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LEPTON FAMILY VIOLATION (LFV) UPPER LIMITS FOR LEP2 EXPERIMENTS

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Abstract. LFV is predicted by many models beyond the Standard Model (SM). Though the SM has been successful in accounting for essentially all the data from the laboratory experiments to date, physicists are looking for phenomena beyond the SM. One of these is lepton family violation in electroweak intercations. LEP experiments have established an upper limit for neutrinoless μ and τ decays and two fermion production at Z^o energy. Data obtained at LEP2 are analysed for establishing upper limits at higher energies.

The forthcoming results are exciting because there are models whih predict LFV at a level attained by LEP and LHC experiment sensitivities. A review of the results both theoretical and experimental is presented along with the cosmological implications.

Keywords: leptons, flavour violation, Minimal Supersymmetric Standard Model

INTRODUCTION

In order to understand any theory of electroweak symmetry breaking dynamics, it is critical to explore and interpret the attendant new TeV–scale physics beyond the Standard Model.

Supersymmetrical models extend Standard Model by postulating fermion –boson symmetry according to which new fermion (boson) particles are corresponding to each known bosons (fermions). The symmetry is broken by the fact that the masses of particles have the same couplings, the masses of the SUSY particles are expected to be of the same order of magnitude as M_W, M_Z , M_H.

It is generally assumed that SUSY particles are produced in pairs with the conservation of a special number R= $(-1)^{3B+L+2S}$ which is +1 for all known particles and -1 for all the superpartners. If R should be conserved (as in MSSM) then there is a lightest superparticle(LPS) which cannot disintegrate into ordinary particles and is stable. For R to be conserved superparticles can be produced only in pairs and their direct search needs energies higher than LEP2 , attained only at LHC or NLC.

The cross sections for producing SUSY particles (sleptons, squarks, charginos, neutralinos) at energies above threshold are typical of weak cross sections
(0. 01 – 0. 1 pb). If such particles are produced at colliders, they should be easy to find.

On the other hand in models whithout R-parity, supersymmetric particles could be observed at lower energy compared to R-parity conserving case and , in the same time, sizable effects in flavour physics.

Several analyses of lepton flavour changing effects such as lepton decays, $l^{\pm} \rightarrow l^{\pm} + l^-_n + l^+_p$ conversion processes $\mu \rightarrow e$, have led to bounds on different models.
We present in this paper the experimental upper limits on lepton flavour violation (LFV) reactions up to date and the model predictions as well as the cosmological implications of these models.

We investigate LFV at LEP2 in L3 experiment in reactions $e^+e^- \rightarrow e^+ e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ by looking for events $e^+ e^- \rightarrow e\,\mu$, $e\,\tau$, $\mu\tau$. Previous search has been done at Z pole at LEP1 by L3 , Aleph , Delphi and Opal collaboarations and no signal has been found at the limit of the sensibility of the experiments. With increasing energy the cross section of SUSY particle production is increasing and there is a hope to find LFV events according to some models at the existing sensibilities.

Using Monte Carlo Standard Model generated events we evaluate the selection efficiency and the sensibility limit. Preliminary results in $e^+e^- \rightarrow e\mu$ channel showed no LFV events at LEP2 energies.

EXPERIMENTAL LIMITS ON LFV IN LEPTON DECAYS

Table 1 shows the experimental results up-to-date on lepton flavour violation in μ and τ decays obtained by different collaborations.

Let us examine some characteristics of these experiments. The first one is a stopped muons experiment. The signature of $\mu^+ \to e^+\gamma$ events is a γ and a positron at 180^o of 52.8 MeV energy. 1.2 10^{11} stops have been detected out of which 3971 events have been completely reconstructed. The limit is given by

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\tilde{\nu})} < \frac{5.1}{N_\mu} = 1.2.10^{-11} \quad \text{for 90\% CL}$$

The background is given by $\mu^+ \to e^+\nu\tilde{\nu}$ and $\mu^+ \to e^+\gamma\nu\tilde{\nu}$ channels.

The same experiment gives for $\mu^- \to e^-e^+e^-$ a limit of 1. $10^{-12.}$

Different theoretical evaluations showed that these limits can be attained at the future Muon Storage Ring at CERN [1] where such experiments are sensitive to rates as low as 10^{-16}.

The neutrinoless τ decays have been investigated in the reactions $e^+e^- \to \tau^+\tau^-$ by Belle, Babar and CLEO collaborations at 10.6 GeV. The signature for $\tau \to 3l$ was a tau pair giving three charged tracks, in one hemisphere and one charged track in the opposite hemisphere. The total charge should be zero and $n_\gamma < 2$ to account for gammas radiated in initial or final state.

For the $\tau \to \mu\gamma$ channel, one single muon identified per event and one single photon at an angle bigger than 20^o with the energy of at least 300 MeV and
$0.4 < \cos\theta_{\mu\gamma} < 0.8$.

The background is given by 2ν events or $\tau \to \mu\gamma\nu\nu$
$\tau \to 2\gamma\mu\nu\nu$.

The confidence limit of 90% is given by the relation [2]:

$$\frac{e^{-(s_0+b)}\sum_{n=0}^{n_0}(s_0+b)^n / n!}{e^{-b}\sum_{n=0}^{n_0} b^n / n!} = 0.1$$

where n_o is the number of observed events
b is the expected background
s_o is the upper limit of the expected number of events.
This gives an upper limit for the branching fraction

$$B(\tau \to \mu\gamma) < \frac{s_0}{2\varepsilon N_{\tau\tau}}$$

where ε is the selection efficiency and other reconstruction in efficiencies added quadratically, and $N_{\tau\tau}$ the number of pairs.

It is seen that the upper limit depends essentially on the number of τ pairs detected in the experiment and the selection and reconstruction efficiencies.

EXPECTED LIMITS ON LFV IN LEP AND LEP2 EXPERIMENTS

LEP experiments are looking for LFV in Z^o decay. Table 2 gives the upper limits found by OPAL, L3 and DELPHI collaborations.

As the energy is increasing above the Z^o peak, the cross sections for Z^o production and decay drops like *1/*s and the expected background is increasing due to other open channels ($e^+e^-\to 4l$, $e^+e^-\to WW$, $e^+e^-\to q\tilde{q}$)

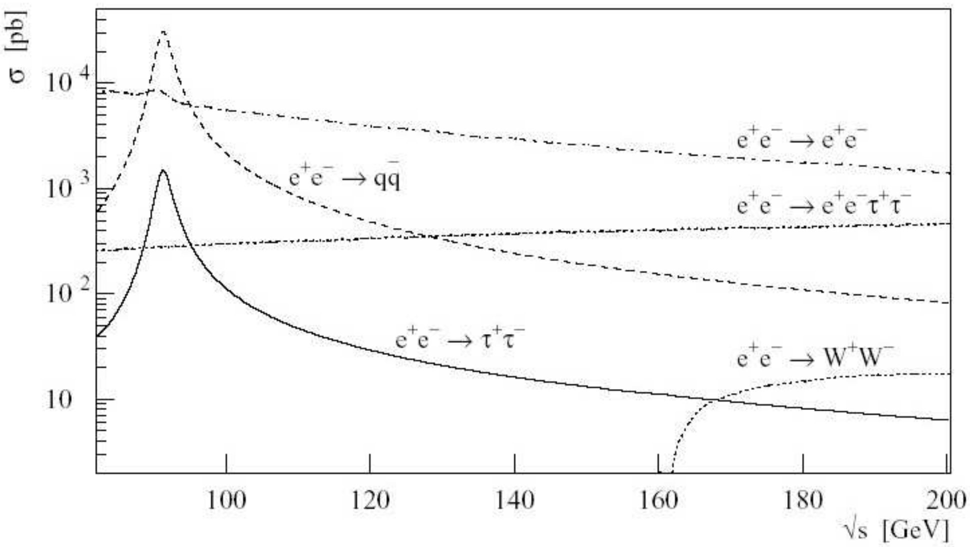

Fig. 1 - Standard Model cross sections at LEP and LEP2 energies

Fig. 1 shows the cross section behaviour according to the SM covered by LEP and LEP2. The Bhabha cross-section decreases less rapidly due to contributions from the *t* channel diagrams. An important background is $e^+e^-\to e^+e^-\tau^+\tau^-$. It is clear from this figure that with increasing energy it becomes more difficult to collect a pure sample of tau events.

The OPAL collaboration has extended the search for LFV in the LEP2 region (189-209 GeV) [3]. Table 3 shows some upper limits for cross sections violating lepton flavour.

One possible candidate eμ with γ initial state radiation is seen, while MC simulations in SM processes gives 0.019 events.

The small number of pairs ($\mu\mu$ *and* $\tau\tau$) is prohibitive for the examination of the decay channels $\mu\to e\gamma$; $\tau\to\mu\gamma$ (more than 3 orders of magnitude higher upper limits) in LEP experiments.

In L3-LEP2 experiment the channels $e\tilde{e}\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ have been separated in order to look for LFV. Cross sections for different channels are computed using the formula:

$$\sigma_m = \frac{N_{data}/\varepsilon^{trig} - N_{bg}}{\varepsilon L}; \quad \Delta\sigma = \frac{\sqrt{N_{data}}/\varepsilon^{trig}}{\varepsilon L}$$

N_{data} is the number of $e^+e^-\to l^+l^-$ selected events

N_{bg} is the expected number of background events

ε - the selection efficiency, L the integrated luminosity and ε^{trig} is the trigger efficiency.

Table 1

Lepton flavour violation decays (experimental limits)

Channel	Γ_i/Γ	Reaction	CM energy	Luminosity [fb^{-1}]	References
$\mu^- \to e^- \gamma$	<1.2 10^{-11}	Stopped muons		1.2 10^{11} stops	Brooks, PRL 83,1521,1999 MEGA/LAMPF
$\mu^- \to e^- e^+ e^-$	<1. 10^{-12}	"			Bellgardt, NP B299,1,1998 SINDRUM coll
$\tau^- \to e^- \gamma$	<2.7 10^{-6}	$e^+e^- \to \tau^+\tau^-$	10.6GeV	87,1 fb^{-1} 79.3 10^6 τ pairs	Edwards, PRD 55R3919,1997 CLEO coll
$\tau^- \to \mu^- \gamma$	<1.1 10^{-6}	$e^+e^- \to \tau^+\tau^-$	10.6GeV	12.6 10^6 τ pairs	Bliss,PRD57, 5903,1998 CLEO coll
$\tau^- \to e^- e^+ e^-$	<2.9 10^{-6}			12.6 10^6 τ pairs	Ahmed,PRD61, 071101R 2000 CLEO coll
$\tau^- \to e^- \mu^+ \mu^-$	<1.8 10^{-6}	$e^+e^- \to \tau^+\tau^-$	10.6GeV	12.6 10^6 τ pairs	Bliss ,CLEOcoll
$\tau^- \to \mu^+ e^- e^-$	<1.5 10-6	$e^+e^- \to \tau^+\tau^-$	10.6GeV	12.6 10^6 τ pairs	Bliss ,CLEOcoll
$\tau^- \to \mu^- \mu^+ \mu^-$	<1.9 10^{-6}				Bliss ,CLEO coll
$\tau^- \to e^- \mu^+ \mu^-$	<1.5 10^{-6}				Bliss , CLEO coll
$\tau^- \to e^- e^+ e^-$	<(1.9÷3.5)10^{-7}	$e^+e^- \to \tau^+\tau^-$	10.6GeV	79.3 10^6 τ pairs 87.1 fb^{-1}	Yusa, hep-ex/0403039 Belle coll
$\tau^- \to e^- e^+ e^-$	<(1.1÷3.3)10^{-7}	$e^+e^- \to \tau^+\tau^-$	10.6GeV	91.5 fb^{-1}	Aubert, PRL92, 121801,2004 BaBar coll

Table 2

LFV limits in Z^o decay at LEP

Channel	Γ_i/Γ	Reaction	Energy (GeV)	CL	References
$Z\to e^{\pm}\mu^{\mp}$	$<1.7\ 10^{-6}$	$e^+e^- \to \mu^+\mu^-\ \tau^+\tau^-$	88-94	95%	Akers, ZPHY, C67, 55,1995 Opal coll
	$<0.6\ 10^{-5}$				Adriani, PLB316,427, 1993 L3 coll
	$<2.5\ 10^{-6}$				Abreu, ZPHY C73, 43,1997 Delphi coll
	$<2.6\ 10^{-5}$				Decamp, PRPL 216, 253,1992 Aleph coll
$Z\to e^{\pm}\mu^{\mp}$	$<9.8\ 10^{-6}$	$e^+e^- \to \mu^+\mu^-\ \tau^+\tau^-$	88-94	95%	Opal coll
	$<1.3\ 10^{-5}$				L3 coll
	$<2.2\ 10^{-5}$				Delphi coll
	$<1.2\ 10^{-4}$				Aleph coll
$Z\to\mu^{+}\tau^{\mp}$	$<1.7\ 10^{-5}$	$e^+e^- \to \mu^+\mu^-\ \tau^+\tau^-$	88-94	95%	Opal coll
	$<1.9\ 10^{-5}$				L3 coll
	$<1.2\ 10^{-5}$				Delphi coll
	$<1\ 10^{-4}$				Aleph coll

Table 3

LEP2 upper limits for LFV

Channel	σ (fb)	Energy (GeV)	CL %	References
$e^+e^-\to e\mu$	<58	189	95	OPAL coll CERN EP-2001 061,2001
	<62	192-196	95	
	<22	200-209	95	
$e^+e^-\to e\tau$	<95	189	95	
	<144	192-196	95	
	<78	200-209	95	
$e^+e^-\to \mu\tau$	<115	189	95	
	<116	192-196	95	
	<64	200-209	95	

The trigger efficiency is the result of five triggers: the energy trigger, the (TEC) inner and outer time expansion chamber trigger, muon trigger and scintillator multiplicity trigger.

$$\varepsilon^{trig} = 1 - \prod(1-\varepsilon_i^{trig})$$

where ε_i^{trig} = *N(events triggered by all triggers)/N(events triggered by 4 of 5 triggers)*

The trigger efficiency for all samples is very close to 100%[4].

N_{bg} is the number of background events, including non-l^+l^- processes, ISR contamination and ISR-FSR contamination.

The selection efficiency is computed from Monte Carlo samples:

$$\varepsilon = \frac{N_{sel}^{e^+e^-}}{N_{gen}^{e^+e^-}} \qquad \Delta\varepsilon = \sqrt{\varepsilon(1-\varepsilon)/N_{gen}^{e^+e^-}}$$

MONTE CARLO GENERATION EVENTS AT LEP LEVEL

LEP1 is the first phase running at the *Z* peak and does not require supersymmetric models. The Standard Model has been tested at LEP1 and all ist parameters measured. Events for channels $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ are generated at the Born level with radiative corrections.

Improved Born level has been used in Monte Carlo generation which implies *H* and t^* exchange, $\alpha(s)$ corrections and effective couplings. All have been tested at LEP energies.

Radioactive corrections have been applied. They reduce the CMS energy in the cross sections:

$$\sigma = \int_{4m_{ff}^2}^{s} R(s,s')\sigma_{Born}(s')ds'$$

where $\sqrt{s'}$ is the energy in CMS after initial radiation.

In this way two Monte carlo samples have been created:

- the inclusive sample ($\sqrt{s'}$ > 75 GeV)
- the non radiative sample ($\sqrt{s'}$ >0.85 $\sqrt{s}$)

The inclusive sample has been used for event selection and systematic effects, having the largest statistics. The non radiative sample (2% at LEP2 energies) is more sensitive to changes resulting from new physics processes compared to the cross sections at the *Z* resonance.

In the inclusive sample soft and hard photons are included, and additional pairs of fermions: $e^+e^- \to e^+e^- f\bar{f}$. This contribution is small and negligible.

Standard Model Monte Carlo events have been generated using KORALZ, BHAGENE3, TEEGG, BHWIDE. The programs DIAG36 and PHOJET have been used for the generation of fermion channels. Samples of ten times data samples have been processed through full simulation of the L3 detector and analysed using the same reconstruction and selection programs as applied to the data.

The event preselection efficiencies are given in table 4.

Table 4

The efficiencies of the preselection as a function of the energy

Energy $\sqrt{s}$ (GeV)	Geometrical acceptance	Preselection efficiency	Detector performance
130	92%	90%	88%
140	92%	90%	87.5%
160	91%	89%	86%
170	90.5%	88.5%	84.5%
180	90.5%	88%	84.5%
190	90%	87%	-

We have seen from fig.1 that the highest cross section at LEP2 energies is for the Bhabha reaction $e^+e^- \to e^+e^-$, which drops much slowly at high energies due to the contribution of the *t* channel diagrams. The cross section of the $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ is decreasing like $1/s$.

Therefore the most important source of background at LEP2 is the Bhabha reaction.

The Born matrix elements are given in fig.2.

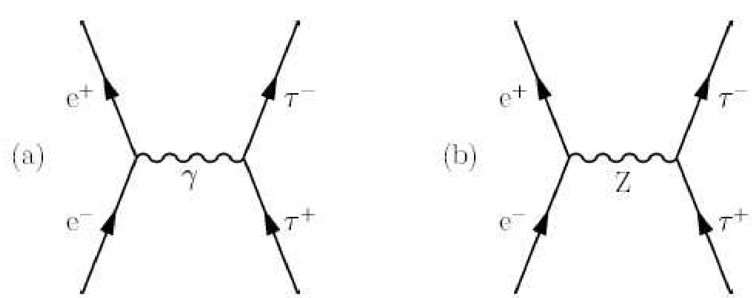

Fig.2 - Born diagrams for τ pair production

Since Higgs-electron coupling is proportional to the electron mass, we can neglect Higgs exchange diagrams for this reaction.

The propagators $\chi^j(s)$ are:

$$\chi^\gamma(s) = \chi^\gamma(t) = 1$$

$$\chi^Z(s) = \frac{s}{s - M_Z^2 + iM_Z\Gamma_\gamma}$$

$$\chi^Z(t) = \frac{t}{t - M_Z^2}$$

The Monte Carlo program takes into account radiative corrections to the Bhabha cross section to order α^3; virtual electromagnetic corrections, soft photon bremsstrahlung in the initial and final state, weak corrections, hard photon corrections have been computed [5].

SUPERSYMMETRIC MODELS FOR LFV IN LEPTON AND Z^0 DECAYS

Neutrino oscillations involve violations of the individual lepton numbers $L_{e,\mu,\tau}$ raising the prospect that observable processes that violate charged lepton number conservation might exist. Ellis[5] proposed a model based on supersymmetric Standard Model to establish limits on LFV in lepton decays like $\mu\to e\gamma$, $\tau\to\gamma\mu$, $\mu\to 3e$, $\tau\to 3\mu/e$.

Fig.3 gives two generic Feynman diagrams for the $\mu\to e\gamma$ decay. $\tilde{l}$ represents a charged s-lepton (a) or s-neutrino (b) and $\tilde{\chi}^{(n)}$ and $\tilde{\chi}^{(c)}$ represent neutralinos (a) and charginos (b).

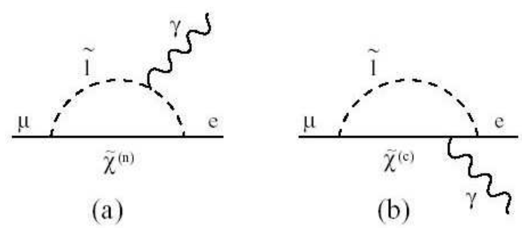

Fig. 3 - Generic Feynman diagrams for $\mu\to e\gamma$ decays

m_0 and $m_{1/2}$ are the masses of s-neutrinos and s-leptons and are the free parameters of the model. Varying these parameters, Ellis found that the most promising channel is $\tau\to\gamma\mu$ with a branching ratio of 10^{-7} close to the experimental sensitivity limit.

Cosmological arguments limit the range for m_0 to values up to 200 GeV. For this astrophysical region, both $\mu\to e\gamma$ and $\tau\to\gamma\mu$ have measurable rates, 10^{-13} and, respectively 10^{-8}.

The same model gives predictions for $\mu\to 3e$ and $\tau\to 3\mu/3e$ channels, which involve more complex exchange diagrams. Compared to $e\gamma$ or $\mu\gamma$ channels, $\tau\to 3e/\mu$ are 6.10^{-3} less probable; the diagrams are those from fig. 3 with a virtual photon decaying into e^+e^- or a Z^* decaying into $\mu^+\mu^-$.

COSMOLOGICAL RESTRICTIONS IN MSSM PARAMETER SPACE

Assuming that the lightest neutralino $\tilde{\chi}$ is the lightest supersymmetric particle (LPS), Ellis[7] evaluated the parameter region (m_0 , $m_{1/2}$) consistent with the cosmological upper limit on the relic LPS density.

The rate equation for a stable particle with density n is:

$$\frac{dn}{dt} = -3\frac{\dot{R}}{R}n - <\sigma v_{rel}>(n^2 - n_{eq}^2)$$

where n_{eq} is the equilibrium number density

and $<\sigma v_{rel}>$ is the normally averaged product of the annihilation cross section σ and the realtive velocity v_{rel} .

The final relic density is determined by integrating the equation down to $x=T/m=0$ and is given by:

$$\rho_\chi = mq(0)h(0)T_0^3$$

where $q(0) = n(0)/T_0^3 h(0)$.

Finding for the coannihilation process the cross section in the form:

$$<\sigma_{12} v_{rel}> = a_{12} + b_{12} x + O(x^2)$$

where a_{12}, b_{12} are kinematic factors depending on masses, the relic density can be simply written as:

$$\Omega h^2 \cong \frac{10^9 GeV^{-1}}{g_f^{1/2} M_{pl}(a_{eff} + b_{eff} x_{f/2})x_f}$$

where $T_f = m_{\tilde{\chi}}/20$ is the freeze-out temperature.

If $\Omega_{\tilde{\chi}} h^2$ is restricted to $0.1 < \Omega_{\tilde{\chi}} h^2 < 0.3$, cosmological bounds in (m_0, $m_{1/2}$) can be found for diferent values of the parameters μ and $tan\beta$.

The limits on decay rates mentioned in the previous chapter are obtained.

At the same time, the most probable values for m0 and $m1_{/2}$ are respectively 200 GeV and 100 GeV in agreement with the fact that $\tilde{\chi}^0$ and $\tilde{\chi}^{(\pm)}$ have not been found by LEP2 experiments.

CONCLUSIONS

Our group is studying LFV at LEP2/ CERN using the events obtained by the L3 collaboration between 189 and 209 GeV.

The reactions selected are $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$. The integrated luminosities are about 200 pb^{-1} for 5 energy regions. An about ten time MC sample of events generated with SM programs has been used to establish the cuts in selecting events reconstructed by the L3 detector.

No LFV candidates have been formed in the $e^+e^- \to e\mu$ sample. New selection criteria using MC generated events should be applied for $e^+e^- \to \tau\mu/\tau e$ channel.

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