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PION PAIR PRODUCTION IN PHOTON-PHOTON COLLISIONS AT SPEAR*

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ABSTRACT

We report a measurement of the cross section for the process $\gamma\gamma \rightarrow \pi^+\pi^-$ at invariant masses 500 MeV/c^2 < $m_{\pi\pi}$ < 2000 MeV/c^2. A value for the radiative width of the f(1270) tensor meson $\Gamma_{f \rightarrow \gamma\gamma} = 3.6 \pm 0.3 \pm 0.5$ keV (helicity $\lambda = 2$) has been obtained from a fit to the observed $\pi\pi$ mass spectrum.

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The process $\gamma\gamma \to \pi\pi$ is an ideal place to study the properties of $J^C = \text{even}^+$ resonances[1] and, at high masses, it becomes a testing ground for QCD[2]. In this Letter we present a study of the process

$$e^+e^- \to e^+e^-\pi^+\pi^- \tag{1}$$

at invariant masses 500 MeV/$c^2 \leq m_{\pi\pi} \leq$ 2000 MeV/c^2. A strong signal at the well-known f(1270) resonance occurs midway in this region. Below the resonance the cross section for reaction (1) is found to be large ($\sim$100nb) while at higher masses it falls rapidly.

The data presented here were taken with the SLAC-LBL Mark II detector[3] at SPEAR with center-of-mass energies between 4.5 GeV/c^2 and 6.5 GeV/c^2. The accumulated luminosity was 13,200 nb^{-1}. Events were selected that contained two detected tracks of opposite charge and no other detected charged particles. Separation of reaction (1) from the large background of two-photon initiated QED processes

$$e^+e^- \to e^+e^- + (e^+e^- \text{ or } \mu^+\mu^-) \tag{2}$$

has been done using the signals from the Mark II liquid argon system. To ensure that each track was within the fiducial acceptance of the liquid argon calorimeters, the laboratory polar angle of each track was required to satisfy $|\cos\theta_L| \leq 0.6$. The outgoing small angle beam electrons were not detected.

Backgrounds to process (1), other than the QED processes (2), include beam-gas events, higher multiplicity two-photon processes, and events from the e^+e^- annihilation channel. The beam-gas contamination was minimized by requiring the vertex of each event to be in the measured interaction region. Sideband subtractions were then made to correct the data for the remaining beam-gas background. Separation of the desired two-prong final state from beam-beam backgrounds was achieved by accepting only those events for which the net transverse momentum of the observed prongs, $|\Sigma\vec{p}_T|$, was less than 100 MeV/c. The two-photon production of the $\eta'(958)$ and of the four pion final state ($\rho^o\rho^o$) produce a cluster of events near the rho mass. Since these processes have previously been observed in the same detector[3a,4], a direct computation of the feed-down from these sources that survives the p_T cut has been made with a Monte Carlo. Remaining backgrounds were determined by fitting the observed $|\Sigma\vec{p}_T|$ distributions in various mass bins with a combination of the shape expected from the photon-photon processes (1) and (2) and the shape expected from events produced in the annihilation channel. The two distributions were determined by Monte Carlo simulations. The detected two-prong mass spectrum is shown in Fig. 1 along with the various contributions as they have been calculated or measured. The non-QED backgrounds are only a few percent of the total two-prong sample, but they become 5-30% in the raw $\pi\pi$ signal that we will present below.

The QED curve shown in Fig. 1 was computed by Monte Carlo[5] and normalized by the measured luminosity of the experiment. Because this normalization is uncertain by ±6%, the extraction of the $\pi\pi$ signal by a direct subtraction of the expected QED from the observed spectrum is impossible. To enhance the $\pi\pi$ signal relative to the QED background, we make use of the relatively large probability that a low momentum pion will interact in the magnet coil which is positioned between the central drift chamber and the liquid argon calorimeters. Unlike the electromagnetic interactions of electrons and muons, the hadronic nature of these pion interactions leads to a substantial probability that a pion will not deposit any energy in the liquid argon along the track trajectory. Accordingly, we identify a particle as a pion if it is assigned less energy by the liquid argon tracking programs than would be expected from a minimum ionizing particle. The event selection criteria include geometrical cuts to guarantee that all accepted events contain two-prongs within the fiducial acceptance of the calorimeters. Sources of pions, muons, and electrons that have been unambiguously identified without the use of the liquid argon signals have been used to calibrate the resulting pion identification probability and the electron and muon misidentification probabilities. The results are given in Fig. 2a. The pion efficiency for momenta below 400 MeV/c was checked using a large sample of two-prong beam-gas events. These events are relatively free of contamination by electrons and muons. Events containing protons, identified by time of flight, were removed. The agreement of the pion efficiency obtained from these events with that in Fig. 2a was found to be better than 10%.

The pion identification criteria have been applied to each event in the two-prong sample (Fig. 1). The histogram in Fig. 2b shows the number of these events that contain at least one identified pion. The points with errors in this figure are the numbers of events that would have satisfied these criteria if the two-prong sample consisted of only electron and muon pairs (reactions 2 above). To compute these points the QED Monte Carlo[5] was used to determine the expected ratio of detected electron pairs to detected muon pairs and then each event in the two-prong sample was weighted by the probability that it is a misidentified electron pair plus the corresponding probability that it is a misidentified muon pair. A definite excess of events at $m_{\pi\pi} \gtrsim 750$ MeV/c^2 is seen from which we extract the $\pi^+\pi^-$ signal. This analysis has been carried out in a completely parallel manner with events that have been required to consist of two identified pions. This latter sample contains negligible QED background at $m_{\pi\pi} \gtrsim 700$ MeV/c^2.

The two-photon cross section $\sigma_{\gamma\gamma \to \pi^+\pi^-}$ is related to the measured cross section $\sigma_{ee \to ee\pi\pi}$ by[6]

$$\frac{d\sigma_{ee \to ee\pi\pi}}{ds_{\pi\pi} d\Omega^*} = \left(\frac{\alpha}{\pi}\right)^2 \frac{f\left(E_b, s_{\pi\pi}\right)}{s_{\pi\pi}} \frac{d\sigma_{\gamma\gamma \to \pi\pi}}{d\Omega^*} \quad , \qquad (3)$$

where $s_{\pi\pi}$ is the $\gamma\gamma$ invariant mass squared, E_b is the beam energy, and $d\Omega^* = d(\cos\theta^*)\, d\phi^*$ is the $\gamma\gamma$ c.m. solid angle element. With the restriction $|\cos\theta_L| \leq 0.6$ there is not much information in the c.m. angular distribution and, so, shown in Fig. 3 is the acceptance corrected cross section $\sigma_{\gamma\gamma \to \pi\pi}(m_{\pi\pi})$ integrated over the range $|\cos\theta^*| \leq 0.35$. The agreement between the results extracted with the two levels of pion identification indicates that the $\pi\pi$ final state has been accurately separated from the QED background. Also included in Fig. 3 is a data point at high mass that was measured using the Mark II muon and liquid argon systems to directly reject muon and electron pairs. This point has been corrected for all backgrounds with previously described techniques, and the pion efficiencies and electron and muon misidentification probabilities have been studied with the test samples previously described. The data tend to fall below the Born cross section[7] at masses $\gtrsim 1.5$ GeV/c^2. The prediction of a recent QCD calculation[2] also shown in the figure, indicates that data from higher beam energies will be needed in order to reach the interesting region at masses above the tail of the f(1270).

The two-prong sample (Fig. 1) exhibits a large enhancement over the QED background in the mass region of the f(1270) meson. We have previously reported[8] that this structure is not consistent with the d-wave Breit-Wigner expected from parameters of the f determined in hadronic reactions[9]. Since we now have a more complete measurement of the $\pi\pi$ mass spectrum it is possible to investigate the hypothesis that the Breit-Wigner for the resonant amplitude is modified by interference with the non-f background[10]. Although it contains a large QED component, the spectrum in Fig. 1 gives the best accuracy for this study. We use the detected spectrum of identified $\pi\pi$ events (with $|\cos\theta_L| < 0.6$) to normalize the QED curve in Fig. 1; this normalization is determined so that the excess of two-prong events over QED in the region 700 MeV/$c^2 \leq m_{\pi\pi} \leq$ 950 MeV/c^2 is consistent with the measured number of $\pi\pi$ events in the same mass region. Shown in Fig. 4 is the resulting non-QED spectrum in the vicinity of the f. Errors in the measured $\pi\pi$ yield result in a ±4% uncertainty in the QED normalization which is taken into account in the fitting procedure described below.

We fit the spectrum in Fig. 4 with the sum

$$\pi\pi(m) = f(m) + \alpha.C(m) + 2\beta.\cos\delta(m).\sqrt{\alpha.C(m).f(m)} + f'(m) \qquad (4)$$

In this expression f(m) is the contribution to the rate appropriate for a relativistic d-wave Breit-Wigner with resonance mass and width equal to 1271 MeV/c^2 and 180 MeV/c^2 respectively. All relevant photon flux factors have been included, and we assume that the f is only produced with helicity ± 2. Two extreme cases for the shape of the non-f $\pi\pi$ production C(m), were considered. The first was the simple Born term at all masses, and the second consisted of using the Born term at masses below 1 GeV/c^2, but replacing it with the QCD prediction at higher masses. (See Fig. 3.) The third term in Eq.(4) is an interference between the first two terms. We take the non-f amplitude to be real (like the Born term) so that the relative phase of these two terms is equal to the resonant phase shift $\delta(m)$, modulo π. Since we are not able to do a partial wave analysis for the $\pi\pi$ spectrum, the parameter β has been included and we do fits for various values $-1 \leq \beta \leq 1$. The last term in Eq.(4) represents the contribution made by the process $\gamma\gamma \to f'(1515) \to K^+K^-$ where the kaons have been misidentified as pions. If we use the SU(3) expectation for the ratio $\Gamma_{f' \to \gamma\gamma}/\Gamma_{f \to \gamma\gamma}$ (= 0.14 assuming an m^3 phase space correction) and take the branching ratio $f' \to K^+K^-$ to be 50%, then a Monte Carlo calculation, which includes losses due to kaon decays, gives this term to be 3.8% of the f. The yield f' events is shown in Fig. 4 for the $\gamma\gamma$ partial width of the f obtained below.

The fitted parameters are the normalization of the non-f background (α) and the $\gamma\gamma$ partial width of the f(1270). Although α varies by a factor of ≈ 1.5 as the QED normalization is varied, the $\gamma\gamma$ partial width of the f depends very little on either the QED normalization, the value of β, or the choice for the continuum C(m). The fits give (for helicity $\lambda = \pm 2$)

$$\Gamma_{f \to \gamma\gamma} = 3.6 \pm 0.3(\text{statistical}) \pm 0.5(\text{systematic})\ \text{keV}, \qquad (5)$$

where the systematic error includes contributions from uncertainties in the luminosity measurement and acceptance calculation, as well as contributions from the fitting procedure. A value of the partial width $6.8 \pm 0.6 \pm 1.0$ keV is obtained if the f is assumed to be produced only with helicity $\lambda = 0$. We display on Fig.4 the results of fits with $\beta = 0$, 0.5, and 1.0 and with C(m) given by the Born term. If hypothesis (4), with C(m) given by the Born term, is correct, then the data require $\beta \geq 0.10$ (95% CL). If the background is parameterized by the QCD prediction above $m_{\pi\pi} = 1.0\ \mathrm{GeV/c^2}$ then the fitted values of $\Gamma_{f \to \gamma\gamma}$ increase by $\approx 10\%$ (included in the systematic error quoted above), and the data require a somewhat larger value of β. The contribution of the f to the $\pi\pi$ spectrum (i.e., $\pi\pi(m) - \alpha.C(m) - f'(m)$ in eq. 4) as determined by this latter fit is given in Fig. 3 for $\beta=0.5$.

Our result (5) can be compared with previously reported values of $\Gamma_{f \to \gamma\gamma} = 2.3 \pm 0.5 \pm 0.35$ keV obtained at PETRA[11] and $\Gamma_{f \to \gamma\gamma} = 9.5 \pm 3.9 \pm 2.4$ keV from another SPEAR experiment[12]. Theoretical predictions of the radiative width of the f are numerous[1] and vary from 1 keV to 20 keV. Our measurement clearly favors the lower end of this range.

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Figure Captions

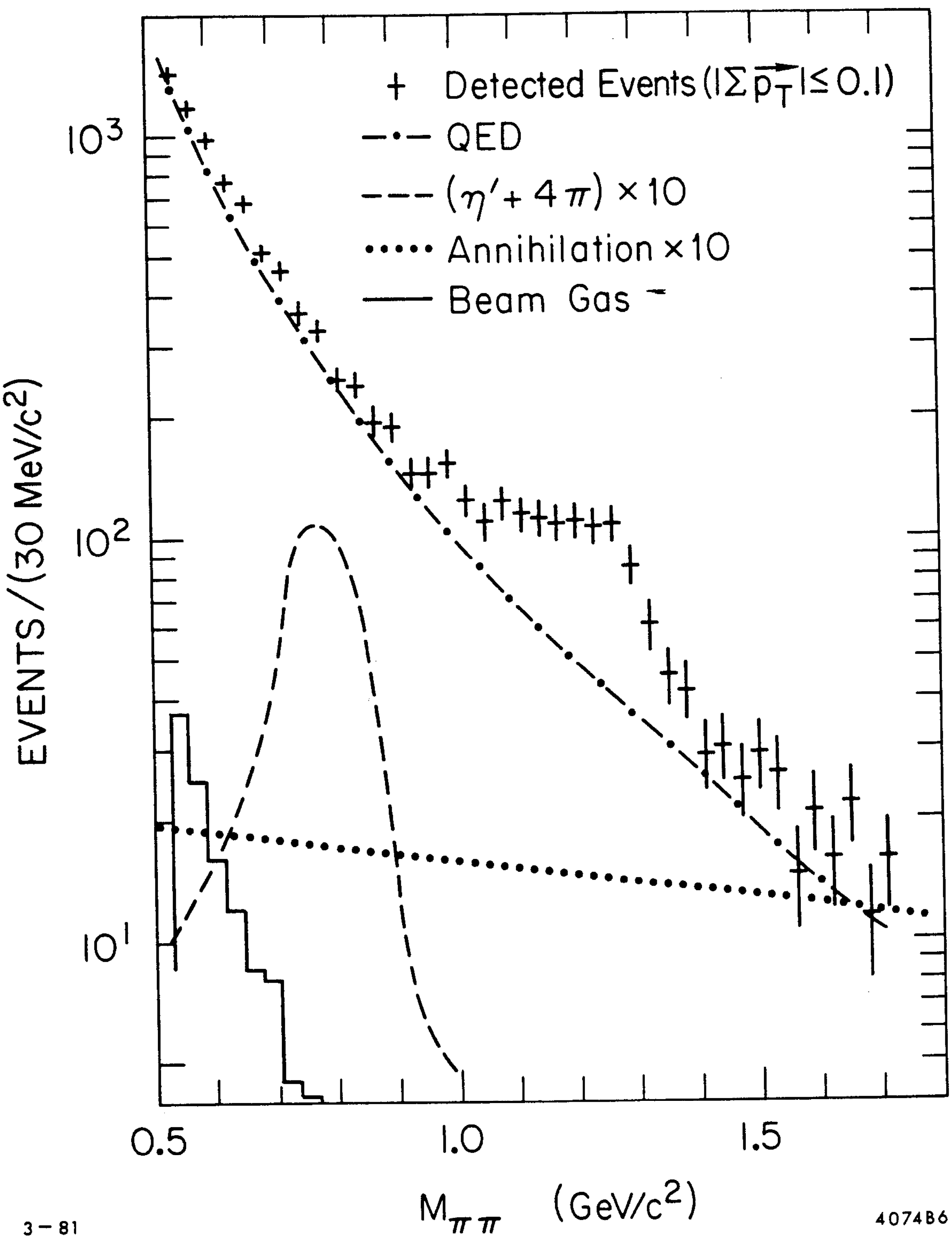
Fig. 1. The observed two-prong mass spectrum. The curves represent various contributions as measured and/or computed.

Fig. 2. (a) Pion identification efficiency and muon and electron misidentification probabilities. The muons are cosmic rays and the electrons come from photons that convert in the beam pipe.

(b) Raw $\pi^+\pi^-$ signal from events with at least one identified pion. The points with errors give the yields that would be expected from QED in the absence of pion pair production. Also shown is the $\pi^+\pi^-$ identification probability.

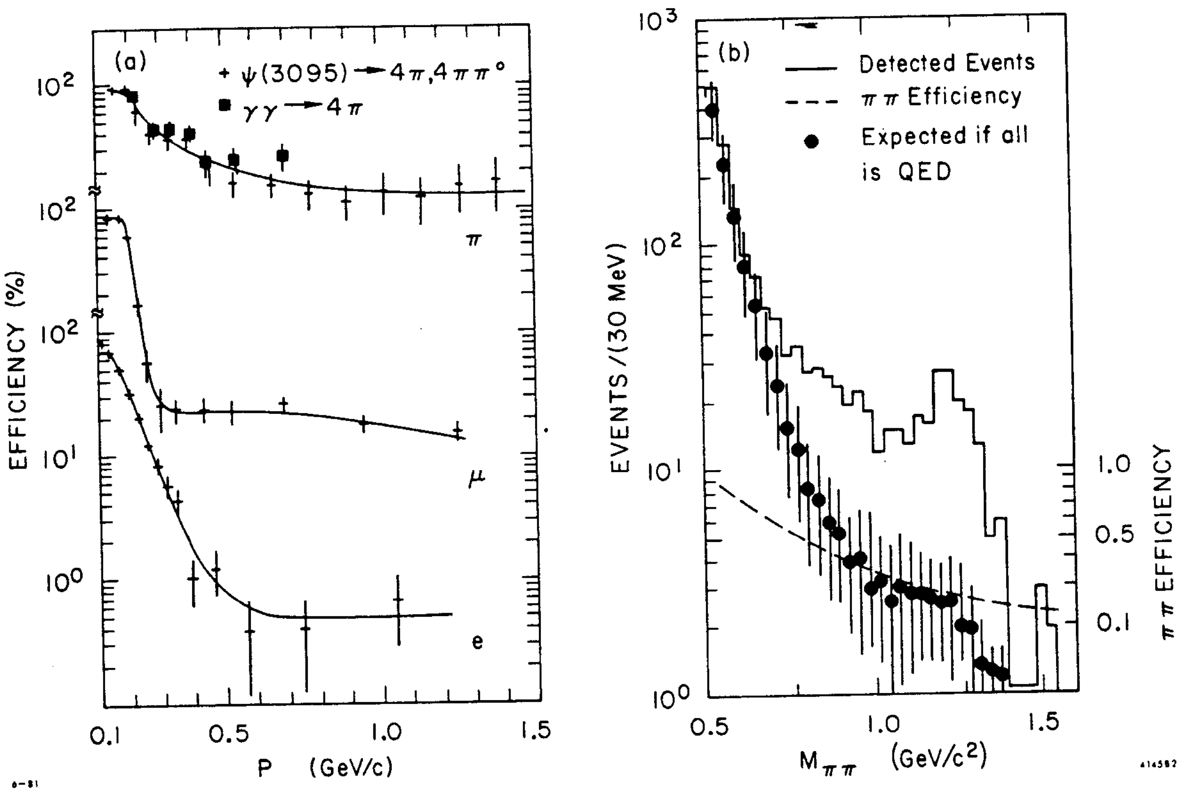
Fig. 3. The cross section $\sigma_{\gamma\gamma \to \pi\pi}$ integrated over the range of c.m. angles $|\cos\theta^*| \leq 0.35$. The curves are: —— Born, ——.—— QCD, and --- f(1270).

Fig. 4. The non-QED spectrum near the f(1270) mass. The number of misidentified $\gamma\gamma \to f'(1515) \to K^+K^-$ expected from SU(3) is shown for a branching ratio $BR(f' \to K^+K^-) = 50\%$. The remaining curves are described in the text.



Detected Events (|Σ $\vec{p_T}$| ≤ 0.1)
QED
(η′ + 4π) × 10
Annihilation × 10
Beam Gas
EVENTS/(30 MeV/c²)
10³
10²
10¹
0.5
1.0
1.5
$M_{\pi\pi}$ (GeV/c²)
3 − 81
407486

Fig. 1



(a)
+ ψ(3095) → 4π,4ππ°
■ γγ → 4π
EFFICIENCY (%)
π
μ
e
P (GeV/c)
(b)
Detected Events
ππ Efficiency
Expected if all is QED
EVENTS /(30 MeV)
ππ EFFICIENCY
M ππ (GeV/c²)

Fig. 2

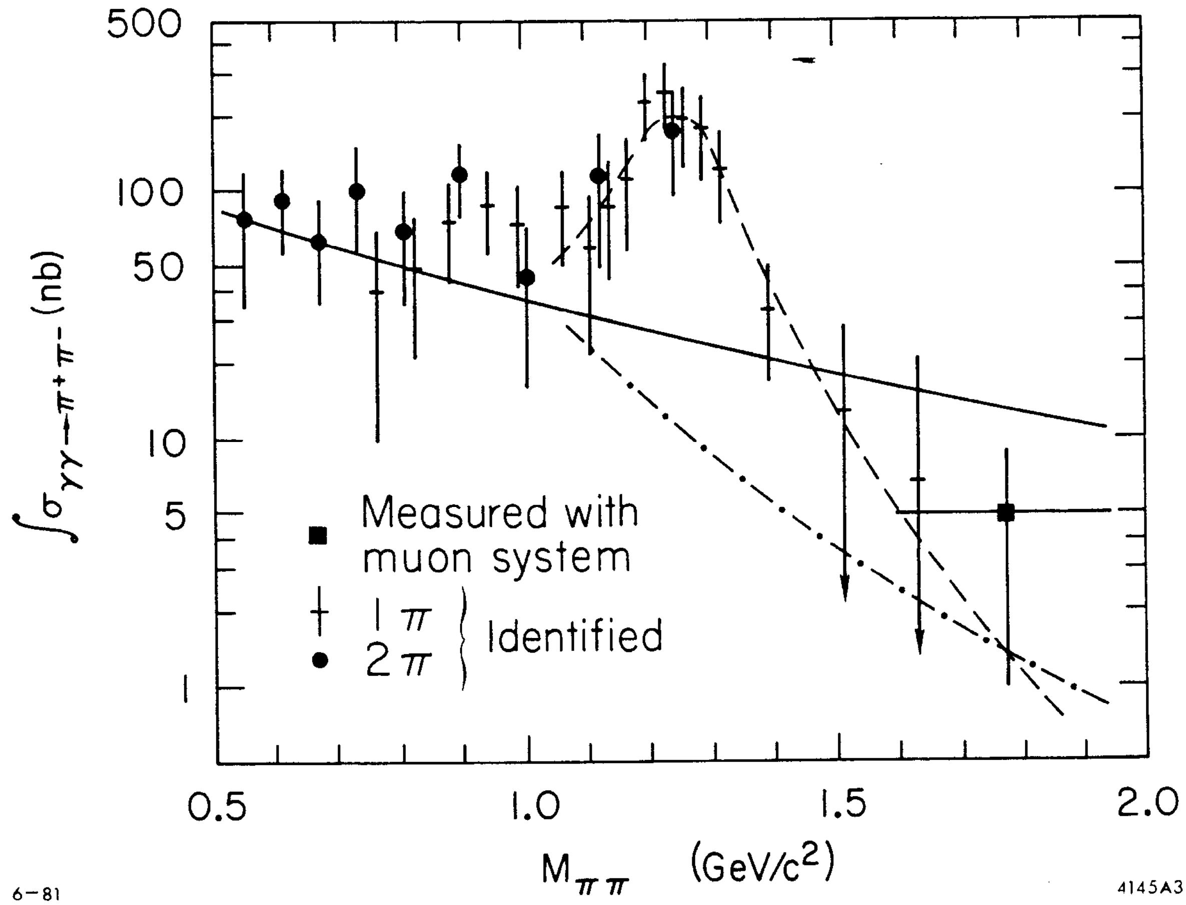
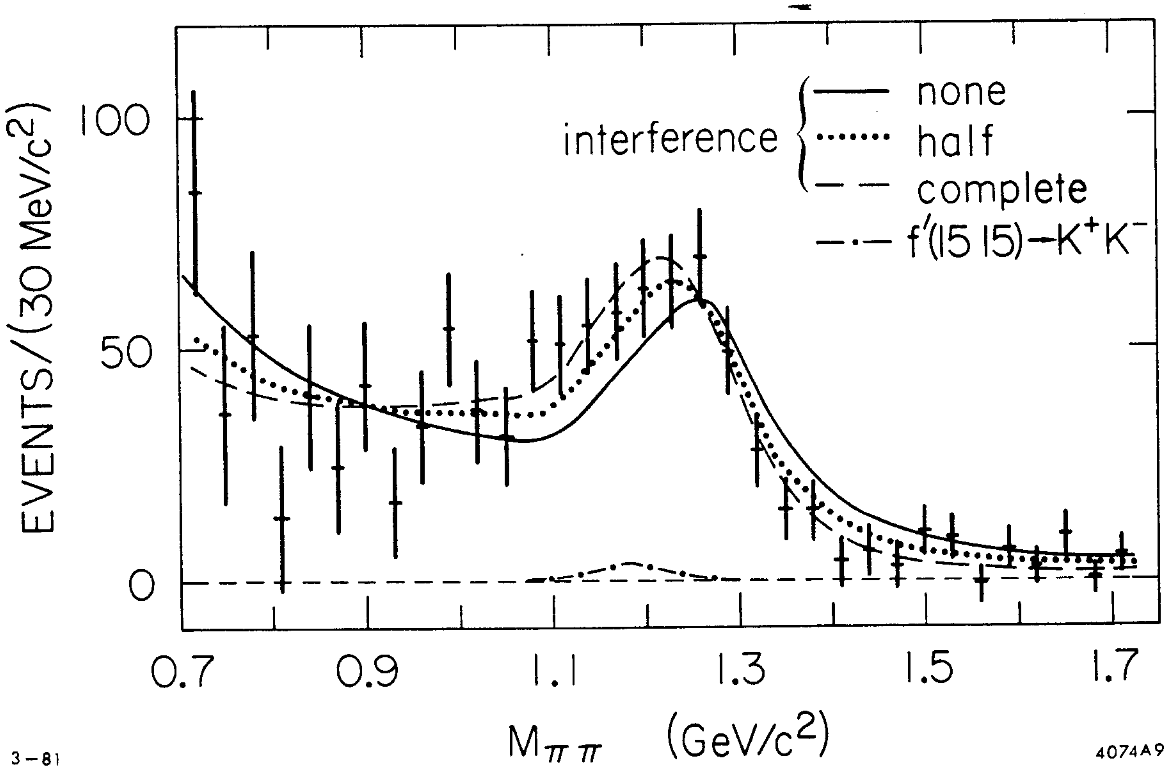

500
100
50
10
5
1
$\int \sigma_{\gamma\gamma \to \pi^+\pi^-}$ (nb)
Measured with muon system
1 π
2 π
Identified
0.5
1.0
1.5
2.0
$M_{\pi\pi}$ (GeV/c^2)
6-81
4145A3

Fig. 3



interference
none
half
complete
f'(1515)→K⁺K⁻
100
50
0
0.7
0.9
1.1
1.3
1.5
1.7
EVENTS/(30 MeV/c²)
Mππ (GeV/c²)
3-81
4074A9

Fig. 4