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THE LEP PHYSICS PROGRAM

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ABSTRACT

The physics program of LEP is reviewed in the context of recent developments from the $Sp\bar{p}S$ collider. LEP offers the unique possibility to unambiguously explore the particle spectrum up to a mass of 100 GeV i.e. over the mass range typical of the electroweak symmetry breaking.

I. INTRODUCTION

It was clear in the 1976 Yellow Report[1] and the 1979 Report[2] from the Les Houches workshop that a first-rate physics program could be envisaged with the LEP machine[3]. This program was based on the postulated existence of the Z° vector boson which, if not too wide, would constitute a prolific source of quarks and leptons — both conventional and possibly unconventional —, and the energy range was tuned so that W bosons could be produced in pairs. These reasonable working assumptions have now been secured, thanks to the spectacular discovery of the W and Z° bosons at CERN[4] and therefore the standard LEP physics program looks very solid.

Since the early expectations, little experimental information came in to suggest new phenomena, despite a flurry of theoretical speculations. Even the top quark, which proved to be above the PETRA energy range, manifests some reluctance to show up in the $p\bar{p}$ collider data[5]. More interestingly, hints for new physics have been discussed : for exemple, radiative Z° decays[6] possibly mediated through compositeness, and unbalanced jets[7] as evidence for supersymmetry. Unfortunately, these effects could not be confirmed at this meeting and we shall have to wait for further analysis and for more data before getting excited.

In the light of the above, we review here the LEP physics program and discuss its potential for new discovery. Exhaustive reviews already exist[1,2,8], so we rather place the emphasis on new aspects made available by theoretical and experimental progress (in particular it was not envisaged seriously in 1979 that toponium physics would be left untouched for LEP).

II. THE DETECTORS

The LEP experiment committee has approved 4 detectors to be built and installed in the LEP underground halls. They should be operational early in 1989 when the machine delivers its first luminosity runs.

1. ALEPH[9]

The design of the ALEPH detector is characterized by its granularity and its uniformity. Only 4 technologies are used : drift chamber for the inner trigger chamber, TPC as the main tracking device, proportional tubes and pad readout in the electromagnetic calorimeter and streamer tubes with pad readout for the hadron calorimeter and muon tracker. (Fig. 1).

A complete study of systematic effects in the TPC has been performed with the help of a large scale prototype. On the basis of these tests, including calibration with laser-induced ionization, a sagitta precision of 100 μ will be obtained leading to a momentum resolution

$$\sigma\left(\frac{1}{P_T}\right) = 1.1\ 10^{-3}$$

falling to 7 10^{-4} when the interaction point is used in the track fit.

For the e-γ calorimeter, granularity is more important for physics than energy resolution. The ALEPH design uses proportional tubes with pad readout organized in narrow towers spanning $1° \times 1° \sin\theta$. The complete calorimeter comprises about 75000 such towers with a 3-fold longitudinal sampling for hadron/electron discrimination.

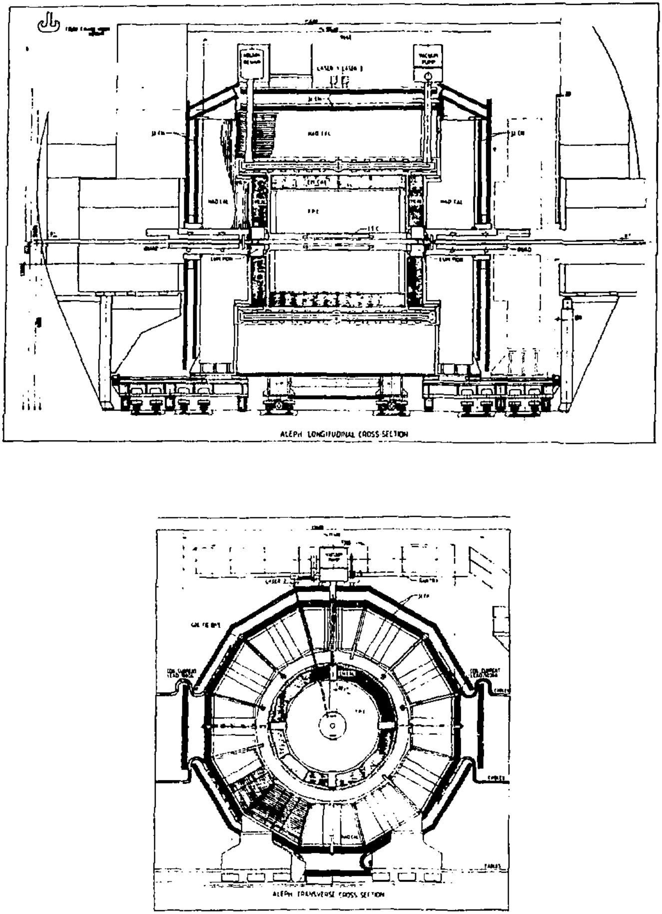


Fig. 1 - The ALEPH detector (a) longitudinal view
(b) transverse view

The hadron calorimeter uses the iron return yoke of the superconducting solenoid and has a granularity 16 times coarser but otherwise arranged in the same projective geometry. Muons can be tracked with strips parallel to the graphite-coated plastic streamer tubes. Together with 2 outer double layers separated by 50 cm, this amounts to about 220 000 digital channels.

A particular effort has been devoted to reducing the dead areas to an absolute minimum imposed by the mechanical structure. ALEPH will thus be a uniform, granular and hermatic apparatus.

2. DELPHI[10)]

A strong emphasis has been placed in the DELPHI design on particle identification through Cerenkov ring imaging. Because of the space required to achieve this function, the central tracker is a relatively small TPC, comparable to that used in the PEP4 experiment at SLAC (Fig. 2).

The Cerenkov counters (RICH) are used both in the barrel and endcap parts and consists of 2 parts : one with a liquid radiator (C_6F_{14}) close to the ring detector and the other with a gas radiator with a mirror system focussing the ring onto the detector. Tests have been performed on a small prototype : drift of single electrons from photon conversion have been achieved over a distance of 2.7 m. On average 10 photoelectrons are collected and algorithms searching for circles yield a precision of 3.4 % on the Cerenkov angle. It will be a challenge to extrapolate these excellent results to a 4π solid-angle device of the required scale.

Like ALEPH, the electromagnetic calorimeter has been optimized for granularity but here a new technique (HPC) employing again long drifts has been chosen. Unfortunately it only works for the barrel part and a different system has to be used in the end caps (lead-glass with phototriodes). In the barrel an intrinsic angular precision of 20 mr is claimed for a 4-GeV shower.

The hadron calorimeter relies also on streamer tubes and pads which build up about 20 000 towers.

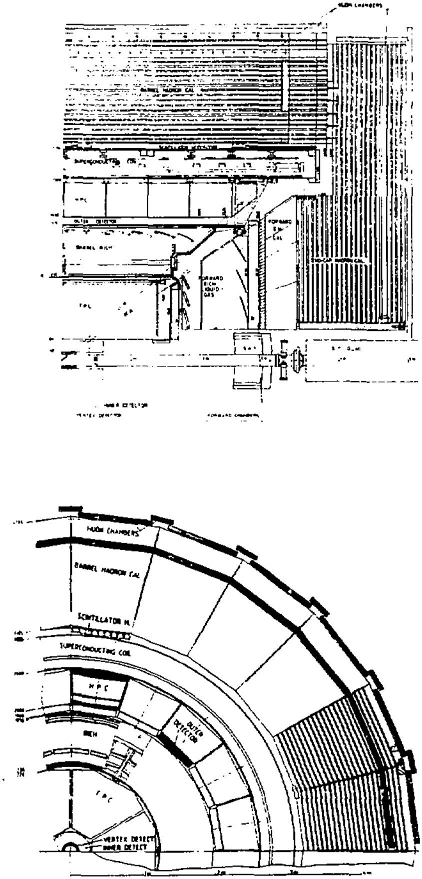


Fig. 2 - The DELPHI detector (a) longitudinal view of one quadrant
(b) transverse view

3. L3[11)]

The L3 experiment emphasizes calorimetry with the most precise energy resolution : BGO for electrons and photons, and a uranium calorimeter for hadrons. A very large muon spectrometer is built all around (Fig. 3).

In order to reduce the cost of BGO, the central detector has been miniaturized (50 cm radius) and uses the time expansion technique to recover accuracy (30 to 50 μ). A 2-track resolution of 300 μ has been achieved on a prototype.

The electromagnetic calorimeter will be built with 12 000 BGO crystals which define the granularity of the system. No longitudinal segmentation is foreseen. The intrinsic energy resolution of BGO is somewhat degraded at lower energy by noise in the photodiodes which are used for light readout because of the magnetic field. It should be possible to achieve a resolution of 1 % above 10 GeV (or may be lower). Radiation damage is still of concern as indicated by tests.

Since the BGO calorimeter represents 1.1 absorption lengths, about 70 % of the energy of jets is deposited there. The rest is measured in a hadronic part where uranium is planned in order to achieve the best energy resolution owing to the compensation provided by uranium fission. Tests indicate that the combined system has a resolution of 60 % $E^{-1/2}$ compared to a value of 85 % $E^{-1/2}$ obtained with iron calorimeters as used by the other detectors.

4. OPAL[12)]

The OPAL detector proceeds with a conservative design : a larger scale replica of the JADE experiment operating at DESY (Fig. 4).

The central detector is a large drift chamber of the "jet" design installed in a warm solenoid delivering 0.4T. A 90:10 Ar-CH_4 mixture at 4 bars should provide a spatial accuracy $\sigma_{r\phi}$ of 100-150 μ. Charge division is used for the longitudinal coordinate which does not provide precise enough measurements : therefore additional drift chambers are used outside the central part.

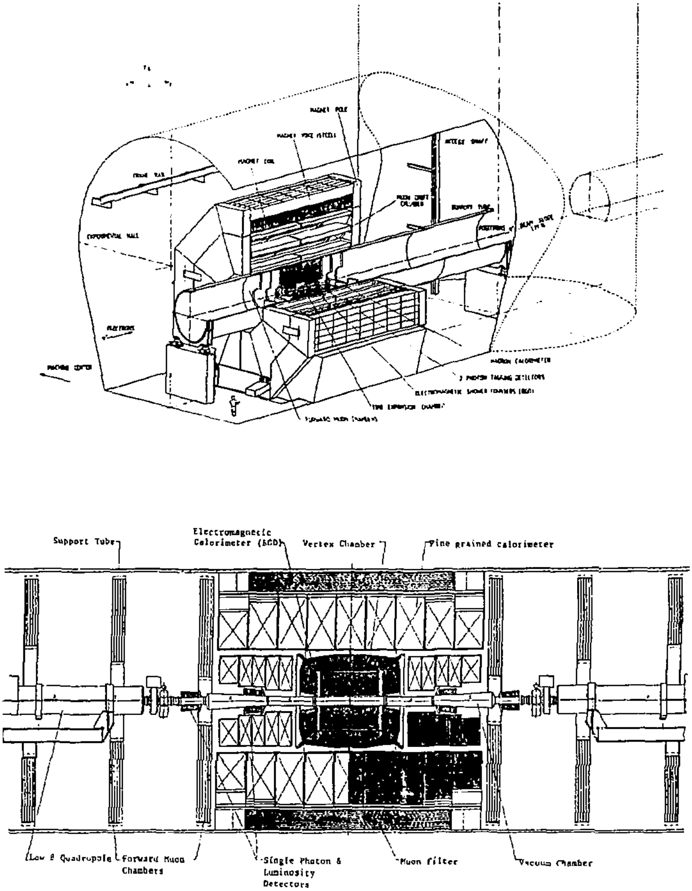


Fig. 3 - The L3 detector (a) overall view
(b) the central part

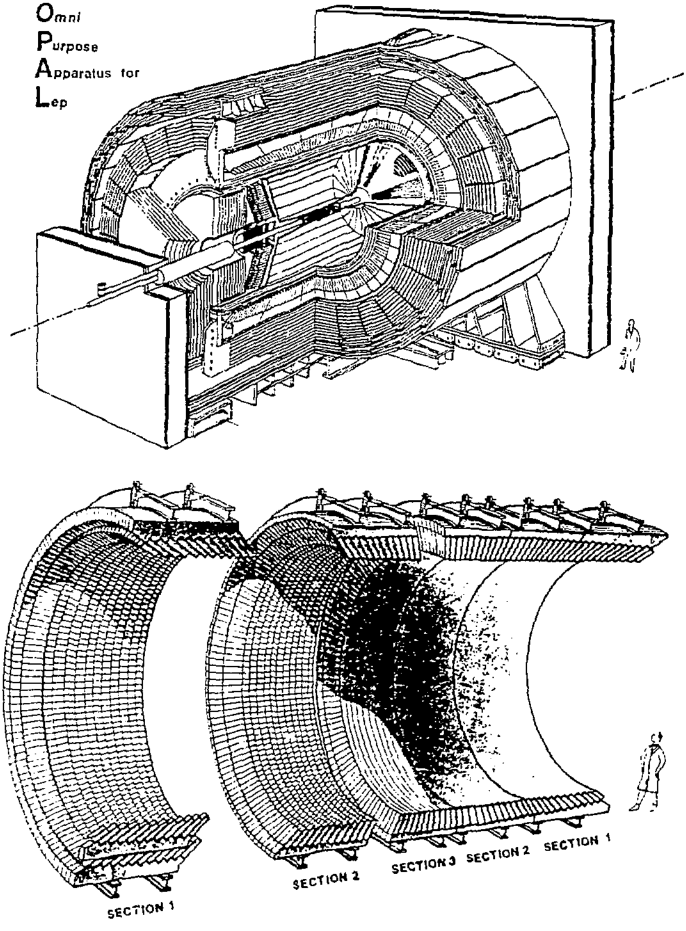


Fig. 4 - The OPAL detector (a) overall view
(b) the leadglass calorimeter

Behind the coil follows the electromagnetic calorimeter -a lead-glass array of 9600 blocks with an additional 2300 blocks in the end-caps. The energy resolution of 9 % $E^{-1/2}$ (not including calibration) reflects the effect of the coil (1.7 X_o at 60° angle). The readout in the end-caps uses vacuum phototriodes.

The hadronic calorimeter follows the same basic design used in ALEPH and DELPHI. Muons are tracked in 4 layers of drift chambers.

III. *TESTING THE STANDARD MODEL*

1. Vector boson masses and fermion neutral couplings

We recall the standard relations of the electro-weak theory giving the boson masses and the leptonic couplings to the Z° :

$$\left| \begin{array}{ll} M_W{}^2 = \dfrac{\pi\alpha}{\sqrt{2}\, G_F\, x(1-r)} & (1) \\[2ex] M_Z{}^2 = \dfrac{M_W{}^2}{\rho(1-x)} & (2) \end{array} \right.$$

$$\left| \begin{array}{l} v_\ell = -1 + 4x \\ a_\ell = -1 \end{array} \right. \qquad (3)$$

where $x = \sin^2\theta_W$

and ρ is determined by the structure of the Higgs fields multiplets of weak SU(2). In the standard model with only Higgs doublets (in fact the minimal model has only one) ρ is equal to one and x can be defined[13)] through the observed W and Z masses

$$x = 1 - \frac{M_W{}^2}{M_Z{}^2} \qquad (4)$$

The quantity r is a 2nd order electro-weak correction : in fact, its value depends mostly on the running of the electromagnetic constant from $q^2 = 0$ to $q^2 = M_W{}^2$, involving e^+e^- annihilation cross sections, but, in addition, it is also sensitive to loops with either fermions pairs or including the Higgs boson. Therefore this quantity is an interesting one, providing information on the fermion mass spectrum and on the Higgs mass, especially if these particles lie well beyond the W mass range. With $m_t \sim 40$ GeV and $M_H \sim 80$ GeV one obtains[14)]

$$r = .0696 \pm .0020$$

where the error is dominated by the uncertainties in the low energy e^+e^- annihilation data. The contribution of heavy quarks ($m_t \gg m_b$)

$$\delta r \simeq -\frac{3\alpha}{16\pi}\,\frac{1-x}{x^2}\,\frac{m_t^2}{M_W^2} \qquad m_t \gg M_W \tag{5}$$

allows a sensitive exploration of the mass range beyond 100 GeV (Fig. 5). This is important because these new quarks will either be produced at LEP if their mass is below 100 GeV or will be detectable through their contribution to r, therefore allowing one to cover the complete mass range up to a point where the standard model probably breaks down. This, together with neutrino counting, will be a formidable tool to experimentally address the family problem. Higgs bosons also contribute to r but, unless their mass is very heavy, the effect is small (Fig. 5):

$$\delta r \simeq \frac{11\alpha}{48\pi x}\,\ln\frac{M_H^2}{M_Z^2} \qquad M_H \gg M_Z \tag{6}$$

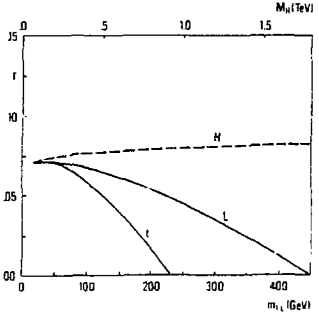


Fig. 5 - The sensitivity of the radiative correction to the boson masses with respect to the mass of heavy fermions (top quark t or heavy lepton L) and the Higgs boson (H) mass.

In conclusion, in order to reach a sensitivity to fermion masses down to 100 GeV and to retain some sensitivity to large Higgs masses, it is necessary to measure r with an accuracy Δr less then .005.

a) measurements at the Z° peak

Measuring the central mass and the width of the Z° resonance will be straightforward at LEP. Radiative corrections are most important and have to be computed to 2nd order. It is envisaged[15] to achieve a precision of 100 MeV rather easily and 50 MeV with some effort. Polarized beams could be used to even lower this value since they allow a very precise energy calibration ($\sim 10^{-5}$) ; conventional methods based on magnet current measurements will be limited to $\sim 3\,10^{-4}$.

Muon-pair asymmetry and τ polarisation (through the $\tau \rightarrow \pi\nu$ mode) will independently measure the weak angle through the leptonic vector couplings. Running for an integrated luminosity of 100 pb^{-1} will yield over $4\,10^6$ Z° bosons and will permit accurate measurements :

$$\Delta A_\mu = .003$$

$$\Delta P_\tau = .025$$

Corrections to A_μ have to be carefully evaluated (2nd order weak effects are at the .003 level[16]); experimental effects can be made negligible. These precisions translate into measurements of $x = \sin^2\theta_W$ with the following accuracies (for x = .22) :

$$\Delta x = \frac{\Delta A_\mu}{24(-1+4x)} = .001$$

$$\Delta x = \frac{\Delta P_\tau}{8} = .003$$

It is therefore reasonable to expect x to be known to about .001 after careful measurements and analyses are performed.

Using eq.(1) and (2), it will be possible to experimentally measure the radiative correction r. With ΔM_Z = 50 MeV and Δx = .001, one gets

$$\Delta r = .0035$$

corresponding to 5 % of the total effect. Clearly, this is a powerful test of the theory : a 3σ deviation could be caused, for example, by a 95-GeV top quark, or by a 150-GeV charged heavy lepton, or by a 800-GeV

Higgs. Larger masses would produce larger deviations.

It is fair to remark that the physics program discussed so far will also be covered by the SLC machine involving yet unproven techniques, but with the clear advantage of being ready 2 years before LEP.

b) measurements at 200 GeV centre-of-mass energy

The reaction

$$e^+e^- \rightarrow W^+W^-$$

offers the distinct advantage of a clean measurement of the W mass. How precise do we need to know M_W in order to match the measurements performed at the Z° peak ?

With ΔM_W = 50 MeV and Δx = .001, M_W is predicted to an accuracy of 70 MeV, if $\rho = 1$. Any experimental deviation would signify an inconsistency within the standard model or would indicate a departure from $\rho = 1$ signaling a higher complexity in the Higgs sector. A determination of the W mass with ΔM_W = 100 MeV translates into a precision

$$\Delta\rho = .003$$

which, as an independent measurement, is 10 to 20 times better than achieved so far.

The W mass can be measured in at least 3 independent ways :

- the threshold behaviour of the cross section (Fig. 6) is well-defined because of the dominance of the ν-exchange graph which involves only well-known couplings. The W signal will be clean : at $\sqrt{s} \sim 180$ GeV, the W cross section is roughly equal to the continuum hadron yield, but the event topologies are different enough and one W can be efficiently tagged by its jet-jet invariant mass. The method for measuring the mass has been already used for $e^+e^- \rightarrow \tau^+\tau^-$ with smaller statistics. Taking into account the W width, one expects a precision

$$\Delta M_W \sim 100 \text{ MeV} \quad (\text{for } 100 \text{ pb}^{-1})$$

The disadvantage of this method is the necessity of an energy scan from M_W to $\sim M_W + 5$ GeV which is not so useful for other purposes. It is therefore worthwhile to look for methods which can be used where the cross section is maximum.

- the lepton spectrum end-points carry information on the W mass[17) (Fig. 7). The absolute calibration of the detectors can be obtained for

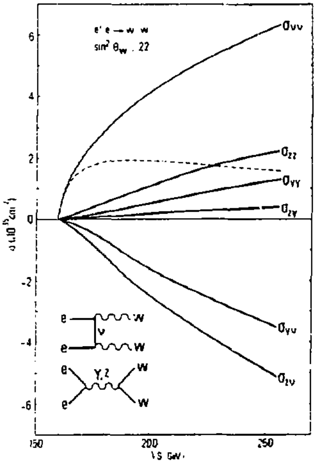


Fig. 6 - The energy dependance of $\sigma(e^+e^- \to W^+W^-)$ analyzed in terms of the various contributions and interferences. The threshold behaviour is determined by ν-exchange

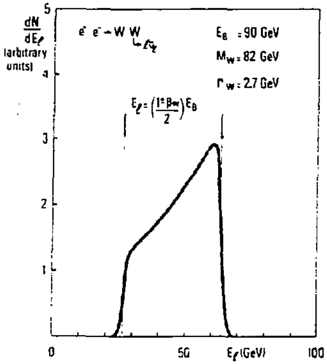


Fig. 7 - The lepton spectrum from $W \to \ell\nu$ decays is sensitive to the W mass

the same energies using Z° decays into e^+e^- and $\mu^+\mu^-$ (a WW event looks like 2 superimposed Z° events, therefore systematic effects can be explored using the large Z° statistics). A 100 pb^{-1} experiment at 180 GeV will yield ∿ 2000 W-pairs (700 events with W → e or μ) with

$$\Delta M_W \sim 200 \text{ MeV}$$

- a direct mass reconstruction can be performed from the observed jets in the 4-jet sample. Using energy conservation a precise mass can be computed ; again the systematic effects can be studied with the Z° sample. Preliminary estimates indicate[15)]

$\Delta M_W \sim 100$ MeV

dominated by systematic effects.

c) conclusions and comparison to $p\bar{p}$ collider

At LEP one can perform stringent tests of the standard model at the level of its radiative corrections. A 5 % measurement of the radiative effects can be achieved at the Z° peak ; it is well matched to the theoretical uncertainty of 3 %. No sensible improvement can be obtained on that from W mass measurements at 200 GeV in the centre-of-mass ; however an independent measurement of ρ is possible with a precision of $3\,10^{-3}$, thus probing the structure of the Higgs sector with an order-of-magnitude increase in precision.

It is interesting to compare these potential results with the $Sp\bar{p}S$ collider measurements of the W and Z masses and those to come in the future at CERN and FNAL. The only relevant observables are M_W and M_Z and clearly it is not possible to separate all the variables (x, r, ρ). Assuming $\rho = 1$, the mass difference $M_Z - M_W$ is a measure of r, but the present measurements do not allow a significant determination. Future measurements with large statistics are foreseen and a careful systematic analysis may result into

$\Delta(M_Z - M_W) \sim 200$ MeV

with an absolute mass scale uncertainty of 1 GeV. This translates into a value of $\Delta r = .02$ —a 30 % measurement only.

2. Vector boson self-couplings

The non-abelian character of the electroweak gauge group is not established so far. For that matter, an unambiguous test would be a direct measurement of the 3-boson couplings, namely the γW^+W^- and $Z°W^+W^-$ couplings. One also expects 4-boson couplings, but they are difficult to get at[8)].

It is now well known that a detailed study of the W-pair production process is the best way to study these self-couplings. The process is mediated by the 3 amplitudes shown in Fig. 6 where the ZWW appears explicitly and the γWW coupling could involve an anomalous magnetic moment K and a quadrupolar electric moment Q, suitable for a spin-1 particle. The standard model claims

$$K = 1 \qquad Q = 0$$

$$g_{ZWW} = e \tan\theta_W$$

Calculations of this process have been performed[19], keeping in mind the possibility that deviations from the standard couplings could occur. Cancellations are very large between the different interference and squared terms : this is obvious in Fig. 8 where the effect of turning off the ZWW coupling is dramatically displayed. So a good sensitivity to that coupling is obtained. The effect of varying K and Q away from the standard values[20] is also important (Fig. 9).

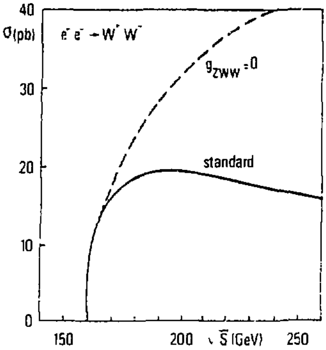


Fig. 8 - The energy dependance of $\sigma(e\ e \to W\ W)$ depends sensitively on the value of the ZWW coupling

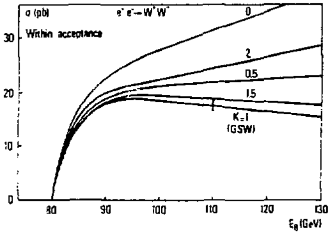


Fig. 9 - The dependance of $\sigma(e\ e \to W\ W)$ on the value of the W anomalous magnetic moment[20] (detector acceptance : $\theta_{\text{jets, leptons}} > 20°$)

It turns out that the W angular distribution is remarkably sensitive to deviations in the couplings[20)]. The sensitivity improves with the beam energy because of the relative increase of the boson exchange amplitudes compared to the ν exchange which largely dominates just above threshold. It is therefore important to run at a centre-of-mass energy of at least 200 GeV -- the higher the better. Fig. 10 shows the expected angular distribution at $\sqrt{s} \sim 220$ GeV. In order to achieve a good sensitivity, it is crucial to measure the W charge which can be achieved if one of produced W's decays leptonically. Also, the W direction can be completely reconstructed. A 100 pb^{-1} experiment will yield the following range for the anomalous magnetic moment

$$.85 < K < 1.3$$

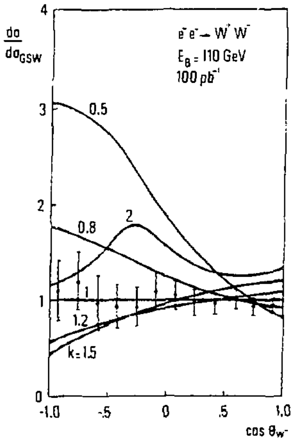


Fig. 10 - The W angular distribution is sensitive to the W anomalous magnetic moment[20)] (detector acceptance : $\theta_{\text{jets,leptons}} > 20°$)

It is also possible to look at other observables : for example, the lepton spectrum from the W decay is also sensitive to the gauge couplings, however the precision is worse[20)].

The production of a pair of W bosons can also be considered at a hadron collider

$$p\bar{p} \to W^+W^- X$$

with however a small rate and potentially dangerous backgrounds[21)]. The physics potential of LEP in this domain is therefore truly unique.

IV. THE MISSING PIECES IN THE STANDARD PICTURE

1. The top quark

PETRA has established a firm lower limit of 23.3 GeV for the mass of the t quark[22)]. Some evidence has been claimed by the UA1 collaboration[5)] for events where the W decays into t $\bar{b}$, followed by a semileptonic t decay. These events and some new ones are still under scrutiny. The experimental problems are obviously harder than assessed early on : we have to wait for a final analysis but, most probably, still more data will be required in order to reach a definitive conclusion about the existence of the top quark in the 40-60 GeV mass range.

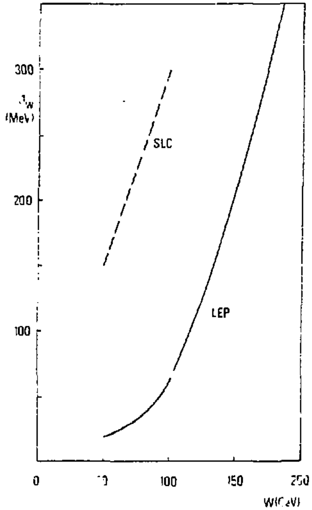


Fig. 11 - The CM energy resolution foreseen for the SLC[31)] and LEP[30)] machines

It is therefore conceivable that the top quark will still be missing when SLC and LEP turn on ; at the very most, not much more than an approximative value for its mass will be known by then. A unique possibility of LEP is the study of toponium states, since its energy resolution far exceeds that of SLC (Fig. 11). It is unreasonable to carry out a complete scan over the full LEP range. But it is unnecessary : looking for $t\bar{t}$ decays of the Z° (2 fat jets) will allow a determination of the t mass to ∿ 1 GeV and it will be enough to scan a ∿ 2 GeV mass range to uncover the various peaks. Should the t quark not show up in Z decays because of its still higher mass, the standard technique of measuring R and searching for large sphericity events at the highest energy will be used. And again an estimate of the t quark mass will narrow down the energy range to be scanned.

The same mechanisms which prevail in ψ and Υ decays are also expected to be active for toponium. However, 2 facts point to a qualitatively different situation : on one hand, if the t mass is large, single quark decay will occur through the weak charged current within toponium ; on the other hand, toponium might have a mass close to the Z° mass in which case the fermion-antifermion decays will be strongly enhanced Fig. 12. This possibly large rate could be a spectacular effect on the Z° "slope" but will be a mostly uninteresting source of events. Pushing this possible coincidence to an extreme case, if the toponium and the Z° are nearly mass-degenerate, the toponium signal might turn into a dip as a consequence of the unitarity limit. Fig. 13 shows the expected decay fractions as a function of the toponium mass[23]: one observes the dominance of Z° mediated decays when the toponium is close to the Z° and the otherwise dominant single quark decay. The important 3-gluon channel in ψ and Υ decays becomes here relatively negligible.

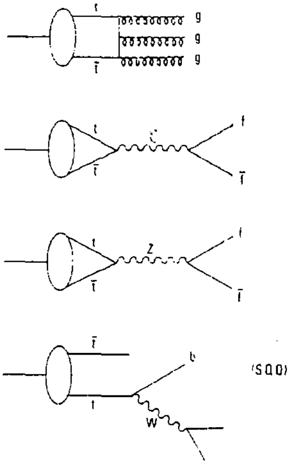


Fig. 12 - Toponium decays

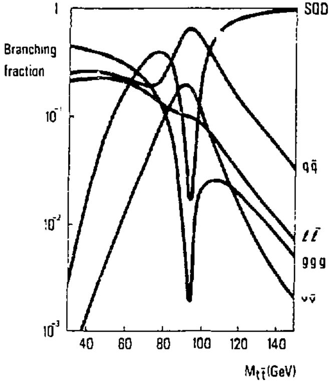


Fig. 13 - The expected branching fractions of the 1S toponium state[23]

The appearance of the different bound states and the onset of the $t\bar{t}$ continuum depend crucially on the top quark mass with respect to the Z° peak. Also the energy fluctuations of the beams will spoil the resolution of the many peaks (about 10 of them). This will make it difficult to determine precisely the open t threshold (Fig. 14).

The possible observation of other $t\bar{t}$ resonances (besides the 1^{--} states) will be problematic because of rate : a 2S state near 80 GeV will decay radiatively into P states at a rate ∿ 1/day and the complete cascade down to the 1S

$$\begin{array}{l} 2S \rightarrow \gamma + P \\ \qquad\quad\ \hookrightarrow \gamma + 1S \end{array}$$

will be at the level of .1 event/day. Fully constrained final states such as $\gamma\gamma\mu^+\mu^-$ and $\gamma\gamma e^+e^-$ with precise angular measurements will permit an accurate measurement of the photon energy ($\Delta E_\gamma \sim 1$ MeV even though $E_\gamma \sim 200$ MeV). The problem is therefore not background, but rate.

In conclusion, the study of toponium at LEP will offer interesting prospects. We have not mentionned the aspect of probing the $q\bar{q}$ binding potential to smaller distances. More fundamentally, a heavy toponium could be a realistic source of Higgs bosons, which is by itself enough of an incentive to investigate toponium decays.

2. The Higgs boson

The Higgs mechanism is generally felt as the most unpleasant part of the standard model. It is certainly the least tested ingredient and so far only indirect evidence has been gathered through the weak boson masses and the fact that ρ is consistent with 1. It is therefore an area that requires a vigorous experimental investigation.

The advantages offered by e^+e^- annihilation in searching for Higgs bosons are well known : processes exist where the Higgs signature is clean i.e. it can be found by missing mass with no requirement imposed on the Higgs system. This is important because the decays can further be investigated without any bias and therefore the Higgs nature of the found state can be clearly established (dominance of heavy fermion pairs). The mass range to be explored is however limited to only ∿ 100 GeV by the maximum energy of LEP.

The standard approaches are (Fig. 15)

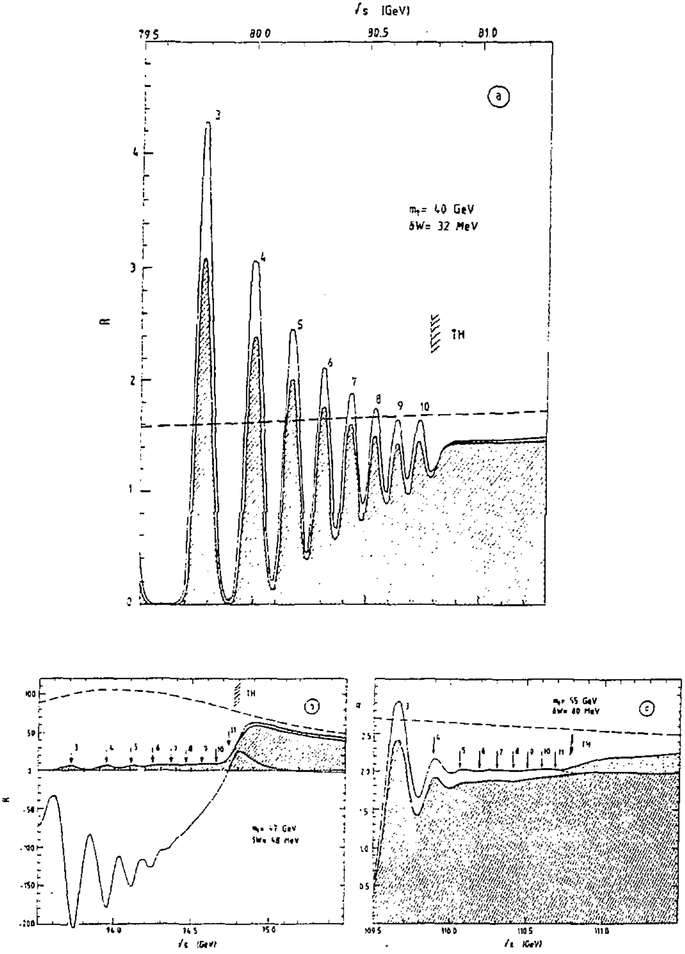


Fig. 14 - The higher toponium states and the opening of the $t\bar{t}$ continuum[24)]

(a) Z° decays where the most promising channel is

$$Z^\circ \to \ell^+\ell^- H^\circ$$

allowing to explore Higgs masses up to ∿ 50 GeV, limited by statistics and background from $t\bar{t}$ decays of the Z°. If H° is produced in this way, the main decay mode will be $H^\circ \to b\bar{b}$ which can be experimentally checked.

(b) toponium decays making use of the Wilzeck mechanism[25)]

$$(t\bar{t}) \to \gamma\ H^\circ$$

This has been studied recently[26)] and compares favourably in rate with the previous method.

(c) heavy Higgs bosons can be searched for using

$$e^+e^- \to Z^\circ H^\circ$$

where the Z° can be tagged by $\ell^+\ell^-$ or $q\bar{q}$ decays. This method can be used all the way to a mass of 80 GeV. If the H° and Z° particles are close in mass, one has to worry about W^+W^- and $Z^\circ Z^\circ$ backgrounds depending on the final state used to tag Z°'s (Fig. 16).

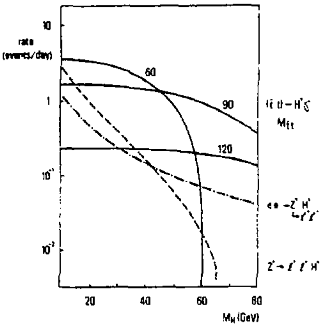


Fig. 15 - Rates for Higgs production at LEP in 3 cases : toponium decay, Z° decay and $Z^\circ H^\circ$ production

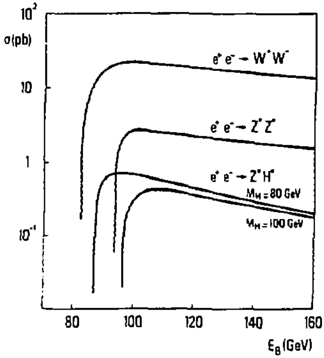


Fig. 16 - Comparison of Higgs production near 100 GeV beam energy to W-pair and Z-pair processes

As far as rate is concerned, the 3 methods are compared in Fig. 15[26]. It is interesting to note that toponium fares quite well in this comparison in terms of rate and also background rejection. The situation is however not under full control since we don't know yet the toponium mass. Also, while large amounts of data are likely to be collected at the Z° peak and near 200 GeV, it is unclear at this moment how much time can be reasonably spent on a possible toponium.

V. LOOKING FOR NON-STANDARD PHENOMENA

1. Deviations from precise measurements

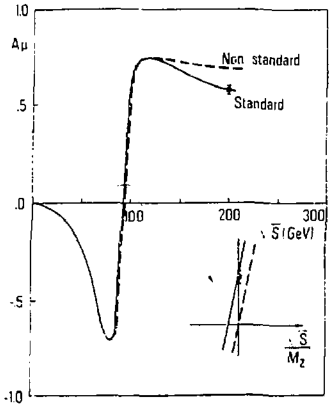
We have outlined above how precise measurements of vector boson masses and fermion couplings could check the standard electroweak model at the level of 5 % of its radiative corrections. If the $SU(2) \times U(1)$ theory is only a low-energy phenomenological "remnant" of a more complete theory, differences can possibly show up through these incisive tests.

Different possibilities can be involved : may be the gauge group is larger, $SU(2)_L \times SU(2)_R \times U(1)$ for instance, and several Z° bosons are to be found ($Z^o_L \sim 93$ GeV and Z^o_R which could be quite heavy) ; or the present theory is only an effective one and the bosons are composite. In the latter case, one could expect a rich spectroscopy of states with several isovector bosons and possibly also isoscalar bosons[27].

Two complementary sets of measurements can then be performed at LEP. In the case of the μ-pair asymmetry, on one hand an accurate value can be obtained at the Z° peak with an accuracy well below 1 % ; on the other hand a less precise determination near 200 GeV centre-of-mass can be very helpful to sort out different explanations for a discrepancy at the Z°. Fig. 17 illustrates this point. The mass scale which is investigated in this way depends on the particular theory but it is generally in the 0.5 to 1 TeV range.

2. Supersymmetry

The idea of supersymmetry is elegant and very attractive ; yet, no



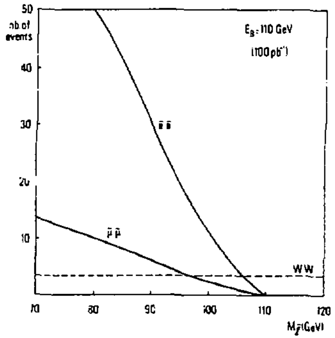


Fig. 17 - Two complementary view to search for deviations from the standard model using the μ-pair asymmetry (schematic) : precise measurement at the Z° pole and measurement at the peak energy of LEP

Fig. 18 - Yield of e^+e^- and $\mu^+\mu^-$ final states with missing energy and momentum at E_B = 110 GeV searching for scalar electrons and muons. Events with both forward-going ℓ^- (cosθ > 0) and ℓ^+ (cosθ < 0) are removed

experimental confirmation has been obtained despite an intense program, mostly at PETRA. We do not know the mass scale of supersymmetry breaking but if the theory is to "explain" the electroweak phenomenology (in particular, it provides a natural way to introduce the Higgs bosons) then it would be hard to understand the mass spectrum if at least a few of the predicted particles did not lie at the electroweak scale ~50 to 100 GeV. This is well matched to the LEP machine : in fact, I think, the real strength of LEP is to explore in a systematic and unambiguous way the particle mass spectrum up to 100 GeV, i.e. over the electroweak mass range.

The first step will be to investigate Z° decays to search for pairs of scalar leptons. However it is conceivable that such a possibility will be ruled out then because of current experiments at PEP and PETRA probing the scalar electron mass range up to 40-60 GeV, provided the photino mass is not too large.

Full calorimetric coverage is a must to carry out these searches since missing energy and momentum are always a signature. Backgrounds are small, except above the W-pair threshold, but even there it is not a serious problem as shown in Fig. 18 for $\tilde{e}$ production (enhanced by t-channel $\tilde{\gamma}$ exchange) and for $\tilde{\mu}$ production (only s-channel amplitude). The distinctly flat lepton angular distribution allows to exclude scalar leptons up to a mass of at least 95 GeV.

It is challenging to look for photinos if they are stable, despite the fact they might be light on the typical SUSY mass scale. Photino-pair production, currently investigated through single photon searches is not applicable to energies much beyond PETRA because the radiative neutrino production becomes a dominant source of single photons, all the way to the maximum LEP energies. A possibility is the associated photino-zino production

$$e^+e^- \to \tilde{\gamma}\,\tilde{z}$$

giving final states analogous to those expected in scalar lepton pairs.

Gluinos are a bit harder to hunt for in e^+e^- annihilation, except on the toponium. The decay (Fig. 19)

$$(t\bar{t}) \to \tilde{g}\,\tilde{g}$$

can occur only if $\tilde{t}_R$ and $\tilde{t}_L$ are non-degenerate, thus inducing a parity violation. Otherwise only C = +1 states can decay in this way. Large rates are expected.

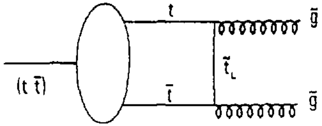


Fig. 19 - Gluino pair decay of toponium is possible if the 2 scalar t quarks ($\tilde{t}_L$ and $\tilde{t}_R$) are not mass-degenerate (P violation)

The fact that experiments at PETRA could set definitive mass limits on the SUSY particle world is an existence proof of working methods which should be reliable at LEP all the way to ∿ 100 GeV masses. If no positive sign of supersymmetry has shown up by then, I suspect the interest in this approach will fade away very rapidly.

3. Compositeness

A composite structure for quarks, fermions and bosons is an interesting proposal. Any deviation from the standard model (masses, couplings, decays, gauge couplings) could be looked at in a scenario where the Z and W bosons are composite. Further, fermions can also be of composite nature : the angular distribution of ee → ee is sensitive to such a substructure and experiments at LEP can probe[28)] a scale $\Lambda \sim 5$ to 10 TeV. Processes like ee → μμ can also be studied with a similar sensitivity, however in this case deviations from the electroweak theory can occur only if the electron and the muon share some types of constituents.

Finally, internal structure can show up more drammatically if new states are uncovered. They could include : excited fermions

$$f^* \to f\gamma$$

which can be looked for up to a mass of 200 GeV ; octet leptons

$$\ell_8 \to \ell g$$

which can be pair-produced if their mass does not exceed 100 GeV, and similarly for leptoquarks

$$\chi \to q\ell$$

leading to final states comprising jets and leptons, with or without missing momentum (depending whether the lepton ℓ is charged or neutral).

VI. CONCLUSION

This very incomplete review of the LEP physics program, with emphasis on the most recent and topical aspects, clearly indicates its potential for new discovery. Of course, we all know the power of hadron colliders for the exploration of large masses. It is also clear that e^+e^- colliders will always operate on a smaller energy scale, yet they have proven to generate very reliable and complete physics programs. As an example, we have been pleased to see at this meeting, for the first time, some evidence for τ production[29)] with a hadron machine, when for the past ten years the detailed properties of our third fundamental lepton have been steadily unraveled at Stanford and Hamburg. There is some exciting time ahead with the experimentation at LEP !

Discussions with many colleagues are acknowledged, in particular with K. Hagiwara, R. Peccei and F. Richard ; many thanks to M. Greco for his efficient organization of this meeting.

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