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Experimental Test of Electroweak Effects at PETRA Energies

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Abstract. The differential cross sections for Bhabha scattering and μ pair production, and the total τ pair cross section as measured by the PLUTO detector at PETRA, have been analyzed to extract information on the weak interaction of leptons. The data are compared with unified gauge theories. Since the observed electroweak effects are still consistent with zero (within errors) we can set experimental limits on neutral current parameters at Q^2 values of 950 GeV^2. In the framework of the standard $SU(2) \times U(1)$ model we find $\sin^2 \Theta_w < 0.52$ (95% c.l.). In the context of general single Z^0 models we can exclude Z^0 masses of less than 40 GeV.

The two reactions

$$e^+e^- \to e^+e^- \quad \text{Bhabha scattering}, \qquad (1)$$

$$e^+e^- \to \mu^+\mu^- \quad \mu \text{ pair production} \qquad (2)$$

are of fundamental importance in e^+e^- colliding beam experiments for two reasons:

i) Both processes provide a testing ground for the validity of QED at high Q^2.

ii) Unified gauge theories predict at the highest PETRA energies measurable deviations from QED (of

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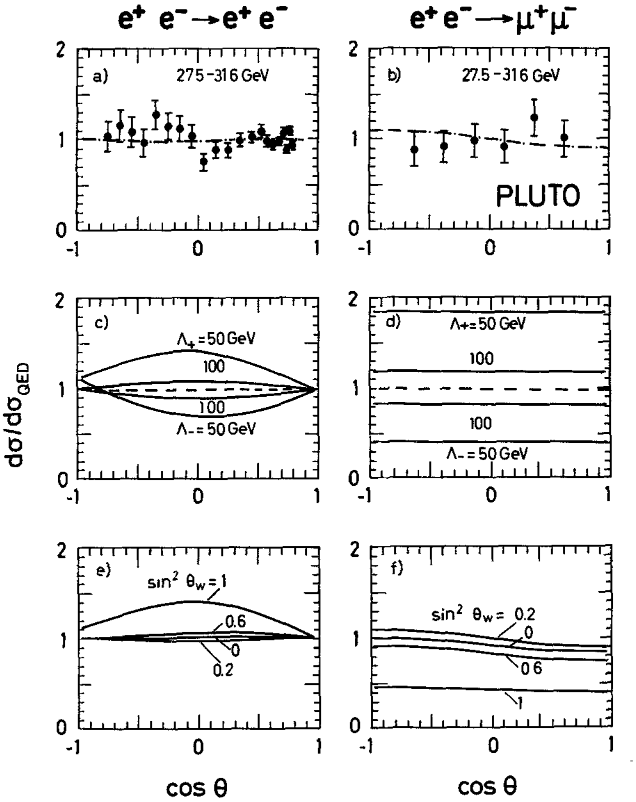

Fig. 1a–f. Ratio $d\sigma/d\sigma_{QED}$ as a function of $\cos\Theta$ for reactions $e^+e^- \to e^+e^-$ (**a, c, e**) and $e^+e^- \to \mu^+\mu^-$ (**b, d, f**). **a, b** Measured ratio in the interval $27.5 \leqq \sqrt{s} \leqq 31.6$ GeV. The curve is the fit with $\sin^2\Theta_w$ as free parameter. **c, d** Deviation from first order QED for assigned values of the cutoff parameter Λ[2] (at $\sqrt{s}=30$ GeV). **e, f** Deviation from first order QED in the standard $SU(2)\times U(1)$ model for assigned values of $\sin^2\Theta_w$ (at $\sqrt{s}=30$ GeV)

the order 2–5%) due to exchange of the neutral Z^0 boson. Hence electroweak models can be tested at values of the momentum transfer which are not accessible in present neutrino experiments.

In this publication the second aspect (ii) will be investigated assuming the exact validity of QED. It is our objective to give limits on the vector and axial vector coupling of the neutral current at Q^2 values of $\simeq 950\,\text{GeV}^2$ and on the vector boson masses in models allowing for several neutral vector bosons. We are thus testing neutral current models in an energy range intermediate between present day neutrino experiments and the Z^0 pole. We also determine the value of $\sin^2\Theta_w$ assuming the validity of the standard $SU(2)\times U(1)$ model [1].

The data have been obtained with the PLUTO detector at the e^+e^- colliding beam facility PETRA in Hamburg. Details of the PLUTO detector and the data acquisition have been published elsewhere [2, 3]. The data used here are fully corrected for detector and radiative effects up to order α^3, including hadronic vacuum polarization [4].

Since the weak contributions to the cross sections are expected to rise linearly with s (where s is the squared c.m. energy) in contrast to the $1/s$ behaviour of the QED part, only data at the highest energy points ($27.5 \leqq \sqrt{s} \leqq 31.6$ GeV) are used. Our data are based on an integrated luminosity of $400\,\text{nb}^{-1}$ at $\sqrt{s}=27.5$ GeV and $2500\,\text{nb}^{-1}$ between 30 and 31.6 GeV.

The differential cross sections for reactions (1) and (2) can be written in the form

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{QED}}{d\Omega}(1+\delta); \qquad \delta = \delta_w + \delta_\Lambda, \tag{3}$$

where δ denotes the deviation from the QED expectation and the subscripts w and Λ refer to effects due to the weak interaction (w) and due to a possible breakdown of QED(Λ); $d\sigma_{QED}/d\Omega$ is the 1st order QED cross section. Note that higher order electromagnetic corrections are already accounted for in the data. To illustrate the magnitude of the corrections $1+\delta$ at $s \sim 900\,\text{GeV}^2$ we show in Fig. 1 the data of reactions (1) (Fig. 1a) and (2) (Fig. 1b) and the expected deviations $1+\delta$ from 1st order QED for various assigned values of the cutoff parameter Λ (Fig. 1c, d) and $\sin^2\Theta_w$ (Fig. 1e, f), the free parameter in the standard $SU(2)\times U(1)$ model (see below).

A fit of reactions (1) and (2) to cutoff parameters Λ gives values consistent with infinity and lower bounds of the order of 100 GeV [2, 3] at 95% c.l. As can be seen from Fig. 1a, b the statistical significance of the data does not allow us to disentangle δ_w and δ_Λ simultaneously. Hence we restrict our analysis of modifications of QED to electroweak effects only. In the following analysis we further assume that the colliding beams have no longitudinal polarization and that the radiative corrections to the weak terms are the same as those to the electromagnetic ones.

We now proceed with the quantitative analysis of reactions (1) and (2) in the framework of unified theories. In a first step we include in the cross sections the weak contributions up to 2nd order [5] in the vector- and axial vector coupling constants v and a. The explicit form of the cross sections, assuming a single Z^0 pole, is given in (A1) and (A2) of the appendix. From the equations we observe the following:

i) The differential cross sections depend on M_z, v^2, and a^2 but not on the sign of the coupling constants.

ii) The contribution of the direct Z^0 term is proportional to s ($M_z^2 \gg s, q^2$) as expected for a pointlike weak coupling.

iii) The interference term in μ pair production produces a forward-backward asymmetry proportional to

a^2 [see (A3)] and modifies the total cross section proportional to v^2.

First we consider the standard $SU(2) \times U(1)$ model in which the coupling constants and the Z^0 mass are functions of a single parameter Θ_w only:

$$v = 1 - 4\sin^2\Theta_w$$
$$a = -1$$
$$M_z = 74.6\,\text{GeV}/\sin(2\Theta_w).$$

We have fitted Eqs. (A1) and (A2) to the measured differential cross sections for reactions (1) and (2). The total cross section value [3] for reaction $e^+e^- \to \tau^+\tau^-$ was also included in the fit. The normalization of the experimental cross sections was based on the radiatively corrected number of Bhabha scatters N in the interval $0.7 < \cos\Theta < 0.8$ via $L = N/\sigma_{\text{electroweak}}$. L is the luminosity and $\sigma_{\text{electroweak}}$ is the integrated cross section from (A1) in the interval $0.7 < \cos\Theta < 0.8$. Of course the normalization depends on the parameters to be fitted. From the fits we find

$$\sin^2\Theta_w < 0.52$$

and an upper limit of

$$\sin^2\Theta_w = 0.22 \pm 0.22$$

at the 95% confidence level. The result is consistent with the world average value of $\sin^2\Theta_w = 0.230 \pm 0.009$ obtained at lower momentum transfers [6]. The dash-dotted line in Fig. 1a and b is the fit to the data.

Analyzing the forward-backward asymmetry in μ pair production we find

$$A = \frac{F-B}{F+B} = 7 \pm 8\,\%\,(\text{stat.}) \pm 2\,\%\,(\text{syst.})$$

compared to the expectation of -5.8% [see (A3)] in the standard model with $\sin^2\Theta_w = 0.23$. The asymmetry was computed in the angular range $|\cos\Theta| < 0.75$ at an average s of $911\,\text{GeV}^2$. Thus our results are consistent with the standard model.

We now relax the condition of the standard $SU(2) \times U(1)$ model and fit the coupling constants v^2 and a^2 to the data in a more general context of single Z^0 models. Note that the relative sign of v and a can only be obtained by experiments with polarized beams. We neglect the width of the Z^0. Using a finite width of $\Gamma_z = 2.5$ GeV our results remain unchanged.

We find for $M_z = \infty$, which of all possible M_z-values gives the weakest constraints in the $v^2 - a^2$ plane,

$$v^2 = -0.09 \pm 0.60\,(\text{stat.}) \pm 0.29\,(\text{syst.})$$
$$a^2 = -0.77 \pm 0.96\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$

with a χ^2 of 31.9 (28 degrees of freedom). The systematic uncertainty of the experimental cross section (4%, mainly from normalization) was taken into account in the fit. The results on v^2 and a^2 have to be compared to the prediction from the standard model with $\sin^2\Theta_w = 0.23$

$$v^2 = 0.0064$$

and

$$a^2 = 1$$

whereas in the absence of weak effects we expect $v^2 = 0$ and $a^2 = 0$. Negative squared coupling constants are favored by the data indicating that we see essentially *no* effect due to the weak interaction. This is, however, a nontrivial result, because it limits the strength of the weak couplings at $Q^2 \simeq 950\,\text{GeV}^2$.

The couplings v and a have been previously determined in elastic neutrino-electron scattering at $Q^2 \ll 1\,\text{GeV}^2$ [6]. But the analysis leads to an ambiguity, which can only be resolved if lepton-hadron processes are included. In order to compare with the couplings derived from νe scattering we have plotted in Fig. 2 the 95% c.l. contours in the $v^2 - a^2$ plane as derived from the fits to our data assuming assigned masses of the Z^0 boson of $M_z = 40$ and 60 GeV (Fig. 2a) and $M_z = 80$ GeV and infinity (Fig. 2b). The

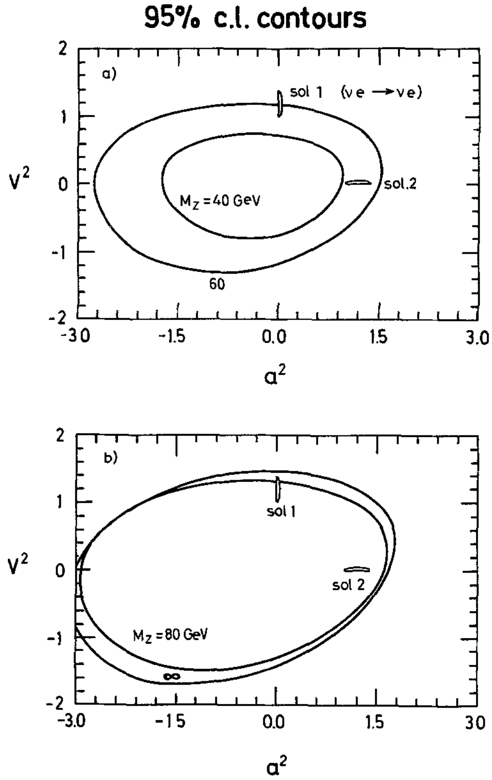

Fig. 2a and b. 95% c.l. contour plots from fits of v^2 and a^2 to the data of Fig. 1a, b. **a** Assuming Z^0 masses of 40 and 60 GeV; **b** assuming Z^0 masses of 80 and ∞ GeV. Also shown are the two solutions for v^2 and a^2 as derived from elastic neutrino electron scattering [6]

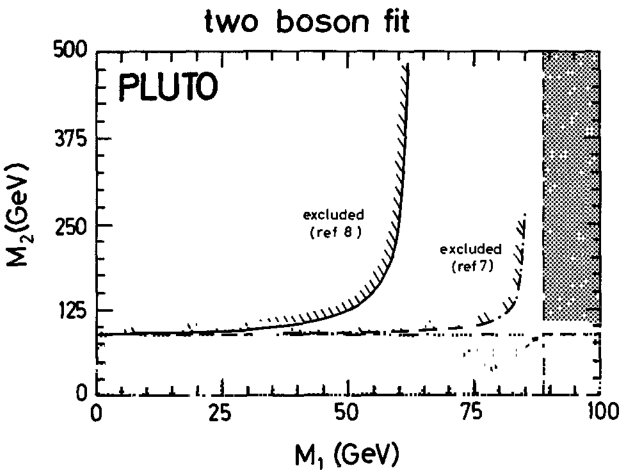

Fig. 3. 95% c.l. limits on the masses of two neutral vector bosons using the models of [7, 8]. The dotted area is excluded by definition ($M_1 < M_z < M_2$)

allowed regions are the areas inside the contour plots. Also shown are the two solutions derived from νe scattering. Our data are inconsistent with the νe results on the 95% c.l. for Z^0 masses $\simeq 40$ GeV. Assuming Z^0 masses of 80 GeV or infinity, the data slightly favor solution 2. This solution, which is dominated by the axial vector coupling, is also favored by experiments on ν-hadron and polarized $e-d$ scattering [6].

Finally we analyse our data in the framework of gauge theories [7, 8] that allow for the existence of several neutral vector bosons. There are essentially two groups of models, extending the standard $SU(2) \times U(1)$ group to $SU(2) \times U(1) \times \tilde{U}(1)$ [7] or $SU(2) \times U(1) \times S\tilde{U}(2)$ [8]. In both cases the effective Hamiltonian can be written as

$$H = \frac{4 \cdot G}{\sqrt{2}}((j^{(3)} - \sin^2\Theta_w j_{em})^2 + C j_{em}^2). \qquad (4)$$

Here $j^{(3)}$ is the third component of the weak isospin current, j_{em} is the electromagnetic current and C measures the deviations from the standard model. In the low energy limit ($s \ll M_z^2$) C can be fitted to the data in a model independent way. Using the world average of $\sin^2\Theta_w = 0.23$ as input we obtain $C < 0.06$ (95% c.l.).

If we consider specifically models with two neutral vector bosons their masses have to fulfil the condition $M_1 < M_z < M_2$, where M_z is the mass of the Z^0 boson in the standard model, as determined by low energy lepton-scattering data.

We can write C as

$$C = \gamma \frac{(M_2^2 - M_z^2)(M_z^2 - M_1^2)}{(M_1 M_2)^2}$$
$$\gamma = \cos^4\Theta_w \text{ in [7]} \qquad (5)$$
$$\gamma = \sin^4\Theta_w \text{ in [8]}.$$

We note that the lepton boson coupling of [7] is much larger than in [8]. Using (5), the limit on C can be directly transformed into boundary conditions for the masses M_1 and M_2. In Fig. 3 the allowed mass region for M_1 and M_2 are displayed and we see that in the strong coupling model [7] both new vector boson masses are restricted to values close to $M_z = 88.6$ GeV.

Analyses along similar lines have been performed with the data from other PETRA experiments [9, 10].

In conclusion, our data at Q^2 values close to 1000 GeV^2 place nontrivial bounds on the parameters of neutral currents in unified theories. The data are consistent with the standard $SU(2) \times U(1)$ model and impose significant mass constraints on models with two neutral vector bosons.

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Appendix

Cross Sections for Bhabha Scattering and μ Pair Production

From the standard 1st order Hamiltonian of the electroweak neutral current one can derive the following differential cross sections [5].

a) $e^+e^- \to e^+e^-$:

$$\begin{aligned} \frac{4s}{\alpha^2}\frac{d\sigma}{d\Omega} &= \left\{\frac{3+x^2}{1-x}\right\}^2 + 2\frac{3+x^2}{(1-x)^2} \\ &\cdot \{(3+x)Q - x(1-x)R\}v^2 \\ &- \frac{2}{1-x}\{(7+4x+x^2)Q + (1+3x^2)R\}a^2 \\ &+ \frac{1}{2}\left\{\frac{16}{(1-x)^2}Q^2 + (1-x)^2R^2\right\}(v^2-a^2)^2 \\ &+ \frac{1}{2}(1+x)^2\left\{\left(\frac{2}{1-x}Q - R\right)\right\}^2 \\ &\cdot (v^4 + 6v^2a^2 + a^4). \end{aligned} \qquad (A1)$$

b) $e^+e^- \to \mu^+\mu^-$:

$$\begin{aligned} \frac{4s}{\alpha^2}\frac{d\sigma}{d\Omega} &= (1+x^2)\{1 + 2v^2R + (v^2+a^2)^2R^2\} \\ &+ 4x\{a^2R + 2v^2a^2R^2\} \end{aligned} \qquad (A2)$$

with

$$Q=\varrho M_z^2 \frac{q^2}{q^2-M_z^2} \to -\varrho q^2 \quad (M_z^2 \gg |q^2|)$$

$$R=\varrho M_z^2 \frac{s}{s-M_z^2} \to -\varrho s \quad (M_z^2 \gg s)$$

$$\varrho=\frac{G}{8\sqrt{2}\pi\alpha}=4.49\cdot 10^{-5}\,(\mathrm{GeV}^{-2})$$

$x=\cos\Theta$, Θ being the polar angle with respect to the beam axis.

$\alpha=1/137$, fine structure constant

M_z = mass of the Z^0 boson

$$q^2=-\frac{s}{2}(1-\cos\theta).$$

The width of the Z^0 has been neglected in the propagators Q and R. A finite width Γ_z of the Z^0 can be taken into account by replacing

$$R^2 \text{ with } R^2\cdot\frac{(s-M_z^2)^2}{(s-M_z^2)^2+M_z^2\Gamma_z^2}.$$

In (A1) and (A2) the terms independent of Q and R correspond to the pure QED contributions, the terms linear in Q, R describe the electroweak interference and the terms in Q^2, R^2 are pure weak contributions.

The interference term in $ee\to\mu\mu$ produces a forward-backward asymmetry A, which is sensitive to a^2.

$$A=\frac{F-B}{F+B}\simeq\frac{3}{4}\frac{2a^2R}{1+2v^2R+a^4R^2} \quad \text{for} \quad v\ll a$$

or more precisely, if R^2 terms are included and the finite angular acceptance is taken into account:

$$A=\frac{6x_1}{3+x_1^2}\frac{a^2R+2a^2v^2R^2}{1+2v^2R+(v^2+a^2)^2R^2}, \tag{A3}$$

where $x_1=\cos\Theta_1$ corresponds to the maximum angle measured.

The coupling constants v and a used here are connected with the variables g_v and g_a from [6] in the following way

$$v=-2g_v$$

$$a=2g_a.$$

References

1. S.Weinberg: Rev. Mod. Phys. **52**, 515 (1980) and references therein
   A.Salam: Rev. Mod. Phys. **52**, 525 (1980) and references therein
   S.L.Glashow: Rev. Mod. Phys. **52**, 539 (1980) and references therein
2. PLUTO Collaboration Ch.Berger et al.: Z. Phys. C **4**, 269 (1980)
3. PLUTO Collaboration Ch.Berger et al.: Lepton pair production and search for a heavy lepton in e^+e^- annihilation (to be published in Phys. Lett. B)
4. F.A.Berends, K.J.F.Gaemers, R.Gastmans: Nucl. Phys. B**57**, 381 (1973)
   F.A.Berends, K.J.F.Gaemers, R.Gastmans: Nucl. Phys. B**63**, 381 (1973)
   F.A.Berends, K.J.F.Gaemers, R.Gastmans: Nucl. Phys. B**68**, 541 (1974)
   F.A.Berends, G.J.Komen: Phys. Lett. **63**B, 432 (1976)
   F.A.Berends, R. Kleiss: DESY 80/66
5. R.Budny: Phys. Lett. **55**B, 227 (1975)
6. K.Winter: Proc. of the International Symposium on Lepton and Photon Interactions at High Energies, Fermilab (1979) 258
7. E.H.de Groot, D.Schildknecht: Phys. Lett. **90**B, 427 (1980)
   E.H.de Groot, D.Schildknecht: University of Bielefeld Report, BI-TP 80/08
8. V.Barger et al.: Phys. Rev. Lett. **44**, 1169 (1980)
9. MARK J Collaboration D.P.Barber et al.: Phys. Lett. **95**B, 149 (1980)
10. R.Marshall: Rutherford Laboratory report RL 80/29 (1980), published in the Proc. of the XV[th] Rencontre de Moriond, (1980), ed. by Tran Than Van
    A.Böhm: Talk at the XX[th] International Conference on High Energy Physics, Madison (USA) July 17–23, 1980, Aachen report PITHA 80/9