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Physics at LEP 200

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Abstract : The Large Electron Positron collider LEP at CERN recently achieved centre of mass energies much above the Z-pole. Recent experimental results from the four LEP experiments, ALEPH, DELPHI, L3 and OPAL at these hitherto unexplored energy regime in e^+e^- interactions are presented.

Keywords : e^+e^- physics, W mass, Higgs search, test of standard model, SUSY searches.

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1. Introduction

The Large Electron Positron collider (LEP) ran at a centre of mass energy above the Z mass region for the first time in November 1995 : at $\sqrt{s}$ values of 130, 136 and 140 GeV. During 1996 the energy was enhanced first to 161 GeV, just above W^+W^- production threshold during June-August 1996 and later to 172 GeV during October-November 1996. Each LEP experiment collected ~5 pb^{-1} during November 1995 and ~10 pb^{-1} at each of the two energies during 1996.

A reminder of the goals of LEP200 :

- Continuing study and precision measurements of Standard Model processes,
- Precision measurement of W Mass and Width,
- Search for SUSY,
- Search for SM and non-minimal Higgs,
- Measurements of Triple Gauge Couplings
- LOOK FOR THE UNEXPECTED

Figure 1 depicts the cross sections of typical SM processes as a function of centre of mass energy at LEP [1].

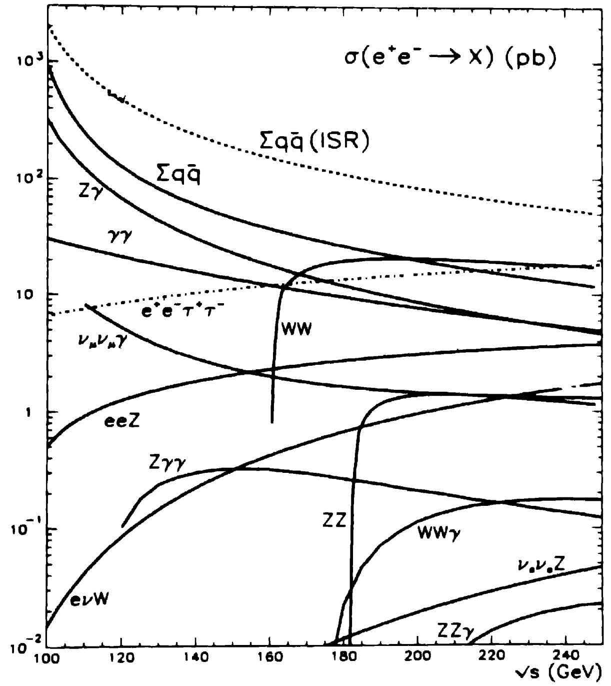

Figure 1. Cross sections of some SM processes

The following topics will be covered in this talk.

(i) Fermion pair production

(ii) W mass measurements

(iii) ALEPH excess of 4-jet events

(iv) Search for Higgs and SUSY particles

(v) QCD studies and α_s

2. Fermion pair production

This is a continuation of the Z lineshape study begun at LEP100. Apart from testing SM predictions the main interest is to determine better the hadronic γ/Z interference term (j^{had}) using *off-peak* points at which the cross section is much more sensitive to it. In a completely model independent (*S*-matrix based) fit the value of M_Z is highly correlated with j^{had}. Thus including off-peak data in such a fit leads to the best model independent values of M_Z as well as j^{had}. Note that the usual Breit-Wigner fits at LEP100 assume the SM value for this interference term.

Before describing the results I would like to point out that inspite of moving away from the Z peak in centre-of-mass energy, a large proportion of the events at LEP200 energies still "remember" the Z. These are called "return to the Z" events and are due to initial state radiation (ISR) in which the hard photon takes away just enough energy to produce a Z as a recoil. Figure 2 shows the $L3$ distribution of the 'reduced' or 'effective'

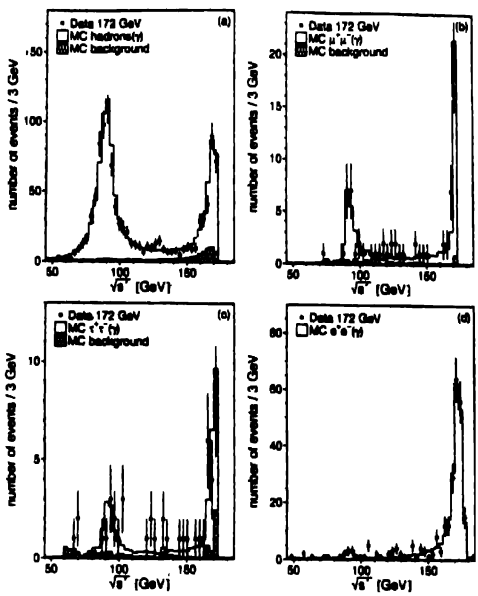

Figure 2. The reconstructed effective centre-of-mass energy, $\sqrt{s'}$, for the selection of (a) $e^+e^- \to$ hadrons (γ) events, (b) $e^+e^- \to \mu^+\mu^-$ (γ) events, (c) $e^+e^- \to \tau^+\tau^-$ (γ) events and (d) $e^+e^- \to e^+e^-$ (γ) events.

centre of mass energy, $\sqrt{s'}$ for the $e^+e^- \to$ hadrons, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$. Except for the $e^+e^- \to e^+e^-$ final state, in which the t-channel is dominates, the Z is clearly seen. An easy way to remove this background is to apply a cut on the value of $\sqrt{s'}$.

Each of the LEP experiments collected ~2000 events at 161 GeV and ~1000 events at 130–140 GeV. Of these ~40% are true high energy events with $\sqrt{s'} > 0.85$. Comparison of measured cross sections with the SM expectation is shown in Figure 3 for the s-channel final states. All measured data (cross sections and lepton forward/backward asymmetries) is in good agreement with the SM. A fit to all LEP100 + LEP130–140 data in the S-matrix formalism leads to

$$M_Z = 91193.6 \pm 4.0\ \text{GeV} \tag{1}$$

$$j^{had} = -0.21 \pm 0.20 \tag{2}$$

This value of j^{had} is ~2σ away from the SM value of +0.23. Inclusion in the fit of TOPAZ data from KEK at $\sqrt{s}$ = 58 GeV yields

$$M_Z = 91191.2 \pm 3.5\ \text{GeV}, \qquad (3)$$

$$j^{had} = -0.07 \pm 0.16. \qquad (4)$$

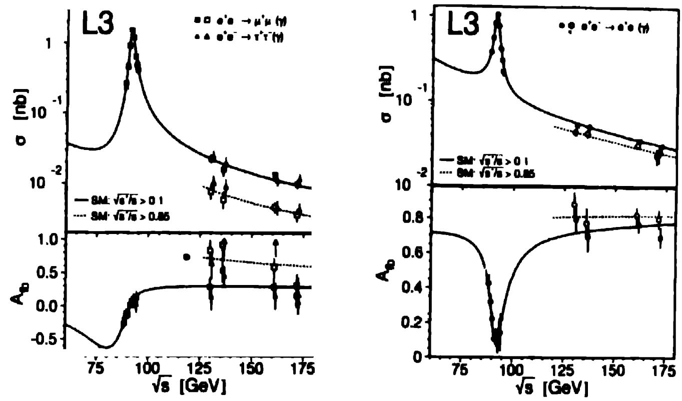

Figure 3. Leptonic cross section and forward-backward asymmetry measurements and comparison with standard model

As pointed out earlier, there is a high correlation between these two parameters : corr $(M_Z, j^{had}) = -78\%$.

3. Determination of W Mass

Pair production of W bosons at LEP became possible in summer 1996 when the LEP energy was enhanced to 161.3 GeV, just above WW production threshold. At that time the world average of M_W was 80.36 ± 0.13 GeV from $p\bar{p}$ experiments at CERN and FNAL. M_W is a fundamental electroweak parameter and any improvement in its precision helps, firstly, in testing the internal consistency of the SM and, secondly, in constraining the value of M_{Higgs} within the SM framework.

During 1996 LEP operated just above WW threshold during summer, at 161.3 GeV, and at 172 GeV during fall.

3.1. Identification of WW signal :

W pairs leading to the hadronic ($qqqq(\gamma)$, 45.6 %), semi-leptonic ($qql\nu(\gamma)$, 14.6% each) and leptonic ($l\nu l\nu(\gamma)$, 10.6% total) final states were identified. Briefly the following selection procedures were followed :

$qqqq(\gamma)$ final state :

This is a purely hadronic final state. The signal strength is ≃1.6 and 5.5 pb at $\sqrt{s}$ = 161 and 172 GeV respectively. The main background is due to QCD processes, $e^+e^- \rightarrow q\bar{q}(\gamma)$, whose cross section is ≃150 pb.

The first step is to reject radiative "return to the Z" events, which are fairly easy to reject by imposing an (s'/s) cut.

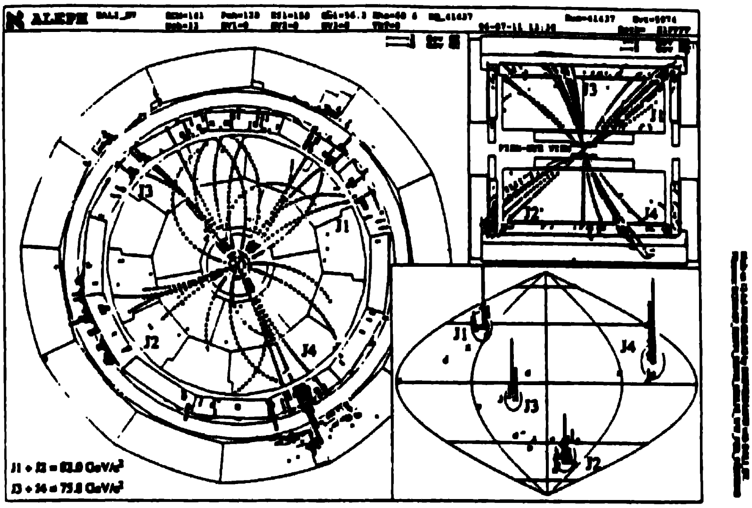

Figure 4. Example of an ALEPH $e^+e^- \to W^+W^- \to qqqq$.

An example of a $e^+e^- \to q\bar{q}'q\bar{q}' \to 4$ jets event observed by the ALEPH collaboration is shown in Figure 4. A typical identification procedure followed for this final state is

- Selection of high multiplicity events without missing energy,
- Forcing of event to four jets,
- Imposition of energy-momentum conservation to carry out a 4C kinematic fit.

The residual (QCD) background is due to $qq \to qq$ gluon bremsstrahlung $\to$ 4 jets in which

- the bremsstrahlung gluons tend to follow the parent quark direction
- they mainly have smaller energies relative to the four decay quarks coming from W pair production.

This is removed either by use of multi-dimensional procedures by the ALEPH [2], L3 [3] and OPAL [4] collaborations or, in the case of DELPHI [5], by the use of a single variable constructed out of fitted energy and angle variables of the event.

$qql\nu(\gamma)$ final state :

The cross section for this final state at 161 and 172 GeV is $\simeq$ 0.5 and 2.5 pb respectively and the main backgrounds are due to $e^+e^- \to q\bar{q}(\gamma)$ and 4-fermion processes, $e^+e^- \to q\bar{q}l^+l^-$, with one lepton undetected.

An example of a $e^+e^- \rightarrow q\bar{q}'\mu\bar{\nu} \rightarrow 2$ jets + μ event seen by the OPAL collaboration is shown in Figure 5.

The selection procedure is

- Identify hadronic event with one high energy, isolated lepton with e, μ and τ tagging as at LEP I
- Cluster the remaining event into 2 jets
- Determine the missing momentum vector due to the neutrino (p_ν)
- Apply selection cuts on the kinematics of the reconstructed 4-fermion system :
  - angles between lepton and jets
  - magnitude and direction of missing energy
  - energies of lepton and jets
  - hadronic and leptonic invariant masses $\left(M_{q\bar{q}}, M_{l\bar{\nu}}\right)$

lvlv(γ) final state :

The expected signal cross section at 161 and 172 GeV is$\simeq$ 0.4 and 1.9 pb respectively and the main backgrounds are dilepton events from $e^+e^- \rightarrow Z(\gamma)$, Bhabha scattering and events due to 2 photon interactions.

An example of a $e^+e^- \rightarrow e^+\mu^-$ event detected by the L3 collaboration is shown in Figure 6. As is evident from the figure such events are rather easy to detect and select owing to the presence of two very high energy leptons accompanied by large missing transverse energy and acoplanarity between the lepton directions.

The selection strategy is then to

- Exclude hadronic events using the multiplicity criterion
- Identify 2 leptons using the e, μ and τ tagging as at LEP I
- Apply selection cuts on
  - acoplanarity angle between the 2 leptons
  - missing transverse momentum (or energy) in the event

Extraction of WW Cross sections :

For a selected number of events N of a particular final state, the cross section is written as

$$\sigma = \frac{N - N_{bgd}}{\varepsilon . A . \mathcal{L}} \tag{5}$$

where N_{bgd} is the number of expected background events, ϵ is the signal selection efficiency, A the detector acceptance and $\mathcal{L}$ the integrated luminosity. The values of ϵ and N_{bgd} depend on the Monte Carlo programs used for signal and background event generation leading to systematic errors in addition to the statistical error. Some sources of systematic error are : variation of selection cuts around nominal value, model parameter variation—

Plate I

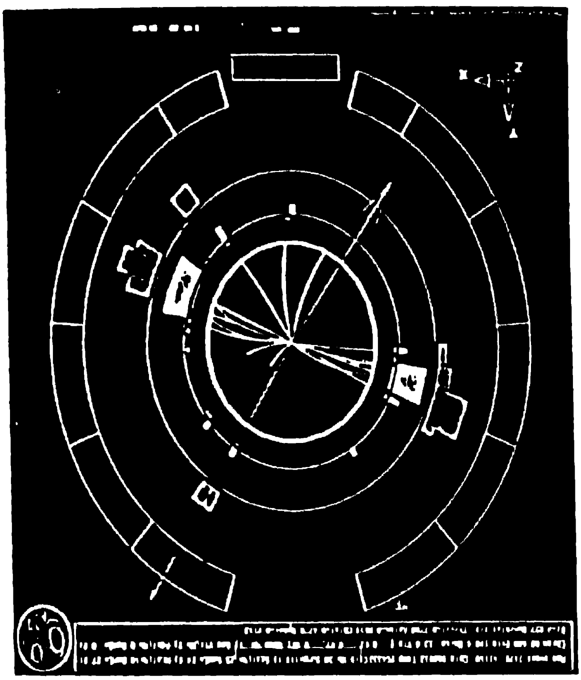

Figure 5. Example of an OPAL $e^+e^- \to W^+W^- \to qq\mu\nu$

signal & backgrounds, model to model variation, W mass dependence, differences between data and Monte Carlo and limited Monte Carlo statistics. At present, the overall errors are dominated by statistics.

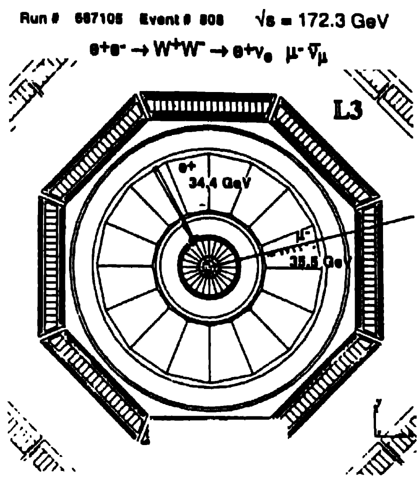

Figure 6.

The physical cross sections one is interested in are those corresponding to $e^+e^- \to W^+W^-$, *i.e.*, where W pair production takes place, the so-called CC03 processes. On the other hand the final states that one detects can some times arise from other SM processes. Most of the events due to these background diagrams are rejected by suitable invariant mass cuts. The residual background is corrected using Monte Carlo programs which can generate both signal and background events given the cuts applied. Typically the correction factors are around 10%.

Summary of selections :

A summary of the selection efficiencies (ϵ) and the numbers of events selected (N_{evt}) by each of the 4 LEP experiments is given below (Table 1) :

Table 1. Selection efficiency and numbers of $e^+e^- \to W^+W^-$ candidate events at 161 and 172 GeV.

Final State	161 GeV		172 GeV	
	ϵ	N_{evt}	ϵ	N_{evt}
$qqqq(\gamma)$	~60	9–15	75–85%	55–65
$qql\nu(\gamma)$	60–80%	11–16	60 – 90%	40–50
$l\nu l\nu(\gamma)$	40–70%	2–6	45 – 80%	5–10
Total		22–36		95–120

Thus all the 4 LEP experiments together detected ~100 WW events at 161 GeV, ~400 WW events at 172 GeV, leading to a total 1996 event sample of ~500 events.

3.2. W mass using the threshold method :

This method consists of measuring the W pair production cross section, σ_{WW}, just above threshold and determining M_W using the dependence of σ_{WW} on M_W. It can be shown that the maximum statistical sensitivity occurs at $\sqrt{s} \simeq 2 \times M_W + 0.5$ GeV, *i.e.*, just above 161 GeV and that is why LEP was run at 161.3 GeV. The values of $e^+e^- \rightarrow W^+W^-$ cross sections in various final states at 161.3 GeV are summarised in Table 2.

Table 2. $e^+e^- \rightarrow W^+W^-$ cross sections.

Final Results at 161 GeV				
Final	CC03 Cross Section (pb)			
	ALEPH	DELPHI	L3	OPAL
$qqe\nu(\gamma)$			$0.62^{+0.38}_{-0.27}$	
$qq\mu\nu(\gamma)$			$0.53^{+0.33}_{-0.24}$	
$qq\tau\nu(\gamma)$			$0.22^{+0.55}_{-0.38}$	
$qql\nu(\gamma)$	$1.85^{+0.51}_{-0.43} \pm .06$	$1.77^{+0.67}_{-0.55} \pm .10$		
$l\nu l\nu(\gamma)$	$0.68^{+0.34}_{-0.26} \pm .03$	$0.31^{+0.39}_{-0.24} \pm .09$	$0.39^{+0.43}_{-0.27}$	
$qqqq(\gamma)$	$1.80 \pm 0.50 \pm 0.19$	$1.56^{+0.67}_{-0.55} \pm .13$	$0.98^{+0.51}_{-0.40}$	
Total	$4.23 \pm 0.73 \pm 0.19$	$3.67^{+0.97}_{-0.85} \pm .19$	$2.89^{+0.81}_{-0.70} + .14$	$3.62^{+0.93}_{-0.82} \pm .16$

In order to obtain a combined LEP average cross section each of the four LEP experiments provided its value of $\sigma(e^+e^- \rightarrow W^+W^-)$ with a symmetrical statistical error based upon the number of *expected* events from SM predictions. The common systematic error was taken as the smallest experimental systematic error of the four. The average LEP

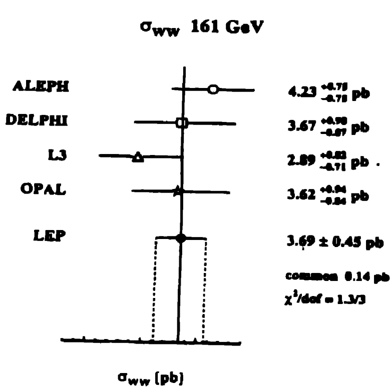

Figure 7.

cross section for the process $e^+e^- \rightarrow W^+W^-$ at 161.3 GeV was determined to be 3.69 ± 0.45 pb; the error includes a common systematic of 0.14 pb. This agrees very well with the SM prediction of 3.80 pb [6]. The measurements and the average are shown in Figure 7. The SM based dependence of σ_{WW} on M_W and the value of the LEP average M_W so derived is shown in Figure 8. Figure 9 depicts the individual determinations of M_W.

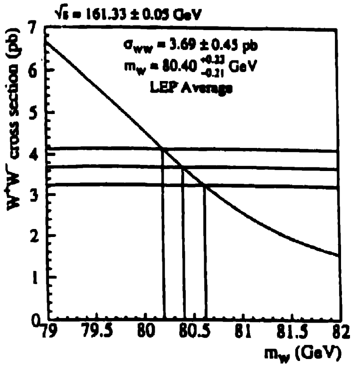

Figure 8. m_W from σ_{WW} at 161 GeV

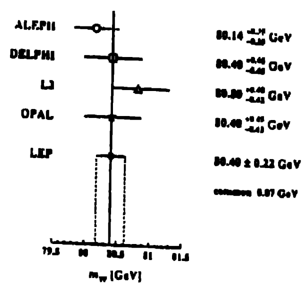

Figure 9. LEP 161 GeV W mass

3.3 W mass from reconstruction method :

In principle the procedure is simple after *WW* identification has been made.

- Calculate jet-jet, lepton-neutrino invariant masses
  For $qql\nu\,(\gamma)$ channels life is simpler : no combinatorics and small background under the signal in M_{inv} plot.
- Apply beam energy constraints to improve reconstructed mass resolution.
  This results in a 4C fit for $qqqq$, a 1C fit for $qql\nu(\gamma)$.
- Application of the beam energy constraint leads to an anti-correlation between the 2 reconstructed W masses. To take care of this effect one
  - either, sets $M_{W1} = M_{W2}$ leading to a 5C fit for qqqq and a 2C fit for $qql\nu(\gamma)$
  - or, studies the fitted $M_{W1} - M_{W2}$ correlation in MC and applies a correction
- Use a Breit-Wigner plus parametrized (or actual) background and fit for M_W and possibly (additionally) Γ_W.

3.3.1 Sources of systematic errors on M_W :

The systematic errors on M_W using the reconstruction method are given below.

- The use of beam energy constraint to improve mass resolution leads to two sources of systematic error
  1. A LEP energy uncertainty, $\Delta E_{LEP} \simeq 30$ MeV, leads to a mass uncertainty of similar magnitude.

2. Initial State Radiation decreases the effective $\sqrt{s}$. Thus using the nominal value of $\sqrt{s}$ results in an increased M_W. Modelling uncertainties of ISR lead to an error on its average value of $\simeq 10$ MeV leading to a similar uncertainty in the fitted M_W.

- Modelling QCD background under the signal : the background also peaks just under the M_W peak. Very detailed studies still being made.
- Detector effects : miscalibration of energy of leptons and mismatch between M.C. and data for energies/angles of jets.
- Fit type dependence :
  - Relativistic *vs* non-rel BW,
  - different parametrisation for backgrounds,
  - variations in fitting procedures (4C, 1C *vs* 5C, 2C)

These effects total to $\simeq$30–50 MeV systematic error on M_W.

The main problem at present is one of low statistics. This makes it difficult to disentangle statistical from systematic effects.

3.3.2. Theoretical systematics in qqqq :

Owing to the short lifetime of the W bosons, to start with the 4 decay quarks are in close vicinity in the $qqqq$ final state. Thus "colour reconnection", due to the possible gluon exchange between quarks from the decay of the two different W's, leads to a distortion of the reconstructed W masses. In principle if one could calculate this distortion theoretically then a suitable correction could be applied. Unfortunately the presently available models give divergent results on this correction and this uncertainty is translated into a theoretical systematic error on M_W determined using the $qqqq$ final state.

Another similar effect of distortion of the reconstructed W mass distribution could be due to Bose-Einstein correlations between identical bosons (*e.g.*, π^0) produced as decay products of the two W's because the hadronisation regions of the W's overlap. Here again a good theoretical understanding of this problem is lacking.

The overall theoretical uncertainty in M_W determination due to both these effects is estimated to be ~100 MeV in the $qqqq$ final state [7]. For a result combining roughly equal numbers of $qqqq$ and $qql\nu(\gamma)$ events the uncertainty will be ~50 MeV.

3.4. Future prospects for W mass at LEP :

In the short term, the 172 GeV data will be analysed and results presented by the time of the European Winter Conferences in March 1997[1]. In the long term each experiment at LEP expects to collect ~500 pb^{-1} of data. If the colour reconnection and Bose-Einstein effects

[1] as of July 1997 the average LEP value of M_W from 172 GeV data is 80.62 ± 0.26 GeV from the $qqqq(\gamma)$ channel, 80.46 ± 0.24 GeV from the $qql\nu(\gamma)$ channel, and averaging with M_W from 161 GeV, the overall LEP M_W = 80.48 ± 0.14 GeV. This agrees well with the latest results from the $p\bar{p}$ experiments 80.41 ± 0.09 GeV leading to a grand world average of 80.43 ± 0.08 GeV.

are brought under control theoretically, then using all final states the final error on M_W from LEP is expected to be as low as ~35 MeV. On the other hand, if these effects remain un-understood then one may not be able to use the $qqqq(\gamma)$ final state and the error may remain ~45 MeV based only upon the $qql\nu(\gamma)$ channels.

4. The ALEPH 4-jet events

While searching for a possible $e^+e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b}$ (4 jet) signal in 5.7 pb^{-1} data at 130 and 136 GeV, the Aleph collaboration observed an excess of 4-jet events and an enhancement in the sum of the two di-jet masses around 105 GeV [8]. Their selection was tailored to minimize SM backgrounds and preserve efficiency for an hA signal for $M_h = M_A = 55$ GeV :

1. Hadronic final state requiring $N_{ch} > 8$; $E_{ch} \geq 10\% \sqrt{s}$
2. Reject radiative return to the Z events
3. Cluster event to 4 jets
4. Require each jet to have $M_{jet} > 1$ GeV assuming charged particles are $\pi^{\pm}$, neutrals are massless
5. To reduce QCD background, require all di-jet masses > 25 GeV, the sum of masses of the two lightest jets, $M_3 + M_4$, > 10 GeV and the sum of their charged multiplicities, $N_3^{ch} + N_4^{ch}$, ≥ 10.

They determine the signal selection efficiency to be 42% and their background rejection to be better than 99.5%. They then select that pairing of jets which minimises the difference in mass between the two di-jets. When they plot the sum of the masses of these two di-jets they observe a clear peak at the expected value of 110 GeV in the signal Monte Carlo sample. The width of the peak is 1.6 GeV This is depicted in Figure 10. Applying the

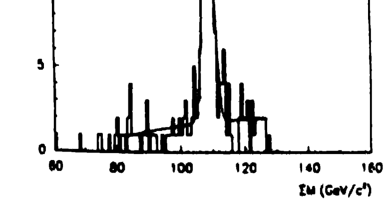

Figure 10. Sum of masses of the two di-jets in selected ALEPH 4-jet events using Monte Carlo. See text for details

same cuts to the data the plot shown in Figure 11 is obtained. A peak at 105 GeV is observed with 9 events contained within two 1 GeV bins. The expected background is only

1 event. If this was indeed the searched for signal, *i.e.*, $e^+e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b}$, then these events should be rich in b quarks. However, at most one event is found compatible with having 2 jets due to b quarks using the lifetime tagging algorithms.

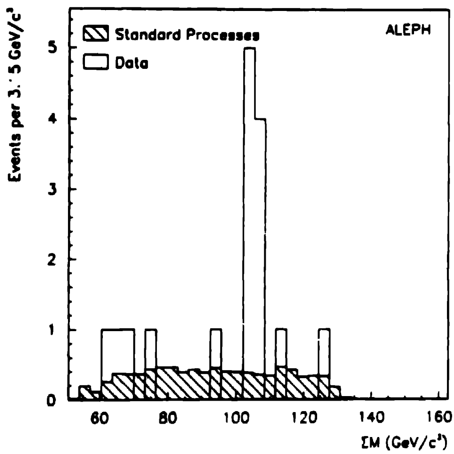

Figure 11. Sum of masses of the two di-jets in selected ALEPH 4-jet events using their data sample. See text for details.

Since that publication ALEPH has continued to see this enhancement, albeit with smaller statistical significance [9] at the higher energies at which LEP has run

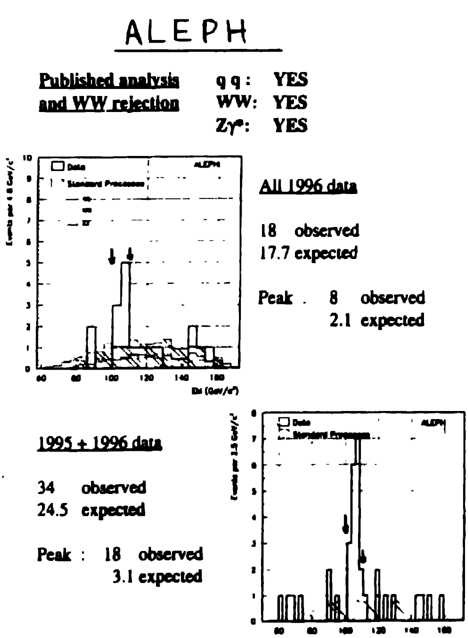

Figure 12. Extended ALEPH analysis on 4-jet events including 1995+1996 data.

161 and 172 GeV. At these energies they have introduced some additional cuts in order to remove the "background" of WW events. Including all 1995 and 1996 data they now observe 34 4-jet events whereas they expect to see 24.5. The number observed in the peak is 18 with a background of 3.1. This is shown in Figure 12. A gaussian fit to the data yields the peak position to be 106.1 ± 0.8 GeV with a width of 2.1 ± 0.4 GeV.

The other three LEP experiments have searched for the ALEPH type events following closely the selection criteria used by ALEPH. None of them finds any enhancement either in the number of 4-jet events or in the distribution of sum of masses of the two di-jets [10]. As a cross check for possible detector resolution effects *etc.*, ALEPH provided the four-vectors of their events to the other LEP collaborations who propagated these through their detectors and confirmed that 65–70% of these events actually ended up in a similar peak. This is a similar percentage as what ALEPH themselves found for their own events. Thus, the detector resolutions and other effects cannot account for the fact that other LEP experiments don't see these events. With accumulation of more data at higher energies one will see if the effect persists or fades away.

5. Search for Higgs and SUSY

When an accelerator progresses into a higher energy regime it is always a time of great excitement to look for particles which are expected and not yet discovered (SM Higgs) and for particles which are theoretically favoured to exist particularly if earlier data hints at such

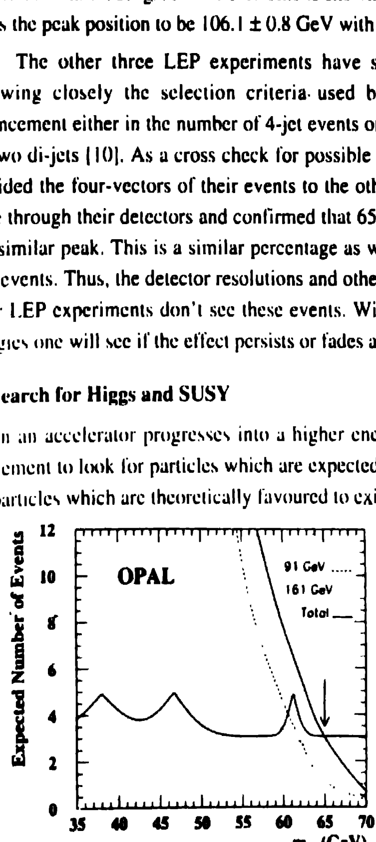

Figure 13. OPAL search for standard model Higgs.

a possibility. The latter was the case for light charginos (SUSY) owing to the existence of the R_b anomaly.

5.1 *SM Higgs* :

While the LEP runs at 130 and 136 GeV were of too low luminosity (~5 pb^{-1}) to provide any improvement over the limit set by LEP100, the OPAL collaboration has been quick to use their 161 GeV data to obtain a new lower limit on the mass of the SM Higgs boson of 65 GeV [11]. Figure 13 shows the OPAL result[2].

[2] as of July 1997 the best lower limit on the SM Higgs is from ALEPH [12] > 70.7 GeV at 95% confidence level using data at all LEP energies (including 172 GeV)

5.2. Search for SUSY :

5.2.1. R_b anomaly and light charginos :

Summer 1995 saw the height of the R_b anomaly. The experimental value of this ratio of $\Gamma_{b\bar{b}}/\Gamma_{hadron}$ in Z decay was 0.2205 ± 0.0017 even after fixing R_c to its SM value of 0.1715. Thus it was 3σ away from the SM expectation of 0.2156. This disagreement provided fertile ground for theorists to suggest that such a situation may be naturally explained within the framework of the MSSM (Minimal Super Symmetric extension of the SM). In the low $\tan\beta$ scenario, the $Z \to \tilde{t}\bar{\tilde{t}} \to b\bar{b}$ with a light χ^+ providing the $\tilde{t}\chi^+ b$ triangle at the $Z^0 \to b\bar{b}$ vertex would do the trick and in the high $\tan\beta$ scenario a light A^0 at the $Z^0 \to b\bar{b}$ vertex would have the same effect. The former (low $\tan\beta$ scenario) is preferred as it leaves completely untouched the SM prediction of $A_{FB}^{0,b}$. For a light chargino mass, ≤ 65 GeV, one could obtain a value of R_b = 0.219 within the MSSM framework which was 1.5σ away from the measured value.

Experimental signatures :

The basic assumptions which have gone into the mainstream LEP searches are

(i) R-parity conservation which ensures that the Lightest Supersymmetric Particles (LSP) will not interact or decay and will escape detection. The lightest neutralino, $\tilde{\chi}_1^0$, is favoured to be the LSP. This assumption leads to a very powerful experimental signature : that of missing energy ($\not{E}$).

(ii) That the sneutrino, $\tilde{\nu}_e$ is heavy and the charginos are Higgsino-like. This ensures large production cross sections for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$.

(iii) That the decay followed is $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 + W^*$, where $W^* \to f\bar{f}'$ are the usual W decay modes.

Thus, in addition to the $\not{E}$ signature due to two undetected $\tilde{\chi}_1^0$'s, the three topologies one looks for are

(i) an *acoplanar lepton pair* with opposite sign leptons,

(ii) a *highly unbalanced* hadronic event,

(iii) an *isolated high energy lepton* accompanied by 2 jets.

The main backgrounds are $e^+e^- \to Z/\gamma^*\ Z/\gamma^*$ or WW^* or $We\nu$ or Zee or Z/γ or two photon interactions. Suitable selections reduce the backgrounds very effectively. The signal efficiency varies between 5% and 60% depending on the mass of the $\tilde{\chi}_1^\pm$ and the mass difference, $\Delta M(\tilde{\chi})$, between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$.

Interpretation within the MSSM framework is done in terms of the five model parameters $\tan\beta$, the gaugino mass parameter, $M \equiv M_2$, the higgsino mixing parameter, μ, the sparticle mass parameter, m_0, and the trilinear coupling in the Higgs sector, A.

Model independent and MSSM based exclusions from L3 and OPAL for the process $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ at $\sqrt{s} \leq 161$ GeV are shown in Figures 14 and 15 respectively [10]. Using 172 GeV data ALEPH [9] set an upper limit of 0.6 pb for "typical"

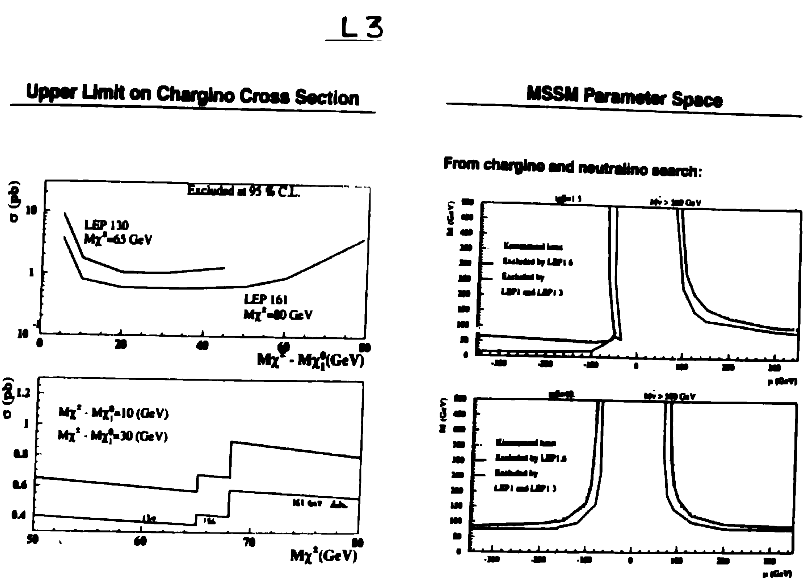

Figure 14. Chargino search by L3 and limits on MSSM parameter space.

$\Delta M(\tilde{\chi})$ = 20–60 GeV and set a lower limit $M_{\tilde{\chi}^\pm} \geq 84$ GeV at 95% C.L. assuming a sneutrino mass > 200 GeV[3].

5.2.2. *Searches for sleptons, neutralinos, stop, sbottom* :

As expected all the LEP experiments have carried out extensive searches for all these SUSY particles. As mentioned above the dominant global signature is one of missing energy ($\not{E}$). For slepton search the event signature is a pair of acoplanar oppositely charged leptons with large $\not{E}$ and $\not{p}$. For neutralino search one assumes a pair production of the lightest, $\tilde{\chi}_1^0$, with the next heavier, $\tilde{\chi}_2^0$, with the latter decaying as $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 f\bar{f}$, f being a normal fermion. Again the search limits depend upon the mass of the searched particle and the difference in mass between it and the LSP. To cut a long story short no SUSY signal has been discovered. Model independent as well as MSSM based limits

[3] to complete the story on the R_b anomaly, much of the problem has lost its urgency as the experimental value is now 0.2179 ± 0.012 which is less than 2σ from the SM expectation.

and plots are obtained by the LEP collaborations [13] which may be referred by the interested reader.

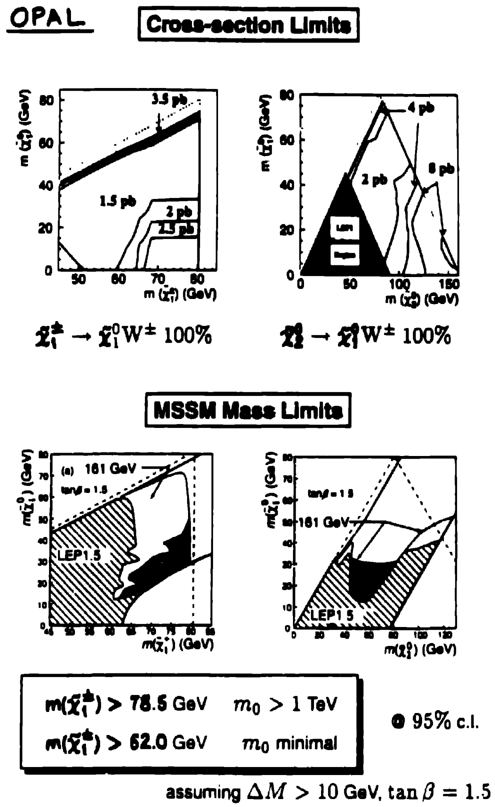

Figure 15. OPAL results on Chargino and neutralino searches

6. QCD studies at LEP

Not to belabour the point, the status of QCD at LEP above Z energies continues to be satisfactory. Variation with centre-of-mass energy of two important event shape quantities, the thrust ($< T >$) and the average charged multiplicity ($< n_{ch} >$) is shown in Figure 16. The same figure also shows the fraction of 2, 3, 4 and 5 jets as a function of Y_{cut}^{Durham} at 161 GeV. As one can see QCD models describe the data very well.

Finally, I say a few words on the continued evolution of the strong coupling constant, α_s. For example, the value measured by L3 at 161 and 172 GeV is $0.103 \pm 0.005 \pm 0.005$ and $0.104 \pm 0.006 \pm 0.005$ respectively [14]. The variation of α_s with centre-of-mass energy or Q is shown in Figure 17. As is evident, the data is well described by the expected QCD evolution.

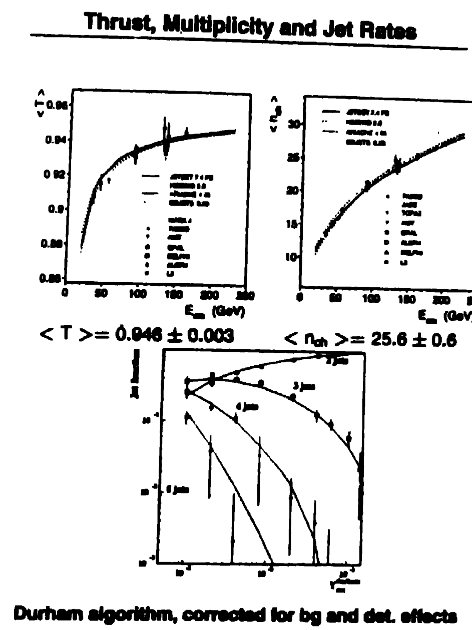

Figure 16. QCD studies at LEP 200. See text for details.

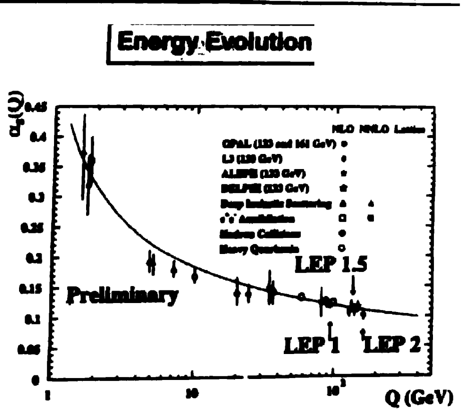

Figure 17. Energy evolution of α_s and comparison with QCD prediction.

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