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PRODUCTION OF $\pi^0\pi^0$ AND $\pi^0\eta$ IN PHOTON-PHOTON-COLLISIONS*

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Abstract

We investigate the four-photon final state produced in $\gamma\gamma$ collisions. In the $\pi^0\pi^0$ channel we observe f(1270) production with predominantly helicity 2 and measure a partial width $\Gamma_{\gamma\gamma}$ $2.9^{+.6}_{-.4} \pm 0.6$ keV (independent of assumptions on the helicity). We observe $A_2(1310)$ production in the $\pi^0\eta$ channel and find a partial width $\Gamma_{\gamma\gamma} = 0.77 \pm 0.18 \pm 0.27$ keV (assuming helicity 2). We give an upper limit for $f \to \eta\eta$.

The collision of two real photons has never been observed for lack of a suitable target. However, with e^+e^- storage rings such a collision can be observed with very nearly real photons. In an e^+e^- collision, each lepton can radiate a low q^2 virtual photon and scatter to a very low or zero angle. In most experiments with quasi-real photons such as the one reported here the scattered leptons are unobserved. The reaction products are detected and their two-photon origin is identified by the very low total transverse momentum with respect to the beam axis. It is necessary to identify and know the momentum of all particles in the exclusive final state.

The reaction $\gamma\gamma \to \pi^+\pi^-$ has been measured by several experiments [1-4]. The main contribution to this final state has been shown to be the f(1270) resonance. Whereas all experiments agree within errors on the value of the partial width $\Gamma(f \to \gamma\gamma)$, there are considerable uncertainties on whether there are additional contributions to this final state and whether the resonance shape of the f is distorted. Up to now, the angular distribution has not been measured accurately enough to determine $\Gamma_{\gamma\gamma}$ independent of assumptions on the helicity of the f. An important reason for these difficulties is background from the reaction $\gamma\gamma \to \mu^+\mu^-$, which in most experiments cannot be distinguished from $\pi^+\pi^-$.

In this experiment, we study the reaction $\gamma\gamma \to \pi^0\pi^0$. All known resonances which can couple to $\gamma\gamma$ and $\pi\pi$ decay in the same ratio (1 : 2) into neutral and charged pions. Non-resonant π-pair production is expected to be an order of magnitude smaller for neutral than for charged pions [5]. There is no background of the order of magnitude of the μ-pair production. This and the use of a large solid angle detector allow us to measure the f helicity. In addition, we measure other 4-photon final states. We observe the production of $A_2 \to \pi^0\eta$ and find the A_2/f ratio to agree with SU(3)-predictions. We also obtain an upper limit for $f \to \eta\eta$.

This investigation was performed with the Crystal Ball detector at the SPEAR e^+e^- storage ring. Details of the experiment have been described elsewhere [6]. Briefly, the Crystal Ball consists of a spherical array of NaI(Tℓ) shower counters which detect photons with good spatial and energy resolution over 93% of 4π solid angle. An additional 5% of 4π are covered by endcap NaI(Tℓ) shower counters. Charged particles are detected in a set of cylindrical spark chambers and multi-wire proportional chambers. The apparatus was triggered by a number of conditions. The one which is most important here requires the total energy deposited in the ball to be above a threshold which was set between 600 and 1200 MeV, depending on running conditions.

The data used for this analysis represent an integrated luminosity of 21 pb^{-1}. Beam energies were at 1.95-2.25 GeV (9.5 pb^{-1}), 2.6 GeV (6.7 pb^{-1}) and 3-3.5 GeV (4.9 pb^{-1}).

To select candidate events for this investigation, we required:

- No charged tracks
- 4 clusters of energy deposited in the ball with $|\cos\theta| < 0.9$ (θ is the angle to the beam) and energy >20 MeV
- Less than 40 MeV in the endcaps
- Total effective mass $W > 720$ MeV and less than twice the beam energy

-- The pattern of lateral energy distribution in each of the four clusters has to be consistent with that of a photon.

5204 events pass these cuts.

Figure 1 shows the square of the total transverse momentum of these events. We see a strong peak at 0 from the $\gamma\gamma$-reaction. We make a cut at 0.03 GeV^2.

We now group the four photons of each event into two pairs (there are three ways to do so) and make a scatter plot of the higher versus the lower pair mass $M_{\gamma\gamma}$. As an example, we show this plot in fig. 2 for events in the f(1270) mass region (1040-1480 MeV). We see a strong peak corresponding to $\pi^0\pi^0$ events and a cluster of $\pi^0\eta$ events. Nearly all other entries are wrong combinations from these two types of events.

To investigate the $\pi^0\pi^0$ signal, we use events with both $\gamma\gamma$ masses in the range 100-170 MeV. To estimate background from non-$\pi^0\pi^0$ events, we use events where one or both combinations are in the sidebands 65-100 MeV and 170-205 MeV. The $\pi^0\pi^0$ mass (W) distribution and the background are shown in fig. 3a. We observe a strong peak in the vicinity of the f mass and no other significant structure.

In order to obtain the cross section for $\gamma\gamma \to \pi^0\pi^0$, the observed background-subtracted event spectrum has to be corrected for the W dependence of the $\gamma\gamma$-flux, the differing trigger conditions and detection inefficiency. We use the formula given by Bonneau, Gourdin and Martin [7] to calculate the $\gamma\gamma$-flux. We neglect contributions from longitudinal photons. We then generate Monte Carlo events which we put into a detector simulation program based on the electromagnetic shower development program EGS [8].

Figure 3b shows the cross section $\gamma\gamma \rightarrow \pi^0\pi^0$ as a function of W integrated over $|\cos\theta^*|$ from 0 to 0.7, where θ^* is the angle between the beam direction and a π^0 measured in the $\pi^0\pi^0$ rest system. The solid line shows a fit with three contributions: a relativistic Breit-Wigner function for the f with mass 1273 MeV and width 178 MeV [9,10,11], the same for a possible S* (980) with mass 980 MeV and width 40 MeV [9], and a straight line to describe the $\pi^0\pi^0$ non-resonant background. The Breit-Wigner functions were folded with Gaussians with widths 22 MeV for the f and 15 MeV for the S* to take the mass resolution into account. We see that the curve does not fit the data well. The f peak seems shifted down by ≈ 40 MeV. A fit with f mass and width as free parameters gives $m = 1238 \pm 14$ MeV and $\Gamma = 248 \pm 38$ MeV (dashed line). We estimate the systematic error of the mass measurement to be 2% or less. This together with the statistical error could account for the observed peak position. We note however that other $\gamma\gamma$ experiments have observed very similarly distorted shapes of the peak [2,3].

In order to measure spin and helicity of the state producing this peak and to correct for events outside the angular acceptance, we investigate the decay angular distribution. Figure 4 shows the acceptance-corrected distribution of $|\cos\theta^*|$. We fit this distribution to the form expected for a spin-2 particle like the f:

$$\frac{dN}{d|\cos\theta^*|} = \sum_{\lambda} N_\lambda \int d\phi \; 2|Y_2^\lambda(\cos\theta^*,\phi)|^2$$

The N_λ, $\lambda = 0,1,2$, are the numbers of events for the different helicities. $\lambda = 1$ can only be produced by longitudinal virtual photons and is expected to be small in our kinematic region. Theoretical models for f production predict $\lambda = 2$ dominance [12].

The fit result and the different helicity contributions are shown as curves in fig. 4. We find that the assumption of total spin 2 gives a good fit and that helicity 2 dominates. The other helicity contributions are $N_0/N_2 = 0.12 \pm 0.39$ and $N_1/N_2 = 0.02 \pm 0.11$.

In a separate fit, we estimate the maximum possible S-wave background by setting $N_1 = N_0 = 0$ and fitting an isotropic contribution N_S. The result is $N_S/N_2 = 0.05 \pm 0.25$.

Assuming that the mass peak is caused by the f resonance, we use the total number of fitted events, $N_0 + N_1 + N_2$, to determine $\Gamma(f \to \gamma\gamma)$. We estimate the number of background events in the f region from adjacent $\pi^0\pi^0$ mass regions to be (10 ± 10)% of the signal. The result is

$$\Gamma_{\gamma\gamma} = 2.9^{+.6}_{-.4} \pm 0.6 \text{ keV}$$

The first error is statistical; it results from the fit of the helicity contributions. The second, systematic error includes the uncertainty of the background determination. For comparison with other experiments, we have determined $\Gamma_{\gamma\gamma}$ also under the assumption $\lambda = 2$, which reduces the statistical error considerably:

$$\Gamma_{\gamma\gamma} = 2.7 \pm 0.2 \pm 0.6 \text{ keV} \qquad (\lambda = 2 \text{ assumed})$$

This agrees well with results from other experiments [1-4].

Other possible contributions to the $\pi^0\pi^0$ final state, some of which might cause a distortion of the f(1270) resonance shape, include:

-- Non-resonant background. The cross section for this process was predicted by Brodsky and Lepage [5] based on QCD. We find that it can produce through interference a large enough shift of the f resonance curve. We do not find the predicted steep W dependence of this cross section, which is however expected to be valid only at high W.

-- The $\varepsilon(1300)$ can produce a similar effect as nonresonant background and is experimentally nearly indistinguishable from it.

-- The S*(980) would show up as a distinct peak rather than a distortion of the f mass. We do not see conclusive evidence for such a signal, and place an upper limit of 0.8 keV (95% C.L.) on $\Gamma(S^* \to \gamma\gamma) \cdot BR(S^* \to \pi\pi)$.

-- Finally, there are predictions of a gluonium state with a mass very close to the f and the same quantum numbers [13]. This state would mix with the ordinary f, thus giving rise to different resonance shapes in different production and decay channels.

With present data we cannot tell how much each of the above reactions contributes to the $\pi^0\pi^0$ yield.

In order to investigate the $\pi^0\eta$ final state, we remove $\pi^0\pi^0$ events to reduce combinatorial background and we tighten the photon identification requirements based on the pattern of energy distribution. We use events in the sidebands next to the $\pi^0\eta$ mass region to estimate the remaining non-$\pi^0\eta$ background. This results in a 7% subtraction in the W region around 1300 MeV. Figure 5 shows the background subtracted $\pi^0\eta$-mass distribution. We see a peak at around 1300 MeV with ~22 events above non-resonant $\pi^0\eta$ background. Identifying this peak as the A_2, we obtain

$$\Gamma(A_2 \rightarrow \gamma\gamma) = 0.77 \pm 0.18 \pm 0.27 \text{ keV}$$

We assumed here a helicity of the A_2 of 2, as there are not enough events to analyze the decay angular distribution. The naive quark model with ideal mixing predicts a ratio of 9/25 = 0.36 for $\Gamma(A_2 \rightarrow \gamma\gamma)/\Gamma(f \rightarrow \gamma\gamma)$. We find 0.29 ± 0.07 ± 0.07 in agreement with the prediction.

If we further remove the events in the $\pi^0\eta$ cluster, we end up with very few events which do not seem to form any cluster. There is no signal for the reaction $\gamma\gamma \rightarrow \eta\eta$ and we obtain an upper limit on the branching ratio $f \rightarrow \eta\eta$:

$$\frac{BR(f \rightarrow \eta\eta)}{BR(f \rightarrow \pi\pi)} < 5\% \text{ (95\% C.L.)}$$

This is less stringent than existing upper limits of 2% [10]. It may however be interesting if one believes that the f signal contains additional unresolved contributions.

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Figure Captions:

1. Distribution of the square of the total transverse momentum of events with 4 photons. The lower histogram shows the same for events where the 4 photons originate from $2\pi^0$'s.

2. Scatter plot of high vs. low $\gamma\gamma$ mass for 4-photon events with $p_T^2 < 0.03$ GeV^2 and $1040 < W < 1480$ MeV (3 combinations per event).

3. a) Distribution of the $\pi^0\pi^0$ mass W, $p_T^2 < 0.03$ GeV^2. The shaded histogram shows non-$\pi^0\pi^0$ background. b) Cross section for $\gamma\gamma \to \pi^0\pi^0$ for $|\cos\theta^*| < 0.7$. The curves are explained in the text.

4. Acceptance-corrected distribution of $|\cos\theta^*|$ for $\pi^0\pi^0$ events in the f mass region (1040-1480 MeV). The solid curve represents the fit explained in the text. The broken curves show the different helicity contributions.

5. Distribution of the $\pi^0\eta$ mass, $p_T^2 < 0.03$ GeV^2, corrected for non-$\pi^0\eta$ background.

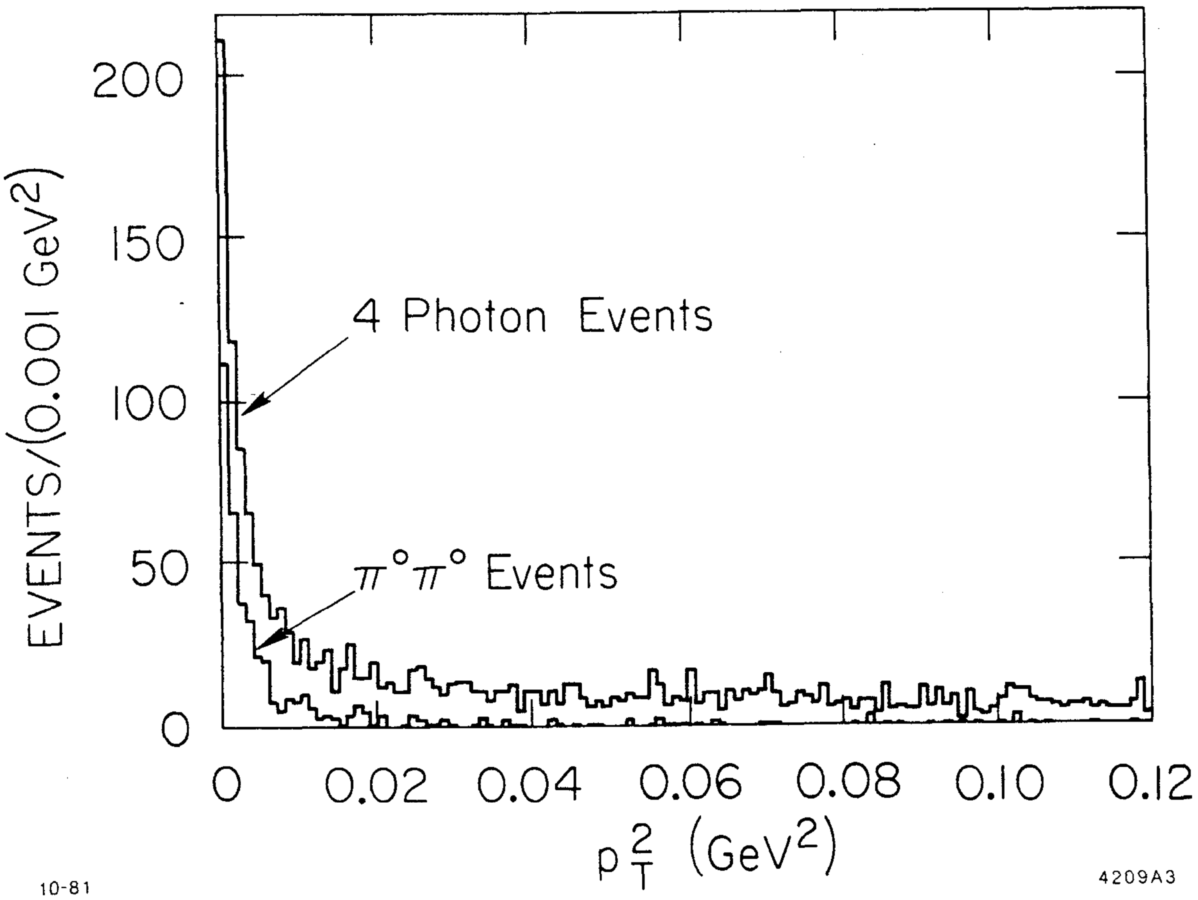
200
150
100
50
0
EVENTS/(0.001 GeV^2)
4 Photon Events
$\pi^\circ\pi^\circ$ Events
0
0.02
0.04
0.06
0.08
0.10
0.12
p_T^2 (GeV^2)
10-81
4209A3

Fig. 1

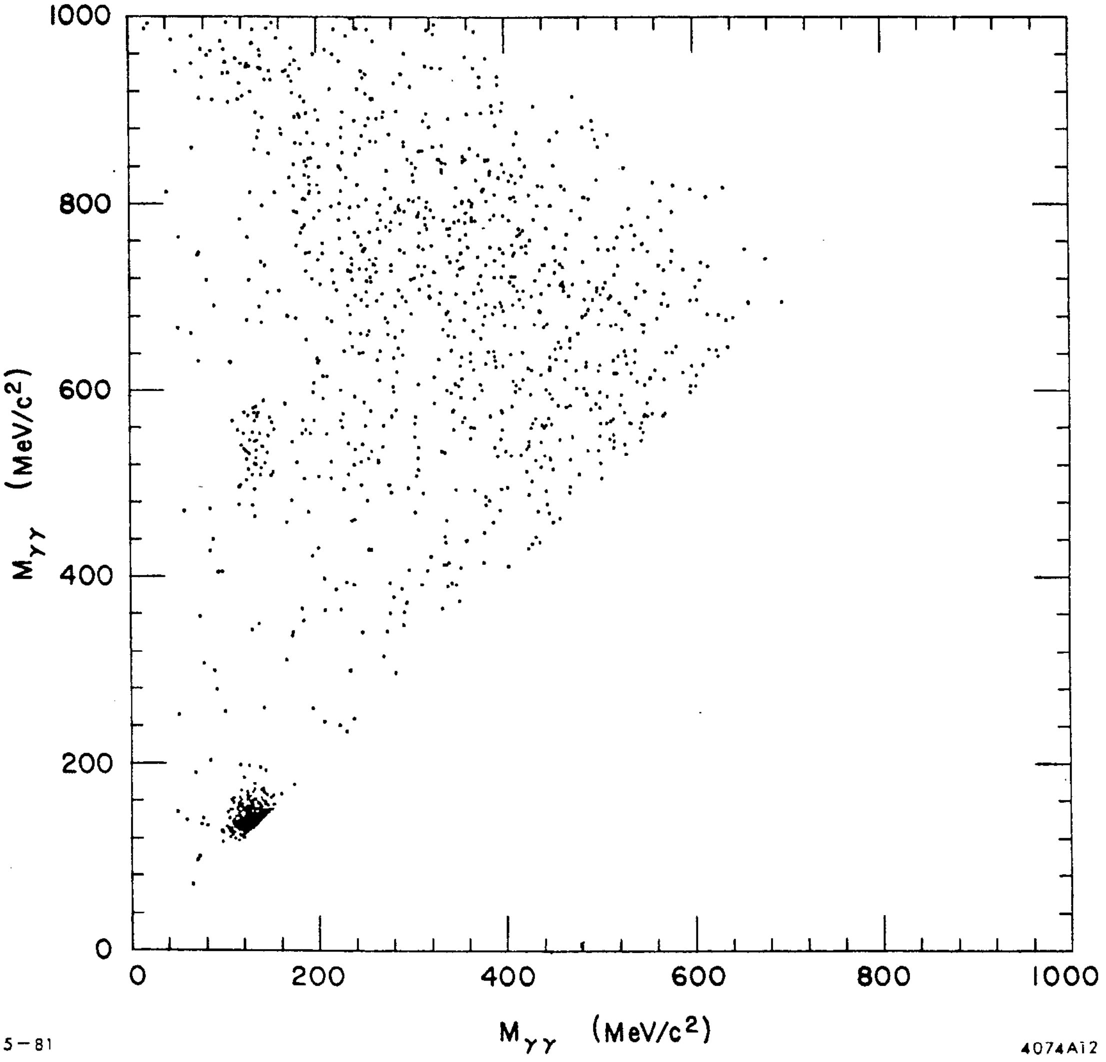
1000
800
600
400
200
0
0
200
400
600
800
1000
$M_{\gamma\gamma}$ (MeV/c^2)
$M_{\gamma\gamma}$ (MeV/c^2)
5-81
4074A12

Fig. 2

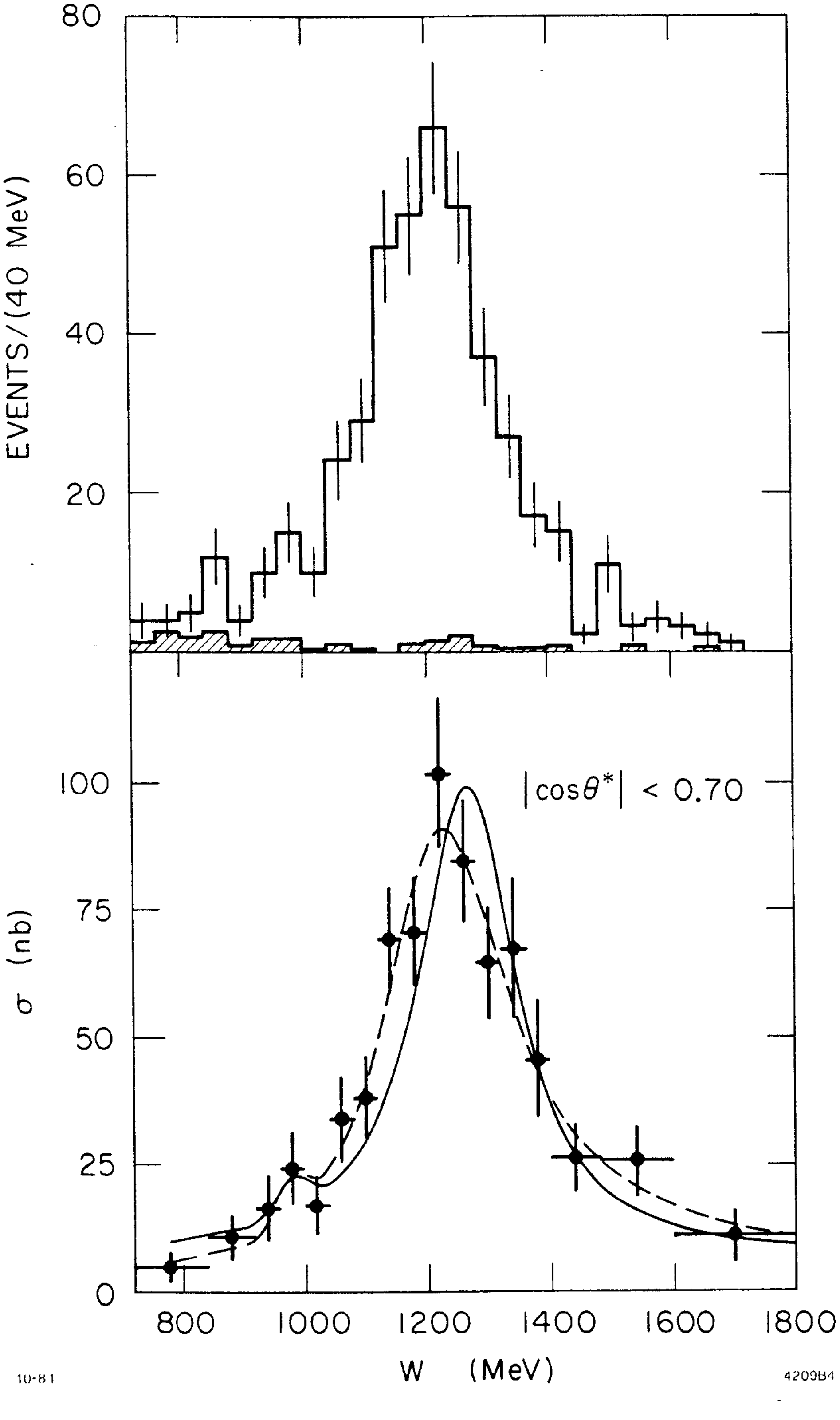
80
60
40
20
EVENTS/(40 MeV)
100
75
50
25
0
σ (nb)
|cosθ*| < 0.70
800
1000
1200
1400
1600
1800
W (MeV)
10-81
4209B4

Fig. 3

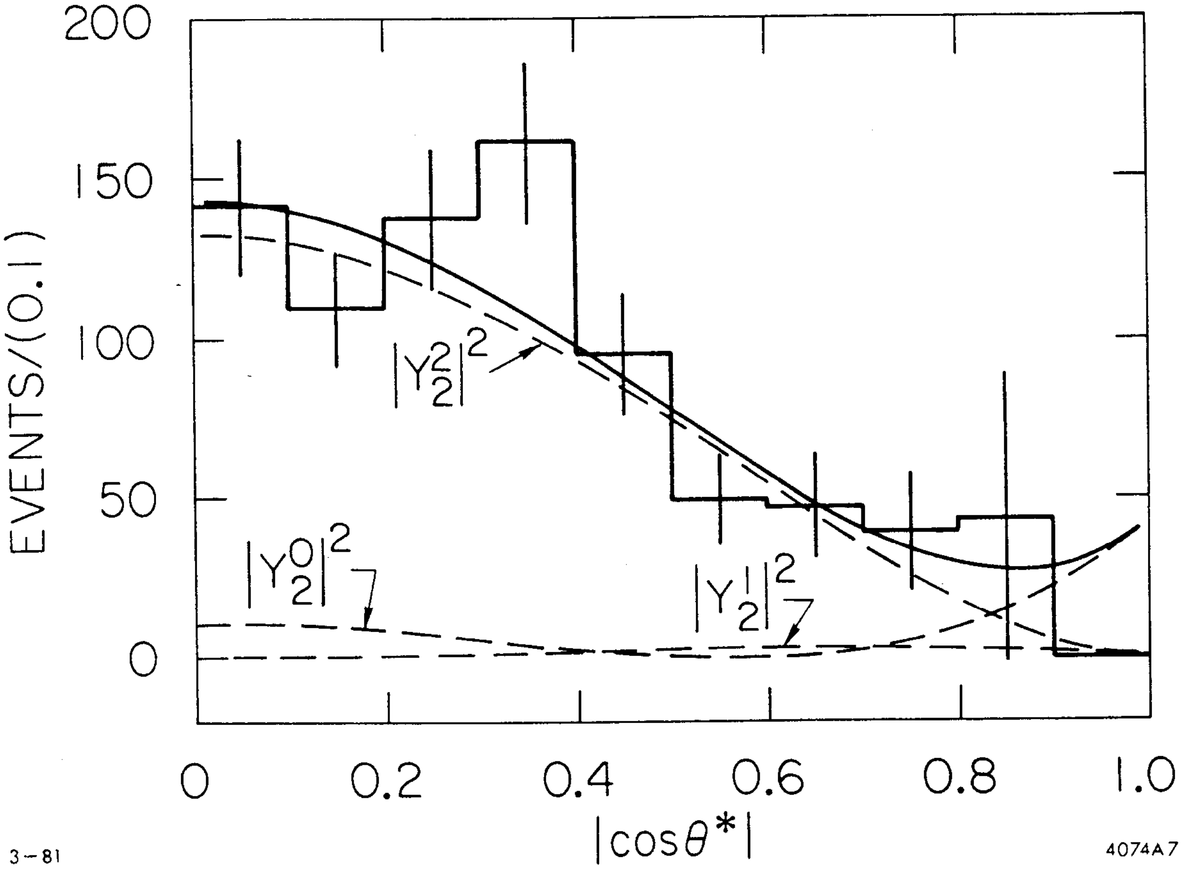
200
150
100
50
0
EVENTS/(0.1)
$|Y_2^2|^2$
$|Y_2^0|^2$
$|Y_2^1|^2$
0
0.2
0.4
0.6
0.8
1.0
$|\cos\theta^*|$
3-81
4074A7

Fig. 4

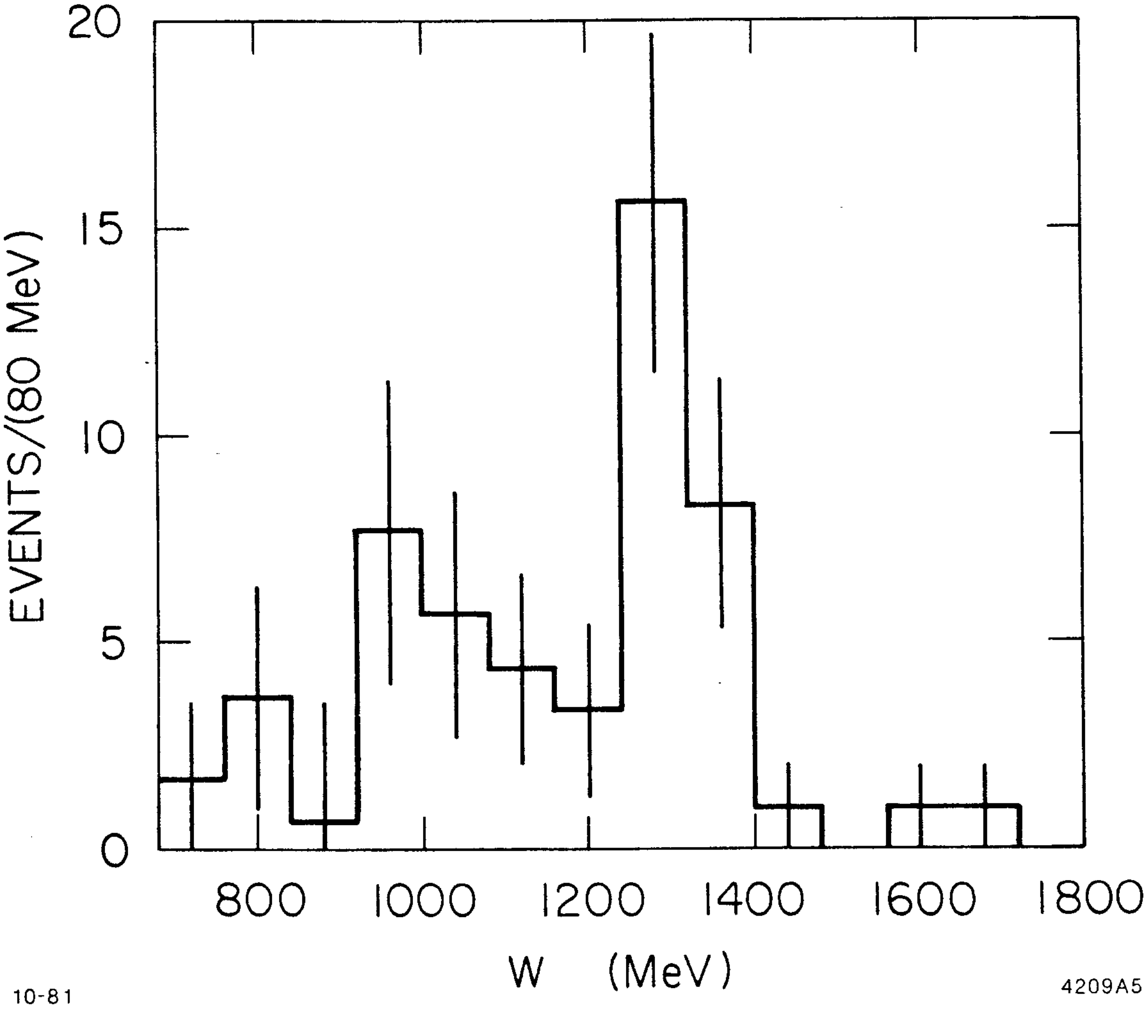
20
15
10
5
0
EVENTS/(80 MeV)
800
1000
1200
1400
1600
1800
W (MeV)
10-81
4209A5

Fig. 5