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Searches for New Particles Produced in Z Boson Decay*†

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ABSTRACT

Searches for events with new particle topologies in 455 hadronic Z decays with the Mark II detector at SLC are presented. 95% confidence level lower limits of 40.7 GeV/c^2 for the top quark mass and 42.0 GeV/c^2 for the mass of a fourth generation charge $-1/3$ quark, regardless of decay mode, are obtained. For a fourth generation sequential Dirac neutrino ν_4, a significant range of mixing matrix elements of ν_4 to other generation neutrinos is excluded for a ν_4 mass up to 43 GeV/c^2. Decays of the Z boson to a pair of non-minimal Higgs bosons ($Z \to H_s^0 H_p^0$), where one of them is relatively light ($\lesssim$10 GeV/c^2), are also considered. Limits are obtained on the $ZH_s^0H_p^0$ coupling as a function of the Higgs boson masses.

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† This report is partly based on previous Mark II publications[1] where more details can be found.

INTRODUCTION

New Quarks[‡]

We specifically search for top (t) quarks, and fourth-generation charge $-1/3$ (b') quarks. We assume pair-production of the new particles through Z decay with couplings and decay widths given by the Standard Model.

One expects t quarks to decay via the virtual-W (W^*) charged current (CC) process $t \to bW^*$. A b' quark may not decay 100% of the time via the CC decay $b' \to cW^*$ ($M_{b'} < M_t$) because of increased suppression of transitions which cross two generations. Consequently, the flavor-changing neutral-current (FCNC) loop decays[2] of $b' \to bg$ and $b' \to b\gamma$ must also be considered. Furthermore, in extensions of the Standard Model with two Higgs doublets, t and b' would dominantly decay into charged Higgs particles (H^+) by $t \to H^+b$ or $b' \to H^-c$ if $M_{H^\pm} < M_t$, $M_{b'}$.

Three types of event topologies are investigated. Type 1 is an event with a high-momentum isolated charged track. The semi-leptonic decays of t and b' or the decays of ν_4 will produce isolated leptons. To keep detection efficiencies high, lepton identification is not used. The type 2 topology is an event with an isolated photon. The decay $b' \to b\gamma$ motivates the search for this topology. Type 3 is the topology produced by a pair of heavy objects each decaying hadronically into two or more jets. Massive particles decaying into jets (*e.g.* $t, b \to qW^*$; $t, b' \to qH$; or $b' \to bg$) tend to produce spherical events which can be characterized by large momentum sums out of the event plane.

Massive Neutrinos[§]

Recently, measurements have been made at SLC[3] and LEP[4] to determine the number of neutrino species. The results rule out at greater than 95% confidence level (CL) the possibility of a fourth generation neutrino. These measurements, however, assume the neutrino to be massless and stable. Thus, we explore the possibility of a fourth generation massive neutrino ν_4.

We restrict our ν_4 search to a sequential fourth generation Dirac neutrino. We assume that $M_{\nu_4} < M_{L^-}$ in the new lepton doublet (ν_4, L^-), and that the weak eigenstates ν_ℓ and mass eigenstat[illegible] the four generations of neutrinos are mixed in analogy with the qu[illegible] sector: $\nu_\ell = \sum_{i=1}^{4} U_{\ell i}\nu_i$. Through this mixing, ν_4 could decay by the weak charged current ($\nu_4 \to \ell W^*$; $\ell = e, \mu, \tau$).

Assuming ν_4 mixes with only one other generation of ℓ, the lifetime of the ν_4

‡ Presented by R. Van Kooten.
§ Presented by C.K. Jung.

can be expressed in terms of the muon lifetime as

$$\tau(\nu_4 \to \ell^- X^+) = \left[\frac{m_\mu}{m_4}\right]^5 \frac{\tau(\mu \to e\nu\bar{\nu}) Br(\nu_4 \to \ell^- e^+ \nu)}{|U_{\ell 4}|^2 f} \quad ,$$

where m_4 is the mass of the neutrino, and f is a phase-space suppression factor[5] for massive final state particles.

The expected characteristics of the topology of ν_4 events is different depending on the values of the mass m_4 and the mixing matrix element $U_{\ell 4}$. We investigate four types of events topologies each of which corresponds to a different region in the m_4 - $|U_{\ell 4}|^2$ plane. For heavy mass and large mixing (short-lived), the topology is similar to the type I isolated charged track topology described above. An invisible or semi-invisible event corresponds to a light mass and small mixing (long-lived) region. The existence of these events would increace the invisible width of the Z boson resonance. We reinterpret the Mark II invisible width measurement (neutrino counting) analysis to obtain an exclusion region. An event with detached vertices corresponds to an intermediate mass and mixing region. These events can be characterized by a large fraction of charged tracks with large impact parameters with respect to the primary vertex. Finally, an event with two charged tracks recoiling against many tracks (2 vs. N) corresponds to a light mass and large mixing region.

Non-Minimal Higgs Bosons¶

For simplicity the model considered is restricted to two Higgs doublet (not necessarily the minimal supersymmetric model). In two doublet Higgs models there are two physical neutral scalar (CP even) Higgs bosons H_1^0 and H_2^0, one pseudoscalar (CP odd) H_p^0, and two charged Higgs bosons H^+ and H^-.

In the following, H_s^0 denotes either H_1^0 or H_2^0. We consider the decay $Z \to H_s^0 H_p^0$. The decay width for two doublet models is given by:[6]

$$\Gamma(Z \to H_s^0 H_p^0) = 0.5 \cdot \Gamma_{\nu\bar{\nu}} \bar{\beta}^3 \cos^2(a-b) \tag{1}$$

where $\bar{\beta} = \{[s-(M_s+M_p)^2][s-(M_s-M_p)^2]\}^{\frac{1}{2}}/s$, $s = E_{cm}^2$, and a and b are mixing angles of the Higgs doublets. Note that processes like $e^+e^- \to Z \to Z^* H_p^0 \to f\bar{f} H_p^0$ or $e^+e^- \to Z^* \to Z H_p^0$ are not allowed, since $Z H_p^0 Z$ coupling is forbidden at the tree level. These processes are allowed for H_s^0 but the rate is smaller than for the minimal Higgs boson by a factor[7] of $\sin^2(a-b)$. Therefore, search for the decay $Z \to H_s^0 H_p^0$ is complimentary to that for the decay $Z \to Z^* H_s^0$, since $\Gamma(Z \to H_s^0 H_p^0)$ is proportional to $\cos^2(a-b)$.

¶ Presented by S. Komamiya.

Higgs bosons are expected to decay dominantly into the heaviest available fermion pair: $H_i^0 \to f\bar{f}$, $(i = 1, 2, p)$. If the scalar mass is more than two times the pseudoscalar mass, $H_s^0 \to H_p^0 H_p^0$ is the dominant decay mode unless it is suppressed by the Higgs mixing.

Apparatus

Details of the Mark II detector can be found elsewhere.[8] A cylindrical drift chamber in a 4.75 kG axial magnetic field measures charged particle momenta. Photons are detected in electromagnetic calorimeters covering the angular region $|\cos\theta| < 0.96$, where θ is the angle with respect to the beam axis. Barrel lead-liquid-argon sampling calorimeters cover the central region $|\cos\theta| < 0.72$ and the remaining solid angle is covered by end-cap lead-proportional-tube calorimeters. The detector is triggered by two or more charged tracks within $|\cos\theta| < 0.76$ or by neutral-energy requirements of a single shower depositing at least 3.3 GeV in the barrel calorimeter or 2.2 GeV in an end-cap calorimeter. This combination results in an estimated trigger efficiency of greater than 99% for hadronic Z decays.

Analysis and Results

Except for the long-lived ν_4 searches, charged tracks are required to project into a cylindrical volume of radius 1 cm and half-length of 3 cm around the nominal collision point parallel to the beam axis. Tracks are required to be within the angular region $|\cos\theta| < 0.82$, and to have transverse momenta with respect to the beam axis of at least 150 MeV/c. An electromagnetic shower is required to have shower energy greater than 1 GeV and $|\cos\theta| < 0.68$ for the central calorimeter and $0.68 < |\cos\theta| < 0.95$ for the endcap calorimeter.

The expected number of produced exotic events before cuts is normalized to the total number of hadronic events (N_{had}) that fulfill hadronic event selection criteria.[3] The expected number of produced exotic events N_x, $x = t\bar{t}, b'\bar{b'}, \nu_4\bar{\nu}_4$, or $H_s^0 H_p^0$ is given by

$$N_x = \frac{N_{\text{had}}\Gamma_x}{\epsilon_{qq}\Gamma_{qq} + \epsilon_x\Gamma_x} \quad ,$$

where Γ_{qq} is the partial width of the Z to u, d, s, c, and b ($udscb$) quarks, ϵ_{qq} is the efficiency for $udscb$ quarks to pass the hadronic event criteria, Γ_x is the partial width of the Z to the exotic particle in question, and ϵ_x is the efficiency for the exotic particle events to pass the hadronic event criteria. First order QCD corrections[9] are used when calculating Γ_q and Γ_x. The data sample corresponds to $N_{\text{had}} = 455$ events and to an integrated luminosity of 19.7 ± 0.8 nb^{-1}.

New Quarks

All events are required to contain at least six charged tracks and the sum of charged particle energy and shower energy (E_{vis}) must be greater than 0.1 E_{cm}. To ensure that the events are well contained within the detector, the polar angle of the thrust axis (θ_{thr}) of each event must satisfy the condition $|\cos\theta_{thr}| < 0.8$.

Type 1 events must have event thrust less than 0.9 and must contain at least one isolated charged track. An isolated track is one with isolation parameter $\rho_i > 1.8$ where ρ_i is defined as follows: The Lund jet-finding algorithm is applied[10] to the charged and neutral tracks excluding the candidate track i. We then define

$$\rho_i \equiv \min_{jets\ j}[(2E_i(1-\cos\theta_{ij}))^{1/2}],$$

where E_i is the track energy in GeV and θ_{ij} is the angle between the track and each jet axis. The ρ value of an event is defined as the maximum value of ρ_i of all charged tracks in an event.

The detection efficiencies (ϵ_D) for t, b', and ν_4 are calculated with a modified Lund 6.3 parton shower Monte Carlo program with Lund symmetric fragmentation.[11] Uncertainties in detection efficiency ($\Delta\epsilon_D/\epsilon_D$) from Monte Carlo statistics ($\approx 3\%$), detector simulation and beam backgrounds ($\approx 1\%$), theoretical uncertainties in semi-leptonic branching ratios ($\approx 2\%$), and fragmentation models are calculated. The last error is estimated using different Monte Carlo generators and fragmentation schemes.[12] For masses in the range 25 – 30 GeV/c^2 the error can be as large as 12%, and we choose to use the value 12% for *all* quark masses.

The number of produced events N_x has both a statistical uncertainty from N_h, and a substantial systematic error (as large as 25% depending on the exotic particle mass) due to uncertainties in higher order QCD corrections[9] in the calculation of Γ_x if x is a t or b' quark. The total error on the expected number of events is calculated by summing the individual statistical and maximum systematic errors in quadrature. Our best estimate of the expected number of exotic events minus the total error is used for setting mass limits.

There is one event satisfying the type 1 event selection criteria in our data sample of 455 hadronic Z decays, while 0.9 events (Lund Shower with Peterson fragmentation[12]) to 1.8 events (Webber 4.1[12]) are expected from QCD five-flavor processes. To be conservative, background subtraction is performed using the smallest value (0.9 events) expected. Using a standard approach,[13] the limits shown in Table 1 are obtained.

For the type 2 event topology we require that the event thrust not exceed 0.9 and that there be at least one isolated photon. An isolated photon is defined as a neutral shower with $\rho_i > 3.0$ where ρ_i is defined as for a charged track. No events were found satisfying the type 2 event selection criteria. From this observation, we obtain $M_{b'} > 45.4$ GeV/c^2 (95% C.L.) if $B(b' \to b\gamma) \geq 25\%$.

The type 3 event topology requires $M_{out} > 18$ GeV/c^2 where

$$M_{out} \equiv \frac{E_{cm}}{E_{vis}} \frac{1}{c} \sum |p_T^{out}|.$$

p_T^{out} is the momentum component of a charged track or neutral shower out of the event plane defined by the sphericity tensor, and the sum is over all charged tracks and neutral showers. Six events are observed in the data with $M_{out} > 18$ GeV/c^2 , while 4.8 events (Lund Matrix Element[12]) to 11.7 events (Webber 4.1[12]) are expected from QCD five-flavor processes. To be conservative, background subtraction is performed using the smallest value (4.8 events) expected.

The above observation allows us to set the limits included in Table 1. The case of the H^- decaying partially into $\tau\bar{\nu}$ is found to weaken the listed limits for $t \to bH$ and $b' \to cH$, but if $B(H^- \to \tau\bar{\nu}) < 70\%$ both limits remain over 40 GeV/c^2 .

Table 1. Summary of the mass limits set by searching for the three event topologies described in the text. For $t \to bH^+$ and $b' \to cH^-$ limits, $M_{H^\pm} \geq 25$ GeV/c^2 , and $H \to c\bar{s}$. The ν_4 limits are for decays with vertices within the described cylindrical fiducial region (i.e. decay length $\lesssim 1$ cm).

Particle	Decay Products (Br = 100%)	Topology	Mass Limit (95% C.L.) (GeV/c^2)
top	bW^*	Isolated Track	40.0
	bW^*	M_{out}	40.7
	bH^+	M_{out}	42.5
b'	cW^*	Isolated Track	44.7
	cW^*	M_{out}	44.2
	cH^-	M_{out}	45.2
	bg	M_{out}	42.7
	$b\gamma$, Br $\geq$ 25%	Isolated Photon	45.4
ν_4	eW^*	Isolated Track	43.7
	μW^*	Isolated Track	44.0
	τW^*	Isolated Track	41.3

Finally, the analyses of the three event topologies are combined to give mass limits on b' as a function of branching ratio into the CC process, assuming that the remaining decays are only through the FCNC decays bg and $b\gamma$ (we assume a Higgs particle is not kinematically accessible). Detection efficiencies are found for the possible combinations of the above decays, and combined to give the result that $M_{b'} > 42.0$ GeV (95% C.L.) for all possible values of the branching ratio into the CC process and all possible mixtures of bg and $b\gamma$ in the FCNC part.

Massive Neutrinos

Mass limits from the isolated track analysis for a short-lived ν_4 ($\beta\gamma c\tau \lesssim 1$ cm) with different generation mixings are given in Table 1 of the previous section, and are shown as exclusion regions in Fig. 1. In Fig. 1, the lower bound of sensitivity along the $|U_{\ell 4}|^2$ axis is due to massive neutrinos decaying at larger radii, and tracks failing to project into the fiducial cylinder centered at the IP described earlier.

For longer ν_4 lifetimes, detached vertices occur, resulting in a large fraction of tracks with large impact parameters. The dominant background of beam-gas and beam-beampipe interaction events are usually forward-scattered, and have low multiplicity and low total energy. To eliminate them, we require an event to have at least eight good charged tracks and to have total visible energy greater than 35% of E_{cm}. In addition, the minimum of energy visible in the forward and backward hemispheres with respect to the electron beam direction must be greater than 7% of E_{cm}. We conservatively estimate that there are less than 0.01 beam-gas and beam-beampipe interaction events in the final 350 event data sample.

The impact parameter b in the plane perpendicular to the beam axis is defined as the distance of closest approach to the average beam position. An event search parameter $\chi_{\rm imp}$ is then defined as the fraction of charged tracks with significance b/σ_b greater than 5.0, where σ_b is the sum in quadrature of the track position error to the track trajectory ($\approx 300\ \mu$m) and the error in the average beam position (200 μm).

Hadronic background events containing charm, bottom, or strange quark decays rarely yield $\chi_{\rm imp}$ greater than 0.5, since there are many other tracks in the event which project to the primary vertex*; however, many $\nu_4\bar{\nu}_4$ events with a reasonable lifetime would yield $\chi_{\rm imp}$ greater than 0.5. We require $\chi_{\rm imp} > 0.6$ for an event for it to be tagged as a $\nu\bar{\nu}_4$ event. No events in the data pass the selection criteria, and Monte Carlo simulations predict less than 0.2 events. Detection efficiencies including full trigger emulation are determined for simulated[14] $\nu_4\bar{\nu}_4$ events of different masses and lifetimes. Uncertainties in detection efficiency ($\Delta\epsilon_D/\epsilon_D$) from Monte Carlo statistics ($\approx 2\%$), detector simulation and beam backgrounds ($\approx 4\%$), tracking efficiencies for tracks with large impact parameters ($\approx 10\%$), and different fragmentation models are estimated. Following the procedure of the previous section, the 95% CL limit contour is determined and illustrated in Fig. 1.

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* The same is true for a hadronic event with one or more particles undergoing a nuclear interaction in the beampipe or detector materials.

From fits to the Mark II Z resonance data where M_Z and the number of *massless* neutrino generations N_ν in the total width $\Gamma_Z^0 = \Gamma_{udscb} + \Gamma_e + \Gamma_\mu + \Gamma_\tau + N_\nu \Gamma_\nu$ are allowed to vary, we find $N_\nu < 3.86$ at 95% CL. A massive neutrino would contribute a fractional neutrino generation due to the mass threshold factor. Assuming that the neutrinos of the first three generations are massless, that ν_4 is a Dirac-type neutrino, and that no other physics intervenes, we obtain a limit of $m_4 > 19.6$ GeV/c^2 for a *stable* ν_4.

In the fits, σ_{peak} is given by $\sigma_{peak} = 12\pi\Gamma_e\Gamma_{vis}^0/M_Z^2\Gamma_Z^2$, where Γ_{vis}^0 is constrained to be the Standard Model prediction (3 generations, 5 quarks) for decays visible in the detector. For an unstable ν_4, the region where the relation

$$\frac{\Gamma_{vis}}{\Gamma_Z^2} = \frac{\Gamma_{vis}^0 + \epsilon\Gamma_{\nu_4}}{(\Gamma_Z^0 + \Gamma_{\nu_4})^2} < \frac{\Gamma_{vis}^0}{(\Gamma_Z^0 + (3.86 - 3)\Gamma_\nu)^2} \quad (1)$$

is true is excluded at 95% CL. ϵ is the efficiency for $\nu_4\bar{\nu}_4$ events to satisfy the visible event selection criteria, and Γ_{ν_4} is the partial width (a function of m_4) for ν_4. The values of ϵ for different m_4 and lifetimes are determined and the region where eqn. (1) is satisfied is shown in Fig. 1.

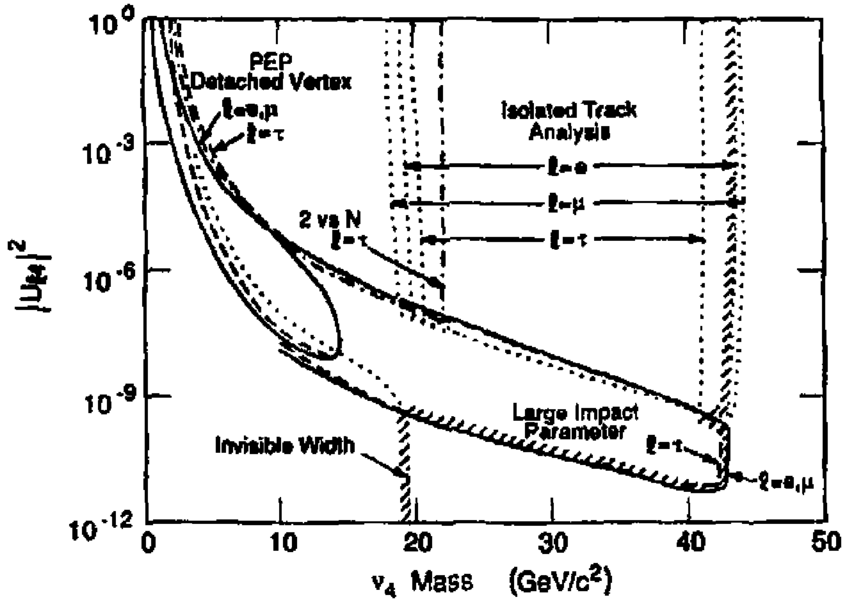

Figure 1. Summary of the 95% CL exclusion regions for a sequential fourth generation Dirac neutrino ν_4 as a function of mass and mixing matrix element (which is related to lifetime). The hatched region is the combined exclusion region for mixing to ν_e only.

We now consider the region $2.5 \lesssim m_4 \lesssim 20$ GeV/c^2 and $\tau(\nu_4) \approx 10$ psec which is not excluded by any prior direct searches by other collaborations for the case of ν_4 mixing to ν_τ. The search topology is two charged tracks recoiling against many (2 versus N, $N \geq 2$). For the mass range considered, $Br(\nu_4 \to 2 \text{ prong}) \gtrsim \frac{1}{3}$, resulting in high detection efficiencies.

Events are divided into two hemispheres with respect to the thrust axis, and the two versus N charged track topology selected. Additional cuts are $|\cos\theta_{\text{thr}}| < 0.8$; $E^{\text{ch}}_{\text{min}} > 6$ GeV, where $E^{\text{ch}}_{\text{min}}$ is the total charged energy in the hemisphere with the minimum charged energy; and sphericity $S > 0.4$ for $m_4 \geq 10$ GeV/c^2. Four masses (2.5, 5.0, 10.0, and 22.0 GeV/c^2) of ν_4 events are simulated at values of $|U_{\tau 4}|^2$ resulting in ν_4 lifetimes long enough to lie in regions excluded by other experiments. These are the most conservative cases in the search region since detection efficiencies are always higher for larger values of $|U_{\tau 4}|^2$ (*i.e.* shorter lifetimes). Results are shown in Table 2 and as an exclusion region in Fig. 1.

Table 2. Results of applying the selection criteria for the 2 versus N topology for data and simulated $\nu_4\bar{\nu}_4$ events and the resultant exclusion levels (no background subtraction).

m_4 (GeV/c^2)	No. of Expected Events	No. of Data Events	Confidence Level for Exclusion
2.5	21.0	4	>99.99%
5.0	15.5	4	>99.94%
10.0	4.9	1	95.6%
22.0	5.8	1	97.9%

Non-Minimal Neutral Higgs Bosons

We concentrate on the case in which one of the produced Higgs bosons $(H_l^0)^*$ is relatively light (less than $2M_b$). We study four typical cases: [A] $M_{H_l^0} < 2M_\mu$, [B] $2M_\mu < M_{H_l^0} < 2M_\tau$ and H_h^0 decays into $f\bar{f}$, and [C] $2M_\mu < M_{H_l^0} < 2M_\tau$ and H_h^0 decays into $H_l^0 H_l^0$. We also investigate the case in which [D] $2M_\tau < M_{H_l^0} < 2M_b$ and H_l^0 decays into $\tau^+\tau^-$.

In case [A] ($Z \to H_l^0 H_h^0$, $H_l^0 \to e^+e^-$ or $\gamma\gamma$, $H_h^0 \to b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$), H_l^0 is sufficiently long lived to escape detection. If the heavier Higgs boson (H_h^0) decays into a heavy fermion pair ($b\bar{b}$, $c\bar{c}$ or $\tau^+\tau^-$) and the mass is smaller than about the beam energy, the signature of $Z \to H_s^0 H_p^0$ events is a monojet topology. If the mass of the heavier Higgs boson is about equal to or greater than the beam energy, the momentum of the unseen H_l^0 is small and hence the event topology

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* We also use notations H_l^0 and H_h^0, where H_l^0 is defined to be lighter than H_h^0 and the two have opposite CP eigenvalues.

is two jets with a large angle between their axes (acoplanar two-jet events). The monojet events are selected with the following criteria: (M1) $|\cos\theta_{th}| < 0.7$ and (M2) the sum of the charged and neutral energy in the lower energy hemisphere (defined by the event thrust axis), E_{back}, is smaller than 3.0 GeV. The acoplanar two-jet events are selected by the following cuts: (P1) $|\cos\theta_{th}| < 0.7$, (P2) P_T of the event must be larger than 15 GeV and (P3) the acoplanarity angle ϕ_{acop} must be greater than 40 degrees. After applying cuts ((M1-2) or (P1-3)), no events survive. The expected number of background events from ordinary quark ($udscb$) production is estimated to be 0.3 to 0.7 using QCD-based Monte Carlo models.[12] In Fig. 2(a), the 95% C.L. contour for the excluded region is shown in the plane of the suppression factor ($\cos^2(a-b)$) vs. $M_{H_h^0}$, assuming H_l^0 is light ($M_{H_l^0} < 2M_\mu$) and stable for the case that H_h^0 decays into $b\bar{b}$ or $c\bar{c}$ [$\tau^+\tau^-$].

For case [B] ($Z \to H_l^0 H_h^0$, $H_l^0 \to \pi^+\pi^-$ or $\mu^+\mu^-$, $H_h^0 \to b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$), the event topology is an isolated particle pair with opposite charge (for instance, $\mu^+\mu^-$, $\pi^+\pi^-$ or K^+K^-) which recoils against jets. We require that E_{vis} be greater than $0.5\sqrt{s}$ and that there be at least one isolated particle pair with opposite charge. An isolated pair of charged particles (i,j) is defined as two oppositely charged particles with momentum sum ($|\vec{p}_i + \vec{p}_j|$) larger than 20 GeV, individual momenta greater than 2 GeV, and isolation parameter $\rho_{ij} > 4.0\ \mathrm{GeV}^{\frac{1}{2}}$. The isolation parameter ρ_{ij} is defined as follows: The Lund jet-finding algorithm is applied to all charged tracks in the event (except the candidate pair ij) and neutral tracks with energy greater than 1.5 GeV. We then define

$$\rho_{ij} \equiv \min_{jets\ J} \sqrt{2E_{ij}(1-\cos\chi_{ijJ})},$$

where E_{ij} is the pair energy assuming the pair to be $\pi^+\pi^-$ and χ_{ijJ} is the angle between the pair momentum direction and the jet axis. For $H_s^0 H_p^0$ events, a peak is seen at $|\vec{p}_i + \vec{p}_j| \approx (\sqrt{s}/2)(1 - M^2_{H_h^0}/s)$. Events are selected if $0.75\ (\sqrt{s}/2)(1 - M^2_{H_h^0}/s) < |\vec{p}_i + \vec{p}_j| < 1.25\ (\sqrt{s}/2)(1 - M^2_{H_h^0}/s)$ for an assumed value for $M_{H_h^0}$. No events survive the selection criteria. The number of expected background events increases with $M_{H_h^0}$ from 0.1 ($M_{H_h^0} = 5$ GeV) to 0.5 ($M_{H_h^0} = 60$ GeV), and is estimated using Monte Carlo models.[12] The limits are shown in Fig. 2(b).

For case [C] ($Z \to H_s^0 H_p^0 \to H_p^0 H_p^0 H_p^0$, $H_p^0 \to \mu^+\mu^-$), the event topology is three pairs of oppositely charged particles. The $H_p^0 \to \mu^+\mu^-$ decay mode is dominant since $\pi\pi$ or $\pi\pi\pi$ modes are suppressed for the H_p^0 decay. We require that the total charged particle energy E_{ch} be greater than $0.5\sqrt{s}$ and that exactly three jets are found using the Lund jet-finding algorithm. We require for each jet that the energy be larger than 4 GeV, the invariant mass be smaller than 4 GeV, and the total charge of each jet be -1, 0 or 1. We further require that the maximum charged multiplicity of the jets be either 2 or 3 and the minimum is either 1 or 2. No events survive the selection criteria. The excluded region is shown in Fig. 2(c).

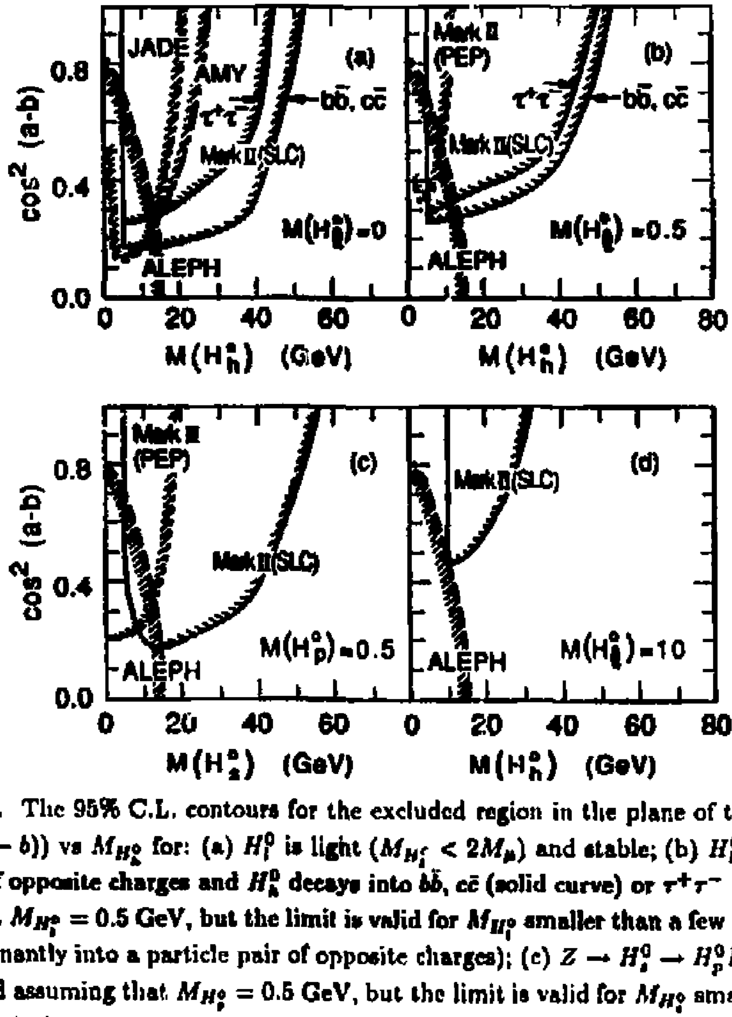

Figure 2. The 95% C.L. contours for the excluded region in the plane of the suppression factor ($\cos^2(\alpha-\beta)$) vs $M_{H_h^0}$ for: (a) H_l^0 is light ($M_{H_l^0} < 2M_\mu$) and stable; (b) H_l^0 decays into a particle pair of opposite charges and H_h^0 decays into $b\bar{b}$, $c\bar{c}$ (solid curve) or $\tau^+\tau^-$ (dashed curve) (assuming that $M_{H_l^0} = 0.5$ GeV, but the limit is valid for $M_{H_l^0}$ smaller than a few GeV as long as it decays dominantly into a particle pair of opposite charges); (c) $Z \to H_s^0 \to H_p^0 H_p^0 \to 3(\mu^+\mu^-)$ or $3(e^+e^-)$ and assuming that $M_{H_p^0} = 0.5$ GeV, but the limit is valid for $M_{H_p^0}$ smaller than a few GeV as long as it decays dominantly into a particle pair of opposite charges; and (d) H_l^0 decays into $\tau^+\tau^-$ with 100% branching fraction and H_h^0 decays into $b\bar{b}$, $c\bar{c}$ or $\tau^+\tau^-$.

For case [D] ($Z \to H_l^0 H_h^0 \to \tau^+\tau^- +$ jets), the Lund jet-finding algorithm is applied. We select events with only two jets in either of the hemispheres defined by the plane perpendicular to the event thrust axis. Further, we require that the two jets be consistent with a tau pair (the invariant mass of each jet is smaller than 2 GeV, the number of charged particles in each jet is one, and charge of the two jets is opposite). Since a $\tau^\pm$ decay involves missing neutrinos, we cannot look for an invariant mass peak of $\tau^+\tau^-$. We look for the peak in the $\tau^+\tau^-$ opening angle. Events are selected between 75% and 150% of the Jacobian peak of the opening angle (24 degrees at $M_{H_h^0} = 10$ GeV and 31 degrees at $M_{H_h^0} = 45$ GeV). After the cuts no events survive in the angular region and the expected number of background events is 0.3-0.5. The excluded region is shown in Fig.2(d) assuming the H_l^0 decays into $\tau^+\tau^-$ with 100% branching fraction.

SUMMARY

The study of Z decays provides an ideal laboratory to search for new particles. The presented results significantly extend limits from e^+e^- annihilation before the advent of Z physics at SLC and LEP. Due to space considerations, detailed comparisons with new limits from LEP with a larger data sample presented in these proceedings are not made; however, our results are consistent with the LEP limits.

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