Search for Lepton Number Violation at LHCb

Update for Majorana Neutrino Search with Like-Sign Di-Muons: $B^- \rightarrow \pi^+ \mu^- \mu^-$ decay

PRELIMINARY, presented for the first time

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Outline

- Lepton Flavor and Lepton Number Violation studies at LHCb
- Lepton Number Violation (LNV) vs. Majorana neutrinos searches
- Searches for Majorana neutrinos at LHCb based on the decay $B^- \rightarrow \pi^+ \mu^- \mu^-$
  - Comparison of „previous” vs „updated” studies
  - The search strategies:
    - based on the neutrino lifetime,
    - based on a function of the neutrino mass,
  - Results: Upper limits
  - Results: Upper limit for coupling to $|V_{\mu 4}|^2$
- Conclusions.
Lepton Flavour and Lepton Number Violation studies at LHCb

1) Searches in tau lepton decays
   • based on 1.0 fb⁻¹ of data
   • first results on the $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decay mode from hadron collider
   • results for $\tau^- \rightarrow \bar{\nu}\mu^+ \mu^-$ and $\tau^- \rightarrow \nu\mu^- \mu^-$ represents the first direct experimental limits on this channel

   \[ BR(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 8.0 \times 10^{-8} \text{ at 90\% CL} \]
   \[ BR(\tau^- \rightarrow \bar{\nu}\mu^+ \mu^-) < 3.3 \times 10^{-7} \text{ at 90\% CL} \]
   \[ BR(\tau^- \rightarrow \nu\mu^- \mu^-) < 4.4 \times 10^{-7} \text{ at 90\% CL} \]


2) $B_s^0 \rightarrow e^\pm \mu^\mp$ and $B^0 \rightarrow e^\pm \mu^\mp$
   • based on 1.0 fb⁻¹ of data
   • results are a factor of 20 lower than those set by previous experiments

   \[ BR(B_s^0 \rightarrow e^\pm \mu^\mp) < 1.1(1.4) \times 10^{-8} \text{ at 90\% (95\%) CL} \]
   \[ BR(B^0 \rightarrow e^\pm \mu^\mp) < 2.8(3.7) \times 10^{-9} \text{ at 90\% (95\%) CL} \]


3) Searches in heavy baryon decays
   underway...

4) Majorana neutrino search
   • Based on 0.41 fb⁻¹ of data

   \[ \Lambda_b^0 \rightarrow h^+ \mu^- \text{ (} h = K, D, D_s \text{) } \]

   Update for $B \rightarrow \pi^+ \mu^- \mu^-$ with 3.0 fb⁻¹ of data presented first time in this presentation...

   \[ \begin{array}{|c|c|c|}
   \hline
   \text{Mode} & B \text{ upper limit} & \text{Approximate limits as function of } M_N \text{ at 95\% CL} \\
   \hline
   D^+ \mu^- \mu^- & 6.9 \times 10^{-7} & \\
   D^{*+} \mu^- \mu^- & 2.4 \times 10^{-6} & \\
   \pi^+ \mu^- \mu^- & 1.3 \times 10^{-8} & (0.4 - 1.0) \times 10^{-8} \\
   D^+_s \mu^- \mu^- & 1.3 \times 10^{-8} & (1.5 - 8.0) \times 10^{-7} \\
   D^0 \pi^+ \mu^- \mu^- & 1.5 \times 10^{-6} & (0.3 - 1.5) \times 10^{-6} \\
   \hline
   \end{array} \]

LNV vs. Majorana neutrinos searches

- **Lepton number** is conserved in the Standard Model but can be violated in a range of new physics models such as those with Majorana neutrinos.

- **Neutrino oscillation** phenomenon have conclusively shown that neutrinos are massive, which is not part of the SM. This is the proof of the Lepton Number Violation, LNV)

- **The Majorana nature of neutrinos** can be experimentally verified only via lepton-number violating processes involving charged leptons in the final state.

- **The LHCb physics program** encompasses the search for Majorana neutrinos in a broad class of exclusive B and D decays.

- The process $B^- \rightarrow \pi^+ \mu^- \mu^-$ is considered to be the most sensitive in B meson decays:

<table>
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Searches for Majorana neutrinos

\[ B^- \rightarrow \pi^+ \mu^- \mu^- \]

- Similarity to neutrinoless double $\beta$ decay, $2\beta_{0\nu}$
  - but $B^- \rightarrow \pi^+ \mu^- \mu^-$ probes LFV with muons while $2\beta_{0\nu}$ involves electrons,

- Final states containing $\pi^+$ are mediated by an on-shell Majorana neutrino
  - b-quark decays can produce a light neutrino that can mix with a heavy neutrino:

![Diagram of the decay process](image)
Searches for Majorana neutrinos @ LHCb

Previous results:

- **0.41 fb⁻¹ of data** collected at the center-of-mass energy of 7 TeV,
- Sensitive to **N with short lifetimes** of the order of 1 ps. (sensitivity quickly worsens for longer lifetimes),
- In the **B⁻** signal region, no statistically significant **signal at any mass has been found**,
- Upper limits: \( \text{BR}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 1.3 \times 10^{-8} \) at 95% C.L.

Update:

- **3 fb⁻¹ of data**: collected at the center-of-mass energy: 1/3 of 7 TeV, 2/3 of 8 TeV
- N lifetimes are long enough, providing that the natural decay width is narrower than the **mass resolution** (\( \sim 0 \) and 20 MeV depending on the mass),
- Upper limits on \( \text{BR}(B^- \rightarrow N(\pi^+ \mu^-)\mu^-) \) for **N with lifetimes up to 1000 ps**, 
- Upper limit on the **coupling of a single 4th generation Majorana neutrino to \( \mu \).**
Dependency on the neutrino lifetime, $\tau_N$:

- Two selections for the signal $B^- \rightarrow N(\pi^+\mu^-)\mu^-$:
  - Short $\tau_N$ (called “S”) – zero lifetime $N$, a common B vertex is formed from $\pi^+\mu^-\mu^-$ (similar to previous analysis);
  - Longer $\tau_N$ up to 1000 ps (called “L”) – N with nonzero lifetime, two vertices reconstructed (new); For lifetimes $\geq 1$ ps, the $\pi^+\mu^-$ from B meson decay can appear as significantly detached from the $B^-$ decay vertex.

Dependency on the neutrino mass, $m_N$:

- The detection efficiency varies as a function of $m_N$.
- For both S and L selections $\pi^+\mu^-\mu^-$ mass is in the $B^-$ signal window ($\pm 2\sigma$ of the $B^-$ mass, $\sigma$ - the mass resolution).
The search strategy

The normalization:

- $B^- \rightarrow J/\Psi (\mu^+ \mu^-)K^-$ used to normalize the branching fractions of the decays to heavy neutrinos:
  \[ BR(B^- \rightarrow J/\psi K^-, J/\psi \rightarrow \mu^+ \mu^-) = (6.037 \pm 0.256) \times 10^{-5} \]
- $282774 \pm 274$ signal events, in $m(B^-)$ [5100, 5500] MeV with a B mass resolution of $(17.9 \pm 0.4)$ MeV.

Upper limit calculations:

- CLs method used to set upper limits,
- The expected background yields and the total number of events determined within the signal B mass range, ± 2 times the invariant mass resolution, [5238.6, 5319.8] MeV:
  - Total number of events: 19 S events, 60 L events,
  - Background fit yields: $17.8 \pm 3.2$ S events, $54.5 \pm 5.4$ L events (in the same region).
Results: Upper limit

Short neutrino lifetimes of 1 ps or less:

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

- Average detection efficiency
- Total systematic uncertainty: 6.6%.

Scanning across the \( m_N \) spectrum:

- 5 MeV step,
- \( \pm 3\sigma \) search window at each step,
- \( \sigma \) – neutrino mass resolution
Results: Two dimensional upper limits

- For the L sample the detection efficiency changes with $\tau_N$. Hence for $L$ candidates, upper limits has been set as a function of both $m_N$ and lifetime:

- Neutrino mass step size of 5 MeV,
- Lifetime step size of 100 ps,
Results: The coupling of a single 4\textsuperscript{th} generation Majorana neutrino to $\mu$

Model dependent upper limits for the $|V_{\mu 4}|^2$, for each value of $m_N$ extracted using the formula from Atre et al. [1]

- Limits on branching fraction can be converted to limits on the $|V_{\mu 4}|^2$,
- 95\% C.L. limit on $|V_{\mu 4}|$ as a function of $m_N$.

[1]. Atre et al. The search for heavy Majorana neutrinos, JHEP 05 (2009)
Conclusions

On-shell Majorana neutrinos coupling to muons in the $B^- \rightarrow \pi^+ \mu^- \mu^-$ decay channel as a function of $m_N$ between 250 – 5000 MeV and for lifetimes up to $\approx 1$ ns have been searched.

No signal found, upper limits on the $B^- \rightarrow \pi^+ \mu^- \mu^-$ branching fraction and the coupling $|V_{\mu 4}|^2$ as a function of the neutrino mass have been set.

These results supersede previous LHCb results, furthermore computed limits are the most restrictive to date.
Backup
**LHCb detector**

- $\epsilon_{PID}(\mu) \approx 97\%$
- $\epsilon_{PID}(K) \approx 95\%$
- $\text{MisID (}\pi \rightarrow \mu\text{)} \approx 1\% - 3\%$
- $\text{MisID (}K \rightarrow \pi\text{)} \approx 5\%$

- Muon System
- RICH Detectors specific for LHCb
- Calorimeters
- Tracking System
- Vertex Detector

\[ \frac{\sigma}{E} \approx 1\% \times \frac{10\%}{\sqrt{E}[\text{GeV}]} \]

- $\epsilon_{PID}(e) \approx 95\%$
- $\text{MisID (}e \rightarrow h\text{)} \approx 5\%$

- $\sigma(\text{IP}) \approx 20\mu\text{m}$
- $\delta p/p = 0.4 - 0.6\%$
- $\epsilon_{track} > 96\%$
The search strategy

Requirements for candidates:

- $\mu$: $p > 3$ GeV, $p_T > 0.75$ GeV
- $h$: $p > 2$ GeV, $p_T > 1.1$ GeV
- $\mu^- \pi^+$: $p_T \geq 700$ MeV.

The normalization:
- The well measured decay channel $B^- \rightarrow J/\Psi (\mu^+ \mu^-)K^-$ is used to normalize the branching fractions of the decays to heavy neutrinos:
  \[ B(B^- \rightarrow J/\psi K^-, \ J/\psi \rightarrow \mu^+ \mu^-) = (6.037 \pm 0.256) \times 10^{-5} \]

Upper limit calculations:
- CLs method has been used to set upper limits.
- The expected background yields and the total number of events has been determined within the signal $B$ mass range (5238.6 – 5319.8 MeV):
  - Total number of events: 19 $S$ events and 60 $L$ events,
  - Background fit yields:
    - $S$: 17.8 $\pm$ 3.2 events
    - $L$: 54.5 $\pm$ 5.4 events (in the same region).
$B^- \rightarrow \pi^+ \mu^- \mu^-$

>> The $\pi^+\mu^-$ mass spectra for both S and L selections within searches for signals as a function of $m_N$

- Masses of $\pi^+\mu^+\mu^-$ candidates restricted to $\pm 2\sigma$ of $B^-$ mass for the (a) S and (b) L selections,
- The shaded regions indicate the estimated peaking backgrounds.
- Backgrounds that peak under the signal in (b) and (c) are (green) shaded.
- The dotted lines show the combinatorial backgrounds only. The solid line the sum of both backgrounds.
\[ B^- \rightarrow \pi^+ \mu^- \mu^- \]

An upper limit on the branching fraction for the S sample

- the average detection efficiency, as determined by simulation, with respect to the normalization mode of 0.687 ± 0.01.
- Included in computations of the limit:
  - the uncertainties on the background yields obtained from the fit to \( m(\pi^+ \mu^- \mu^-) \) distribution,
  - the 6.6% systematic uncertainty:
    - \( B (B^- \rightarrow J/\psi \text{ K}^-) \) (4.2%)
    - modeling of the efficiency ratio (3.5%) and backgrounds (3.5%),
    - relative particle identification efficiencies (0.5%),
    - tracking efficiency differences for kaons versus pions (0.5%),
    - yield of the normalization channel (0.4%).

Note: it is possible for virtual Majorana neutrinos of any mass to contribute to this decay via a process where the b quark transforms to a virtual \( W^- \) and a u quark while the u quark transforms to a virtual \( W^+ \) and a d quark, the ud form a \( \pi^+ \), and the Majorana communicates between the \( W^- \)'s causing emission of two \( \mu^- \) leptons.
Two dimensional upper limits  >> The strategy

For the L sample the detection efficiency changes with $\tau_N$ hence for $L$ candidates, upper limits has been set as a function of both $m_N$ and lifetime:

- the same scan in mass as before, but applying efficiencies appropriate for individual lifetime values starting at 1 ps up to 1000 ps.

- The number of background events is extracted from the sum of combinatorial and peaking backgrounds in the fit to the $m(\pi^+\mu^-)$ distribution in the same manner as for the S sample.

- The estimated signal yield is the difference between the total number of events computed by counting the number in the interval and the fitted background yield.

- The $\tau_N$ dependence has been taken into account by using different efficiencies for each lifetime step.
The strategy

Model dependent upper limits for the $|V_{\mu 4}|^2$, for each value of $m_N$ are extracted using the formula from Atre et al. *The search for heavy Majorana neutrinos*, JHEP 05 (2009), where the total neutrino decay width is a function of $m_N$ and proportional to $|V_{\mu 4}|^2$:

1) The total neutrino decay width, $\Gamma_N$, is a function of $m_N$ and proportional to $|V_{\mu 4}|^2$.
2) Model for the total width for Majorana neutrino decay:

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

3) To obtain upper limits on $|V_{\mu 4}|^2$ for each value of $m_N$ we assume a value for $|V_{\mu 4}|$, and calculate $\Gamma_N$. This allows us to determine the $\tau_N$ dependent detection efficiency.
4) To find the branching fraction:

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

5) The value of $|V_{\mu 4}|$ is then iterated to match the previously determined upper limit value,
6) Limits have been derived for other experiments by Atre et al. using different assumptions about $\Gamma_N$ and thus cannot be directly compared.