Searches for heavy long-lived particles at LHCb

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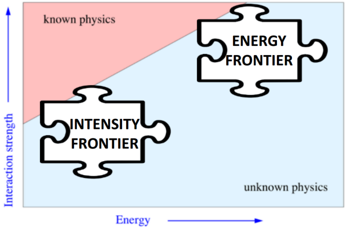
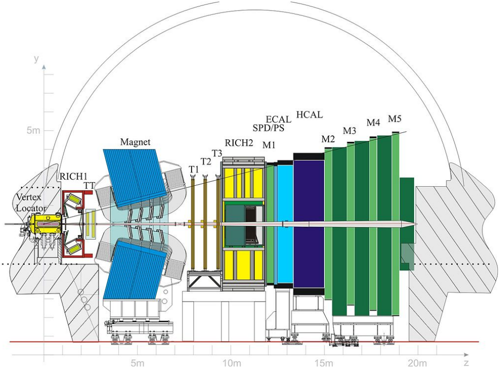
Why long-lived particles?

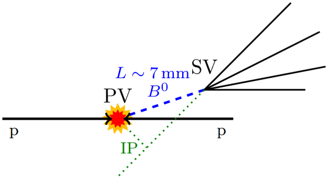
- We all know here that the SM is incomplete.
- Unfortunately we do no know what is the scale of NP.
- NP still can come from the Higgs sector $\Rightarrow$ not all properties are yet constrained.
- There is a long list of theoretical models that predict the existence of new particles that couple to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

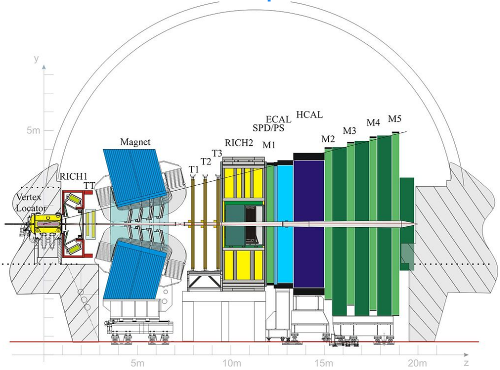
LHCb detector - tracking

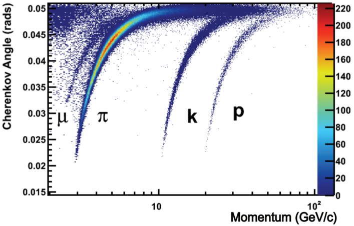




- Excellent Impact Parameter (IP) resolution ($20\ \mu$m).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim$ 40 fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass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

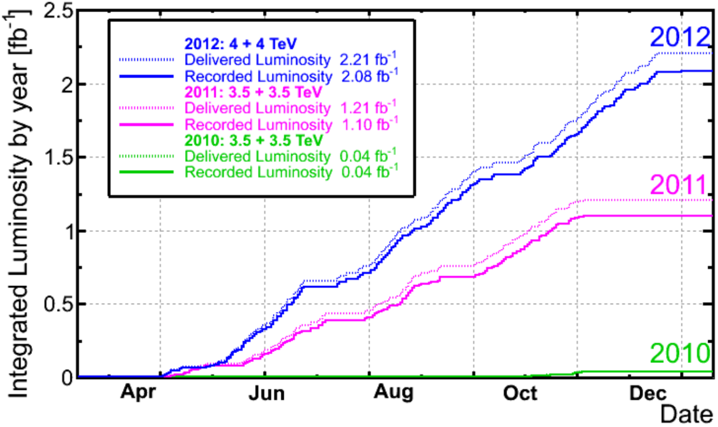
LHCb detector - particle identification





- 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: $p_T > 1.76 \mathrm{GeV}$ at L0, $p_T > 1.0 \mathrm{GeV}$ at HLT1,
  $B \to J/\psi X$: Trigger $\sim 90\%$.

Data taken by LHCb

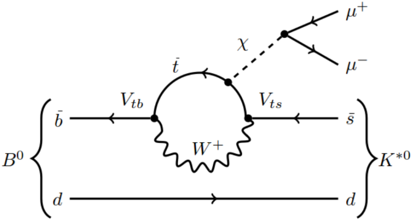


- In 2011 and 2012 LHCb has gathered $3\ \mathrm{fb}^{-1}$ of pp collisions.

$B \to K^* \chi(\mu\mu)$ 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 $\propto \frac{m_f}{f_\chi}$.

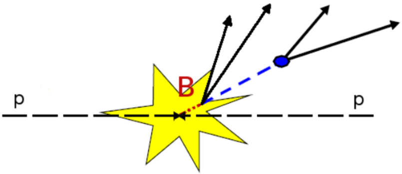
All those particles have width much smaller than resolution of LHCb detector.

Signal properties

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

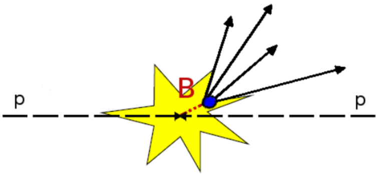
Long lifetime (> 0.2 ps)

- 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

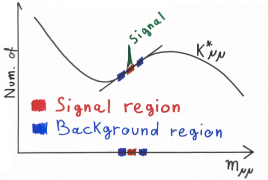
- Trigger on muons.
- Multivariate selection: $\mu\mathrm{BDT}$ JINST 8(2013)
  - $\mu\mathrm{BDT}$ ensures flat efficiency in lifetime of χ.
- Optimized on Punzi figure-of-merit:

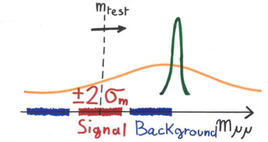
$$P_a = \frac{S}{\frac{5}{2} + \sqrt{B}},$$

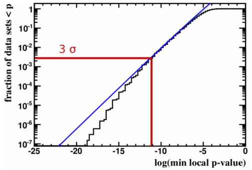
  with S and B are signal and background yields.
- Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\mathrm{prompt}} \bigotimes \mathcal{L}^{\mathrm{displaced}}$
  - Prompt: $\tau < 3\sigma_\tau$
    $\mapsto$ SM background of $B^0 \to K^* \mu^- \mu^+$
  - Displeased: $\tau > 3\sigma_\tau$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

Search strategy

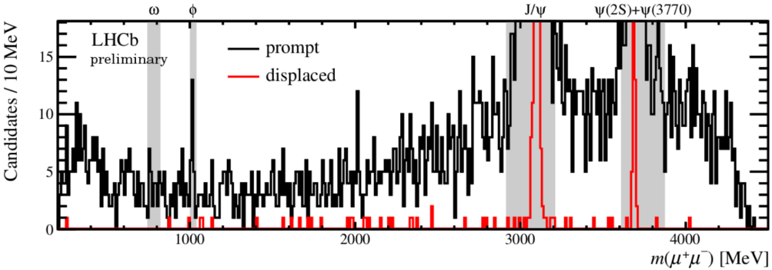
- B^0 mass constrained.
- Di-muon mass resolution $\sigma_m = 1 - 7\ \mathrm{MeV}$.
- Scan m_{test} in steps of $0.5\ \sigma_m$.
    - Wide resonances can't affect the search.
    - Narrows resonances we veto.
- Calculations performed in each m_{test} window.







Results



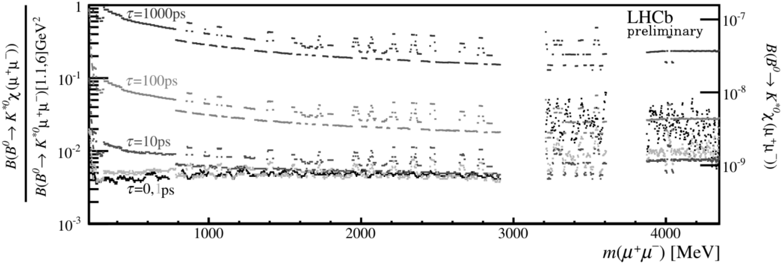
⇛ Grey regions correspond to vetoed regions where narrow resonances are expected.

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

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

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

Branching fraction exclusion limit



⇛ 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.

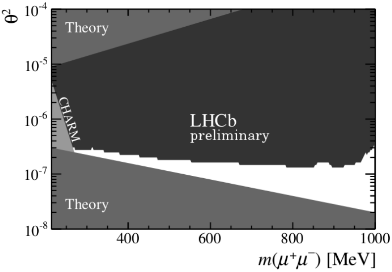
Benchmark models

⇒ Interpretation of the results in two specific models:

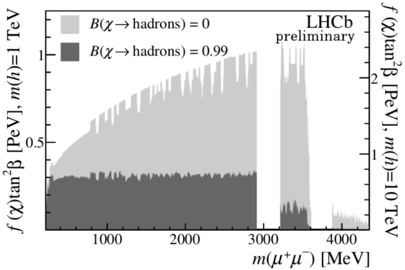
(Specific) inflaton model

Axion portal

[LHCb-PAPER-2015-036 in preparation]



Include 3 sterile neutrinos N_I



MSSM-like two Higgs doublet model.

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

$\Rightarrow$ Long living particles can also be produced in the PV.

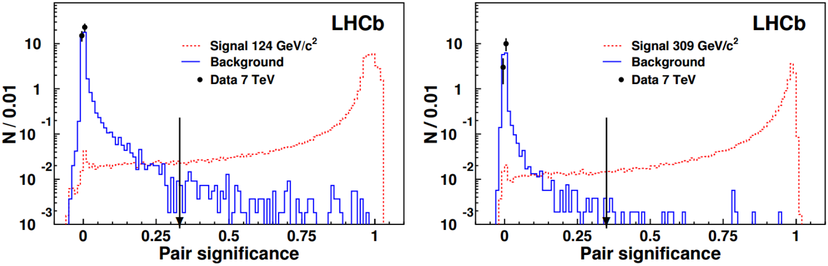
- This kind of particles would be produce in relatively low velocities and could be identified by their time -of-flight, dE/dx or in Cherenkov detectors.

$\Rightarrow$ LHCb performed a search for long living $\tilde{\tau}$ particles.
$\Rightarrow$ $\tilde{\tau}^{+}\tilde{\tau}^{-}$ produced by Drell-Yan process.

$\tilde{\tau}$ analysis strategy

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

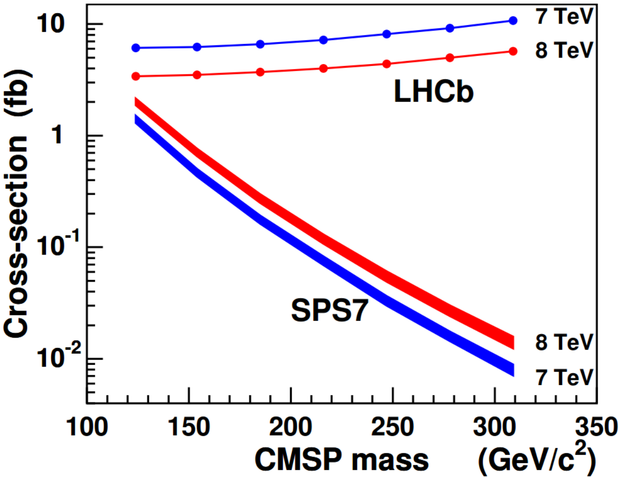
⇛ After the loose preselection to reduce normal Drell-Yan production.



⇛ After the preselection an 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.

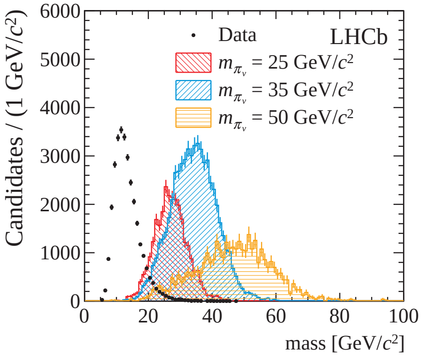


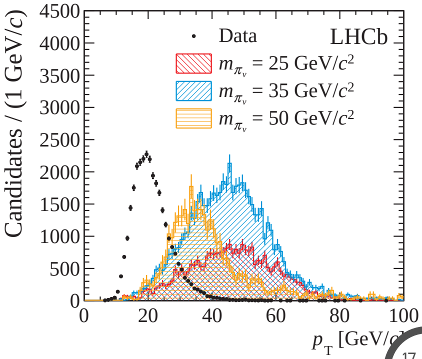
Hidden valley searches

- 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.

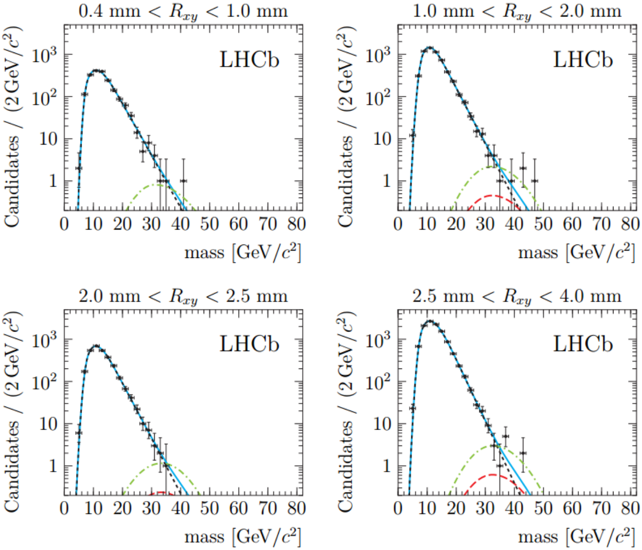
Analysis strategy

- 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.



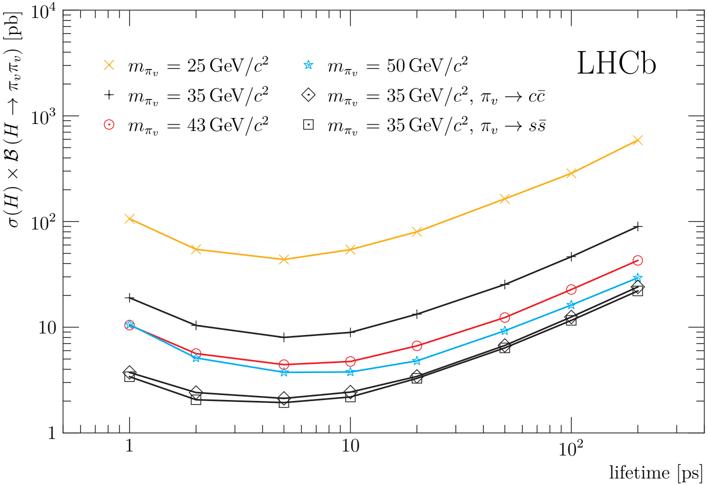


Di-jet distribution



- Signal component fit result, Background component

Results



$m_{\pi_v} = 25\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 43\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 50\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2,\ \pi_v \to c\bar{c}$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2,\ \pi_v \to s\bar{s}$
LHCb
$\sigma(H) \times \mathcal{B}(H \to \pi_v \pi_v)$ [pb]
lifetime [ps]
1
10
10^2
10^3
10^4

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