Lepton Number Violation and Lepton Flavour Violation at LHCb

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Abstract. Searches for heavy Majorana neutrinos in B^- decays with final states containing hadrons plus a $\mu^-\mu^-$ pair are performed using 0.41 fb^{-1} of data collected with the LHCb detector in proton-proton collisions at a center-of-mass energy of 7 TeV. No signals are found and upper limits are set on Majorana neutrino production and B^- decay branching fractions as a function of the Majorana neutrino mass.

A search is also made for the lepton flavour violating decay $\tau \to \mu^+\mu^-\mu^-$ using 1.0 fb^{-1} of data collected by LHCb in 2011. The observed number of events is consistent with the background expectation, and an upper limit on the branching ratio is set. Using a similar procedure, the lepton flavour violating and baryon number violating decays $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ are searched for, and upper limits provided at 95% confidence level.

1. Introduction

Leptons constitute a crucially important sector of elementary particles. Half of the leptons are neutrinos. Yet we do not know if they are Dirac or Majorana particles, the latter case characterized by being their own antiparticles [1]. Since the observation of neutrino oscillations has indisputably established that neutrinos have non-zero mass, it is possible to distinguish the two types experimentally. Finding neutrinoless double β decay has long been advocated as a premier demonstration of the possible Majorana nature of neutrinos [2]. An impressive lower limit from neutrinoless double β decays in nuclei has already been obtained on the half-life of $\mathcal{O}(10^{25})$ years [3] for coupling to e^-.

Similar processes can occur in B^- decays. The diagram is shown in Fig. 1(a). In this reaction there is no restriction on the mass of the Majorana neutrino as it acts as a virtual particle. Unlike in neutrinoless double beta decays, a like-sign dimuon is considered rather than two electrons. The only existing limit is from a recent Belle measurement [4] using the $B^- \to D^+\mu^-\mu^-$ channel. We consider only final states where the $c\bar{d}$ pair forms a final-state meson, either a D^+ or a D^{*+}, so the processes we are looking for are $B^- \to D^{(*)+}\mu^-\mu^-$. Mention of a specific reaction also implies inclusion of the charge conjugate reaction, throughout the report.

There are other processes involving b-quark decays that produce a light neutrino that can mix with a heavy neutrino, designated as N. The heavy neutrino can decay as $N \to W^+\mu^-$. In Fig. 1(b) we show the annihilation processes $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, where the virtual W^+ materializes either as a π^+ or D_s^+. These decays have been discussed in the literature [5, 6]. The lifetime of N are not predicted. It is assumed here that they are long enough that the natural decay width is narrower than the LHCb mass resolution, which varies between 2 and 15

MeV, depending on mass and decay mode. For $B^- \to \pi^+\mu^-\mu^-$, we can access the Majorana mass region between approximately 260 and 5000 MeV while for $B^- \to D_s^+\mu^-\mu^-$, the Majorana mass region is between 2100 and 5150 MeV. In the higher mass region, the W^+ may be more likely to form a D_s^+ meson than a π^+. The $B^- \to \pi^+\mu^-\mu^-$ search was first performed by Mark-II [7] and then by CLEO [8]. LHCb also performed a similar search using a smaller 0.04 fb^{-1} data sample [9] giving an upper limit of 5.8×10^{-8} at 95% confidence level (CL). The decay of $B^- \to D_s^+\mu^-\mu^-$ has never been investigated.

Finally, in Fig. 1(c) it is shown how prolific semileptonic decays of the B^- can result in the $D^0\pi^+\mu^-\mu^-$ final state. This process has never been probed [10]. It benefits from the higher value of the CKM coupling $|V_{cb}|$ relative to $|V_{ub}|$ in the annihilation processes shown in Fig. 1(b). The accessible region for Majorana neutrino mass is between 260 and 3300 MeV. For all the modes reported here, only decays with muons in the final state are searched for, though electrons, and τ leptons in cases where sufficient energy is available, could also be produced. Searches have also been carried out looking for like-sign dileptons in hadron collider experiments [11].

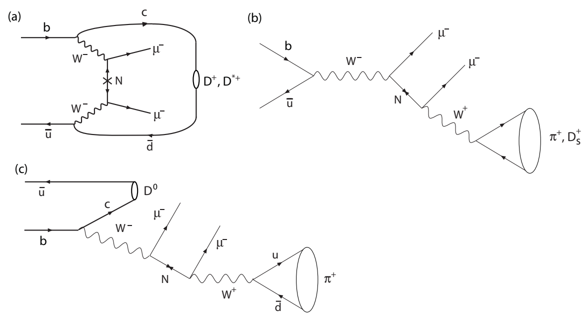

Figure 1. Feynman diagrams for B decays involving an intermediate heavy neutrino (N). (a) $B^- \to D^{(*)+}\mu^-\mu^-$, (b) $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, and (c) $B^- \to D^0\pi^+\mu^-\mu^-$.

A second topic discussed in this communication is lepton flavour violation searches by the LHCb experiment. 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 smaller than 10^{-40}. New physics (NP) could significantly enhance the rates, but charged lepton flavour violating (cLFV) decays like $\mu^- \to e^-\gamma$ $\mu^- \to e^+e^-e^-$ $\tau^- \to l^-\gamma$ and $\tau^- \to l^+l^-l^-$ with $l^- = e^-, \mu^-$ have not been observed so far even with steadily improving experimental sensitivity. Numerous beyond the Standard Model theories predict enhanced LFV in τ^- decays over μ^- decays. with branching fractions within experimental reach [12]. An observation of cLFV would thus be a clear sign for NP, while lowering the experimental upper limit will help to further constrain exotic theories. The inclusive τ^- production cross section at the LHC is large (about 80 μb) and muon final states provide clean signatures in the LHCb detector. This decay is favoured with respect to the decays $\tau^- \to \mu^-\gamma$ and $\tau^- \to e^+e^-e^-$ due to considerably better particle identification of the muons and better possibilities for background discrimination. We report here a first result by the LHCb collaboration [17] on the $\tau^- \to \mu^+\mu^-\mu^-$ decay which demonstrates an experimental sensitivity comparable with the current best experimental upper limit, from Belle $\mathrm{B}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% confidence level (CL) [14]).

We also report here LHCb searches which violate both lepton number (LNV) (and hence also lepton flavour) and baryon number (BNV) conservation. Taking advantage of the high inclusive τ^- production at the LHC, a search has been performed [19] for the two decay modes $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$, using the same τ^- normalization as for the $\tau^- \to \mu^+\mu^-\mu^-$

decay search.

BaBar and Belle have searched for τ^- decays with $|(B-L)| = 0$ and $|(B-L)| = 2$ using the modes $\tau^- \to \Lambda h^-, \bar{\Lambda} h^-$ (with $h^- = l^-, K^-$). Limits of order 10^{-7} were obtained, and the results are summarised in Ref [21]. BaBar has also searched for B-meson decays $B^0 \to \Lambda_c^+ h^-, B^- \to \Lambda h^-$ (both having $|(B-L)| = 0$) and $B^- \to \bar{\Lambda} h^-$, $|(B-L)| = 2$, with 90% CL upper limits in the range 3.2 to 520×10^{-8} [22]. No measurements currently exist for the $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ decay modes; this analysis presents the first of such searches. These modes probe LNV and BNV similarly to the above-mentioned modes studied by BaBar and Belle.

2. Searches for Majorana neutrinos in B^- decays

Values for branching fractions will be normalized to well measured channels that have the same number of muons in the final state and equal track multiplicities. The first such channel is $B^- \to J/\psi K^-$. Its branching fraction is $\mathcal{B}(B^- \to J/\psi K^-) = (1.014 \pm 0.034) \times 10^{-3}$ [3]. We use the $J/\psi \to \mu^+\mu^-$ decay mode. The product branching fraction of this normalization channel is $(6.013 \pm 0.021) \times 10^{-5}$, and is known to an accuracy of $\pm 2\%$.

The invariant mass of $K^-\mu^+\mu^-$ candidates is shown in Fig. 2(a). In this analysis the $\mu^+\mu^-$ invariant mass is required to be within 50 MeV of the J/ψ mass. Using an unbinned log-likelihood fit yields 47,224±222 $B^- \to J/\psi K^-$ events. Within a $\pm 2\sigma$ signal window about the peak mass, taken as the signal region, there are 44,283 of these events. with a systematic uncertainty of 0.3%. The width of the signal peak is found to be 19.1±0.1 MeV.

For final states with five tracks, we change the normalization channel to $B^- \to \psi(2S)K^-$, with $\psi(2S) \to \pi^+\pi^- J/\psi$, and $J/\psi \to \mu^+\mu^-$. The branching fraction for this channel is $\mathcal{B}(B^- \to \psi(2S)K^-) = (6.48 \pm 0.35) \times 10^{-4}$ [3]. Events are selected using a similar procedure as for $J/\psi K^-$ but adding a $\pi^+\pi^-$ pair, that must have an invariant mass when combined with the J/ψ which is compatible with the $\psi(2S)$ mass, and that forms a consistent vertex with the other B^- decay candidate tracks. The total efficiency for $\mu^+\mu^-\pi^+\pi^-K^-$ is (0.078±0.002)%, without inclusion of the $\psi(2S)$ or J/ψ branching fractions. The B^- candidate mass plot is shown in Fig. 2(b). From analysis of the mass spectrum, 767±29 signal events are found in a $\pm 2\sigma$ window about the peak mass, with 0.7% systematic uncertainty on the yield.

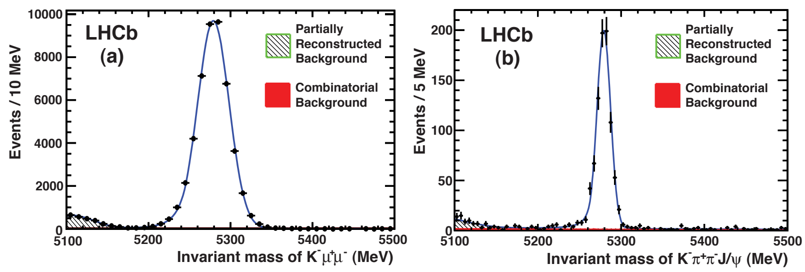

Figure 2. Invariant mass of (a) candidate $J/\psi K^-$ decays, and (b) candidate $J/\psi K^-\pi^+\pi^-$ decays.

2.1. Analysis of $B^- \to D^+\mu^-\mu^-$ and $D^{*+}\mu^-\mu^-$

Decay diagrams for $B^- \to D^{(*)+}\mu^-\mu^-$ are shown in Fig. 1(a). Since the neutrinos are virtual, the process can proceed for any value of neutrino mass. The $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$ channels are used. The decay products of the D^+ and D^0 candidates are required to have invariant masses within ±25 MeV of the charm meson mass, and for D^{*+} candidate selection the mass difference $m(\pi^+K^-\pi^+) - m(K^-\pi^+)$ is required to be within ±3 MeV of the known $D^{*+} - D^0$ mass difference. The $D^{(*)+}\mu^-\mu^-$ candidate mass spectra is analysed and no signals are apparent.

Using Poission statistics on the value of $(S + B)$, where S indicates the expectation value of signal and B background, the following upper limits on the branching fractions at 95% CL are set:

$$\begin{aligned} \mathcal{B}(B^- \to D^{\ +}\mu^-\mu^-) &< 6.9 \times 10^{-7} \text{ and} \\ \mathcal{B}(B^- \to D^{*+}\mu^-\mu^-) &< 2.4 \times 10^{-6} \ . \end{aligned} \tag{1}$$

The limit on the D^+ channel is more stringent than a previous limit from Belle of 1×10^{-6} at 90% CL [4], and the limit on the D^{*+} channel is the first such result.

2.2. Analysis of $B^- \to \pi^+\mu^-\mu^-$

The selection of $\pi^+\mu^-\mu^-$ events uses the same criteria as described for $J/\psi K^-$ above, except for like-sign rather than opposite-sign dimuon charges and pion rather than kaon identification. The invariant mass distribution of $\pi^+\mu^-\mu^-$ candidates is analysed with a mass resolution for this final state 20.3±0.2 MeV. The signal region is defined by an interval of $\pm 2\sigma$ centered on the B^- mass, where 7 events are found, but no signal above background is apparent. The peaking background, estimated as 2.5 events, is due to misidentified $B^- \to J/\psi K^-$ or $J/\psi\pi^-$ decays. The combinatorial background is determined to be 5.3 events from a fit to the $\pi^+\mu^-\mu^-$ mass distribution excluding the signal region. The total background in the signal region then is 7.8 ± 1.3 events.

Since the putative neutrinos considered here decay into $\pi^+\mu^-$, and are assumed to have very narrow widths, more sensitivity is obtained by examining this mass distribution for events in the B^- signal region. No statistically significant signal is found at any mass.

Many systematic errors in the signal yield cancel in the ratio to the normalization channel. The largest sources of error are the modeling of the detector efficiency (5.3%) and the measured branching fractions $\mathcal{B}\,(B^- \to J/\psi K^-)$ (3.4%), and $\mathcal{B}\,(J/\psi \to \mu^+\mu^-)$ (1.0%) [3].

To set upper limits on the branching fraction, the number of events $N_{\rm obs}$ at each M_N value (within $\pm 3\sigma_N$) are counted, and the procedure described above is applied. Estimated backgrounds are taken from the sidebands of the mass spectreum. Upper limits on $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$ as a function of M_N are derived at 95% CL. For most of the neutrino mass region, the limits on the branching ratio are $< 8 \times 10^{-9}$. Assuming a phase space decay of the B^- we determine

$$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 1.3 \times 10^{-8} \text{ at 95\% CL.}$$

These limits improve on previous results from CLEO ($< 1.4 \times 10^{-6}$ at 90% CL) [8], and LHCb [9] ($< 5.8 \times 10^{-8}$ at 95% CL).

2.3. Analysis of $B^- \to D_s^+\mu^-\mu^-$

The process $B^- \to D_s^+\mu^-\mu^-$ is similar to $B^- \to \pi^+\mu^-\mu^-$, with the difference being that the heavy neutrino can decay into $D_s^+\mu^-$. Here we consider only $D_s^+ \to K^+K^-\pi^+$ decays. Our analysis follows a similar procedure used for the $\pi^+\mu^-\mu^-$ channel. Candidate $D_s^+ \to K^+K^-\pi^+$ decays are selected by having an invariant mass within ±25 MeV of the D_s^+ mass. A Majorana neutrino candidate decay is then looked for by having the D_s^+ candidate decay tracks form a vertex with an opposite-sign muon candidate. Then this neutrino candidate must form a vertex with another muon of like-sign to the first one consistent with a B^- decay detached from the primary vertex. The invariant mass spectrum of $D_s^+\mu^-\mu^-$ candidates is analysed, with the mass resolution being 15.5±0.3 MeV. After selecting the events in the B^- signal region, the $D_s^+\mu^-$

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invariant mass distribution is also analysed. A background estimate is made using the sideband data in B^- candidate mass, and the data in the signal region is consistent with the background estimate.

The overall efficiencies and resolution for different values of M_N are determined from simulation. As done previously, during the scan over the accessible Majorana neutrino mass region we use a $\pm 3\sigma_N$ mass window around a given Majorana mass. The main contribution comes from errors in the branching fractions and trigger efficiencies. Again we provide upper limits as a function of the Majorana neutrino mass, only taking into account combinatorial background in this case as the peaking background is absent. For neutrino masses below 5 GeV, the limits on the mass dependent branching fractions are mostly $< 6 \times 10^{-7}$. We also determine an upper limit on the total branching fraction. We observe 12 events with an expected background yield of 22 events and use the CL_s method for calculating the upper limit [23]. Assuming a phase space decay of the B^- we find

$$\mathcal{B}(B^- \to D_s^+ \mu^- \mu^-) < 5.8 \times 10^{-7} \text{ at } 95\% \text{ CL.}$$

2.4. Analysis of $B^- \to D^0 \pi^+ \mu^- \mu^-$

Majorana neutrinos could be produced via semileptonic decays as shown in Fig. 1(c). Here the mass range probed is smaller than in the case of $\pi^+ \mu^- \mu^-$ due to the presence of the D^0 meson in the final state.

After a similar selection procedure as described above, the invariant mass distribution of $D^0 \pi^+ \mu^- \mu^-$ is analysed in search of a B^- signal, the mass resolution being 14.4±0.2 MeV. Peaking backgrounds are essentially absent. The largest source is $B^- \to D^0 \pi^- \pi^- \pi^+$ which contributes only 0.13 events in the signal region. The combinatorial background, determined by a linear fit to the sidebands of the B^- signal region, predicts 35.9 events, while the number of observed is 33. The $\pi^+ \mu^-$ invariant mass for events within two standard deviations of the B^- mass is also analysed.

Upper limits for $\mathcal{B}(B^- \to D^0 \pi^+ \mu^- \mu^-)$ as a function of the $\pi^+ \mu^-$ mass are set for Majorana neutrino masses < 3.0 GeV, the upper limits being less than 1.6×10^{-6} at 95% CL. The final limit on the branching fraction assuming a phase space decay is

$$\mathcal{B}(B^- \to D^0 \pi^+ \mu^- \mu^-) < 1.5 \times 10^{-6} \text{ at } 95\% \text{ CL.}$$

3. Search for the lepton flavour violating decay $\tau \to \mu^+ \mu^- \mu^-$

In this analysis, the full 2011 LHCb data sample, corresponding to $1.0 fb^{-1}$ collected at $\sqrt{s} = 7\ TeV$, is used to search for the $\tau^- \to \mu^+ \mu^- \mu^-$ decay. Two selections are implemented, one for the signal mode and the other for the normalisation channel $D_s^- \to \phi \pi^-$ followed by $\phi \to \mu^+ \mu^-$. These cut-based selections are 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 over a binned three-dimensional distribution in:

- a likelihood based on the three-body decay properties (M_{3body})
- a likelihood based on muon identification (M_{PID})
- the invariant mass of the 3μ candidate ($\mathrm{M}_{3\mu}$).

The initial studies were performed blind, with 3 muon candidates with mass within 30 MeV (3 σ) of the τ^- mass excluded from the analysis. The analysis strategy and limit-setting procedures are similar to those used for the LHCb analyses of $B_{s,d} \to \mu^+ \mu^-$ [15].

To estimate the signal branching fraction we normalise the number of observed signal events to the number of events in the $D_s \to \phi(\mu^+ \mu^-)\pi^-$ calibration channel using the equation

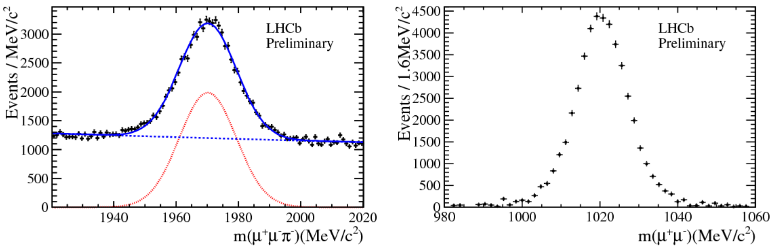

Figure 3. (a) Invariant mass distribution of the $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ events with a Gaussian fit (fine dashed line), an exponential background (dashed line) and the combined fit as the solid line. (b) Invariant mass distribution of the $\phi \to \mu^+\mu^-$ events obtained using the sPlot[12] technique.

$$B(\tau^- \to \mu^+\mu^-\mu^-) = B(D_s \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f^{\tau}_{D_s}}{B(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon^{REC|SEL}_{cal}\,\epsilon^{TRIG|SEL}_{cal}}{\epsilon^{REC|SEL}_{sig}\,\epsilon^{TRIG|SEL}_{sig}} \times \frac{N_{sig}}{N_{cal}} = \alpha \times N_{sig} \quad (2)$$

where α is the overall normalisation factor and N_{sig} is the number of observed signal events. $B(D_s \to \tau^-\bar{\nu}_\tau)$ is the branching fraction for $D_s \to \tau^-\bar{\nu}_\tau$ taken from [16]. The quantity $f^{\tau}_{D_s}$ is the fraction of τ^- leptons which originate from D_s^- decays, calculated using the $b\bar{b}$ and $c\bar{c}$ cross sections as measured by LHCb [18] and the inclusive $b \to \tau^-$ and $c \to \tau^-$ branching fractions as measured by the LEP experiments [3].

The reconstruction and selection efficiency $REC|SEL$, is itself a combination of the detector acceptance for the particular decay, the muon identification efficiency and the selection efficiency. They are determined from simulation.

The branching ratio of the control channel $B(D_s^- \to \phi(\mu^+\mu^-)\pi^-)$ is determined from the combination of known branching fraction measurements [17]. The yield of $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ events in data, N_{cal}, is extracted by a fit to the signal and background components of the reconstructed D_s^- mass distribution. It is found to be:

$$N(D_s^- \to \phi(\mu^+\mu^-)\pi^-) = 45520 \pm 420_{stat} \pm 820_{syst} \quad (3)$$

where the systematic uncertainty contains the dependence on the fit model. The background subtracted dimuon invariant mass spectrum of the $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ events is shown in Fig. 3 (b). The $\phi(1020)$ resonance is seen with a very low background level.

The expected number of background events per bin in M_{3body}, M_{PID} and $M_{3\mu}$ likelihood space is calculated from an extended, unbinned maximum likelihood fit to the mass spectrum, excluding the signal window. The background processes for the rare decay $\tau^- \to \mu^+\mu^-\mu^-$ consist of long decay chains of heavy mesons with three real muons in the final state or including one or two real muons in combination with one or two mis-identified particles.

The CL_s method [23, 24] is used as a statistical framework. It provides two estimators, CL_s and CL_b, which give the level of compatibility with the signal and background hypotheses, respectively. CL_s is used to set the exclusion (upper) limit on $\tau^- \to \mu^-\mu^+\mu^-$ whereas CL_b is used to claim an incompatibility with the background-only hypothesis for an observation. The distribution of the observed CL_s values is calculated as function of the assumed branching fraction, and the observed upper limit is found to be: $B(\tau^- \to \mu^+\mu^-\mu^-) < 7.8 \times 10^{-8}$ at 95% CL.

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4. Search for the baryon number violating decays $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$

The same data sample and a similar procedure as for $\tau^- \to \mu^+\mu^-\mu^-$ is used to search for $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ decays. Three selections are implemented, two for the $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ signal modes, and one for the normalisation channel, which is $D_s^- \to \phi(\mu^+\mu^-)\pi^-$. Discrimination between potential signal and backgrounds is performed using particle identification cuts and a binned two-dimensional distribution in two variables: a likelihood based on the 3-body kinematics of the event, and the invariant mass of the $p(\bar{p})\mu\mu$ candidate. The observed limits for the branching fractions $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ are found to be: 4.5×10^{-7} and 6.0×10^{-7} respectively, at 95% CL.

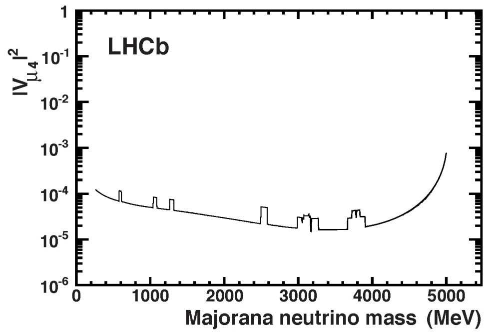

Figure 4. Upper limits on $|V_{\mu 4}|^2$ at 95% CL as a function of the Majorana neutrino mass from the $B^- \to \pi^+\mu^-\mu^-$ channel.

5. Conclusions

A search has been performed for Majorana neutrinos in the B^- decay channels, $D^{(*)+}\mu^-\mu^-$, $\pi^+\mu^-\mu^-$, $D_s^+\mu^-\mu^-$, and $D^0\pi^+\mu^-\mu^-$ which has only yielded upper limits. The $D^{(*)+}\mu^-\mu^-$ channels may proceed via virtual Majorana neutrino exchange and thus are sensitive to all Majorana neutrino masses. The other channels provide limits for neutrino masses between 260 and 5000 MeV. The bounds are summarized in Table 1. These limits are the most restrictive to date.

Table 1. Summary of upper limits on branching fractions. Both the limits on the overall branching fraction assuming a phase space decay, and the range of limits on the branching fraction as a function of Majorana neutrino mass (M_N) are given. All limits are at 95% CL.

Mode	$\mathcal{B}$ upper limit	Approx. limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
$\pi^+\mu^-\mu^-$	1.3×10^{-8}	$(0.4 - 1.0) \times 10^{-8}$
$D_s^+\mu^-\mu^-$	5.8×10^{-7}	$(1.5 - 8.0) \times 10^{-7}$
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}	$(0.3 - 1.5) \times 10^{-6}$

Our search has thus far ignored the possibility of a finite neutrino lifetime. Experimental sensitivity is lost for lifetimes longer than 10^{-10} s to 10^{-11} s, depending on the decay mode. Note that for the $D^{(*)+}\mu^-\mu^-$ final states the detection efficiency is independent of the neutrino lifetime, since the neutrino acts a virtual particle.

Our upper limits in the $\pi^+\mu^-\mu^-$ final state can be used to establish neutrino mass dependent upper limits on the coupling $|V_{\mu 4}|$ of a heavy Majorana neutrino to a muon and a virtual W. The matrix element has been calculated in Ref. [5]. The results are shown in Fig. 4 as a function of M_N.

A model dependent calculation of $\mathcal{B}(B^- \to D^0\pi^+\mu^-\mu^-)$ can also be used to extract $|V_{\mu 4}|$ [10], but the $\pi^+\mu^-\mu^-$ mode is more sensitive. For the $D^{(*)+}\mu^-\mu^-$ channels upper limits cannot be extracted until there is a theoretical calculation of the hadronic form-factor similar to those available for neutrinoless double β decay.

LHCb has performed additional searches for lepton flavour violation, and baryon number violation, using τ^- lepton decays from a data sample with integrated luminosity of 1.0 fb^{-1}, collected at $\sqrt{s} = 7$ TeV in 2011. The τ^- production rate has been normalised to the control channel $D_s^- \to \phi(\mu^+\mu^-)\pi^-$. The following upper limits have been set on the branching fraction of $\tau^- \to \mu^+\mu^-\mu^-$:

$$B(\tau^- \to \mu^+\mu^-\mu^-) < 6.3 \times 10^{-8} \quad at \quad 90\% \;\; CL \tag{4}$$

$$B(\tau^- \to \mu^+\mu^-\mu^-) < 7.8 \times 10^{-8} \quad at \quad 95\% \;\; CL \tag{5}$$

The above limits are not significantly dependent on the dimuon mass spectrum assumed in the decay model. In addition, the lepton flavour violating and baryon number violating decays $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ have been searched for, and the observed numbers of events are consistent with the background expectations. The upper limits $B(\tau^- \to \bar{p}\mu^+\mu^- < 4.5(3.4)10^{-7}$ $B(\tau^- \to p\mu^-\mu^- < 6.0(4.6)10^{-7}$ have been set at 95% (90%) confidence level.

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