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Search for lepton flavour violation at LHCb

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Abstract

We report the first searches for lepton flavour violating τ decays at a hadron collider. In particular, a search for the decay $\tau \to \mu\mu\mu$ is presented, using data corresponding to an integrated luminosity of 1.0 fb^{-1} collected at 7 TeV by LHCb in 2011. The upper limit on the branching ratio could be set, $B(\tau^- \to \mu^+\mu^-\mu^-) < 8.0 \times 10^{-8}$ at 90 % confidence level (the inclusion of the charge conjugate process is included).

In addition, we report on the search for heavy Majorana neutrinos in lepton number violating $B^- \to \pi^+\mu^-\mu^-$ decay (as well as in its charge conjugate). In this case, the whole LHCb dataset is used (1.0 fb^{-1} at $\sqrt{s} = 7$ TeV and 2 fb^{-1} at $\sqrt{s} = 8$ TeV). No signal is found, and a limit on the branching ratio is set, $\mathrm{B}(B^- \to \pi^+\mu^-\mu^-) < 4 \times 10^{-9}$ at 95 % confidence level. This limit is then used to set limits on the coupling between the hypothetical Majorana neutrino and muons.

Keywords: lepton flavour violation, lepton number violation, Majorana neutrinos, Rare Decays, LHCb

1. Introduction

The introduction of mass terms for neutrinos in the Standard Model (SM) allows lepton flavour violation in the charged lepton decays, but with very low predicted branching fractions, of the order of 10^{-40} within the SM [1]. Some beyond the Standard Model (BSM) theories predict larger values for the branching fractions, e.g., [2], that could be reachable at the LHC [3].

The LHCb experiment has good sensitivity to these τ decays due to the copious production of τ leptons at $\sqrt{s} = 7$ TeV (mainly coming from D_s mesons) and the clean experimental signature provided by the three muons. The current limits on the branching ratio for this channel are 3.3×10^{-8} from BaBar [4] and 2.1×10^{-8} from Belle [5] at 90 % confidence level.

On the other hand, lepton number violation (LNV) is forbidden in the SM, although allowed through lepton mixing by non-SM particles, such as Majorana neutrinos. In LHCb, we can search for the presence of these Majorana neutrinos by looking for decays of charged B mesons to final states with like-sign leptons. These decays are forbidden in the SM, but are possible through the exchange of an on- or off-shell Majorana neutrino. The existence of these decays translates into the existence of new physics.

2. Search for lepton flavour violating $\tau \to \mu\mu\mu$ decays

The analysis of the $\tau \to \mu\mu\mu$ decay at LHCb uses an integrated luminosity of 1 fb^{-1} of pp collision data collected at $\sqrt{s} = 7$ TeV [6].

A cut-based selection is applied. Requirements on the track identification and track quality criteria as well as cuts in the μ transverse momentum and the displacement of the tracks with respect to the primary vertex are applied. Regarding the tau lepton, a good quality vertex is required and the decay length should be larger than 100μm. The cut-based selection also includes requirements concerning the pointing angle between the momentum vector of the τ lepton and the line that links the primary and the decay vertices. Vetoes on the di-muon mass are applied to deal with backgrounds comprising $\phi(\mu\mu)$ and $\eta(\mu\mu\gamma)$ (for the case of the ϕ, the decay would

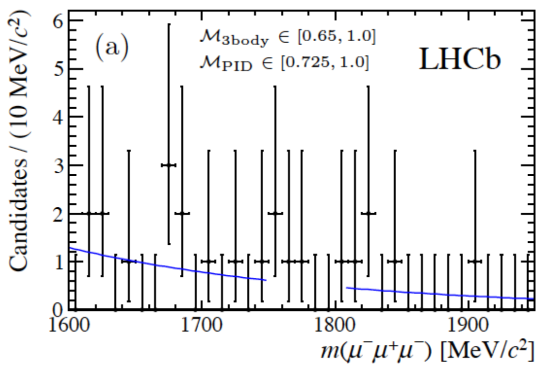

Figure 1: Invariant mass distribution and fit to the sidebands in data for three muon candidates in the four merged bins that contain the highest signal probabilities.

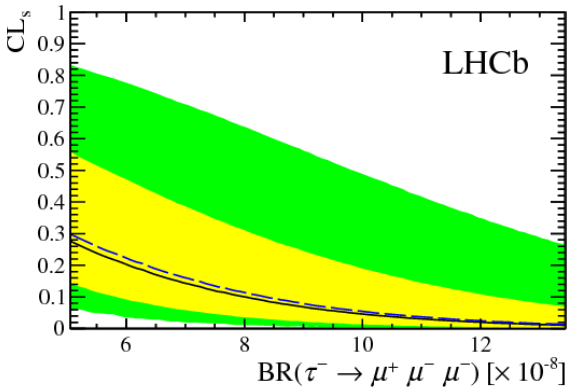

Figure 2: Calculation of the branching ratio for the $\tau \to \mu\mu\mu$ decay as a function of the CL_s method output.

be $D_s \to \phi\pi$, where the π is incorrectly identified as a μ). The signal region is defined by $\pm 20\,\mathrm{MeV/c^2}$ around the τ nominal mass.

To increase the sensitivity of the analysis, the data sample is binned using three different variables:

- Three-body-like likelihood M_{3body}: A boosted decision tree method [7] combines the IP and IPχ^2 of the tracks, the transverse momentum of the τ, the vertex quality and the vertex displacement.
- PID likelihood M_{PID}: Neural network with information from variables coming from the RICH detectors, the calorimeters and the muon stations.
- The invariant mass of the three muon system.

The binning is optimized for M_{3body} and M_{PID} to maximise the sensitivity. The invariant mass is divided into equally wide bins in the signal region. Different channels are used for the calibration. For the M_{3body}, the chosen one is $D_s \to \phi(\mu\mu)\pi$ and for the M_{PID} the chosen one is $J/\psi \to \mu\mu$.

Combinatorial background dominates the data sample. The number of these events is calculated by fitting the mass of the τ candidates outside the signal region for each of the M_{3body} and M_{PID} bins. No evidence of an excess of signal candidates is found, as shown in Fig. 1, so the CL_s method [8] is used to set the upper limit on the branching fraction of the $\tau \to \mu\mu\mu$ decay:

$$B(\tau^- \to \mu^+\mu^-\mu^+) < 8.0 \times 10^{-8} \text{ at } 90\,\%\text{ CL}$$

This is the first upper limit obtained for this kind of decay at a proton collider. Fig 2 shows how the branching ratio limit has been calculated with respect to the CL_s method output.

The search was for violating τ decays was also performed for the $\tau \to p\mu\mu$ decay, resulting in a branching ratio limit [6].

3. Searches of Majorana neutrinos in B$^+$ decays

In this case, the analysis makes use of the complete LHCb dataset, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$ ($1\,\mathrm{fb}^{-1}$ from 2011, taken at a centre of mass energy of 7 TeV and $2\,\mathrm{fb}^{-1}$ from 2012, taken at a centre of mass energy of 8 TeV).

Processes in which two like-sign leptons are found in the final state are forbidden in the SM (lepton number is conserved in the SM, even if the lepton flavour is not), but are one of the most sensitive ways to look for Majorana neutrinos of any mass produced on-shell. The analysis [9] is based on a previous analysis [10] but it extends the sensitivity to neutrino lifetimes (τ_N) from 1 ps to 1000 ps and divides the analysis in two different strategies. The selection includes cuts on the momentum of the muons in order to reduce tracks and demands high quality regarding the track resolution. The chosen normalization channel $B^- \to J/\psi K^-$ where the J/ψ resonance decays to a pair of muons. The requirements related to the vertex formed by the tracks are different for the different strategies.

The CL_s method is used to set upper limits. The signal region is defined as the mass interval within $\pm 2\sigma$ of the charged B meson mass, where σ is the mass resolution. The detection efficiency varies as a function of the neutrino mass m$_N$. At 95 % confidence level, the following limit is found:

$$B(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$$

A signal as a function of the neutrino mass is also searched for. No evidence for a signal is found, and upper limits on the coupling of the hypothetical Majorana neutrino and muons can be set by scanning the m_N spectrum and making use of the following formula by Atre *et al.*[11]:

$$B(B^- \to \pi^+\mu^+\mu^-) = \frac{G_F^4 f_B^2 f_\pi^2 m_B^5}{128\pi^2\hbar}|V_{ub}V_{ud}|^2 \times \tau_B(1 - \frac{m_N^2}{m_B^2})\frac{m_N}{\Gamma_N}|V_{\mu 4}|^2$$

This limit does not take into account the Majorana neutrino mass, which is the sum of the mass of the μ and the π for an on-shell Majorana neutrino and assumes that it is short lived. The total neutrino decay width is a function of the neutrino mass and is proportional to $|V_{\mu 4}|$. To set limits on the coupling, a model for the decay width is required. The purely leptonic modes are specified in [11]. For the hadronic modes we use the fraction of times the charged current manifests itself as a single charged pion in τ^- and B^- decays, giving an additional m_N^3 dependent factor in the decay width. With all this, the decay width can be written as [6]:

$$\Gamma_N = [3.95 m_N^3 + 2.00 m_N^5 (1.44 m_N 3 + 1.14)] \times 10^{-13} |V_{\mu 4}|^2$$

where both the mass and the decay width are in GeV. The upper limit is calculated by assuming a value for the coupling and then calculate the decay width. This allows a determination of the τ_N dependent detection efficiency. Fig 3 shows the coupling value as a function of the Majorana neutrino mass.

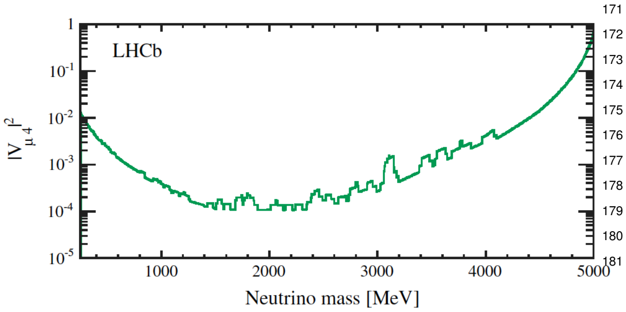

Figure 3: Value of the coupling of the Majorana neutrino to muons as a function of the mass of the neutrino.

4. Conclusions

The search for lepton flavour violation and heavy Majorana neutrinos has been presented.

For the first case, clean τ decays into three μ have been studied. No signal found, and the first limit at a hadron collider has been established.

Regarding Majorana neutrinos, a limit on the branching ratio for the $B^+ \to \pi^-\mu^+\mu^+$ decay is set and the result is used to set limits on the coupling between the hypothetical fourth generation Majorana neutrinos and muons.

Since ICHEP 2014, the LHCb experiment has updated its analysis of $\tau \to \mu\mu\mu$, using a dataset corresponding to 3 fb^{-1} [12]. Using this larger dataset, LHCb sets a limit on the branching ratio for $\tau \to 3\mu$ of 4.6 $\times 10^{-8}$ at 90 % CL.

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