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Cascade Radiative Decays of $\psi'(3684)$ and Evidence for a New Intermediate State of Even C-Parity*

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Abstract

Branching ratios are given for several cascade electromagnetic decays of $\psi'(3684)$ into $J/\psi(3093)$. Evidence is presented for a new C = + intermediate state of mass 3.59 or 3.18 GeV. No signal is seen for a state at 3.45 GeV.

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The interpretation of the resonant states J/ψ and ψ' as respectively the 1^3S_1 and 2^3S_1 states of charmonium leads to the prediction of further charmonium states with masses between those of J/ψ and ψ'. If such intermediate states have even C-parity, they can be reached via radiative transitions from ψ' and can also decay radiatively into J/ψ.

Several such states have been observed in ψ' decays, in cascade decays[1,2,3,6] of the type

$$\psi' \rightarrow \gamma P_c/\chi \rightarrow \gamma\gamma\; J/\psi, \tag{1}$$

as monochromatic lines in the inclusive γ spectrum[3,4,6], and in hadronic decay modes[5,6].

Three intermediate states are experimentally well established at masses of 3.41, 3.50 and 3.55 GeV. They are generally interpreted as being the $^3P_{0,1,2}$ states of charmonium, respectively. There is some evidence for a fourth state at 3.45 GeV seen only in the cascade decay (1)[3,6]. It has been suggested that this is the 2^1S_0 state, known as η_c'.

The present paper reports on branching ratios for the cascade reactions (1) observed in a high statistics experiment at the DORIS storage rings at DESY. The J/ψ resonance is identified by its decay into μ-pairs so that the final state topology is two photons and two charged particles.

The detector has been described in previous publications[7,8]. γ rays are registered as energy clusters in the counter arrays, and the photon directions are calculated from the observed energy sharing to an accuracy which ranges from ± 30 to ±220 mrad. Better directional information is obtained for photons which convert either in a 1-radiation length lead absorber situated in front of the last cylindrical drift chamber or in a two radiation length NaI counter array which is followed by planar drift chambers. In this case photon directions can be reconstructed to within $\Delta\phi = \Delta\theta = \pm 80$ mrad. The energy resolution for γ rays is not uniform over the whole detector. It is on the average $\Delta E/E = \pm 16$ % for photons in the energy range relevant for this analysis, i.e. from about 50 - 600 MeV.

A total of 624500 ψ' decays were observed in this experiment corresponding to an integrated luminosity of 1119 nb^{-1}. From this sample events with two prongs and two photons have been selected.

The typical energy loss of μ's in the energy detector is 300 MeV. In order to exclude electrons from the decay $J/\psi \rightarrow e^+e^-$ *) and to suppress events with additional photons emitted in the direction of a μ, it is required that the energy associated with a track be less than 500 MeV. In case one of the two photons is close to a μ track the energy limit is raised to 800 MeV.

Kinematic reconstruction of the events can be made by using the measured directions of the four particles. The mass resolution however is improved by requiring that the invariant mass of the two μ be equal to the mass of the J/ψ resonance and by treating the event vertex along the beam axis (z-vertex) as a free parameter in the fit. Events were rejected whenever this fitted z-vertex was farther than 20 mm from the centre of the luminous region, which has a width of 16 mm FWHM.

Because the kinematic reconstruction is sensitive to the mass difference between ψ' and J/ψ, this quantity has been determined from the well known decay

$$\psi' \rightarrow \eta(549) + J/\psi \qquad (2)$$

with the η meson decaying into two photons. If the mass difference between ψ' and J/ψ is chosen to be 591 MeV, the η is reconstructed with its correct mass. The mass of the ψ' resonance has been set to 3.684 GeV.

The measured energies have not been used in the fitting procedure because systematic errors in the measured energies would deteriorate the mass resolution. However, the calculated photon energies have been compared with the ones measured in the NaI/lead glass counters whenever possible, i.e. whenever the measured energy is not distorted by excessive shower leakage at the edges of the detector or by confusion with the energy deposited by another particle. Events were accepted for further analysis only if such a comparison was possible for at least one photon and were rejected if for any photon the measured and calculated energies disagreed by more than 2.5 times the error on the measured energy. The effect of this energy cut can be seen in Fig. 1, which shows the difference between measured and cal-

*) This decay mode is excluded from the present analysis since the directions of electrons are less well determined in our apparatus.

culated photon energies normalized to the measurement error. The sample thus obtained consists of 772 events.

The main background to genuine 2-prong 2γ final states originates from the decay

$$\psi' \rightarrow \pi^0\pi^0 \, J/\psi \qquad (3)$$

where two of the four photons escape detection, either by falling outside the acceptance of the apparatus, or by being too close to charged tracks or other photons to be resolved. In order to reduce this type of background, the sum of measured photon energies was required to exceed 450 MeV. This cut reduces the event sample to 685 events. By Monte-Carlo-methods it is estimated that the remaining background is 12 ± 3 %.

No background is expected to arise from events where the final state muons are not positively identified, since it is observed that in 99 % of the cases where charged particle tracks point to a muon chamber, the expected hits are seen. The small discrepancy is consistent with the known inefficiency of the μ chambers.

The mass spectrum of the two photon system is shown in Fig. 2a. A clear peak at the mass of $\eta(549)$ is seen, corresponding to reaction (2). The spectrum has been fitted with an experimental resolution function for the η signal and with contributions from reactions (1) and (3).

A total of 164 ± 13 events can be attributed to reaction (2). The overall detection efficiency of 27.5 ± 1.5 % has been calculated by Monte-Carlo-methods, and a branching ratio of

$$\frac{\Gamma\,(\psi' \rightarrow \eta\, J/\psi)}{\Gamma\,(\psi' \rightarrow \text{all})} = (3.6 \pm 0.5) \cdot 10^{-2}$$

is obtained.

The isospin forbidden decay

$$\psi' \to \pi^0 \, J/\psi \tag{4}$$

could also be observed in the same topology. However, the spectrum in Fig. 2a shows no signal for this decay and from the number of events above background in the π^0 mass region the following upper limit for the branching ratio:

$$\frac{\Gamma(\psi' \to \pi^0 \, J/\psi)}{\Gamma(\psi' \to \text{all})} < 1.0 \cdot 10^{-3} \quad (90\ \%\ \text{C.L.})$$

is obtained. This value is consistent with theoretical predictions[9].

In order to study the cascade decays of reaction (1), events belonging to the decay channel (2) have been removed by a mass cut $m_{\gamma\gamma} < .520$ GeV. The spectrum of masses formed by the J/ψ - particle and the highest energy photon is shown in Fig. 2b. The number of events is 450.

Two peaks, corresponding to the previously observed states $P_c(3500)$ and $\chi(3550)$ are visible and in addition weakly resolved enhancements around 3.4 and 3.6 GeV. In order to improve on the mass resolution for the intermediate states we now select events for which the uncertainty on each of the two azimuthal and two polar photon direction angles is less than 200 mrad.

The data sample thus selected contains 275 events of which 20 were rejected after a visual scan because of wrong assignments made in the pattern recognition program.

Those 255 events which fulfil the additional requirements are shown in Fig. 2c. The estimated background (5 ± 2 %) is also indicated. The two peaks belonging to the states $P_c(3500)$ and $\chi(3550)$ are well separated from each other, and the signals near 3.4 and 3.6 GeV are now better separated from the main peaks.

Resolution functions for the 3.50 and 3.55 GeV resonances have been obtained by Monte-Carlo methods and are found to have non gaussian tails. The mass spectrum of Fig. 2c has been fitted with these resolution functions, with the amplitude and mass of each resonance as a free parameter.

A fit with only two states can accomodate neither the accumulation of events near 3.4 GeV nor the enhancement near 3.6 GeV. A fit with two additional resolution functions, corresponding to masses of 3.42 and 3.59 GeV, agrees with the data.

The events near 3.4 GeV are attributed to the cascade decay via the well established state at that mass (3.413 ± 0.005 GeV), which decays predominantly into hadrons.

The events near 3.6 GeV can be attributed to a new state. In fig. 2c the high energy photon γ_2 is combined with the J/ψ. The second possibility, the combination of the low energy photon γ_1 with the J/ψ, leads to a state at 3.18 GeV. No discrimination between the two alternatives is possible in this experiment. In Fig. 2c the number of events expected in the mass region between 3.58 and 3.61 GeV is 1 event from background and 3 events from the tail of the resonance at 3.55 GeV, while 16 events are seen. The probability to observe 16 events or more when 4 events are expected is $4 \cdot 10^{-6}$. The evidence for a state at 3.59 (3.18) GeV is corroborated by the subsample restricted to events with the best mass resolution, i.e. to those events where both photon conversions are observed in the drift chambers. Fig. 3 shows a two-dimensional plot of $m(J/\psi, \gamma_1)$ vs. $m(J/\psi, \gamma_2)$ for this sample.

In previous experiments [3,6] evidence has been reported for a state at 3.45 GeV. We do not observe any statistically significant signal at this mass and therefore derive only an upper limit for the cascade branching ratio via this state.

The branching ratios for electromagnetic cascade decays are calculated from the observed number of events as obtained in the fit using four mass states and from the efficiencies as determined by Monte-Carlo methods. The results are summarized in Table 1. The mass values as determined in the fit are also given. The errors include the uncertainty of the fit as well as an estimated 2 MeV systematic error from the event reconstruction method. The values agree well with previous measurements[6,10].

The measured branching ratios for the decays ψ' into η J/ψ and the cascade decays via $\chi(3.41)$, $P_c(3.50)$ and $\chi(3.41)$ are in good agreement with previous measurements[4,6,10,11]. A state at 3.45 GeV has not been observed in this experiment. The upper limit given in Table 1 is to be compared with the previously quoted value of $(0.8 \pm 0.4) \times 10^{-2}$ [3,6].

A new state of even C-parity is observed at a mass of 3.59 or 3.18 GeV. The branching ratio for the electromagnetic decay via this state is similar to the branching ratio via the state at 3.41 GeV. Although no distinction can be made between the two mass solutions it is suggestive to assume the high mass solution to be the correct one and to interpret it as a candidate for the η_c' or the $^1D_2$ state. It could also be interpreted as a bound state of four quarks. Estimates of masses of such states have been made by de Rujula and Jaffe who predict a $J^C = 0^+$ state at about 3.6 GeV[12].

An upper limit of 10^{-3} is obtained for the branching ratios of any cascade decays via further intermediate states with masses between 3.60 and 3.63 GeV.

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References

1. W. Braunschweig et al., Physics Letters 57B, 407 (1975)
2. W. Tanenbaum et al., Phys. Rev. Letters 35, 1323 (1975)
3. J.S. Whitaker et al., Phys. Rev. Letters 37, 1596 (1976)
4. C.J. Biddick et al., Phys. Rev. Letters 38, 1324 (1977)
5. G.J. Feldman et al., Phys. Rev. Letters 35, 821 (1975)
6. W. Tanenbaum et al., Phys. Rev. D17, 1731 (1978)
7. J.E. Olsson, DESY-Heidelberg-Collaboration, Proc. of the 8th Intern. Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977, and DESY 77/70 (1977)
8. W. Bartel et al., Phys. Letters 77B, 331 (1978)
9. G. Segre and J. Weyers, Phys. Letters 62B, 91 (1976)
10. E. Gaderman, DASP-Collaboration, Thesis, DESY Internal Report F22-78/05 (1978)
11. W. Tanenbaum et al., Phys. Rev. Letters 36, 402 (1976)
12. A. de Rujula and R.L. Jaffe, Proc. Exptl. Meson Spectroscopy, Northeastern University, Boston, April 1977, and MIT-Preprint CTP 658 (August 1977)

Table 1: Branching Ratios for the Electromagnetic Cascade Decays $\psi' \to \gamma P_c/\chi \to \gamma\gamma\, J/\psi$

State (Mass in GeV)	Branching Ratio (%)	
3.42 ± .01	.14 ± .09	
3.45	< .25	(90 % C.L.)
3.505 ± .003	2.5 ± .4	
3.551 ± .004	1.0 ± .2	
3.591 ± .007	.18 ± .06	
3.60 - 3.63	< .1	(90 % C.L.)

Figure Captions:

Fig. 1 Differences between measured and calculated photon energies, normalized to the measurement errors.
The cut is explained in the text.

Fig. 2a Mass distribution for the two photon system.
The fit is explained in the text.

Fig. 2b Mass distribution for the J/ψ and highest energy photon.
The two photon mass is required to be less than .520 GeV.

Fig. 2c Mass distribution for the J/ψ and highest energy photon.
The two photon mass is required to be less than .520 GeV and photon angular errors to be less than 200 mrad.
The fit is explained in the text.

Fig. 3 Scatterplot of mass $(J/\psi,\gamma_1)$ vs. mass $(J/\psi,\gamma_2)$ for events with two photon conversions observed in the drift chambers and otherwise with the same cuts as in Fig. 2c.

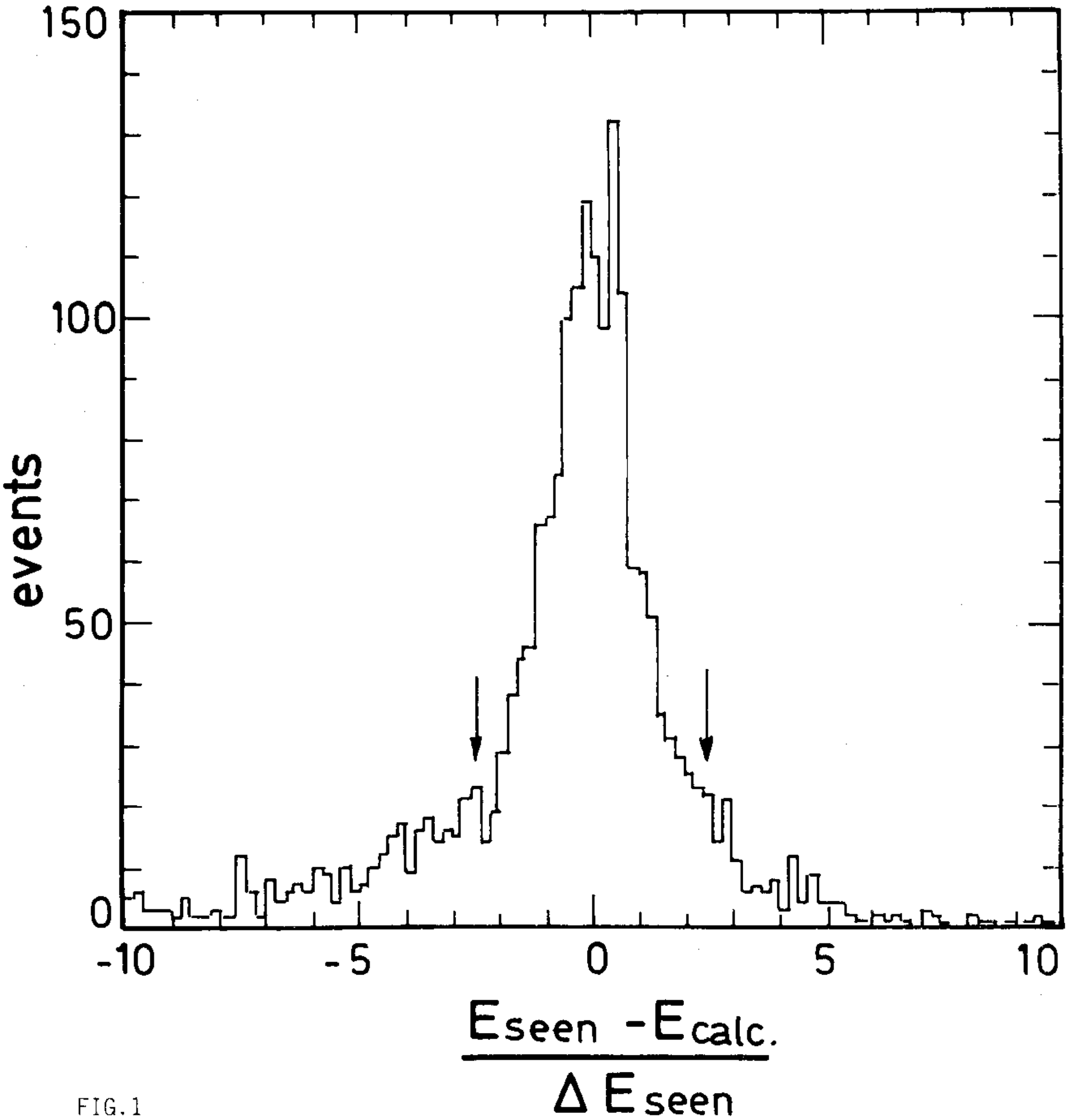


FIG.1

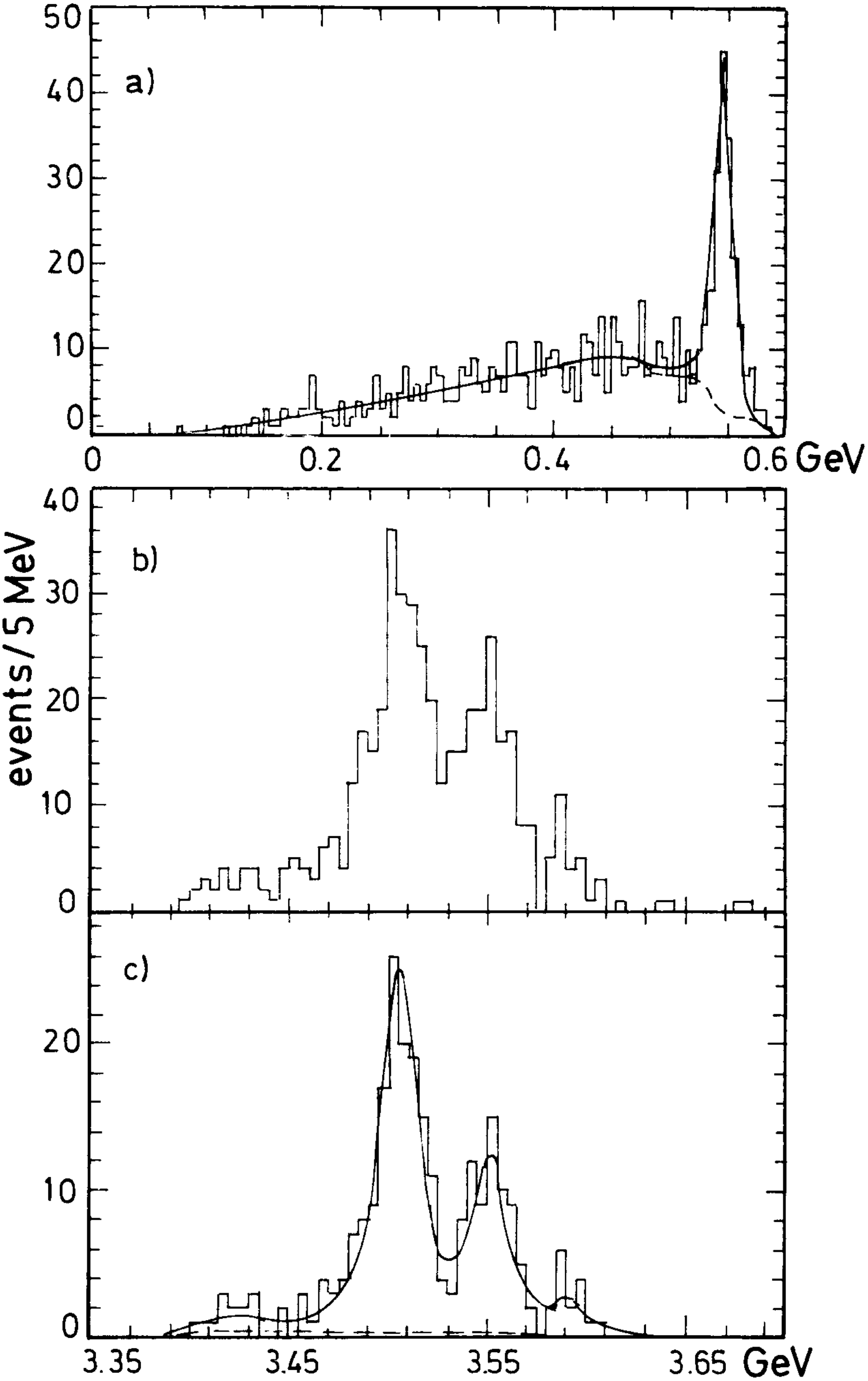
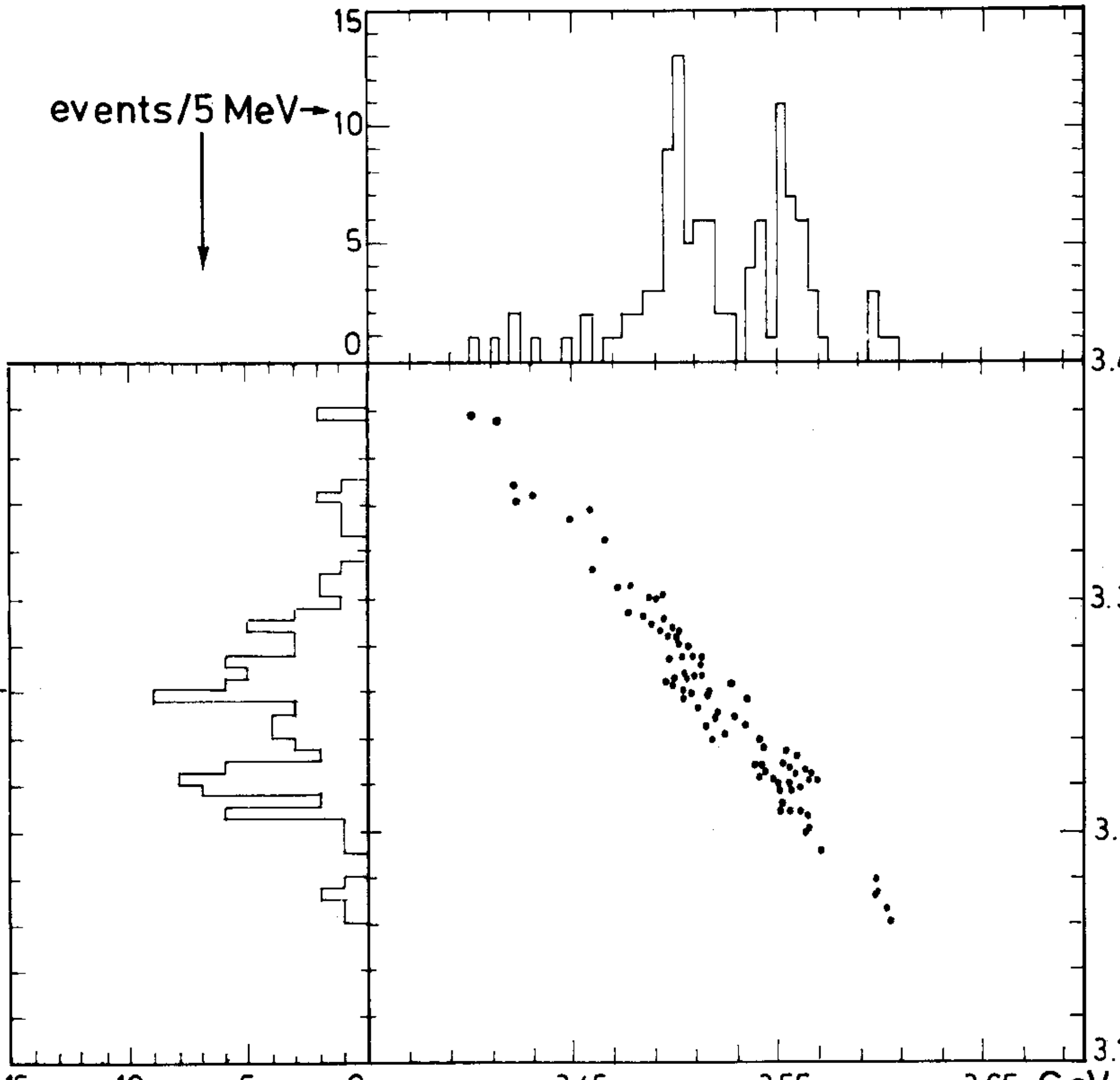

50
40
30
20
10
0
a)
0
0.2
0.4
0.6 GeV
40
30
20
10
0
b)
events/5 MeV
20
10
0
c)
3.35
3.45
3.55
3.65 GeV

FIG.2



events/5 MeV
15
10
5
0
3.4
3.3
3.2
3.1
m(J/ψ,γ1)
15
10
5
0
3.45
3.55
3.65
GeV
m(J/ψ,γ2)

FIG.3