Searches for long-lived light particles at LHCb

Marcin Chrząszcz
mchrzasz@cern.ch
University of Zurich[UZH]

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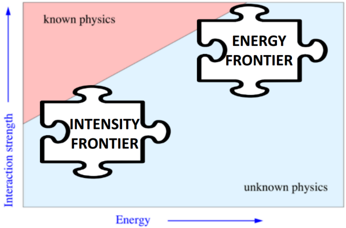
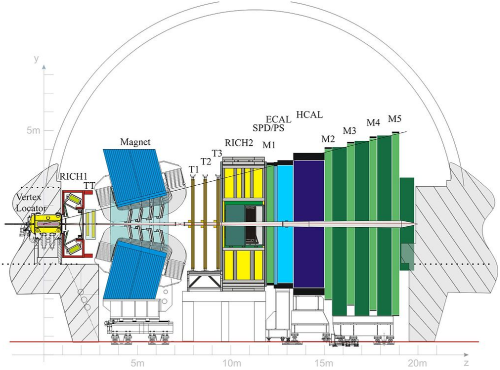
Why long-lived particles?

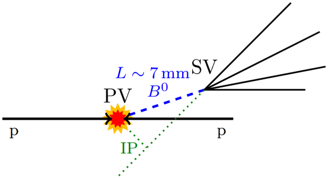
- We all know here that the SM is incomplete.
- Unfortunately we do no know what is the scale of NP.
- NP still can come from the Higgs sector $\Rightarrow$ not all properties are yet constrained.
- There is a long list of theoretical models that predict the existence of new particles that couple to the SM sector by mixing with the Higgs.



  - Inflaton, axion-like, dark matter mediator models also predict the new boson to be light.
  - SUSY models also can have stable long living particles like $\widetilde{q}$, $\widetilde{\ell}$.

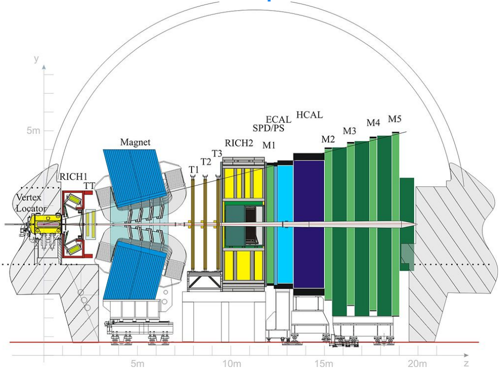
LHCb detector - tracking

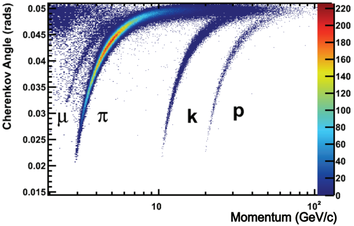




- Excellent Impact Parameter (IP) resolution ($20\ \mu$m).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass resolution.
  $\Rightarrow$ Low combinatorial background.

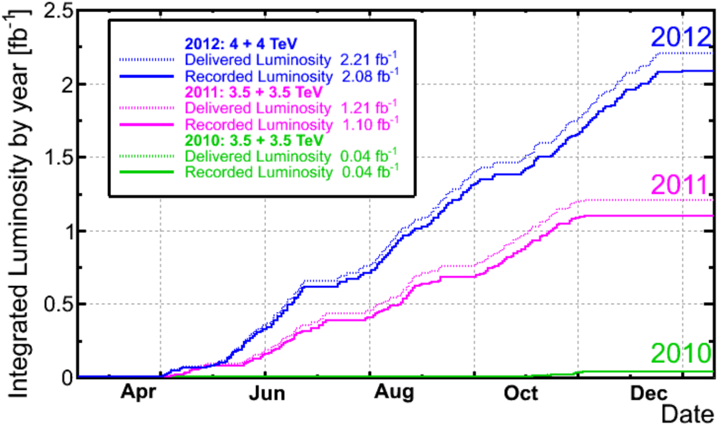
LHCb detector - particle identification





- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds. Muons: $p_T > 1.76\text{GeV}$ at L0, $p_T > 1.0\text{GeV}$ at HLT1,
  $B \to J/\psi X$: Trigger $\sim 90\%$.

Data taken by LHCb

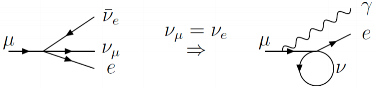


- In 2011 and 2012 LHCb has gathered $3\ \mathrm{fb}^{-1}$ of pp collisions.

Lepton Flavour/Number Violation

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

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

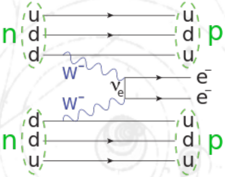


I.I.Rabi:
"Who ordered that?"

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

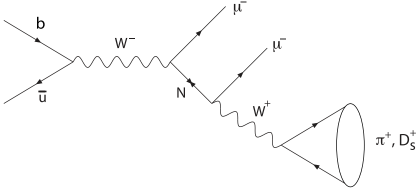
Lepton Number Violation (LNV)

- 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.

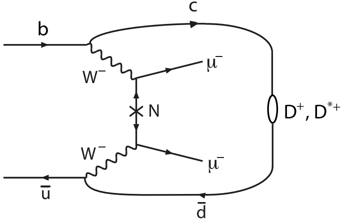


LNV in bottom decays

on-shell neutrino



virtual neutrino

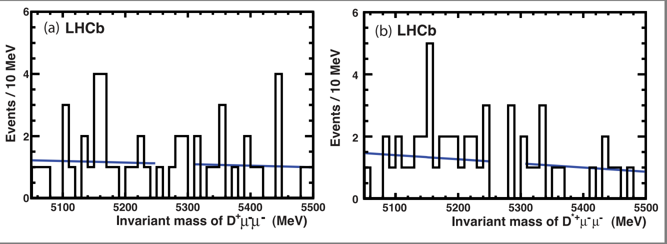


- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-, \pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

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

Virtual Majorana neutrinos

$B^- \to D^+\mu^-\mu^-$ $\quad$ $B^- \to D^{*+}\mu^-\mu^-$



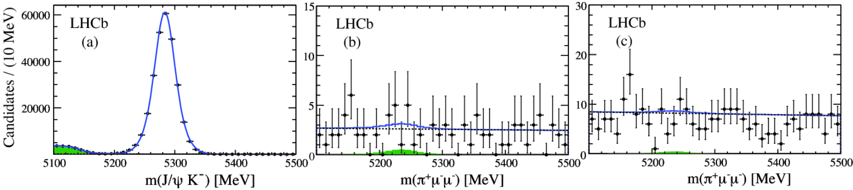
$\mathcal{B}(B^- \to D^+\mu^-\mu^-) < 6.9 \times 10^{-7}$
@ 95 % CL
Based on $0.41\ \mathrm{fb}^{-1}$ $7\ \mathrm{TeV}$ data.

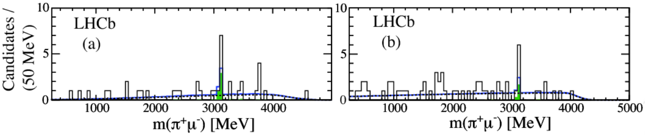
$\mathcal{B}(B^- \to D^{*+}\mu^-\mu^-) < 2.4 \times 10^{-6}$
@ 95 % CL

Phys. Rev.D85 (2012) 112004

On-shell Majorana neutrinos

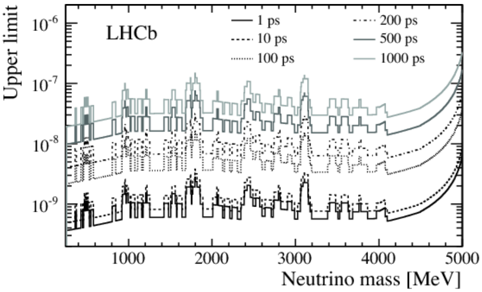
- $B^- \to \pi^+\mu^-\mu^-$ searched with full data set $3\ \mathrm{fb}^{-1}$.
- Cut based analysis.
- Normalization channel $B^+ \to J/\psi(\mu\mu)K^+$.
- Searches performed for two scenarios:
  - Short life-time neutrinos: $\tau_4 < 1ps$
  - Long life-time neutrinos: $\tau_4 \in (1, 1000)ps$

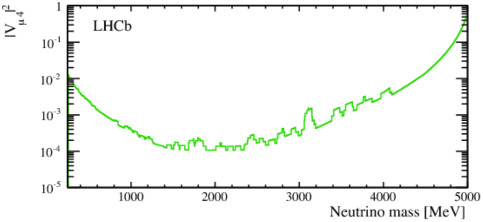




Phys. Rev. Lett. 112, 131802

On-shell Majorana neutrinos





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

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

Summary on LNV in decays

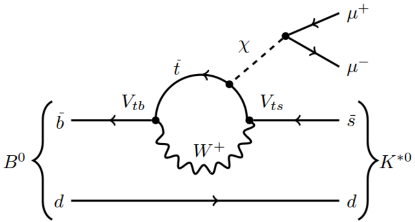
channel	limit		
$\mathcal{B}(B^- \to \pi^+ e^- e^-)$	$< 2.3 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^+ e^- e^-)$	$< 3.0 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^{*+} e^- e^-)$	$< 2.8 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to \rho^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % 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)

$B \to K^* \chi(\mu\mu)$ search

- Search for displaced di-muon vertex coming form B meson.

$$B^0 \to K^* \chi(\mu^- \mu^+)$$



- If χ mixes with the Higgs and it is light:
  - $\Gamma(K \to \pi\chi) \propto m_t^4 \lambda^5$
  - $\Gamma(D \to \pi\chi) \propto m_b^4 \lambda^5$
  - $\Gamma(B \to K\chi) \propto m_t^4 \lambda^2$
- In addition; $K^* \to K^+ \pi^-$ helps in vertex reconstruction.
- High $\mathcal{B}(\chi \to \mu^- \mu^+)$.

$B \to K^*\chi(\mu\mu)$ motivation

Discussed models:

1. **Inflaton:** Phys.Lett. B736 (2014) 494
   - $\tau_\chi = 10^{-8} - 10^{-10}\ s$
   - $m_\chi\ \mathcal{O}(1\ \mathrm{GeV})$
   - $\mathcal{B}(B \to K\chi)\ \sim 10^{-6}$
   - effective couplings to SM particles:
     - $g_Y \frac{m_f}{v_{EW}},\ g_Y = \sin\theta$
2. **Axion portal:** Phys.Rev.D81:034001,2010
   - Prompt decay.
   - Large allowed masses.
   - Axion decay constant: $f_\chi \sim 1 - 3\ \mathrm{TeV}$
     - Coupling $\propto \frac{m_f}{f_\chi}$.

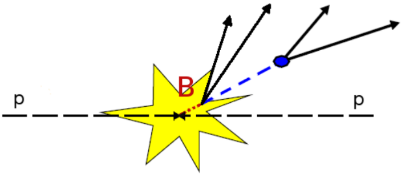
All those particles have width much smaller than resolution of LHCb detector.

Signal properties

⇒ Depending on the coupling of the hidden sector we can identify two lifetime regimes:

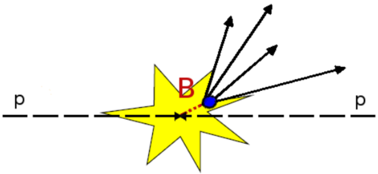
Long lifetime (> 0.2 ps)

- Inflaton JHEP 1005:010
- Displaced vertex.
- Almost background free.
- Lower reconstruction efficiency.



Short lifetime ($\leqslant 0.2$ ps)

- Dark matter mediator Phys. Lett. B727
- Axion Phys.Rev.D81
- Prompt decay.
- Contaminated via SM decay.



Selection

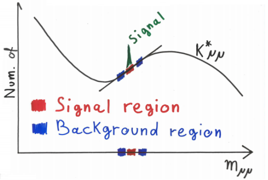
- Trigger on muons.
- Multivariate selection: $\mu\mathrm{BDT}$ JINST 8(2013)
  - $\mu\mathrm{BDT}$ ensures flat efficiency in lifetime of χ.
- Optimized on Punzi figure-of-merit:

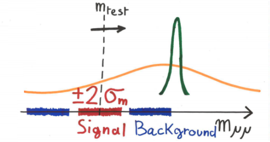
$$P_a = \frac{S}{\frac{5}{2} + \sqrt{B}},$$

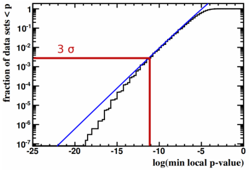
  with S and B are signal and background yields.
- Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\mathrm{prompt}} \bigotimes \mathcal{L}^{\mathrm{displaced}}$
  - Prompt: $\tau < 3\sigma_{\tau}$
    $\mapsto$ SM background of $B^0 \to K^{*}\mu^{-}\mu^{+}$
  - Displeased: $\tau > 3\sigma_{\tau}$
    $\mapsto$ Almost background free.

Search strategy

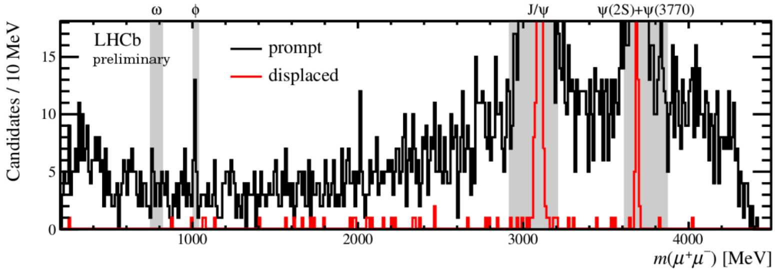
- B^0 mass constrained.
- Di-muon mass resolution $\sigma_m = 1 - 7\ \mathrm{MeV}$.
- Scan m_{test} in steps of $0.5\ \sigma_m$.
  - Wide resonances can't affect the search.
  - Narrows resonances we veto.
- Calculations performed in each m_{test} window.







Results



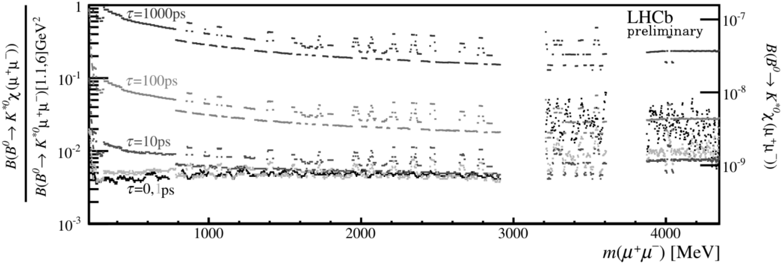
⇛ Grey regions correspond to vetoed regions where narrow resonances are expected.

⇛ Largest deviation seen in $m_\chi = 253$ MeV.

↣ Not statistically significant: local p-value $= 0.2$.

⇛ LHCb-PAPER-2015-036 submited to PRL.

Branching fraction exclusion limit



$\Rightarrow$ No deviations from background only hypothesis is observed.

- We set a 95% CL upper limit as function of mass and lifetime of the new particle (in the LHCb accessible range).
- Lower lifetimes have better limit due to higher reconstruction efficiency.

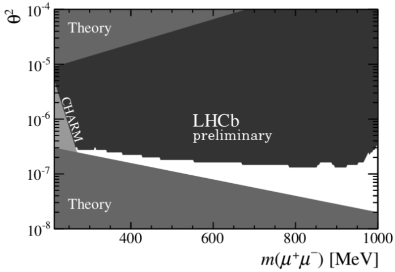
Benchmark models

⇒ Interpretation of the results in two specific models:

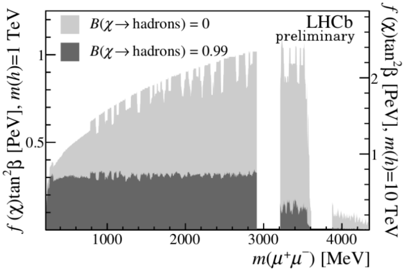
(Specific) inflaton model

Axion portal

[LHCb-PAPER-2015-036 in preparation]



Include 3 sterile neutrinos N_I



MSSM-like two Higgs doublet model.

Conclusion

- A search for a dark boson in the decay channel $B^0 \to K^* \mu^- \mu^+$ has been presented.
  - No deviations from SM observed.
- Results are the most constraining exclusion limit on the process.
- LHCb is suited for search for long lived particles.
- Stay tuned, more searches like this are on they way.

Backup