Searches for exotica at LHCb

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Abstract

Direct and indirect searches for the existence of particles beyond the Standard Model can be performed at the LHCb detector exploiting its unique forward acceptance, high vertex and momentum resolution, and excellent particle identification. In these proceedings, the latest results obtained with the LHCb detector are presented, focusing on rare \( \tau \) and \( B \) decays and on decays involving \( b\bar{b} \) pairs in the final state.

Keywords: LHCb, Exotics, New Physics

1. Introduction

Many theoretical models predict the existence of new particles, where their existence can be detected either directly through the production of on-shell particles or indirectly through virtual contributions in loop processes. Physics beyond the Standard Model (SM) via the production of these particles has been searched for at the LHC without success so far. The results provided by the LHCb experiment contribute both to the direct and to the indirect searches. During the first run of \( pp \) collisions at the LHC, the LHCb detector [1] has collected an integrated luminosity of 1 fb\(^{-1}\) and 2 fb\(^{-1}\) of data at a center-of-mass energy of 7 and 8 TeV, respectively. In these proceedings, the indirect searches in lepton and baryon number violating \( \tau \) and \( B \)-meson decays, and the direct searches in decays with \( b\bar{b} \) pairs in the final state are presented. Very rare \( \tau \) and \( B \) decays are strongly suppressed in the SM and are only produced via loop diagrams. High-mass particles can contribute virtually to the loop modifying the total branching fraction of the process. In this context, the indirect search for the presence of new particles can reach masses well beyond the current energy limit provided by the accelerators, and can provide an unambiguous signature of physics beyond the Standard Model (BSM). As far as the direct searches are concerned, the excellent capabilities in the reconstruction of displaced vertices and the high momentum resolution of the LHCb detector makes it an ideal place to look for the presence of new particles decaying into \( b\bar{b} \) pairs.

2. LFV and BNV in \( \tau \) decays

Lepton flavour violating (LFV) processes are allowed within the context of the SM with massive neutrinos, but their branching fractions are of order \( 10^{-40} \) [2, 3] or smaller, and have not yet been observed to date. Baryon number violation (BNV) is believed to have occurred in the early universe, although the mechanism is unknown. If charged LFV or BNV were to be discovered, measurements of the branching fractions for a number of channels would be required to determine the nature of the BSM physics. In the absence of such a discovery, improving the experimental constraints on the branching fractions for LFV and BNV decays would help to constrain the parameter spaces of BSM models. The search for LFV and BNV in \( \tau \) decays at LHCb [4] takes advantage of the large inclusive \( \tau \) production cross-section at the LHC, where \( \tau \) leptons are produced almost entirely from the decays of \( b \) and \( c \) hadrons. Using the \( b\bar{b} \) and \( c\bar{c} \) cross-sections measured by LHCb [5, 6] and the inclusive \( b \to \tau \) and \( c \to \tau \) branching fractions [7], the inclusive \( \tau \) cross-section is estimated to be 85 \( \mu b \) at 7 TeV.
The LFV decay $\tau^+ \rightarrow \mu^+\mu^+\mu^-$ is searched using 1 fb$^{-1}$ of $pp$ collision data at a center-of-mass energy of $\sqrt{s} = 7$ TeV. No evidence of an excess of signal candidates over the expected background is observed, so the CL$_s$ method [8] is used to set an upper limit on the branching fraction of the process. Figure 1 shows the distribution of the CL$_s$ values as a function of the tau branching fraction into three muons.

The result obtained is

$$\mathcal{B}(\tau^+ \rightarrow \mu^+\mu^+\mu^-) < 8.0 \times 10^{-8} \text{ at } 90\% \text{ CL}_{s\nu},$$  

which is compatible with previous limits. An updated result using 3 fb$^{-1}$ of data has been recently published [9] yielding a result of

$$\mathcal{B}(\tau^+ \rightarrow \mu^+\mu^+\mu^-) < 4.6 \times 10^{-8} \text{ at } 90\% \text{ CL}_{s\nu},$$  

which can start contributing to the world average when included with the results of BaBar and Belle [10, 11]. This result represents the first limit on the lepton flavour violating decay mode $\tau^+ \rightarrow \mu^+\mu^+\mu^-$ obtained at a hadron collider and indicates that with the additional luminosity expected from the LHC in Run II, the sensitivity of LHCb will become comparable with, or exceed, those of the B-factories.

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3. Searches for Majorana neutrinos

The lepton number violating process $B^- \rightarrow \pi^0\mu^-\mu^-$ is forbidden in the SM, but can proceed via the production of on-shell Majorana neutrinos or on off-shell Majorana neutrinos of any mass contributing to this decay. Using the full data sample of Run I corresponding to 3 fb$^{-1}$ of data acquired in $pp$ collisions LHCb has investigated the $B^- \rightarrow \pi^0\mu^-\mu^-$ decay [12].

Upper limits as a function of both the neutrino mass $m_N$ and the neutrino lifetime $\tau_N$ are set by performing a scan in the neutrino mass from 250 to 5000 MeV/c$^2$, for individual lifetime values between 1 and 1000 ps. As there is no evidence of signal, upper limits are set using

First direct upper limits have been placed on the branching fractions for two $\tau$ decay modes that violate both baryon number and lepton flavour, $\tau^- \rightarrow \bar{p}\mu^+\mu^-$ and $\tau^- \rightarrow p\mu^-\mu^-$. Using a similar procedure as the one explained above, the CL$_s$ value as a function of the branching fraction has been evaluated for these decays, and are shown in Figs. 2 and 3, from where limits on the branching fraction of the processes can be extracted to be

$$\mathcal{B}(\tau^- \rightarrow \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7} \text{ at } 90\% \text{ CL}_{s\nu},$$  

$$\mathcal{B}(\tau^- \rightarrow p\mu^-\mu^-) < 4.4 \times 10^{-7} \text{ at } 90\% \text{ CL}_{s\nu}.$$
the CLs method. The model independent upper limit of $\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-)$ as a function of the neutrino mass for six different neutrino lifetimes is plotted in Fig. 4.

Model-dependent upper limits on the coupling of a single fourth-generation Majorana neutrino to muons $|V_{\mu 4}|$ for each value of $m_N$ are extracted using the formula from Atre et al. [13]

$$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) = \frac{G_F^2 f_N^2/m_h^2}{128\pi^2 \hbar} |V_{\mu 4}|^2 \times \tau_B (1 - m_N^2/m_{\pi}^2)^{1/2} \Gamma_N |V_{\mu 4}|^2$$

where the total neutrino decay width, $\Gamma_N$, is a function of $m_N$ and is proportional to $|V_{\mu 4}|^2$. A model for $\Gamma_N$ including the purely leptonic and hadronic modes is used, where the total width for Majorana neutrino decay is

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

with $m_N$ and $\Gamma_N$ in GeV/c². Values of $\Gamma_N$ are calculated for each value of $m_N$ and of $|V_{\mu 4}|^2$, which are then used to find the branching fraction. The resulting 95% CLs limit on $|V_{\mu 4}|^2$ is shown in Fig. 5 as a function of $m_N$.

These limits cannot be directly compared to other experiments due to the different choice of the dependence of $\Gamma_N$ on $m_N$. The limits on the $B^- \to \pi^+ \mu^- \mu^-$ branching fraction are improved with respect to the previous results [14], and the lifetime range of the Majorana neutrino search has been extended to 1 ns.

4. Higgs-like bosons decaying into long-live particles

A variety of models for physics beyond the Standard Model feature new massive Long-Lived Particles (LLP) which coupling to lighter particles is sufficiently small that they may have a macroscopic distance of flight. If they decay to SM particles and have a lifetime in the range [1-1000] ps, characteristic of weak decays, these particles can be identified using the excellent vertex resolution of the LHCb detector.

In the framework of weak scale supersymmetry with R-parity violation the lightest super partner may decay into SM particles [15]. In particular, it has been proposed that the lightest neutralino $\tilde{\chi}_1^0$ may decay into three quarks [16]. A significant portion of the parameter space of the model allows for the production of $\tilde{\chi}_1^0$ pairs through the decay of the light Higgs boson $h^0$ with a mass between 110–130 GeV/c², implying a $\tilde{\chi}_1^0$ mass in the range 20–60 GeV/c². At a small value of tan$\beta$, the SUSY $h^0$ is essentially equivalent to the SM Higgs boson, and a production cross-section of about 20 pb at 7 TeV in $pp$ collisions is expected.

A more general model called the “Hidden Valley” scenario [17, 18] makes the hypothesis that an additional non-abelian gauge group exists, so far “hidden”
by a large energy scale, which may be accessible at the LHC. This new sector can manifest itself by the production of new scalar particle, \( \pi \), that decay into SM particles. If the mass of the \( \pi \) is below the ZZ mass threshold it will predominantly decay into \( b\bar{b} \) pairs. Moreover, the Higgs boson may possibly decay with a significant branching fraction as \( h \rightarrow \pi \pi \rightarrow b\bar{b}b\bar{b} \). Another characteristic of the new Hidden Valley scalars is that the lightest among them is a potential dark matter candidate.

All these models have in common the presence of several displaced \( b \)-jets in the final state. Using 35 \( pb^{-1} \) of data collected at a center-of-mass energy of \( \sqrt{s} = 7 \) TeV, limits on the production cross-section of the Higgs like boson particle as a function of the LLP mass and lifetime are set [19].

The approximate sensitivity range cover LLP lifetimes from 3 to 25 ps, for masses from 30 up to 55 GeV/c\(^2\) and Higgs masses in between 100–125 GeV/c\(^2\). No events compatible with the expected topology have been found, so limits in the production cross-section have been placed as a function of LLP and Higgs masses, and LLP lifetime.

The results show that for a Higgs with mass between 100–125 GeV/c\(^2\), decaying to two heavy particles with masses between 30–55 GeV/c\(^2\) and a lifetime of 10 ps we can exclude production cross-sections between 29 and 179 \( pb \) (see Tab. 1). For the same range of LLP masses and a fixed Higgs mass of 114 GeV/c\(^2\), the lifetime window of 3–25 ps can be excluded with cross-section upper limits from 25 to 410 \( pb \) (see Tab. 2). All the results are consistent with SM and do not indicate the presence of New Physics contributions. A publication with more than twenty times the statistics is in preparation.

Table 1: Upper limits at 95 % CL\(_s\) on the cross-section in \( pb \) for the production of a Higgs boson, as a function of the LLP and Higgs masses for a LLP lifetime of 10 ps for the SUSY with R-parity violation model.

<table>
<thead>
<tr>
<th>( m_{\text{LLP}} ) (GeV/c(^2))</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>48</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{h^0} ) (GeV/c(^2))</td>
<td>100</td>
<td>101</td>
<td>58</td>
<td>44</td>
<td>58</td>
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<tr>
<td></td>
<td>105</td>
<td>100</td>
<td>75</td>
<td>44</td>
<td>39</td>
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<td>120</td>
<td>148</td>
<td>93</td>
<td>58</td>
<td>34</td>
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<tr>
<td></td>
<td>125</td>
<td>179</td>
<td>90</td>
<td>61</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 2: Upper limits at 95 % CL\(_s\) on the cross-section in \( pb \) for the production of a Higgs boson as a function of the LLP mass and lifetime for a Higgs mass of 114 GeV/c\(^2\) for the SUSY with R-parity violation model.

<table>
<thead>
<tr>
<th>( m_{\text{LLP}} ) (GeV/c(^2))</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>48</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{\text{LLP}} ) (ps)</td>
<td>3</td>
<td>210</td>
<td>156</td>
<td>136</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>145</td>
<td>101</td>
<td>68</td>
<td>58</td>
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<td>25</td>
<td>142</td>
<td>100</td>
<td>61</td>
<td>34</td>
</tr>
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</table>

5. Charge asymmetry in \( b \)-quark production

Measurements by the DØ and CDF collaborations of the \( \bar{t}t \) asymmetry in \( p\bar{p} \) collisions at the Tevatron [20, 21, 22, 23, 24, 25] suggest that physics beyond the Standard Model may play a role in the production of top-antitop \((\bar{t}t)\) pairs [26]. Many extensions to the SM have been proposed to explain this discrepancy. These theories couple new particles to quarks in a variety of ways. Therefore, constraints on quark-antiquark production charge asymmetries other than \( \bar{t}t \) could discriminate between models and be used as a probe of non-SM physics.

Some theories proposed to explain the Tevatron results also predict a large charge asymmetry in \( b\bar{b} \) production [27]. No measurement has been made to date of the \( b\bar{b} \) charge asymmetry at a hadron collider.

The symmetric initial state of proton-proton collisions at the LHC does not permit a charge asymmetry to be manifest as an observable defined using the direction of one beam relative to the other. However, the asymmetry in the momentum fraction of quarks and antiquarks inside the proton means that a charge asymmetry can lead to a difference in the rapidity distributions of beauty quarks and antiquarks. The forward-central \( b\bar{b} \) charge asymmetry in \( pp \) collisions is defined as

\[
A_C \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},
\]

where \( \Delta y \equiv |y_b| - |y_{\bar{b}}| \) is the rapidity difference between jets formed from the \( b \) and \( \bar{b} \) quarks.

A first measurement of this type of asymmetry in three \( M_{bb} \) regions using 1 fb\(^{-1} \) of data collected at center-of-mass energy of 7 TeV is presented [28]. Figure 6 shows the corrected \( \Delta y \) distribution summed over all \( M_{bb} \) regions considered \((M_{bb} > 40 \text{ GeV/c}^2\)). The LO
branching fraction of the $\tau^- \rightarrow \mu^- \mu^- \mu^-$ and $\tau \rightarrow p\mu\mu$ decays have been presented. The search for Majorana neutrinos either virtual or on-shell has been presented in the $B^- \rightarrow \pi^- \mu^- \mu^-$ decays where model-dependent limits on the coupling between the Majorana neutrino and the muon have been placed. Limits in the production cross-section of long-lived particles decaying into $b\bar{b}$ pairs, as well as the first measurement of the forward-central charge asymmetry in $b\bar{b}$ production have been placed.

All the results presented are consistent with the Standard Model expectations and demonstrate the excellent capabilities of the the LHCb detector as a general purpose high-resolution forward spectrometer. The upcoming Run II period will increase the collision energy, production cross-sections and acceptance of signal candidates improving the sensitivity of the analyses.

6. Conclusions

LHCb has used the large data sample available from Run I to perform studies of processes beyond the Standard Model. The first limit at a hadron machine of the SM prediction, which includes LO QCD and $Z \rightarrow b\bar{b}$, obtained from Pythia [29] is also shown. The SM uncertainty includes contributions from the renormalization and factorization scales, and from the parton distribution functions. The LO result is sufficient to demonstrate agreement between the theory and unfolded $b\bar{b}$ pair-production distribution.

The final results on the charge asymmetry in $b\bar{b}$ pair production in the three regions of $M_{b\bar{b}}$ are

$$A_C^{b\bar{b}}(40, 75) = 0.4 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (syst)}\%, \quad (8)$$

$$A_C^{b\bar{b}}(75, 105) = 2.0 \pm 0.9 \text{ (stat)} \pm 0.6 \text{ (syst)}\%, \quad (9)$$

$$A_C^{b\bar{b}}(> 105) = 1.6 \pm 1.7 \text{ (stat)} \pm 0.6 \text{ (syst)}\%, \quad (10)$$

where the ranges denote the regions of $M_{b\bar{b}}$ in units of GeV/$c^2$. The measurements are corrected to a pair of particle-level jets each with $2 < \eta < 4$ and $E_T > 20$ GeV and an opening angle between the particle-level jets in the transverse plane $\Delta \phi > 2.6$ rad. All the results are consistent with the SM expectations.

References


[10] P. del Amo Sanchez, et al., Searches for the baryon- and lepton-number violating decays $B^0 \rightarrow \Lambda^0 c\bar{c}$, $B^- \rightarrow \Lambda^+ c$, and $B^- \rightarrow \Lambda^0 c$, Phys.Rev. D83 (2011) 091101. arXiv:1101.3830, doi:10.1103/PhysRevD.83.091101.


