SEARCH FOR LEPTON NUMBER VIOLATION AT THE LHCb. AN UPDATE FOR MAJORANA NEUTRINO SEARCH WITH LIKE-SIGN DI-MUONS: $B^- \to \pi^+\mu^-\mu^-$ DECAY*

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(Received May 6, 2014)

Lepton number is conserved in the Standard Model, therefore, any evidence for its violation would indicate the existence of New Physics models. This paper presents selected searches of rare decays performed by the LHCb experiment. An update for the studies dedicated to on-shell Majorana neutrinos coupling to muons in the $B^- \to \pi^+\mu^-\mu^-$ decay channel is also presented.

DOI:10.5506/APhysPolB.45.1575
PACS numbers: 13.50.Hw, 11.30.Fs, 14.60.Fg, 14.60.St

1. Introduction

Lepton number is conserved in the Standard Model (SM) but can be violated in a range of New Physics models. The LHCb physics program covers searches for lepton number violating (LNV) and lepton flavour violating (LFV) in a broad class of exclusive B and D meson decays. A short review of recent searches for LNV is presented starting from published results from inclusive τ lepton decays and the $B^0_{(s)} \to e^\pm\mu^\mp$ decays modes.

A search for Majorana neutrinos can be performed in heavy flavor decays. One of the most sensitive decay is $B^- \to \pi^+\mu^-\mu^-$. It is forbidden within SM, but can proceed via the production of on-shell Majorana neutrinos. An update for Heavy Majorana Neutrino searches in the $B^- \to \pi^+\mu^-\mu^-$ decay using LHCb data is presented.

* Presented at the Cracow Epiphany Conference on the Physics at the LHC, Kraków, Poland, January 8–10, 2014.

2. Lepton flavour and lepton number violation studies at the LHCb

2.1. Searches in tau lepton decays

The neutrinoless $\tau^- \to \mu^-\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$, $\tau^- \to \bar{p}\mu^+\mu^-$ decay modes are of particular interest at the LHCb, since the experimental signature with the two- or three-muon final state is very clean in the detector and the ring-imaging Cherenkov (RICH) detectors give excellent identification of protons. The LHCb has performed a search for the decay $\tau^- \to \mu^-\mu^+\mu^-$ using 1.0 fb^{-1} of data [1]. The inclusive τ^- production cross-section at the LHCb is relatively large, at about 80 μb (approximately 80% of which comes from $D_s \to \tau^-\bar{\nu_\tau}$) [1]. The upper limit on the branching ratio was found to be

$$\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$

This is the first result on this decay mode that has been pursued in a hadronic environment. The current best experimental upper limit comes from the Belle Collaboration: $\mathrm{BR}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% C.L. [2]. Thus the LHCb measurement of this quantity is comparable in spite of the harsh environment of hadronic collisions. It is worth noticing that this result is based on a one-third of the total LHCb dataset.

The results for two decay modes that violate both baryon number and lepton flavour, $\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \bar{p}\mu^+\mu^-$, are:

$$\mathrm{BR}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7} \text{ at } 90\% \text{ C.L.}$$

$$\mathrm{BR}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7} \text{ at } 90\% \text{ C.L.}$$

These results represent the first direct experimental limits on these channels.

2.2. $B_s^0 \to e^\pm\mu^\mp$ and $B^0 \to e^\pm\mu^\mp$ decays

The decays $B^0_{(s)} \to e^\pm\mu^\mp$ are forbidden within the SM. One of the scenarios beyond the SM that allows these decays is the Pati–Salam model of leptoquarks [3]. This model predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons, that carry both color and lepton quantum numbers.

The search for the decays $B^0_{(s)} \to e^\pm\mu^\mp$ has been performed with a data sample corresponding to an integrated luminosity of 1.0 fb^{-1} [4]. The observed number of candidates is consistent with the background expectation. Upper limits on the branching ratios of both decays have been determined:

$$\mathrm{BR}\left(B_s^0 \to e^\pm\mu^\mp\right) < 1.1(1.4) \times 10^{-8} \text{ at } 90\% \text{ } (95\%) \text{ C.L.}\,,$$

$$\mathrm{BR}\left(B^0 \to e^{\pm}\mu^{\mp}\right) < 2.8(3.7) \times 10^{-9} \text{ at } 90\% \ (95\%) \text{ C.L.}$$

These limits are the most restrictive to date and are a factor of 20 lower than those set by any previous experiment [4].

2.3. Majorana neutrino search

New Physics models with Majorana neutrinos can be tested within LNV processes. The observation of neutrino oscillation indisputably established that neutrinos have non-zero mass which allows to perform the analysis of the Majorana nature of neutrinos via the LNV processes involving charged leptons in the final states. LHCb carries out such searches in a broad class of exclusive B and D meson decays. These searches showed that $B^- \to \pi^+\mu^-\mu^-$ process, illustrated in Fig. 1, is the most sensitive in B meson decays [5].

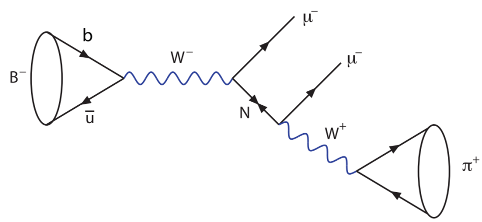

Fig. 1. Feynman diagram for $B^- \to \pi^+\mu^-\mu^-$ decay via a Majorana neutrino labeled N.

So far, a search for heavy Majorana neutrinos in B^- decays using final states containing a hadron and dimuon pair was performed at the LHCb with 0.41 fb^{-1} of data collected at the centre-of-mass energy of 7 TeV. That search was only sensitive to Majorana neutrinos with short lifetimes of the order of 1 ps. Since in the B^- signal region no statistically significant signal has been found, an upper limit has been set

$$\mathrm{BR}\left(B^- \to \pi^+\mu^-\mu^-\right) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ C.L. [5]}\,.$$

3. An update for Majorana neutrino search

As mentioned above, previous LHCb studies at $B^- \to \pi^+\mu^-\mu^-$ decay quoted the branching ratio for short lifetimes of the order of 1 ps. An update of this analysis has been performed with 3.0 fb^{-1} of data. Since the lifetimes of Majorana neutrinos are not predicted, it is assumed that they are long enough that the natural decay width is narrower than the mass resolution, which varies between 0 and 20 MeV, depending on the mass. Improved selection criteria allowed for efficient detection of neutrinos with lifetimes up to 1 ns.

The upper limit that has been set led to an improvement in neutrino mass dependent upper limits on the coupling of a single fourth generation Majorana neutrino to muons. The strategy of the search includes two selections for the signal candidates, taking into account the neutrino lifetime. The first one, similar to the previous analysis where neutrino has zero lifetime, is based on the search for a B decay vertex formed by three tracks. The second selection for neutrinos that have non-zero lifetime reconstructs two decay vertices: one for the B vertex and the other one for the neutrino decay vertex.

The reconstructed neutrino mass resolution depends on the invariant mass of the neutrino. Considering this, candidates were required to be within the B signal window for both selections. Taking these two points together, upper limits on the branching ratio for this process have been set as a function of the neutrino mass and lifetime.

To normalize the branching ratio of the decays to heavy neutrinos, the well measured decay channel $B^- \to J/\psi(\to \mu^+\mu^-)K^-$ has been used. The invariant mass spectrum of the selected candidates for the normalization channel is shown in the left plot of Fig. 2. The normalization was obtained from the number of $J/\psi K^-$ events and the known rate of $\mathrm{BR}(B^- \to J/\psi K^-, J/\psi \to \mu^-\mu^-) = 6.037 \times 10^{-5}$ [6, 7]. The middle plot of Fig. 2 shows the invariant mass distribution with fits overlaid of candidate mass spectra for the first selection and the right plot for the second selection.

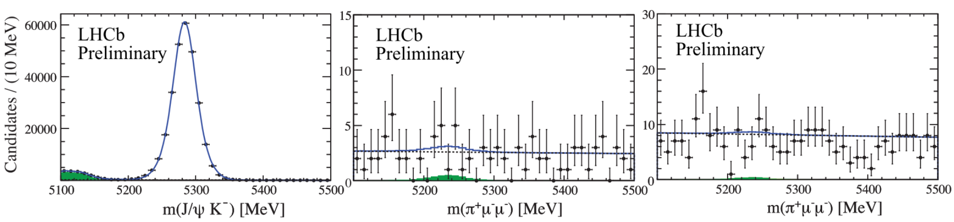

Fig. 2. Invariant mass distributions with fits overlaid of candidate mass spectra for $J/\psi K^-$ (left), $\pi^+\mu^-\mu^-$ for short lifetime (middle), and $\pi^+\mu^-\mu^-$ for long lifetime (right). Backgrounds that peak under the signal in middle and right-hand side figures are gray/green shaded. The dotted lines show the combinatorial backgrounds only. The solid lines indicate the sum of both backgrounds.

Taking the average detection efficiency for the first selection (for short lifetime neutrinos) the following upper limit on branching fraction has been found at 95% C.L. and a total systematic uncertainty 6.6%: $\mathrm{BR}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$.

From the searches for a signal as a function of the neutrino mass, no evidence for a signal has been found, and thus the upper limit was set at 95% C.L. The result of this scan is presented in Fig. 3.

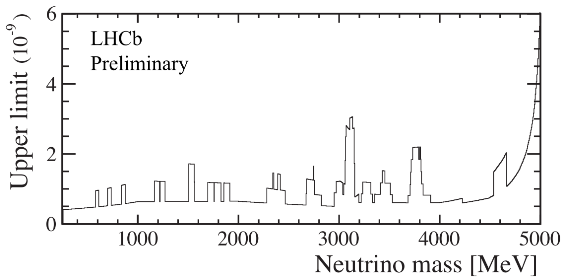

Fig. 3. Upper limit on $\mathrm{BR}(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of neutrino mass with 5 MeV intervals, $\pm\sigma$ search window at each step (σ — neutrino mass resolution) for the short lifetime selection.

Taking into account the detection efficiency dependence on the neutrino lifetime and the neutrino mass, a two-dimensional scan for the upper limit has been done. Results are presented in Fig. 4. This scan covers neutrino masses up to 5 GeV with a step size of 5 MeV and lifetimes up to 1 ns with a step size of 100 ps.

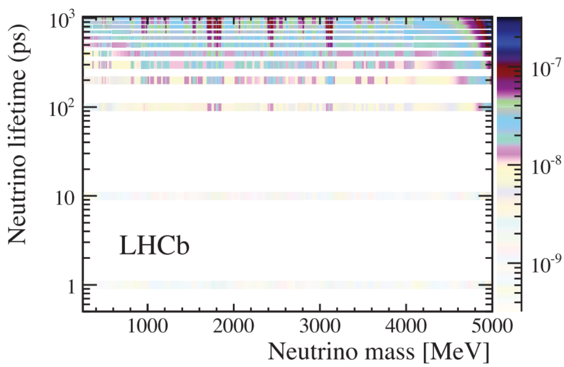

Fig. 4. Upper limit on $\mathrm{BR}(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of neutrino mass for specific lifetimes. The upper limit at 1 ps lifetime is approximately 10^{-9}.

The calculations of the limits on the coupling of putative Majorana neutrinos to leptons were presented in Ref. [8]. Using that model, limits on branching fraction can be converted to limits on the coupling. Such a method was used and limits on the coupling were set at 95% C.L. as a function of neutrino mass between 250–5000 MeV and for lifetimes up to ~ 1 ns, shown in Fig. 5. This results cannot be directly compared with other experiments up to date. This is because the transformation from branching ratio to the coupling strength requires model dependent calculations.

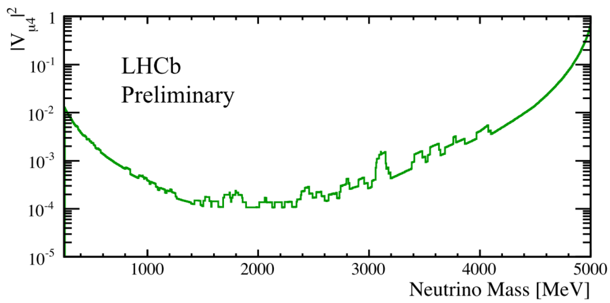

Fig. 5. Upper limits at 95% C.L. of the Majorana neutrinos coupling to muons as a function of neutrino mass for the long lifetime selection.

4. Conclusion

The LHCb physics programme includes a broad class of analyses with baryon and lepton number violation. Results for searches in tau lepton decays, $B^0_{(s)} \to e^\pm \mu^\mp$ decays and an update of a Majorana neutrino search was presented. Results from this latest analysis supersede previous LHCb results. The measurements of upper limits are the most restrictive to date.

The author of this document is encompassed by the scholarship program performed at the Marian Smoluchowski Kraków Research Consortium "Matter–Energy–Future" granted by the status of a Leading National Research Centre (Polish acronym: KNOW) in years 2012–2017 in science. This research was supported in part by PL-Grid Infrastructure.

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