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

- 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 $\sim 90\%$. 
• In 2011 and 2012 LHCb has gathered 3 fb$^{-1}$ of $pp$ collisions.
$B \rightarrow K^*\chi(\mu\mu)$ search

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

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

- If $\chi$ 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 $\mathcal{B}(\chi \rightarrow \mu^-\mu^+)$. 

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

Discussed models:

   - $\tau_\chi = 10^{-8} - 10^{-10}$ s
   - $m_\chi \mathcal{O}(1 \text{ GeV})$
   - $\mathcal{B}(B \rightarrow K \chi) \sim 10^{-6}$
   - effective couplings to SM particles:
     - $g_Y \frac{m_f}{v_{EW}}$, $g_Y = \sin \theta$

   - Prompt decay.
   - Large allowed masses.
   - Axion decay constant: $f_\chi \sim 1 - 3$ 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** ($> 0.2 \text{ ps}$)
- Inflaton *JHEP* 1005:010
- Displaced vertex.
- Almost background free.
- Lower reconstruction efficiency.

**Short lifetime** ($\leq 0.2 \text{ ps}$)
- Dark matter mediator *Phys. Lett. B*727
- Axion *Phys.Rev.D*81
- Prompt decay.
- Contaminated via SM decay.

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Selection

- Trigger on muons.
- Multivariate selection: $\mu\text{BDT}$ JINST 8(2013)
  - $\mu\text{BDT}$ ensures flat efficiency in lifetime of $\chi$.
- 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: $\tau < 3\sigma_{\tau}$
    - $\leftrightarrow$ SM background of $B^0 \rightarrow K^*\mu^-\mu^+$
  - Displeased: $\tau > 3\sigma_{\tau}$
    - $\leftrightarrow$ Almost background free.
Search strategy

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

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Benchmark models

⇒ Interpretation of the results in two specific models:

(Specific) inflaton model

Axion portal

Include 3 sterile neutrinos $N_f$

MSSM-like two Higgs doublet model.
Long living charged particles like $\tilde{\tau}$

⇒ 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.

⇒ 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 an Neural Net is trained based on Cherenkov detectors to calculate to further suppress the remaining background.
• 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 $\pi_\nu$ 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

![Graph showing the cross section \( \sigma(H) \times B(H \rightarrow \pi_v \pi_v) \) vs. lifetime [ps] for different masses of the particle \( m_{\pi_v} \).](image)

- \( m_{\pi_v} = 25 \text{ GeV}/c^2 \)
- \( m_{\pi_v} = 50 \text{ GeV}/c^2 \)
- \( m_{\pi_v} = 35 \text{ GeV}/c^2 \)
- \( m_{\pi_v} = 35 \text{ GeV}/c^2, \pi_v \rightarrow c\bar{c} \)
- \( m_{\pi_v} = 43 \text{ GeV}/c^2 \)
- \( m_{\pi_v} = 35 \text{ GeV}/c^2, \pi_v \rightarrow s\bar{s} \)

LHCb

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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 the way.