SLAC-PUB-1005

Measurements of $\rho - \omega$ Interference in the Reaction $\pi^- p \to \pi^+ \pi^- n$ at 15 GeV/c *

B. N. Ratcliff et al.

ERRATA

p. 348: The sentence beginning line 6 should read
" We find that $C > 0.3$ (95% CL) with . . ."

p. 348: Line 16 in the 2nd paragraph should read
"agreement with the value $\Phi = -0.26 \pm 0.52$ (rad) "

p. 348: Line 23 in the 2nd paragraph should read
"the transverse ω and ρ amplitudes themselves is"

SLAC-PUB-1005
(EXP)
December 1971

MEASUREMENT OF ρ-ω INTERFERENCE IN THE REACTION $\pi^- p \to \pi^+\pi^- n$ at 15 GeV/c*

B. N. Ratcliff,** F. Bulos,** R. K. Carnegie, E. E. Kluge,†
D. W. G. S. Leith, H. L. Lynch, B. Richter, H. H. Williams,††
and S. H. Williams

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

In a study of the reaction $\pi^- p \to \pi^+\pi^- n$ at 15 GeV/c we observe pronounced ρ-ω interference effects between the transverse helicity states of the vector mesons. The relative phase of the interfering amplitudes is determined to be -1.40±0.45 rad, and the branching ratio $\omega \to 2\pi$ is found to be $2.1^{+2.8}_{-0.9}$%.

(Submitted to Phys. Rev. Letters)

*Work supported by the U. S. Atomic Energy Commission.

** Present address, Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

† Present address, Institut für Hochenergiephysik, Heidelberg, Germany.

†† Present address, Brookhaven National Laboratory.

In 1961, Glashow[1] suggested that spectacular I-spin violating electromagnetic interference effects between the ρ and ω meson might be observed in the dipion mass spectrum since the masses of the two particles were so nearly identical. Many searches for the ρ-ω interference effect have been made,[2] and recently, the existence of ρ-ω mixing has been conclusively demonstrated in several high statistics experiments.[2-7] There remains, however, substantial uncertainty about the precise nature of the mixing parameters, particularly for the strong production experiments. Moreover, the effect has been observed only at low energies so that high energy behavior is unknown. We present here the results of a wire spark-chamber experiment, performed at the Stanford Linear Accelerator Center, which studies ρ-ω interference in the reaction $\pi^-p \rightarrow \pi^+\pi^-n$ at an incident beam momentum of 15 GeV/c. We find a strong ρ-ω interference in the transverse polarization states of the mesons with an overall relative phase of $\approx -\pi/2$ (rad).

Detailed descriptions of our apparatus and general methods of analysis have been published previously.[8] The properties of the apparatus of particular importance for this experiment are as follows: The acceptance of the spectrometer varied slowly as a function of the dipion mass ($m_{\pi\pi}$) and the momentum transfer squared to the nucleon (t). The acceptance was zero for very asymmetric decays ($|\cos\theta^H| > 0.8$ where θ^H is the polar angle of the outgoing π^- in the helicity frame) and was peaked near $\cos\theta^H = 0$ with the result that the observed data distributions preferentially contained transverse ρ and ω decays. The mass resolution of the spectrometer at the ω mass was calculated from the measurement uncertainties in the spark chambers to be $\sim\pm 8$ MeV. This resolution was verified by observation of the decay $K_S^o \rightarrow \pi^+\pi^-$ which also implied a resolution of 8 MeV in the region of the ω. The absolute mass scale calibration was checked by the position of the K^0 peak and was shown to be accurate to better than 2 MeV at the ω mass.

The observed $\pi^+\pi^-$ mass spectra are shown in Fig. 1 for several different cuts on the momentum transfer. There is clearly no dramatic effect either for the entire sample [Fig. 1(a)] or for $|t| < 0.1\ (\mathrm{GeV/c})^2$ [Fig. 1(b)]. However, for $0.1 < |t| < 0.3\ (\mathrm{GeV/c})^2$, a pronounced peak is observed which is centered somewhat above the ω at ~790 MeV. The interference is expected to be most striking in this t region since the ω differential cross section peaks here. There is evidence of a slight dip below the ω mass. This dip can be enhanced by cutting the data on $\cos\theta^H$ so as to increase the fraction of transverse decays in the sample as shown in Fig. 2(a). The shaded histogram shows data with $|\cos\theta^H| < 0.2$, whereas the unshaded histogram includes data with $|\cos\theta^H| < 0.4$. As the fraction of the transverse decays accepted increases, the dip below the ω mass becomes extremely pronounced, and indeed the mass distribution looks almost like a split ρ^0 meson.[9] The inset shows the data for $|\cos\theta^H| < 0.4$ on a finer mass scale (5 MeV bins). The structure is well centered at the ω mass, with a dip and a peak of rather equal size on either side. This shape is to be expected if the phase between the interfering amplitudes is $\sim -90^\circ$.

The $\pi^+\pi^-$ angular distribution in this experiment has been shown to require the presence of only S and P waves for the $m_{\pi\pi} \leq 0.9$ GeV.[8] Using this information, we can correct the mass distribution for acceptance losses. This correction is determined by fitting the observed decay angular distribution, D, as a function of mass by the form,

$$D(\theta, \phi, m) = E(\theta, \phi, m)\, N(m)\, W(\theta, \phi)$$

where $W(\theta,\phi)$ is the angular distribution for S and P waves, $E(\theta,\phi,m)$ is the detection efficiency of the spectrometer, θ and ϕ are the polar and azimuthal decay angles, respectively, of the outgoing π^- in the dipion rest frame and N(m) is the corrected number of events in the fitted dipion mass interval. The resultant mass spectrum is shown in Fig. 2(b). It is dominated by longitudinal production, and the interference dip is much less pronounced. This is consistent with the behavior of the raw mass spectra; as cuts which preferentially select more-and-more transverse production, are made on the data, the dip below the ω becomes increasingly more pronounced. The most straightforward explanation of this behavior is that the ω is produced predominately transversely in this t range at 15 GeV/c as has been observed directly in the charge conjugate reaction $\pi^+ n \rightarrow \omega p$ at 7 GeV/c.[10]

In order to study the $\rho - \omega$ mixing quantitatively, we have used a phenomenological approach. The observed dipion mass distribution is assumed to be given by the square of a sum of ρ, ω and background amplitudes integrated over the angular distribution and momentum transfer intervals. The decay angular distribution used to describe the ω decay is taken from the 7 GeV/c $\pi^+ n \rightarrow \omega p$ data[10] whereas the ρ^0 angular distribution is taken from the present data. The form of the background distribution is taken to be a simple polynominal in the mass. In practice, the significance and parameters of the $\rho - \omega$ interference are quite insensitive to the forms assumed for the decay amplitudes. Using a method similar to that suggested by Flatte,[11] we have shown that a significant ($>4\sigma$) effect indeed exists in the data for $0.1 < |t| < 0.3$ $(\text{GeV/c})^2$ both in the overall sample and for $|\cos\theta^H| < 0.4$. For $|t| < 0.1$ $(\text{GeV/c})^2$, there is no significant effect.

In order to determine the $\rho - \omega$ interference parameters, we have assumed that the background is incoherent with the ρ and ω amplitudes. We then fit the

$\pi^+\pi^-$ mass spectrum to

$$\frac{d\sigma}{dm} = PS \cdot \left[E_\rho \alpha_\rho^2 |BW_\rho|^2 + E_\omega \alpha_\omega^2 |BW_\omega|^2 + 2C\sqrt{E_\rho E_\omega}\alpha_\rho \alpha_\omega Re(e^{i\Phi} BW_\rho^* BW_\omega) + a + bm \right] \quad (1)$$

where $E_\rho(E_\omega)$ is the efficiency averaged over the $\rho(\omega)$ decay distribution; Φ is the relative phase between the ω and ρ amplitudes averaged over the decay angles;[12] $C(0 \leq C \leq 1)$ represents an average relative coherence between the amplitudes; a and b are parameters for fitting the background; BW_V is a Breit-Wigner amplitude similar to that described in Pisut and Roos;[13] and PS is the phase space factor.

To determine the ρ resonance parameters, we fit the dipion mass spectrum for $0.1 < |t| < 0.3$ $(GeV/c)^2$, excluding the ω region, to Eq. 1. The values of mass and width obtained for the ρ were $m_\rho = 0.764 \pm 0.003$ GeV and $\Gamma_\rho = 0.157 \pm 0.003$ GeV. The position and width for the ω were assumed to be 0.7837 and 0.0119 GeV,[14] respectively. Using these values, we fit the entire dipion mass distribution in our t region to determine the $\rho - \omega$ interference parameters. In general, the fits are excellent when the $\rho - \omega$ interference is included as is shown by the solid line in Fig. 1(c). Unlike previous experiments at lower energy, we see a dip-peak structure rather than a pure peak; therefore the phase Φ and the coherence parameter C can be determined without any additional assumptions.

The parameters C and Φ are coupled in the fit. In order to demonstrate this clearly, Fig. 3 shows contour plots of $\Delta\chi^2$ plotted in C, Φ space for three different "cuts" on the decay angular distribution. It is convenient to quote values with one standard deviation errors and we will do so below. The nonlinear character of these errors as demonstrated in Fig. 3 should, however, be remembered. The reported values are insensitive to small shifts in the absolute mass scale, and the quoted error includes conservative estimates for our scale uncertainty. Figure 3(a) shows the fit to the total data sample with $0.1 < |t| < 0.3\ (\mathrm{GeV/c})^2$. We find that $C > 0.3$ (95% CL) with $\Phi = -1.40 \pm 0.45$ (rad). It was noted previously that if we cut the data so as to preferentially select transverse vector mesons ($|\cos\theta^H| < 0.4$), the dip below the ω becomes much more pronounced. We therefore expect to find a larger value for C from these data. In Fig. 3(b), we find that this expectation is correct. We observe that $C > 0.41$ (95% CL) and $\Phi = -1.45 \pm 0.45$ (rad).

The phase of $\approx -\pi/2$ found from our data differs both from the prediction of Goldhaber, Fox and Quigg[15] and the lower energy data of Hagopian et al.[4] by $\approx -\pi/2$. Because the $\pi^+\pi^-n$ experiment of Haopian et al. observes a peak structure, it is of interest to fit the efficiency-corrected mass distribution (Fig. 2(b)) since we also see a similar peak structure here and since this is the distribution which is observed in a 4π solid angle detector such as a bubble chamber. From Fig. 3(c), we see that, as expected, the value of C is not well determined. In addition, Φ is well determined only if C is ≥ 0.6 (Hagopian et al. found the Φ was well determined in their data if $C \geq 0.4$). We then find the $\Phi = -0.60 \pm 0.45$ (rad) in good agreement with the value $\Phi = 0.26 \pm 0.52$ (rad) from the lower energy experiment. We have noted previously that the ω is quite transverse in the region $0.1 < |t| < 0.3\ (\mathrm{GeV/c})^2$. The above observations thus suggest that in the "cut" distributions we are relatively insensitive to the longitudinal contribution, and that the phase between the transverse ω and amplitudes themselves is $\approx -\pi/2$.

From our data alone the branching ratio for $\omega \rightarrow 2\pi$ [B.R. $= \Gamma(\omega \rightarrow 2\pi)/\Gamma(\omega \rightarrow 3\pi)$] cannot be determined. In order to calculate B.R., it is necessary to know the cross section $d\sigma/dt\ (\omega)$ for the reaction $\pi^- p \rightarrow \omega^0 n$ at 15 GeV/c, and little information exists on this reaction. However, several experiments have studied the charge conjugate reaction $\pi^+ n \to \omega p$ at lower energies.[16] If we extrapolate the data[10] from 7 GeV/c using a scaling in incident beam momentum of $p^{-2.25}$, which fits the energy dependence of the cross section from 2 to 7 GeV/c very well, and also assume that the t dependence at 15 GeV/c is identical with that at 7 GeV/c,[17] we find that

$$\text{B.R.} = 2.1 \begin{smallmatrix} +2.8 \\ -0.9 \end{smallmatrix} \%.$$

We note that the above branching ratio is consistent with those derived previously in other experiments. For example, the Orsay storage ring experiment[7] obtains the values B.R. $= 4.0 \begin{smallmatrix} +2.3 \\ -1.8 \end{smallmatrix} \%$, thereas the photoproduction experiment of Alvensleben et al.[5] obtains B. R. $= 1.22 \pm 0.3\%$.

We conclude that we have observed a significant ($>4\sigma$) $\rho-\omega$ interference effect for $0.1 < |t| < 0.3$ $(\text{GeV/c})^2$ in the reaction $\pi^- p \to \pi^+\pi^- n$ at 15 GeV/c. The overall phase observed in this experiment is dominated by the transverse production amplitudes and is shown to be $\approx -\pi/2$. This phase differs by $\approx -\pi/2$ from both the prediction Goldhaber, Fox and Quigg, and the previous experiment of Hagopian et al. in the same reaction at 2.3 GeV/c. We emphasize the importance of studying the interference effect in each helicity amplitude separately in order to unambiguously interpret the data.

REFERENCES

1. S. L. Glashow, Phys. Rev. Letters, 7, 469 (1961).
2. For a discussion of these experiments see, G. Goldhaber, talk given at the International Conference on Experimental Meson Spectroscopy, Philadelphia, Pennsylvania (1970), published in Experimental Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (Columbia University Press, N. Y., 1970), p. 59.
3. G. Goldhaber et al., Phys. Rev. Letters, 23, 1351 (1969).
4. S. Hagopian et al., Phys. Rev. Letters, 25, 1050 (1970).
5. H. Alvensleben et al., Phys. Rev. Letters, 24, 888 (1971).
6. P. J. Biggs et al., Phys. Rev. Letters, 24, 1197 (1970).
7. J. E. Augustin et al., Lett. al Nuovo Cimento II, 214 (1969). More recent results were reported by J. Lefrancois at the 1971 International Symposium on Electron and Photon Interactions at High Energies, Cornell, New York.
8. F. Bulos et al., Phys. Rev. Letters, 26, 1453 (1971) and SLAC-PUB-884; F. Bulos et al., SLAC-PUB-801; B. Ratcliff, Stanford Doctoral Dissertation (SLAC Report No. 141).
9. It is amusing that the dipole form used by the CERN spectrometer groups to describe the split A_2 meson also fits our $|\cos\theta^H| < 0.2$ data very well ($\chi^2/\nu \approx 1.0$). The χ^2 for the dipole fit is better than that of simple Breit-Wigner by 20. For A_2 data see G. E. Chikovani et al., Phys. Letters, 25B, 44 (1967); H. Berry et al., Phys. Letters, 28B, 223 (1968).
10. J. A. J. Matthews et al., Phys. Rev. Letters, 26, 400 (1971). Since the preparation of this manuscript the data of Holloway et al., Phys. Rev. Letters, 27, 1671 (1971), became available. They presented density matrix elements on the reaction $\pi^- p \rightarrow \omega n$. Their results are sufficiently similar to Matthews et al., that none of our conclusions is changed.

11. S. M. Flatte, Phys. Rev., D1, 1 (1970).

12. Note that the relative phase can be different for the different helicity amplitudes.

13. J. Pisut and M. Roos, Nucl. Phys. B6, 325 (1968).

14. These values are from the compilation by the Particle Data Group, Phys. Letters, 33B, 1 (1970).

15. A. S. Goldhaber, G. C. Fox and C. Quigg, Phys. Letters, 30B, 249 (1969).

16. For example, G. Benson, et al., Phys. Rev. Letters, 22, 1074 (1969); G. Abrams, B. Eisenstein and H. Gordon, Phys. Rev. Letters, 23, 673 (1969); N. Armenise et al., Nuovo Cimento, 65A, 637 (1970).

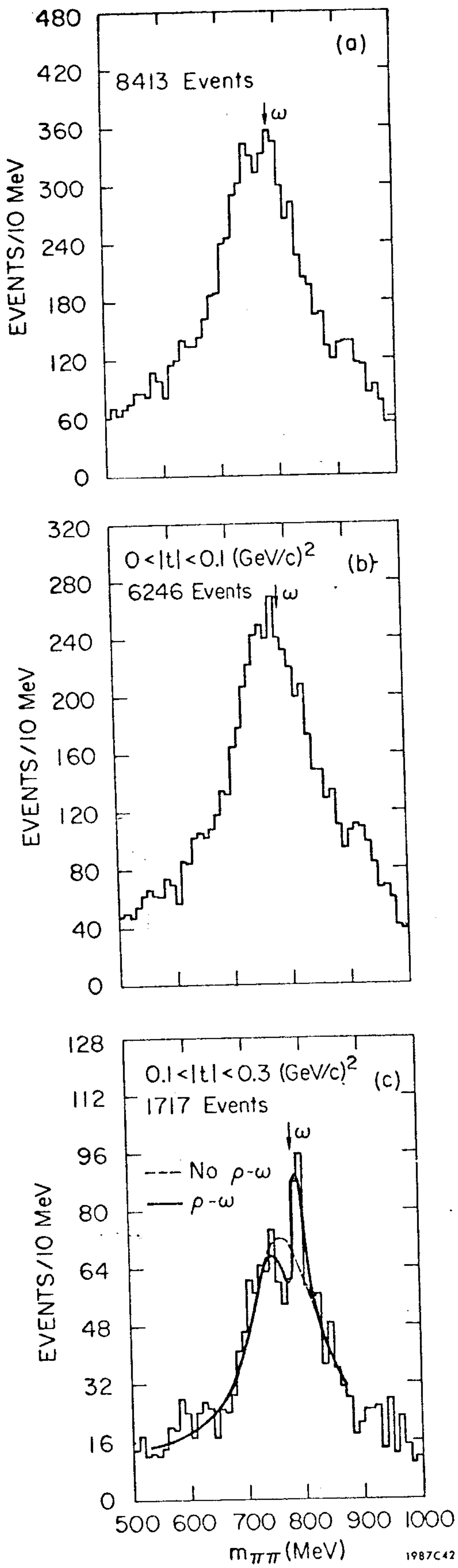
17. We have assumed a 25% error contribution for the extrapolation of the cross section.

FIGURE CAPTIONS

1. Observed mass distributions for different regions of t: (a) all data, (b) $0<|t|<0.1$, and (c) $0.1<|t|<0.3$. Part c shows the result of fits with and without $\rho - \omega$ interference.

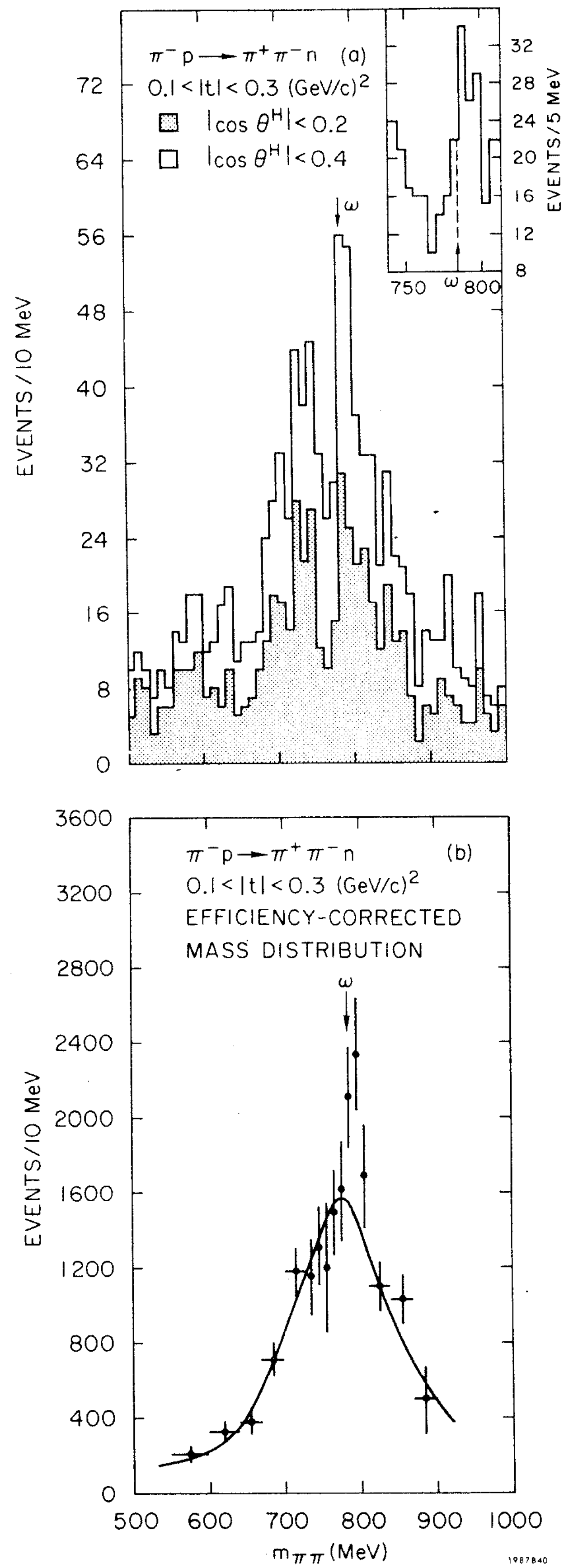
2. (a) Observed mass distributions for $0.1<|t|<0.3$ for different cuts on $\cos\theta^H$. The inset shows the data for $|\cos\theta^H|<0.4$ on a finer mass scale. (b) The mass distribution corrected for geometric losses. The solid line is the mass distribution of a pure ρ plus background, using $m_\rho = 0.764$ GeV and $\Gamma_\rho = 0.157$ GeV. The difference between (a) and (b) is due to the preferential selection by the apparatus of transverse helicity states.

3. Contour plots of χ^2 in $C - \Phi$ space for $0.1<|t|<0.3$ using (a) all events, (b) events satisfying $|\cos\theta^H| < 0.4$, and (c) efficiency-corrected mass distribution. The number on the contour indicates the increase of χ^2 over the minimum value.



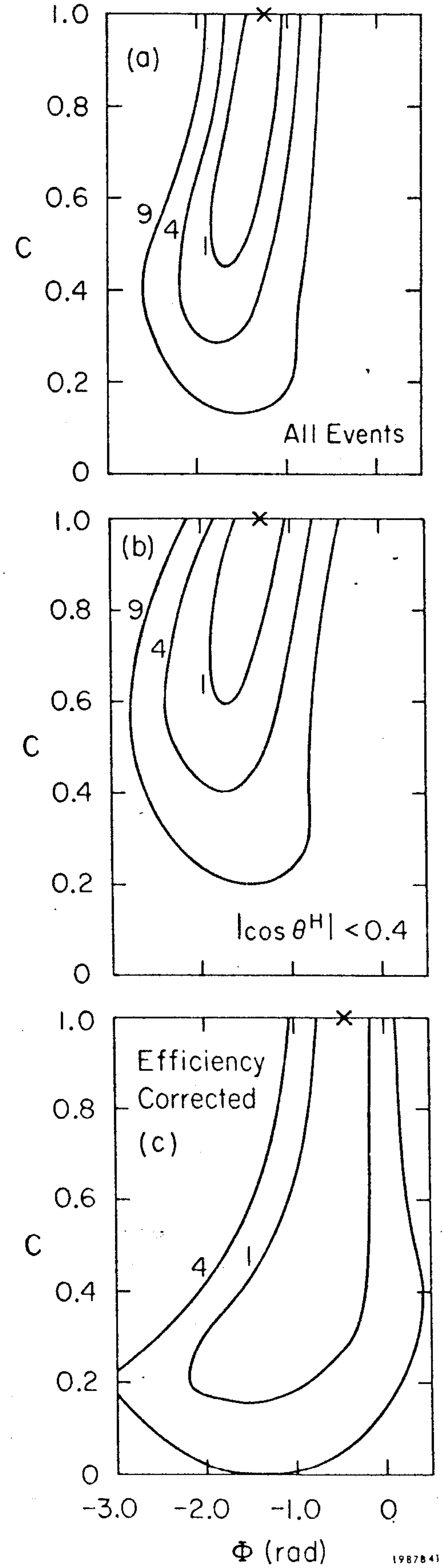
(a)
8413 Events
ω
EVENTS/10 MeV
480
420
360
300
240
180
120
60
0
(b)
0<|t|<0.1 (GeV/c)²
6246 Events
ω
EVENTS/10 MeV
320
280
240
200
160
120
80
40
0
(c)
0.1<|t|<0.3 (GeV/c)²
1717 Events
ω
--- No ρ-ω
— ρ-ω
EVENTS/10 MeV
128
112
96
80
64
48
32
16
0
500 600 700 800 900 1000
mππ (MeV)
1987C42

Fig. 1



$\pi^- p \to \pi^+ \pi^- n$ (a)
$0.1 < |t| < 0.3$ (GeV/c)^2
$|\cos\theta^H| < 0.2$
$|\cos\theta^H| < 0.4$
ω
EVENTS/10 MeV
72
64
56
48
40
32
24
16
8
0
EVENTS/5 MeV
32
28
24
20
16
12
8
750
800
$\pi^- p \to \pi^+ \pi^- n$ (b)
$0.1 < |t| < 0.3$ (GeV/c)^2
EFFICIENCY-CORRECTED
MASS DISTRIBUTION
3600
3200
2800
2400
2000
1600
1200
800
400
0
500
600
700
800
900
1000
$m_{\pi\pi}$ (MeV)
1987840

Fig. 2



1.0
0.8
0.6
0.4
0.2
0
C
(a)
9
4
1
All Events
(b)
9
4
1
|cos θ^H| < 0.4
Efficiency
Corrected
(c)
4
1
-3.0
-2.0
-1.0
0
Φ (rad)
1987B41

Fig. 3