Laboratori Nazionali di Frascati

LNF-87/101(P)
23 Novembre 1987

M. Greco:

PHYSICS AT FUTURE COLLIDERS

Invited talk given at the
INFN ELOISATRON project Workshop on
"New Aspects of Very High Energy Proton-Proton Physics"
Erice, June 1987

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ABSTRACT

The physics potential of next generation colliders are briefly reviewed, with emphasis on the CERN Large Hadron Collider (LHC) and e^+e^- Linear Collider (CLIC). Results are based on realistic calculations from several studies, especially the 1987 La Thuile-CERN Workshop on Physics at Future Accelerators.

Much of activity has been recently devoted to explore the physics possibilities of next generation hadron and lepton colliders, in the TeV region[1-3]. Indeed the success of the standard $SU(3)\otimes SU(2)\otimes U(1)$ gauge theory of strong and electroweak interactions and, at the same time, its well known limitations suggest that the frontier of new physics has to be expected in the energy range up to the order of a TeV in the parton-parton centre of mass. Although one may look forward to major discoveries from experiments at present or next coming machines as the $Sp\bar{p}S$ collider, the Tevatron, the SLC, LEP and Hera, it is unlikely that some specific issues of and beyond the Standard Model, and foremost the problem of electroweak symmetry breaking, will be settled there.

Over the past few years several studies[1] have been undertaken in the USA to explore the physics possibilities of a 40 TeV c.m. energy Superconducting pp Supercollider (SSC). More recently the discovery potentials of a Large Hadron Collider

(LHC) in the LEP tunnel, at 16 TeV c.m. energy, with an e-p option at $\sqrt{s} \approx 1.8$ TeV, and of an e^+e^- linear collider (CLIC) at $\sqrt{s} \cong 2$ TeV have been investigated at CERN[4]. In these studies a comparison has been made of the physics interest and the feasibility of experiments at the three types of particle colliders, with nominal luminosities $L = 10^{33} (\rightarrow 10^{34})$ $cm^{-2}s^{-1}$ for the pp and e^+e^- options.

In the present talk I will review the main physics points emerging from the La Thuile-CERN Workshop. More detailed considerations, as well as specific questions on experimental instrumentation and machine performances, can be found in the Workshop's Proceedings[4].

Spontaneous symmetry breaking in the minimal Standard Model[5] leads to the existence of a single neutral Higgs boson. As well known, there is no precise prediction for its mass. One can, however, use arguments of self-consistency to get qualitative lower and upper bounds which usually place m_H in the range (10-1000) GeV, although there is no argument that m_H cannot be several TeV. For $m_H \gtrsim 1$ TeV, where weak interactions become strong, one has $\Gamma_H \approx m_H{}^3/2$, where Γ_H and m_H are in TeV units, and the particle identification becomes subtle. There is however hope to find the Higgs at LEP in the channels $ee \rightarrow ZH$ or $\theta(t\bar{t}) \rightarrow H\gamma$, provided the toponium θ is in the LEP range[7]. At future colliders experiments will be designed to detect the Higgs boson with $m_H \leq 0(1$ TeV) and either it will be discovered or the emergence of some new physics will be found.

Higgs production in pp collisions occurs via two dominant mechanisms, the gg and WW(ZZ) fusion (see Fig. 1)

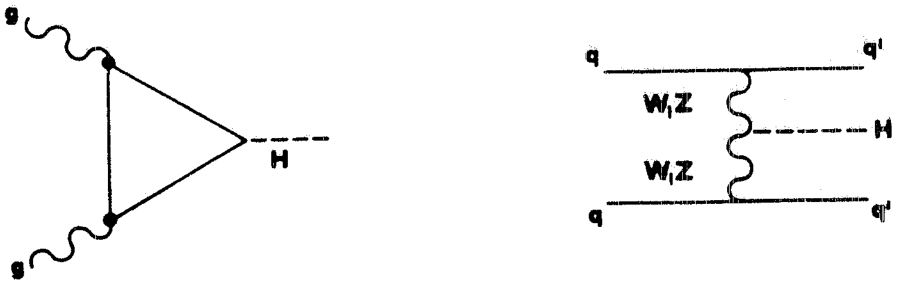


FIG. 1

The first[2,8] dominates for low m_H, and is very sensitive to the spectrum of the heavy particles which could contribute in the fermion loop, in particular to m_{top}. The latter can be computed[9,10] quite unambigously and dominates for large m_H. A large value of m_{top}, which is presently suggested by the large mixing effects observed[11] in the $B\bar{B}$ system, enhances sizeably the gg mechanism, as shown in Fig.2 [12]. Clearly the WW cross section, shown in Fig.3 [10] for various beam energies, represents a minimal reference value for future experiments, the actual H production rate depending critically upon m_{top}. The question of the actual detection of the Higgs, according to the value of its mass and the corresponding main decay modes, and the critical problem of distinguishing the signal from the QCD background, will be discussed later.

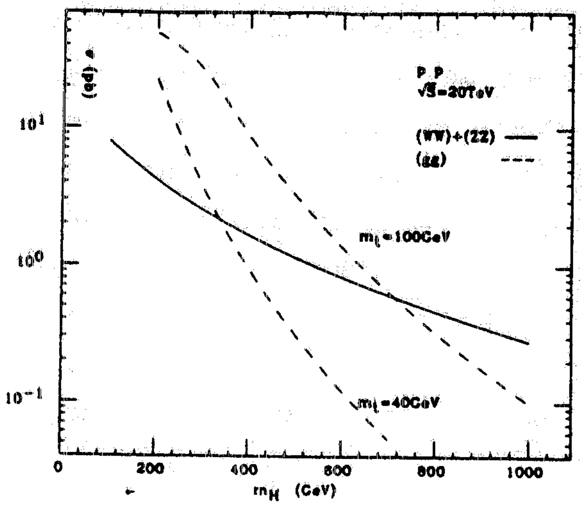


FIG. 2

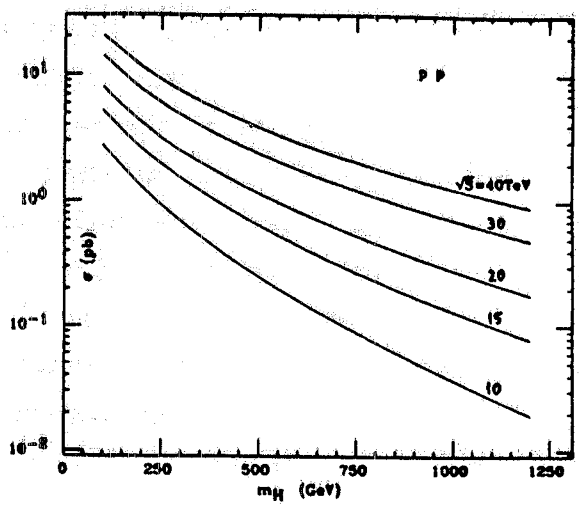


FIG. 3

In e^+e^- annihilation it is important to note that all cross sections can be computed precisely and they fall into two categories, according to their energy dependence. The first includes all processes that are mediated by an s-channel γ or Z and fall like s^{-1}, as the $\mu^+\mu^-$ cross section $\sigma_{point} \approx 10^{-1} \times$ pb/s(TeV^2). A typical example is the reaction $e^+e^- \to Z \to ZH$, which is dominant at LEP energies[7]. The cross section for $e^+e^- \to W^+W^-$ at high energy is $\pi\alpha_W^2 \ln(s/M_W^2)/2s$, with $\alpha_W \equiv \alpha/\sin^2\theta_W$, and also falls. On the other hand the cross sections which proceed through $\gamma\gamma$, WW or ZZ exchanges are scaled by M_W^{-2} and increase logarithmically with s, as for example $\sigma(e^+e^- \to \nu\bar{\nu}H) \approx \alpha_W^3 \ln(s/M_H^2)/16M_W^2$. They are shown in Fig. 4 [12,13].

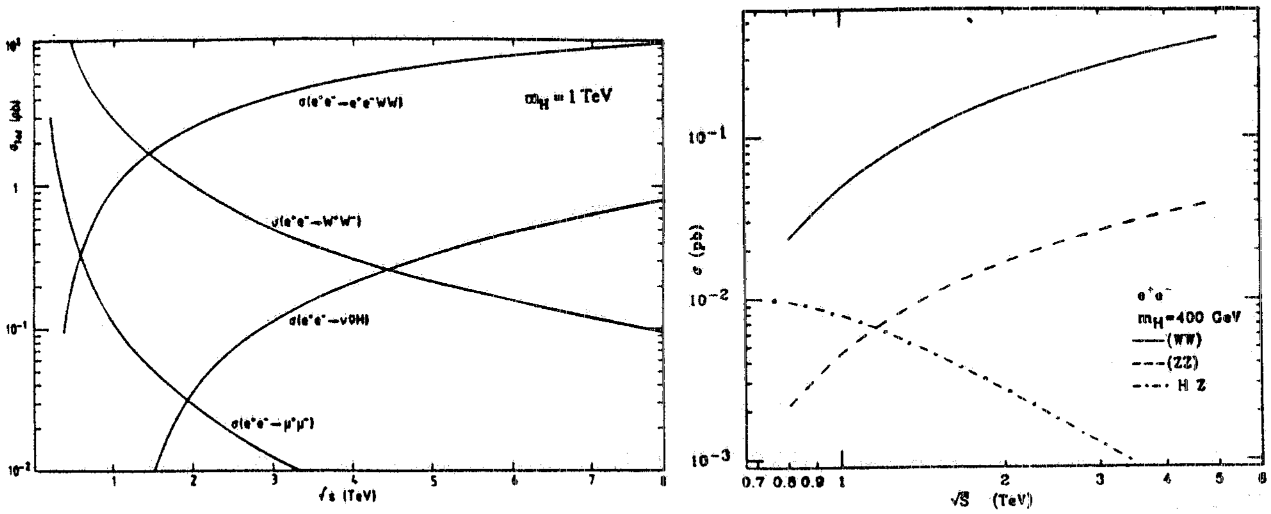


FIG. 4

The WW fusion mechanism has been studied estensively, particularly when $M_H>2M_W$. Previous estimates[9] in the real W approximation, where one calculates WW→WW for real W's, folding thereafter with the W structure functions - similarly to the Weizsäcker-Williams approximation - have been recently implemented by exact calculations[10]. In particular, exact expressions have been derived for the differential cross sections with respect to the Higgs trimomentum, which are relevant for the background separation. For example the Higgs p_T distribution $d\sigma/dp_T$[10], shown in Fig. 5, is peaked near $p_T \approx m_W$ for all values of $\sqrt{s}$ and m_H of interest. This feature plays an important role in the separation of the Higgs signal from the $\gamma\gamma$ background ($\gamma\gamma \to WW$) which is concentrated at $p_T \approx 0$.

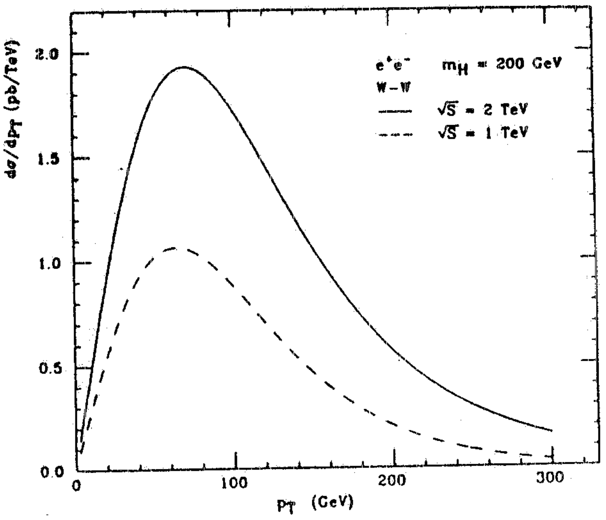


FIG. 5

In case of a "light" Higgs ($M_Z<m_H<2M_W$), when the dominant decay mode is into heavy quarks $H \to Q\bar{Q}$, (Q = b/t for $m_H</>2m_t$), e^+e^- annihilation is practically the only viable mechanism for observing the Higgs. Indeed the peaking of the p_T-distribution as $p_T \approx m_W$, mentioned above, allows a clear separation of $H \rightarrow Q\bar{Q}$ from the $Q\bar{Q}$ pairs produced through $\gamma\gamma$ and γW fusion - which is the most relevant background - peaked at $p_T \approx 0$. This is shown in Fig. 6. On the contrary the detection is almost impossible in pp collisions, because of the overwhelming QCD background from $gg \rightarrow Q\bar{Q}$[14]. Some rare decay mode ($H \rightarrow \gamma\gamma$, $\tau^+\tau^-$) have been envisaged to overcome the problem, particularly at SSC energies, but the detection limitations are very severe. Therefore an e+e- collider is the ideal facility for the discovering of a "light" Higgs.

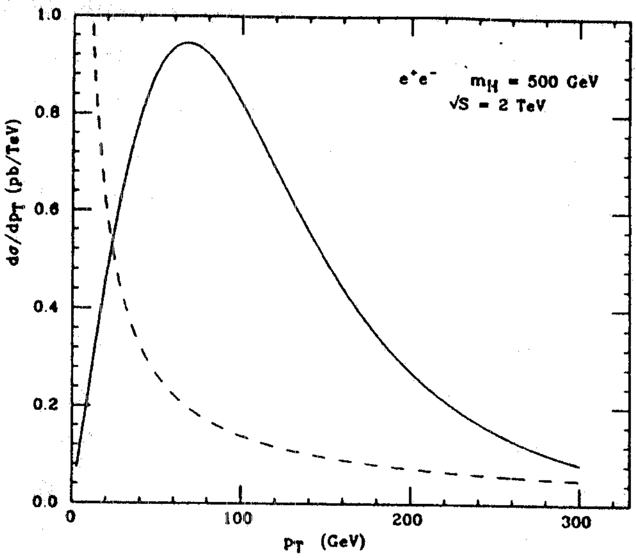


FIG. 6

When $m_H > 2m_{W,Z}$, as well known, the main decay modes are $H \rightarrow WW, ZZ$ with $\Gamma(H \rightarrow WW)/\Gamma(H \rightarrow ZZ) = 2$, with $\Gamma H \approx m_H^3/2$ for $m_H \gg 2m_W$. In pp collisions the production cross sections are comfortably large, as discussed above and explicitly shown in Fig. 3. The main problem is the background and here the value of the energy plays an important role. Indeed, for SSC, one can clearly use the fully leptonic decay mode $H \rightarrow ZZ \rightarrow 2l\bar{l}$, reaching a discovery limit of $m_H \lesssim 1.2$ TeV. At LHC, on the contrary, this decay mode is not enough and a limit of only $m_H \lesssim 0.6$ can be obtained through the channel $H \rightarrow Z \rightarrow \nu\bar{\nu} + e\bar{e}(\mu\bar{\mu})$. On the other hand, the QCD background in the mixed channels Wjj or Zjj or even the ZZ production with subsequent decay $t \rightarrow b+W$, when $m_t > m_W$, are extremely hard to beat. The only hope of detecting heavy Higgs in the hadronic final states is restricted to the possibility of realizing an efficient system of tagging the outgoing quarks, after the emission of the W's or Z's producing the Higgs by fusion.

In e^+e^- annihilation the detection of the W's or Z's in the jet-jet mode, possible because of the absence of serious background problems, compensates the lower absolute production rates. The luminosity is the only crucial parameter which fixes the upper bounds of the discovery limits. Indeed, for $L=10^{33} (10^{34}) cm^{-2}s^{-1}$ one gets $m_H \lesssim 0.7$ (1.1) TeV. Luminosity is also crucial for the detection of possible charged Higgs bosons, which are almost an impossible task for pp machines. Indeed "normal" charged Higgs, i.e. those expected in a natural supersymmetric extension of the Standard Model, do not couple as $H^{\pm}W^{\mp}Z$ or $H^{\pm}W^{\mp}\gamma$ at the tree level. Therefore the production rates in pp collisions are quite low and impossible to compete with the QCD background. In e^+e^- annihilation H^+H^- pairs can be produced via γ or Z exchange or via $\gamma\gamma$, and if $m_{H^{\pm}}$ is not to close to m_W - the reactions $e\bar{e}\rightarrow W^+W^-$ or $\gamma\gamma W^+W^-$ are otherwise a serious problem - one can reach a limit[12] $m_{H^{\pm}} \lesssim 0.8\ E_{beam}$ for $L \geq 10^{33}$ $cm^{-2}s^{-1}$.

The production and detection of heavy quarks and leptons of sequential type in the S.M. has been studied extensively and does not pose any problem. The heavy leptons (quarks) are expected to decay into W and $\nu(q')$ and can be revealed up to about 0.5 TeV (0.8 TeV) and 0.8 TeV (0.8 E_{beam}) in LHC and CLIC respectively[12,17]. These upper limits are slightly higher for SSC.

The study of the physics possibilities of LHC and CLIC in a framework going beyond the Standard Model has been confined[18] to a few topics - Supersymmetry, Additional Neutral Z' Bosons, Compositness and Leptoquarks - also for complementarity to previous studies[1,3]. Some general detector characteristics have been assumed, which include energy and momentum resolutions, granularity and angular coverage of the detector. The analysis performed by the study groups[18] cover a variety of cases which is hard to summarize shortly. We will just mention here a few illustrative examples, giving emphasis, in particular, to physics possibilities of CLIC.

The LHC machine can only produce sparticles with masses 0(1) TeV with observable cross sections if they are strongly interacting, i.e. squarks or gluinos. Furthermore, because of the high and difficult background situation for jets, a number of different topological cuts have to be applied, leading[18] to a bound of about 1 TeV for the sparticle masses. The SSC could reach out to ≈1.5 TeV. In Fig. 7 we show a typical distribution[19] for the process $pp \to \tilde{g}\tilde{q}$ assuming $m_{\tilde{g},\tilde{q}} \cong 300$ GeV and the decay modes $\tilde{g} \to \tilde{q}\bar{q}$, $\tilde{q} \to q\tilde{\gamma}$. Similarly in Table I a comparison of the expected SUSY signal/QCD background is reported[18,19].

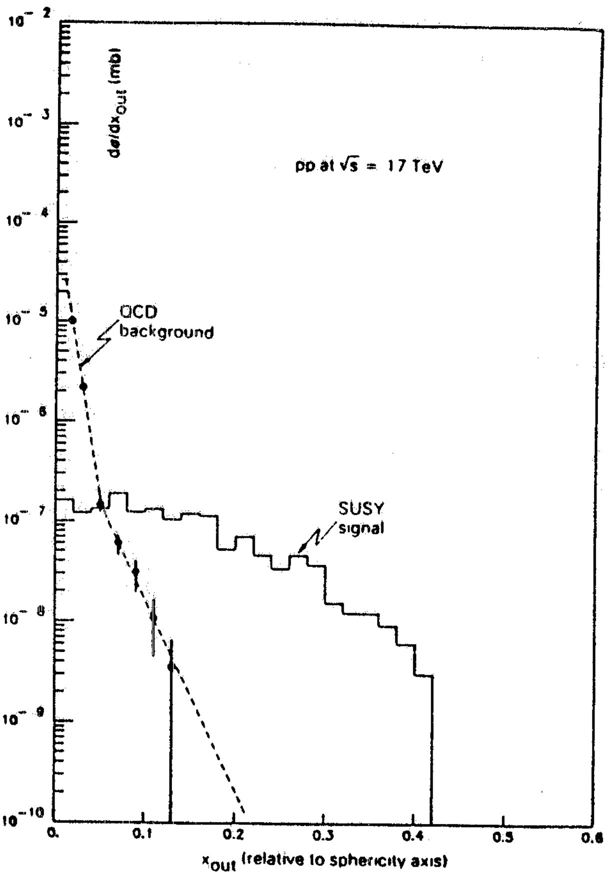


FIG. 7

TABLE I

Sparticle masses (GeV)		σ (mb)	Signal/background ratio (% of signal retained)			
$m_{\tilde{g}}$	$m_{\tilde{q}}$		No cut	$\not{E}_T > 200$ GeV	$x_E > 0.24$	$x_{out} > 0.08$
210	483	0.59×10^{-5}	0.21	13 (7.6%)	8.7 (6%)	94 (29%)
315	285	1.84×10^{-6}	0.06	21 (42%)	14 (31%)	58 (50%)
350	805	0.47×10^{-6}	0.21	5 (27%)	4 (11%)	17 (32%)
525	475	1.3×10^{-7}	0.06	3.3 (63%)	4.2 (41%)	9 (54%)
700	1610	0.74×10^{-8}	3.4×10^{-3}	0.27 (65%)	0.1 (12%)	0.54 (40%)
1050	950	1.92×10^{-7}	8.4×10^{-2}	0.75 (80%)	0.1 (52%)	0.2 (68%)

Supersymmetric events are in general much cleaner at CLIC, where all heavy, electroweakly interacting sparticles, including sleptons can be produced. The cross sections are generally small, since for producing a generic spin-0 $s\bar{s}$ one has

$$R \equiv \sigma(e^+e^- \to \gamma \to s\bar{s})/\sigma(e^+e^- \to \gamma \to \mu\bar{\mu}) = 1/4 Q_s^2 N_c \beta^3,$$

where $\beta = p/E$, Q_s is the charge of s and N_c is the number of colours it has (one for sleptons, three for squarks). The standard pointlike cross section $\sigma(e^+e^- \to \gamma \to \mu\bar{\mu}) = 4\pi\alpha^2/3s = 87$ fb/[s(TeV^2)] gives 220 $\mu\bar{\mu}$ pairs per year at $\sqrt{s}=2$ TeV, for $L = 10^{33}$ cm^{-2}s^{-1}. Some typical cross sections[18] for $e\bar{e} \to$ sparticles are shown in Fig. 8, including Z and γ exchanges. To do some reasonable physics one needs $L = 4\text{x}10^{33}$ cm^{-2}s^{-1} at $\sqrt{s} = 2$ TeV, corresponding to ~10^3 $\mu\bar{\mu}$/year.

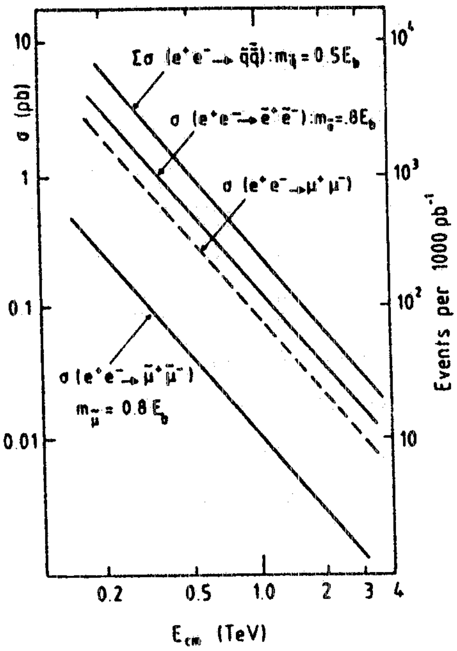


FIG. 8

The characteristic signature of supersymmetric particle pair-production is events with missing energy, missing transverse and total momentum, and dijet or dilepton final states which are acollinear and acoplanar. A typical example[20] is shown in Fig. 9, where the signal for $e^+e^- \to \mu^+\mu^-$ is compared to the background. In general, it can be concluded that CLIC, with an integrated luminosity of about 50 fb^{-1} at $\sqrt{s} = 2$ TeV, would allow detection of almost all sparticles with electroweak couplings in the mass range of 500 to 850 GeV.

Many different possible additional neutral gauge bosons Z' occur in different models. Some have been considered in previous studies[1]. Superstring inspired models[21] include extra U(1) subgroups, in addition to the Standard Model $SU(3)\otimes SU(2)\otimes U(1)$ and therefore predict one or two new Z' with masses $\lesssim$ 1 TeV. With a certain ambiguity on the models and the corresponding Z' couplings, some illustrative examples[22] for the production cross-sections and the total widths of the Z' are shown in Fig. 10 for pp collisions. One can clearly probe for a high-mass Z' at the LHC, but CLIC could be used as a Z' factory to study its properties in great detail. This example explicitly shows the complementarity of the two machines.

A concise and schematic summary[12,18] of the discovery potentials of the two machines, including also some limits obtainable with the LHC ep option, are finally shown in Tables

II-III. It is clear that LHC represents the most natural continuation of the actual physics programmes at CERN and Fermilab, but it cannot compete with the physics expectations from SSC. On the other hand a future high energy e^+e^- collider, with a luminosity $L \gtrsim 10^{33}$ $cm^{-2}s^{-1}$, could offer additional exiting results which are certainly required for a full elucidation of new phenomena in the TeV energy region.

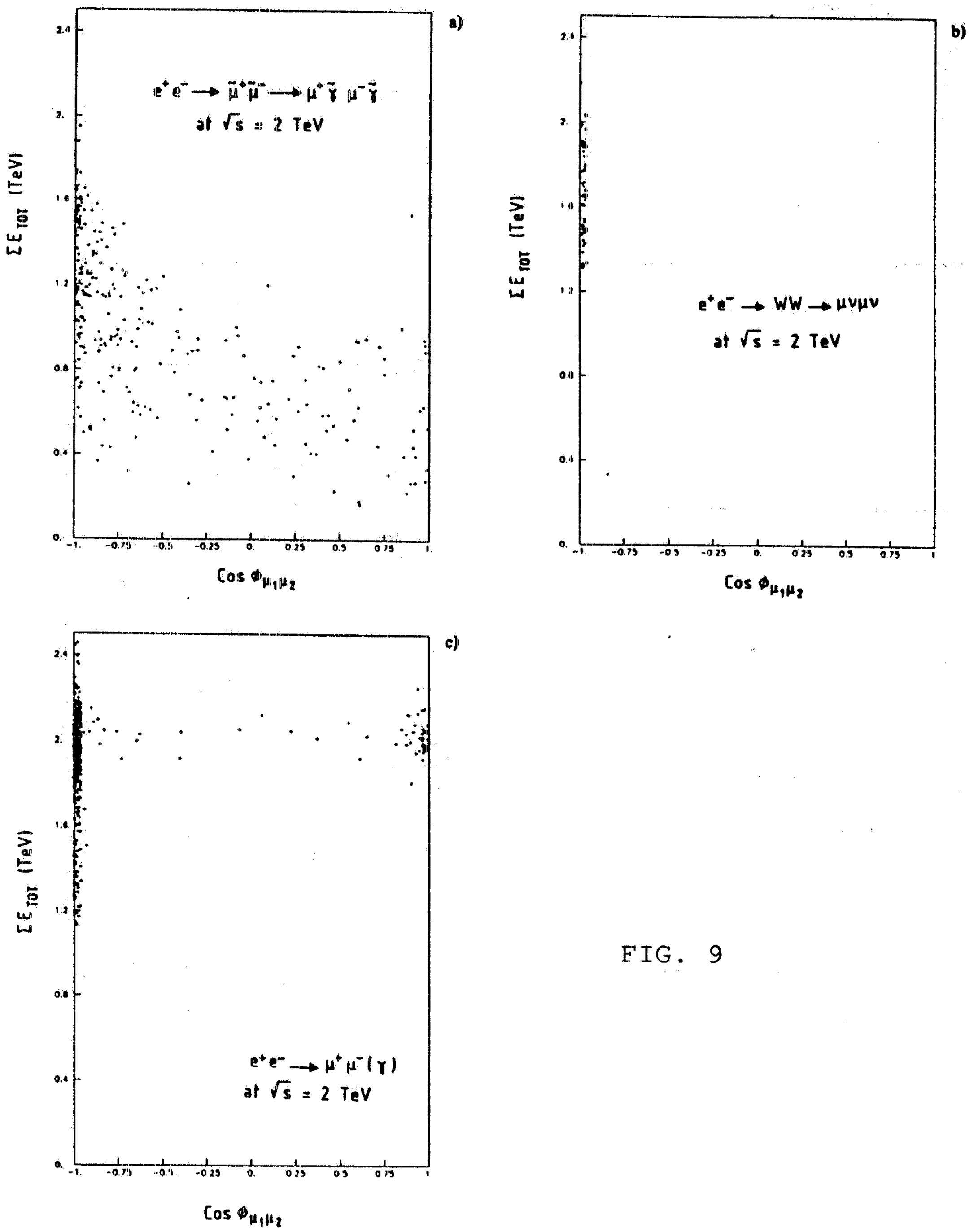


FIG. 9

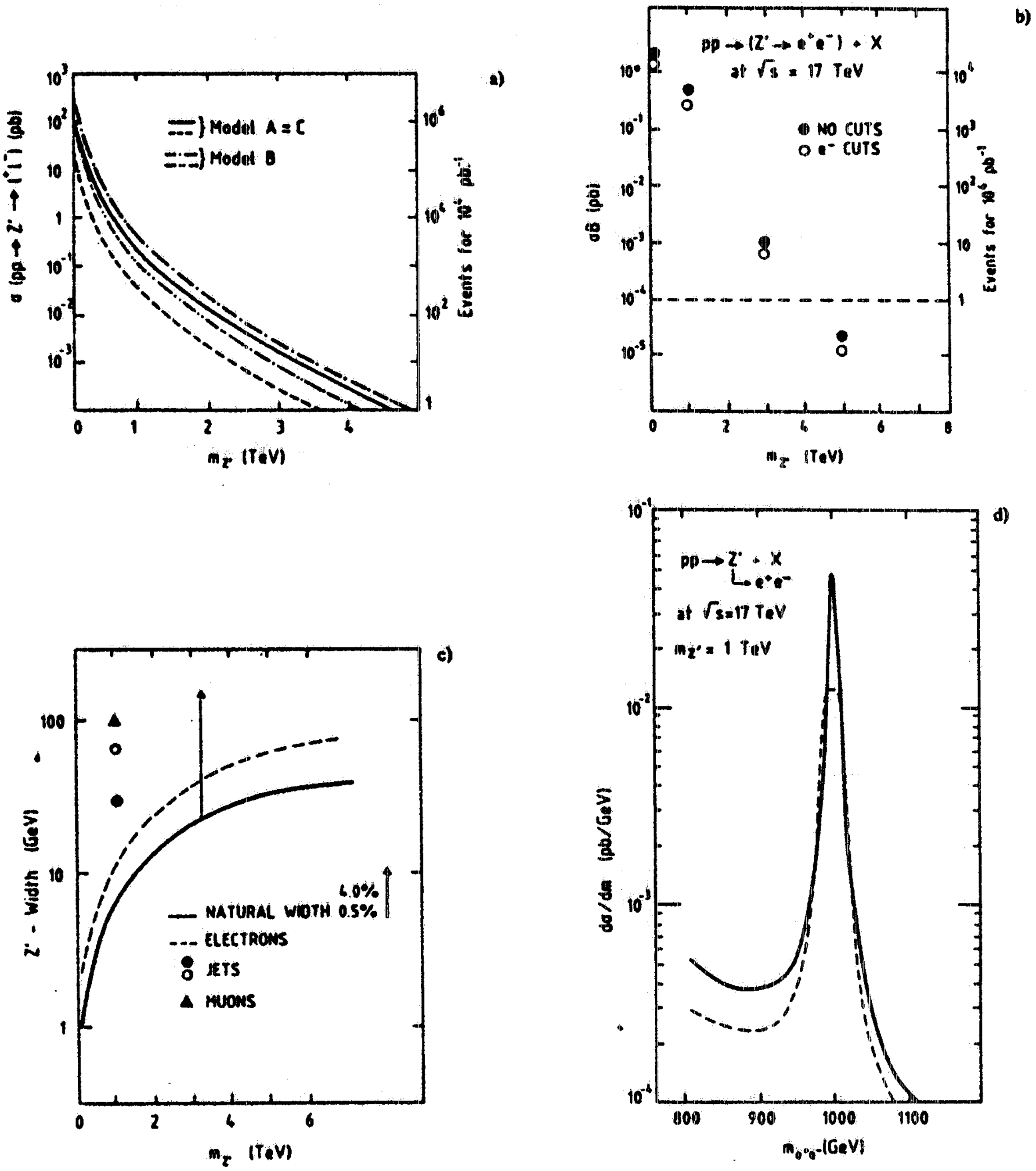
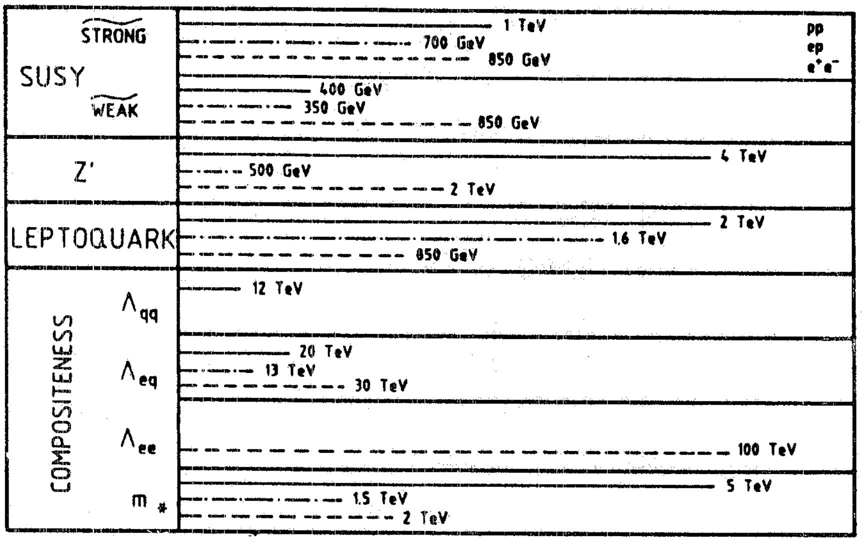

a)
σ (pp → Z' → l⁺l⁻) (pb)
Events for 10⁴ pb⁻¹
Model A = C
Model B
m_Z' (TeV)
b)
pp → (Z' → e⁺e⁻) + X
at √s = 17 TeV
NO CUTS
e⁻ CUTS
σB (pb)
Events for 10⁴ pb⁻¹
m_Z' (TeV)
c)
Z' - Width (GeV)
4.0%
NATURAL WIDTH 0.5%
ELECTRONS
JETS
MUONS
m_Z' (TeV)
d)
pp → Z' + X
↳ e⁺e⁻
at √s=17 TeV
m_Z' = 1 TeV
dσ/dm (pb/GeV)
m_e⁺e⁻ (GeV)

FIG. 10

TABLE II

	CLIC	LHC
Intermediate-mass Higgs: $m_Z < m_H < 200$ GeV $H \to Q\bar{Q}$ (Good up to $m_H < 300$ GeV)	Yes $\sqrt{s} \approx 1$ TeV also good ($L \approx 10^{32}$ cm^{-2}s^{-1} → marginal, $L \approx 10^{33}$ OK)	No (SSC: No)
Heavy Higgs: $m_H > 200$ GeV $H \to WW$ $H \to ZZ$	Yes $H \to 4$ jets, $m_H < 0.6$–0.8 TeV (If $L = 10^{34}$ cm^{-2}s^{-1}, $m_H < 1$-1.2 TeV: luminosity crucial)	Yes $H \to ZZ \to$ $\to \nu\nu + e^+e^-, \mu^+\mu^-$, $m_H < 0.6$ TeV ($m_H < 1$ TeV with quark tagging), SSC: $m_H < 1$-1.2 TeV, $\sqrt{s}$ crucial.
Charged Higgs: $H^+ \to t\bar{b}$	Difficult: $\sqrt{s} = 2$ TeV 60 ev. per year $\sqrt{s} = 1$ TeV 250 ev. per year. May be possible for $2m_W < m_H < 0.8E_{beam}$, Large m_H better; Luminosity crucial.	No (SSC: No)
Heavy leptons: $L \to \nu W$	$m_L < 0.8E_{beam}$ Possible $\sqrt{s} = 1$ TeV: better S/B	Possible $m_L < 0.5$ TeV (SSC: 0.7 TeV)
Heavy u,d quarks: $Q \to qW$	Yes (easy) $m_Q < 0.8E_{beam}$ Large m_Q better	6 Jets: No 4j + $\ell\nu$: Promising $m_Q < 0.8$ TeV (SSC: 1 TeV)

TABLE III



REFERENCES

1. Proc. 1982 Summer Study on "Elementary Particle Physics and Future Facilities", Snowmass, Colo., (1982), eds. R. Donaldson, R. Gustafson and F. Paige (AIP, New York, 1983); Proc. 1984 Summer Study on the "Design and Utilization of the Superconducting Super Collider", Snowmass, Colo., (1984), eds. R. Donaldson and J. Morfin (AIP, New York, 1985); Proc. 1986 Summer Study on the "Physics of the Superconducting Super Collider", Snowmass, Colo., (1986), eds. R. Donaldson and J. Marx, in preparation; Supercollider Physics, Proc. Oregon Workshop on "Super High Energy Physics", Eugene, Oregon (1985), ed. D.E. Soper (World Scientific, Singapore, 1986).
2. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579.
3. Proc. ECFA-CERN Workshop on a "Large Hadron Collider in the LEP Tunnel", Lausanne and CERN (1984) ed. M. Jacob (ECFA 84/85, CERN 84-10, Geneva, 1984).
4. Proc. of the Workshop on "Physics at Future Accelerators", La Thuile-CERN (1987), CERN 87-07.
5. S.L. Glashow, Nucl. Phys. 22 (1961) 579; S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264; A. Salam, in Proc. of the 8th Nobel Symposium, ed. N. Svartholm (Almquist and Wiksell, Stockholm 1968) 367; S.L. Glashow, J. Iliopoulos, L. Maiani, Phys. Rev. D2 (1970) 1285, G. 't Hooft, Nucl. Phys. B33 (1971) 173 and B35 (1971) 167.
6. M. Veltman, Acta Phys. Pol. B8 (1977) 475; B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. D16 (1979) 1519; J.J. Van der Bij and M. Veltman, Nucl. Phys. B231 (1984) 205; J.J. Van der Bij, Nucl. Phys. B161 (1985) 341; M.B. Einhorn, Nucl. Phys. 264B (1984) 75; P.Q. Hung and H.B. Thacker, Phys. Rev. D31 (1985) 2866; R. Casalbuoni, D. Dominici and R. Gatto, Phys. Lett. 147B (1984) 419 and 155B (1985) 95, Nucl. Phys. B282 (1987) 235; M.S. Chanowitz and M.K. Gaillard, Phys. Lett. 142 (1984) 85, Nucl. Phys. B261 (1985) 379; M.S. Chanowitz, Berkeley preprint LBL-21973 (1986) presented at the 23rd Int. Conf. on "High Energy Physics", Berkeley (1986); M.S. Chanowitz, Les Rencontres de Physique de la Vallée d'Aoste, La Thuile, March 1987, ed. by M. Greco (Editions Frontières).

7. For reviews of LEP/SLC Physics, see for example: Proceedings of the "1978 LEP Summer Study", CERN 79-01 (1979); "Cornell Z^0 Theory Workshop", February 1981; M.E. Peskin and S.H. Tye editors; SLC Workshop, SLAC Report 247 (1982); Workshop on "Radiative Corrections in $SU(2)_L$ xU(1)", Trieste 1983, B.W. Lynn and J.F. Wheater editors; Conference on "Tests of Electroweak Theories", Trieste 1985, B.W. Lynn and C. Verzegnassi editors; Physics of LEP, ed. by J. Ellis and R. Peccei, CERN 86-02 (1986).
8. H.M. Georgi et al., Phys. Rev. Lett. 40 (1978) 692.
9. R. Cahn and S. Dawson, Phys. Lett. 136B (1984) 196; E 138B (1984) 464. See also D. Jones and S. Petcov, Phys. Lett. 84B (1979) 440 and Z. Hioki, S. Midorikawa, and H. Nishiura, Prog. Theor. Phys. 69 (1983) 1484. For the effective *W* approximation see M. Chanowitz and M. Gaillard, Phys. Lett. 136B (1984) 196; S. Dawson, Nucl. Phys. B29 (1985) 42; G. Kane, W. Repko, and W. Rolnick, Phys. Lett. 148B (1984) 367.
10. G. Altarelli, B. Mele and F. Pitolli, Nucl. Phys. B287 (1987) 285.
11. ARGUS Collaboration, D.G. Cassel at the Rencontres de Physique de la Vallée d'Aoste, La Thuile, March 1987, ed. by M. Greco (Editions Frontières).
12. G. Altarelli et al., The Standard Theory Group, ref. 4.
13. G.L. Kane and J.J.G. Scanio, CERN-TH 4532/86 (1986).
14. M. Greco, Phys. Lett. 156B (1985) 109; J.F. Gunion, Univ. California Davis preprint UCD-86-39 (1986).
15. J.F. Gunion et al., Phys. Rev. D34 (1986) 181.
16. J.F. Gunion, Z. Kunszt and M. Soldate, Phys. Lett. 163B (1985) 389, E168B (1986) 427; W.J. Stirling, R. Kleiss and S.D. Ellis, Phys. Lett. 163B (1985) 261; J.F. Gunion and M. Soldate, Phys. Rev. D34 (1986) 826.
17. D. Froidevanx, ref. 4.
18. J. Ellis and F. Pauss, Beyond the Standard Model, ref. 4.
19. A. Savoy-Navarro and N. Zaganidis, ref. 4. See also S. Dawson and A. Savoy-Navarro in Proc. Snowmass '84, ref. 1.
20. C. Dionisi and M. Dittmar, ref. 4.
21. For reviews see J. Ellis, preprint CERN-TH 4439/86 (1986; H.P. Nilles, preprint CERN-TH 4444/86 (1986); L.E. Ibáñez, preprint CERN-TH 4459/86 (1986).
22. P. Bagnaia, ref. 4.