Search for Lepton Number Violation at *LHCb*

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

P R E L I M I N A R Y , 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 $B^- \to \pi^+ \mu^- \mu^-$
  - 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 $\tau^- \to \mu^-\mu^+\mu^-$ decay mode from hadron collider
- results for $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ represents the first direct experimental limits on this channel

$BR(\tau^- \to \mu^-\mu^+\mu^-) < 8.0 \times 10^{-8}$ **at 90% CL**
$BR(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ **at 90% CL**
$BR(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$ **at 90% CL**

Phys. Lett. B724 (2013) 36-45

2) $B_s^0 \to e^\pm\mu^\mp$ and $B^0 \to e^\pm\mu^\mp$

- based on 1.0 fb^{-1} of data
- results are a factor of 20 lower thatnthose set by previous experiments

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

Phys. Rev. Lett.111 (2013) 141801

3) Searches in heavy baryon decays

$\Lambda_b^0 \to h^+\mu^- \ (h = K, D, D_s)$

underway…

4) Majorana neutrino search

- Based on 0.41 fb^{-1} of data

at 95% CL

Mode	$\mathcal{B}$ upper limit	Approximate limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
$\pi^+\mu^-\mu^-$	1.3×10^{-8}	$(0.4 - 1.0) \times 10^{-8}$
$D_s^+\mu^-\mu^-$	5.8×10^{-7}	$(1.5 - 8.0) \times 10^{-7}$
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}	$(0.3 - 1.5) \times 10^{-6}$

Phys.Rev. D85 (2012) 112004

Update for $B \to \pi^+\mu^-\mu^-$ with 3.0 fb^{-1} of data presented first time in this presentation…

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 $\boldsymbol{B^- \to \pi^+ \mu^- \mu^-}$ is considered to be the most sensitive in B meson decays:

Mode	$\mathcal{B}$ upper limit	Approx. limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
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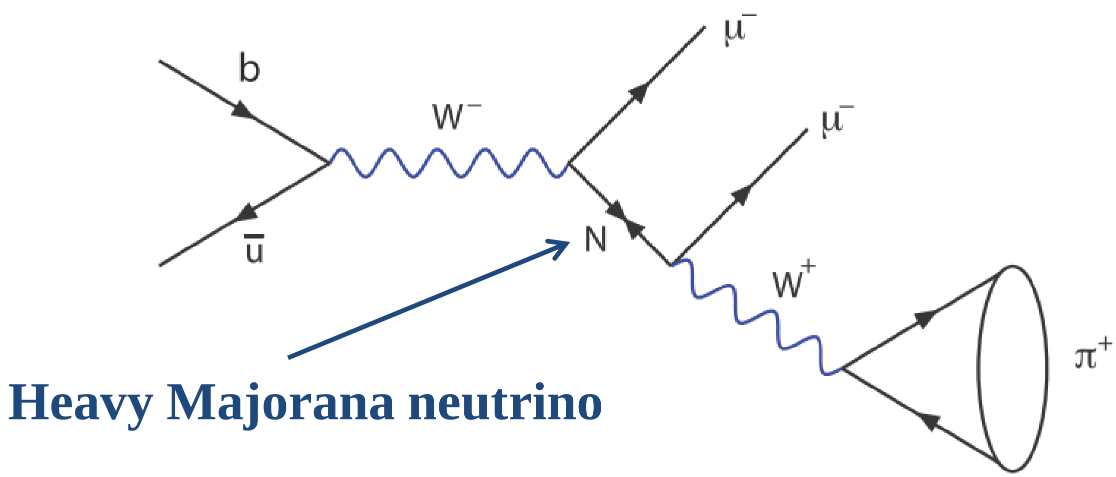
Phys. Rev. D 85, 112004 (2012)

[1]. LHCb Collaboration, R.Aaij et al., ***Searches for Majorana neutrinos in B^- decays***, Phys.Rev. D85 (2012) 112004
[2]. Atre et al. ***The search for heavy Majorana neutrinos,*** JHEP 05 (2009)

$B^- \rightarrow \pi^+ \mu^- \mu^-$

- Similarity to **neutrinoless double β 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 π^+ are mediated by an on-shell Majorana neutrino
  - b-quark decays can produce a **light neutrino that can mix with a heavy neutrino:**



Searches for Majorana neutrinos @ LHCb

Previous results:

LHCb Collaboration, R. Aaij et al., *Searches for Majorana neutrinos in B^- decays*, Phys.Rev. D85 (2012) 112004

- **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: $\mathbf{BR(B^- \to \pi^+ \mu^- \mu^-) < 1.3 \times 10^{-8}}$ **at 95% C.L.**

Update:

PRELIMINARY

- **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** (~ 0 and 20 MeV depending on the mass),
- Upper limits on $BR(B^- \to N(\pi^+\mu^-)\mu^-)$ for **N with lifetimes up to 1000 ps,**
- Upper limit on the **coupling of a single 4th generation Majorana neutrino to μ**.

$B^- \to \pi^+\mu^-\mu^-$ >> The search strategy

Dependency on the neutrino lifetime, τ_N :

- Two selections for the signal $B^- \to N(\pi^+\mu^-)\mu^-$:
  - **Short τ_N (called "S")** – zero lifetime N, a common B vertex is formed from $\pi^+\mu^-\mu^-$ **(similar to previous analysis);**
  - **Longer τ_N up to 1000 ps (called "L")** – N with nonzero lifetime, two vertices reconstructed **(new)**; For lifetimes ≥ 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 (± 2σ of the B^- mass, σ - the mass resolution).

$B^- \to \pi^+\mu^-\mu^-$ >> The search strategy

The normalization:

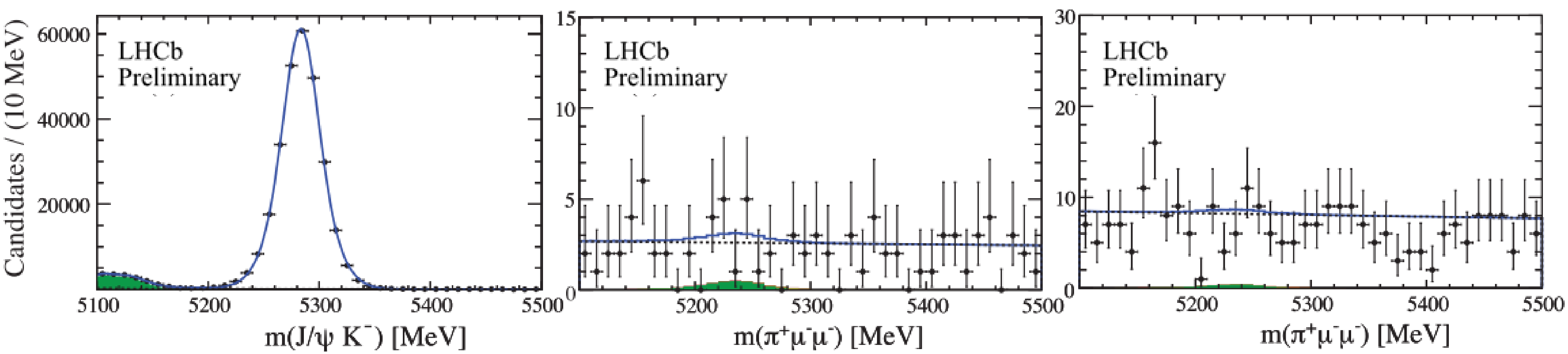
- $B^- \to J/\Psi\,(\mu^+\mu^-)K^-$ used to normalize the branching fractions of the decays to heavy neutrinos:

$$\mathrm{BR}(B^- \to J/\psi\, K^-,\ J/\psi \to \mu^+\mu^-) = (6.037 \pm 0.256) \times 10^{-5}$$

- **282774 ± 274 signal events**, in m(B^-) [5100, 5500] MeV with a B mass resolution of (17.9 ± 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 ± 3.2 *S* events , 54.5 ± 5.4 *L* events** (in the same region).



Results: Upper limit

Short neutrino lifetimes of 1 ps or less:

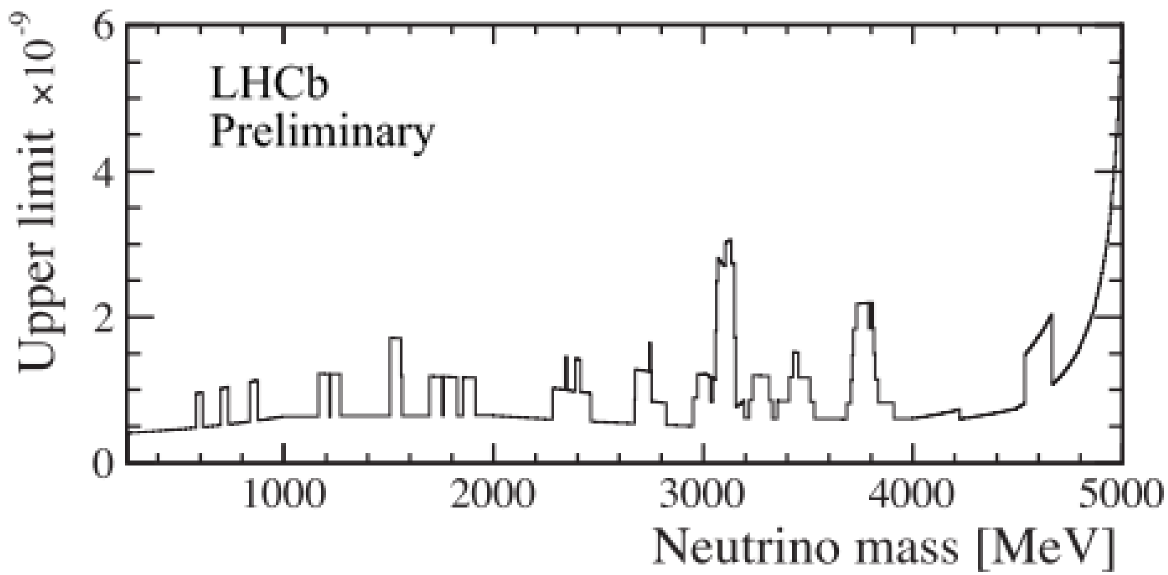
BR ($B^- \rightarrow \pi^+ \mu^- \mu^-$) < 4.0×10^{-9} at 95% C.L.

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

Scanning across the m_N spectrum:

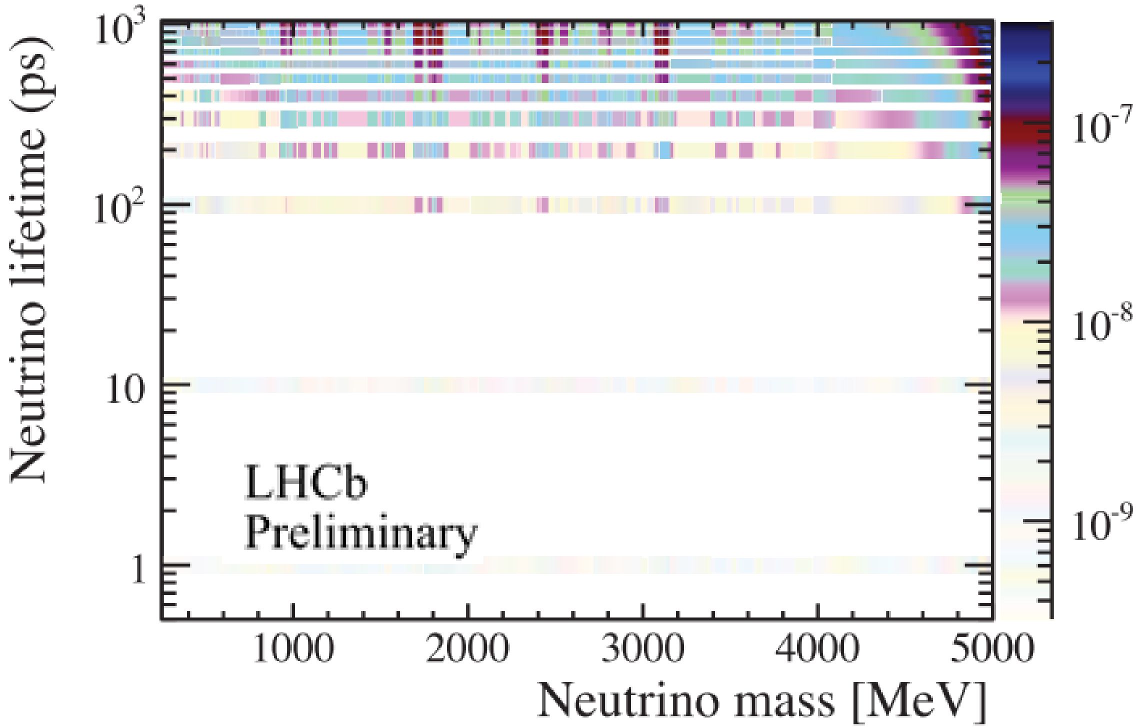
- ✓ 5 MeV step,
- ✓ ± 3σ search window at each step,

σ – neutrino mass resolution



Results: Two dimensional upper limits

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

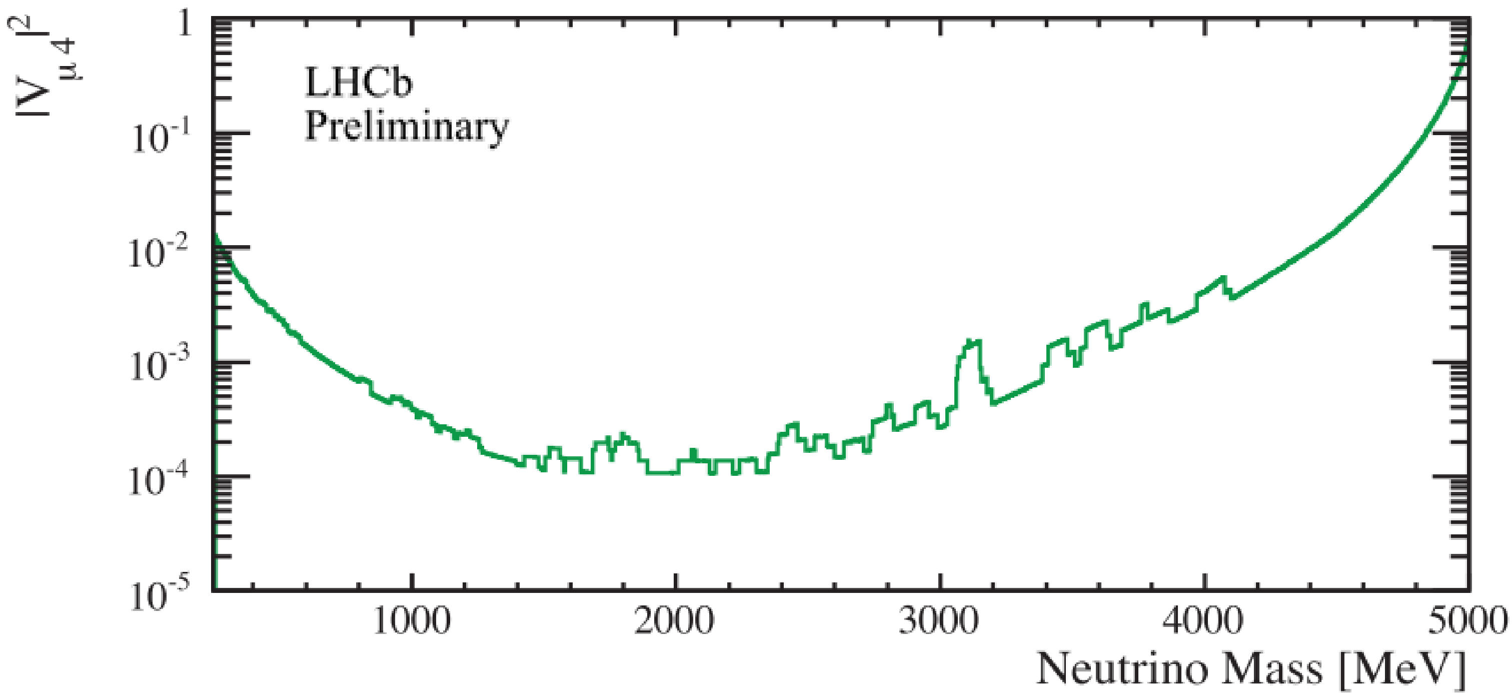


- Neutrino mass step size of 5 MeV,
- Lifetime step size of 100 ps,

Results: The coupling of a single 4th generation Majorana neutrino to μ

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

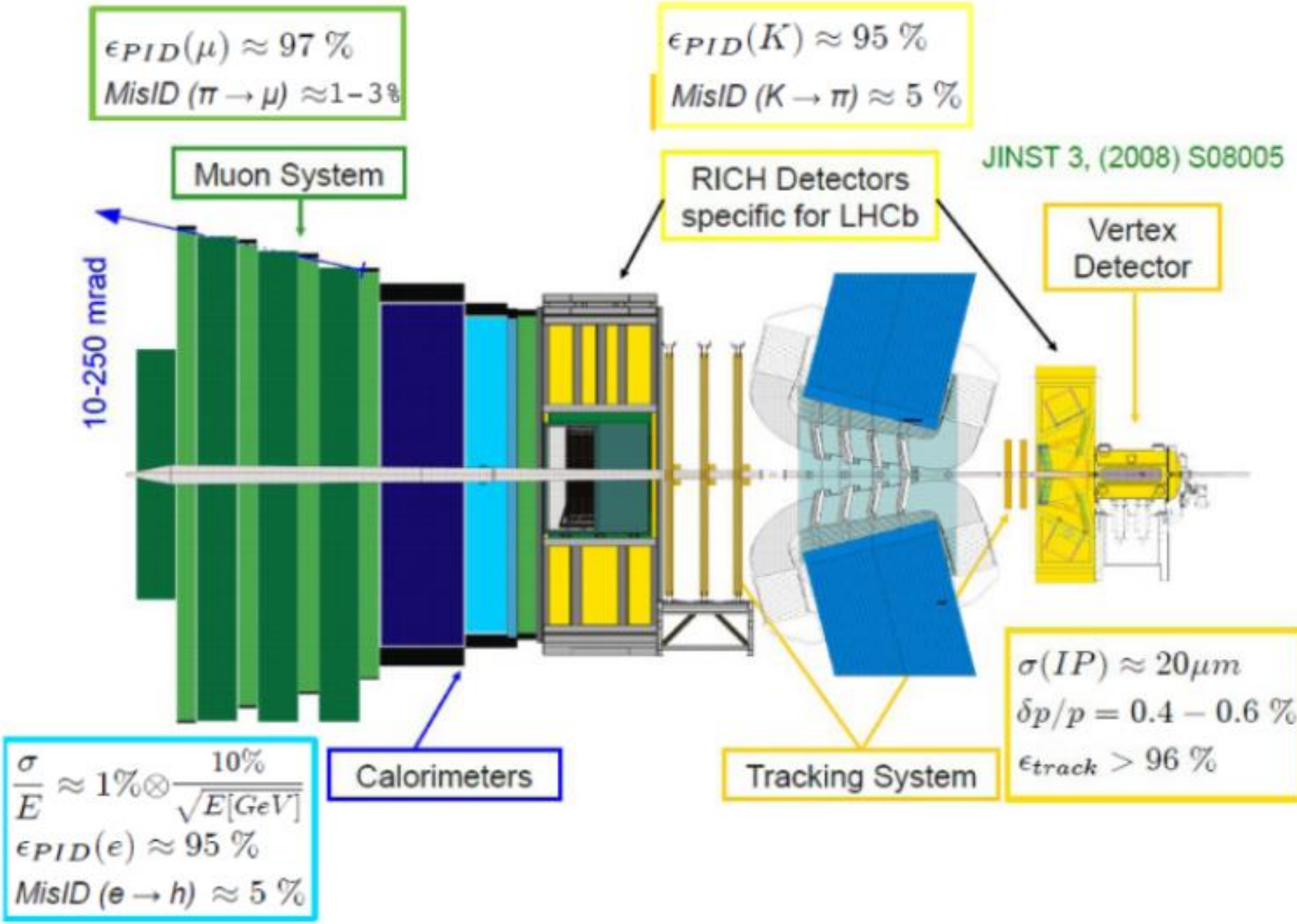
On-shell Majorana neutrinos coupling to muons in the $B^- \to \pi^+\mu^-\mu^-$ decay channel as a function of m_N between 250 − 5000 MeV and for lifetimes up to ≈ 1 ns have been searched.

No signal found, upper limits on the $B^- \to \pi^+\mu^-\mu^-$ 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



Requirements for candidates:

μ : 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 $B^- \to J/\Psi\ (\mu^+\mu^-)K^-$ is used to normalize the branching fractions of the decays to heavy neutrinos:

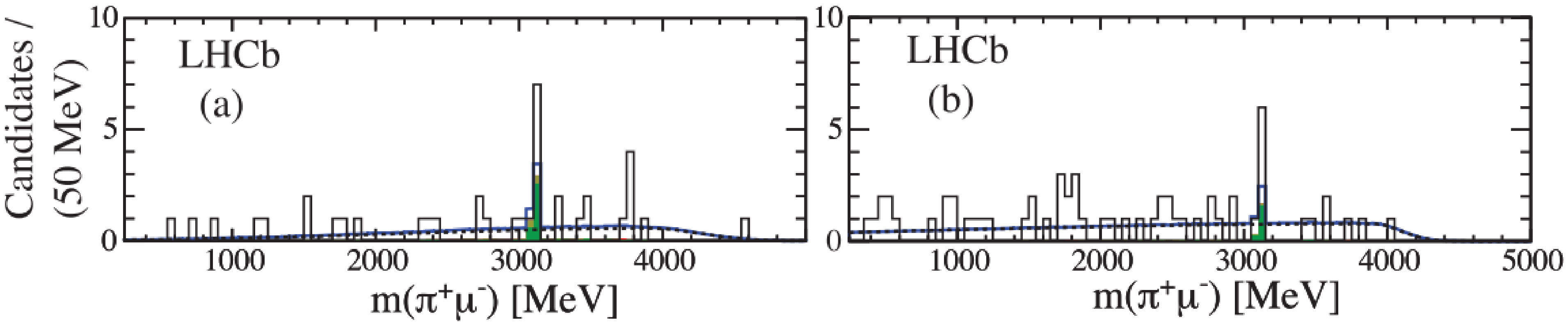
$$\mathbf{B(B^- \to J/\psi\ K^-,\ J/\psi \to \mu^+\ \mu^-) = (6.037 \pm 0.256) \times 10^{-5}}$$

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 ± 3.2 events**
    - **L: 54.5 ± 5.4 events** (in the same region).

$B^- \to \pi^+\mu^-\mu^-$

>> 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.

>> 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 ($B^- \to J/\psi K^-$) (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 π^+ , and the Majorana communicates between the W 's causing emission of two μ^- leptons.

Two dimensional upper limits >> The strategy

For the L sample **the detection efficiency** changes with τ_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 τ_N dependence has been taken into account by using different efficiencies for each lifetime step.

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

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

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 Γ_N . This allows us to determine the τ_N dependent detection efficiency.
4) To find the branching fraction:

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

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 Γ_N and thus cannot be directly compared.