FPP: The Tau lepton

Section 1: Generations

The quarks and leptons are often presented in a 4×3 matrix, to bring out the 3 'generations' or 'families'.

Quark species do occur as doublets, uplike and downlike, related by weak isospin. The u is linked with the d - or rather with the CKM-rotated d'. That is to say: under a rotation in the (fictional) weak-isospin space, a u quark becomes some mixture of u and d', just as a spin-up electron becomes a mixture of spin-up and spin-down.

Lepton species also occur as doublets, linked by the same weak isospin transformation. ('Weak isospin' referes to ispspin for the weak interactions. Doesn't imply the ispspin is weak! 'Strong isospin' is to do with protons and neutrons.) Each charged lepton is in a doublet with a neutral lepton. These are not the mass eigenstates so mixing occurs between them, but that's another story.

Quarks also form triplets under colour rotations. Leptons don't. Fact.

It would be nice if this grouping method could be extended to bring quarks and leptons together within a familiy, or even to bring different families toghether. This 'Grand Unification' scheme has not succeeded - and not for want of trying. Such models put quarks and leptons in the same multiplet. This tends to predict quark-lepton conversion at some level, and thus proton decay. Suggested multiplets may accommodate all 16 members of a generation, or more, leaving room for dark matter candidates etc, or less (SU(5) predicted 15plets with no righthanded neutrinos. It was popular - for a while.)

In any such scheme there is actually no evidential link between the quarks and leptons of the generations, as they are usually drawn. If there is such a scheme, it could be that u,d,and μ belong in the same family. The mass hierarchy doesn't have to be the same.

Having 3 families of quarks and 3 families of leptons is more than just neat. Something called the Ward Anomaly arises in the vertex of 3 photon lines, connected by a charged particle loop, unless the total charge of all particle species is zero. This is satisfied within each generation as $3 \times (\frac{2}{3} - \frac{1}{3}) - 1 + 0 = 0$.

The τ was the first member of the 3rd generation to be discovered, in 1974 by Marty Perl at SLAC. It motivated people to look hard for further quarks which were found soon (the b) and eventually (the t). The τ neutrino also took a long time to be discovered, by the DONUT experiment at FNAL which used an 800 GeV proton beam dump to produce ν_τ particles and then see the $\nu_\tau \to \tau$ reactions in an emulsion detector.

Section 2: Tau Production

The τ interacts electromagnetically and weakly. It can be produced in pairs by photons and/or Z bosons or with its neutrino by W bosons.

The relevant coupling strengths are as large for the τ as they are for the μ or e. The interaction must have at least enough energy to provide for the τ mass of 1.777 GeV, and preferably a lot more, to avoid the low phase space factors that come from producing slow particles. If the (virtual) photons have masses well about 3.5 GeV, they will make $\tau^+\tau^-$ pairs almost as often as $\mu^+\mu^-$ pairs. Thus PEP-II is also a τ factory. The cross section for $e^+e^- \to \tau^+\tau^-$ is 0.94 nb, almost as much as the 1.05 nb cross section for the $\Upsilon(4S)$. LEP also produced lots of τ pairs. A real W (or Z) has clearly got plenty of phase space, so there are lots of taus produced at the Tevatron and the LHC. For virtual Ws the mass of the W (and thus the phase space) depends on the process concerned.

Section 3: Tau properties

In the standard model, all tau decays proceed by the conversion of a charged tau to a tau (anti) neutrino and the emission of a virtual W. The universality of the weak current predicts that the W produce an electron + neutrino, or a muon+neutrino, or hadrons, in the ratio 1:1:3. Phase space and QCD corrections modify these slightly. The measured branching ratios are 17.8% for electrons and 17.3% for muons, with the rest being hadronic decays.

The τ was discovered through e^+e^- collisions around 4 GeV, at threshold for τ pair production. They can be seen as a step in the R ratio, but that is confused by the charm threshold which is in pretty much the same place. What made the signal unique was the decays in which one tau decayed to an electron and the other decayed to a muon. This gave $e^+e^- \to \mu^+e^-$ decays (and μ^-e^+) which apparently violated lepton number and needed a radical explanation.

These leptonic decays involve two final state neutrinos: they are 3-body decays and the energy of the charged lepton (in the tau rest frame) has a continuous spectrum, like that of the electron in beta decay.

The main hadronic decays are to $\pi\nu$ (12%), $\rho\nu$ (25%) and $a_1\nu$ (18%). Adding up the possibilities, the τ decays to 1 charged track about 85% of the time, and to 3 charged tracks about 15% of the time.

So a typical tau pair event has two produced particles which are not back-to-back (distinguishing them from e^+e^- and $\mu^+\mu^-$ pairs) and have energy less than E_{beam} because of the neutrinos. These can be hard to pull out of the leptonic backgrounds, and the 1-3 topology (1 charged track against 3 charged tracks) may be cleaner, though the numbers are smaller. The 3-3 sample tends to be contaminated by $q\overline{q}$ pairs, and there are very few of them anyway.

The decays to $e\nu\nu$ and $\mu\nu\nu$ are characteristic modes used to 'tag' tau decays, as are (to a lesser extent) the $\pi\nu$ and $\rho\nu$ modes. Having tagged one tau, whatever remains in the event must be the other tau from the $\tau^+\tau^-$ pair.

Section 3.1: The Mass

The mass of the τ is not predicted in the Standard Model. But it is important to measure it accurately as it occurs in lots of prediction formulae, e.g. for the lifetime. It is not easy to measure by mass combination as the missing neutrino is unseen - and there are two of them, one from each τ, so you can't deduce it from energy-momentum conservation. The best measurements come from observations (eg by BES at BEPC) at the tau pair threshold - just. The cross section is given (to first order) by

$$\sigma_{\tau\tau} = \frac{4\pi\alpha^2}{3s}\beta\frac{3-\beta^2}{2}$$

The B factories are now competitive, using the 3π channel. The current best value is 1776.9 ± 0.3 MeV.

Section 3.2: The lifetime

The finite lifetime of the τ can be seen from the tracks it leaves in emulsion detectors such as DONUT and CHORUS. This is not, however, the way to make a precision measurement as the statistics are low and the time-dilation γ factor can only be guessed/estimated. It has been measured precisely measured at LEP, and can also be measured precisely at BaBar thanks to high statistics and good vertex resolution even though the flight distances are shorter. The combined world average is $(290.6 \pm 1.0) \times 10^{-15}$ sec. The measurement is now limited by systematic uncertainties in the position of the Silicon detectors.

Section 3.3: Lepton Universality

Within the standard model, the $W^\pm$ coupling is the same to all charged leptons. This can be tested in tau decays, first by the near-equality of the $\tau \to \mu\nu\overline{\nu}$ and $\tau \to e\nu\overline{\nu}$ branching ratios (there is a phase space correction factor of 0.97), and second by the relation $\tau_\tau = \frac{192\pi^3}{G_F^2 m_\tau^5}(1+\Delta)Br(\tau \to e\nu\overline{\nu}) = (1632.1 \pm 1.4) \times 10^{-15} Br(\tau \to e\nu\overline{\nu})$. Δ includes small and well known corrections due to the finite electron mass, the W propagator, and QED radiative corrections with extra photons.

Section 3.4: Hadronic decays

Decay of the τ to the $\pi^\pm\pi^0$ is dominated by the $\rho(770)$ but there are also higher resonances and signs of further structure.

Decays $\tau^\pm \to \pi^+\pi^-\pi^\pm\nu$ have revealed the structure of the a_1. The a_1 is a broad meson, with a mass of 1230 MeV and a width somewhere between 250 and 600 MeV. It is the $L = 1, J = 1, S = 1$ triplet of u and d, which decays to a $\rho\pi$ state.

There are many other meson physics studies waiting to be done, e.g. of the b_1 and the f_0. These have specified spin structure which dictates angular correlations in the decays: by studying the angular correlations one can analyse the spin structure of the mesons that produced them.

Section 3.5: Strange decays

τ decays to a K in place of a π are restricted by Cabibbo suppression and by phase space. Thus the $\tau \to K\nu$ branching ratio is only 0.7%. This can be expressed in terms of the strange quark mass and this potentially gives a very good way of measuring it.

Section 3.6: High multiplicity tau decays

The decay $\tau \to 5\pi$ does occur at the 1% level and has been measured. This is an especially good channel to measure the mass of the Tau neutrino. There is little energy given to the neutrino and the low momenta of the 5 tracks mean they are well measured.

Any finite tau neutrino mass limits the mass of the 5π system - it must be less that $m_\tau - m_{\nu_\tau}$ and the energy of the 5π system. Often an experiment plots these both on the same plot to obtain a combined limit: total $M_{5\pi}$ against $E_{5\pi}/E_{beam}$. The best limit is currently 18.2 MeV.

Section 3.7: Polarisation

When a τ pair is produced by a photon (or Z^0) of spin 1, the two τ spins must be aligned. This leads to correlations between the spins of the two τ leptons, which also depend on the polar angle of the τ pair in the CMS. For taus emitted along the beam axis, one must be left handed (LH) and one must be right handed (RH) - LH and RH are also described as negative and positive helicity respectively. At 90 degrees there is no such constraint as the polarisation is transverse.

If the Z^0 is important/dominant (which is true at LEP but not at BaBar) then the parity violating nature of the weak force gives a difference between the LH/RH and RH/LH possibilities, though this s not as simple as the maximal parity violation of the charged weak current.

The polarisation of a τ can be measured (depending on its decay mode.) Consider the decay $\tau^- \to \pi^- \nu$. The neutrino has to carry all the spin of the tau (as the π is spinless and there is no orbital angular momentum). As this is a charged weak decay, the neutrino prefers to be left handed and so tends to emerge (in the τ CMS) in the direction opposed to the τ spin. Conservation of momentum means that the π emerges along the spin direction. So if the τ^- in the pair is produced with positive helicity, its decay π^- tends to be produced along the direction of the boosted τ frame, and thus have high energy. The τ^+ will have negative helicity, but the logic in the decay to a $\overline{\nu}$ works in the opposite sense, so the decay π^+ also has a high energy.

So in decays in which both tau leptons decay to a single pion, the energy of these pions is correlated: high energy π^+ tend to be accompanied by high energy π^-, and likewise low energy with low energy. For other decay modes the same arguments apply though the algebra is more complicated.

These correlations can be used to tell us about the helicity states of the tau pair - they also mean you have to be careful in doing efficiency calculations.

Section 3.8: Search for Rare decays

Beyond the Standard Model there are decays such as $\tau \to \mu\gamma$ which violate lepton number. These are predicted by various theories. They are in principle easy to spot, as the decay products (in this case the μ and the γ) have a combined mass of m_τ. A number of such channels have been examined ($\tau \to eee$, $\tau \to e\omega$) and so far nothing has been seen, though limits have been set.

This is a lot of work going on in this area in the hope that something beyond the standard model will show up. Neutrino oscillations mean that Lepton Flavour Violation does exist - at a very low level.

In most BSM theories there are extra Higgs particles (or suchlike) which couple more strongly to more massive particles, hence the τ is a more promising place to look than the e or μ.