Decay-mode independent searches for new scalar bosons with OPAL

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Abstract

Topological searches for neutral scalar bosons S^0 produced in association with a Z^0 boson via the Bjorken process $e^+e^- \to S^0Z^0$ at centre-of-mass energies of 91 GeV and 183–209 GeV are described. These searches are based on studies of the recoil mass spectrum of $Z^0 \to e^+e^-$ and $\mu^+\mu^-$ events and on a search for S^0Z^0 with $Z^0 \to \nu\bar{\nu}$ and $S^0 \to e^+e^-$ or photons. They cover the decays of the S^0 into an arbitrary combination of hadrons, leptons, photons and invisible particles as well as the possibility that it might be stable.

No indication for a signal is found in the data and upper limits on the cross section of the Bjorken process are calculated. Cross-section limits are given in terms of a scale factor k with respect to the Standard Model cross section for the Higgs-strahlung process $e^+e^- \to H^0_{SM}Z^0$.

These results can be interpreted in general scenarios independently of the decay modes of the S^0. The examples considered here are the production of a single new scalar particle with a decay width smaller than the detector mass resolution, and for the first time, two scenarios with continuous mass distributions, due to a single very broad state or several states close in mass.

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1 Introduction

Searches for new neutral CP even scalar bosons S^0 with the OPAL [1] detector at LEP are described. The new bosons are assumed to be produced in association with a Z^0 boson via the Bjorken process $e^+e^- \rightarrow S^0Z^0$.

The analyses are topological searches and are based on studies of the recoil mass spectrum in $Z^0 \rightarrow e^+e^-$ and $\mu^+\mu^-$ events and on a subsequent search for S^0Z^0 events with $S^0 \rightarrow e^+e^-$ or photons and $Z^0 \rightarrow \nu\bar{\nu}$. They are sensitive to all decays of S^0 into an arbitrary combination of hadrons, leptons, photons and invisible particles, and to the case of a long-lived S^0 leaving the detector without interaction. Hence they are decay-mode independent and result in absolute mass limits. The analyses are applied to LEP 1 Z^0 on-peak data (115.4 pb^{-1} at $\sqrt{s} = 91.2$ GeV) and to 662.4 pb^{-1} of LEP 2 data collected at centre-of-mass energies in the range of 183 to 209 GeV. The results are presented in terms of limits on the scaling factor k, which relates the S^0Z^0 production cross section to the Standard Model (SM) cross section for the Higgs-strahlung process:

$$\sigma_{S^0Z^0} = k \cdot \sigma_{H^0_{SM}Z^0}(m_{H^0_{SM}} = m_{S^0}), \tag{1}$$

where it is assumed that k does not depend on the centre-of-mass energy for any given mass m_{S^0}. Since the analysis is independent of the decay mode of the S^0, these limits can be interpreted in any scenario beyond the Standard Model. The most general case is to provide upper limits on the cross section or scaling factor k for a single narrow new scalar boson independent of its couplings to other particles. In a more specific interpretation, assuming the S^0Z^0 production cross section to be identical to the Standard Model Higgs boson one, the limit on k can be translated into a lower limit on the Higgs boson mass[1]. For the first time we give limits not only for a single mass peak with small width, but also for a continuous distribution of the signal in a wide mass range. Such continua appear in several recently proposed models which are introduced in the next sections.

1.1 Continuous Higgs scenarios

The Uniform Higgs scenario

This model, as described in Ref. [3], assumes a broad enhancement of the signal over the background expectation in the M_X mass distribution for the process $e^+e^- \rightarrow Z^0X$. This enhancement is due to numerous additional neutral Higgs bosons h^0_i with masses $m_A \leq m(h^0_i) \leq m_B$, where m_A and m_B indicate the lower and upper bound of the mass spectrum. The squared coupling, g^2, of the Higgs states h^0_i to the Z^0 is modified by a factor k_i compared to the Standard Model H^0Z^0 coupling: $g^2_{Z^0h^0_i} = k_i \cdot g^2_{Z^0h^0_{SM}}(m_{h^0_i} = m_{h^0_{SM}})$.

If the Higgs states are assumed to be closer in mass than the experimental mass resolution, then there is no means to distinguish between separate k_i. In this case the Higgs states and their reduction factors k_i can be combined into a coupling density function, $\tilde{K}(m) = \mathrm{d}k/\mathrm{d}m$. The model obeys two sum rules which in the limit of unresolved mass peaks can be expressed as integrals over this coupling density function:

$$\int_0^\infty \mathrm{d}m\ \tilde{K}(m) = 1 \qquad \text{and} \qquad \int_0^\infty \mathrm{d}m\ \tilde{K}(m)m^2 \leq m_C^2, \tag{2}$$

[1]Dedicated searches for the Standard Model Higgs boson by the four LEP experiments, exploiting the prediction for its decay modes, have ruled out masses of up to 114.4 GeV [2].

where $\tilde{K}(m) \geq 0$ and m_C is a perturbative mass scale of the order of 200 GeV. The value of m_C is model dependent and can be derived by requiring that there is no Landau pole up to a scale Λ where new physics occurs [3]. If neither a continuous nor a local excess is found in the data, Equation 2 can be used to place constraints on the coupling density function $\tilde{K}(m)$. For example, if $\tilde{K}(m)$ is assumed to be constant over the interval $[m_\mathrm{A}, m_\mathrm{B}]$ and zero elsewhere, then certain choices for the interval $[m_\mathrm{A}, m_\mathrm{B}]$ can be excluded. From this and from Equation 2 lower limits on the mass scale m_C can be derived.

The Stealthy Higgs scenario

This scenario predicts the existence of additional $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ singlet fields (phions), which would not interact via the strong or electro-weak forces, thus coupling only to the Higgs boson with strength ω [4]. Therefore these singlets would reveal their existence only in the Higgs sector by offering invisible decay modes to the Higgs boson. The width of the Higgs resonance can become large if the number of such singlets, N, or the coupling ω is large, thus yielding a broad spectrum in the mass recoiling against the reconstructed $\mathrm{Z^0}$. The interaction term between the Higgs and the additional phions in the Lagrangian is given by $\mathscr{L}_\mathrm{interaction} = -\frac{\omega}{2\sqrt{N}}\vec{\varphi}^2\phi^\dagger\phi$, where ϕ is the Standard Model Higgs doublet, ω is the coupling constant, and $\vec{\varphi}$ is the vector of the new phions. An analytic expression for the Higgs width can be found in the limit $N \to \infty$:

$$\Gamma_\mathrm{H}(m_\mathrm{H}) = \Gamma_\mathrm{SM}(m_\mathrm{H}) + \frac{\omega^2 v^2}{32\,\pi\, m_\mathrm{H}}, \tag{3}$$

where v is the vacuum expectation value of the Higgs field. This expression results when setting other model parameters to zero, including the mass of the phions [4].

In section 3.2.2 we derive limits on the Stealthy Higgs model. By simulating signal spectra for different Higgs widths Γ_H we constrain the ω-m_H plane in the large N limit.

2 Decay-mode independent searches for $\mathrm{e^+e^-} \to \mathrm{S^0Z^0}$

The event selection is intended to be efficient for the complete spectrum of possible $\mathrm{S^0}$ decay modes. As a consequence it is necessary to consider a large variety of 2-fermion, 4-fermion, and 2-photon background processes. Suppression of the background is performed using the smallest amount of information possible for a particular decay of the $\mathrm{S^0}$. The decays of the $\mathrm{Z^0}$ into electrons and muons are the channels with highest purity, and therefore these are used in this analysis. The signal process can be tagged by identifying events with an acoplanar, high momentum electron or muon pair.

Different kinematics of the processes in the LEP 1 and the LEP 2 analysis lead to different strategies for rejecting the background. At LEP 2 the invariant mass of the two final-state leptons in the signal channels is usually consistent with the $\mathrm{Z^0}$ mass, while this is not true for a large part of the background. Therefore a cut on the invariant mass rejects a large amount of background. Remaining two-fermion background from radiative processes can partially be removed by using a photon veto without losing efficiency for photonic decays of the $\mathrm{S^0}$. In the LEP 1 analysis the invariant mass of the lepton pair cannot be constrained. Therefore, stronger selection cuts have to be applied to suppress the background, resulting in an insensitivity to the decays $\mathrm{S^0} \to$ photons and $\mathrm{S^0} \to \mathrm{e^+e^-}$ at low masses. These decay modes are recovered in a search dedicated to $\mathrm{e^+e^-} \to \mathrm{S^0Z^0}$ with $\mathrm{Z^0} \to \nu\bar{\nu}$ and $\mathrm{S^0} \to$ photons (or photons plus invisible particles) or $\mathrm{e^+e^-}$. Details of the selection procedure can be found in [5].

$\sqrt{s}$ (GeV)	Data	Total bkg.	2-fermion	4-fermion	2-photon	Signal (m_{S^0}=30 GeV)
Electron channel						
91.2	45	55.2 ±3.0 ± 3.0	20.5	34.4	0.3	15.61 ±0.31 ± 0.47
183–209	54	46.9 ±0.6 ± 3.5	12.8	33.7	0.4	7.97 ±0.06 ± 0.25
Muon channel						
91.2	66	53.6 ±2.7 ± 2.1	17.0	35.4	1.2	21.55 ±0.45 ± 0.69
183–209	43	51.6 ±0.3 ± 2.5	12.2	38.6	0.8	9.43 ±0.06 ± 0.37

Table 1: Selected data events, background Monte Carlo and signal expectation for a 30 GeV Standard Model Higgs boson. The first error is statistical and the second error is systematic.

3 Results

The results of the decay-mode independent searches are summarised in Table 1. The total number of observed candidates from all lepton channels combined is 208, while the Standard Model background expectation amounts to 207.3 ± 4.1(stat.) ± 11.1(syst.). The efficiency for the signal process is around 30 % for most of the mass range. Figure 1 and 2 show the recoil mass spectra for the lepton channels at LEP 1 and LEP 2. As no excess over the expected background is observed in the data, limits on the cross section for the Bjorken process $e^+e^- \to S^0Z^0$ are calculated.

The limits are presented in terms of a scale factor k, which relates the cross section for S^0Z^0 to the Standard Model one for the Higgs-strahlung process $e^+e^- \to H^0_{SM}Z^0$ as defined in Equation 1. The 95% confidence level upper bound on k is obtained from a test statistic, $\mathcal{L}_{s+b}/\mathcal{L}_b$, for the signal and the signal+backgrund likelihood, by using the recoil mass distributions of the data, the background and the signal (applying the Higgs decay with the smallest efficiency) and the weighted event-counting method described in [6]. The systematic uncertainties are included as described in [7]. To give a conservative limit only the lepton channels are used in the limit calculation, because the channel with $Z^0 \to \nu\bar{\nu}$ is complementary to the lepton channels in the LEP 1 search, and it has a much higher sensitivity.

The limits are given for three different scenarios: 1. Production of a single new scalar S^0 2. The Uniform Higgs scenario 3. The Stealthy Higgs scenario.

3.1 Production of a single new scalar S^0

In the most general interpretation of the results, a cross-section limit is set on the production of a new neutral scalar boson S^0 in association with a Z^0 boson.

In Figure 3 the limits obtained for scalar masses down to the lowest generated signal mass of 1 keV are shown. They are valid for the decays of the S^0 into hadrons, leptons, photons and invisible particles (which may decay inside the detector) as well as for the case in which the S^0 has a sufficiently long lifetime to escape the detector without interacting or decaying. The observed limits are given by the solid line, while the expected sensitivity, determined from a large number of Monte Carlo experiments with the background-only hypothesis, is indicated by the dotted line. The shaded bands indicate the one and two sigma deviations from the expected sensitivity. The existence of a Higgs boson produced at the SM rate can be excluded up to 81 GeV even from decay-mode independent searches. For masses of the new scalar particle well below the width of the Z^0, *i.e.* $m_{S^0} \lesssim 1$ GeV, the obtained limits remain constant at the level of $k^{95}_{\text{obs.}} = 0.067$, and $k^{95}_{\text{exp.}} = 0.051$.

3.2 Limits on signal mass continua

3.2.1 The Uniform Higgs scenario

Limits are obtained for the Uniform Higgs scenario where $\tilde{K}$ = constant over the interval [m_{A}, m_{B}] and zero elsewhere. Both the lower mass bound m_{A} and the upper bound m_{B} are varied between 1 GeV and 350 GeV (with the constraint $m_{\mathrm{A}} \leq m_{\mathrm{B}}$). An upper limit is set on the first integral in Equation 2. Figure 4 shows the mass points (m_{A},m_{B}) for which the obtained 95 % CL limit on $\int \mathrm{d}m\,\tilde{K}$ is less than one. These are the signal mass ranges $m_{\mathrm{A}} \leq m_{\mathrm{h}_i^0} \leq m_{\mathrm{B}}$ which can be excluded assuming a constant $\tilde{K}$.

The horizontal line illustrates an example for excluded mass ranges: The line starts on the diagonal at $m_{\mathrm{A}} = m_{\mathrm{B}} = 35$ GeV and ends at $m_{\mathrm{B}} = 99$ GeV. This value of m_{B} is the highest upper mass bound which can be excluded for this value of m_{A}. All mass ranges with an upper bound m_{B} below 99 GeV are also excluded for $m_{\mathrm{A}} = 35$ GeV. The highest excluded value of m_{B} ($m_{\mathrm{B}} = 301$ GeV) is achieved for m_{A} set to 0 GeV.

Using the maximal exluded mass ranges and the two sum rules from section 1.1 for constant $\tilde{K}$, lower limits on the perturbative mass scale m_{C} can be derived, as shown in Figure 5. It is also possible to set limits on a non-constant coupling density. Details can be found in Ref. [5].

3.2.2 The Stealthy Higgs scenario

To set limits on the Stealthy Higgs scenario we have simulated the spectrum of a Higgs boson with a width according to Equation 3 and the cross section from Ref. [4].

The excluded regions in the ω-m_{H} parameter space are shown in Figure 6. To illustrate the Higgs width according to Equation 3, for a given mass m_{H} and coupling ω 'isolines' for some sample widths are added to the plot. The maximal excluded region of the coupling ω is achieved for masses around 30 GeV, where ω can be excluded up to $\omega = 2.7$. For lower masses the sensitivity drops due to the rapidly increasing width of the Higgs boson, and for higher masses due to the decreasing signal cross section.

4 Conclusions

Decay-mode independent searches for new neutral scalar bosons S^0 decaying to hadrons of any flavour, to leptons, photons invisible particles and other modes have been performed based on the data collected at $\sqrt{s} = m_{\mathrm{Z}}$ and 183 to 209 GeV by studying $\mathrm{S}^0\mathrm{Z}^0$ production in the channels with $\mathrm{Z}^0 \to \mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-$ and the channel where the Z^0 decays into $\nu\bar{\nu}$ and the S^0 into photons or $\mathrm{e}^+\mathrm{e}^-$. No excess of candidates in the data over the expected Standard Model background has been observed. Upper limits on the production cross section for associated production of S^0 and Z^0, with arbitrary S^0 decay modes, were set at the 95 % confidence level. Upper limits in units of the Standard Model Higgs-strahlung cross section of $k < 1$ for $m_{\mathrm{S}^0} < 81$ GeV were obtained. In further interpretations, limits on broad continuous signal mass shapes to which previous analyses at LEP had no or only little sensitivity were set for the first time. Two general scenarios in the Higgs sector were investigated: A uniform scenario, when the signal arises from many unresolved Higgs bosons, and a Stealthy Higgs model, when the Higgs resonance width is large due to large Higgs-phion couplings.

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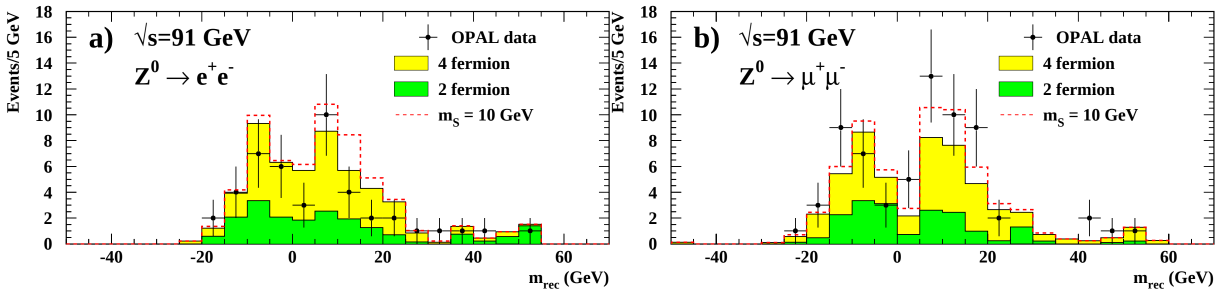

Figure 1: The recoil mass spectra from $\sqrt{s}$ =91.2 GeV a) for the decays $Z^0 \rightarrow e^+e^-$ and b) for $Z^0 \rightarrow \mu^+\mu^-$. OPAL data are indicated by dots with error bars (statistical error), the four-fermion background by the light grey histograms and the two-fermion background by the dark grey histograms. The dashed lines for the signal distributions are plotted on top of the background distributions with normalisation corresponding to the cross section excluded at 95% confidence level from the combination of both channels.

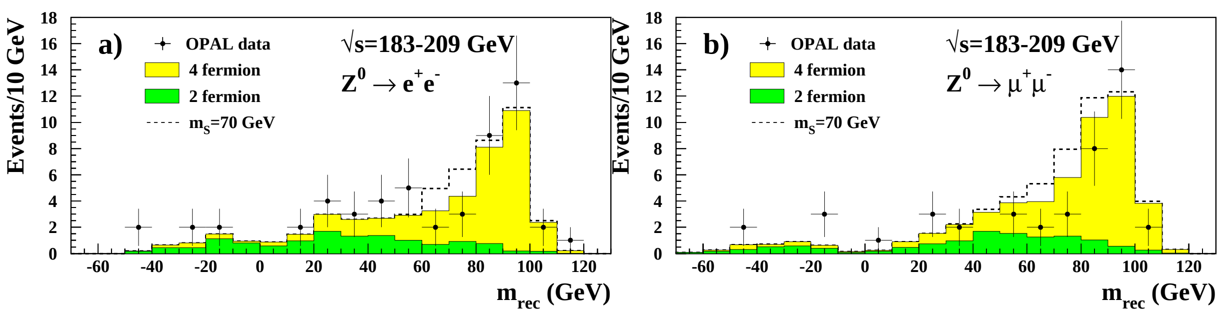

Figure 2: The recoil mass spectrum from 183–209 GeV a) for the decays $Z^0 \rightarrow e^+e^-$ and b) for $Z^0 \rightarrow \mu^+\mu^-$ (lower plot). OPAL data are indicated by dots with error bars (statistical error), the four-fermion background by the light grey histograms and the two-fermion background by the medium grey histograms. The dashed lines for the signal distributions are plotted on top of the background distributions with normalisation corresponding to the excluded cross section from the combination of both channels.

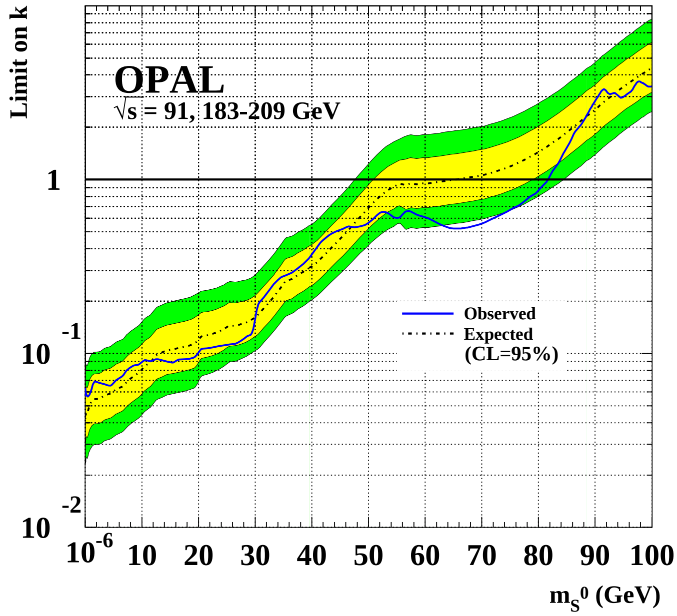

Figure 3: The upper limit on the scale factor k on the cross section for the production of a new scalar boson in the Higgs-strahlung process (solid line). The dot-dashed line represents the expected median for background-only experiments. Both limits are calculated at the 95 % confidence level. The dark (light) shaded bands indicate the 68% (95%) probability intervals centred on the median expected values. For masses $m_{S^0} \lesssim 1$ GeV the limits are constant. The lowest signal mass tested is 10^{-6} GeV.

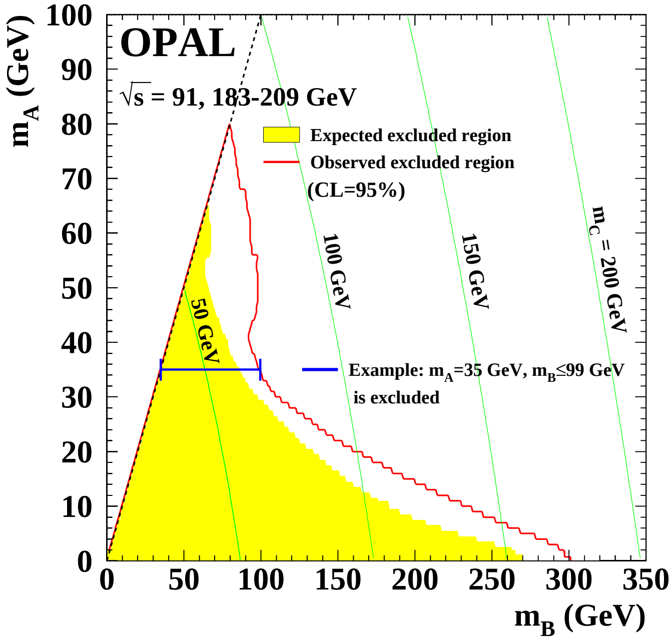

Figure 4: Exclusion limits for the Uniform Higgs scenario at the 95 % confidence level. All mass intervals (m_A, m_B) within the area bordered by the dark line are excluded from the data. The shaded area marks the mass points which are expected to be excluded if there were only background. The light grey curves indicate isolines for several values of m_C. All intervals (m_A, m_B) to the right of each isoline are theoretically disallowed from Equation 2. By definition, only intervals (m_A, m_B) right to the dashed diagonal line are valid, *i.e.* $m_A \leq m_B$.

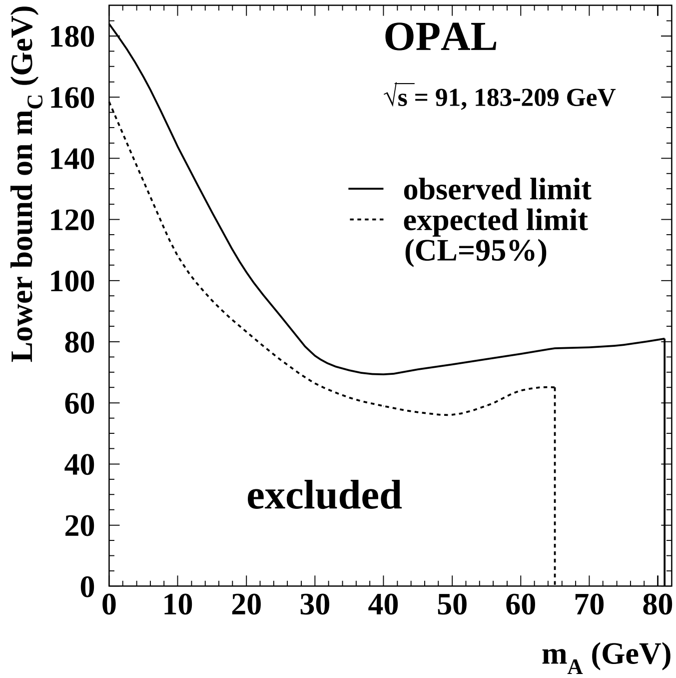

Figure 5: Exclusion limits on the perturbative mass scale $m_{\rm C}$ for constant $\tilde{K}$. The solid line represents the limits obtained from the data, and the dotted line shows the expected limit if there were only background. Values for $m_{\rm C}$ below the lines are excluded by this analysis at the 95 % confidence level.

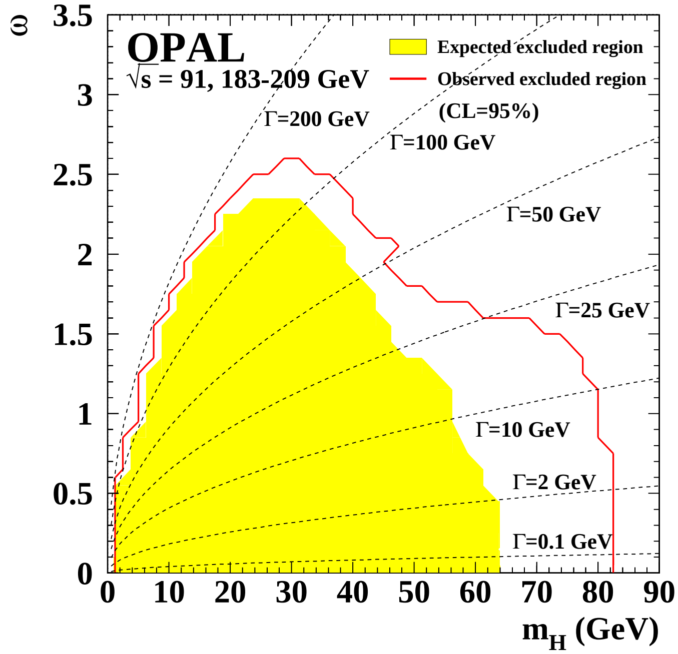

Figure 6: Excluded parameter regions for the Stealthy Higgs scenario at the 95 % confidence level. The solid line marks the region which is excluded from the data. The shaded area marks the region which would be excluded if there were only background. The dashed lines indicate the Higgs width depending on $m_{\rm H}$ and ω.