PHYSICS WITH THE MISSING ENERGY SIGNATURE AT COLLIDERS*

M. Dittmar

Eidgenössiche Technische Hochschule,
ETH Zürich, CH-8093 Zürich, Switzerland

(*Received October 31, 1994*)

Missing energy and momentum experiments in high energy particle physics are reviewed. The techniques, problems and succeses of such experiments are discussed using the historical example of the β decay, as well as the discoveries of the τ lepton and of the W boson. Recent missing energy experiments at the Z^0 peak, demonstrate the feasibility of the indirect neutrino detection method in large multi purpose detectors. The importance of missing energy detection capabilities for future experiments is emphasized with several search studies for new exotic phenomena at LEP2, the LHC and at a linear e^+e^- collider.

PACS numbers: 14.60. Fg, 14.70. Hp, 23.40. -s

1. Introduction

The most fascinating aspect of particle physics is the discovery of new fundamental phenomena with their subsequent theoretical explanations, as well as the experimental confirmation of new theoretical predictions. A large fraction of such surprises are related to the weak interaction and the neutrino. The **continuous β spectrum** [1], the **parity violation** in weak decays [2] and the observation of the **W** [3] and **Z^0** bosons [4] are a few well known examples. These experiments are often discussed as being examples for the relevance of good electron and muon identification of a detector. However, as will be shown, the indirect detection of the "invisible" neutrino has probably played an even more important role for these measurements.

The study of the weak interaction has also allowed to develop the theoretical framework of the so called Standard Model of electro-weak interactions [5], which currently describes the majority of high energy physics

* Presented at the XXXIV Cracow School of Theoretical Physics, Zakopane, Poland, June 1–10, 1994.

experiments to an astonishing accuracy. Nevertheless, the large number of unexplained "free parameters" is unsatisfactory thus motivating the search for new theoretical models. Examples of such exotic ideas are: Grand Unified Theories, Supersymmetry, massive right handed neutrinos and extensions of the bosonic sector of the Standard Model. Naturally, these ideas ask for new experiments about weak interaction phenomena in particular.

Neutrinos, which see only the weak force, are an ideal tool to study weak interaction phenomena. Unfortunately, the direct neutrino detection in a colliding beam experiment is impossible. However, the indirect detection of neutrino like particles with the missing energy and momentum technique has revealed many details of the weak interaction and will help study the W and Z^0 production dynamics at very high energies. In addition, a large fraction of exotic new particles would show up directly in missing energy experiments.

In the following text, some experimental and theoretical aspects of **Missing Energy Experiments** are discussed. Starting from the historical example of β decay, principle ideas of missing energy experiments in colliders and its use for the discovery of the τ lepton and the W boson are described. Searches for new phenomena with the missing energy technique at the Z^0 peak are reviewed and examples for the use of the neutrino in τ– and b–decay physics are given. Finally, some future prospects of missing energy physics at LEP2, the LHC and a hypothetical linear e^+e^- collider are discussed.

2. The missing energy signature of the β decay

A modern β spectrum, measured by Sherwood, [6] in 1966, for the muon decay ($\mu \rightarrow e\nu\nu$) at rest is shown in Fig. 1. The observed high precision continuous electron energy spectrum reveals immediately some basic properties of the muon decay:

- The muon has to decay into at least three particles as the two body decay is excluded, due to the absence of any structure in the decay spectrum[1].
- The mass of the emitted two additional particles has to be small, as energy and momentum constraints require that the maximum possible electron energy is half the muon mass minus the mass of the two emitted particles.
- The average electron energy is larger than one third of the muon mass. This unequal energy sharing demonstrates polarisation and parity violation in the muon decay. The resulting value of the Michel parameter,

[1] A hypothetical two body component to the μ decay would result in a kinematically constrained fixed energy value for the electron.

$\rho = 0.76 \pm 0.009$, was found in agreement with the V–A expectation of 0.75.

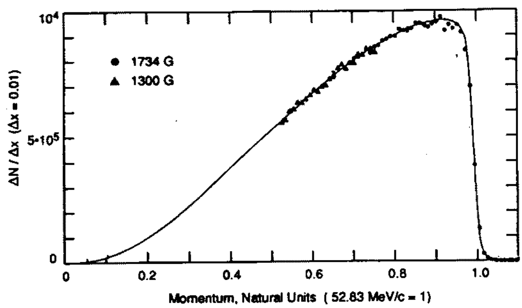

Fig. 1. A modern (1966) continuous β energy spectrum from the decay $\mu^- \to e^- \nu_e \nu_\mu$, [6], obtained with different magnetic fields.

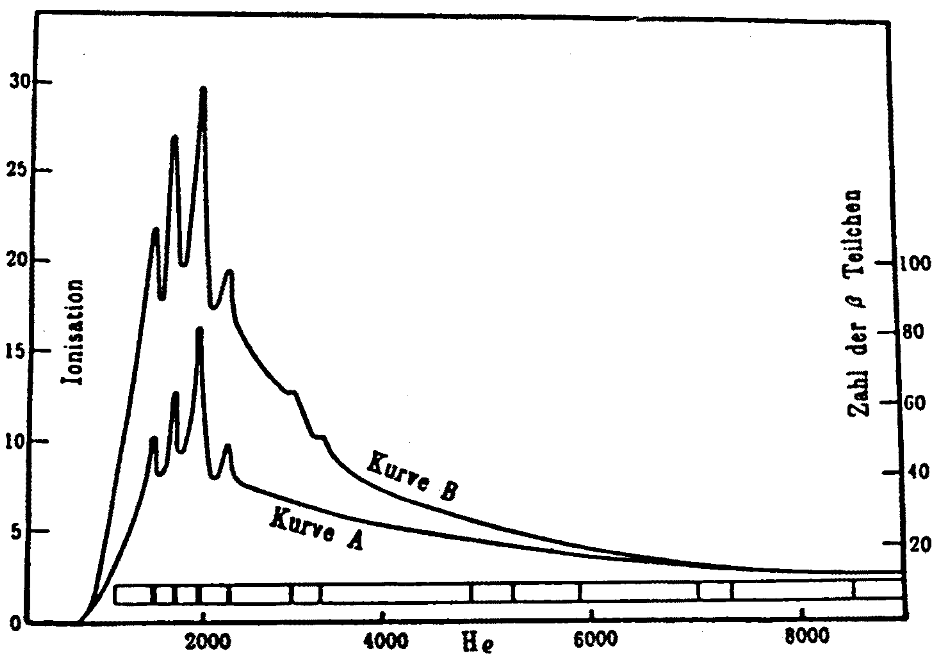

Fig. 2. The first continuous β decay energy spectrum 1914 [1], curve A and B are the results for different magnetic fields. The indicated black lines were the results from Rutherford and Robinson.

The electron energy spectrum obtained by Chadwick, [1] in 1914 for the nuclear β decay is shown in Fig. 2. Despite the much more complicated structure, this spectrum demonstrated for the first time that the electron spectrum in the nuclear β decay is continuous. The results of previous photographic experiments, also indicated in Fig. 2, found only the peaks in the spectrum and missed this discovery. This experiment was *unwanted*, as its only explanation at that time was a violation of the energy and momentum conservation law, a solution which was supported by Bohr [7]. Only 16 years later, in December 1930, Pauli proposed *"desperately"* a possible explanation of the β spectrum by introducing a hypothetical neutral particle with a small mass and spin 1/2 [8]. He presented his idea for the first time at the Pasadena APS meeting in 1931, but hesitated for two more years to publish it [9].

While the direct neutrino detection by Cowan, Reines and collaborators was made in 1956 [10], the first indirect neutrino detection experiment, using energy and momentum constraints, was published in 1952 by Rodeback and Allen [11]. They measured, using a time of flight technique, a monoenergetic recoil spectrum of Cl^{37} atoms, produced in the electron capture reaction $Ar^{37} + e^- \rightarrow Cl^{37} + \nu$. This recoil spectrum, shown in Fig. 3, provided evidence for the emission of a single neutral particle with a very small mass.

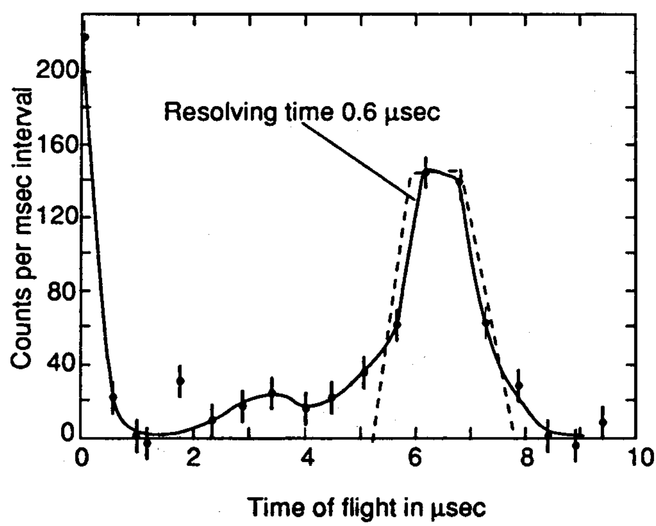

Fig. 3. The first indirect neutrino detection in 1952. Shown is the time of flight spectrum of Cl^{37} atoms in the reaction $Ar^{37} + e^- \rightarrow Cl^{37} + \nu$, [11]. The dashed curve is the distribution expected from monoenergetic recoils.

3. Concepts and motivations of missing energy experiments

Starting with the principle of energy and momentum conservation in a given process, the mass and momentum of an initial system of particles has to be recalculable, within the experimental errors, from the four momentum vectors of all final state particles. This principle allows, if the initial state is known, to estimate the energy and momentum of undetectable neutrino like particles. The basic ideas of indirect neutrino detection experiments are outlined in the following subsections.

3.1. The basic ideas of missing energy experiments

The simplest case, a two body decay of a particle with known mass and momentum–vector allows trivially, with the measurement of the mass and energy of one particle, to obtain the momentum and mass of the other perhaps undetected particle. For example, in the process $e^+e^- \to Z^0 \to \tau^+\tau^-$, the τ energy is half the Z^0 mass and for the subsequent decay $\tau \to \nu\pi$ the energy of the neutrino is the difference between the τ energy and the observed pion. Three body final states, like $\tau \to \mu\nu\nu$ are more complicated as the mass and energy of the two undetected particles are in general not fixed. Four and more body final states as well as cascade decays are non trivial. For example, a complicated exotic process like the pair production of the supersymmetric partner of the τ lepton, $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ with the subsequent decays $\tilde{\tau} \to \tau\tilde{\gamma}$ and $\tau \to \nu X$ involves at least four undetected particles. Nevertheless, a statistical analysis of a large number of well classified events, allows to distinguish between different possibilities as will be shown in the context of the τ–lepton discovery in the next section.

Even when the kinematics of a certain reaction are perfectly known, the real experimental challenge is to make sure that the missing particles are not introduced due to instrumental detection gaps and measurement errors. Having this challenge in mind, a good missing energy experiment has to fulfill the following criteria:

- The initial mass and momentum–vector of the analysed reaction or decay has to be known with the best possible precision. The cleanest conditions are found in e^+e^- collider experiments. Because of initial state photon radiation and two photon processes, even then missing energy and mass along the beam direction can not be excluded. Nevertheless, as these escaping particles are emitted with essentially zero transverse momentum, kinematic constraints in the plane transverse to the beam direction remain a powerful analysis tool. The possible constraints in collider experiments with protons, are reduced as the original center of mass energy of the interacting partons is not fixed. Still, the presence of neutrino like particles can be determined from the imbalance of the momentum vector transverse to the beam direction.

- The experiment has to be sensitive to charged and neutral hadrons, electrons, muons and photons and measure them with good precision over a very large fiducial volume. Unavoidable detection gaps in a large detector, will immediately show up as events with missing energy. With some efficiency loss, such geometrical well defined regions can be excluded with the requirement that the missing momentum vector is not pointing to this part of the detector. Most particles can be measured by different detector components and even short time failures of a specific component can be compensated by this large redundancy. The possible redundancy for photons is limited by the smallness of electromagnetic showers. As isolated energetic photons from bremsstrahlung have a relatively large cross section, a very good detection or veto efficiency for photons is essential for a sensitive missing energy analysis.
- As such a complete 4π detector is essentially impossible in a colliding beam experiment, the selection criteria for *interesting* missing energy events should reflect the kinematically possible missing energy due to resolution and detector gaps. For example, the missing transverse energy in two photon events ($e^+e^- \to e^+e^-$ X) can become quite large. In an experiment at a hypothetical e^+e^- collider at 500 GeV center of mass energy, which has a detection gap around the beam pipe of about 0.05 rad, the missing transverse momentum can be as large as 25 GeV ($2 \times 0.05 \times 250$ GeV) if both electrons are undetected. A discovery of a new process with a handful of events requires therefore that the observed candidates show a much larger missing transverse momentum than the detector related backgrounds.
- To obtain believable missing energy signals from neutrino like particles, the quality of a missing energy experiment should be demonstrated by well understood reactions. Reactions like the decay $Z^0 \to \ell^+\ell^-\gamma$ are for example an ideal tool to study resolutions and the power of geometrical constraints.

An example of a non exotic missing energy analysis, is given in [12]. Using the available geometrical constraints, the OPAL group has measured the photon energy in events of the type $e^+e^- \to \mu^+\mu^-(\gamma)$ where the photon escapes undetected along the beam line. The events were selected with the requirement that only two charged particles, identified as being muons, are seen. The two muons were required to be coplanar in the plane transverse to the beam direction and acolinear, indicating a large missing energy along the beam direction. The observed events can be explained with the two photon process $e^+e^- \to e^+e^-\mu^+\mu^-$ and with the reaction $e^+e^- \to \mu^+\mu^-(\gamma)$ with hard initial state photon radiation. Assuming that a photon has escaped along the beam direction, its energy was determined from the angles of the observed particles. With the requirement that the energy of the event, obtained from the momentum of the two muons plus the calculated photon energy, was close to the actual center of mass energy, a background free event sample of the type $e^+e^- \to \mu^+\mu^-(\gamma)$ with hard initial state photon radiation was selected. The rate for this process is proportional to the cross section at the observed mass of the $\mu^+\mu^-$ system. The observed seven events could thus be used to measure for the first time a cross section, of the reaction $e^+e^- \to \mu^+\mu^-$ at center of mass energies from 60–75 GeV. This result is shown in Fig. 4 together with the direct measurements at TRISTAN and LEP.

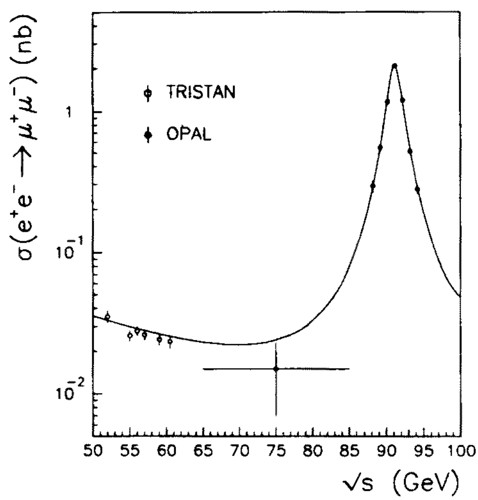

Fig. 4. The result of the indirect cross section measurement $\sigma(e^+e^- \to \mu^+\mu^-)$ at a center of mass energy of 75 GeV using the missing energy technique, in 1991 [12], precise direct measurements at LEP and TRISTAN are also shown.

3.2. Some motivations for future missing energy searches

Following the above requirements, a good missing energy experiment is able to see the presence of neutrinos or even more exotic objects. As neutrinos can only be produced in the weak interaction their presence is a clear sign of virtual or real W or Z particles. In addition, supersymmetric models predict a large number of heavy exotic particles, which could be detected by their decays into visible and undetectable neutrino like particles. The proposed searches for supersymmetric particles are therefore essentially all based on the detection of events with large missing energy. The indirect detection of neutrino like objects can thus be considered as a tool to study the weak interaction and hopefully even more exotic phenomena. The accuracy of such neutrino detection is not great, and clearly not competitive with the accuracy obtainable with electrons, muons or charged hadrons. However, this disadvantage is compensated by several facts:

- W's and Z's like to decay into neutrinos which are found in about 33% of all W–decays ($\rightarrow \ell\nu$) and in about 20% of all Z decays. This should be compared to W and Z BR's of 11% and 3.3% for each charged lepton type.
- The above branching ratio arguments favour even more the detailed study of hadronic final states. The abundant production of hadrons in the strong interaction limits their use for the study of weak decays in complex processes[2].
- The identification of electrons and muons with excellent accuracy and small backgrounds has become a standard in large colliding beam experiments. Unfortunately, charged leptons are not a unique sign of the weak interaction as electrons and muons are copiously produced in processes involving the "conventional" electromagnetic interactions.
- The disadvantage of the relative bad accuracy for neutrino measurements is reduced as in most weak decays, a continuous energy spectrum of all the decay products is expected.
- The accuracy for neutrino energy measurements is in general as good as the obtainable accuracy for the sum of all visible particles. Therefore, as will be described in Section 7.2, neutrinos inside a jet can be measured in e^+e^- collisions from the difference between the beam energy and the observed jet energy, $E_\nu \approx E_{beam} - E_{jet}$. As the relative jet energy resolution decreases roughly proportionally to $\sqrt{E_{jet}}$ an energetic neutrino from a semileptoni B–hadron decay at LEP can be measured with a quite good accuracy. For example, a 30 GeV neutrino can be detected indirectly with an accuracy of about 2 GeV, if the associated 15 GeV jet is measured in a calorimeter with an energy resolution of $50\%/\sqrt{E_{jet}}$. Such an accuracy is almost comparable to measurement errors for high energy muons; a resolution of better than $0.3\% \times p_t$ is required to measure a 30 GeV muon with a similar precision.
- While neither the lepton–charge nor the vertex of the originating particle can be obtained for the neutrino, the left handedness of the *known* neutrinos allows to determine the parity violation strength in a given weak process. The presence of the neutrino in τ decays allows for example to perform τ polarisation measurements.

---

[2] The accurate and efficient tagging of b–flavoured jets uses the long b–lifetime and the large number of charged hadrons in B–decays. This method provides currently the most accurate measurement of the Z^0 decay into a pair of b–quarks.

- Unfortunately, the beauty of missing energy experiments is almost proportional to its complexity. While the potential physics background is small, a plague for such experiments are known and unknown detector gaps and non gaussian measurement errors for all types of particles.

The feasibility of the missing energy detection in large collider experiments has been proven for example at LEP, where about 25% of all experimental LEP publications are based on (being able to see) nothing. Similar examples can be found from other large collider experiments.

The difficulties of the indirect neutrino detection are more than compensated by the few outstanding discoveries, which could be made in missing energy experiments. This success should encourage the continuation of such searches and should have an important impact on the design of the future omni purpose experiments.

4. Major discoveries with the missing energy technique

Two major discoveries in particle physics, the observations of the τ lepton and of the W boson, were essentially made with the missing energy signature and some moderate identification of electrons and muons.

4.1. The discovery of the τ lepton

The discovery of the τ lepton is usually discussed as an example for the importance of the good electron and muon identification power of an experiment. In contrast to this belief, one finds in the original τ discovery paper from 1975, [13], that the missing energy and momentum detection was at least equally important. This is documented already in the first sentence of the abstract:

"We have found events of the form $e^+e^- \to e^{\pm}\mu^{\mp}$ + **missing energy**, *in which no other charged particle or photon are detected."*

While at that time, the detection techniques of charged particles and photons with electron and muon identfication had become already standard in collider experiments, the geometrical almost 4π coverage had not. This incomplete geometrical coverage was the origin of the search restriction to lepton final states, which have the now known small branching ratio of about 17.5%. The τ discovery was therefore made with a detector, which could exploit only about 6% of the total $\tau^+\tau^-$ cross section.

Nevertheless, as will become clear from the following summary of the first publications [13], even with the "bad" neutrino detector, the missing energy characteristics of the events allowed to demonstrate the exotic (at that time) origin of the events. The most important kinematic properties of the observed events, shown in Fig. 5a-c, allowed to claim the observation of the now called τ lepton. The main criteria were:

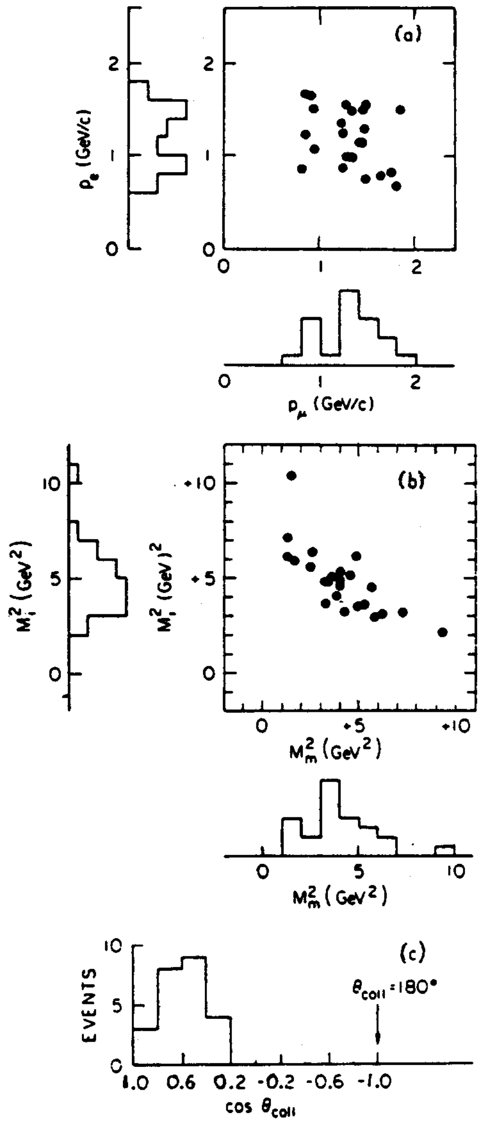

Fig. 5. The most significant distributions for the τ discovery 1975 [13]. The figures show (a) the electron and muon momenta (b) the invariant mass and the missing mass squared and (c) the colinearity angle.

- The energy distribution of both charged leptons did not show any structure and was much smaller than the beam energy.
- The observed mass and the missing mass distributions are continuous and clearly different from 0, demonstrating that at least two particles escape the detection.
- The observed two leptons are acoplanar and acolinear.

The opposite charge of the two leptons indicated that possible failures or inefficiencies for charged particles could be excluded as the origin of these events. Such detector problems would have resulted in about the same number of events with opposite and same charge lepton pairs. As the missing mass of these events was clearly different from 0, at least two energetic photons had to be produced and escape unseen by the experiment; again the observed rate and the missing mass distribution could not be explained by such processes. Consequently a new phenomenon had been observed. Fig. 5a-c show the experimental distributions which allowed to claim the observation of the later called τ lepton.

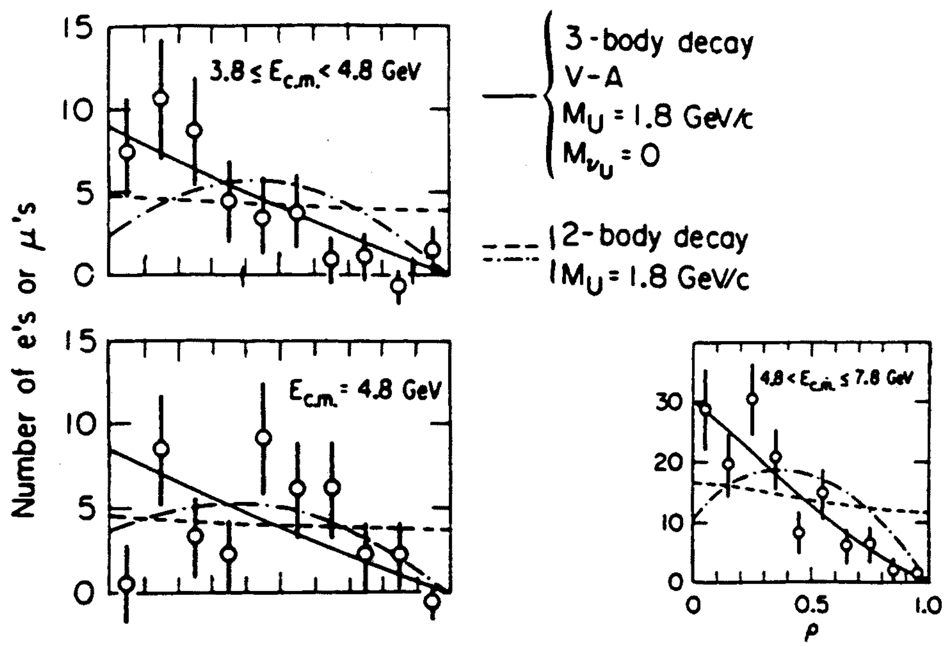

Fig. 6. The 1979 [13] evidence for the three body leptonic τ decays, $\tau \rightarrow \ell\nu\nu$, the variable ρ is defined as $\rho = (p_\ell - 0.65)/(p_{max} - 0.65)$.

In the following paper (1976), which could use a slightly larger data sample, it could be demonstrated that this new particle had the properties of a new heavy lepton with a mass almost 20 times heavier than the muon or twice as heavy as the proton. It was also shown that the hypothesis of pair produced new heavy leptons gave an excellent description of the observed events. In detail using the acollinearity angle and the observed energy spectrum it could be shown that the mass of a new pair produced particle had to be between 1.6 GeV and 2 GeV and that its observed decay was inconsistent with a two body decay. The charged lepton energy distributions were found to be consistent with the ones expected from the three body decay of a new heavy particle with a V–A decay structure. Furthermore, the mass of the two invisible neutrino like particles had to be small. These conclusions are based mainly on the observed lepton energy spectra, shown in Figs 6a-c.

In the third paper (1977), the τ mass could be determined with a 5% accuracy and the corresponding neutrino mass was found to be smaller than 600 MeV (at 95% c.l.) using the distribution shown in Fig. 7. Furthermore, the leptonic branching ratio was measured to be around 18%.

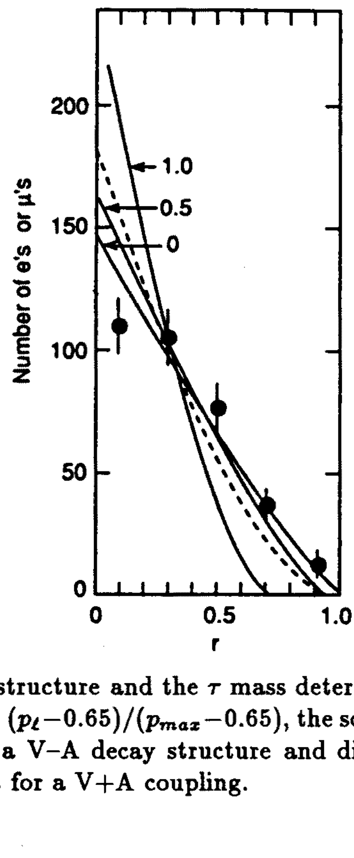

Fig. 7. The V–A decays structure and the τ mass determination in 1977 [13]. The observed distribution $r = (p_\ell - 0.65)/(p_{max} - 0.65)$, the solid curves are expectations for m_τ = 1.9 GeV with a V–A decay structure and different neutrino masses in GeV, the dashed curve is for a V+A coupling.

4.2. The discovery of the $W^{\pm}$

Based on the well defined predictions of the W–properties, as mass, branching ratios and cross section, experiments for the detection of W$\rightarrow \ell^{\pm}\nu$ at the CERN $p\bar{p}$ collider were designed. The importance of the missing transverse energy detection capabilities for the UA1 collaboration is documented in the UA1 proposal (1978) [14]. The discrimination power of the combined measurement of energetic charged leptons and the missing transverse energy and momentum of the event is shown in Fig. 8.

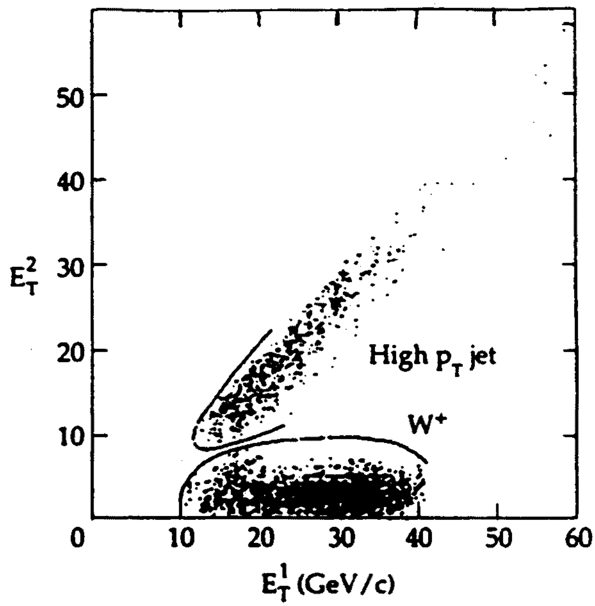

Fig. 8. The expected missing energy signal for electron candidates with a p_t above 10 GeV from the UA1 proposal [14]. Essentially no energy is deposited opposite to electrons from the decay $W \rightarrow e^{\pm}\nu$. In contrast to the missing energy signal events, the p_t of wrongly identified electrons is balanced by a large energy deposit due to a jet.

The simulation shows a clear separation between the expected W–boson signal and possible backgrounds. The relevance of this missing energy detection is also described in a recent report by Rubbia about the W and Z discovery [15], where he is pointing out especially the missing transverse energy detection capabilities of the UA1 experiment saying on page 258-260:

"There are several important things in the UA1 proposal that should be mentioned. One of these was the idea of the missing transverse energy that allows the characterisation of events by their energy flow balance. The processes to be observed were the decays of the W into a charged lepton and a neutrino. ... This (the indirect neutrino detection) was achieved with the appropriately designed detector which was quite uniformly sensitive and hermetic. ... This was a crucial aspect of the experiment which at the beginning, was not sufficiently understood, since many people thought that we would not be able to discover either the W, because of lack of signature, or the Z^0 *because of the low production rate."*

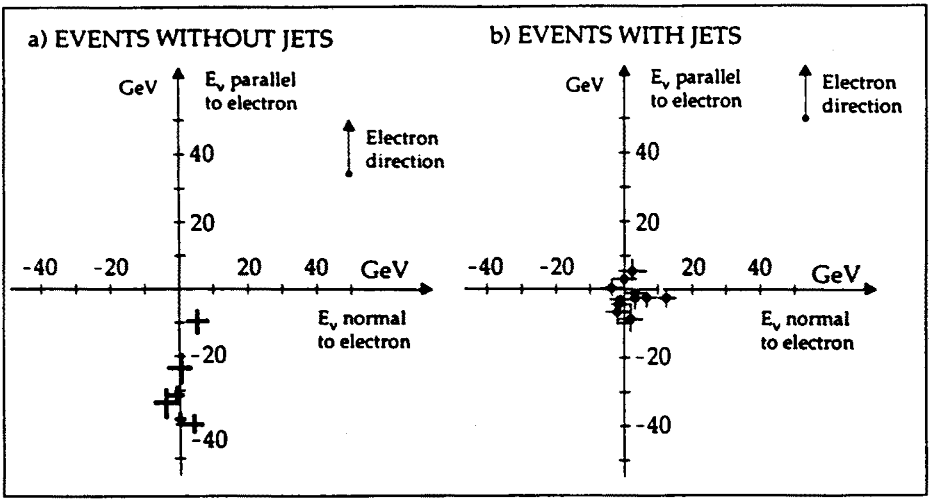

Fig. 9. The discovery signal of the decay W$\to e^{\pm}\nu$ from UA1 in 1983 [3], shown are the missing energy signals (a) for the W–candidates and (b) for backgrounds.

This possibility of a missing energy experiment in a hadron collider experiment was prompted by skepticism, but the reality of this proposal was demonstrated only a few years later (1983) with the discovery of a handful of W events by UA1 and UA2 [3], using exactly the proposed combination of the charged lepton and neutrino identification with the missing energy technique. The missing energy associated to electron candidates from UA1, the proof for the W observation, is shown in Figs 9a and 9b. After having improved the statistics considerably, the missing energy signals from UA1 and UA2 in 1987 are shown in Figs 10a and b [16]. The small shoulder seen in the UA2 case is not competitive with the clear neutrino signal from UA1. The reason for this difference originates from the original UA2 design (Fig. 11a), with large detection gaps around the forward region of the experiment [17]. These detection gaps were closed in the upgraded UA2 experiment (Fig. 11b) [18], which allowed them to exploit the large statistics phase of the CERN $p\bar{p}$ collider with a high precision W mass measurement with a relative accuracy of about 0.5% [19].

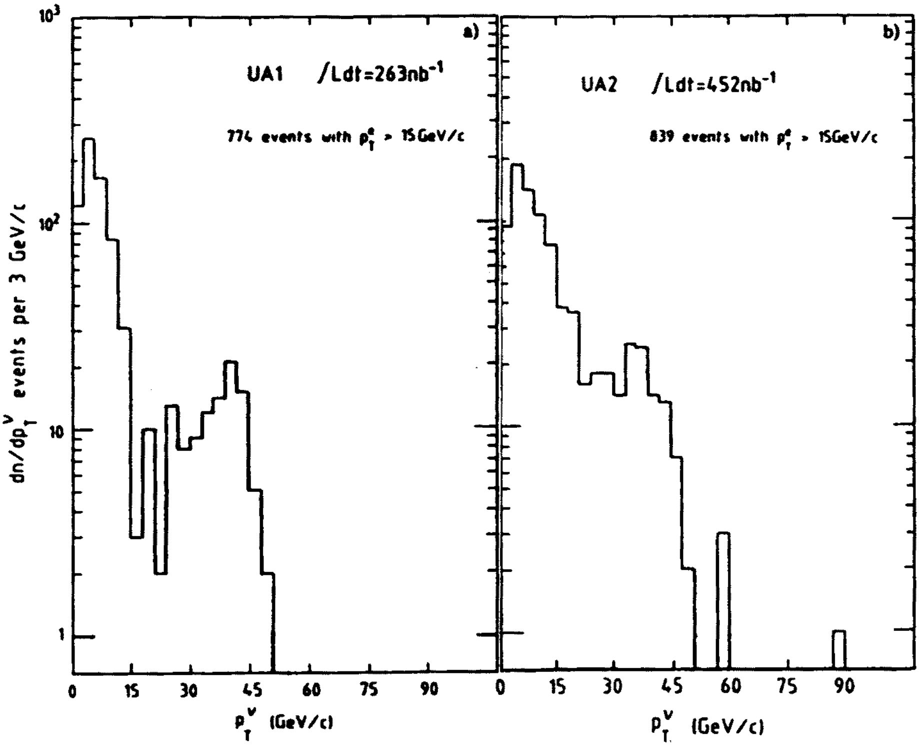

Fig. 10. The 1987 missing energy signals from UA1 and UA2 for the decay $W \rightarrow e^{\pm}\nu$ [16].

5. Missing energy searches for new physics at the Z^0 peak

Searches at a new collider can be devided into the search for new particles and the search for rare particle decays. While the first type of searches is sensitive to a kinematically limited mass range, the second type of searches uses the high production rate of particles like the Z^0 , the b–quark and the τ to look for decay rates which are not explained within the Standard Model. A large fraction of these searches exploit the presence of neutrinos or neutrino like particles in the decay. A few examples of such missing energy searches at LEP will be described.

5.1. Early searches

Early direct searches for new physics at LEP concentrated on the search for the pair production of new heavy particles like supersymmetric particles, new heavy charged or neutral leptons and new quarks. In most cases, the Z^0 decay Branching Ratio into these exotic new particles can be calculated as a function of their mass and spin. In the case that no signal

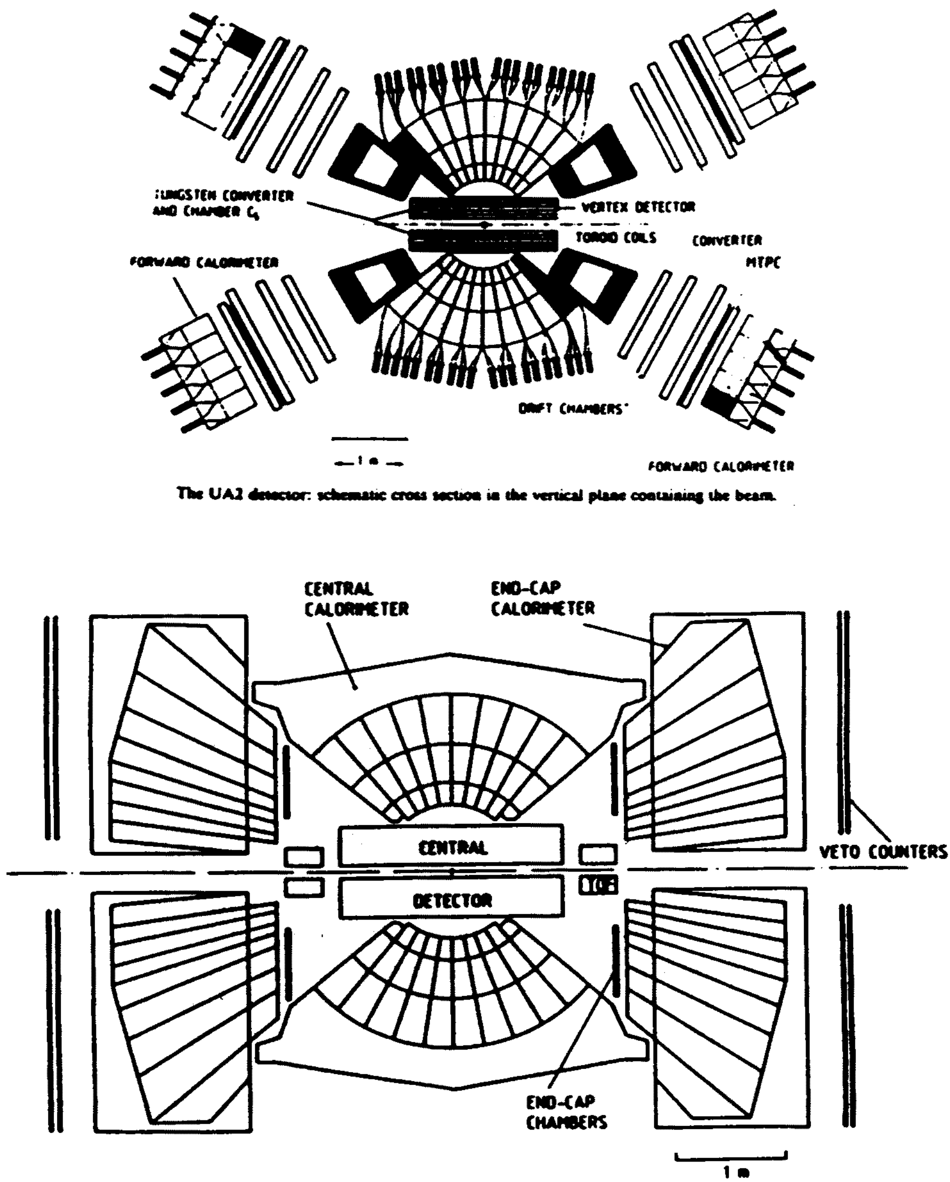

Fig. 11. The orignal [17] and the upgraded UA2 experiment [18].

is observed, the absence of the searched for signatures can be turned into mass limits. With the high cross section at the Z^0 pole, even with only 0.5 pb^{-1} essentially the kinematic limit of half the Z^0 mass were reached, allowing to exclude these particles much before a similar precision from the

Z^0 lineshape measurements was obtained. Examples of such searches in Z^0 decays are charged and neutral heavy leptons ($L^\pm$, N^0), the charged Higgs ($H^\pm$) or supersymmetric particles like the $\tilde{\tau}$:

- $Z^0 \to L^+L^- \to W^{*+}W^{*-}\nu\nu$
- $Z^0 \to N^0N^0 \to Z^*Z^*\nu\nu$
- $Z^0 \to N^0N^0 \to W^{*+}W^{*-}\ell^-\ell^+$
- $Z^0 \to H^+H^- \to \tau\nu\tau\nu$
- $Z^0 \to \tilde{\tau}^+\tilde{\tau}^-$ with $\tilde{\tau} \to \tau\tilde{\gamma}$ and $\tau \to \nu X$

As seen from the above list, many of these exotic particles would decay into at least one neutrino like particle. The detailed and most up to date limits obtained from specific searches can be found for example in [20]. As no exotic missing energy signal has been observed so far at LEP, we prefer, instead of going into details of a certain excluded model, to discuss some general aspects of these missing energy searches.

An example for such a general search is given in an early publication from OPAL (1989) [21], where especially the search strategy for acoplanar τ like jets was motivated by a general search for events with large missing energy due to one or more isolated neutrino like particles. This isolation requirement for neutrinos is obtained by requiring that the observed particles or jets are very acoplanar in the plane transverse to the beam direction. To be as sensitive as possible no requirement for any particle identification was used in this analysis. In the case of a hypothetical signal, detailed studies of the events, including particle identification, is required to understand the origin of the observed events. The studied signature was low multiplicity events with 2-8 charged particles and the visible energy of the detected particles had to be larger than 5% of the center of mass energy. The tracks and calorimeter clusters were then combined into jet like objects if they were found within a geometrical cone with an opening angle of smaller than 20 degrees. The size of the cone was chosen such that most of the τ decay products would be found in this cone.

The events were then classified into different jet multiplicities. For this analysis, exactly two such jets, each with a minimum energy of 3 GeV were required. The distribution for the acoplanarity angle between these jets is shown in Fig. 12a. The observed events are not completely back to back as especially Z^0 decays into $\tau^+\tau^-$, with the subsequent τ decays into νX will result in a small acoplanarity between the observed jets. Pair produced heavy new particles, which would decay into τ and neutrino like particles would show an essentially flat acoplanarity distribution of the two jets as also shown in Fig. 12a for supersymmetric $\tilde{\tau}$ leptons with a mass of 40 GeV. The non existence of events with an acoplanarity angle of more than 20 degrees due to missing neutrino like particles allowed to exclude the existence of $\tilde{\tau}$ particles with a mass of less than 43 GeV.

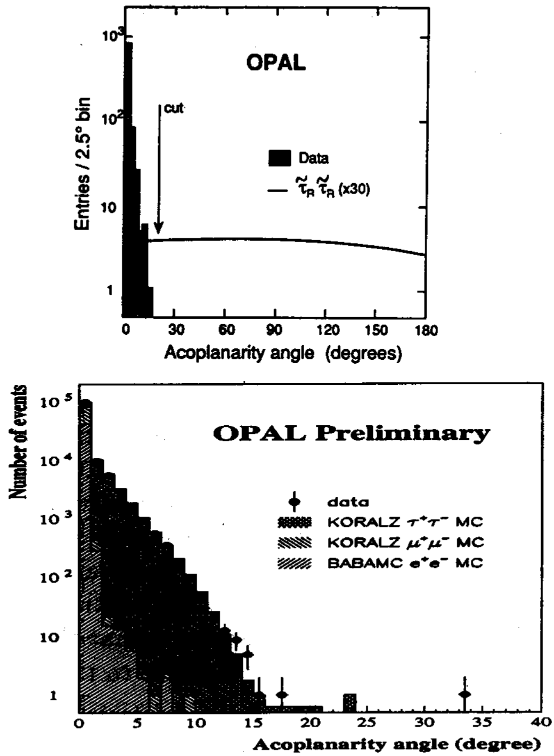

Fig. 12. The observed acoplanarity distribution of low multiplicity 2–jet events from OPAL, (a) from about 17k Z^0 decays (0.5 pb^{-1}) in 1989 [21] and (b) with about 2100k Z^0 decays (60.8 pb^{-1}) in 1994 [22].

Having immediately excluded the pair production of new particles, the search for such clean and background free acoplanar events at LEP has continued. For example OPAL has updated the search for acoplanar low multiplicity 2–jet like events [22], using essentially identical criteria as in the 1989 analysis. The preliminary acoplanarity distribution of the events, which corresponds to more than two million produced Z^0 decays, is shown in Fig. 12b together with the expectations from leptonic Z^0 decays. The data are obviously well described and only one event, with an acoplanarity angle between the two jet like objects of 33 degrees is found. From a detailed study of this event the authors conclude that the most likely interpretation of the event is a rare but still non exotic $\tau^+\tau^-$ event.

5.2. Higgs search

The Higgs particle [23], expected within the Standard Model, could be produced at LEP in the following process:

$Z^0 \rightarrow Z^*H$ with subsequent decays of the Higgs $H \rightarrow b\bar{b}$, $\tau^+\tau^-$ and $c\bar{c}$. For Higgs masses above 15–20 GeV, the expected dominant decay mode is the one into b–flavoured jets; the Z^* is expected to decay about 70% into $q\bar{q}$, 20% into neutrinos and 3.3% into each pair of charged leptons.

The largest event rate is expected for the four or more jet final states, but a signal would be hidden in the huge background from multi jet hadronic Z^0 decays. The signature with two jets and two charged leptons or two neutrinos is found to give a detectable signature up to a Higgs mass of slightly above 65 GeV at the Z^0 peak.

Looking into the early pre LEP simulations of the Higgs search, the simple decays of the Z^* into charged leptons were considered as the most significant signal types and were of major importance for the design of the LEP experiments [24]. These early studies concluded also that almost background free Higgs signals can be obtained for masses up to 50 GeV, if the Z^* decays into electrons or muons. The Higgs detection in the neutrino channel was assumed to give a less significant signal.

In contrast to these early expectations, the cleanest and most significant results from the four LEP experiments are obtained in the case where the Z^* decays into neutrinos and the Higgs into hadrons or into $\tau^+\tau^-$ pairs. The reason is not only the larger branching ratio of the Z^* to neutrinos but also the small background.

Using about 2–2.5 million produced Z^0 events per experiment, all LEP experiments report a few events for the charged lepton channel with a recoil mass of the hadronic system above 30 GeV [25]; ALEPH finds 3 candidate events, DELPHI sees 4 events, L3 has observed 4 events and OPAL finds 1 event. No clustering at any recoil mass is seen for these events. The observed event rate is in good agreement with expectations from 4–fermion Monte Carlo simulations. A large fraction of these background events can be further distinguished from signal events by their small fraction of $b\bar{b}$–jets. Thus, with the additional requirement of a positive b–jet identification, with for example a b–lifetime tagging, backgrounds are further reduced and only one Higgs candidate event, with a mass of 61.2 ± 1 GeV, remains. This event is found by OPAL in the $\mu^+\mu^-$ jet-jet channel and fulfills b–tagging requirements.

For the Higgs searches with the Z^* decaying to neutrinos, no candidate event with a mass above 30 GeV is found in any of the four LEP experiments. Therefore, in contrast to the early studies, the missing energy Higgs searches, are not only very sensitive, but provide also the most relevant results, as can be seen for example in Fig. 13. Furthermore, it is the absence of any candidate in the neutrino channel, which allows to exclude the existence of a Standard Model Higgs with a mass below 64.5 GeV (95% c.l.), using the combination of the four LEP experiments [26].

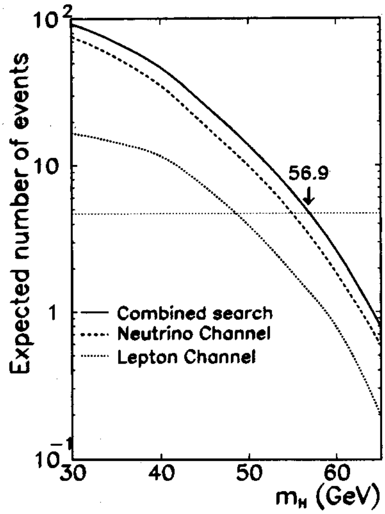

Fig. 13. The 1994 Higgs search results from OPAL [25], showing the importance of the neutrino channel. The dotted horizontal line indicates the 95% c.l. upper limit of 4.7 events obtained from the candidate event in the $\mu^+\mu^-$ jet–jet channel; the result from the neutrino channel alone would give an upper limit of 3 events with a slightly higher mass limit.

5.3. Searches for rare exotic Z^0 *decays*

The negative results from the early searches have allowed to exclude the pair production of new heavy particles with a mass of up to half the Z^0 mass. With the improved statistics of up to a few million Z^0 decays per experiment, the detection of rare Standard Model forbidden Z^0 decays became an interesting possibility. While neither masses nor mixing angles can be predicted, searches will result in either the observation of events which can not be explained within the Standard Model or will limit these exotic Z^0 branching ratios. The below given possible Z^0 decays would be detectable as events with large missing energy:

- $Z^0 \to N^0\nu$ with $N^0 \to W^+l^-$ or $N^0 \to Z^*\nu$
- $Z^0 \to W\pi$
- $Z^0 \to \tilde{Z}\tilde{\gamma}$ with $\tilde{Z} \to Z^*\tilde{\gamma}$

The observable decay products are non back to back and for a relatively small mass of the N^0, all the decay products would be found in a narrow jet. The resulting events, a single low mass jet with large missing energy and momentum, are often called monojet events. A typical example of such a signature, the single production of a massive neutrino via mixing has been investigated in [27]. The expected Z^0 branching ratio for a fixed mixing angle ε as a function of the N^0 mass is shown in Fig. 14a. It was found that

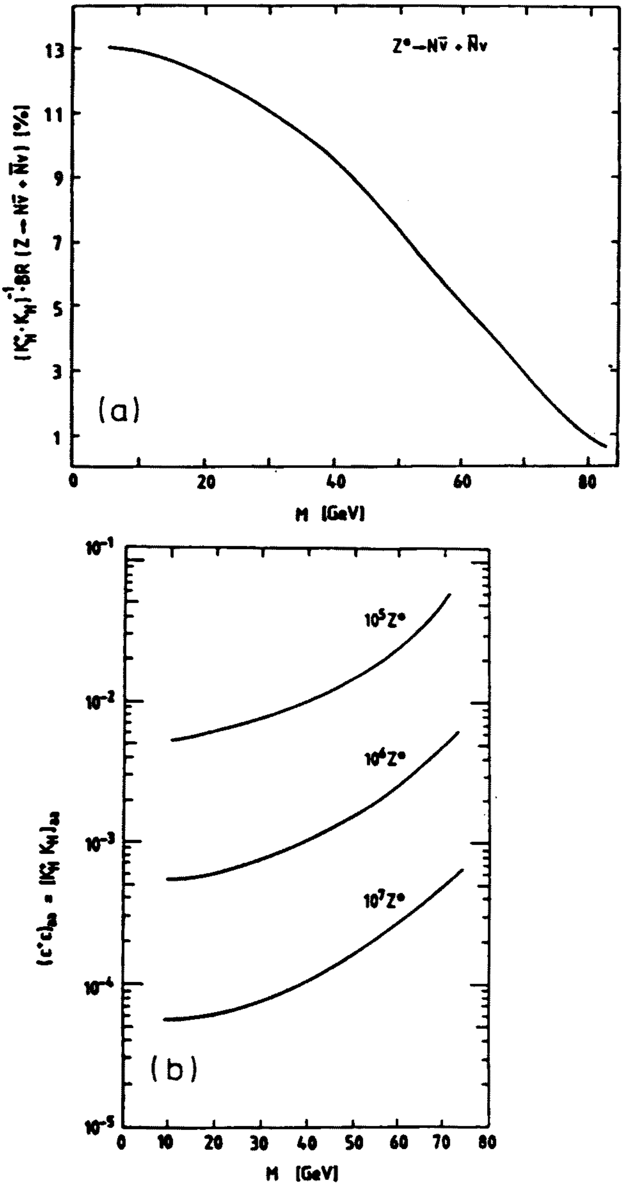

Fig. 14. Expected Z^0 Branching ratio (a) and (b) sensitivity for the decay, $Z^0 \to N^0\nu$, as a function of the mass and mixing angle ϵ of an exotic isosinglet neutrino N^0 [27].

the considered single massive neutrino (N^0), could be detected with high efficiency and without essentially any background from Standard Model sources up to a few million Z^0 decays. The studied signature were monojets and acoplanar τ like jets with large missing energy. The obtainable mixing angle is shown in Fig. 14b as a function of the N^0 mass and the number of used Z^0 decays.

Because of the long list of possible rare exotic Z^0 decays, the search for such acoplanar events and monojets has continued in all LEP experiments. The high statistics search for acoplanar events from OPAL has already been described in section 7.1 and searches from the other experiments are discussed for example in [28]. About one such candidate event including background is found per million Z^0 decays limiting such exotic Z^0 decays to BR's smaller than about 5×10^{-6}. Unfortunately, the results are difficult to combine as detector related backgrounds were sometimes allowed.

Recently, the ALEPH collaboration has published the observation of three monojet events which were found in a sample of about 2.8 million Z^0 decays [29]. The described analysis excludes detector related backgrounds to a negligible level of less than 0.04 events. From a detailed study of various higher order reactions involving the production and decays of virtual W and Z^0 bosons, they expect to find about 2.75 events in good agreement with the data. However, two out of the three observed events show rather untypical transverse momenta and masses; these events are shown in Figs 15a and b. The authors conclude that the considered higher order reactions can explain the observed events with a rather high probability of about 5%. As the other three collaborations did not report similar events the combined significance for a possible exotic origin of the events is further reduced.

From another point of view, assuming that the detector related backgrounds have been excluded while keeping a similar signal efficiency, about 8 additional monojet events should be seen by the other three LEP experiments. Surprisingly, the other collaborations did not find or report on any such monojet events. This apparent contradiction between the observed three rather untypical ALEPH events and a total expectation of more than 10 monojet events can be solved only once similar detailed analysis are performed by the other LEP experiments. Regardless of the outcome of future detailed searches, we believe that the existence of these spectacular events is already a justification for further high luminosity LEP running at the Z^0 pole.

Another area of rare Z^0 decay searches are Standard Model forbidden decays involving lepton flavour violation, like the decay $Z^0 \rightarrow \tau\ell$, with ℓ being an electron or a muon. Such decays could exist if the lepton sector of the Standard Model could be described in a similar way as the quark sector with some small Cabbibo like mixing angles. This could be the case if neutrinos would have a small mass. So far no lepton flavour violation has been observed but the search technique for Z^0 decays into a τ and

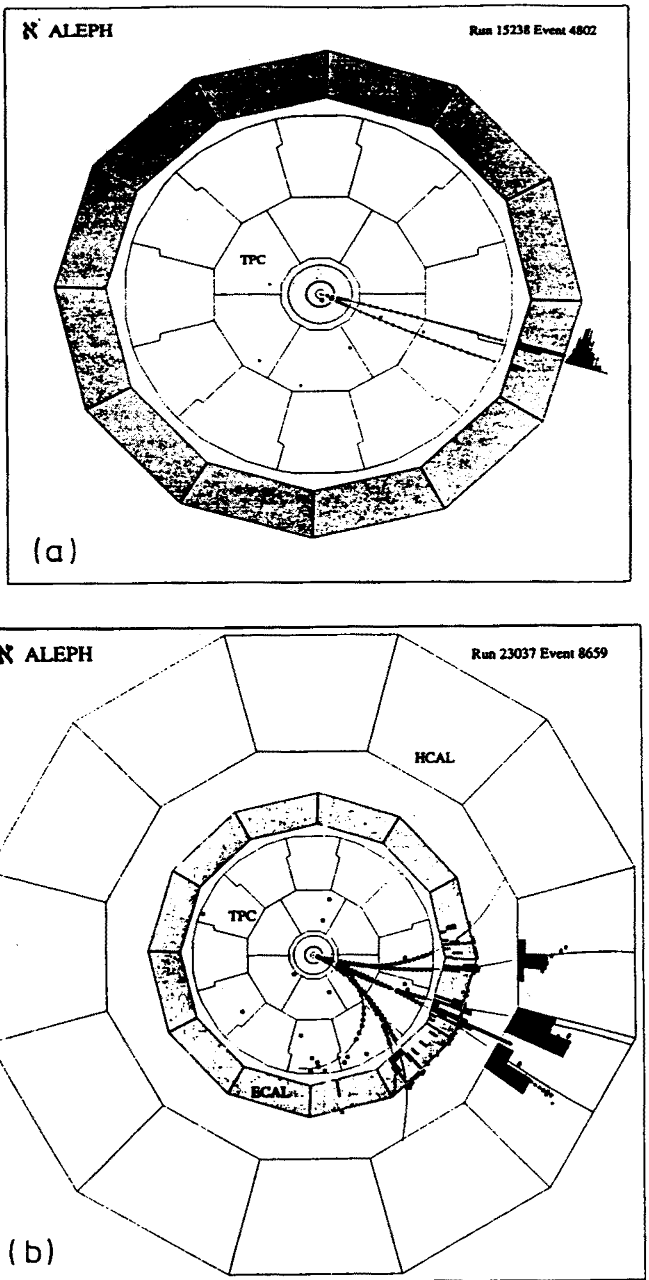

Fig. 15. The two spectatular "monojet" events from ALEPH [29], (a) shows the event with two electrons, their mass is 3.3 GeV and the calculated invisible recoil mass is 61.3 ± 0.6 GeV; (b) shows the single hadronic jet with a mass of 5.3 GeV, the invisible recoil mass is 69 GeV.

an electron or a muon is quite challenging as a possible signal has to be separated from the large background of leptonic Z^0 decays.

For this search one has to look for events with an electron or a muon with exactly the beam energy, recoiling against the decay products of a τ. The identification of the τ is based on the visible τ decay products and the large missing energy associated to the emitted neutrino. The background from leptonic τ decays into energetic electrons and muons can be reduced from

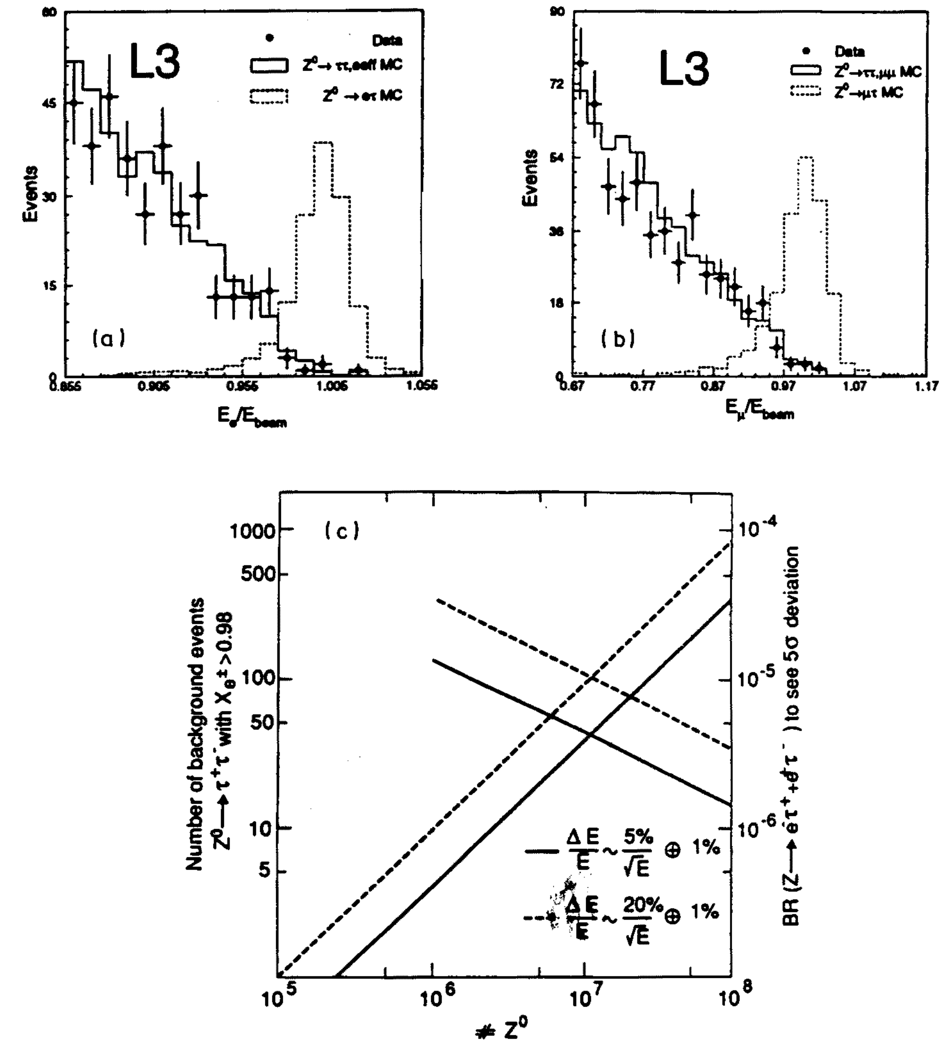

Fig. 16. The L3 energy spectra of high energy (a) electrons and (b) high energy muons recoiling against the decay products of a τ from 1994 [31]; (c) shows an early prediction for the number of background events and the expected sensitivity [32] for the decay $Z^0 \to e\tau$ as a function of the number of analysed Z^0 decays.

the detailed analysis of the highest energy electron and muon candidates. Because of the presence of two neutrinos, the maximum lepton energy in τ decays is slightly smaller than the beam energy. A sensitive search at the level of a Z^0 branching ratio in the region 10^{-5} and smaller requires an excellent resolution for high energy electrons and muons. The first search of this type has been performed by OPAL in 1990, using about 200k Z^0 decays [30]. They had reached a BR limit of 7×10^{-5} for the decay $Z^0 \to e\tau$. Currently, the L3 experiment, which has the best resolution for this type of analysis has reached a limit of less than 10^{-5} using about 2 million Z^0 decays [31]. The L3 electron and muon endpoint spectra recoiling against the decay products of a τ are shown in Figs 16a and b. While a few background events are seen, the absence of a peak at the beam energy allows only to place a limit. Unfortunately without an improvement on the energy resolution, the future increase in statistics will result only in some small improvements on the sensitivity. A possible signal with a branching ratio of about 10^{-6} can only be observed, if at all with at least 10^8 Z^0 decays as can be seen from Fig. 16c [32].

A different and now almost classical missing energy experiment in e^+e^- annihilation is the neutrino counting with single photon events [33]. These events are expected from initial state bremsstrahlung and a Z^0 decaying into neutrinos. While the accurate Z^0 lineshape measurements have currently achieved a much higher accuracy for the number of light neutrinos, the single photon energy spectrum remains interesting. For example very high energy single photon events have been considered as an indication for excited

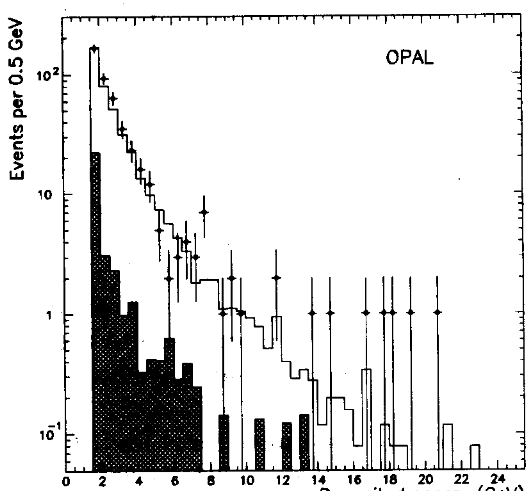

Fig. 17. The observed single photon energy spectrum from OPAL in 1994 [34], using a statistic of about 1500k Z^0 decays, (40.5 pb^{-1}).

neutrinos ν^* in the decay $Z^0 \to \nu\nu^*$ and $\nu^* \to \nu\gamma X$. The recent high statistics single photon energy spectrum from OPAL [34] is shown in Fig. 17. While the overall photon spectrum is well described by the Monte Carlo simulation, the small excess of high energy photons should encourage the other LEP experiments to look for energetic single photon events.

6. τ and B–physics with neutrinos

Missing energy experiments are usually discussed only in the exotic environment of particle searches. The few examples, given below, show that the neutrino has become also an important tool to study the weak interaction in the context of τ and b–quark physics.

6.1. Neutrinos as a tool for the study of τ physics

In the context of τ physics, it is worth mentioning that so far the presence of τ leptons is only seen by its decay characteristics into neutrinos. For example, the selection of Z^0 decays into $\tau^+\tau^-$ is based essentially on the following characteristics:

- Because of the small mass of the τ with respect to the beam energy, the decay products are found in a narrow cone of roughly 10–15 degrees around the original τ direction;
- $\tau^+\tau^-$ events can be distinguished from $e^+e^-(\gamma)$ and $\mu^+\mu^-(\gamma)$ events using the missing energy and the presence of hadrons.

Based on the above characteristics, all LEP experiments can identify $\tau^+\tau^-$ events and study τ decays with a high efficiency and very little background from other reactions. Comparing the achieved systematic errors for $\tau^+\tau^-$ cross section with the ones for e^+e^- and $\mu^+\mu^-$ events, no difference is found and precision measurements with accuracies of about 0.5% have been achieved. In addition to the cross section and forward backward charge asymmetry measurements, the weak τ decays are an excellent tool to study parity violation phenomena at the Z^0 and the μ and τ lepton universality. In fact, it is the presence of the neutrino which allows to measure the τ polarisation, which provides currently the best precision at LEP for $\sin\theta_W$ in neutral current processes. Furthermore, despite the invisible neutrino, τ life time and branching ratio measurements have now reached an impressive precision.

The new measurement of the upper mass limit for the ν_τ by ALEPH, which has reached a value of 23 MeV (1994) at 95% c.l. [35], demonstrates that indirect neutrino measurements have become a high precision physics tool. As the original τ energy is the beam energy, the observed mass, energy and missing mass can be used to determine the mass of the ν_τ in hadronic

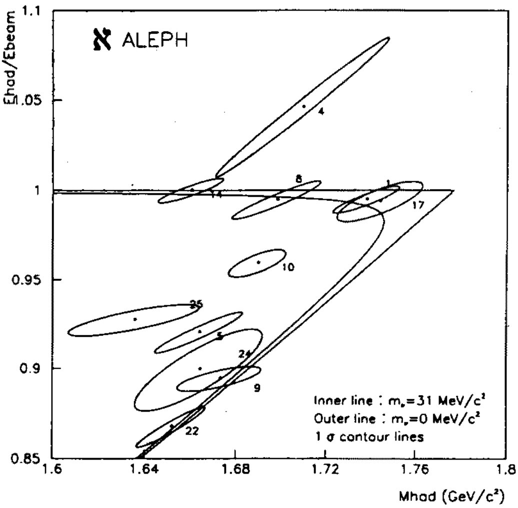

Fig. 18. The observed mass and energy of the hadrons in the τ decay into 5 charged particles from ALEPH [35]. The upper limit of 23 MeV (95% c.l.) for the τ neutrino mass is obtained mainly from events 1 and 17.

decays. The analysis used τ decays into 5 charged particles (pions) which carry a large fraction of the mass and the τ energy. The analysis uses the correlation between the observed mass and energy to obtain the above somehow unexpected accuracy for the neutrino mass [36]; the observed two dimensional distribution is shown in Fig. 18.

6.2. The neutrino energy spectrum in B–decays

As the direct measurement of neutrinos from semileptonic B–decays is impossible, little theoretical and experimental attention has been put into details of the neutrino energy spectrum. Recently, the feasibility of an indirect neutrino measurement in e^+e^- collisions, using the difference between the beam energy and the observed jet energy, has been discussed in the context of semileptonic B–decays [37]. It was shown that such a measurement at LEP allows to study details of the underlying structure of the weak charged current in B–hadron decays. The charged lepton and neutrino energy spectra for the free quark B–hadron decay model with a V–A×V–A decay structure is shown in Fig. 19; for the exotic V+A×V–A structure the two spectra would be simply exchanged. For example, the simultaneous measurement of the charged lepton and the neutrino energy spectrum would allow to distinguish between the above two cases. While the charged lepton spectra can be described by almost any model, a strong difference would show up in the average neutrino energy. The neutrino energy in the V+A case would be about 1.1 GeV larger than in the V–A case, using realistic charged lepton selection criteria. The possibility that hadronic corrections in B–hadron decays would destroy any polarisation of the virtual W, like in the decay K→ $\pi e \nu$, would result in a roughly 500 MeV harder neutrino spectrum. Such large differences should clearly be observable if the jet energy can be measured with an absolut accuracy of about 100–200 MeV.

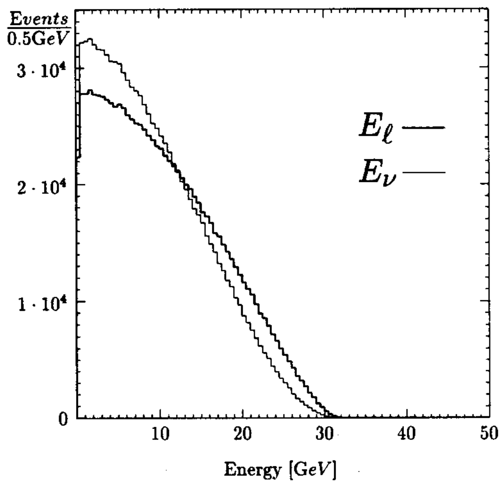

Fig. 19. The neutrino and the electron energy spectrum in semileptonic B–hadron decays, assuming a V–A×V–A decay structure according to the free b–quark decay picture [37].

Such a preliminary neutrino energy measurement has recently been reported by L3 using the data collected between 1991 and 1992 [38]. Requiring that the events show a two jet structure and that the jets are pointing to the hermetic barrel region of the experiment, a total of 350k hadronic Z decays could be analysed.

Starting from these two jet events, the neutrino energy is obtained from the difference between the beam energy and the jet energy, which is determined from the energy deposited in the electromagnetic and hadronic calorimeter. Using a technique which separates hadronic and electromagnetic showers in the calorimeter and a correction for the energy dependent calorimeter response to hadrons, 45 GeV jets are measured with a gaussian energy resolution with a sigma of about 4.3 GeV in the data and 4.6 GeV in the Monte Carlo simulation.

Semileptonic B–hadron decays are selected using electron (muon) candidates with an energy above 3 GeV (4 GeV) and a transverse momentum of more than 1.4 GeV with respect to the closest hadronic jet. With these criteria, about 5k inclusive electron and about 10k muon events are selected.

The obtained purity of correctly identified semileptonic B–hadron decays is found to be 78.4% for the electron sample and 69% for the muon sample.

The observed p and p_t charged lepton spectra in the data are reproduced by the Jetset Monte Carlo [40] simulation, if the weakly decaying B–hadrons are generated with an average energy of 72% of the beam energy using the Peterson fragmentation function [41] and if the B–hadron decays are simulated with a virtual W polarization according to the V–A×V–A structure. Alternatively, the charged lepton spectra can also be described with a V+A×V–A B–hadron decay structure and a roughly 5% harder fragmentation function.

The neutrino energy spectra obtained from the missing energy of the jet associated to the charged lepton, are shown in Fig. 20a for the electron tagged events and in Fig. 20b for the muon tagged events. The data are well described by a Monte Carlo with a V–A×V–A decay structure. The difference in the average neutrino energy in the data and in the Monte Carlo (with a V–A×V–A structure) ΔE_ν is found to be −90 ± 160 MeV (stat.) for the electron sample and +10 ± 110 MeV (stat.) for the muon sample. Systematic uncertainties of the measured neutrino spectrum arise mainly from three sources. These are the uncertainties due to the jet energy calibration, the purity of the inclusive charged lepton sample and efficiency uncertainties of the charged lepton selection. The resulting total systematic error of the average neutrino energy, adding the different contributions in quadrature, is found to be 220 (200) MeV for the neutrino energy associated to the b→ e(μ)νX decays. Comparing the data with a V+A×V–A decay simulation, one finds that the average neutrino energy in the data is too soft by 890 MeV (for the electron sample) and 690 MeV (for the muon sample) with the above statistical and systematic errors. Combining the two measurements, the exotic possibility of a V+A×V–A decay structure is excluded with a significance of about 5 standard deviations. The alternative, of a pointlike B–hadron decay structure with unpolarized virtual W's with a V× V–A structure would result in a roughly 400 (350) MeV larger average neutrino energy and is clearly disfavoured by the data.

Inclusive branching ratio (BR) measurements depend on the assumed lepton energy spectra. As predictions for these spectra vary for the different B–hadron decay models, it is important to constrain these models using many different types of measurements. Obviously, once the neutrino energy spectrum can be obtained from the missing energy in b–flavoured jets, the branching ratio BR(b→ νX) can be measured. Such a measurement is interesting, as inconsistencies between the BR measurement of b→ νX and b→ ℓX could be used to distinguish between B–decay models. For such a measurement one has to assume that the inclusive semileptonic B–hadron decays (b→ $\ell \nu X$), with ℓ being electron, muon and τ, occur in a certain

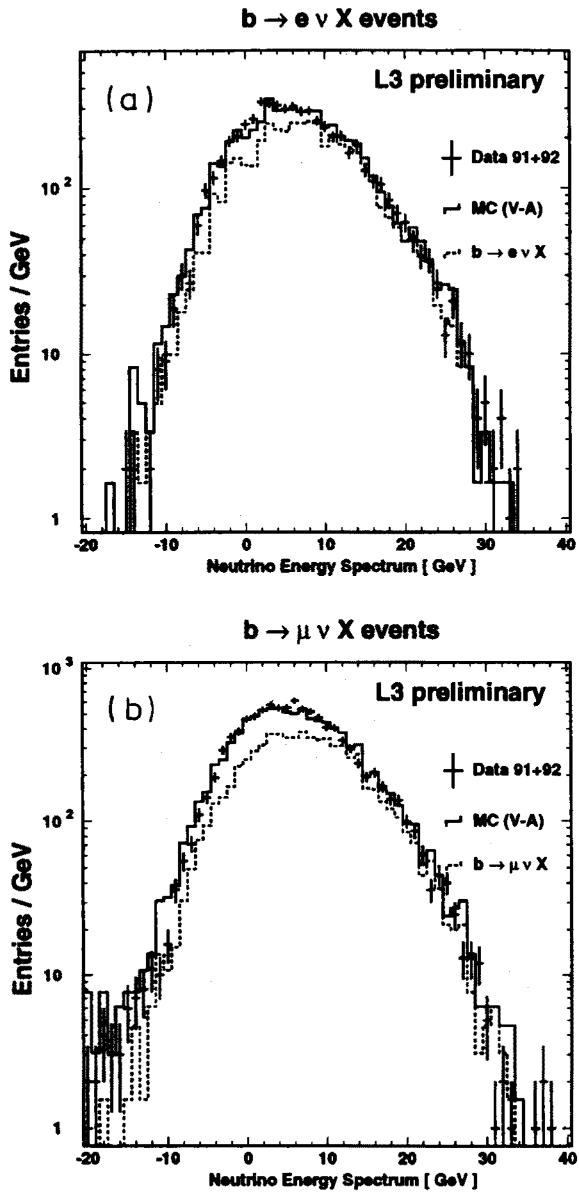

Fig. 20. The observed neutrino energy spectrum from L3 (94) [38]; (a) $b \to e^{\pm}\nu X$ events and (b) $b \to \mu^{\pm}\nu X$ events.

ratio. Because of the large τ mass, the BR(b→ $\tau\nu X$) is expected to be smaller by a factor of 0.26 ± 0.03 [42] or 0.22 ± 0.02 [43] than the other semileptonic BR's. According to these estimates, one can assume that the inclusive leptons are produced in the ratios 1:1:0.25 (± 0.05).

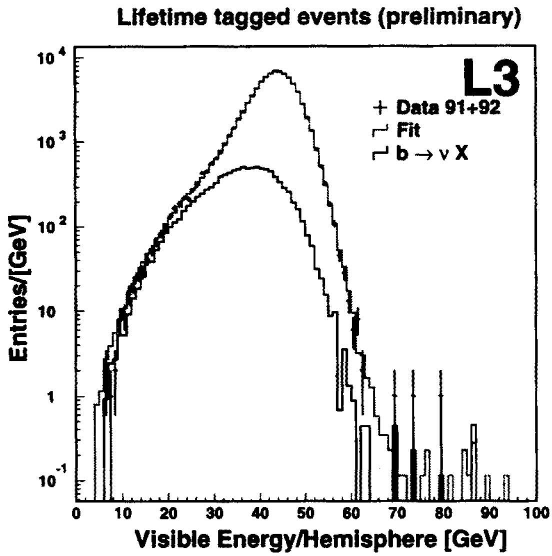

Fig. 21. The visible energy spectrum per hemisphere in lifetime tagged $b\bar{b}$ events from L3 (94) [38]. The estimated contribution from the decays $b \to \nu X$ and the results from the fit are also shown.

The visible energy spectrum from L3, using lifetime tagged $b\bar{b}$ events is shown in Fig. 21 together with the results of a fit and the estimated neutrino contribution. For this fit, the shape of the hadronic background has been determined from the data using b–quark depleted event selections. The shape of the neutrino energy spectrum is from the Monte Carlo, where semileptonic B–decays were simulated with a V–A×V–A structure and the relative BR's were fixed with the above ratios. Using this procedure, L3 finds a BR($b \to \nu X$) of 22.7 ± 0.8% ± 1.5% (preliminary) [38]. The dominant systematic errors of this measurement are from the uncertainty in the b–purity of the lifetime event sample and from the uncertainties of the predicted neutrino energy spectrum. The purity uncertainty has been estimated to be smaller than 2.5%, using the measured BR($Z^0 \to b\bar{b}$). The uncertainty of the assumed neutrino energy spectrum was determined to be accurate within ± 200 MeV, using the results of the analysis, described in the previous section. A change of either the purity or the neutrino energy spectrum with the above errors would change the above BR by roughly ± 1%. This measurement can be transformed into a result for BR $(b \to e(\mu)\nu X)$ of 10.1±0.4(stat.)±0.7(syst.)%. This result is in very good agreement with the direct BR measurements from ARGUS and CLEO with an average of 10.29% ±0.06(stat.)±0.27(syst.)% [39].

Instead of fixing the ratio between the different semileptonic decays, one can constrain the directly measurable BR(b→ $e(\mu)\nu X$). The b→ $\tau\nu X$ component can be enhanced using a hard veto against jets which contain electron or muon candidates. A remaining excess of the jets with large missing energy can then be associated to the decay b→ $\tau\nu X$. Such a measurement has first been performed by the ALEPH collaboration in 1992 and has been updated using the 1991 to 1993 data sample [44]; a similar measurement has also been performed by L3 [45]. Both groups have assumed a value of 11% ± 0.5% for the BR(b→ $e\nu X$). As theoretical calculations exist only for the ratio BR(b→ $\tau\nu X$)/BR(b→ $e\nu X$), we prefer to give the measured ratios instead of the obtained BR's. ALEPH obtains a ratio of 0.284 ± 0.033(stat.) $\pm\, 0.034$(syst.); the one from L3 is 0.218 ± 0.064(stat.) $\pm\, 0.057$ (syst.) (L3). The results are in agreement with the above given non exotic theoretical estimations.

7. Supersymmetry searches at LEP2 and beyond

The hope to find an experimental indication for a supersymmetric world [46] is based mainly on the detection capabilites of true missing energy at future high energy collider experiments. The so called R-parity conservation[3] requires that supersymmetric particles are produced in pairs and that the unstable ones decay promptly into a neutral stable invisible neutralino ($\tilde{\chi}^0$) and the corresponding fermion or boson, like $\tilde{W}^{\pm} \to \tilde{\chi}^0 W^{\pm}$.

As the possible search strategies for Supersymmetry have already been discussed in several review articles about Supersymmetry we will discuss here only a few examples of these future experiments and refer to the literature for further details [48–51]. While at low energies negligible background for Supersymmetry searches is found, at center of mass energies, above the W and Z^0 boson production threshold, acoplanar events with large missing transverse momentum are expected from the leptonic W and Z^0 bosons decays.

It has been shown that, despite of these important backgrounds, supersymmetric particles can be discovered at LEP2 if their masses are not larger than 80–85 GeV [48]. This is shown in Fig. 22, where the detected event rates from the hypothetical $\tilde{\mu}$ pair production signal is compared with the background from W^+W^- pairs both decaying into $\mu\nu$. Another example is shown in Figs 23a and 23b, where the expected distribution from the pair

---

[3] Drastically different signatures can be expected from Supersymmetric Models with R-parity violation [47]. The missing energy signature in these models becomes smaller but the presence of electrons or muons from lepton number violation can be expected.

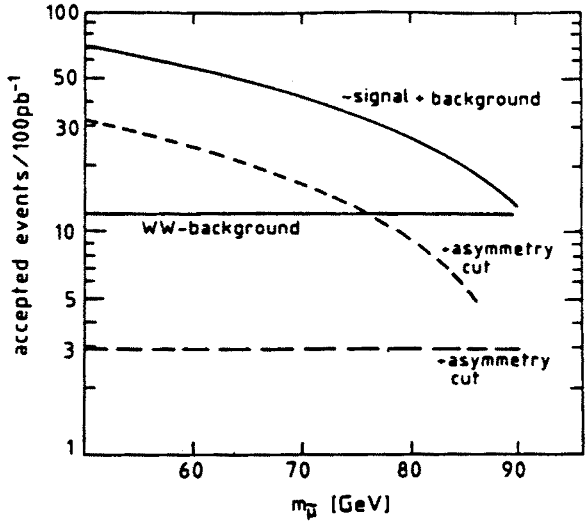

Fig. 22. Expected event rates at LEP2 for the supersymmetric $\tilde{\mu}$ particles as a function of the mass. The background expectation from W–pair events is also shown [48].

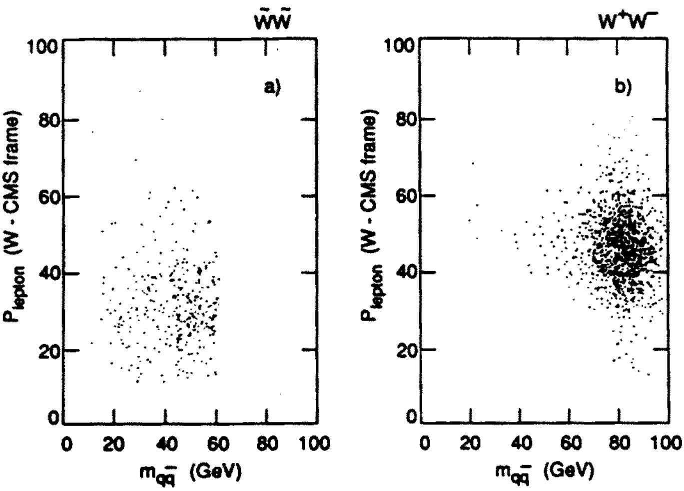

Fig. 23. Simulation of a LEP2 search for the chargino, $\tilde{W}$, the supersymmetric partner of the W, (a) the signal and (b) the background [48].

production of $\tilde{\mathrm{W}}\tilde{\mathrm{W}}$ with subsequent decays $\tilde{\mathrm{W}} \to \mathrm{W}\tilde{\chi}^0$ are compared with a simulation of W–pair production at LEP2. In both cases, it is assumed that one W decays into hadrons and the other one into leptons ($\ell\nu$). Shown is the mass of the hadronic system against the charged lepton momentum in the estimated rest frame of the assumed W boson. A clear separation between a signal and the background is obvious. The importance of the W and Z^0 backgrounds decreases again at even higher center of mass energies

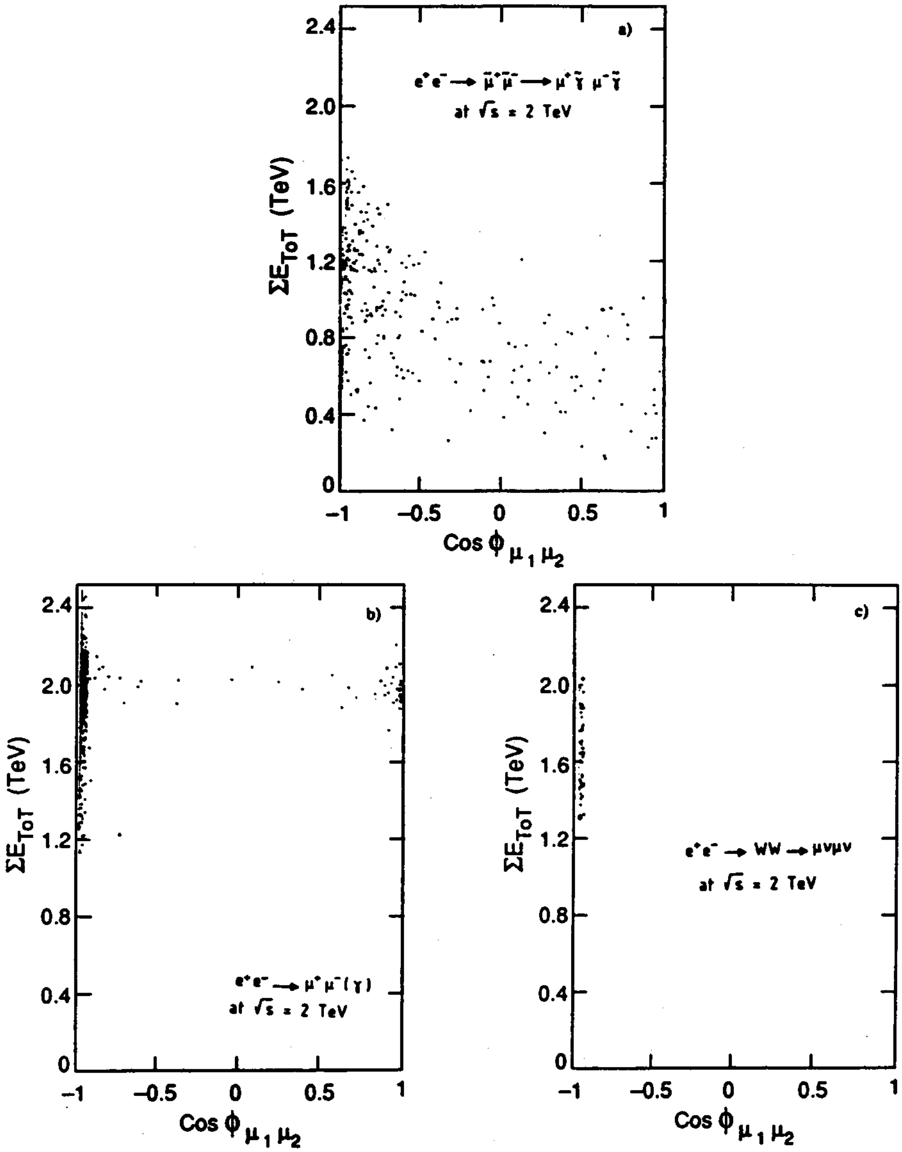

Fig. 24. Simulation of a search for the supersymmetric partner of the μ with a mass of 500 GeV at a hypothetical linear collider with a 2 TeV center of mass energy. The distributions show the acoplanarity distributions of the 2 muons against the observed visible energy of the events for (a) the signal, (b) and (c) show the considered backgrounds [49].

as envisaged for example with the future linear e^+e^- collider with center of mass energies of up to 2 TeV [49]. As can be seen from Figs 24a–c, a signal from pair produced $\tilde{\mu}$ particles with a mass of 500 GeV, remains acopla-

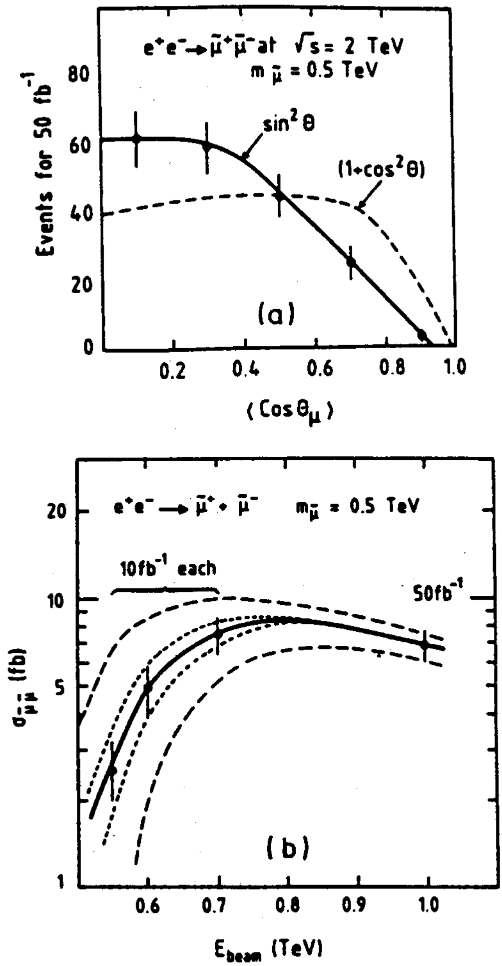

Fig. 25. Simulation of the determination of (a) the spin and (b) the mass for a supersymmetric $\tilde{\mu}$ signal at a high energy e^+e^- linear collider [49].

nar, while backgrounds from $\mu^+\mu^-(\gamma)$ and W^+W^- events becomes again coplanar. The reason is, like for the $\tau^+\tau^-$ production at the Z^0 peak, that the W–decay products have to be very collimated as the W–energy is much larger than its mass.

Furthermore, not only the backgrounds for these hypothetical particles can be controlled, but it is also possible to determine the mass and the spin of the new particles. While the mass can best be determined from the threshold behaviour of the observed cross section, the spin can be determined from the observed angular distribution of the decay products as shown in Figs 25a and b.

Searches for squarks and gluinos at the LHC are much more challenging as large QCD–backgrounds in combination with true missing energy signals from the t–quark, W and Z^0 decays are expected [50]. For example, it has been concluded at the Aachen LHC workshop (1990) that the event rate from the above standard neutrino sources, with a missing E_t of more than 500 GeV is still by a factor of about 5 larger than the expected Supersymmetry signals. However, using more clever selection criteria for the observed jets and the missing energy and missing mass, clear signals seem to be feasible at the LHC. This conclusion requires however that additional background due to detector gaps can be kept small and that a good jet energy resolution can be obtained by the experiments.

8. Higgs searches with missing energy at LEP2 and the LHC

As discussed in section 6.2, the searches for the Higgs particle at the Z^0peak are dominated by the missing energy signature from $Z^0 \to Z^*H \to \nu\nu b\bar{b}$. As in the case of Supersymmetry searches, at higher energies serious backgrounds are expected from processes involving W and Z production. Even though the expected event rates at LEP2 are low, simulation studies show that with a total luminosity of about 500 pb^{-1}, the LEP experiments can discover a Higgs up to a mass which is roughly 100 GeV lower than the highest possible center of mass energy at LEP2. This sensitivity requires however that all Z^0 decay channels can be used in combination with some effective b–jet tagging [52]. However, using only the neutrino channel, a signal of up to a mass of about 75 GeV should still be detectable. A further increase of the e^+e^- center of mass energy and the luminosity, as has been considered for example with linear colliders of up to the TeV range would drastically improve the sensitivity to a Higgs particle. It has been shown for example, [53] that a Higgs with a mass of up to 200 GeV could easily be found at an e^+e^- collider operating at a center of mass energy of about 300 GeV.

Different search strategies for the Higgs at the LHC were discussed for example at the Aachen workshop on LHC physics [54]. The sensitivity for the different considered signatures as a function of the mass is shown in Fig. 26 [54]. For Higgs masses above 200 GeV, the decays of the type $H^0 \to Z^0Z^0$where considered. The studies show significant signals for the case when both Z^0 decay into electron or muon pairs with a branching ratio of about 0.4% and for the missing energy case, with one Z^0 decaying into a pair of neutrinos and the other one into electron or muon pairs which has a branching ratio of about 2.6%. The performed studies indicate that the most significant signals can expected from the missing energy signature, which allows to detect a Higgs with a mass between 200 GeV and 700 GeV already with a luminosity of $10^{33}cm^{-2}sec^{-1}$.

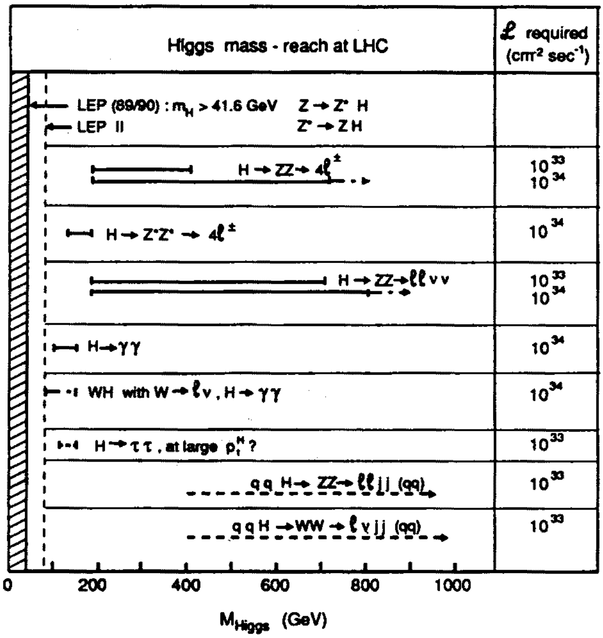

Fig. 26. Compilation of the Higgs search strategies for different mass regions at the LHC from Denegri 1990 [54]. The full lines indicate the regions were clean signals can be expected. Signals for large masses are expected in the missing energy channel with a luminosity of 10^{33} cm^{-2} sec^{-1}.

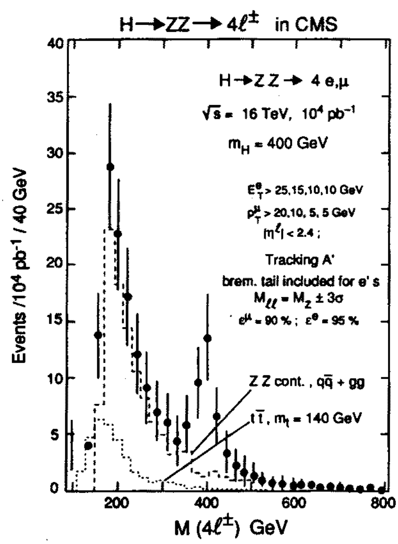

Fig. 27. The expected mass peak for a Higgs mass of 400 GeV in the channel $H \rightarrow Z^0Z^0 \rightarrow \ell^+\ell^-\ell^+\ell^-$ from CMS at the LHC [55] (10^4pb^{-1}).

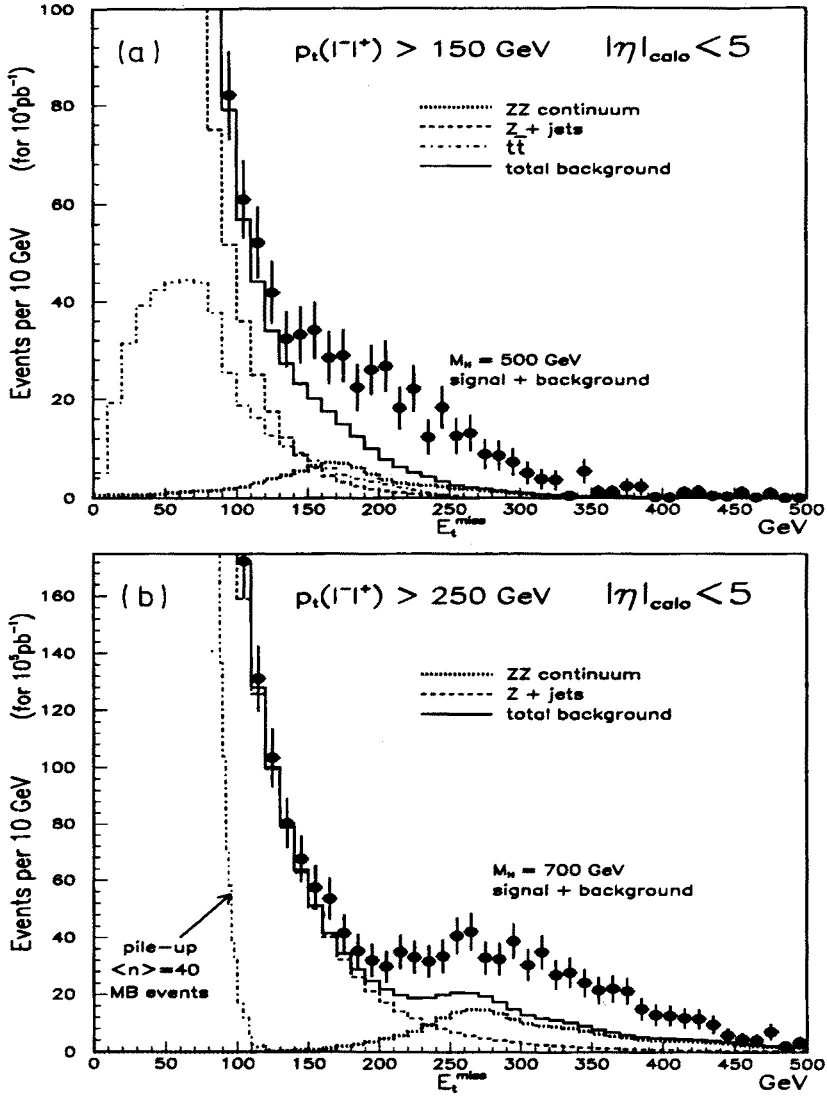

Fig. 28. The expected Higgs signals in the channel $H \to Z^0Z^0 \to \nu\nu\ell\ell$ for a Higgs mass of (a) 500 GeV with $10^4 pb^{-1}$; and of (b) 700 GeV with $10^5 pb^{-1}$ from ATLAS at the LHC [56].

Below a mass of 200 GeV, the observation of a Higgs at LHC becomes a real challenge and current simulation studies show possible signals in the channel ZZ* decaying into charged leptons and in the decay into $\gamma\gamma$. Both of these channels require extraordinary detector performance in the hostile luminosity environment of $10^{34}cm^{-2}sec^{-1}$. This technical challenge to find or exclude the Higgs particle also for masses below 200 GeV has currently a higher priority for the design of the experiment than the missing energy capabilites.

Nevertheless, even with the currently non specialized missing energy detectors, the neutrino channel seems to provide the most significant signal for masses above 200 GeV. The expected high mass signals from detailed simulations performed for the design of CMS and ATLAS are shown in Fig. 27 for the four charged lepton channel from CMS, [55], and for the missing energy channel from ATLAS in Figs 28a and b [56]. It seems that the conclusions from the Aachen LHC workshop, namely that the missing energy channel will provide the first LHC Higgs signal if its mass is larger than 200 GeV, remain valid.

9. Summary and conclusions

The importance of missing energy experiments for high energy particle physics has been reviewed. It is shown that the indirect detection of neutrinos has become an important and sometimes very precise tool to study weak interaction phenomena in large colliding beam experiments. In particular it is found that:

- Missing energy and momentum experiments have a long and outstanding history in particle physics. Such experiments have not only provided important information about the nature of the weak interaction, but were also essential for two recent discoveries in particle physics, the one of the τ lepton and the one of the W–boson.
- Missing energy signals are a direct sign for the weak interaction and are an important tool to study details of the weak interaction and its parity violation strength in τ, charm and beauty hadron decays. The large missing energy signals which are expected from leptonic W and Z^0 decays will allow to study details of the W and Z boson production dynamics at future high energy colliders like the LHC.
- Current and future missing energy experiments are shown to have a very high sensitivity to possible new exotic particles and interactions. Examples for this are the searches for Supersymmetry and for rare exotic Z^0 decays. Furthermore, the most sensitive results on the Higgs are coming currently from the missing energy signature at the Z^0 and can also be expected for LEP2 and the LHC.

To summarize, the missing energy signature has become an important and accurate tool to study weak interaction phenomena. We believe that a well designed missing energy experiment has the best chances to find new physics at LEP2 and the LHC. Therefore, this review about missing energy experiments is concluded with the visionary Niels Bohr, who knew already in 1932 [7]:

"Notwithstanding all the recent progress we must still be prepared for new surprises (with the weak interaction)".

It is a pleasure to thank the organizers for the nice atmosphere and the interesting program of the school. I also want to thank my colleagues in ALEPH, DELPHI, L3, OPAL, ATLAS and CMS for many helpful discussions about their latest results and for providing me with the most recent figures. For the help with several older figures I want to thank C. Rigoni, I am grateful to D. Haztifotiadou, C. Petridou and Z. Wąs for their critical suggestions and comments on this review.

REFERENCES

[1] J. Chadwick Verhandl. Dtsch. Phys. Ges. **16**, 383 (1914).
[2] C.S. Wu *et al.*, *Phys. Rev.* **105**, 1413 (1957).
[3] UA1 Collaboration, G. Arnison *et al.*, *Phys. Lett.* **B122**, 103 (1983); UA2 Collaboration, M. Banner *et al.*, *Phys. Lett.* **B122**, 476 (1983).
[4] UA1 Collaboration, G. Arnison *et al.*, *Phys. Lett.* **B126**, 398 (1983); UA2 Collaboration, P. Bagnaia *et al.*, *Phys. Lett.* **B129**, 130 (1983).
[5] S.L. Glashow, *Nucl. Phys.* **22**, 579 (1961); S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967); A. Salam, in: *Elementary Particle Theory*, ed. N. Svartholm, Almquist and Wiksell, Stockholm 1968 p. 367.
[6] B. A. Sherwood, *Phys. Rev.* **156**, 1475 (1967).
[7] N. Bohr, *Faraday Lecture, Chemistry and the Quantum Theory of Atomic Constitution, Journ. of Chem. Soc.*, London 1932 p. 349–384.
[8] R. Kronig, V. F. Weisskopf, eds. *Collected Scientific Papers by Wolfgang Pauli*, Vol. 2, Wiley-Interscience, New York 1964 p. 1316.
[9] Septieme Conseil de Physique Solvay 1933: Noyaux Atomique, Paris 1934 p. 324.
[10] C.L. Cowan *et al.*, *Science* **124**, 103 (1956); F. Reines, C.L. Cowan *Nature* (London) **178**, 446 (1956)..
[11] G.W. Rodeback, J.S. Allen, *Phys. Rev.* **86**, 446 (1952).
[12] OPAL Collaboration, P.D. Acton *et al.*, *Phys. Lett.* **B273**, 338 (1991).
[13] M.L. Perl *et al.*; *Phys. Rev. Lett.* **35**, 1489 (1975); *Phys. Lett.* **B63**, 466 (1976) and *Phys. Lett.* **B70**, 487 (1977).
[14] UA1 Collaboration, A. Astbury *et al.*, CERN/SPSC/78-06, SPSC/P92 30 January 1978.
[15] C. Rubbia, *Phys. Rep.* **239**, 241 (1994).
[16] L. DiLella, Proceedings of a NATO Advanced Study Institute on Particle Physics held August 3–21, in Cargese, France, NATO ASI Series B: Physics Vol. 173.
[17] UA2 Collaboration, M. Banner *et al.*, CERN/SPSC/78-8, SPSC/P93 31 January 1978.

[18] UA2 Collaboration, J. Alitti. *et al.*, CERN/SPSC/87-45/M435 and *Z. Phys.* **C47**, 11 (1990).
[19] UA2 Collaboration, J. Alitti. *et al.*, *Phys. Lett.* **B276**, 354 (1992).
[20] *Particle Data Group*, L. Montanet *et al.*, *Phys. Rev.* **D50**, 1173 (1994).
[21] OPAL Collaboration, M.Z. Akrawy *et al.*, *Phys. Lett.* **B240**, 261 (1990).
[22] OPAL Collaboration, R. Akers *et al.*, Internal Physics Note 151, July 18, 1994.
[23] P. Higgs, *Phys. Rev. Lett.* **12**, 132 (1964); *Phys. Rev. Lett.* **13**, 504 (1964), and *Phys. Rev.* **145**, 1156 (1966).
[24] See for example: *Physics at LEP*, eds J. Ellis and R. Peccei CERN 86-02 Vol. 1 p. 318–325.
[25] OPAL Collaboration, R. Akers *et al.*, *Phys. Lett.* **B327**, 397 (1994); ALEPH Collaboration, Contribution to ICHEP94, GLS0568; DELPHI Collaboration, internal note, DELPHI 94–129 PHYS 441; and L3 Collaboration, internal note and contribution to ICHEP94, GLS0642.
[26] M. Pohl, Talk given at the 27th Int. Conf. on High Energy Physics, Glasgow, July 1994.
[27] M. Dittmar *et al. Nucl. Phys.* **B332**, 1 (1990).
[28] M. Dittmar, Status and Prospects of Rare Exotic Z^0 Decay Searches, Proceedings of the 4th Hellenic School on Elementary Particle Physics, Corfu September 1992, Greece.
[29] ALEPH Collaboration, D. Buskulic *et al.*, *Phys. Lett.* **B334**, 244 (1994).
[30] OPAL Collaboration, M.Z. Akrawy *et al.*, *Phys. Lett.* **B254**, 293 (1991).
[31] I. Vorobiev, Third workshop on τ Lepton Physics Montreux, Switzerland, September 1994.
[32] M. Dittmar, J.W.F. Valle, FTUV/90-19 and CERN/91–02.
[33] See for example ASP Collaboration, C. Hearthy *et al.*, *Phys. Rev. Lett.* **17**, 1711 (1987).
[34] OPAL Collaboration, R. Akers *et al.*, preprint CERN–PPE/94–104.
[35] F. Cerutti, Third workshop on τ Lepton Physics Montreux, Switzerland, September 1994.
[36] J. Raab, ALEPH internal note, ALEPH–Phys 91–134.
[37] M. Dittmar, Z. Wąs, *Phys. Lett.* **B332**, 168 (1994).
[38] M. Dittmar, Talk given at the 27th Int. Conf. on High Energy Physics, Glasgow, July 1994.
[39] R. Patterson, Talk given at the 27th Int. Conf. on High Energy Physics, Glasgow, July 1994.
[40] T. Sjöstrand, *Comput. Phys. Commun.* **27**, 243 (1982); "PYTHIA 5.6 and JETSET 7.3: Physics and manual", CERN preprint CERN-TH.6488/92.
[41] C. Peterson *et al.*, *Phys. Rev.* **D27**, 105 (1983).
[42] P. Heiliger, L.M. Sehgal, *Phys. Lett.* **B229**, 409 (1989).
[43] A. Falk *et al.*, *Phys. Lett.* **B326**, 145 (1994).
[44] ALEPH Collaboration, D. Buskulic *et al.*, *Phys. Lett.* **B298**, 479 (1993); ICHEP94 Ref. 0582.
[45] L3 Collaboration, M. Acciarri *et al.*, *Phys. Lett.* **B332**, 201 (1994).

[46] For reviews see H.P. Nilles, *Phys. Rep.* **110**, 1 (1984); G.G. Ross, *Grand Unified Theories*, Benjamin Cummings (1985); H.E. Haber, G.L. Kane, *Phys. Rep.* **117**, 75 (1985).

[47] For a discussion of Supersymmetry signatures with R–parity violation see for example: H. Dreiner, G. G. Ross, *Nucl. Phys.* **B365**, 597 (1991).

[48] C. Dionisi *et al.*, Proceedings of the Aachen Workshop on LEP200, CERN-87/08, p. 380.

[49] C. Dionisi, M. Dittmar, Proceedings of the Workshop on Future Physics from Future Colliders, La Thuile, January 1987, CERN-87 07 Vol. 2.

[50] Supersymmetry, Proceedings of the Large Hadron Collider Workshop Aachen, October 1990, CERN-90 10 Vol. 2, p. 605-683.

[51] F. Zwirner, G.F. Grivaz, contributions to the ICFA Workshop on Physics and Experiments with Linear Colliders Saariselkä Finland, September 9–14, 1991, World Scientific 1992, Vol. 1.

[52] See for example: J. Alcaraz *et al.*, Higgs Discovery Potential of the L3 detector, CERN–PPE/93-28 (1993).

[53] See for example: S. Komamiya, contribution to the ICFA Workshop on Physics and Experiments with Linear Colliders Saariselkä Finland, September 9–14, 1991, World Scientific 1992, Vol. 1.

[54] D. Denegri, Proceedings of the Large Hadron Collider Workshop Aachen, October 1990, CERN-90 10 Vol. 1, p 56.

[55] CMS Collaboration, D. Denegri *et al.* TN/93–79 and 101 to appear in the CMS Technical Proposal.

[56] ATLAS Collaboration, D. Gingrich *et al.*, Letter of Intent, CERN/LHCC 92–4, p. 88–89.