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Search for $\mathcal{C}P$ violation in the decay $\mathbf{Z} \rightarrow \tau^+\tau^-$

The ALEPH Collaboration

Abstract

Data collected by ALEPH in the years 1990, 1991 and 1992 have been used to update a previous search for $\mathcal{C}P$ violation in the decay of the Z into $\tau^+\tau^-$. The measurement of the weak dipole form factor of the τ lepton has been performed by studying correlations between the τ leptons. No signal of $\mathcal{C}P$ violation was found. The weak dipole form factor is found to be $\tilde{d}_\tau = (+0.15 \pm 0.58_{stat} \pm 0.38_{sys})10^{-17} e \cdot \mathrm{cm}$, obtained with 19628 identified $\tau^+\tau^-$ events. This gives an upper limit on the weak dipole form factor of $|\tilde{d}_\tau| < 1.5 \cdot 10^{-17} e \cdot \mathrm{cm}$ at the 95% confidence level.

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1 Introduction

The decay of the Z boson into $\tau^+\tau^-$ is an appropriate process to search for signals of $\mathcal{C}P$ violation caused by new interactions. Since in the Standard Model $\mathcal{C}P$ violation occurs only in the couplings of the charged current as described in the CKM scheme, $\mathcal{C}P$ odd contributions to the reaction $Z \to \tau^+\tau^-$ are at most of the order of 10^{-7}[1] compared to the electroweak amplitude at the Born level. On the other hand extensions of the Standard Model, such as models with leptoquarks or with extended Higgs sectors, but also left – right symmetric or supersymmetric interactions can generate $\mathcal{C}P$ violating effects at the $Z\tau\tau$ vertex[2]. The parametrization of these contributions by the weak dipole form factor of the τ lepton at the Z resonance gives a model independent description of the on – shell amplitude, which in this case consists of the coherent sum of the electroweak amplitude and an amplitude proportional to the weak dipole form factor $\tilde{d}_\tau$.

An indirect limit on the weak dipole form factor can be derived from the measurement of the Z partial width Γ_τ, since there would be an additional contribution from the weak dipole form factor $\Delta\Gamma_\tau \approx |\tilde{d}_\tau|^2 m_Z^3/(24\pi)$ [1]. From the comparison of the value measured at LEP, $\Gamma_\tau = (84.26 \pm 0.34)$MeV[3], and the theoretical prediction of the Standard Model, $\Gamma_\tau^{SM} = (83.7 \pm 0.4)$MeV[4], one obtains an indirect upper limit on the weak dipole form factor of $|\tilde{d}_\tau| < 2.3 \cdot 10^{-17}\, e \cdot$cm (95 % *c.l.*). However, if there are new physics effects, there may also be $\mathcal{CP}$ even contributions to the partial width, which can cancel partially the contribution from $\tilde{d}_\tau$.

In order to measure the dipole form factor directly from $\mathcal{C}P$ odd correlations between the τ leptons, we use the following $\mathcal{C}P$ odd tensor observables[5, 6]:

$$\hat{T}_{ij} = (\hat{p}_+ - \hat{p}_-)_i \cdot \frac{(\hat{p}_+ \times \hat{p}_-)_j}{|\hat{p}_+ \times \hat{p}_-|} \quad + \quad (i \longleftrightarrow j) \qquad \text{i,j} = 1,2,3 \tag{1}$$

$\hat{p}_+$ ($\hat{p}_-$) denotes the normalized momentum vector of one of the decay particles of the τ^+ (τ^-), i, j are cartesian coordinate indices. The relation between the observable and the dipole form factor $\tilde{d}_\tau$ is given by[5, 6]:

$$\left\langle \hat{T}_{ij} \right\rangle_{AB} = \frac{m_Z}{e} \cdot \tilde{d}_\tau \cdot \hat{c}_{AB} \cdot s_{ij} \tag{2}$$

A and B are the decay modes of τ^- and τ^+, respectively. The constants $\hat{c}_{AB}$ describe the sensitivity of the angular distributions of the decay particles used to build $\hat{T}$ to the spin states of the τ leptons. Therefore these constants depend in magnitude and sign explicitly on the decay mode of τ^- and τ^+. This analysis uses the major τ decay modes $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$, and $a_1\nu$, with $a_1 \to \pi\pi^+\pi^-$ and $a_1 \to \pi 2\pi^0$. This results in 18 different classes, the three classes $a_1 - a_1$ are not used due to low statistics and high backgrounds. The matrix $s_{ij} = \text{diag}(-\frac{1}{6}, -\frac{1}{6}, \frac{1}{3})$ is a diagonal matrix representing the tensor polarisation of the Z boson in the coordinate system in which the z axis is determined by the direction of the incident positron beam. As can be seen from the matrix s_{ij}, $\hat{T}_{33}$ is the most sensitive component and will give the largest signal if $\tilde{d}_\tau \neq 0$. Since in addition the three diagonal elements are strongly correlated due to the fact that the trace of $\hat{T}$ must be zero and since the systematic checks are easier to perform for $\hat{T}_{33}$, only $\hat{T}_{33}$ is used in this analysis.

The analysis described in this paper improves upon and supersedes the result published by the ALEPH Collaboration ($|\tilde{d}_\tau| < 3.7 \cdot 10^{-17}\, e \cdot$ cm at the 95 % *c.l.*)[7]. This is due to a better selection, yielding about 30 % more acceptance, the inclusion of the τ decays into a_1 and a doubling of the collected data. A limit on the weak dipole form factor of the τ has also been published by the OPAL Collaboration ($|\tilde{d}_\tau| < 7.0 \cdot 10^{-17}\, e \cdot$ cm at the 95 % *c.l.*)[8].

2 ALEPH Detector and Event selection

The ALEPH detector is described in detail elsewhere[9]. The main components used to measure the energies and the momenta are the electromagnetic calorimeter (ECAL) and the tracking devices, namely the vertex detector (VDET), the inner tracking chamber (ITC) and the time projection chamber (TPC). The particle identification relies on the dE/dx measurement in the TPC, on the ECAL, on the hadronic calorimeter (HCAL) and the muon chambers.

This analysis employs data collected by ALEPH in the years 1990, 1991 and 1992, corresponding to 57000 produced τ pairs. The event selection is based on a method developed for the analysis of the τ polarisation[10], and which is therein referred to as the neural net method. This includes particle identification and the cuts applied to classify the τ decays as well as to reject the background from non – τ events. In contrast to the polarisation analysis, events with both τ leptons decaying into electrons are

Event class	Selection-efficiency	Background fractions from τ events	Background fractions from other processes
e – e	36.4 ± 0.6	2.8 ± 0.3	3.6 ± 1.2
e – μ	67.9 ± 0.4	3.2 ± 0.2	1.0 ± 0.3
e – π	39.3 ± 0.5	9.9 ± 0.5	0.3 ± 0.3
e – ρ	33.3 ± 0.4	7.4 ± 0.4	0.2 ± 0.2
e – $\pi\pi^+\pi^-$	41.7 ± 0.7	5.5 ± 0.5	0.2 ± 0.2
e – $\pi 2\pi^0$	25.2 ± 0.6	26.8 ± 1.0	0.4 ± 0.3
$\mu - \mu$	60.3 ± 0.6	3.2 ± 0.2	2.5 ± 0.7
$\mu - \pi$	55.5 ± 0.5	8.9 ± 0.4	0.3 ± 0.2
$\mu - \rho$	42.3 ± 0.4	7.2 ± 0.3	< 0.1
$\mu - \pi\pi^+\pi^-$	50.4 ± 0.7	5.1 ± 0.4	0.3 ± 0.3
$\mu - \pi 2\pi^0$	32.8 ± 0.6	27.9 ± 0.9	0.3 ± 0.3
$\pi - \pi$	47.1 ± 1.0	14.3 ± 0.9	1.0 ± 0.7
$\pi - \rho$	36.4 ± 0.5	13.6 ± 0.5	0.2 ± 0.2
$\pi - \pi\pi^+\pi^-$	42.8 ± 0.8	13.7 ± 0.8	0.2 ± 0.2
$\pi - \pi 2\pi^0$	27.6 ± 0.7	32.3 ± 1.2	0.5 ± 0.5
$\rho - \rho$	28.3 ± 0.4	12.4 ± 0.6	0.2 ± 0.2
$\rho - \pi\pi^+\pi^-$	30.9 ± 0.5	10.8 ± 0.4	0.3 ± 0.2
$\rho - \pi 2\pi^0$	22.2 ± 0.5	30.3 ± 0.9	< 0.1

Table 1: *Efficiencies and background with statistical errors for the event classes used in the analysis. All numbers are given in percent.*

retained and the decay of the a_1 into $\pi 2\pi^0$ is included. Event classes involving the latter decays can be used safely despite the large background and the uncertainty in the description of the multipion decays of the τ, because the sensitivity of these classes comes mainly from the lepton, π or ρ in the opposite hemisphere. The decay $a_1 \rightarrow \pi 2\pi^0$ is identified by cutting on the reconstructed masses of the a_1, of the intermediate ρ and of the reconstructed π^0's. In the case of two – electron events, severe cuts on the energy and $cos\theta_{Thrust}$ are applied to reduce background from Bhabha events as much as possible, because these events could fake a $\mathcal{C}P$ violating effect due to bremsstrahlung in the detector material and to the forward – backward asymmetry of the t – channel distribution. The resulting efficiencies and the background fractions for all classes are listed in table 1.

3 Data analysis

The constants $\hat{c}_{AB}$ are determined channel by channel using a Monte Carlo generator for the process $Z \rightarrow \tau^+\tau^-$ with $\mathcal{C}P$ violating couplings[11]. The $\hat{c}_{AB}$'s can be determined from the generated distributions with known $\tilde{d}_\tau$ using relation (2). Since there are 18 different classes, which all have to be treated separately, several million events must be generated. Therefore, in order to save computing time a simplified detector simulation was used. Kinematic cuts were implemented at generator level, whereas acceptance variations in the kinematic variables were taken care of by a weighting procedure based on acceptances for single event hemispheres. These weights have been determined from the Monte Carlo including the full detector simulation. To test the effects of the detector resolution, events with the full detector simulation were generated for three classes. It was found that the differences between the constants $\hat{c}_{AB}$ computed that way and using the simplified detector simulation were negligible.

Misidentification of τ decay modes and background events change the value of the constants $\hat{c}_{AB}$ in the various event classes. This is considered computing effective values by making the sum of the $\hat{c}_{AB}$ of the event class and the contributing background channels weighted by their relative fraction. The uncertainties on the $\hat{c}_{AB}$ of the background channels due to the cuts applied to reject that background were estimated from the effects of the cuts on the $\hat{c}_{AB}$ of the event classes, where the cuts have been implemented in the Monte Carlo. These uncertainties resulted in an additional error on the effective sensitivities.

For the τ decays into ρ or a_1 mesons one can either use the reconstructed total momentum vector of the ρ or a_1 to build $\hat{T}_{33}$, or the momentum vector of a single pion from the decay, which is the charged pion in the case of the ρ and the pion with unique charge in the case of the a_1. It was pointed out in [12]

Event class	Number of events	$\hat{c}_{AB}$	$\tilde{d}_\tau$	$\Delta\tilde{d}_\tau^{stat}$	$\Delta\tilde{d}_\tau^{sys}$	$\Delta\tilde{d}_\tau^{c}$	$\Delta\tilde{d}_\tau^{Ecal}$
e − e	668	+0.59	+5.1	4.2	1.5	0.6	–
e − μ	2449	+0.72	−3.5	2.0	1.1	0.3	–
e − π	1101	−0.89	−0.5	2.3	1.1	< 0.1	–
e − ρ	1801	+0.36	+1.5	4.7	2.6	0.3	–
e − $\pi\pi^+\pi^-$	804	+0.49	−0.9	5.2	2.2	0.2	–
e − $\pi 2\pi^0$	560	+0.44	+2.5	6.9	1.9	0.7	–
$\mu-\mu$	1260	+0.90	+2.2	2.2	0.4	0.2	–
$\mu-\pi$	1463	−0.57	−5.8	3.3	0.6	0.7	–
$\mu-\rho$	2291	+0.39	+3.8	3.8	0.4	0.6	–
$\mu-\pi\pi^+\pi^-$	937	+0.49	−3.9	4.8	1.1	0.3	–
$\mu-\pi 2\pi^0$	730	+0.63	+0.9	4.3	0.6	0.2	–
$\pi-\pi$	479	−1.88	−1.4	1.7	0.2	0.1	–
$\pi-\rho$	1352	−1.53	±0.0	1.2	0.2	< 0.1	0.4
$\pi-\pi\pi^+\pi^-$	564	−1.54	+1.3	1.9	0.4	0.2	–
$\pi-\pi 2\pi^0$	467	−1.45	+1.1	2.2	0.4	0.2	1.1
$\rho-\rho$	1100	−0.95	+1.9	2.1	0.6	0.2	0.6
$\rho-\pi\pi^+\pi^-$	889	−0.70	+6.2	3.4	1.1	1.6	0.8
$\rho-\pi 2\pi^0$	713	−0.72	−2.7	3.7	1.3	0.6	2.2

Table 2: *The dipole form factors and the errors (in units of $10^{-17}\,e\cdot$cm) and the constants $\hat{c}_{AB}$ for the event classes used in the analysis. The specification of the errors is given in the text.*

that the sensitivity in the classes with a leptonic decay on the other side will be higher if a single pion is taken to build $\hat{T}_{33}$, whereas for a hadronic decay it is better to use the momentum of the ρ or a_1 meson. The resulting values of the $\hat{c}_{AB}$'s are shown in table 2.

Even though all steps of the selection are built to be $\mathcal{C}$ and $\mathcal{P}$ blind, the $\mathcal{CP}$ invariance of the selection was checked. Further checks concern the radiation of photons, which affects the measurement of the momenta, and the event reconstruction from the subdetectors used in the analysis.

In order to avoid any systematic uncertainty from possible misalignments of the tracking devices a method is applied which ensures that the determination of $\tilde{d}_\tau$ is not affected by a possible shift in $\hat{T}_{33}$ due to uncertainties in the track measurement. From equation (2) it follows that the influence of a systematic shift in $\hat{T}_{33}$ on $\tilde{d}_\tau$ depends on the value of $\hat{c}_{AB}$. The measured $\tilde{d}_{AB}$ for each individual class can be written as the sum of the physical dipole form factor $\tilde{d}_\tau$ and a part originating from a detector shift $\Delta\hat{T}$, as discussed in [7]:

$$\tilde{d}_{AB} = \tilde{d}_\tau + 3\frac{\Delta\hat{T}}{\hat{c}_{AB}}$$

The shift can be eliminated in the combined result $\tilde{d} = \Sigma\lambda_{AB}\tilde{d}_{AB}$ if the constraint $\Sigma\frac{\lambda_{AB}}{\hat{c}_{AB}} = 0$ is imposed. The λ_{AB} are then determined by minimising the square of the error on $\tilde{d}_\tau$ with the two constraints $\Sigma\lambda_{AB} = 1$ and $\Sigma\frac{\lambda_{AB}}{\hat{c}_{AB}} = 0$. It can be noted that compared to the combined result of all classes with no constraint, this solution has practically the same statistical precision; this is due to the fact that the constants $\hat{c}_{AB}$ have different signs. The result is:

$$\tilde{d}_\tau = (+0.15 \pm 0.58_{stat})10^{-17}e\cdot\text{cm} \quad \text{and} \quad \Delta\hat{T} = +0.004 \pm 0.008$$

The ECAL, used for the reconstruction of π^0's, enters the measurement only in a few classes. Therefore a shift from the ECAL cannot be eliminated with the above method. To test it, an event mixing method is used. The observable $\hat{T}_{33}$ is built from combinations of ρ's and a_1's, respectively, originating from different events and having an acollinearity between the charged pions greater than 170^0 for the ρ and 160^0 for the a_1. Detector effects are then still visible in the mean value $\langle\hat{T}_{33}\rangle$, but a shift due to a true $\mathcal{CP}$ violation will vanish. In all these cases no systematic effect was found, and the statistical errors of the methods are used as systematic uncertainties on $\langle\hat{T}_{33}\rangle$.

4 Results and Conclusion

Using the data collected in the years 1990, 1991 and 1992 no signal of $\mathcal{CP}$ violation was found. Table 2 shows the results for $\tilde{d}_\tau$ in the individual classes with the following errors:

- $\Delta\tilde{d}_\tau^{stat}$: statistical error of the data.
- $\Delta\tilde{d}_\tau^{sys}$: systematic error, resulting from the checks concerning the $\mathcal{CP}$ invariance of the selection and the radiation of photons. The contribution of $\Delta\hat{T}$ is not propagated, because it is negligible and cancels out in the combined result of all classes.
- $\Delta\tilde{d}_\tau^{c}$: error from the combined errors of the constants $\hat{c}_{AB}$.
- $\Delta\tilde{d}_\tau^{ECAL}$: error originating from the uncertainty of the event mixing.

Correlations in the systematic errors between the classes have been taken into account for the combination of the individual measurements. The result obtained with 19628 identified $\tau^+\tau^-$ events considering the τ decay modes $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$ and $a_1\nu$ is:

$$\tilde{d}_\tau = (+0.15 \pm 0.58_{stat} \pm 0.38_{sys})\, 10^{-17}\, e \cdot \mathrm{cm}$$

$$\left|\tilde{d}_\tau\right| < 1.5 \cdot 10^{-17}\, e \cdot \mathrm{cm} \quad (95\,\%\ c.l.)$$

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