Lepton flavour and number violation measurements at LHCb

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on behalf of the LHCb collaboration

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Heavy Quarks and Leptons 2014

September 7, 2014

1. LHCb detector
2. Lepton Flavour Violation
3. **B** decays
   - $B^- \to h^+ \ell^- \ell^-$
   - $B_{(s)} \to \ell_1^+ \ell_2^-$
4. $\boldsymbol{\tau}$ decays
   - $\tau^- \to \mu^- \mu^- \mu^+$

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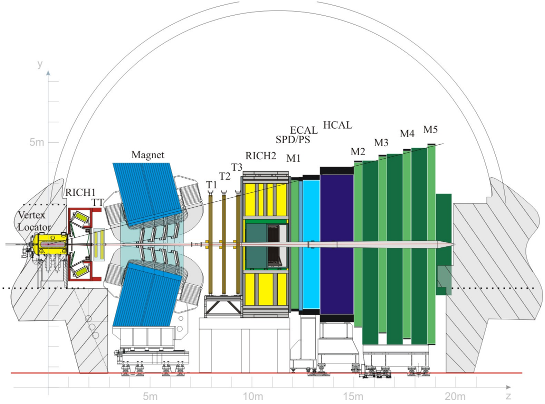
LHCb detector



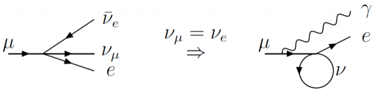
LHCb is a forward spectrometer:

- Excellent vertex resolution.
- Efficient trigger.
- High acceptance for τ and B.
- Great Particle ID

Lepton Flavour/Number Violation

Lepton Flavour Violation(LFV):
After μ^- was discovered it was natural to think of it as an excited e^-.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless another ν, in intermediate vector boson loop, cancels.



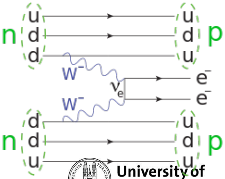
I.I.Rabi:

"Who ordered that?"

- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector (oscillations).

Lepton Number Violation (LNV)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict it violation(Majorana neutrinos)
- Searched in so called Neutrinoless double β decays.



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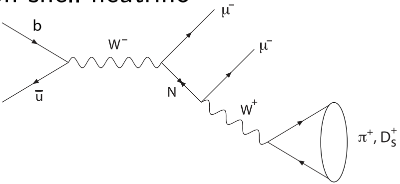
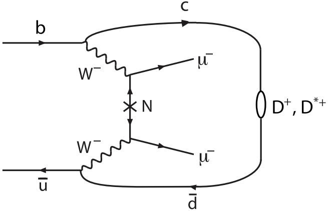
LNV in bottom decays

on-shell neutrino



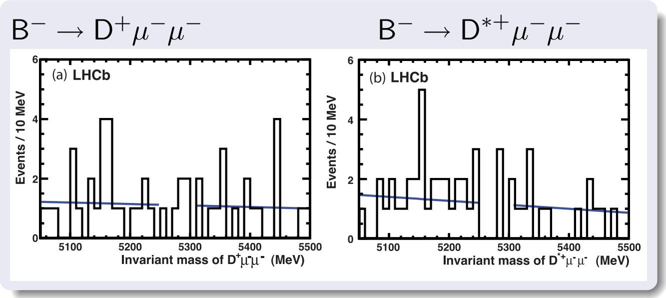
virtual neutrino



- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

Diagram without mass restriction
Cabbibo favoured for B $\to$ D
Analogous to double β decay.

Virtual Majorana neutrinos



$\mathcal{B}(B^- \to D^+\mu^-\mu^-) < 6.9 \times 10^{-7}$
@ 95 % CL
Based on 0.41 fb^{-1} 7 TeV data.

$\mathcal{B}(B^- \to D^{*+}\mu^-\mu^-) < 2.4 \times 10^{-6}$
@ 95 % CL

Phys. Rev.D85 (2012) 112004

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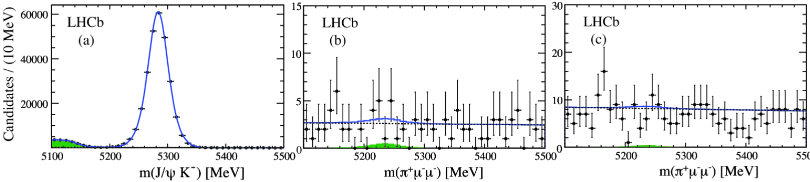
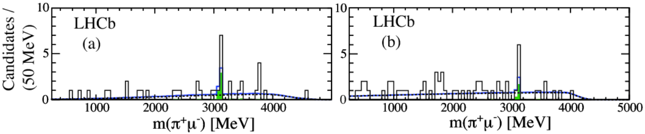
- $B^- \to \pi^+\mu^-\mu^-$ searched with full data set 3 fb^{-1}.
- Cut based analysis.
- Normalization channel $B^+ \to J/\psi(\mu\mu)K^+$.
- Searches performed for two scenarios:
  - Short life-time neutrinos: $\tau_4 < 1ps$
  - Long life-time neutrinos: $\tau_4 \in (1, 1000)ps$





Phys. Rev. Lett. 112, 131802

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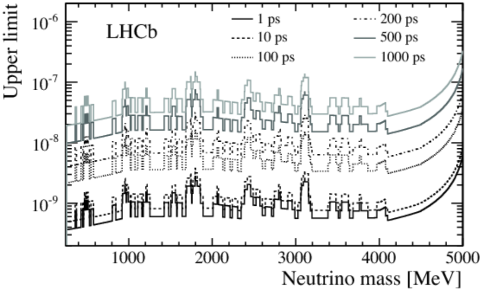
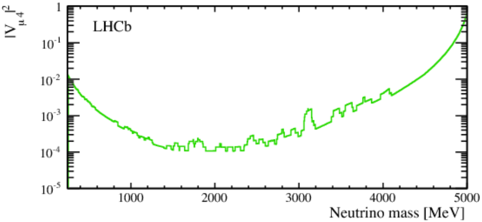
On-shell Majorana neutrinos





- In absence of signal UL. were set.
- $Br(\mathrm{B}^- \to \pi^+\mu^-\mu^-)$ in range 10^{-9}.
- Limits also set for the coupling $|V_{\mu 4}|^2$

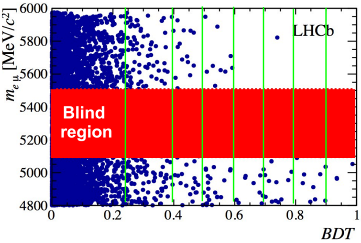
$$Br(\mathrm{B}^- \to \pi^+\mu^-\mu^-) = \frac{G_f^4 f_B^2 f_\pi^2}{128\pi\hbar}\tau_B m_B^5 |V_{ub}V_{ud}|^2 |V_{\mu 4}|^4 (1 - \frac{m_4^2}{m_B^2})\frac{m_4}{\Gamma_{N_4}}$$

channel	limit		
$\mathcal{B}(B^- \to \pi^+ e^- e^-)$	$< 2.3 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^+ e^- e^-)$	$< 3.0 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^{*+} e^- e^-)$	$< 2.8 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to \rho^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to D^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to D^+ e^- \mu^-)$	$< 1.8 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to K^+ \mu^- \mu^-)$	$< 5.4 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^+ \mu^- \mu^-)$	$< 6.9 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-)$	$< 2.4 \times 10^{-6}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D_s^+ \mu^- \mu^-)$	$< 5.8 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^0 \pi^- \mu^- \mu^-)$	$< 1.5 \times 10^{-6}$	@95 % CL	[e]

[a] BaBar,Phys. Rev. D **85**, 071103 (2012)
[b] CLEO, Phys. Rev. D **65**, 111102 (2002)
[c] Belle, Phys. Rev. D **84**, 071106(R), (2011)
[d] LHCb, Phys. Rev. Lett. 108 101601 (2012)
[e] LHCb,Phys. Rev. Lett. (112) 131802 (2014)

$B_{(s)} \to e^- \mu^+$

- A separate physics interest is LFV B decays.
- Predicted by various NP models: lepto-quarks, SUSY, GUT.
- Analysis based on 1 fb^{-1} 2011 data.
- Analogous to our $B^0_s \to \mu\mu$ analysis (PRL 111 (2013) 101804)



1. Loose preselection based on topology and PID.
2. Classifier trained on MC signal and $b\bar{b} \to \ell\ell X$
3. Calibration channel: $B^0{}_{(s)} \to h^+ h'^-$
4. Normalization Channel: $B^0 \to K^+\pi^-$
5. CLs[1] method for limit extraction.

Phys. Rev. Lett. 111, 141801 (2013)

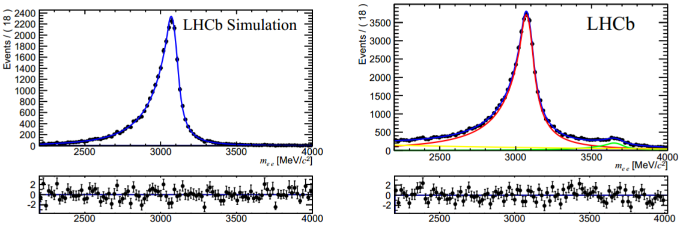
[1] A.L.Read, The CLs technique, Journal of Physics G (2012)

$B_{(s)} \to e^{-}\mu^{+}$ mass calibration

LHCb philosophy: data driven approach when/where possible.

- Electrons undergo Breamsstrahlung $\to$ recover the lost energy.
- Re-weight MC to match event multiplicity.
- Parametrize signal shape by Crystal Ball.
- Validate the approach on J/$\psi \to$ e^{-}e^{+}.
- Observe agreement between data and MC J/ψ line shape.

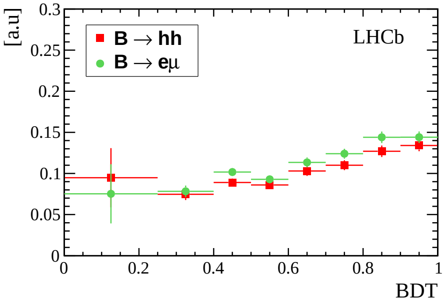
Simulation: $J/\psi \to e^{+}e^{-}$(not re-weighted) Data: $J/\psi \to e^{+}e^{-}$



$B_{(s)} \to e^- \mu^+$ BDT calibration

- Hadronic two body B decays are an excellent proxy!
- Same topology and kinematics.
- Select and inclusive sample of $B_{(s)} \to h^+ h'^-$
- Apply BDT to selected hadronic sample and correct MC signal efficiency:

$$\epsilon^{sig}_{DATA} = \frac{\epsilon^{norm}_{DATA}}{\epsilon^{norm}_{MC}} \times \epsilon^{sig}_{MC} \quad (1)$$



1. $B_{(s)} \to h^+ h'^-$ BDT shape in data.
2. $B_{(s)} \to e\mu$ BDT shape after corrections.

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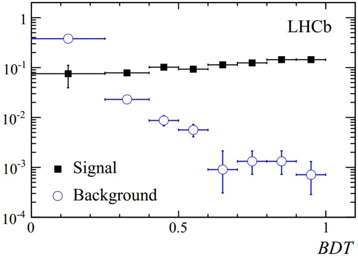
$B_{(s)} \to e^- \mu^+$ background

- Number of expected background candidates extrapolated from side bands: $[4,9,5.0] \bigcup [5.5,5.9]$ GeV
- Peaking backgrounds:
  - $B_{(s)} \to h^+ h^-$, model using miss ID rates. Expect 4 events in the full BDT range.



- Semileptonic backgrounds:
  - $\Lambda_b \to p\mu\nu$
  - $B \to \pi\mu\nu$
  - $B_c^+ \to J/\psi(\mu\mu)e\nu$
  - $B_c^+ \to J/\psi(ee)\mu\nu$
- Can be modelled in a fit

BDT	Expected from sideband fit	$B^0_{(s)} \to h^+ h'^-$	Observed
0-0.25	2222 ± 51	0.67 ± 0.12	2332
0.25-0.4	$80.9^{+10.1}_{-9.4}$	0.47 ± 0.09	90
0.4-0.5	$20.4^{+5.0}_{-4.5}$	0.40 ± 0.08	19
0.5-0.6	$13.2^{+3.9}_{-3.6}$	0.37 ± 0.06	4
0.6-0.7	$2.1^{+2.9}_{-1.4}$	0.45 ± 0.08	3
0.7-0.8	$3.1^{+1.9}_{-1.4}$	0.49 ± 0.08	3
0.8-0.9	$3.1^{+1.9}_{-1.4}$	0.57 ± 0.09	3
0.9-1.0	$1.7^{+1.4}_{-1.0}$	0.54 ± 0.12	1

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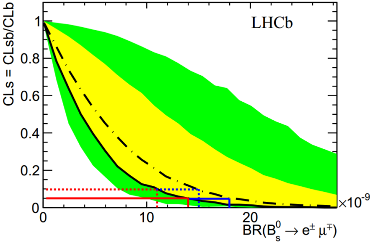
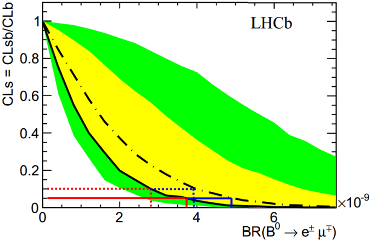
$B_{(s)} \rightarrow e^- \mu^+$





Upper limits

	$Br(\mathrm{B} \rightarrow e\mu)$ @ 90(95)%CL	$Br(\mathrm{B}_s \rightarrow e\mu)$ at 90(95)%CL
Expected	$3.8(4.8) \times 10^{-9}$	$1.5(2.0) \times 10^{-8}$
Observed	$1.5(1.8) \times 10^{-9}$	$1.1(1.4) \times 10^{-8}$

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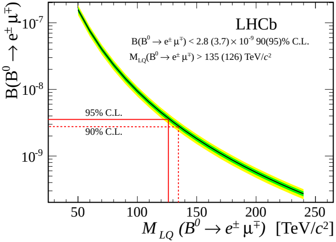
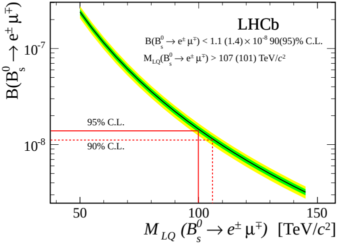
- LHCb limits two times better than previous ones from CDF[2].
- CDF implications to lepto-quarks mass[3].
  - $m_{LQ}(B^0_s \rightarrow e\mu) > 47.8(44.9)$ TeV 90(95%) @CL.
  - $m_{LQ}(B^0 \rightarrow e\mu) > 59.3(56.3)$ TeV 90(95%) @CL.





LHCb limits:

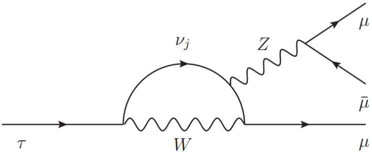
- $m_{LQ}(B^0_s \rightarrow e\mu) > 107(101)$ TeV 90(95%) @CL.
- $m_{LQ}(B^0 \rightarrow e\mu) > 135(126)$ TeV 90(95%) @CL.

[2] Phys. Rev. Lett. 102 (2009) 201801

[3] Theoretical formula Phys. Rev. D 50 (1994) 6843

$\tau \longrightarrow \mu\mu\mu$

1. In SM small $\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+) \sim 10^{-40}$
2. NP can enhance $\mathcal{B}$.
3. Nature still hides $\tau^- \to \mu^-\mu^-\mu^+$ from us.
4. Current limits:



Experiment	90% CL limit
BaBar [4]	3.3×10^{-8}
Belle [5]	2.1×10^{-8}

- Can a hadron collider change the picture?

[4] Phys.Rev.D81:111101(R),2010
[5] Phys.Lett.B687:139-143,2010

Analysis approach

$\mathcal{B}$ factories

1. signal: $e^+e^- \rightarrow \tau^+\tau^-$
2. 1.2×10^9 τ pairs
3. Calculate the thrust axis
4. Tag the other τ
5. Small cross section $0.919nb$

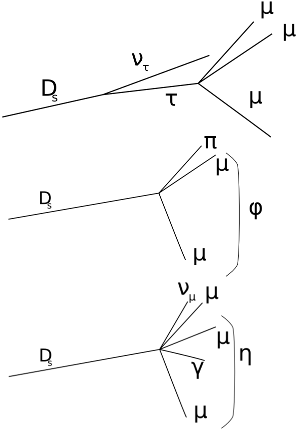
LHCb, (7 TeV, 2011 data)

1. Inclusive τ cross section: 79.5 ± 8.3 μb.
2. $8 \times 10^{10}\tau$ produced.
3. Dominant contribution: $D_s \rightarrow \tau\nu_\tau$ (78%)
4. No partial tag possible.

Strategy

- Loose cut based selection
- Classification in 3D space:
  - invariant mass
  - decay topology (multivariate)
  - particle identification (multivariate)
- Classifier trained on simulation
- Calibration with control channel
- Normalization with $D_s \to \phi(\mu\mu)\pi$
- CLs method to extract the result

Signal & Calibration & Background channel:



Signal likelihoods

particle identification

- hits in muon chambers
- energy in calorimeters
  - compatible with MIP
- RICH response

3 body decay likelihood

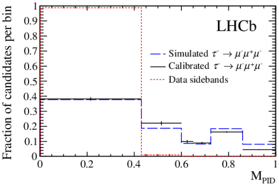
- vertex properties
  - vertex fit, pointing
- track quality
- isolation

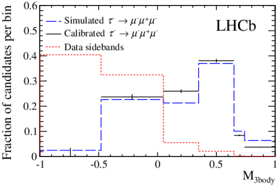
Calibration

$J/\psi \to \mu^+\mu^-$

Calibration

$D_s \to \phi\pi$





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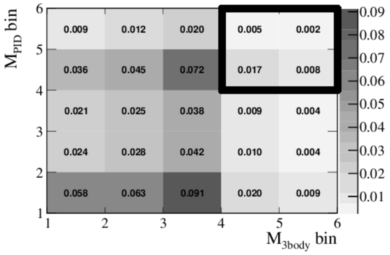
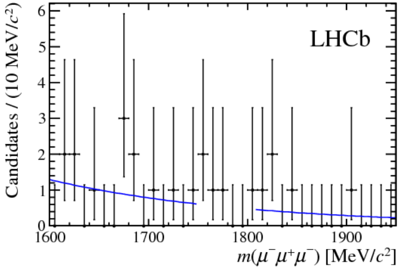
Signal likelihoods

combined signal distribution

- events distributed over 25 likelihood bins
- background estimate from mass side-bands

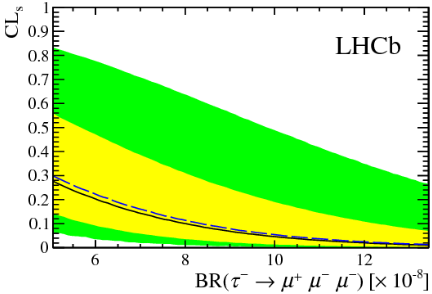
Signal efficiency in 3-BODY BDT vs PID BDT plane.





Extracted upper limit

Upper limits			
	observed	expected	CL
$\mathcal{B}(\tau \to \mu\mu\mu)$	8.0×10^{-8}	8.3×10^{-8}	90%
	9.8×10^{-8}	10.2×10^{-8}	95%



1 fb^{-1}

PLB 724 (2013) 36-45

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Summary

- Analyses of LFV and LNV processes are going very well in LHCb
- We already have a number of best limits in our hands.
- Stay tuned, more new results coming up soon.