Search for heavy long-lived exotic particles in LHCb

Veerle Heijne
On behalf of the LHCb collaboration

DARK 2012, Frascati
16 October - 19 October 2012
**Motivation**

**Long-lived exotic particles**

- Many new-physics models feature massive long-lived exotics (\(\tilde{\chi}_0^0, \pi_\nu^0, \ldots\)) which decay into Standard Model particles.
- A decaying long-lived particle produces a displaced vertex, which LHCb would be able to trigger and reconstruct.
- Standard Model background is low.

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![Graph showing mass vs. mean lifetime for various particles like leptons, strange hadrons, charm hadrons, bottom hadrons, \(K_S, K^\pm, K_L\), and \(\pi^0\).]

- *mass [GeV/c^2]*
- *mean lifetime [s]*

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Long-Lived Exotics  
DARK 2012
**Signature of the Displaced Vertex**

- Large decay length → LHCb is sensitive to $\sim 1\text{mm} - 1\text{m}$
- High track multiplicity → for decay to quarks
- High mass $\rightarrow \gtrsim 20\ \text{GeV}$
- Fully hadronic, semi-leptonic, fully leptonic
- Combine pairs of back-to-back long-lived particles
  $\rightarrow$ reducing background

Long-lived particles can be produced in pairs through Higgs decay: $h^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$
Example Model

- mSuGRA with baryon number violation [Carpenter, Kaplan, Rhee]
  \[ \tilde{\chi}^0 \rightarrow q\bar{q} \rightarrow q\{qq\} \]

Monte Carlo sample "BV48":
  \[ m_{h_0} = 114 \text{ GeV}, \ m_{\tilde{\chi}^0} = 48 \text{ GeV}, \ \tau_{\tilde{\chi}^0} = 10 \text{ ps} \]

Other options:

- Hidden Valley \( h_0 \rightarrow \pi^0 \pi^0 \rightarrow b\bar{b}b\bar{b} \) Monte Carlo sample "HV10" [Strassler, Zurek]

- SUSY with R parity violation, unstable Lightest SUSY Partner
  \( (\tilde{\chi}^0 \rightarrow \nu\ell^+\ell^-, \ \tilde{\chi}^0 \rightarrow \nu q\bar{q}, \ \tilde{\chi}^0 \rightarrow \ell q\bar{q}) \) [Carpenter, Kaplan, Rhee], [De Campos, Eboli, et al]
LHCb is designed to detect $b$-hadrons, produced in the forward region

- Reconstruct $b$- and $d$-hadron decays (flight distance $\sim 1\text{cm}$)
- Measure CP-violation
- Search for rare decays

This analysis uses 2010 data ($35.8 \text{ pb}^{-1}$)
LHCb detector

[2008 JINST 3 S08005]
**LHCb detector**

2008 JINST 3 S08005

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Long-Lived Exotics

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Why LHCb?

- Displaced vertex trigger
- VELO provides excellent vertex reconstruction
- Unique coverage: $2 < \eta < 5$ (ATLAS/CMS tracking systems: $|\eta| < 2.5$)

Distribution of MC signal samples at generator level
(BV48 $\rightarrow$ mSuGRA, HV10 $\rightarrow$ Hidden Valley)

- 25% of the generated events have a long-lived particle in the acceptance
- For the 2010 dataset (35.8 pb$^{-1}$) we expect about 50-100 events with two decay vertices in the acceptance for the model BV48
Reconstruction of 1-100 ps lifetime is possible.

- Flight distance <40cm: Tracks include VELO segment
- Flight distance 20cm-2m: Tracks without VELO segment (future analysis)
The trigger reduces the total data rate from 40 MHz to 3 kHz

40 MHz
L0, high $p_T$ objects
1 MHz
HLT1, displaced tracks, $\mu$
50 kHz
HLT2, inclusive + exclusive triggers
3 kHz
(4.5 kHz in 2012)

Our displaced vertex trigger lines
(output $\sim$20 Hz)

**Vertexing**

- VELO tracking, PV reconstruction run at 1 MHz
- Displaced vertex reconstruction run at 50 kHz
- Make seed with neighbouring tracks, run adaptive least square fit
Trigger on a displaced vertex:

**Trigger Selection**

- At least two displaced vertices
- Radius $\geq 0.4$ mm
- N tracks $\geq 4$
- Mass $\geq 3$ GeV (charged particles only)
- Passes material veto

- The trigger efficiency on reconstructible MC signal is $\sim 40\%$
- In 2010 the efficiency on offline reconstructed events was 67%
- Improved trigger for 2011 and 2012 data taking
**Backgrounds**

- **Primary vertices**
  - Centered in interaction region
  - → Reject by requiring large radius from beamline
- **Interactions with detector material**
  - High track multiplicity, large mass
  - → Material veto

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**Figure 8**: Left: longitudinal position of PV candidates. Right: radial position to the calculated beam axis. The vertical bar indicates the region considered for the PV selection, \( r < 0.3 \text{ mm} \).

**5.2 Event preselection**

Once the set of PVs identified, all the other RVs are candidates for the decay position of LLPs. The event preselection requires at least one PV in the event and at least one LLP with:

- at least 4 forward tracks
- no backward tracks
- an invariant mass reconstructed from tracks larger than 3 GeV/c
- a distance to the beam line of more than 0.3 mm.

We give in Figure 9 the \( e^\pm \) efficiencies to find a vertex as a function of the distance from the PV inferred from MC events. True MC values are used to define the coordinates of the PV and of the LLP vertices and it is necessary that the decay leaves at least 6 charged particles in the acceptance. After reconstruction the RV is declared detected when satisfying the first two of the above listed criteria (the cuts on the mass and the distance to the beam are not active).

From the analysis of MinBias MC events we can estimate the quark flavors responsible for the vertices selected by the preselection. This is shown in Figure 10 as a function of the distance from the true PV. The large light flavor component (non-c non-b) is mainly background due to interactions in matter.

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**Vertex reconstruction**

- **Ak algorithm**
- **Minimal requirements**
  - \( N_{tr} \geq 4 \), \( m_{\text{vertex}} > 3 \text{ GeV} \), \( \text{Radial distance to the beam line} \geq 0.4 \text{ mm} \). Including Velo: flies less than 40 cm, resolution \( \mathcal{O}(100 \mu\text{m}) \).
- **Without Velo**: flies between 20 cm and 2 m, resolution \( \mathcal{O}(1 \text{ mm}) \) - Not in preliminary analysis.

**Main backgrounds**: Hadronic interaction with matter, B hadrons.

**Matter Veto** has been developed.

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**Velo Silicon sensor**

Region accepted by the matter veto

**RF foil**

**Velo Silicon sensor**

RF foil

Region accepted by the matter veto

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**Long-Lived Exotics**

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Decay of Standard Model particles

- Inclusive $b\bar{b}$, $c\bar{c}$, $t\bar{t}$
- Displaced, low track multiplicity, low mass
- These should not fall in the signal region, but they will if we make a mistake in the vertex reconstruction (e.g. merge two $b$-vertices or include a primary vertex track in the displaced vertex)

$\rightarrow b\bar{b}$ is the main background
Preliminary analysis on 35.8 pb\(^{-1}\) (2010 data)

Expected number of \(b\bar{b}\) events: 75 ± 13 \(\times\) 10\(^3\)

Observed in data: 59 \(\times\) 10\(^3\) events

Shapes compatible with \(b\bar{b}\) background

[LHCb-CONF-2012-014]
Candidates coming from a low-$p_T$ $h0$ are back-to-back
Select pairs of long-lived particles with $\Delta \phi > 2.8$ to reconstruct the $h_0$ candidate
We are left with 13,893 candidate pairs, which are consistent with $b\bar{b}$ background:

![Mass Distribution](image)

**Final selection to remove SM background**

- Two candidates
- $|\Delta \phi| > 2.8$ rad
- N tracks $\geq 6$
- Mass $\geq 6$ GeV

No events left in data

Total efficiency on signal: $0.384\% \pm 0.017\%$

→ expect 2 events for mSuGRA model
Detection efficiency of reconstructible long-lived particle (LLP) candidates determined on signal MC:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>$\epsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One LLP in acceptance (generator cut)</td>
<td>29.4</td>
</tr>
<tr>
<td>LLP preselection</td>
<td>44.1</td>
</tr>
<tr>
<td>Trigger</td>
<td>35.5</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>95.8</td>
</tr>
<tr>
<td>LLP selection</td>
<td>66.4</td>
</tr>
<tr>
<td>Two LLP found</td>
<td>19.1</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi</td>
</tr>
<tr>
<td>Total</td>
<td>0.384</td>
</tr>
<tr>
<td>Total without trigger</td>
<td>0.589</td>
</tr>
</tbody>
</table>

(Pre)selection is optimised to reduce backgrounds
Trigger has limited bandwidth
Main loss from the first (HLT1) level of the software trigger for very displaced vertices. A dedicated algorithm has been implemented for future analyses
Requiring two LLP and $|\Delta \phi|$ to reduce backgrounds
**Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>%</th>
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<tbody>
<tr>
<td>Integrated luminosity</td>
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<tr>
<td>Trigger</td>
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</tr>
<tr>
<td>Track reconstruction</td>
<td>7</td>
</tr>
<tr>
<td>$p_T$ and mass calibration</td>
<td>6</td>
</tr>
<tr>
<td>Vertex reconstruction</td>
<td>12</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>4</td>
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<tr>
<td>Beam line position</td>
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</tr>
<tr>
<td>Total</td>
<td>22</td>
</tr>
</tbody>
</table>

**Trigger**

15% sensitivity in the comparison of efficiencies in data and MC by using $b\bar{b}$ events with relaxed cuts

**Vertex reconstruction**

Account for differences in vertex resolution between data and MC
Monte Carlo generated for different parameters of the mSuGRA model:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\tau_{LLP}$ ps</th>
<th>$m_{LLP}$ GeV/$c^2$</th>
<th>$m_{h^0}$ GeV/$c^2$</th>
<th>$\epsilon$ (%)</th>
<th>$\sigma_{UL}$ pb</th>
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</thead>
<tbody>
<tr>
<td>BV48-5</td>
<td>5</td>
<td>48</td>
<td>114</td>
<td>$0.184 \pm 0.011$</td>
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</tr>
<tr>
<td>BV48</td>
<td>10</td>
<td>48</td>
<td>114</td>
<td>$0.384 \pm 0.017$</td>
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<td>48</td>
<td>114</td>
<td>$0.418 \pm 0.017$</td>
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<td>BV20-10</td>
<td>10</td>
<td>20</td>
<td>114</td>
<td>$0.010 \pm 0.003$</td>
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<td>BV35-10</td>
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<td>35</td>
<td>114</td>
<td>$0.146 \pm 0.010$</td>
<td>84</td>
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<tr>
<td>BV48-mh100</td>
<td>10</td>
<td>48</td>
<td>100</td>
<td>$0.190 \pm 0.013$</td>
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<tr>
<td>BV48-mh125</td>
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<td>48</td>
<td>125</td>
<td>$0.293 \pm 0.019$</td>
<td>42</td>
</tr>
</tbody>
</table>

Preliminary result

The mSuGRA model BV48 with:
$m_{h^0} = 114$ GeV, $m_{\tilde{\chi}^0} = 48$ GeV, $\tau_{\tilde{\chi}^0} = 10$ ps

gives a 95% confidence level upper limit of 32 pb [LHCb-CONF-2012-014]
To extrapolate the results to a larger variety of models, use a fast simulation of the LHCb detector

Fast Simulation

- Generate charged particles and feed them to the vertexing algorithm
- Apply inefficiencies as function of vertex position
- Enables us to extend the results for different $m_{h0}$, $m_{\tilde{\chi}}$, and $\tau_{\tilde{\chi}}$

For a fixed lifetime $\tau_{\tilde{\chi}}$ respectively fixed $m_{h0}$:

95% CL upper limit [pb]

<table>
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<tr>
<th>$m_{LLP}$</th>
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<th>48</th>
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<tr>
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<td>101</td>
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<table>
<thead>
<tr>
<th>$m_{LLP}$</th>
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<th>48</th>
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<tbody>
<tr>
<td>$\tau_{LLP}$</td>
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<td>142</td>
<td>100</td>
<td>61</td>
<td>34</td>
<td>25</td>
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</tbody>
</table>

→ Good agreement with full simulation in control points
A search was performed for a Higgs-like boson decaying to a pair of long-lived particles in 35.8 pb$^{-1}$ of 2010 data [LHCb-CONF-2012-014]

No events passed our selection, which was optimised to reduce the main background components (detector material and $b\bar{b}$ events)

A preliminary 95 % CL upper limit for the production cross-section of 32 pb has been set for one specific model: mSUGRA with baryon number violation ($m_{h_0} = 114$ GeV, $m_{\tilde{\chi}_0} = 48$ GeV, $\tau_{\tilde{\chi}_0} = 10$ ps)

The result can be extended to other models using a fast simulation
Outlook

- ~70 times more integrated luminosity from 2011: $1 \text{ fb}^{-1}$ and 2012: $\sim 2.2 \text{ fb}^{-1}$

- More inclusive analysis:
  - Single-vertex signatures
  - Specific searches for semileptonic decays

- Improve systematic uncertainties:
  - Add more control trigger lines to better estimate uncertainty

- Improve efficiency:
  - More advanced selection
  - Improve vertex reconstruction efficiency
  - Use substructure and flavour to distinguish between models and to reduce background
  - Improve mass reconstruction using jets