Search for Higgs boson decay to neutral long-lived particles decaying to $b\bar{b}$ in $pp$ collisions at $\sqrt{s} = 1.96$ TeV


(The DØ Collaboration)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Universidade Federal do ABC, Santo André, Brazil
5 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6 University of Alberta, Edmonton, Alberta, Canada; Simon Fraser University, Burnaby, British Columbia, Canada; York University, Toronto, Ontario, Canada and McGill University, Montreal, Quebec, Canada
7 University of Science and Technology of China, Hefei, People’s Republic of China
8 Universidad de los Andes, Bogotá, Colombia
9 Center for Particle Physics, Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
10 Czech Technical University in Prague, Prague, Czech Republic
11 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12 Universidad San Francisco de Quito, Quito, Ecuador
13 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14 IPHC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16 LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
17 LPNHE, IN2P3/CNRS, Universités Paris VI et VII, Paris, France
18 CEA, Ifeu, SPP, Saclay, France
19 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
20 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22 Physikalisches Institut, Universität Bonn, Bonn, Germany
23 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
24 Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
25 Institut für Physik, Universität Mainz, Mainz, Germany
26 Ludwig-Maximilians-Universität München, München, Germany
27 Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany
28 Panjab University, Chandigarh, India
29 Delhi University, Delhi, India
30 Tata Institute of Fundamental Research, Mumbai, India
31 University College Dublin, Dublin, Ireland
32 Korea detector Laboratory, Korea University, Seoul, Korea
33 SungKyunKwan University, Suwon, Korea
34 CINVESTAV, Mexico City, Mexico
We report on a first search for production of Higgs bosons decaying into neutral long-lived particles (NLLP) which each decay to a $b\bar{b}$ pair, using 3.6 fb$^{-1}$ of data recorded with the D0 detector at the Fermilab Tevatron collider. We search for pairs of displaced vertices in the tracking detector at radii in the range 1.6–20 cm from the beam axis. No significant excess is observed above background, and upper limits are set on the production rate in a hidden-valley benchmark model for a range of Higgs boson masses and NLLP masses and lifetimes.

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A class of hidden-valley (HV) models [1] predicts a new, confining gauge group that is weakly coupled to the standard model (SM), leading to the production of HV particles (v-particles). The details of v-particle decay depend on the specific model, but the HV quarks always hadronize due to confinement producing “v-hadrons” that can be long-lived. One particular model used as a benchmark for this search is the SM Higgs boson ($H$)
mixing with a HV Higgs boson that gives mass to v-particles. The SM Higgs boson could then decay directly to v-hadrons through this mixing with a substantial branching fraction [2]. These v-hadrons may couple preferentially to heavy SM particles, such as b quarks, due to helicity suppression. The result is a striking experimental signature of highly displaced secondary vertices (SV) with a large number of attached tracks from the b quark decays. Direct searches at the CERN LEP collider have excluded a Higgs boson decaying to \( bb \) or \( \tau \bar{\tau} \) with \( M_H < 114.4 \) GeV at the 95% C.L. [3]. But if the Higgs boson dominantly decays to long-lived v-particles which then decay inside the detector to \( b\bar{b} \), only the most general LEP limit is relevant, \( M_H > 81 \) GeV, for any Higgs boson radiating off a Z boson [4]. Cosmological constraints require that one of the light v-hadrons have a lifetime \( \ll 1 \) second to be consistent with models of big bang nucleosynthesis [1].

In this Letter, we present the first search for pair-produced neutral long-lived particles (NLLP), each decaying to a b quark pair, using the D0 detector [5] at the Fermilab Tevatron \( p\bar{p} \) collider. The b quarks are required in order to provide a high transverse momentum (\( p_T \)) muon for triggering with high efficiency. The data were collected from April 2002 to August 2008 and correspond to an integrated luminosity of 3.6 fb\(^{-1} \) at \( \sqrt{s} = 1.96 \) TeV. The D0 central tracking detector comprises a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. The SMT, extending from a radius of \( \approx 2 \) cm to \( \approx 10 \) cm, has six-barrel longitudinal structure, each with a set of four layers arranged axially around the beam pipe, and interspersed with 16 radial disks. The CFT, extending from a radius of \( \approx 20 \) cm to \( \approx 50 \) cm, has eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers. Secondary vertices are reconstructed by combining charged particle tracks found in the tracking detector, which effectively limits the analysis to NLLP decays occurring within a maximum radius of 20 cm, well within the tracker volume. We also exclude vertex radii less than 1.6 cm since the background from heavy flavor production is large in that region. Known sources of SVs other than heavy-flavor decays include decays in-flight of light particles, inelastic interactions of particles with nuclei of detector material, and photon conversions. Vertices may also be mimicked by pattern recognition errors.

\textsc{Pythia} [6] is used to simulate signal and background events, which are then passed through a full \textsc{geant3}-based [7] D0 detector simulation and the same reconstruction as for collider data. For signal, the SM \( gg \rightarrow H \) process is generated, the Higgs boson is forced to decay to a pair of long-lived A bosons (a heavy, neutral scalar, representing a v-hadron), and each A boson is forced to decay to a pair of b quarks. The Higgs boson mass (\( M_H \)) is varied from 90 to 200 GeV, the v-hadron mass (\( m_{HV} \)) from 15 to 40 GeV and the average v-hadron proper decay length (\( L_d = ct \)) from 2.5 cm to 10 cm. For background, inclusive \( p\bar{p} \) multijet events are generated. Approximately one hundred thousand Monte Carlo (MC) events for each signal sample and ten million events of multijet background are generated and are overlaid with data to simulate detector noise and pile-up effects from additional \( p\bar{p} \) interactions.

At least two jets with a cone radius of 0.5 [8] are required, each with \( p_T > 10 \) GeV. And at least one muon is required with \( p_T > 4 \) GeV, matched within \( \Delta R < 0.7 \) to one of the jets, where \( \Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \) with \( \phi \) being the azimuthal angle and \( \eta \) the pseudorapidity. The muon requirement is more efficient for signal than background due to the presence of a \( b \rightarrow \mu \) or \( b \rightarrow c \rightarrow \mu \) decay from at least one of the four \( b \) quarks, and is also required for an accurate measurement of the trigger efficiency. Primary vertices (PVs) are reconstructed by clustering tracks and correspond to \( p\bar{p} \) interaction locations. To ensure good SV reconstruction, we further require fewer than four PVs be reconstructed and that the selected PV with the largest \( \sum_i \log p_{T,i}^2 \), summed over all vertex tracks \( i \), be located within \( |z| < 35 \) cm and \( r < 1 \) cm, where \( x \) and \( y \) are the horizontal and vertical components of the distance \( r \) with respect to the beam axis, and \( z \) is the distance along the beam axis from the center of the detector. An initial selection requires that each event has at least one SV with 2D decay length from the PV in the plane transverse to the beam (\( L_{d}^{SV} \)) larger than 1 cm and decay length significance (decay length divided by its uncertainty) greater than five. The momentum of the SV, reconstructed from the vectorial sum

![Material map in the plane transverse to the beamline](image.png)
of the momenta of its associated tracks, must point away from the PV to reduce combinatoric background. SVs are reconstructed using a track selection so as to efficiently combine the $b$ and $\bar{b}$ decay products of each v-hadron into a single SV. Approximately 50 million data events satisfy these requirements, dominated by dijet and heavy-flavor production.

To maximize the discovery potential of this analysis we use an OR of all triggers. The most frequently fired triggers that make up the dataset passing the initial selection involve a muon and jet at the first trigger level and refinements of these objects at higher levels. The overall trigger OR efficiency is estimated by first measuring the efficiency for a single trigger per data collection period using known muon and jet trigger efficiencies. Then the number of events fired by that single trigger is compared to the total number of data events passing the OR of all triggers, as a function of sensitive variables, such as muon $p_T$, jet $p_T$, jet angles, etc. No significant dependence is found, except on jet $p_T$, thus the overall trigger OR efficiency is modeled as a function of jet $p_T$.

Further selections are optimized by maximizing the expected signal significance $(S/\sqrt{S+B})$, where $B$ and $S$ are the number of MC background and signal events, respectively. The heavy-flavor background, mainly $b$ hadrons with $cT \approx 0.3$ cm, produces a very large number of SVs, but their number decreases exponentially as the radial distance of the SV from the PV increases. SVs are required to have $L_{sv}^x > 1.6$ cm. We expect signal events to preferentially produce SVs with a large number of attached tracks, therefore we require SVs with track multiplicity of at least four. Interactions of primary collision particles ($\pi$, protons, etc.) with detector material, such as silicon sensors, cables, etc., are the major source of background. In order to quantify the material regions, we construct a map of SV density in data, using SV with track multiplicity of three, in the $xy$ (see Fig. 1) and $rz$ projections. SVs that occur in regions of high SV density are then removed. After this “pre-selection” is performed, the multijet background MC sample is normalized to the data (see Table I). Finally, at least two SVs are required in each event, and they are required to have $\Delta R(SV1, SV2) > 0.5$, to prevent cases where a single true vertex is mis-reconstructed as two nearby separate vertices. No events in data have more than two SVs.

Two more variables are used to select the signal: SV invariant mass and SV collinearity. The invariant mass is reconstructed from the four-momenta of the outgoing tracks attached to a SV, assuming the pion mass for all particles. Collinearity is defined as the cosine of the angle between the vector sum of the momenta of the attached tracks and the direction to the SV from the PV. Depending on the signal point, one of these two variables is used to perform the final separation of signal and background. The quality of the background model is of primary importance so we develop a method of tuning the multijet background to data after pre-selection.

<table>
<thead>
<tr>
<th>$N_{bkgd}$</th>
<th>$N_{data}$</th>
<th>$m_{HV}$</th>
<th>$m_{HV}$</th>
<th>$L_d = 5$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced</td>
<td>-</td>
<td>2712</td>
<td>2712</td>
<td>40 GeV</td>
</tr>
<tr>
<td>Initial selection</td>
<td>-</td>
<td>$4.9 \times 10^7$</td>
<td>235</td>
<td>173</td>
</tr>
<tr>
<td>Trigger</td>
<td>-</td>
<td>$4.9 \times 10^7$</td>
<td>174</td>
<td>77</td>
</tr>
<tr>
<td>SV $L_{sv}^x &gt; 1.6$ cm</td>
<td>-</td>
<td>$3.2 \times 10^7$</td>
<td>153</td>
<td>66</td>
</tr>
<tr>
<td>SV mult. $\geq 4$</td>
<td>-</td>
<td>$1.8 \times 10^5$</td>
<td>72</td>
<td>25</td>
</tr>
<tr>
<td>SV density</td>
<td>-</td>
<td>$6.0 \times 10^4$</td>
<td>60</td>
<td>15</td>
</tr>
</tbody>
</table>

| Num. SV $\geq 2$ | 37.5 | 26 | 5.1 | 0.6 |

**FIG. 2:** The minimum mass of the two SVs, for data, background MC, and signal MC with $M_H = 120$ GeV, $m_{HV} = 15$ GeV, and $L_d = 5$ cm. The hatched region shows the uncertainty on the background MC.

**FIG. 3:** The maximum collinearity of the two SVs, for data, background MC, and signal MC with $M_H = 120$ GeV, $m_{HV} = 40$ GeV, and $L_d = 5$ cm. The hatched region shows the uncertainty on the background MC.
background simulation of the SV invariant mass and SV collinearity distributions to data. The events after pre-
selection are divided into two distinct sets: the first con-
tains events with only one SV (1SV), whereas the second contains events with at least two SVs (2SV). Since the signal content of the 2SV set is expected at about 4% as compared to only 0.04% for the 1SV set, we use the 1SV set to compare the data and MC and perform corrections to the MC. Gaussian smearing functions are applied to the background MC for the SV invariant mass and SV collinearity distributions, which are then also applied to all MC signal samples. For $m_{HV} < 20$ GeV, a require-
ment on the minimum SV mass in an event $>2.5$ GeV is most effective (Fig. 2). For heavier v-hadrons, we take advantagae of the SV’s decay products being more widely spread in angle, which is better measured than the invariant mass. Requiring the maximum SV collinearity in an event to be $<0.9937$ maximizes the expected significance (Fig. 3).

The uncertainty on the signal acceptance is dominated by the modeling of trigger efficiency and is (13–17)%. The uncertainty on the background due to the difference in track reconstruction efficiency between MC and data is estimated by using two methods of normalization and found to be 28%. We estimate the effect of smearing the MC samples by performing the entire analysis without smearing. For the requirements applied to the collinear-
ity, smearing results in a difference of 18% on the multijet background yield and a negligible difference on the signal acceptance. Smearing also has no effect on the optimized requirement values. To estimate the uncertainty from re-
quiring a small SV density, we compare the difference in the number of remaining events between multijet back-
ground and data before and after making the density requirement, and find agreement within (8–15)%. The uncertainty on the integrated luminosity is 6.1% [9].

The final results after all selections are sum-
marized in Table II. No significant excess is observed, so 95% C.L. limits are set on $\sigma(H+X)\times\text{BR}(H\rightarrow HVHV)\times BR^2(H\rightarrow b\bar{b})$ using a modified frequentist method [11], which includes all system-
tic uncertainties on signal acceptance, background, and luminosity. Depending on the signal parameters, Higgs boson production about 1–10 times the SM cross section is excluded, if the Higgs boson always decays to a pair of long-lived v-hadrons decaying only to $b\bar{b}$ (see Fig. 4). These results also provide the first constraints on pair-produced NLLPs decaying to $b\bar{b}$ jets in the radial range of 1.6–20 cm at a hadron collider.

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dation (Germany).

![Fig. 4: The expected and observed 95% C.L. limits on $\sigma(H+X)\times\text{BR}(H\rightarrow HVHV)\times BR^2(H\rightarrow b\bar{b})$ for each $M_H$ studied, $m_{HV} = 15, 40$ GeV, and various values of v-hadron $L_d$. The green band shows the ±1 standard deviation on the expected limit. The reference Higgs boson cross section from the SM [10] is shown by the solid red line, which assumes 100% for BR($H\rightarrow HVHV$) and BR($HV\rightarrow b\bar{b}$). (color online)
## TABLE II: Results for each simulated signal: the numbers of background, signal, and data events after all selections, overall signal efficiency, SM Higgs production rate, and observed and expected 95% C.L. upper limits on the signal cross section.

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>$m_{H^0}$ (GeV)</th>
<th>$L_d$ (cm)</th>
<th>$N_{bkgd}$ ± stat ± sys</th>
<th>$N_{sig}$ ± stat ± sys</th>
<th>$N_{data}$</th>
<th>Efficiency (SM Higgs) (pb)</th>
<th>Limit obs. [exp.] (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>15</td>
<td>5</td>
<td>4.8 ± 1.0 ± 1.7</td>
<td>3.3 ± 0.3 ± 0.5</td>
<td>3</td>
<td>0.06%</td>
<td>2.0</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>5</td>
<td>4.8 ± 1.0 ± 1.7</td>
<td>3.6 ± 0.3 ± 0.5</td>
<td>3</td>
<td>0.13%</td>
<td>1.1</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>2.5</td>
<td>4.8 ± 1.0 ± 1.7</td>
<td>5.7 ± 0.3 ± 0.7</td>
<td>3</td>
<td>0.21%</td>
<td>1.1</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>10</td>
<td>4.8 ± 1.0 ± 1.7</td>
<td>1.5 ± 0.2 ± 0.3</td>
<td>3</td>
<td>0.06%</td>
<td>1.1</td>
</tr>
<tr>
<td>200</td>
<td>15</td>
<td>5</td>
<td>4.8 ± 1.0 ± 1.7</td>
<td>0.8 ± 0.1 ± 0.1</td>
<td>3</td>
<td>0.16%</td>
<td>0.2</td>
</tr>
<tr>
<td>90</td>
<td>40</td>
<td>5</td>
<td>0.07 ± 0.07 ± 0.02</td>
<td>0.15 ± 0.07 ± 0.03</td>
<td>1</td>
<td>0.003%</td>
<td>2.0</td>
</tr>
<tr>
<td>120</td>
<td>40</td>
<td>5</td>
<td>0.07 ± 0.07 ± 0.02</td>
<td>0.38 ± 0.07 ± 0.06</td>
<td>1</td>
<td>0.01%</td>
<td>1.1</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
<td>5</td>
<td>0.07 ± 0.07 ± 0.02</td>
<td>0.16 ± 0.03 ± 0.02</td>
<td>1</td>
<td>0.03%</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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[a] Visitor from Augustana College, Sioux Falls, SD, USA.
[b] Visitor from Rutgers University, Piscataway, NJ, USA.
[c] Visitor from The University of Liverpool, Liverpool, UK.
[d] Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.
[e] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
[f] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[g] Visitor from Universitat Bern, Bern, Switzerland.
[h] Visitor from Universitat Zürich, Zürich, Switzerland.
[i] Deceased.

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