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GLUEBALLS — A STATUS REPORT*

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ABSTRACT

The current experimental status of glueballs is reviewed. The possibility that the $\iota(1440)$ and $\theta(1640)$ are glueballs is examined.

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I. INTRODUCTION

It is expected from quantum chromodynamics (QCD) that glueballs,[1-4] bound states which contain gluons but no valence quarks, should exist. To date, no conclusive evidence for glueballs has been presented. After a brief review of the expected properties and experimental signatures of glueballs, I will discuss the status of some glueball candidate states.

Bound states of both two gluons and three gluons are expected to exist. The gluon self-coupling implies that these states will not be pure two-gluon (gg) or three-gluon (ggg) states. However, the admixture of ggg component in the lowest-lying gg states (which are probably the states of immediate experimental interest) is expected to be small and will be ignored in the subsequent discussion.

gg states are required to have even charge conjugation parity (C-parity) while ggg states are allowed to have either even or odd C-parity depending on whether the SU(3) coupling is antisymmetric or symmetric. Except for the lowest lying states, the spin-parity (J^P) classification of glueballs is a function of the model used to construct the states. Table I gives the spin-parities of the lowest lying states.[1] (The J^{PC} = 1^{-+} state is not allowed for massless gluons by Yang's theorem.[5]) For the quantum numbers of higher excited states and ggg states, one should refer to the literature.[1]

Most theoretical predictions place the masses of the lowest lying glueballs between approximately 1 and 2 GeV.[1-3] As an example, the masses predicted by the naive bag model without intergluon interactions[2] are given in Table I. In general, it is expected that hyperfine splittings due to intergluon interactions will push the masses of the spin 2 states up relative to the masses of the spin 0 states.[3]

Based on OZI suppression arguments, it is expected that glueball widths are relatively narrow compared to quark state ($q\bar{q}$) widths. This can be seen by comparison of the quark-line diagrams for glueball decay and OZI suppressed quark state decay (e.g., $\phi \rightarrow \rho\pi$). Since the glueball decay diagram is half the quark state decay diagram, the glueball width is expected to be suppressed by the square root of a typical OZI suppression factor. Thus, glueball widths are expected to be about an order of magnitude smaller than non-suppressed quark state widths.

It is clear that unambiguous identification of a glueball will not be easy. Observation of a state in a "glueball-favored" channel, i.e., a channel in which an intermediate state of two or more gluons is produced, is the first indication that a state is a glueball. The classic glueball-favored channel is the process $\psi \rightarrow \gamma + X$. The leading-order diagram for this process[6] is shown in Fig. 1. The inclusive branching ratio for this process is predicted to be approximately 8%. Experimental confirmation of this direct-photon component in ψ decays with approximately the correct branching ratio has been made by the Mark II.[7] Thus, if gg states exist in the kinematically allowed mass range for this process, they are expected to be produced here. The particular states which are likely to be produced are those with $J^P = 2^+$, 0^-, and 0^+ as predicted by a spin-parity analysis of the γgg final state.[8]

A second process which is a likely channel for production of glueballs is $\pi^- p \rightarrow \phi\phi n$.[9] This OZI suppressed process is shown in Fig. 2 compared with the OZI allowed process $\pi^- p \rightarrow K^+K^-K^+K^- n$. Thus, one does not expect strong $\phi\phi n$ production relative to the $K^+K^-K^+K^- n$ background unless there are one or more glueballs which couple to $\phi\phi$ in the intermediate state.

As there are glueball-favored channels, there are also glueball-disfavored channels. Since the coupling of gluons to photons is expected to be small, states which are observed in $\gamma\gamma$ interactions are not likely to be glueballs. In addition, most states produced in standard hadronic processes (e.g., πp or Kp) are expected to be ordinary quark states.

After observation of a new state, an important clue to its identification as a glueball is the difficulty in accommodating the state as a member of a standard $q\bar{q}$ SU(3) nonet. For example, one might find that there are three isoscalar states with the same quantum numbers, and hence one of them would be a candidate for a glueball state.

Decay modes of a state also give important clues as to its identification. Glueballs are unitary singlets and hence they couple to all quark flavors equally. On the other hand, quark states couple in a non-OZI violating manner. Thus, glueballs and quark states with the same quantum numbers have different sets of allowed and forbidden decay modes and different relations can be derived among the allowed decay modes.[4] Unfortunately, the situation might be confused by mixing between glueballs and nearby quark states which have the same quantum numbers. However, no matter how strong the mixing between glueball and quark states, a glueball will manifest itself as an extra state which cannot be accounted for in the quark model.

II. $\iota(1440)$

The $\iota(1440)$ was first observed in ψ radiative transitions by the Mark II.[10] It was seen in the decay

$$\psi \to \gamma K_S K^{\pm} \pi^{\mp} \qquad (1)$$

and was originally identified as the E(1420) as this meson has a mass, width, and decay mode similar to the ι. The ι was subsequently observed by the Crystal Ball[11] in the decay

$$\psi \to \gamma K^+K^-\pi^o \quad . \tag{2}$$

The mass, width, and branching ratio measurements from the two experiments are consistent and are listed in Table II. Figures 3 and 4 show the $K\bar{K}\pi$ invariant mass distributions for events consistent with (1) and (2) from the Mark II and Crystal Ball experiments. The "δ cut" requirement (i.e., the requirement that the $K\bar{K}$ mass be low) enhances the peaks as shown by the shaded regions.

The spin-parity of the ι was determined to be 0^- from a partial-wave analysis of the $K^+K^-\pi^o$ system in (2) by the Crystal Ball.[11] Five partial waves were included in the analysis:

$K\bar{K}\pi$ flat

$K^*\bar{K}$ + c.c. ($J^P = 0^-$)

$K^*\bar{K}$ + c.c. ($J^P = 1^+$)

$\delta\pi$ ($J^P = 0^-$)

$\delta\pi$ ($J^P = 1^+$) .

Only three partial waves contributed significantly to the likelihood in the analysis. Their contributions are shown in Fig. 5 as functions of $K^+K^-\pi^o$ invariant mass. The $K^*\bar{K}$ + c.c. ($J^P = 1^+$) partial wave [see Fig. 5(b)] is fairly independent of mass and shows no evidence for resonance structure. [This is the partial wave in which one would expect to see the E(1420).] On the other hand, the $\delta\pi$ ($J^P = 0^-$) partial wave [see Fig. 5(c)] shows a significant peak at the mass of the ι. There is no evidence for $\delta\pi$ production off resonance.

From the time of the original observation of the ι by the Mark II, there has been much controversy over the interpretation of this state.[3,11-15] Much of the confusion resulted from the assumption that the ι and the E(1420) were the same state. Since the spin-parity of the E had been measured[16] to be 1^+, it was difficult to understand why this state would be produced so strongly in ψ radiative decays since the two-gluon system is not allowed to couple to $J^P = 1^+$ states. The measurement of the spin-parity of the ι has established that this state is different from the E, but its interpretation is still subject to controversy.

One possibility is that the ι is a glueball. It is produced with a large branching ratio in a glueball-favored channel. The branching ratio for $\psi \to \gamma\iota$ is larger than any other known radiative branching ratio from the ψ to a non-charmonium state. Equally interesting is the fact that there is no evidence for ι production in πp interactions, a glueball-disfavored channel. (Possible ι production in $\bar{p}p$ annihilations at rest has been observed, but the evidence is not overwhelming.[13,14,17]) An additional factor supporting this hypothesis is that there exists at least three isoscalar, $J^P = 0^-$ mesons, the η, η', and ι. All three of these states cannot be pure $q\bar{q}$ ground state mesons. Finally, the $\delta\pi$ decay mode is allowed for a $J^{PC} = 0^{-+}$ unitary singlet state whereas the $K^*\bar{K}$ + c.c. decay mode is not.[4] The ι is observed to decay into $\delta\pi$ with no evidence for a $K^*\bar{K}$ + c.c. decay mode.[10,11] Note that the E(1420) decays primarily into $K^*\bar{K}$ + c.c.[16]

Although there appears to be no problem with the identification of the ι as a glueball, there is also the possibility that the ι is a radially-excited quark state. However, there are difficulties with this interpretation. Transitions to radially-excited states are expected to have smaller branching ratios than transitions to ground states with the same quantum numbers. Thus, it is expected that $B(\psi \to \gamma\iota)$ would be smaller than $B(\psi \to \gamma\eta')$, which is in disagreement with the experimentally determined branching ratios. However, it might be possible to understand the experimental numbers if the ground and excited states are mixed significantly.[18]

There is the additional problem of understanding the $\zeta(1275)$[13] which has been observed in

$$\pi^- p \to \eta\pi^+\pi^- n \qquad (3)$$

at 8.45 GeV/c.[19] The ζ has a mass of 1275 ± 15 MeV, a width of 70 ± 15 MeV, and is observed to decay into $\eta\pi\pi$. The spin-parity has been determined to be 0^- from a partial-wave analysis. Cohen and Lipkin,[20] based on a model in which the η' is a mixture of ground state and radially-excited state wave functions, predict a pseudoscalar meson with mass near 1280 MeV. Thus, it is logical to associate the ζ with this radially-excited state. It can be shown that the ι is not the partner of the ζ.[13,14]

First, the ζ is not observed in $\psi \to \gamma K\bar{K}\pi$ (see Figs. 3 and 4) or in $\psi \to \gamma\eta\pi\pi$.[10,15] ζ production is clearly smaller than ι production in $K\bar{K}\pi$, and smaller than η' production in $\eta\pi\pi$. Thus, $B(\psi \to \gamma\zeta) << B(\psi \to \gamma\iota)$. Since the two-gluon system couples only to SU(3) singlet states, the ι must be mostly singlet and the ζ mostly octet if they are members of the same nonet. One then expects[14]

$$\frac{\sigma(\pi^- p \to \iota n)}{\sigma(\pi^- p \to \zeta n)} \approx 2 \quad . \qquad (4)$$

In (3), there is possible evidence for an additional $J^P = 0^-$ state near 1400 MeV.[19] However, the enhancement is not really consistent with the ι as the mass appears to be too low and the state appears in the $\varepsilon\eta$ (rather than the $\delta\pi$) partial wave. Even if it were the ι, the cross section is approximately five times smaller than the prediction of Eq. (4). The process

$$\pi^- p \rightarrow K_S K^\pm \pi^\mp n \tag{5}$$

at 3.95 GeV/c has been studied also.[16] The spin-parity of the E(1420) was determined from a partial-wave analysis of this data. In the $J^P = 0^-$ partial wave, there is at best a one standard deviation enhancement at the mass of the ι. Even if one were to assume that this was evidence for ι production, the cross section would again be in serious disagreement with Eq. (4). [Since the ζ is not observed in (5), the calibration between (3) and (5) is made by comparing all cross sections with D(1285) production which is observed in both channels.] Despite this arguement, there is still the possibility that the ζ is not a radially-excited state and the ι is, but then one would have the equally difficult problem of interpreting the ζ.

III. θ(1640)

The θ(1640) was recently observed by the Crystal Ball in the decay process[11,21]

$$\psi \rightarrow \gamma\eta\eta \quad . \tag{6}$$

Figure 6 shows the $\eta\eta$ invariant mass distribution for events consistent with (6). The solid curve represents a fit to the mass distribution for a single Breit-Wigner resonance plus a flat background. The parameters of the θ are listed in Table III.

Because of the limited statistics, it is not possible to establish that the $\eta\eta$ peak consists of only one resonance. The f'(1515) has mass

$M = 1516 \pm 12$ MeV, width $\Gamma = 67 \pm 10$ MeV, and $J^{PC} = 2^{++}$. No $\eta\eta$ decay mode has been observed, but the upper limit on the branching ratio is 50%.[22] The results of a two-resonance fit which includes an f' contribution are also listed in Table III. The dashed curve in Fig. 6 shows the fit to the mass distribution.

The spin-parity of the θ is favored to be 2^+ as determined from a maximum likelihood fit[11,21] to the angular distribution[23] $W(\theta_\gamma, \theta_\eta, \phi_\eta)$ for the process

$$\psi \to \gamma\theta, \quad \theta \to \eta\eta \quad . \tag{7}$$

(The relative probability of the spin 0 hypothesis is 5%.) θ_γ is the polar angle of the γ with respect to the beam direction; θ_η and ϕ_η are the polar and azimuthal angles of one of the η's with respect to the γ in the rest frame of the θ. Figure 7 shows the $|\cos\theta_\gamma|$ and $|\cos\theta_\eta|$ projections for (7) compared to the best fit curves for spin 0 and spin 2.

As the θ has the quantum numbers expected for the gg ground state, it is a likely candidate for a glueball. Like the ι, the θ is observed only in a glueball-favored channel. Although the measured branching ratio for (7) is somewhat small (nearly a factor of ten smaller than the corresponding ι branching ratio), it is expected that $B(\theta \to \eta\eta)$ is fairly small and hence $B(\psi \to \gamma\theta)$ is relatively large.

There are some possible problems with the identification of the θ as a glueball. If it is assumed that both the ι and the θ are glueballs, one has the peculiar situation of a gg ground state with a higher mass than the first excited state. However, as mentioned previously, intergluon interactions are expected to push up the spin 2 masses relative to the spin 0 masses. Various calculations have predicted hyperfine splittings which are in agreement with the experimental measurements.[3] Also, the width of the θ is larger than one might naively expect. However, the number of allowed decay modes is large and the width is not so unreasonable when compared with the width of the ι.

The most serious problem is the nonobservation of a $\pi\pi$ decay mode of the θ. Figure 8 shows the $\pi^+\pi^-$ invariant mass distribution for $\psi \to \gamma\pi^+\pi^-$ from the Mark II[11,15] and Fig. 9 shows the $\pi^o\pi^o$ invariant mass distribution for $\psi \to \gamma\pi^o\pi^o$ from the Crystal Ball.[11,24] The 90% confidence level upper limits for $B(\psi \to \gamma\theta) \times B(\theta \to \pi\pi)$ are 6×10^{-4} from the Crystal Ball[11,21] and 2×10^{-4} from the Mark II. (Isospin correction factors have been applied in both calculations.) Based on the postulated unitary singlet nature of the θ, one expects $B(\theta \to \pi\pi) = 3B(\theta \to \eta\eta)$ (without phase space corrections). From the measurement of $B(\psi \to \gamma\theta) \times B(\theta \to \eta\eta)$, one predicts $B(\psi \to \gamma\theta) \times B(\theta \to \pi\pi) = (6.0 \pm 2.1) \times 10^{-3}$ (where p^{2L+1} phase space corrections have been applied). The Mark II limit is a factor of 30 times smaller than the expected branching ratio. Even if it is assumed that the θ is spin 0, the Mark II limit is still an order of magnitude smaller than expected.

Before ruling out completely the glueball interpretation of the θ, let me comment on the naivety of the unitary symmetry calculation. The relation between the $\pi\pi$ and $\eta\eta$ branching ratios is based on the assumption that only the diagram shown in Fig. 10 contributes in the decay and that there is an equal probability of pulling any $q\bar{q}$ pair out of the vacuum. The most serious shortcoming of this calculation is that there is no allowance for multibody decays. It is likely (because of phase space) that the all-pion decay modes would favor 4π decays over $\pi\pi$ decays.

[See, for example, the relative branching ratios for $\rho'(1600)$ and $g(1700)$ decays.[22]] The $\eta\eta$ decays are less likely to have additional pions.

The possibility that the θ is a radially-excited state seems rather unlikely. The mass is too close to the $f(1270)$ and $f'(1515)$ masses, but see Ref. 18 for a possible explanation. In addition, the branching ratio for $\psi \to \gamma\theta$ is probably larger than expected for a radial excitation, assuming that $B(\theta \to \eta\eta)$ is a reasonable (i.e., small) number. If it were to turn out that $B(\theta \to \eta\eta)$ is large ($\gtrsim 30\%$) so that $B(\psi \to \gamma\theta)$ is reasonable, it would be difficult to understand why a normal quark state would have such a large $\eta\eta$ branching ratio.

An exotic possibility is that the θ is a $q\bar{q}q\bar{q}$ state.[25] In general, it is expected that such states "fall apart" into two $q\bar{q}$ states (as in Fig. 11) and hence have widths of the same order as their masses.[26] Such states would not be observable experimentally. An exception occurs in the case of a $q\bar{q}q\bar{q}$ state that is below threshold for all kinematically allowed fall apart modes, in which case the state will be relatively narrow. A state with which the θ might be identified is $(1/\sqrt{2})[u\bar{u} + d\bar{d}]s\bar{s}$.[14] This state has no kinematically allowed fall apart modes. The prominent two-body decay modes are $\eta\eta$ and $K\bar{K}$ with $B(\theta \to K\bar{K}) \approx 2B(\theta \to \eta\eta)$. $\theta \to \pi\pi$ is not allowed. Thus, this interpretation of the θ not only explains the lack of a $\pi\pi$ decay mode, but it also places $B(\psi \to \gamma\theta)$ in the expected range for a $q\bar{q}q\bar{q}$ state.

IV. $\psi \to V + X$

It is of interest to compare the process $\psi \to \gamma + X$ with the process $\psi \to V + X$, where V is an isoscalar vector meson (i.e., ω or ϕ). One expects glueballs to be produced only in the first process. The only final state X for which all three channels have been studied is $\pi\pi$. Figure 12(a) shows the $\pi^+\pi^-$ invariant mass distribution for $\psi \to \omega\pi^+\pi^-$ from the Mark II[27] after background subtraction for events under the peak. The distribution is dominated by the f(1270). An S*(980) peak is observed in Fig. 12(b) which shows a similar distribution for $\psi \to \phi\pi^+\pi^-$ from the Mark II.[27,28] In the process $\psi \to \gamma\pi\pi$ (see Figs. 8 and 9), one sees evidence for only an f(1270) peak. Not only is there no evidence for new resonance structure which might indicate a glueball, but there is also no evidence for the S*(980). Thus, the S*(980) is probably not a glueball.

V. $\phi\phi$ GLUEBALLS

The processes

$$\pi^- p \to K^+K^-K^+K^- n \tag{8}$$

$$\pi^- p \to K^+K^-\phi n \tag{9}$$

$$\pi^- p \to \phi\phi n \tag{10}$$

were studied by a BNL/CCNY collaboration at 22.6 GeV/c.[29] As discussed earlier, reactions (8) and (9) are OZI allowed while reaction (10) is OZI suppressed. Thus, one expects to see no enhancement of (10) over the background from (8) and (9). Experimentally, it is found that (10) is not suppressed, but instead is enhanced by a factor of approximately 1500 over the surrounding background from (8). One possible explanation for this enhancement is the existence of one or more glueballs which are produced in $\pi^- p$ interactions and which decay into $\phi\phi$. Figure 13 shows the $\phi\phi$ invariant mass distribution from the BNL/CCNY experiment.[9,29] (No background subtraction has been made for events under the ϕ peaks.) No significant resonance structure is observed, but the data sample will be increased by about a factor of 20 in the near future.

Inclusive $\phi\phi$ production has been studied in two other experiments,

$$\pi^- Be \rightarrow \phi\phi + X \tag{11}$$

at 175 and 100 GeV/c,[30] and

$$pp \rightarrow \phi\phi + X \tag{12}$$

at 400 GeV/c.[31] In (11), 48 ± 23 excess $\phi\phi$ events are observed in the 175 GeV/c data sample and 21 ± 8 excess $\phi\phi$ events in the 100 GeV/c data sample. Figure 14 shows the $\phi\phi$ invariant mass distributions at the two energies. The solid curves show the expected backgrounds from ϕK^+K^- and $K^+K^-K^+K^-$ events. The dashed curves show the total backgrounds including the estimated contributions from uncorrelated $\phi\phi$ production. There is a four standard deviation peak at about 2100 MeV in the 100 GeV/c data.

Only very preliminary data for (12) is now available but it is expected that more data will be taken soon. An excess of 9 ± 6 $\phi\phi$ events is observed in the current data sample. Interestingly enough, most of the excess events are in a single bin near 2100 MeV.

VI. CONCLUSIONS

Although there are no known problems or inconsistencies with a glueball interpretation of the $\iota(1440)$, the evidence in favor of this hypothesis is far from conclusive.

The nonobservation of $\iota \rightarrow \eta\pi\pi$ is somewhat of a worry since $\iota \rightarrow \delta\pi$ and the δ is believed to decay into both $K\bar{K}$ and $\eta\pi$.[22] However, the only published limits are fairly large.[10,15] It is important that a good measurement be made by the Crystal Ball. It is also important that a reliable determination of the relative $K\bar{K}$ and $\eta\pi$ branching ratios of the δ be made.

An effort should be made to find the partner of the $\zeta(1275)$ in hadronic interactions. Observation of such a state would rule out any possibility that the ι is a radial excitation. The partner of the ζ is expected to be somewhat higher in mass than the ι.[20] Thus, a study of $K\bar{K}\pi$ and $\eta\pi\pi$ production up to masses of 1.6 GeV is necessary.

The spin-parity determination of the E(1420) is based on a single experiment. Additional studies of $K\bar{K}\pi$ production near 1.4 GeV in hadronic interactions might prove interesting. Some preliminary results of $K\bar{K}\pi$ production in $\bar{p}p$ interactions at 5 GeV/c are expected within the next few months.[32] A proposed study of π^-p, K^-p, and $\bar{p}p$ production of $K\bar{K}\pi$ between 6 and 8 GeV/c is expected to have enough data for a partial-wave analysis of the $K\bar{K}\pi$ system in the region of the E.[33] Another channel which would be useful to study is $K\bar{K}\pi$ production in $\bar{p}p$ annihilations at rest. There are indications that the enhancement observed near 1400 MeV in this channel is not the E(1420).[13,14] In fact, a spin analysis from one experiment[17] favors $J^P = 0^-$ over 1^+ for this state.

The present meager data on the $\theta(1640)$ seems to disfavor a glueball interpretation for the θ. It is crucial that a better theoretical understanding of the relative branching ratios for two-body decay modes be obtained as the naive arguements based on unitary symmetry may be totally wrong. In particular, it is necessary to understand whether the non-existence of a $\pi\pi$ decay made of the θ really rules out a glueball interpretation.

Results from the Mark II on $\psi \to \gamma K^+K^-$ are expected soon. If the θ is a glueball, one expects $B(\theta \to K^+K^-) \approx 2B(\theta \to \eta\eta)$. The naive arguments may be more reliable in this case as the K and η masses are relatively close. If the θ is a $q\bar{q}q\bar{q}$ state, one expects $B(\theta \to K^+K^-) \approx B(\theta \to \eta\eta)$, and if the θ is just an ordinary $s\bar{s}$ state (which would also explain the lack of a $\pi\pi$ decay mode), then $B(\theta \to K^+K^-) \approx 1.5\, B(\theta \to \eta\eta)$.

Results on $\psi \to \gamma\rho\rho$ are also expected in the near future from both the Mark II and the Crystal Ball. The $\rho\rho$ decay of the θ is expected to be small for a $q\bar{q}q\bar{q}$ state, but not necessarily so for a glueball.

Conclusions on possible $\phi\phi$ glueballs will have to wait until the new data are available.

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Table I

gg Quantum Numbers and Masses

State	J^{PC}	Mass [a]
ground	0^{++}, 2^{++}	960 MeV
first excited	0^{-+}, (1^{-+}), 2^{-+}	1290 MeV

[a] Ref. 2.

Table II

$\iota(1440)$ Parameters

Parameter	Experimental Measurement	
	Mark II	Crystal Ball
M (MeV)	1440^{+10}_{-15}	1440^{+20}_{-15}
Γ (MeV)	50^{+30}_{-20}	55^{+20}_{-30}
$B(\psi \to \gamma\iota) \times B(\iota \to K\bar{K}\pi)$ [a]	$(4.3 \pm 1.7) \times 10^{-3}$ [b]	$(4.0 \pm 1.2) \times 10^{-3}$
C	+	+
J^P		0^-

[a] I = 0 was assumed in the isospin correction.

[b] This product branching ratio has been corrected by me to account for the efficiency correction required under the spin 0 hypothesis.

Table III

$\theta(1640)$ Parameters

Parameter	One-resonance Fit	Two-resonance Fit
M (MeV)	1640 ± 50	1670 ± 50
Γ (MeV)	$220 {}^{+100}_{-70}$	160 ± 80
$B(\psi \to \gamma\theta) \times B(\theta \to \eta\eta)$	$(4.9 \pm 1.7) \times 10^{-4}$	$(3.8 \pm 1.6) \times 10^{-4}$
$B(\psi \to \gamma f') \times B(f' \to \eta\eta)$		$(0.9 \pm 0.9) \times 10^{-4}$

FIGURE CAPTIONS

Fig. 1. Leading order diagram for $\psi \to \gamma + X$.

Fig. 2. Diagrams for (a) $\pi^- p \to \phi\phi n$ and (b) $\pi^- p \to K^+K^-K^+K^- n$.

Fig. 3. $K_S K^\pm \pi^\mp$ invariant mass for events consistent with $\psi \to \gamma K_S K^\pm \pi^\mp$ from the Mark II. $M_{K\bar{K}} < 1.050$ GeV for events in the shaded region.

Fig. 4. $K^+K^-\pi^o$ invariant mass for events consistent with $\psi \to \gamma K^+K^-\pi^o$ from the Crystal Ball. $M_{K\bar{K}} < 1.125$ GeV for events in the shaded region.

Fig. 5. Partial-wave contributions (corrected for efficiency) as functions of $K^+K^-\pi^o$ mass for (a) $K\bar{K}\pi$ flat, (b) $K^*\bar{K}$ + c.c. ($J^P = 1^+$), and (c) $\delta\pi(J^P = 0^-)$.

Fig. 6. $\eta\eta$ invariant mass distribution for events consistent with $\psi \to \gamma\eta\eta$ from the Crystal Ball. Solid (dashed) curve represents fit to one (two) Breit-Wigner resonance(s) plus flat background.

Fig. 7. (a) $|\cos\theta_\gamma|$ and (b) $|\cos\theta_\eta|$ projections for $\psi \to \gamma\theta$, $\theta \to \eta\eta$. Solid (dashed) curves represent best fits for spin 2 (spin 0). Insert shows $|\cos\theta_\eta|$ distribution for $0.9 \le |\cos\theta_\eta| \le 1.0$.

Fig. 8. $\pi^+\pi^-$ invariant mass distribution for events consistent with $\psi \to \gamma\pi^+\pi^-$ after subtraction for feeddown from $\psi \to \rho\pi$ from the Mark II. Solid curve shows fit to f(1270) plus background.

Fig. 9. $\pi^o\pi^o$ invariant mass distribution for events consistent with $\psi \to \gamma\pi^o\pi^o$ from the Crystal Ball. Solid curve shows fit to f(1270) plus background. Dashed curve shows background contribution.

Fig. 10. Diagram for gg decay.

Fig. 11. Diagram for $q\bar{q}q\bar{q}$ decay.

Fig. 12. $\pi^+\pi^-$ invariant mass distributions for (a) $\psi \to \omega\pi^+\pi^-$ and (b) $\psi \to \phi\pi^+\pi^-$ from the Mark II. Background subtractions for events under the ω and ϕ peaks have been made.

Fig. 13. $\phi\phi$ invariant mass distribution for $\pi^- p \to \phi\phi n$ at 22.6 GeV/c.

Fig. 14. $\phi\phi$ invariant mass distributions for $\pi^- Be \to \phi\phi + X$ at (a) 175 GeV/c and (b) 100 GeV/c. Curves are discussed in text.

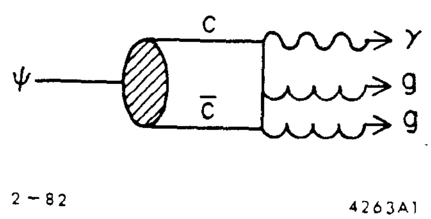
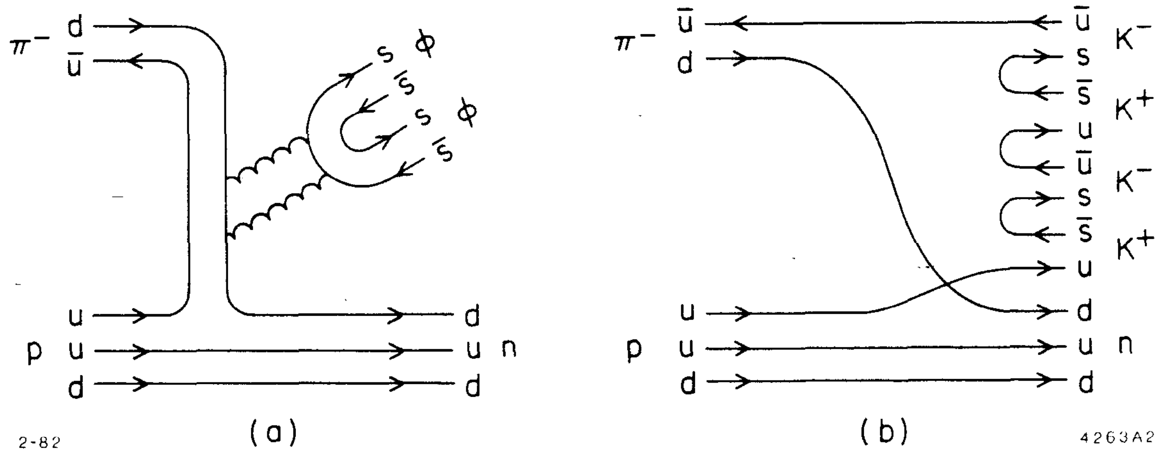


Fig. 1



π⁻
d
ū
u
p
u
d
s
s̄
s
s̄
ϕ
ϕ
d
u
d
n
2-82
(a)
π⁻
ū
d
u
p
u
d
ū
s
s̄
u
ū
s
s̄
u
d
u
d
K⁻
K⁺
K⁻
K⁺
n
(b)
4263A2

Fig. 2

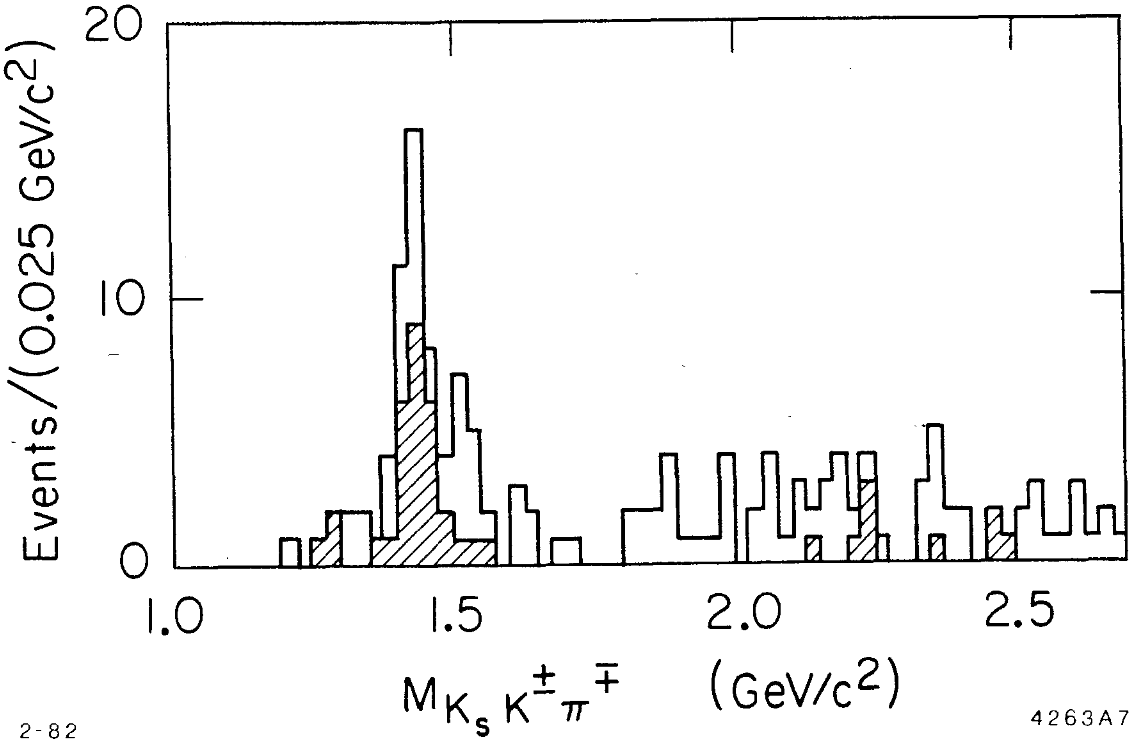

20
10
0
Events/(0.025 GeV/c²)
1.0
1.5
2.0
2.5
$M_{K_s K^{\pm} \pi^{\mp}}$ (GeV/c²)
2-82
4263A7

Fig. 3

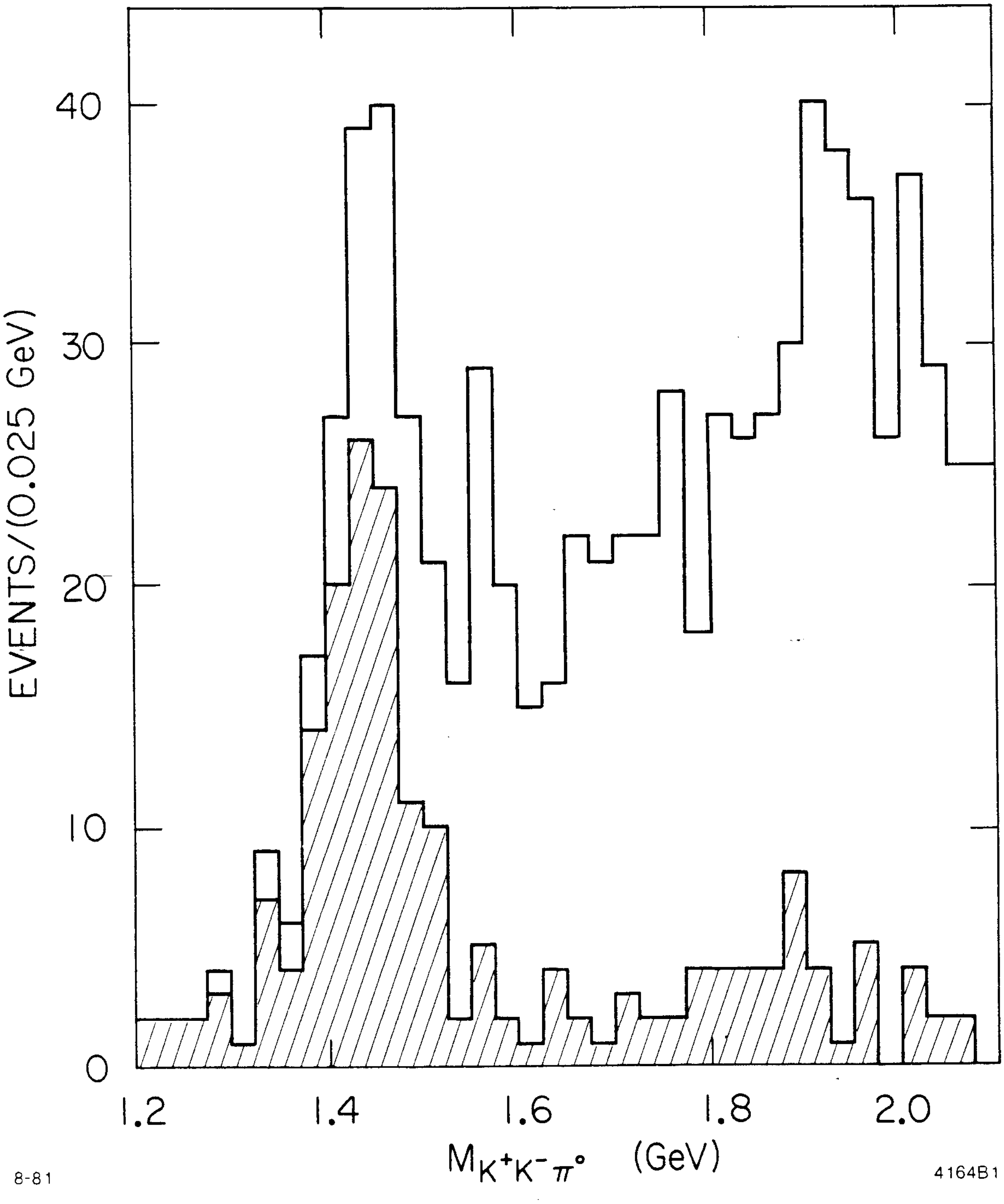
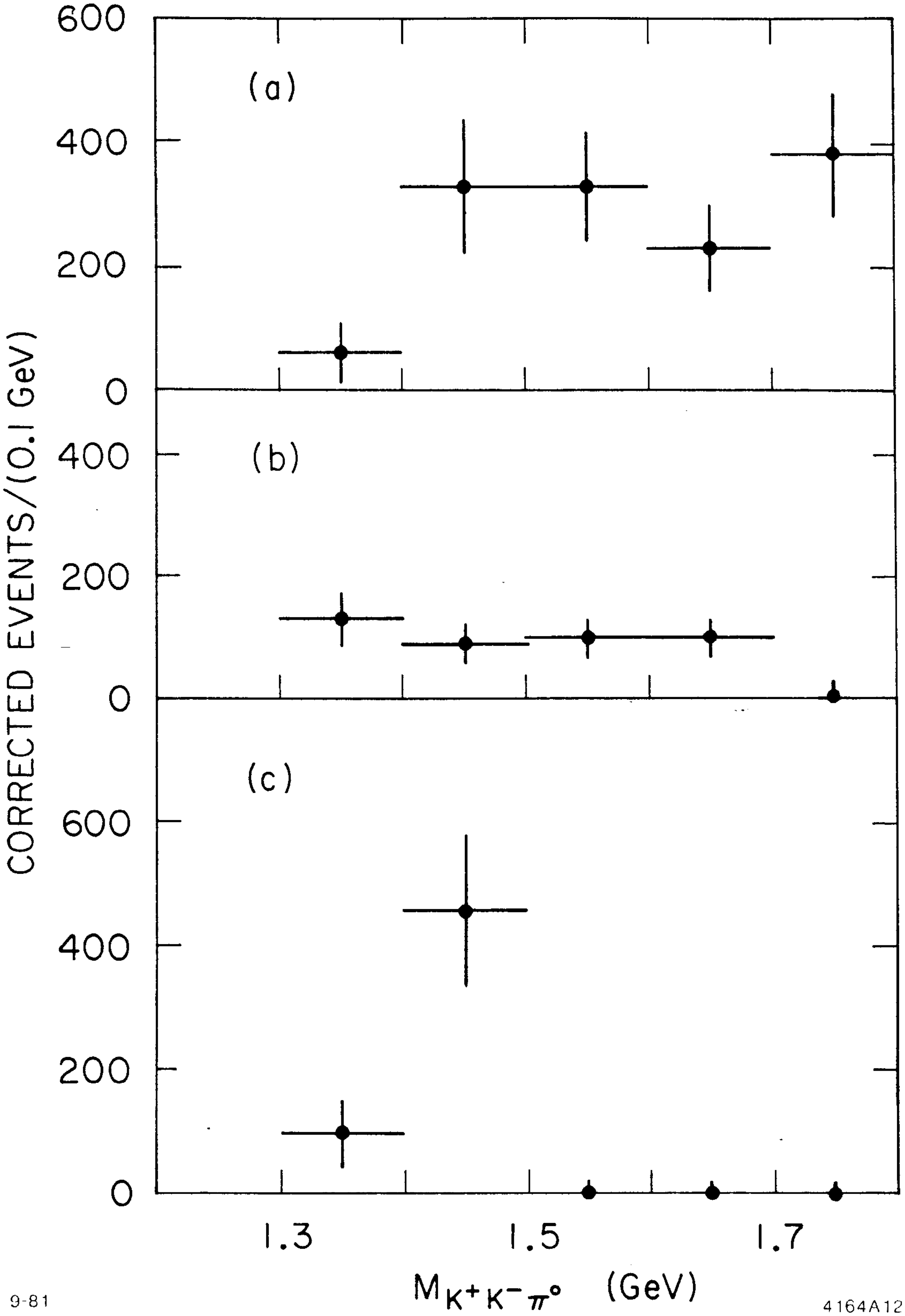

EVENTS/(0.025 GeV)
40
30
20
10
0
1.2
1.4
1.6
1.8
2.0
$M_{K^+K^-\pi^\circ}$ (GeV)
8-81
4164B1

Fig. 4



600
400
200
0
(a)
400
200
0
(b)
600
400
200
0
(c)
CORRECTED EVENTS/(0.1 GeV)
1.3
1.5
1.7
$M_{K^+K^-\pi^0}$ (GeV)
9-81
4164A12

Fig. 5

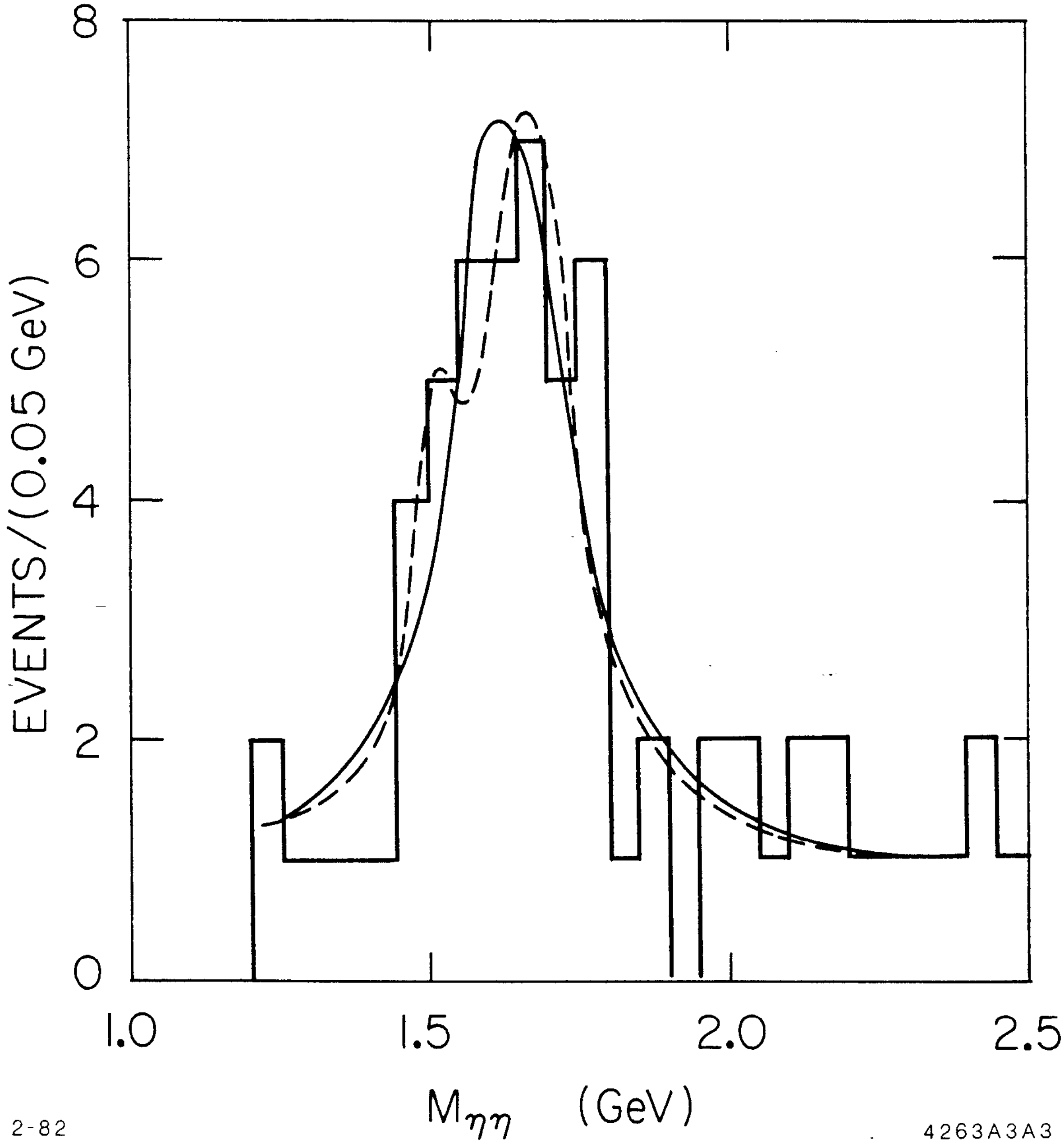
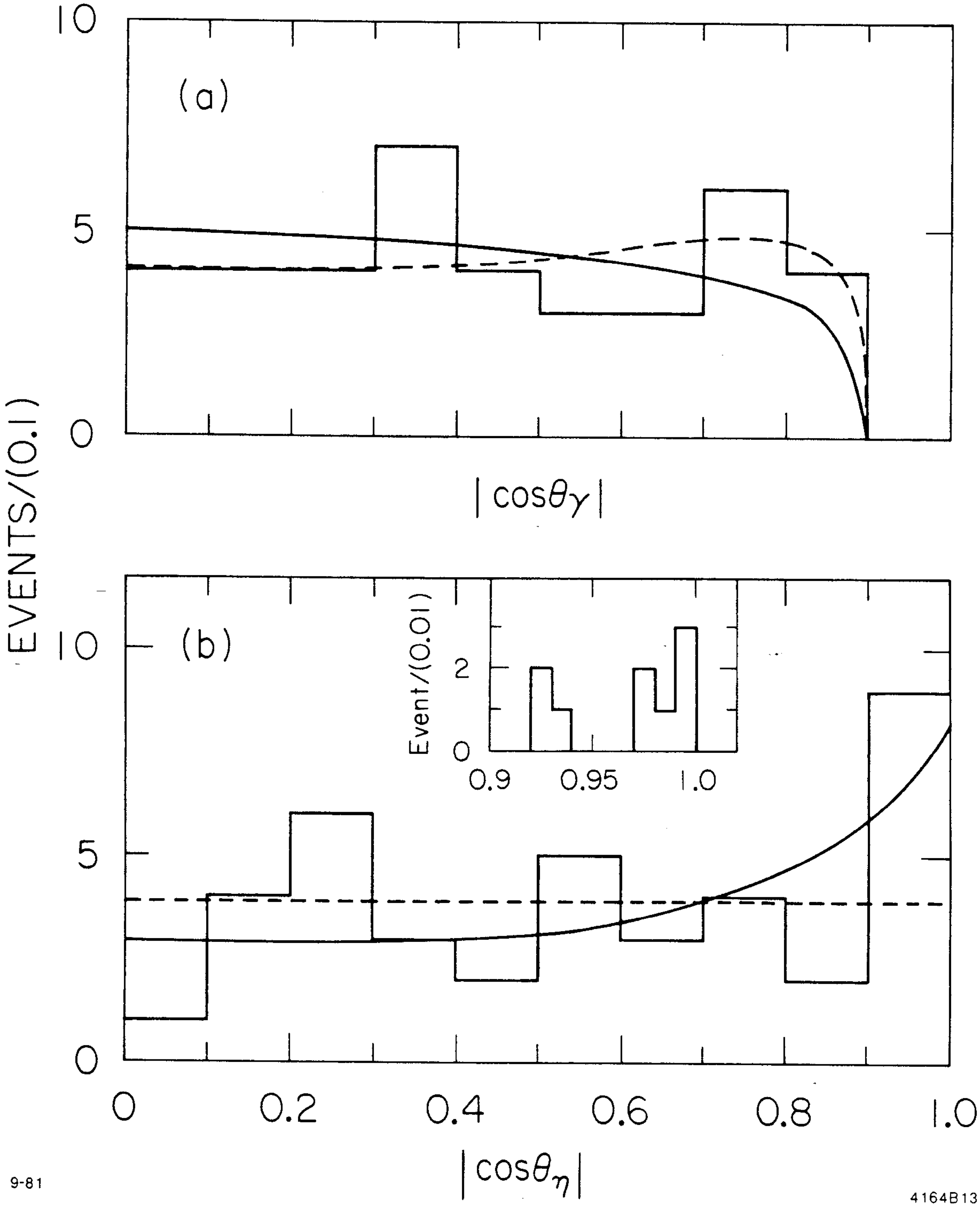
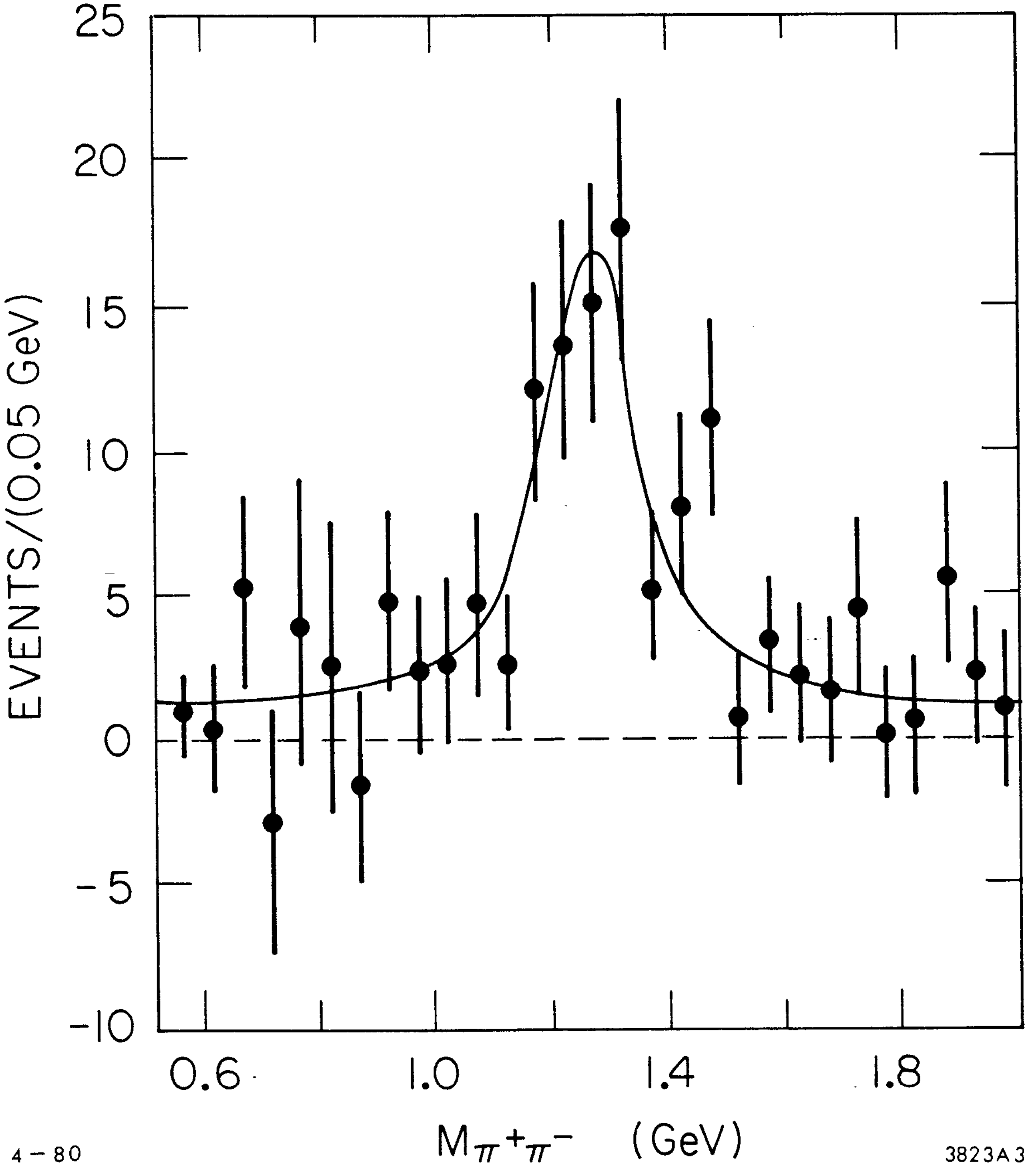


Fig. 6



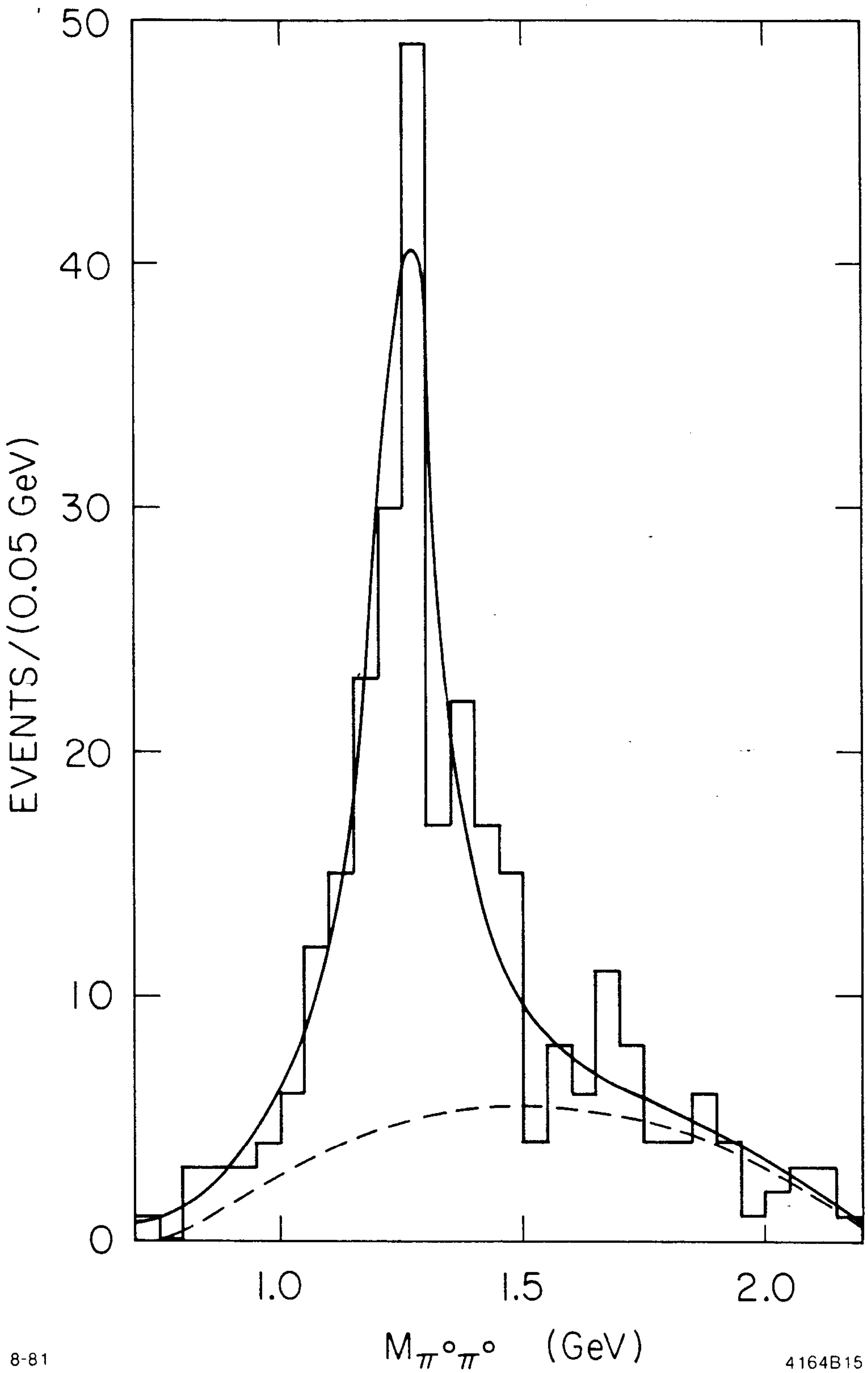
(a)
(b)
EVENTS/(0.1)
10
5
0
|cosθγ|
Event/(0.01)
2
0
0.9
0.95
1.0
0
0.2
0.4
0.6
0.8
1.0
|cosθη|
9-81
4164B13

Fig. 7



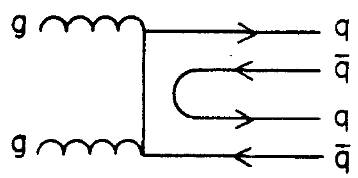
25
20
15
10
5
0
-5
-10
EVENTS/(0.05 GeV)
0.6
1.0
1.4
1.8
$M_{\pi^+\pi^-}$ (GeV)
4-80
3823A3

Fig. 8



EVENTS/(0.05 GeV)
50
40
30
20
10
0
1.0
1.5
2.0
$M_{\pi^\circ\pi^\circ}$ (GeV)
8-81
4164B15

Fig. 9



2 – 82 4263A9

Fig. 10

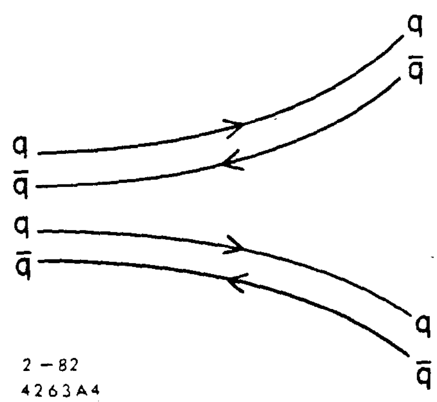
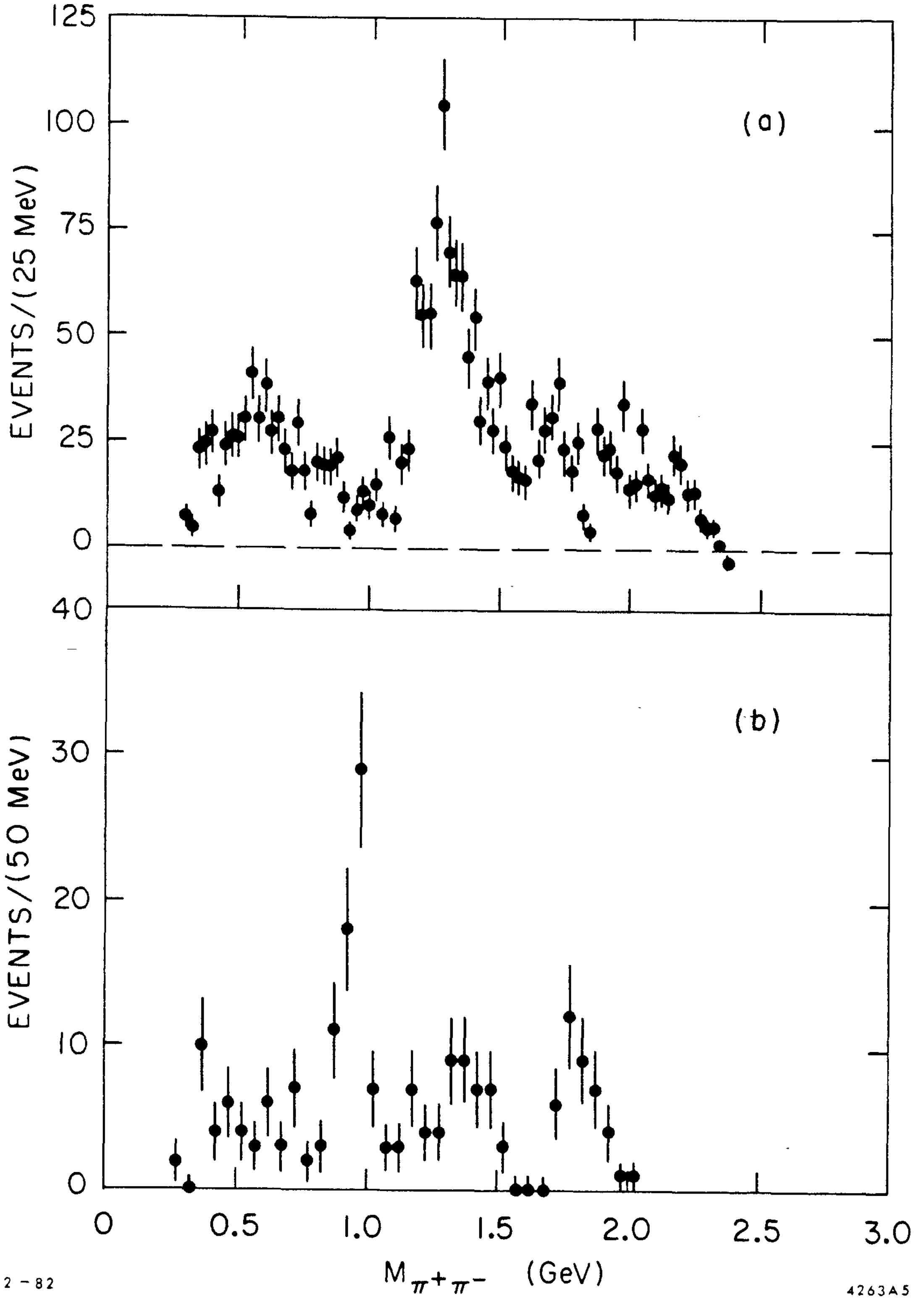


Fig. 11



125
100
75
50
25
0
40
30
20
10
0
(a)
(b)
EVENTS/(25 MeV)
EVENTS/(50 MeV)
0
0.5
1.0
1.5
2.0
2.5
3.0
$M_{\pi^+\pi^-}$ (GeV)
2 - 82
4263A5

Fig. 12

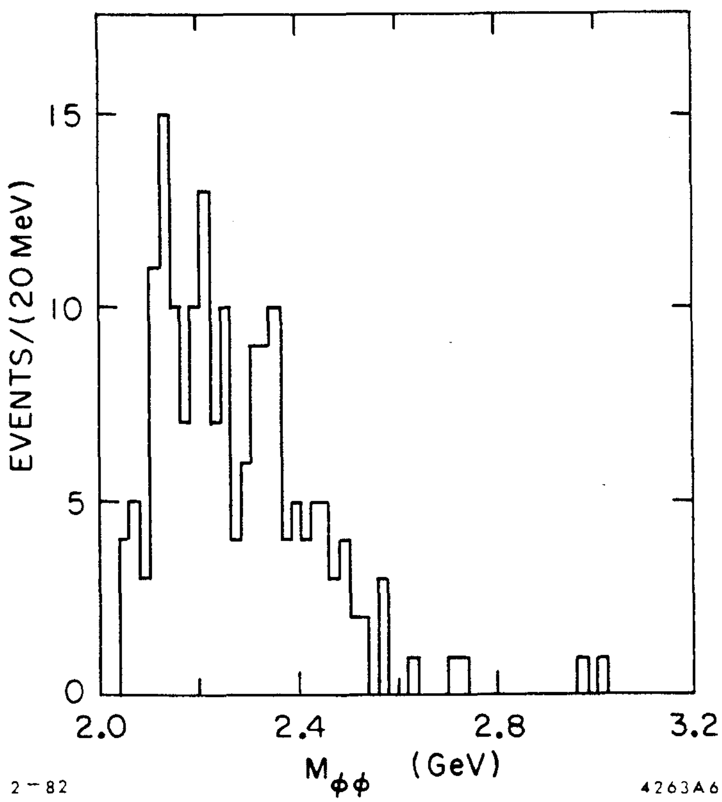


Fig. 13

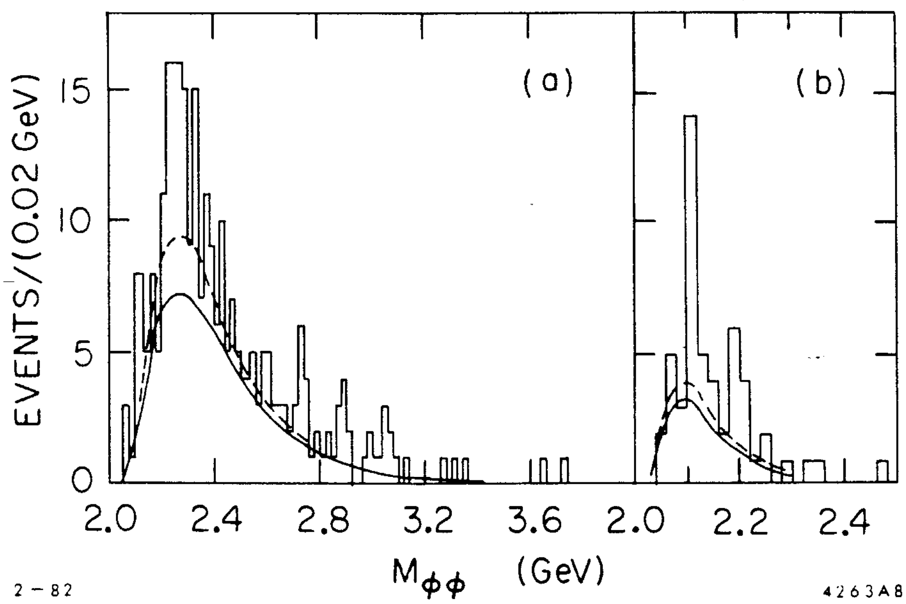

EVENTS/(0.02 GeV)
15
10
5
0
(a)
(b)
2.0
2.4
2.8
3.2
3.6
2.0
2.2
2.4
$M_{\phi\phi}$ (GeV)
2-82
4263A8

Fig. 14