A MEASUREMENT OF THE MUON PAIR PRODUCTION IN e^+e^- ANNIHILATION AT $38.3 \leqslant \sqrt{s} \leqslant 46.8$ GeV

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The $e^+e^- \to \mu^+\mu^-$ reaction has been studied at centre of mass energies ranging between 38.3 and 46.8 GeV with the CELLO detector at PETRA. We present results on the cross section and the charge asymmetry for this channel. Combining all the data at the average energy $\langle\sqrt{s}\rangle = 43$ GeV we obtain $R_{\mu\mu} = \langle\sigma_{\mu\mu}/\sigma_0\rangle = 0.98 \pm 0.04 \pm 0.04$, $\langle A_{\mu\mu}\rangle = (-14.1 \pm 3.7 \pm 1.0)\%$, where σ_0 is the QED cross section and $A_{\mu\mu}$ is the charge asymmetry corrected for pure radiative effects. These results are in good agreement with the expected values of $R_{\mu\mu} = 1.01$ and $A_{\mu\mu} = -14.5\%$ at that energy.

1. Introduction

The $e^+e^- \to \mu^+\mu^-$ reaction has been studied with the CELLO detector at energies ranging from 38.3 to 46.8 GeV which is the highest energy obtained at the PETRA e^+e^- collider. We present here our results for the cross section and the charge asymmetry for this channel.

In the standard model [1], the lowest order differential cross section for the pair production of muons is given by

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to \mu^+\mu^-) = \frac{\pi\alpha^2}{2s}[C_1(1+\cos^2\theta) + C_2\cos\theta] ,$$

with

$$C_1 = 1 + 2v_e v_\mu \mathrm{Re}(\chi) + (v_e^2 + a_e^2)(v_\mu^2 + a_\mu^2)\,|\chi_0|^2 ,$$

$$C_2 = 4a_e a_\mu \mathrm{Re}(\chi_0) + 8v_e a_e v_\mu a_\mu\,|\chi_0|^2 ,$$

$$v_e = v_\mu = -1 + 4\sin^2\theta_W , \quad a_e = a_\mu = -1 ,$$

and χ_0 parametrized in the so-called "on-shell" renormalization scheme as

$$\chi_0 = \frac{1}{16\sin^2\theta_W(1-\sin^2\theta_W)}\,\frac{s}{s - M_Z^2 + \mathrm{i}M_Z\Gamma_Z} ,$$

where $\sqrt{s}$ is the centre of mass energy, M_Z and Γ_Z are the mass and width of the Z^0 intermediate vector boson and θ_W is the Weinberg angle. The terms proportional to $\mathrm{Re}(\chi_0)$ arise from the interference between γ and Z^0 exchange and those proportional to $|\chi_0|^2$, from the direct Z^0 exchange. The forward–backward asymmetry in the differential cross section is

$$A_{\mu\mu} = \left(\int_0^1 \frac{d\sigma}{d\cos\theta}\,d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\,d\cos\theta\right) \times \left(\int_0^1 \frac{d\sigma}{d\cos\theta}\,d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\,d\cos\theta\right)^{-1} = 3C_2/8C_1 .$$

Since the vector coupling constants for leptonic final states are small and the weak amplitude is small compared to the electromagnetic one at PETRA energies, one can use the following approximation:

$$A_{\mu\mu} \simeq \tfrac{3}{2}a_e a_\mu \mathrm{Re}(\chi_0) .$$

In the on-shell parametrization [‡1] the QED radiative corrections to the Z^0 exchange happen to cancel the one-loop corrections to the Z^0 propagator at our energies [2], at least within the accuracies of our experimental results. Therefore, to correct the measured value of the charge asymmetry it is sufficient to apply only the pure α^3 QED corrections to the one-photon exchange graph ("reduced QED" correc-

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[‡1] As long as $\sin^2\theta_W$ was not precisely measured, it was customary to use a parametrization of χ where the Fermi coupling constant G_F – rather than $\sin^2\theta_W$ – entered as a free parameter, since G_F is well known from the muon lifetime. This parametrization gives the same prediction for the asymmetry provided that the dominant weak correction to the muon decay graph (i.e. the W-boson self-energy [2]) is taken into account.

tions). Monte Carlo programs [3] are available to compute these corrections for given experimental cuts. Taking $M_Z=93$ GeV/c^2 [4] and $\sin^2\theta_W=0.23$ [5], the value of asymmetry at the Born level predicted by the standard model is -15.5% at $\sqrt{s}=44$ GeV and -11.5% at $\sqrt{s}=39$ GeV.

2. Detector description

The data were taken with the CELLO detector at PETRA, at CM energies between 38.3 and 46.8 GeV. The total integrated luminosity is 46 pb^{-1} [6] and the average energy is 43 GeV.

CELLO [7] is a general purpose magnetic detector equipped with a thin superconducting solenoid. Charged particles are measured in a central detector made of interleaved cylindrical drift and proportional chambers in a 1.3 T magnetic field, yielding a momentum resolution of $\sigma(p)/p=2\%$ p (p in GeV/c) without vertex constraint and 1% p with vertex constraint, over 91% of the full solid angle. For neutral-particle detection and charged-lepton identification, we use the barrel part of a fine-grain liquid-argon calorimeter which covers a solid angle of 86% of 4π. Each of the 16 calorimeter modules samples in depth the energy deposited by particles in the liquid argon; the energy is collected on lead strips with three different orientations up to a maximum depth of 20 radiation lengths for normal incidence. For each shower, this information is combined to give 7 samplings in depth. The energy resolution is $\sigma(E)/E=5\%+10\%/\sqrt{E}$ (E in GeV), and the angular resolution varies from 6 to 10 mrad. The muons are detected behind a 80 cm thick iron absorber by large planar drift chambers [8] covering 92% of 4π. The spatial resolution of these chambers is 0.6 cm. Events used in this analysis were required to fulfill the following charged trigger conditions: at least two charged tracks in the azimuthal plane (R–φ) and at least one charged track in a plane containing the beam axis (R–z). To keep the charged trigger rate at an acceptable level, the minimum number of hits per track was adjusted to the background conditions. Furthermore, at least one pair of tracks was required to have an opening angle in the R–φ plane above 135° or 158°, depending on the beam induced background conditions in the central detector.

3. Data selection

μ-pair event candidates were required to have two reconstructed charged tracks, each one with:

(a) $|\cos\theta|$ less than 0.85, θ being the μ^- scattering angle with respect to the incident e^- beam,

(b) a measured momentum greater than $E_{\text{beam}}/2$,

(c) a deposited energy in the liquid argon calorimeter less than 1.3 GeV,

(d) a distance to the interaction vertex along the beam axis, $\delta(R-z)$ less than 2.5 cm and in the transverse plane, $\delta(R-\varphi)$, less than 0.3 cm.

In addition, the acollinearity angle in space was required to be less than 25° for the total cross-section measurement and less than 10° for the angular distribution.

The charged tracks were propagated from the central detector up to the muon chambers. The uncertainty σ on the distance between the extrapolated point in the muon chamber and the nearest hit in this chamber was obtained by taking into account the multiple scattering in the material encountered by the particle as well as the errors on the track parameters and on the hit coordinates of the muon chambers [9]. The quantity $q=d/\sigma$, where d is the distance between the extrapolated point in the muon chamber and the actual hit, is used to qualify the association of a central detector track to the corresponding hit in the muon chamber. In the present analysis, at least one of the charged tracks had to be associated to a hit in the muon chambers within a distance of 5σ.

Cuts (b) and (d) reject cosmic ray events. A further rejection of such events was based on the timing information [9] of both innermost drift chambers [10] and of both outermost drift chambers of the central detector. The cut applied accepted more than 99% of Bhabha (and hence μ-pair) events while it rejected about 30% of the cosmic-ray events satisfying all other μ-pair criteria.

Because of varying experimental conditions, our data sample is subdivided into five groups, each corresponding to specific PETRA running periods at different CM energies, between the autumn of 1982 and the end of 1985 (see table 1).

4. Backgrounds

The two main sources of background are residual cosmic ray events and Bhabha events. Because of the

Table 1
μ-pair cross sections. The first error is the statistical one, the second is the systematic one.

$\sqrt{s}$ [GeV]	$\mathscr{L}$ [nb^{-1}]	$N_{\mu\mu}$	f_{corr}	$\sigma_{\mu\mu}$ [pb]	$R_{\mu\mu}$
38.3	7800	289±20	1.55	57.4±4.2±2.3	0.97±0.07±0.04
41.3	3601	67±11	2.91	54.1±8.9±2.1	1.06±0.17±0.04
43.6	16900	328±23	2.27	44.1±3.3±1.7	0.97±0.07±0.04
44.2	12489	278±24	2.01	44.7±4.0±1.7	1.01±0.09±0.04
46.2	4278	77±13	2.16	38.9±8.9±1.5	0.95±0.22±0.04

strong forward–backward asymmetry of Bhabha scattering due to the *t*-channel exchange, a good knowledge of the Bhabha contamination in the μ-pair sample is necessary. Other background sources, such as $e^+e^-\to\tau^+\tau^-$ or $e^+e^-\to(e^+e^-)\mu^+\mu^-$ are below the 0.25% level and contribute insignificantly to the asymmetry.

(*i*) *Cosmic ray events.* The cosmic ray background is estimated using the distribution $\delta(R-\varphi)$. Tracks with $\delta(R-z)$ greater than 2.5 cm are safely classified as cosmic ray events. Hence, using the $\delta(R-\varphi)$ distribution for these tracks, the cosmic ray background under the μ-pair signal is determined and subtracted statistically from the μ-pair candidate sample. The $\delta(R-\varphi)$ distribution of these cosmics was cross-checked with that obtained in separate cosmic ray runs processed through the same selection chain. This background, representing about 25% of the final μ-pair sample in typical conditions, was then subtracted bin by bin from the cos θ distribution of the μ-pair candidate sample used to determine the charge asymmetry.

(*ii*) *Bhabha events.* Some Bhabha events with at least one track associated to a background hit in a muon chamber could fulfill our μ-pair selection criteria if the event tracks were pointing to one of the small gaps between the liquid argon calorimeter modules. To determine the number of such events, we use our sample of events with back to back charged tracks each with less than 1.3 GeV deposited in the calorimeter and no hit in the muon chambers within a distance much larger than the 5σ required by our μ identification criteria (50σ). Such a sample consists of the kind of Bhabha events we are interested in. It contains as well a few μ-pair and cosmic ray events for which the muon chambers were inefficient. This number of μ-pair and cosmic ray events can be deduced from a study of pure cosmic ray data taken in separate runs and then subtracted to obtain the number of Bhabha events with less than 1.3 GeV deposited energy. The latter number has still to be multiplied by the probability of a spurious hit in the muon chambers taking place within 5σ of either one of the two tracks. This probability is obtained from the distribution of the muon chamber association factor as observed in a large sample of unambiguous Bhabha events. The contamination by Bhabha events was found to be about 0.5% of the μ-pair sample, depending on the experimental background conditions in the muon chambers [9]. A cross check done with a sample of Monte Carlo Bhabha events processed with a full detector simulation yielded the same result. The angular distribution was corrected bin by bin for the Bhabha contamination in the μ-pair sample.

5. $e^+e^-\to\mu^+\mu^-$ total cross section

(*i*) *Correction and normalization factors.* An overall acceptance factor to account for the various cuts applied is determined using a sample of fully simulated μ-pair events processed through the same reconstruction and selection routines as the normal sample. The efficiency of the charged trigger is determined using a sample of Bhabha events and cross-checked on a sample of simulated Monte Carlo Bhabha events with full trigger simulation. The combined efficiency varied between 67% and 90%, depending on experimental conditions. The muon detection efficiency is determined using cosmic ray events fulfilling all selection criteria except that the momentum had to be greater than 3 GeV/*c* and the distances $\delta(R-\varphi)$ or $\delta(R-z)$ had to be greater than 0.5 cm or 2.5 cm respectively. Radiative corrections are calculated by a Monte Carlo program [3] run in such a way that only the "reduced QED" corrections discussed above are taken into account. This correction amounts to a factor of $(1+\delta_{rad})\simeq 1.30$ in our energy range, within our acceptance and acollinearity cuts. Table 1 shows for each of the running periods the value of the overall correction factor f_{corr} by which the data have to be multiplied. It is defined as $f_{corr}=1[\epsilon_{tot}(1+\delta_{rad})]$, where ϵ_{tot} is the product of the efficiencies and of the acceptance factor mentioned above.

(*ii*) *Errors.* The statistical errors take into account the cosmic ray background subtraction. The systematic error is of the order of 4%. The main contributions to the latter error come from the errors on the luminosity measurement [6] (3.6%), the cosmic background subtraction [9] (0.5%), the trigger [9] (1%) and the muon chamber efficiencies [9] (1%), which were all added quadratically.

(*iii*) *Results.* The total cross-section results are presented in table 1 for the five data sets. We define $R_{\mu\mu}$ as $\sigma_{\mu\mu}/\sigma_0$ with $\sigma_0=4\pi\alpha^2/3s$. The energy dependence of the total cross section is shown in fig. 1. The solid line is the QED cross section. Previously published lower energy data have also been included [11] [‡2]. The results are in good agreement with the theoretical expectations and the average value of $R_{\mu\mu}$ at $\sqrt{s}=$ 43 GeV is: $\langle R_{\mu\mu}\rangle=0.98\pm0.04\pm0.04$. At these energies, the effect of the Z^0 propagator on the total cross section is very small and the predicted value for $R_{\mu\mu}$ is 1.01. Possible deviations from QED can be parametrized by introducing form factors $F(s)$ in the cross section: $\sigma=\sigma_0|F(s)|^2$ with $F(s)$ expressed in terms of the cut-off parameters $\Lambda_\pm$ as follows:

$$F(s)=1\mp\frac{s}{s-\Lambda_\pm^2}\,.$$

By fitting the function $\delta_\Lambda=1-R_{\mu\mu}=1-|F(s)|^2$ to this data, we obtain with 95% CL: $\Lambda_+>230$ GeV and $\Lambda_->171$ GeV. This can be interpreted as a conformation of the validity of QED down to distances of $\simeq 10^{-16}$ cm.

6. $e^+e^-\to\mu^+\mu^-$ angular distribution

The distribution in polar angle θ was studied for the complete set of data divided into two ranges with $\langle\sqrt{s}\rangle=39$ GeV and $\langle\sqrt{s}\rangle=44$ GeV, respectively. The same selection criteria as for the total cross-section measurements were used with the additional requirements that the two tracks be reconstructed with opposite charge signs and their acollinearity

‡2 The cross section for the 14 GeV point is lower by 19.5% with respect to the value published in ref. [11] after a better determination of the integrated luminosity.

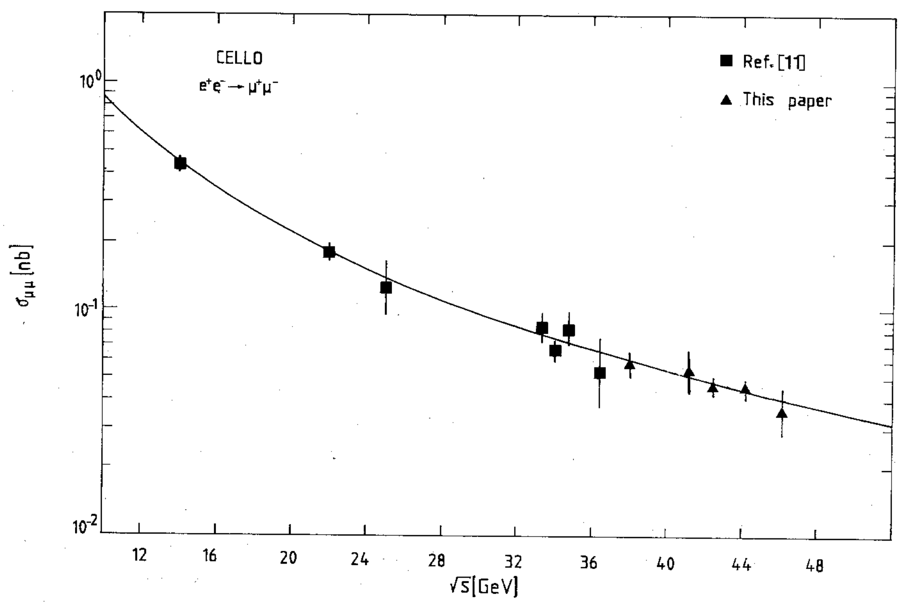
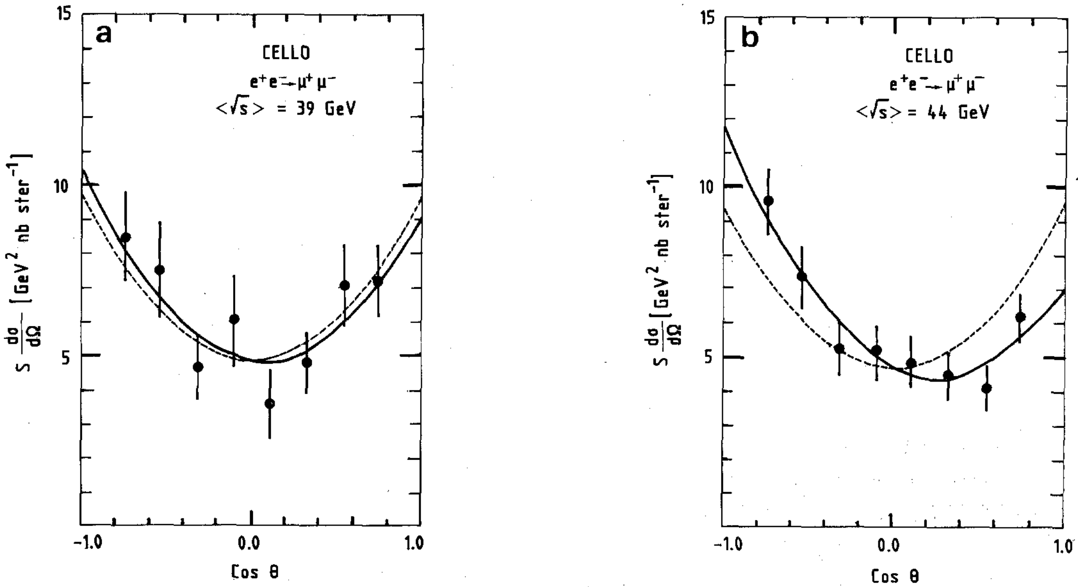


Fig. 1. The $e^+e^-\to\mu^+\mu^-$ cross section. The full line shows lowest order QED prediction. Triangles correspond to this data and squares to lower energy data previously published [11].



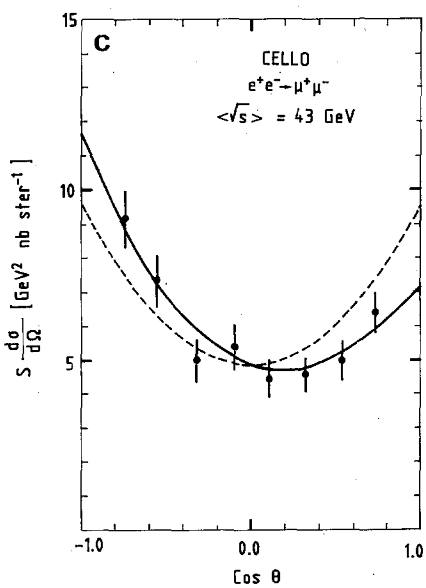


Fig. 2. The $e^+e^- \to \mu^+\mu^-$ corrected angular distribution for (a) $\langle\sqrt{s}\rangle = 39$ GeV, (b) $\langle\sqrt{s}\rangle = 44$ GeV, (c) $\langle\sqrt{s}\rangle = 43$ GeV for the combined data. The full line shows the result of the fit and the dashed line the QED prediction.

angle be less than 10°. Each one of the cos θ bins is corrected for trigger and reconstruction efficiencies, acceptance, Bhabha contamination and pure QED radiative effects. The contribution of the cosmic ray background is subtracted bin by bin as mentioned above. Fig. 2 shows the corrected angular distributions, with the values of $s\mathrm{d}\sigma/\mathrm{d}\Omega$ for each bin given in table 2. The statistical errors include the errors on the subtraction of cosmics, as well as the statistical errors on the luminosity measurement and the total acceptance factor.

The angular distribution is asymmetric and can be expressed as $f(\cos\theta) = C(1 + \cos^2\theta + b\cos\theta)$, where C is a normalization constant and $b = C_2/C_1$. The asymmetry is related to the parameter b by $A_{\mu\mu} = 3b/8$.

The values for the asymmetry obtained by fitting the function given above to the angular distributions

Table 2
QED corrected values of $sd\sigma/d\Omega$ for data at $\langle\sqrt{s}\rangle = 39$ and 44 GeV. Values at 43 GeV were obtained by combining all data.

	$\langle\sqrt{s}\rangle$ [GeV]	$\cos\theta$	Number of events	$sd\sigma/d\Omega$ [GeV^2 nb ster.$^{-1}$]
	39	$-0.85 \to -0.6375$	53 ± 8	8.48 ± 1.30
		$-0.6375\to -0.425$	40 ± 7	7.47 ± 1.37
		$-0.425 \to -0.2125$	28 ± 5	4.56 ± 0.95
		$-0.2125\to 0$	30 ± 6	5.96 ± 1.28
		$0 \to 0.2125$	17 ± 4	3.65 ± 1.08
		$0.2125\to 0.425$	31 ± 6	4.81 ± 0.94
		$0.425 \to 0.6375$	42 ± 7	7.04 ± 1.19
		$0.6375\to 0.85$	47 ± 7	7.07 ± 1.11
	44	$-0.85 \to -0.6375$	165 ± 13	9.57 ± 1.02
		$-0.6375\to -0.425$	101 ± 11	7.39 ± 0.84
		$-0.425 \to -0.2125$	54 ± 8	5.26 ± 0.78
		$-0.2125\to 0$	58 ± 9	5.19 ± 0.79
		$0 \to 0.2125$	51 ± 8	4.88 ± 0.78
		$0.2125\to 0.425$	44 ± 8	4.54 ± 0.70
		$0.425 \to 0.6375$	49 ± 7	4.12 ± 0.63
		$0.6375\to 0.85$	89 ± 10	6.17 ± 0.73
all data	43	$-0.85 \to -0.6375$	218 ± 15	9.24 ± 0.81
		$-0.6375\to -0.425$	141 ± 12	7.41 ± 0.72
		$-0.425 \to -0.2125$	82 ± 9	5.06 ± 0.62
		$-0.2125\to 0$	88 ± 11	5.42 ± 0.67
		$0 \to 0.2125$	68 ± 9	4.50 ± 0.63
		$0.2125\to 0.425$	75 ± 10	4.62 ± 0.56
		$0.425 \to 0.6375$	91 ± 10	5.00 ± 0.57
		$0.6375\to 0.85$	136 ± 12	6.44 ± 0.61

are shown in the third column of table 3. The main contributions to the systematic error [9] on this asymmetry are the errors due to the Bhabha contamination, to the subtraction of cosmics and to the uncertainty in the muon charge assignment. All systematic errors were added quadratically to yield a total systematic error of 1.0%. As mentioned above, only "reduced QED" radiative corrections were applied to the data. We may compare our results directly to the theoretical prediction given in the fourth column of table 3. The average value of the asymmetry obtained by combining all the data at the average energy of $\sqrt{s}=43$ GeV is $\langle A_{\mu\mu}\rangle = (-14.1\pm3.8\pm1.0)\%$ which is in good agreement with the standard model prediction of -14.5% and with results from other groups [12].

Using the value of $\langle A_{\mu\mu}\rangle$ from the combined data, and $a_e = -0.99\pm0.05$ from ref. [13], we obtain for

Table 3
Corrected experimental results for the μ-pair asymmetry compared to the standard model predictions. The last row gives the result obtained by combining all the data. The first error is the statistical one, the second is the systematic one.

	$\langle\sqrt{s}\rangle$ [GeV]	$N_{\mu\mu}$	$A_{\mu\mu}$ [%]	A_{GSW} [%]
	39	288 ± 18	$-4.8\pm6.5\pm1.0$	-11.5
	44	611 ± 30	$-18.8\pm4.5\pm1.0$	-15.5
all data	43	899 ± 35	$-14.1\pm3.8\pm1.0$	-14.5

the coupling constant a_μ: $a_\mu = -1.14 \pm 0.30$.

Conversely, setting $a_e = a_\mu = -1$ as expected in the standard model and using our value of $\langle A_{\mu\mu} \rangle$ from the combined data, we obtain $\sin^2\theta_W = 0.22 \pm 0.04$, which is in good agreement with other determinations [4,5,14].

7. Conclusion

We have measured the cross section and the charge asymmetry for the $e^+e^- \to \mu^+\mu^-$ reaction at centre of mass energies between 38.3 and 46.8 GeV. We have obtained the average values $\langle R_{\mu\mu} \rangle = 0.98 \pm 0.04 \pm 0.04$ and $\langle A_{\mu\mu} \rangle = (-14.1 \pm 3.8 \pm 1.0)\%$, which are in good agreement with the theoretical expectations of 1.01 and -14.5%, respectively.

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