MEASUREMENT OF $e^+e^- \to \tau^+\tau^-$ AT HIGH ENERGY AND PROPERTIES OF THE τ LEPTON

CELLO Collaboration

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The $e^+e^- \to \tau^+\tau^-$ process has been measured using the CELLO detector at a mean total centre of mass energy of 34.2 GeV using essentially all the decay channels of the τ lepton. The measured cross section yields $R_\tau = 1.03 \pm 0.05$ (stat) ± 0.07 (syst). Topological branching fractions are given for $\tau \to 1$, 3 or 5 charged tracks. The angular distribution shows a clear $1 + \cos^2\theta$ dependance with a forward–backward asymmetry of -0.103 ± 0.052 corresponding to an axial-vector coupling a_τ of the τ to the weak neutral current given by $a_\tau = -1.12 \pm 0.57$.

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Since its discovery in 1975 [1] the τ lepton has been compared to the electron and to the muon for a possibly different behaviour: except for those properties due to its higher mass, nothing has yet been found In this letter we report on new measurements of τ properties from the analysis of the process $e^+e^- \to \tau^+\tau^-$ with the CELLO detector [2] operating at PETRA with centre of mass energies ranging from 32.0 to 36.8 GeV with a mean energy of 34.2 GeV. All the $\tau^+\tau^-$ final states are used (except e^+e^- + neutrinos and $\mu^+\mu^-$ + neutrinos which amount to only 6%) so that a significant statistics is reached allowing the total cross section and the angular distribution to be measured with a precision comparable to the $e^+e^- \to \mu^+\mu^-$ process. Similar electroweak tests can thus be made for τ, μ and e [3].

The CELLO detector was triggered by any 2 charged particles with $p_T \gtrsim 200$ MeV/c – an essential feature to measure the dominant two-prong configuration of the $\tau^+\tau^-$ final state. In addition $\tau^+\tau^-$ events could be obtained using a trigger which is based on the electromagnetic energy deposition in the surrounding lead–liquid-argon calorimeter or by a mixed trigger which requires a charged track and neutral energy. For the analysis presented here only the charged particle trigger was used, but the neutral energy triggers were very useful to perform a completely independent analysis, therefore providing a powerful consistency check and a monitor of most systematic effects. The integrated luminosity used for this analysis was 11300 nb^{-1}. It was measured using small angle Bhabha scattering and checked with large angle Bhabha events detected in the barrel calorimeter.

Event candidates were filtered from the main data stream making use of the relatively low multiplicity and the distinct back to back topology of $\tau^+\tau^-$ events. A full reconstruction was performed for charged tracks. and showers in the calorimeter whether or not linked to charged tracks. The following cuts were applied to the events:

– For all events: the least 2 tracks satisfying

(a) $p_T > 350$ MeV/c with respect to the beam axis.

(b) $|\cos\theta| < 0.86$, where θ is the polar angle relative to the beam direction.

– For two -prong events

(c) $|\boldsymbol{p}_1| + |\boldsymbol{p}_2| > 5$ GeV/c.

(d) Total momentum transverse to the beam >300 MeV/c.

(e) Acolinearity in space >20 mrad and <0.7 rad.

(f) Angle between the prongs in the projection containing the beam direction >3.5 mrad.

(g) Angle between the prongs in the projection transverse to the beam >10 mrad.

– For ⩾ four-prong events

(h) $\Sigma|\boldsymbol{p}| > 4$ GeV/c.

(i) At least one track in 2 back to back sectors 80° wide in the projection transverse to the beam direction.

(j) Number of tracks ⩽8.

The acolinearity cuts (e), (f), (g) suppressed contributions from Bhabhas, μ pairs and cosmic muons. Background due to 2γ processes was removed by the cuts (c), (d) and (e). Multihadronic events were significantly rejected by the multiplicity cut (j), residual beam–gas events by the back to back requirement (i) and energy cut (h). The polar angle cut ensured a high efficiency for the charged trigger and also that the tracks entered the sensitive region of the liquid argon barrel calorimeter.

In addition, most Bhabha events were suppressed by the requirement of an energy deposition <15 GeV in at least one of the two back-to-back calorimeter modules corresponding to the direction of the final particles.

This selection procedure yielded about 4000 candidates which were double scanned in order to remove the remaining background events. A fraction of 45% of the scanned sample were Bhabha events, mostly radiative, with a conversion in the beam pipe, or entering the dead regions of the central calorimeter: besides edge effects, one of the 16 modules was not in operation. The events from the process $e^+e^- \to (e^+e^-)e^+e^-$ were also removed on the basis of their typical showering behaviour in the liquid argon calorimeter. The multihadron events (14%) were rejected by requiring fo the good events a total charged multiplicity ⩽8 using all visible tracks – whether reconstructed or not – and, in each of the back-to-back sectors, an odd number of tracks with an invariant mass <3 GeV/c^2.

As in the case of the e^+e^- final state, no attempt was made to use the $\mu^+\mu^-$ final state because of the large background of events due to the $e^+e^- \to (e^+e^-)\mu^+\mu^-$ process. All μ-paor events were rejected during scanning by removing events where the 2 visually associated showers in the liquid argon calorimeter had an energy deposition <600 MeV each. The correction for τ decays involving only non-interacting pions was made using the Monte Carlo simulation.

Finally 434 events were retained with an estimated maximum contamination of 8 multihadronic events and 9 events from the process $e^+e^- \to (e^+e^-)\,\tau^+\tau^-$. An additional contribution of 6 ambiguous events, including 2 possible Bhabhas was considered for the cross section calculation but was not taken into account for the angular distribution.

The trigger acceptance, the event reconstruction efficiency and the acceptance of the selection cuts were determined by Monte Carlo generation of $\tau^+\tau^-$ pairs including initial state radiation (essentially down to $\tau^+\tau^-$ threshold). The simulation of τ decays included both leptonic and two-body channels; multihadronic decays were generated with a statistical model [4]. These events were propagated through all the detector components of CELLO using the measured efficiencies and resolutions.

The Monte Carlo sample was subsequently processed through the same analysis chain as the one used for the real data. The acceptance was determined separatly for the different charge multiplicies in order to measure the branching fractions and the total cross section independently. The average overall efficiency (for geometrical acceptance, triggering, reconstruction, selection and scanning) was 48% for events with no hard radiation

After individual correction, the different topological samples were used to measure the branching fractions B_1, B_3, B_5 into 1, 3, 5 charged tracks. Proper care was taken to correctly identify the converted photons so that the true charged-track topology could be restored. Table 1 presents our results on charged branching fractions B_1, B_3 and B_5 where the errors include both statistical and systematic uncertainties which are of comparable magnitude.

Radiation corrections were applied following the procedure of ref. [5], including vacuum polarization terms with a maximum energy for the radiated photon equal to 98% of the beam energy. The correction amounted to 1.35. We obtain for the total cross section for $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s} = 34.2$ GeV.

$$\sigma_\tau = 76.7 \pm 3.7 \text{ (stat.)} \pm 5.1 \text{ (syst.) pb}$$

which can be expressed in terms of the QED point-like cross section to give

$$R_\tau = \sigma_\tau/\sigma_{\mathrm{pt}} = 1.03 \pm 0.05 \text{ (stat.)} \pm 0.07 \text{ (syst.)}\,.$$

The systematic uncertainties due to the determination of the luminosity (3%), the radiative corrections (2%), the acceptance calculations (5%), and the contamination of various background (1% multihadrons, 1% 2γ processes, and 1.5% ambiguous events) are added in quadrature.

As an overall check of our measurement, we have determined the cross section in a completely independent fashion using also the calorimetric triggers. These events are processed with a different filter, emphasizing neutral energy and therefore the corrections are quite different in nature. This method yields $R_\tau = 0.93 \pm 0.08$ (stat.) $\pm\, 0.10$ (syst.) on a subsample of the data.

Our measurement agrees with previous PETRA determinations [6,7]: unlike them, however it does not have to rely on the precise knowledge of specific branching fractions.

The differential cross section was determined by taking the vector sum of the momenta of the τ charged decay products. This is a good estimater of the τ line of flight since the smearing due to unseen neutrinos is only typically $\sim 10°$. The same procedure was applied to Monte Carlo events. The τ charge was measured unambiguously except for 3 events which were removed. In addition the angular range was restricted to $|\cos\theta_\tau| < 0.8$ in order to avoid edge effects. A correction to the angular distribution from higher order QED contribution was also applied [5]. The corresponding forward–backward asymmetry is +1.1%. The resulting angular distribution (fig. 1) shows in first order a pronounced $(1 + \cos^2\theta)$ distribution which is an independent confirmation of the spin 1/2 nature of the τ lepton.

In order to search for electro-weak interference the forward–backward asymmetry was computed:

Table 1
Charged branching fractions of the τ lepton.

Charge multiplicity	Observed number of decays	Branching fraction
B_1	672	0.840 ± 0.020
B_3	186	0.150 ± 0.020
B_5	10	0.010 ± 0.004

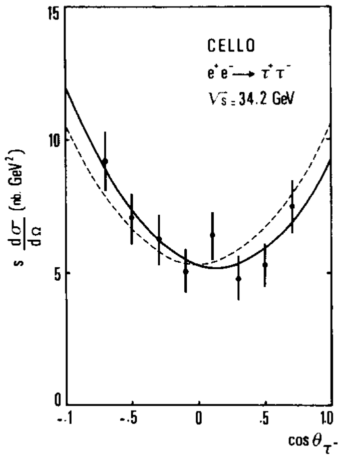

Fig. 1. The differential cross section for the reaction $e^+e^- \to \tau^+\tau^-$ at an average $\sqrt{s} = 34.2$ GeV. The dotted line represents lowest order QED, and the full line is the best fit to weak-electromagnetic interference.

$$A_\tau(\cos\theta) = \frac{d\sigma_\tau(\cos\theta) - d\sigma_\tau(-\cos\theta)}{d\sigma_\tau(\cos\theta) + d\sigma_\tau(-\cos\theta)},$$

with the result shown in fig. 2. A fit of the angular distribution to the function $(1 + \cos^2\theta + b\cos\theta)$ yields

$b = -0.27 \pm 0.14$,

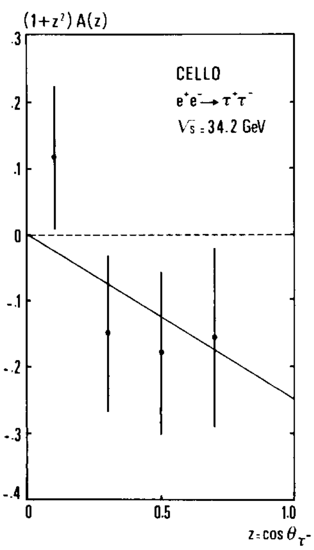

Fig. 2. The quantity $(1 + (\cos^2\theta_{\tau^-}) A(\cos\theta_{\tau^-})$ plotted against $\cos\theta_{\tau^-}$. The dotted line represents lowest order QED, and the full line is the best fit to weak–electromagnetic interference.

which can be expressed as an average forward–backward asymmetry

$\langle A_\tau \rangle = \frac{3}{8} b = -(10.3 \pm 5.2) \times 10^{-2}$,

which is in broad agreement with the recent result of ref. [7]. This number agrees with the corresponding value for $e^+e^- \to \mu^+\mu^-$ [8].

This result shows that the electro-weak behaviour of the τ lepton does not depart from that of the electron or of the muon within the sensitivity of our experiment. The standard GWS theory [9], with full e, μ, τ universality, predicts for our experimental conditions

$R_\tau^{GWS} = 1.003$ (with $\sin^2\theta_W = 0.22$) ,

$\langle A_\tau \rangle^{GWS} = -9.2 \times 10^{-2}$,

in agreement with our measurements.

In a more model-independent way, we can relate $\langle A_\tau \rangle$ to the axial vector coupling of the τ and e to the neutral weak current:

$\langle A_\tau \rangle = \frac{3}{2} [gsM_Z^2/(s - M_Z^2)]\, a_\tau a_e$,

with $g = 4.5 \times 10^{-5}$ GeV^{-2}. Using the known electron coupling [10] and $M_Z = 90$ GeV, we deduce

$a_\tau = -1.12 \pm 0.57$,

in agreement with the value $a_\tau = -1$ of the standard model. The τ vector coupling is much less constrained since it enters in R_τ multiplied by the small electron vector coupling.

Finally we can translate the measurement of R_τ into a limit for the τ size. Parametrizing the cross section as usual

$\sigma_\tau = \sigma_{pt}[1 \pm s/(s - \Lambda_\mp^2)]^2$,

we get the following values:

$\Lambda_- > 121$ GeV , $\Lambda_+ > 142$ GeV

(95% confidence level) .

This value can be expressed as a limit of 4×10^{-3} fermi for the τ charge radius.

In conclusion, we have measured with good statistics the reaction $e^+e^- \to \tau^+\tau^-$ at the highest available energies. Our results on the total and differential cross sections show – to an accuracy comparable with that of $\mu^+\mu^-$ measurement – that the τ lepton behaves indeed like the electron and the muon as far as its neutral weak coupling and its point-like nature are concerned.

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