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Searches for the Standard Higgs Boson

The ALEPH Collaboration*)

Abstract

A data sample corresponding to about 100,000 hadronic Z decays collected by ALEPH at LEP has been used to search for the Standard Higgs boson produced in the reaction $e^+e^- \rightarrow H^0 Z^{0*}$. No indication for any signal was found, and a 95% C.L. lower limit on the Higgs boson mass has been set at 41.6 GeV.

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1.- Introduction.

With a data sample of about 25,000 hadronic Z decays collected in 1989 by ALEPH at the Large Electron-Positron collider (LEP) at CERN, a search for a Standard Higgs boson H^0 in the process $e^+e^- \rightarrow H^0 Z^* \rightarrow H^0 f\bar{f}$ resulted in the exclusion of the mass range between 0 and 24 GeV at the 95% confidence level.[1,2,3] Excluded domains have also been reported by DELPHI[4], by L3[5] and by OPAL.[6] With the data sample collected up to June 1990, close to 100,000 hadronic Z decays have become available, which gives the opportunity to explore a higher mass domain.

The previous analyses have been modified to increase the overall Higgs search efficiency. Table 1 shows the various channels which have been studied, and the total numbers of events expected to be produced for a 40 GeV Standard Higgs boson. At such a mass, the Higgs boson decay branching ratio into hadrons is 94%, and 6% into a τ pair. These branching ratios vary little for the Higgs mass from a few GeV above $b\bar{b}$ threshold up to 50 GeV where, with the present statistics, the limiting factor is the production cross section. Therefore, a uniform analysis procedure has been applied from 11 GeV to 50 GeV.

In the computation of the expected numbers of events presented in Table 1, the $e^+e^- \rightarrow H^0 Z^*$ cross section has been determined as described in Ref. 1, and the Higgs branching ratios calculated with the simulation program presented in this same reference. The overall normalization has been derived from the numbers of hadronic Z decays recorded at each centre of mass energy during the scan around the Z peak. These numbers have been obtained by counting, when all components of the detector were simultaneously in good working condition, a total of 98,713 events with at least five charged particle tracks coming from the interaction vertex and carrying a scalar sum of momenta in excess of 10% of the centre of mass energy. The efficiency of this selection has been determined to be 97.5±0.6%, with negligible background,[7] leading to a total number of 101,200 hadronic Z decays. A detailed description of ALEPH can be found in Ref. 8, and a brief account, together with a description of the relevant trigger conditions, in Ref. 3.

2.- Search in the $(H^0 \rightarrow hadrons)(Z^* \rightarrow \nu\bar{\nu})$ channel.

As shown in Table 1, the channel $e^+e^- \rightarrow H^0 Z^* \rightarrow hadrons\ \nu\bar{\nu}$ has a fairly large branching ratio. The characteristic topology is an acollinear, acoplanar pair of jets, with missing energy and momentum. The determination of the total energy, the total momentum and the jet directions is therefore essential for this analysis.

2.a.- The energy reconstruction algorithm.

For each event, the energy flow is reconstructed using charged particle tracks and calorimeter clusters in the following way:

- charged particle tracks, with at least four space coordinates reconstructed in the TPC and originating from the beam-crossing point within 7 cm along the beam direction and 2.5 cm in the transverse direction, are counted as charged energy;

- V^0's (long-lived neutral particles decaying into two oppositely-charged particles) are kept if they point to the interaction vertex within the same tolerances as those defined for charged particle tracks;
- photons, identified in the electromagnetic calorimeter through their characteristic longitudinal and transverse shower profiles, are counted as neutral electromagnetic energy;
- the remaining neutral hadronic energy is finally determined from the calorimeter clusters, defined as sets of calorimeter cells topologically connected. The typical cell size is smaller than $1° \times 1°$ in the electromagnetic calorimeter, and $3° \times 3°$ in the hadron calorimeter.

  In a given cluster, let E_{ecal} be the energy in the electromagnetic calorimeter not attributed to photons, and E_{hcal} the energy in the hadron calorimeter, and let $E_{charged}$ be the energy of the charged tracks, if any, topologically associated to the cluster. The difference

$$E_{neutral} = E_{hcal} + rE_{ecal} - E_{charged}$$

  is counted as neutral hadronic energy if $E_{neutral} > \xi\sqrt{E_{charged}}$, with $E_{neutral}$ and $E_{charged}$ in GeV.

  Here r is the ratio of the responses for electrons and pions in the electromagnetic calorimeter ($r \sim 1.3$), and ξ is related to the energy resolution of the calorimeters for hadronic showers: $\xi = 0.5$ for a shower fully contained in the electromagnetic calorimeter, $\xi = 1.0$ for a shower fully contained in the hadron calorimeter, and $\xi = (0.5rE_{ecal} + E_{hcal})/(rE_{ecal} + E_{hcal})$ in the general case.

In the following, measured quantities like energies, momenta, angles, masses refer to the ones determined by the energy flow algorithm unless stated otherwhise. Using this algorithm, the energy of well contained hadronic events (thrust axis more than 40° away from the beam axis) is reconstructed with a resolution of 8% of the centre of mass energy. The charged, V^0, neutral electromagnetic and neutral hadronic energy fractions are 56%, 3%, 26% and 15% respectively. A Gaussian fit yields a resolution of 8 GeV on the visible mass for $Z \to hadrons$ events (both on real data and on fully simulated events), while a 40 GeV Higgs boson would lead to a 5 GeV resolution.

2.b.- A control analysis.

In order to check the latter resolutions, a control analysis has been performed on hard-radiative $q\bar{q}$ events, an example of which is shown in Figure 1. Ignoring the hard photon, this final state resembles a hadronic Higgs boson decay and gives the opportunity to check the energy reconstruction algorithm on "Higgs-like" real data. The selected events must have a photon† with an energy greater than 30 GeV. Then, the photon is "removed" and the remaining $q\bar{q}$ system must satisfy the selection cuts

† Some events with an energetic isolated π^0 may also be retained in this sample, but this does not affect the validity of the check performed here.

applied to isolate the Higgs signal from the background (see below). In the data, 246 such events have been found, while 160 have been selected from a sample of about 60,000 simulated $q\bar{q}$ events.

These events provide two methods for the determination of the mass of the hadronic system: the above direct determination from the charged particle momenta and the calorimeter cluster energies, and an indirect method, computing the recoil mass from the photon energy, known with a resolution of $\Delta E/E = 0.017 + 0.19/\sqrt{E}$ with E in GeV.[8] The distribution of the difference ΔM between the two values of the hadronic mass is shown in Figure 2a for the data and for the Monte Carlo prediction. The normalization of the Monte Carlo prediction is absolute with respect to the number of hadronic Z decay events in the data. Both distributions are well centered at 0 and have similar shapes, which shows the reliability of the direct determination of the hadronic mass, the only method usable for Higgs events. Also shown in Figure 2b are the distributions of the difference $\Delta p_{\perp}$ between the momenta transverse to the beam of the photon and of the hadronic system.

In these events, the photon energy distribution clusters near 30 GeV, and therefore the mass of the recoiling system peaks around 50 GeV. In this configuration, the resolutions on ΔM and on $\Delta p_{\perp}$ are dominated by the uncertainties on the hadronic system, and not by the uncertainty on the photon energy. The 6 GeV resolution inferred from this sample for the direct mass-determination method is consistent with that expected for a 50 GeV Higgs by Monte Carlo simulation.

2.c.- The selection procedure.

To select Higgs events in the $H^0\nu\bar{\nu}$ topology, the following procedure is used. First, a preselection is performed, requiring a minimum charged particle multiplicity of 5, with a scalar sum of the momenta in excess of 8 GeV. The distribution of the visible mass at this point is shown in Figure 3a, together with the expectation from hadronic Z decays.

In order to avoid energy losses at small polar angle, the energy measured within 12° of the beam line is required to be less than 3 GeV. This is a region where boundaries between calorimeters are more numerous, and where the energy resolution is therefore degraded. The loss due to this veto, studied on events triggered randomly, amounts to 0.3%. To avoid asymmetric events from $\gamma\gamma$ collisions or with hard initial state radiation, the total momentum along the beam line is required to be less than 30 GeV. The total momentum transverse to the beam direction is expected to be approximately 20 GeV for a Higgs boson mass between 20 and 40 GeV, while it should be small for events from $\gamma\gamma$ collisions and for most $q\bar{q}$ events. A minimum total transverse momentum of 5 GeV is therefore required.

To define jet directions, the events are divided into two hemispheres with respect to the thrust axis. Each hemisphere is called a "jet", and the total momenta in each hemisphere define the jet directions. If one of the hemispheres contains no energy, the event is called a "monojet". Otherwise, let the acollinearity η be the angle between the two jets, and the acoplanarity ψ be the angle between the two jet directions projected onto a plane transverse to the beam. As the $q\bar{q}$ events with missing energy are found to be mainly produced at low angle, it is further required that at least one jet with energy above 2 GeV be found more than 35° away from the beam axis. Finally, as the signal events are expected to be either monojets or acollinear, acoplanar pairs of jets, while the $q\bar{q}$ events at large angle with missing energy carried away by neutrinos are expected to remain rather collinear and coplanar, it is required either that the event be a monojet, or that $\cos\eta > -0.95$ and $\psi < 175°$.

2.d.- The results.

The distribution of the visible mass after these cuts is shown in Figure 3b. The agreement between the expectation from hadronic Z decays and the observation is satisfactory, both in shape and normalization. Out of the 1510 initial events with mass below 50 GeV, none survives the selection cuts. For comparison, the expectation from a 40 GeV Higgs boson is shown in Figure 3c. The overall search efficiency is shown in Table 2 for various values of the Higgs mass, including a visible mass cut at 50 GeV (the additional inefficiency introduced by this cut is 3.6% at 42 GeV). In the mass range from 25 to 42 GeV, the efficiency exceeds 75%.

3.- Search in the $(H^0 \to hadrons)(Z^* \to l^+l^-)$ channels.

This analysis relies only on the charged particles. The characteristic topology in these channels is a hadronic system with two energetic, isolated leptons. It is thus essential to define criteria for charged particle isolation and for lepton identification.

A charged particle is called isolated if its momentum exceeds 5 GeV and if no other charged particle with a momentum greater than 800 MeV is found in a cone of half-opening angle equal to 16.3°.

Electron identification in ALEPH has already been reported.[9] The estimator R_T, which compares the momentum of the charged particle to the energy deposited in the four towers of the electromagnetic calorimeter closest to the extrapolation of the track, is constructed to have a normalized Gaussian distribution for electrons. Two criteria are defined using this estimator:

- a "tight" criterion requiring R_T to be greater† than −5, and
- a "loose" criterion requiring R_T to be greater than −5, except when the charged particle goes into a region where R_T cannot be calculated reliably (electromagnetic calorimeter cracks, overlap between endcap and barrel parts of the electromagnetic calorimeter).

For isolated electrons, the efficiency of the tight (loose) criterion is 80% (> 99%).

The muon identification uses the 23 layers of 1 cm-wide streamer tubes in the hadron

† No cut on high R_T values is applied to allow for momentum losses by Bremsstrahlung.

calorimeter, and again two criteria are defined:

- a "tight" criterion requiring at least one layer fired in the last ten, and, within a 10 cm-wide road around the extrapolation of the track, the RMS width of the hit pattern in the 23 layers to be smaller than 2.5 cm (3cm) in the barrel region (endcap regions), and
- a "loose" criterion, identical as to the RMS width of the pattern, and requiring at least one layer fired in the last ten except when the charged particle goes into an insensitive region of the hadron calorimeter.

For isolated muons, the efficiency of the tight (loose) criterion is 94% (97%).

Note that even the "tight" criteria described here are loose with respect to the usual ALEPH criteria. This is made possible by the high selectivity of the isolation cut. For a 30 GeV Higgs for instance, 86% of the events are expected to have two isolated charged particles, while only 0.3% of the $Z \to hadrons$ events satisfy this criterion.

To select events potentially coming from the $H^0 e^+ e^-$ and $H^0 \mu^+ \mu^-$ final states, the following procedure has been applied. A minimum charged particle multiplicity of 7 is required, and at least one pair of charged particles, with energies E_1 and E_2, must fulfill the conditions:

- $E_1 > 10$ GeV and $E_2 > 5$ GeV,
- the two particles are oppositely charged,
- both particles are isolated,
- the invariant mass of the two particles is greater than 5 GeV,
- the mass recoiling against the pair is smaller than 50 GeV,
- the two particles are either two electrons or two muons, of which at least one is "tight".

No events survive, with an efficiency of 69% in $H^0 \mu^+ \mu^-$ and 71% in $H^0 e^+ e^-$ for a 40 GeV Higgs, as shown in Table 2.

4.- Search in the $(H^0 \to \tau^+ \tau^-)$ channels.

In the $H^0 \to \tau^+ \tau^-$ decay mode, the channels $H^0 \nu \bar{\nu}$ and $H^0 l^+ l^-$, with very clear signatures and almost no background, have been analyzed in order to increase slightly the overall sensitivity of the search.

To select $\tau^+ \tau^- \nu \bar{\nu}$ final states, a search for two acoplanar jets in topologies 1-1 or 1-3 is performed (the numbers refer to the charged multiplicities in the jets). Each jet is required to have a mass smaller than 2 GeV and a charge ± 1. The selection criteria are essentially identical to those used in the search for acoplanar lepton pairs reported in Ref. 10. The efficiency of these criteria is about 40%, and is independent of the Higgs mass in the range considered. No events were found.

To select the events coming from the $\tau^+ \tau^- l^+ l^-$ final state $(l = e, \mu, \tau)$, four jets, each with a mass smaller than 2 GeV and with a charge ± 1, are required in topologies 1-1-1-1 or 1-1-1-3. In addition, a missing energy in excess of 10 GeV is required to account for the energy carried away by the neutrinos from the τ decays. No events survive this selection with an efficiency of about 60%, also independent of the Higgs mass.

5.- Limit on the Standard Higgs boson mass.

The numbers of events expected from a 40 GeV Higgs in the various channels are shown in Table 1. The total number of expected events is 3.86 for this mass, corresponding to an overall analysis efficiency of 75%. The total number of expected events is presented in Figure 4 as a function of the Higgs mass, in the range from 11 to 50 GeV. Having observed 0 events, it is possible to exclude at the 95% confidence level the Higgs masses which would lead to more than 3 events. The $H^0\nu\bar{\nu}$ channel alone excludes Higgs masses up to 39.8 GeV. When all the channels are combined, masses below 41.8 GeV are excluded at 95% C.L.

The systematic error has been estimated to be about 3%:

Normalization to the 100,000 hadronic events	0.6%
Ratio of the H^0Z^* and hadronic cross sections	1.5%
Variation with the selection criteria	2%
Monte Carlo statistics	1.5%

Accounting for these systematics, the 95% C.L. limit becomes 41.6 GeV.

6.- Conclusion.

Using a data sample corresponding to approximately 100,000 hadronic Z decays, the process $e^+e^- \rightarrow H^0Z^*$ has been studied in the ($H^0 \rightarrow$ *hadrons* or $\tau^+\tau^-$)($Z^* \rightarrow \nu\bar{\nu}$ or l^+l^-) final states in order to search for the Standard Higgs boson H^0. No events have been found in any of these analyses, thus allowing a substantial extension to higher masses of the domain previously excluded by ALEPH[2] and other LEP experiments.[4,5,6] Taking into account previous ALEPH results,[1,3] the whole Higgs mass range between 0 and 41.6 GeV is excluded at 95% C.L.

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10. D. Decamp et al., (ALEPH Coll.), CERN-EP/90-63, "Search for Neutralino Production in Z decays", to be published in *Phys.Lett.***B**.

Figure Captions.

1. A $q\bar{q}\gamma$ event used in the control analysis (see text). The hard photon, represented by a wiggled arrow, carries an energy of 36 GeV. The mass recoiling against it is 43 GeV, while the visible mass of the hadronic system is 39 GeV, consistent with the 5 GeV mass resolution expected from a 40 GeV Higgs Monte Carlo simulation. The total visible mass of the event is 89 GeV. Also indicated: the inner tracking chamber (ITC), the time projection chamber (TPC), the electromagnetic calorimeter (ECAL) and the hadron calorimeter (HCAL).
2. Results of the control analysis (see text):
   (a) Difference between the hadronic mass and the mass recoiling against the photon.
   (b) Difference between the hadronic and the photon momenta transverse to the beam.
   Triangles with error bars: the data. Histogram: Monte Carlo simulation (absolute normalization).
3. Visible mass distributions in the $H^0\nu\bar{\nu}$ search:
   (a) After the preselection,
   (b) After all cuts,
   (c) For a 40 GeV Higgs.
   Triangles with error bars: the data. Histogram: Monte Carlo simulation (absolute normalization).
4. Number of expected events as a function of the Higgs mass, from the $H^0\nu\bar{\nu}$ channel only (a), and from all the channels analyzed (b). The horizontal line at three events corresponds to the 95% confidence level.

Table Captions.

1. For a 40 GeV Higgs boson, branching ratios of the channels which were analyzed, numbers N_{40}^{tot} of events expected to be produced, search efficiencies, and numbers N_{40}^{exp} of events expected to be found.

2. Search efficiencies in the ($H^0 \rightarrow hadrons$) final states.

Table 1.

Channel		Branching ratio	N_{40}^{tot}	Efficiency	N_{40}^{exp}
H^0	Z^*				
hadrons	$\nu\bar{\nu}$	18.8%	3.58	80%	2.86
hadrons	e^+e^-	3.1%	0.60	71%	0.43
hadrons	$\mu^+\mu^-$	3.1%	0.60	69%	0.41
$\tau^+\tau^-$	$\nu\bar{\nu}$	1.2%	0.23	40%	0.09
$\tau^+\tau^-$	l^+l^-	0.6%	0.11	60%	0.07
Total		34.1%	5.12	75%	3.86

Table 2.

m_{H^0} (GeV)	$H^0\nu\bar{\nu}$ (%)	$H^0e^+e^-$ (%)	$H^0\mu^+\mu^-$ (%)
11	55	69	67
15	63	72	71
20	73	76	76
30	82	72	71
35	83	71	70
40	80	71	69
42	76	67	67
45	70	65	66

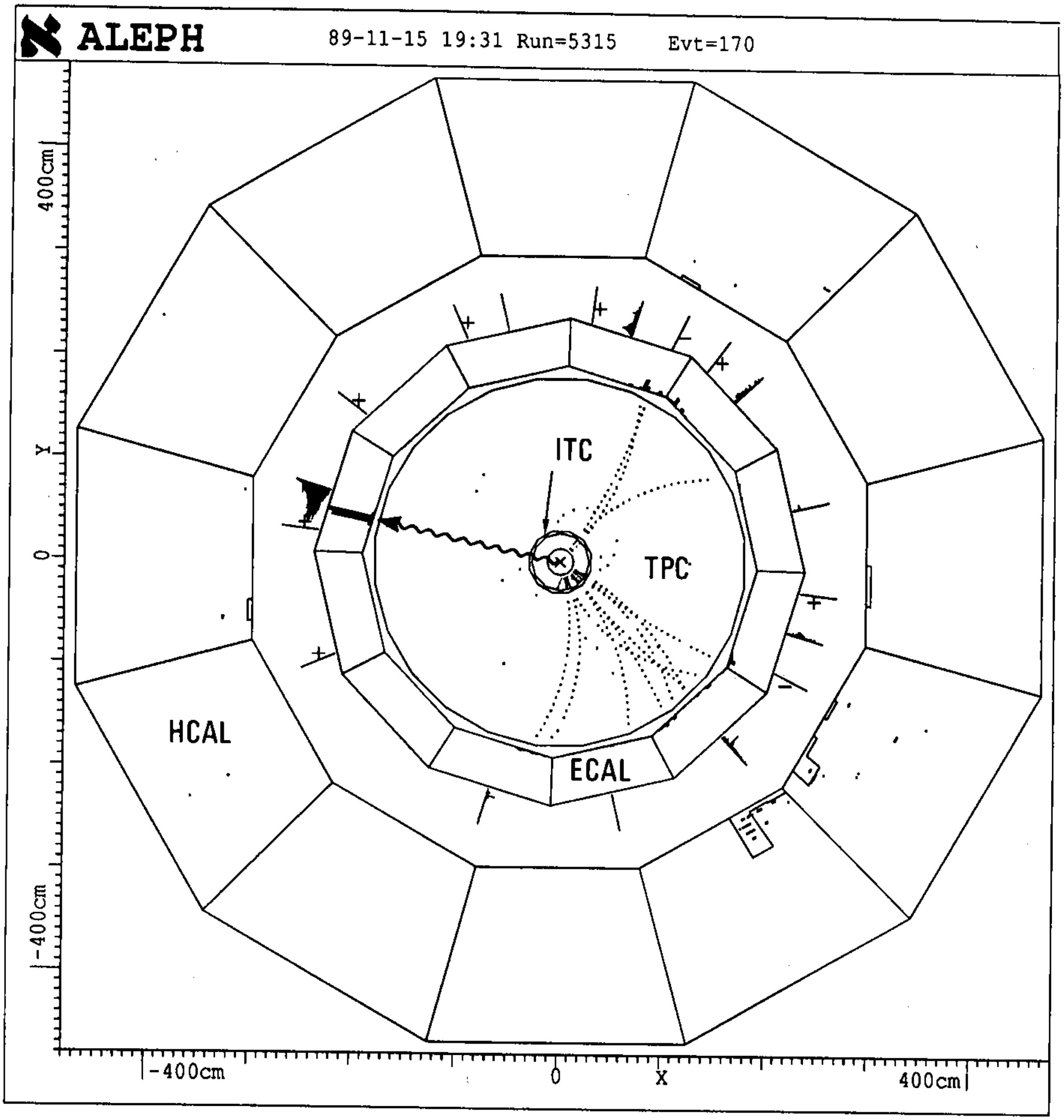

ALEPH
89-11-15 19:31 Run=5315 Evt=170
400cm
Y
0
-400cm
-400cm
0
X
400cm
ITC
TPC
HCAL
ECAL

Fig.1

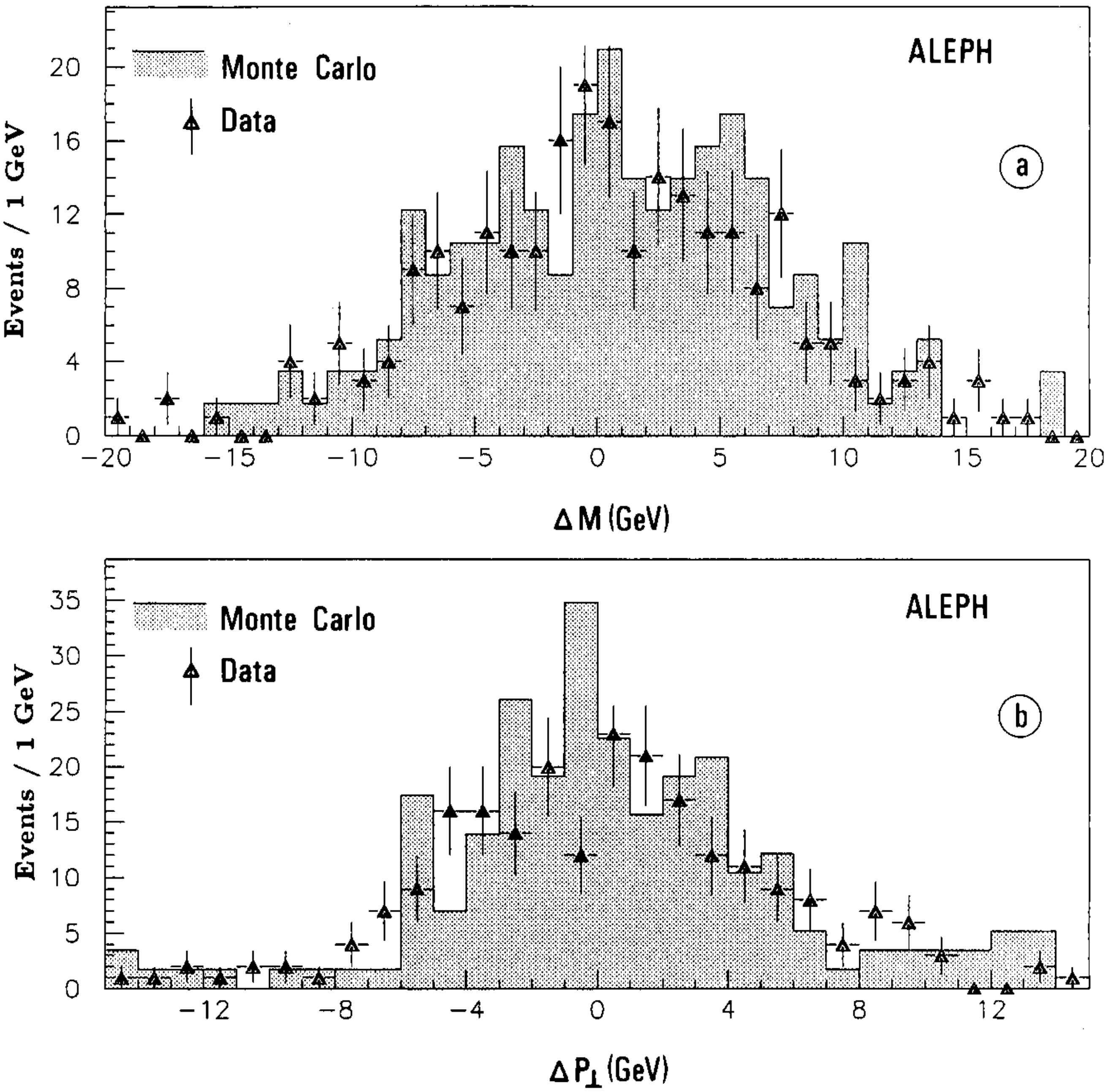
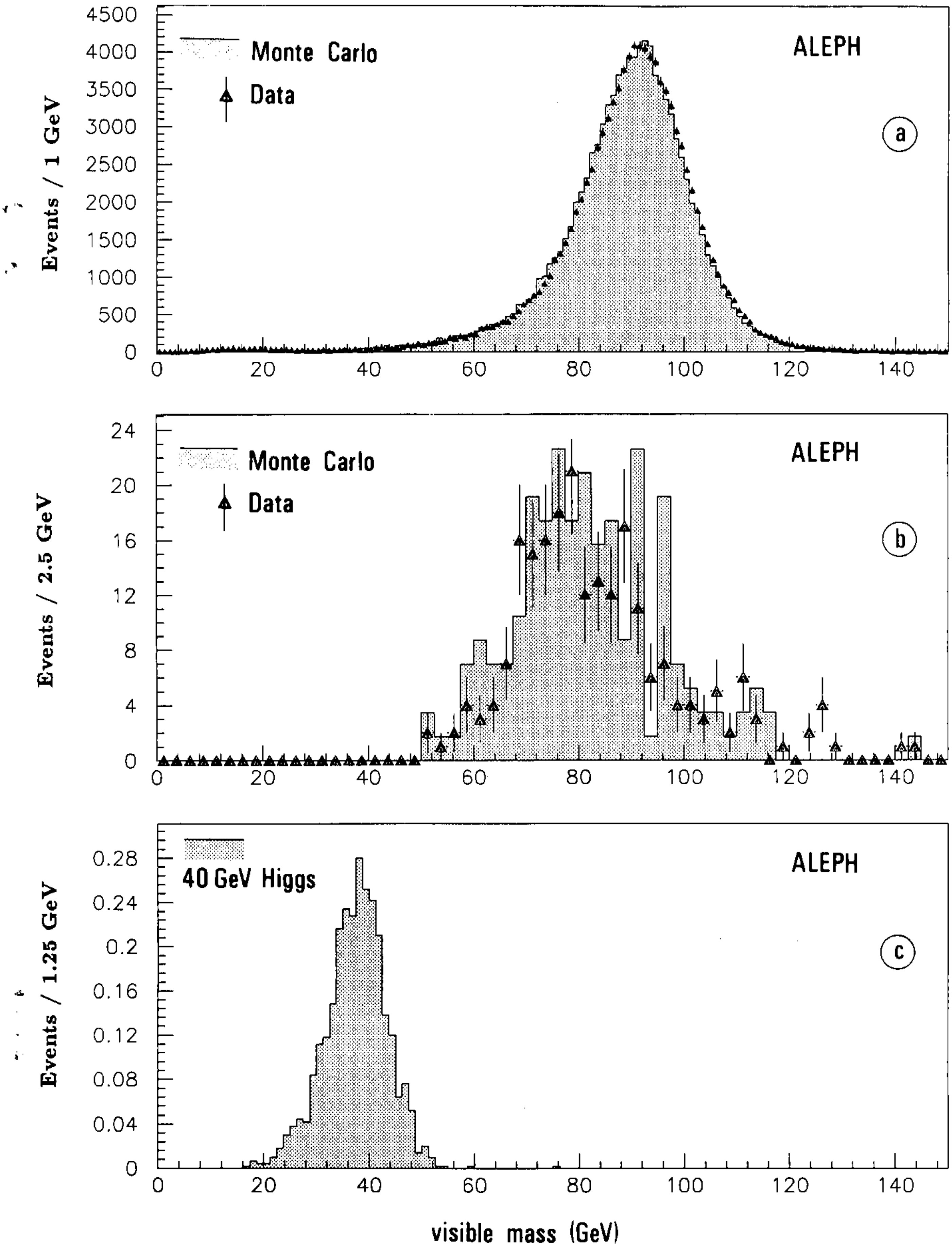

Monte Carlo
Data
ALEPH
a
Events / 1 GeV
ΔM (GeV)
Monte Carlo
Data
ALEPH
b
Events / 1 GeV
ΔP⊥ (GeV)

Fig. 2



Monte Carlo
Data
ALEPH
a
Events / 1 GeV
Monte Carlo
Data
ALEPH
b
Events / 2.5 GeV
40 GeV Higgs
ALEPH
c
Events / 1.25 GeV
visible mass (GeV)

Fig. 3

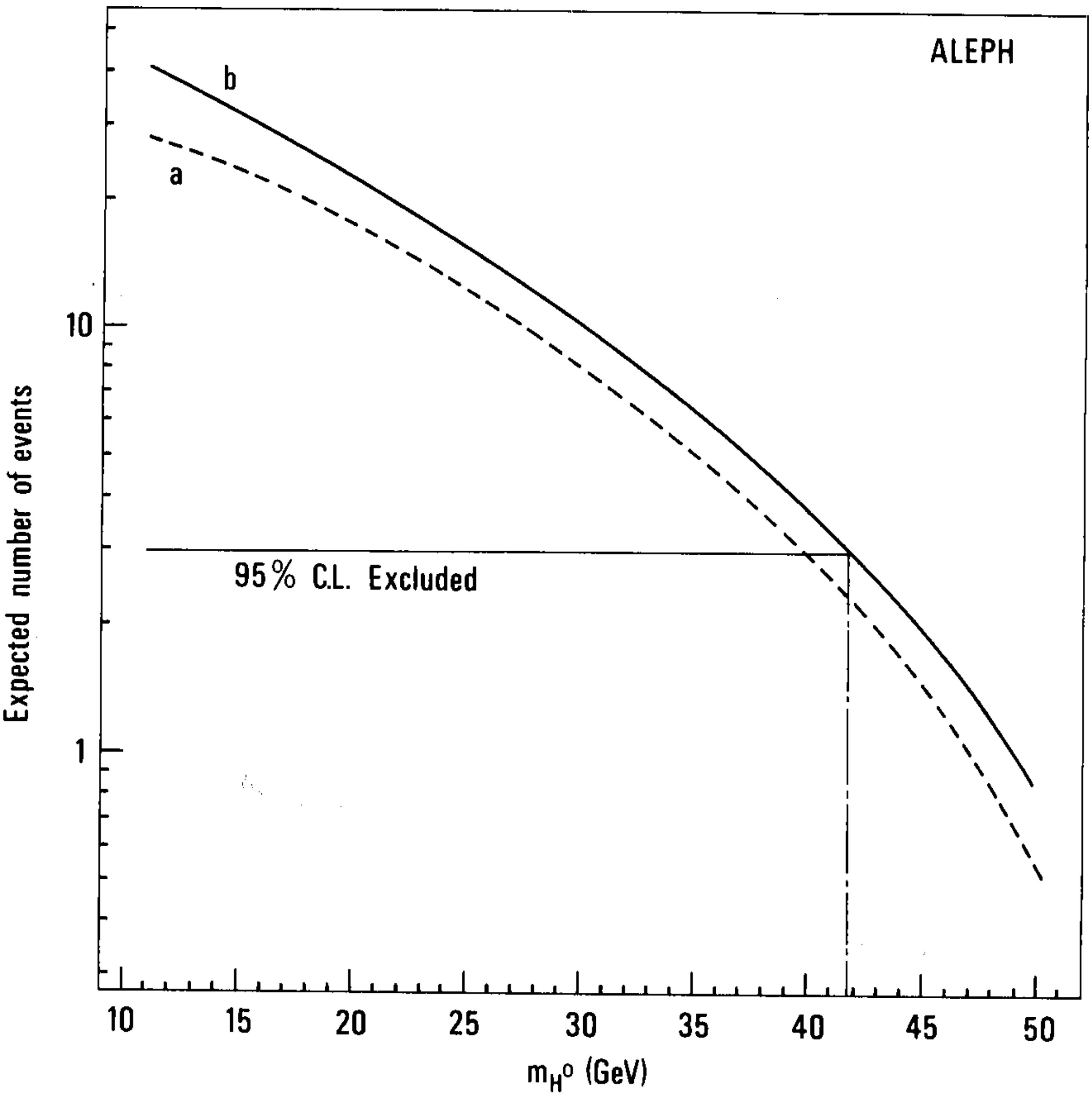


Fig. 4

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