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ELEMENTARY PARTICLES AND FIELDS
Experiment

The Lepton Flavor Violating Decay $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ at LHCb*

A. Keune**

Laboratoire de Physique des Hautes Energies, Ecole Polytechnique Fédérale de Lausanne, Switzerland

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Abstract—The possibility of improving the limit on the branching fraction of the lepton flavor violating decay $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ at LHCb is discussed. It is shown that a simple, cut-based analysis is sufficient to improve the upper limit on this branching fraction within the lifetime of LHCb.

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1. INTRODUCTION

Lepton flavor conservation is explicitly assumed in the Standard Model. However, with the discovery of neutrino oscillations, establishing that lepton flavors mix in the neutral sector, it is conceivable to have lepton flavor violating charged lepton decays. Lepton flavor conservation in the charged sector is measured to a high precision, but is not a consequence of a known gauge symmetry; almost every model beyond the Standard Model predicts lepton flavor violation. With the known neutrino oscillation contribution immeasurably small, any observation of lepton flavor violation would imply New Physics.

The lepton flavor violating decay $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ is an ideal decay mode for LHCb to probe. The muons are easily identified and triggered upon. The mode can be reconstructed with high efficiency and precision, using the vertex detector which is specifically designed to identify secondary vertices. This results in a precise determination of the τ-vertex location and an excellent τ-mass resolution (σ), since there is no missing neutrino. As most τ's come from b and c hadrons, its vertex will be sufficiently displaced to pass the impact parameter requirements, designed to select B mesons in the LHCb trigger.

2. NEW PHYSICS PREDICTIONS AND CURRENT LIMITS

The $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ branching fraction through neutrino oscillation is proportional to the term $(m_\nu/m_W)^4 \sim 10^{-50}$, where m_ν and m_W are the neutrino and W mass, respectively. This allowed branching fraction is thus undetectable. Its decay diagram is depicted in Fig. 1. New Physics models, like mediating boson models or supersymmetry (SUSY) models, predict much higher branching fractions. The nonuniversal Z' model predicts a branching fraction of the order 10^{-8} [1], whereas the minimal supersymmetric model predicts it to be 10^{-9} [2]. These decay diagrams are depicted in Figs. 2 and 3, respectively.

Upper limits on the branching fraction have been set by BaBar and Belle. BaBar has obtained a limit of 3.3×10^{-8} [3], but the strongest limit of 2.1×10^{-8} [4] is currently set by Belle at a 90% confidence limit. These limits are in the range of many New Physics predictions and any improvement will have a direct effect on the understanding of New Physics.

3. $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ SIGNAL AND BACKGROUND AT LHCb

The total τ cross section at LHCb is estimated to be $\sim$111 μb at $\sqrt{s} = 14$ TeV. A nominal year (10^7 s) of data taking yields 2 fb^{-1} of data and 2.22×10^{11} τ particles will be produced. The geometrical efficiency of the tauons decaying to three muons, i.e. all three daughters are in the acceptance of LHCb ($10 < \theta <$ 400 mrad), is estimated from the Monte-Carlo (MC)

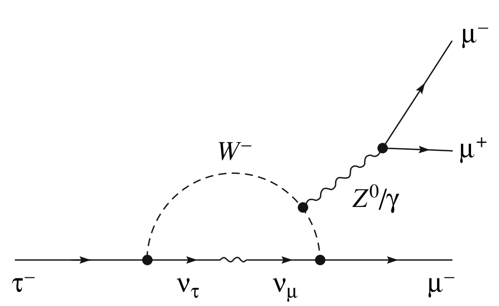

Fig. 1. Feynman diagram of the lepton flavor violating decay $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ through neutrino oscillation.

*The text was submitted by the author in English.

**E-mail: anne.keune@epfl.ch

simulation to be ∼19.5%. The branching fraction of this decay is currently known to be smaller than 2.1×10^{-8} (Belle's limit). There are therefore less than 910 signal events in LHCb per nominal year. The reconstruction efficiency, with minimal pre-selection, is ∼25%, resulting in less than 228 signal events before applying any selection criteria.

Around half, 52% of the signal, of τ's come from prompt D_s mesons, 34% come directly from B mesons and the remaining 14% come from D_s mesons through B-meson decays. The main source of background originates from di-muons produced in b and $\bar{b}$ quark decays associated with one random track. Other sources of background considered are the light quark events and inclusive $c\bar{c}$ events. An optimal selection can be made using different selection methods for the different τ sources, however, due to the similar τ property distributions, all τ sources will initially be treated simulatenously. In addition, it is noted that the di-muon background sample most resembles the signal. A selection strategy that fully suppresses this source is sufficient to remove all events from other background types, as was checked in MC simulation.

For this study a background sample of ∼15M di-muon events with candidates within a mass window of $\sim 10\sigma$ ($\Delta m_\tau = 200$ MeV) are considered. This sample is equivalent to 1/377 of a nominal year of data. The normalization factor needed for the signal events depends on the unknown branching fraction. It is 0.0104 for a branching fraction of 1×10^{-8}.

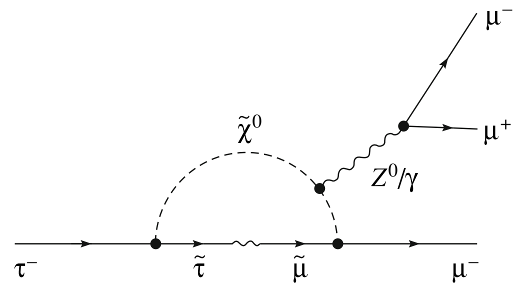

Fig. 3. The decay diagram of $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ through slepton mixing as predicted by the minimal supersymmetric model.

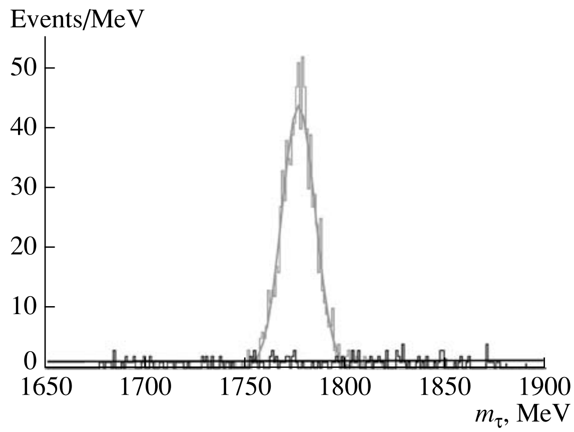

Fig. 4. The mass distributions of the MC true signal candidates (gray) and the background candidates (black) before the particle identification cut.

4. A CUT-BASED SELECTION

Rough initial cuts are made on individual kinematic and geometrical variables, assuming zero correlation between them. The cuts are tuned to optimize the signal significance, defined as $s/\sqrt{s+b}$, where s and b are the number of selected signal and background events, both normalized to the same size data set. For the uncorrelated variables this is indeed the optimal cut value. For the variables that exhibit some interdependence, these cuts are loosened by exploiting their relative correlations.

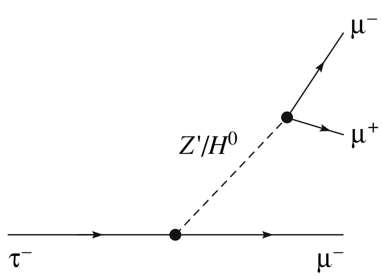

Fig. 2. The decay diagram of $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ through a mediating anomalous Z' boson or Higgs as predicted by the nonuniversal Z' model or any mediating Higgs model.

The strongest cuts are made on the χ^2 of the τ end-vertex and the particle identification likelihood of each muon. Both variables are uncorrelated to any other. The mass distributions of the signal and background candidates before the particle identification cut are shown in Fig. 4. The third strongest cut is made on the χ^2 of the muon impact parameter. This variable is highly correlated to the actual impact parameter of the muon and the flight distance of the τ (especially for the signal candidates).

5. FIRST RESULTS

By applying the selection cuts, an efficiency of ∼5% is obtained. Candidates in events, which have not passed the L0 hardware trigger, are also excluded from the selection.

This simple selection leaves 526 signal events and 1 background event in a wide mass window ($\Delta m_\tau =$ 200 MeV). Selecting a smaller signal mass window of $\sim 2\sigma$ ($\Delta m_\tau = 40$ MeV) there are 511 signal events left; the background is scaled linearly to $1/5 = 0.2$ of expected background events. As the normalization factor for the di-muon sample is 377, the total expected background in this mass window is $75.4 + 2\sqrt{75.4} \simeq 93$ candidates. Although the selection was only done using the di-muon sample, it has been verified that the same event selection has also cut away 100% of the available minimum bias and inclusive c backgrounds. As the normalization factor of the signal is 0.0104 for a branching fraction of 1×10^{-8}, an upper limit on the branching fraction of 3.2×10^{-8} can be set within one nominal year of data taking with a confidence level of 90%. This number matches BaBar's current limit, but would not be an improvement on Belle's limit.

Within the lifetime of LHCb, which corresponds to 10 fb^{-1}, the branching fraction can be probed down to 1.3×10^{-8}. Thus, it is seen that even with a simple selection procedure an improved limit on the $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ branching fraction will be set within the lifetime of LHCb.

6. FURTHER WORK

The single background candidate left in the selection consists of one muon coming from a D_s decay, a second muon from a $D^\pm$ decay and one ghost track. A better choice of cut variables, for instance considering vertex isolation, may also eliminate the last background candidate.

An improved selection efficiency of 8% using more advanced selection methods is considered realistic. The current upper limit on the branching fraction would then be reached within one nominal year of LHCb data taking.

Using the first data the detector effects are currently being studied and the event generator tuned. Following this work, the selection on the simulation can be further refined.

7. CONCLUSION

A simple, cut-based selection is sufficient to show that within the lifetime of LHCb new limits will be set on the $\tau^\pm \to \mu^\pm\mu^\pm\mu^\mp$ branching fraction.

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