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Quasi-real Compton Scattering Measurement and e^* Search with DELCO at PEP*

G.R.Bonneaud, A.Courau[(a)], R.Johnson[(b)], H.Yamamoto,
W.B.Atwood, B.C.Barish, G.J.Donaldson[(c)], R.Dubois[(d)], M.M.Duro[(b)],
E.E.Elsen[(e)], S.Q.Gao[(f)], Y.Z.Huang[(f)], G.M.Irwin, H.Kichimi[(g)], J.Kirkby[(b)],
D.E.Klem, D.E.Koop[(h)], J.Ludwig[(i)], G.B.Mills[(j)], A.Ogawa, T.Pal[(b)],
R.Pitthan, D.L.Pollard[(c)], C.Y.Prescott, L.S.Rochester, W.Ruckstuhl[(k)],
M.Sakuda[(g)], S.Sherman[(l)], R.Stroynowski, S.Q.Wang,[(f)]
S.G.Wojcicki, W.G.Yan,[(f)] C.C.Young

DELCO Collaboration

California Institute of Technology,
Pasadena, California 91125
Stanford Linear Accelerator Center and Physics Department
Stanford University, Stanford, California 94305

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ABSTRACT

We report on a measurement of the elastic scattering of quasi-real photons generated by one beam with the particles of the other in e^+e^- interactions at $\sqrt{s} = 29$ GeV performed using the DELCO detector at PEP. The events are characterized by coplanar and anti-tagged $e\gamma$ pairs with large visible energy where the charge of the electron is correlated with the acolinearity angle. We also use our result to search for the on-shell production of a hypothetical excited electron e^*. We find that the data agree well with the predictions for the QED Compton process, and set upper limits on the $e^*e\gamma$ coupling parameter λ to be below 10^{-2} (95% C.L.) in the range $15 \lesssim M_{e^*} \lesssim 27$ GeV.

In e^+e^- collisions, a quasi-real photon emitted by one of the incoming particles can be elastically scattered by the other (Fig. 1). The spectator electron, which radiates the photon, tends to be emitted at a very small angle relative to the beam axis and escape detection, while the scattered $e\gamma$ pair may be detected at large angles in the central detector. The measurement of this process was proposed many years ago,[1] and was first performed at the ACO storage ring[2] where the result was found to be consistent with the quasi-real Compton process. In addition to the test of QED, this process also provides an opportunity to search for the on-shell production of a hypothetical excited electron e^*,[3–6] yielding an upper limit on the $e^*e\gamma$ coupling for $e\gamma$ masses up to the full c.m. energy of the e^+e^- collision.

An excited electron is naturally expected in composite models of quarks and leptons.[7] The searches for such a particle have been performed in the channel $ee \rightarrow \gamma\gamma$ where the e^* contributes in the t-channel,[8–10] and in $ee \rightarrow e^*e \rightarrow ee\gamma$[9,10] where all the three particles in the final state are observed. The latter is essentially the same interaction as the one addressed in this paper. However, it excludes the near-pole region of the quasi-real photon, and the expected cross section reduces accordingly. On the other hand, even though the $\gamma\gamma$ channel can probe an e^* of mass greater than the available c.m. energy $\sqrt{s}$, it is less sensitive than the process used in this paper for e^* masses less than $\sqrt{s}$. The e^* has also been searched for in the channel $e^+e^- \rightarrow e^*e^* \rightarrow ee\gamma\gamma$.[10] Although this mode probes the very existence of e^* through the known $e^*e^*\gamma$ Dirac coupling, the e^* mass range is limited by the beam energy.

The data presented here were collected using the DELCO detector at PEP with $\sqrt{s}$ of 29 GeV and an integrated luminosity of 216 pb^{-1}. The DELCO detector has been described elsewhere.[11] However, it is pertinent to recall those characteristics relevant to this study. The tracking system consists of 16 layers of inner cylindrical drift chambers and 6 layers of outer planar drift chambers. About half of the layers have stereo wires which give polar angle information. For an 8 GeV electron, the azimuthal angle resolution σ_ϕ is $\sim$ 2 mrad and the polar angle resolution σ_θ is $\sim$ 3 mrad. For this analysis, only the direction and charge of the detected electron are used, and the magnitude of the momentum is not used except as a cross check. A 36-cell gas Čerenkov counter is located between the inner and outer tracking systems, and the Čerenkov efficiency for a high energy electron is virtually 100 %. A barrel of lead-scintillator shower counters is used to measure electromagnetic energy and to detect photons. The innermost scintillators run the full length of the barrel shower counter, and the polar angle of a photon is given by the time difference of the signals from the two ends of a scintillator. The resolution in the photon direction is limited in the azimuthal view by the granularity of the shower counter ($\sigma_\phi \sim$ 70 mrad) and in the polar view by the counter time resolution ($\sigma_\theta \sim$ 35 mrad). Forward calorimeters provide detection of electrons scattered at small angles and their acceptance extends down to 24 mrad relative to the beam axis.

The final state of interest in our study is well characterized by the following properties (providing that radiative events are eliminated as explained later):[6]

(*a*) Since the events considered are dominated by quasi-real photons, the spectator electron is scattered mostly by a very small angle and escapes detection.

(*b*) Correspondingly, the direction of the velocity β of the observed $e\gamma$ final state is almost parallel to the beam axis. In particular, the $e\gamma$ final state is nearly coplanar with the beam axis.

(*c*) The energy of the $e\gamma$ final state, $E_{\rm vis}$, is larger than the beam energy E.

(*d*) The direction of β is given by the beam direction of the electron of the same charge as the observed electron. In other words, the acolinearity angle of $e\gamma$ final state determines which beam was involved in the Compton scattering in each event.

Accordingly, we apply the following cuts to the raw data:[12] (1) No hit in the forward calorimeters (anti-tagging). (2) Two electromagnetic energy depositions observed in the barrel shower counters in the range $|\cos\theta_{e,\gamma}| < 0.6$. They are required to be back-to-back within one unit in the ϕ view (there are 24 units in 2π). (3) Only one fully-reconstructed track found in the event and it is associated with one of the energy depositions. (4) To reject Bhabha events with an electron missed by the tracking and which could then simulate an $e\gamma$ event, we require that there be no other Čerenkov counter coplanar to the one associated with the charged track in a window of 500 mrad. (5) A scatter plot of the shower counter pulse heights for the electron and the photon is shown in Fig. 2. The cluster of events at low pulse heights is found to be due to radiative effects where the electron that participates in the Compton scattering loses most of its energy before the scattering. To remove these events, we put an additional cut on the sum of both shower pulse heights corresponding to a cut on $E_{\rm vis}$ roughly equal to half the beam energy. This cut is shown in Fig. 2 by the dashed line. Since the low energy cluster is well separated from the main cluster, our result is insensitive to the exact location of the cut.

The anti-tagging insures the quasi-real photon to be indeed nearly on-shell and along the beam axis. On the other hand, the effect of the cut on $E_{\rm vis}$ is that the radiation from the electron that enters the Compton scattering is insignificant. Under these conditions, the kinematics of the interaction are over-constrained, and various physical parameters are related to each other by

$$\frac{E_\gamma}{E} = \frac{W^2}{s} = \frac{E_{\rm vis} - E}{E} = \frac{1-\beta}{1+\beta},$$

with

$$\beta = \frac{\sin(\theta_e + \theta_\gamma)}{\sin\theta_e + \sin\theta_\gamma},$$

where E_γ is the energy of the quasi-real photon, W is the $e\gamma$ invariant mass, and θ_e and θ_γ are the polar angles of the Compton-scattered electron and photon with respect to the direction of the beam with the same charge as the observed electron. We have chosen the set $\{E, \theta_e, \theta_\gamma\}$ as independent parameters from which other parameters are derived. Since we generally measure the angles better than the energies, this set gives the best resolutions especially for the reconstructed invariant mass ($\sigma_W \sim 0.750$ GeV/c^2). Note that the velocity β as defined above is expected to be positive for our signal, and the 'wrong' correlation between the charge of the observed electron and the acolinearity angle (i.e. $\theta_e + \theta_\gamma > \pi$) gives a negative β. Also, the $e\gamma$ invariant mass W is uniquely determined for a given β; in particular, $W_{\max} = \sqrt{s}$ corresponds to $\beta = 0$, while $W_{\min} \sim \sqrt{s}/2$ is determined by the maximum β allowed by the $\theta_{e,\gamma}$ acceptance. Alternative sets of variables could be $\{E, \theta_e, \theta_\gamma\}$, $\{E, P'_e, \theta_e\}$, or $\{P'_e, \theta_e, \theta_\gamma\}$, where P'_e is the measured momentum of the electron track. The variables such as W and β have been computed using these different sets and found to be consistent within the experimental resolutions.

The data sample consists of 1314 events and Fig. 3 shows the distribution of β (points with error bars). The large excess of events observed at positive β agrees with what is expected for the quasi-real Compton scattering process. The peak of events with β close to zero in Fig. 3 corresponds to approximately colinear $e\gamma$ final states and is identified as coming from the reaction $e^+e^- \rightarrow \gamma\gamma$, where one photon has converted in the beam pipe region. The momenta of the converted pair are high and the tracks hardly separate in the magnetic field. Consequently, they are generally found as one-track events by the tracking system. The average Čerenkov-counter pulse height for the converted pair, however, should be twice the value for single tracks. The shaded histogram shows the β distribution for those events with more than 1.5 times the normal Čerenkov response. In this way, about 55% of those events with $|\beta| < 0.1$ are identified as converted $\gamma\gamma$ events. This rate agrees with the estimated identification efficiency of photon conversion indicating that most of the events in the region $|\beta| < 0.1$ are converted $\gamma\gamma$ events. The slight excess of the positive β's for the shaded histogram is consistent with these being genuine $e\gamma$ final states misidentified as converted $\gamma\gamma$ events due to the statistical fluctuation of the Čerenkov response. Furthermore, a Monte Carlo simulation of $e^+e^- \rightarrow \gamma\gamma$ with radiative and resolution effects reproduces the negative β distribution down to $\beta \sim -0.25$. Since the identification of the photon conversion is not efficient enough to remove most of the $\gamma\gamma$ background, we have chosen to remove this background, which is symmetric in β, by subtracting bin by bin the events with negative β from those with positive β within the range $|\beta| < 0.25$.

There are 30 events in the range $\beta < -0.25$. The β distribution and the yield of these events, relative to the ones with positive β, are compatible with the rate of charge misidentification of the tracking system, and these events are analysed by reversing the track's charge.

To compare the data with the expected QED quasi-real Compton scattering process, we generated $e\gamma$ events with a Monte Carlo program[13] using the Weiszäcker-Williams approximation of the Equivalent Photon Spectrum and the classical Compton cross section according to

$$\frac{d^3\sigma}{dW\,dq^2du} = \frac{\alpha^3}{W^3}\left[\frac{s^2+(s-W^2)^2}{2s^2} - \frac{(s-W^2)q^2_{\rm min}}{sq^2}\right]\left[\frac{(1-u)^2+4}{(1-u)q^2}\right]$$

for a given charge of the observed electron, where u is the cosine of the scattering angle in the electron-photon c.m. system which is limited by the angular acceptance ($|u|_{\rm max} < |\cos\theta_{e,\gamma}|_{\rm max} = 0.6$), and q the mass of the quasi-real photons limited from above by the anti-tagging condition and from below by the finite mass of electron: $q_{\rm min} = m_e W^2/\sqrt{s(s-W^2)}$. The experimental efficiencies and resolutions are simulated using empirical expressions describing the geometry and measurement errors of the apparatus. For the photon, the efficiencies and resolutions have been estimated by comparing the shower counter information for the electrons with the measurements made by the tracking system. The radiation from the initial-state electron of the Compton process is taken into account by generating a relative energy loss k according to the probability distribution[14]

$$dP(k) = \eta k^{\eta-1}(1-k+\frac{k^2}{2})dk,$$

with $\eta = (2\alpha/\pi)[\ln(2E/m_e)-1]$. Consequently, the total energy $\sqrt{s}$ is replaced by $\sqrt{s(1-k)}$ in the expression for the differential cross section.

The Monte Carlo is found to reproduce various measured parameters and their correlations even before the E_{vis} cut; in particular, the cluster of events with low visible energies in Fig. 2 agrees with the QED prediction. The final $e\gamma$ invariant mass distribution is shown in Fig. 4(a). The data and the Monte Carlo are normalized to the same number of events. The normalization is consistent with the estimated detection efficiency within the uncertainty in the luminosity ($\sim$ 5%) and that in the detection efficiency ($\sim$ 10%). The data is in good agreement ($\chi^2 = 10.2/14D.F.$) with the QED prediction for Compton scattering.

If there exists an e^* in the accessible mass range, it would appear as a bump in Fig. 4(a), and the absence of any deviation from the QED prediction allows us to set upper limits on the strength of the $e^*e\gamma$ coupling in the given mass range. The gauge-invariant effective $e^*e\gamma$ interaction, where e^* is an excited electron of spin 1/2, is magnetic and usually written as[15]

$$L_{\text{eff}} = \frac{\lambda e}{2M_{e^*}} \overline{\Psi}_{e^*}\sigma_{\mu\nu}\Psi_e F^{\mu\nu} + h.c.,$$

where λ, which is taken to be real and positive,[16] parametrizes the coupling strength. Assuming the e^* to be narrow, the interference with Compton scattering can be neglected, and the expected excess of events due to the e^* can then be easily calculated as a function of λ and M_{e^*}. For this purpose, Monte Carlo events are generated with the same experimental conditions and effective luminosity, according to [5,6]

$$\frac{d^2\sigma(M_{e^*},\lambda)}{dq^2du} = \frac{2\pi\alpha^2\lambda^2}{M_{e^*}^2}\left[\frac{s^2+(s-M_{e^*}^2)^2}{2s^2} - \frac{(s-M_{e^*}^2)q_{\text{min}}^2}{sq^2}\right]\frac{1}{q^2}$$

for a given e^* charge, where the branching fraction $B(e^* \to e\gamma)$ is assumed to be 100 %.

The upper limit on λ (95% confidnece level) has been derived with a likelihood method using the bin counts of the data and the Monte Carlo predictions. The result is shown in Fig. 4(b) as a function of M_{e^*}. Our results can be compared to similar results obtained with the CELLO detector at PETRA.[10] Over the range $15 \lesssim M_{e^*} \lesssim 27$ GeV/c^2, our upper limit on λ is below 10^{-2} and is slightly better than the CELLO result obtained using the quasi-real Compton process.

In the above, it was assumed that the decay width Γ_{e^*} is much smaller than the mass resolution. The decay rate $e^* \to e\gamma$ is given by[3]

$$\Gamma_{e^*} = \frac{\lambda^2 \alpha}{2} M_{e^*},$$

where α is the electromagnetic fine structure constant, and the limit $\lambda < 0.01$ leads to $\Gamma_{e^*} < 10$ KeV which is consistent with the assumption.

In conclusion, we have shown that the quasi-real $e\gamma$ scattering measured at PEP agrees with the QED predictions for the standard Compton scattering process. From this measurement, we have set upper limits on the coupling parameter λ of the $e^* e\gamma$ vertex. For an e^* mass in the range 15 to 27 GeV/c^2, our 95% C.L. upper limit on λ is less than 10^{-2}.

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(a) Present address: Laboratoire de l'Accelerateur Lineaire, L.A.L. - Orsay, Bat. 200, Orsay 91405, France.

(b) Present address: CERN, EP-division, CH-1211, Geneva 23, Switzerland.

(c) Present address: Watkins-Johnson Co., 2525 North 1st Street, San Jose, CA 95131-1097.

(d) Present address: U. of Victoria, Dept. of Physics, P.O. Box 1700, Victoria, B.C. V8W 2Y2, Canada.

(e) Present address: DESY, F-22, Notkestrasse 85, D-2000 Hamburg 52, West Germany.

(f) Present address: Institute of High Energy Physics, P.O. Box 918, Beijing, The People's Republic of China.

(g) Present address: National Lab. for High Energy Physics, KEK, Oho-machi, Tsukuba-gun, Ibaraki-ken, 305 Japan.

(h) Present address: Spectra Physics, 3333 North 1st St, San Jose, Ca. 95134-1995.

(i) Present address: Fakultät für Physik, Albert-Ludwigs-Universität, Hermann -Herder Strasse 3, 7800 Freiburg, West Germany.

(j) Present address: University of Michigan, Dept. of Physics, Ann Arbor, Michigan 48109.

(k) Present address: University of Geneva, Dept. of Physics, 32 Boulevard d'Yuoy, 1211 Geneva, Switzerland.

(l) Deceased.

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11. C. Young, in *Proceedings of the 11th SLAC Summer Institute on Particle Physics* (Stanford, 1983), p. 607; Particle Data Group, Lawrence Berkeley Laboratory Report Hr. LBL-91 Suppl. UC-37 (1983).
12. The relevant triggers are: at least one charged track associated with a Cerenkov hit and a barrel shower counter hit, or at least one charged track and at least two hits in different sextants of the barrel shower counter. The inefficiency due to the trigger is estimated to be negligible.

13. That program applies the same methods as the one used for $\gamma\gamma$ interactions studied at DELCO; see: A. Courau, SLAC-PUB-3363 (1984).

14. Based on the semiclassical method described in: E. Etim, G. Pancheri and B. Touschek, Nuovo Cimento **51B** (1967) 276; G. Pancheri, *ibid.* **60A** (1969) 321.

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16. A more general form (see Ref.3,5) is $(e/2M_{e^*})\overline{\Psi}_{e^*}\sigma_{\mu\nu}\,(a-b\gamma^5)\Psi_e F^{\mu\nu}$, where a and b are complex numbers. This will change the u distribution from flat to $1+[2\mathrm{Re}(a^*b)/(|a|^2+|b|^2)]^2u$. However, the angular acceptance being symmetric, our result is still valid when λ is replaced by $\sqrt{|a|^2+|b|^2}$.

Figure Captions

*Fig.*1. Configuration for the quasi-real Compton process $e^+e^- \rightarrow e^+e^-\gamma$.

*Fig.*2. Photon versus electron shower pulse heights for $e\gamma$ events. The cluster at low energy is interpreted as the events where the initial-state electron of the Compton process loses most of its energy by radiation. The dashed line corresponds to the cut on the sum of both shower pulse heights.

*Fig.*3. Distribution of the velocity β for all observed $e\gamma$ events (data points) and for those with the electron identified as converted photon (shaded histogram).

*Fig.*4. (a) Measured distribution of the $e\gamma$ invariant-mass W (data points) compared to the QED prediction (histogram). (b) Upper limit obtained, at 95% confidence level, for the $e^*e\gamma$ coupling parameter λ as a function of the e^* mass.

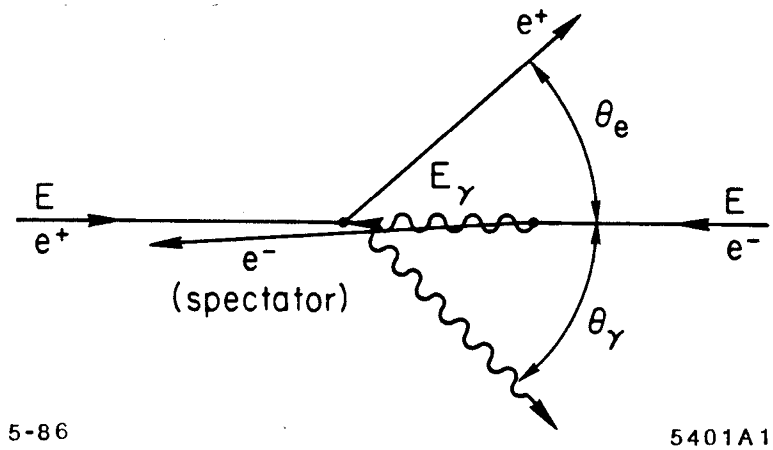
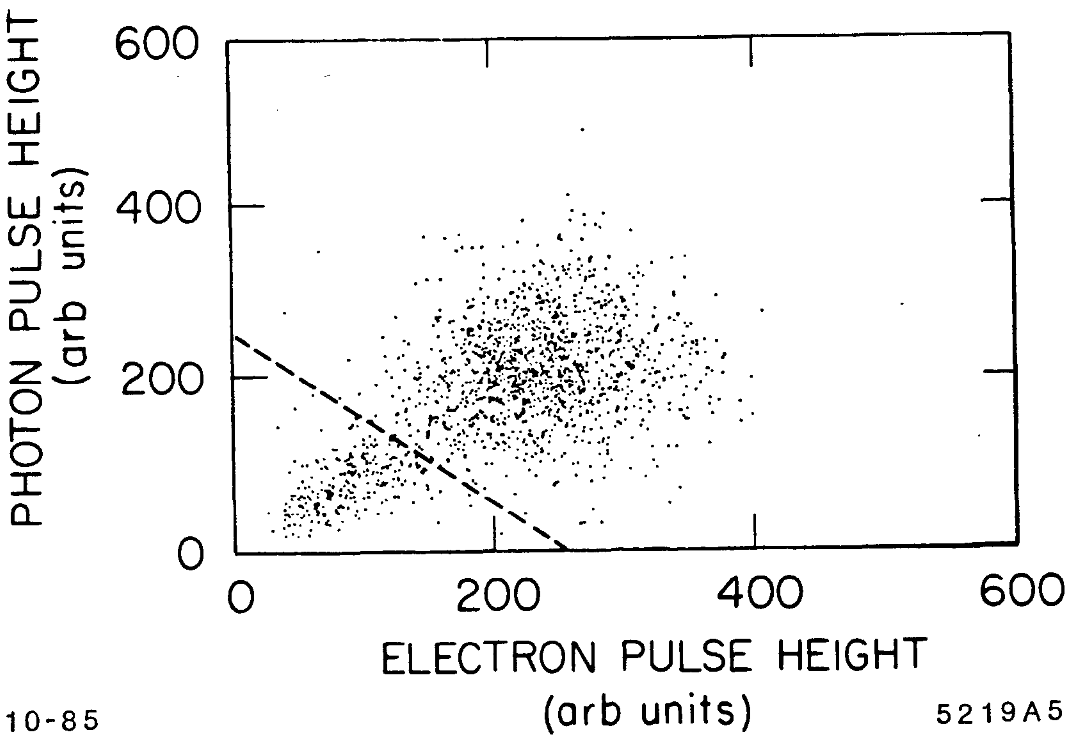


Fig. 1


PHOTON PULSE HEIGHT
(arb units)
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400
200
0
0
200
400
600
ELECTRON PULSE HEIGHT
(arb units)
10-85
5219A5

Fig. 2

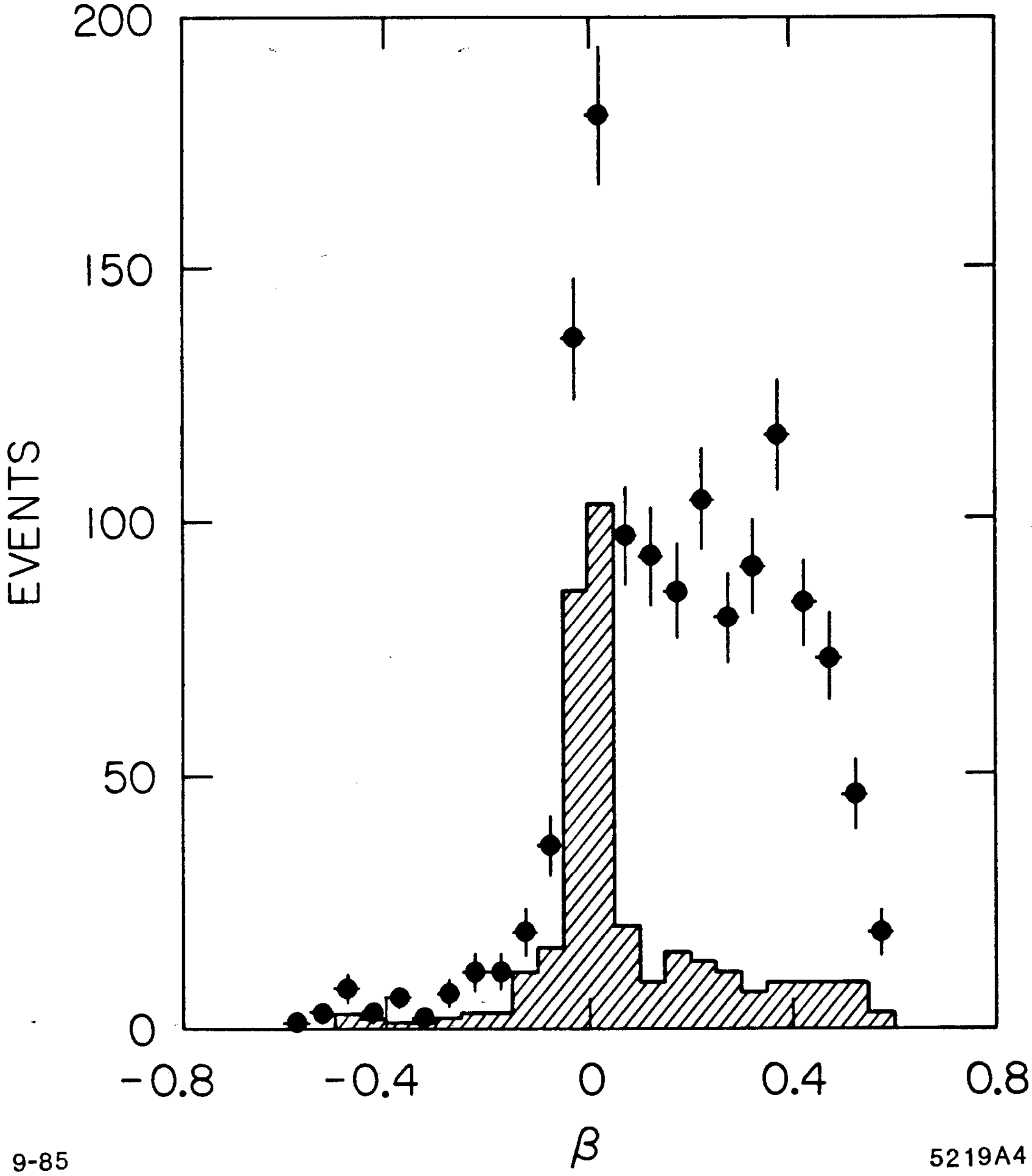
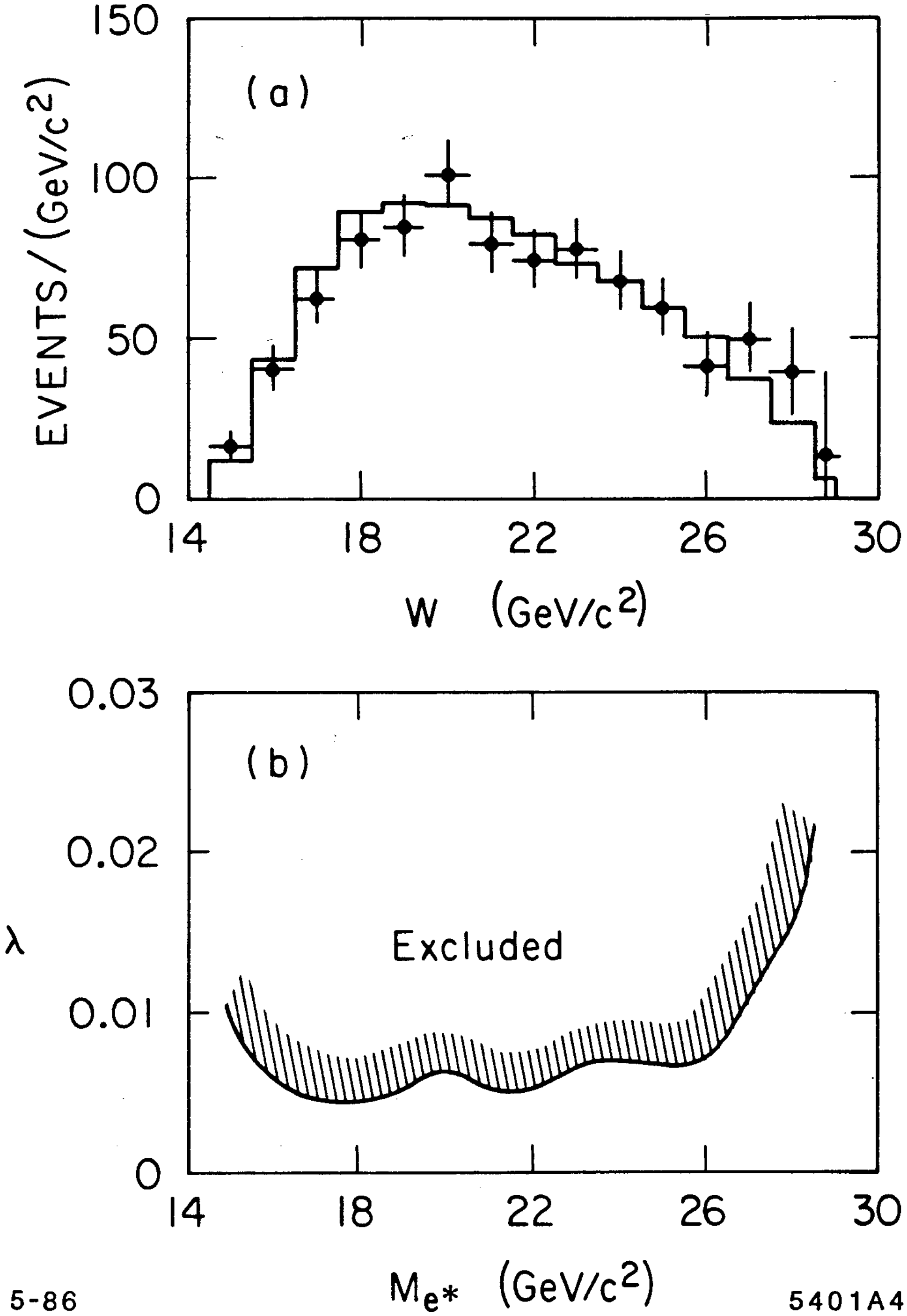


Fig. 3



(a)
EVENTS/(GeV/c²)
150
100
50
0
14
18
22
26
30
W (GeV/c²)
(b)
0.03
0.02
0.01
0
λ
Excluded
14
18
22
26
30
Me* (GeV/c²)
5-86
5401A4

Fig. 4