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# EVIDENCE FOR AN $\eta\eta$ RESONANCE IN $J/\psi$ RADIATIVE DECAYS*

C. Edwards, R. Partridge, C. Peck, and F. C. Porter
Physics Department, California Institute of Technology
Pasadena, California 91125

and

D. Antreasyan, Y. F. Gu,[a] W. Kollmann,[b] M. Richardson,
K. Strauch, K. Wacker, and A. Weinstein
Physics Department, Harvard University
Cambridge, Massachusetts 02138

and

D. Aschman, T. Burnett,[c] M. Cavalli-Sforza, D. Coyne,
C. Newman, and H.F.W. Sadrozinski[d]
Physics Department, Princeton University
Princeton, New Jersey 08544

and

D. Gelphman, R. Hofstadter, R. Horisberger, I. Kirkbride,
H. Kolanoski,[e] K. Königsmann, R. Lee, A. Liberman,[f]
J. O'Reilly,[g] A. Osterheld, B. Pollock, and J. Tompkins
Physics Department and High Energy Physics Laboratory, Stanford University
Stanford, California 94305

and

E. Bloom, F. Bulos, R. Chestnut, J. Gaiser, G. Godfrey, C. Kiesling,[h]
W. Lockman, M. Oreglia,[i] and D. L. Scharre
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94305

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ABSTRACT

Evidence for a new resonance $\theta \to \eta\eta$ in the process $J/\psi \to \gamma\eta\eta$ is presented. The resonance parameters of the $\theta$ are $M = 1640 \pm 50$ MeV and $\Gamma = 220 {}^{+100}_{-70}$ MeV. $J^{PC} = 2^{++}$ is preferred over $0^{++}$.

This letter reports on a new state $\theta \to \eta\eta$ which we have observed in $J/\psi \to \gamma\eta\eta$. We have determined that $J^{PC} = 2^{++}$ is preferred from an analysis of the decay angular distribution. The $\theta$ cannot be a member of the $2^{++}$ ground state nonet since the two isoscalar members of that nonet have already been identified. A possible hypothesis is that the $\theta$ is a bound state of two gluons. The existence of 2-gluon resonances[1] is expected within the framework of QCD.

The data were collected with the Crystal Ball detector at the SLAC $e^+e^-$ storage ring facility SPEAR at the peak of the $J/\psi(3095)$ resonance. The detector, event trigger, and data reduction have been described in detail elsewhere.[2] The relevant parameters are summarized here. The detector consists primarily of a segmented array of NaI(Tℓ) crystals for high resolution measurements of the energy and position of electromagnetic showers. The photon energy resolution is $\sigma_E/E = 2.6\%/E^{1/4}$ (E in GeV) and the photon angular resolution is 1-2 degrees, depending on energy. The solid angle coverage of the main array is 93% of $4\pi$ sr and is extended to 98% with crystals in the endcap regions. The beam pipe is surrounded by magnetostrictive spark chambers and multiwire proportional chambers for charged particle tagging and tracking. The innermost spark chamber layer covers 94% of the solid angle.

This analysis is based on a sample of $2.2 \times 10^6$ produced $J/\psi$ events. Each event is required to have five $\gamma$'s with observed energy greater than 10 MeV. Photons are identified by energy deposits in clusters of several adjacent crystals. Photon directions are determined from the position in space of the shower center relative to the interaction point. Tracks tagged by the chambers are rejected as charged. To enhance charged particle tagging efficiency, we require $|\cos\theta_\gamma|<0.9$ for each $\gamma$, where $\theta_\gamma$ is the polar angle of the $\gamma$ with respect to the beam axis. In order to avoid problems with overlapping showers, we require $\cos\theta_{\gamma\gamma} < 0.9$, where $\theta_{\gamma\gamma}$ is the angle between any two photons.

Figure 1 shows a scatter plot of pairs of $\gamma\gamma$ invariant mass combinations for events which satisfy 3-constraint (3C) fits[3] to the hypothesis

$$J/\psi \to 5\gamma \qquad (1)$$

with $\chi^2 < 20$. Despite the fact that there are 15 combinations per event, clear evidence for the $\gamma\eta\eta$ and $\gamma\pi^0\pi^0$ final states[4] can be seen.

Events which satisfied fits to (1) were further constrained to the process

$$J/\psi \to \gamma\eta\eta \quad , \quad \eta \to \gamma\gamma \quad . \qquad (2)$$

Figure 2 shows the $\eta\eta$ invariant mass distribution for events which satisfy 5C fits to (2) with $\chi^2 < 20$. (In approximately 10% of the events, there is more than one good fit. In such cases, only the fit with the best $\chi^2$ is plotted.) A clear signal near 1600 MeV is observed. We have named this state $\theta$. A fit to the mass distribution between 1200 and 2400 MeV with a relativistic Breit-Wigner resonance plus a flat background yields 39 ± 11 resonance events over a background of 0.9 events per 50 MeV. The statistics are too limited to permit a more complicated background function to be used in the fit. We obtain the following resonance parameters: M = 1640 ± 50 MeV and $\Gamma = 220\ ^{+100}_{-70}$ MeV, where the estimated systematic uncertainties are included in the quoted errors. The mass error is dominated by systematic uncertainties while the error in the width is predominantly statistical. The width is considerably larger than the 20 MeV fitted mass resolution.

The detection efficiency for (2) was determined to be 0.037 (including factors for the $\eta \to \gamma\gamma$ branching ratio) by Monte Carlo calculation. This efficiency is approximately constant over the entire mass region of interest. From this and the number of observed $\theta$ events, the product branching ratio for

$$J/\psi \to \gamma\theta \quad , \quad \theta \to \eta\eta \qquad (3)$$

is calculated to be $B(J/\psi \to \gamma\theta) \times B(\theta \to \eta\eta) = (4.9 \pm 1.4 \pm 1.0) \times 10^{-4}$. The first error is statistical and the second is the estimated systematic uncertainty.

The C-parity of the $\theta$ is even since it is produced in a radiative decay from the $J/\psi$. The $\eta\eta$ decay mode establishes both the spin and the parity to be even, i.e., $J^P = 0^+, 2^+, \ldots$. We have determined that $J^P = 2^+$ is favored over $0^+$ from a comparison of the likelihoods of the 3-dimensional decay angular distributions $W(\theta_\gamma, \theta_\eta, \phi_\eta)$ for spin 2 and spin 0 hypotheses. (Spins greater than 2 were not considered.) For spin 0,

$$W(\theta_\gamma, \theta_\eta, \phi_\eta) = 1 + \cos^2\theta_\gamma \quad .$$

For spin 2,[5]

$$W(\theta_\gamma,\theta_\eta,\phi_\eta) = 3x^2 \sin^2\theta_\gamma \sin^2 2\theta_\eta$$
$$+ (1 + \cos^2\theta_\gamma) [(3\cos^2\theta_\eta - 1)^2 + \frac{3}{2}y^2 \sin^4\theta_\eta]$$
$$+ \sqrt{3}x \sin 2\theta_\gamma \sin 2\theta_\eta [3\cos^2\theta_\eta - 1 - \frac{1}{2}\sqrt{6}y \sin^2\theta_\eta] \cos\phi_\eta$$
$$+ \sqrt{6}y \sin^2\theta_\gamma \sin^2\theta_\eta (3\cos^2\theta_\eta - 1) \cos 2\phi_\eta \quad ,$$

where $x = A_1/A_o$, $y = A_2/A_o$, and $A_\lambda$ are the $\theta$ helicity amplitudes. $\theta_\gamma$ was defined earlier and $(\theta_\eta,\phi_\eta)$ are the polar and azimuthal angles of one of the $\eta$'s with respect to the $\gamma$ direction in the $\theta$ rest frame. ($\phi_\eta = 0$ is defined by the electron beam direction.) The probability for the spin 0 hypothesis relative to the spin 2 hypothesis is 0.045. (The best fit for spin 2 was obtained with $x = 0.87 \pm 0.20$ and $y = -0.64 \pm 0.39$.) Possible systematic uncertainties were not included in the calculation of the relative probabilities for the two hypotheses. However, these uncertainties are not expected to significantly change the results of the analysis, in light of the large statistical errors.

It is of interest to look at the $|\cos\theta_\gamma|$ and $|\cos\theta_\eta|$ distributions for (3), although the spin determination depends also on additional information in the correlations between the angles which cannot be displayed in these projections. Figure 3 shows these projections along with the best fit distributions for spin 2 and the expected distributions for spin 0. These curves are based on Monte Carlo calculations and include detection efficiency. Whereas both the spin 0 and spin 2 curves agree reasonably well with the $|\cos\theta_\gamma|$ distribution, the $|\cos\theta_\eta|$ distribution is fit better by the spin 2 curve than the spin 0 curve. This is primarily due to the excess of events with $|\cos\theta_\eta| > 0.9$. The insert in Fig. 3(b) shows these events on an expanded scale. There is no evidence that these events are anomalous.

The radiative decay

$$J/\psi \rightarrow \gamma\pi^0\pi^0$$

was studied for evidence of the decay $\theta \rightarrow \pi\pi$. This analysis was based on the sample of events with four observed neutral particles, one of which is identified as a $\pi^0$ from the lateral shower distribution (see Ref. 4). Other than this, the event selection is identical to that used for the 5-$\gamma$ analysis described above.

No strong evidence for a signal near 1600 MeV is observed, but there is significant background from $J/\psi \rightarrow \gamma f(1270)$, $f(1270) \rightarrow \pi^0\pi^0$.[6] The 90% confidence level upper limit on the product branching ratio is $B(\psi \rightarrow \gamma\theta)\ x B(\theta \rightarrow \pi\pi) < 6 \times 10^{-4}$, where the branching ratio has been corrected to account for all $\pi\pi$ charge combinations.

The $\theta$ is particularly interesting because of the channel in which it is observed. According to leading-order QCD predictions, the radiative decays of the $J/\psi$ are dominated by the final state $\gamma gg$.[7] The 2-gluon system must be a color singlet and hence this process is a likely place for the production of C-even, 2-gluon resonances. The 2-gluon ground states are expected to have $J^{PC} = 0^{++}$ and $2^{++}$, and hence the $\theta$ is a likely candidate. Although first-order bag model calculations[8] of the mass of the $2^{++}$ ground state (~960 MeV) are somewhat lower than the $\theta$ mass, introduction of spin-splitting terms can push the predicted mass as high as 1650 MeV.[9]

An alternative hypothesis is that the $\theta$ is a $q\bar{q}q\bar{q}$ state. A bag model calculation by Jaffe[10] predicts that the lowest lying $2^{++}$ $q\bar{q}q\bar{q}$

state has a mass of 1650 MeV. Although the mass agreement is good, it is expected that if the θ were a $q\bar{q}q\bar{q}$ state, the width should be much larger than the observed width and there would be no evidence for resonant structure.[11]

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[a] On leave from the Institute of High Energy Physics, Academia Sinica, Beijing, People's Republic of China.

[b] Present address: Wentorfer Strasse 149, D-2050 Hamburg, Federal Republic of Germany.

[c] Present address: Physics Department, University of Washington, Seattle, Wash. 98195.

[d] Present address: SCIPP, University of California at Santa Cruz, Santa Cruz, Ca. 95064.

[e] Present address: University of Bonn, Bonn, Federal Republic of Germany.

[f] Present address: Schlumberger-Doll Research Center, Ridgefield, Conn. 06877.

[g] Present address: Systems Control Technology, Palo Alto, Ca. 94304.

[h] Present address: Max-Planck Institute of Physics and Astrophysics, D-8000 Munich (40), Federal Republic of Germany.

[i] Present address: Enrico Fermi Institute, University of Chicago, Chicago, Ill. 60637.

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3. Although such a fit would ordinarily be a 4C fit, one constraint is removed in the determination of the vertex position along the beam direction which cannot otherwise be determined for an all neutral event.

4. In nearly all decays $J/\psi \to \gamma\pi^0\pi^0$, one or both $\pi^0$'s is sufficiently energetic that the two $\gamma$'s from the $\pi^0$ decay produce showers which overlap in the NaI and hence appear as a single neutral particle. These events are not included in the event sample shown in Fig. 1.

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## FIGURE CAPTIONS

1. $\gamma\gamma$ vs. $\gamma\gamma$ invariant mass (15 combinations per event) for events consistent with $J/\psi \to 5\gamma$.

2. $\eta\eta$ invariant mass distribution for events consistent with $J/\psi \to \gamma\eta\eta$. Solid curve represents fit to mass distribution. Dashed curve represents background.

3. a) $|\cos\theta_\gamma|$ and b) $|\cos\theta_\eta|$ distributions for $J/\psi \to \gamma\theta$, $\theta \to \eta\eta$. Solid curves are best fit distributions for spin 2. Dashed curves are expected distributions for spin 0. Events with $|\cos\theta_\eta| > 0.9$ are shown in insert.

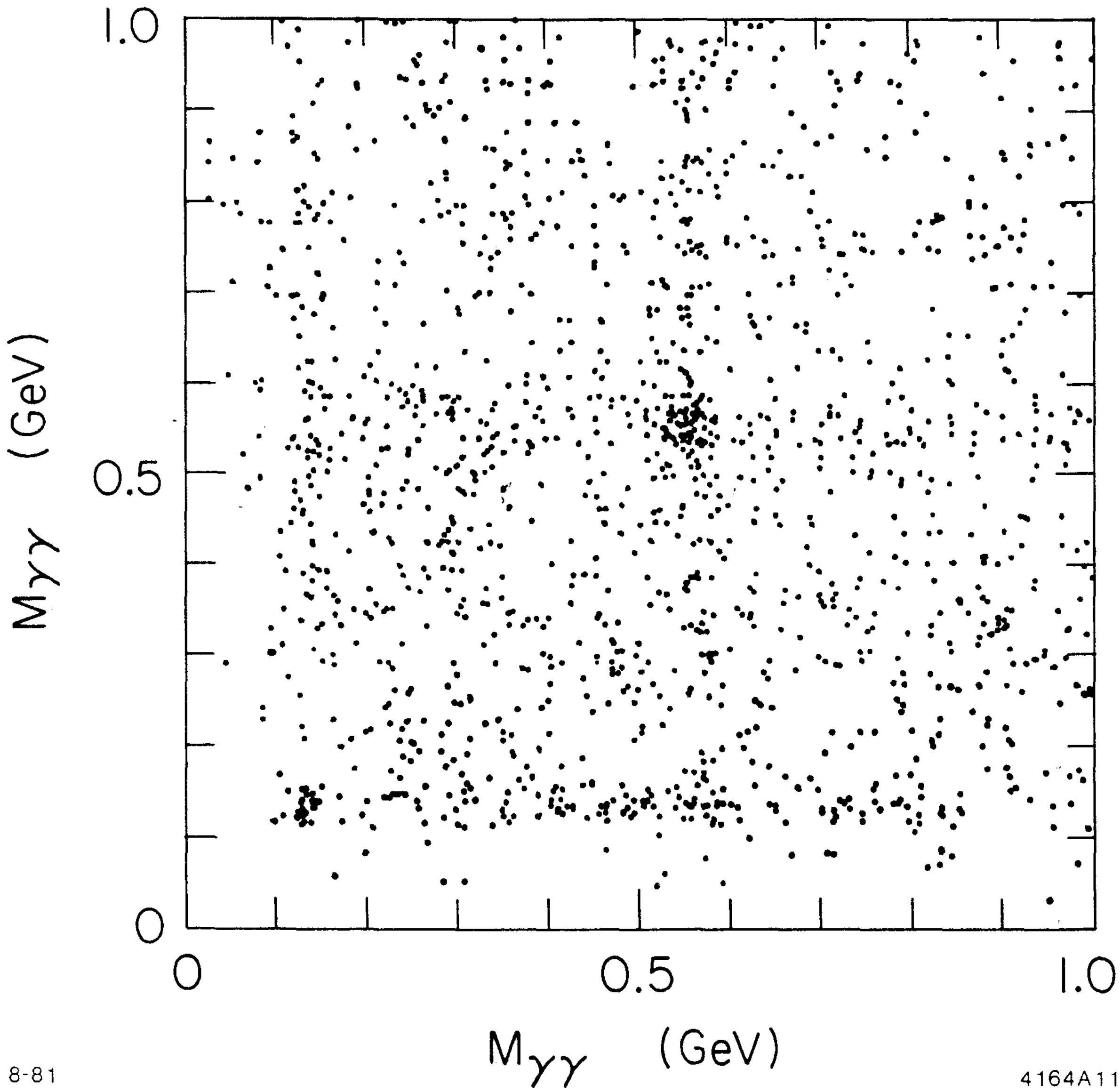



Fig. 1

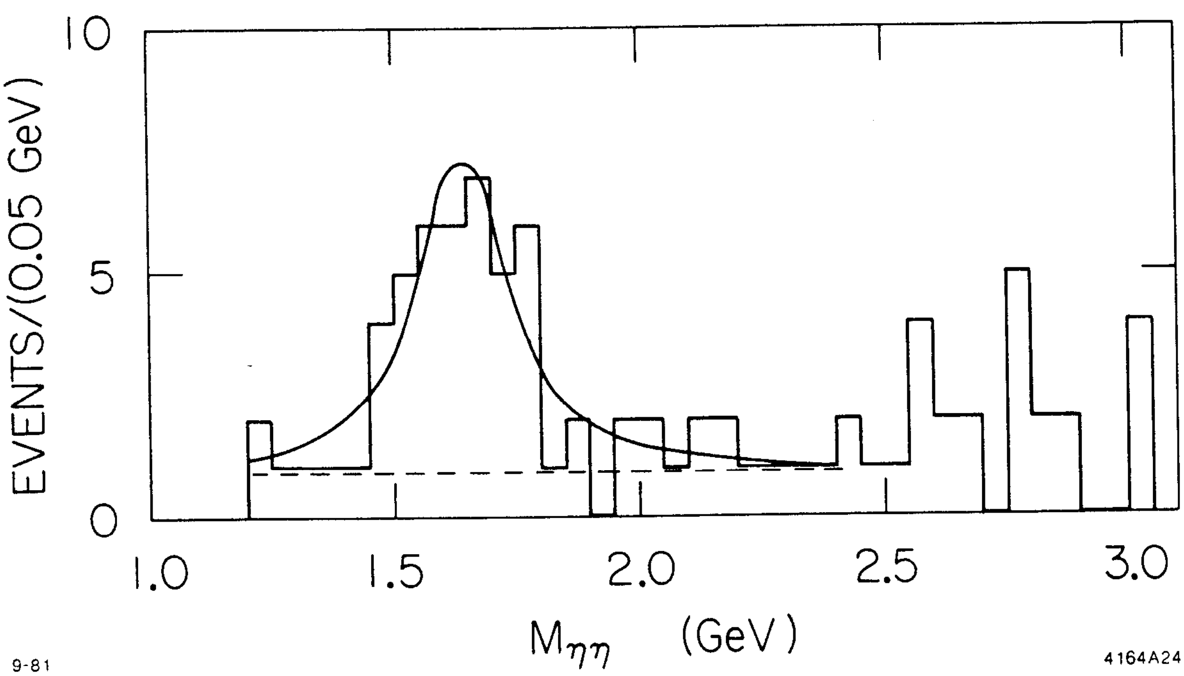
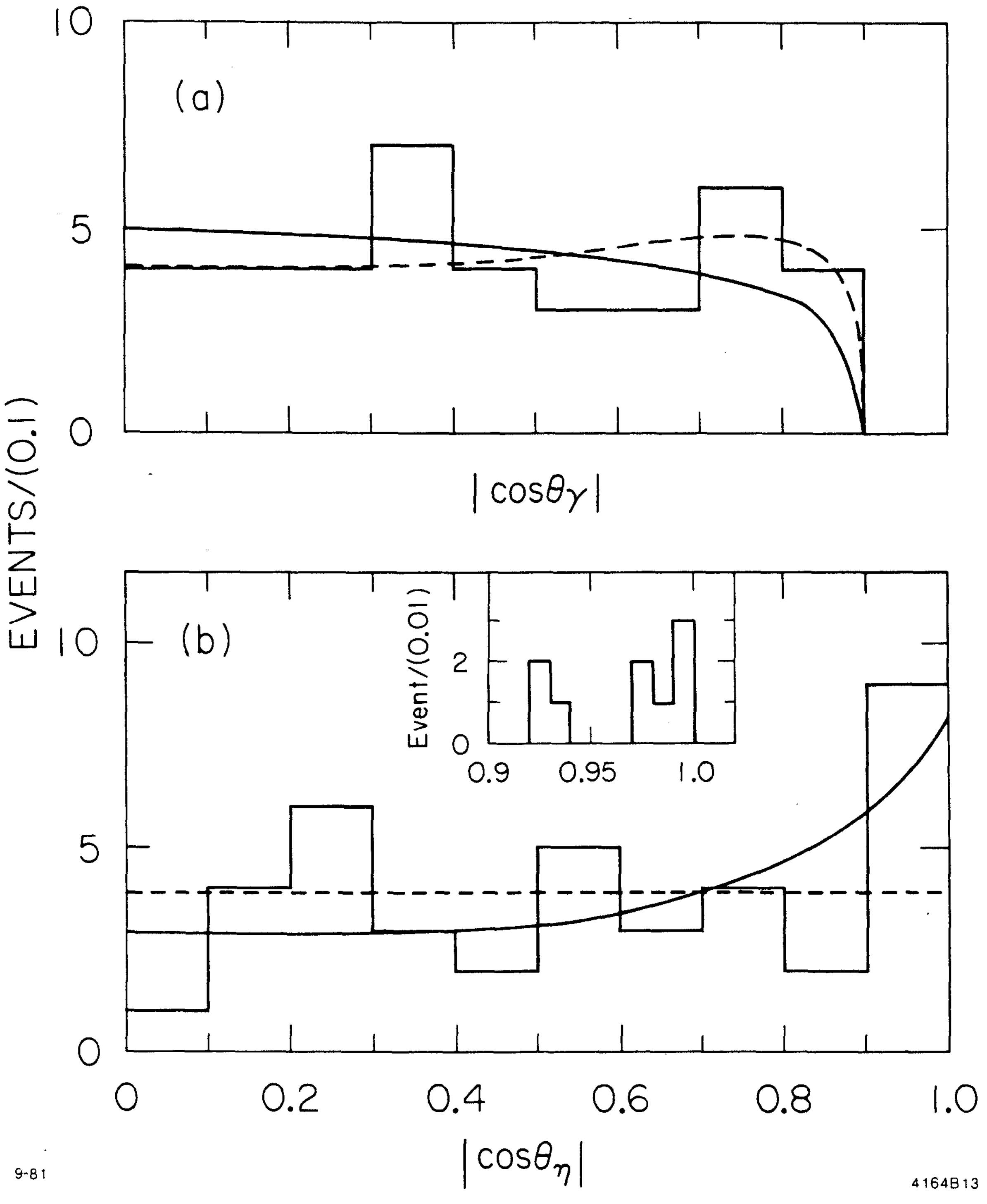



Fig. 2



10
(a)
5
0
EVENTS/(0.1)
|cosθγ|
(b)
10
5
0
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. 3