SLAC-PUB-2430
November 1979
(T/E)

THE DECAY $J/\psi \to 3\gamma$ AND A SEARCH FOR THE η_c *

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

W. Kollmann,† M. Richardson, K. Strauch and K. Wacker
Lyman Laboratory of Physics, Harvard University
Cambridge, Massachusetts 02138

D. Aschman, T. Burnett,‡ M. Cavalli-Sforza, D. Coyne and H. Sadrozinski
Physics Department, Princeton University
Princeton, New Jersey 08540

E. Bloom, F. Bulos, R. Chestnut, J. Gaiser,
G. Godfrey, C. Kiesling and M. Oreglia
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94305
and
R. Hofstadter, I. Kirkbride, H. Kolanoski, A. Liberman,§
J. O'Reilly and J. Tompkins
Physics Department and HEPL, Stanford University
Stanford, California 94305

ABSTRACT

The decay J/ψ into 3γ final states has been studied. We find no evidence for the existence of the X(2.83) or any heavy narrow state (e.g., the η_c) decaying into two photons. We give upper limits on the branching ratio $J/\psi \to \eta_c$, $\eta_c \to 2\gamma$ for η_c masses in the $2.7 \to 3.0$ GeV region. In addition, we have measured the branching ratios $J/\psi \to \gamma\eta$, $\gamma\eta'$. We find that the η' branching ratio is higher than previously reported.

(Sub. to Phys. Rev. Lett.)

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*This work was supported in part by the Department of Energy under contract numbers DE-AC03-76SF00515 (SLAC), EY-76-C02-3064 (Harvard) and EY-76-C03-0068 (CIT); and in part by National Science Foundation numbers PHY78-00967 (HEPL), PHY78-07343 (Princeton) and PHY75-22980 (CIT).

†Present address: Wentorfer Strasse 149, 2050 Hamburg, West Germany.
‡Permanent address: Physics Department, University of Washington, Seattle, Washington 98195.
§Present address: Schlumberger-Doll Research Center, Ridgefield, Connecticut 06877.

Using a non-magnetic neutral particle detector, the "Crystal Ball", we are studying the e^+e^- annihilation process with the SPEAR storage ring at various energies. We report here our results for the decay of the J/ψ into 3γ final states with the J/ψ produced directly via $e^+e^- \to J/\psi$, and indirectly via $e^+e^- \to \psi' \to \pi^+\pi^- J/\psi$.

The three photon final states of the J/ψ can be reached through either $J/\psi \to \gamma X$ where X is any state which decays into 2γ's (e.g., π^0, η, η'), or $J/\psi \to 3\gamma$ (direct). When the J/ψ is produced directly, the QED reaction $e^+e^- \to 3\gamma$ also contributes. There is no such contribution when the J/ψ originates from ψ' decays.

The η_c, which is the $^1S_0$ state of charmonium predicted by charmonium models,[1] is a further possibility for the X. Evidence for a state at a mass of 2.83 GeV has been reported by another experiment[2] in a study of the reaction $e^+e^- \to J/\psi \to 3\gamma$. However, the strength of the signal at the reported mass is inconsistent with the prediction of these models and has posed serious difficulty to their advocates.

The Crystal Ball is shown schematically in Fig. 1. The main components are:

1) The Ball, consisting of two hemispherical shells of NaI(Tℓ) sixteen radiation lengths thick, centered around the interaction region and covering 94% of 4π steradians. Each hemisphere is divided into 336 modules. Each module has the shape of a truncated pyramid with a triangular cross section, is optically separated from its neighbors, and is viewed by a phototube.

2) Central cylindrical wire chambers, consisting of a proportional chamber sandwiched between two magnetostrictive readout spark chambers. The assembly surrounds a thin wall (1.5 mm) Aℓ beampipe. The 3 chambers cover 94%, 80% and 71% of 4π.

3) Endcaps, consisting of planar magnetostrictive readout spark chambers followed by individually sealed hexagonal NaI(Tℓ) modules twenty radiation lengths thick. These endcaps increase the solid angle coverage to 98% of 4π.

A photon deposits all its energy in a cluster of several modules leaving no hits in the wire chambers. The direction of such a "neutral track" is obtained by joining the center of the interaction region to the shower center determined by shower pattern methods. We have achieved, in the Ball, an angular resolution for photons of $\sigma = 2^{\circ}$ and an energy resolution for photons and electrons of $(\sigma/E) = 2.8\% / \sqrt[4]{E}$. References 3, 4 and 5 contain detailed descriptions of the detector, the electronics and trigger, and calibration procedures.

Our results are based on an integrated luminosity of 1700 nb^{-1} at the ψ' ($\sim 8 \times 10^{5}$ ψ'), and 327 nb^{-1} at the J/ψ ($\sim 9 \times 10^{5}$ J/ψ). The experimental trigger used in the present study is a total energy trigger which requires > 900 MeV deposited in the Ball. Since the full mass of the J/ψ is deposited by the three photons in the Ball, this trigger alone is fully efficient.

For the selection of 3γ events from direct J/ψ production, we require 3 neutral tracks with a total energy > 2.7 GeV in the Ball and $\leq$ 25 MeV in the endcaps. To enhance charged particle tagging efficiency, we require $|\cos\theta_{\gamma}| \leq 0.8$ for each photon where θ_{γ} is the photon polar angle with respect to the beam. We also require a momentum imbalance $\leq$ 500 MeV and for each photon an energy E_{γ} > 20 MeV. A total of 865 events fulfill these criteria.

In order to avoid problems with overlapping showers we require $\cos\theta_{\gamma\gamma} \le 0.85$ where $\theta_{\gamma\gamma}$ is the angle between any two photons. This cut also eliminates most events from $J/\psi \to \gamma\pi^0$, hence the present analysis cannot give any results for this reaction.

The main source of background is the decay $J/\psi \to \gamma\pi^0\pi^0$ where the two decay photons from a π^0 overlap to produce a single merged shower with an unusually large lateral spread. Events with one or more such showers are rejected using a lateral shower distribution algorithm developed with the help of Monte Carlo calculations.

Each surviving event is subjected to a 4-constraint kinematic fit. The final sample of 405 events is estimated to contain ~ 14 background events. Of these, ~ 3 are due to radiative Bhabha scattering where neither electron is detected by the spark chambers. The remaining ~ 11 events come from $\gamma\pi^0\pi^0$ final states which pass our selection criteria; their distribution in the Dalitz plot is nearly uniform.

For the selection of events where the J/ψ originates from ψ' decay, we require two charged particles, and three photons with an invariant mass $2.82 < M_{\gamma\gamma\gamma} < 3.25$ GeV and each photon with an energy $E_\gamma > 20$ MeV. In order to increase the acceptance, we relax the angular limits to $|\cos\theta_\gamma| < .85$ and $\cos\theta_{\gamma\gamma} < .90$. The rest of the procedure remains the same except that the remaining events undergo a 3-constraint fit with $M_{\gamma\gamma\gamma}$ constrained at the J/ψ mass. Twenty-nine events remain.

From each final sample we obtain a Dalitz plot of the highest and lowest invariant mass squared $(M_{\gamma\gamma})^2_{low}$ and $(M_{\gamma\gamma})^2_{high}$. Figures 2 and 3 show such plots for directly and indirectly produced J/ψ. Histograms of

$(M_{\gamma\gamma})_{low}$ and $(M_{\gamma\gamma})_{high}$ are also shown in Figures 4a and 4b for J/ψ produced directly. η and η' peaks stand out clearly in Figure 4a. On the basis of the results of Ref. 2 and our mass resolution ($\sim$ 30 MeV), a peak containing 46 ± 19 events above background is expected in the two bins containing the X(2.83) in Figure 4b. We see no such peak.

In order to find the contributions from individual reactions in $J/\psi \to \gamma X$, $X \to 2\gamma$, a two-dimensional maximum likelihood fit to the Dalitz plot was carried out. For J/ψ produced directly, events from each individual reaction were simulated in the detector by Monte Carlo shower calculations using a $(1 + \cos^2 \theta)$ distribution for the monochromatic photon. For direct 3γ and QED, the matrix elements given in References 6,7 were used. The energy resolution as well as photon conversion corrections were introduced into the Monte Carlo. The events were then subjected to the same selection and analysis as the data, yielding a Dalitz plot density and an overall acceptance for each reaction. These were used in the Dalitz plot fit leaving only the individual numbers of events from the various reactions as free parameters. Such fits have been carried out for several values of the η_c mass, and upper limits obtained at each mass. In addition to the fit we have also calculated the absolute contribution from QED at the J/ψ and $\psi''(3770)$. The calculations were found in very good agreement with the data at the ψ'' (where QED is the only source for the 3γ final state), and with the QED contribution obtained from the fit at J/ψ.

From the fit to the Dalitz plot we obtain an upper limit for the branching ratio product at an X mass of 2.83 GeV:

$$BR(J/\psi \to \gamma X) \cdot BR(X \to 2\gamma) < 2.2 \times 10^{-5} \text{ (90\% C.L.)}.$$

Figure 5 shows this product as a function of η_c mass, and a theoretical prediction from Reference 8 for comparison. Reference 8 also contains a discussion of the difficulty posed by an η_c mass of 2.83 GeV.

Since the only significant contributions found were from η, η' and QED, a fit to the Dalitz plot has been carried out using these only. This fit yields the following branching ratios:[9] $BR(J/\psi \to \gamma\eta) = (1.17 \pm .17) \times 10^{-3}$, $BR(J/\psi \to \gamma\eta') = (6.87 \pm 1.71) \times 10^{-3}$. The first is in good agreement with previous measurements.[2,10] The second is higher than earlier results.[2,11] Our value of 5.88 ± 1.46 for the ratio of the two decay rates $\rho \equiv BR(J/\psi \to \gamma\eta')/BR(J/\psi \to \gamma\eta)$ can be compared to earlier experimental results[10] $\rho = 1.8 \pm 0.8$, $\rho = 2.8 \pm 2.2$ (derived from Ref. 2), and the theoretical value[12] $\rho \approx 3.9$.

For the 3γ decay of J/ψ obtained from ψ', all events in the Dalitz plot (Figure 3) are in the η and η' mass bands. In particular, there are no contributions from X(2.83). As stated before, this reaction is free from QED. The Dalitz plot was therefore fitted with only η, η', X(2.83) and direct 3γ. Our present knowledge of the hadronic showers in the Ball does not allow us to calculate reliably the efficiency of event selection. We therefore normalized the branching ratios by comparing the total number of $\eta + \eta'$ from this method with that from J/ψ produced directly. This procedure is justified because the selection inefficiencies due to the charged particles should be independent of the 3γ final state.

Since the sum of the η, η' is used in the normalization, we can give only the value for the ratio ρ defined above. We find: $\rho = 10.1 \pm 4.1$.

The fit to the Dalitz plot gives no events from X(2.83). Using the normalization above we obtain an upper limit on the branching ratio product $BR(J/\psi \to \gamma\, X(2.83)) \times BR(X(2.83) \to 2\gamma) < 1.0 \times 10^{-4}$ (90% C.L.).

Also, no contribution from direct 3γ decay is required by the fit and we obtain the upper limit $BR(J/\psi \to \text{direct } 3\gamma) < 5.5 \times 10^{-5}$ (90% C.L.) For the convenience of the reader, the results appearing in various parts of the text were compiled in Table 1.

Acknowledgments

A complex detector such as the "Crystal Ball" could not have been designed, built and operated without considerable technical and administrative help from many individuals. Our sincere thanks go to all of them even though space limits us to name only: A. Baumgarten and J. Broeder (SLAC); R. Parks (HEPL, Stanford University).

B. Beron and E. B. Hughes (HEPL, Stanford University) were valued participants in the early phases of the program.

This work was supported by the Department of Energy under Contract Numbers DE-AC-3-76SF00515 (SLAC), EY-76-C02-3064 (Harvard) and EY-76-C03-0068 (CIT), and by the National Science Foundation Contract Numbers PHY78-00967 (HEPL), PHY78-07343 (Princeton) and PHY75-22980 (CIT). Support for individuals came from the listed institutions plus NATO-Fellowship-West Germany, Chaim Weizmann Fellowship and Sloan Foundation.

Table I. Branching Ratios $J/\psi \to 3\gamma$

Channel	Branching Ratio
$J/\psi \to \gamma\eta$	$(1.17 \pm .17) \times 10^{-3}$
$J/\psi \to \gamma\eta'$	$(6.87 \pm 1.71) \times 10^{-3}$
$(J/\psi \to \gamma\eta')/(J/\psi \to \gamma\eta)$	(5.88 ± 1.46)
$J/\psi \to 3\gamma$ (Direct)*	$< 5.5 \times 10^{-5}$
$J/\psi \to \gamma X(2.83)$, $X \to 2\gamma$	$< 2.2 \times 10^{-5}$

* Here J/ψ is obtained from the decay $\psi' \to J/\psi\ \pi^+\pi^-$

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9. We use the following branching ratios for η, $\eta' \to 2\gamma$: $BR(\eta \to 2\gamma) = (38.0 \pm 1.0) \times 10^{-2}$, $BR(\eta' \to 2\gamma) = (1.9 \pm .3) \times 10^{-2}$.
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11. W. Bartel et al., Phys. Lett. 64B, 483 (1976).
12. H. Fritzsch and J. D. Jackson, Phys. Lett. 66B, 365 (1977).

Figure Captions

Fig. 1. Schematic of Crystal Ball Detector.

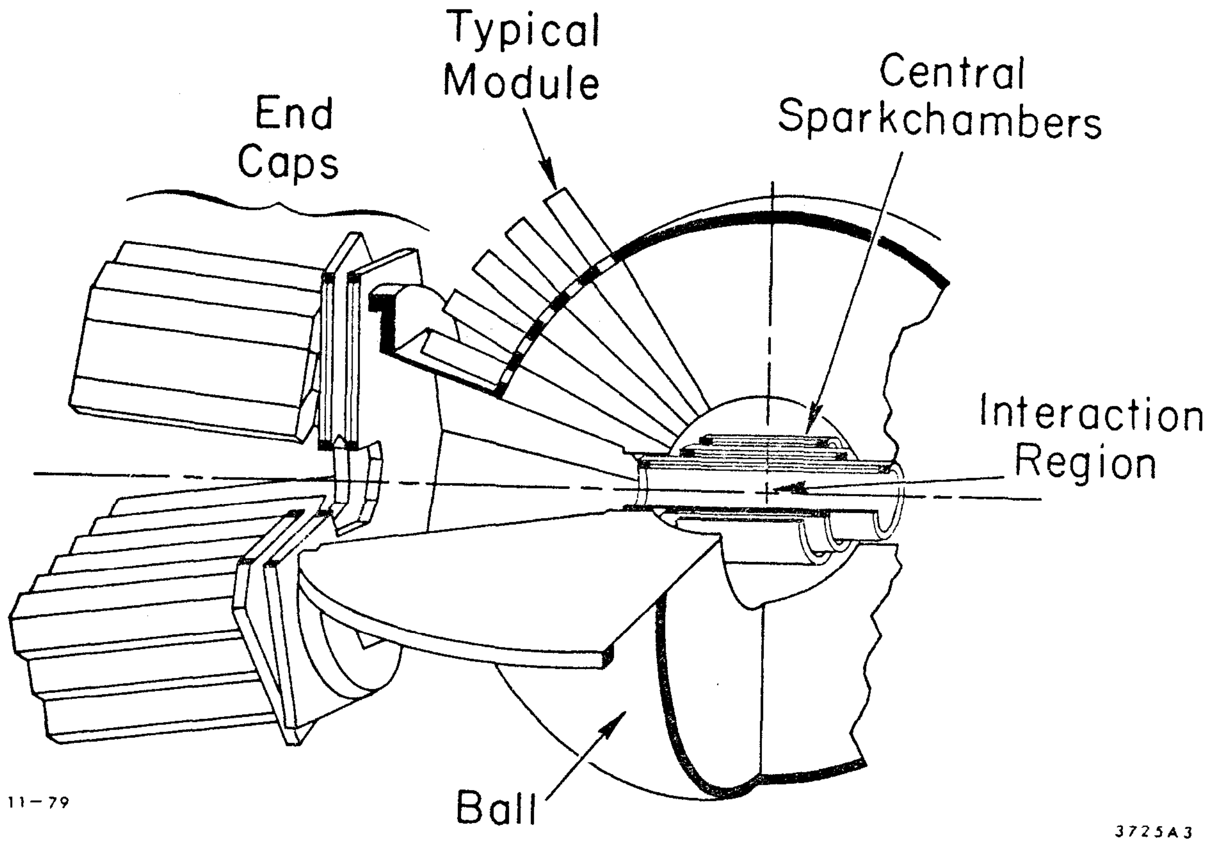
Fig. 2. Dalitz plot $J/\psi \to 3\gamma$.

Fig. 3. Dalitz plot $\psi' \to J/\psi\pi^+\pi^-$, $J/\psi \to 3\gamma$.

Fig. 4. (a) Histogram $(M_{\gamma\gamma})_{low}$, $J/\psi \to 3\gamma$.

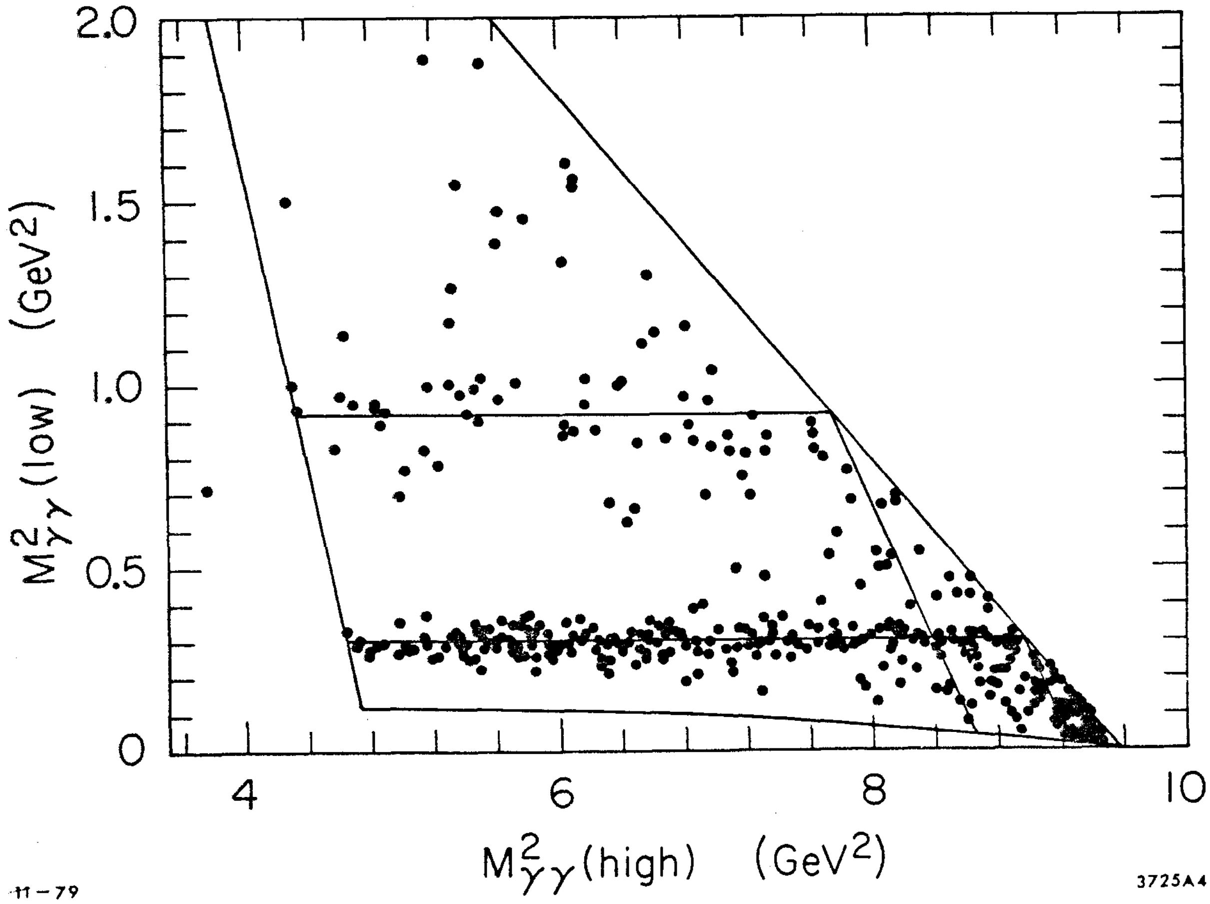
(b) Histogram $(M_{\gamma\gamma})_{high}$, $J/\psi \to 3\gamma$.

Fig. 5. Upper limits: $BR(J/\psi \to \gamma\eta_c) \times BR(\eta_c \to 2\gamma)$.



Typical
Module
End
Caps
Central
Sparkchambers
Interaction
Region
Ball
11-79
3725A3

Fig. 1



2.0
1.5
1.0
0.5
0
4
6
8
10
$M^2_{\gamma\gamma}$ (low) (GeV^2)
$M^2_{\gamma\gamma}$ (high) (GeV^2)
11-79
3725A4

Fig. 2

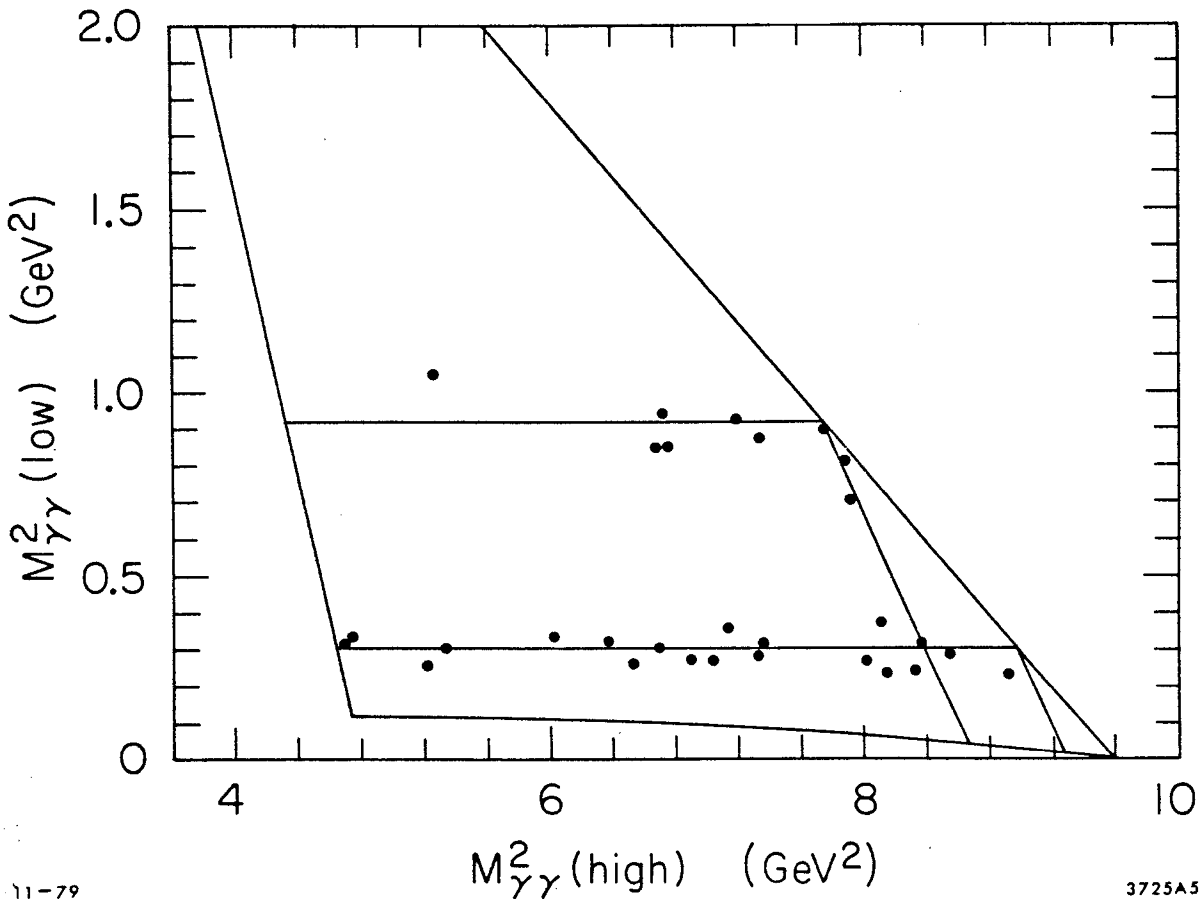

2.0
1.5
1.0
0.5
0
$M^2_{\gamma\gamma}$ (low) (GeV^2)
4
6
8
10
$M^2_{\gamma\gamma}$(high) (GeV^2)
11-79
3725A5

Fig. 3

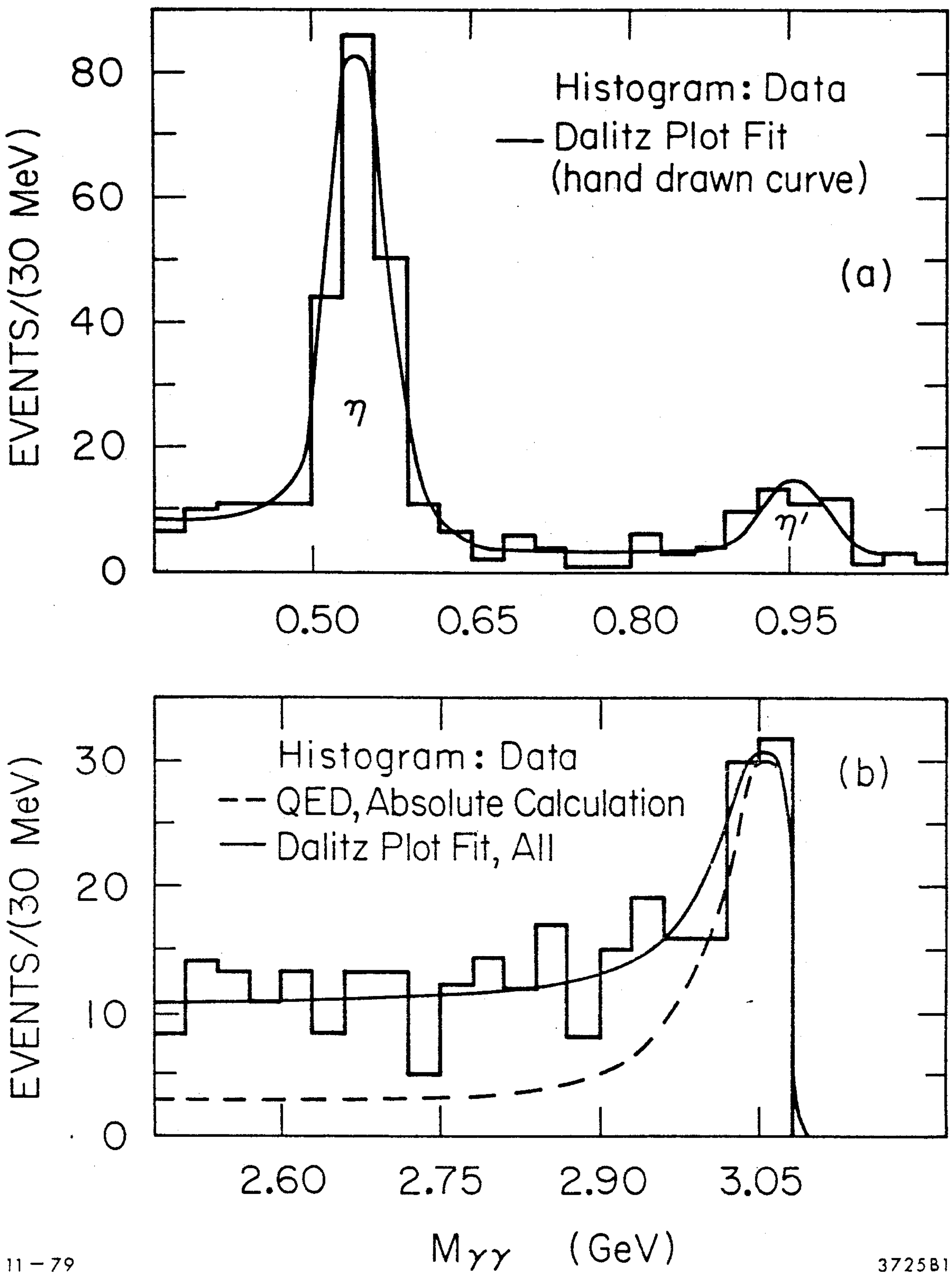

EVENTS/(30 MeV)
80
60
40
20
0
Histogram: Data
— Dalitz Plot Fit
(hand drawn curve)
(a)
η
η′
0.50
0.65
0.80
0.95
EVENTS/(30 MeV)
30
20
10
0
Histogram: Data
-- QED, Absolute Calculation
— Dalitz Plot Fit, All
(b)
2.60
2.75
2.90
3.05
Mγγ (GeV)
11-79
3725B1

Fig. 4

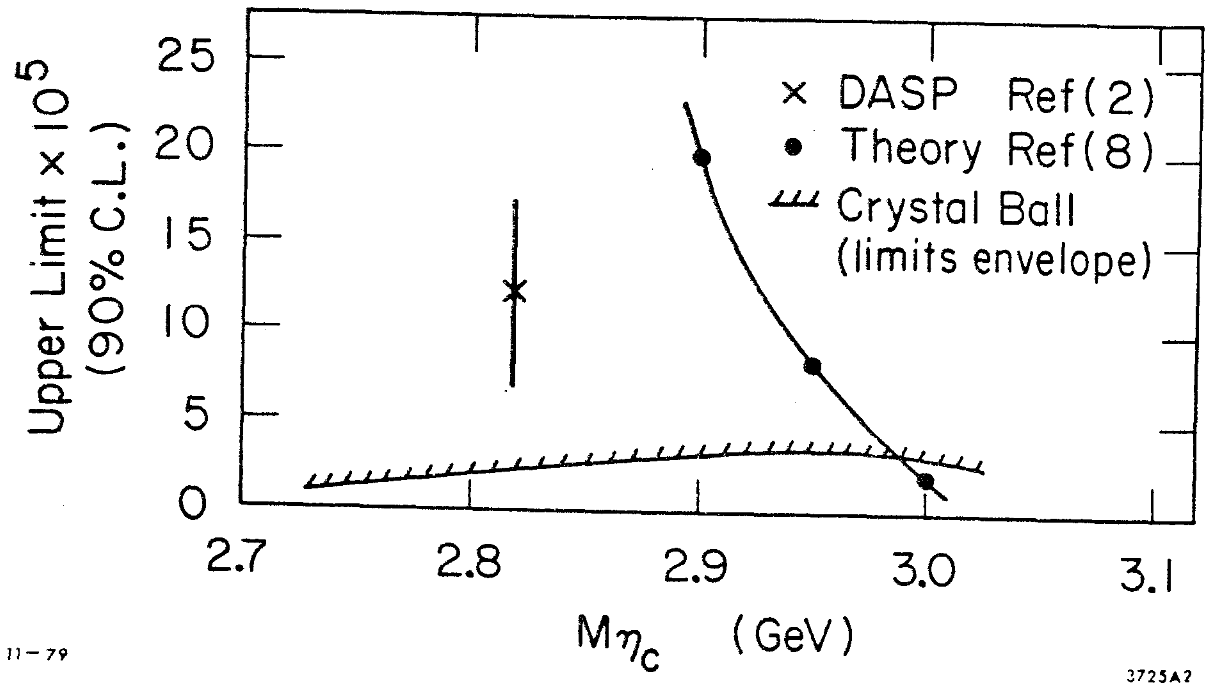

× DASP Ref(2)
• Theory Ref(8)
Crystal Ball (limits envelope)
Upper Limit × 10^5 (90% C.L.)
25
20
15
10
5
0
2.7
2.8
2.9
3.0
3.1
Mηc (GeV)
11-79
3725A2

Fig. 5