Some recent \( \tau \)-physics results are presented from the BaBar and Belle experiments at the SLAC and KEK B factories, which produce copious numbers of \( \tau \)-lepton pairs. Measurements of the tau mass and lifetime allow to test lepton universality and CPT invariance, while searches for lepton-flavour violation in tau decays are powerful ways to look for physics beyond the Standard Model. In semihadronic, non-strange tau decays, the vector hadronic final state is particularly important in helping determine the hadronic corrections to the anomalous magnetic moment of the muon, while studies of strange final states are the best available ways to measure the CKM matrix element \( V_{us} \) and the mass of the strange quark.

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1. Tau-Pair Production at B Factories

The SLAC and KEK B factories are asymmetric e\(^+\)e\(^-\) colliders which run at centre-of-mass energies at, and close to, the \( \Upsilon(4S) \) resonance. At these energies, around 10.58 GeV, the cross section for tau-pair production, at 0.89 nb, is close to the 1.05 nb cross section for \( B\bar{B} \) production. These machines are therefore also tau factories, and the experiments BaBar and Belle have between them so far recorded over \( 10^9 \) tau-pair events. In comparison, the four LEP experiments each recorded only about \( 10^5 \) tau-pair events, mainly running on the \( Z \) resonance, while CLEO-III at CESR took about \( 7 \times 10^6 \) tau-pair events. However, it should be noted that experimental conditions for tau physics at LEP were particularly clean, resulting in relatively small systematic errors. For channels with large branching fractions, where systematic errors dominate, the LEP results will remain competitive for some time.
2. Testing the Standard Model

Measuring static properties of the tau, such as mass, lifetime and electroweak couplings, allow tests of lepton universality and CPT invariance. Searches for lepton-flavour violation (LFV) in tau decays are particularly topical. In the Standard Model (SM), minimally augmented with massive neutrinos and neutrino oscillations, LFV decays of the tau are allowed, but at an unobservably low level\(^1\). However, various extensions to the SM predict LFV rates accessible to the B factories, with branching fractions of order \(10^{-8}\) and higher\(^2\).

\[2.1. \text{Tests of CPT and lepton universality}\]

Belle has used 3-prong tau decays from the process \(\tau^- \rightarrow \pi^- \pi^- \pi^0 \nu_{\tau}\), in a sample of \(414 \text{ fb}^{-1}\) of data, to measure the tau mass and to put an upper limit on the relative mass difference of the two charge states of the tau\(^3\). They construct the pseudomass\(^4\), a kinematic quantity which, in the absence of initial and final state radiation, displays a sharp edge at the tau mass. By fitting the edge (see Fig. 1), they obtain a mass \(M_{\tau} = 1776.71 \pm 0.13 \pm 0.32 \text{ MeV}/c^2\) and a relative mass difference \(|M_{\tau^+} - M_{\tau^-}|/M_{\tau} < 2.8 \times 10^{-4}\) at the 90\% confidence level (CL). The measurement of the relative mass difference represents a significant improvement over the previous limit on this quantity.

BaBar has made a preliminary measurement of the tau lifetime and the relative

![Fig. 1. The distributions of the pseudomass (from Belle) for the decays \(\tau^{\pm} \rightarrow 3\pi^{\pm} \nu_{\tau}\) shown separately for \(\tau^+\) (solid points) and \(\tau^-\) (open points) decays. The solid curves show fits to obtain the tau mass.](image-url)
lifetime difference of the two charge states, using an 80 fb$^{-1}$ data sample. They measure a lifetime of $\tau = 289.40 \pm 0.91 \pm 0.90$ fs and a relative difference, $(\tau_{\tau^{-}} - \tau_{\tau^{+}})/(\tau_{\tau^{-}} + \tau_{\tau^{+}})$, of $0.12 \pm 0.32\%$ (the systematic error has still to be evaluated). All of the measurements to date are consistent with CPT invariance and with lepton universality.

2.2. Searches for lepton flavor violation in tau decays

Belle has recently published results on searches for the LFV decays of the tau to a lepton plus two pseudoscalar mesons ($\pi^{\pm}$ or $K^{\pm}$), including the cases where the mesons are decay products of a $K_{S}^{0}$, $\rho$, $K^{*}$ or $\phi$. The most promising channel among these may be $\tau^{-} \rightarrow \mu^{-}\rho^{0}$, where the minimal supersymmetric standard model (MSSM) with small tan $\beta$ could give a branching fraction as large as $10^{-8}$.

These decay modes may also be sensitive to new physics models with heavy Dirac neutrinos and to models with dimension-six effective fermionic operators that induce $\tau - \mu$ mixing. With a data sample of 158 fb$^{-1}$, Belle set 90% CL upper limits that vary from $1.6 \times 10^{-7}$ for $\tau^{-} \rightarrow e^{-}\pi^{-}K^{+}$ to $8.0 \times 10^{-7}$ for $\tau^{-} \rightarrow \mu^{-}K^{-}K^{+}$. Using 281 fb$^{-1}$ they obtain limits of $5.6 \times 10^{-8}$ for $e^{-}K_{S}^{0}$ and $4.9 \times 10^{-8}$ for $\mu^{-}K_{S}^{0}$.

Belle has also made a search for the decay $\tau^{-} \rightarrow \mu^{-}\eta$ putting an upper limit at $3.4 \times 10^{-7}$ at 90% CL. The Belle results improve on previous LEP and CDF exclusion limits in the tan $\beta$ versus $m_{\text{SUSY}}$ plane.

BaBar has recently used a data sample of 233 fb$^{-1}$ to search for the decay $\tau^{-} \rightarrow \mu^{-}\gamma$. In MSSM with the seesaw mechanism, the branching fraction for this process is directly related to the value of tan $\beta$ and the mass of lightest chargino. BaBar excludes this process with an upper limit on the branching fraction of $6.8 \times 10^{-8}$ at 90% CL.

3. Semihadronic Tau Decays

The non-strange hadronic tau decays are dominated by vector and axial hadronic states, with the vector part of the so-called spectral function being particularly important as input to the calculation of the muon magnetic moment anomaly, $a_{\mu} = (g_{\mu} - 2)/2$. The largest uncertainty in this calculation comes from the lowest order hadronic correction to the photon propagator, whose value is inferred from measurements of the cross section for the process $e^{+}e^{-} \rightarrow$ hadrons at low energies. Almost three-quarters of this correction is due to the $\pi^{+}\pi^{-}$ final state, dominated by the $\rho(770)^{0}$. The $e^{+}e^{-}$ annihilation data can be related, by isospin invariance (conserved vector current), to the decay $\tau^{-} \rightarrow \pi^{-}\pi^{0}\nu_{\tau}$ for which much higher statistics measurements are available. In principle, therefore, the tau decay data could provide more precise input for $a_{\mu}$; however there remains a discrepancy between the $e^{+}e^{-}$ and $\tau$ data which currently is not understood. A recent review can be found in Ref. 9.

Studies of the strange spectral functions in hadronic tau decays are the route to the world-best measurements of the CKM matrix element $V_{u\tau}$ and the mass of the
strange quark. All measurements to date of the strange tau decays are limited by statistics, and so the B-factory data have a very important role to play. Already, the BaBar and Belle preliminary measurements of the $\tau \to K\pi\nu_\tau$ modes are more precise than the previous world averages.

3.1. $\tau^- \to \pi^-\pi^0\nu_\tau$ and muon $g-2$

Belle has used a sample of 72 fb$^{-1}$ to make a first study of their $\pi^-\pi^0$ mass spectrum from $\tau$ decay\textsuperscript{10}. They fit to the phenomenological model of Gounaris and Sakurai\textsuperscript{11} which includes a set of three interfering $\rho$ Breit-Wigner amplitudes, and they find the need for a $\rho(1700)$ state in addition to the two well-known $\rho(770)$ and $\rho(1450)$ resonances (see Fig. 2). Belle reports a branching fraction $\text{BF}(\tau^- \to \pi^-\pi^0\nu_\tau) = (25.15 \pm 0.04 \pm 0.31)\%$. The result for $a^{\tau\pi}_\rho$ is in agreement with previous tau measurements from ALEPH\textsuperscript{12} and CLEO\textsuperscript{13} and in disagreement with the numbers deduced from the $e^+e^-$ data\textsuperscript{9}.

3.2. The decay $\tau^- \to 3h^-2h^+\nu_\tau$

In a recent BaBar analysis\textsuperscript{14}, a data sample of 232 fb$^{-1}$ has been used to study the process $\tau^- \to 3h^-2h^+\nu_\tau$. The branching fraction is measured as $(8.56 \pm 0.05 \pm 0.42) \times 10^{-4}$, representing a significant improvement on the previous world average. The mass spectrum of the hadronic system, with all tracks taken as

![Fig. 2. Belle measurement of the pion form factor (solid circles), fitted using a Gounaris-Sakurai model with all parameters allowed to float. The open points show the ALEPH results from Ref. 12.](image_url)
pions, is shown in Fig. 3(a), where it is compared to the output of the Tauola Monte Carlo model. Fig. 3(b) shows the inclusive $\pi^+\pi^-$ mass spectrum, indicating a significant contribution from $\rho(770)^0$. The $2\pi^+2\pi^-$ spectrum (Fig. 3(c)) shows a signal from the $f_1(1285)$ meson, from which the branching fraction is measured to be $\text{BF}(\tau^- \rightarrow f_1 h^- \nu_\tau) = (3.9 \pm 0.7 \pm 0.5) \times 10^{-4}$. These data will be used to improve the implementation of these channels in the Tauola Monte Carlo.

![Mass spectra from BaBar for the decay $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$, for (a) the 5$\pi$ system; (b) inclusive $\pi^+\pi^-$ systems, and (c) $2\pi^+2\pi^-$ (with a fit including the $f_1(1270)$ meson.](image)

**Fig. 3.** Mass spectra from BaBar for the decay $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$, for (a) the 5$\pi$ system; (b) inclusive $\pi^+\pi^-$ systems, and (c) $2\pi^+2\pi^-$ (with a fit including the $f_1(1270)$ meson.

### 3.3. Searches for $\tau^- \rightarrow 3\pi^-2\pi^+2\pi^0\nu_\tau$ and $\tau^- \rightarrow 4\pi^-3\pi^+(\pi^0)\nu_\tau$

BaBar has looked for evidence for decays of the $\tau$ to seven or more pions, which would be highly suppressed by phase space. In principle, the rate of such decays would be sensitive to the mass of the $\tau$ neutrino, but recent results on the neutrino mass differences has somewhat reduced the interest in this, since indications are that the neutrino masses are too small to be probed by high-multiplicity $\tau$ decays.
Using 232 fb$^{-1}$ of data, BaBar has placed the following upper limits on branching fractions at 90\% CL: $3.4 \times 10^{-6}$ for $\tau^- \to 3\pi^- 2\pi^0 2\nu_\tau$; $5.4 \times 10^{-7}$ for $\tau^- \to 2\omega(782)\pi^- \nu_\tau$; $4.3 \times 10^{-7}$ for $\tau^- \to 4\pi^- 3\pi^0 2\nu_\tau$; and $2.5 \times 10^{-7}$ for $\tau^- \to 4\pi^- 3\pi^0 \pi^0 \nu_\tau$.

3.4. Strange hadronic tau decays

BaBar has made a preliminary measurement of $\tau^- \to K^- \pi^0 \nu_\tau$ with 124 fb$^{-1}$ of data, obtaining a branching fraction of $(0.438 \pm 0.004 \pm 0.022)\%$. For the complementary mode, $\tau^- \to K_S^0 \pi^- \nu_\tau$, Belle uses 351 fb$^{-1}$ to measure a branching fraction of $(0.391 \pm 0.004 \pm 0.014)\%$. The two measurements are consistent. In preliminary fits to their K$\pi$ mass spectrum, Belle finds some evidence for the presence of the K$^*(1410)$ together with a scalar state (the so-called $\kappa$).

4. Outlook

Each of BaBar and Belle expects to accumulate samples of close to, or greater than, 1000 fb$^{-1}$ by the end of 2008. Thus there is the potential for much more $\tau$ physics in the coming years. Limits on LFV could be reduced down to $\sim 10^{-8}$ for some channels, with even the possibility of the emergence of evidence for new physics. In semihadronic decays, measurements of the strange spectral functions should provide an improved measurement of the CKM matrix element $V_{us}$ and perhaps also of the mass of the strange quark. Measurements of the non-strange channels will include the important vector spectral functions, which should continue to aid understanding of the non-perturbative, hadronic contribution to the anomalous magnetic moment of the muon.

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