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A STUDY OF TWO PHOTON PRODUCTION OF TWO-BODY FINAL STATES WITH INVARIANT MASS GREATER THAN 2.0 GeV

by

PLUTO Collaboration

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ABSTRACT

We have measured the electron, muon, and charged-hadron pair production rates in two-photon interactions for invariant masses above 2.0 GeV over a large range of momentum transfers. The cross sections for electron and muon pairs show good agreement with the QED predictions at both small and large momentum transfers. The observed rate of hadron production is less than 6 % of the rate that QED predicts for point-like hadrons, consistent with recent leading-order QCD calculations.

A current area of interest in high energy physics is the reaction $e^+ e^- \to e^{+\prime} e^{-\prime} X$. /1/ The final state "X" here is a C = +1 hadronic system or pair of charged leptons, and $e^{+\prime}$, $e^{-\prime}$ are the scattered initial state electrons. This reaction is often interpreted as X production in a two-photon interaction, initiated by e^+e^- scattering at high energies:

$$\begin{array}{l} e^+ e^- \to e^+ e^- \; \gamma^*\gamma^* \\ \qquad\qquad\qquad\quad \hookrightarrow X \end{array}$$

QED provides a framework for the exact calculation of the two-photon differential cross section when X is a pair of leptons or point-like hadrons. In practice, these calculations must be done numerically in order to obtain differential cross sections in that small portion of the two-photon phase space which is experimentally accessible. Programs for doing such calculations have been developed. /2/ The programs currently available do not include higher order QED radiative corrections. Recent calculations, however, suggest that such corrections are on the order of a few percent. /3/

As noted above, QED can be used to make predictions for two-photon hadron production in the Born approximation, in which hadrons are treated as point-like. A more realistic treatment, of course, recognizes that hadrons are not point-like and involves some theory of hadron dynamics. Recent leading-order QCD calculations have considered exclusive reactions, such as two-photon production of meson and baryon pairs, at large angles and large invariant masses. /4,5/ As the authors point out, these processes provide important tests of QCD as a candidate theory of hadron dynamics: unlike standard experimental tests (such as scaling violations in deep inelastic scattering), QCD can predict for these exclusive reactions the absolute normalizations of the cross sections, as well as their functional forms.

In this paper we present results on the measurements of

$$(1) \qquad e^+ e^- \to e^+ e^- \; + \; \begin{array}{l} e^+ e^- \\ \mu^+ \mu^- \\ h^+ h^-, \text{ a pair of charged hadrons} \end{array}$$

with the PLUTO detector at PETRA for $\sqrt{s} \sim 31$ GeV. This study is restricted to observations of the produced system X in the angular region given by $|\cos\vartheta| < 0.56$, where ϑ is the polar angle from the e^+ beam in the lab frame, with the full azimuthal range. Our data sample corresponds to a total integrated luminosity of 2600 nb^{-1}.

It has been reported previously that for $W < 2.0$ GeV (where W is the invariant mass of the produced two-body system), there is a significant deviation of the measured cross section of (1) from the QED prediction. /6,7/ This observation is interpreted as production of the C = +1, J = 2, f^0 (1270) meson in two-photon interactions. The purpose of this study is to examine the reactions (1) in the invariant mass region $W > 2.0$ GeV. /8/

The details of the PLUTO detector have been given elsewhere. /9/ We mention here only those features which bear directly on this study. The scattered initial state electrons from the two-photon reaction can be detected in a forward tagging system. This system is divided into two parts. The "Small Angle Tagger" (SAT) is an array of lead glass blocks, 12.5 radiation lengths deep, which covers the polar angular region from 23 to 70 mrad in the laboratory system. The "Large Angle Tagger" (LAT) covers the range from 70 to 260 mrad and consists of 18 lead-scintillator sandwiches, 14.5 radiation lengths thick. This tagging system can also be employed in the "anti-tagging" mode: by requiring no significant signal in any part of the SAT/LAT and small transverse momentum imbalance in the central detector, we can choose two-photon events which have low momentum transfer ($\langle Q^2 \rangle = 0.007\ \text{GeV}^2$, where $Q^2 = -(p-p')^2$ is the squared four-momentum transfer and p and p' are the beam particle's four-momentum before and after scattering, respectively.)

The angular region of this study provides efficient means of lepton identification. Electromagnetic shower detection in this region uses lead-scintillator sandwich counters which contain a total of 8.6 radiation lengths. Muon identification is accomplished by 100 cm of iron absorber outside the inner detector, with proportional and drift chambers located after 75 and 100 cm, respectively, to detect penetrating particles. These chambers cover approximately 85 % of the angular region of this study.

We first report on the results in the low Q^2, "untagged" data sample. After selection of charge-balanced, two-prong events, further cuts are applied to choose the two-photon reaction and to isolate it from its various backgrounds. These cuts and their purposes are summarized in Table 1.

After these cuts, 67 events with $W_{\pi\pi} > 2.0$ GeV (where $W_{\pi\pi}$ is the invariant mass of the produced system as calculated by assigning the pion mass to both prongs [1]) remain. This sample is relatively free from backgrounds. Contamination from the production of electron-pairs, muon-pairs, and hadrons via the one-photon (annihilation) channel, from many-prong two-photon events, and from beam-gas interactions is less than one event. Annihilation channel tau production produces an estimated background of 0.6 event. Residual cosmic ray contamination is less than 2 events.

Particle identification can now be attempted on these events. For the particles in this sample, the momentum is typically $p \sim W_{\pi\pi}/2 \gtrsim 1.0$ GeV/c. In this momentum range, muons are minimum-ionizing and can penetrate the 75-100 cm of iron to reach the detection chambers. Electrons, on the other hand, should deposit most of their energy in the shower counters. Thus, to be identified as a muon, the particle is required to have an associated chamber hit. To minimize the effects of background chamber hits, it is further required that this hit be at a position consistent with the particle's expected multiple Coulomb scattering through the iron. To be identified as an electron, the particle is required to have measured energy in the shower counters greater than half its energy as determined from the track curvature in the central detector. An event which cannot be identified as containing muons or electrons can be considered a candidate for two-photon hadron production.

Of the 67 untagged events, 33 are identified as containing at least one muon. (Seventeen have both particles identified as muons. All particles in these 33 events, however, are minimum-ionizing: they deposit only 100 ± 50 MeV in the shower counters.) Twenty-eight events are identified as containing electrons, 27 of them with both electrons positively identified. Six events, all with invariant mass between 2.0 and 2.5 GeV, remain unidentified. The particles in these 6 events have shower energies consistent with minimum ionization.

The particle identifications given above are rather unambiguous. Misidentification of a hadron as a muon (due to hadronic punchthrough or decay or a spurious chamber hit) has a probability of less than 2 %. The probability of a hadron being misidentified as an electron is estimated to be 0.2 %. The probability of a muon being identified as an electron is less than 0.03 %.

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[1] $W_{\pi\pi} > 2.0$ GeV corresponds to $W > 2.2$ GeV for K+K- and $W > 2.7$ GeV for $p\bar{p}$.

In order to convert the above observations into cross sections, several corrections are necessary. In addition to straight forward corrections for the losses due to the cuts required to reduce backgrounds (as described in Table 1), two other corrections are important. First, the observed spectrum of electrons must be corrected for the effects of radiation losses in the central detector. Second, the efficiencies of the event identification procedures must be calculated.

Variation in the thickness of iron between the inner detector and the muon detection chambers leads to a weak correlation between W and the muon identification efficiency. The efficiency for identifying at least one muon in the event ranges from 80 % in the lowest invariant mass bin to 95 % for $W > 3.0$ GeV. For the electrons the event identification efficiency is above 98 % in all invariant mass bins.

Corrected differential cross sections in the invariant mass for the muons and electrons are shown in Figures 1a and 1b, respectively. The solid curves are the absolute QED predictions as calculated by the program of Vermaseren, et. al. /2/ The integrated cross sections for $W > 2.0$ GeV in the angular region of this study, along with the QED values (as calculated from ref. 2) are given in Table 2. Both the observed invariant mass spectra and the integrated cross sections are in agreement with the QED predictions.

In contrast, the QED predictions for point-like hadrons are clearly inconsistent with our data: Monte Carlo calculations, including simulation of detector effects and the experimental acceptance, predict 21 pion, 12 kaon, and 20 proton pair events with $W_{\pi\pi} > 2.0$ GeV in our angular region. (The loss of events due to nuclear interactions in the beam pipe and central detector chamber walls is estimated to be between 5 and 10 percent.)

To quantify the observed level of hadron production, we proceed as follows. For each of the 39 non-electron events we can calculate the probability that, if the event indeed contained muons, it would be so identified. (This probability calculation takes into account the particles' momentum measurement errors, the thickness of the iron the particles must traverse to reach the detection chambers, and the chamber coverage around the particles' expected positions of exit from the iron.) Such a calculation leads us to estimate 5.0 unidentifiable events in our sample, in agreement with the six we actually observe.

In order to put the most stringent limit consistent with our data on the two-photon hadron production, we further restrict our sample of non-electron events to those for which the above described muon identification probability is greater than 80 %. This additional cut reduces the total sample of non-electron events from 39 to 33 and the estimated number of unidentifiable muon events from 5.0 to 1.2. (It also reduces the previously given Born-term expectations by about 15 %.) After this cut, one non-electron event which is not positively identified as containing a muon remains. We thus find for $W_{\pi\pi} > 2.0$ GeV and low Q^2, ($<Q^2> = 0.007$ GeV^2),

$$\sigma(e+e- \rightarrow e+e-h+h-) \; < \; 2.1 \; \text{pb} \qquad (90\ \%\ \text{c.l.})$$

for the angular region of this study. (This result has been corrected for losses due to detector effects, the cuts given in Table 1, and the above described cut on the identification probability.)

The Born-term calculations for $\pi+\pi-$, K+K-, and $p\bar{p}$ production in the angular region of this study are given in Table 2. The above result makes it clear that in all cases they are large overestimates: the total production of untagged charged-hadron pairs with $W_{\pi\pi} > 2.0$ GeV is less than 6 % of the Born-term prediction.

This result is consistent, however, with the leading-order QCD calculations of references 4 and 5. These predictions for $W_{\pi\pi} > 2.0$ GeV in the angular region of this study are also given in Table 2. The QCD prediction for the combined rate of pion, kaon, and proton production at $W_{\pi\pi} > 2.0$ GeV in the angular region of this study is only about 2 % of the Born-term prediction.

We now briefly discuss the high Q^2 data sample. Events are again selected according to Table 1, except that cut (e) is reversed: we require a signal of at least 4.0 GeV in some section of the forward tagging system. Also, cut (f) is not imposed. [2]

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[2] A cut on the total momentum transverse to the beam -- including that of the tagged electron -- can be made here. (A slightly larger imbalance must be allowed in order to account for energy measurement errors in the tagging system.) The backgrounds, however, are sufficiently small to make such a cut unnecessary.

After these cuts we find 43 single-tagged events with $W_{\pi\pi} > 2.0$ GeV. Backgrounds from the annihilation channel (including initial state radiation), beam-gas interactions, and other two-photon processes are negligible. Because of the tag in the forward tagging system, residual cosmic background can also be neglected.

Twenty-six of these tagged events are identified as containing at least one muon. (Thirteen events have both particles identified as muons. All 52 particles are minimum-ionizing.) Sixteen events contain electrons, all but one of which have both particles identified. One event, with $W_{\pi\pi} = 2.10$ GeV is unidentified; the particles in this event, however, have shower energies compatible with minimum ionization. As in the untagged sample, the probability of particle misidentification is small.

The corrected differential cross sections in W and Q^2 for the muons and electrons are shown in Figures 2 and 3. The integrated cross sections for $W_{\pi\pi} > 2.0$ GeV in the angular region of this study are given in Table 3. There is good agreement with the QED predictions. The Q^2 distribution falls off approximately as $(Q^2)^{-5/4}$ in the region of observation.

Using the same procedure as in the untagged sample, we calculate for $W_{\pi\pi} > 2.0$ GeV and large Q^2, ($0.1 < Q^2 < 10.0$ GeV^2),

$$\sigma(e+e- \rightarrow e+e-h+h-) \; < \; 0.8 \; \text{pb} \qquad (90\ \%\ \text{c.l.})$$

in the given angular region.

Table 3 also gives the Born-term calculations for the charged hadrons in this high Q^2 region. As in the untagged sample, the hadron production with $W_{\pi\pi} > 2.0$ GeV in the high Q^2 region is less than 6 % of the Born term prediction. (We make no comparison of our results here to QCD because the presently available QCD calculations apply only to the annihilation of real photons.)

We have noted that our results on the hadron production in the low Q^2 region are consistent with the leading-order QCD predictions. An important feature of these predictions is the rapid fall-off of the differential cross section with the invariant mass. Dimensional counting leads to $d\sigma/dW \sim W^{-7}$ for mesons and $d\sigma/dW \sim W^{-11}$ for baryons, up to logarithmic factors. (In comparison, the Born-term calculation yields $d\sigma/dW \sim W^{-3}$.) Our results therefore do not preclude substantial continuum production of hadron pairs at smaller invariant masses. In fact, the Born-term and QCD predictions for charged pion production from the continuum are comparable at W ~ 1 GeV and large angles. Thus, unlike the Born-term prediction, the QCD calculation can accomodate both our result on hadron production at large invariant masses and possible resonance-continuum interference effects near the f^0. /7,10/

Finally, we note the recent measurement of two-photon proton-antiproton production by the TASSO Collaboration. /11/ In the invariant mass range $2.0 < W < 2.6$ GeV, they find the cross section to be approximately 10 % of the Born term. It is not clear, however, how this measurement can be compared to the QCD calculations of ref. 5, which assume large transverse momenta.[3]

In conclusion, we have measured the two-photon production of electron and muon pairs for $W > 2.0$ GeV over a large Q^2 range. We find good agreement with the QED predictions for both the shape and the absolute magnitude of the W and Q^2 distributions. The QED predictions for point-like hadrons, on the other hand, appear to be large overestimates. At both small and large Q^2 we find the combined production of $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ to be less than 6 % of the Born term prediction for $W_{\pi\pi} > 2.0$ GeV (90 % c.l.). This result is consistent with leading-order QCD predictions.

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[3] A naive application of the QCD calculations to this near-threshold region yields a cross section which seems consistent with the TASSO result.

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TABLE 1

Event Selection Criteria
for the "Untagged" Data Sample

	Criterion	Purpose
(a)	$\lvert\cos\theta\rvert < 0.56$ for each track, where θ is the polar angle measured in the lab frame from the e+ beam axis	To insure uniform efficiency of the central detector
(b)	$p_T > 0.4$ GeV/c for each track, where the transverse momentum is measured with respect to the beam axis	
(c)	$\lvert z_0\rvert < 40.0$ mm, where z_0 is the interaction vertex's displacement from the beam crossing point, measured along the beam axis.	To eliminate beam-gas interactions and cosmic ray events
(d)	Total energy in the central detector < 10.0 GeV	To eliminate e+ e- annihilation events
(e)	Less than 4.0 GeV deposited in any section of the forward tagging system	To isolate "untagged", low Q^2 events
(f)	$\lvert \sum \vec{p}_T \rvert < 0.5$ GeV/c, where the sum is over the particles in the central detector. (For events with identified electrons, this cut is relaxed to 1.5 GeV/c.)	
(g)	No electromagnetic shower greater than 0.2 GeV which is unassociated with a track	To eliminate events with extra photons or neutral pions
(h)	Acollinearity between the tracks greater than 15 degrees	To eliminate cosmic ray events
(i)	Time difference between the event and the beam-crossing signal less than 15 nsec	

TABLE 2

Cross Sections for e+ e- --> e+ e- X
for $W_{\pi\pi} > 2.0$ GeV and $\lvert\cos\theta\rvert < 0.56$
($\langle Q^2\rangle = 0.007$ GeV^2)

Produced System X	Observed Cross Section (pb)	QED Prediction (pb)	QCD Prediction (pb)
$\mu^+\mu^-$	$22.8\ {}^{+\,4.3}_{-\,3.6}$	31.4 ± 0.4	----
e+e-	$25.5\ {}^{+\,5.3}_{-\,4.4}$	30.7 ± 0.4	----
$\pi^+\pi^-$	< 2.1 (90 % c.l.)	13.3 ± 0.2	0.30 ± 0.03
K+K- (W > 2.2 GeV)		7.9 ± 0.1	0.35 ± 0.04
$p\bar{p}$ (W > 2.7 GeV)		13.8 ± 0.1	0.025 ± 0.003

TABLE 3

Cross Sections for $e^+ e^- \rightarrow e^+ e^- X$
for $W_{\pi\pi} > 2.0$ GeV and $|\cos\theta| < 0.56$
(High Q^2)

Produced System X	Observed Cross Section (pb)	QED Prediction (pb)
$\mu^+\mu^-$	$13.2^{+2.9}_{-2.3}$	12.5 ± 0.4
e^+e^-	$10.7^{+3.0}_{-2.4}$	12.6 ± 0.4
$\pi^+\pi^-$	< 0.8 (90 % c.l.)	4.8 ± 0.2
K^+K^- ($W > 2.2$ GeV)		3.0 ± 0.1
$p\bar{p}$ ($W > 2.7$ GeV)		6.3 ± 0.2

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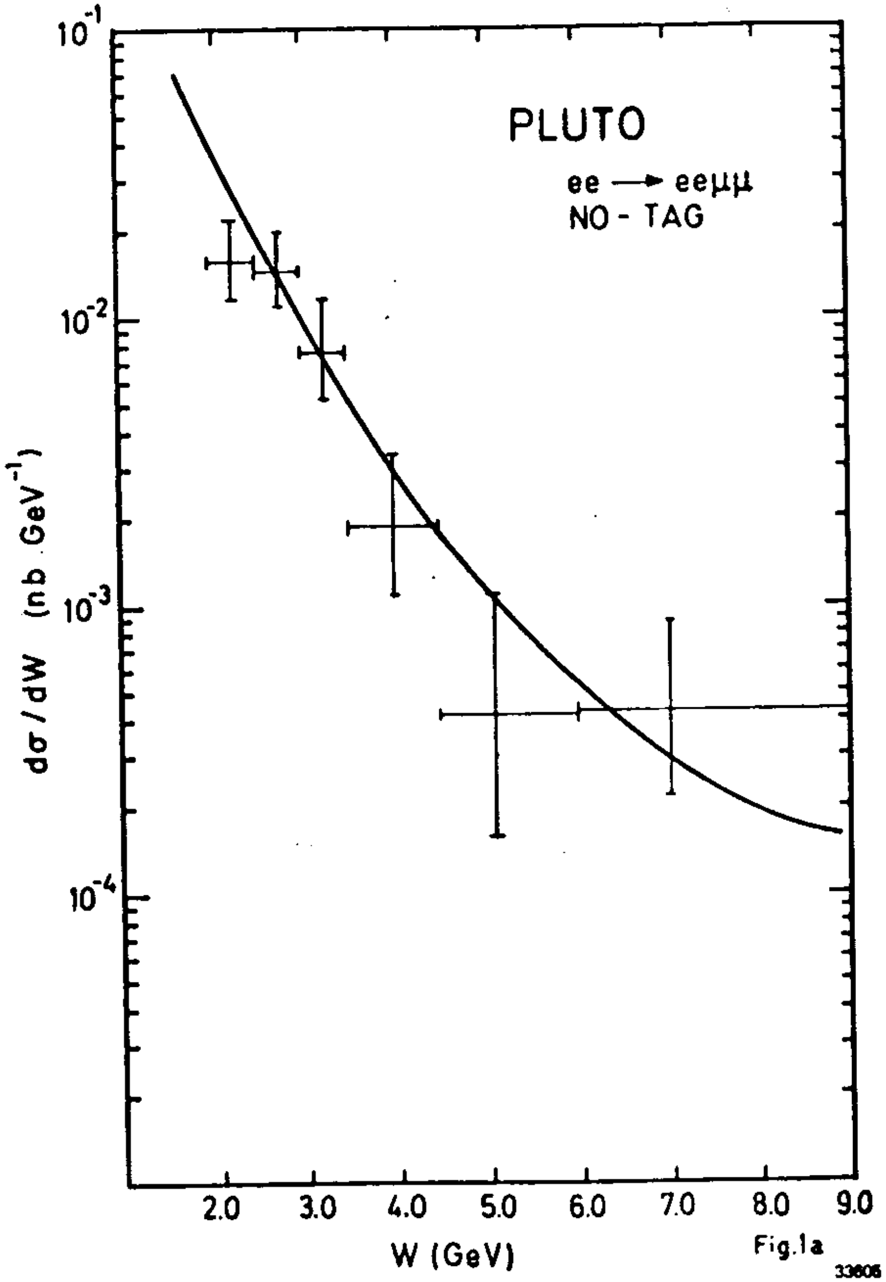
FIGURE CAPTIONS:

1. Differential cross sections in the invariant mass for muon and electron pairs in the untagged, low Q^2 region. The solid curve is the absolute QED prediction.

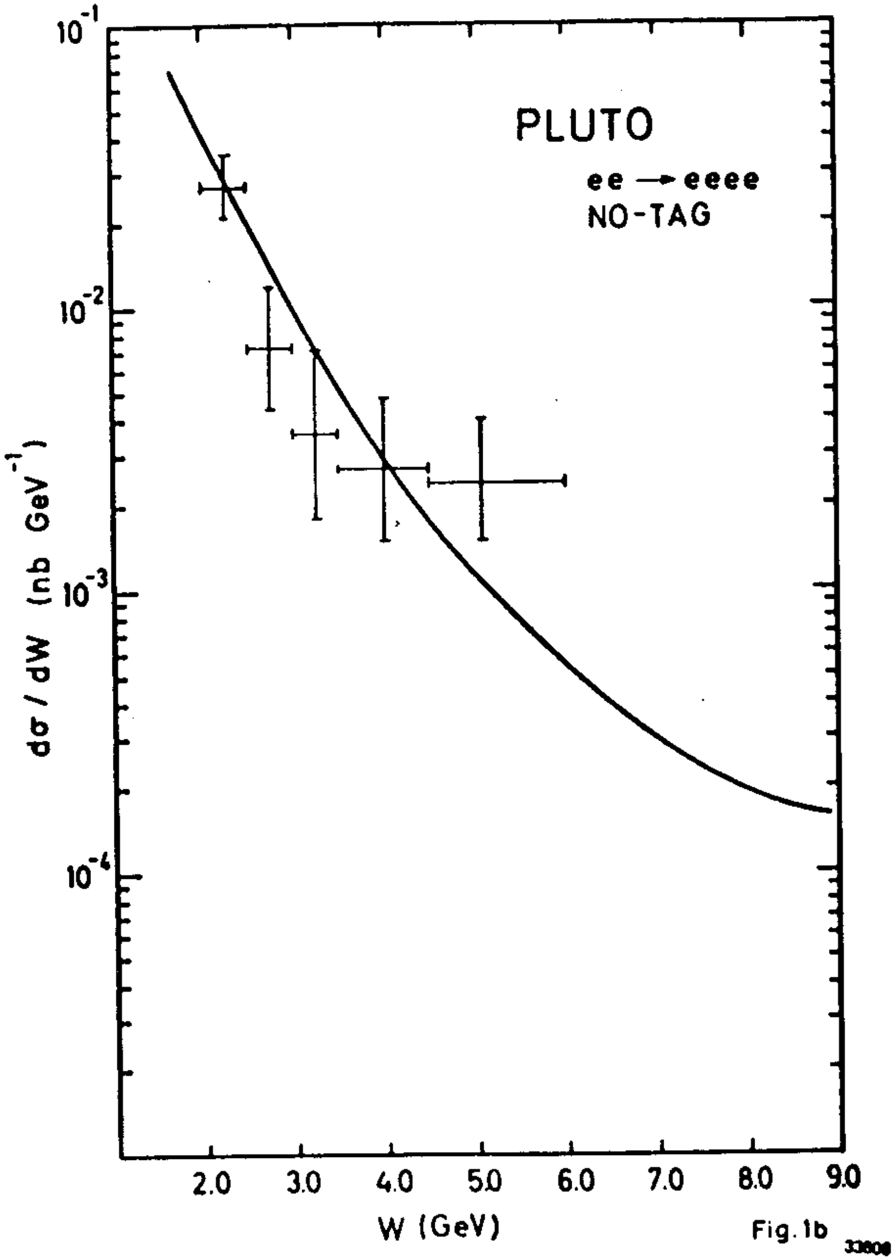
2. Differential cross sections in the invariant mass for muon and electron pairs in the single-tagged region. The solid curve is the absolute QED prediction.

3. Differential cross section in Q^2, the squared four—momentum transfer, for muon and electron pairs in the single-tagged sample. The solid curve is the absolute QED prediction.



10^{-1}
10^{-2}
10^{-3}
10^{-4}
$d\sigma / dW$ (nb GeV^{-1})
PLUTO
$ee \longrightarrow ee\mu\mu$
NO - TAG
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
W (GeV)
33606

Fig.1a



10^{-1}
10^{-2}
10^{-3}
10^{-4}
$d\sigma / dW$ (nb GeV^{-1})
PLUTO
$ee \longrightarrow eeee$
NO-TAG
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
W (GeV)
33608

Fig.1b

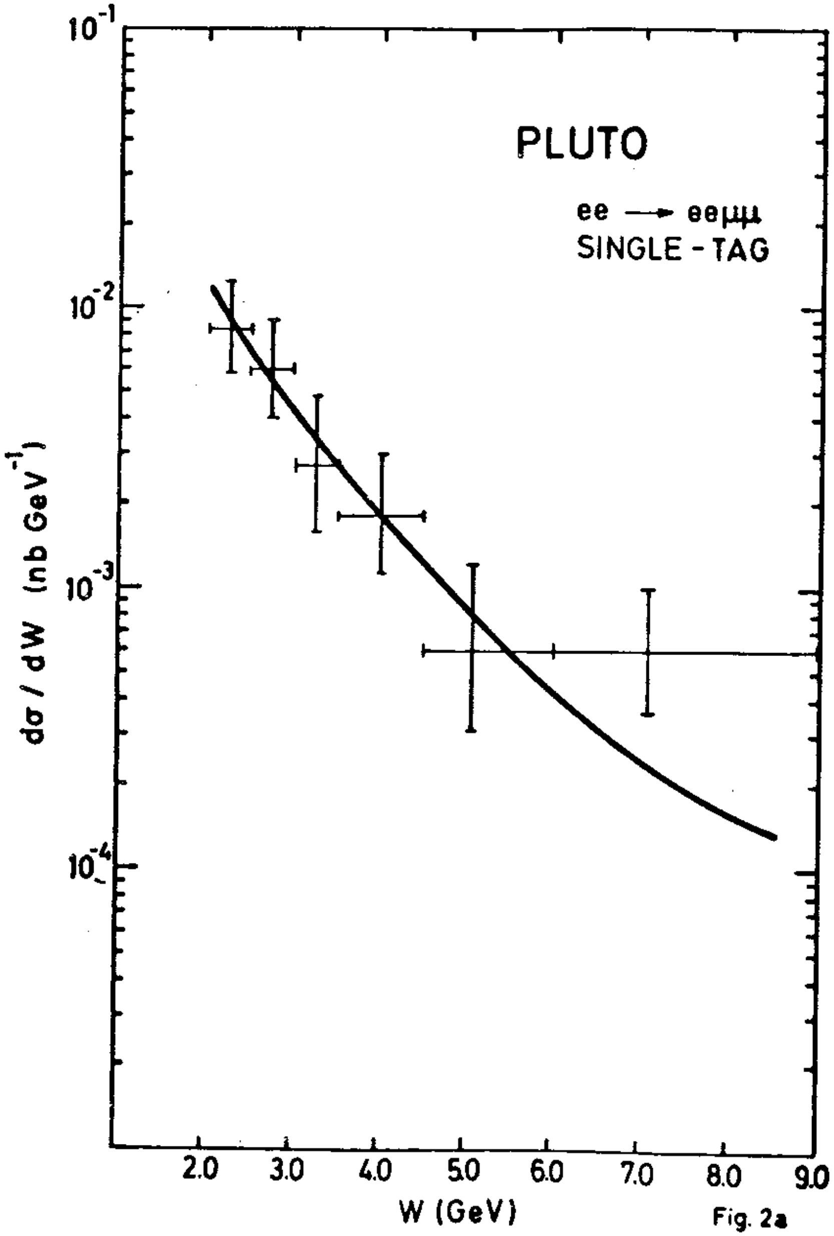


Fig. 2a

33609

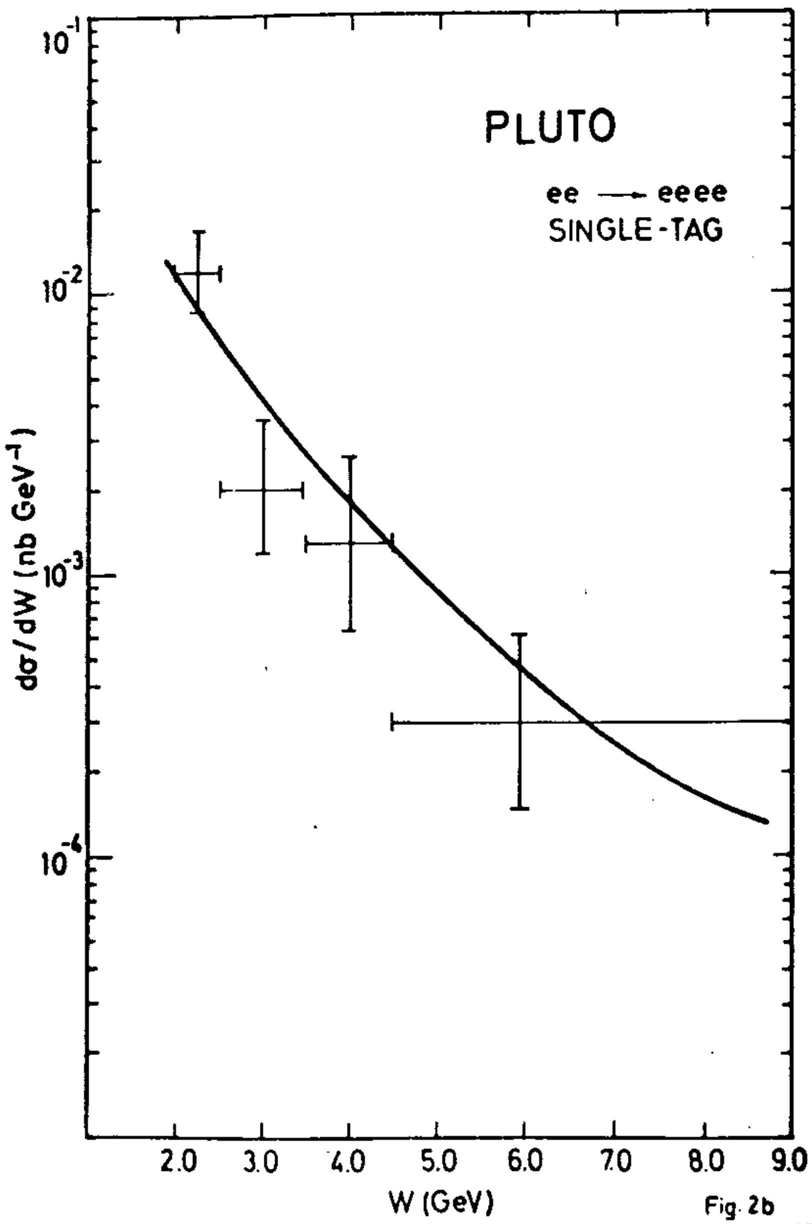


Fig. 2b

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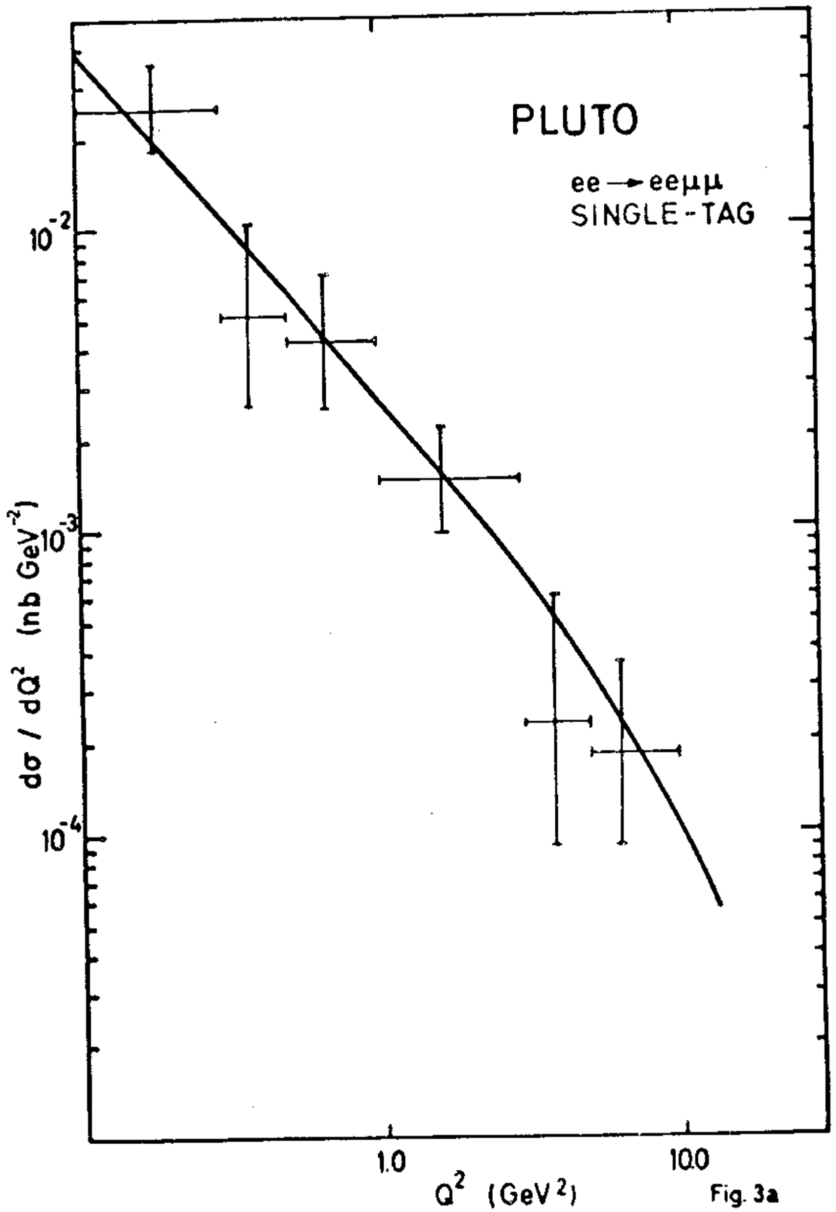

Fig. 3a

33701

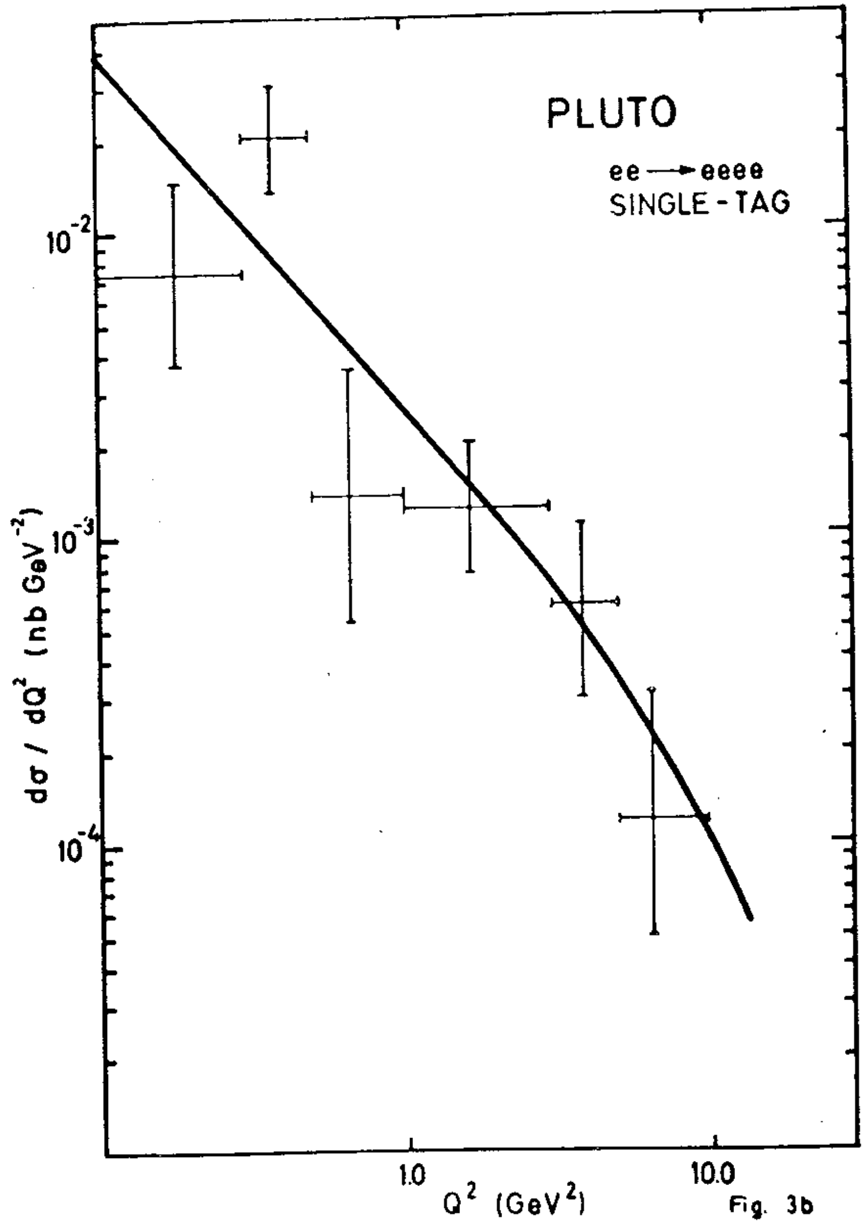

Fig. 3b

33702