Searches for low mass dark bosons

Andrea Mauri

On behalf of the LHCb collaboration

University of Zurich

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Motivation

• The Higgs discovered in 2012 at LHC is consistent with a SM Higgs boson
  ○ but it could still have non SM properties (coupling to exotic particles)

• 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

\[
\begin{pmatrix}
H \\
\chi
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
H' \\
\chi'
\end{pmatrix}
\]

• Inflaton, axion-like, dark matter mediator models also predict the new boson to be light.
The LHCb detector

3 fb$^{-1}$ of collected data in 2011 and 2012.
Why at LHCb?

Main production via B meson:

If $\chi$ mix with the Higgs and it is light enough

$$
\Gamma(K \rightarrow \pi \chi) \propto (m_t^2 \left| V_{ts}^* V_{td} \right|)^2 \propto m_t^4 \lambda^5
$$

$$
\Gamma(D \rightarrow \pi \chi) \propto (m_b^2 \left| V_{cb}^* V_{ub} \right|)^2 \propto m_b^4 \lambda^5
$$

$$
\Gamma(B \rightarrow K \chi) \propto (m_t^2 \left| V_{ts}^* V_{tb} \right|)^2 \propto m_t^4 \lambda^2
$$

Advantages of the LHCb detector:

- low $p_T$ trigger $\rightarrow$ low masses accessible
  - single muon, $p_T > 1.76$ GeV/$c$
  - di-muon, $p_{T_1} \times p_{T_2} > (1.6$ GeV/$c)^2$
  - high efficiency for muon trigger ($\sim 90\%$)

- very precise vertex reconstruction (VELO)
  - impact parameter resolution, $\sigma_{IP} = 20 \mu m$
  - lifetime resolution, $\sigma_\tau \sim 0.2$ ps (for $\tau = 100$ ps)
Signal properties

Depending on the coupling to the SM/hidden sector, we can identify two lifetime regimes:

\[
\begin{bmatrix}
\text{detector resolution} \\
\sigma_{\tau} \sim 0.2 \text{ ps}
\end{bmatrix}
\]

**Long lifetime:**
- Inflaton [JHEP1005(2010)010]
- Displaced vertex
- Almost background free
- Lower reconstruction efficiency

**Short lifetime:**
- Prompt decay
- Contamination from SM background
The decay

- Looking for dark boson decaying into muons

\[ B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-) \]

- \( K^{*0} \rightarrow K^+ \pi^- \):
  - helps to reconstruct the B decay vertex

- \( B(\chi \rightarrow \mu^+ \mu^-) \):
  - dominant till the hadronic threshold (\( \chi \rightarrow 2h, \chi \rightarrow 3h \))
  - always significant \( O(10^{-2}) \) in the full mass range
$B^0 \rightarrow K^*^0 (\chi \rightarrow \mu^+ \mu^-)$: motiva\-tion

Benchmark models:

1. **Inflaton**: arXiv:1403.4638
   - $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
   - $m_\chi < \mathcal{O}(1 \text{ GeV}),$
   - $B(B \rightarrow K \chi) \sim 10^{-6}$
   - effective coupling to SM particles:
     - $g_Y \frac{m_f}{v_{EW}}$, $g_Y \equiv \sin \theta$
     - Interesting parameter values, in the range we can test!

   - prompt decay
   - large allowed mass range
   - axion decay constant: $f_\chi \sim 1 - 3 \text{ TeV}$
     - coupling $\propto m_f / f_\chi$

All models predict dark boson with width $\sim 0.$
$B^0 \to K^{*0}(\chi \to \mu^+\mu^-)$: motivation

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Existing experimental limit

Similar analysis in BaBar [1] and Belle [2] with $B \to K\mu\mu$ decay

Selection

1. Triggered on muons

   - performance independent of mass and lifetime of $\chi$

   \[ P_a = \frac{S}{\frac{5}{2} + \sqrt{B}} \]
   with $S$ and $B$ signal and background yields.

4. Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\text{prompt}} \cdot \mathcal{L}^{\text{displaced}}$
   - prompt, $\tau < 3\sigma_\tau$
     - irreducible SM background $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
   - displaced, $\tau > 3\sigma_\tau$
     - (almost) background free
Strategy of the search

Looking for di-muon resonance:

- $B^0$ mass constrained
- Di-muon mass resolution $\sigma_m = 1 \div 7$ MeV
- Scan $m_{test}$ in steps of $1/2 \sigma_m$
  - wide resonances are safe
  - narrow resonances must be vetoed
- Test statistic performed for each $m_{test}$
- A global $p$-value is assigned from the minimum local $p$-value observed
  - fraction of toys that have a minimum local $p$-value less than the observed in data
  - takes account of the Look Elsewhere Effect
Results

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

[LHCb-PAPER-2015-036 in preparation]

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

- local $p$-value = 0.02
Exclusion limit

No deviation from the 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)
- The new particle is assumed to be a scalar
- Lower lifetimes have better limit due to higher reconstruction efficiency

![Graph showing exclusion limits for different masses and lifetimes.](LHCb-PAPER-2015-036 in preparation)
Exclusion limit: two benchmark models

Interpretation of the result in two specific model:

- **(Specific) inflaton model**
  - Include 3 sterile neutrinos $N_1$

- **Axion portal**
  - MSSM-like two Higgs doublet model.

[Image 17x49 to 173x156]
[Image 190x50 to 346x157]
Conclusion

1. A search for a dark boson in the decay channel $B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-)$ has been presented
   - No deviation from the background only hypothesis is observed

2. Results are the most constraining exclusion limit on the process

3. LHCb is able to exclude almost all the theoretical predicted parameter space of a specific Inflaton model
Backup
Strategy

- **signal region** defined as: $|m_{\text{test}} - m| < 2\sigma_m$
- **background region** defined as: $3\sigma_m < |m_{\text{test}} - m| < (2x + 3)\sigma_m$
- $\mathcal{O}(10\%)$ deviations from local linearity are allowed
  - $x = 5$ below the $J/\psi$ mass
  - $x = 1$ above the $J/\psi$ mass
# Trigger

<table>
<thead>
<tr>
<th>Level</th>
<th>Trigger line</th>
<th>Level</th>
<th>Trigger line</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>L0Hadron</td>
<td>L0</td>
<td>L0Muon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>L0DiMuon</td>
</tr>
<tr>
<td>HLT1</td>
<td>Hlt1TrackAllL0</td>
<td></td>
<td>Hlt1TrackMuon</td>
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<td></td>
<td></td>
<td></td>
<td>Hlt1DimuonLowMass</td>
</tr>
<tr>
<td>HLT2</td>
<td>Hlt2TopoMu2BodyBBDT</td>
<td></td>
<td>Hlt2TopoMu3BodyBBDT</td>
</tr>
<tr>
<td></td>
<td>Hlt2Topo2BodyBBDT</td>
<td></td>
<td>Hlt2Topo3BodyBBDT</td>
</tr>
<tr>
<td></td>
<td>Hlt2SingleMuon</td>
<td></td>
<td>Hlt2DiMuonDetached</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hlt2Topo4BodyBBDT</td>
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</table>
# Pre-selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{dir}}(B^0)$</td>
<td>$&lt; 0.03$ rad</td>
</tr>
<tr>
<td>$\chi_{\text{vtx}}(B^0)$</td>
<td>$&lt; 15$</td>
</tr>
<tr>
<td>$\chi_{\text{IP}}(B^0)$</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>$\text{DLL}_{K\pi}(K)$</td>
<td>$&gt; -5$</td>
</tr>
<tr>
<td>$\text{DLL}_{K\pi}(\pi)$</td>
<td>$&lt; 25$</td>
</tr>
<tr>
<td>$\text{DLL}<em>{K\pi}(K) - \text{DLL}</em>{K\pi}(\pi)$</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td>$</td>
<td>m(K^+\pi^-) - 895.6</td>
</tr>
<tr>
<td>$FD_T(\chi)$</td>
<td>$&gt; 0.1$ mm</td>
</tr>
<tr>
<td>$\text{isMuon}(K,\pi)$</td>
<td>False</td>
</tr>
</tbody>
</table>
## Selection

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>$\chi^2_{\text{VLF}/\text{ndf}}$ &lt; 25</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{FP}}$ &lt; 50</td>
</tr>
<tr>
<td></td>
<td>$\tau$ &gt; 0.2 ps</td>
</tr>
<tr>
<td></td>
<td>$m$ $\in$ [4800, 5800] MeV</td>
</tr>
<tr>
<td></td>
<td>$p_T$ &gt; 1000 MeV</td>
</tr>
<tr>
<td></td>
<td>$\cos\theta_{\text{dir}}$ &gt; 0</td>
</tr>
</tbody>
</table>

|           | $\chi^2_{\text{VLF}/\text{ndf}}$ < 10 |
|           | $\chi^2_{\text{FD}}$ < 25 |
|           | $p_T$ > 250 MeV |
|           | DOCA < 0.2 mm |
|           | DOCA $\chi^2$ < 25 |

| Tracks    | $\chi^2_{\text{trk}/\text{ndf}}$ < 3 |
|           | $\text{min}(\chi^2_{\text{FP}})$ > 9 |
|           | $P_{\text{gh}}$ < 0.3 |

| $K$, $\pi$ | $p_T$ > 250 MeV |
|            | $p$ > 2000 MeV |
|            | $\chi^2_{\text{FP}}$ > 9 |
| $K$        | ProbNNK > 0.1 |
| $\pi$      | ProbNNpi > 0.2 |
| $\mu$      | $p_T$ > 100 MeV |
|            | PIDmu > -5 |

| GEC       | $N_{\text{tracks}}$ $\leq$ 250 |
Multivariate selection

Input variables:

<table>
<thead>
<tr>
<th>uBDT Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B^0)$</td>
</tr>
<tr>
<td>FD($B^0$)</td>
</tr>
<tr>
<td>$\theta_{\text{dir}}(B^0)$</td>
</tr>
<tr>
<td>$\chi^2_{\text{IP}}(K^*)$</td>
</tr>
<tr>
<td>$\min \text{ProbNN}_\mu(\mu^\pm)$</td>
</tr>
</tbody>
</table>

uBDT selection is 85 % efficient on signal
Background rejection

- Narrow SM resonances are vetoed:
  - $\omega$, $\phi$, $J/\psi$, $\psi(2S)$
- Background from particle mis-identification:

<table>
<thead>
<tr>
<th>Mass</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m(K^+\pi^- \leftrightarrow K^+K^-) - m^{PDG}_\phi</td>
</tr>
<tr>
<td>$</td>
<td>m(\mu^+\mu^- \leftrightarrow \pi^+\pi^-) - m^{PDG}_{K^0}\rangle</td>
</tr>
<tr>
<td>$</td>
<td>m(\mu^+\mu^- \leftrightarrow K^+\pi^-) - m^{PDG}_{D^0}</td>
</tr>
<tr>
<td>$</td>
<td>m(\mu^+\mu^- \leftrightarrow p\pi^-) - m^{PDG}_\Lambda</td>
</tr>
<tr>
<td>$</td>
<td>m(p_\pi K^-\mu^+\mu^-) - m^{PDG}_{A_0}</td>
</tr>
</tbody>
</table>
$\chi$ spin

Results are presented with the assumption that $\chi$ is spin 0

![Graph showing efficiency as a function of $m(\mu^+\mu^-)$]
Inflaton benchmark model

Reference: arXiv:1403.4638

- Light inflaton: $0.1 < m_\chi < 1$ GeV
- Lifetime $10^{-5} - 10^{-12}$ s
- 3 sterile neutrinos $N_i$
  - siglets with respect to the SM gauge group
  - Yukawa-type coupling to inflaton provides Majorana masses
  - the lightest, $N_1$, may serve as DM produced by inflaton decays in the early Universe
    - $1$ keV $< M_1 < 1$ MeV
Axion-like benchmark model


- $\mathcal{L}_{\text{int}} = \frac{c_\psi}{f_\chi} \bar{\psi} \gamma_\mu \gamma^5 \psi \partial_\mu \chi$
- effective coupling constant $c_\psi m_\psi / f_\chi$
- The axion arises from spontaneous Peccei-Quinn symmetry breaking in a two Higgs doublet model (2HDM)
  - two Higgs doublet:
    \[ h_u = \begin{pmatrix} v_u \exp\left[ \frac{i \cot \beta}{\sqrt{2} v_{EW}} A^0 \right] \\ 0 \end{pmatrix}, \quad h_d = \begin{pmatrix} 0 \\ v_d \exp\left[ \frac{i \tan \beta}{\sqrt{2} v_{EW}} A^0 \right] \end{pmatrix} \]
- $\chi$ mixes with the $CP$-odd Higgs $A^0$
  \[ a_{\text{phys.}} = a \cos \theta - A^0 \sin \theta, \quad A^0_{\text{phys.}} = a \sin \theta + A^0 \cos \theta, \quad \text{with} \quad \tan \theta = \frac{n v_{EW}}{f_a} \frac{\sin 2\beta}{2} \]