# ELECTROWEAK COUPLING CONSTANTS IN THE LEPTONIC REACTIONS $e^+e^- \to e^+e^-$ AND $e^+e^- \to \mu^+\mu^-$ AND SEARCH FOR SCALAR LEPTONS

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A high statistics experiment was performed on Bhabha scattering at energies between 14 and 34 GeV. Good agreement with QED was observed. The combined data on Bhabha scattering and $\mu$ pair production were found to agree with the standard theory of electroweak interaction giving $\sin^2\theta = 0.27^{+0.06}_{-0.07}$. Assuming for the $Z^0$ mass a value of 90 GeV the leptonic weak coupling constants were determined to $g_V^2 = -0.04 \pm 0.06$ and $g_A^2 = 0.35 \pm 0.09$. A search for scalar leptons sets lower limits on the mass of scalar electrons of $M_{s_e} > 16.6$ GeV and of scalar muons of $M_{s_\mu} > 16.4$ GeV.

The reactions $e^+e^- \to \ell^+\ell^-$ ($\ell = e, \mu, \tau$) at high energies provide sensitive tests of electroweak theories. First results on a sizeable forward–backward asymmetry in $\mu$ pair production due to electroweak interference have been reported by this and other experiments [1,2]. In this letter we report on a high statistics experiment on Bhabha scattering, $e^+e^- \to e^+e^-$. The data were used to test QED and, when combined with our results on $\mu$ pair production [1], to determine the electroweak coupling constants. We also used our data to search for the production of scalar leptons.

The data presented here have been taken with the TASSO detector at PETRA at average CM energies $W$ = 14.0 GeV (integrated luminosity 1.63 $pb^{-1}$), 22.0 GeV (2.89 $pb^{-1}$) and 34.4 GeV (51.37 $pb^{-1}$). The detector has been described elsewhere [1,3]. The event selection and analysis procedure for Bhabha scattering follows closely ref. [3] and is described only briefly. The selected events were required to have two oppositely charged tracks [‡1] within the polar angle acceptance $|\cos\theta| < 0.80$ and with an acollinearity angle less than 10°. The momentum of each track had to be larger than 20% and the sum of both momenta larger than 70% of the beam momentum. The tracks had to originate from the nominal interaction point within a volume of 0.6 cm radius and ±7.5 cm length along the beam line. Cosmic rays were rejected by demanding that the measured and predicted time-of flight for each track satisfy $-3.0 < t^{\text{measured}} - t^{\text{predicted}} < 2.0$ ns. In this data sample background from two-photon processes $e^+e^- \to e^+e^-\ell^+\ell^-$ and cosmic rays is entirely negligible. The contribution from $\mu$ pairs (5%) and $\tau$ pairs (1%) has been subtracted statistically bin by bin taking into account our measured angular asymmetry [1]. The data sample contains 10662 events at $W$ = 14 GeV, 7126 events at $W$ = 22 GeV and 49908 events at $W$ = 34 GeV.

In ref. [1] it was shown that the trigger efficiency $\epsilon_t$ and the reconstruction efficiency $\epsilon_r$ of two-prong events as selected above do not depend on the polar angle. For the data presented here $\epsilon_t = 0.962 \pm 0.002$ and $\epsilon_r = 0.985 \pm 0.010$. The electrons/positrons from Bhabha events tend to produce secondary particles due to showering in the material in front of the tracking chambers (0.13 radiation length). The restriction to events with exactly two charged tracks leads to losses which depend on the polar angle. The acceptance has been calculated with Monte Carlo techniques. Bhabha events were generated including higher order QED effects [4] [‡2] and the particles were followed through the detector. Electromagnetic interactions were simulated with the EGS shower program [5]. Taking into account radiative effects and shower formation the resulting acceptance is almost flat for $|\cos\theta| < 0.5$ with a value of 0.80 and falls roughly with a $1/\sin\theta$ behaviour to 0.72 at $|\cos\theta| = 0.7$. In order to check the simulation of shower formation we selected 6970 Bhabha candidates without the multiplicity cut with the electron and positron identified in the liquid argon calorimeter and with at least two tracks satisfying the above mentioned selection criteria. Of these events (13.4 ± 0.5)% had additional charged

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[‡1] Even at the highest energy the loss resulting from events having two tracks with the same charge assignment is less than 1.0%.

[‡2] We thank F.A. Berends and R. Kleiss for providing us with their Bhabha event generator.

tracks with momenta $p > 0.1$ GeV/$c$. This fraction agrees with the Monte Carlo prediction of (12.4 ± 0.2)%. Good agreement between data and Monte Carlo simulation was also obtained for the momentum spectrum and multiplicity distribution of the detected charged particles. We estimate the overall uncertainty due to shower corrections to be less than 2% and the uncertainty in the variation of the bin-to-bin polar angle acceptance to be less than 1%. All data have been corrected for detector and analysis efficiencies. Radiative corrections were applied up to order $\alpha^3$ including leptonic and hadronic vacuum polarization. The systematic uncertainty of all corrections amounts to ±3.5%. For the determination of the Bhabha cross section at $W = 14$ GeV the data were normalized to QED in the interval $0.7 < \cos\theta < 0.8$, while at $W \geqslant 22$ GeV the luminosity measurement of the forward detector was used. At the highest CM energies the luminosity has a systematic uncertainty of ±4.5%.

The corrected differential cross sections for the three different CM energies are shown in fig. 1. The data are well described by the QED prediction (solid curve in fig. 1). A breakdown of pure QED can be parametrized by modifying the timelike and spacelike amplitudes with form factors

$$F_T(s) = 1 + \Lambda_T^{-2}\, s/(1 - s/|\Lambda_T^2|) = 1 \mp s/(s - \Lambda_{T\pm}^2), \tag{1a}$$

$$F_S(t) = 1 + \Lambda_S^{-2}\, t/(1 - t/|\Lambda_S^2|) = 1 \mp t/(t - \Lambda_{S\pm}^2), \tag{1b}$$

where $s = W^2$ and $t = -\frac{1}{2}s\,(1 - \cos\theta)$. Assuming $\Lambda_S = \Lambda_T = \Lambda$ a fit to the data yielded $1/\Lambda^2 = (1.4 \pm 1.9) \times 10^{-5}$ GeV$^{-2}$ or $\Lambda_+ > 150$ GeV and $\Lambda_- > 251$ GeV. Allowing different form factors for the timelike and spacelike channels we obtained $1/\Lambda_T^2 = (3.1 \pm 3.1) \times 10^{-5}$ GeV$^{-2}$ or $\Lambda_{T+} > 110$ GeV and $\Lambda_{T-} > 223$ GeV and $1/\Lambda_S^2 = (1.4 \pm 1.9) \times 10^{-5}$ GeV$^{-2}$ or $\Lambda_{S+} > 149$ GeV and $\Lambda_{S-} > 243$ GeV (all limits at 95% CL). Hence Bhabha scattering is well described by QED up to the highest energy of $s \simeq 1200$ GeV$^2$ and implies that electrons behave as pointlike particles down to distances of $10^{-16}$ cm.

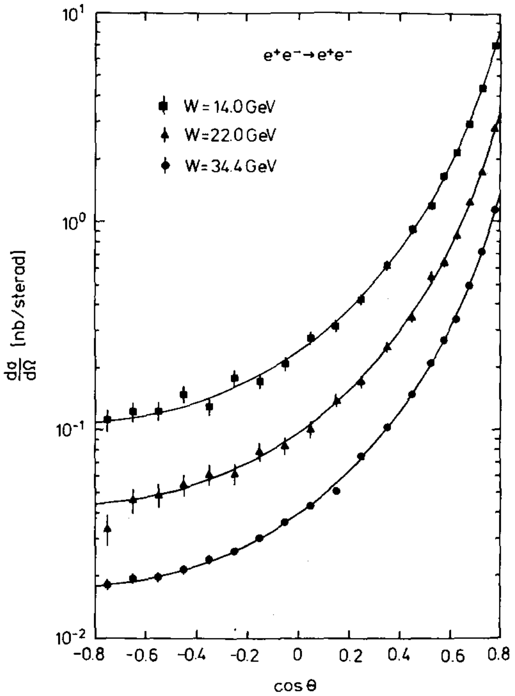


Fig. 1. The differential cross section $d\sigma/d\Omega$ for Bhabha scattering at CM energies of 14, 22 and 34.4 GeV. The curves are the predictions from QED.

We now turn to the investigation of electroweak effects in leptonic reactions. The cross section for Bhabha scattering with unpolarized beams including electromagnetic and weak neutral currents can be written in the following form [6]

$$d\sigma/d\Omega = (\alpha^2/8s)[4B_1 + (B_3 + B_2)(1 + \cos^2\theta) + 2(B_3 - B_2)\cos\theta], \tag{2}$$

with

$$B_1 = (s/t)^2 |1 + (g_V^2 - g_A^2)\xi|^2,$$

$$B_2 = |1 + (g_V^2 - g_A^2)\chi|^2,$$

$$2B_3 = |1 + s/t + (g_V + g_A)^2 [(s/t)\xi + \chi]|^2 + |1 + s/t + (g_V - g_A)^2 [(s/t)\xi + \chi]|^2,$$

$$\chi = (G_F M_Z^2 / 2\sqrt{2}\pi\alpha)\, s/(s - M_Z^2 + iM_Z\Gamma),$$

$$\xi = (G_F M_Z^2 / 2\sqrt{2}\pi\alpha)\, t/(t - M_Z^2 + iM_Z\Gamma),$$

where $G_F$ is the Fermi coupling constant, $M_Z$ and $\Gamma$ the mass and width of the intermediate $Z^0$ boson. In this analysis the $Z^0$ width has been neglected. In the standard Glashow–Weinberg–Salam (GWS) theory [7] the weak coupling constants are expressed by one parameter $\sin^2\theta_W$: $g_V = -\frac{1}{2}(1 - 4\sin^2\theta_W)$, $g_A = -\frac{1}{2}$ and $M_Z = 74.6$ GeV$/\sin 2\theta_W$.

Information on the vector coupling $g_V$ can be obtained from the total lepton pair cross section. Assuming the measured value [8] of $\sin^2\theta_W = 0.228$, the effect in the total cross section is expected to be extremely small, however. The axial vector coupling $g_A$ gives rise to a deviation of the polar angle distribution from the QED prediction. In order to extract the maximum information on the weak coupling constants in purely leptonic reactions a simultaneous analysis was performed of Bhabha and $\mu$ pair data at the highest CM energies assuming e–$\mu$ universality. The theoretical $\mu$ pair cross section can be derived from eq. (2) by setting all terms with $s/t$ to zero. The results from the $\mu$ pair production measurement alone have been presented in ref. [1]. An uncertainty of 5% in overall normalization and 3% in the relative normalization of both data samples was used. In figs. 2a, b the measured cross sections divided by the QED cross section are shown as function of the scattering angle $\theta$ for Bhabha scattering and $\mu$ pair production.

For Bhabha scattering good agreement with QED is found, while the $\mu$ pair angular distribution shows a definite deviation from QED, resulting in a forward–backward asymmetry [1] $A_\mu = -0.161 \pm 0.032$. Within the GWS theory a combined fit to the data gave $\sin^2\theta_W = 0.27^{+0.06}_{-0.07}$ (shown as dashed curves in figs. 2a, b). Assuming $M_Z = 90$ GeV, a simultaneous fit to the vector and axial-vector coupling yielded $g_V^2 = -0.04 \pm 0.06$ and $g_A^2 = 0.35 \pm 0.09$. The results are displayed in the $g_V^2 - g_A^2$ plane of fig. 3a. Also shown are the two solutions obtained in neutrino–electron scattering experiments [‡3]. Note that these are also purely leptonic reactions. Our data are only compatible with one of the two solutions, namely the one which is in agreement with the standard theory $g_V^2 = 0.0016$ and $g_A^2 = 0.25$. If we fix the coupling constants $g_V^2$ and $g_A^2$ to the values obtained in neutrino scattering at low $q^2$ ($g_V^2 = 0.0016$ and $g_A^2 = 0.25$) we can fit for the mass of an intermediate boson $M_Z$. The result is $1/M_Z^2 = (4.09^{+0.74}_{-1.05}) \times 10^{-4}$ GeV$^{-2}$ or $M_Z = 50^{+8}_{-4}$ GeV. The 95% confidence limits are $43.1 < M_Z < 81.8$ GeV.

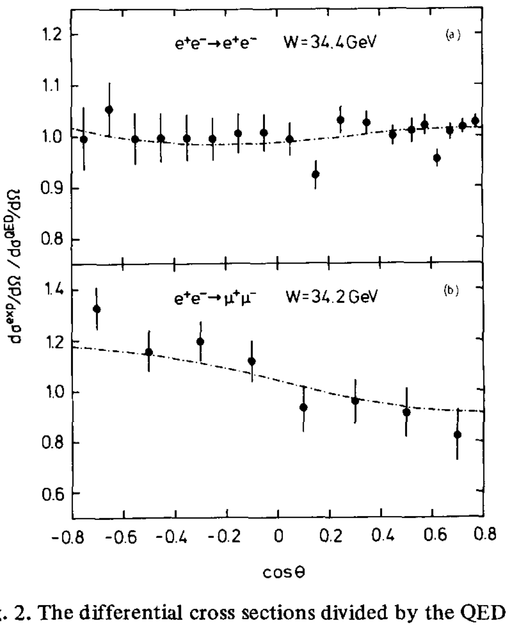


Fig. 2. The differential cross sections divided by the QED expectation for the reactions (a) $e^+e^- \to e^+e^-$ and (b) $e^+e^- \to \mu^+\mu^-$. The curves show the fits to the data of the GWS theory with $\sin^2\theta_W = 0.27$.

The standard theory may be extended to include more than one neutral Z boson [10] by adding to the hamiltonian a term of $C$ times the electromagnetic current squared. Such an effect should be observable only in $e^+e^-$ reactions. Formally it leads to a modification of the vector coupling $g_V^2 = \frac{1}{4}(1 - 4\sin^2\theta_W)^2 + 4C$, leaving all other parameters of the GWS theory unchanged. Assuming $\sin^2\theta_W = 0.228$ a fit yielded $C = -0.006 \pm 0.016$, or $C < 0.020$ with 95% confidence. This upper bound restricts the parameter space of multiboson models considerably. In particular in the models SU(2) × U(1) × U′(1) and SU(2) × U(1) × SU′(2) the $C$ parameter is related to the masses of two neutral vector bosons, $Z_1$ and $Z_2$, one being lighter and the other being heavier than the $Z^0$ boson of the standard theory. The region allowed by the data is shown in fig. 3b.

Our results on the leptonic weak coupling constants can be compared to those obtained in other recent experiments, which is shown in table 1.

We have used out two-prong data sample at $W = 34$ GeV to search for the production of saclar leptons [12]. In supersymmetric gauge theories scalar leptons, $s_\ell$, are the charged spin 0 partners of the familiar spin 1/2 leptons. For each lepton $\ell$ there exist two types of scalar leptons ($s_\ell$, $t_\ell$) differing in a new quantum number. For simplicity we assume that the masses and production rates of both particles are the same and use the generic name $s_\ell$ for both. In $e^+e^-$ interactions they

‡3 For a recent review see Barbiellini [9].

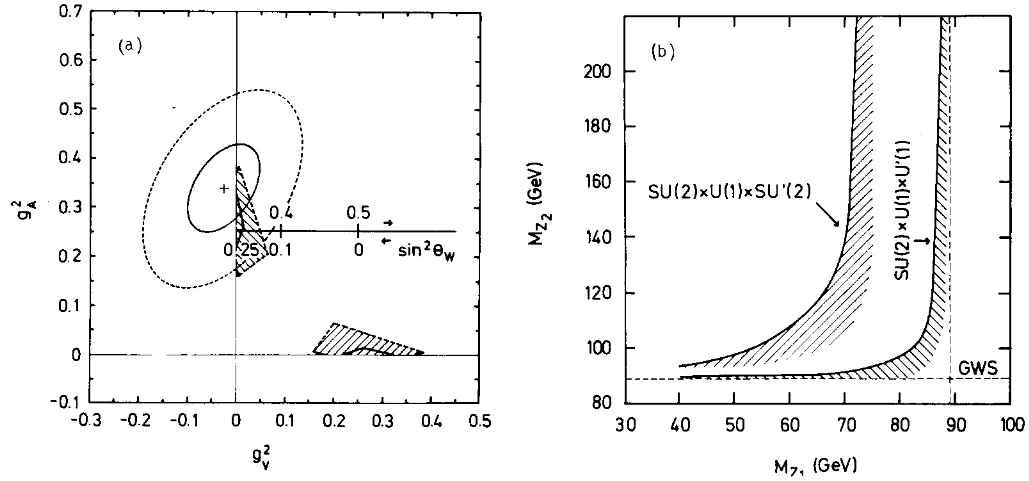


Fig. 3. (a) Results of a fit to $g_V^2$ and $g_A^2$ with 68% (solid curve) and 95% (dashed curve) confidence contours. The shaded areas show the two solutions obtained by neutrino electron experiments. They indicate the overlap of the 1 SD (solid line) and 2 SD (dashed line) contours obtained by the different types of neutrino experiments. (b) Limits on $M_{Z_1}$ and $M_{Z_2}$ in models with two $Z^0$ bosons. The allowed regions are shaded. The $Z^0$ mass in the GWS is shown by the dashed lines.

could be pair produced with a cross section

$$d\sigma(e^+e^- \to s_\ell \bar{s}_\ell)/d\Omega = (\alpha^2\beta^3\sin^2\theta/8s)$$

$$\times \{1 + [1 - 4K/(1 - 2\beta\cos\theta + \beta^2)]^2\}, \qquad (3)$$

with $K = 0$ for $\ell = \mu$, $K \geqslant 1$ for $\ell = e$. For the following analysis we used $K = 1$ for $\ell = e$.

Scalar leptons are expected to decay, with an extremely short lifetime, to the corresponding lepton and a massless, undetectable photino or goldstino ($s_\ell \to \ell + \lambda$). Thus the signature for scalar lepton production is $e^+e^- \to \ell^+\ell^-$ + missing momentum, a topology similar to the QED reactions discussed above. In our lepton pair data light scalar leptons would produce a pronounced increase of events around $\cos\theta = 0$, while heavy scalar leptons would be detected by a noticeable excess of events with large acoplanarity angle. For the data shown in figs. 2a, b an additional contribution according to eq. (3) can be ruled out for scalar electrons with a mass $M_{s_e} < 2.0$ GeV and scalar muons with a mass $M_{s_\mu} < 4.0$ GeV at 95% confidence level. To search for heavier scalars we investigated the acoplanarity distribution of two-prong events. These data were taken with a trigger that demanded at least two tracks in the central tracking chambers with an event vertex within ≈15 cm of the interaction point along the beam direction. The latter requirement was imposed by a hardware processor using the proportional chamber cathode information [13]. The events were selected with the same criteria as above but without a cut on the acollinearity angle. In fig. 4a the acoplanarity distribution is shown for the reaction $e^+e^- \to e^+e^-$ where at least one electron is identified by the liquid argon calorimeter. The contribution from $\tau$-pair pro-

Table 1

| Collaboration | Data | $\sin^2\theta_W$ | $g_V^2$ | $g_A^2$ |
|---|---|---|---|---|
| TASSO | ee, $\mu\mu$ | $0.27^{+0.06}_{-0.07}$ | $-0.04 \pm 0.06$ | $0.35 \pm 0.09$ |
| TASSO b) | $\mu\mu$ | $0.29^{+0.09}_{-0.11}$ | $-0.09 \pm 0.11$ a) | $0.45 \pm 0.09$ a) |
| CELLO c) | ee, $\mu\mu$ | $0.25 \pm 0.13$ | – | $0.17 \pm 0.17$ |
| JADE c) | ee, $\mu\mu$ | $0.25 \pm 0.15$ | $0.05 \pm 0.08$ | $0.39 \pm 0.11$ |
| MARK J c) | ee, $\mu\mu$ | $0.24 \pm 0.11$ | $0.01 \pm 0.05 \pm 0.06$ | $0.28 \pm 0.06 \pm 0.03$ |

a) The values of ref. [1] have been reevaluated assuming $M_Z = 90$ GeV. b) Ref. [7]. c) Refs. [2,11].

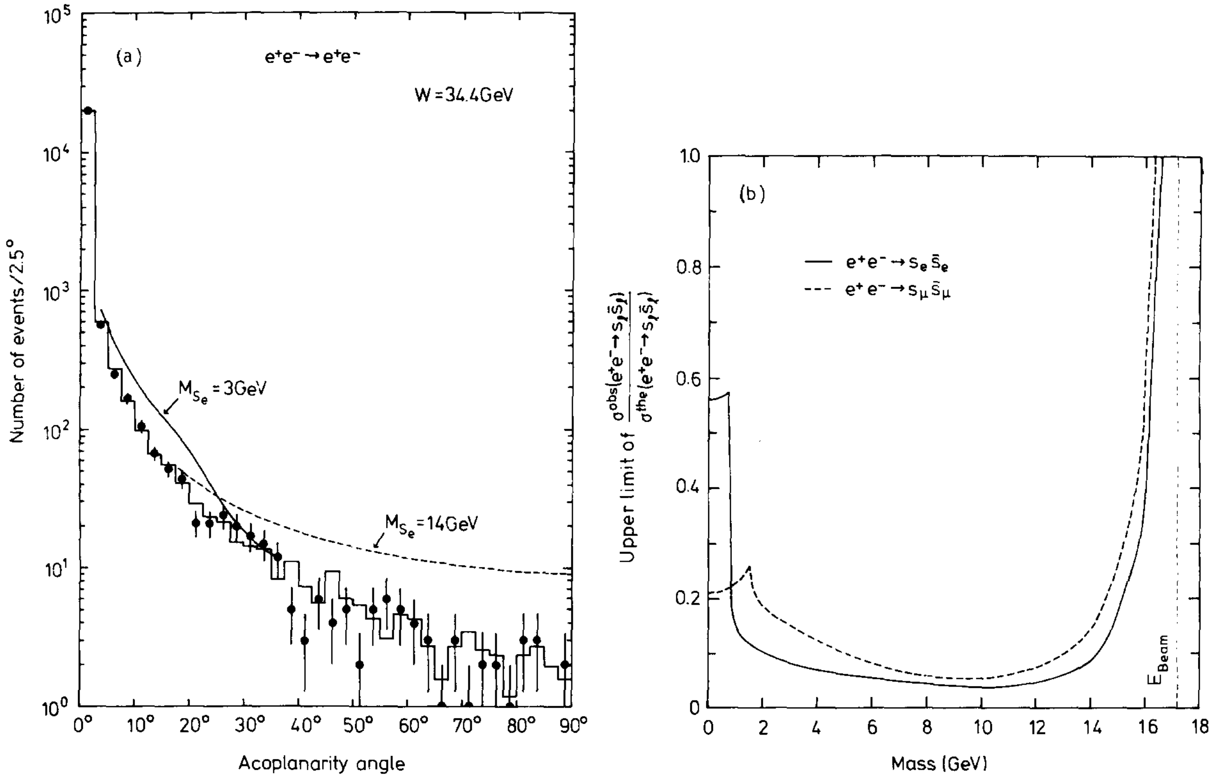


Fig. 4. (a) The observed acoplanarity distribution for the reaction $e^+e^- \to e^+e^-$. The histogram shows the QED prediction up to the order $\alpha^3$. The solid and dashed lines indicate possible contributions from scalar electrons with masses of 3 GeV and 14 GeV.
(b) Upper limit on the ratio of observed to theoretical cross section for supersymmetric scalar lepton production. The symbols $s_e$, $s_\mu$ denote the sum of the two types of scalars.

duction was calculated to be less than 0.5%. The background from two-photon processes is negligible. The data in fig. 4a agree well with the calculations for Bhabha scattering in QED to order $\alpha^3$ and including the residual $\tau$ fraction. The expected contributions from scalar leptons were calculated by a Monte Carlo method using eq. (3) and simulating the detector effects and selection criteria. Fig. 4a shows the predictions for two values of the $s_e$ mass, $M_{s_e}$ = 3 GeV and $M_{s_e}$ = 14 GeV. They are clearly ruled out by the data. A similar analysis was carried out for the reaction $e^+e^- \to \mu^+\mu^-$ in which at least one track was identified as a muon in the muon chamber or the liquid argon calorimeter. Together with the search for light scalars the data rule out scalar electrons for masses lower than 16.6 GeV and scalar muons for masses lower than 16.4 GeV with 95% confidence. Fig. 4b shows as a function of $M_{s_\ell}$ the upper limit for the ratio of the observed to the predicted cross section [eq. (3)]. For $4 < M_{s_\ell} < 14$ GeV the upper limit for the cross section is at least a factor of ten smaller than predicted. In this analysis radiative corrections were not applied to the production of scalar leptons. Inclusion of radiative corrections is expected to yield somewhat tighter limits. Our mass limits on possible scalar leptons are similar to those obtained by other experiments [14]. Comparing our results with other experiments one should note that we have assumed that both types of scalar leptons ($s_\ell$, $t_\ell$) are produced with the same rate and cannot be distinguished experimentally. Therefore the cross section eq. (3) (for $K = 0$) is twice the QED cross section for scalar particle production.

In summary we have measured the reaction $e^+e^- \to e^+e^-$ at average CM energies between 14 and 34 GeV and found good agreement with the QED prediction. We obtained the following values for the cut off parameters $\Lambda_+ > 150$ GeV and $\Lambda_- > 251$ GeV (95% CL). The data on Bhabha scattering and $\mu$ pair production support the standard theory of electroweak interaction, and yield $\sin^2\theta_W = 0.27^{+0.06}_{-0.07}$. With a $Z^0$ mass of 90 GeV the leptonic weak coupling constants were determined to $g_V^2 = -0.04 \pm 0.06$ and $g_A^2 = 0.35 \pm 0.09$. The precision reached in these processes is comparable to that of the combined neutrino–electron scattering experiments [9]. Thus the standard theory is found to describe purely leptonic processes over more than four orders of magnitude in squared momentum transfer, namely $q^2 \lesssim 0.1$ GeV$^2$ for $\nu e^- \to \nu e^-$ scattering and $q^2 \simeq 1200$ GeV$^2$ for $e^+e^- \to \ell^+\ell^-$ production. The possible existence of scalar leptons can be ruled out for masses less than 16.6 GeV (scalar electrons) and 16.4 GeV (scalar muons) with 95% confidence.

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