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Diffraction Scattering of Virtual Pions and the A_1 Enhancement*

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In our study of the π^+p interactions at 3.65 BeV/c and π^-p at 3.7 BeV/c, leading to $\rho^0\pi^\pm p$ in the final state, we have observed evidence for the Drell process: i.e., diffraction scattering of a virtual pion from the proton.[1] The mass of the $\rho^0\pi^\pm$ system for the events associated with the "diffraction scattering effect" shows a considerable enhancement in the A_1(1080) mass region. On the other hand, the events in the A_2(1320) mass peak are not associated with diffraction scattering. Thus at the energy investigated here the A_1 enhancement can be accounted for by the presence of diffraction scattering. This result is in accordance with the model proposed by Deck[2] and later elaborated by Maor and O'Halloran.[3]

The work on the π^+ interaction was carried out in the Brookhaven National Laboratory 20-inch hydrogen bubble chamber exposed in the Brookhaven-Yale beam at the AGS. The work on the π^- interactions was carried out in the Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber exposed in a negative-particle beam at the Bevatron. We have identified 1784 events of the type $\pi^+p \to \pi^+\pi^-\pi^+p$, which we analyzed by conventional methods, and 1286 events of the type $\pi^-p \to \pi^+\pi^-\pi^+p$, which we analyzed on the LRL Flying-Spot Digitizer (FSD) and by associated programs.[4]

Let us first consider the proton vertex in the Feynman diagram shown in Fig. 1. Here events are selected with at least one $\pi^+\pi^-$ combination in the ρ^0 band.[5] To study this vertex we have looked at the correlation between the $\pi^\pm p$ mass for the outgoing particles and the p_{in}, p_{out} scattering angle α_{pp} in the $\pi^\pm p$ rest system. This is shown in Fig. 1a and 1c. Here we note two distinct features: (a) An enhancement of events in the region of the 3/2, 3/2 resonances $N^{*++}(1238)$ and $N^{*0}(1238)$, the latter at about 10% the intensity of the former; (b) a very strong enhancement of events at small scattering angles, $\cos\alpha_{pp} \geq 0.8$, for both the π^+p and π^-p data. As may be noted from Fig. 1, the $\cos\alpha_{pp}$ distribution becomes more forward peaked with increasing mass of the outgoing $\pi^\pm p$ system, $M(\pi^\pm p)$, in a manner characteristic of diffraction scattering. To further investigate this effect we have divided the $\pi^\pm p$ mass distribution into four intervals of width 0.25 BeV, starting at 1.09 BeV. These intervals were chosen so that the corresponding differential cross sections represent averages over the various known N^* resonances. Thus the first interval includes the $N^*_{3/2}(1238)$ resonances. The next two intervals encompass the $N^*_{1/2}(1510)$ and $N^*_{1/2}(1690)$ resonances respectively in the π^-p system. The last interval, 1.84 to 2.09 BeV, includes the $N^*_{3/2}(1920)$ resonance. The differential cross sections for the first three energy bands are given in Fig. 2 for a Δ^2 cutoff to the $\pi^\pm p$ system of 1.0 $(\text{BeV}/c)^2$. This has the effect of virtually eliminating the contributions from the A_2 meson. The corresponding $\pi^\pm p$ mass projections are shown shaded in Fig. 1b and 1d. For the mass interval 1.84 to 2.09 BeV our small sample of events did not permit us to eliminate events with $\Delta^2_{\pi^\pm p} > 1\ (\text{BeV}/c)^2$. In order to investigate this mass region as well we have chosen to remove events associated with the A_2 band ($1.26 < M_{\pi^\pm \rho^0} < 1.38$ BeV).

We have taken two distinct approaches in parameterizing these experimental data as follows.

a. <u>Diffraction Scattering at the $\pi^\pm p$ vertex</u>

If we interpret our data in terms of diffraction scattering we can define a four-momentum transfer squared, $t = -2k^2(1-\cos\alpha_{pp})$, where k is the momentum in the c.m. of the outgoing $\pi^\pm p$ system. This corresponds to treating the proton vertex as elastic $\pi^\pm p$ scattering on the mass shell at a total energy given by $M(\pi^\pm p)$. We can now consider the average cross section $d^2\sigma/d\Omega dM$ in mb $(sr)^{-1}$ $(BeV)^{-1}$ for each of the four different mass bands. We find that the data at small α_{pp} values can be represented by the same variation with t, namely e^{-at}, which holds for π^+p and π^-p scattering <u>on the mass shell.</u> We find that the a_+ and a_- values for "virtual" π^+p and π^-p scattering lie in the region 8 to 12 $(BeV)^{-2}$. There is a slight indication that the $a_\pm$ parameters increase with increasing mass of the $\pi^\pm p$ system. Our limited statistics and systematic uncertainties do not permit us to determine these values more closely. The trend we observe is for the $a_\pm$ values to be somewhat larger than those obtained for $\pi^\pm p$ scattering on the mass shell. The dashed lines on the semilog plots in Fig. 2 indicate that at small angles a good fit can be obtained with an exponential dropoff.

b. Comparison with Elastic $\pi^{\pm}p$ scattering experiments

Here we have taken the available experimental π^+p and π^-p elastic differential scattering cross sections from counter experiments[6] and have averaged these over the four mass intervals specified above, i.e.,

$$\left\langle \frac{d\sigma_{el}}{d\Omega} \right\rangle = \int_{M_i}^{M_j} \frac{d\sigma_{el}}{d\Omega}\, dM \Big/ (M_j - M_i) \ .$$

To carry out a quantitative comparison of our experimental data with the elastic scattering[7] we would need to take into account the ρ^0 coupling constant and the off-the-mass-shell corrections for the various high-spin isobars involved as well as form factors for pion exchange[8] or absorption effects[9] or both. While such a detailed comparison may eventually be possible, we have for the purposes of the present note taken an empirical approach. We have compared the $\left\langle \frac{d\sigma_{el}}{d\Omega} \right\rangle$ distributions with our experimental $\frac{d^2\sigma}{d\Omega dM}$ distributions by normalizing the elastic differential cross section to the experimental points in the $\cos\alpha_{pp}$ region 0.8 to 1.0. The normalization factor, b, can be expressed by $b = \left(\left\langle \frac{d\sigma_{el}}{d\Omega} \right\rangle \Big/ \frac{d^2\sigma}{d\Omega dM} \right)_{\alpha=0}$. We find that (a) the general shapes of our experimental distribution are remarkably close to the distributions of $\left\langle \frac{d\sigma_{el}}{d\Omega} \right\rangle$, (b) for the $N^{*++}(1238)$ and $N^{*0}(1238)$ resonance bands the parameter b is essentially the same ($b \approx 23$ BeV), while for the $N^{*0}(1510)$ and $N^{*0}(1690)$ bands the parameter b increases slowly with total energy (see Table I). The "errors" in the parameter b quoted in Table I reflect rough limits over which the curves could be fitted to the data. Furthermore we note that an additional systematic uncertainty in this parameter may be of the order of 30%. This comes from (i) the uncertainty in the absolute cross section calibration, (ii) the treatment of "double ρ" events, which constitute about 20% of all events with ρ mesons (we have included both $\pi^{\pm}p$ combinations for these events with a weight factor of 1/2 for each combination), (iii) residual background effects.

We now turn to the question of the A_1 and A_2 "mesons", which are observed as enhancements in the $\pi^{\pm}\rho^0$ system. If we limit ourselves to the sample of events primarily associated with diffraction scattering--i.e., $\cos\alpha_{pp} \geq 0.8$ and $M(p\pi^{\pm}) \geq 1.34$ BeV--we find a broad enhancement in $M(\pi^{\pm}\rho^0)$, with evidence of peaking at the A_1 and A_2 bands. Aside from a small A_2 contribution this mass distribution can account for the entire A_1 enhancement observed in our data. On the other hand, eliminating the events associated with diffraction scattering--i.e., $\cos\alpha_{pp} < 0.8$ and leaving the same condition on $M(p\pi^{\pm})$--we remain with a clear A_2 peak (see Fig. 3a and 3b), whereas the A_1 peak has completely disappeared.

Finally, we observed a striking difference between the A_1 and A_2 by examining the decay products of the two "resonances.". Both decay into a ρ and a π meson. For the A_1 "resonance" we find the resulting ρ^0 meson to be strongly aligned relative to the incident pion direction (see Fig. 4). This indicates that the ρ^0 meson is probably produced directly via an OPE mechanism, aligned with m = 0, giving an angular distribution $I(\cos\alpha) = \cos^2\alpha$. For the A_2 resonance the resulting ρ^0 mesons are not aligned with respect to the incident pion direction, indicating that they are indeed decay products of a distinct resonance.

From all the evidence presented here we conclude that the A_1 enhancement as observed in our data results from diffraction scattering of virtual pions.

To completely rule out the possibility of a bona fide A_1 resonance it will be necessary to analyze the very marked A_1 enhancement observed at higher energies[10] in a similar manner, and to check whether or not a residual A_1 resonant state is present after accounting for diffraction effects. A number of observations on similar experiments have recently appeared[11-13] which favor the conclusion we have reached about the A_1 enhancement.

We wish to thank Luis W. Alvarez for making the 72-inch bubble chamber available to us; the FSD crew under Howard S. White and our own scanning staff at Berkeley; R. Shutt at Brookhaven National Laboratory for making the 20-inch bubble chamber available to us; and H. Brown for helping with our run at Brookhaven. Finally we wish to acknowledge the help of John L. Brown and George H. Trilling in various stages of this work.

Table I. Adjustment parameters $b_\pm$ corresponding to the ratio of the forward scattering cross section $d^2\sigma/d\Omega dM$ of a virtual pion in $\rho^0\pi^\pm p$ production to that in elastic $\pi^\pm p$ scattering averaged over the same energy intervals. For the first three average intervals the data have a cutoff in momentum transfer $\Delta^2(\rho^0) \leq 1.0\ (\mathrm{BeV})^2$.

$\pi^\pm p$ Mass Interval (BeV)	$\pi^+ p$ b_+ (BeV)	$\pi^- p$ b_- (BeV)
1.09 - 1.34	$23 \pm {}^{5}_{4}$	$24 \pm {}^{5}_{4}$
1.34 - 1.59	11 ± 2	$25 \pm {}^{7}_{6}$
1.59 - 1.84	$14 \pm {}^{4}_{3}$	$37 \pm {}^{11}_{8}$
1.84 - 2.09	$16 \pm {}^{5}_{3}$ [a]	——

a. A_2 band out; no $\Delta^2(\rho^0)$ cutoff.

Footnote and References

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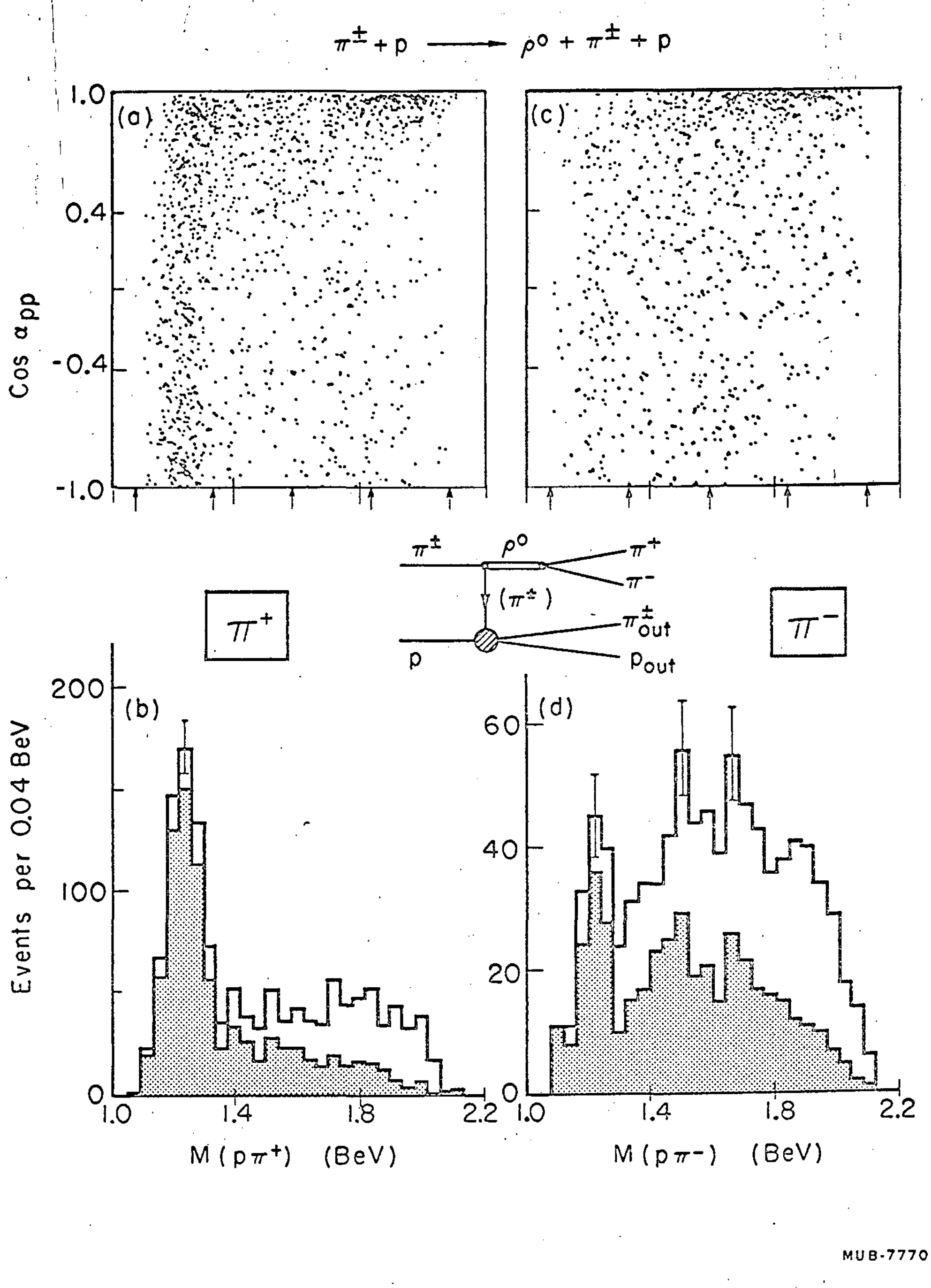
Figure Captions

Fig. 1. Scatter plots of $\cos\alpha_{pp}$ versus $M(p\pi^{\pm})$ for $\pi^{+}p$ and $\pi^{-}p$ interactions. The mass projections are shown in (b) and (d) respectively. The shaded regions correspond to $\Delta^{2}(p\pi^{\pm}) \leq 1.0$ $(\text{BeV}/c)^{2}$. The arrows delineate the four mass regions discussed in the text.

Fig. 2. The differential cross section $d^{2}\sigma/(d\Omega dM)$ for the four $M(p\pi^{\pm})$ regions. Fig. 2 a, b, c and e, f, g correspond to $\Delta^{2}(p\pi^{\pm}) \leq 1.0$ $(\text{BeV})^{2}$. In Fig. 2 d and h no Δ^{2} cutoff is applied. The A_2 band is removed, however. The curves correspond to elastic $\pi^{\pm}p$ scattering cross sections averaged and normalized as discussed in the text. The dotted lines illustrate the exponential dropoff at small angles.

Fig. 3. The $M(\pi^{\pm}\rho^{0})$ mass distribution with the N^{*++} band removed. Figure 3a shows the distribution for $\cos\alpha_{pp} \geq 0.8$, i. e., for the events we have associated with "diffraction scattering." Figure 3b shows the events with $\cos\alpha_{pp} < 0.8$.

Fig. 4. The distribution of $\cos\alpha_{\pi\pi}$, the $\pi\pi$ scattering angle in the ρ^{0} c. m. The data shown are selected with $\pi^{\pm}\rho^{0}$ mass in the A_1 and A_2 bands respectively and for $(\pi^{\pm}p)_{out}$ masses above the $N^{*}(1238)$ band.



$\pi^{\pm} + p \longrightarrow \rho^0 + \pi^{\pm} + p$
(a)
(c)
Cos α_{pp}
1.0
0.4
-0.4
-1.0
$\pi^{\pm}$
ρ^0
π^+
π^-
$(\pi^{\pm})$
$\pi^{\pm}_{out}$
p
p_{out}
π^+
π^-
(b)
(d)
Events per 0.04 BeV
200
100
0
60
40
20
1.0
1.4
1.8
2.2
M (pπ^+) (BeV)
M (pπ-) (BeV)
MUB-7770

Fig. 1

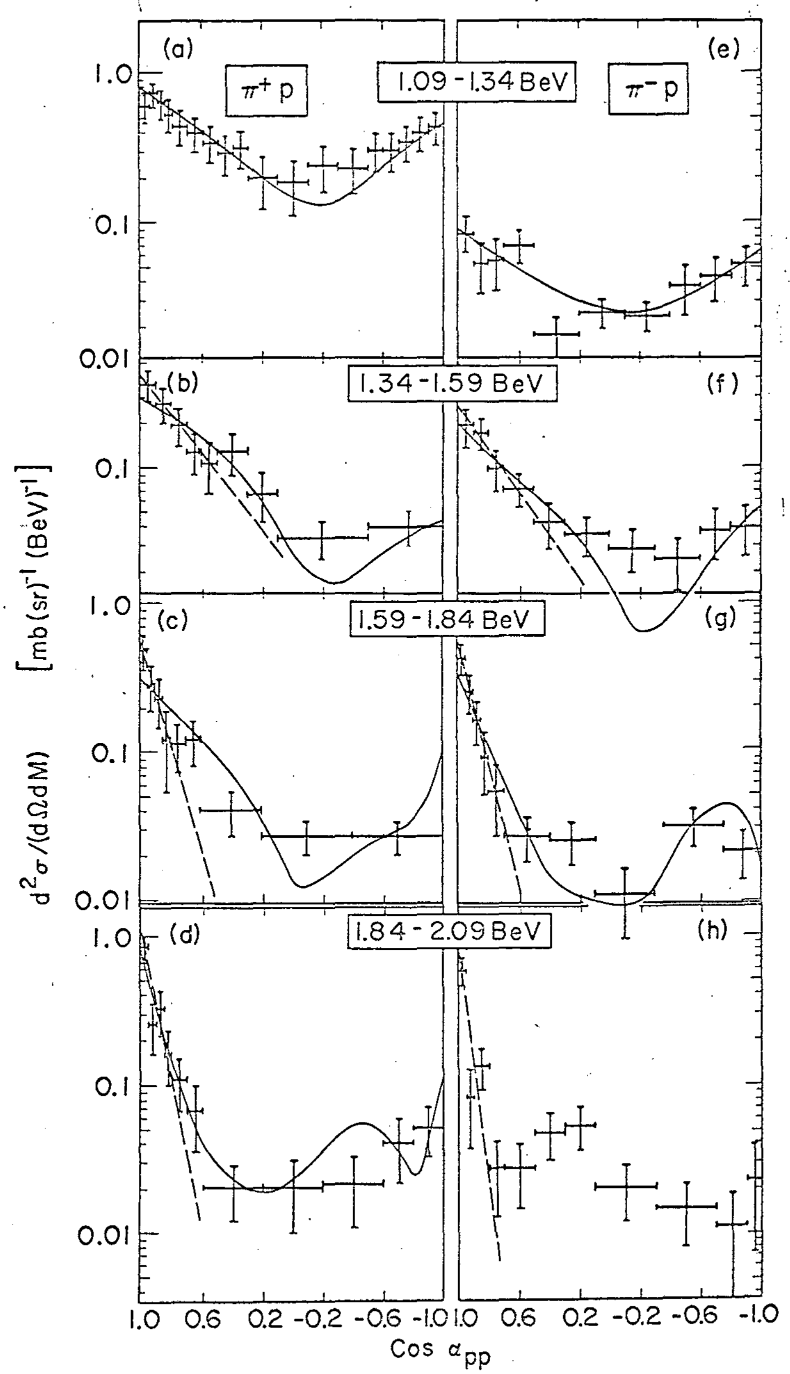
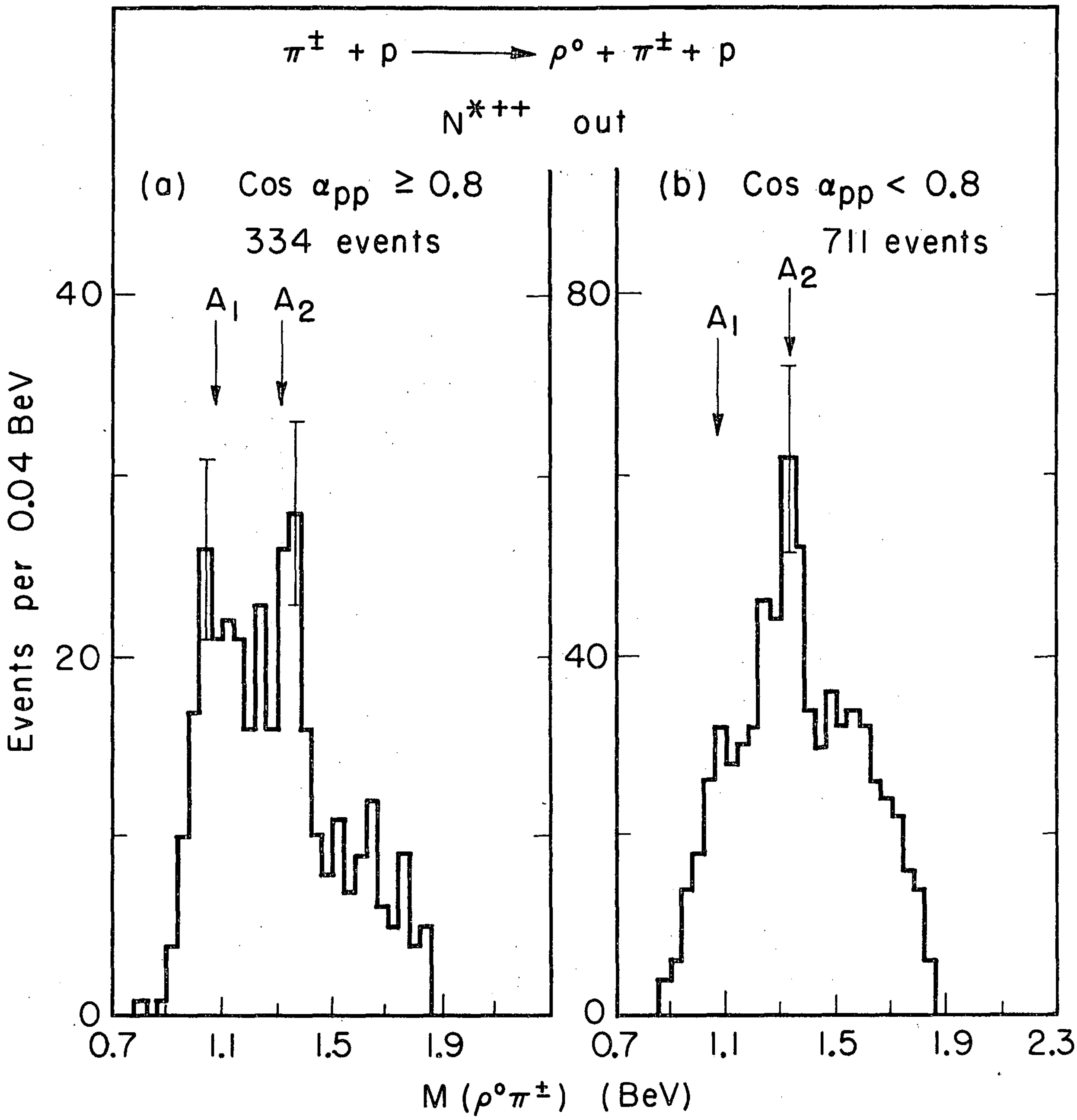
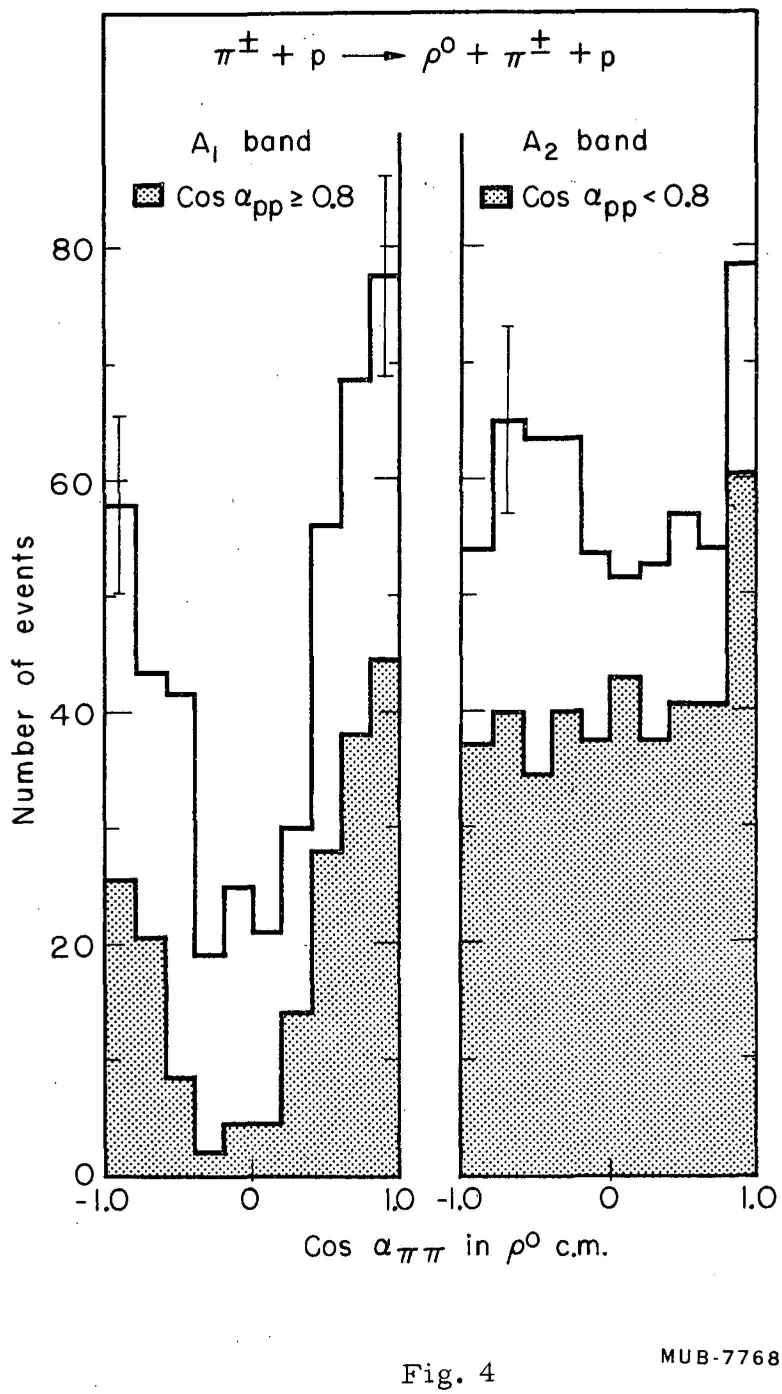

(a)
$\pi^+ p$
1.09 - 1.34 BeV
(e)
$\pi^- p$
(b)
1.34 - 1.59 BeV
(f)
(c)
1.59 - 1.84 BeV
(g)
(d)
1.84 - 2.09 BeV
(h)
1.0
0.1
0.01
$d^2\sigma/(d\Omega dM)$ [mb(sr)$^{-1}$(BeV)$^{-1}$]
1.0 0.6 0.2 -0.2 -0.6 -1.0
Cos α_{pp}

Fig. 2



MUB-7769

Fig. 3



$\pi^{\pm} + p \longrightarrow \rho^0 + \pi^{\pm} + p$
A_1 band
Cos $\alpha_{pp} \geq 0.8$
A_2 band
Cos $\alpha_{pp} < 0.8$
Number of events
80
60
40
20
0
-1.0
0
1.0
-1.0
0
1.0
Cos $\alpha_{\pi\pi}$ in ρ^0 c.m.
MUB-7768

Fig. 4