Recent Results on Searches for Heavy Majorana Neutrinos

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on behalf of the LHCb, *BABAR* and Belle collaborations

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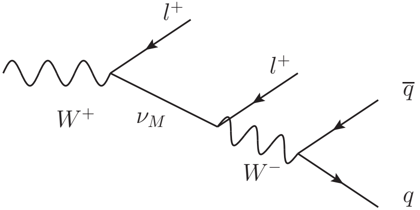
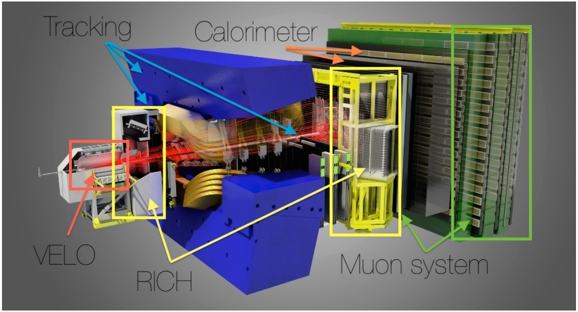
Heavy Majorana neutrinos at LHCb and the B factories

- ➜ Majorana neutrinos are theoretically well motivated
- ➜ See previous talks (e.g. F. Deppisch) for more information
- ➜ Focus today on searches for the decays of heavy mesons to final states with two same sign leptons



The LHCb Detector



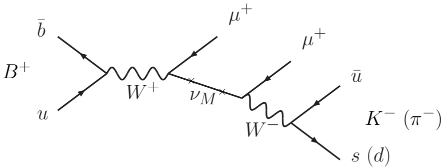
A dedicated flavour physics experiment in the forward region at the LHC

3.0 fb^{-1} of integrated luminosity from pp collisions at 7 and 8 TeV

- Precise vertex reconstruction: $<$ 10μm vertex resolution in x and y
- Excellent charged particle separation: $\pi^{\pm}$ misID of 10% for 95% $K^{\pm}$ efficiency
- Clean identification of muons: misID of 1% for 98% $\mu^{\pm}$ efficiency
- Excellent mass resolution: typically 7–20 MeV
- Flexible low-p_T trigger

Searches for Majorana neutrinos in $B^+ \to h^- \mu^+ \mu^+$ at LHCb

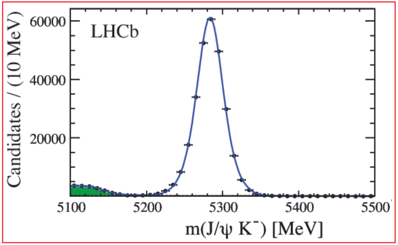
- $B^+ \to h^- \mu^+ \mu^+$ decays probe a wide range of Majorana neutrino masses
- Search performed for a range of neutrino lifetimes

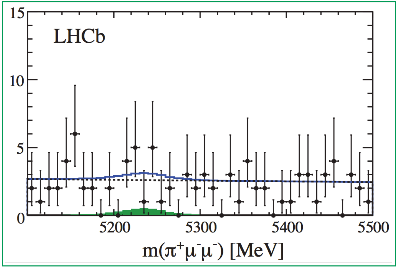


- Results from 3 LHCb papers: LHCb-PAPER-2013-064, LHCb-PAPER-2011-038 and LHCb-PAPER-2011-009
- Encompass $h^- = \pi^-$, D^-, D^{*-}, D_s^- and $D^0\pi^-$ and K^-

Analysis strategy

- Results use between 36 pb^{-1} (7 TeV) and 3.0 fb^{-1} (7 TeV + 8 TeV) of LHCb data
- Split into short ($\mathcal{S}$) and long ($\mathcal{L}$) neutrino lifetimes due to detached vertex
- Normalise to $B^+ \to J/\psi K^+$ (3-body) and $B^+ \to \psi(2S)K^+$ (5-body) with charmonium backgrounds (green) estimated from data
- Search for signal in 2σ around B^+ mass

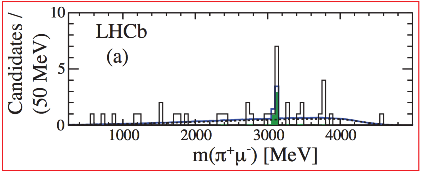




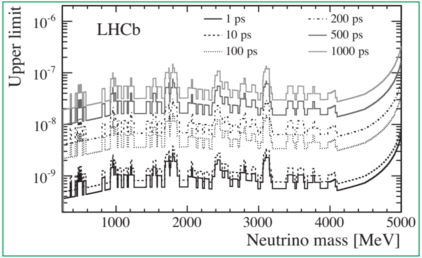
$\mathcal{S}$ data

Mass and lifetime dependence

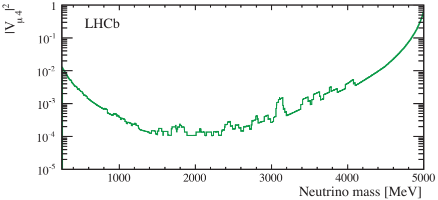
- No signal observed
- Limit for $\mathcal{S}$ from average detection efficiency using $\mathrm{CL_s}$ method
- Also scan limit in 5 MeV steps of neutrino mass from 250 – 5000 MeV with varying σ
- For $\mathcal{L}$ scan in both mass and neutrino lifetime
- Dominant systematic from $\mathcal{B}(B^+ \to J/\psi K^+)$



$\mathcal{S}$ data



$B^+ \to h^- \mu^+ \mu^+$ results



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

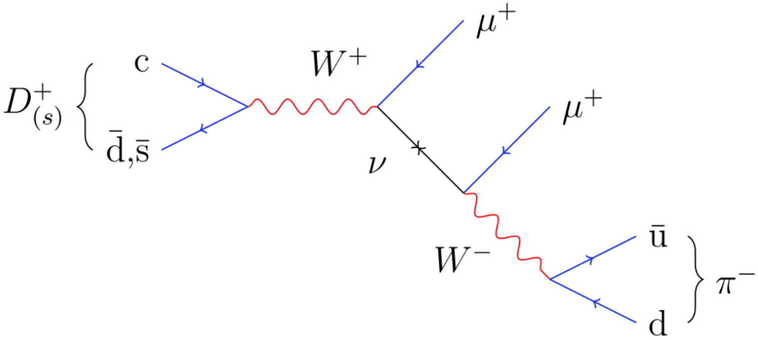
- Limits on fourth generation couplings, $|V_{\mu 4}|^2$, as a function of neutrino mass

Channel	$\mathcal{B}_{UL}$ 95% CL
$B^+ \to K^- \mu^+ \mu^+$	5.4×10^{-8}
$B^+ \to D^- \mu^+ \mu^+$	6.9×10^{-7}
$B^+ \to D^{*-} \mu^+ \mu^+$	2.4×10^{-6}
$B^+ \to \pi^- \mu^+ \mu^+$	4.0×10^{-9}
$B^+ \to D_s^- \mu^+ \mu^+$	5.8×10^{-7}
$B^+ \to D^0 \pi^- \mu^+ \mu^+$	1.5×10^{-6}

- All limits are world's bests
  $\to$ improved by as much as $\sim \times 100$

Search for Majorana neutrinos in $D^+_{(s)} \to \pi^- \mu^+ \mu^+$ at LHCb

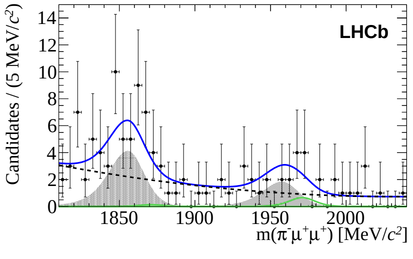
- Majorana neutrino-mediated $D^+_{(s)} \to \pi^- \mu^+ \mu^+$ decays can occur in a similar manner to $B^+ \to h^- \mu^+ \mu^+$
- World's best experimental limits from *BABAR* of 2×10^{-6} for $D^+ \to \pi^- \mu^+ \mu^+$ and 1.4×10^{-5} for $D^+_s \to \pi^- \mu^+ \mu^+$



$D^+_{(s)} \to \pi^-\mu^+\mu^+$ results

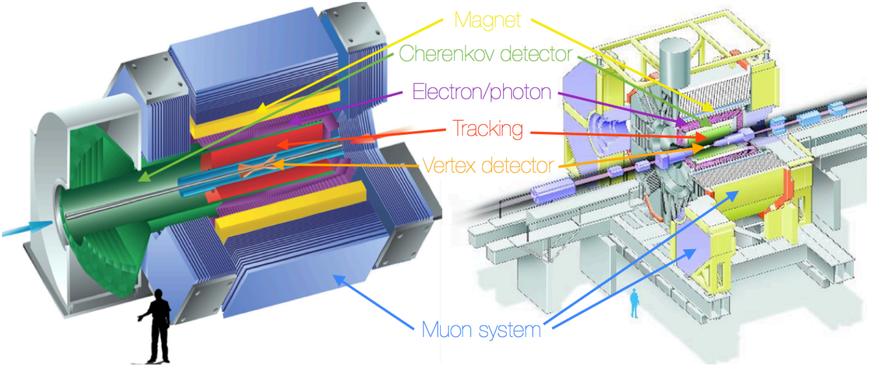
- Analysis uses 1.0 fb^{-1} of 7 TeV data collected in 2011
- Normalisation to $D^+_{(s)} \to \phi(\mu^+\mu^-)\pi^+$
- Classification of signal and background from PID cuts and a BDT using kinematic and geometric variables, trained on 2010 data

- Peaking background from $D^+_{(s)} \to \pi^+\pi^+\pi^-$ decays with shape (dark fill) measured from data
- Fit in bins of $m(\pi^-\mu^+)$ to improve statistical significance
- Limit of 2.2×10^{-8} for D^+ and 1.2×10^{-7} for D^+_s decays (90% CL) are a factor of fifty improvement



LHCb-PAPER-2012-051

The *BABAR* and Belle detectors



BABAR, $\sim 550\ \mathrm{fb}^{-1}$ Belle, $\sim 1\ \mathrm{ab}^{-1}$

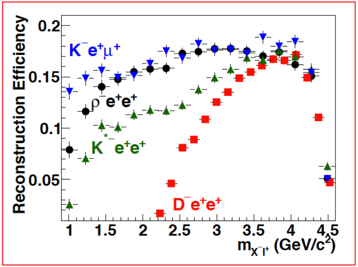
➜ Data collected mostly at the $\Upsilon(4S)$ resonance

➜ Excellent K/π separation; γ, e and μ identification

Search for $B^+ \to X^- l^+ l'^+$ at *BABAR*

- Search for 11 LNV processes $B^+ \to X^- l^+ l'^+$ with $X^- = K^-, \pi^-, \rho^-(\pi^-\pi^0), K^{*-}(K^0_s\pi^-/K^-\pi^0)$, or $D^-(K^+\pi^-\pi^-)$ and $l^+ l'^+ = e^+$ or μ^+ using 471 ± 3 million $B\overline{B}$ pairs
- Previously published (here) $h^- = K^-, \pi^-$ with $l^+ l'^+ = e^+ e^+$ or $\mu^+ \mu^+$

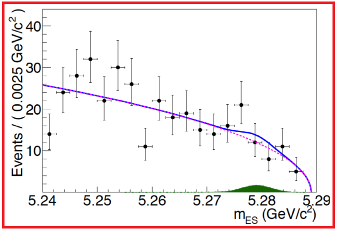
- Use MC for selection efficiencies, systematics and backgrounds from $e^+e^- \to q\overline{q}$, Bhabha elastic scattering, Drell Yan, $B\overline{B}$ and diphoton events
- Require 4 charged tracks, with 2 or more leptons that pass PID and kinematic criteria
- Veto photon conversions and misidentified J/ψ decays

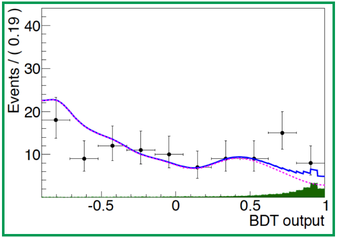


BABAR-PUB-13/016

Signal and background discrimination

- Suppress backgrounds with cuts on:
  1) $m_{ES} = \sqrt{(s/2 + \mathbf{p_0} \cdot \mathbf{p_B})^2 / E_0^2 - \mathbf{p_B}^2}$
  2) $\Delta E = E_B^* - \sqrt{s}/2$
  3) BDT with 9 input variables trained using simulation and on-resonance data
- For multiple candidates select the one with the smallest B vertex fit χ^2
- Signal yields from unbinned maximum likelihood fit to m_{ES}, ΔE, resonance mass (if applicable) and BDT output
- Test fit quality on toy MC, background samples and blinded on-resonance data





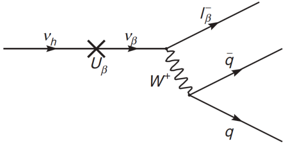
BABAR results

- Use a Bayesian approach to set 90% CL upper limits
- Statistical uncertainties are dominant
- Limits in the range $(1.5 - 26) \times 10^{-7}$
- Limits on the ρ^-, π^- and K^- modes are an order of magnitude improvement on previous results

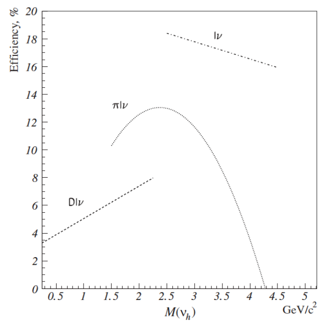
Channel	$\mathcal{B}_{UL}(\times 10^{-7})$
$B^+ \to K^{*-} e^+ e^+$	4.0
$B^+ \to K^{*-} e^+ \mu^+$	3.0
$B^+ \to K^{*-} \mu^+ \mu^+$	5.9
$B^+ \to \rho^- e^+ e^+$	1.7
$B^+ \to \rho^- e^+ \mu^+$	4.7
$B^+ \to \rho^- \mu^+ \mu^+$	4.2
$B^+ \to D^- e^+ e^+$	26
$B^+ \to D^- e^+ \mu^+$	21
$B^+ \to D^- \mu^+ \mu^+$	17
$B^+ \to K^- e^+ \mu^+$	1.6
$B^+ \to \pi^- e^+ \mu^+$	1.5

Search for heavy neutrinos at Belle

- Direct search for $\nu_h \to l^\pm \pi^\mp$ using $B \to X l \nu_h$ with $X = D^{(*)}$, a light meson, or nothing and $l = e$ or μ using 772 million $B\overline{B}$ pairs



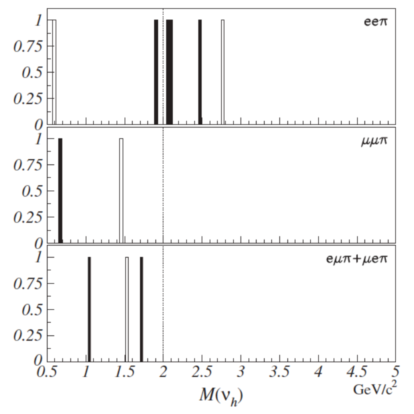
- MC for generic background samples and signal efficiencies
- Partial reconstruction technique to increase sensitivity to large neutrino flight distances, require > 4 charged tracks with PID and kinematic cuts
- Split analysis into small mass ($D^{(*)} l \nu_h$) and large mass (all other)
- Efficiency depends on the neutrino mass and B meson decay mode



Belle 2012-28

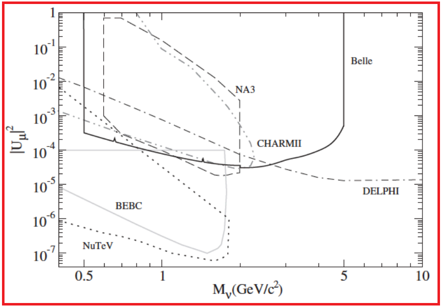
Analysis details

- In the small mass analysis reduce backgrounds via:
  1) The recoil mass, $M_X = (E_{CM} - E_{ll\pi})^2 - P_{ll\pi}^2 - P_B^2$, which peaks at the $D^{(*)}$ mass
  2) A proton veto using PID
- Few remaining events are consistent with background expectations and are categorised depending on hits in the SVD
- Number of detected neutrinos is proportional to the coupling constants between Majorana and SM neutrinos



Belle results

- Set upper limits on the coupling constants $|U_e|^2$, $|U_\mu|^2$ and $|U_e||U_\mu|$ from $ee\pi$, $\mu\mu\pi$ and $e\mu\pi + \mu e\pi$ decay modes using Feldman Cousins
- Maximum sensitivities around 2 GeV/c^2 of 3.0×10^{-5}, 3.0×10^{-5} and 2.1×10^{-5} for $|U_e|^2$, $|U_\mu|^2$ and $|U_e||U_\mu|$



Corresponds to an upper limit (at 90% CL) of

$$\mathcal{B}(B \to Xl\nu_h) \times \mathcal{B}(\nu_h \to l\pi^+) < 7.2 \times 10^{-7} \text{ for } l = e \text{ or } \mu$$

Summary

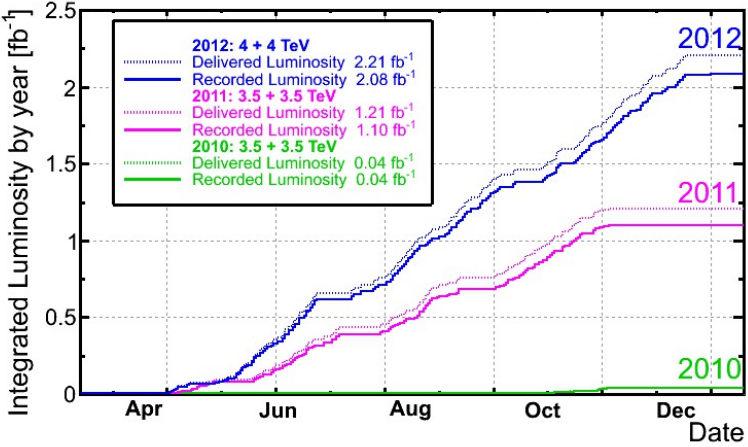
A number of new results on searches for Heavy Majorana neutrinos

- World's best limits on $B^+ \to h^- \mu^+ \mu^+$ and $D^+_{(s)} \to \pi^- \mu^+ \mu^+$ decays from LHCb
- The B factories continue to exploit their datasets
- Expect further results from LHCb following the restart of the LHC

Even more to come in the future from Belle 2 and the LHCb Upgrade

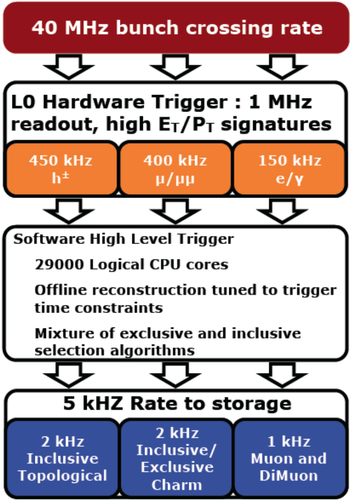
Backup

LHCb integrated luminosity



The LHCb trigger: 2010 + 2011

- The trigger reduces the event rate via:
  1. L0: Hardware selection using calo clusters and muon system hits
  2. HLT1: Loose software selection using VELO and tracking station tracks
  3. HLT2: Full software reconstruction creates composite particles



The LHCb trigger: 2012

- Introduction of partial deferred triggering in 2012
- 20% of events passing L0 saved to disk and processed inter-fill
- Effective 20% increase in CPU power
- Used to reduce track p_T thresholds from 500 to 300 MeV
  $\rightarrow$ significant trigger efficiency improvements for decays with low p_T tracks
- Further improvements for Run II