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Search for Neutral Higgs Boson in Z° Decay

The L3 Collaboration

ABSTRACT

We have searched for the neutral Higgs boson produced in the decays of the Z° through the processes $Z^\circ \rightarrow H^\circ\mu^+\mu^-$, $Z^\circ \rightarrow H^\circ e^+ e^-$ and $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$. The data sample analysed corresponds to about 50200 $Z^\circ \rightarrow$ hadrons. Combining the results of all three processes we exclude a Minimal Standard Model Higgs boson in the mass range $2 < M_{H^\circ} < 32$ GeV at 95% confidence level.

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Introduction

The Standard Model[1] has been very successful in describing all data concerning electroweak interactions. In this model Z and W bosons acquire mass through the Higgs mechanism[2] which, in its minimal formulation, predicts the existence of one neutral boson H°. Although the theory precisely predicts its coupling to both vector bosons and fermions it leaves unpredicted the value of its mass. If the Higgs boson is lighter than the Z° it can be produced in Z° decays through the Bjorken Bremsstrahlung process[3]:

$$e^+e^- \rightarrow Z^\circ \rightarrow H^\circ + Z^{\circ *} \rightarrow H^\circ + f\bar{f}$$

where the off shell $Z^{\circ *}$ decays into a pair of fermions.

In this letter we describe our search for the Minimal Standard Model Higgs boson in the channels $Z^\circ \rightarrow H^\circ \mu^+\mu^-$, $Z^\circ \rightarrow H^\circ e^+e^-$ and $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ performed at LEP using data collected by the L3 detector during a scan of the Z° resonance in the Spring 1990. In this period about 50200 Z° decays into hadrons have been detected and they are used here as normalization.

The L3 Detector

The L3 detector covers 99% of 4π with calorimetry. The detector consists of a central vertex chamber, a high resolution electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a very accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 Tesla along the beam axis. The detector is described in detail elsewhere[4].

H° production and decay

The $e^+e^- \rightarrow Z^\circ \rightarrow H^\circ + Z^{\circ *}$ cross section is predicted by the Standard Model and depends on the Higgs mass[5]. The Higgs decay partial widths into fermions are also well established for mass of the H° greater than 2 GeV[6]. Since Higgs coupling to fermions is proportional to the square of the fermion mass, Higgs decays predominantly into $b\bar{b}$ for masses above 11 GeV and into $\tau^+\tau^-$ and $c\bar{c}$ in the mass range 4-11 GeV. Between 2 and 4 GeV it will predominantly decay into $s\bar{s}$. Below 2 GeV non perturbative effects make the prediction of the branching ratios of the Higgs boson decaying into hadrons and leptons less firm[6], leading to large uncertainties in the detection efficency of light Higgs. For this reason, even if we have searched for the Higgs boson down to the mass values of few hundreds MeV, we present here results in the mass range $M_{H^\circ} > 2$ GeV.

In order to determine the acceptance of our detector and the efficiency of our selection a Monte-Carlo simulation for the above processes has been performed. This simulation includes both initial and final state photon radiation. The decay of the Higgs boson into hadrons has been simulated using the Lund Model (JETSET 6.3)[7]. The response of the detector has been simulated using the L3 detector simulation program[8].

$Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ events selection

In this process a large fraction of the energy is carried by the neutrinos which escape detection. Depending on the Higgs mass and the Lorenz boost the decay products can either be close to each other appearing as a single jet or be well separated in space forming two jets. Thus the signature is one jet or two acollinear jets and large missing energy and transverse momentum.

$e^+e^- \rightarrow Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ events are detected by the energy trigger, the charged track trigger and by a "cluster" trigger which requires an angular matching between a charged track and a calorimetric cluster with energy greater than 3 GeV. The trigger efficiency has been evaluated using two methods. In the first a simulated trigger has been applied to the Monte-Carlo generated $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ events. The second method uses the trigger information from a data sample selected with criteria relaxed with respect to those described below. The two methods agree within 5% for $M_{H^\circ} < 15$GeV where the estimated trigger efficiency is about 80% and to better than 1% above this mass where the trigger efficiency is close to 100%.

The main sources of background for the $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ process are $Z^\circ \rightarrow q\bar{q}(g)$, $Z^\circ \rightarrow \tau^+\tau^-(\gamma)$, $e^+e^- \rightarrow e^+e^-q\bar{q}$, beam-gas and beam-wall interactions. Unlike the Higgs events the hadronic decays of Z° are characterized by two collinear or more than two jets, good energy balance, small missing energy and high multiplicity of energy clusters. $\tau^+\tau^-$ events have high thrust, low multiplicity of energy clusters and back-to-back jets. Four fermion final states are characterized by large longitudinal energy imbalance, low multiplicity of energy clusters and good transverse energy balance. Beam-gas interactions produce tracks in the central tracking detector which are not coming from the beam intersection region and deposit large energy in the luminosity monitor.

For the selection of $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ we use the following criteria:

1) Total energy, E_{tot} of the event should be less than 70 GeV. The effect of this cut on hadrons is illustrated in fig 1a;

2) Transverse energy imbalance should be greater than 28% of E_{tot}. Fig. 1b shows the comparison of the Monte Carlo distributions for $e^+e^-q\bar{q}$ final state and the 30 GeV Higgs;

3) The energy of the 3^{rd} jet (if any) should be less than 5 Gev;

4) Total number of clusters in the calorimeters should be at least 9 and not more than 45;

5) For multi-jet events the acollinearity angle between the two most energetic jets should be greater than 35°. In fig 1c the Monte Carlo distributions of this quantity are compared for τ pairs and the 30 GeV Higgs;

6) The thrust of the event should be less than 0.98;

7) There should be at least one jet with following properties:
- at least 6 GeV of energy,
- at least 3 calorimetric clusters,
- at least 1 track in the central tracking detector,
inside a 35° cone around the jet axis;

8) Energy deposited in the luminosity calorimeter should be less than 10% of E_{tot};

9) Longitudinal energy imbalance should be less than 75% of E_{tot};

10) There should be at least two charged tracks with transverse momentum greater than 0.5 GeV and the distance of closest approach to the beam axis of less than 5 mm.

We observe no events in the data satisfying the above criteria. From the Monte Carlo studies we expect 1.4 background events from hadrons, 0.2 events from the tau pairs and 0.8 events from the four fermion final states.

The dependence of Higgs selection efficiency, including the trigger efficiency discussed above, is plotted versus the Higgs mass in fig 2.

$Z^\circ \rightarrow H^\circ e^+e^-$ and $Z^\circ \rightarrow H^\circ \mu^+\mu^-$ events selection

$Z^\circ \rightarrow H^\circ l^+l^-$ events are characterized by the presence of two high momentum isolated leptons, coming from the off shell $Z^{\circ *}$, recoiling against one or two hadronic jets coming from the H° decay.

The two muons are identified requiring two tracks in the muon chambers with $P_\mu > 3$ GeV coming from the vertex and associated with at least one hit in the scintillator barrel in time with the beam crossing. The sum of their momenta should be greater than 20 GeV.

The two electrons are identified requiring two electromagnetic clusters in the BGO calorimeter with energy greater than 2 GeV. The sum of their energies should be greater than $40\%\sqrt{s}$ and less than $94\%\sqrt{s}$;

The angle between the two leptons should be between 90° and 177°.

For the detection of the Higgs decay products we require that two calorimetric clusters (of which one is associated to a charged track) are present beside the ones associated to the leptons.

These cuts remove cosmic rays and Z° decays in electron, muon and tau pairs. The requirement of at least one charged track not associated to any lepton removes radiative dilepton events.

The isolation of the two leptons is ensured by requiring that:

for each electron cluster, the ratio of the energy sum of 9 BGO crystals surrounding the most energetic crystal to that of 25 BGO crystals is greater than 0.95;

for the case of muons no other calorimetric cluster, beside the one associated to the μ, is present in a cone of 35° around at least one muon.

These cuts remove heavy flavour (mainly $b\bar{b}$) events in which both quarks decay into leptons.

In order to increase the acceptance we also search for events in which one of the two muons escapes detection. In this case we require the following additional conditions to be satisfied:

The μ should have a momentum larger than 15 GeV, its angle with respect to the nearest jet should be between 23° and 169° and its $P_{\perp}$ with respect to the nearest jet should be larger than 10 GeV;

Above cuts remove events containing a muon produced in the decays of hadrons and taus.

The trigger efficiency has been checked using electron, muon and tau pair events and has been found to be close to 100% due to the redundancy of the muon, energy and charged track triggers used.

Simulated Higgs events of masses ranging from 2 to 40 GeV were passed through the same selection criteria and gave the selection efficiencies presented in fig.2.

The same analysis applied to simulated $Z^{\circ} \to b\bar{b}$ events shows that 0.7 events are expected from this channel in 50200 Z° hadronic decays.

We have also simulated four fermion final state events[9] produced in e^+e^- interactions at energies around the Z° mass. This analysis shows that, applying a 5 GeV invariant mass cut to any pair of produced fermions, 0.42 events pass the previous cuts. This number almost doubles if we decrease the invariant mass cut to 3 GeV.

Two events of the kind $e^+e^- \to e^+e^- + X$ pass the above selection criteria. One is identified as $e^+e^- \to e^+e^- + \mu^+\mu^-$ which has a measured mass of the dimuon system of 0.6 GeV and is, therefore, outside the mass range under investigation. The second one has a measured missing mass with respect to the e^+e^- pair of 9.5 GeV. Taking into account the mass resolution we can put an upper limit to this mass value of 12 GeV at 95% confidence level. Both events are consistent with the expected rate of 4 fermion final state processes.

Results and conclusions

Fig.3 shows the number of expected events for the processes $Z^{\circ} \to H^{\circ}\mu^+\mu^-$, $Z^{\circ} \to H^{\circ}e^+e^-$ and $Z^{\circ} \to H^{\circ}\nu\bar{\nu}$ as a function of the Higgs mass correponding to 50200 $Z^{\circ} \to$ hadrons decays. To set a conservative mass limit we have reduced the number of expected events by 8% to account for systematic errors coming from uncertainties in the Higgs production cross section, in our events selection and in the trigger efficiency. In Fig.3 is also shown the line corresponding to the 95% confidence level limit. Below 12 GeV the limit takes into account the fact that one event is observed and 0.42 background events are expected from the reaction

$e^+e^- \rightarrow$ four fermions. We conclude that, combining the results from all three processes, we can exclude a Minimal Standard Model Higgs boson in the mass range $2 < M_{H^\circ} < 32$ GeV at 95% confidence level. This result improves previous published measurements.[10].

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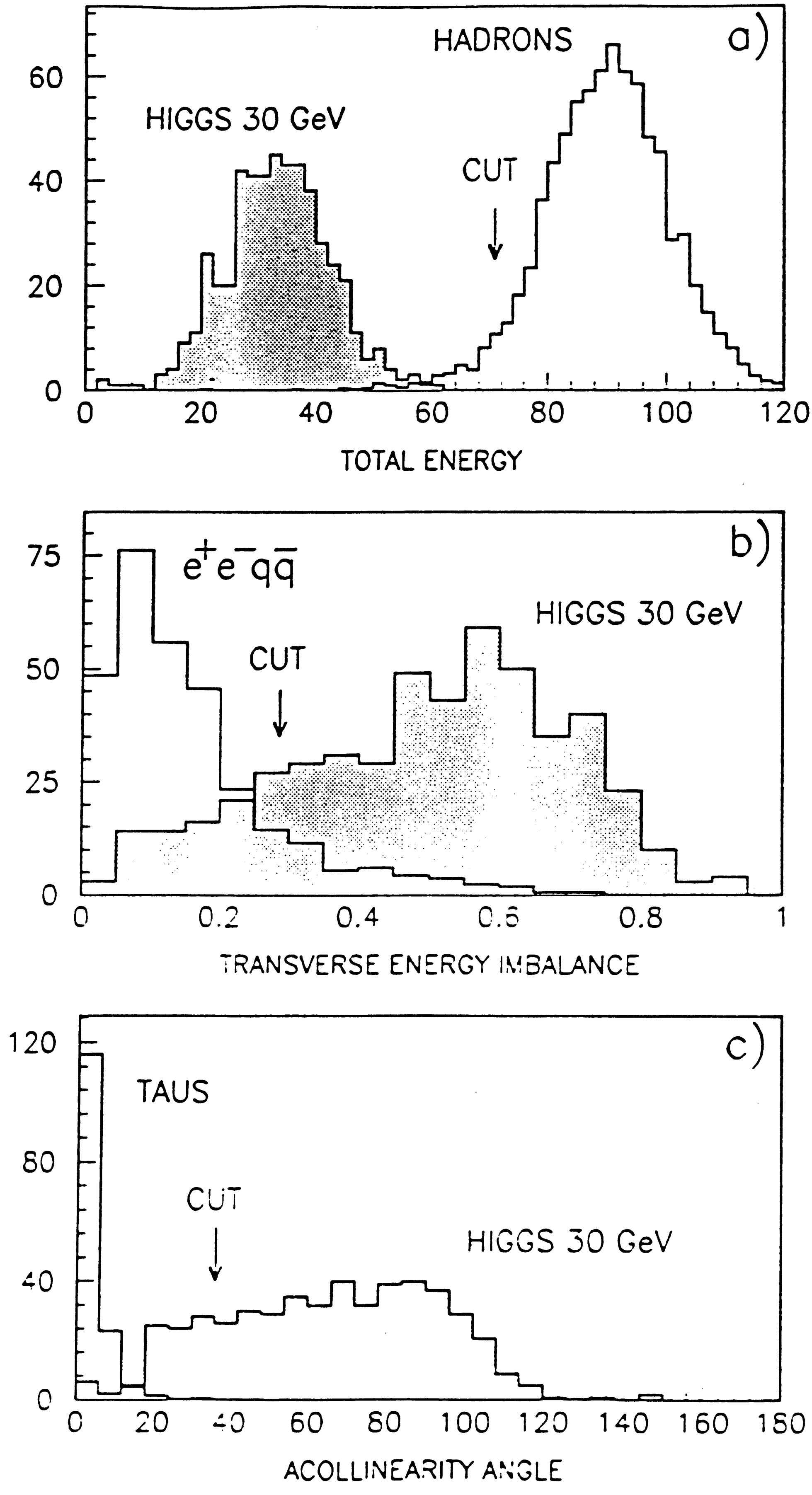
FIGURE CAPTIONS:

Fig.1 Comparison between Monte Carlo generated $e^+e^- \rightarrow Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ events for a mass of the Higgs boson of 30 GeV (shaded histogram) and simulated background processes.
a) Total event energy distibution for the processes $e^+e^- \rightarrow Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ and $e^+e^- \rightarrow Z^\circ \rightarrow$ hadrons.
b) Transverse energy imbalance distibution for the process $e^+e^- \rightarrow Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ and $e^+e^- \rightarrow e^+e^-q\bar{q}$.
c) Distribution of the acollinearity angle between the two most energetic jets for the processes $e^+e^- \rightarrow Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ and $e^+e^- \rightarrow \tau^+\tau^-$.
The arrows indicate the position of the cuts used in the events selection. The normalization between the two histograms is arbitrary.

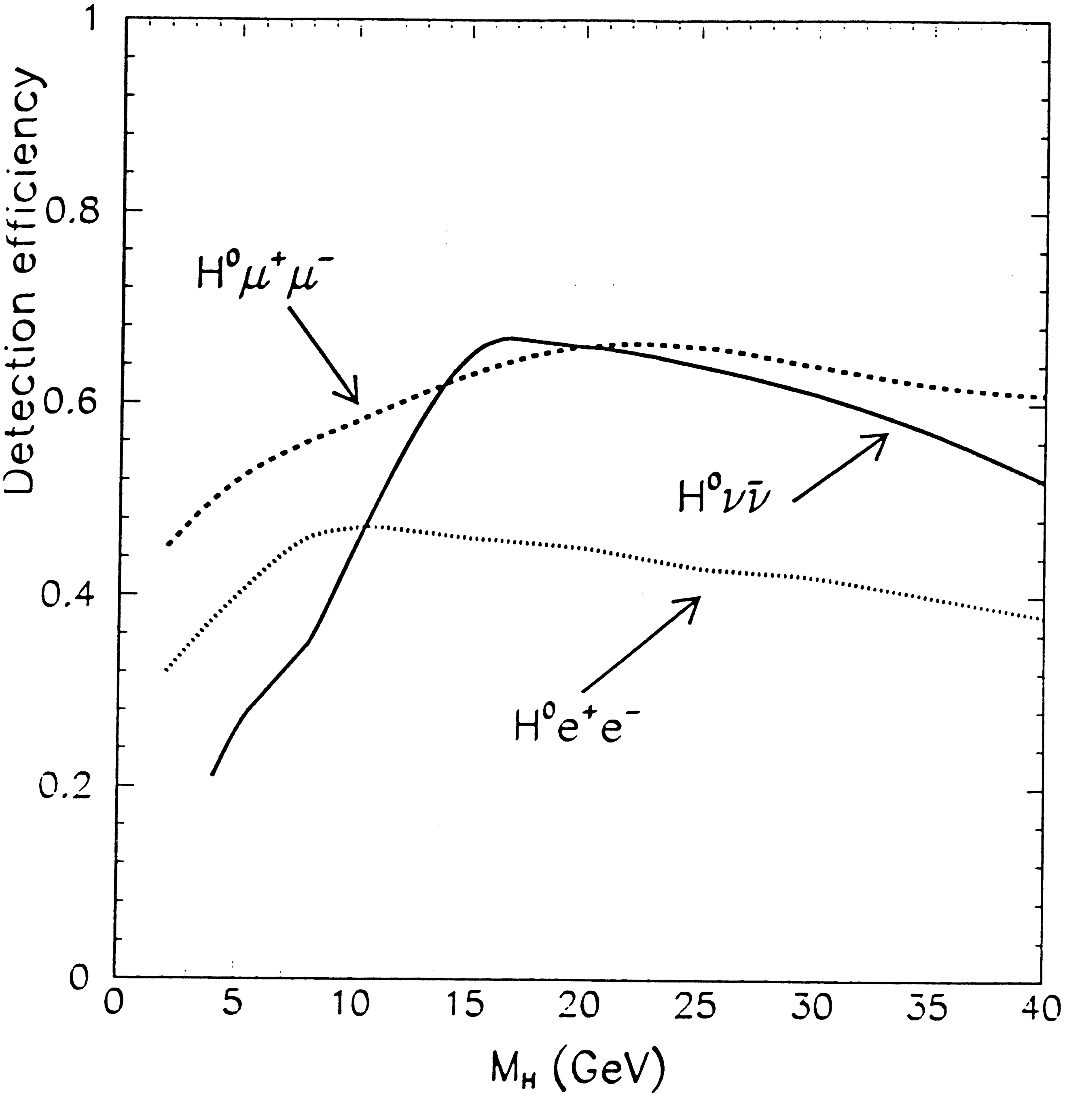
Fig.2 Detection efficiency for the processes $Z^\circ \rightarrow H^\circ\mu^+\mu^-$, $Z^\circ \rightarrow H^\circ e^+e^-$ and $Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ as a function of the Higgs mass. It includes geometrical acceptance and selection and trigger efficiencies.

Fig.3 The number of events expected from the processes $Z^\circ \rightarrow H^\circ\mu^+\mu^-$, $Z^\circ \rightarrow H^\circ e^+e^-$ and $Z^\circ \rightarrow H^\circ\nu\bar{\nu}$ and the sum of the above channels as a function of the mass of the Higgs boson. Also displayed is the 95% confidence level limit.



a)
HADRONS
HIGGS 30 GeV
CUT
TOTAL ENERGY
b)
$e^+e^-q\bar{q}$
HIGGS 30 GeV
CUT
TRANSVERSE ENERGY IMBALANCE
c)
TAUS
CUT
HIGGS 30 GeV
ACOLLINEARITY ANGLE

Figure 1



1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
Detection efficiency
M_H (GeV)
$H^0\mu^+\mu^-$
$H^0\nu\bar{\nu}$
$H^0e^+e^-$

Figure 2

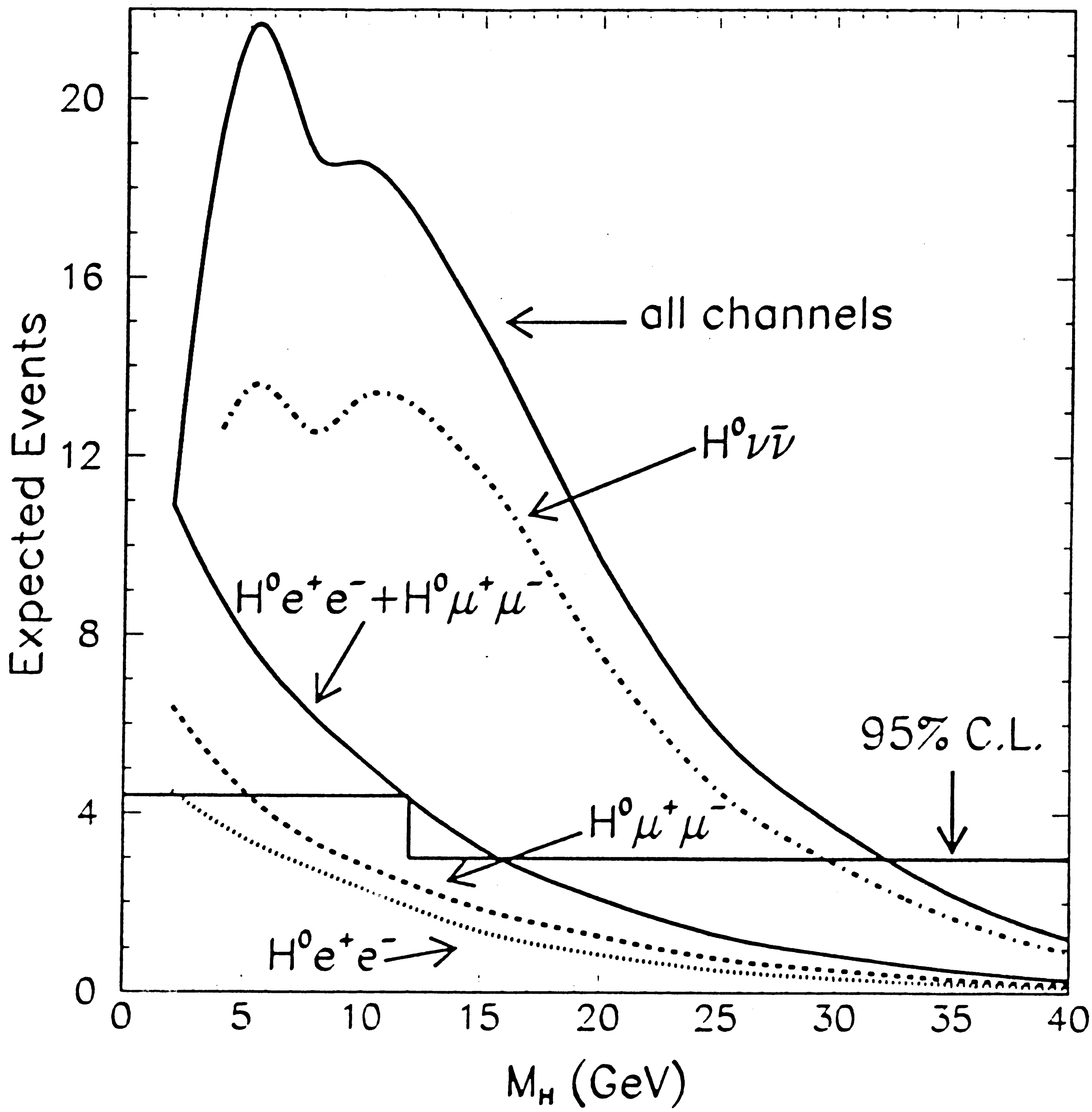


Figure 3

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