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Effects of anomalous charged current dipole moments of the tau on the decay $\tau^- \to \nu_\tau \pi^- \pi^0$

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Abstract: We analyse the process $\tau^- \to \nu_\tau \pi^- \pi^0$ allowing for anomalous weak charged current magnetic and electric dipole moment interactions and determine the effects on the differential and total decay rates. Using recent experimental data we determine the following values for the anomalous magnetic and electric dipole moment parameters, respectively: $\kappa = 0.16 \pm 0.08$; and $|\tilde{\kappa}| = 0.88^{+0.25}_{-0.35}$.

Keywords: Weak Decays, Beyond Standard Model.

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Contents

1. Introduction

In the Standard Model the charged current interactions of the tau lepton are mediated by the W boson with a pure $V-A$ coupling. We consider new derivative couplings in the Hamiltonian which are parametrised by the parameters κ and $\tilde{\kappa}$, the (CP-conserving) magnetic and (CP-violating) electric dipole form factors respectively [1, 2]. These are the charged current analogues of the weak neutral current dipole moments, measured using $Z \to \tau^+\tau^-$ events [3, 4, 5, 6, 7], and the electromagnetic dipole moments [8, 9], measured using $Z \to \tau^+\tau^-\gamma$ events [10, 11, 12]. The only limits so far obtained for κ and $\tilde{\kappa}$ are derived from analyses of the partial widths for $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, for $\ell = \mathrm{e}, \mu$ [1, 13, 14].

In this paper we consider for the first time the effects of anomalous charged current dipole moments on tau decays involving hadrons. We analyse the $\tau^- \to \nu_\tau \pi^- \pi^0$ process which has largest branching fraction of all the tau decay modes. This process is particularly topical due to a recently reported difference of 2.2σ between the measured $\tau^- \to \nu_\tau \pi^- \pi^0$ branching fraction and the (lower) value predicted using $e^+e^- \to \pi^+\pi^-$ data in the neighbourhood of the ρ meson resonances and the Conserved Vector Current (CVC) hypothesis [15]. While this could be attributed to a fluctuation, we note that non-zero values of κ and $\tilde{\kappa}$ would also yield a higher measured value for $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$.

We present predictions for the differential $\tau^- \to \nu_\tau \pi^- \pi^0$ decay distributions and the partial width, $\Gamma(\tau^- \to \nu_\tau \pi^- \pi^0)$, as functions of κ and $\tilde{\kappa}$. The sensitivity of the differential distributions is analysed for typical samples of $\tau^- \to \nu_\tau \pi^- \pi^0$ decays in $e^+e^- \to \tau^+\tau^-$ events which are reconstructed by the LEP and SLC experiments. The partial width is compared to the experimental measurements of BR$(\tau^- \to \nu_\tau \pi^- \pi^0)$ to yield quantitative constraints on κ and $\tilde{\kappa}$.

2. Parametrisation of anomalous couplings in $\tau^- \to \nu_\tau \pi^- \pi^0$ decays

The matrix element for the decay $\tau^- \to \nu_\tau \pi^- \pi^0$ is given by

$$M = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{ud} J^\mu H_\mu \, , \tag{2.1}$$

where $G_{\mathrm{F}} = (1.16639 \pm 0.00001) \times 10^{-5}\mathrm{GeV}^{-2}$ is the Fermi constant, $V_{ud} = (0.9740 \pm 0.0010)$ is the appropriate CKM matrix element [16], and J^μ and H_μ are the leptonic and hadronic currents respectively. The effects of anomalous weak charged current dipole moment couplings at the $\tau \nu_\tau W$ vertex are parametrised by augmenting the usual $V - A$ charged current such that J^μ is given by

$$J^\mu = \bar{u}_\nu \left(\gamma^\mu \left(1 - \gamma^5\right) - \frac{i\sigma^{\mu\nu} q_\nu}{2m_\tau} (\kappa - i\tilde{\kappa}\gamma_5) \right) u_\tau \, , \tag{2.2}$$

where $\sigma^{\mu\nu} {=} \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, q^μ is the four-momentum transfer, and $m_\tau {=} (1777.05^{+0.29}_{-0.26})$MeV [16] is the tau mass. The parameters κ and $\tilde{\kappa}$ are in general complex but henceforth we assume that $\tilde{\kappa}$ is real, as required by CPT invariance. The hadronic current is parametrised as

$$H^\mu = \sqrt{2} F(q^2)(q_1 - q_2)^\mu \, , \tag{2.3}$$

where q_i denote the four-momenta of the two final-state pions and $F(q^2)$ is a form factor.

A convenient choice for the kinematic observables, following Kühn and Mirkes [17], is q^2, the invariant mass-squared of the hadronic system; $\cos\theta$, the cosine of the angle between the tau spin-vector and the hadronic centre-of-mass direction as seen in the tau rest frame; and $\cos\beta$, the cosine of the angle between the charged pion and the axis pointing in the direction of the laboratory viewed from the hadronic centre-of-mass frame (henceforth referred to as the z-axis).

2.1 Differential decay rate, $d\Gamma(\tau^- \to \nu_\tau \pi^- \pi^0)/dq^2 d\cos\theta d\cos\beta$

After integration over the unobservable neutrino direction and the azimuthal angle of the charged pion, and neglecting the mass difference between the charged and neutral pions, the differential decay rate is given by

$$\begin{aligned} d\Gamma = &\frac{1}{(4\pi)^3}\frac{G_F^2}{4m_\tau^3}|V_{ud}|^2|F(q^2)|^2 S_{EW}(q^2-4m_\pi^2)^{3/2}(m_\tau^2-q^2)^2 \times \\ &\times\Big\{\Big[f_0+Re(\kappa)f_1+(|\kappa|^2+\tilde{\kappa}^2)f_2\Big]+P_\tau\Big[g_0+Re(\kappa)g_1+\tilde{\kappa}Im(\kappa)g_2\Big]\Big\}\times \\ &\times\frac{dq^2}{\sqrt{q^2}}\frac{d\cos\beta}{2}\frac{d\cos\theta}{2}, \end{aligned} \tag{2.4}$$

where $m_\pi^2=(m_{\pi^-}^2+m_{\pi^0}^2)/2$ and P_τ is the tau polarisation. The factor of $S_{EW}=1.0194$ accounts for electroweak corrections to leading logarithm [18]. The functions f_i and g_i $(i=0,1,2)$ are given by

$$\begin{aligned} f_0 &= 2\left[1+\frac{m_\tau^2-q^2}{q^2}Y\right], \\ f_1 &= 1, \\ f_2 &= \frac{1}{4}\left[1-\frac{m_\tau^2-q^2}{m_\tau^2}Y\right], \\ g_0 &= 2\left[\frac{2m_\tau}{\sqrt{q^2}}X-\cos\theta\right], \\ g_1 &= \frac{m_\tau^2+q^2}{m_\tau\sqrt{q^2}}X-\left[1+\frac{(m_\tau^2-q^2)^2}{2m_\tau^2q^2}Y\right]\cos\theta, \\ g_2 &= \frac{\cos\theta}{2}-\frac{\sqrt{q^2}}{m_\tau}X, \end{aligned} \tag{2.5}$$

where

$$\begin{aligned} Y &= \frac{1}{3}\left[1+(3\cos^2\psi-1)\frac{3\cos^2\beta-1}{2}\right], \\ X &= \frac{m_\tau^2+q^2}{2m_\tau\sqrt{q^2}}Y\cos\theta+\sin\theta\frac{\sin 2\psi}{2}\frac{3\cos^2\beta-1}{2}, \end{aligned} \tag{2.6}$$

and ψ is the angle between the tau direction of flight in the hadronic rest frame and the z-axis. At LEP energies the following approximation is valid:

$$\cos\psi=\frac{\eta+\cos\theta}{1+\eta\cos\theta}, \qquad \text{with} \qquad \eta=\frac{m_\tau^2-q^2}{m_\tau^2+q^2}. \tag{2.7}$$

$F(q^2)$ describes the resonant structure of the two-pion invariant mass and the model used to describe it is discussed in more detail in the following section.

2.2 Dependence of apparent polarisation on anomalous couplings

The usual determination of tau polarisation from energy and angular distributions of decay products of the tau depends crucially on the assumed $V-A$ structure of the charged current to serve as a polarimeter. Additional couplings in $\tau \to \rho\nu$ decays will produce measured values of polarisation which differ from analyses of other τ decay modes and the predictions from global fits to Electroweak parameters in the context of the Standard Model. The observed agreement of polarisation measured in $\tau^- \to \nu_\tau \pi^- \pi^0$ decays with other determinations may be used to constrain κ and $\tilde{\kappa}$.

We first integrate the differential width presented above with respect to q^2 and $\cos\beta$. The q^2 dependence of F must be explicitly considered prior to this integration. $F(q^2)$ for the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel is dominated by the $\rho(770)$ vector meson with a small admixture of $\rho'(1450)$ and a negligible contribution from the $\rho''(1700)$, as verified by the ALEPH experiment [19]. We work within the context of the Kühn and Santamaria model [20] in which the ρ and ρ' resonances are each described by a Breit-Wigner propagator with an energy-dependent width [21]

$$B_x(q^2) = \frac{m_x^2}{m_x^2 - q^2 - i\sqrt{s}\Gamma_x(q^2)}\,, \tag{2.8}$$

where

$$\Gamma_x(q^2) = \Gamma_x^0 \frac{m_x^2}{q^2}\left(\frac{p(q^2)}{p(m_x^2)}\right)^3 \tag{2.9}$$

and

$$p(s) = \frac{1}{2}\sqrt{s - 4m_\pi^2}\,. \tag{2.10}$$

where Γ_x^0 is a constant. The normalisation is fixed by chiral symmetry constraints in the limit of soft meson momenta, such that the form factor is given by

$$F(q^2) = \frac{B_\rho(q^2) + \beta B_{\rho'}(q^2)}{1+\beta}\,. \tag{2.11}$$

where $\beta = -0.145$ [20]. The differential width, retaining only the θ dependence, is of the form

$$d\Gamma = \Gamma^0(A + BP_\tau \cos\theta)\frac{d\cos\theta}{2}\,. \tag{2.12}$$

Where Γ^0 is the partial width in the absence of anomalous couplings, i.e. $\kappa = \tilde{\kappa} = 0$. It is determined from $e^+e^- \to \pi^+\pi^-$ data using CVC [15], as discussed below. The coefficients A and B depend on κ and $\tilde{\kappa}$ and are given by

$$\begin{aligned} A &= 1 + Re(\kappa) f_1^\dagger + (|\kappa|^2 + \tilde{\kappa}^2) f_2^\dagger \\ B &= g_0^\dagger + Re(\kappa) g_1^\dagger + \tilde{\kappa} Im(\kappa) g_2^\dagger\,, \end{aligned} \tag{2.13}$$

where, for $\beta = -0.145$, we obtain the following numerical values

$$\begin{aligned} f_1^\dagger &= 0.202 \\ f_2^\dagger &= 0.037 \\ g_0^\dagger &= 0.399 \\ g_1^\dagger &= -0.067 \\ g_2^\dagger &= 0.059 \end{aligned} \tag{2.14}$$

Comparison of the results for the measured "apparent polarisation" from $\tau^- \to \nu_\tau \pi^- \pi^0$ channel with other channels or the results of Electroweak fits would permit constraints to be placed on κ and $\tilde{\kappa}$.

2.3 Dependence of the total width, $\Gamma(\tau^- \to \nu_\tau \pi^- \pi^0)$ on anomalous couplings

Integration of eq. 2.12 over $\cos\theta$ yields the effect of the anomalous couplings on the total rate

$$\Gamma(\tau^- \to \nu_\tau \pi^- \pi^0) = \Gamma^0 \left[1 + f_1^\dagger Re(\kappa) + f_2^\dagger(|\kappa|^2 + \tilde{\kappa}^2)\right], \tag{2.15}$$

which naturally is independent of the polarisation (the polarisation term is proportional to $\cos\theta$ and therefore integrates to zero).

3. Sensitivity of the differential decay rate to κ and $\tilde{\kappa}$

The sensitivity of eq. 2.4 to the dipole moment couplings was studied for the case of CP-conserving interaction, i.e. κ real and $\tilde{\kappa} = 0$. We consider the quantity

$$\sigma\sqrt{N} = \left[\int d\Omega \frac{1}{f}\left(\frac{\partial f}{\partial \kappa}\right)^2\right]^{-1/2} \tag{3.1}$$

as a function of the τ polarisation, where σ is the expected error one standard deviation on κ, N is the number of $\tau^- \to \nu_\tau \pi^- \pi^0$ decays, and $d\Omega$ is the elemental phase space volume. The choice of the quantity $\sigma\sqrt{N}$ simply reflects the $1/\sqrt{N}$ dependence of the statistical error σ.

The distribution f is given by eq. 2.4 for the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel and eq. 11 of Rizzo [1] for $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-$. Figure 1 shows $\sigma\sqrt{N}$ as a function of P_τ for the particular case $\kappa \approx 0$ for (a) the $\tau^- \to \nu_\tau \pi^- \pi^0$ decay mode, and (b) the $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-$ decay mode ($\ell =$ e or μ, not both combined).

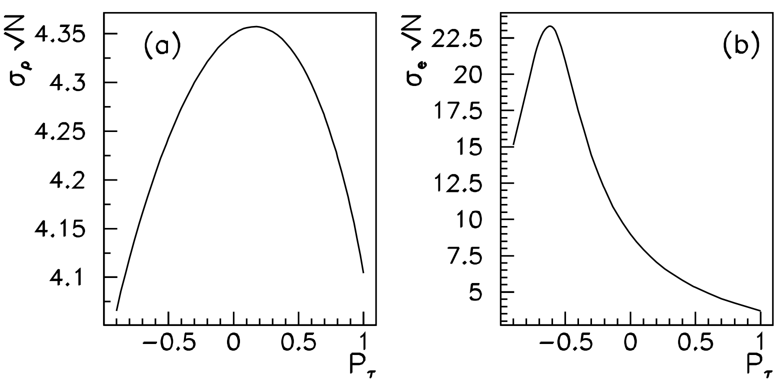

Figure 1: The κ sensitivity quantity, $\sigma\sqrt{N}$, as a function of P_τ for $\kappa \approx 0$, for (a) the $\tau^- \to \nu_\tau \pi^- \pi^0$ decay mode and (b) the $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-$ decay mode.

The $\tau^- \to \nu_\tau \pi^- \pi^0$ mode is intrinsically more sensitive than the leptonic decay modes and is less dependent on the τ polarisation. In addition, the branching fraction for $\tau^- \to \nu_\tau \pi^- \pi^0$ is larger than each leptonic channel.

For example, at the Z peak ($P_\tau \approx -0.15$) with a typical sample of reconstructed decays for each LEP experiment ($\sim$ 45 000 $\tau^- \to \nu_\tau \pi^- \pi^0$ decays and $\sim$ 30 000 $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-$ decays) the predicted statistical errors are:

$$\sigma_\rho \sim 0.020\,, \qquad \text{and} \qquad \sigma_\ell \sim 0.065\,, \tag{3.2}$$

where detector effects are neglected, apart from their influence on the reconstruction efficiency which is reflected in the number of decays assumed. The corresponding statistical error for the combined e and μ channels is $\sim$0.046 which is more than a factor of two less precise than from the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel alone.

A practical disadvantage of the semileptonic decay is the multi-dimensional character of the distribution function. In the analysis of the tau polarisation, this problem has been overcome using a single "optimal variable" [22]. Although the optimal variable for the tau polarisation is not the optimal variable for κ (nor for $\tilde{\kappa}$), we find it still provides distinguishing power. We fit hypothetical distributions of the optimal variable for simulated samples of 45 000 $\tau^- \to \nu_\tau \pi^- \pi^0$ decays each, generated with $P_\tau = -0.15$ to represent τ's produced at the Z peak. Typical errors are $\sigma_\rho \sim 0.038$ which is degraded compared to the full multi-dimensional fit but is still statistically more sensitive than the combined e and μ channels.

The apparent disadvantage of the leptonic channels is, however, mitigated by the need to know $F(q^2)$ for the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel which has a non-negligible systematic error, as discussed below.

In this paper we cannot derive constraints on κ and $\tilde{\kappa}$ from fits to the differential decay distributions due to a lack of the necessary experimental information. We can, however, determine constraints from the (intrinsically less sensitive) measurements of $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$, as described below.

4. Constraints on κ and $\tilde{\kappa}$ from $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$

We derive quantitative constraints on κ and $\tilde{\kappa}$ by considering the likelihood for the theoretical prediction for $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ to agree with the experimentally determined average value [23] of

$$\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0) = (25.31 \pm 0.18)\%, \tag{4.1}$$

as a function of κ and $\tilde{\kappa}$. Γ^0 of eq. 2.15 is determined from $e^+e^- \to \pi^+\pi^-$ data using CVC. A combined analysis of all data, allowing for radiative corrections and $\rho - \omega$ interference, yields the CVC prediction of [15]

$$\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0) = (24.52 \pm 0.33)\%, \tag{4.2}$$

where the error includes statistical and systematic uncertainties and conservatively allows for a possible systematic discrepancy of the DM1 data compared to CMD, CMD-2, and OLYA. The experimental value of $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ is higher than the CVC prediction by 2.2 standard deviations of the combined error.

We fix Γ^0 to the CVC prediction of $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ so that only $f_1^\dagger$ and $f_2^\dagger$ depend on the description of hadronic spectral function. This reduces the sensitivity of the results to the details of the hadronic modelling.

We construct likelihoods as a function of κ and $\tilde{\kappa}$ assuming in each case that the other parameter is zero. The errors are propagated numerically [24] taking into account the error on the experimental measurement of $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ (eq. 4.1), the uncertainty on the CVC prediction (eq. 4.2), a systematic error of 0.5% for radiative corrections not included in S_{EW} [18], and a systematic error of 0.3% for the effect of $\rho - \omega$ interference [25]. Figure 2 shows the likelihood distributions for (a) κ and (b) $\tilde{\kappa}$. The distribution for κ has a single peak due to the dominance of the term linear in κ in eq. 2.15. The distribution for $\tilde{\kappa}$ has two symmetric peaks due to the lack of a term linear in $\tilde{\kappa}$ in eq. 2.15, therefore it is more appropriate to constrain the quantity $|\tilde{\kappa}|$. We determine

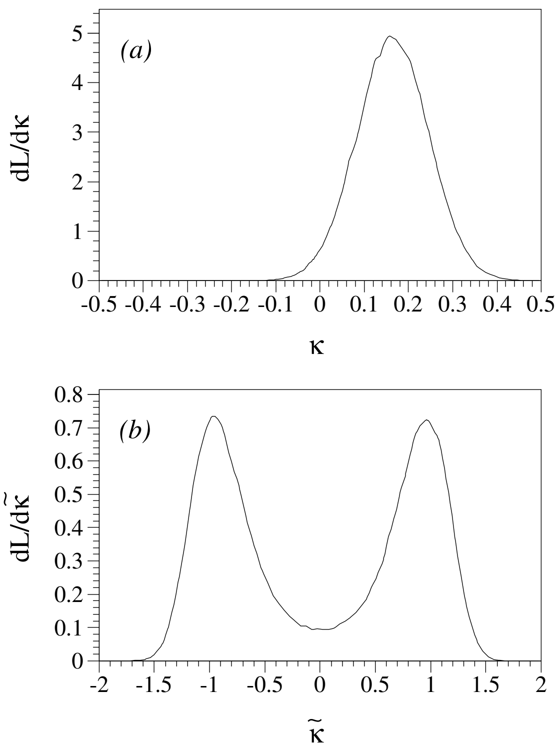

Figure 2: The likelihood distributions for (a) κ and (b) $\tilde{\kappa}$.

$$\kappa = 0.16 \pm 0.08\,, \qquad \text{and} \qquad |\tilde{\kappa}| = 0.88^{+0.25}_{-0.35}\,, \tag{4.3}$$

where the errors correspond to the 68% confidence level. At the 95% confidence level we constrain κ and $\tilde{\kappa}$ to the ranges:

$$0.00 < \kappa < 0.32\,, \qquad \text{and} \qquad 0.13 < |\tilde{\kappa}| < 1.33\,. \tag{4.4}$$

The effect of neglecting the mass difference of the charged and neutral pions was estimated by varying m_π between m_{π^0} and m_{π^-}. This changed $f_1^\dagger$ and $f_2^\dagger$ by $< O(1\%)$ and had negligible a effect on the results for κ and $|\tilde{\kappa}|$.

These results are slightly more than two standard deviations from the SM expectations of zero which, though intriguing, cannot be considered statistically compelling evidence of new physics.

The results may be compared to complementary results previously obtained from purely leptonic tau decays [13], which are $\kappa = 0.001 \pm 0.008$ and $\tilde{\kappa} = 0.00 \pm 0.16$ or $-0.014 < \kappa < 0.016$ and $|\tilde{\kappa}| < 0.26$ at the 95% C.L. [13]. These are more restrictive than those we obtain from $\tau^- \to \nu_\tau \pi^- \pi^0$ decays. This is partly due to the larger uncertainties in the theoretical and experimental values of the $\tau^- \to \nu_\tau \pi^- \pi^0$ branching fractions. In principle these effects could be counteracted by a higher intrinsic sensitivity of the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel due to larger values of a_1 and a_2 relative to the leptonic modes. From our calculations, however, we see in retrospect that the numerical values for a_1 and a_2 are smaller than their leptonic counterparts (0.5 and 0.1 respectively). Therefore, if only the total rate information is used the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel is less sensitive than the leptonic channels, in contrast to the higher statistical sensitivity of the $\tau^- \to \nu_\tau \pi^- \pi^0$ channel when the differential decay distribution is analysed.

5. Summary

We present calculations of the differential and total decay rates for the process $\tau^- \to \nu_\tau \pi^- \pi^0$, allowing for anomalous charged current magnetic and electric dipole moments, κ and $\tilde{\kappa}$ respectively. This constitutes the first such analysis of a hadronic tau decay mode.

The analysis of the differential distributions for the $\tau^- \to \nu_\tau \pi^- \pi^0$ decay mode is found to be statistically more sensitive than the corresponding analysis of purely leptonic modes, $\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-$, irrespective of the tau polarisation. The branching fraction, $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$, is also sensitive to κ and $\tilde{\kappa}$ although less so than for the leptonic branching fractions.

By comparison of the measured value of $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ with the predictions of CVC, we determine $\kappa = 0.16 \pm 0.08$ and $|\tilde{\kappa}| = 0.88^{+0.25}_{-0.35}$. which differ from the SM expectations by approximately two standard deviations.

The values for κ and $\tilde{\kappa}$ obtained from $\mathrm{BR}(\tau^- \to \nu_\tau \bar{\nu}_\ell \ell^-)$ are consistent with zero. This could mean that the measured result for $\mathrm{BR}(\tau^- \to \nu_\tau \pi^- \pi^0)$ and CVC differ only due to a fluctuation, or that there is an experimental or theoretical uncertainty which is not correctly taken into account. For example, it is worth noting that the theoretical predictions for the $\tau^- \to \nu_\tau \pi^-$ channel changed by 1.1% between an initial calculation [18] and a later and more detailed calculation[26].

The new $e^+e^- \to \pi^+\pi^-$ data in the neighbourhood of the ρ meson resonances should reduce the experimental uncertainty in the CVC prediction by a factor of almost two in 1999 [15]. Hopefully these data will clarify whether this is a statistical or systematic effect or the first indication of some new physics which affects hadronic tau decays but not purely leptonic decays.

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