

Sterile neutrino and other long lived particle searches at LHCb



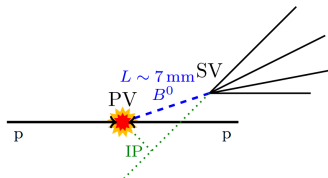
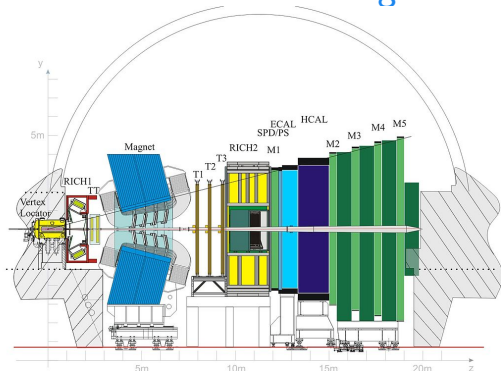
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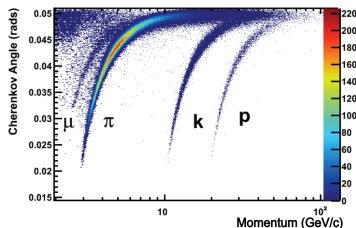
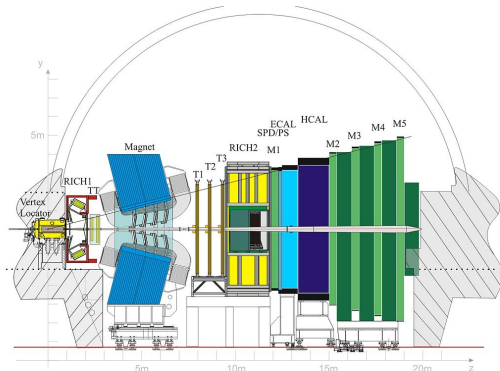
University of
Zurich ^{UZH}

NuFact 2016, Quy Nhon, 21-27 August, 2016

- ⇒ LHCb detector and operations.
- ⇒ Majorana neutrino search.
- ⇒ Inflaton search in $B \rightarrow K^* \chi(\mu\mu)$.
- ⇒ Hidden valley searches.

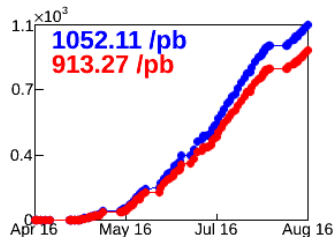
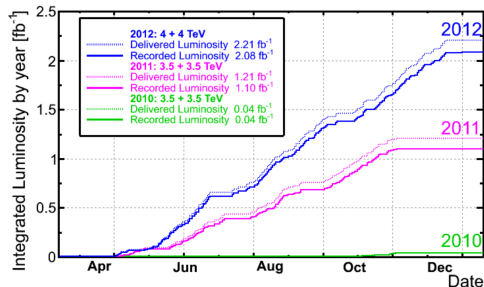


- Excellent Impact Parameter (IP) resolution ($20 \mu\text{m}$).
 \Rightarrow Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40 \text{ fs}$.
 \Rightarrow Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.5 - 1.0\%$) and inv. mass resolution.
 \Rightarrow Low combinatorial background.



- Excellent Muon identification $\epsilon_{\mu \rightarrow \mu} \sim 97\%$, $\epsilon_{\pi \rightarrow \mu} \sim 1 - 3\%$
- Good $K - \pi$ separation via RICH detectors, $\epsilon_{K \rightarrow K} \sim 95\%$, $\epsilon_{\pi \rightarrow K} \sim 5\%$.
 \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,
 $B \rightarrow J/\psi X$: Trigger $\sim 90\%$.

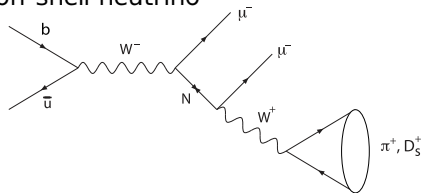
Data taken by LHCb



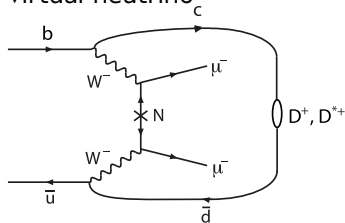
- In 2011 and 2012 LHCb has gathered 3 fb^{-1} of pp collisions.
- Got 1 fb^{-1} in 2016 already!
- The cross section are now two times bigger compared to Run1.

Majorana neutrinos in bottom decays

on-shell neutrino



virtual neutrino

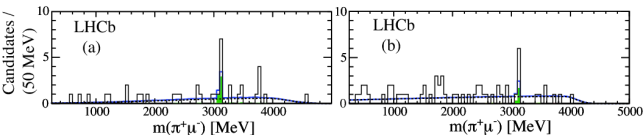
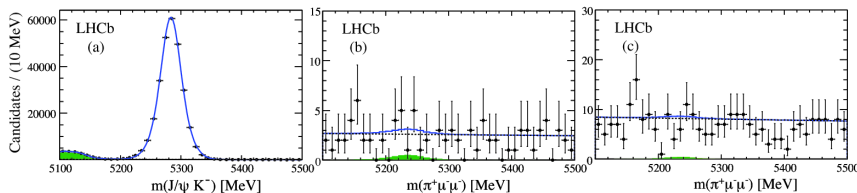


- resonant production in accessible mass range
- rates depend on Majorana neutrino-lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-, \pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

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

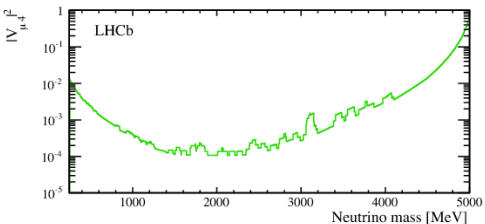
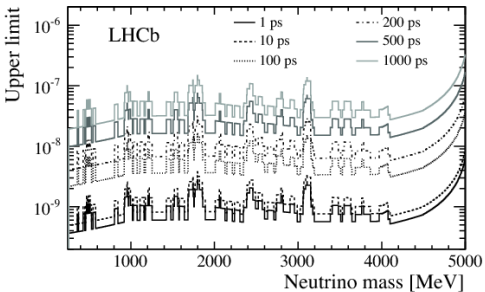
On-shell Majorana neutrinos

- $B^- \rightarrow \pi^+ \mu^- \mu^-$ searched with full data set 3 fb^{-1} .
- Searches performed for two scenarios:
 - Short life-time neutrinos: $\tau_4 < 1 \text{ ps}$
 - Long life-time neutrinos: $\tau_4 \in (1, 1000) \text{ ps}$



Phys. Rev. Lett. 112,
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On-shell Majorana neutrinos



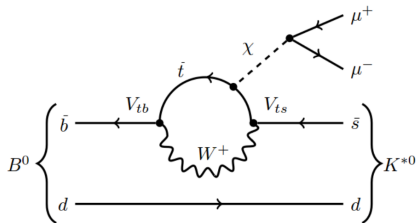
- In absence of signal UL. were set.
- $Br(B^- \rightarrow \pi^+ \mu^- \mu^-)$ in range 10^{-9} .
- Limits also set for the coupling $|V_{\mu 4}|^2$

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

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

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

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



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

$B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-)$: motivation

Benchmark models:

1. Inflaton: [arXiv:1403.4638](https://arxiv.org/abs/1403.4638)

- $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
- $m_\chi < \mathcal{O}(1 \text{ GeV})$,
- $\mathcal{B}(B \rightarrow K\chi) \sim 10^{-6}$

2. Axion portal: [Phys.Rev.D81\(2010\)034001](https://arxiv.org/abs/hep-th/0602232)

- prompt decay are favourite
- axion decay constant: $f_\chi \sim 1 - 3 \text{ TeV}$
- $\mathcal{B}(\chi \rightarrow \mu\mu)$:
 - is dominant for $360 < m_\chi < 800 \text{ MeV}$
 - $\sim \mathcal{O}(10^{-2})$ for $800 \text{ MeV} < m_\chi < 2m_\tau$

$B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-)$: motivation

Benchmark models:

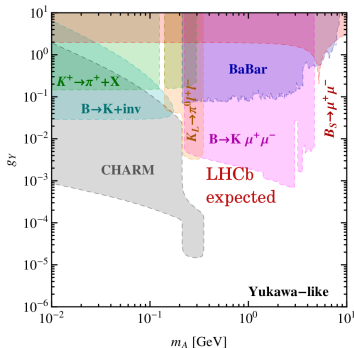
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Existing experimental limit



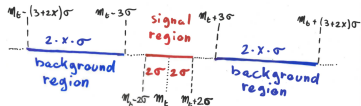
[JHEP 1503 (2015) 171]

$B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-)$: strategy of the search

- Looking for di-muon resonance: [JINST 10(2015)P06002]
 - scan in step of $1/2 \sigma_m(\chi)$

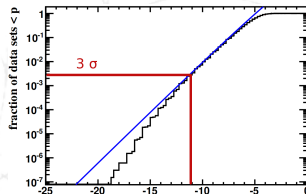
- Definition of search regions:

- *signal*: $|m_{test} - m| < 2\sigma_m$
- *background*:
 $3\sigma_m < |m_{test} - m| < (2x + 3)\sigma_m$



- Background evaluation assume local linearity:

- wide resonances are safe (small deviation from local linearity)
- narrow resonances must be vetoed
- $\mathcal{O}(10\%)$ deviations are allowed
 - $x = 5$ below the J/ψ mass
 - $x = 1$ above the J/ψ mass
- A global p -value is assigned from the minimum local p -value observed



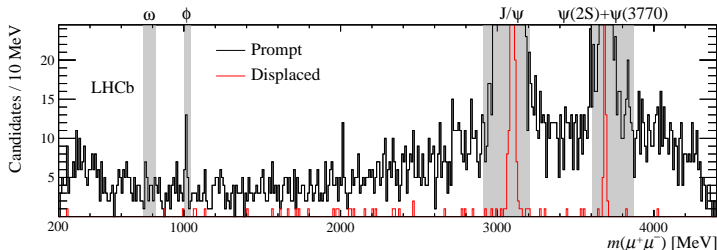
- Trigger on muons.
- Multivariate selection: μ BDT JINST 8(2013)
 - μ BDT ensures flat efficiency in lifetime of χ .
- Optimized on Punzi figure-of-merit:

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

with S and B are signal and background yields.

- Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\text{prompt}} \otimes \mathcal{L}^{\text{displaced}}$
 - Prompt: $\tau < 3\sigma_\tau$
↳ SM background of $B^0 \rightarrow K^* \mu^- \mu^+$
 - Displaced: $\tau > 3\sigma_\tau$
↳ Almost background free.

Grey regions correspond to narrow SM di-muon resonances and are vetoed in the analysis

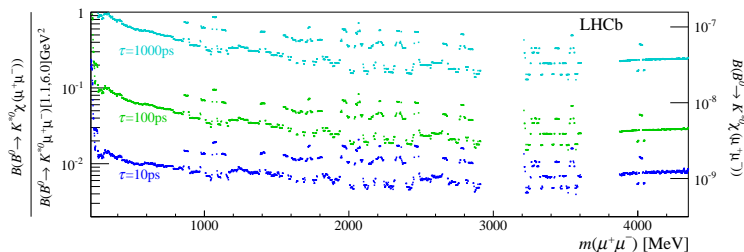


Largest deviation at $m_\chi = 253$ MeV, not statistically relevant:

- local p -value = 0.02

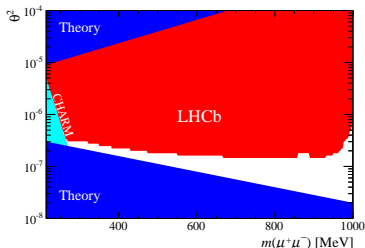
No deviation from the standard model is observed

- 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
- The new particle is assumed to be a scalar

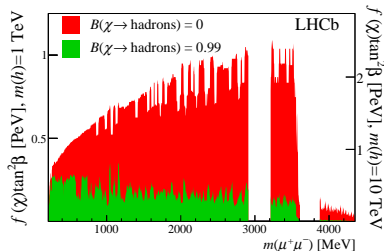


Interpretation of the result in two specific model:

Inflaton model



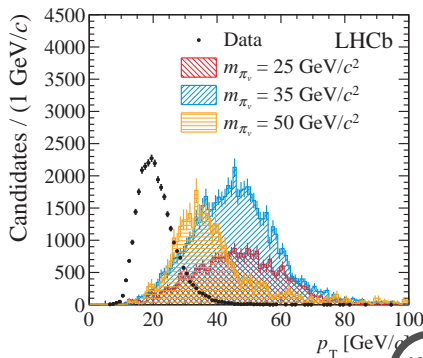
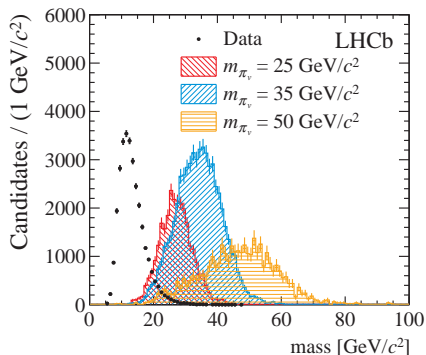
Axion portal

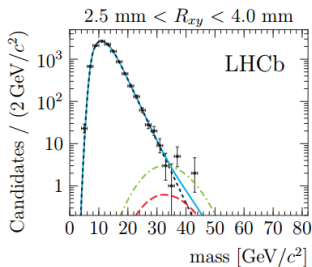
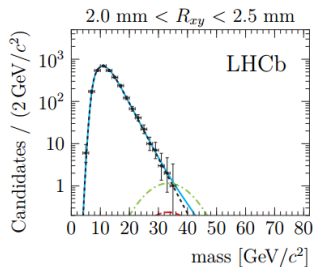
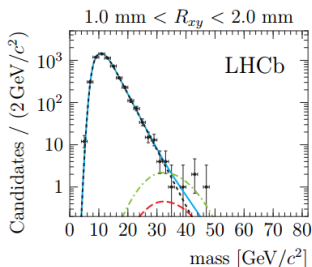
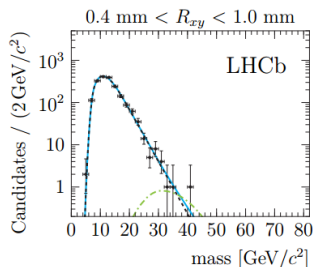


1. Able to exclude the large part of inflaton parameter space
2. Two exclusion limits are shown in the interpretation of the axion portal
 - χ dominantly decaying into muons
 - $\mathcal{B}(\chi \rightarrow \mu\mu) \sim \mathcal{O}(10^{-2})$ (when $\chi \rightarrow 3\pi$ becomes dominant)

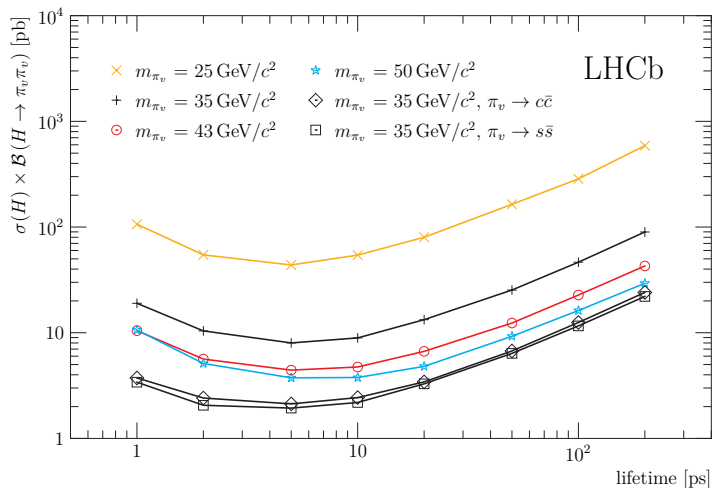
- A possible extensions of the SM are models where the new particles have a small couplings to the SM particles.
- Such models are:
 - Lightest SUSY
 - B/LNV
 - Gravity mediated SUSY
 - Hidden Valleys
- LHCb have performed a search for π_ν particles that are pair produced from Higgs like SM particle.
- They have a long lifetime and decay to pair of jets.

- Efficient trigger for long living particles.
- Reconstruction of two jets.
- MVA used for vertex search.
- Search performed in different regions of displaced vertexes (R_{xy}).
 - $0.4 < R_{xy} < 4$ mm, removes heavy flavour and material interaction backgrounds.





- Signal component fit result, Background component

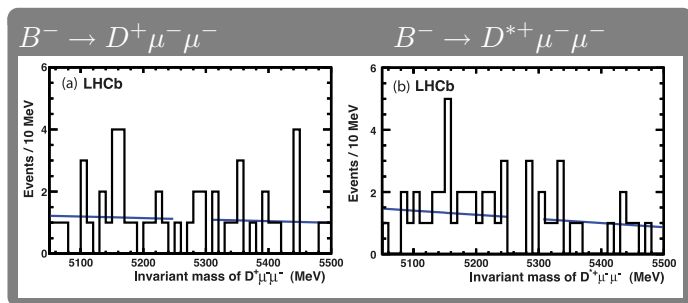


Conclusion

1. Three examples of displaced vertex searches for new physics have been presented, using the Run I LHCb data set
 - very clear new physics signature, SM background highly suppressed
 - more channels are going to be studied
2. Results are the most up-to-date exclusion limit on the processes
3. LHCb is able to exclude almost all the theoretical predicted parameter space of a specific Inflaton model

Backup

Virtual Majorana neutrinos



$$\mathcal{B}(B^- \rightarrow D^+ \mu^- \mu^-) < 6.9 \times 10^{-7} \\ \text{@ 95\% CL}$$

Based on 0.41 fb^{-1} 7 TeV data.

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

Phys. Rev.D85 (2012)
112004

Long living charged particles like $\tilde{\tau}$

⇒ Long living particles can also be produced in the PV.

- This kind of particles would be produced in relatively low velocities and could be identified by their time-of-flight, dE/dx or in Cherenkov detectors.

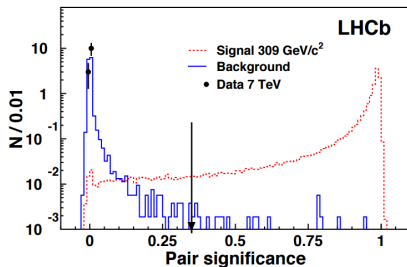
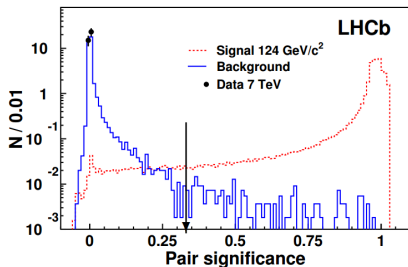
⇒ LHCb performed a search for long living $\tilde{\tau}$ particles.

⇒ $\tilde{\tau}^+\tilde{\tau}^-$ produced by Drell-Yan process.

$\tilde{\tau}$ analysis strategy

⇒ Search performed $\tilde{\tau}$ in mass range of 124 – 309 GeV.

⇒ After the loose preselection to reduce normal Drell-Yan production.



⇒ After the preselection a Neural Net is trained based on Cherenkov detectors to calculate to further suppress the remaining background.

$\tilde{\tau}$ results

- No significant signal yield has been observed.
- 95 % upper limit has been set.

