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Pion-Pair Production from $\gamma\gamma$ Interactions at PEP and the Radiative Width of the f^0 Meson*

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ABSTRACT

Results are presented of an untagged $e^+e^- \rightarrow e^+e^- + \pi^+\pi^-$ experiment performed at PEP with the DELCO detector. In the invariant-mass range $0.7 \leq W_{\pi\pi} < 2.0\,\mathrm{GeV/c^2}$, the QED e^+e^- background is identified and eliminated, and both the $\pi^+\pi^-$ predictions and the $\mu^+\mu^-$ and K^+K^- background subtractions are normalized to the measurement of the e^+e^- events. The results agree with a simple model of superposition and interference of the $f^0(1270)$ resonance, produced with helicity 2, with a Born-term continuum. From a fit of the model to the data, the radiative width of the f^0 is determined to be $\Gamma_{f^0\rightarrow\gamma\gamma} = 2.70 \pm 0.21\,\mathrm{keV}$.

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The two-photon process $e^+e^- \to e^+e^- + \pi^+\pi^-$ has been studied by several experiments.[1] A structure in the $\pi^+\pi^-$ invariant-mass spectrum was found near 1 GeV and attributed to the reaction $\gamma\gamma \to f^0(1270) \to \pi^+\pi^-$. In those experiments, because it was not possible to separate lepton pairs from the $\pi^+\pi^-$ signal in the range of the resonance, it was necessary to subtract the large QED background and derive the $\pi^+\pi^-$ cross section using a normalization generally determined from the small amount of data at high invariant mass, which was assumed to be due only to lepton production.

In the DELCO experiment the process $e^+e^- \to e^+e^- + e^+e^-$ is well separated from others, even at low momenta, by a clean identification of the electrons. For background rejection in such an untagged experiment, events are selected with limited total transverse momentum. For the resulting sample of quasi-real photon interactions the $e^+e^- \to e^+e^- + X$ cross section may be factorized into a product of a $\gamma\gamma$ luminosity function and a $\gamma\gamma \to X$ cross section. Then the e^+e^- production can be used to measure the experimental $\gamma\gamma$ luminosity function corresponding to a particular acceptance, allowing normalization of other channels. Thus the electron identification reduces the statistical error by permitting elimination instead of subtraction of the e^+e^- part of the QED background, and it reduces the systematic errors by providing a measurement of the experimental $\gamma\gamma$ luminosity to be used in subtracting the remaining backgrounds and in measuring the $\gamma\gamma \to \pi^+\pi^-$ cross section.

The DELCO experiment at PEP has been described previously.[2] For the process of interest here, the key element of the detector is the threshold Čerenkov counter, which provides clean identification of electrons below the muon threshold at 2.0 GeV/c and within an angular acceptance of $|\cos\theta| \leq 0.6$, relative to the beam direction. The momenta of charged particles are measured by the tracking system, which consists of an open-geometry magnet with drift chambers located before and after the Čerenkov counters. By making cuts on the Čerenkov pulse heights of the two prongs in each event, we can divide the untagged $\gamma\gamma \to x^+x^-$ candidates into an electron pair sample and a sample with no electrons.

We select the untagged $\gamma\gamma \to x^+x^-$ candidates first by requiring two prongs of opposite charge in the central detector with no pulse height above noise level in the shower counters located in the forward and backward regions on the magnet pole tips. In order to select pairs of tracks originating in the beam-beam interaction region and remaining within the Čerenkov and trigger acceptance, we require for each track

$$|\Delta z| \leq 4.0\,\mathrm{cm}, \qquad \Delta r \leq 0.5\,\mathrm{cm}, \quad \text{and} \quad |\cos\theta| \leq 0.6,$$

where $|\Delta z|$ and Δr are the distances of a track from the beam interaction centroid, respectively, along the beam and transverse to the beam, and θ is the track's polar angle. Events produced by the interaction of quasi-real photons are then selected by the requirements

$$\cos\Delta_{1,2} \leq 0.98, \qquad |\vec{p}_t^{\,1} + \vec{p}_t^{\,2}|/W \leq 0.2, \text{ and } \quad 0.6 \leq W \leq 2.6\,\mathrm{GeV/c^2},$$

where $\Delta_{1,2}$ is the acolinearity angle of the pair, and $\vec{p}_t$ is a track's momentum component transverse to the beam. W is the invariant mass of the pair, calculated by assuming electron masses for the electron sample and pion masses for all other events.

The e^+e^- sample is compared with QED predictions using the Double-Equivalent-Photon Approximation (DEPA) with a Weizsäcker-Williams photon spectrum.[3] The calculation is done both by analytic integration of the factorized cross section over the detector acceptance[4] and by Monte Carlo generation[5] of events within the acceptance, where the latter calculation allows for simulation of the detector resolution and efficiency. Both calculations agree[6] well with the experimental distributions. The agreement has been checked to be independent of the details of the cuts. As an example, figure 1 shows a comparison of the data with calculations of the W and p_t distributions with the following additional requirement, designed to give an acolinearity cut which corresponds to a simple integration limit in the analytic calculation:

$$\frac{\sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2} \geq 0.13$$

The data in figure 1 have been corrected, by no more than 8% in any single bin, for a small trigger inefficiency for low momentum particles and an inefficiency of the Čerenkov identification for tracks which have their polar angle near 90 degrees.

In the analysis of the $\pi^+\pi^-$ pairs we avoid the region of trigger and Čerenkov inefficiency and impose additional constraints on $\cos\theta$ and W so that $0.05 \leq |\cos\theta| \leq 0.60$ for each track and $0.7 \leq W \leq 2.0\,\mathrm{GeV/c^2}$. Within these cuts the efficiency for selecting non-electron events is 0.97. Applied to the electron pair sample, these cuts yield 10913 events with an identification efficiency of 0.98. Using the DEPA Monte Carlo, we determine the integrated effective luminosity for observing two prongs within the acceptance to be $\mathcal{L}^{eff} = \epsilon\mathcal{L}(e^+e^-) = 43.4 \pm 0.4\,(\mathrm{stat.})\,\mathrm{pb}^{-1}$, where ϵ is the two prong detection efficiency.

From the non-electron event sample $\mu^+\mu^-$ and K^+K^- contaminations are subtracted and the results compared with the $\pi^+\pi^-$ predictions, using the same DEPA Monte Carlo $\gamma\gamma$ generator for both signal and background calculations.

The simple model of the $\gamma\gamma$ hadronic-pair cross section[7] involves a superposition of a continuum Born cross section with spin-2 resonances produced with helicity 2, including interference between the helicity-2 components, according to

$$\frac{d\sigma}{d\Omega} = \left|F_B^{\lambda=0}\right|^2 + \left|F_B^{\lambda=2} + F_R\right|^2,$$

where the relative phase of the helicity-2 amplitudes gives constructive interference below the f^0 and destructive interference above. Though we cannot from our data verify that the f^0 is produced with helicity 2, there are theoretical[8] and experimental[9] reasons for assuming that to be true for the tensor mesons. F_B^λ and F_R are, respectively, the amplitudes of the Born term in helicity λ and the resonances in helicity 2, as follows:[10]

$$F_B^{\lambda=0} = \frac{\alpha}{W} \cdot \sqrt{\frac{\beta}{2}} \cdot \frac{1-\beta^2}{1-\beta^2\cos^2\theta}$$

$$F_B^{\lambda=2} = \frac{\alpha}{W} \cdot \sqrt{\frac{\beta}{2}} \cdot \frac{\beta^2(1-\cos^2\theta)}{1-\beta^2\cos^2\theta} \cdot e^{2i\phi}$$

$$F_R = \frac{1}{W} \cdot \frac{[8\pi(2J+1)W_0\Gamma_{\gamma\gamma}W\Gamma_{x^+x^-}]^{\frac{1}{2}}}{W_0^2 - W^2 - iW_0\Gamma_{tot.}} \cdot Y_J^2(\theta,\phi).$$

The angles θ and ϕ are, respectively, polar and azimuthal angles of the particles, x^+x^-, defined with respect to the beam direction in the $\gamma\gamma$ center of mass, and $\beta = p/W$, where $p = \frac{1}{2}\sqrt{W^2 - 4m_x{}^2}$. We define $\Gamma_{x^+x^-} = \mathrm{B.R.}(x^+x^-) \cdot \Gamma_{tot.}$, and $\Gamma_{tot.}$ is parameterized as[11]

$$\Gamma_{tot.} = \left(\frac{p}{p_0}\right)^5 \cdot \frac{(p_0 r_0)^4 + 3(p_0 r_0)^2 + 9}{(p r_0)^4 + 3(p r_0)^2 + 9} \cdot \Gamma_0,$$

where $r_0 = 1\,\mathrm{fermi}$, $p_0 = \frac{1}{2}\sqrt{W_0^2 - 4m_x{}^2}$, and W_0 and Γ_0 are, respectively, the nominal mass and total width of the resonance.[12] The K^+K^- subtraction includes contributions from the f^0 (1270), f'^0 (1515), and A_2 (1320) with radiative widths as determined by TASSO.[13] The only resonance included in the $\pi^+\pi^-$ prediction is the f^0.

With the assumption of equal detection efficiencies for all particle types, figure 2 shows the invariant-mass distribution of the data sample with electron pairs removed. Also shown are the predicted $\mu^+\mu^-$ and K^+K^- contaminations, which must be subtracted to give the $\pi^+\pi^-$ spectrum. A structure is observed near $1.2\,\mathrm{GeV/c^2}$ above a large $\pi^+\pi^-$ continuum. When this spectrum is fitted to the model with the radiative width as the only free parameter, the statistical error for $\Gamma_{f^0\to\gamma\gamma}$ is found to be $0.05\,\mathrm{keV}$.

In order to take into account small differences in detection efficiency for the various particle types and the statistical uncertainty in $\mathcal{L}^{eff}$, we introduce relative efficiencies for muons and pions with respect to electrons,[7] which are estimated from the data to be within the ranges

$$1.00 < \frac{\epsilon_\mu}{\epsilon_e} < 1.02, \text{ and } \quad 0.95 < \frac{\epsilon_\pi}{\epsilon_e} < 1.00 .$$

The systematic error due to these uncertainties is accounted for in all of the fits discussed below by allowing the relative efficiencies to vary within the given ranges.

To check the consistency of the model and evaluate its contribution to the systematic error in the measurement of the radiative width, we first make a fit in which we introduce an additional factor, α_B, into the overall normalization of the Born term and vary it as a free parameter. The fit over the entire range of W gives the result $\alpha_\mathrm{B} = 1.00 \pm 0.08$. If we leave free either the mass or the total width, with $\alpha_\mathrm{B} = 1$, and fit only on the range of the resonance ($1.0 \le W \le 1.4\,\mathrm{GeV/c^2}$), we find the values:

$$W_0 = 1276 \pm 7\,\mathrm{MeV/c^2}, \qquad \Gamma_0 = 192 \pm 23\,\mathrm{MeV}.$$

These are in good agreement with the published values for the f^0 of[12]

$$W_0 = 1273 \pm 5\,\mathrm{MeV/c^2}, \qquad \Gamma_0 = 179 \pm 20\,\mathrm{MeV}.$$

When making the final fits to determine the radiative width of the f^0, the width Γ_0 is fixed at the published value.

Figure 3 shows the comparison between the $\pi^+\pi^-$ spectrum and the predictions of the best fit to the model. The result of the fit is insensitive to whether it is done on the entire measured range of W or restricted to the f^0 region. It leads to a determination of the radiative width of the f^0,

$$\Gamma_{f^0 \to \gamma\gamma} = 2.70 \pm 0.21\,\mathrm{keV},$$

where the quoted error includes both statistical (0.05 keV) and systematic uncertainties. This result is compared in Table I with previously published measurements, all of which have been made at e^+e^- storage rings and assume pure helicity-2 production of the f^0.

For the 2^{++} resonances there are no absolute predictions of the radiative widths, only their ratios. When compared with previously published values of the radiative width of the $f'^0(1515)$, our measurement of $\Gamma_{f^0 \to \gamma\gamma}$, which is close to the average of previous measurements, is in agreement[18] with SU(3) predictions, assuming fractional quark charges and a mixing angle for the isoscalar octet with the isoscalar singlet of 28 ± 3 degrees.[19] However, there remains a discrepancy[18] when the same model is used to compare with published values of the $A_2(1320)$ radiative width.

Below the f^0 we see no statistically significant evidence of contributions to the spectrum from direct coupling of the $\gamma\gamma$ state to scalar resonances, as the measured $\pi^+\pi^-$ spectrum down to $0.7\,\mathrm{GeV/c^2}$ is in good agreement with the assumption of interference of the f^0 with the Born term alone. Above the f^0 there is a significant discrepancy around $1.5\,\mathrm{GeV/c^2}$, but the data remain between our prediction and what is predicted by the Born term alone.

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7. Because the predicted number of K^+K^- events in any bin is smaller than the statistical fluctuation of the data, the results are sensitive neither to the model for kaons nor to any relative inefficiency in the detection of kaons.
8. See, for example, P. Grassberger and R. Kögerler, Nucl. Phys. **B106**, 451 (1976).
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10. The cross section can be expressed in the equivalent form:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_B + \left(\frac{d\sigma}{d\Omega}\right)_R + 2B(W,\Omega)\cos\delta \cdot \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_B \cdot \left(\frac{d\sigma}{d\Omega}\right)_R},$$

where

$$B(W,\Omega) \equiv \frac{F_B^{\lambda=2}}{\sqrt{(F_B^{\lambda=0})^2 + (F_B^{\lambda=2})^2}}$$

remains close to unity within the entire acceptance. The analysis of J.R. Smith *et al.* (Mark II Collaboration), SLAC-PUB-3205 and LBL-16687, uses this form with B as a free constant parameter.

11. The dependence of $\Gamma_{tot.}$ on the invariant mass was checked by comparing the calculated $\pi\pi$ phase shift with the analysis of C.D. Frogatt and J.L. Petersen, Nucl. Phys. **B91**, 454 (1975), Nucl. Phys. **B129**, 89 (1977).

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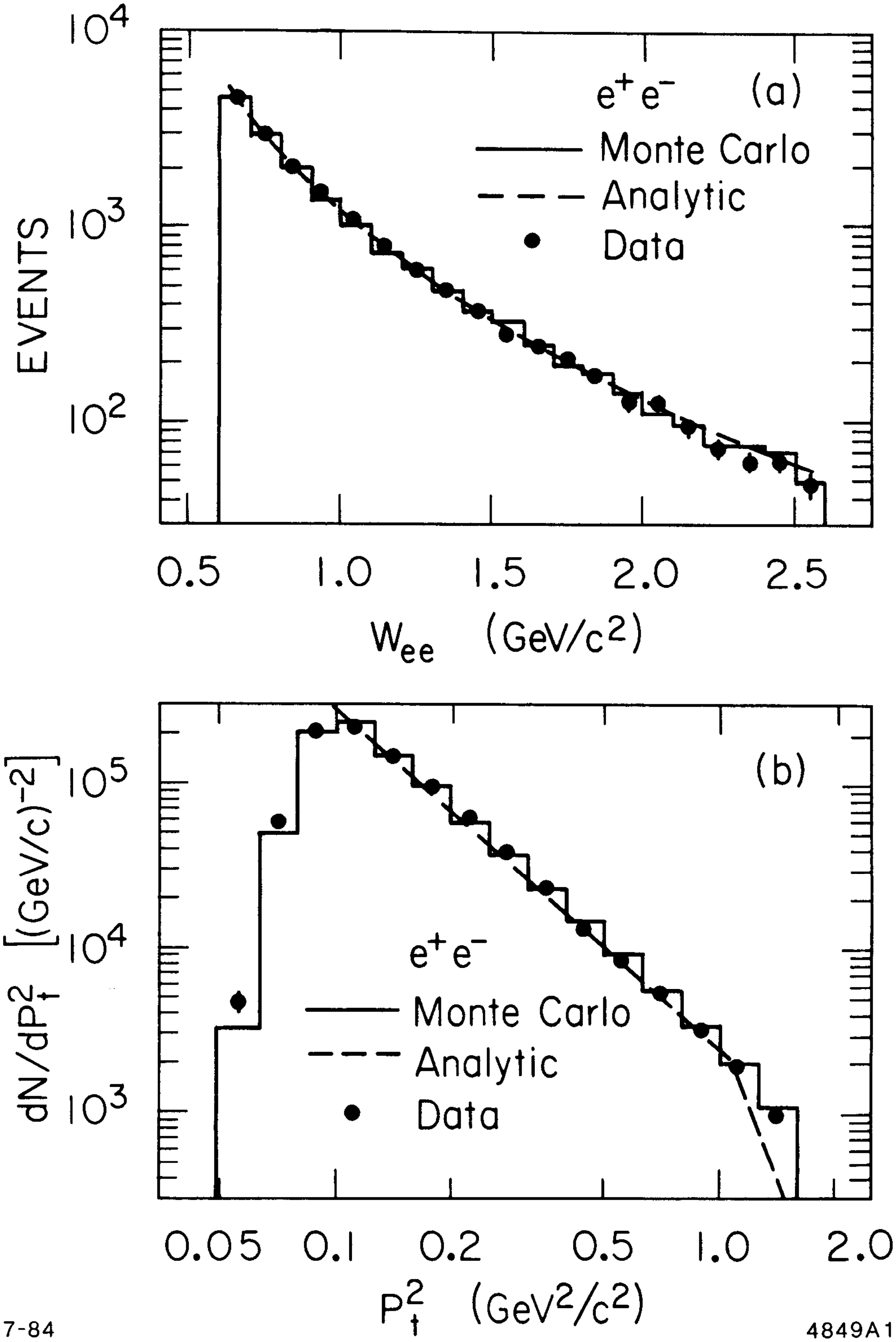
19. Ideal mixing, in which the physical states are pure $s\bar{s}$ and pure $u\bar{u}$, $d\bar{d}$, corresponds to a mixing angle of 35.3 degrees.

Table I. Published measurements of the two-photon width of the f^0. All results assume pure helicity 2 production of the f^0. For each measurement the first error given is statistical and the second is systematic.

Collaboration	Reference	$\Gamma_{f^0 \to \gamma\gamma}$ [keV]	Final State
Pluto	14	$2.3 \pm 0.5 \pm 0.3$	$\pi^+\pi^-$
TASSO	15	$3.2 \pm 0.2 \pm 0.7$	$\pi^+\pi^-$
MARK II (SPEAR)	16	$3.6 \pm 0.3 \pm 0.5$	$\pi^+\pi^-$
Crystal Ball	9	$2.7 \pm 0.2 \pm 0.6$	$\pi^0\pi^0$
CELLO	17	$2.5 \pm 0.1 \pm 0.5$	$\pi^+\pi^-$
MARK II (PEP)	10	$2.52 \pm 0.13 \pm 0.38$	$\pi^+\pi^-$
DELCO		$2.70 \pm 0.05 \pm 0.20$	$\pi^+\pi^-$

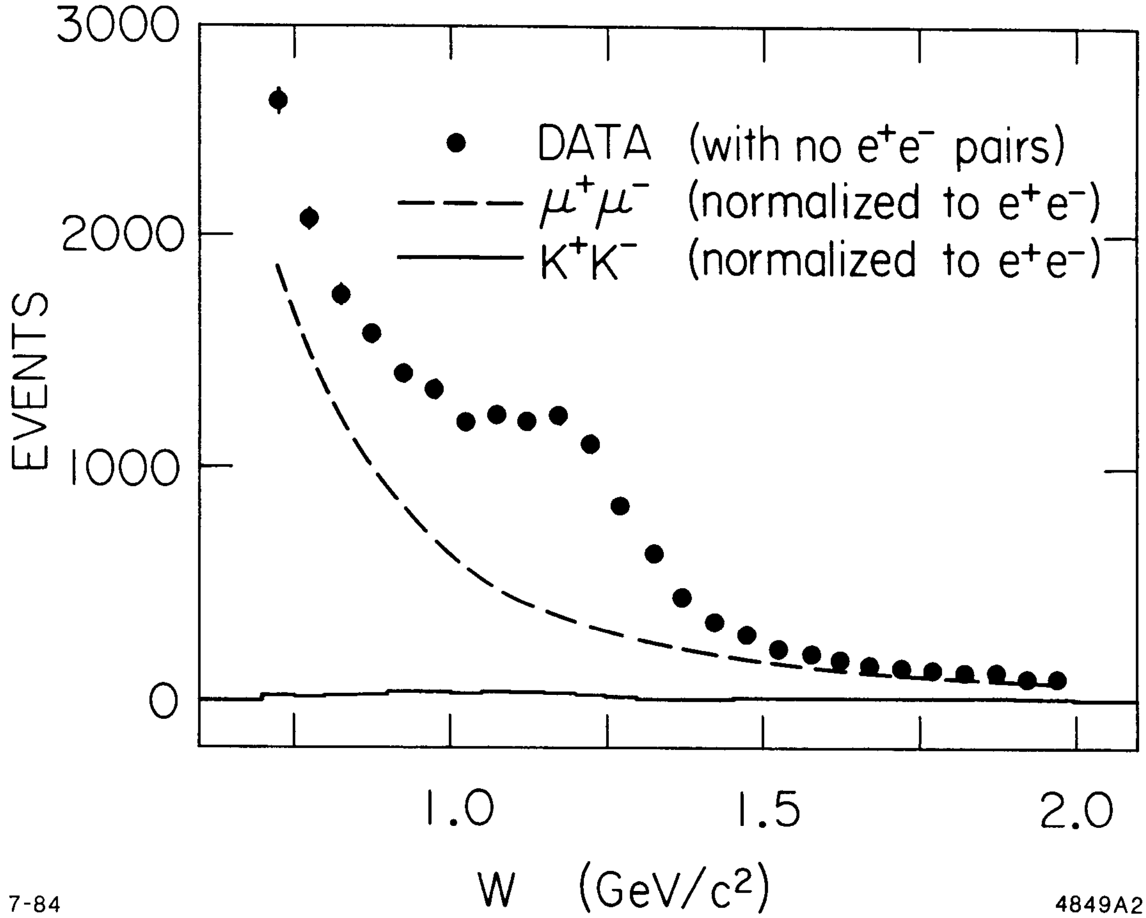
FIGURE CAPTIONS

1. Comparison of the $\gamma\gamma \rightarrow e^+e^-$ data with distributions of a) W_{ee} and b) p_t calculated using the Double-Equivalent-Photon Approximation. The p_t distribution includes one entry for each electron.
2. The invariant-mass distribution of the data and the predicted $\mu^+\mu^-$ and K^+K^- backgrounds.
3. Comparison between the $\pi^+\pi^-$ spectrum and the predictions of the best fit to the model.



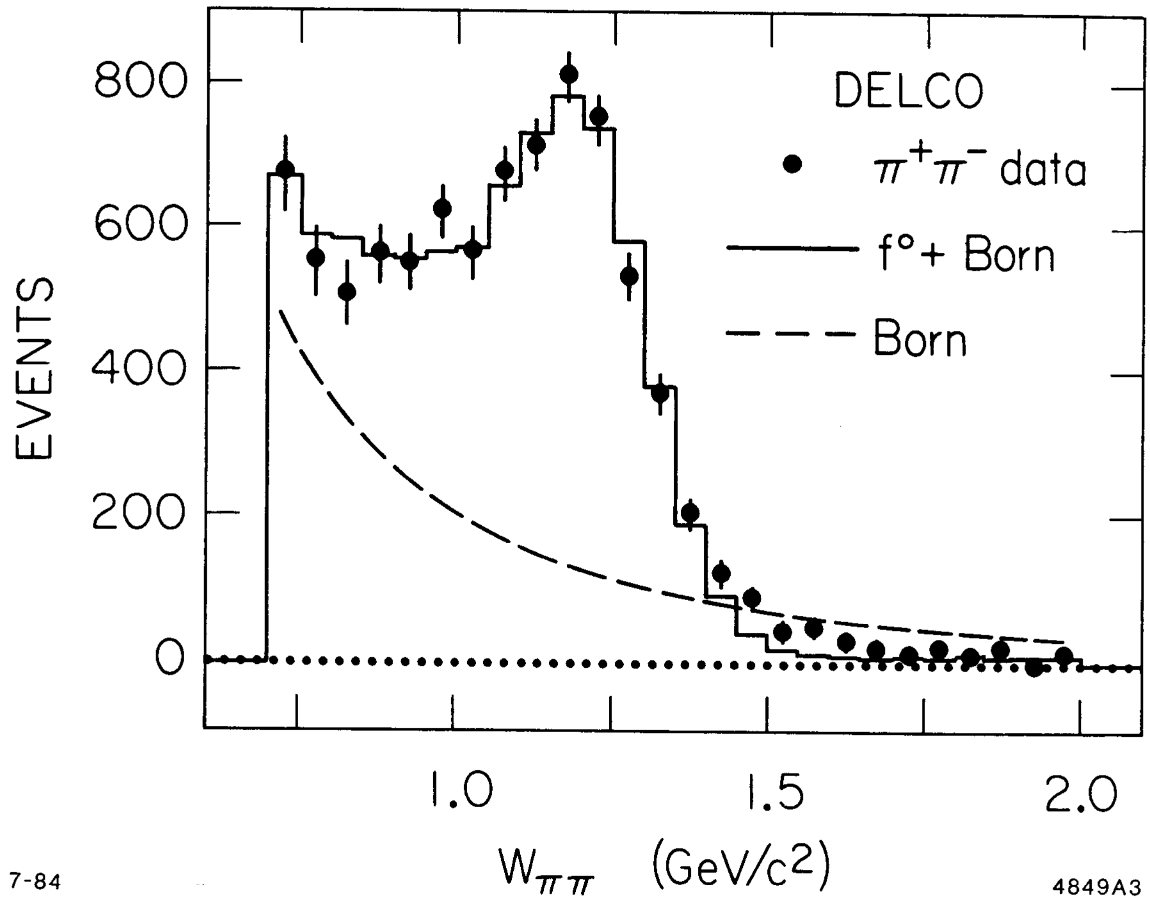
EVENTS
10^4
10^3
10^2
e^+e^- (a)
Monte Carlo
Analytic
Data
0.5 1.0 1.5 2.0 2.5
W_{ee} (GeV/c^2)
dN/dP_t^2 [$(GeV/c)^{-2}$]
10^5
10^4
10^3
(b)
e^+e^-
Monte Carlo
Analytic
Data
0.05 0.1 0.2 0.5 1.0 2.0
P_t^2 (GeV^2/c^2)
7-84
4849A1

Fig. 1



3000
2000
1000
0
EVENTS
DATA (with no e⁺e⁻ pairs)
μ⁺μ⁻ (normalized to e⁺e⁻)
K⁺K⁻ (normalized to e⁺e⁻)
1.0
1.5
2.0
W (GeV/c²)
7-84
4849A2

Fig. 2



800
600
400
200
0
EVENTS
DELCO
π+π− data
f°+ Born
Born
1.0
1.5
2.0
Wππ (GeV/c2)
7-84
4849A3

Fig. 3