CERN PLANS FOR THE FUTURE

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I. INTRODUCTION.

Predicting the future of a laboratory like CERN is almost like looking in a crystal ball. Since CERN is only a few kilometres away from the village where philosopher Voltaire lived it may be appropriate to quote him when he said in 1766:

"Les Philosophes qui font des systèmes sur la secrête construction de l'Univers sont comme nos voyageurs qui vont à Constantinople et qui parlent du Sérail; ils n'en ont vu que les dehors et ils prétendent savoir ce que fait le Sultan avec ses favorites!" [1] that is, translated in the language of Shakespeare: " The philosophers, with the systems they build on the hidden structure of the Universe, are like those travellers of ours, who go to visit Constantinople and come back talking of the Seraglio: they have only seen the outside, yet they claim to know what the Sultan does with his favourites! "

The goal of CERN is to provide the scientific community of the fifteen European Member States with those research facilities they may need in the field of elementary particles (HEP) and which because of their price, complexity or otherwise cannot be built on a national basis. CERN's user population is characterized by a rapid growth which can be well parametrized as an exponential with a doubling rate of about five years (another Livingston plot!, see Fig. 1). The participation of scientists from Non Member States has grown more than percentage-wise over the last decade from about 10% to about 20% of the users. It can be estimated that today CERN provides access to its facilities for over 5000 physicists, welcoming about 50% of the World's population in HEP.

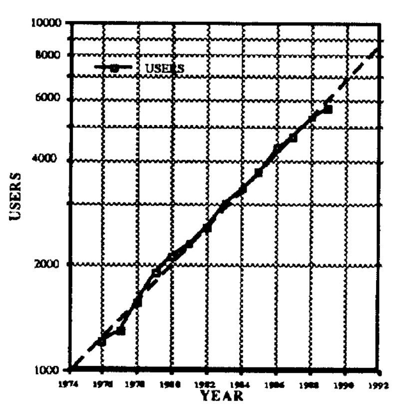

Fig. 1. Time evolution of the number of CERN users.

Amongst them there is a large, flourishing community of young physicists around the golden age of 25-35 years. On the other hand the in-house population of staff research physicists is small and it amounts to about 300 people.

CERN's goal is to provide the scientific community with the best research facilities, mostly characterized by their uniqueness, although some partial duplication with projects in other continents is unavoidable and sometimes desirable for fostering a variety of different approaches to the fundamental questions. A significant proof of the complementarity between the US and CERN's programmes is the rapid increase of "transatlantic" users which now for the first time shows balance.

The future programmes of CERN are directly connected with on-going activities and they represent in essence a further exploitation of already identified potentialities. The backbone of the CERN programme is a series of rings connected to each other by injection/transfer lines (Fig. 2). The $\bar{p}$ production and accumulation is not shown in the diagram, although low energy $\bar{p}$'s are an important part of the current CERN programmes. After a rather elaborated injection system, these rings currently accelerate beams of ions, protons, antiprotons, electrons and positrons, first injected into the CPS (R = 100 m), then transferred and accelerated in the SPS (R = 1100 m) before reaching the largest ring LEP, whose 27 km tunnel — presently limited to electron-positron collisions — is intended to house colliding protons and ions, the so-called LEP-LHC complex. Collisions between LEP and LHC will also offer high energy, high luminosity e-p collisions.

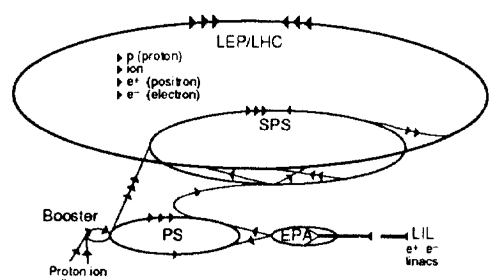

Fig. 2. Schematic view of the CERN accelerator complex.

Both CPS and SPS have extended the utilization of extracted beams. A typical CPS super-cycle (Fig. 3) shows the complexity of operation, which involves electrons, positrons, protons, antiprotons, oxygen, sulphur, etc. essentially as part of a chain process. At each new cycle within the magnetic supercycle a different type of particle is accessed and fed into the system. Antiprotons for LEAR and the antiproton accumulator (AA+ACOL), SPS feeding, PS feeding, etc., are all interrelated into an extremely complicated operation. The SPS is a similarly complex system for protons, antiprotons, electrons and positrons and various ions.

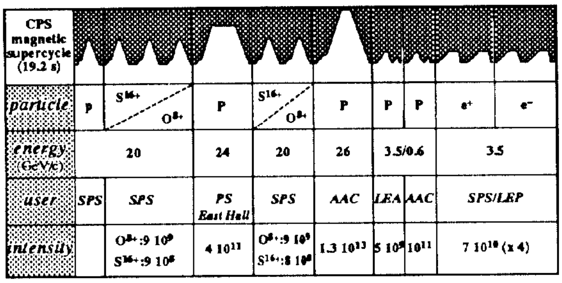

Fig. 3. Schematic display of a typical CPS super-cycle.

The wealth of facilities thus provided permits to handle a large diversity of CERN programmes which include fixed target physics and neutrino physics (19%), high energy p-$\bar{p}$ collisions at the Sp$\bar{p}$S Collider (10%), low energy $\bar{p}$ collisions with LEAR (13%), electron-positron collisions with LEP (40%), ion physics (13%) and short-lived isotope studies with ISOLDE (5%), to name only the main subjects (figures within parenthesis provide an indication of the fraction of CERN users for each activity). At present the Sp$\bar{p}$S collider and the synchro-cyclotron (SC) are being closed down to leave room for future programmes within a rigourously constant budget. ISOLDE will be continued by transferring it from the SC to the CPS-Booster where spare pulses are left available once they have served as injectors to the CPS.

Such a richness and variety is also exemplified by the extremes in the size of the storage devices of CERN. If the largest is by far LEP, the smallest is an antiproton trap (PS196) which has stored $\bar{p}$'s for months in a volume < 1 cm^3 (Fig. 4).

PS196

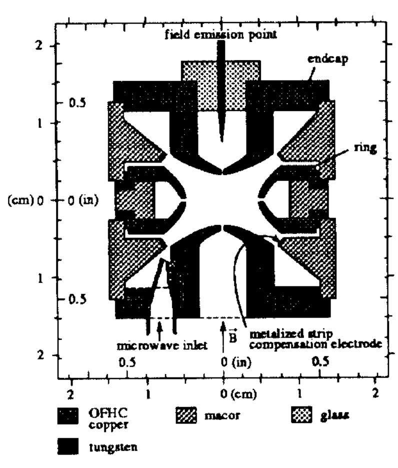

Fig. 4. Schematic view of the Penning trap

The $\bar{p}$'s are accumulated and cooled in AA+ACOL and after a transit in LEAR they are slowed down through interactions in matter to reach a momentum of about 1 KeV in a Penning trap where they are further cooled to electron volts and finally to milli-electron volts, through resistive cooling, thus reaching the temperature of the container, 4.2 K. By studying the cyclotron motion one can measure with great accuracy the ratio of the $\bar{p}$ to p mass (Fig. 5) [2]. This Penning trap method promises improvements of many orders of magnitude on several fundamental parameters of the $\bar{p}$'s.

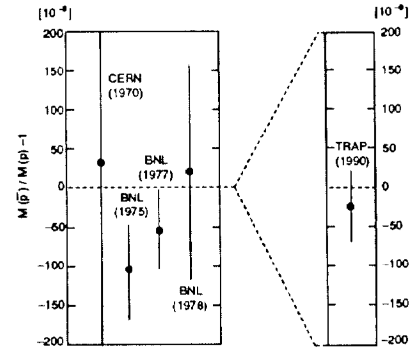

Fig. 5. Comparison with other experiments of the measurement of the ratio of the proton to antiproton masses from the Penning method.

II. FUTURE SCIENTIFIC PLANS

A. General strategy issues

It is impossible to elucidate the full extent of the future programmes of CERN within the five allotted pages. Therefore I shall focus on the high energy frontier represented by the LEP-LHC complex. A global approach is taken, in which both LEP and LHC play a parallel complementary role in the understanding of the phenomenology in the energy scale domain below 1 TeV.

Many of LEP results indicate that important discoveries may lay in the energy domain just above the one presently explored, namely the one of LEP200 and of LHC. Much of the precursory ability of LEP is due to the extraordinary precision of the results. A clear illustration appears in Fig. 6.

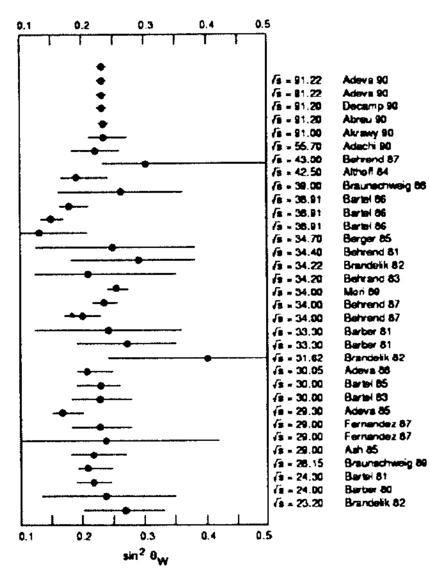

Fig. 6. History of the measurements of the electro-weak mixing parameter $\sin^2\Theta_W$. The last five points are from LEP.

The superior accuracy of LEP measurements [3] is clearly visible. A second illustration of LEP's extraordinary accuracy are the measurements of the axial and vector leptonic weak couplings, respectively g_A and g_V (Fig. 7) [4]. The line representing electro-weak expectations is also drawn. The expanded circle shows the enormous progress which occurred in the understanding of weak interactions thanks to LEP. Such a remarkable precision and the high quality of these new results permit to limit considerably the physics possibilities ahead of us and guide us in our future plans. I shall limit such considerations to a few cases:

1) *Higgs and top quark masses are related within the Standard Model.* Fig. 8 shows the constraints on the top quark and the Higgs masses, obtained taking into account the most

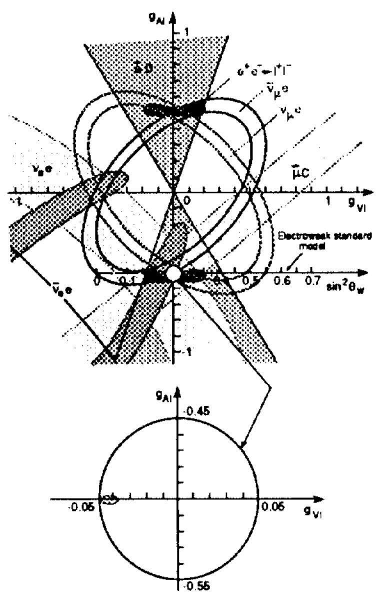

Fig. 7. Allowed region of the plane of the axial versus vector weak couplings. In order to be able to see the combined LEP results, the small white circle on the g_A axis must be expanded by a factor 10 .

recent results from LEP and the higher-order correction loops. The top quark mass should be larger than the present limits of the CDF experiment only by a factor two at most [5].

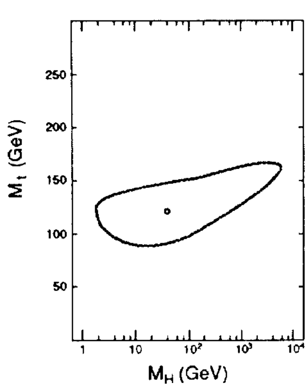

Fig. 8. Allowed contour in the m_{top}-m_{Higgs} plane at 68% C.L.

Unfortunately little or no information can be obtained about the Higgs. However the direct searches for the Higgs have given limits for the mass ≈ 50 GeV/c^2, substantially higher than the predictions of the expert "futurologists" [6]. This search is of extraordinary importance since the Minimal SUSY model predicts that — at least at the "tree level" — one Higgs has a mass ≤ Z^0 mass, hence it is accessible with the planned LEP200 improvements. The top quark spectroscopy — because of its relatively "low" mass — is ideally suited for LHC, even if it is most likely beyond the range of LEP200.

2) *The Beauty complex exhibits mass oscillations in analogy to the well known K_L-K_S system thus opening the possibility for a major progress in our understanding of CP violation.* The B lifetime has been measured to be τ_B = 1.29±0.06(stat.)±0.10(syst.) ps by the ALEPH group [7]. The study of B^0–$\bar{B}^0$ mixing has started. The mixing parameter for $B_{s,d}{}^0$ is presently measured to be $\chi = 0.132 \pm 0.022^{+0.027}_{-0.026}$ [8], an accuracy comparable to that of the pioneering measurements of UA1 [9], ARGUS [10] and CLEO [11]. The potentialities of LEP are evidenced by an example of a B event observed by DELPHI (Fig. 9a). Fig. 9b shows the $\mu^+\mu^-$ pair invariant mass distribution with the identification of the B decay process. Further luminosity increases of LEP and later LHC — a strong source of B mesons — will permit a systematic study of this fundamental phenomenon.

3) *Accurate measurements of the coupling strength of electro-weak and strong interactions from LEP indicate a new global picture of fundamental forces.* The Standard Model — if valid — may indeed represent the "summa summarum" of the knowledge of this century, the same way as Maxwell equations over 100 years ago. In order to accomplish it the overall unification between forces is necessary. The simplest Grand Unification Theory (GUT) is the minimal $SU(3)_C \times SU(2)_L \times U(1)$ model with three families of matter and one Higgs doublet. The coupling constants should evolve smoothly until they become identical at the unification scale.

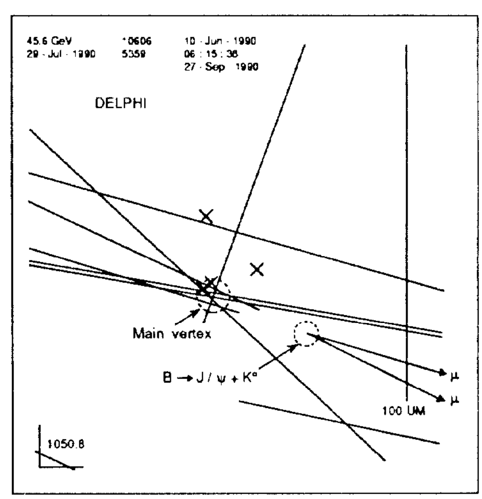

Fig. 9 a). Example of a DELPHI event in which a B decay into a J/ψ is observed.

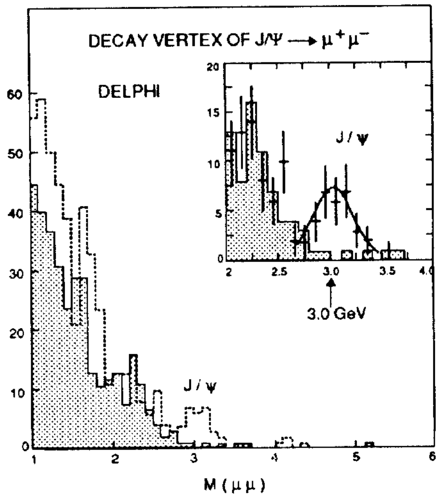

Fig. 9 b). Invariant mass distribution of $\mu^+\mu^-$ pairs as measured by DELPHI.

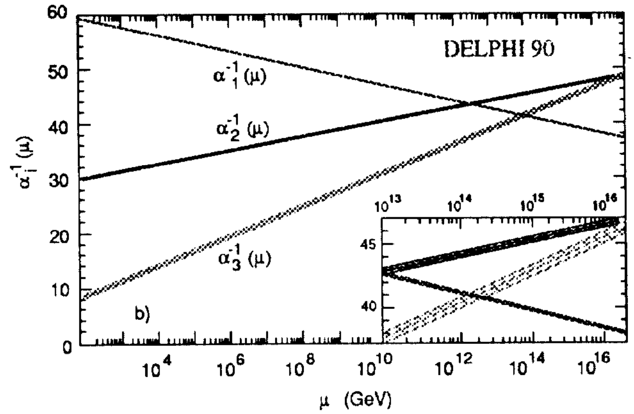

Fig. 10 Extrapolation of the fundamental coupling constants to the unification scale.

Here we make the simplifying assumption that at the unification point the couplings cross without changing slopes (the effect of this simplification for the crossing region is not large compared with the present experimental errors). Earlier data supported the idea of a minimal Standard Model with 3 families and one Higgs doublet. Note that the unification scale was then of the order of 10^{15} GeV or less. The proton lifetime, which is proportional to the fourth power of this scale, is then expected to be of the order of 10^{31} years. Present lower limits are considerably higher: $\tau_{proton} > 5.5\ 10^{32}$ years for the decay mode $p \rightarrow \pi + e$ which is expected to dominate. Therefore, both the non-observation of proton decay and the non-unification of the coupling constants independently rule out any minimal GUT, which leads to the Standard Model below the unification point.

Compared to the results of 1987 the errors coming from LEP are considerably smaller. It is clear that a single unification point can no longer be obtained within the present errors: the α_3 coupling constant misses the crossing point by more than 7 standard deviations (Fig. 10) [12].

Within the framework of GUT this non-unification implies new physics. The combination of precise data on the electroweak and strong coupling constants measured at LEP with the limits on the proton lifetime allows for stringent consistency checks of unified models. The evolution of the coupling constants within the minimal Standard Model with one Higgs doublet does not lead to Grand Unification, but if one adds five additional Higgs doublets, unification can be obtained at a scale below 10^{14} GeV. However, such a low scale is excluded by the limits on the proton lifetime.

On the contrary, the minimal super-symmetric extension of the Standard Model leads to unification at a scale of $10^{(16\pm0.3)}$ GeV (Fig. 11). Such a large unification scale is compatible with the present limits on the proton lifetime of about 10^{32} years. Note that the Plank mass (10^{19} GeV) is well above the unification scale of 10^{16} GeV, so presumably quantum gravity does not influence our results.

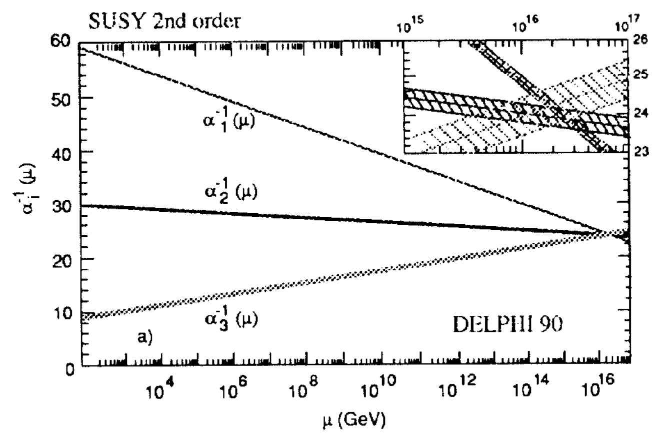

Fig. 11. Same as Fig. 10 within the framework of the minimal Supersymmetric extension of the Standard Model.

Also the non-minimal SUSY models with four or more Higgs doublets — having masses around or below the SUSY scale — can yield unification. However, once more, the unification scales are below the limits allowed by the proton decay experiments. *Therefore only the minimal SUSY model gives a unification scale which may be compatible with the proton lifetime limit.* The best fit to the allowed minimal SUSY model is obtained for a SUSY scale around 1000 GeV or more precisely, $M_{SUSY} = 10^{(3\pm1)}$ GeV, where the error mainly comes from the uncertainty in the strong coupling constant. If this minimal super-symmetric GUT describes nature, SUSY particles, which are expected to have masses of the order M_{SUSY}, could be within the reach of the present or next generation of accelerators. Likewise, proton decay at the rate $10^{(33.2\pm1.2)}$ years could be detected either in Icarus or in Superkamiokande.

As already pointed out, if minimal SUSY is correct, a Higgs particle should be essentially within the range of LEP200. Furthermore SUSY's new particle spectroscopy is presumed to be within the range of LHC.

B. Timetable

The following scenario is envisaged :

- The first step is to collect $5x10^6$ Z^0 events with each LEP experiment before 1993. In order to achieve that goal the number of bunches in LEP will be increased to eight [13] .

- By 1994 the energy of LEP will be pushed to the highest possible limit. This is determined by the necessity of getting as many W pairs as possible and by the interest in searching for Higgs particles at the highest possible energies. Fig. 12 shows that the total $e^+e^- \rightarrow$ hadrons cross section decreases by three orders of magnitude from the Z^0 peak to the W pair threshold region. A decision has been taken not to go by steps but to jump from the Z^0 to the highest available energy. Starting in 1994 we intend to run LEP intensively for three years in order to collect 500 pb^{-1} at the W^+W^- pair energy region.

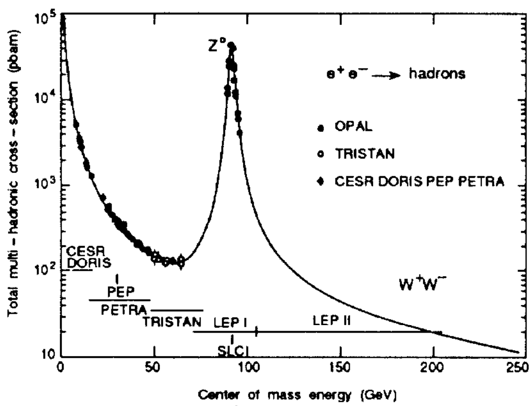

Fig. 12. Cross section for $e^+ e^- \rightarrow$ hadrons as a function of $\sqrt{s}$.

- By 1998 we expect to start the LHC operation, after a one year shut-down in which LHC will be installed. Also LEP will be probably modified in order to increase the luminosity by about one order of magnitude using the "Pretzel scheme". In these conditions LEP will probably run on the Z^0 peak and longitudinal polarization will become an important added parameter.

- By the time LEP is eventually losing momentum, sometimes after the turn of the century, one or more beam crossing regions can be converted into electron-proton collisions with 7 times the HERA energies and a good luminosity.

The foreseen schedule is given in Fig. 13, with LEP running every year, except for the 1997 long shut-down and the LHC starting by 1998. However, although the schedule is well defined for LEP, for LHC it depends on its timely final approval. The reason for a cautious approach to LHC is that it is a programme aiming at a very careful design in order to obtain the most performant and most cost-effective device. A substantial gain is obtained by a twin-aperture magnet working at very low temperatures(2K). It should then be possible to reach magnetic fields perhaps as large as 10 Tesla, corresponding to $\sqrt{s}$=16 TeV and a luminosity in excess of 2.0 10^{34} cm^{-2} s^{-1} for at least three crossing points.

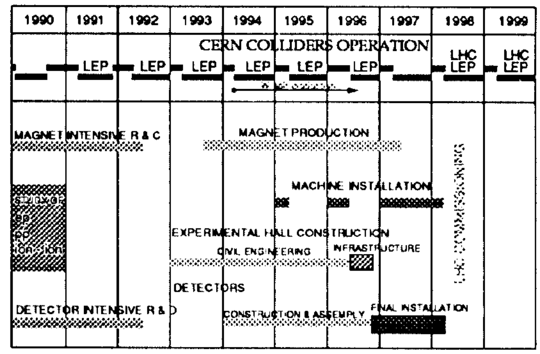

Fig. 13. Foreseen schedule for LEP operation and LHC construction.

III. CONCLUSIONS

Today CERN is playing a major role in the world community of High Energy Physics, offering services to more than one half of the world's users. Its programme is broadly diversified and it offers a large variety of particles and energies. Its chain of connected rings allows an optimum cost-effectiveness ratio. The most recent facility, LEP, has already provided an unprecedented number of Z^0's. It is a unique facility worldwide in view of its luminosity and the potentialities of energy upgrades. The full exploitation of the LEP tunnel — the so-called LEP-LHC complex — is the cornerstone of CERN's future strategy aiming at the definitive exploration of the phenomenology below 100 GeV with LEP200 and the systematic mapping of the domain up to 1 TeV with proton-proton and ion-ion collisions with the LHC.

LEP200 first and LHC later will pave the way[14] for further explorations of the 1 TeV energy scale and beyond with new linear colliders and higher energy hadronic colliders.

IV. REFERENCES

[1] Voltaire, Pensées Philosophiques, 1766.

[2] G. Gabrielse et al., Phys. Rev. Lett. 65 (1990) 1317.

[3] For a recent review see H. Burkhardt et al., CERN-PPE / 91-50, to be published in Ann. Rev. of Nucl. and Part. Sci. vol 41 (1991).

[4] F. Dydak et al., Rapporteur's talk, Proceeding of the 25th International Conference on High Energy Physics, Singapore 2 - 8 Aug. 1990, CERN-PPE-91-14.

[5] F. Abe et al., Argonne preprint ANL-HEP-PR-90-109, submitted to Phys. Rev. D.

[6] The Higgs Hunter's Guide, J. F. Gunion et al., Frontiers in Physics, Addison-Wesley (1990).

[7] D. Decamp et al., Phys. Lett. B257 (1991) 492.

[8] D. Decamp et al., Phys. Lett. B258 (1991) 236.

[9] C. Albajar et al., Phys. Lett. B186 (1987) 247; CERN PPE / 91-55. submitted to Phys. Lett.

[10] H. Albrecht et al., Phys. Lett. B192 (1987) 245.

[11] M. Artuso et al., Phys. Rev. Lett. 62 (1989) 2233.

[12] U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. B260 (1991) 447.

[13] J. P. Koutchouk, Performance of LEP, proceedings of this conference.

[14] Proceedings of "Large Hadron Collider Workshop", Aachen, 4-9 October 1990, Vol. I, II and III, CERN 90-10, ECFA 90-133.