Lepton-number and lepton-flavour violation in B decays

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on behalf of the LHCb collaboration
Overview

• Lepton-number violation - search for Majorana neutrinos
  • $B^- \rightarrow \pi^+ \mu^- \mu^-$

• Lepton-flavour violation
  • $B_s^0 \rightarrow e \mu$ and $B^0 \rightarrow e \mu$
  • $\tau^- \rightarrow \mu^+ \mu^- \mu^-$
Rare Decays at LHCb

- Currently no sign of New Physics from direct searches

- Decays that are forbidden in SM or have very small branching fractions allow to probe contributions from new processes/heavy particles at a scale beyond that of direct searches

- Rare decay measurements used to set constraints on theories beyond the SM

- LHCb particularly well suited for rare decay searches
  - Efficient triggering
  - Excellent particle identification
  - Precise vertexing (VELO)
Lepton-number violating decay
\[ B^- \to \pi^+ \mu^- \mu^- \]

- \( B^- \to \pi^+ \mu^- \mu^- \) decay forbidden by SM as it violates conservation of lepton-number.

- May proceed via production of Majorana neutrinos – similar to neutrinoless double beta decay.

- Most sensitive B meson decay channel for Majorana searches.

- Sensitive to neutrino lifetimes up to 1000 ps and neutrino masses 250-5000 MeV.

- Previous best measurement by LHCb (0.41 fb\(^{-1}\))

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \mathcal{B} (B^- \to \pi^+ \mu^- \mu^-) \text{ (fb)} )</th>
<th>C.L.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>( &lt; 1400 \times 10^{-9} )</td>
<td>90%</td>
<td>PRD65:111102(2002)</td>
</tr>
<tr>
<td>Babar</td>
<td>( &lt; 107 \times 10^{-9} )</td>
<td>90%</td>
<td>PRD85:071103(2012)</td>
</tr>
<tr>
<td>LHCb (0.41fb(^{-1}))</td>
<td>( &lt; 13 \times 10^{-9} )</td>
<td>95%</td>
<td>PRD85:112004(2012)</td>
</tr>
</tbody>
</table>

Here neutrino is its own antiparticle.
Analysis Method

- Use full 3 fb⁻¹ of data collected by LHCb at 7/8 TeV centre-of-mass energy

- Use normalization channel \( B^- \rightarrow K^- J/\psi (\rightarrow \mu^+ \mu^-) \)

- Split selection process based on neutrino lifetime:
  
  for short \( \tau_N \leq 1 \text{ ps} \) (S)
  
  assume \( N \) has zero lifetime, \( B \) decay vertex formed by \( \pi^+ \mu^- \mu^- \) i.e. \( B^- \rightarrow \pi^+ \mu^- \mu^- \)

  for long \( \tau_N \leq 1000 \text{ ps} \) (L)
  
  \( \pi^+ \mu^- \) vertex significantly detached from \( B \), reconstruct \( B \) decay vertex and \( N \) decay vertex i.e. \( B^- \rightarrow N(\pi^+ \mu^-) \mu^- \)

282,774 ± 543 events

\( B^- \rightarrow K^- J/\psi (\rightarrow \mu^+ \mu^-) \) normalization channel
Results

• No signal observed for either S or L selection channels

• Use CLs method to set upper limit on branching fraction \[\text{[Nucl.Instrum.Meth. A434 (1999)]}\]

\[\mathcal{B}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9}\] at 95% C.L. (S)  

Best limit to date

• Detection efficiency varies as a function of \(m_N\) and \(\tau_N\)

• Calculate branching fraction upper limits (95% C.L.) as function of \(m_N\) (S) or \(m_N\) and \(\tau_N\) (L)
Results

Branching fraction upper limits as a function of $m_N$

Branching fraction upper limits as a function of $m_N$ and $\tau_N$
Results

• Set upper limits on coupling of single 4th-generation Majorana neutrino to muons $|V_{\mu 4}|$, as function of $m_N$ (95% C.L.)

\[ \mathcal{B}(B^- \rightarrow \pi^+ \mu^- \mu^-) = \frac{G_F^4 f_{B^0} f_{\pi}^2 m_{B^0}^5}{128 \pi^2 \hbar} |V_{ub} V_{ud}|^2 \tau_B \left(1 - \frac{m_N^2}{m_B^2}\right) \frac{m_N}{\Gamma_N} |V_{\mu 4}|^4 \]

[JHEP05(2009)030]

where

\[ \Gamma_N = [3.95 m_N^3 + 2.00 m_N^5 (1.44 m_N^3 + 1.14)] \times 10^{-13} |V_{\mu 4}|^2 \]
Lepton-flavour violating decays
\( \tau^- \rightarrow \mu^+ \mu^- \mu^- \)

• Decay forbidden in SM due to lepton-flavour conservation

• Observation of neutrino oscillations indicates charged LFV decays possible via loops, \( \mathcal{B} < 10^{-40} \)

• New physics can enhance branching fractions (e.g. new heavy particles entering loops, models with doubly charged Higgs) to as high \( \sim 10^{-7} \)

• Previous measurements at B factories
  Belle \( \mathcal{B} (\tau^- \rightarrow \mu^+ \mu^- \mu^-) < 2.1 \times 10^{-8} \) at 90% C.L. [PLB 687(2010) 139]
  Babar \( \mathcal{B} (\tau^- \rightarrow \mu^+ \mu^- \mu^-) < 3.3 \times 10^{-8} \) at 90% C.L. [PRD 81,111101(R) (2010)]

Electroweak penguin diagram for cLFV decay where neutrino flavour oscillates

Possible new physics decay involving doubly charged Higgs
Analysis Method

- Use 1 fb\(^{-1}\) of data collected by LHCb in 2011 at 7 TeV centre-of-mass energy

- LHCb collected \(\sim 8 \times 10^{10}\) \(\tau\) in detector acceptance in 2011 [PRB 724 (2013)]

- Normalization channel \(D_s^- \rightarrow \phi (\mu^+ \mu^-) \pi^-\)

- Study events in binned 3-D space:
  - Likelihood variable based on 3-body decay topology (BDT)
    Including vertex quality and displacement from primary vertex
  - Likelihood variable based on muon particle identification (Neural network)
    Including information from RICH, calorimeters, muon stations and kinematics
  - Invariant mass of \(\tau^-\) candidate
Results

• Number of observed $\tau^- \rightarrow \mu^+ \mu^- \mu^-$ events compatible with background expectation

• Use CLs method to set upper limit on branching fraction
  $$\mathcal{B} (\tau^- \rightarrow \mu^+ \mu^- \mu^-) < 8.0 \ (9.8) \times 10^{-8}$$
  at 90% (95%) C.L.

• First limit on $\tau^- \rightarrow \mu^+ \mu^- \mu^-$ obtained at a hadron collider

• Result compatible with limits set by Belle, expect 50 fb$^{-1}$ post upgrade
Lepton-flavour violating decays
\[ B_s^0 \rightarrow e \mu \text{ and } B^0 \rightarrow e \mu \]

- \( B_s^0 \rightarrow e \mu \) and \( B^0 \rightarrow e \mu \) forbidden by lepton-flavour conservation in SM

- Allowed in BSM models such as SUSY and Pati-Salam Leptoquark model \([\text{Phys. Rev. D 10}(1974) 275]\)

- Prediction of new interaction between leptons and quarks mediated by spin-1 gauge boson leptoquark

- Direct production searches for leptoquarks at ATLAS and CMS – only leptoquarks coupling quarks and leptons of same generation
  Lower bounds on leptoquark masses in range >0.4 to >0.9 TeV/c²

- These indirect searches probe leptoquarks which couple quarks and leptons from different generations

- Previous best branching fraction measurements from CDF \([\text{PRL 102, 201801}]\)
  \[ \mathcal{B} (B_s^0 \rightarrow e \mu) < 2.6 \times 10^{-7} \quad \mathcal{B} (B^0 \rightarrow e \mu) < 7.9 \times 10^{-8} \] at 95% C.L.
Analysis Method

- Use 1 fb$^{-1}$ of data collected by LHCb at 7 TeV centre-of-mass energy

- Use normalization channel $B^0 \rightarrow K^+ \pi^-$

- Two-stage multivariate analysis (BDT) – most important discriminating variables: B impact parameter, angle between B momentum and vector joining primary and secondary vertices

- Correct electron momenta for loss due to bremsstrahlung

- Study events in binned 2-D plane:
  - Invariant mass of B candidate
  - Output of second multivariate discriminant (BDT)

- Remaining dominant background $e\mu$ pairs originating from different B decays
Results

- Data consistent with background-only hypothesis
- Set upper limits on branching fractions using CLs method

\[ \mathcal{B}(B_s^0 \rightarrow e \mu) < 1.1(1.4) \times 10^{-8} \]
\[ \mathcal{B}(B^0 \rightarrow e \mu) < 2.8(3.7) \times 10^{-9} \] at 90% (95%) C.L.

\[ \rightarrow \] lower bounds on masses of Pati-Salam Leptoquarks

\[ M_{LQ}(B_s^0 \rightarrow e \mu) > 101(107) \text{ TeV}/c^2 \]
\[ M_{LQ}(B^0 \rightarrow e \mu) > 135(126) \text{ TeV}/c^2 \] at 90% (95%) C.L.

Factor 20 lower than those set previously
Factor 2 higher than those set previously
Summary

- In absence of signal upper limits set on branching fractions of:
  - Lepton-number violating decay $B^{-} \rightarrow \pi^{+}\mu^{-}\mu^{-}$, probing Majorana neutrinos
  - Lepton-flavour violating decays $B_{s}^{0} \rightarrow e\mu$ and $B^{0} \rightarrow e\mu$, leading to lower bounds on masses of Pati-Salam leptoquarks
  - Lepton-flavour violating decay $\tau^{-} \rightarrow \mu^{+}\mu^{-}\mu^{-}$, first limit set on this decay at hadron collider

\[
\mathcal{B} (B^{-} \rightarrow \pi^{+}\mu^{-}\mu^{-}) < 4.0 \times 10^{-9} \quad \text{at 95\% C.L.} \quad \text{Best limit to date}
\]

\[
\mathcal{B} (B_{s}^{0} \rightarrow e^{\pm}\mu^{\pm}) < 1.1 \ (1.4) \times 10^{-7} \quad \text{at 90\% (95\%) C.L.} \quad \text{Factor 20 lower than those set previously}
\]

\[
\mathcal{B} (B^{0} \rightarrow e^{\pm}\mu^{\pm}) < 2.8 \ (3.7) \times 10^{-8} \quad \text{at 90\% (95\%) C.L.}
\]

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\mathcal{B} (\tau^{-} \rightarrow \mu^{+}\mu^{-}\mu^{-}) < 8.0 \ (9.8) \times 10^{-8} \quad \text{at 90\% (95\%) C.L.} \quad \text{First at hadron collider}
\]
LHCb Detector

Single-arm forward spectrometer with pseudorapidity range $2 < \eta < 5$
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