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Lepton flavour violation in τ and B meson decays.

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Lepton flavour violations in the charged sector can be foreseen as a consequence of the observation of neutrino oscillations, they are expected with enhanced probabilities in many extentions of the Standard Model. An overview of recent experimental searches for lepton flavour violation in τ and B meson decays is presented. In particular, the results from the first search for $\tau^- \to \mu^+\mu^-\mu^-$ performed at an hadron collider by the LHCb experiment is described. Lepton number violations related to the possible existence of a massive Majorana neutrino are also discussed and upper limits on the branching fraction of B meson decays into hadrons and a like-sign leptons pair are presented.

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1. Lepton flavour violation

The experimental observation of neutrino oscillations was the first evidence of lepton flavour violation (LFV). The consequent introduction of mass terms for the neutrinos in the Standard Model already implies lepton family number violation also in the charged sector, but with branching fractions below any present and future experimental reach. Numerous beyond the Standard Model theories predict enhanced LFV rates [1]. The branching fractions of LFV in μ and τ decays depend on the specific model and its flavour structure, therefore model independent searches in many different flavour decays modes are necessary to cover the various possibilities. In this review τ decays are considered while μ decays are discussed in other contributions to this Conference [2].

1.1 Lepton flavour violation in τ decays at B factories

Searches for LFV in τ decays have been performed in e^+e^-collisions by different experiments using data collected at the $\Upsilon(4S)$ and above. The production cross section is $\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb and a total of about 1.5×10^9 τ pairs have been collected by BaBar and Belle experiments so far. Searches have been performed in a variety of channels, some of the latest results will be presented here, a comprehensive collection of all available measurements can be found in ref. [3].

In experiments at e^+e^-colliders the production in $\tau^+\tau^-$ pair is exploited to reconstruct and identify the rare decay. The event is divided into two hemispheres, using a plane perpendicular to the thrust axis. In one hemisphere (signal τ) the LFV decay topology is reconstructed while in the other (tag τ) decays into one charged track and any number of additional photons and neutrinos are usually considered. The signal identification is also based on the expected equality, in the center-of-mass system, of the signal τ energy to the beam energy. Since each decay mode has different sources of background, the event selection criteria are optimized separately mode by mode. The main background sources are $q\bar{q}$ from continuum production, two-photons production, generic $\tau^+\tau^-$ events, $\mu^+\mu^-$ and Bhabha events.

No evidence has been found so far for the existence of the radiative decays $\tau \to \mu\gamma$, $\tau \to e\gamma$ whose branching fractions are expected to be enhanced for example in see-saw SUSY models at large $\tan\beta$ [4]. Currently the lowest upper limits are set by BaBar [5]

$$\mathscr{B}(\tau \to e\gamma) < 3.3 \times 10^{-8} \text{ at 90\% CL,} \tag{1.1}$$

$$\mathscr{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ at 90\% CL.} \tag{1.2}$$

If the τ decay is mediated by a new heavy particle, the decay mode into three leptons can be favored with respect to radiative one. Searches into final states with electrons and muons have been performed and no evidence of signal above the expected background contributions has been found. The lowest upper limits on the branching fractions come from the Belle analysis of 782 fb^{-1}of data [6], they are reported in Table 1.1.

The decay of a τ into a muon (or electron) and a vector meson (ρ, ω, ϕ and K^{0*}) are also considered. The lowest upper limits on the branching fractions are those obtained by Belle with 851 fb^{-1}of data [7], they are in the range $\mathscr{B}(\tau \to \ell V^0) < (1.2-8.4) \times 10^{-8}$, at 90% CL, depending on the decay mode.

Searches for LFV decays of a τ into an electron or muons and a neutral pseudoscalar meson ($\pi^0, \eta, \eta', K^0_S$) have been performed by BaBar and Belle. The preliminary results of the Belle

Decay mode	$\mathcal{B}$ $(\times 10^{-8})$
$\tau^- \to e^- e^+ e^-$	< 2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	< 2.1
$\tau^- \to e^- \mu^+ \mu^-$	< 2.7
$\tau^- \to \mu^- e^+ e^-$	< 1.8
$\tau^- \to e^+ \mu^- \mu^-$	< 1.7
$\tau^- \to \mu^+ e^- e^-$	< 1.5

Table 1: Upper limits at 90% CL on branching fractions for LFV τ decays into three leptons, from [6].

analysis with 901 fb^{-1} of data [8] provides upper limits in the range $\mathcal{B}(\tau \to \ell P^0) < (2.2-4.4)\times 10^{-8}$ at 90 % CL, depending on the specific decay mode.

In the case of τ decays into a lepton and a pair of charged hadrons ($\pi^{\pm}$, $K^{\pm}$), decay modes violating the total lepton number were also considered, like $\tau^- \to \mu^+ \pi^- \pi^-$. No evidence of signal was found above background in any decay mode, the preliminary result from Belle in ref. [8] provide upper limits on branching fraction at the level of few times 10^{-8}.

1.2 Lepton flavour violation in τ decays at LHCb

A search for LFV in τ decays at an hadronic collider has been performed for the first time by the LHCb experiment. The inclusive τ production cross section at the LHC in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is $\sim 80\mu$b, therefore about 8×10^9 τ leptons are produced in $1.0\,\text{fb}^{-1}$, which is the integrated luminosity of the data sample collected by LHCb in the 2011 run. The challenge of a τ analysis in pp collisions are related to the high tracks multiplicity of the event and to the lack of a priori knowledge of the τ momentum. Muon final states provide clean signatures in the LHCb detector and the $\tau^- \to \mu^+\mu^-\mu^-$decay has been considered [9]. The signal is selected with a cut-based selection designed to give maximal efficiency but at the same time reduce the dataset to a manageable level. The real discrimination between potential signal and backgrounds is done with likelihoods based on the three-body decay properties, muon identification properties and the invariant mass of the 3μ candidate. The $D_s \to \phi\pi^-$ decay followed by $\phi \to \mu^+\mu^-$, is used as a normalisation channel and also to calibrate on data the three-body decay likelihood. Inclusive $J/\psi \to \mu^+\mu^-$ decays are used to calibrate the muon identification likelihood. The use of a normalization channel with a $\pi\mu\mu$ final state similar to the signal one allows to cancel most systematic uncertainties in the determination of the ratio of trigger and selection efficiencies. The initial studies are performed blind, with candidates with mass within $\pm 30\,\text{MeV}/c^2 (\sim 3\sigma)$ of the τ mass excluded from the analysis. The number of background events in the signal region is determined from a fit to the 3μ mass distribution in the signal sidebands, performed separately in different bins of the three-body and the muon identification likelihoods. An example of a fit to the mass distribution in a high signal likelihood region is shown in Fig. 1.

The CL_S method [10] is used as a statistical framework to determine the branching fraction. In Fig. 1 the distribution of expected CL_Svalues is shown as a dashed line, as a function of the assumed branching fraction, under the hypothesis to observe background events only. The light (yellow) and dark (green) bands cover the regions of 68% and 95% containment respectively. Opening the mass box no excess was found over the estimated background. The distribution of observed $\mathrm{CL_S}$values is shown as a solid black line in Fig. 1. The observed upper limit for the branching fraction of $\tau^- \to \mu^+\mu^-\mu^-$is found to be:

$$\mathscr{B}(\tau^- \to \mu^+\mu^-\mu^-) < 6.3(7.8)\times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL.} \tag{1.3}$$

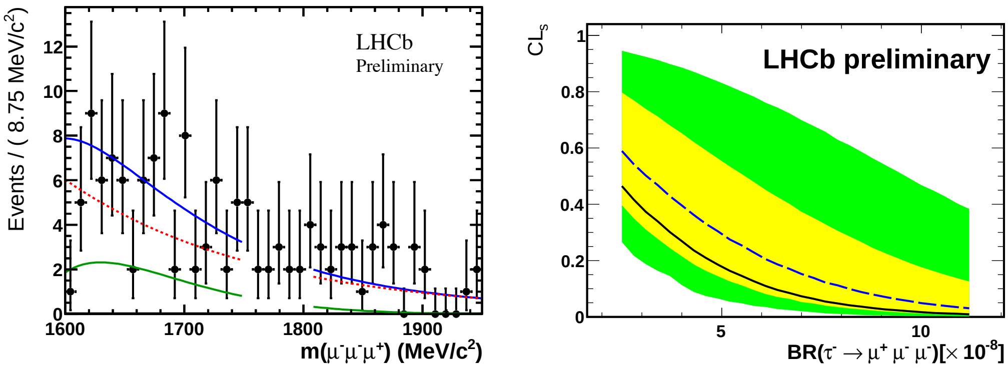

Figure 1: Left: fits to the mass distribution of events observed in high signal likelihood region. The combinatorial exponential contribution (red dotted line), the $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$ contribution (green line) and the combined background PDF (blue line) are shown. Right: distribution of $\mathrm{CL_S}$values as a function of the assumed branching fraction, under the hypothesis to observe background events only. The dashed line indicates the expected curve, the solid line the observed one. The light (yellow) and dark (green) bands cover the regions of 68% and 95% containment, respectively.

This limit is of the same other of magnitude as the one from B-Factories, significant improvements are expected with the additional data collected by LHCb since 2012.

1.3 Lepton flavour violation in B decays

LFV decays in the τ sector can be probed also in B meson decays. The recent analysis from BaBar, using a data sample corresponding to 472×10^6 $\bar{B}B$ pairs searches for eight possible LFV decay modes $B^\pm \to h^\pm \tau \ell$ $(h = K,\pi; \ell = e,\mu)$ [11]. The search uses events where one B meson is fully reconstructed in one of several hadronic final states. Using the momenta of the reconstructed B, h, and ℓ candidates, the τ four-momentum is determined. The resulting τ candidate mass is the main discriminant against combinatorial background. The eight B decay modes are independently analyzed, restricting the selection to one-prong τ decays. No evidence for any of these decays is found and upper limits on the branching fraction are set at the level of a few times 10^{-5}, at 90% CL. Using the limits on the branching fractions in the $B^+ \to \pi^+\tau\mu$ and $B^+ \to K^+\tau\mu$ modes the model-independent bounds on the energy scale of New Physics in flavor-changing effective operators reported in [12] are improved of about a factor five up to $\Lambda_{\bar{b}d} > 11$ TeV and $\Lambda_{\bar{b}s} > 15$ TeV.

2. Lepton number violation

The total lepton number is a conserved quantity in the SM, although there is no known symmetry associated to it. Many NP models allow for lepton number violation (LNV). Finding neutrino-less double β decay has long been advocated as a premier evidence of a LNV process and a demonstration of the possible Majorana nature of neutrinos [13]. The corresponding Feynman diagram describing the process at the fundamental quark and lepton level are shown in Fig. 2(a). Similar process can occur in B meson decays, as shown with the diagram in Fig. 2(b). In this reaction there is no restriction on the mass of the Majorana neutrino, as it acts as a virtual particle. A like-sign electron pair, as in double β decay, but also a like-sign muon pair can be produced.

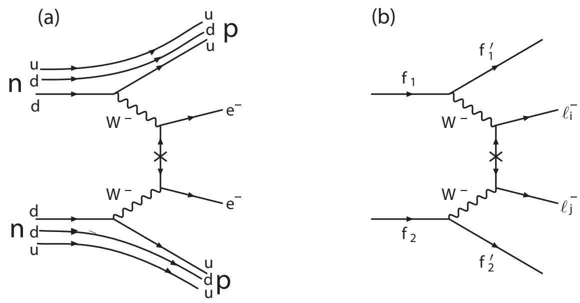

Figure 2: (a) Diagram of neutrino-less double β decay when two neutrons in a nucleus decay simultaneously. (b) The fundamental diagram for changing lepton number by two units.

There are several process involving b-quark decays that can produce a light neutrino that can mix with a heavy neutrino, designated as N. The virtual production can be probed in decays like $B^- \to D^{(*)+}\mu^-\mu^-$, as shown in Fig. 3(a). In the annihilation process $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, shown in Fig. 3(b), the heavy neutrino decays as $N \to W^+\mu^-$ and the virtual W^+ materializes in a pion or a D_s^+ meson. The branching fraction is enhanced for resonant production when the mass of the neutrino is between approximately 260 and 5000 MeV, or 2100 and 5150 MeV, in the case of π^+ or D_s^+, respectively.

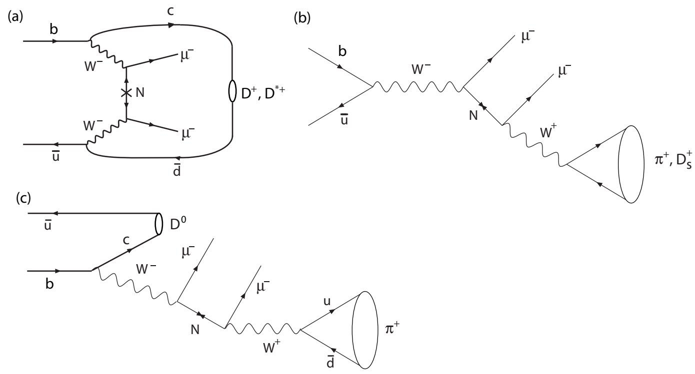

Figure 3: Feynman diagrams for B decays involving intermediate heavy neutrinos (N). (a) $B^- \to D^{(*)+}\mu^-\mu^-$, (b) $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, and (c) $B^- \to D^0\pi^+\mu^-\mu^-$.

No evidence has been found so far for the existence of a massive Majorana neutrino from direct searches.

Searches were performed at CLEO for $B^- \to h^+\ell^-\ell^-$ ($\ell = e,\mu$, $h = \pi,\rho,K,K^*$) decays [14], and provided upper limits on the branching fraction in the range $(1.0-8.3)\times 10^{-6}$ at 90% CL, depending on the decay mode. More stringent limit was obtained by BaBar from the analysis of

471×10^6 $B\bar{B}$ events [15]. The result is a function of the Majorana neutrino mass, assuming a phase space decay of the B meson, the upper limits on the branching fraction $B^- \to \pi^+(K^+)\ell^-\ell^-$ are set to $2.3(3.0) \times 10^{-8}$ and $10.7(6.7) \times 10^{-8}$, at 90% CL, for like-sign electrons or muons, respectively.

2.1 Search for Majorana neutrino at LHCb

At LHC, in pp collision at $\sqrt{s} = 7$ TeV, the inclusive cross section for b$\bar{\text{b}}$ production is about 300 μb. Searches for LNV decays are performed in B decay modes into a pion and/or a charmed meson and a like-sign muon pair. The first 0.4 fb^{-1}of data collected by LHCb at $\sqrt{s} = 7$ TeV were used for the results presented here [16].

The search for virtual Majorana neutrinos is performed in the $B^- \to D^{(*)+}\mu^-\mu^-$ decay modes. On-shell Majorana neutrinos are searched for in $B^- \to \pi^+\mu^-\mu^-$, $B^- \to D_s^+\mu^-\mu^-$ and in the semileptonic $B^- \to D^0\pi^+\mu^-\mu^-$ decay modes.

The branching fractions for LNV decays are calculated relative to a normalization channel. The decay mode $\mathrm{B}^- \to J/\psi K^-$ or $\mathrm{B}^- \to \psi(2S)K^-$, $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$, are chosen in such a way to have the same total track multiplicity in the final state, in order to minimize the differences in the selection and trigger efficiencies.

In the searches for virtual neutrinos no excess over the combinatorial background is found in the reconstructed B mass distribution and upper limits of $\mathscr{B}(B^- \to D^+\mu^-\mu^-) < 6.9 \times 10^{-7}$ and $\mathscr{B}(B^- \to D^{*+}\mu^-\mu^-) < 2.4 \times 10^{-6}$ are set, at 95% CL. These limits are independent on the neutrino mass and are the most stringent available so far in these channels.

In the case of the $B^- \to \pi^+\mu^-\mu^-$ decay, since the Majorana neutrino is assumed to have a very narrow widths and to decay into $\pi^+\mu^-$ pair, the $\pi^+\mu^-$ mass distribution is studied. The mass resolution σ_N and the detection efficiency are determined from simulation, as a function of the Majorana neutrino mass. There is no statistically significant signal at any mass. Upper limits on the existence of a massive Majorana neutrino are set at each $\pi^+\mu^-$ mass by searching a signal region whose width is $\pm 3\sigma_N$. The limits are shown in Fig. 4(a).

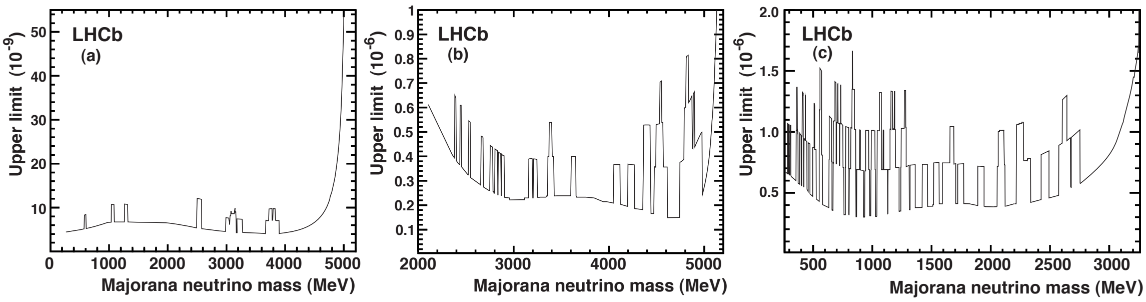

Figure 4: Upper limits at 95% CL as a function of the Majorana neutrino mass, (a) for $\mathscr{B}(B^- \to \pi^+\mu^-\mu^-)$ as a function of the $\pi^+\mu^-$ mass, (b) for $\mathscr{B}(B^- \to D_s^+\mu^-\mu^-)$ as a function of the $D_s^+\mu^-$ mass (c) for $\mathscr{B}(B^- \to D^0\pi^+\mu^-\mu^-)$ as a function of the $\pi^+\mu^-$ mass

Assuming a phase space decay of the B the limit $\mathscr{B}(B^- \to \pi^+\mu^-\mu^-) < 1.3 \times 10^{-8}$ at 95% CL is determined, this is the most stringent so far in this channel. The $B^- \to D_s^+\mu^-\mu^-$ decay mode is sensitive to higher neutrino masses, as the neutrino should decay into $D_s^+\mu^-$. No excess over background is found also in this channel and the upper limit on the branching fraction as a function

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of the $D_s^+\mu^-$ mass is shown in Fig. 4(b). Assuming a phase space decay of the B the limit on the branching fraction $\mathscr{B}(B^- \to D_s^+\mu^-\mu^-) < 5.8\times10^{-7}$ at 95% CL is determined. For the first time a search is performed also in the semileptonic decay mode $B^- \to D^0\pi^+\mu^-\mu^-$, this can occur through the diagram shown in Fig. 3(c) and is sensitive to intermediate values of the neutrino mass. No excess over background is found and the limit on the branching ratio is shown in Fig. 4(c).

The upper limit on $\mathscr{B}(B^- \to \pi^+\mu^-\mu^-)$ can be used to establish neutrino mass dependent limits on the coupling $|V_{\mu4}|$ of a heavy Majorana neutrino to a muon and a virtual W. The matrix element has been calculated as in Ref. [17]. The results are shown in Fig. 5.

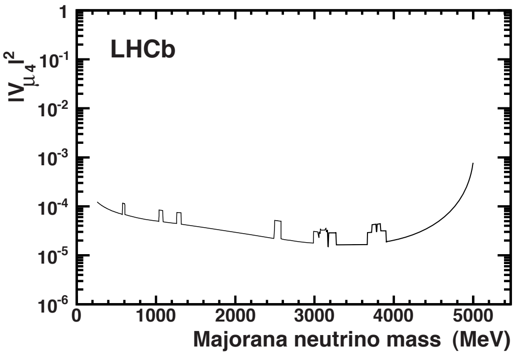

Figure 5: Upper limits on $|V_{\mu4}|$ at 95% CL as a function of the Majorana neutrino mass, from the $B^- \to \pi^+\mu^-\mu^-$ channel.

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