixing m_ρ at 770 MeV or leaving it as an adjustable parameter. Rochester-Cornell-NAL experiment.

	Carbon	Aluminum	Lead
m_ρ (MeV)	770	770	770
$\xi \times 10^2$	1.34 ± 0.12	1.35 ± 0.16	1.45 ± 0.19
φ (deg)	94.7 ± 4.5	79.4 ± 5.2	77.8 ± 6.0
m_ρ (MeV)	767.6 ± 1.4	771.1 ± 1.8	771.8 ± 1.7
$\xi \times 10^2$	1.24 ± 0.12	1.38 ± 0.18	1.51 ± 0.20
φ (deg)	92.4 ± 5.0	80.3 ± 5.6	81.2 ± 6.6

Table IV. Distribution of zeros for matrix elements corresponding to $\pi^+\pi^-\pi^0$ decay for $J^P = 1^-$ with $I = 0$ to 3.

I = 0	1	2	3
			

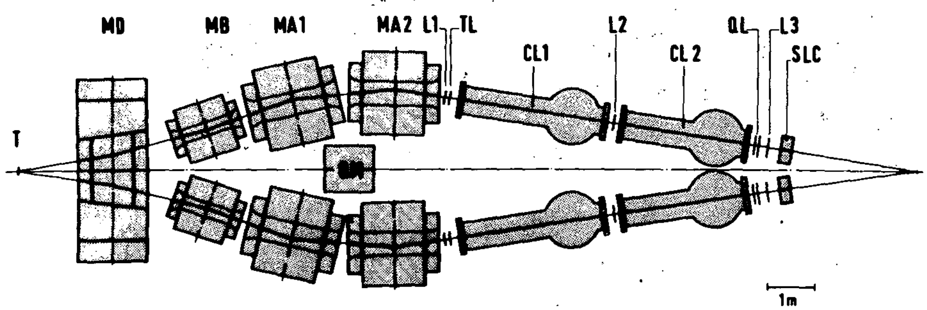
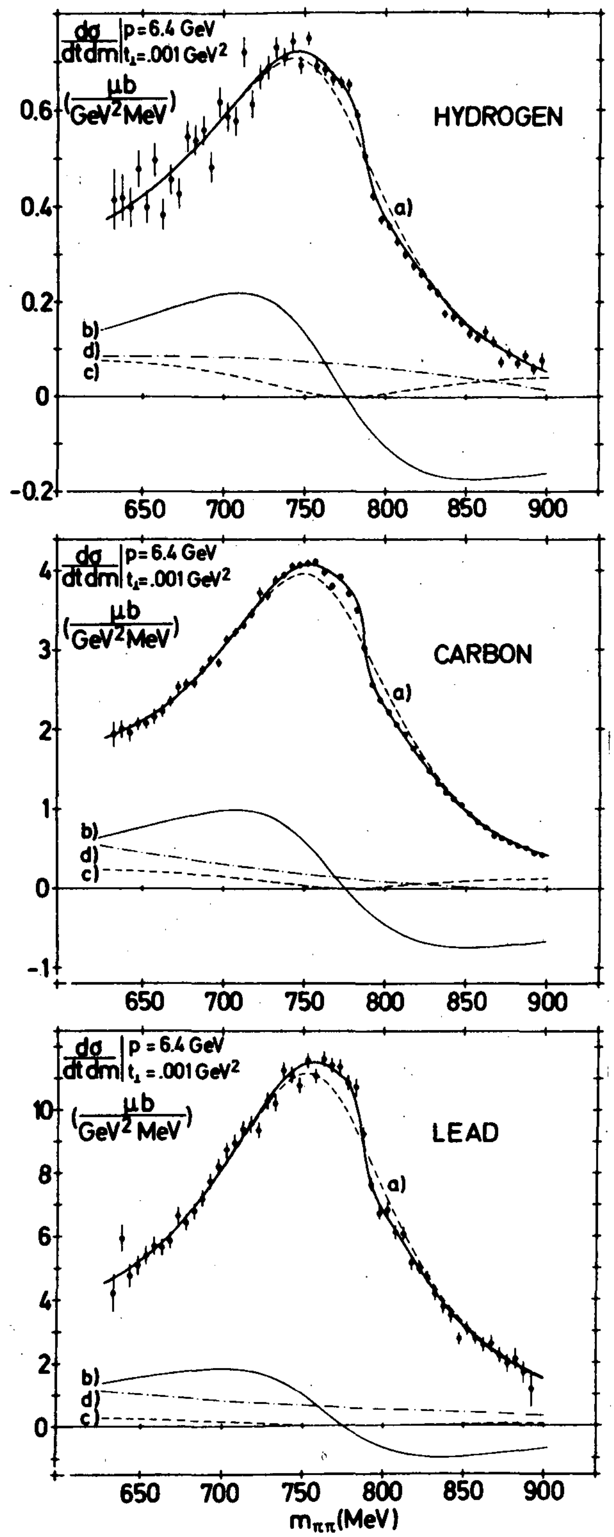


Fig. 1. The DESY-MIT double-arm spectrometer.



XBL 7111-1712

Fig. 2. DESY-MIT data. Cross sections for hydrogen, carbon, and lead. The solid curve is the simultaneous fit to the data using $R_2(m)$. The other curves are (a) the same fit with $\xi = 0$ (no ω contribution), (b) the interference with nonresonant $\pi\pi$ amplitude, (c) the nonresonant $\pi\pi$ amplitude squared, and (d) other background.

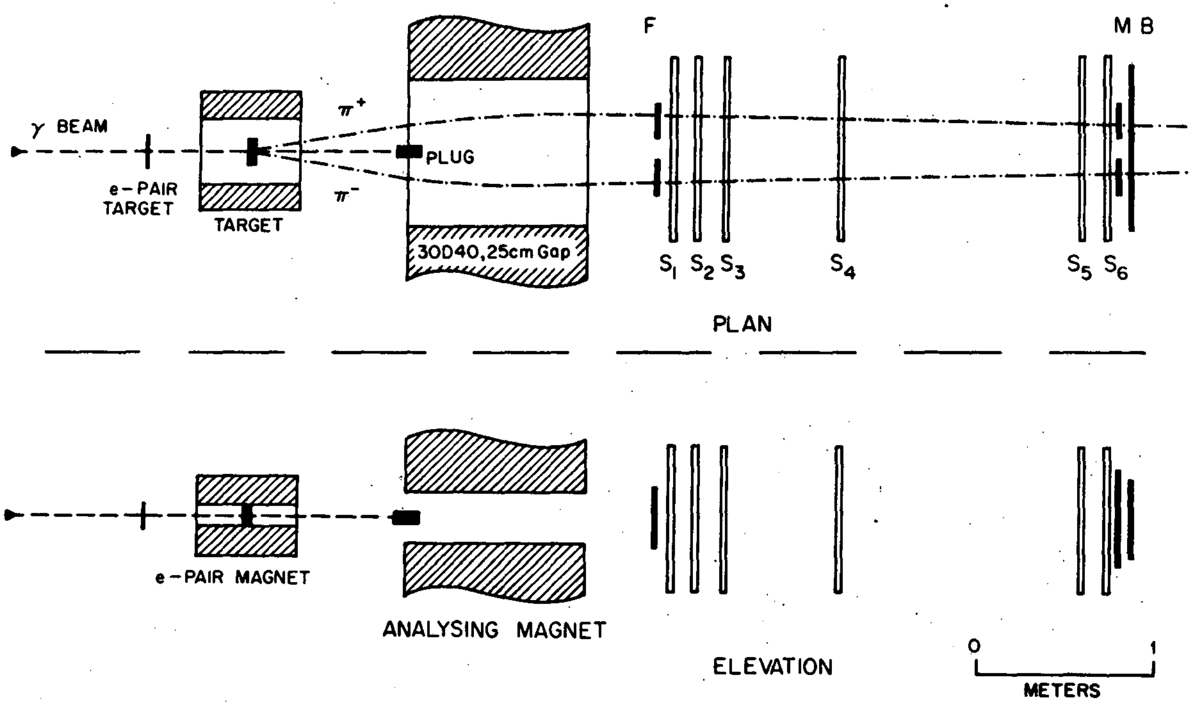
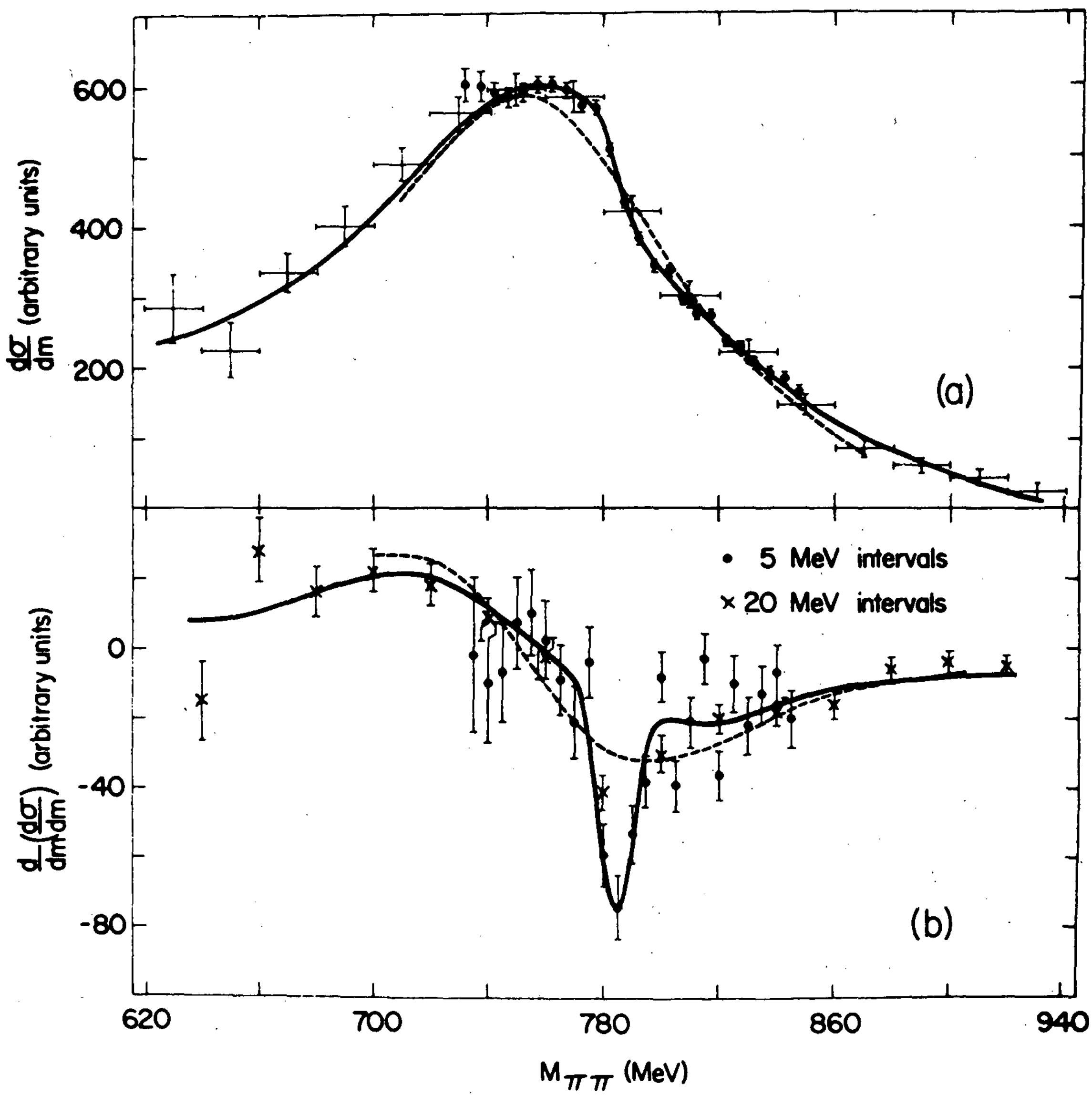


Fig. 3. Plan and elevation views of the experimental layout of the Rochester-Cornell-NAL group.



XBL 7111-1711

Fig. 4. Experimental results of the Rochester-Cornell-NAL group. (a) Mass spectrum and (b) first derivative of the mass spectrum of the π pairs photoproduced from carbon. The solid and dashed curves are fits with and without ρ^0-ω interference.

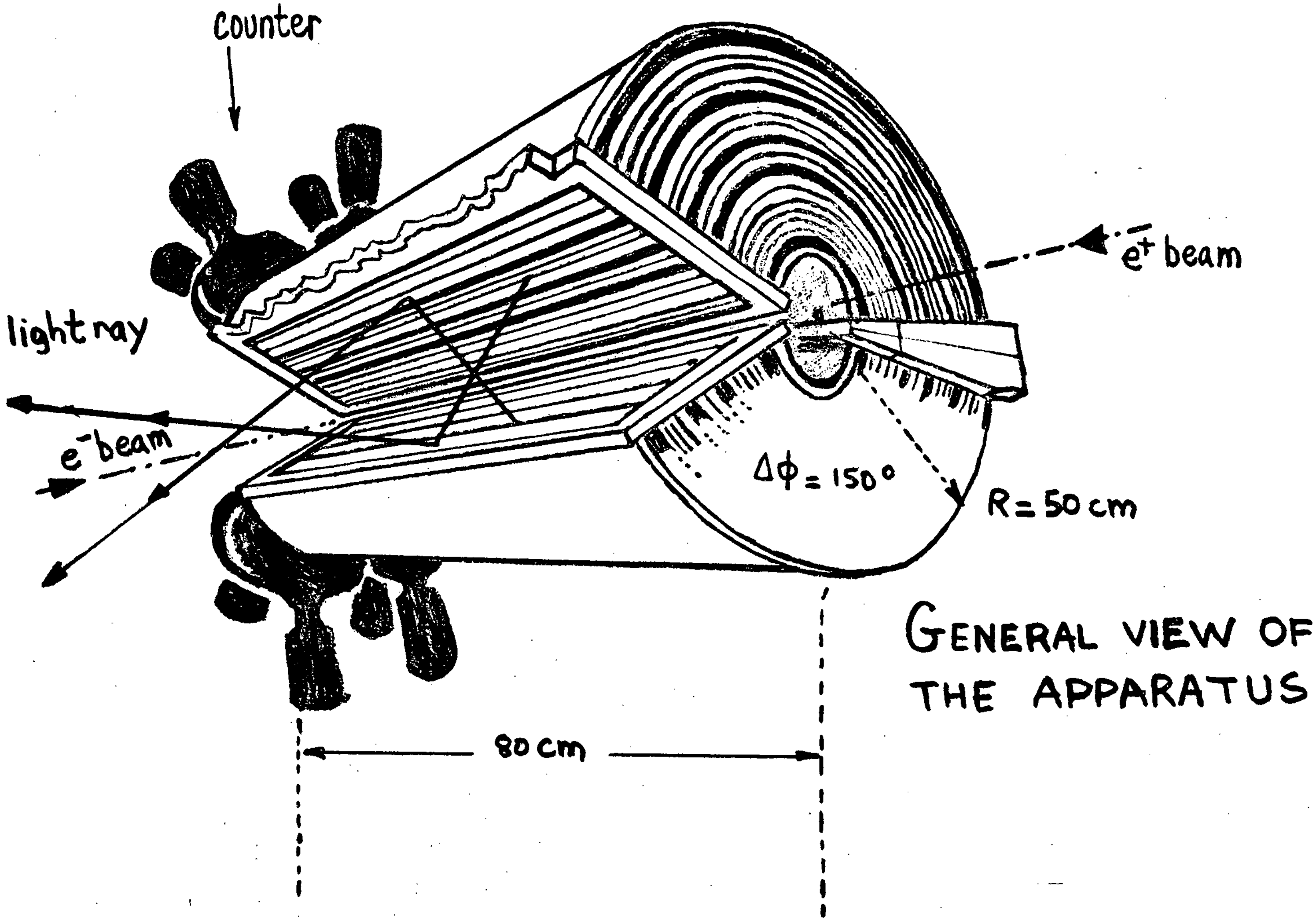
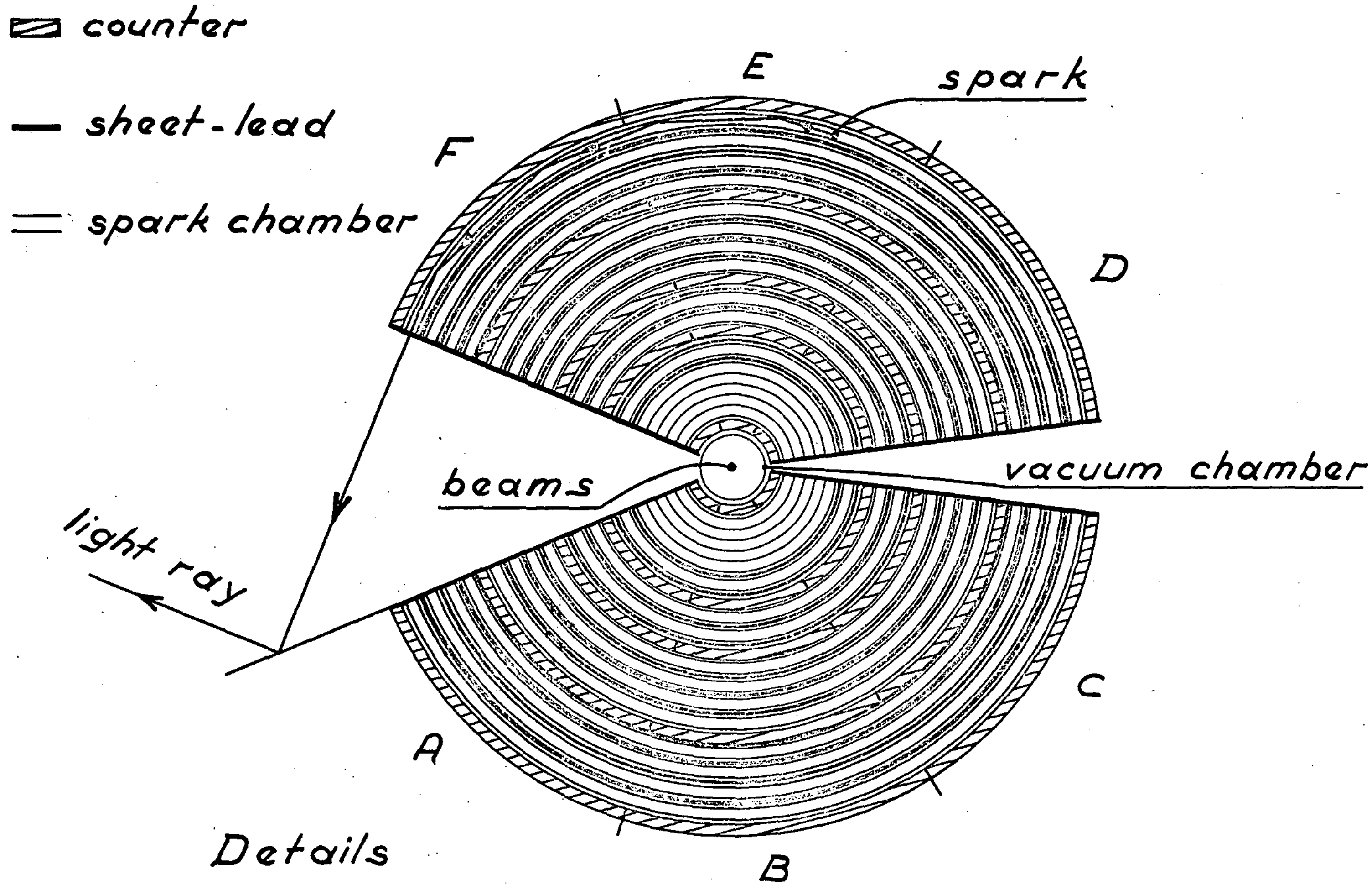


Fig. 5a. Sketch of cylindrical spark chamber arrangement used in the Orsay experiment.

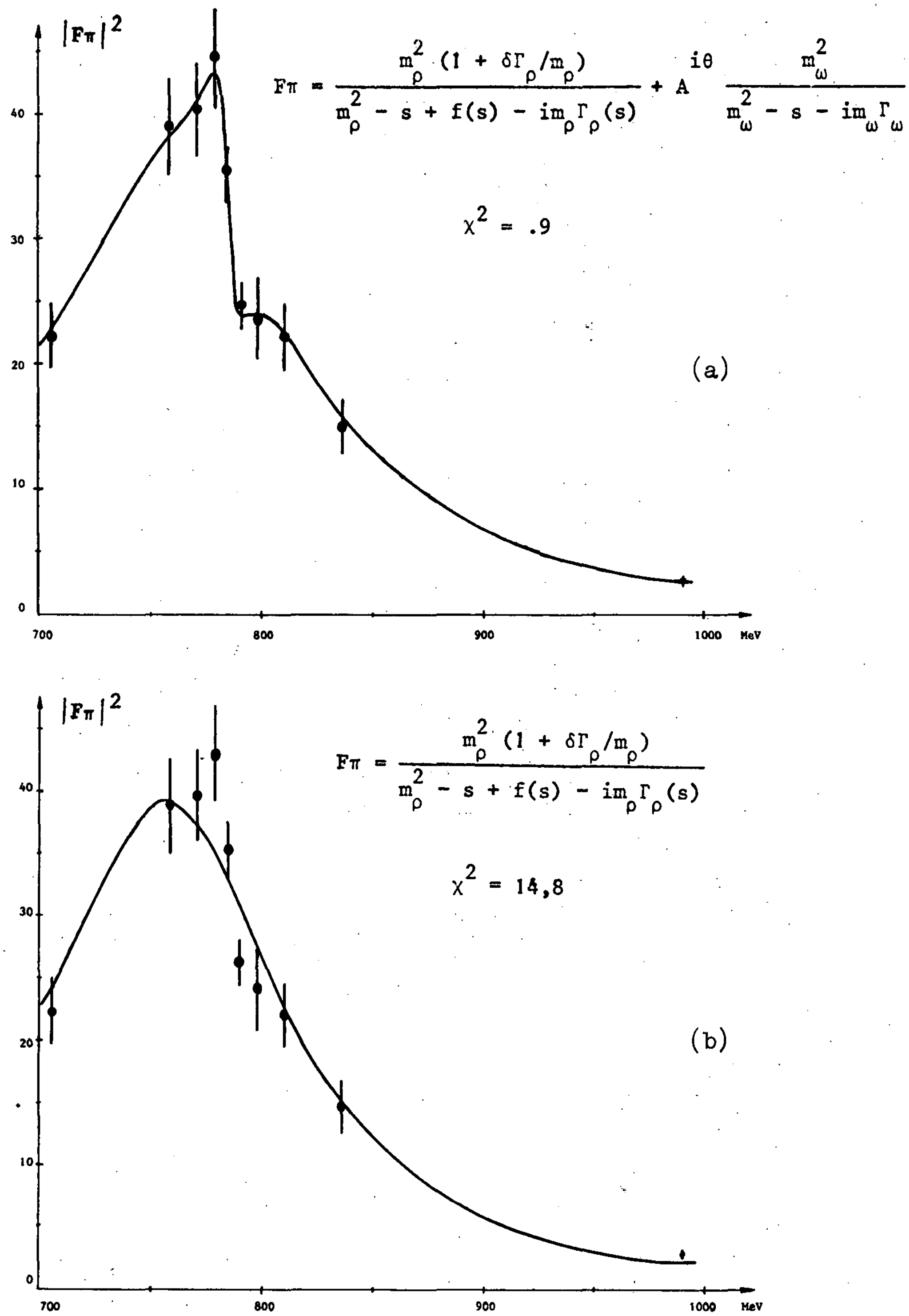
XBL 7111-1704



Details of the arrangement of the chambers, counters, and sheets-lead.

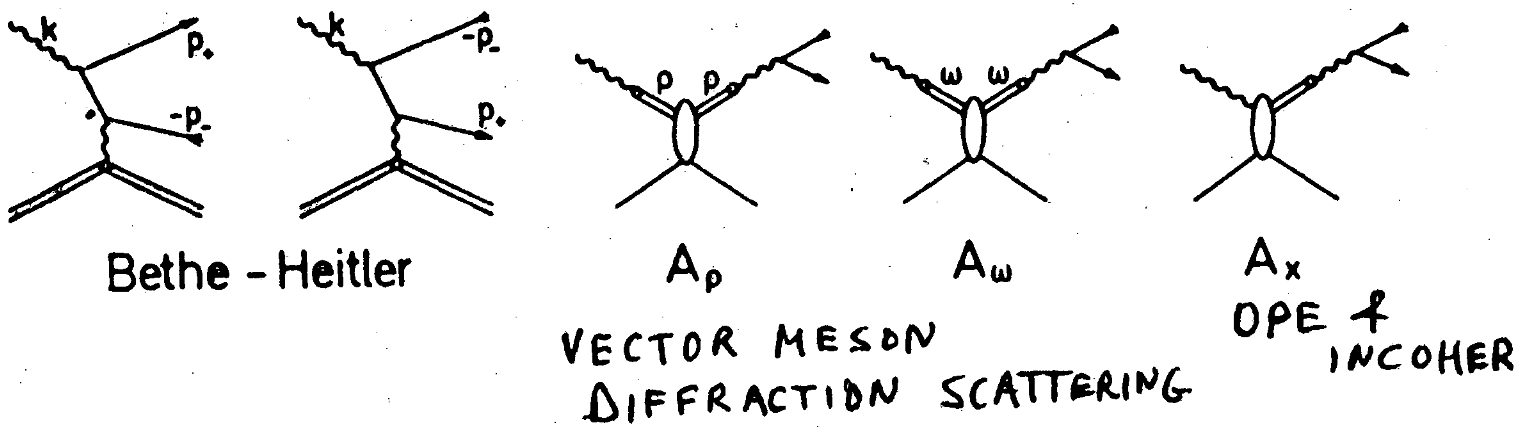
XBL 7111-1714

Fig. 5b



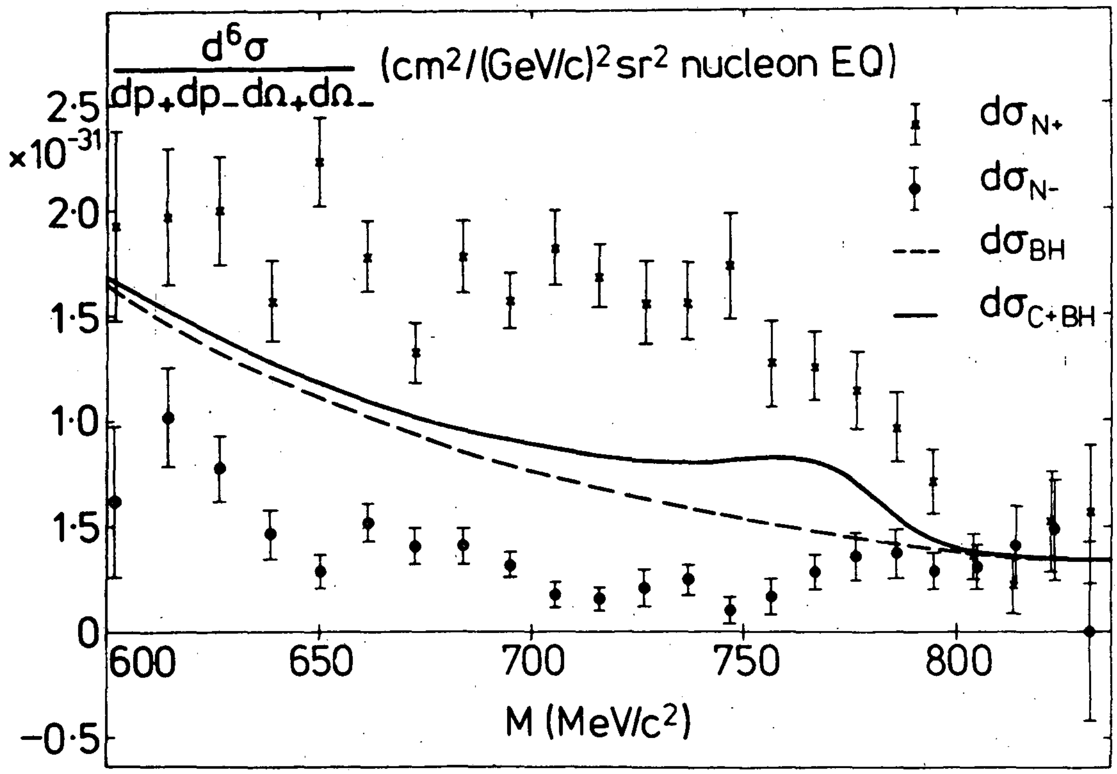
XBL 7111-1705

Fig. 6. New Orsay data for the reaction $e^+e^- \rightarrow \pi^+\pi^-$. (a) Curve corresponds to pion form factor with ω-ρ mixing. (b) Curve corresponds to pion form factor with the ρ only.



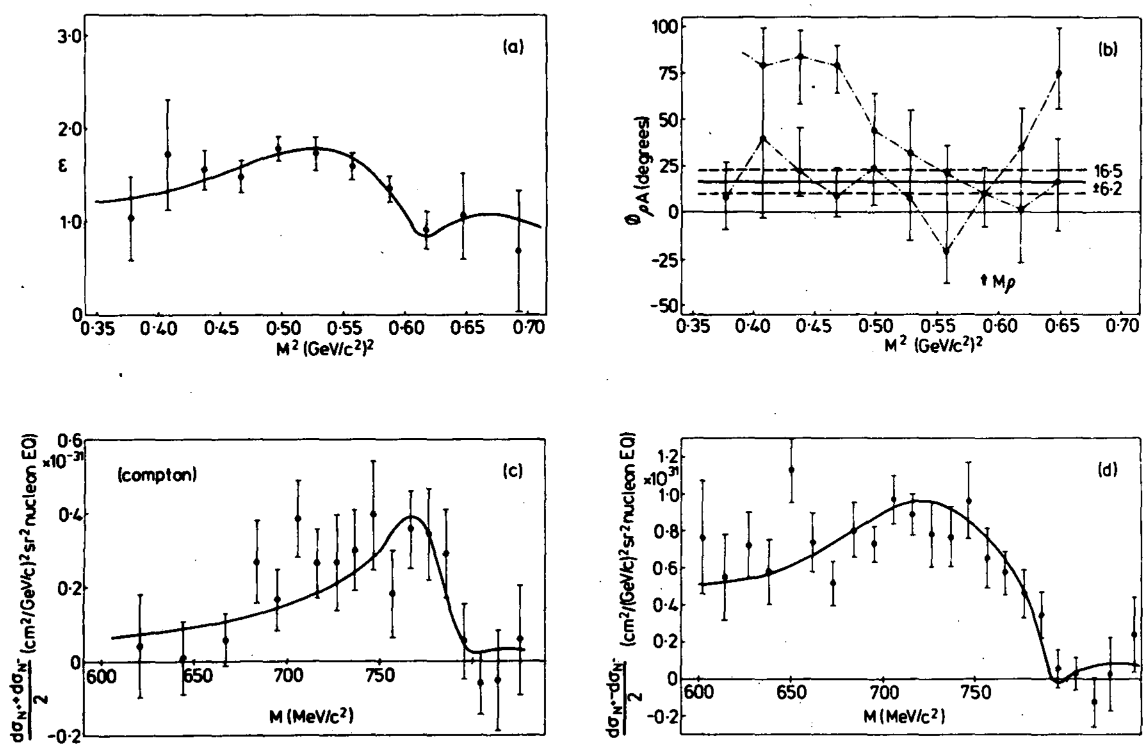
XBL 7111-1707

Fig. 7. Various diagrams for photoproduction of e^+e^- pairs on a nucleus.



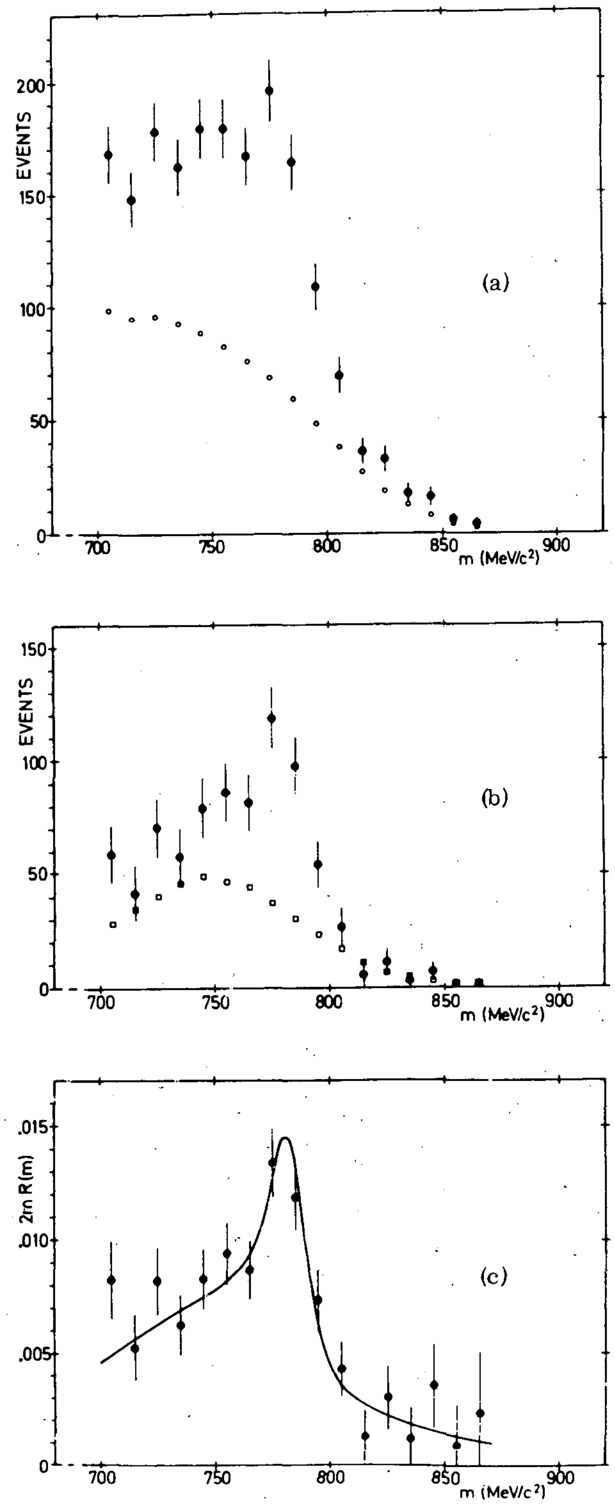
XBL 7111-1710

Fig. 8. Asymmetric pair data from the Daresbury experiment. The differential cross section for the $N^{\pm}$ yields as a function of invariant pair mass. The dashed like is the theoretical BH cross section, and the continuous line is the sum of the BH and fitted Compton cross sections.



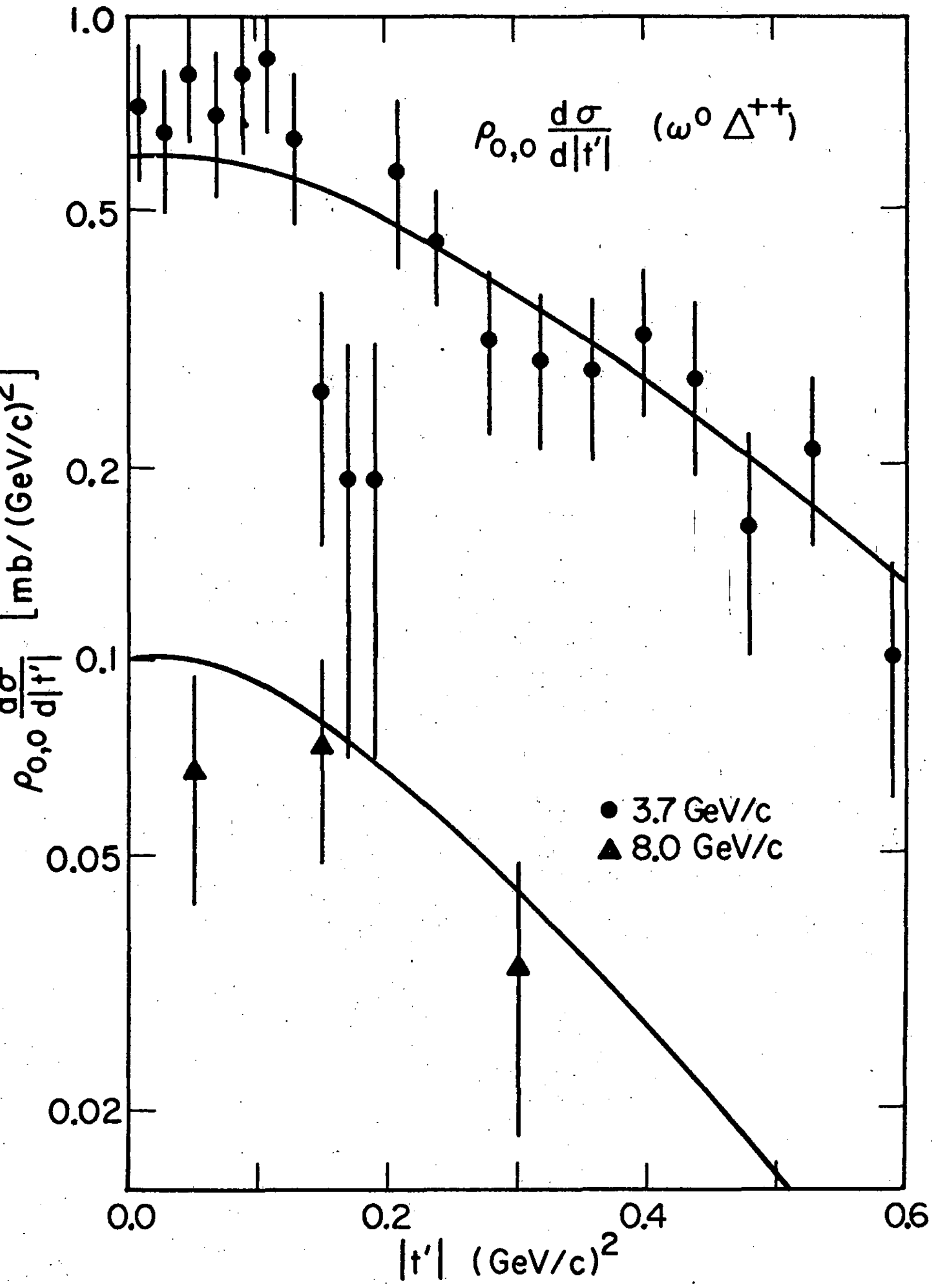
XBL 7111-1709

Fig. 9. Results from the asymmetric-pair experiment at Daresbury. (a) The asymmetry parameter ϵ as a function of m^2. (b) The values of the phase $\varphi_{\rho A}$ obtained by fitting the individual mass points $\epsilon(m^2)$. The origin of the double-valued solutions is discussed in the text. The differential cross section as a function of invariant pair mass for (c) the Compton process including ρ-ω interference and (d) the BH-Compton interference process. The solid curves are the best fit to the total mass spectrum in each case.



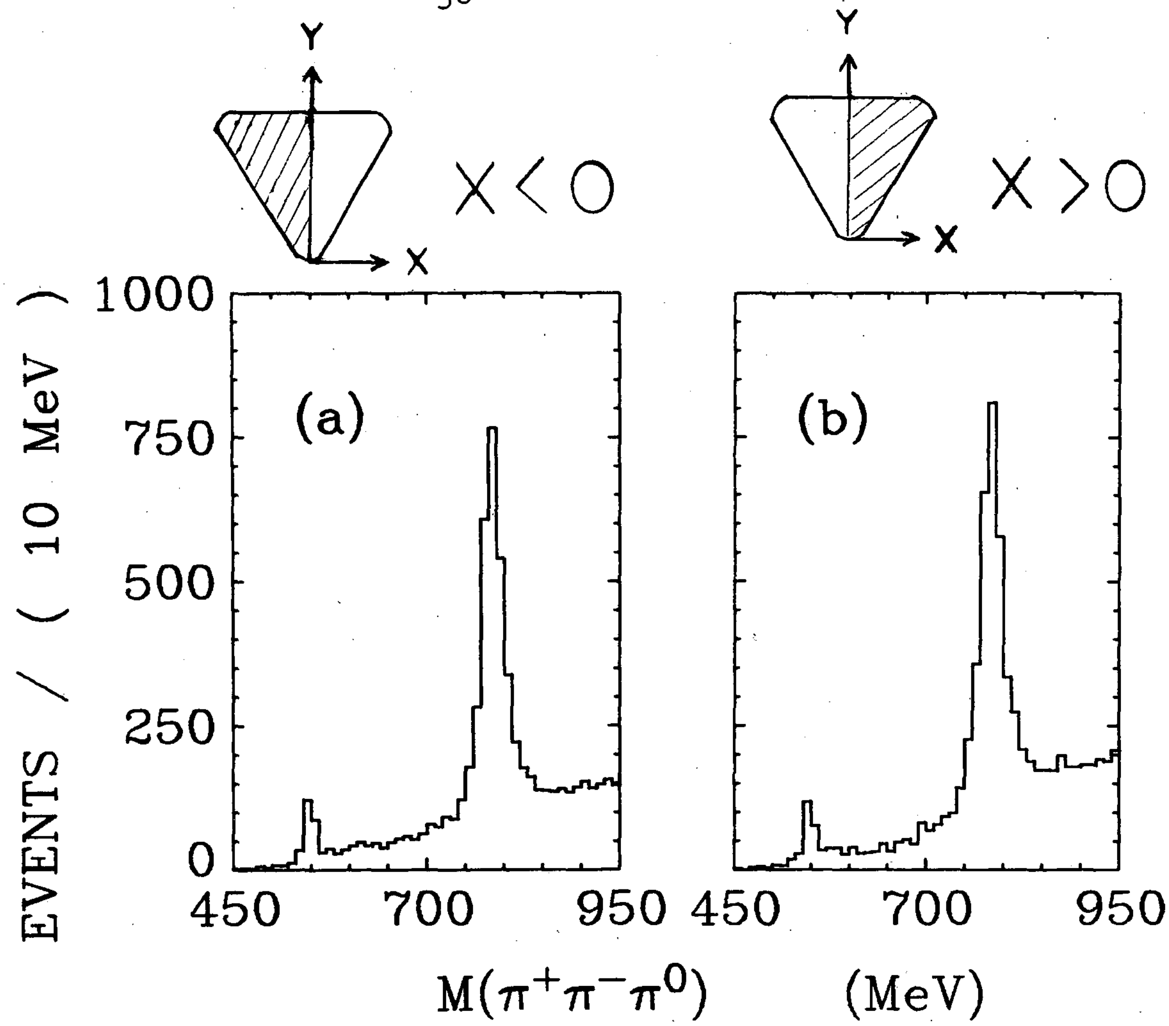
XBL 7111-1713

Fig. 10. Results of the symmetric-pair experiment by the DESY-MIT group. (a) The black dots are the experimentally measured event distribution (2841 events). The open circles are the calculated contribution of the BH process (1618 events). (b) The black dots are the event distribution attributed to the Compton terms. The squares are the contribution from $\rho \rightarrow e^+e^-$ alone. (c) Experimentally measured mass spectrum 2mR(m). The curve is the best fit.



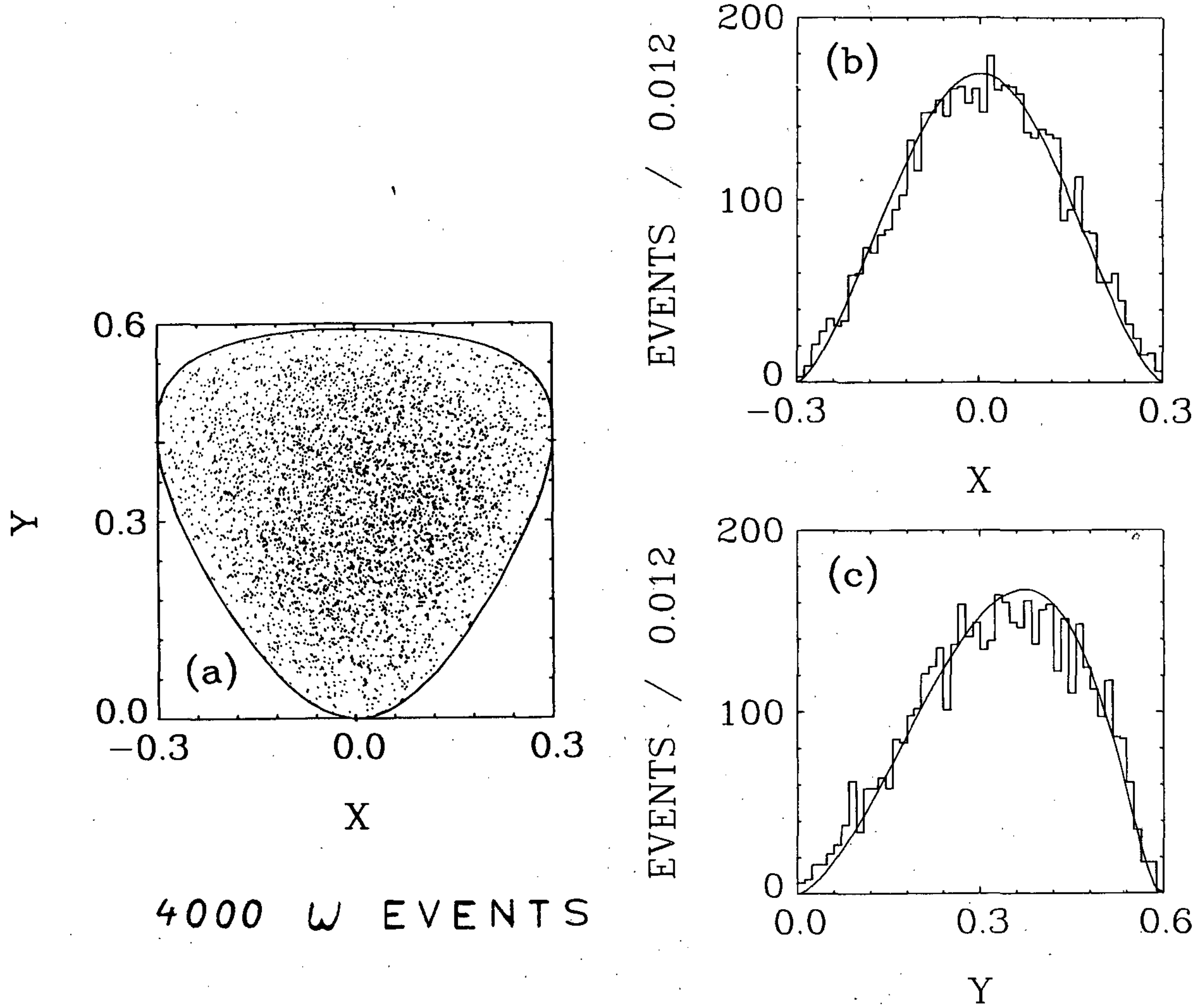
XBL 705-2889

Fig. 11. $\pi^+ p \rightarrow \omega\Delta^{++}$ at 3.7 GeV/c. Data of Abrams et al.[12] The distribution of $\rho_{o,o}$ $(d\sigma/d|t'|)$.



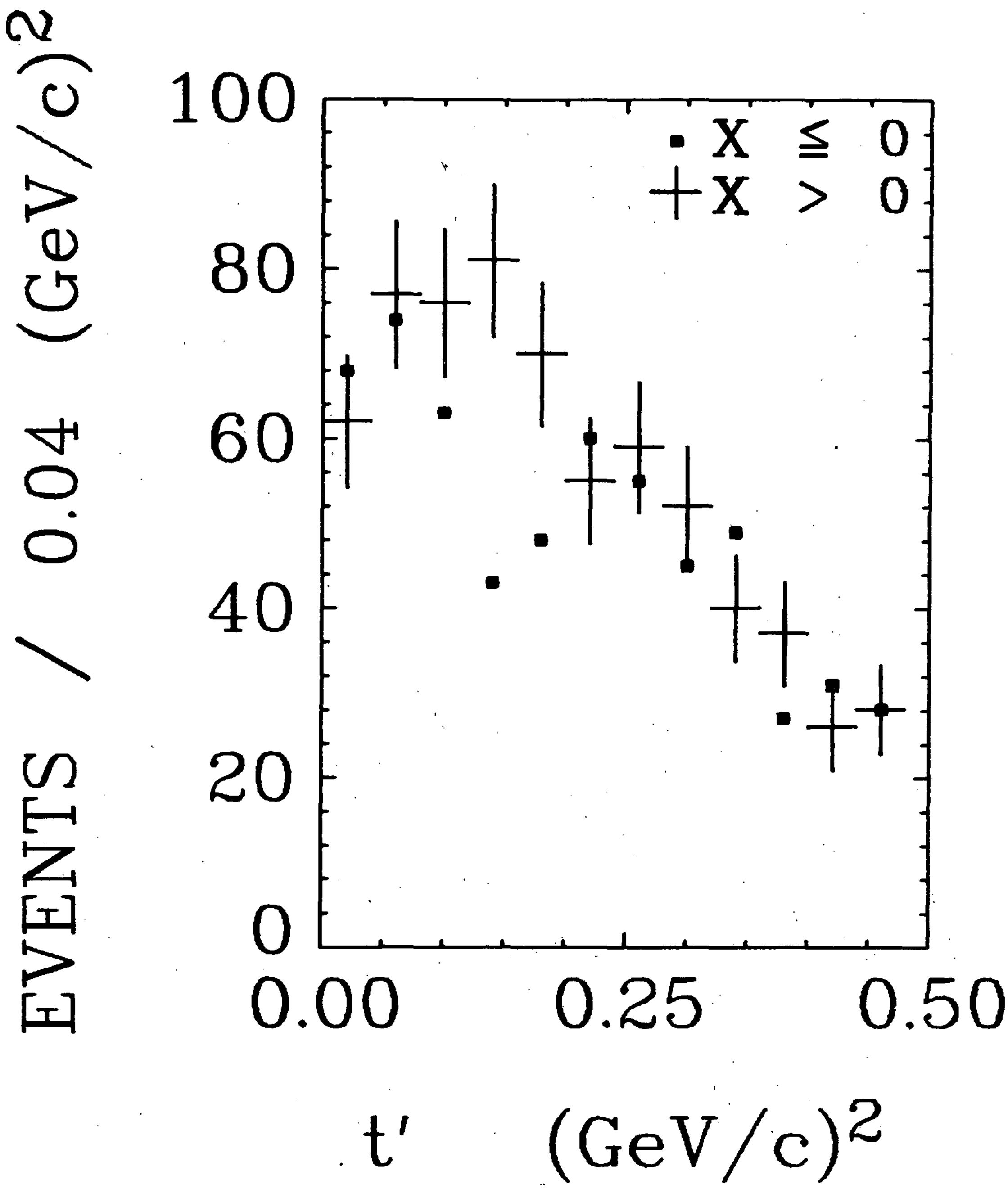
XBL 712-169

Fig. 12. The $\pi^+\pi^-\pi^0$ mass distribution (a) for the left-hand side of the Dalitz plot, (b) for the right-hand side of the Dalitz plot shown for all events of the experiment quoted in Fig. 11.



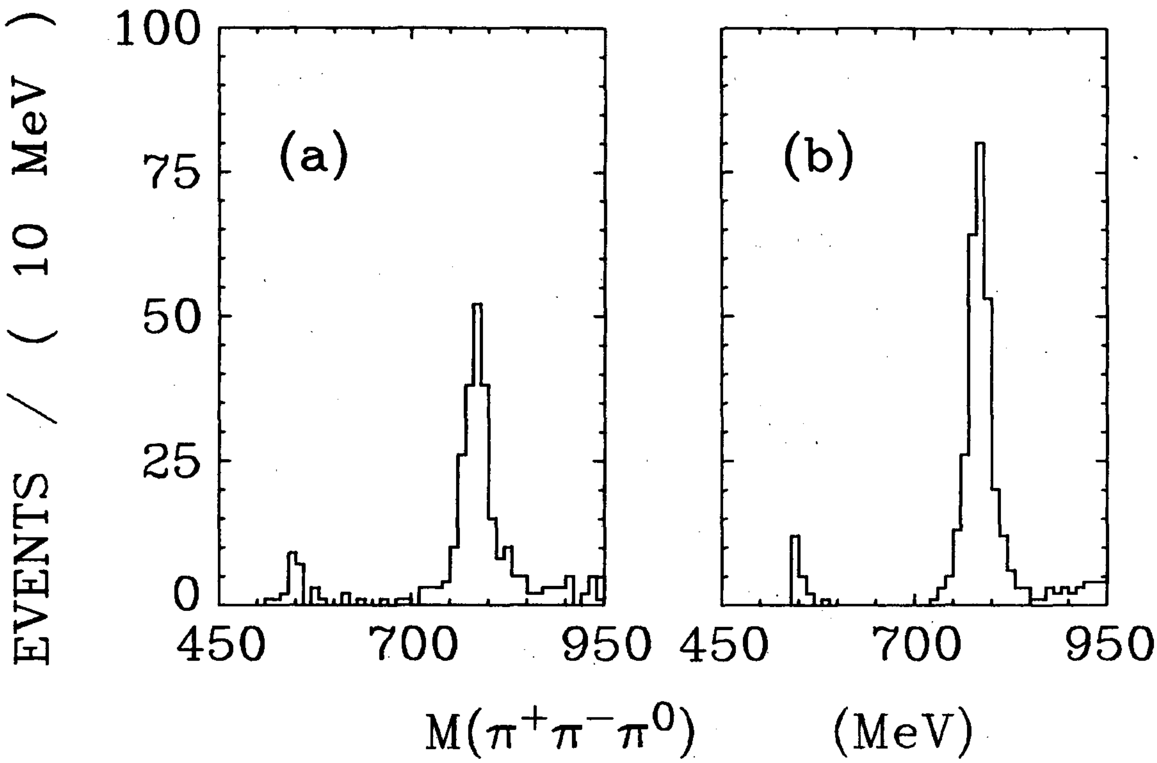
XBL 712-201

Fig. 13. (a) The Dalitz plot and its X and Y projections (b) and (c) shown for all events quoted in Fig. 11.



XBL 712-171

Fig. 14. The dσ/dt distribution for the left-hand side (■) and right-hand side of the Dalitz plot (+). The statistical errors are only indicated for the right-hand side points; they are of similar magnitude for the left-hand side points but are not shown for sake of clarity.



XBL 712-168

Fig. 15. The $\pi^+\pi^-\pi^0$ mass distribution (a) for the left-hand side of the Dalitz plot, (b) for the right-hand side of the Dalitz plot shown for the events with t' given by $0.08 \leq t' < 0.2$ $(\mathrm{GeV}/c)^2$, namely the region for which an asymmetry effect was observed.

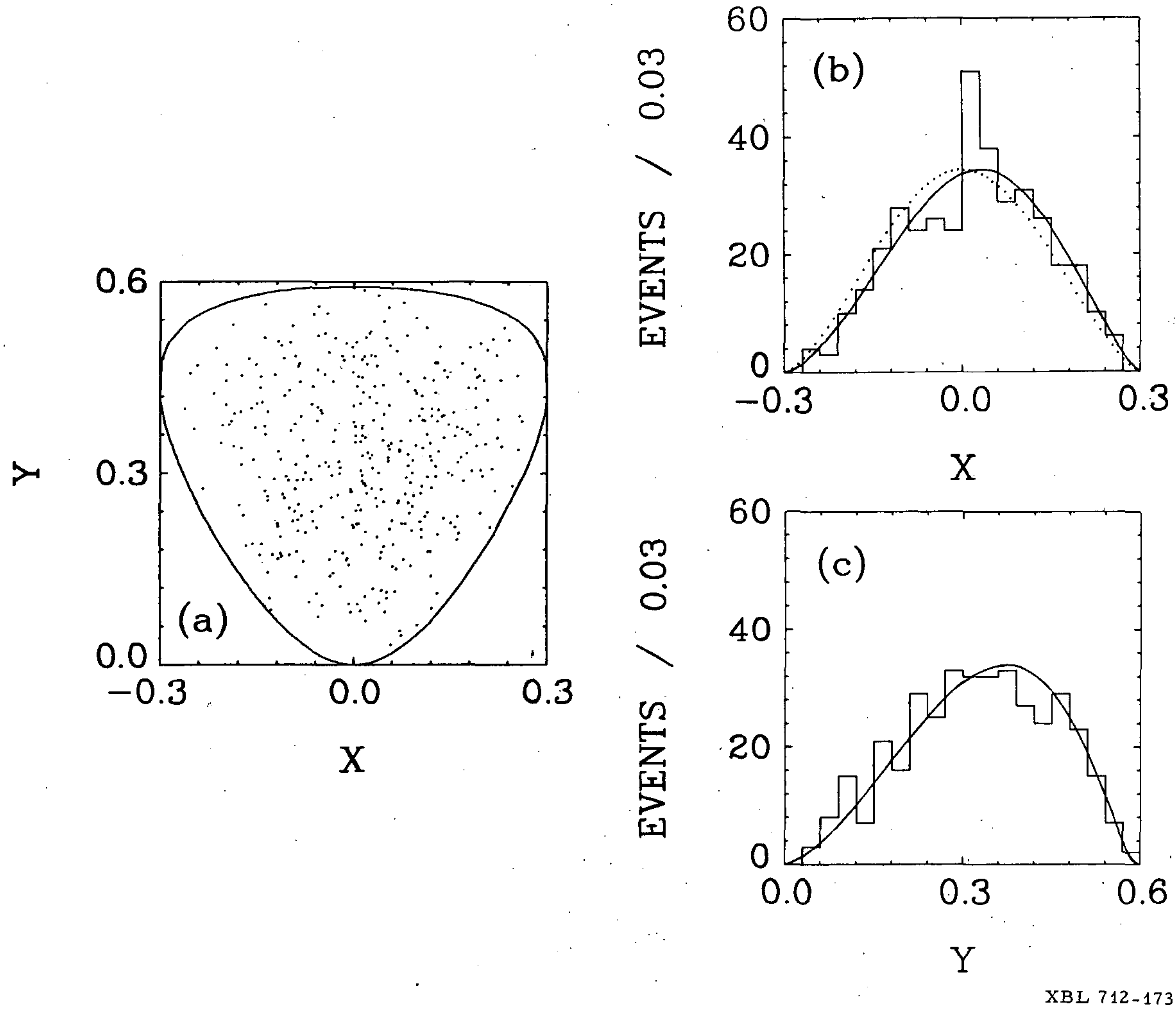


Fig. 16. (a) The Dalitz plot and its X and Y projections (b) and (c). This here shown for the t' region given by $0.08 \leq t' < 0.2$ $(\mathrm{GeV}/c)^2$. The solid curve in (b) corresponds to the best fit to the data with $b = 0.67 \pm 0.22$. The dotted curve in (b) corresponds to a fit assuming no asymmetry.

II. THE A_2 PUZZLE BECOMES A MYSTERY

The main discussion of the A_2 problem will be given in Dr. Weilhammer's talk. I will thus confine myself here to just a few remarks on the A_2.

If we were to take a public pole of physicists at this time I believe that the majority would feel that the overwhelming statistical evidence of the Northeastern-Stony Brook A_2 experiments[1] have settled the question of the A_2 splitting; namely, that there is no splitting. Fortunately, or unfortunately, the ultimate physics results do not depend on public opinion polls. My own feeling is that at this point in time more data on the A_2 problem is needed. I would be very surprised if, when all the answers are in, the A_2 will end up as a perfectly simple single Breit-Wigner resonance. Of course, I have been surprised before, so this is possible. What I mainly want to emphasize is that we should not close the books at this time on the possibility of structure in the A_2 meson.

What particular influences me in this opinion are the results of the LBL Group A experiment (Alston-Garnjost et al.[2]) which first showed that all was not well with a dipole interpretation of the A_2 splitting. If you study their results carefully (see Fig. 1), you will note that while their mass distribution clearly shows no splitting it does however <u>not</u> look like a simple Breit-Wigner but has a distinctly narrower mass peak on the low side of the A_2. In Fig. 2 I show a compilation from the same reaction $\pi^+ p \rightarrow \pi^+\pi^-\pi^+ p$ at three different incident momenta,[3-5] and in Fig. 3 I show the sum of these two; namely all the available bubble chamber data on this reaction. All these figures correspond to a t cut of $|t| > 0.1$ $(\mathrm{GeV}/c)^2$, to eliminate the effect of the A_1 meson, and with Δ^{++} out. It may be noted that none of these three distributions look like a simple Breit-Wigner resonance.

These results prompted Keith Barnham and myself to consider a model of two interfering Breit-Wigner resonances to explain the A_2 meson. This work was done before the Northeastern-Stony Brook result became available and I present it herewith together with a postscript we added at the time of the Pasadena Conference on Phenomenology in Particle Physics which refers to the Northeastern-Stony Brook work.[6]

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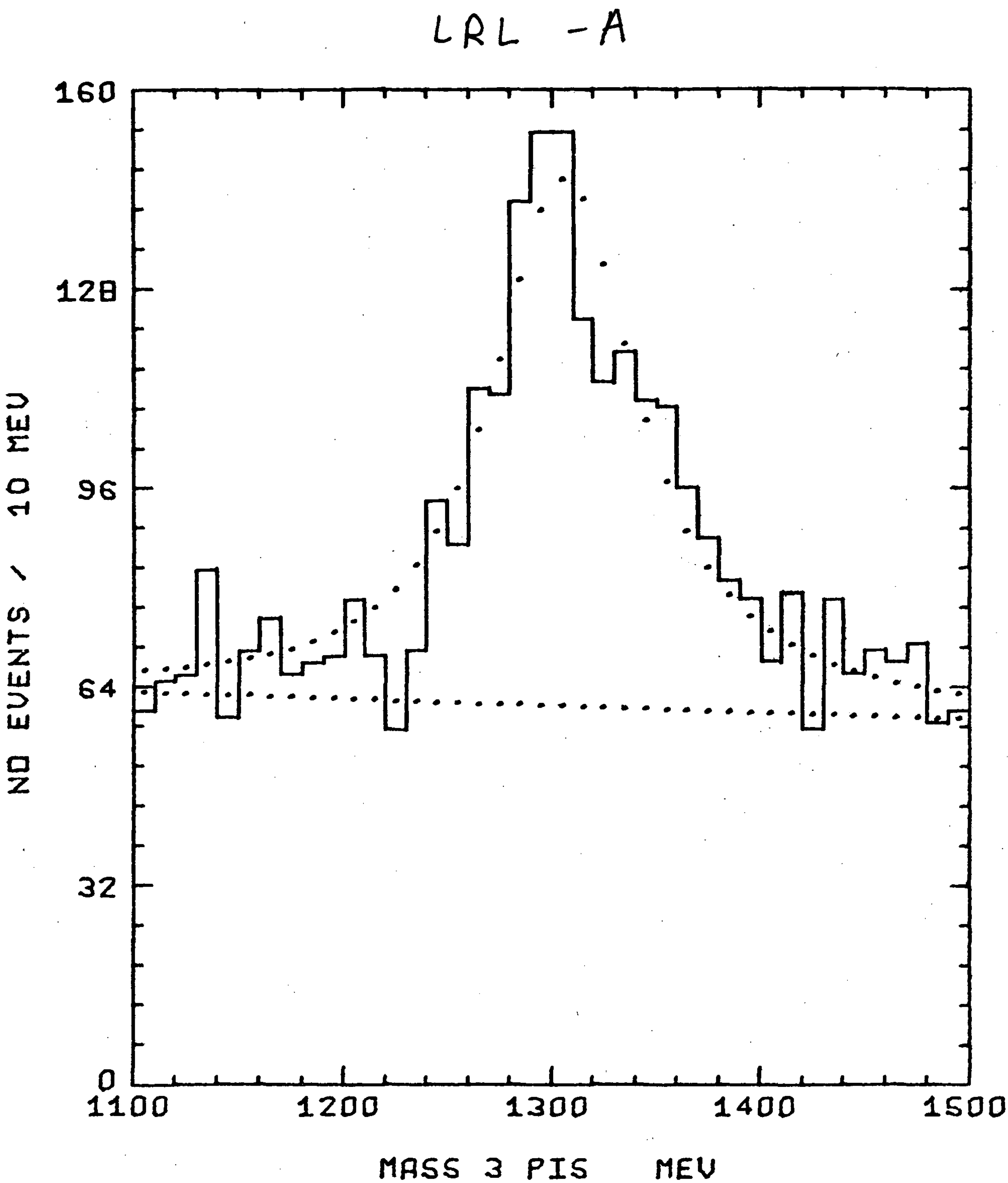

Fig. 1. The reaction $\pi^+p \to \pi^+\pi^-\pi^+p$ at 7 GeV/c. Data from Alston-Garnjost et al.[2] The dotted curve shown is a best fit Breit-Wigner to the data.

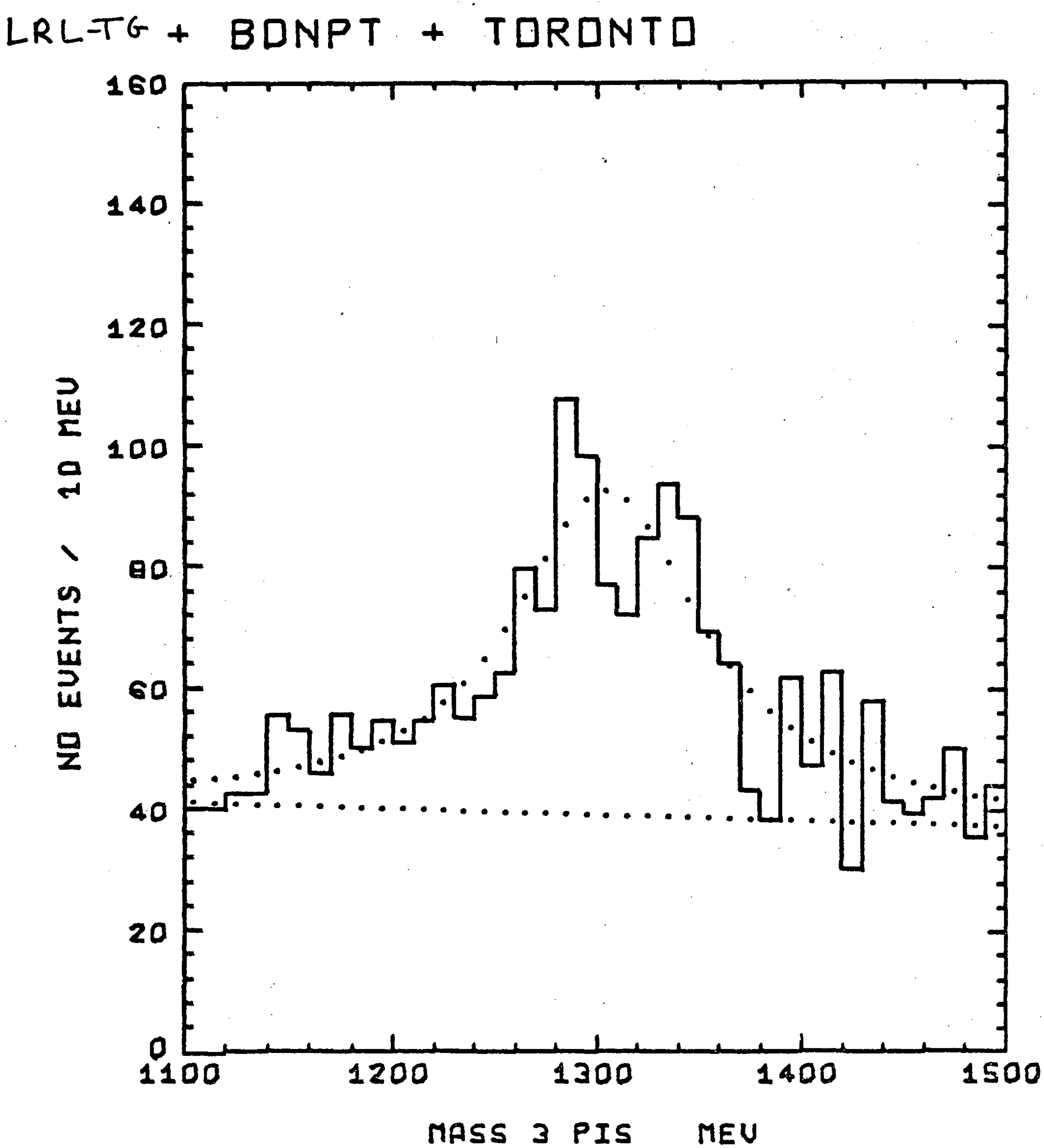

Fig. 2. The reaction $\pi^+p \to \pi^+\pi^-\pi^+p$ at 3.7-5.5 GeV/c. Compilation of bubble chamber data from Refs. 3-5.

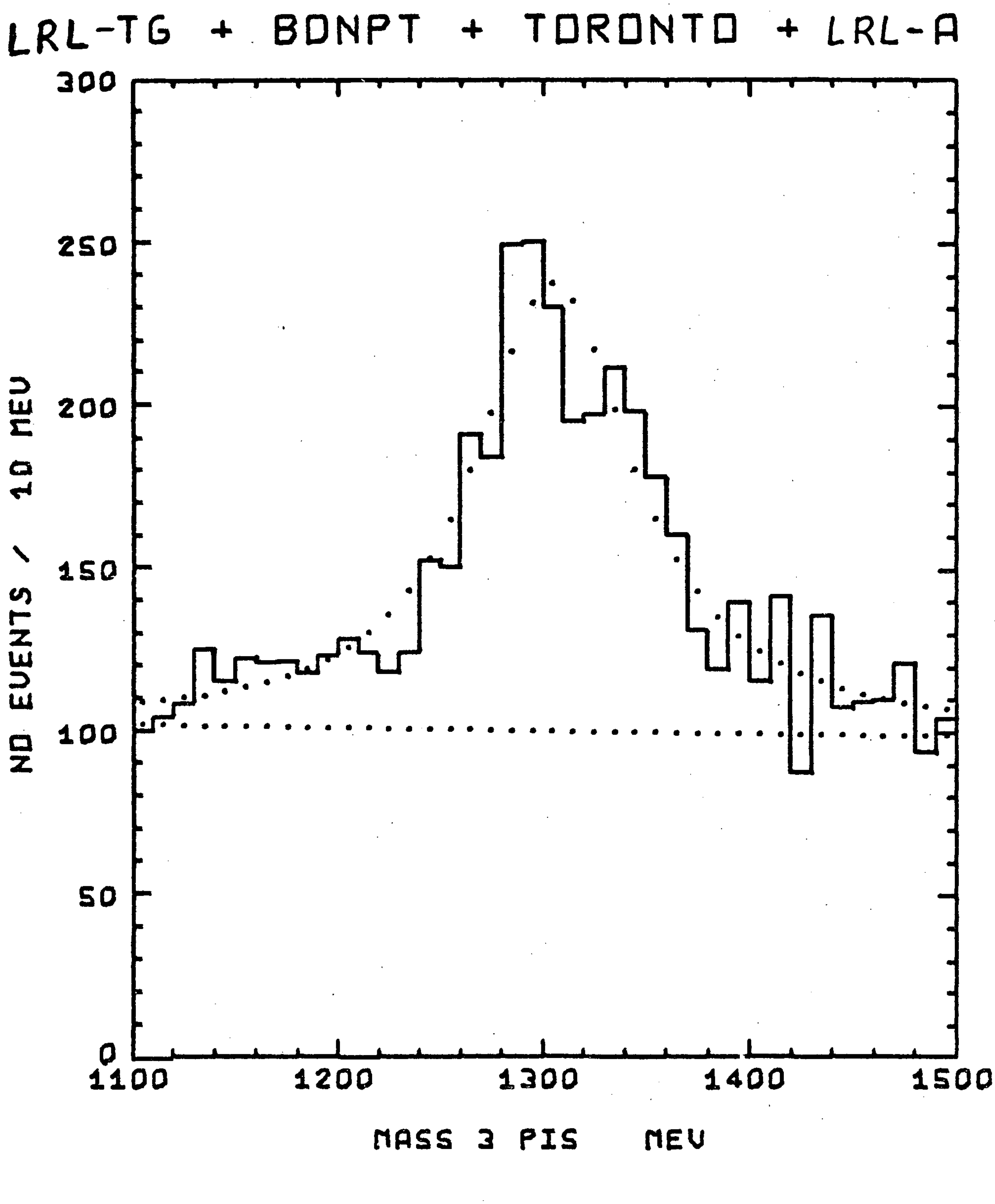

Fig. 3. A compilation of the data shown in Figs. 1 and 2. The dotted curve is a best fit Breit-Wigner. The parameters are M_0 = 1305 MeV, Γ = 94 MeV. The fit is poor, namely it gives a χ^2/d.o.f. = 55.1/35 which corresponds to a confidence level of ~ 1%. In the more restricted region 1.2-1.38 GeV the χ^2/d.o.f. = 27.7/11 which corresponds to a confidence level of ~ 0.4%.