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Search for Pair Produced Stable Singly-Charged Heavy Particles in Z^0 Decays

The OPAL Collaboration

Abstract

A direct search for the exclusive pair production of stable singly-charged heavy (SCH) particles in Z^0 decays at the LEP e^+e^- collider is presented. In a scan around the Z^0 resonance of 0.4 pb^{-1} integrated luminosity, no evidence is seen for the production of slow-moving charged particles as measured by their time-of-flight. We set an upper limit of 1×10^{-3} on the Z^0 branching ratio into a pair of SCH fermions in the mass range $29\text{--}40 \text{ GeV}/c^2$, corresponding to a 3 MeV upper limit on such a contribution to the total width of the Z^0 . We exclude a fourth generation SCH lepton in the mass range $18.5\text{--}42.8 \text{ GeV}/c^2$. We also exclude a stable supersymmetric partner of the right-handed lepton, $\tilde{l}_R$, in the mass range $21.5\text{--}38.8 \text{ GeV}/c^2$. All limits are at 95% confidence level.

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Introduction

The LEP e^+e^- accelerator at CERN, with its copiously produced Z^0 's, provides an ideal laboratory for searches for the production of new particles. Initial particle searches at LEP have excluded much of the kinematically available mass region for many new particles [1].

In this letter we report on the results of a search for pair-produced stable charged heavy (SCH) particles in Z^0 decays using the OPAL detector at LEP. We search for two-prong events where both charged tracks have long flight times. There are several possible sources for SCH particles: a fourth generation lepton which is lighter than its accompanying neutrino, mirror fermions [2], supersymmetric (SUSY) scalar leptons [3] with mass less than the photino, and stable heavy hadrons hypothesised by Frampton and Glashow [4]. The two main production mechanisms for SCH leptons are (i) the SCH leptons are directly pair produced and (ii) a pair of heavy neutrinos is produced and decays as: $L^0 \rightarrow L^- W^{*+}$, where L^0 is the heavy neutrino and L^- is the SCH lepton. The latter case results in final states with more than two charged particles. Only direct, pair-produced SCH leptons are considered in this letter. The case of charged heavy lepton production with subsequent decay to an associated lighter stable neutrino has already been excluded at LEP energies [5].

Particle searches at lower energies have either set limits on the production cross-section of stable charged heavy particles as a function of mass [6], or excluded their existence up to some mass within the fourth generation lepton framework [7,8]. The VENUS [8] collaboration at TRISTAN set a lower limit on the mass of $27.6 \text{ GeV}/c^2$. Recently, negative results have also been reported for Z^0 decays by MARKII [9] with a mass limit of $36.3 \text{ GeV}/c^2$, and mass limits on stable SUSY scalar leptons have been set by DELPHI [10]. All these limits are at 95% confidence level (CL).

In the following we describe the detector and in particular the time-of-flight (TOF) apparatus. We then discuss the event selection and the procedures used to estimate and check the efficiency. Finally we set limits on the production of stable charged heavy particles. We present mass limits on a fourth generation lepton, on a right-handed SUSY scalar lepton, and a more general upper limit on the branching ratio of the Z^0 into a pair of stable charged heavy particles.

The Detector

The OPAL detector has been described previously [11]. This analysis is based on data taken in the 1989 run. Here we recall the features of the apparatus that are important for this analysis. In our coordinate system, z is the coordinate along the beam direction, while θ and ϕ are the polar and azimuthal angles, respectively.

The tracking of charged particles is performed with a jet chamber, a large volume drift chamber divided into 24 azimuthal sectors with 159 layers of sense wires, together with a vertex detector and z -chambers. This central tracking detector is positioned inside a solenoidal coil, which is surrounded by a time-of-flight counter array, a lead-glass electromagnetic calorimeter with a presampler, an instrumented magnet return yoke serving as a hadron calorimeter and four layers of outer muon chambers. Forward detectors serve as a luminosity monitor.

The TOF apparatus consists of 160 bars of 4.5 cm thick scintillator of length 6.84 m, at a mean radius of 2.36 m, covering $|\cos\theta| < 0.82$ and 2π in azimuth. The scintillator light pulse is detected at both ends by conventional photo-multipliers, which are instrumented with constant

fraction discriminators specially designed to reduce amplitude dependence in the timing of the output signal. Each discriminated signal stops a time-to-digital converter (TDC) which is started by the beam crossing signal. In addition, the discriminated signals are used to form a mean-timer (MT) coincidence of left and right photo-multipliers, for use in the trigger. The MT coincidence ensures that the time of the trigger signal is directly related to the flight time. In the 1989 run, these counters were measured to be 82% efficient for single muons with $|\cos\theta| < 0.7$, when both left and right discriminators fired. This includes a 3% geometrical inefficiency due to gaps between bars. A flight time resolution of about 0.5 ns, and a z measurement (from the time difference) with a resolution of 7.5 cm are achieved.

Trigger and Filter

The OPAL trigger provides much redundancy for standard two-prong decays of the Z^0 . The present implementation includes triggers based on both a single detector (tracking, TOF, electromagnetic or muon) and on two-fold coincidences between the various detectors. In this search for pair-produced stable heavy particles, only triggers based on the track trigger and the TOF detector are considered. The four conditions that could each trigger data-taking and are pertinent to this analysis are :

- At least two charged tracks in the barrel region $|\cos\theta| < 0.77$.
- At least one pair of back-to-back charged tracks $|\cos\theta| < 0.9$.
- At least one charged track in the barrel region matched to the TOF in azimuth.
- At least one pair of back-to-back TOF hits in azimuth ($\Delta\phi > 144^\circ$)

where the track trigger requires a transverse momentum, p_T , with respect to the beam direction of at least 0.5 GeV/c. Details of the trigger system are given in [12]. The first three triggers are each 90% efficient and the last trigger is 68% efficient for muon-pair events. The muon-pair event sample [13], with an angular acceptance of $|\cos\theta| < 0.7$, an efficiency of 98%, and a background of 4% (mainly from tau-pairs), is used to estimate the event selection efficiency. The combined trigger efficiency within the geometrical acceptance of this analysis (including the effect of correlations) is estimated to be 98% for pair-produced SCH particles.

An online filter was used to flag interesting events for subsequent offline reconstruction. Most standard physics processes were flagged efficiently by criteria based on correlating signals in the electromagnetic calorimeter and TOF. For this study, these criteria cannot generally be used because they introduce considerable uncertainties close to the lead-glass Čerenkov threshold ($\beta = 0.541$). Therefore, we primarily rely on the filter criterion which demanded back-to-back tracks and has an efficiency of 68% for muon pairs; we consider only this criterion in the efficiency calculation. We do, however, accept all filter flagged events, independent of filter criteria.

Event Selection

To ensure reliable event reconstruction and evaluation of efficiencies, we require the jet chamber, the track trigger, the lead-glass barrel calorimeter, the TOF and the luminosity calorimeter all to be fully operational. We also require that an event-by-event measurement of the TOF start time

be available - this was commissioned for later running in 1989. The integrated luminosity and the centre of mass (CM) energy for each scan point for samples of data satisfying the above criteria are listed in Table 1.

The events are selected from a sample of low multiplicity events; the low multiplicity preselection requires that the events have at least one charged track with $p_T > 2$ GeV/c and that there are no more than 10 reconstructed tracks with $p_T > 100$ MeV/c and no more than 12 electromagnetic clusters with more than 250 MeV energy. We apply further requirements on the track parameters to ensure proper reconstruction and then demand that there are exactly two such good tracks in the event. Each track must have at least 20 hits in the central detector chambers, a distance of closest approach to the beam axis smaller than 1 cm, an offset from the interaction point of less than 100 cm along the beam direction, and p_T greater than 2 GeV/c. We also demand that the two tracks be separated by at least 45° in azimuth. The requirement of exactly two good tracks is measured to have an efficiency of 97.5% on the muon-pair sample. The apparent inefficiency has contributions from split tracks, tau-pair background, and photon conversions.

We ensure that each track is well measured by the TOF system by demanding that each track matches a TOF hit to better than 15° in ϕ and that the hit is measured at both ends of the scintillator bar. With a hit at both left and right ends, the flight time can be determined (under the assumption of a single hit in the bar) with no need for an external z measurement; 68% of muon-pair events satisfy this TOF reconstruction requirement.

Both tracks are required to have $|\cos\theta| < 0.7$. If a cluster in the lead-glass calorimeter is associated to the track, then the measurement of θ is taken from the cluster; otherwise the measurement is taken from the TOF.

We find 502 events satisfying the above criteria. This candidate event sample consists mostly of di-leptons i.e. e^+e^- , $\mu^+\mu^-$, 2-prong $\tau^+\tau^-$.

Identification of Slow Particles

We look for particles with long flight times. The flight time of a particle is defined as the elapsed time between the e^+e^- collision and the arrival of the particle at the TOF scintillator. The distribution of measured flight time minus expected flight time for each track in the muon-pair sample is well represented by a Gaussian having an rms of 465 ± 20 ps. A similar resolution is obtained for TOF signals in multi-hadron events.

We consider $\frac{1}{\beta}$, the reciprocal of the particle's velocity normalised to the velocity of light, c , defined by

$$\frac{1}{\beta} = \frac{c\tau}{L}$$

where L is the length of the trajectory and τ the measured flight time. The resolution on $\frac{1}{\beta}$ is approximately constant, and is found to be 0.058 ± 0.003 for muon-pairs, as shown in Figure 1. We determine L using the z from the TOF, neglecting the curvature of the particles in the magnetic field.

Two experimental conditions limit the acceptance in $\frac{1}{\beta}$. Firstly the TOF trigger gate and the TDC dynamic range impose a limit on the maximum flight time which can be measured. This has been studied with a sample of cosmic ray events, where the TOF hits fire the TOF trigger

and have TDC digitisings at both ends of the scintillator. The apparent flight time distribution is consistent with a uniform distribution, with the edges being depleted by the above acceptance effects, indicating that flight time measurements start to lose efficiency above 40 ns. Flight times of less than 33 ns are judged to be measured with full efficiency. In this analysis, we will only consider mass hypotheses if the expected flight time for all values of $|\cos\theta| < 0.7$ is less than 33 ns. This corresponds to hypotheses for which $\frac{1}{\beta} < 3$.

The second important experimental condition is that stable charged heavy particles of low velocity may stop in the aluminium of the solenoid and never reach the TOF. Particles originating from the interaction point traverse between 2.0 and 2.8 radiation lengths of material, depending upon polar angle, before reaching the TOF [11]. From range tables of the energy loss by ionisation of low energy protons in aluminium [14], one can deduce the range of singly charged particles of 45.6 GeV energy as a function of $\frac{1}{\beta}$. Particles of $\frac{1}{\beta}$ of 3.8 have a range of 25 cm ($2.8 X_0$) in aluminium and a range of 62.5 cm ($7 X_0$) is found for particles with $\frac{1}{\beta}$ of 3.0. Even for a 20% uncertainty on the knowledge of the material in the detector, the energy loss limit on the acceptance would be at $\frac{1}{\beta}$ of 3.7. For $\frac{1}{\beta}$ values near the acceptance limit, the measured $\frac{1}{\beta}$ will be increased relative to the value of $\frac{1}{\beta}$ at production due to deceleration of the particle in material. In the worst case $\frac{1}{\beta}$ is measured to be at most 3.05 instead of 3.0. For lower values ($\frac{1}{\beta} < 2.0$), the effect is completely negligible compared to the resolution. We have also checked the material effects with a full Monte Carlo simulation [15] of the OPAL detector based on the GEANT code for particle tracking through materials. No effect on TOF efficiency due to stopping in material was observed for $\frac{1}{\beta} = 3.0$ within the geometrical acceptance. For an extreme value, $\frac{1}{\beta} = 4.0$, in about one third of events, at least one track did not reach the TOF scintillator. However tracks that did reach the TOF were extremely efficient at firing it because of their high ionisation. As regards energy loss, particles of $\frac{1}{\beta} = 4.0$ are as efficient as muon-pairs in satisfying the TOF requirements.

For the 502 events in the two-prong sample, we show in Figure 2 the distribution of $\frac{1}{\beta}$ for the second track versus $\frac{1}{\beta}$ for the first track. The track with the higher vertical coordinate at the TOF is chosen as the first track. Signal events would lie on the line $\frac{1}{\beta_2} = \frac{1}{\beta_1}$, with a value of $\frac{1}{\beta}$ greater than unity. Eleven of the events are identified as cosmic ray events by measuring the time difference between the TOF hits and as such are removed. The time difference is defined to be consistent with a downward moving cosmic if it is within 4 ns of expectation. These events tend to lie along the line $\frac{1}{\beta_2} = \frac{1}{\beta_1} + 2$ as expected. The one event at coordinates of (0,1) which lies neither in the cosmic region nor in the central cluster of events has been scanned graphically and is consistent with a $\tau^+\tau^-$ event where a decay pion interacts hadronically in the beam pipe. The event has two good tracks, but the hemisphere with the anomalous TOF measurement has 4 other tracks near the good track and much electro-magnetic activity. It is known that the TOF measurement can be unreliable in a high multiplicity environment because of multiple hits in the bar.

We form the two-track average of $\frac{1}{\beta}$ for each event. This distribution is shown in Figure 3 for the 491 remaining candidates. The corresponding distribution (hatched histogram) for a SCH particle mass of 35 GeV/ c^2 is shown for comparison; a full detector simulation has been performed. For each mass hypothesis at each CM energy, we look for events with two-track average of $\frac{1}{\beta}$ greater than the expected value minus 3 standard deviations (loose search zone). One standard deviation is taken to be 0.045 ± 0.003 as determined from the muon-pair sample. One observes that a separation of more than two standard deviations is achieved for masses above 18 GeV/ c^2 . The loose search zone has been designed to maximise efficiency for high masses. For low masses, the hypothesised signal is not so well separated from conventional Z^0 two-prong decays, and the size of the search zone needs to be chosen so as to better optimise signal to background. A tight search zone is defined as

greater than the expected value of the two-track average of $\frac{1}{\beta}$ minus 0.5 standard deviations. The loose and tight search zones are illustrated for the simulated events in the same figure. The tight search zone has an efficiency of $68.8 \pm 3.9\%$ for muon-pairs. The loose search zone has negligible inefficiency.

Limits on New Particle Production

The expected number of events from the production of a SCH lepton is estimated using the analytic formulae of [16]. The TIPTOP generator [17] is used to estimate the geometrical acceptance for heavy fermion production. The geometrical acceptance is estimated to be $61.5 \pm 1.2\%$ at the muon mass, and is slightly larger for the highest masses considered. This small variation is ignored and a mass independent acceptance of 61.5% is assumed.

The geometrical acceptance for the production of a scalar particle with an angular distribution of $\sin^2 \theta$ is estimated to be 88%. The average efficiency within the geometrical acceptance is taken conservatively to be the same as for fermion production. We estimate the number of events expected for the partner of the right-handed lepton $\tilde{l}_R$ with the assumption that the photino is heavier. We choose $\tilde{l}_R$ because the expected cross-section is lower and in most SUSY models the $\tilde{l}_R$ is lighter than the $\tilde{l}_L$. The cross-section relative to SCH lepton production was estimated using the Born terms for each process.

For each energy point, a given mass hypothesis implies a nominal value of $\frac{1}{\beta}$. We omit the energy point from consideration for that mass hypothesis, if the nominal value of $\frac{1}{\beta}$ is greater than 3. The luminosity used is listed as a function of mass hypothesis in Table 1. Initial state radiation can cause a large increase of $\frac{1}{\beta}$ compared to the nominal value. The size of the effect is estimated using TIPTOP by demanding that each produced particle has $\frac{1}{\beta} < 3$ and a correction is applied to the expected number of events. The correction is negligible for masses below 42 GeV/c², about 10% at 42.5 GeV/c², 20% at 42.8 GeV/c², and 90% at 44 GeV/c². The effect is most pronounced for CM energies above the Z^0 peak.

The event selection efficiency is estimated directly, using 221 muon-pair events from the same data-taking period and with the same geometrical acceptance. The muon-pair sample is thought to be a fair representation of signal events. Initial state radiation is implicitly included. The effects of final state radiation (FSR) are exaggerated (for the highest masses FSR is a factor of ten less than for muon-pairs). For the highest masses considered, the energy loss in scintillator is typically 10 MeV/cm compared to 2 MeV/cm for minimum-ionising particles. On balance, the muon-pair sample is expected to somewhat underestimate the efficiency. Events are counted as successes if they satisfy the track and TOF quality cuts and also the trigger and filter conditions which are appropriate to heavy particles. We find that 100 muon-pair events are retained, corresponding to an efficiency estimate of $45.2 \pm 3.3\%$. Various sources of error, including the statistical error on the above estimate and the tight search zone efficiency estimate, the error on the luminosity determination, and the error on the estimated cross-section are combined in quadrature to give a systematic error on the overall efficiency. This estimate, reduced by one standard deviation, is used as the final efficiency. Details are given in Table 2. For the loose search zone the efficiency for selecting a heavy-particle event within the geometrical acceptance is 40%, and for the tight search zone it is 27%.

For high masses, $M \geq 29$ GeV/c², no candidate events are found within the loose search zone. Similarly, no events are found for $M \geq 24$ GeV/c² within the tight search zone. In this case of

no observed events, upper limits on the branching ratio are set at 95% CL corresponding to the observation of 3 events. For mass hypotheses where events are observed, we extract conservative upper limits by assuming that all observed events are signal events and then applying the method advocated in [18] to obtain the number of events, N_{CL95} , which can be excluded at 95% CL. The two search zone methods cross over in exclusion power at about a mass of 28 GeV/ c^2 . At this mass we choose the search zone method with the higher upper limit. Upper limits on the decay rate of the Z^0 to any SCH fermion pair normalised to the rate expected for SCH leptons are also calculated. The observed and expected numbers of events, and upper limits on the normalised decay rate are given in Table 3 for a range of masses. The exclusion zone is illustrated in Figure 4. All quoted limits are only strictly applicable to singly-charged ($Q = 1$) particles. For $Q < 1$, it is difficult to reliably estimate the efficiency. For $Q > 1$, the efficiency is high, but the $\frac{1}{\beta}$ acceptance can be reduced significantly relative to the singly-charged case by the smaller range in the solenoid.

The absence of a signal sets an upper limit on the branching ratio of 1×10^{-3} for the decay of the Z^0 into a pair of SCH fermions in the mass range 29 to 40 GeV/ c^2 , corresponding to a 3 MeV upper limit on such a contribution to the total width of the Z^0 . The ratio of the partial width of the Z^0 into any pair of stable singly charged fermions relative to the expected partial width for stable charged heavy lepton production is limited to less than 0.13 for the 23 to 35 GeV/ c^2 mass range. This experiment excludes a fourth generation stable charged heavy lepton in the mass range of 18.5 GeV/ c^2 to 42.8 GeV/ c^2 . This substantially extends and overlaps existing limits from other e^+e^- colliders [6,7,8,9]. The production of a stable supersymmetric partner of the right-handed lepton, $\tilde{l}_R$, is also excluded for the mass range of 21.5 to 38.8 GeV/ c^2 . The same exclusion range can be set for a stable $\tilde{l}_L$. All limits are given at the 95 % confidence level.

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$E_{CM}(GeV)$	Lumi (nb^{-1})	$M_{max}(GeV/c^2)$	Lumi($M < M_{max}$)(nb^{-1})
88.28	46.60	41.61	384.1
89.28	3.81	42.09	337.5
90.28	35.68	42.56	333.7
91.03	48.31	42.91	298.0
91.29	37.03	43.03	249.7
91.53	99.56	43.15	212.7
92.28	19.10	43.50	113.2
93.29	22.45	43.97	94.0
94.28	71.60	44.44	71.6

Table 1. The total integrated luminosity is listed for each centre of mass energy E_{CM} . The highest mass, M_{max} , for which the detector is deemed to be sensitive is listed for each energy. The second part of the table shows the integrated luminosity used in searching for particles with $M < M_{max}$.

Contribution	Fractional error (%)
Muon-pair sample (stat.)	7.4
Muon-pair sample (syst.)	3.3
Absolute normalisation	2.2
Error on estimated cross-section	8
Loose (tight) search zone	- (5.7)
Total	11.6 (12.9)
Overall efficiency	loose (tight)
Estimate	45.2 ± 5.2 % (31.1 ± 4.0 %)
Final value	40 % (27 %)

Table 2. Summary of the systematic errors on the efficiency calculation. The systematic error is estimated taking into account the normalisation errors of both the experiment and the theoretical prediction. The final efficiency (within the geometrical acceptance) is conservatively taken to be the estimated efficiency fluctuated down by one standard deviation. The values are given for both the loose and tight search zones, the latter being displayed in parentheses.

Mass (GeV/c ²)	N_{loose} $\epsilon = 0.40$	N_{tight} $\epsilon = 0.27$	N_{CL95}	N_{SCHL}	$\frac{\Gamma_{X^+X^-}}{\Gamma_{L^+L^-}}$
15.0	()	123	143	50.7	2.8
18.0	(452)	46	58.5	46.1	1.3
19.0	(424)	20	28.8	44.5	0.65
21.0	(338)	7	13.2	41.1	0.32
24.0	(114)	0	3	36.6	0.082
27.0	(7)	0	3	31.7	0.095
28.0	1	(0)	4.7	44.0	0.11
29.0	0	(0)	3	41.1	0.073
35.0	0	(0)	3	23.9	0.13
40.0	0	(0)	3	10.6	0.28
42.0	0	(0)	3	5.7	0.53
42.5	0	(0)	3	4.4	0.68
42.8	0	(0)	3	3.3	0.92
43.0	0	(0)	3	2.4	1.2
44.0	0	(0)	3	0.2	-

Table 3. Observed numbers of events, N_{loose} and N_{tight} as a function of mass hypothesis. The search method not used in setting limits is given in parentheses. Also listed is the number of events excluded at 95% CL, the number of events expected to be observed in the stable charged heavy lepton framework, N_{SCHL} , and the upper limit on the ratio of the partial width of the decay to any SCH particle pair relative to that expected for a SCH lepton with the standard model coupling, $\frac{\Gamma_{X^+X^-}}{\Gamma_{L^+L^-}}$.

Figure Captions

Figure 1. Distribution of $\frac{1}{\beta}$ for each particle in muon-pair events.

Figure 2. Plot of $\frac{1}{\beta_2}$ for the track with lower vertical coordinate at the TOF against $\frac{1}{\beta_1}$ for the other track for all 502 two-prong candidate events. The 11 cosmic-ray events in the sample are clearly seen to lie approximately on a line of unit gradient displaced from the line of equality by two units of $\frac{1}{\beta}$.

Figure 3. Two-track average of $\frac{1}{\beta}$ for candidate events (open histogram), and for Monte Carlo events of $35 \text{ GeV}/c^2$ stable singly charged heavy particles generated at $\sqrt{s} = 91.2 \text{ GeV}$ (hatched histogram). The MC normalisation is arbitrary. The loose and tight search zones are illustrated for a mass hypothesis of $35 \text{ GeV}/c^2$ and $\sqrt{s} = 91.2 \text{ GeV}$. Also shown is the mass (GeV/c^2) corresponding to each value of $\frac{1}{\beta}$ at $\sqrt{s} = 91.2 \text{ GeV}$.

Figure 4. The 95% CL exclusion region (solid boundary) for the ratio of the decay rate of the Z^0 to any SCH fermion pair normalised to the rate expected for SCH leptons, $\frac{\Gamma_{X^+X^-}}{\Gamma_{L^+L^-}}$. The dashed line illustrates the expected value of 1 for the SCH lepton case. The dotted curve shows the expected ratio for right-handed SUSY scalar leptons (taking $\sin^2 \theta_W = 0.23$). This curve falls off quickly near the kinematic limit because of the β^3 dependence of the scalar cross-section. SCH leptons are excluded from 18.5 to 42.8 GeV/c^2 and SUSY scalar leptons from 21.5 to 38.8 GeV/c^2 . Production of SCH particles with non-standard couplings is typically limited to less than 10% of the standard expectation for masses around 30 GeV/c^2 .

Figure 1

Figure 2

Figure 3

Figure 4