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Measurement of the Reaction $e^+e^- \to \mu^+\mu^-$ for $14 \leqq \sqrt{S} \leqq 36.4$ GeV

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Abstract. The reaction $(e^+e^- \to \mu^+\mu^-)$ has been measured between $\sqrt{S}=14.0$ GeV and $\sqrt{S}=36.4$ GeV. The total cross section result is in good agreement with the QED prediction and the following Λ values have been obtained: $\Lambda_+=186$ GeV, $\Lambda_-=101$ GeV. The angular distribution at high energy ($\langle\sqrt{S}\rangle=34.2$ GeV) shows a fitted charge asymmetry of -0.064 ± 0.064 in agreement with the $W-S$ model prediction of -0.092, corresponding to an axial coupling parameter $a^2=4g_a^2=0.69\pm0.69$.

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I. Introduction

The measurement of the reaction $e^+e^- \to \mu^+\mu^-$ at Petra energies provides tests of the validity of QED at small distances and of the predictions of electroweak theories [1].

In the framework of these theories, the lowest order differential cross section of this reaction, involving both electromagnetic and neutral weak currents, assuming e, μ universality, but neglecting the Z° width, is [1]:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4S}\left[(1+\cos^2\theta)(1+2g_v^2C+C^2(g_a^2+g_v^2)^2)+4\cos\theta(g_a^2C+2g_a^2g_v^2C^2)\right]$$

where $C=\frac{GM_z^2}{2\sqrt{2}\pi\alpha}\cdot\frac{S}{S-M_z^2}$

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θ being the angle between the incoming e^+ and the outcoming μ^+

G being the Fermi weak coupling constant (in the Weinberg Salam model, $g_a = -\frac{1}{2}$ and $g_v = -\frac{1}{2} + 2\sin^2\theta_W = -0.044$ when using the measured value $\sin^2\theta_W = 0.228$).

At present PETRA energies, the total cross section is not yet sensitive to the neutral weak current effect (the deviation from QED is, in this case, of the order of $3 \cdot 10^{-3}$). Nevertheless a deviation from the QED prediction can already be determined in a sensitive way, by measuring the asymmetry in the polar angular distribution, proportional to g_a^2 (to the first order approximation in G).

In this experiment we have measured the $e^+e^- \to \mu^+\mu^-$ cross section over a wide range of energies (14 GeV $\leqq \sqrt{S} \leqq$ 36.4 GeV) and compared its energy dependence to the QED prediction. The polar angular distribution in the above reaction is presented for the high energy data, and the observed forward-backward charge asymmetry is compared to the electroweak theory prediction.

II. The CELLO Detector

The CELLO detector has been described elsewhere [2]; it is designed to identify and measure similtaneously leptons, photons and hadrons with high precision over almost the entire solid angle. Essential features of the detector, enabling a good track reconstruction and a good Bhabha rejection up to $|\cos\theta| = 0.85$ are the following:

- a central tracking device covering 0.91 of 4π with $\Delta P_t/P_t = 0.02 P_t$ (P_t in GeV/c) in a 1.3 T magnetic field;
- a fine grain liquid Argon calorimeter covering 0.96 of 4π;
- a muon detector consisting of an 80 cm thick iron hadron absorber and one layer of muon chambers [3] covering 0.92 of 4π;
- a fast two prong charged trigger [4];
- a neutral trigger using analogue sums of the liquid Argon calorimeters.

Since there are no time of flight counters, the final sample of events contains cosmic ray events which crossed the detector during the 70 ns proportional wire chamber gate, and which satisfied the required trigger conditions as well as software cuts.

Using the vertex distribution of two prong events along the beam axis (Z-distribution), cosmic ray events with an apparent vertex outside the beam interaction region permit subtraction of the cosmis ray background in the fiducial region of Z (see Sect. IV).

III. Event Selection

Events are selected by a trigger requiring at least two tracks of $P_t > 200$ MeV/c, with at least one originating within ± 10 cm from the interaction point along the beam axis.

The following software cuts are applied, using the central tracking device, the muon chambers and the liquid Argon calorimeter.

a) Topology of Events in the Central Detector

Two track events are selected if they satisfy the following cuts:

1. $|\cos(\theta)| \leqq 0.85$ where θ is the polar angle of the track;
2. acolinearity $\leqq 60$ degrees for the cross section measurement and $\leqq 10$ degrees for the polar angular distribution;
3. distance to the interaction point less than 0.4 cm in the azimuthal plane and less than 7.5 cm along the beam axis;
4. mean momentum of the two tracks greater than 2.5 GeV/c at $\sqrt{S} = 14$ GeV, 4 GeV/c at $22 \leqq \sqrt{S} \leqq 25$ GeV and 8 GeV/c at $33 \leqq \sqrt{S} \leqq 36$ GeV.

b) Muon Chambers

Tracks are propagated from the central detector up to the muon chambers. The uncertainty σ on the extrapolated point in the muon chamber is obtained by taking into account:

- the multiple scattering in the material between the central detector and the muon chambers (mainly the lead plates and liquid Argon of the calorimeter and the iron of the muon filter);
- the error on the hit coordinates in the muon chamber [3].

Typically a 15 GeV track, normal to the calorimeter and iron gives a σ of 0.8 cm in the muon chambers.

The quantity $q = d/\sigma$, where d is the distance between the extrapolated point in the muon chamber and the actual hit, is used as quality factor for the association between a central detector track and the corresponding hit in the muon chamber.

In the present analysis, at least one associated muon chamber hit with a quality factor less than 6 is required per two-track event.

c) Liquid Argon

Events are then processed through the liquid Argon shower reconstruction program and are rejected if at least one particle has deposited more than 1 GeV ($14 \leqq \sqrt{S} \leqq 25$ GeV data) or 1.5 GeV ($33 \leqq \sqrt{S} \leqq 36.4$ GeV data) in the calorimeter.

IV. Background Reduction

The two main sources of background are cosmic ray events and Bhabha events ($e^+e^- \to e^+e^-$).

Cosmic Rays

From Bhabha events we know that no μ pair event can be expected at a Z distance (along the beam axis) greater than 2.5 cm. Events with $2.5\,\text{cm} \leqq |Z| \leqq 7.5$ cm are thus certainly cosmic ray events kept by the wide Z cut mentioned previously. The contribution of this background within the $|Z| < 2.5$ cm cut is calculated by interpolation and subtracted bin by bin in the event distribution in $\cos\theta$.

Figure 1 shows the Z-distribution for the final sample of high energy μ pairs, as well as the distribution for cosmic ray events, after all cuts, except $|Z| < 2.5$ cm.

Bhabha Events

In order to estimate the fraction of Bhabha events satisfying our μ-pair criteria, i.e. at least one muon chamber associated to one of the tracks and a small deposited charge in the liquid Argon because of local inefficiencies or dead spaces in the calorimeter, a sample of genuine Bhabha events was used to determine the probability of such events having at least one muon chamber hit associated to one of the tracks.

For the data taken in 1980 this probability was 2% because of inadequate beam shielding leading to many background hits in most of the muon chambers.

This probability dropped to 0.5% for the 1981 data. These rejection factors combined with an efficiency of more than 96% for Bhabha detection give upper limits for Bhabha contamination in μ pair samples:

- less than 1 Bhabha for 40 μ pairs for the 1980 data
- less than 1 Bhabha for 150 μ pairs for the 1981 data, which are 80% of the total data sample, leading to a maximum total Bhabha contamination of 4.5 events.

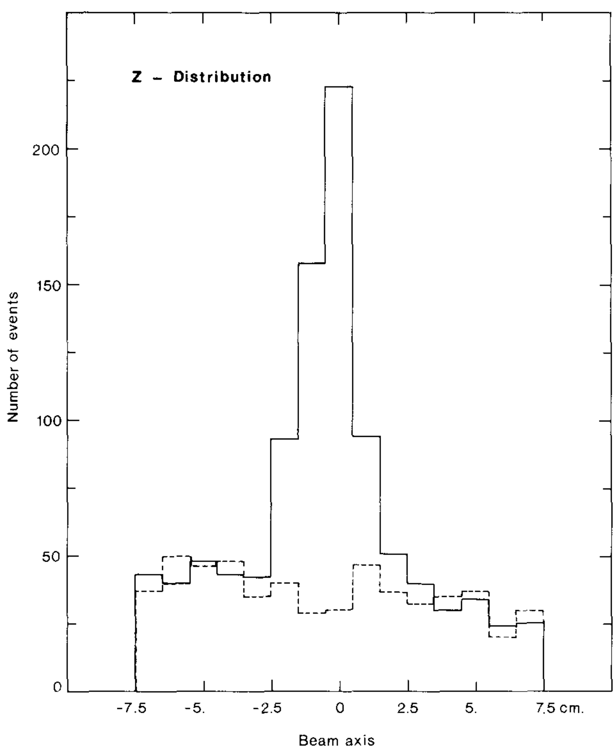

Fig. 1. Vertex distribution along the beam axis of selected events (full line) compared with that of cosmic ray events (dashed line)

Other Sources of Background

A Monte Carlo study on the reaction ($e^+e^- \to \tau^+\tau^-$) gives a contamination of $0.8\% \pm 0.5\%$ and similarly $0.5\% \pm 0.5\%$ for the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$.

V. $e^+e^- \to \mu^+\mu^-$ Cross Section

Details of the corrections applied to the cross section calculation and a description of the errors are given before presentation of the final result.

Correction and Normalisation Factors

The trigger efficiency is determined as the proportion of events satisfying the charged 2 track trigger requirement [4], among a sample of clean, two track Bhabha events detected using the neutral trigger (energy in the liquid Argon calorimeter).

The muon detector efficiency over a given data taking period is determined using cosmic ray events satisfying cuts (1) (2) and (4) but crossing the detector well outside the interaction region with a distance to the interaction point in the azimuthal plane greater than 0.5 cm and greater than 2.5 cm along the beam axis.

Both efficiencies are determined separately for each bin of the event distribution in $\cos\theta$. In the calculation of the muon detector efficiency, the difference in the azimuthal distribution between cosmic ray events and that of μ-pair events was taken into account.

Muon losses due to the liquid Argon cuts come from two different phenomena: first, radiative muons associated to a photon very much aligned to the charged track and carrying enough energy to give a fake electron signal in the calorimeter, second, muons giving a high deposition in the calorimeter due to local effects (such as Bremsstrahlung). These losses are calculated by studying the charge deposition in the calorimeter for tracks associated to a hit in the muon chambers before doing the liquid Argon cut. The results are compatible with Monte Carlo studies (for radiative events) and with a study on cosmic ray events (for local effects). These losses give a 4% correction.

The acceptance of the central detector with the geometrical cuts previously described is calculated with Monte Carlo μ pair samples processed through a simulator of the central detector and through the same selection chain as the real events.

Radiative corrections are calculated by Monte Carlo [5] for normalisation of the experimental cross section to the first order QED cross section, including hadronic polarization terms.

The luminosity is calculated using the end cap calorimeters and forward detector and is cross checked with the large angle Bhabha cross section measurements.

Errors

Statistical errors take into account the cosmic background subtraction.

Systematic error contributions are mainly from trigger efficiency (3%), muon chamber efficiency (2%) and luminosity (3%). All other contributions (for all other correction factors previously described) amount to 1.5%, giving a total systematic error for the cross section measurement of 5% (errors added in quadrature).

Results

The cross section results are presented for 7 different calues of $\sqrt{S}$ in Table 1. The luminosity and the

Table 1. Cross section of the reaction $e^+e^- \to \mu^+\mu^-$

$\sqrt{S}$ (GeV)	Lumi. (nb^{-1})	Events	$\sigma_0 \pm \Delta\sigma_{st} \pm \Delta\sigma_{syst}$
14	1,014	299 ± 23.8	516 ± 41 ± 26
22	2,482	242 ± 19.3	179.4 ± 14.3 ± 9.1
25	253	17 ± 4.9	131.7 ± 38 ± 6.6
33.3	1,589	69 ± 10	81.2 ± 11.8 ± 4.1
34	7,407	252 ± 18.4	64.6 ± 4.7 ± 3.2
34.7	1,382	47 ± 9.1	79.9 ± 15.5 ± 4
36.4	781	19 ± 6.6	53 ± 18.4 ± 2.7

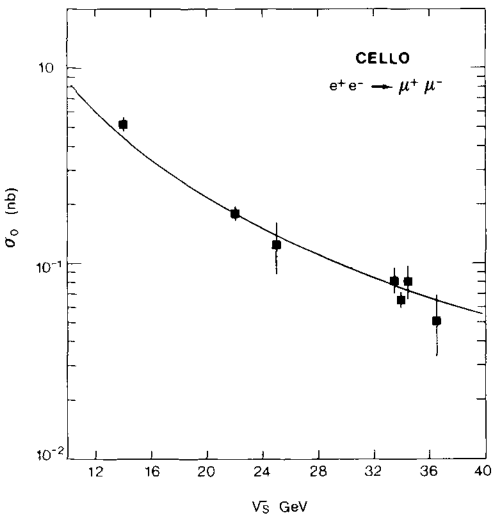

Fig. 2. Total cross section of reaction $e^+e^- \to \mu^+\mu^-$. The solid line corresponds to the theoretical QED prediction

number of μ pairs found are given for each energy. The measurement is compared to the first order QED cross section (Fig. 2). The agreement between theory and experiment is found to be good.

As the electroweak effect on the total cross section is negligible in the framework of the Weinberg-Salam model at these energies, the cross section results can be used to give lower limits on the Λ parameters [5], introduced in the following form factor:

$$F(q^2) = 1 \pm q^2/(q^2 - \Lambda_{\mp}^2).$$

The $\Lambda_{\mp}$ values are computed with the high energy points, the systematic and statistical errors being quadratically combined:

$\Lambda^+ > 186$ GeV (95% C.L.).

$\Lambda^- > 101$ GeV (95% C.L.).

This result can be interpreted as a confirmation of the validity of QED down to a distance of $4 \cdot 10^{-16}$ cm.

VI. Angular Distribution

The polar angular distribution has been studied using $33 \leq \sqrt{S} \leq 36.4$ GeV data. The same selection criteria as for the cross section measurement are used, with the extra requirements that the two tracks be reconstructed with opposite signs and their acolinearity angle be less than 10°. This distribution is corrected bin by bin for trigger efficiency, Bhabha contamination, acceptance and QED radiative effects.

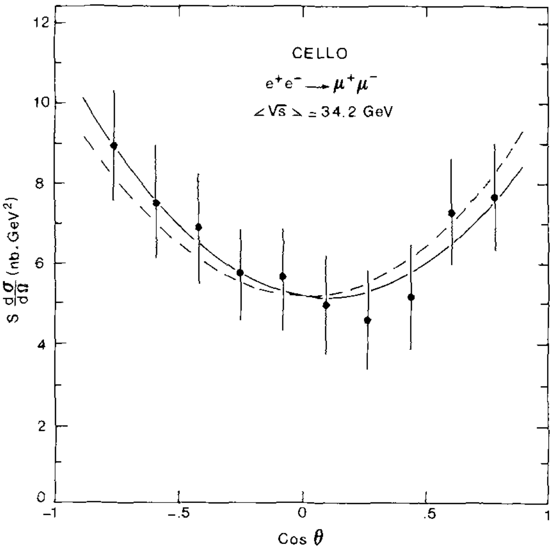

Fig. 3. Differential cross section with respect to the polar angle for $\langle\sqrt{S}\rangle = 34.2$ GeV, corrected for acceptance, trigger efficiency, Bhabha contamination and QED asymmetry contribution. The following cuts are applied: momentum > 8 GeV and acolinearity ≤ 10 degrees. A fit of the data to the function

$f(\cos(\theta)) = p(1+\cos^2(\theta)+q\cos(\theta))$

is superimposed (full line). The QED prediction is also shown (dashed line)

The probability of having a wrong sign determination with the requirement of two opposite sign tracks is 0.04%.

Statistical errors take into account the bin by bin cosmic subtraction.

Sources of systematic error for the asymmetry measurement are the following:

- Bhabha contamination. The systematic error is computed bin by bin from the estimated Bhabha contamination and from the angular distribution of Bhabhas having a fake association in the muon chambers. This contamination is included linearly in the error bars;
- QED radiative corrections and acceptance correction. The systematic error due to these two sources amounts to 0,5% per bin of the distribution and was determined by Monte Carlo.

Figure 3 shows the differential cross section obtained for $\langle\sqrt{S}\rangle = 34.2$ GeV. The error bars include both statistical and systematic errors.

VII. Results Compared to the Electroweak Predictions

A Monte Carlo program [5] is used for calculation of the Weinberg Salam model prediction on the asymmetry in the polar angular distribution. Two different presentations are shown:

Table 2. Charge asymmetry results

a. *Results from CELLO*

$\sqrt{S}$ (GeV)	L (nb^{-1})	$A1=(F-B)/(F+B)$ ($\lvert\cos\theta\rvert<0.85$)		$A2=3/8q$ ($\lvert\cos\theta\rvert<1$)	
		$A1_{exp}$	$A1_{th}$	$A2_{exp}$	$A2_{th}$
34.2	11,159	-0.075 ± 0.066	-0.082 ± 0.002	-0.064 ± 0.064	-0.091 ± 0.005

b. *Results from other* PETRA *experiments* [8, 9, 10]

	$\langle\sqrt{S}\rangle$ (GeV)	L (nb^{-1})	A_{exp}	A_{th}	$\lvert\cos\theta\rvert_{max}$
TASSO	34.22	35,370	-0.161 ± 0.032	-0.092	1
JADE	33.5	19,020	-0.118 ± 0.038	-0.078	0.8
MARK-J	34.6	48,300	-0.081 ± 0.021	-0.076	0.8

1) The global experimental asymmetry which is computed with the usual formula $A_1 = \frac{(S_+ - S_-)}{(S_+ + S_-)}$ where S_+ is the corrected cross section for $0 < \cos\theta < 0.85$ and S_- the similar quantity for $-0.85 < \cos\theta < 0$.

2) The corrected angular distribution is fitted to the following function of $\cos(\theta)$, derived from the differential cross section expression given in the introduction of this letter:

$$f(\cos(\theta)) = p(1+\cos^2(\theta)+q\cos(\theta)).$$

The $\cos\theta$ term gives a direct measurement of the total asymmetry,

$$A_2 = \frac{F-B}{F+B} = 3/8q,$$

with

$$F = \int_0^1 f(\cos(\theta))\, d(\cos(\theta))$$

and

$$B = \int_{-1}^{0} f(\cos(\theta) d(\cos(\theta)).$$

It also allows calculation of the parameter a from the following relation:

$q = 4Cg_a^2 = Ca^2$ where C has been previously
$= -0.246a^2$ defined (for $\sqrt{\langle S\rangle} = 34.2$ GeV).

Results are presented for both methods in Table 2, a where they are compared to the Weinberg Salam model [1] prediction. The errors include the contribution from the systematic error. A negative charge asymmetry is observed, which is of the same magnitude as that measured in the CELLO τ pair analysis [7], both being compatible with the electroweak prediction. The value obtained for the a parameter is: $a^2 = 4g_a^2 = 0.69 \pm 0.69$ for an expected value of 1.

In Table 2b are also presented, for comparison, the results of other PETRA groups [8–10].

VIII. Conclusion

The cross section of the reaction ($e^+e^- \to \mu^+\mu^-$) has been measured over a wide energy range and compared to the QED prediction. Good agreement has been found between experimental results and theory. In the polar angular distribution at $\sqrt{\langle S \rangle} = 34.2$ GeV, an asymmetry of -0.064 ± 0.064 compatible with the electroweak theory prediction has been observed, corresponding to a value of $a^2 = 4g_a^2 = 0.69 \pm 0.69$.

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