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Evidence for the Goldhaber Effect in pp Interactions at 300 GeV/c.*

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ABSTRACT

We have observed evidence for the Goldhaber effect among pion pairs produced in six- and eight-prong events in pp interactions at 300 GeV/c. We observe a pronounced difference between the opening angle distributions for pairs of pions of like and unlike electric charge. This effect decreases rapidly with increasing all-charged-pion mass. Calculations indicate that resonance production can account for only about 30% of the observed effect. A search for the Goldhaber effect in high-charged-multiplicity events ($n_c \geq 20$) gives only inconclusive results.

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I. Introduction.

The Goldhaber effect was first observed in $\bar{p}p$ annihilations into four and six charged pions at 1.05 GeV/c[1]. The effect was observed as a marked deviation in the opening angle distributions in the $\bar{p}p$ center-of-mass of pairs pions of like charge from the predictions of a Lorentz-invariant-phase-space statistical model. The opening angle distributions of pairs of unlike-charged pions, in both the four- and six-prong events, were in only fair agreement with the model, which predicted a strong enhancement near $\cos\theta_{\pi\pi} = -1$, but the distributions of like-charged pions were in sharp disagreement with the model, being consistent with isotropy. The deviations observed were attributed to the presence of additional pion-pion correlations and/or to the effects of possible resonances.

Since that time, controversy about the Goldhaber effect has continued. Although the experimental observation has not been questioned, and the same effect confirmed in many other experiments[2,3,4], the interpretation has been controversial. The effect has been attributed to the present of resonances, especially the ρ^0, in the $\pi^+\pi^-$ pairs, but not in the like-charge pairs, $\pi^\pm\pi^\pm$, which must be in a pure I = 2 state. It has also been attributed to the effects of Bose-Einstein statistics on pairs of like-charged pions[2]. Support for this view has been given by the fact that the observed effect decreases rapidly with increasing all-pion mass, i.e. increasing relative momentum of individual pions.

In this work we report observation of the Goldhaber effect in an entirely new region: In the production of pions in pp interactions at 300 GeV/c. We also present the results of a simple calculation which demonstrates that only about 30% of observed effect can be attributed to the presence of resonances, specifically the ρ^o and the f^o, in the $\pi^+\pi^-$ channel. We therefore conclude that the alternative explanation of Bose-Einstein statistics (and/or similar short-range correlations) must play a major role in producing the observed effect.

II. Observation of the Effect.

The data are from a 34000-picture exposure of the Fermilab 30-inch hydrogen bubble chamber to a 300 GeV/c proton beam. Details of the scanning, measuring, and event processing have been published[5].

We wish to isolate a sample of events of the type shown in figure 1a, in which the pions are produced in the central region and leading particle effects have been removed. We emphasize the fact that the selection of events of the type shown in figure 1a allows the invariant mass of the charged pion system to be less than 1.88 GeV, a region which is kinematically inaccessible in $\bar{p}p$ annihilations. Thus, this experiment can explore a kinematic region of very low relative pion momenta. We select a sample of fully measured six- and eight-prong events in which the proton in the target fragmentation region is identified by ionization. Events in which the lowest momentum track in the laboratory frame is not the proton cannot be described by figure 1a and are rejected. We assign the positive particle with the largest laboratory momentum as the proton in the beam fragmentation region. Events in which the particle with largest laboratory momentum is negatively charged cannot be described by figure 1a and are also rejected. We are left with a sample of 430 six-prong and 107 eight-prong events, which we use in the analysis.

We use all-charged-pion invariant mass (denoted by M) as a quantitative guide to the correctness of the picture shown in figure 1a. If this mass is very large then some of the pions are presumably associated with a fragmentation region. Thus, events with pions from leading particle effects, e.g. $p \to N^* \to p\pi^+\pi^-$, will have large values for M. (The decay $N^* \rightarrow p\pi^+\pi^+\pi^-\pi^-$ is small.) Figure 1b shows the invariant mass distribution of all the charged pions in each event. A total of 159 events have their all-charged-pion invariant mass below 2 GeV/c in the region inaccessible to $\bar{p}p$ annihilations. For the subsequent analysis we divide all the events into three groups; those with (i) M < 2 GeV, (ii) 2 < M < 4 GeV, and (iii) M > 4 GeV.

Figure 2 shows the distributions in the opening angle in the all-charged-pion rest frame between pion pairs of like and unlike charges in the three selected M regions. We note that for a six-prong event with $2\pi^+$ and $2\pi^-$ there are 2 like-charge and 4 unlike-charge dipion combinations, and for an eight-prong event there are 6 like-charge and 9 unlike-charge combinations. We observe that in the lowest M region, the like-charge distribution ($Q = \pm 2$) is nearly isotropic, while the unlike-charge distribution ($Q = 0$) is strongly peaked near $\cos\theta_{\pi\pi} = -1$. In the larger M regions this difference is reduced. The sharp peaking in the angular distributions in the higher M regions is the result of kinematics. If, for example, a group of four pions has a very large invariant mass, then the opening angle in the four pion rest frame between any two of them tends toward $\cos\theta = \pm 1$.

We point out that the apparent absence of the Goldhaber effect in the region 2 < M < 4 GeV in no way contradicts the original observation by Goldhaber et al.[(1)]. In that experiment, the total center of mass energy, which is equivalent to M in our experiment, was 2.08 GeV. In our data, although statistics are poor, the Goldhaber effect is clearly seen for events with $M \sim 2$ GeV, but the effect diminishes rapidly with increasing all-charged-pion mass. Thus the effect is washed out in the relatively large bin from 2 to 4 GeV. The dependence of the Goldhaber effect upon M will be discussed in more detail below.

Although information on the detailed shape is lost, we use as a convenient measure of the size of the effect, the forward-backward ratio, defined as $R = \frac{F - B}{F + B}$, where F is the number of events with $\cos\theta_{\pi\pi} > 0$, and B is the number with $\cos\theta_{\pi\pi} < 0$. The forward-backward ratios for the six angular distributions are given in Table I. We see that in the region with $M < 2$ GeV, the magnitude of the Goldhaber effect, approximated in this manner, is more than six standard deviations.

In order to determine the dependence of the Goldhaber effect on M, and also to compare our observations with the original results of Goldhaber et al.[1] we have plotted R as a function of M for both like- and unlike-charged pion pairs. In making this particular plot we have rebinned the data to provide for a bin in the neighborhood of 2.08 GeV for a direct comparison with the original result, i.e. we have divided the data into four regions of M: (i) $M < 1.8$ GeV, (ii) $1.8 < M < 2.4$ GeV, (iii) $2.4 < M < 4$ GeV, and (iv) $M > 4$ GeV. These data are shown in figure 3, and the original results of Goldhaber et al.[1] are shown as the black dots at 2.08 GeV[6]. The agreement between the two experiments is excellent. We can see that the forward-backward asymmetry in the opening angle distribution for neutral dipions at $M < 1.8$ GeV is even larger than that reported in reference 1, and this asymmetry decreases rapidly with increasing M. The doubly-charged dipions show no such trend; in that case the asymmetry increases somewhat with increasing M. This increase is due to the lessening of the effect of Bose-Einstein statistics as the relative momenta of pion pairs increases (on the average). This causes the asymmetry to begin to resemble the unlike-charge case at low M where Bose-Einstein statistical effects do not contribute, and where the effect of resonances is small. The decrease in the asymmetry in the unlike-charge case with increasing M is due to the onset of resonance effects and to kinematic effects.

III. Resonance Contributions.

We wish now to determine the effect of resonance production on this effect. In figure 4 we show the neutral and doubly charged invariant mass distributions for the same three M regions shown in figure 2 and Table I. The doubly-charged distributions are smooth, as they should be. In the neutral dipion distribution there is no evidence for f^o production, but there are shoulders which allow the presence of substantial ρ^o production. In the past the effect of such resonance production on the opening angle distributions shown in figure 2 has been estimated by complicated Monte Carlo calculations, in which resonances are produced according to various models, allowed to decay, etc. In the present work we estimate the effect of resonance production in the neutral dipion channel on the opening angle distribution by a simple calculation on the real events.

In this calculation we assume that there are no exotic resonances in the I=2 doubly-charged dipion channel, and therefore the mass and opening angle distributions of the doubly-charged dipions represent the effects of kinematics plus any possible additional non-resonant pion-pion correlations, e.g. Bose-Einstein statistics. We then attempt to use the doubly-charged dipions to reproduce the mass and opening angle distributions of the neutral dipions by suitably weighting the dipions to simulate the presence of resonances. This is done by taking the observed doubly-charged dipions and weighting each dipion by the factor:

$$W = 1 + A_1 BW(\rho^o) + A_2 BW(f^o) \ ,$$

in which BW means a Breit-Wigner intensity:

$$BW = \frac{(\Gamma/2)^2}{(M_{\pi\pi} - M_o)^2 + (\Gamma/2)^2} \quad .$$

For the ρ^o and f^o resonances we use the Particle Data Group[7] parameters of $M_\rho = 0.770$ GeV, $\Gamma_\rho = 0.150$ GeV, $M_f = 1.270$ GeV, and $\Gamma_f = 0.170$ GeV. A_1 and A_2 are free parameters which are to be varied in the fit. These doubly-charged dipion combinations, suitably weighted, are then histogrammed, renormalized to the number of neutral dipion combinations, and compared via calculation of chisquare with the observed neutral dipion distributions in mass and opening angle. The parameters A_1 and A_2 are then varied to minimize this chisquare. This method thus automatically includes in the "generation" of the expected distributions all the correct kinematics plys all the real correlations between dipion mass and dipion opening angle. If the observed differences in the distributions are due entirely to the presence of resonances in one channel and not the other, then it should be possible to reproduce the neutral dipion distributions using the doubly-charged dipions suitably weighted.

The results are shown as the dashed histograms in figures 2a, b, c and 4a, b, c. In all three regions of M the fits do not require any f^o production and in fact the chisquares are minimized for $A_2 = 0$. We concentrate first on the region with M < 2 GeV, where the Goldhaber effect appears strongly. It is clear that the dashed histograms in figures 2a and 4a do not reproduce the solid dipion data. In fact the best fit chisquare is 103.8 for 30 degrees of freedom (33 bins minus 2 parameters minus one normalization). The forward-backward ratio for this dashed histogram in figure 2a is $R_W = -0.23 \pm 0.04$, which is closer to the neutral dipion value of $R_{+-} = -0.47 \pm 0.03$ than the unweighted doubly-charged dipion value of $R_{\pm\pm} = -0.12 \pm 0.05$, but is still 4.8 standard deviations away. If we use these forward-backward ratios as a crude quantitative guide to the magnitude of the Goldhaber effect, then we may say that the addition of resonances to the doubly-charged channel moves the opening angle distribution only about 30% of the way towards the neutral dipion opening angle distribution.

In the two higher M regions, where the Goldhaber effect is not observed, the reproduction of the neutral dipion opening angle distributions by the weighted doubly charged dipions is somewhat improved as can be seen in figures 2b, 2c, 4b and 4c. The best fit chisquares for these two regions are 97.3 for 48 degrees of freedom and 134.0 for 60 degrees of freedom respectively. The forward-backward ratios for the dashed histograms in figures 2b and c are $R_W = -0.37 \pm 0.04$ and $R_W = -0.19 \pm 0.13$ respectively, being only 3.8 and 2.4 standard deviations away from the values for the neutral dipions.

We have also considered the possible effect of the $\varepsilon^{o}(700)$ upon the dipion opening angle distributions. Specifically, we have added a term, A_3 BW(ε^{o}) to the weight for the doubly-charged dipions, in which we have used the values $M_\varepsilon = 0.7$ GeV, $\Gamma_\varepsilon = 0.6$ GeV[6]. The inclusion of this somewhat questionable resonance does not significantly affect any results. For example, in the region with $M < 2$ GeV, the best fit chisquare becomes 93.4 for 29 degrees of freedom, and the forward-backward ratio becomes $R_W = -0.25 \pm 0.04$, which is still 4.4 standard deviations away from the neutral dipion value. In other words, the doubly-charged dipion value has moved only 37% of the way toward the neutral dipion value. In the higher M regions the values of chisquare are 92.3 for 47 degrees of freedom and 124.8 for 59 degrees of freedom respectively. The forward-backward ratios are $R_W = -0.34 \pm 0.04$ and $R_W = -0.14 \pm 0.03$ respectively, being only 3.2 and 1.7 standard deviations away from the neutral dipion values.

The calculations thus described assume that the resonances are produced unpolarized. Polarized rho mesons, for example, may introduce an additional correlation between the dipion mass and its opening angle in the all-charged-pion rest frame. We have investigated this question by studying the distributions in the helicity angle of the dipion system; i.e. the angle between the momentum of one pion in the dipion rest frame and the momentum of one pion in the dipion system in the all-charged-pion rest frame. In the region with $M < 2$ GeV, the helicity angle distributions are consistent with isotropy for both neutral and doubly-charged dipion systems which is consistent with no polarization. Nevertheless, we have attempted to reproduce the neutral dipion distributions using the doubly charged dipions now weighted to include polarized resonances; i.e.

$$W = 1 + A_1 BW(\rho) |Y_1^m (\alpha)|^2 + A_2 BW(f^o) |Y_2^{m'} (\alpha)|^2$$

where α is the helicity angle just described, Y is a spherical harmonic, and $m = 0$ or 1 and $m' = 0$, 1, or 2. There is no improvement in chisquare probability using this model over unpolarized resonances. Although a modest reduction in the contribution to chisquare from the opening angle distribution in the region with $M < 2$ GeV, can be achieved with, for example, $m = 0$, (i.e. $\cos^2 \alpha$), this can only be done at the expense of greatly distorting the helicity angle distribution of the weighted doubly-charged dipions, so it no longer resembles the isotropic helicity angle distribution of the neutral dipions. If we include the helicity angle distributions in our calculation of chisquare, the best fit chisquare probability for polarized ρ mesons is considerably worse than that for unpolarized ρ mesons. (The contribution from the f^o is, as always, neglible.)

We have not considered the possibility of interference terms between a resonant amplitude and background in these calculations, but we expect this effect to be small. If the square of a resonant amplitude does not distort the isotropic doubly-charged dipion opening angle distribution enough to make it resemble the backward peaked neutral dipion distribution, then the resonant amplitude itself times a background amplitude (which must correlate with an isotropic distribution) probably can do even less. We conclude that the observed Goldhaber effect cannot be entirely explained by the presence of resonances in the neutral dipion channel, and therefore a major part of the observed effect must be due to Bose-Einstein statistics.

IV. Higher Charged Multiplicities.

We have also searched for evidence of the Goldhaber effect in high-charged-multiplicity events, i.e. $n_c \geq 20$ prongs, and have failed to find statistically significant evidence for it. We attribute this failure to the overwhelming effects of the combinatorial background and to our inability to adequately define pion clusters, in whose rest frames the dipion opening angle would be calculated. In the high multiplicity events we first adopt the same experimental procedure as used in the six- and eight-prongs. The fragmentation region protons are rejected and the opening angle distributions of pion pairs are plotted in the all-charged-pion rest frame. No statistically significant difference between the neutral and doubly-charged distributions can be seen. This is due to the overwhelming presence of an enormous number of dipion combinations where the two pions really have nothing to do with each other, i.e. they do not belong to the same cluster. In fact, pion cluster size is known to be on the average only about two charged particles[8,9,10].

It is critical for observation of the Goldhaber effect that the correct Lorentz frame be chosen for the opening angle distribution. This may be demonstrated from the fact that in the six- and eight-prong events, if the opening angle distributions of dipions are calculated in the overall center of mass, rather than in the all-charged-pion rest frame, the six standard deviation Goldhaber effect observed is washed out to the point where it is less than two standard deviations.

In the high multiplicity events, we have tried defining each cluster as (i) the collection of all charged pions, (ii) all neutral four-pion systems, in analogy with the six-prong events and (iii) three, four, and five adjacent pions in rapidity space, with various choices of charge. In no case was the observed effect of more than two standard deviations. In short, the Goldhaber effect requires a reliable method for isolating pion clusters to be seen. In the high multiplicity events this has not been done; in the low-multiplicity six- and eight-prongs the charged pions form a cluster sufficiently frequently for the effect to have been observed.

V. Conclusions.

In conclusion we have observed evidence for the Goldhaber effect in pion pairs produced in six- and eight-prong events in pp interactions at 300 GeV/c. Measured in terms of the forward-backward ratios the effect is more than six standard deviations in the region where $M < 2$ GeV, and the effect decreases rapidly with increasing M. A simple calculation indicates that the presence of resonances, especially the ρ^o, in the neutral dipion channel cannot account for the entire effect. In terms of the forward-backward ratio, resonances can account for about 30% of the observed effect.

VI. Acknowledgements.

We thank the staffs of the accelerator, Neutrino Lab., 30-inch Bubble Chamber, and Film Analysis Facility at the Fermi National Accelerator Laboratory for their help with the experiment. We also thank Tom Clark for his excellent work on the ionization.

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(2) $\bar{p}p \to 3\pi^+3\pi^-$ at 3 GeV/c: O. Czyzewski and M. Szeptycka, Phys. Letters 25B, 482 (1967); or see review paper by Kacper Zalewski in the Proceedings of the Colloquium on High Multiplicity Hadron Interactions, Ecole Polytechnique, Paris, May 13-15, 1970, and the following discussions.

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(5) A. Firestone et al., Phys. Rev. D10, 2080 (1974).

(6) The data of reference 1 were presented in terms of $\gamma = B/F$, rather than the ratio $R = \frac{F - B}{F + B}$. We have used the published values of γ and $N = B + F$ to calculate R for the data of reference 1. We have also combined the four- and six-prong annihilation events of reference 1, in exact analogy with our own six- and eight-prongs, and these data are shown as the black dots in figure 3.

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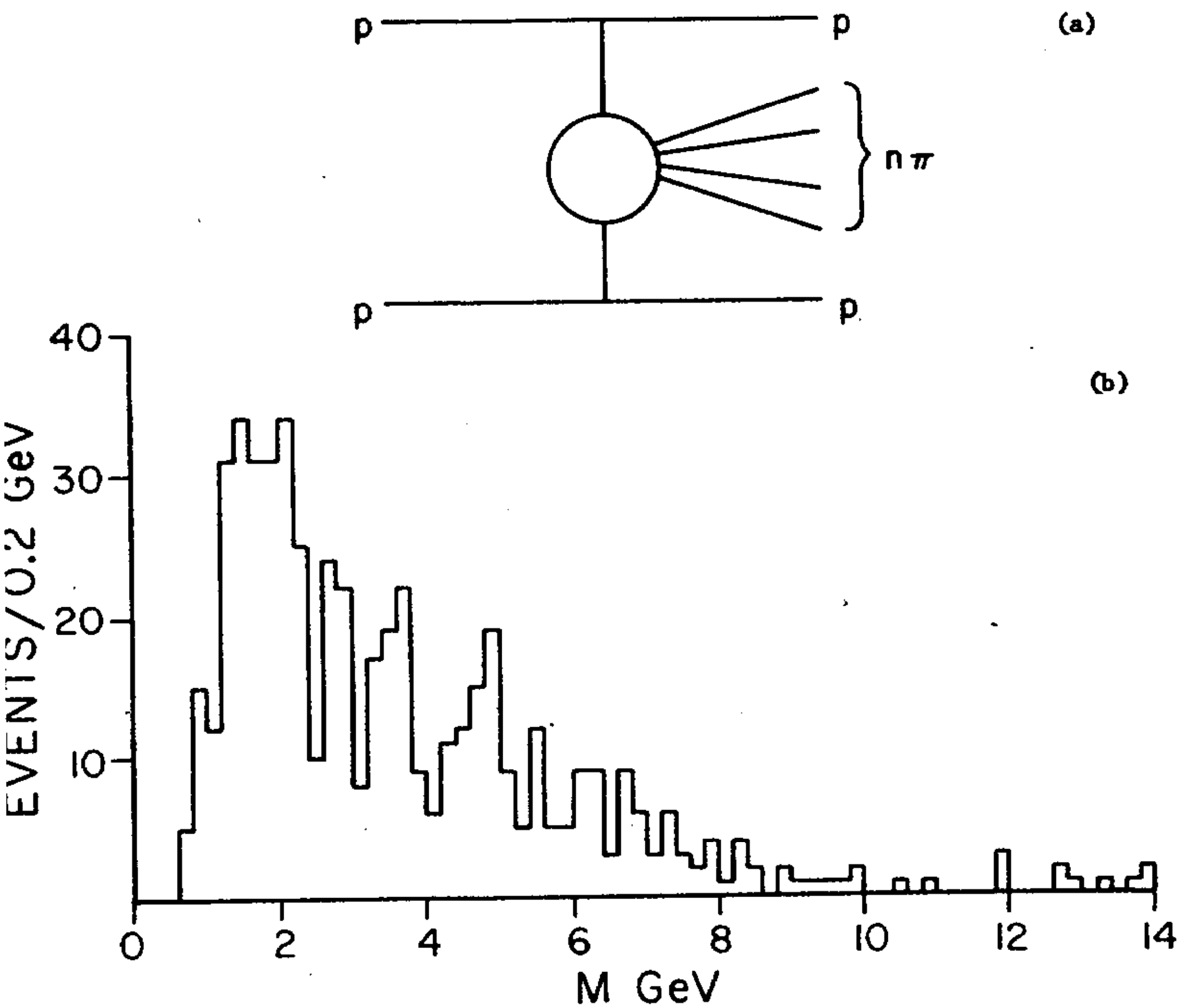
Table 1

	M < 2 (159 events)	2 < M < 4 (190 events)	M > 4 (188 events)
Q = 0	651 dipion combinations R = −0.47 ± 0.03	965 dipion combinations R = −0.18 ± 0.03	1049 dipion combinations R = −0.07 ± 0.03
Q = ±2	330 dipion combinations R = −0.12 ± 0.05	544 dipion combinations R = −0.36 ± 0.04	616 dipion combinations R = −0.26 ± 0.04

Table Caption

Table 1: Forward-backward ratios of the opening angle distributions for the three regions of the charged pion mass and for neutral and doubly-charged dipion systems.



igure 1 (a): Diagram of pion production in the central region in pp interactions.

(b): Invariant mass distribution of the charged-pion system in the six- and eight-prong events.

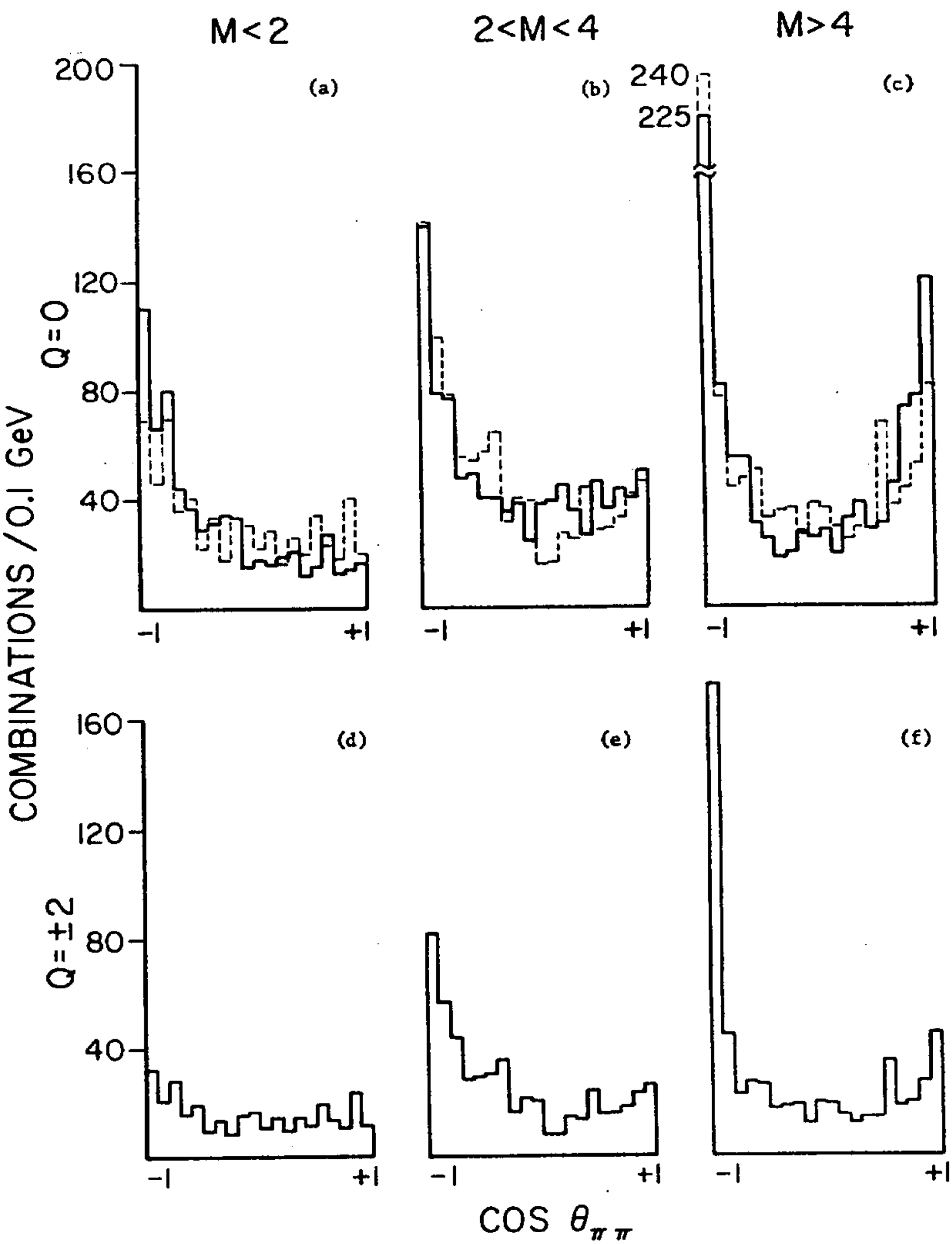


Figure 2: Distributions in the opening angle between pion pairs in the all-charged-pion rest frame for the three regions of the charged pion mass and for neutral and doubly-charged dipion systems. The dashed histograms represent the results of a calculation which is described in the text.

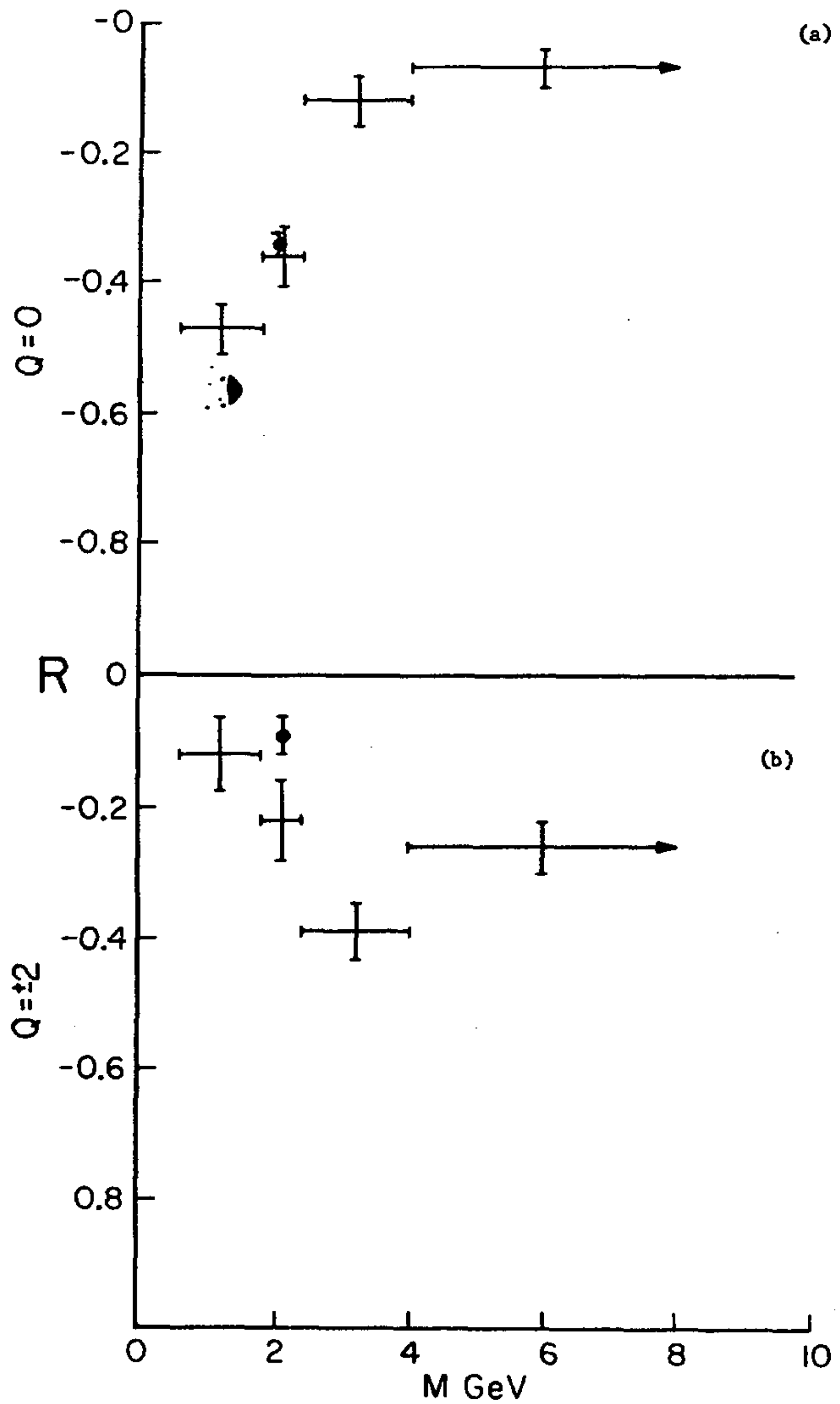


Figure 3: Forward-backward ratio, R, of the opening angle distribution as a function of M for neutral and doubly-charged dipion system. The black dots at 2.08 GeV represent the original observations reported in reference 1.

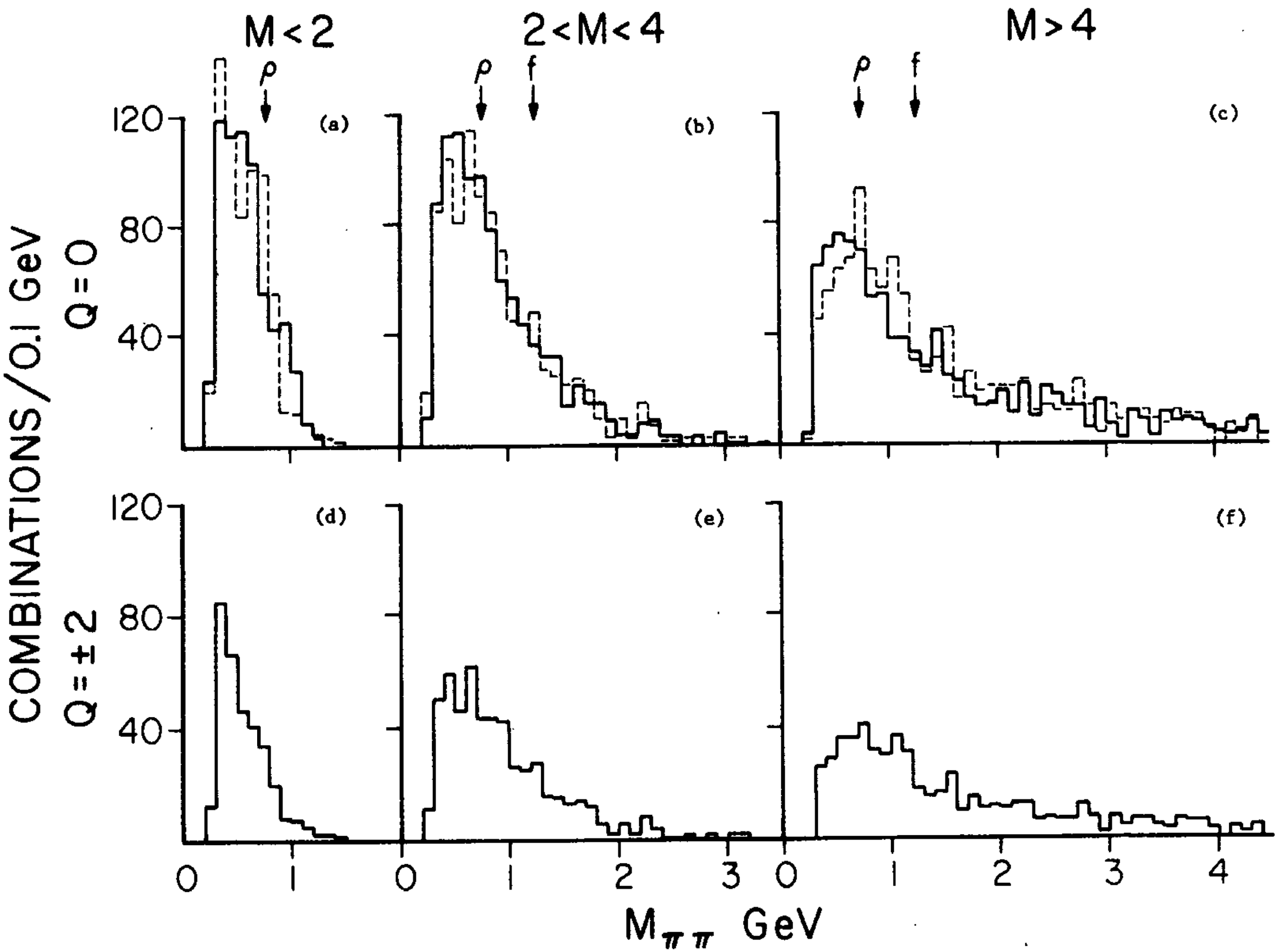


Figure 4: Distributions in the invariant mass and for neutral and doubly-charged dipion systems. The dashed histograms represent the results of a calculation which is described in the text