Search for Neutral Long-Lived Particles Decaying to $b\bar{b}$ at DØ

Exploring the hidden-valley: a novel path to Higgs discovery

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for the DØ collaboration

Is the Higgs Boson hiding here?
Beyond the SM

- Many SM extensions contain a “Hidden-Valley”
  - Hidden-Valley mirror to the SM
    - energetically inaccessible
  - \(v\)-particles are uncharged in SM
  - SM interacts with HV through a communicator

  - predicts a confining gauge group, weakly-coupled to the SM
  - \(v\)-hadrons may couple preferentially to heavy fermions
  - some \(v\)-particles could be long-lived (but \(< < 1\) second)
The Benchmark Signal

- Higgs mixes with $\phi$
  - decays to two long-lived $\pi^0_{HV}$
  - $\pi^0_{HV} \rightarrow Z' \rightarrow b \bar{b}$
  - signal has a striking signature: highly displaced secondary-vertices (SVs) with a large number of attached tracks – **We can see this!**
  - branching fraction could be substantial
  - motivation: if the Higgs only decays through a HV, then they would be invisible to previous analyses
  - evades SM LEP limits, most general: Higgs radiating from a $Z$, LEP excludes: $m_H < 82$ GeV
• $H \rightarrow \pi_{HV}(\rightarrow b\bar{b})\pi_{HV}(\rightarrow b\bar{b})$

• Two or more highly displaced secondary vertices, SV (>$1$ cm from the primary vertex, PV) – reco. large SV

• Focus on v-hadrons (HV particles) decaying to two b's ($m_{HV} > 2b$)

• Large number of tracks attached to SV from multiple b decays
Tracker – position & momentum

- Position and momentum of charged particles
- Inside in a 2T solenoid
- Silicon Microstrip Tracker (SMT)  
  - very high resolution (~10μm)
- Central Fiber Tracker (CFT)
A signal event from MC

- $H \rightarrow \pi_{HV}(\rightarrow b\bar{b})\pi_{HV}(\rightarrow b\bar{b})$
- Event display
  - silicon detector
  - 3 SV event (only two pass pre-selection)
• Sources of highly displaced secondary-vertices:
  − in-flight decays of known particles (eg. pion, kaon)
  − material interactions
    • photon conversions
      \[ \gamma + N \rightarrow N + e^+ + e^- \]
    • pi-nucleus inelastic scattering in detector material
  − coincidences that produce vertices
  − pattern recognition errors

example QCD event: 6 reconstructed tracks, material interaction
There are a few handles that can be used to distinguish background like events from signal like events

Use MC to obtain a model of the background
- MC modeling of material is difficult (cables, support structure, etc)
- compare to data with little signal (v-particles)
  - events with one SV; tiny amount of signal ($\sim.04\%$)
- then cuts are made on events with two or more secondary-vertices; large signal content ($\sim4\%$)

Cuts are optimized on MC

Finally, apply the cuts to data

Set a limit (or make a discovery!)
• There are a few handles that can be used to distinguish background like events from signal like events

• Use MC to obtain a model of the background
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Finally, apply the cuts to data.

Set a limit (or make a discovery!)
Discriminating: SV multiplicity

- SV track multiplicity
  - more significant for $\nu$-particles which are more boosted
Discriminating: SV collinearity

- **SV collinearity**
  - cosine of the angle between the vector sum of the momenta of the decay products and the direction of the parent
  - more significant for \( v \)-particles which are less boosted
SV mass
- invariant mass
- more significant for $\nu$-particles which are more boosted – better track reconstruction
Data

- Data collected April, 2002 - August, 2008: 3.6 fb$^{-1}$
- Skim requirements, muon+jets result from b-decays:
  - 1 muon, matched to a jet $\Delta R<0.7$, muon $p_T>4$GeV
  - at least 2 jets with $p_T>10$GeV
- $|PVZ|<35$ cm; $r<1$ cm (for track reconstruction)
- Require <3 additional, non-hard scatter $p\bar{p}$
  - too many fake tracks, pattern recognition problems
- 50M events

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$
$$\eta = -\ln \tan(\theta/2)$$

Chad Johnson -- Columbia University
Monte-Carlo

- **Background MC:** ~10M multijet events (label: “QCD”)
  - generated by Pythia: $10 \text{ GeV} < p_T < 980 \text{ GeV}$
  - GEANT 3 detector simulation
  - reconstructed in the same way as data
- **Signal MC:** Pythia
  - Higgs production: $gg \rightarrow H$
  - Model $\pi_{HV}$ with pseudoscalar supersymmetric Higgs (A):
    $$H \rightarrow A(\rightarrow b\bar{b})A(\rightarrow b\bar{b})$$
  - 8 signal hypotheses, varying the parameters: Higgs mass, $\pi_{HV}$ mass, $\pi_{HV}$ decay length
Signal Hypotheses

• Higgs mass:
  - 90 GeV min Higgs mass: just above the LEP limit
  - 200 GeV max Higgs mass: small SM production xsec

• $\pi_{HV}$ mass:
  - there is no most likely HV model, but the simplest models, $15 \ \text{GeV} \leq m_{HV} \leq 40 \ \text{GeV}$

• decay length determined by experimental constraints:
  - $<1 \ \text{cm}$, swamped by QCD $b\bar{b}$
  - $>20 \ \text{cm}$, beginning of the outer tracker, want enough layers in the tracker
Pre-selection increases signal significance for future cuts and removes poorly modeled portions of the data:

- 2D decay-length > 1.6 cm: remove b-decays within beam-pipe
- SV track multiplicity >= 4: remove low multiplicity events – increase fraction of signal
Pre-selection: SV density

- density of SVs
  - indicates material interaction
  - exclude SV in material

SV per 0.0016 cm²

DO Preliminary, 1.1 fb⁻¹

DO Preliminary, 2.6 fb⁻¹
Pre-selection: SV density

- SV density (zr and xy plane)
  - remove regions of high density (material regions)

\[
cut = 121/0.0016 \text{ cm}^2
\]

\[
cut = 225/0.0016 \text{ cm}^2
\]
Pre-selection

- Cutflow

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{bkgd}}$</th>
<th>$N_{\text{data}}$</th>
<th>$m_{HV} =$</th>
<th>$m_{HV} =$</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 GeV</td>
<td>40 GeV</td>
</tr>
<tr>
<td>Generated</td>
<td>-</td>
<td>-</td>
<td>2712</td>
<td>2712</td>
</tr>
<tr>
<td>Initial selection</td>
<td>-</td>
<td>4.9\times10^7</td>
<td>235</td>
<td>173</td>
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<tr>
<td>Trigger</td>
<td>-</td>
<td>4.9\times10^7</td>
<td>174</td>
<td>77</td>
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<tr>
<td>SV $L_d^D &gt; 16$ mm</td>
<td>-</td>
<td>3.2\times10^7</td>
<td>153</td>
<td>66</td>
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<tr>
<td>SV mult. $\geq 4$</td>
<td>-</td>
<td>1.8\times10^5</td>
<td>72</td>
<td>25</td>
</tr>
<tr>
<td>SV density</td>
<td>6.0\times10^4</td>
<td>6.0\times10^4</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Num. SV $\geq 2$</td>
<td>37.5</td>
<td>26</td>
<td>5.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

- After pre-selection, QCD is normalized to data
Optimize Final Cut

- Require 2SVs per event (4% signal)
- Optimize final cut on MC: mass or collinearity – maximize significance:

\[
\text{significance} = \frac{\text{signal}}{\sqrt{\text{signal} + \text{background}}}
\]

- Signal is significant compared to background
Results

Results for two signal hypotheses:

\[ m_H = 120 \text{ GeV}, \quad m_{HV} = 15 \text{ GeV}, \quad dl = 50 \text{ mm} \]

\[ m_H = 120 \text{ GeV}, \quad m_{HV} = 40 \text{ GeV}, \quad dl = 50 \text{ mm} \]

Limits for all signal hypotheses
Final Cut – Mass

- maximize significance
- cut on minimum of the mass

\[ m_H = 120 \text{ GeV}, \quad m_{HV} = 15 \text{ GeV}, \quad dl = 50 \text{ mm} \]
Final Cut – Collinearity

- maximize significance
- cut on maximum of the collinearity

\[ m_H = 120 \text{ GeV}, \quad m_{HV} = 40 \text{ GeV}, \quad dl = 50 \text{ mm} \]
### Results

- **Significance and p-value**

<table>
<thead>
<tr>
<th></th>
<th>$m_H = 120, m_{HV} = 15, dl = 50$</th>
<th>$m_H = 120, m_{HV} = 40, dl = 50$</th>
</tr>
</thead>
<tbody>
<tr>
<td>background events</td>
<td>$4.84 \pm 21% (stat) \pm 35% (syst)$</td>
<td>$0.069 \pm 100% (stat) \pm 30% (syst)$</td>
</tr>
<tr>
<td>signal events</td>
<td>$3.64 \pm 7% (stat) \pm 15% (syst)$</td>
<td>$0.375 \pm 19% (stat) \pm 17% (syst)$</td>
</tr>
<tr>
<td>data events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-value/significance</td>
<td>$23% \mid 0.8\sigma$</td>
<td>$7% \mid 1.4\sigma$</td>
</tr>
</tbody>
</table>

**DØ Run II Preliminary**
Limit Results

- SM Higgs production benchmark – results can be scaled
Conclusion

We search for two highly displaced secondary-vertices (SVs) with a large number of attached tracks:

\[ H \rightarrow \pi_{HV}(\rightarrow b \bar{b}) \pi_{HV}(\rightarrow b \bar{b}) \]

This is an entirely novel analysis; no other search of this kind has ever been undertaken at LEP or the Tevatron.

No significant excess is observed in the present data set which excludes a Higgs decaying through a HV sector with a cross-section close to, or above the SM.
Backup slides follow
**Figure 1:** SM Higgs production cross sections for $p\bar{p}$ collisions at 1.96 TeV [26].

**Figure 3:** Branching ratios for the main decays of the SM Higgs boson [34].
Fermilab: home of the Tevatron

- World's highest energy collider (for now!), 2 TeV
- Superconducting $p \bar{p}$ collider
The DØ Detector

6000 tons
Experimental Constraints on HV

• Big-Bang Nucleosynthesis
  - demands that at least one HV particle have
    \[ \tau \ll 1 \text{sec} \]
Discriminating: SV multiplicity

- SV track multiplicity
  - more boosted:
    - less likely to fail
    - track dca cut
  - better track reconstruction

more boosted

less boosted
Object Reconstruction

- Secondary-vertex main object for this analysis
- Constructed from tracks in the CFT or SMT
- Algorithm starts with all two-track combinations
  - build-up approach, adds tracks to the seed
  - $\chi^2 / ndof < \chi^2_{max}$
• Standard analyses consider SVs within the beampipe (b-tagging); its parameters are not suitable for us

• Adjust SV reconstruction algorithm
  - $dca_{xy} < 0.15 \text{ cm} \rightarrow 10 \text{ cm} \quad dca_z < 0.4 \text{ cm} \rightarrow 10 \text{ cm}$
  - remove seed location requirement: $L_{xy} < 2.6 \text{ cm} \quad L_z < 5 \text{ cm}$
  - $\chi^2_{max} = 15 \rightarrow 500$
Run IIa: $1.1 \text{ fb}^{-1}$ (good quality data)

Run IIb: $2.6 \text{ fb}^{-1}$

Run IIa  Run IIb
Secondary-Vertices per Event

![Graph showing the distribution of secondary-vertices per event with data, QCD, and signal components. The x-axis represents the number of secondary-vertices, and the y-axis represents the number of events on a logarithmic scale. The graph is labeled with DØ, 3.6 fb⁻¹.]
### Signal Hypotheses

- choose 8 HV hypotheses:

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$m_{HV}$ (GeV)</th>
<th>$c\tau$ (mm)</th>
<th>SM $\sigma_{gg\rightarrow H}(pb)$</th>
<th>$N_{generated}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>15</td>
<td>50</td>
<td>2.0</td>
<td>135,788</td>
</tr>
<tr>
<td>90</td>
<td>40</td>
<td>50</td>
<td>2.0</td>
<td>108,871</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>25</td>
<td>1.09</td>
<td>95,168</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>50</td>
<td>1.09</td>
<td>116,738</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>100</td>
<td>1.09</td>
<td>140,251</td>
</tr>
<tr>
<td>120</td>
<td>40</td>
<td>50</td>
<td>1.09</td>
<td>119,750</td>
</tr>
<tr>
<td>200</td>
<td>15</td>
<td>50</td>
<td>0.19</td>
<td>101,402</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
<td>50</td>
<td>0.19</td>
<td>103,213</td>
</tr>
</tbody>
</table>

**expected number of signal events**

$$\frac{\sigma_{SM} \cdot \int L}{N_{generated}}$$
Trigger Efficiency

- Probability for trigger to pass signal
- measure the efficiency for a single, well modeled trigger
- extrapolate to the combined triggers (p20 or p17)
  - use pre-selected data
  - very similar to signal, as far as the trigger is concerned
- parameterize jet $p_T$ and muon $p_T$ trigger turn-on

<table>
<thead>
<tr>
<th>signal sample $m_H$ (GeV), $m_{HV}$ (GeV), dl (mm)</th>
<th>average trigger efficiency</th>
<th>average uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H = 90$, $m_{HV} = 15$, dl = 50</td>
<td>47%</td>
<td>14%</td>
</tr>
<tr>
<td>$m_H = 90$, $m_{HV} = 40$, dl = 50</td>
<td>34%</td>
<td>17%</td>
</tr>
<tr>
<td>$m_H = 120$, $m_{HV} = 15$, dl = 25</td>
<td>76%</td>
<td>13%</td>
</tr>
<tr>
<td>$m_H = 120$, $m_{HV} = 15$, dl = 50</td>
<td>77%</td>
<td>13%</td>
</tr>
<tr>
<td>$m_H = 120$, $m_{HV} = 15$, dl = 100</td>
<td>79%</td>
<td>13%</td>
</tr>
<tr>
<td>$m_H = 120$, $m_{HV} = 40$, dl = 50</td>
<td>48%</td>
<td>17%</td>
</tr>
<tr>
<td>$m_H = 200$, $m_{HV} = 15$, dl = 50</td>
<td>91%</td>
<td>13%</td>
</tr>
<tr>
<td>$m_H = 200$, $m_{HV} = 40$, dl = 50</td>
<td>87%</td>
<td>15%</td>
</tr>
</tbody>
</table>
Systematics

- Luminosity
- Trigger efficiency
- Background multiplicity – reweight MC to match data
- Smearing MC – rerun analysis with no smearing
- SV density modeling – difference between MC and data near the cut

<table>
<thead>
<tr>
<th>quantity</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>6.1%</td>
</tr>
<tr>
<td>trigger efficiency (average)</td>
<td>14%</td>
</tr>
<tr>
<td>background multiplicity</td>
<td>28%</td>
</tr>
<tr>
<td>smearing mass (QCD only)</td>
<td>18%</td>
</tr>
<tr>
<td>xy-density modeling</td>
<td>p20: 15% p17: 8%</td>
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</table>
Min Mass > 2.5 GeV

<table>
<thead>
<tr>
<th>Dataset</th>
<th>p17 SV 1</th>
<th>p17 SV 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV property</td>
<td></td>
<td></td>
</tr>
<tr>
<td>collinearity</td>
<td>0.999228</td>
<td>0.999373</td>
</tr>
<tr>
<td>mass (GeV)</td>
<td>3.13607</td>
<td>3.20391</td>
</tr>
<tr>
<td>multiplicity</td>
<td>4</td>
<td>4</td>
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<tr>
<td>xy density</td>
<td>9.27303</td>
<td>5.32185</td>
</tr>
<tr>
<td>zr density</td>
<td>24.6338</td>
<td>33.9927</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>10.7155</td>
<td>1.7585</td>
</tr>
<tr>
<td>2d decay length (cm)</td>
<td>4.94491</td>
<td>3.60939</td>
</tr>
<tr>
<td>$\phi$</td>
<td>2.82179</td>
<td>0.0120206</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-0.615191</td>
<td>-1.42852</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>2.92512</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dataset</th>
<th>p20 SV 1</th>
<th>p20 SV 2</th>
<th>p20 SV 1</th>
<th>p20 SV 2</th>
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<tbody>
<tr>
<td>SV property</td>
<td></td>
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</tr>
<tr>
<td>collinearity</td>
<td>0.999725</td>
<td>0.999959</td>
<td>0.999079</td>
<td>0.998535</td>
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<td>mass (GeV)</td>
<td>2.50203</td>
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<td>2.70078</td>
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<tr>
<td>multiplicity</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
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<tr>
<td>xy density</td>
<td>4.71381</td>
<td>4.69033</td>
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<tr>
<td>zr density</td>
<td>42.6499</td>
<td>54.7864</td>
<td>54.7864</td>
<td>25.081</td>
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<tr>
<td>$\chi^2$</td>
<td>1.73224</td>
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<td>2d decay length (cm)</td>
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<td>7.3195</td>
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<td>$\phi$</td>
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<td>$\Delta R$</td>
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<tr>
<td>Dataset</td>
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<td>SV 2</td>
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<tr>
<td>------------------</td>
<td>----------</td>
<td>------</td>
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<td>0.0351337</td>
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<tr>
<td>$\Delta R$</td>
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