A Search for Technipions and Charged Higgs Bosons at LEP

The OPAL Collaboration.

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Abstract

A search has been performed for unstable charged scalar particles \((S^\pm)\) such as technipions or charged Higgs bosons, pair-produced in \(e^+e^-\) annihilation at energies near the \(Z^0\) pole. No evidence for such particles was observed in the decay modes \(e^+e^- \rightarrow S^+S^- \rightarrow (cs)(\tau\nu), (\tau\nu)(\tau\nu)\) and \((cs)(cs)\). A lower limit (at the 95\% C. L.) of 33 GeV/c\(^2\) is obtained for the mass of the charged scalar particles, independent of the branching ratio.
1 Introduction

The recent operation of the Large Electron Positron Collider, LEP, at CERN provides an excellent opportunity to extend the search for technipions and charged Higgs bosons with masses up to approximately half the $Z^0$ mass. We report in this paper on such a search using the OPAL detector. The existence of technipions is predicted by the technicolor model[1]. Since the technipion is a pseudo-Goldstone boson, its mass is expected to be much smaller than the typical energy scale of the technicolor model. Although technipions are composite particles, their sizes are expected to be of order $1/\Lambda$, where $\Lambda$ is the typical energy scale of the technicolor model ($1\sim 1$ TeV); they should therefore behave as pointlike particles at $Z^0$ energies. Therefore, searches for technipions can be a powerful way of probing the energy region much higher than the one presently accessible with the LEP accelerator. The PETRA experiments[2] at DESY have placed a lower limit on the technipion mass of about 19 GeV/c$^2$. In the present search, we have extended the mass limit towards half of the $Z^0$ mass ($M_{Z^0}$).

The present study also applies to the charged Higgs particles which are predicted by some theories other than the minimal Standard Model[3]. Both the technipions and charged Higgs particles will be referred to generically as $S^\pm$. They are expected to decay predominantly into the heaviest quarks and leptons that are kinematically allowed. The dominant decay modes of $S^\pm$ are then expected to be $(cs)$ and $(\tau \nu)$, since the $(cb)$ decay mode is likely to be suppressed by a factor due to a mass mixing term[4]. The present search is based on a study of the following channels: $e^+ e^- \rightarrow S^+ S^- \rightarrow (cs)(\tau \nu)$, $(\tau \nu)(\tau \nu)$ and $(cs)(cs)$. We present mass limits as functions of $B_{\nu} = \frac{r(S \rightarrow \tau \nu)}{r(S \rightarrow CS) + r(S \rightarrow CS)}$, since this ratio is model dependent. The results also hold if $S^\pm$ decays into flavors other than $(cs)$ [5], as the analysis is not dependent explicitly on the quark flavors.

2 Apparatus

The data were recorded with the OPAL detector during a scan of the $Z^0$ resonance with the center of mass energies ranging from 88.3 to 95.0 GeV. These data correspond to an integrated luminosity of 1120 nb$^{-1}$. The OPAL detector is a multipurpose apparatus consisting of a system of central tracking chambers inside a solenoid which provides a uniform magnetic field of 0.436 T. The most important tracking element for this analysis is a cylindrical drift chamber, four meters in length and two meters in radius, containing 159 layers of sense wires in 24 azimuthal sectors. The solenoid is surrounded by time-of-flight (TOF) scintillation-counters, and a lead glass electromagnetic calorimeter. Similar calorimetry covers the two endcaps of the detector. The electromagnetic calorimeter consists of a cylindrical array of 9,440 lead-glass blocks, each 10 cm $\times$ 10 cm in cross-section with 24.6 radiation lengths thickness, oriented to point approximately towards the interaction point, and two endcaps of 1,132 lead glass blocks each, with 20.0 radiation lengths thickness, oriented parallel to the beam direction. A small-angle calorimeter and tube chambers, called the forward detector, serves as a luminosity monitor. The components of the OPAL detector are described in more detail elsewhere.[6]
3 Analysis

3.1 The \((cs)(\tau\nu)\) mode

For this decay mode a multihadron sample consisting of approximately 22000 events with the tracking chamber at full operating voltage was used. The selection criteria and relevant triggers are described in a previous publication[7]. The cleanest signature of the \((cs)(\tau\nu)\) channel is an event topology with one isolated charged particle from the \(\tau\) decay, with or without neutrals, recoiling against two hadronic jets coming from the \(c\) and \(s\) quarks. The \(\tau\nu\) side should show large missing energy and momentum due to undetected neutrinos, while the hadron side should have almost the full beam energy. The missing momentum of the neutrinos results in a large acoplanarity angle for the events. The following cuts were applied to select this class of events in the sample:

1. \(|\cos \theta_T| \leq 0.7\), where \(\theta_T\) is the angle between the thrust axis of the event and the beam direction. This cut enhances the signal to background ratio because the angular distribution for \(e^+e^- \rightarrow S^+S^-\) is expected to be proportional to \(\sin^2 \theta\) while the dominant multihadronic background process has a distribution approximately proportional to \(1 + \cos^2 \theta\). Furthermore, this angle cut improves the containment of the events.

For the calculation of the thrust angle and the quantities used in the selection which follows, both charged tracks and electromagnetic clusters were used. Here tracks were defined as follows:

- The impact parameter in the transverse plane was required to be less than 2 cm,
- the absolute value of the \(z\) coordinate of the point of closest approach to the interaction point was required to be less than 70 cm, and
- the number of hits associated to the track was required to be greater than 35.

The energy of electromagnetic clusters was required to be larger than 100 MeV in the barrel region and 200 MeV in the endcap region. To avoid the double counting of particle energy, clusters in the electromagnetic calorimeter with an associated charged track were eliminated, provided their energy was less than 1.5 GeV, or the ratio between the energy of the cluster and the momentum of the associated track was greater than 0.7 but less than 1.5. Thus we define "charged tracks" and "neutral clusters". Next, the following cuts were applied:

2. \(E_{vis} < 70\) GeV, where \(E_{vis}\) is the sum of the energy of charged tracks (assuming zero mass) and neutral clusters as defined above. Fig.1(a) shows the observed visible energy distribution.

3. At least one isolated charged track with momentum greater than 4 GeV/c, with no other charged tracks having momenta greater than 0.2 GeV/c, was required to be inside an "isolation cone" of 45° half angle.

4. At least 5 charged tracks were required to be outside the isolation cone.

For each surviving event, the acoplanarity angle \(\Delta \phi\) was defined as:

\[
\cos(\Delta \phi) = \frac{(\vec{p}_{in} \times \vec{p}_e) \cdot (\vec{p}_{out} \times \vec{p}_e)}{|\vec{p}_{in} \times \vec{p}_e| \cdot |\vec{p}_{out} \times \vec{p}_e|},
\]

where \(\vec{p}_{in}\) and \(\vec{p}_{out}\) are the sum of the momenta of charged tracks and neutral clusters inside and outside the isolation cone, respectively, and \(\vec{p}_e\) is the momentum of the incoming electron. Fig.1(b)
shows the observed acoplanarity angle distribution. Possible $S^+S^-$ events have large acoplanarity angles due to the large missing momentum. They also have an invariant mass which is approximately equal to $M_S$, the mass of the $S^*$, on the $(cs)$ side and a small mass on the $(\tau\nu)$ side. The following additional cuts were therefore applied to the remaining events:

(5) $\Delta \phi \geq 5^\circ$

(6) $M_{in} \leq 2.5 \text{ GeV}/c^2$ and $M_{out} \leq 42 \text{ GeV}/c^2$,

where $M_{in}$ and $M_{out}$ are the reconstructed invariant masses of all the charged and neutral particles inside and outside the isolation cone, respectively. No events survived these cuts. Fig.1(c) shows the two-dimensional event distribution of $M_{out}$ versus $M_{in}$ after the cuts (1) through (5) (solid dots). To check the reliability of the reconstructed invariant mass, the procedures of the isolated charged track finding and the mass reconstruction were performed on a sample of $\tau\tau$ events and on KORALZ[8] Monte Carlo events. The satisfactory agreement of the reconstructed mass distributions between the real events and the Monte Carlo events is shown in Fig.1(d).

The significance of this null result was estimated using Monte Carlo simulation. An $S^+S^-$ pair was created according to the following point-like differential cross section folded with the effect of the initial state radiation as described in [9];

$$\frac{d\sigma}{d\Omega} = \sigma_{peak}^{had} \frac{s \Gamma_Z^2}{(s - M_Z^2)^2 + s^2 \Gamma_Z^2 / M_Z^2} \frac{\Gamma_{SS}^2}{\Gamma_{had}^2} \sin^2 \theta,$$

where $\Gamma_Z$, $\Gamma_{had}$ and $\Gamma_{SS}$ are the $Z^0$ total width and the partial width into hadrons and $S^+S^-$, respectively, and $\sigma_{peak}^{had}$ is the peak cross section of the hadronic channel. $\Gamma_{SS}$ is given by $\frac{G_F^2 M_L^2}{6\sqrt{2}} (\frac{1}{2} - \sin^2 \theta_W)^2 \cdot \beta_S^3$, where $G_F$, $\theta_W$ and $\beta_S$ are the Fermi constant, the electroweak mixing angle and the velocity of the produced $S^*$, respectively. For $M_Z$, $\Gamma_Z$, $\Gamma_{had}$ and $\sigma_{peak}^{had}$ we have used the values given in Ref.[7] (91.1 GeV/c$^2$, 2.53 GeV/c$^2$, 1.85 GeV/c$^2$ and 41 nb, respectively), while $\sin^2 \theta_W$ was taken to be 0.23. The $S^+$ and $S^-$ were then allowed to decay into $(\tau\nu)$ and $(cs)$; the $\tau$ decay branching ratios were taken from Ref.[10]. The quark pair fragmentation into hadrons was modelled using the LUND Monte Carlo program JETSET7.2 [11]. The Monte Carlo events were passed through the detector simulation[12], and then through the same analysis program as the real data to determine the efficiencies of the selection criteria. Fig.1 also shows all the relevant distributions of the simulated events for $M_S = 30$ GeV/c$^2$ (dotted histogram and circles). Table 1 summarizes the total number of $S^+S^-$ events expected to be produced with the present luminosity together with the detection efficiencies as a function of $M_S$. The inefficiency due to the trigger was negligible, and the efficiency of the pre-selection criteria was estimated to be larger than 94% using the Monte Carlo events. The quoted errors on the efficiencies given in Table 1 include statistical errors and systematic uncertainties of 8%. The systematic error includes the uncertainties in the luminosity measurement, the detector simulation and in the fragmentation model as well as the uncertainties on the parameters used in the cross section calculations. The effects of the top quark loop corrections were not included in this analysis.

Upper limits (at the 95% confidence level) on the product of the branching ratios $B_{\tau\nu} B_{cs}$ ($B_{cs} = 1 - B_{\tau\nu}$) were calculated from the total expected number of $S^+S^-$ events, the efficiencies decreased by the assigned error and the upper limits on the number of observed events. The $S^\pm$ was assumed to decay into $(\tau\nu)$ and $(cs)$ but not into $(cb)$. The region in the $B_{\tau\nu}$ versus $M_S$ plane excluded by this mode is indicated by curve (A) in Fig.5.
3.2 The \((\tau \nu)(\tau \nu)\) mode

This decay mode leads to a characteristic signature of acoplanar \(\tau\) pairs due to large missing momenta carried by undetected neutrinos.

The trigger conditions relevant to this process were:

(i) More than 6 GeV was deposited in the barrel electromagnetic calorimeter.

(ii) At least 2 tracks with \(|\cos \theta| < 0.7\), or at least 3 tracks, were found by the central detector trigger processor.

(iii) More than 4 GeV was deposited in the barrel electromagnetic calorimeter and there was at least one track or one TOF counter hit.

Using the three redundant triggers, we determined the overall trigger efficiency to be at least 80%.

In the search for events with \(\tau\) pairs the following selection cuts were applied:

(1) The total energy reconstructed in the lead glass was between 3% and 80% of the center of mass (CM) energy. The lower cut was applied to reject muon pairs and the higher cut to reject electron positron pairs.

(2) Energy deposited in the forward calorimeter was less than 5 GeV.

(3) The visible energy, defined as in the previous section, had to be larger than 18% of the CM energy. Cuts (2) and (3) were effective in rejecting two-photon interaction events.

(1) The total number of electromagnetic clusters had to be less than 10. This cut was applied to reject the multihadronic events.

(5) The number of charged tracks found in the central drift chamber had to be at least 2 but not more than 7.

(6) \(|\cos \theta_{\text{mis}}| \leq 0.95\), where \(\theta_{\text{mis}}\) is the direction of the missing momentum with respect to the beam direction, calculated from the lead glass clusters only.

(7) The direction of the thrust axis was required to satisfy \(|\cos \theta_T| \leq 0.7\). The thrust axis was calculated from the charged tracks and the neutral clusters.

We then determined the directions of the two \(\tau\)'s. To this purpose, the events were analysed in terms of low multiplicity jets. In this context a "jet" could be a single charged particle or a narrow jet of a few charged or neutral particles, as produced by \(\tau\) decays. Starting with the highest momentum charged particle, we searched for the particles with the highest momentum among the rest of the charged or neutral particles in a cone of 20° half angle. If a particle was found, the sum of the momenta of the two particles was used to define the center of a new cone. This procedure was repeated until no more particles could be added. Of the remaining charged particles, the one with the largest momentum was used as the center for a new cone and the above method was repeated until all charged particles were assigned to a jet. Neutral particles were allowed to be left unassigned. Jets with final energies less than 3 GeV were ignored. With the jets defined in this way the following two selection criteria were applied to eliminate events from \(e^+e^- \rightarrow \mu\mu\gamma\) and \(\tau\tau\gamma\) processes:

(8) Exactly 2 jets were required.
(9) There was no unassigned neutral cluster with energy greater 3 GeV.

The sum of the momenta of the neutral and charged particles in each jet was then calculated. The acoplanarity angle $\Delta \phi$ between these two momenta was defined as for the $(\tau\nu)(cs)$ search mode. The observed acoplanarity angle distribution is shown in Fig.2(a). For comparison, we also show in the same figure the distribution of the simulated $\tau$ pair events generated using the KORALZ Monte Carlo program [8]. The distribution of the simulated events of the process $e^+e^- \rightarrow S^+S^- \rightarrow (\tau\nu)(\tau\nu)$ with $M_S = 30$ GeV/c$^2$ is also shown in Fig.2(b). The $(\tau\nu)(\tau\nu)$ final state was simulated in the same way as the $(cs)(\tau\nu)$ final state. We then applied the final cut,

(10) $\Delta \phi \geq 15^\circ$

As can be seen from Fig.2(a), no event remained after this cut. From the simulation of $S^+S^-$ production, one can calculate the detection efficiency for this process with these selection cuts. The fourth column of Table 1 summarizes the trigger and detection efficiencies for given values of $M_S$. The uncertainties on the total efficiency include both statistical and systematic errors. The curve (B) in Fig.5 shows the region of $B_{\tau\nu}$ and $M_S$ excluded at the 95% confidence level by the search for this mode.

3.3 The $(cs)(cs)$ mode

For this decay mode the multihadron sample was again used. Two analyses were performed: one for the low mass region ($M_S \lesssim 30$ GeV/c$^2$) and one for the high mass region ($M_S \gtrsim 30$ GeV/c$^2$).

If $M_S$ is small compared to the beam energy, the charged scalar particles are boosted; thus the decay products of one charged scalar particle are wellcontained in one hemisphere. To enhance the signal over the background, two cuts were applied:

(1) The sphericity of the event calculated from charged tracks and neutral clusters had to be greater than 0.05.

(2) $|\cos \theta_T| \leq 0.7$, where $\theta_T$ is the angle between the thrust axis of the event and the beam direction.

The event was then divided into two hemispheres by the plane normal to the thrust axis, and the invariant mass of each hemisphere was calculated (it is expected to be $M_S$). To improve the resolution of the reconstructed mass, the total energy in each hemisphere was scaled to the beam energy:

$$\tilde{p}_i,\text{corr} = \alpha \tilde{p}_i$$

$$\alpha = \frac{E_{\text{beam}}}{\Sigma_i |\tilde{p}_i|}$$

where $i$ indicates the $i$-th particle in each hemisphere. The distribution of $\alpha$ had a mean of 1.2 and an r.m.s. width of about 0.2. Fig.3(a) shows the event distribution of the mass difference ($M_{\text{dif}}$) between the hemispheres divided by their average ($M_{\text{ave}}$) after cuts (1) and (2). The same distribution for the Monte Carlo events for an $S^\pm$ mass of 20 GeV/c$^2$ is also shown by the dotted histogram. For $S^+S^-$ events $M_{\text{dif}}$ is expected to be zero, so the following cut was applied:

(3) $-0.22 \leq M_{\text{dif}}/M_{\text{ave}} \leq 0.22$.

Approximately 1300 events remained after these cuts. The distribution of $M_{\text{ave}}$ is shown by the solid-line in Fig.3(b). The contribution from a hypothetical $S^+S^-$ signal, with mass $M_S = 20$ GeV/c$^2$,
is indicated by the dotted histogram. After the selections (1),(2) and (3), 80% of the $S^+S^-$ events fall between $(M_S - 3)$ GeV/c$^2$ and $M_S$ GeV/c$^2$. For $M_S = 30$ GeV/c$^2$, this number is 60%. The measured distribution is adequately described by the 5-flavor QCD Monte Carlo, and there is no indication for a salient “peak” having the width of the hypothetical $S^+S^-$ signal.

For a given mass $M_S$, the number $N_{SS}$ of events which can be attributed to a possible $S^+S^-$ signal is given by

$$N_{SS}(M_S) = N_{obs}(M_S) - N_{BG}(M_S)$$

where $N_{obs}(M_S)$ is the observed number of events with mass between $(M_S - 3)$ GeV/c$^2$ and $M_S$ GeV/c$^2$ and $N_{BG}(M_S)$ is the estimated QCD background in the same mass range. The latter was obtained from a fourth order polynomial fit to the Monte Carlo distribution, normalized to the data while excluding the mass range from $(M_S - 3)$ GeV/c$^2$ to $M_S$ GeV/c$^2$. The calculation of $N_{SS}(M_S)$ was performed for $M_S$ between 15 and 33 GeV/c$^2$, in steps of 1 GeV/c$^2$, and took into account the error on the estimation of the background and the statistical error on the observed events. The detection efficiency together with the statistical and systematic errors is shown in the fifth column of Table 1, as a function of $M_S$. The systematic error includes the uncertainties on the detector simulation, on the luminosity measurement and on the cross section calculation. The upper limit on the branching ratio $B_{SS}$ was calculated using $N_{SS}$ increased by its error, the detection efficiency and the total number of expected $S^+S^-$ events; this limit is indicated by curve (C) in Fig.5.

When the mass of the charged scalar particle is heavy, the 4 jets are likely to be separated because of the small boost of the $S^\pm$ particles. The following requirements were thus applied:

1. The sphericity of the event had to be greater than 0.16.
2. The aplanarity of the event had to be greater than 0.02.
3. The direction of the thrust axis was confined to $|\cos \theta_T| \leq 0.75$.

In this analysis, double counting of the energy from charged particles was reduced by requiring the number of lead glass blocks in an electromagnetic cluster to be $< 3$ if a charged track was associated to the cluster and to be $\geq 3$ otherwise (photon showers spread over many blocks, while charged tracks usually deposit their energy in one or two neighbouring blocks).

The LUND cluster algorithm[11] was applied to determine the number of jets in the remaining events. Only 4-jet events were accepted. For the jet resolution parameter $D_{join}$, the value 6.0 was found to be optimal to enhance the signal over the QCD background.

The correct pairing of the four jets to form the $S^+$ and $S^-$ systems was chosen by the following consideration: The opening angle ($\theta_{open}$) between the two jets from the decay of the $S^+$, and the one from the decay of the $S^-$, are nearly equal and have definite values for a given $S^\pm$ mass. This is not the case for the QCD background, as can be seen in Fig.4(a) and (b), respectively.

Therefore, the correct jet pairing was selected by the requirement

$$\theta_{i} \leq \theta_{open}^{i} \leq \theta_{2} \ (i = 1, 2)$$

where the limiting angles $\theta_1$ and $\theta_2$ are $M_S$ dependent; they are given in Table 2 for $M_S$ from 20 to 40 GeV/c$^2$. In the case that several combinations satisfied this requirement, the one with the smallest difference $|\theta_{open}^{1} - \theta_{open}^{2}|$ was chosen.
Once the correct pairing of jets was found, the momentum vectors ($\vec{p}_S$, and $\vec{p}_S$) of the charged scalar particles were obtained by adding the two jet momenta. The following cuts were then imposed on the direction, acolinearity angle, energy and velocity of these particles:

\begin{enumerate}
\item $|\cos \theta_{S_i}| \leq 0.6$ (i = 1,2)
\end{enumerate}

where $\theta_{S_i}$ are the angles between $\vec{p}_S$ and the beam direction.

\begin{enumerate}
\item The acolinearity angle between $S_1$ and $S_2$ was required to be less than 25 degrees.
\item $|E_{S_i} - E_{S_j}| \leq 8 \text{ GeV}$.
\item $\beta_1 \leq \beta_{S_1} \leq \beta_2$ (i = 1,2)
\end{enumerate}

where $\beta_{S_1}$ is the velocity of $S_1$. The limiting values $\beta_1$ and $\beta_2$ depend on $M_S$ and are listed in Table 2. Fig.1(c) shows $\beta_{S_1}$ versus $M_S$ for the data. The distribution of the same quantity for the generated $S^+ S^-$ signal with $M_S = 35 \text{ GeV/c}^2$ is shown in Fig.1(d). The two mass dependent cut parameters were applied to the data in steps of 5 GeV/c\(^2\) for $M_S$ between 20 and 40 GeV/c\(^2\). No event survived these cuts except one event at 30 GeV/c\(^2\), where the expected signal is an order of magnitude higher. This is in agreement with the Monte Carlo simulation.

The detection efficiency (column 6 of Table 1) ranges from 4 to 6% for $M_S$ between 20 and 10 GeV/c\(^2\). The quoted errors include the systematic and statistical uncertainties. The limit on $B_{\tau\nu}$ from this analysis is indicated by curve (D) in Fig.5. Because our analyses for the $(cs)(\tau\nu)$, $(\tau\nu)(\tau\nu)$, and $(cs)(cs)$ modes were independent, the results were combined; the limit thus obtained is indicated by curve (E) in Fig.5.

4 Conclusion

We have found no evidence for the signatures $e^+e^- \rightarrow S^+ S^- \rightarrow (cs)(\tau\nu)$, $(\tau\nu)(\tau\nu)$ or $(cs)(cs)$, where the $S^+ S^-$ are unstable charged scalar or pseudo-scalar particles such as technipions or charged Higgs bosons. The mass limit at 95% confidence level is almost independent of the branching ratio $\Gamma(S \rightarrow \tau\nu)/\Gamma(S \rightarrow all)$; the weakest limit of 35 GeV/c\(^2\) is obtained for the case where $S^\pm$ decay exclusively into $(cs)$ pairs.

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<table>
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<th>$M_S$ $(GeV/c^2)$</th>
<th>$N_{exp}$</th>
<th>$\epsilon(\tau\nu)(cs)$ (%)</th>
<th>$\epsilon(\tau\nu)(\tau\nu)$ (%)</th>
<th>$\epsilon(cs)(cs)$ (%)</th>
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<td>15</td>
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<td>23.2 ± 2.9</td>
<td>30.7 ± 3.3</td>
<td>33.0 ± 4.0</td>
<td>6.3 ± 0.6</td>
</tr>
<tr>
<td>35</td>
<td>81.5 ± 0.4</td>
<td>17.6 ± 2.4</td>
<td>30.7 ± 3.3</td>
<td>7.0 ± 1.9</td>
<td>3.8 ± 0.4</td>
</tr>
<tr>
<td>40</td>
<td>33.9 ± 0.2</td>
<td>11.8 ± 1.8</td>
<td>29.3 ± 3.2</td>
<td>—</td>
<td>3.6 ± 0.5</td>
</tr>
<tr>
<td>45</td>
<td>1.1 ± 0.0</td>
<td>1.6 ± 1.1</td>
<td>29.4 ± 3.2</td>
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<td>—</td>
</tr>
</tbody>
</table>

Table 1: Total number of events expected to be produced with the present luminosity and the detection efficiency for each mode as functions of the $S^\pm$ mass.

<table>
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<tr>
<th>$M_S$ $(GeV/c^2)$</th>
<th>$\theta_1$ (degrees)</th>
<th>$\theta_2$ (degrees)</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
</tr>
</thead>
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<td>20</td>
<td>47.0</td>
<td>54.0</td>
<td>0.86</td>
<td>0.95</td>
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<td>25</td>
<td>52.0</td>
<td>72.0</td>
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<td>0.88</td>
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<td>30</td>
<td>70.0</td>
<td>90.0</td>
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<tr>
<td>35</td>
<td>85.0</td>
<td>105.0</td>
<td>0.60</td>
<td>0.72</td>
</tr>
<tr>
<td>40</td>
<td>115.0</td>
<td>135.0</td>
<td>0.45</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 2: The selection cut parameters for the $(cs)(cs)$ mode analysis as functions of the $S^\pm$ mass.
Figure Captions

Fig.1. The distributions of (a)visible energy, (b)acoplanarity angle and (c)reconstructed mass outside the isolation cone versus the mass inside the cone before applying the corresponding cuts of the $((cs)(\tau\nu))$ mode analysis. Solid histograms and solid dots show the distribution for the data, while dotted histograms and circles show those for the $S^\pm$ Monte Carlo events ($M_S = 30$ GeV/c$^2$). (d)The reconstructed mass distribution for $\tau\tau$ events (solid dots) and that for the Monte Carlo events (histogram).

Fig.2. (a)Acoplanarity angle distribution of the data (solid dots) and tau pair production Monte Carlo events (histogram) after cuts (1) through (9) of the $((\tau\nu)(\tau\nu))$ mode analysis (corresponding to the same integrated luminosity). (b)Acoplanarity angle distribution of $S^\pm$ Monte Carlo events with $M_S = 30$ GeV/c$^2$.

Fig.3 (a)Event distribution of the mass difference ($M_{\text{dif}}$) between $M_1$ and $M_2$ normalized by the average of them ($M_{\text{ave}}$) (solid histogram). Dotted histogram shows the distribution of the same quantity for the $S^\pm$ Monte Carlo events with $M_S = 20$ GeV/c$^2$. The two arrows indicate the selected region corresponding to the cut of $-0.22 \leq M_{\text{dif}}/M_{\text{ave}} \leq 0.22$. (b)Distribution of $M_{\text{ave}}$ after the above cuts (solid histogram). The possible contribution of $S^\pm$ events ($M_S = 20$ GeV/c$^2$) is also shown by the dotted histogram.

Fig.4 (a)Opening angle distribution between the jet-pairs in observed 4-jet events. $\theta_1$ is the angle between one jet-pair out of the 4, and $\theta_2$ is between the remaining jet-pair (there are three entries per event). (b)Distribution of the same quantity for the $S^\pm$ Monte Carlo simulation with $M_S = 35$ GeV/c$^2$. The selection cut for this mass is indicated by the dashed line. (c)Distribution of the velocities of the correct pairings in observed 4-jet events. (d)Distribution of the same quantity for the $S^\pm$ Monte Carlo simulation with $M_S = 35$ GeV/c$^2$. The selection cut for this mass is indicated by the dashed line.

Fig.5. The 95% confidence level limits on the branching ratio $\Gamma(S \rightarrow \tau\nu)/\Gamma(S \rightarrow \text{all})$ as a function of $M_S$. The curves (A) and (B) represent the limits obtained from the analysis of the $(cs)(\tau\nu)$ and $(\tau\nu)(\tau\nu)$ modes, respectively. The curves (C) and (D) show the limits obtained from the two analyses of the $(cs)(cs)$ mode; the former applies to the analysis for the low $M_S$ region and the latter for the high $M_S$ region. Combining these limits, the region on the low mass side of curve (E) is excluded with 95% confidence level.
Fig. 1(a), (b)
Fig. 1(c), (d)
Fig. 2
Fig. 3
Fig. 4(a), (b)
Fig. 4(c), (d)