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Measurement of the Muon Pair Asymmetry in e^+e^- Annihilation at $\sqrt{s}=34.7$ GeV

PLUTO Collaboration

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Abstract. The reaction $e^+ e^- \to \mu^+ \mu^-$ has been studied with the PLUTO detector at the c.m. energy of 34.7 GeV, based on an integrated luminosity of $46\,\mathrm{pb}^{-1}$. The total cross section agrees with QED predictions, and the corresponding lower limits for the Λ_+ and Λ_- QED cutoff parameters are 267 and 126 GeV respectively (95% c.l.). A forward-backward asymmetry parameter $A = -(13.4 \pm 3.1 \pm < 1)\%$ is observed, which is in agreement with the standard model, as well as with other PETRA results obtained at the same energy.

The standard model for electroweak interactions [1] has been tested and verified in several experimental approaches. In particular, recent evidence has been reported [2, 3] for the observation of the intermediate vector bosons $W^\pm$ and Z^0 with masses consistent with the model expectations. A convenient method to study the electroweak theory at high q^2 values ($q^2 = -s$) is provided by the reaction $e^+e^- \to \mu^+\mu^-$, where there is an angular asymmetry resulting from the interference between the electromagnetic and the weak neutral current associated with the Z^0. Significant asymmetry values in this reaction have already been reported by several experiments carried out with the e^+e^- colliding beam accelerators PETRA and PEP [4] and were found to be consistent with the expectation of the electroweak model. This reaction has been previously studied with the PLUTO detector at c.m. energies $9.4 \leqq \sqrt{s} \leqq 31$ GeV [5]. Here we report on a new high-statistics result of this reaction at a higher energy of $\sqrt{s} = 34.7$ GeV. Since the interference term increases almost linearly with s (see below), the electroweak effect in the new data should be more pronounced than in our previous study.

The lowest order differential cross section for μ pair production can be written in a model-independent way in the following form,

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} R(1 + \cos^2\vartheta + \tfrac{8}{3} A \cos\vartheta) \qquad (1)$$

where ϑ is the angle between the scattered μ^+ and the incoming e^+. R denotes the ratio of the total cross section for μ-pair production to the total pure QED cross section, given by

$$R = 1 + 2v_e v_\mu \chi + (v_e^2 + a_e^2)(v_\mu^2 + a_\mu^2)\chi^2 \qquad (2)$$

where v_e and v_μ are the weak vector charges of the electron and muon respectively, and a_e and a_μ are the corresponding weak axial vector charges. The parameter A in (1) is given by

$$A = \tfrac{3}{2} a_e a_\mu \chi (1 + 2 v_e v_\mu \chi)/R \qquad (3)$$

and corresponds to the forward-backward asymmetry for the full solid angle ($-1 \leqq \cos\vartheta \leqq 1$), namely,

$$A = \frac{\sigma(\cos\vartheta > 0) - \sigma(\cos\vartheta < 0)}{\sigma(\cos\vartheta > 0) + \sigma(\cos\vartheta < 0)}.$$

χ is given by

$$\chi = g \frac{m_Z^2 s}{s - m_Z^2}$$

where $g = G_F/(8\sqrt{2}\pi\alpha) = 4.49 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$ with G_F being the Fermi coupling constant and m_Z is the mass of the Z^0 boson. The terms in (2) and (3) which are linear in χ come from the s channel interference of the pure QED (one photon) diagram and the weak neutral current diagram involving the Z^0 boson. The terms which are quadratic in χ are due to the weak diagram only.

Using the experimental value of $\sin^2\vartheta_w = 0.229$ [6], the standard model sets the following values:

$$a_e = a_\mu = -1$$

$$v_e = v_\mu = -1 + 4\sin^2\vartheta_w = -0.084$$

$$m_Z = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \cdot \frac{1}{\sin\vartheta_w \cos\vartheta_w} = \frac{37.3\,\mathrm{GeV}}{\sin\vartheta_w \cos\vartheta_w} = 89\,\mathrm{GeV}. \qquad (4)$$

This value for the Z^0 mass is consistent with the recent direct measurements [3]. For a c.m. energy of $\sqrt{s} = 34.7$ GeV the value of χ is -0.0638. The standard model value of A is determined from the interference term to be -9.5% whereas the pure weak contribution to A is negligible. The value of R turns out to differ from 1 only by $\sim 0.3\%$.

The measurement reported here was carried out with the PLUTO detector which consists of a central part and two forward spectrometers. For the μ-pair analysis we used only the central detector whose main features are: a magnetic field of 1.65 Tesla provided by a superconducting solenoid, an inner detector consisting of 13 layers of proportional chambers, and an array of barrel and endcap lead scintillator shower counters, which cover almost the full solid angle of the inner detector and also give timing information.

The detector was triggered by requiring two tracks with $|\cos\vartheta| < 0.8$ and with transverse momenta larger than 350 MeV/c separated by an azimuthal angle (φ) of more than 94°. The trigger inefficiency (partly due to the chambers and partly due to the trigger system itself) was estimated from Bhabha events which had a redundant energy trigger, using the shower counters of the central detector. It varies with $|\cos\vartheta|$, the average value for the efficiency over the whole range of interest ($|\cos\vartheta|<0.752$) is $(81.2 \pm 0.2)\%$. Further details concerning the PLUTO detector are described elsewhere [7].

The integrated luminosity was calculated from the Bhabha event rate in the central part of the detector ($|\cos\vartheta|<0.8$) and the value obtained was $45\,950\,\mathrm{nb}^{-1}$ with a systematic error of 3%. The muon pair events were selected by requiring two tracks to yield a successful fit to the vertex in the $r-\varphi$ plane. In the event sample with this selection the main sources of contamination are Bhabha events, cosmic ray muons and muon pairs produced in two photon interactions. To remove these background events, we have imposed on the sample the following cuts:

1. The momentum of each charged track must be larger than 5 GeV/c.
2. The z-coordinate of the common vertex must be within 40 mm from the expected interaction point.
3. To maintain the full momentum resolution and trigger acceptance of the inner detector, the polar angle between the track (averaged over both tracks) and the beam line was required to satisfy $|\cos\vartheta|<0.752$. With this cut, 67% of the $\mu^+\mu^-$ total cross section in lowest order QED is accepted.
4. The acollinearity angle between both tracks must be smaller than 10°.
5. To reject Bhabha events, an upper limit of 2 GeV was imposed on the total energy measured in the barrel and endcap shower counters.
6. Remaining cosmic ray events were removed by timing cuts using the barrel and endcap counters, as outlined below:

The time difference between the lower and the upper barrel hits is plotted in Fig. 1 for preselected events whose trigger signal coincides within a certain interval with the beam-beam interaction time. The distribution shows that the cosmic ray muons can be clearly separated. For the sample of events hitting the endcap counters (20% of all events), where the cosmic muon rate is relatively small, the timing resolution is somewhat worse and $\sim 5\%$ cosmic background was left in the sample and had to be subtracted statistically. Another contribution to the cosmic background comes from events where only one track gave timing information (3.4% out of all events). The timing cuts remove $(2.9 \pm 0.2)\%$ of genuine μ-pair events.

Imposing these cuts, a total number of 1 553 events was left for final physics analysis. In this sample the remaining estimated background of 3.6%

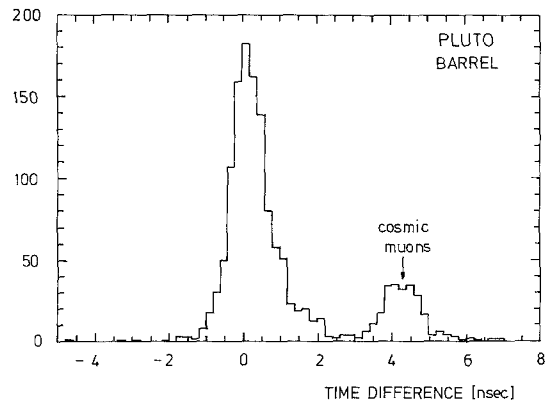

Fig. 1. Distribution of μ-pair candidates in the time difference between the lower and upper barrel hits of events after a preliminary rejection of a large fraction of the cosmic ray muon background (see text). The genuine μ-pairs are peaked around 0 while the remaining cosmic muons are peaked around 4.2 ns. The cut was made at 2.8 ns

could be assigned to the following sources: cosmic muons (1.4%), $e^+e^-\to\tau^+\tau^-$ (1.6%), $e^+e^-\to e^+e^-\mu^+\mu^-$ (0.4%), and $e^+e^-\to e^+e^-$ (0.2%).

In evaluating the total μ pair cross section the influence of the cuts 1, 2, 4 and 5, folded with higher QED radiative effects was calculated. This was done by generating events using the Berends, Kleiss and Jadach Monte Carlo program [8], followed by a complete detector simulation and μ-pair analysis. We obtained a value of $(90.5 \pm 0.8)\%$ for the selection efficiency. After subtracting the background (3.6%) and taking into account the above mentioned acceptance cut (leaving 67% of the events), the efficiencies of the trigger (81.2%) and the timing cuts (97.1%) we obtain,

$$\sigma_{\mu\mu} = (68.1 \pm 1.9 \pm 2.9)\ \mathrm{pb}$$

which is plotted in Fig. 2 together with PLUTO values measured at lower energies [5]. The statistical error of 1.9 pb includes the statistical uncertainties in the correction factors. The systematic error of 2.9 pb is due to the luminosity uncertainty of 3% and the efficiency uncertainties of the trigger (2%), event selection (2%) and timing cuts (1%). Our experimental value agrees within errors with the lowest order QED value of 72.1 pb.

The QED cutoff parameters $\Lambda_\pm$ are commonly used to investigate a possible deviation of the total μ-pair cross section from the QED prediction. In terms of these parameters, the $\mu\mu$ cross section is given by,

$$\sigma = \sigma_0 (1 \pm 2s/\Lambda_\pm^2)$$

where σ_0 is the pointlike electroweak cross section. Our experimental result for σ corresponds to the following lower limits on Λ_+ and Λ_- (statistical and systematic errors added in quadrature),

$$\left.\begin{array}{l}\Lambda_+ > 267\,\mathrm{GeV}\\ \Lambda_- > 126\,\mathrm{GeV}\end{array}\right\} (95\,\%\,\mathrm{c.l.}).$$

Next we turn to the measurement of the muon pair asymmetry, where the understanding of the systematic effects is of major importance. One problem concerns the possibility of wrong charge assignment originating from the finite momentum resolution of the detector. We found that this resolution is improved when both tracks of the event are fitted to one continuous common track. Figure 3 shows a scatter plot of $1/P$ versus $\cos\vartheta$ where P is the momentum fitted to one common track. Most of the events are concentrated around $1/P = 0.057\,\mathrm{GeV}^{-1}$ as expected for $\sqrt{s} = 34.7\,\mathrm{GeV}$. The number of events with a small $1/P$ value (i.e. those events which might have a wrong charge assignment) is small. Hence their effect on the asymmetry measurement is negligible as long as the charge misassignment probability is small and random with respect to forward and backward scattering. A non-random situation can arise if the detector is twisted around the beam pipe. Such a deformation would result in a dependence of $1/P$ on $\cos\vartheta$, which is not seen in our data (see Fig. 3). We estimate that a possible twist deformation which is compatible with our data (Fig. 3) would change the asymmetry by not more than 0.2%. This estimate was confirmed by Monte Carlo simulations introducing an artificial detector deformation.

A disadvantage of the common track fit is the treatment of events where a hard photon was radiated, which occurs more often in backward scattering [9]. Since these events obviously fit poorly one common track, they will have an increased chance of ending up with a wrong charge assignment, thereby reducing the observed asymmetry. A further reduction of the asymmetry value comes from the radiative effects in addition to the detector deficiencies and analysis discussed above. The Monte Carlo generator based on [8] takes into account all QED diagrams up to order α^3 as well as a small contribution ($\approx -1.0\%$) from the most important weak diagrams. The contribution from the diagrams not taken into account in [8] is estimated to be negligible at the present value of $\sqrt{s}$ [10].

Our raw $\cos\vartheta$ distribution was corrected bin by bin. After background subtraction each bin was divided by the efficiency of the trigger and the timing cuts and finally it was multiplied by the radiative corrections folded with detector and analysis effects which were calculated from the Monte Carlo $\cos\vartheta$

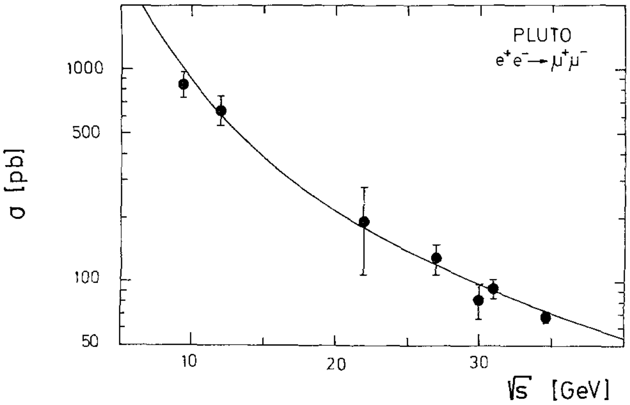

Fig. 2. The total cross section for muon pair production as a function of the c.m. energy. The total cross section has been corrected for limited acceptance, detection efficiency and radiative effects. The curve shown represents the lowest order QED expectation

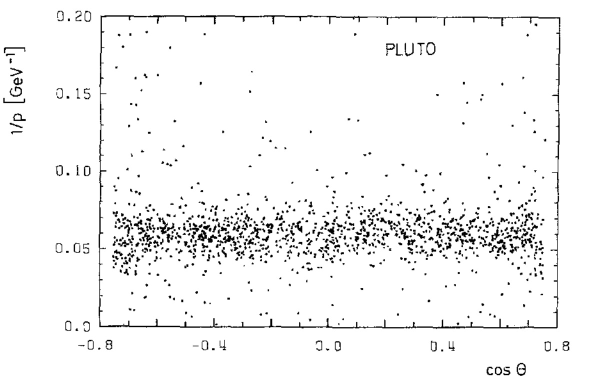

Fig. 3. Scatter plot of the inverse measured momentum, $1/P$, vs. $\cos\vartheta$ for the final μ-pair sample

distributions. The resulting difference between the corrected asymmetry and the measured one turned out to be -6.1%, mostly due to the pure radiative effects and the common track fitting method (-3.4% and -2.4% respectively). The corrected differential cross section is shown in Fig. 4, where the error bars indicated in the figure are statistical only and do not include the overall normalisation uncertainty of 4.2%.

A fit to a pure QED behaviour of the form $a\cdot(1+\cos^2\vartheta)$ which is shown by the dashed line in Fig. 4, does not describe the data and in fact has a χ^2 of 25.5 for 7 degrees of freedom. On the other hand, a good fit to the data is obtained by adding the electroweak term of $\frac{8}{3}A\cdot\cos\vartheta$ (1) which is shown by the solid line in the same figure. This latter fit yields a χ^2 of 6.3 for 6 degrees of freedom, and from it, the asymmetry for the full polar angle range is found to be

$$A = -(13.4 \pm 3.1 \pm <1)\,\%.$$

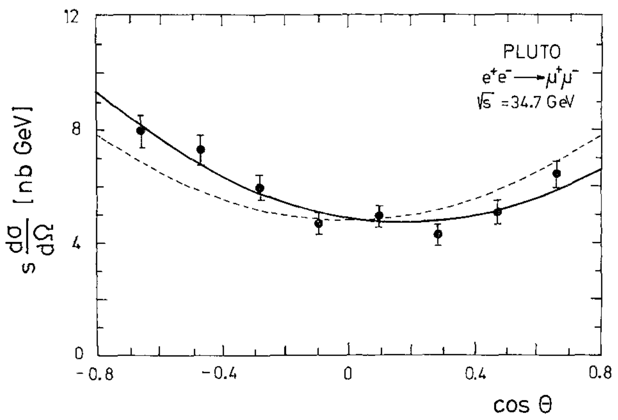

Fig. 4. The differential cross section $s\,d\sigma/d\Omega$ for μ-pair production. The data are corrected for detection efficiency and radiative effects. The dashed line represents the result of a fit to pure QED prediction while the solid line includes also the electroweak term. The error bars do not include an overall normalization uncertainty of 4.2%

The quoted statistical error includes the statistical uncertainties in the correction factors. The systematic error is estimated to be smaller than 1% and is therefore negligible compared with the statistical one. The value of A agrees within $1.3\,\sigma$ with the standard model prediction of -9.5%, and also with the results obtained by the other PETRA experiments at the same energy [11].

Assuming a Z^0 mass of 89 GeV and the standard model value of -0.084 for the weak vector charges v_e and v_μ (4), we obtain from our asymmetry result a value of 1.41 ± 0.33 for the product of the weak axial vector charges $a_e a_\mu$, compared with the standard model prediction of 1.

In summary, we have measured the reaction $e^+e^- \rightarrow \mu^+\mu^-$ at the c.m. energy of 34.7 GeV. The total cross section agrees with QED expectation and yields lower limits (95% c.l.) for the QED cutoff parameters Λ_+ and Λ_- of 267 and 126 GeV respectively. The differential cross section shows a significant forward-backward asymmetry of $-(13.4 \pm 3.1 \pm <1)\%$ in agreement with the standard model of electroweak interactions.

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