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Limit on tau branching ratios into 7 or more charged particles and into undetected particles.

The ALEPH Collaboration

Abstract

A single hemisphere based tau identification method is applied to investigate the possibility, for tau leptons, to decay into a large number of charged particles or into undetectable ones. Since these decay channels are strongly suppressed by physics and phase space limitations, preselection of an unbiased sample of taus is needed. Such a sample is created selecting the hemispheres opposite to the identified ones; in fact those are free from cut induced systematics if the spin correlation between the two taus is neglected. Since no cuts involving the whole events can be applied, stringent topological and phase space selections are required to reduce the background contamination to an acceptable amount; as a consequence the selection efficiency cannot be very high.

Considering that the branching ratios are preserved in this sample, one can look at the suppressed decay modes and quote directly the respective branching ratios or put limits on them.

In this analysis we searched for tau decays into seven or more charged particles (phase space considerations allow the tau to decay into up to twelve pions) or into undetected particles, i.e. particles that do not interact with the apparatus (like neutrinos) or that do not reach the active parts of it. In practice we counted the hemispheres with more than six charged particles or completely empty, quoting at the end a limit on tau decays into these channels.

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1 Introduction.

It is well known that the tau lepton decays into a small number of charged and neutral particles; In almost the totality of cases the charged multiplicity of tau decays is less or equal to three particles with a small presence of 5-prong decays. No evidence of 7(or more)-prong (we will call them $\geq$7-prong in what follows) decays was discovered till now, but no physics constraints nor phase space limitations forbid the tau to decay into up to twelve charged pions; so a measurement of this branching fraction or at least a limit on it have to be quoted to have a full study of the topology of tau decays. On the other hand, also a check of the number of undetected tau decays, i.e. decays where the products are not seen by the apparatus, needs to be done for the same reason. This check also allows to put a limit on the contribution from possible new physics on this branching fraction, when one subtracts the Monte Carlo simulated "standard physics" contributions that we know exist: for instance the tau pairs can decay into an electron and two neutrinos, with the electron transverse momentum smaller that few tens of MeV; due to the magnetic field, such an electron has not enough energy to reach the active parts of the inner ALEPH detectors, and so it is not detected.

Simply speaking, when studying the topological branching fractions, generally one selects the sample of tau-tau events and counts the decays into a particular topological family. Unfortunately, if the branching ratio is very small compared with the background contamination of the selection or if the structure of the topology is such that it is not possible to identify it with an acceptable background, this kind of analysis cannot be applied. In order to count the decays belonging to these topologies one needs to find a way to preselect an absolutely unbiased sample of events, i.e. a sample that preserves the relative contributions of the decay modes. In this analysis this goal is reached by applying a hemisphere based tau selection.

In symmetric e^+e^- machines, tau pairs are produced back-to-back, and at LEP, due to the high centre of mass energy they decay into very collimated *"jets"*, so it is rather easy to separate the particles coming from one tau or the other. Knowing that, one can try to identify separately the two taus applying separate cuts in the two hemispheres associated in some way (here by means of the thrust axis) to these particles. neglecting the spin anticorrelations and assuming that the two taus decay independently, we can create a sample of single tau *semi-events* free from selection cut biases by "selecting" the hemisphere opposite to the "identified" one. This is the core of this analysis. We used the "selected" sample of taus to estimate the various branching fractions. Of course, a single hemisphere identification cut cannot be very efficient compared to the classical one, as no full event information can be used, but as the sample is unbiased and with a small background it is possible to investigate the rare topologies escaping the usual tau-tau selection.

2 The single hemisphere tau preselection.

In order to have an unbiased sample of tau candidates, one must avoid to apply any cut on the kinematical or topological quantities related to this lepton. At LEP, where the $\tau^+\tau^-$ pairs decay into *"jets"* that are roughly back-to-back, very collimated and with small charge multiplicity, it is generally straightforward to assign the final particles to one or the other lepton, and so one can limit his analysis on the daughters of a single tau and, after applying identification cuts, take the remaining part of the event as a tau candidate. We know that the τ^+ and τ^- helicities are mostly anticorrelated, so there is not a complete "disconnection" between the two half-events informations, but as the tau polarization is small, this will introduce negligible biases into the final tau sample.

Using this "identify-one-and-select-the-other" method it is possible to collect at the end a sample of single taus that preserves completely all topologies and allows a study of rare configurations that are unavoidably and drastically biased if one applies any kind of full event selection.

The single tau preselection is based on particle identification and on kinematical cuts depending on the hemisphere topology.

First of all, each event is divided in two hemispheres by the plane orthogonal to the thrust axis. The following cuts are applied separately to the two so defined hemispheres.

Only hemispheres with one or three "good" charged tracks are accepted (a track is defined "good" if it has at least four hits in the ALEPH time projection chamber [2], its distance from the interaction point in the transverse (x, y) plane is less than 2 cm, the corresponding distance in the z coordinate less than 10 cm and its momentum greater that 100 MeV). On the "good" tracks we apply the same particle identification procedures used for the standard ALEPH tau branching ratios analysis and described in [1]. Just to recall we say that electron identification is based on dE/dx in the time projection chamber and on two variables that take advantage of the transverse granularity and the longitudinal segmentation of the electromagnetic calorimeter, and measure the degree to which an energy deposit in the calorimeter towers near the extrapolated track conforms to the expected from an electron. For muon and pion (or kaon) separation the hadronic calorimeter and muon chambers informations are used [2]. A particle with hard penetration and narrow shower profile or with associated hits in the muon chambers is identified as a muon. A likelihood method is used to combine all these informations and to produce the best estimate for the particle type.

As photons play a fundamental role in the identification, it is important to efficiently identify them. Also in this case we use the procedures described in [1]. We simply recall here that a photon is identified as a local maximum in the electromagnetic calorimeter towers of the first two stacks (this calorimeter is composed of three stacks [2]), when this tower is not associated to a charged track.

When a hemisphere has a single good track, the following cuts are applied (energies, momenta and masses are in GeV, GeV/c and GeV/c^2 respectively):

(i) If the charged particle is identified as an electron the hemisphere is rejected. This drastic cut is required to remove all backgrounds from Compton scattering events.

(ii) ($\tau \to \mu\nu\nu$-like *half event*): if the charged particle is identified as a muon the hemisphere is accepted if $10 < P_\mu < 30$ and there is at most one photon with $E_\gamma > 3$.

(iii) If the charged particle is identified as pion, the half event is accepted if $10 < P_\pi < 35$ and passes one of the following sets of cuts (photons must be understood as ordered by decreasing energy):

  (1) ($\tau \to \pi\nu$-like *half event*): no photons;

  (2) ($\tau \to \rho\nu$-like *half event*): one photon with $P_\gamma > 5$ and $0.2 < M_{\pi\gamma} < 1.0$;

  (3) ($\tau \to \rho\nu$-like *half event*): two photons with $0.1 < M_{\gamma_1\gamma_2} < 0.2$ and $0.5 < M_{\pi\gamma_1\gamma_2} < 1.5$;

  (4) ($\tau \to a_1\nu$-like *half event*): three photons with $0.5 < M_{\pi\gamma_1\gamma_2\gamma_3} < 1.5$ and ($0.08 < M_{\gamma_1\gamma_2} < 0.20$ and $P_{\gamma_3} > 4$ or $0.06 < M_{\gamma_1\gamma_3} < 0.22$ and $P_{\gamma_2} > 4$ or $0.04 < M_{\gamma_2\gamma_3} < 0.22$ and $P_{\gamma_1} > 4$);

  (5) ($\tau \to a_1\nu$-like *half event*): Four photons with $0.5 < M_{\pi\gamma_1\gamma_2\gamma_3\gamma_4} < 1.5$ and $0.08 < M_{\gamma_1\gamma_2} < 0.20$ and $0.02 < M_{\gamma_3\gamma_4} < 0.20$ (or the same with $M_{\gamma_1\gamma_3}$, $M_{\gamma_2\gamma_4}$ or $M_{\gamma_1\gamma_4}$, $M_{\gamma_2\gamma_3}$)

In the 3-prong case the hemisphere is accepted if there are fewer than five charged tracks, P_{tot} <40 GeV and $0.6 < M_{p_1p_2p_3} < 1.6$ and at least one particle is identified as pion ($\tau \to a_1\nu$ like *half event*).

After this the overall efficiency, as predicted by the Monte Carlo simulation is (24.14±0.07)% on hemispheres, which means 42.5% on events. This selection efficiency, as anticipated, is not very high, due to the very stringent selection cuts (the direct tau selection in ALEPH has an efficiency of about 78% [3]), to the requirement of having a small background contamination and to the fact that no cuts involving the full event topology or kinematics can be applied.

In addition a cut, asking to have no charged particles with $|\cos\theta| > 0.9$, must be introduced to remove hemispheres with particles too near the "badly covered" small theta region. This cut reduces the efficiency to (21.9±0.1)% and is used only for the "undetected decays" analysis.

1992 sample									
Sel.	Data 1992	All MC	$\tau^+\tau^-$ MC	Bkg MC	e^+e^- MC	$\mu^+\mu^-$ MC	$e^+e^-\mu^+\mu^-$ MC	$e^+e^-\tau^+\tau^-$ MC	$q\bar{q}$ MC
All	14112±119	14055±201	13565±200	491±17	187±10	110±6	147±10	35±8	13±2
ii (μ)	4620±68	4550±68	4333±67	217±11	-	71±5	144±9	3±1	-
iii-1 (π)	2836±53	2770±43	2607±43	163±9	129±8	26±3	3±1	3±1	2±1
iii-2 ($\pi\gamma$)	900±30	963±18	899±17	63±5	49±5	12±2	-	-	2±1
iii-3 ($\pi 2\gamma$)	2177±47	2190±36	2186±36	4±1	0.5±0.5	-	-	0.3±0.3	3±1
iii-4 ($\pi 3\gamma$)	818±29	780±16	777±16	3±1	0.5±0.5	-	-	-	2±1
iii-5 ($\pi 4\gamma$)	636±25	567±12	564±12	2±1	-	-	-	-	2±1
3-prong (3π)	2135±46	2236±37	2198±37	39±7	8±2	0.3±0.3	-	29±6	1±1

Table 1: Comparison between the number of selected hemispheres on 1992 data sample and normalized Monte Carlo predictions for the various selections. The error on data is statistical only, whereas the error on Monte Carlos take into account the error on luminosities and cross sections used to normalize them. Other Monte Carlo samples, like $e^+e^- \to e^+e^-e^+e^-$ or $e^+e^- \to e^+e^-q\bar{q}$, do not appear simply because they do not contribute in any channel. The "Bkg MC" column is the sum of the following ones.

1993 sample (peak only)									
Sel.	Data 1993	All MC	$\tau^+\tau^-$ MC	Bkg MC	e^+e^- MC	$\mu^+\mu^-$ MC	$e^+e^-\mu^+\mu^-$ MC	$e^+e^-\tau^+\tau^-$ MC	$q\bar{q}$ MC
All	9827±99	9705±134	9365±133	339±11	129±7	76±4	101±7	24±5	9±2
ii (μ)	3297±57	3141±46	2992±45	150±7	-	49±3	99±6	2±1	-
iii-1 (π)	1941±44	1912±29	1800±28	113±6	89±5	18±2	2±1	2±1	1±1
iii-2 ($\pi\gamma$)	646±25	665±12	572±14	44±4	34±3	9±1	-	-	1±1
iii-3 ($\pi 2\gamma$)	1507±39	1512±24	1509±24	3±1	0.3±0.3	-	-	0.2±0.2	2±1
iii-4 ($\pi 3\gamma$)	561±24	538±11	537±11	2±1	0.3±0.3	-	-	-	2±1
iii-5 ($\pi 4\gamma$)	427±21	391±8	390±8	2±1	-	-	-	-	2±1
3-prong (3π)	1507±39	1544±25	1517±25	27±5	6±1	0.2±0.2	-	20±4	1±1

Table 2: Same as tab. 1 but with 1993 data sample at $E_{cm} = 91.2$ GeV.

Selection	Data 1992/MC	Data 1993/MC
All	1.005±0.017	1.013±0.018
ii (μ)	1.015±0.022	1.050±0.024
iii-1 (π)	1.024±0.026	1.015±0.028
iii-2 ($\pi\gamma$)	0.935±0.036	0.972±0.043
iii-3 ($\pi 2\gamma$)	0.994±0.027	0.997±0.030
iii-4 ($\pi 3\gamma$)	1.049±0.042	1.042±0.049
iii-5 ($\pi 4\gamma$)	1.123±0.051	1.092±0.058
3-prong (3π)	0.955±0.026	0.976±0.030

Table 3: Ratio between data and normalized Monte Carlo samples.

No studies of efficiency are needed in this analysis, as the selected sample of half events, assumed as unbiased, will be taken as input for the following studies and represents a "starting sample" for the measurement.

Details on the number of selected hemispheres on data and comparison between this and the Monte Carlo predictions can be found in tables 1 to 3 (the quoted values are after the $\cos\theta$ cut). In these tables Monte Carlos are normalized to data by luminosity. For the computations of background contamination out of peak we assumed a flat distribution for gamma gamma backgrounds and we used the Caffo and Remiddi formula [4] to take into account the t channel of the Bhabha scattering.

As can be seen in these tables, the agreement between data and Monte Carlo simulations is within one sigma; disagreements are present in selections *ii*, *iii-2*, *iii-5* and *3-prong*, in particular on 1992 data; considering that background subtraction is not critical in these analyses, we add a 25% systematic error due to these inconsistencies.

Considering the hemispheres opposite to the identified ones, we have a sample of unbiased tau decay hemispheres with a small (6% without the $\cos\theta$ cut or less than 4% with this cut) contamination from $e^+e^- \to e^+e^-, \mu^+\mu^-, e^+e^-\mu^+\mu^-$. What one has to do, then, is to "count" the number of hemispheres with 7-prong or no signal.

3 The "≥7-prong" selection.

At this point we have an "unbiased" sample of tau half events on which it is possible to apply the selection for the ≥7-prong tau decay candidates. To have an easy-to-study procedure, we tried to reduce as much as possible the cuts maintaining on the other hand a good selection efficiency. The final selection is:

$$(N_{good} \geq 7 \ and \ M_i^{trk} < 1.9) \ or \ (N_{good} = 6 \ and \ M_i^{trk} < 1.55)$$

Where M_i^{trk} are the invariant masses (in GeV/c^2) of the good tracks present in the *half event*. Studies on a Monte Carlo sample of 2,000 $\tau^+\tau^- \to (7 - prong)(any)$ events [1] predict an overall efficiency of this selection of $(78.3 \pm 5.8)\%$ (the error is due to Monte Carlo statistics only).

To have an estimate of the systematics in this selection we varied the cuts on M_i^{trk} by ±0.1 GeV/c^2. The biggest variation of the efficiency is for $(N_{good} \geq 7 \ and \ M_i^{trk} < 1.8) \ or \ (N_{good} = 6 \ and \ M_i^{trk} < 1.45)$ that decreases the efficiency by 5.1%; we take this value as systematic error.

3.1 Results

In table 4 one can see the summary of the results. Contaminations are estimated using Monte Carlo simulations. As mentioned above, due to the small impact of this choice on the results, we take a 25% systematic error on background subtraction.

As already said, for the off peak 1993 data, normalizations are estimated using an analytical algorithm [4] for the Bhabha cross sections and assuming a flat cross section for non resonant $e^+e^-\ell^+\ell^-$ events. No events on data pass the selection. A visual scan of the sample of data hemispheres preselected and with $N_{good} > 5$ shows that no one looks like a tau event with a 7-prong decay.

The limits quoted in table 4 come from the relation:

$$B(\tau \to \geq 7\pi^\pm \ \nu \ n\gamma)(x\%C.L.) \leq \frac{N_x}{(N_{hem.} - N_{bkg} - E_{bkg}) \cdot (\epsilon_7 - E_{\epsilon_7})}$$

where E_i are the errors and N_x is 2.3 or 3 for x=90 or 95% confidence level.

This analysis allows a determination of the upper limit on the tau branching ratio that confirms the one presented in ref. [6]. The limit obtained using the data collected in ALEPH from 1991 to 1993 is:

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[1] To generate these events we used KORALZ 4.0 [5] with TAUOLA 2.5 that allows a flat phase space multipion tau decay into up to nine final pions.

Selected hemispheres (1991 peak)	6099
Selected hemispheres (1992)	17147
Selected hemispheres (1993 peak-1)	2161
Selected hemispheres (1993 peak)	11488
Selected hemispheres (1993 peak+1)	3307
Selected hemispheres (1991-1993)	40202
Total Background on 1991 peak data	348.8 ± 6.6
Total Background on 1992 data	972.9 ± 18.3
Total Background on 1993 peak-1 data	271.4 ± 5.4
Total Background on 1993 peak data	684.2 ± 12.9
Total Background on 1993 peak+1 data	285.1 ± 5.4
Total Background (1991-1993)	$2562.4 \pm 24.5 \pm 640.6$
Efficiency on 7-prong ϵ_7	$0.783 \pm 0.058 \pm 0.051$
7-prong candidates selected on data	none
$B(\tau \to \geq 7\pi^\pm\ \nu\ n\gamma)$ (90% C.L.)	$8.8 \cdot 10^{-5}$
$B(\tau \to \geq 7\pi^\pm\ \nu\ n\gamma)$ (95% C.L.)	$1.2 \cdot 10^{-4}$

Table 4: Final results for the 7-prong (or more) tau decays. In the quoted numbers, the first quoted errors are from Monte Carlo statistics, the second ones (if present) are from systematics (see text). the word "peak" refers to a beam energy of about 45.6 GeV.

$$B(\tau \to \geq 7\pi^\pm\ \nu\ n\gamma) < 1.2 \cdot 10^{-4}\ (95\% C.L.)\ (n \geq 0)$$

4 The "empty hemispheres" selection.

The first obvious request, for this selection, is to have no charged tracks in the hemisphere. For this analysis we used only the sample collected by ALEPH in 1992 and 1993. On data 130 events pass this cut (72 from the 1992 sample and 68 from the 1993 one). One can divide this sample of events in few well defined classes according to the topological characteristics:

- events where there is an obvious non reconstructed track, generally contained in the inner part of the detector;
- events with an energetic photon in the "empty" hemisphere, very collinear with the opposite charged track(s);
- events with signal in the ALEPH luminosity calorimeter [2] or with an indication of (charged) particles in the very forward or backward region;
- events where all particles are in one hemisphere: typical case for $\gamma - \gamma$ events or for events with a strong longitudinal initial state radiation;
- events with really nothing in one hemisphere and a "tau-like" topology in the other, that is what we look for.

With some additional cuts it is possible to reduce the sample without losing any of the good events. These requirements are:

i Less than 1 GeV in the luminosity calorimeter;

ii Less than 5 GeV in the electromagnetic calorimeter in a 90° cone around the thrust axis;

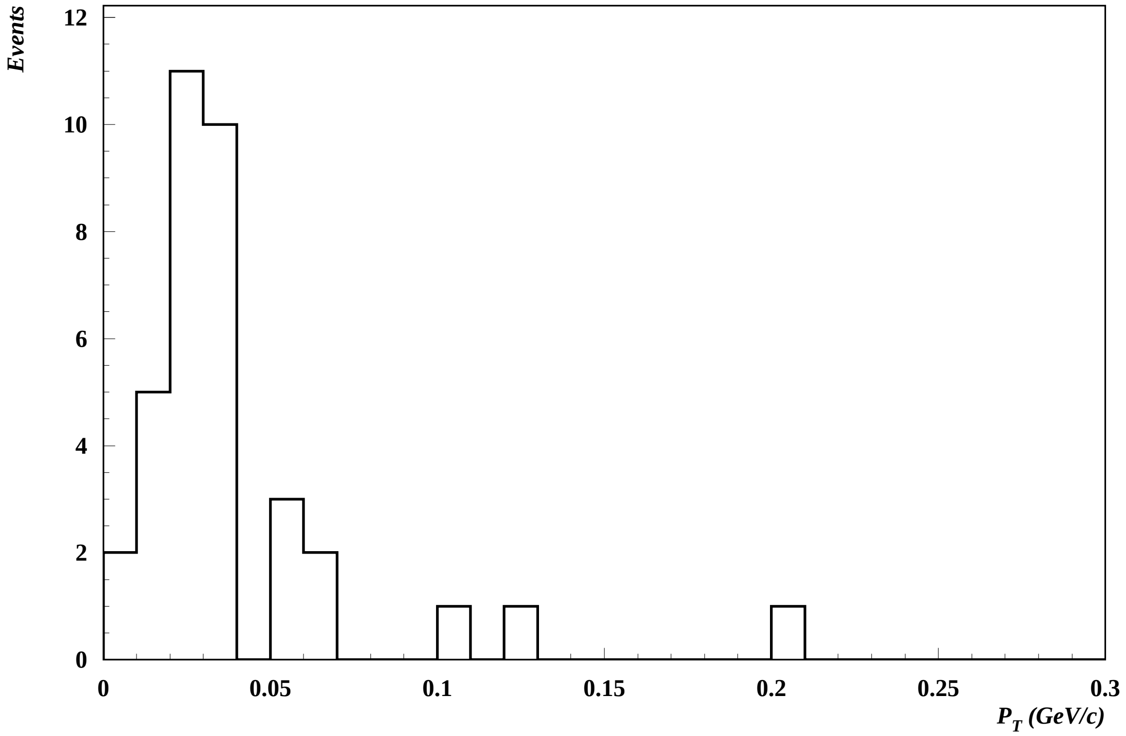

Figure 1: True transverse momenta of the "undetected" charged particles produced in Monte Carlo simulated tau decays. Particles with few tens of MeV cannot reach the active part of the ALEPH inner detectors, the generally die in the beam pipe or in the inner wall of the vertex detector.

iii Less than 1 GeV in the hadronic calorimeter in a 90° cone around the thrust axis;

iv Less than 3 ITC hits in a 78° ($\cos\psi > 0.2$) cone around the thrust axis.

v No hadron calorimeter cluster not associated to charged tracks and with more than 10 fired planes with one of more of them in the last 10 (the active part of the ALEPH hadronic calorimeter consists of 23 streamer tubes planes [2]).

Sel.	Data	Data 1992	Data 1993	$\tau^+\tau^-$ MC	Bkg MC	All MC
All	17	8	2+5+2	10.9±1.9	0.7±0.7	11.5±2.0
ii	4	0	0+2+2	5.9±1.4	-	5.9±1.4
iii-1	4	4	0+0+0	1.2±0.6	-	1.2±0.6
iii-2	1	0	0+1+0	0.3±0.3	-	0.3±0.3
iii-3	2	1	0+1+0	1.6±0.7	-	1.6±0.7
iii-4	1	0	0+1+0	-	-	-
iii-5	0	0	0+0+0	0.3±0.3	-	0.3±0.3
3-prong	5	3	2+0+0	1.6±0.7	0.7±0.7	2.2±1.0

Table 5: Comparison between the number of selected hemispheres on data samples and renormalized Monte Carlo predictions for the various selections. The error on Monte Carlos take into account the error on luminosities and cross sections used to normalize them. Monte Carlos are normalized to the full data sample luminosity. The three values for 1993 are for 89.5, 91.2 and 93.0 GeV centre of mass energies.

At the end we remain with 17 data events with an "empty hemisphere". The tau Monte Carlo predicts 10.9±1.9 events (these are events where one tau decays into an electron with a very low transverse momentum, as can be seen in fig. 1). Looking at the other Monte Carlo

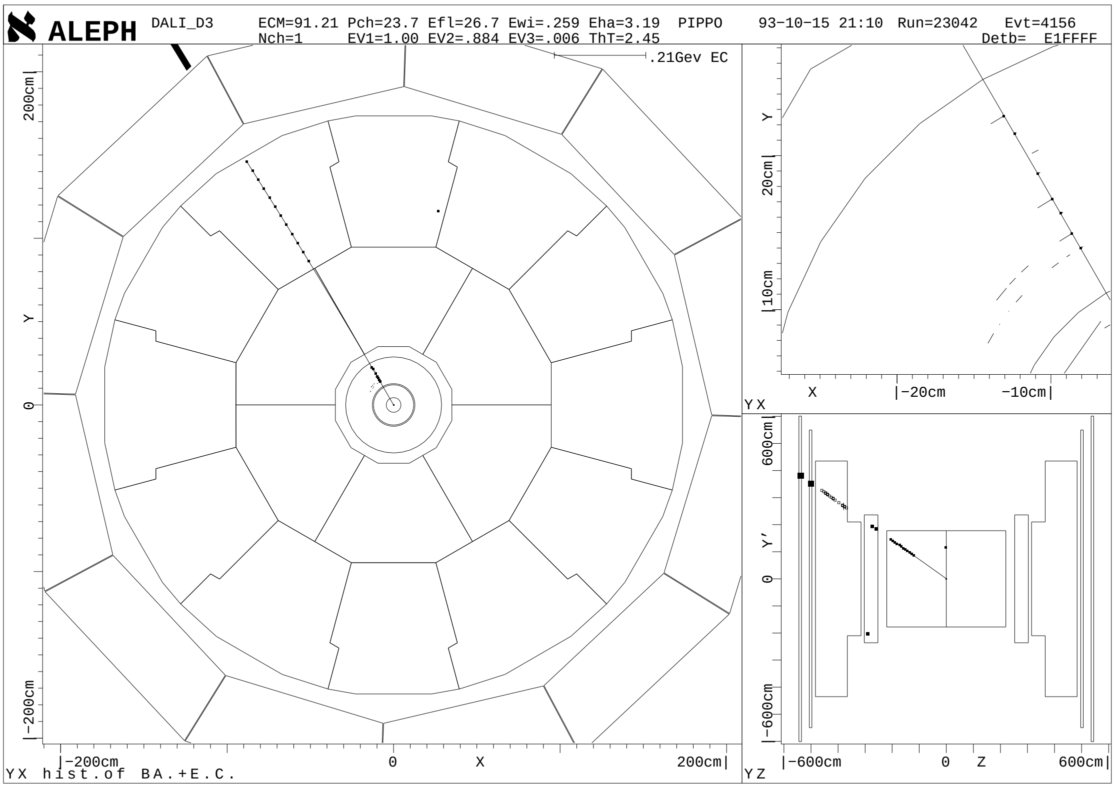

Figure 2: ALEPH, run 14984 event 5853.

Selected hemispheres (1992)	14122
Selected hemispheres (1993 peak-1)	1991
Selected hemispheres (1993 peak)	9827
Selected hemispheres (1993 peak+1)	2921
Selected hemispheres (1992-1993)	28861
Total Background on 1992 data	491.1 ± 13.2
Total Background on 1993 peak-1 data	146.3 ± 4.1
Total Background on 1993 peak data	339.0 ± 9.1
Total Background on 1993 peak+1 data	143.8 ± 3.9
Total Background (1992-1993)	$1120.2 \pm 17.0 \pm 280.1$
“empty” hemispheres selected on data	17
“empty” hemispheres predicted by tau Monte Carlo	10.9 ± 1.9
“empty” hemispheres predicted by background Monte Carlo	0.7 ± 0.7
“empty” hemispheres predicted by all Monte Carlos	11.5 ± 2.0
$B(\tau \rightarrow \ undetected)$ (95% C.L.)	$8.9 \cdot 10^{-4}$
$B'(\tau \rightarrow \ undetected)$ (95% C.L.)	$5.3 \cdot 10^{-4}$

Table 6: Final results for tau decays into undetected particles. In the quoted numbers, the first quoted errors are from Monte Carlo statistics, the second ones (if present) are from systematics (see text). The word “peak” refers to a beam energy of about 45.6 GeV. See text for the meanings of B and B'.

samples, only one $e^+e^- \to e^+e^-\tau^+\tau^-$ event is accepted, that means, normalizing to luminosity, 0.7±0.7 events. There is no way to remove it: unfortunately one of the two taus is at very low theta, so it is invisible to ALEPH.

In table 5 are summarized the number of selected events, for the various kinds of preselections.

4.1 Results

The final numbers are shown in table 6. In figure 2 is shown one of these events with a single muon track. The relation used for estimating the quoted upper limit is:

$$B(\tau \to \text{“}undetected''')(95\% C.L.) \leq \frac{N_{95\%}}{(N_{hem.} - N_{bkg} - E_{bkg})}$$

Where $N_{95\%}$ takes into account the background contamination for $B(\tau \to \text{“}undetected'')$, and also the tau Monte Carlo prediction for $B'(\tau \to \text{“}undetected'')$. The way to estimate an upper limit at some confidence level in presence of a non exactly know background contamination is described for instance in ref. [7].

As we select 17 data events with an empty hemisphere, we expect to have less than 24.5 events with a 95% C.L. Taking into account the tau Monte Carlo prediction, the 95% C.L. upper limit on events with empty hemispheres due to physics processes not included in the simulation is 14.5. So the upper limit on tau branching ratios into undetectable charged particles is (as in the ≥7-prong analysis we take a 25% systematic error on background subtraction):

$$B(\tau \to \text{“}undetected'') < 8.9 \cdot 10^{-4} \text{ 95\% C.L.,}$$

and if we statistically subtract also the tau Monte Carlo contribution we can quote a limit on tau decays into an electron with $P_T < 40$ MeV/c and undetectable neutrals not included in the standard description of tau decays as used in the Monte Carlo simulation:

$$B'(\tau \to \text{“}undetected'') < 5.3 \cdot 10^{-4} \text{ 95\% C.L.}$$

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