Search for Heavy Resonances Decaying to Long-Lived Neutral Particles in the Displaced Lepton Channel

The CMS Collaboration

Abstract

A search is performed for a heavy resonance decaying to two long-lived massive neutral particles. The process would manifest itself as a distinct topological signature appearing as a pair of leptons originating from a vertex far displaced from the LHC beam spot. The events were selected during pp collisions at 7 TeV using approximately 1.1 fb$^{-1}$ of integrated luminosity collected by the CMS detector at the LHC. No significant excess is observed above Standard Model background, and a 95% CL upper limit is set on the production cross section times the branching ratio as a function of the long-lived particle lifetime.
1 Introduction

Several exotic physics models predict the existence of long-lived massive particles, which would decay to leptons within the volume of the CMS detector. Examples of these include ‘hidden valley’ models [1], various SUSY scenarios such as ‘split SUSY’ [2] or SUSY with very weak R-parity violation [3], and long-lived neutrinos produced in Z’ decays [4].

Existing experimental limits on these processes mainly come from the Tevatron. The DØ collaboration, for example, searched for displaced dileptons from $4^\text{th}$ generation quark production $b\bar{b}' \rightarrow XhXb$, where $X$ is a long-lived, massive, exotic boson decaying to dileptons [5]. It has also searched for the pair production of long-lived neutralinos each decaying to $\mu^+\mu^-\nu$ [6].

We present here a search for one of the simplest of such processes, where a massive resonance taken to be a Higgs boson $H^0$ subsequently decays to two long-lived, spinless, neutral particles $X$, which then each have a finite branching ratio to decay to dileptons; i.e., \( H^0 \rightarrow 2X, X \rightarrow \ell^+\ell^- \) [7]. The signature of these events is one or two displaced vertices within the CMS tracker volume, formed by a pair of oppositely charged reconstructed leptons (electrons or muons).

2 The CMS Detector

The central feature of the CMS [8] apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Within the field volume are the silicon pixel and strip trackers, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are identified in gas-ionisation detectors embedded in the solenoid’s steel return yoke.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the \( x \)-axis pointing to the centre of the LHC, the \( y \)-axis pointing up (perpendicular to the LHC plane), and the \( z \)-axis along the anticlockwise-beam direction. The polar angle, \( \theta \), is measured from the positive \( z \)-axis and the azimuthal angle, \( \phi \), is measured in the \( x-y \) plane.

The silicon tracker is composed of pixel detectors (three barrel layers and two forward disks on either end of the detector, made of 66 million $100 \times 150 \, \mu m^2$ pixels) surrounded by micro-strip detectors (ten barrel layers plus three inner disks and nine forward disks on either end of the detector, with strips of pitch between 80 and 184 \( \mu m \)). They cover the pseudorapidity range $|\eta| < 2.5$. All tracker layers provide hit position measurements in the \( r-\phi \) plane, but only the pixel tracker and a subset of the strip tracker layers (those with stereo layers) provide 3D hit position measurements. Thanks to the strong magnetic field and the high granularity of the silicon tracker, promptly produced charged particles with $p_T = 100 \, \text{GeV}/c$ are reconstructed with a resolution in transverse momentum $p_T$ of $\sim 1.5\%$ and in transverse impact parameter $d_0$ of $\sim 15 \, \mu m$. The silicon tracker also reconstructs the primary vertex position, with $\sim 15 \, \mu m$ accuracy.

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes based on one of three technologies: drift tubes in the barrel region, cathode strip chambers in the endcaps, and resistive plate chambers in the barrel and part of the endcaps.

The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 3$.

The first level (L1) of the CMS trigger system, composed of custom hardware processors, selects the most interesting events using information from the calorimeters and muon detectors. The High Level Trigger (HLT) processor farm further decreases the event rate employing the full...
Data and Monte Carlo Simulation Samples

LHC data taken at 7 TeV centre-of-mass energy during 2011 are used in the analysis. Only data taken during periods of good detector performance are used. These data correspond to an integrated luminosity of 1136 $\text{pb}^{-1}$ ($1167 \text{ pb}^{-1}$) in the electron channel (muon channel).

For the electron channel, events are selected by requiring two identified photons with $E_T > 33$ GeV and in the muon channel, events are selected by requiring two identified muons in the muon systems, not necessarily originating from the beam spot, with $p_T > 23 \text{ GeV/c}$ each.

Simulated signal Monte Carlo samples were generated with \textsc{Pythia} [9], which was requested to simulate Higgs production through gluon-gluon annihilation. The Higgs was forced to decay to two long-lived, spin 0, exotic particles $H^0 \rightarrow XX$, which then each decayed to dileptons $X \rightarrow \ell^+\ell^-$. In these simulated samples, the X boson has a 50% branching ratio to dielectrons and a 50% branching ratio to dimuons. Several different samples, with different Higgs and X boson masses and X boson lifetimes were generated, as listed in Table 1. The lifetime used in these samples was chosen to give a mean transverse decay length in the laboratory frame of approximately 20 cm.

Several simulated background samples were used, corresponding to $t\bar{t}$, $Z/\gamma \rightarrow \ell^+\ell^-$, $W^\pm/Z$ boson pair production with leptonic decays, and QCD events.

In all simulated samples, the response of the detector was simulated in detail using \textsc{Geant}4 [10]. These samples were processed through the trigger emulation and event reconstruction chain of the CMS experiment.

Table 1: Simulated signal samples used in the analysis. The masses of the Higgs and X bosons are given, as is the mean proper decay length of the X boson.

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<thead>
<tr>
<th>$M_{H^0}$ (GeV/c$^2$)</th>
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Event Reconstruction and Selection

4.1 Displaced Track Reconstruction

The performance of the track reconstruction algorithms has been studied with data [11]. CMS exploits a so-called ‘iterative tracking’ algorithm to reconstruct tracks in the tracker [11, 12]. The first tracking iteration is dedicated to finding tracks originating near the primary vertex, since these are easiest to reconstruct. It seeds the tracks with pairs or triplets of hits from the pixel tracker, which provides high resolution 3D position measurements. It then extrapolates
these seeds outwards, assigning to the track additional hits from the pixel or strip trackers using the Kalman filter algorithm. Hits assigned to these tracks are excluded from further searches, so simplifying the task for subsequent iterations. A total of five iterations is used, with some of the additional ones being dedicated to finding very low momentum tracks, and others being dedicated to finding highly displaced tracks. The reconstruction of very displaced tracks uses seeds produced from hits in pairs of strip tracker stereo layers (since these provide 3D hit position measurements). A beam spot constraint is used to help find these tracks, as is the case for the earlier tracking iterations. However, the constraint is extremely loose (tens of centimetres). The tracking efficiency is respectable (although significantly less than 100%) for X bosons that decay up to 50 cm from the beam-line. (Tracks produced farther from the beam-line than this are unlikely to produce hits in the outermost pair of strip tracker stereo layers). The tracking efficiency is very small for tracks whose impact parameters exceed about 25 cm. This is a result of the loose beam spot constraint used during track finding. Figure 1 shows the tracking efficiency for single, isolated particles as a function of the transverse impact parameter. When making this plot, only tracks classified as high purity are used. This requirement, which is imposed on all tracks used in this paper, is defined in Ref. [11].

4.2 Displaced Lepton Identification

The standard CMS electron reconstruction algorithms [13] do not make use of the very large impact parameter tracks found by the final iteration of the track finding algorithm. In addition, the standard CMS muon reconstruction algorithms [14] include some assumptions about the muon being produced near the beam spot. Therefore, no offline lepton identification is applied in this analysis. Instead, tracks are considered to be identified as leptons if they can be matched to ‘trigger objects’ from the triggers used within a cone of size $\Delta R < 0.1$ (where $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$).

For the electron channel, because of bremsstrahlung, the measured track momentum does not provide a precise estimate of the electron’s initial momentum. Instead, the electron is matched, using a cone of size $\Delta R < 0.2$ around the track, to an ECAL ‘super-cluster’ [13] that the electron should have produced. The energy of the electron is estimated from this super-cluster rather...
than the reconstructed track. Despite the relatively large matching cone here, the fraction of tracks in selected dielectron candidates that are not genuine electrons is extremely small. The isolation requirements, described in Sect. 4.3, make it highly unlikely that the ECAL cluster and track were not produced by the same particle.

4.3 Selection of Long-Lived Exotica

Several cuts are applied to select events resulting from pp collisions. Cosmic rays are largely eliminated by the requirement that the event should contain a primary vertex with at least four associated tracks, whose position is less than 2 cm from the centre of CMS in the direction transverse to the beam and $\pm 12$ cm from the origin in the direction along the beam. Furthermore, to reject ‘scraping’ events produced by the interaction of beam-related protons with the LHC collimators, the fraction of tracks classified as high purity must exceed 25%.

The selection of displaced lepton candidates begins by searching for high purity tracks with transverse momentum $p_T > 38$ GeV/$c$ (25 GeV/$c$) for the electron (muon) channel. These cuts are slightly higher than the corresponding trigger thresholds, to minimise dependence on the trigger performance, as shown in Sect. 5.5. The tracks are required to have pseudorapidity $|\eta| < 2$, since the displaced tracking becomes inefficient beyond this, and the background from pile-up is high in the forward region. To reject promptly produced particles, the tracks must have a transverse impact parameter significance with respect to the beam-line of $|d_0/\sigma| > 3$ (2) in the electron (muon) channel.

X boson candidates are formed from pairs of oppositely charged displaced lepton candidates. The two corresponding tracks are fitted to a common vertex, which is required to have $\chi^2/\text{ndf} < 5$. The vertex must lie a distance of more than 8 (5) standard deviations from the beam line, for the electron (muon) channel. The two tracks are required to have a total of no more than one hit in front of the vertex.

To reject residual cosmic rays in the muon channel, back-to-back tracks are rejected with the requirement $\cos(\alpha) > -0.95$, where $\alpha$ is the angle between the two tracks. Background from misidentified leptons is reduced by requiring that the two lepton candidates are not both matched to the same trigger object. Additional background rejection is achieved by requiring that, projected into the plane perpendicular to the beam-line, the reconstructed momentum vector of the candidate should be collinear, with the vector from the primary to the secondary vertex. The cut on the collinearity angle is 0.8 (0.2) radians in the electron (muon) channel. In the muon channel, the two tracks must be separated by $\Delta R > 0.2$. This cut is motivated by the observation described in Sect. 5.5 that the dimuon trigger efficiency is poor for closely spaced muon pairs. It reduces any associated systematic uncertainties.

Both lepton candidates are also required to be isolated, to reject background from jets. An isolation cone is constructed around each candidate of radius $\Delta R < 0.3$, excluding narrow cones of radius $\Delta R < 0.03$ around both candidates. Within this isolation cone, the $\sum p_T$ of all high purity tracks with $p_T > 1$ GeV/$c$ must be less than 4 GeV/$c$. This cut has good efficiency for signal. The dependency on the number of pile-up interactions is small. According to simulation, the mean $\sum p_T$ in the isolation cone increases from 0.6 to 1.2 GeV/$c$ as the number of pile-up interactions increases from 0 to 20.

If more than one X candidate is selected in a given event, all the selected candidates are retained.

Figure 2 shows the distribution of the transverse decay length significance in data as compared with the simulated background, with all cuts applied except the one on the decay length sig-
Significance itself.

Figures 3 shows the reconstructed dilepton mass for dielectron and dimuon candidates after all selection cuts. In the dielectron channel, the background is dominated by Z bosons, which survive the cut on the decay length significance, as a result of bremsstrahlung giving non-Gaussian tails to the resolution function. In the dimuon channel, the simulated background is dominated by a single QCD event which has a large weighting.

By inverting the cut on the transverse decay length, one can obtain a control sample which is dominated by promptly produced dileptons. The dilepton mass spectrum obtained with this inverted cut is shown in Fig. 4. Good agreement is seen in both shape and normalisation between data and Monte Carlo simulation.

Figure 2: The transverse decay length significance of the candidates for the dielectron (left) and dimuon (right) channels. It is required to be more than 8 for dielectron candidates and more than 5 for dimuon candidates.

5 Systematic Uncertainties and Corrections

5.1 Luminosity

For the running period corresponding to this analysis, CMS estimates the relative uncertainty on the luminosity to be 4.5% [15].

5.2 Effect of Pile-Up

The number of reconstructed primary vertices in data and simulation gives rise to a relative systematic uncertainty in the signal selection efficiency of less than 2% for all mass points.

5.3 PDF, Renormalisation and Factorisation Scale Uncertainties

All simulated samples were generated using the CTEQ6L1 [16] PDF set. Systematic uncertainties on the acceptances due to uncertainties in this PDF set are evaluated using the procedure [17], which uses the uncertainty eigenvector sets of MSTW2008nlo [18] and CTEQ66 [19]. For all mass points, the relative uncertainty in the efficiency to select a $X \rightarrow \ell^+\ell^-$ arising from this source is less than 1%.
Figure 3: The reconstructed dilepton mass in the dielectron (left) and dimuon (right) channels after all selection cuts have been applied. The dielectron channel shows residual $Z$ background in the selection, whereas in the dimuon channel, the predicted background is dominated by a single QCD event with a large weighting.

Figure 4: The invariant mass distribution of dielectron (left) and dimuon (right) candidates after applying all selection cuts except the ones on transverse impact parameter and on vertex flight direction, and with the decay length significance cut inverted. This predominantly selects prompt background such as $Z$ bosons. The agreement of both shape and normalisation between data and Monte Carlo simulation demonstrates a good understanding of the Standard Model backgrounds.
The dependence of the acceptance on the choice of QCD renormalisation and factorisation scales which are chosen to be equal was found to be well below 0.5%.

5.4 Track Finding Efficiency

Three methods have been explored to understand if the efficiency to reconstruct displaced tracks is correctly modelled by the simulation. The first exploits cosmic rays and checks the efficiency to reconstruct isolated particles. The second embeds individual simulated displaced tracks in real data events and so determines the reconstruction efficiency in a high-occupancy environment. The third, which merely provides a cross-check, uses \( K^0 \) decays. Since the physics analysis pursued here searches for isolated leptons, the first of these three methods is considered to be more pertinent, so is presented in most detail here.

None of the three methods explicitly measures the tracking efficiency for displaced electrons. However, simulation predicts that this is only about 10% smaller than for displaced muons. The slightly lower tracking efficiency for electrons is caused by bremsstrahlung. Since the material budget in the tracker is modelled in simulation with an accuracy better than 10% [20], it is assumed that the difference in tracking efficiency between electrons and muons is modelled with similar precision. It can therefore be neglected in comparison with the much larger systematic uncertainty on the generic tracking efficiency addressed below.

5.4.1 Tracking Efficiency from Cosmic Muons

Cosmic muons provide an abundant source of very displaced tracks, with which the tracking efficiency for displaced, isolated muons can be measured. Cosmic muons were collected during a period without beam, and with the tracker readout configuration adjusted to make it insensitive to the fact that the tracker readout time can not be perfectly synchronized with the arrival of individual cosmic rays. The data are compared with simulated cosmic rays. The cosmic ray muons are reconstructed with a dedicated cosmic ray tracking algorithm [21] using the muon chambers alone. To select cosmic muons that are well-reconstructed in the muon chambers, exactly one cosmic muon in the event with \( p_T > 35 \text{ GeV}/c \) and \(|\eta| < 2\) is required. In addition, cosmic muons for which the uncertainties on the transverse and longitudinal impact parameters are unusually large, given their \( p_T \), are rejected.

Tracker tracks are reconstructed using the standard algorithm used in pp collisions. They are matched in a \( \Delta R \) cone to the reconstructed cosmic muon track; for each cosmic ray muon, two tracker tracks (on either side of the centre) are searched for. Tracker tracks are selected with same cuts used for the physics analysis.

The efficiency to find a tracker track associated to a cosmic muon found in the muon chambers as a function of the transverse and longitudinal impact parameters is shown in Fig. 5. Data and simulation agree to within \( \sim 10\% \). The corresponding relative systematic uncertainty on the efficiency to reconstruct dilepton candidates is inferred to be 20%.

5.4.2 Tracking Efficiency from Embedding

A Monte Carlo generator was used to simulate events containing only a single muon of \( p_T = 25 \text{ GeV}/c \) passing through the tracker. The production point of these muons was varied over a range of distances up to 50 cm from the beam axis and all angles. Only ‘reconstructable’ muons, defined as those successfully reconstructed in the tracker in these single particle events, were considered further. The fraction of these ‘reconstructable’ muons that could still be reconstructed after hits from a pp collision data event were superimposed on top of each simulated
Figure 5: Efficiency of the tracker to find a track given a cosmic muon reconstructed in the muon chambers, as a function of the transverse (left) and longitudinal (right) impact parameters (with respect to the centre of CMS). Data is in black full points, and simulation in red open points. When making the left-hand plot, a cut was applied on the longitudinal impact parameter $|z_0| < 10$ cm, whereas for the right-hand plot, a cut on the transverse impact parameter $|d_0| < 4$ cm was used.

single muon event was measured. This fraction is a measure of how a high occupancy environment affects the tracking efficiency. It is found to always exceed 90%, even for muons with impact parameters of up to 30 cm. Repeating the same exercise but superimposing hits from simulated pp collision events on top of the single muon events gave results which were compatible within 2%. This suggests that the 10% systematic uncertainty on the tracking efficiency assigned in Sect. 5.4.1 is conservative.

5.4.3 Verification of Displaced Tracking Efficiency using $K_0^s$

CMS has previously used displaced tracking for a measurement of $K_0^s$ production [22]. In that paper, it was verified that $K_0^s$ reconstructed in CMS can be used to measure the $K_0^s$ lifetime, and that the result is within 1% of its world average value. Although this agreement cannot be translated into a measurement of the displaced tracking efficiency, it does provide additional evidence that its dependence on decay length is well modelled in the simulation.

5.5 Trigger Efficiency Measurement

The trigger efficiency is measured using the Tag and Probe method. In this method, one looks for pairs of muons coming from the decay of a resonance, chosen here to be the Z boson. One of the two muons (referred to as the Tag) is required to pass tight muon selection criteria, including the requirement to match within $\Delta R < 0.5$ with a single muon trigger object with $p_T > 17$ $\text{GeV}/c$. The other candidate (referred to as the Probe) is used to estimate the efficiency that a muon passing the offline selection cuts of the analysis (Sect. 4.3), would also match within $\Delta R < 0.5$ with one of the dimuon trigger objects used to select events in this analysis.

In addition, it is also required that the tag and the probe are separated by $\Delta R > 0.2$ at the innermost muon chamber layer, in order to avoid the complications arising from nearby muons.

The systematic uncertainty was evaluated by taking the difference between the estimates from data and Monte Carlo simulation, yielding a total uncertainty of $\pm 11\%$. As a cross-check, the
tag and probe procedure was repeated with a requirement for the tag to pass a higher signal muon $p_T$ threshold of 40 GeV/c, yielding a 1% difference and demonstrating the robustness of the method.

The performance of the di-photon trigger used to select events in this analysis can be taken from the study done for the $Z' \rightarrow e^+ e^-$ analysis [23]. That analysis studied the turn-on curve of this same trigger, and showed that it is almost fully efficient for electrons with $E_T > 35$ GeV in the ECAL barrel and $E_T > 38$ GeV in the ECAL endcap. As, in this analysis, the offline selection for the electron channel requires tracks to have $p_T > 38$ GeV/c and to have pseudorapidity $|\eta| < 2$, the trigger is effectively fully efficient.

As explained in Sect. 4.2, in the electron channel, tracks are required to be matched to ECAL super-clusters. Monte Carlo simulation shows that this matching is virtually 100% efficient for genuine electrons, so no systematic uncertainty is considered for this.

5.6 Background Estimate

The systematic uncertainty on the background estimate as described in Sect. 6.2 is used as a nuisance parameter when setting the limit in Sect. 6.3. We obtain the systematic uncertainty by estimating the background in two different ways and taking the difference, resulting in an estimate of $0.79 \pm 0.99$ events in the electron channel and $0.02 \pm 2.28$ events in the muon channel.

6 Results

6.1 Selected Events

The efficiency to select $H^0 \rightarrow XX$ candidates is determined for two cases, one in which two long-lived exotics decay to the chosen lepton species $e_2$, and also for events in which only one long-lived exotic does this $e_1$. For larger X boson masses, $e_1$ and $e_2$ are very similar, indicating that the efficiency to select a candidate is not strongly affected by the number of X bosons in the event decaying to the chosen mode. In general the efficiency is approximately 20-30% in the dimuon channel and 10-20% in the dielectron channel, depending on the Higgs and X masses. For a $M_{H^0} = 200$ GeV/c$^2$ in the electron channel, the efficiencies become very small (1-2%), so we do not set limits in this case.

In order to obtain results for a range of X boson lifetimes, the efficiencies are evaluated after reweighting the signal Monte Carlo simulation so as to emulate the production of X bosons with lifetimes several times shorter or longer than in the original samples. For extremely long lifetimes, such that most X bosons decay too far from the primary vertex to be reconstructed, the efficiency will scale in inverse proportion to the lifetime $\tau$ of the X boson.

6.2 Background Estimation

An estimate of the amount of background is obtained by counting the number of Monte Carlo simulated events passing the selection requirements, as seen in Fig. 3. Counting the raw number of background events yields $0.27 \pm 0.03$ ($2.30 \pm 2.30$) events in the electron (muon) channel. However, because very few simulated events pass the signal selection criteria, this estimate leads to a large systematic uncertainty on the estimate of the remaining background. Therefore, in order to check the validity of the background prediction and its corresponding systematic uncertainty, an alternative estimate is performed using the decay length significance $L_{xy}/\sigma$. 
The results are then used as an input into the data-driven method using the dilepton mass distribution for the final fit, as described in Sec. 6.3.

From Fig. 2, one can observe that the decay length significance \( L_{xy}/\sigma \) provides a good separation between signal and background. (The distribution for electrons is wider because of bremsstrahlung from the electrons, but is still much reduced in the signal region.) Hence, the background is fitted with a sum of two falling exponentials in the background region and extrapolate out to the signal region to obtain a separate estimate of the background contribution in the muon channel. Figure 6 shows the results of these fits. Using these results, the estimate of the background is 0.79 ± 0.99 events in the electron channel, and 0.02 ± 0.76 events in the muon channel, consistent with the simple estimate from the raw number of simulated events passing the selection requirements. The difference between the two is taken as a systematic uncertainty on the final background estimate.

**Figure 6**: Fit to the transverse decay length significance of the candidates in Monte Carlo simulated events for the dielectron (left) and dimuon (right) channels. From these fits, a background estimate of 0.79 ± 0.99 events in the electron channel, and 0.02 ± 0.76 events in the muon channel is obtained.

### 6.3 Upper Limits

As the mass spectrum seen in data is consistent with Monte Carlo simulation predictions, an upper limit is quoted on the cross section to produce \( H^0 \rightarrow XX \) multiplied by the branching ratio \( B \) of \( X \rightarrow \ell^+ \ell^- \), where \( \ell \) denotes either electron or muon.

As a first step, the mass spectrum is used to place an upper limit, expressed as a function of the \( X \) boson mass, on the expected number \( S \) of \( X \) boson candidates passing the selection cuts. To do this, one needs the following quantities:

- A **Gaussian signal PDF** to represent the mass resolution function of the signal. Its width increases as a function of the \( X \) boson mass. This dependence is obtained by fitting a smooth curve through width estimates obtained from the various simulated signal samples.

- A **background PDF** representing the mass distribution expected for Standard Model processes. The background PDF is assumed to be independent of the \( X \) boson mass, except in the case of the electron channel, where an additional gaussian component
at the Z peak, corresponding to the residual Z background, is included. The background determination is as described in Sec. 6.2. For the electron channel, as can be seen from Fig. 3, all of the background is expected to be in the Z peak.

An upper limit on $S$ is calculated using a CL$_s$ method, where the mass axis is divided into bins and in each bin the limit is calculated given the number of signal and fitted background events in the bin. The region with X boson mass below 15 GeV/$c^2$ is excluded, thus avoiding the need to model background due to J/ψ, γ conversions, and other similar sources.

The uncertainty of the background determined in Sect. 6.2, is treated as a systematic uncertainty by modelling the overall normalisation of the background as a nuisance parameter. Such nuisance parameters are modelled as having their own Gaussian PDF, whose width corresponds to their uncertainty. This Gaussian PDF multiplies the general model PDF, which contains signal plus background PDFs.

The resulting upper limit on $S$ at a 95% confidence level is 3.0 for all X boson masses in the muon and electron channels, except near the Z mass in the electron channel, where the limit increases to 4.75. By definition, these results have no dependence on the H$^0$ mass.

The observed number of signal events $S$ passing the selection cuts can be expressed as:

$$S = 2\mathcal{L}\epsilon_1\sigma B [1 + B(e_2/e_1 - 1)]$$

where $\mathcal{L}$ is the integrated luminosity, $\sigma$ the cross section for the pair production of $X X$, $B$ the branching ratio of $X \rightarrow \ell \ell$, and $\epsilon_{1,2}$ are defined in Sect. 6.1. This expression takes into account that either one or both X bosons in an event may decay to the chosen lepton species and that, as shown in Sect. 6.1, the efficiency to select such an X boson is slightly different in the two cases.

Because of the two terms $\epsilon_{1,2}$ and the $B$ present in Eq. 1 cannot be decoupled, it is not possible to translate the limit on $S$ to a limit on $\sigma B$ without assuming a given value of $B$. Given that the efficiencies in Eq. 1 already depend on three quantities (the Higgs and X boson masses and the X boson lifetime), it would be impractical to present the results as a function of $B$ as well.

We observe in Eq. 1 that one can eliminate the effect of the term $(e_2/e_1 - 1)$ by assuming a small value of $B$, so we fix $B = 0.01$ so that the second term is negligible and hence we obtain the most conservative limit.

With this fixed value of $B$, limits are obtained for each combination of the Higgs and X boson masses listed in Table 1 and for a range of X boson lifetimes, treating the systematic uncertainties on the luminosity and efficiencies as nuisance parameters. The results are shown in Figs. 7–9. For the electron channel, the expected background away from the Z peak is very small, so the expected limit is identical to the observed limit and is not visible in the plots.

It should be noted that in an alternative signal model, in which $H^0 \rightarrow XY$, where the Y boson never decays to leptons, the expected number of signal events $S$ passing the selection cuts can be expressed as $S = \mathcal{L}\epsilon'_1\sigma B$, where $\epsilon'_1$ is the efficiency to select signal candidates in this scenario. If the X and Y bosons have identical mass, then $\epsilon'_1 = \epsilon_1$, and comparison with Eq. 1 shows that the limits would be a factor 2 worse than those presented above.
Figure 7: 95% confidence level upper limits on $\sigma B$ for the electron and muon channels for a Higgs mass of 1000 GeV/$c^2$. The expected limit band for the electron channel is too small to be visible.

Figure 8: 95% confidence level upper limits on $\sigma B$ for the electron and muon channels for a Higgs mass of 400 GeV/$c^2$. The expected limit band for the electron channel is too small to be visible.
7 Conclusions

For pp collisions at $\sqrt{s} = 7$ TeV, upper limits are placed on the production cross section of a heavy resonance decaying to two long-lived, spinless, neutral particles X, where the massive resonance is taken to be a Higgs boson $H^0$, multiplied by the branching ratio $B$ of $X \rightarrow l^+l^-$, where $l$ denotes either electron or muon. For Higgs masses of 200-1000 GeV/c^2 and X boson masses of 20-350 GeV/c^2, these limits are typically in the range 0.003-0.03 pb, for X bosons whose lifetime is such their mean transverse decay length is less than about 1 metre.

References


Conclusions


